### The Super-Bigbite Spectrometer for Jefferson Lab Hall A

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#### Abstract

A Super-Bigbite spectrometer is proposed for Hall A at Jefferson Lab. Based on an existing dipole magnet and modern tracking device, the spectrometer will provide momentum resolution of 1% at 8 GeV/c and solid angle up to 70 msr. Starting with the proton electric form factor experiment the spectrometer will find application in a wide physics program with the 11 GeV beam in Hall A. The physics considerations for several key experiments are outlined. In this report we describe the concept of main components of the apparatus, the calculations of the detector rates, and the plan of implementation for three high momentum transfer nucleon form factor experiments.

## Chapter 1

## Introduction

A vigorous physics program is expected with the 12 GeV cw electron beam at TJNAF [1]. Doubling the CEBAF energy will increase the achievable 4-momentum transfer,  $Q^2$ , in elastic electron-nucleon scattering to 18 GeV<sup>2</sup>. Separated proton form factors will be measured to 15 GeV<sup>2</sup>, almost twice that achieved with the present accelerator. Even more dramatic advances will be in the studies of deepinelastic scattering and semi-inclusive deep-inelastic scattering, where the kinematics will be well into the scaling regime.

#### **1.1 The Super-Bigbite Spectrometer**

The JLab accelerator will be capable of delivering beams of up to 85  $\mu$ A, which corresponds in some experiments to luminosities up to 10<sup>39</sup> electron/s-nucleon/cm<sup>2</sup><sup>1</sup>. The JLab detectors in the four experimental halls have a variety of solid angles: on the one hand about 4-6 msr for focusing magnetic spectrometers (HRS, HMS, SHMS), and on the other hand several sr for CLAS, CLAS12 and GlueX. The maximum luminosity is significantly limited for the large acceptance detectors to the level of  $10^{35}$  cm<sup>-2</sup>s<sup>-1</sup> in the case of CLAS12 and much lower for CLAS and GlueX. **The Super-Bigbite Spectrometer, SBS, will provide an intermediate value of the solid angle of 70 msr, with a detector package which will be capable of operating at the largest possible luminosity.** Such parameters will allow SBS to be used in a set of optimized experiments described in Chapter 6.

Small cross sections for the most interesting channels put severe constraints on the maximum momentum transfer in actual experiments and require optimization of the experimental apparatus. Use of large solid angle detectors is the approach chosen in the CLAS12 and GlueX 12 GeV. It is important to optimize between the cost of running, which is defined mainly by the duration of the experiment, and the cost of construction of a specialized setup. When the beam-on-target time for an experiment approaches several months, a specialized setup provides a cost effective approach if it allows data to be collected several times faster. The magnet and the detector package of SBS present a flexible kit, from which specialized setups can be arranged for a number of important experiments.

#### **1.2** Concept of the spectrometer

Designing a high momentum magnetic spectrometer at small scattering angle presents a known challenge and always leads to restriction of the solid angle. For example, the HRS spectrometer has a

<sup>&</sup>lt;sup>1</sup>abbreviated below as cm<sup>-2</sup>s<sup>-1</sup>

solid angle of 6 msr and a minimum angle of  $12.5^{\circ}$  [2]. A significantly smaller central angle of  $6^{\circ}$  was achieved by means of the septum magnet, but with a solid angle reduced to 4 msr. The concept of the spectrometer proposed here is based on recent advances in tracking detector technology, namely GEM chambers [3], which allows tracking detectors to be used at a luminosity of  $10^{39}$  cm<sup>-2</sup>/s in direct view of the target and at a relatively short distance of several meters. This novel tracker, in addition to the high rate capability, also provides a superior spatial resolution, 70  $\mu$ m. Such resolution, combined with the modest momentum resolution of 1% required for a large set of experiments, allows planning for a magnet with a relatively small field integral, several Tesla-meter, which will achieve a large solid angle. An iron dominated magnet can easily provide a 2-3 Tesla-meter field integral with a horizontal field direction, Such a magnet can be used at small angles relative to the incident beam with a cut made in the mid-plane of the yoke to achieve small angles without loss of field quality in the dipole gap.

This document extends a previous report [4] and presents more detailed parameters of the SBS spectrometer, construction aspects, and a background Monte Carlo (MC), and shows that the SBS will be usable over a wide range of studies from exclusive scattering, to DIS, and to SIDIS. The document is divided into a number of chapters and a set of appendices with more detailed descriptions of the components as follows.

In Chapter 2 we give an overview of the equipment to be constructed. In Chapter 3 the magnet parameters and technical considerations are presented. In Chapter 4 we describe parameters of the spectrometer (*i.e.*, magnetic optics, momentum and angular resolutions). In Chapter 5 we describe the results of several investigations of the detector counting rates in previous experiments at JLab and in GEANT based MC simulations. In Chapter 6 we summarize the physics goals of the proposed project. In the set of appendices we present the concept of the polarimeter, and details of the trackers, the calorimeters and the trigger electronics. The collaboration list, responsibilities, funding plans, and the project schedule are presented in Chapters 7 and 8.

### Chapter 2

## **Experimental Equipment**

The proposed instrumentation, that we refer to collectively as the Super Bigbite Project, includes a set of components that will be used in three different configurations for each of our measurements of  $G_E^n$ ,  $G_E^p$ , and  $G_M^n$ , respectively. In all cases, the design philosophy incorporates the use of large open-geometry detection, high-rate-handling capability through the use of GEM technology, and the ability to measure at relatively forward angles. We describe our proposed instrumentation below, including the various configurations in which they will be used for our three proposed measurements.

The design of the Super Bigbite apparatus draws extensively from many experiments. Included is E04-108, or GEp(3), an experiment that employs a significantly different design, but one that provides a crucial launching point for our present efforts. Of significant importance also is E02-013, the Hall A  $G_E^n$  experiment, during which the feasibility of the BigBite spectrometer and its open-geometry philosophy was thoroughly demonstrated. We also include E99-114, the Real Compton Scattering experiment in which a calorimeter was employed that can be viewed as the predecessor of BigCal.

The Super Bigbite Project also incorporates demonstrated experimental technologies that allow us to increase our relevant Figure-of-Merit for measuring electromagnetic form factors by one to two orders of magnitude over our previous efforts at JLab. Here we mention specifically the revolutionary development of GEM technology by the RD51 collaboration [5] and operational experience with the GEM-based tracker in COMPASS. Also of enormous importance is the use of a large dipole that has been modified so that the beam can pass through the yoke (the configuration similar to the so-called "Lambertson magnet" known in accelerator design). This permits us to place the magnet quite close to the target, resulting in very large angular acceptance at small scattering angles.

The proposed Super Bigbite apparatus is shown in Fig. 2.1 in the configuration for the GEp(5) experiment [6]. The key features of the apparatus are:

- The dipole magnet, which is an existing 48D48 used previously at BNL.
- Large solid angle (Table 2.1), which is 10-15 times larger than in focusing spectrometers, such as HRS/HMS/SHMS.
- Large momentum acceptance, from 2 GeV/c at nominal field settings.
- High luminosity capability, up to  $8 \times 10^{38}$  electron/s×nucleon/cm<sup>2</sup>, *e.g.*, in GEp(5).
- Small scattering angle capability, down to 3.5°, see Table 2.1.
- Full acceptance for the long target (up to  $y \approx \pm 20$  cm).

- Very good angular resolution,  $\sigma_{\theta}$ [mrad] = 0.14 + 1.3/p [GeV/c].
- Good vertex resolution,  $\sigma_u \approx 1-2$  mm.
- Good momentum resolution,  $\sigma_p/p = 0.0029 + 0.0003 \times p \,[{\rm GeV/c}].$
- High energy trigger threshold through the use of a hadron calorimeter.

$\theta_{central}$	Ω	Distance	Horizontal	Vertical
(degree)	(msr)	from target	acceptance	acceptance
		(meter)	(degree)	(degree)
3.5	5	9.5	± 1.3	$\pm 3.3$
5.0	12	5.8	$\pm 1.9$	$\pm 4.9$
7.5	30	3.2	$\pm 3.0$	$\pm 8$
15	72	1.6	$\pm 4.8$	$\pm$ 12.2
30	76	1.6	$\pm 4.9$	$\pm$ 12.5

Table 2.1: Super Bigbite solid angle vs. central angle.

The Super-Bigbite apparatus will be used in GEp(5) as a large-acceptance spectrometer, a Super Bigbite spectrometer (SBS). The plan is based on an existing, resistive coil dipole magnet, 48D48, available from Brookhaven National Laboratory. It will provide angular coverage up to  $\approx$ 70 msr, with a detector package that will be capable of operating at the largest possible luminosity, almost  $10^{39}$  electron/s×nucleon/cm<sup>2</sup>. The use of a simple dipole placed close to the target allows one to achieve the high acceptance in the spectrometer. Such an installation is possible by means of a deep cut through the iron yoke of the magnet for the beam line. The magnet deflects charged particles vertically and will be used with a field integral up to 2.5 T·m. The field in the beam line will be reduced to an acceptable level by specially developed magnetic shields. The relatively small bend angle is compensated for by the high coordinate resolution (70  $\mu$ m) of the front GEM-based chambers resulting in a momentum resolution of 0.5% at 8 GeV/c in GEp(5) with the 40-cm long LH<sub>2</sub> target. The GEM technology solves the main challenge of this spectrometer, the very high counting rates, allowing tracking at background rates even higher than those expected for the experiments presented here. **These features combined will give SBS at least a factor of 10 advantage compared with any existing or proposed spectrometer at Jefferson Lab for nucleon form-factor measurements.** 

An expert technical committee appointed by JLab management reviewed all aspects of the SBS in November of 2008. A comprehensive Conceptual Design Report (CDR) of the SBS was prepared for this review. The updated CDR document contains detailed parameters of the SBS spectrometer, descriptions of the design and construction plans for all SBS sub-systems, and results of background Monte Carlo (MC) simulations. The original and updated CDR and the technical committee reports are available on the web [15]. The magnet and the detector package of the SBS present a flexible ensemble from which specialized setups can be arranged for each of the three nucleon form-factor experiments.

In accordance with the recommendation from the review panel we modified the configuration of the trackers. A new configuration will use only one type technology, GEM, for the trackers. We also added a tracker in front of the BigCal. This one-dimensional two-plane tracker allows to reach a superior resolution in angular correlation between the electron and the proton scattering planes and an additional a factor of 10 suppression of the inelastic background.



Figure 2.1: A three-dimensional view of the proton arm in the GEp(5) experiment.

#### The components of the SBS for which this proposal is seeking the funds include:

- The magnet modification: a cut for the beam line in the yoke, a field clamp between the target and the magnet, and two new coils.
- The vacuum extension for the scattering chamber and vacuum pipe through the magnet.
- The magnet installation fixture, the support platform, the infrastructure for the power supply, the magnet cooling.
- Two large trackers for the polarimeter, the Second tracker, ST, and the Third tracker, TT, which will be constructed using GEM technology.
- The coordinate detector, CD, in front of the electron arm of GEp(5).
- A segmented hadron calorimeter to provide a trigger with a high energy threshold for GEp(5) and an efficient neutron detector with very good position resolution for the GMn and GEn(2) experiments.
- The trigger electronics for the GEp(5) experiment, which uses the angular correlation (two-body kinematics) between the elastically scattered electron and the recoil proton at the trigger level.

#### 2.1 Beam and targets

The electron beam parameters, such as energy, polarization, intensity and size, required for the Electromagnetic Form Factor (EMFF) measurements are all within the 12-GeV specifications, as shown in Table 2.2.

A critical component of the GEn(2) experiment is an upgraded polarized <sup>3</sup>He target [7]. The new target will be able to withstand beam currents in excess of  $80 \,\mu\text{A}$  (a factor of five increase) due to the use of a novel target-cell design that uses convection to ensure rapid mixing between the portion

of the target in the beam and the portion of the target in which the <sup>3</sup>He nuclei are polarized. The convection design has already been demonstrated in bench tests, and is key to taking full advantage of improvements in polarized <sup>3</sup>He technology that have taken place in recent years. Development of the target cell design and its instrumentation is the responsibility of the University of Virginia (G. Cates *et al.*). The target infrastructure will be upgraded by Hall A personnel.

The GEp(5) experiment will use a 40-cm long liquid hydrogen target. Such a target will fit inside the existing 100-cm diameter scattering chamber. The projected beam heat load is 800 W, which is below the routinely achieved parameters of the existing Hall A cryogenic target. A wide vacuum snout from the scattering chamber to the magnetic shield needs to be constructed. The snout will avoid a direct view of the detector from the beam-line vacuum pipe elements.

The GMn experiment [8] will use the 10-cm cryogenic targets of hydrogen and deuterium, which are standard equipment in Hall A.

#### 2.2 Magnet of Super-Bigbite

The magnet was chosen on the following considerations:

- Large aperture with aspect ratio, at least 2/1 (vertical to horizontal),
- Horizontal field direction,
- Beam path through an opening in the magnet return yoke,
- Modular design of the magnet yoke with a maximum component weight of 20 tons.

The selected dipole 48D48 is a warm coil magnet, with an  $\approx 3 \text{ T} \cdot \text{m}$  field integral at 4 kA excitation current. It was used at BNL for the fixed target program with the AGS and BNL management agreed to provide the magnet at transportation cost. This dipole will be used in the SBS spectrometer. Figure 2.2 shows a drawing of the magnet as it was used at BNL.

The vertical bend will be achieved by rotating the magnet by  $90^{\circ}$ , directing the magnetic field in the horizontal plane. Installation of the magnet at small angles is possible by implementing a deep cut in the iron yoke (see Fig. 2.3). The cut (which is parallel to the field lines in the gap) results in only a moderate distortion of the magnetic flux flow in the yoke and of the field distribution in the magnet gap. The right coil, which is closer to the beam line, needs to be modified to allow for the beam line path.

The magnet weighs 100 tons total. It consists of five iron slabs and can be assembled inside Hall A with the existing overhead crane. Figure 2.4 shows a design model of the SBS magnet at the pivot in Hall A.

experiment	energy	polarization	current	diameter
	(GeV)		(µA)	(mm)
GEn(2), E12-09-016	4.4; 6.6; 8.8	85%	60	0.5
GEp(5), E12-07-109	4.4; 11	85%	75	0.5
GMn, E12-09-019	4.4; 6.6; 8.8	none	25	0.5

Table 2.2: CEBAF beam parameters in the EMFF measurements.



Figure 2.2: An assembly drawing of the 48D48 magnet with its field oriented vertically, as it was used at BNL.



Figure 2.3: A conceptual view of the beam path through the dipole.

#### Magnet configuration for GEn(2) and GMn

The neutron form-factor experiments, GEn(2) and GMn, will use the 48D48 magnet to deflect the high energy protons for an unambiguous identification of the quasi-elastic electron-neutron events. In that case the field integral, Bdl, will be set to allow no more than a 5% admixture of protons in the neutron event sample, which results from the overlap of the proton and neutron distributions at the detector front face. A veto counter will be used to reduce the proton admixture in calibration runs. In the GEn(2) experiment, the required value of Bdl is 1.7 T·m, while in GMn it is only 0.8 T·m.



Figure 2.4: A three-dimensional view of the 48D48 magnet in Hall A.

#### Magnet configuration for GEp(5)

For the GEp(5) experiment, where only part of the full magnet aperture is required, two iron inserts will be placed inside the magnet. The inserts will collimate the acceptance to its required value, reduce the vertical size of the pole at the entrance, and reduce the gap between poles. Such an adjustment will not affect the field on the beam line, but it will increase the field integral to its desired level, with a spin rotation angle closer to the optimum value of  $90^{\circ}$ .

A new coil will be designed for the 2 kA current required for a field integral of 2.5 T·m, which will lead to much less saturation of the yoke. The resulting high magnetic permeability of the iron in the yoke is essential in limiting the magnetic field along the beam path through the yoke. The smaller coil current will also allow us to reduce the cross section of the conductor and increase the vertical aperture usable for the experiment to 150-160 cm. Additional information about the magnet and its field configuration can be found in the SBS Conceptual Design Report [15] on page 14.

#### 2.3 Trackers of the Super-Bigbite apparatus

Three trackers are required in the SBS for the GEp(5) experiment. The first tracker (FT) will be used to measure the proton momentum and its direction before interaction with the first  $CH_2$  analyzer. The second tracker (ST) will measure the proton track after the proton passes through the first  $CH_2$  analyzer. The third tracker (TT) will measure the direction of the track after the proton passes through the second  $CH_2$  analyzer.

At the FT we expect background hit rates of about 400 kHz/cm<sup>2</sup> (based on GEANT simulations) due to the direct view of the target [15]. This background is dominated by soft photons originating from the target. Low-momentum charged particles are swept away by the magnet. The rates on the second and third trackers are expected to be 130 kHz/cm<sup>2</sup> and 64 kHz/cm<sup>2</sup>, respectively, dominated by soft electrons/positrons produced by photons converting in the analyzers.

#### Front Tracker (INFN contribution)

The Italian members of the GEp(5) collaboration have the responsibility for the development and con-



Figure 2.5: The configuration of the Front tracker GEM chamber. The front-end-cards (FEC) are placed in the blue area at the perimeter of each read-out-board, ROB. Dark blue indicates a section where FECs are installed in the perpendicular plane, in the shadow of a 2-cm wide insensitive area of the chamber. The ROB is made of a double-layer PC board from two glued kapton foils with the copper strips in X/Y or U/V directions.

struction of the front tracker. They have obtained a four-year project approval of the funding institution (INFN) and have already started prototyping the detector and its electronics. This prototype with an active area of  $40 \times 50$  cm<sup>2</sup> will include two-dimensional read-out following three GEM amplification foil planes. The chamber structure is similar to the proven COMPASS design. The 2-D read-out patterns will be oriented along X/Y or U/V directions. As shown in Fig. 2.5, the direction of the X-strips is along the magnetic field, while the directions of the U/V-strips are  $\pm 45^{\circ}$  relative to X-strips. The maximum length of a read-out strip will be 56 cm. All GEM foils and the read-out boards for the trackers will be produced at CERN. The read-out-board (ROB) as well as the GEM foils, will be divided into three  $40 \times 50$  cm<sup>2</sup> sections, as shown in Fig. 2.5. A 2 cm gap between the ROBs will be used to house the front-end-cards (FEC). The FEC will be based on the APV25 analog pipeline chip, for which there is a considerable amount of expertise in the RD51 collaboration [5], in which INFN and the College of W&M are participants. The front-end cards will be developed by the INFN group for the FT and duplicated by the NSU collaborators for use in the other trackers. The total number of read-out channels in the FT will be approximately 49,000.

#### **Polarimeter Trackers**

The front tracker will be followed by a double polarimeter consisting of two trackers each preceded by a  $CH_2$  analyzer. The FT will define the initial proton track needed both for the determination of the proton momentum and for polarimetry. The ST measures the secondary particle after the primary proton scatters in the analyzer. The proton polarization components in the plane perpendicular to the initial trajectory will be determined from the azimuthal asymmetry of the secondary trajectory with respect to the initial one. The second  $CH_2$  block and the TT work in exactly the same way, analyzing the polarization of the protons not scattered in the first polarimeter or measuring for a second time the polarization of the scattered protons. Adding this second polarimeter increases the Figure-of-Merit by



Figure 2.6: The configuration of the polarimeter tracker GEM chamber. The chamber units are A,B,C,D, and E. The blue area around each unit will be used for the front-end-cards (FEC). The dark blue area between the chamber units is used for FECs installed in the plane perpendicular to the chamber plane.

a factor of 1.7, equivalent to a 30% reduction of the experimental statistical errors.

While the resolution of the FT must be high in order to achieve good momentum and angular resolutions, for the second and the third trackers we require an angular resolution sufficient to preserve the analyzing power of the polarimeter. This required resolution is approximately 1.5 mrad and is similar to the magnitude of multiple scattering in the analyzer.

The sizes of the polarimeter trackers are much larger than that of the FT, due to the larger distance from the target to the detector and the larger acceptance needed after the proton scatters in the analyzer. The dimensions of the ST and the TT were chosen to be  $50 \times 200$  cm<sup>2</sup> to keep the Figure-of-Merit above 90% of the ideal value (for trackers of unlimited size).

The ST and TT need to have only four chambers each (compared to the six in the FT) because of the reduced demand on coordinate resolution and the lower counting rates. Each chamber of the ST/TT will consist of five  $50 \times 40$  cm<sup>2</sup> sub-sections as shown in Fig. 2.6 (denoted A,B,C,D,E). These sub-sections will be similar to those in the FT. Two chambers in each tracker will have X/Y readout and the other two will have U/V readout. The total number of readout channels in ST and TT will be approximately 27,200.

#### 2.4 Hadron calorimeter

The EMFF experiments deal with very small cross sections, so for meaningful results the luminosity should be as high as possible. Arrangement of the trigger and the detector structure for the high luminosity should take maximum advantage of the high energy of the recoil nucleon. The energy of

the nucleon in the EMFF experiments ranges from 2 to almost 10 GeV, depending on the measurement. In GEp(5), the large energy of the proton will allow the use of a 3-4 GeV energy threshold in the calorimeter without a significant loss of detection efficiency. Such a high energy threshold leads to the suppression of pion triggering and opens the possibility of using a coincidence for the DAQ trigger. The hadron calorimeter also provides a good position resolution which will be advantageous in the data analysis.

#### Configuration in GEn(2)/GMn

The total active area of the HC will be  $5.5 \text{ m}^2$ , which is similar to that of the GEn(1) neutron detector. In spite of the longer path from the target to the detector, it will be sufficiently large thanks to the kinematical focusing of quasi-elastic nucleons at the large momentum transfer of the experiments. The hadron calorimeter has a good time resolution of 1.5 ns, high granularity ( $15 \times 15 \text{ cm}^2$ ), a very good coordinate resolution of 2 cm, and, in addition, a high energy threshold [9]. All these features make the HC an attractive neutron detector for the neutron FF experiments. The time resolution of a traditional scintillator plastic bar detector (for example, the one used in GEn(1)) is of order 0.5 ns, much better than the time resolution for a hadron calorimeter. However, even the 0.5 ns resolution of a scintillator plastic bar detector is not sufficient for the selection of the exclusive process by Time-of-Flight at the large neutron energies of the proposed experiment. Instead, the angular correlation between the momentum transfer and the neutron momentum will be used to select the exclusive process. For the HC, the energy threshold in the timing channel can be set as large as 1 GeV, much higher than 3 MeV, the value required in a neutron detector based on scintillator bars. This results in a reduction in background rate of two orders of magnitude . The coordinate resolution of the HC is 3-5 times better than that of the scintillator bar system of GEn(1).

#### **Configuration in GEp(5)**

The hadron calorimeter, HC, positioned at the end of the SBS detector package will be used to trigger the DAQ, in coincidence with the signals from the existing electromagnetic calorimeter, BigCal, used as the electron detector to register the elastic electron. In addition, these two calorimeters will provide coordinate information that will be used to locate the proton track in the FT and in the TT by applying kinematic constraints. The energy and coordinate resolutions of BigCal of about 5-7% and 7 mm, respectively, for 2.5 GeV electrons satisfy the trigger and tracking requirements. We expect 20% energy resolution and 2-cm coordinate resolution for 8 GeV protons in the hadron calorimeter. The active size of the HC in the GEp(5) experiment will be  $150 \times 300 \text{ cm}^2$ , which is a little smaller than its full size, and the total number of active modules will be 200. Detailed information on the design of the hadron calorimeter module can be found in the SBS Conceptual Design Report [15], page 94.

#### 2.5 Electron arm

In all three measurements in the EMFF experiment both the (quasi) elastically scattered electron and the recoil nucleon will be detected. This allows for the selection of the exclusive process, which has a very small cross section at high momentum transfer.

#### **BigBite spectrometer**

The existing Hall A BigBite spectrometer will be used for the detection of electrons in the GEn(2) and GMn experiments. In its most recent configuration (that was used for the polarized <sup>3</sup>He Transversity

experiments) BigBite included a tracker system based on Multi Wire Drift Chambers (MWDCs), a gas Cherenkov counter, and a double-layer lead glass shower counter. The MWDC tracker in the BigBite spectrometer cannot handle the expected high hit rate of about 60 kHz/cm<sup>2</sup> in the upcoming Super Bigbite EMFF experiments. Therefore, three of the chambers that will be used in the front tracker (FT) of the SBS, and two of the chambers that will be used in the second tracker (ST) of the SBS will comprise the tracker system in the upgraded BigBite spectrometer. This switch does not require any reconfiguration of the chambers, and the Cherenkov counter and the large double-layer shower detector will be used more-or-less as is.

#### Large Calorimeter BigCal

The existing BigCal calorimeter will be used in the GEp(5) experiment for detection of the scattered electron. The calorimeter has 1744 lead-glass blocks coupled to PMTs of type FEU-84. Two sets of blocks are used, one  $38 \times 38 \times 450$  mm<sup>3</sup> and the other slightly larger,  $40 \times 40 \times 400$  mm<sup>3</sup>. Blocks will be arranged in a matrix  $20 \times 76$ , a shape optimized for the largest acceptance at  $Q^2 = 14.5$  GeV<sup>2</sup>. The electronics for the calorimeter, including the custom-built summing modules, the HV supply, the FASTBUS ADC and TDC (which were used in the GEp(3) experiment) will be reused in the GEp(5) experiment. The calorimeter will be installed 3 m from the target at a central angle of  $39^{\circ}$  (at the largest  $Q^2$ ). It will be shielded from the target by a 20 cm Al plate to reduce the radiation dose on the lead glass. This also reduces the hit rate in the Coordinate Detector.

#### **Coordinate Detector for BigCal**

The angular correlation between the scattered electron and the recoil proton will be measured very accurately, especially the angle between the electron scattering plane and the proton recoil plane. Because of the small size of the electron beam, the angles of the electron and of the recoil proton can be determined with a very good accuracy of  $\sim 0.5$  mrad. This corresponds to a 5 MeV/*c* uncertainty in the perpendicular momentum balance. Such an uncertainty is much smaller than the typical out-of-plane momentum for inelastic events, 150 MeV/*c*, which results in a powerful suppression of the background. In order to achieve this, a 1 mm coordinate accuracy is required for the scattered electron. It will be provided by the Coordinate Detector, CD, with a two-plane GEM-based chamber. The subsections of this chamber will be similar to those of the polarimeter chambers. The overall dimensions are  $80 \times 300$  cm<sup>2</sup> with 6 sections in 2 vertical columns. The total number of the read-out channels in the CD is 12,000.

#### 2.6 Experimental trigger

For the EMFF experiments, we plan to re-use existing FASTBUS and VME electronics for BigBite and BigCal, whereas new, pipelined electronics will be used for all the GEM chamber read-outs and the hadron calorimeter read-out (when it is in the GEp(5) configuration). The DAQ trigger will have two levels: The first-level trigger will have a relatively short delay,  $\approx 100$  ns, relative to the particle detection. It will be generated by the electron arm. This signal is required for operation of the GEM read-outs; despite their pipelined architecture, the APV25 front-end chips used in the GEMs require a fast trigger for marking "interesting" samples [15]. Such a fast first-level trigger also eliminates the need for long delay lines for the conventional FASTBUS and VME electronics. The second-level trigger will be formed using a relatively complex coincidence logic, described below. It can have a latency of several microseconds. Please see section G for more information on the DAQ.

#### **Trigger in GMn and GEn(2)**

The Bigbite spectrometer is used as the electron arm in the GMn and the GEn(2) experiments. It has a gas Cherenkov counter and a two-layer shower calorimeter. This gives an efficient on-line selection of the electron so that the DAQ trigger rate will already be at the level of 2–3 kHz without requiring an on-line coincidence with the hadron arm.

#### Trigger in GEp(5)

The trigger is a critical part of the GEp(5) experimental design. Achieving a reasonable data rate in this measurement is particularly challenging given the high luminosity of  $8 \times 10^{38}$  cm<sup>-2</sup>/s with open detectors. To address this challenge, the trigger for GEp(5) will have two main features: (1) a high energy threshold in the calorimeters in both arms (3-4 GeV for the proton and 2.5 GeV for the electron); and (2) "smart" coincidence electronics based on Field-Programmable Gate Arrays (FPGAs) that allow second-level triggering on the spatial correlations of hits in the two detector arms.

The high energy thresholds will reduce the rate in the electron arm to 60 kHz and in the proton arm to about 1.5 MHz. With a coincidence time window of 50 ns, forming a simple coincidence between the two arms would result in a trigger rate of at least 5 kHz, which is too high (or at least close to the limit) for the expected total event size of  $\sim 20$  kB (see Section G). Noting that, in the GEp(5) experiment, the proton trajectory in Super Bigbite has a very small deflection, it becomes possible to use the angular correlation between the elastic electron and the proton trajectories, at the trigger level, to reduce the coincidence trigger rate further by a factor of five.

In designing our second-level triggering system, it is important to note that real (not noise) calorimeter hits always cause several adjacent blocks to fire. We therefore construct what we call "macroblocks", consisting of the sums of the individual signals from several nearby blocks. In HCAL, the size of the macroblocks is  $4 \times 4$  (we call this a "sum-16"), and in the ECAL the size is  $8 \times 4$  ("sum-32"). The different macroblocks overlap each other, such that each individual block contributes to the sums associated with several different (overlapping) macroblocks. In this way, at least one macroblock will always contain a large fraction of the deposited energy associated with a real hit. In the HCAL, we place the macroblock centers on a  $7 \times 17$  grid that is centered in the calorimeter region; hence, 119 "sum-16" sums need to be calculated. Similarly, the ECAL macroblock centers are placed on a  $4 \times 37$ grid, for a total of 148 "sum-32" sums.

To take advantage of the strong kinematic correlation between the electron and the recoil proton at the (second-level) trigger level, we need to quickly establish whether a hit in a given macroblock in one arm corresponds to a hit in a given macroblock in the other arm. For example, a given vertical hit position in the ECAL limits the vertical location of a possible coincidence hit in the HCAL to a relatively small region. This is illustrated in Figure 2.7 in which both HCAL and ECAL are shown, and the hits corresponding to a good coincidence are shown in pink. Another hit in ECAL corresponding to a correlation that is kinematically excluded is shown in green. To quickly establish whether or not to exclude a particular coincidence, the ECAL is sub-divided into four non-overlapping regions of  $4 \times 19 = 76$  macroblocks, and the HCAL is sub-divided into four overlapping regions of  $7 \times 7 = 49$ macroblocks. These regions are also illustrated in Fig. 2.7. The coincidence logic can then be realized with four FPGA modules with 76 + 49 = 125 input channels each. 128-input FPGAs are readily available commercially.

In practice, the "sum-32" ECAL signals will be formed by first forming sums of  $2 \times 4$  blocks with custom "sum-8" units, which provide amplification by a factor of 5, analog output to ADC, and four copies of the analog sum of the 8 inputs. A LeCroy fan-in unit will then be used to sum the "sum-8" signals to form the "sum-32" signals. These summing modules as well as discriminators for the



Figure 2.7: Illustrated is the configuration of the second-level trigger logic for the GEp(5) experiment. The electron arm has 148 "sum-32" signals (each comprised of a group of individual blocks) arranged in a  $7 \times 17$  matrix. The hadron arm has 119 "sum-16" signals arranged in a  $4 \times 37$  matrix. They are divided into four groups each and fed into four FPGA units to form the coincidence signal.

"sum-32" outputs are already available from previous experiments.

On the HCAL side, we plan to use the 250 MHz 12-bit pipelined flash ADCs ("FADC"), which have recently been developed by the JLab electronics group for GlueX, along with additional custom electronics to do the summing of the signals digitally. The FADCs store 2048 samples (8  $\mu$ s pipeline depth) and have 16 inputs each. The 200 HCAL channels thus require 13 FADC modules, which will fit into one VME crate. The data from these modules will be sent to a custom-built Crate Trigger Processor ("Smart HCAL") for digital summing. Because of bandwidth constraints, each FADC will only send the most significant 8 bits of its data (128 bits total) to the "Smart HCAL" every 16 ns, instead of the full 12 bits at the 4 ns digitization interval. This is still compatible with a 50 ns coincidence window, and the full time and amplitude resolution can be recovered from the FADC data offline. The "Smart HCAL" will then compute the required 119 "sum-16" digital sums and provide logical outputs for them on external connectors, corresponding to the four  $7 \times 7$  vertical subdivisions shown in Figure 2.7. In this way, the "Smart HCAL" module also handles the signal discrimination (via a programmable software threshold) and fan-out without additional hardware. The latency of this type of trigger formation is expected to be on the order of a microsecond.

The "sum-16" outputs from the "Smart HCAL" processor as well as the discriminated signals from the ECAL "sum-32" units will be sent, appropriately delayed, to the coincidence FPGA units

(CAEN v1495, 128 inputs each) to form the coincidence with the hadron arm requiring the geometrical correlation for elastic kinematic. Processing in the FPGAs will add roughly another microsecond to the overall trigger formation time. The total trigger latency will be substantially less than the shortest pipeline lookback time of 4.8  $\mu$ s of the APV25s in the GEM readout. We expect a five-fold reduction of the trigger rate with this scheme.

#### 2.7 Plan for the large GEM trackers

A cost-effective solution for large-area tracking in a high-rate environment is provided by the Gas Electron Multiplier (GEM) technology, invented by F. Sauli [3] in 1997. The GEM is based on gas avalanche multiplication within small holes (on a scale of 100  $\mu$ m), etched in a Kapton foil with a thin layer of copper on both sides. The avalanche is confined to the hole, resulting in very fast (about 10-20 ns rise time) signals. Several GEM foils (amplification stages) can be cascaded to achieve high gain and stability in operation. The relatively small transparency of the GEM foils reduces the occurrence of secondary avalanches in cascaded GEM chambers. All these properties result in very high rate capabilities, up to 100 MHz per cm<sup>2</sup>, and an excellent position resolution, 70  $\mu$ m. Figure 2.9 illustrates the principle of operation of a triple (three foils) GEM chamber. Triple GEM chambers have been successfully used in the COMPASS experiment at CERN for 5+ years now [10].

The sizes of the trackers have been optimized using Monte Carlo simulations. For the GEp(5) experiment the active area required for each GEM chamber in the polarimeter trackers is  $50 \times 200$  cm<sup>2</sup>. Since this is larger than the size of the GEM foils CERN can currently produce, we will construct each chamber by combining five  $40 \times 50$  cm<sup>2</sup> modules, the current "standard size". The GEM modules used for the large GEM trackers will be identical to the GEM modules of the Front Tracker described in Appendix B. Since the chamber modules are described in detail in that appendix, only a brief account is given here.

The SBS GEM chamber modules are modeled after COMPASS GEM chambers except for the larger active area of our chamber modules and the demanding compactness of the mechanical structure and electronics. The  $40 \times 50$  cm<sup>2</sup> GEM foils can be produced at CERN at modest cost. Furthermore, there are several large area GEM detector projects currently underway in the world [11, 12]. Over the last few years the Micro Pattern Gas Detectors (MPGD) group at CERN has conducted a considerable amount of research toward building large-area GEM detectors. Their new achievements in the perfection of the technology, if completed soon enough, will be applied to our chamber development. We will optimize the  $40 \times 50$  cm<sup>2</sup> GEM chamber units, as outlined below.

An assembly view of one chamber section is shown in Fig. 2.8. To provide a gain as large as 10,000, we will have three amplification stages. The chamber consists of a drift foil, three GEM foils and a readout board, all assembled on a layer of honeycomb material. The foils with an active area of  $40 \times 50$  cm<sup>2</sup> will be mounted on Permaglas TE630 frames with a frame width of 8 mm. The thin spacers indicated inside the frame are to maintain the rigidity of the frame and to ensure proper foil spacing. The width of the spacers will be less than 0.5 mm, and they will be located at GEM sector borders. Therefore they will contribute minimally to the non-active area of the chamber.

The read-out of the two first chambers of the ST and TT will be along the X and Y directions (0° and 90° with respect to the dispersive direction) while the read-out of the last two chambers will be arranged along U and V directions (45° and -45° with respect to the dispersive direction). The read-out boards will have strips with a pitch of 400  $\mu$ m chemically etched on a PC board, exactly as in the COMPASS GEM chambers. A 3D view of a read-out board is shown in Fig. 2.9. The sizes of the strips



Figure 2.8: Schematic assembly view of one GEM chamber section.

Figure 2.9: Top: Principle of triple GEM operation; bottom: three-dimensional view of the readout board.

in the two directions are chosen in such a way as to allow equal sharing of the charge between the X and Y (or U and V) strips. The size of the electron cloud arriving at the strips is about 500  $\mu$ m and, therefore, the pitch can not be more than 400  $\mu$ m. However, only a 1.6 mm read-out pitch is required to provide the necessary spatial resolution for the ST. Thus, every four read-out strips will be bridged into a single read-out channel to reduce the number of electronics channels. With this effective strip pitch of 1.6 mm, the occupancy levels are small enough to perform efficient tracking. For the expected rate of 130 kHz/cm<sup>2</sup>, the occupancy level of the strips will be 8%.

Having four chambers in each polarimeter tracker, and having both X/Y and U/V readouts, ensures that we are able to reject random hits and reconstruct straight tracks comfortably at the above occupancy level. In this case we expect random and pseudo (spurious) trajectories at a level of 0.1% per event. The proposed four-chamber configuration also ensures high tracking efficiency even if one of the detector planes is inefficient for a given event.

The gas volume of each chamber section will be contained by the cathode foil from one side, and by the anode read-out board from the other side. The GEM chamber sections forming one chamber will be mounted between two rigid aluminum frames as indicated in Fig. 2.8. Since the proposed experiments do not require absolute cross-section measurements, some dead zones in between the chamber sections are acceptable. However, these areas need to be minimized for maximum efficiency. The use of thin polyglass frames for the mounting of the GEM foils will help in this. Furthermore, the Front-End-Electronics will be mounted perpendicular to the chamber plane behind Permaglas frames to avoid obstructions to the chamber active area. The total dead area is estimated to be  $\sim 5\%$  of the total.

## **Chapter 3**

## **SBS Spectrometer Magnet**

The considerations for the magnet selection are:

- Large aperture with aspect ratio of 2/1 (vertical to horizontal);
- Horizontal field direction;
- Beam path through the opening in the magnet return yoke;
- Modular configuration of the magnet yoke with an element weight below 20 ton.

The dipole labeled 48D48 is a warm coil magnet, with about 3 Tm field integral at 4 kA excitation current. It was used at BNL for the fixed target program. This dipole will be used in the SBS spectrometer. Figure 3.1 shows a drawing of the magnet as it was used at BNL.



Figure 3.1: The assembly drawing of the 48D48 magnet for vertical field orientation as it was used at BNL.

The vertical bend will be achieved by rotation of the magnet by  $90^{\circ}$ , putting the magnetic field direction in the horizontal plane. Installation of the magnet at small angles is possible by means of a deep cut in the iron yoke (see Fig. 3.2). Configuration of the cut (mainly parallel to the field lines in the gap) leads to a moderate distortion of the magnetic flux flow in the yoke and field distribution in

the magnet gap. The right coil, which is closer to the beam line, will be modified to allow for the beam line path.

The magnet weights 100 tons total. It consists of five iron slabs of 20 tons each, so it can be assembled inside the Hall A by means of the existing overhead crane. Figure 3.3 shows a design model of the SBS magnet at the pivot in Hall A.



Figure 3.2: The concept of the beam path through the dipole.

#### **3.1** Characteristics of the 48D48 magnet

In fixed-target experiments with high energy incident beams, a forward angle detector covers a large portion of kinematic phase space. A simple, dipole magnet can provide the basis of a highly effective, large acceptance spectrometer if high momentum resolution is not required. This technique has worked extremely well in the lepton beam facilities at HERMES and COMPASS and is also applicable to experiments with an 11 GeV electron beam in Hall-A of Jefferson Laboratory.

The central component of the Super-Bigbite spectrometer (SBS) is the 48D48 dipole magnet, which has previously been used on the kaon beamline of the AGS accelerator at BNL. This  $\sim$  100 ton device (Fig. 3.4) has aperture dimensions of 469×1219×1219 mm and employs saddle-type coils to generate the magnetic field.

The characteristics of the magnet are summarized in Table 3.1.

#### **3.2** Magnet configuration for GEp(5)

For the GEp(5) experiment, where only 30 msr solid angle is required, we are going to make two iron inserts in the magnet. The inserts will collimate acceptance to the required value, reduce the vertical size of the pole, and reduce the gap between poles. Such adjustment will make no difference (or just



Figure 3.3: The 3-d view of the magnet in Hall A.

Weight of iron yoke	75 ton	Density	7.872 g/cm <sup>3</sup>
Yoke Material	SAE 1008 Steel	C <0.06%	Mn < 0.38%
Coil	120 turns	Resistance $\sim 0.1\Omega$	
Power Supply	Max current 4kA		
Power Consumption	@1kA $\sim 100 \text{ kW}$	$@2kA \sim 400 \text{ kW}$	@ $3kA \sim 900 kW$
Integrated field	1.05 T·m	2.06 Tm	2.79 T⋅m

Table 3.1: Characteristics of the 48D48 dipole. Integrated field is calculated (without any pole shim) along the central trajectory through the pole gap.

reduce variation) of the field on the beam line, however it will produce an increase in the field integral closer to desirable level, and a spin rotation angle closer to the optimum value of  $90^{\circ}$ .

#### 3.3 Magnet configuration for GEn(2) and GMn

The neutron form factor experiments, GEn(2) and GMn, will use the 48D48 magnet for deflection of the high energy protons to allow unambiguous identification of the quasi-elastic electron-neutron events. In such a case the required value of the field integral, Bdl, will be defined to allow a 5% admixture of the protons in the neutron event sample, which is due to overlap of the proton and neutron distributions at the detector front face. A veto counter will be used for further reduction of the proton admixture. In the GEn(2) experiment the required value of Bdl is 1.7 Tm while in GMn it is just 0.8 Tm.



Figure 3.4: The 48D48 Magnet with the outlines of the iron yoke and coils highlighted. Dimensions are in mm (inch).



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10 July 2007

Dr. Kees De Jager Thomas Jefferson National Accelerator Facility 12000 Jefferson Ave. Newport News, VA 23606

Dear Dr. De Jager:

Bogdan Wojtsekhowski has expressed an interest in obtaining a 48D48 spectrometer magnet with associated power supply for use at JLAB for an experiment to be proposed to PAC32. This letter is to confirm the availability of such a system for use at JLAB. This would be administratively handled as a transfer of ownership from BNL to JLAB. JLAB is expected to cover the costs for transportation.

Sincerely

Philip Pile, Head, C-AD Experimental Support and Facilities Division Collider-Accelerator Department

Figure 3.5: The letter from BNL regarding 48D48 magnet.

### **Chapter 4**

## **Optics of the SBS Spectrometer**

J.J. LeRose, L. Pentchev Thomas Jefferson National Accelerator Facility, Newport News, VA 23606

The COSY code [16] and SNAKE [17] were used to model the SBS. The spectrometer has only one simple dipole which makes it easy to simulate the optical properties [18]. A maximum value of 2.5 Tm has been assumed for the field integral. The relatively small bend angle of 5-6° in the 7-8.5 GeV momentum region is compensated partially by the high resolution of the GEM chambers resulting in a momentum resolution of about 0.5%. The magnet has relatively wide angular acceptance and allows the use of a long target. The spin transport is also simple [19] making it easier to control the systematic errors in the polarization transfer measurements. To estimate the acceptance, the GEANT model of SBS has been used as described in Sec.5 except that protons were generated at the target instead of electrons.

#### 4.1 SBS optics

The COSY and SNAKE models of the SBS dipole include standard fringe fields, but don't take into account the effect of the beam hole through the dipole yoke. When detailed modeling of the magnet with this beam hole produces a reliable field map of the magnet, inserting that map into the SNAKE model in place of the analytic magnet model now used will be trivial and the tests described herein will be repeated. It is anticipated that such details will not significantly affect the resolution or acceptance properties of the SBS. The COSY generated first order coupling constants are shown in Table 4.1 in case of 2.5 Tm field integral and 8 GeV central momentum.

Because of the simplicity of the magnet, higher order calculations were not used for the COSY based estimates presented here. The hole in the magnet, not taken into account here, will only affect higher order terms, which contribute negligibly as indicated by the accompanying SNAKE analysis. If keeping the field integral constant and changing the central momentum,  $p_0$ , (and therefore the central trajectory) the coupling constants from the last line scale with  $p_0$ :  $(x|\delta) = 0.086 \times 8/p_0$ ,  $(x'|\delta) = 0.085 \times 8/p_0$ , while all the rest remain the same.

	X	x'	У	y'
$x_{tar}$	1.000	0.000	0.000	0.000
$x'_{tar}$	3.304	1.000	0.000	0.000
$y_{tar}$	0.000	0.000	0.995	0.005
$y'_{tar}$	0.000	0.000	3.296	0.988
δ	0.086	0.085	0.000	0.000

Table 4.1: First order coupling constants from COSY model of the SBS dipole. Coordinates and angles at the first GEM chamber (top line) at 325 cm from the target can be calculated by summing all the numbers in the corresponding column multiplied by the parameters in the first column: the coordinates at the target and the relative deviation of the momentum p from the central one  $p_0$  ( $\delta = (p - p_0)/p_0$ ). x coordinates are in the dispersive and y – in the non-dispersive direction. All dimensions are in meters and radians.

#### 4.2 SBS momentum, position, and angular resolution

We use the first order COSY results from the previous section to estimate the resolution of the spectrometer. For the first GEM tracker we assume a coordinate resolution of 70  $\mu$ m, resulting in an angular resolution of 0.14 mrad on a base of 70 cm. In addition the multiple scattering in the front GEM chambers contributes to the angular resolution. We assume that two GEM chambers, each 0.5% X<sub>0</sub> thick (X<sub>0</sub> is the radiation length), are at the front of the tracker, which gives 1.36/*p* mrad (*p* is the momentum in GeV) addition to the angular resolution. Thus, for the resolutions of the first GEM tracker we have:

$$\Delta x' = \Delta y' = 0.14 \operatorname{mrad} + \frac{1.36}{p} \operatorname{mrad}$$
(4.1)

$$\Delta x = \Delta y = 0.07 \,\mathrm{mm} \tag{4.2}$$

We plan to have helium bags inside the magnet, from the scattering chamber to the first GEM, and the multiple scattering there has a negligible effect.

The target is placed at the central horizontal plane of the magnet and therefore  $x_{tar} = 0$ . Thus, we have the following expressions for the coordinate and the angle at the first GEM in dispersive direction:

$$x = (x|x'_{tar})x'_{tar} + (x|\delta)\delta$$
(4.3)

$$x' = (x'|x'_{tar})x'_{tar} + (x'|\delta)\delta$$
(4.4)

Solving for  $x'_{tar}$  and  $\delta$  and using the above coordinate and angular resolutions ( $\Delta x$  and  $\Delta x'$ ) at the first GEM tracker one can estimate the error of the reconstructed momentum and angle at the target in the dispersive plane. In the same way we can reconstruct the target position and angle,  $y_{tar}$  and  $y'_{tar}$ , in the non-dispersive plane, being functions of y and y' only. The spectrometer resolutions in case of 2.5 Tm field integral are shown in Table 4.2 as functions of the momentum p.

SNAKE was used to check whether these simple first order considerations were sufficient to characterize the expected resolutions achievable with the SBS. Once the magnet was setup in SNAKE 3000 random trajectories spanning close to the full geometric acceptance of the magnet with  $\delta$  ranging from -12.5% to +12.5% (7-9 GeV/c) were traced through the magnetic field to the face of the 1st GEM tracker. Those trajectories were used as input to a fitting program (MUDIFI [20]) that determines the best-fit polynomials reconstructing the target parameters ( $\delta$ ,  $\theta$ , y, and  $\phi$ ) of the trajectories based on

quantity	resolution
$\delta,\%$	0.03p+0.29
$x'_{tar}$ , mrad	0.09 + 0.59/p
$y_{tar}$ , mm	0.53 + 4.49/p
$y'_{tar}$ , mrad	0.14+1.34/p

Table 4.2: Spectrometer resolutions for 2.5 Tm field integral as functions of the momentum in GeV.

the positions and angles measured in the detectors. The results of the fitting are shown in Fig. 4.1. The sensitivity to measurement errors in the detectors can then be explored in a Monte Carlo fashion.

The Monte Carlo simulation assumed a position resolution at the detectors of 70 microns and an angular resolution of 0.3 mrad at 8 GeV/c, essentially the same as in (4.1) and (4.2). The resulting delta resolution averaged over the full range of delta was 0.48%. The resolutions for  $\theta$ , y, and  $\phi$  were 0.16 mrad, 0.9 mm, and 0.30 mrad, respectively, all in good agreement with the results in table 4.2 for 8 GeV/c (see Fig. 4.2. Furthermore, the angular and position resolutions did not vary at all as a function of  $\delta$  and the  $\delta$  resolution only varied minimally (0.39-0.57%).

#### 4.3 SBS spin transport

The COSY model of the SBS magnet has been used to calculate the matrix that transports the measured spin components at the polarimeter to the target. For the transferred polarization measurements, the magnet is used to rotate the longitudinal spin component,  $P_\ell$  so that it can be measured in the polarimeter. The simplicity of the magnet makes it easy to model the spin transport. The magnet deflection in the non-dispersive plane is very small and easily controlled. This is very important, because such deflection mixes the longitudinal and transverse components of the recoil proton and is important source of error when reconstructing their ratio [19]. To demonstrate this one can calculate the non-dispersive deflection in the magnet using the COSY results from Table 4.1:  $y' - y'_{tar} = 0.005y_{tar} - 0.012y'_{tar}$ . In case of the GEp(5) experiment (SBS at 14.1° and 40 cm target) the total range of the deflection is  $\pm 1.75$  mrad, and the error of its reconstruction is 100 times smaller. The view of the front chambers from the target allows to directly relate the target and polarimeter coordinate systems. Therefore, we estimate the error of the non-dispersive deflection to be less than 0.1 mrad.

#### 4.4 SBS acceptance

The GEANT simulations explained above were used to estimate the acceptance of SBS. The dipole is placed at  $14.1^{\circ}$  137 cm from the target and has a gap of  $14.5^{"}$  at its end at 259 cm. Protons were generated in the 40 cm long target to cover the whole angular acceptance and were counted at the first GEM chamber ( $50 \times 100 \text{ cm}^2$  at 325 cm from the target). The angular acceptance is shown in Fig. 4.3 resulting in 41 msr.



Figure 4.1: Four plots show the quality fits to test trajectories from SNAKE.Plotted are histograms showing the difference between  $\delta$  from the fit function and the actual  $\delta$  (upper left); the difference between  $\theta$  from the fit function and the actual  $\theta$  (upper right); the difference between  $\phi$  from the fit function and the actual  $\phi$  (lower left); and the difference between y from the fit function and the actual y (lower right). Notice that the fit is significantly better than the desired resolutions.



Figure 4.2: The same as the preceding figure except now measurement errors as discussed in the text are folded into the reconstruction of each quantity.



Figure 4.3: Angular acceptance of SBS;  $\theta$  is horizontal (centered at 14.1°) and  $\phi$  vertical angle. The total integral is 41 msr.

### Chapter 5

# **Detector Counting Rates and Tracking Analyses**

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The open geometry of the SBS, while offering a large solid angle and large momentum acceptance, also results in high background rates, whose minimization requires special attention to the beam line and the shielding configuration. The principal geometry of the SBS equipment configuration in the GEp(5) experiment is shown in Fig. 5.1.

The main hit rate of the Front Tracker is due to interaction of soft photons from the target (from 100 keV up to few MeV) with the material before and inside the tracking detector. Electrons with energy as low as 1 keV in the detector sensitive volume could produce hits. The MeV range electrons produced in the target can not reach the detector, which is located behind the magnet, however they produce photons when interacting with high Z material, like the iron of the magnet. These photons could contribute to the detector hit rate. At the same time the fringe field in front of the magnet repels the electrons approaching that material and helps to reduce the background. The location of the material hit by electrons with respect to the beam line, magnet field, and the detector view, and its type plays a key role in the background intensity. If for example, the scattering chamber has a thick wall it becomes a source of photons. When the chamber has a small diameter it is in the direct view of the detector and the photon rate on the detector is very large. Development of the shielding configuration for the GEp(5) experiment is the most challenging task because of the required high luminosity and non-trivial magnetic shielding of the beam line.

The GEp(5) experiment will use the maximal available luminosity of  $\sim 10^{39} \text{ s}^{-1} \text{ cm}^{-2}$ . For the expected high hit rates, tracking (with the proposed readout configuration) is possible only because the information from the electron arm imposes constraints on the elastic proton track in the SBS. Similarly, we use the hadron calorimeter information to find the proton track on the rear trackers. Finally, the tracking in the Second Tracker can be done with the help of the already reconstructed tracks in the Front and Third Trackers.



Figure 5.1: The location and dimension of the GEp(5) experiment components.

#### 5.1 Counting rates

We start with a review of the target parameters and the particle flux produced from the target. The parameters of the liquid hydrogen target are presented in Table 5.1. P. Degtyarenko [21] has calculated

Length	Diameter,	Protons	Energy	fraction of radiation	Ionization, MeV,
(cm)	(cm)	per cm <sup>2</sup>	loss (W)	length	for electron of the beam
40	2	$1.7 \times 10^{24}$	800	4.5%	11

Table 5.1: Parameters of the liquid hydrogen target in the GEp(5) experiment.

the particle rates from such a target. Results are presented in 5.2. At angles below  $25^{\circ}$  the electrons are the dominant particles followed by the photons.

The large length of the target results in a very large yield of low energy particles, *e.g.*, in the forward angles below  $25^{\circ}$  the flux of the few MeV electrons is about  $10^{14}$  per second. This calculation also shows a modest non-linear effect of the target thickness. In the MeV energy range the yield of the photons from a 40 cm long target is almost 4 times higher than the yield from a 15 cm long target.



Figure 5.2: The energy and the angular dependences for electron yield from a hydrogen target with 11 GeV beam.

The Front Tracker of the SBS has a direct view of the target and the flux of the primary photons (produced from the target) can be  $\sim 120$  kHz photons per cm<sup>2</sup> with energy above 1 MeV at the middle of the Front Tracker.

Another source of the background is the interaction of the high energy electrons of the beam halo with the experimental equipment. For the target described in Table 5.1 the probability of a single scattering of a beam electron at angles above 25 mrad (the opening of the vacuum line to the beam dump) is about  $0.5 \times 10^{-5}$ . This relatively low probability of large angle scattering corresponds to

about 4 W energy deposition in the hall, which is acceptable from the radiation safety point of view.

According to our experimental study during the GEn(1) experiment the 5 cm thick iron plate provides sufficient protection of the detector against the room background after which the background flux from the target becomes dominant.

If further Monte Carlo (MC) and experimental studies show significant background produced in the beam pipes, the beam line area will be covered by a lead blanket of required thickness. The space between the beam pipe and the Front Tracker is sufficient for a wall of 30 cm thickness.

#### 5.1.1 Photon detection probability of the GEM chambers



Figure 5.3: Top: Efficiency of registration in a single chamber of a soft photon as function of its energy. Bottom: probability for correlated hits in two or three chambers (provided there was a hit in one of the chambers) caused by a single soft photon as function of its energy.

A GEANT-4 code was used to investigate the photon detection probability. The GEM geometry and materials were chosen to be the same as in the COMPASS chambers [10]. The probability to produce a secondary electron in the drift gap of the chamber as a function of the energy of the initial soft photon is shown in Fig.5.3. It is about  $10^{-3}$  at 100 keV and increases up to  $\sim 4 \times 10^{-3}$  at 1 MeV. Above 1 MeV the photon efficiency (Fig. 5.4) increases but does not exceed 1%. In the same figures, bottom panels, the probability for correlated hits in two or more chambers is shown. This happens when one photon produces secondary electrons in several chambers. One can see that this probability is negligible for photon energies below 1 MeV, and the hit rates on the chambers are dominated by uncorrelated random hits.

The rate at the detector was calculated by convoluting the number of the photons with an energy above 100 keV with the photon detection efficiency of the GEM chamber. The average photon efficiency was found to be 0.33% for the first GEM chamber. Figure 5.12 shows an example of 10


Figure 5.4: Same as Fig.5.3 but in the 1-10 MeV region.

simulated events for a 75  $\mu$ A beam current and a 40 cm long target with the magnet set at a central angle of 14°.

The distance from the pivot to the magnet yoke is 65 inches. As one can see, the contribution from the beam dump is very small. The beam line related background is completely suppressed. The observed final rate in the Front Tracker is 400 kHz/cm<sup>2</sup>, which is mostly due to the direct photon flux from the target. In the rear trackers, the rates are dominated by MeV electron/positrons produced in the CH<sub>2</sub> analyzers by the target photons. The simulations predict hit rates of 130 kHz/cm<sup>2</sup> and 64 kHz/cm<sup>2</sup> for the Second and Third Tracker, respectively.

### 5.1.2 Monte Carlo simulation of the hit rate in the GEp(5) setup

The background rates have been estimated using a simulation code written by P. Degtyarenko. The code is a modified version of the GEANT-3 package and has been used for many years at JLab to calculate the experimental background and radiation budgets.

Figure 5.5 shows a view of the GEANT model, which includes:

- a target, including Al side walls and end-caps;
- a scattering chamber with a large exit snout and a vacuum window in front of the magnetic field clamp;
- the magnet, including a field clamp, its aperture and magnetic field, and the opening for the beam line;
- the beam line lead shielding behind the magnet;
- a region with magnetic field on the beam line;

- a detector presented by a sensitive volume at 325 cm from the target (not shown in the Figure);
- a diffuser in the beam dump at 28 m from the target (not shown);



Figure 5.5: Section of the GEANT model (the detector and diffuser are not shown). The boxes with numbers indicate magnetic field volumes with the field given in kG.

The field on the beam line was included in the model as a 70 cm long region with 70 G field oriented transverse to the beam and 8 kG along the beam obtained from 3-D magnetic field calculations. Even when the MC was repeated with a 10 times larger transverse field in this region, the background rate in the detector did not change.

### 5.1.3 Magnet calculation

The magnet 3-d calculation was done with the MERMAID code [22]. Figure 5.6 shows the cross section of the magnet in the horizontal plane. Calculations were done with a current of 2 kA in the

coils. The cross section of the coils is reduced compared to the original BNL coils, which were used with 4 kA excitation.

A view of the magnet model used in the calculation is shown in Fig. 5.7. The resulting field on the





central trajectory is shown in Fig. 5.8. The total field integral is about 2.5 Tm, as was used in the design of experiments with SBS. The value of the field in the target area is below 2 Gauss,  $\sim 200$  cm from the magnet.

Figure 5.9 shows the field along the beam,  $B_s$ , and transverse to the beam,  $B_t$ . The longitudinal field reaches 8 kG in the area between the clamp and the yoke. The field map (Figs. 5.10, 5.11) shows that a solenoid wound around the pipe with 1 kA/cm current density is able to de-gauss the iron pipe. As a result the pipe provides shielding against the transverse field. The remaining field has an integral of 70 G × 70 cm. The effect of this field on the beam is small and the effect on the background rate in the detector was analyzed using the GEANT MC (see next section).

### 5.1.4 Parameters of the model elements

### **Cryogenic target**

The target is a 40 cm long, 2 cm diameter cylinder filled with liquid hydrogen. The Al side wall is 0.10 mm thick. The end-caps are 50  $\mu$ m thick. Standard practice calls for an 0.18 mm thick side wall,



Figure 5.7: View of the upper part of the magnet in the MERMAID model.



Figure 5.8: The field on the central trajectory of the SBS magnet,  $B_x$  - transverse, big component,  $B_y$  - normal, small component.



Figure 5.9: The field on the beam line.  $B_s$  is along and  $B_t$  is transverse to the beam direction.

which leads to 12% higher background. We expect that 0.10 mm could be achieved for the proposed cell diameter.

### Scattering chamber

The diameter and thickness of the scattering chamber are taken as they are in the existing Hall A chamber. A  $30^{\circ}$  cone around beam line is removed from the chamber front wall (see Fig. 5.5). A custom extension was added with flat Al walls at the field clamp. This snout will be attached to the scattering chamber via a flat bellows. The window needed for the spectrometer aperture (40.5 cm wide) is made of 0.5 mm thick Kapton film (0.25% radiation length). The beam-line vacuum pipe is welded to the same flange on the snout.

### Beam line lead shielding

The beam line vacuum pipe has a  $\pm 25$  mr opening which leads to  $\sim 10^{-5}$  probability for an electron hitting the front end of the pipe. Due to the significant length of the target there is a probability that



Figure 5.10: The field map in the area of the beam line inside the yoke. The numbers in the field give the field value in kG.

electrons of the beam scattered by the same 25 mr will hit different places on the beam line vacuum pipe. As result, for background suppression, a lead cover must be added all along the beam line where it passes in front of or near the detector. This shielding consists of a 30 cm thick lead "tube" around the beam line behind the magnet and additional lead between the front clamp and the yoke.

### Beam dump

The vacuum pipe of the beam line has a 25 mr opening ending 5 m inside the beam dump tunnel. The beam passes through a 30 cm diameter Be window and a diffuser, which present the main source of background. We represented the diffuser as a 1" thick Al plate located 28 m from the pivot.

### 5.1.5 Detector counting rate

The rate at the detector was calculated from the number of the photons with energy above 100 keV and an average detection efficiency of photons in the GEM chamber. The later was found from an independent MC to be 0.33%. Figure 5.12 shows an example of 10 events.

Table 5.2 presents the resulting hit rates in the front GEM chamber for several conditions. Configuration "Target" has only the target and the detector. The rates of photons and electrons are presented



Figure 5.11: The field on the beam line with additional shielding.

Table 5.2: Counting rate in the First Tracker in  $kHz/cm^2$  for different configurations of the MC simulation. The statistical error of the results is 2%.

Configuration	Counting rate, kHz/cm <sup>2</sup>	Comments
Liquid hydrogen	244	due to photons
Target $(T) = LH + Al cell$	288	due to photons
T + Scattering Chamber	306	due to photons
T + Magnet (including the clamp, Pb)	362	all particles
Final = T + Magnet + Diffuser(1")	367	all particles

separately. Configuration "T + Scattering Chamber" has the target and the scattering chamber. Configuration "T + Magnet" has in addition the 48D48 Magnet with the clamp and the beam line magnetic shielding (the solenoid and the iron pipe). Configuration "T + Magnet + Diffuser" includes the diffuser in the beam dump tunnel.

A 75  $\mu$ A beam current and 40 cm target was assumed. The spectrometer central angle is 14°. Distance from the pivot to the magnet yoke is 65 inches. As one can see the contribution of the beam dump is very small. The beam line related background is totally suppressed. The observed final rate is close to the direct flux from the target.

As for the rear trackers, the rates are dominated by MeV electron/positrons produced in the  $CH_2$  analyzers from the target photons. The MC calculations give hit rates of 180 kHz/cm<sup>2</sup> and 90 kHz/cm<sup>2</sup>



Figure 5.12: Sample of the simulated events. Red lines indicate electron tracks.

for the Second and Third Tracker, respectively. A reduction of these rate is possible by adding lead plate in front of the first analyzer. A 1cm Pb plate reduces the rates on the Second and Third Trackers by 30% down to 130 kHz/cm<sup>2</sup> and 64 kHz/cm<sup>2</sup>.

**Summary of counting rates:** A complete simulation of the configuration of GEp(5) resulted in a hit rate in the Front Tracker of less than 400 kHz/cm<sup>2</sup>. The predicted hit rates in the Second and Third Trackers are 130 kHz/cm<sup>2</sup> and 64 kHz/cm<sup>2</sup>.

As presented above a direct test of the simulation accuracy shows a potential underestimate of the photon-induced rates by at most a factor of two. If this is confirmed in a dedicated test (which will use a target in a vacuum for the beam and the BigBite magnet at forward angle) the read-out boards in the Front Tracker will be modified. The read-out strips of the GEM chamber will be separated in the middle and the number of read-out channels will be doubled. This modification will reduce the effective counting rate by half. The modification would be required only for the Front Tracker, which is under development by the INFN group (the polarimeter trackers are located behind  $CH_2$  analyzers and the photon flux is not essential) and will have no impact on the funding request to DOE. A reduction of the material budget in the GEM structure could also lower the photon detection efficiency and hence the counting rate. About 60% of the mass in the GEM chamber is in the honeycomb plates, half of which could be replaced by stretched films in the Front Tracker.

### 5.1.6 Counting rate in the calorimeters

The hadron and electro-magnetic calorimeter thresholds used in the trigger are well above 1 GeV, so the Feynman variable  $x_F$  is larger than 0.1-0.2, the particle multiplicity is low and GEANT predictions, even with the custom hadron package, are not accurate. Therefore, we estimated the trigger rates in these detectors by using the measured cross-sections at SLAC, as well as, the rate measurements with the electromagnetic calorimeter in the WACS experiment at 5.7 GeV. Then we extrapolated the results to the 11 GeV beam energy. The resulting rate for the hadron calorimeter was found to be of 1.5 MHz for an energy threshold of 4.5 GeV. The rate for the electron calorimeter was found of to be 60 kHz for a threshold equal to 85% of the elastically scattered electron energy.

### **5.2** Track reconstruction for the GEp(5) experiment

In this section we describe the tracking procedure for the GEp(5) measurement. With a luminosity of  $8 \times 10^{38} \text{ s}^{-1} \text{ cm}^{-2}$  and the Super Bigbite Spectrometer at an angle of  $12^{\circ}$ , the tracking of the proton is challenging. In contrast, the two neutron form-factor experiments, GEn(2) and GMn, will run with a luminosity that is a factor of ~ 20 lower compared to GEp(5), and with a correspondingly lower background, the tracking will be much easier. We thus focus our discussion here on GEp(5).

The open geometry of the Super Bigbite Spectrometer requires a detailed investigation of the background rates. Complete GEANT simulations of the SBS together with the beam line have been performed. The results for the hit rates in the four trackers for the highest- $Q^2$  measurements in the GEp(5) experiment are shown in Table 5.3. We note also that we have done corresponding simulations of several BigBite experiments, including the recent Transversity run which took place at 6 GeV. We see quite reasonable agreement with actual measurements, as discussed in detail in Section 5.3.2.

The background particles mainly come from the target and, in the direction of the SBS, are dominated by soft electrons. These, however, are swept away by the magnet so that the hit rate on the front tracker is due to photons that produce soft charged particles in the chamber material. The background on the second and third tracker originates from the interactions of the target photons with the analyzers and the hit rates in the trackers are dominated by charged particles. As for the BigCal tracker (Coordinate Detector or CD), which is at an angle of 39°, the target flux can be reduced to a manageable level using a 20 cm aluminum absorber.

Even if the hit rates are orders of magnitude below the maximum rates that the GEM detector can sustain, the track reconstruction requires a separate investigation. Normally, GEMs at such high rates are used with pad read-out that significantly increases the number of electronic channels. As will be demonstrated below, the strip configuration of the read-out boards will provide reliable and efficient track reconstruction for the elastic reactions of interest here. The advantages of these elastic measurements are:

- 1. By applying high thresholds on the calorimeters one can significantly reduce the number of possible electron and proton hits.
- 2. By using kinematic correlations between the proton and electron tracks, one can identify small regions and angular ranges in the SBS trackers within which one should look for the proton track.

Based on the background rates per unit area, r, the occupancy levels l were calculated using the expression l = trS, where t is the integration time and S is the area of the strip. The results are shown in Table 5.3. We used t = 75 ns for the front SBS tracker, t = 50 ns for the second and third trackers, and

t = 25 ns for the BigCal chambers. In fact the integration time of the APV25 chip is 25 ns. However, to reduce the noise and improve the resolution in the SBS chambers, the chip will be operated in three/two sample mode resulting in a 75 ns/50 ns integration time. For each tracker, the area S is calculated assuming the width of the pitch plus 0.4 mm. The 0.4 mm takes into account the size of the electron cloud arriving at the read-out board. At such high occupancy levels, the main problem for the track reconstruction is the big number of spurious hits. Tracking in the front tracker relies on the information from the electron arm that imposes kinematic constraints on the elastic proton track in the SBS. Similarly, tracking in the rear trackers relies on information from the hadron calorimeter. The track reconstruction procedure consists of:

- reconstruction of the hit position in the electron arm,
- finding the ranges of the elastic proton track parameters on the front SBS chamber,
- reconstructing the track in the Front Tracker,
- track reconstruction in the Third Tracker, using the coordinate information from the HC,
- tracking in the Second Tracker with the help of the already reconstructed tracks in the FT and TT.

### 5.2.1 Tracking procedure

The tracking procedure starts from the electron arm. The Coordinate Detector in front of the electromagnetic calorimeter, BigCal, has two GEM planes separated by 4 cm, each having only horizontal read-out strips of 40 cm length with 1 mm pitch. BigCal gives the position of the electron with an accuracy of 4 mm for electron energies of about 3.3 GeV. Considering  $\pm 3\sigma$  range (BigCal position resolution) in the vertical direction, one would expect the electron within this 2.4 cm, to correspond to 24 strips on the rear chamber plane of the Coordinate Detector. Of these, 0.58 strips may have a pseudo-hit within the integration time. The strips are horizontal as is the target, thus providing a good definition of the vertical electron angle. Thus, even though one does not know the interaction point, for each of the strips fired on the rear plane one should look for a hit in at most two strips on the front plane. On two strips we expect 4.8% probability for a pseudo-hit which gives 0.028 pseudo-hits in total from the two planes.

We apply  $\pm 3\sigma$  cuts on the electron position, as given by the Coordinate Detector in the vertical direction and by BigCal in the horizontal. Thus, the area on the front SBS chamber where the elastic proton is expected is narrowed down to  $0.2 \times 18$  cm<sup>2</sup> in the worst case, as investigated with simulations that take multiple scattering into account. The horizontal size of 18 cm is dominated by the uncertainty in the interaction point along the target. Therefore, in the electron arm, improving the horizontal coordinate resolution by using vertical strips in the Coordinate Detector is not required.

### 5.2.2 Tracking in the first tracker

The Front tracker consists of six chamber planes, each equipped with two orthogonal sets of strips with a pitch of 400  $\mu$ m. A pair of chamber planes, spaced by 4 cm and incorporating X and Y strips, is placed at the front. Another pair of chambers also with X and Y strips is positioned at the end of the tracker, at 70 cm from the the front pair. The last two chambers, both with U and V strips are in the middle of the tracker. Since the rate on the Front tracker is induced by the photon background, the hit rate increases from the first to the sixth chamber due to the increase of the amount of the material. For

the "standard" (COMPASS type) GEM chamber, the hit rate increases from 400 kHz/cm<sup>2</sup> at the front to about 1 MHz/cm<sup>2</sup> at the rear chamber. That is why, to reduce the occupancy levels, the strips on the last two chambers are divided into two halves.

On an area of  $0.2 \times 18 \text{ cm}^2$  one expects 41 pseudo-hits due to the rate on the strips which intersect this area. The real hits produce correlated signals on the X and Y strips. Using the correlation between the analog strip signals the number of spurious hits may be reduced by a factor of three to 13.7. Due to the 4 cm distance to the second chamber plane, and using angular constraints on the elastic proton track, one can further significantly reduce this number. For each pseudo-hit in the front chamber one has 0.28 pseudo-hits in the small area of the second chamber on which one expects a hit. As a result we estimate 3.9 pseudo-hits in the front pair of chambers. Applying a similar procedure for the second pair, we obtain 0.53 pseudo-hits for each hit at the front pair. As for the rear pair of chambers, we use the tracks reconstructed from the other two pairs. For each track we expect a hit in a region of only  $3 \times 3$  strips on the rear chambers and  $7.9 \times 10^{-3}$  pseudo-hits there. Therefore, we expect the number of pseudo-tracks in the first tracker to be about  $1.65 \times 10^{-2}$  per event, as is shown in Table 5.3.

Tracker	Area of interest	Rate,	Strip pitch,	Strip occu-	Number of pseudo-	Number of	
	for tracking, cm <sup>2</sup>	kHz/cm <sup>2</sup>	mm	pancy, %	tracks per event	strip planes	
First	0.20 x 18	400	0.4	13.5	$1.65 \times 10^{-2}$	12	
Second	$2\pi \ 0.35^2$	130	1.6	7.4	$8.7 \times 10^{-6}$	8	
Third	$\pi$ 4.8 $^2$	64	1.6	3.6	$5.2 \times 10^{-4}$	8	
BigCal	$\pi \ 1.2^2$	173	1	2.4	$2.8\times10^{-2}$	2	

Table 5.3: Parameters related to the track reconstruction in the four trackers as explained in the text. For the first tracker the rate and occupancy level correspond to the front chamber.

### 5.2.3 Tracking in the second and third Trackers

The Second and Third Trackers will use the same type of chamber units as the first one, except that groups of 4 strips will be bridged into one, resulting in a strip pitch of 1.6 mm. The Trackers will consists of two pairs of chamber planes, 50 cm apart. The first pair will have X and Y strips on both chamber planes and the second pair will have U and V strips.

The hadron calorimeter determines the proton hit position with a resolution of 1.6 cm. Thus, one expects the elastic proton on the rear plane of the Third Tracker to be within a circle of 4.8 cm radius. In such an area one expects 0.055 pseudo-hits in the rear pair of chambers. By reconstructing the track from the two rear chamber planes one can show that the proton is expected within a circle of radius 2.4 cm at the front pair of chambers where  $9.5 \times 10^{-3}$  spurious hits are estimated. Therefore, we expect in the Third Tracker about  $5.2 \times 10^{-4}$  pseudo-tracks per event.

For the Second Tracker we will use the tracks reconstructed in the First and Third Trackers. Based on the experience with a very similar double polarimeter in the GEp(3) experiment, we know that events in which the proton has scattered either in the first or in the second analyzer but not in both, contribute about 86% to the total Figure-of-Merit. For such events, the area on each of the chambers where the proton is expected, is represented by two spots. They correspond to the tracks in the Front or in the Third Tracker in the situation where the proton did not scatter in the first or in the second analyzer. The radius of the spots is defined by the multiple scattering in the analyzer. We estimate  $2.1 \times 10^{-3}$  pseudo-hits in each of the chamber pairs for one spot, or  $8.7 \times 10^{-6}$  pseudo-tracks in the Second Tracker. For the events where the proton scatters in both analyzers we expect a significant number of pseudo-tracks that will reduce the effective analyzing power. However, these events only contribute about 14% to the total Figure-of-Merit.

### 5.2.4 Summary

Based on the analysis presented here, using the rates predicted from the simulations (see the counting rates section in this chapter), the numbers of expected pseudo-tracks per event, shown in Table 5.3 for the three trackers, represent the inefficiency of the track reconstruction due to the high rates. One can scale these results for different hit rates. If one has used N strip planes for a particular tracker (given in Table 5.3), the number of the pseudo tracks is proportional to the strip rate to the power of N. For example, if we assume that the rates on the strips in the Front Tracker are a factor of 1.5 higher, we would have  $1.65 \times 10^{-2} \times 1.5^{12} = 2.14$  pseudo-tracks per event. If this is the case we plan to replace one of the two honeycomb plates in the chamber, that corresponds to 29% of the total chamber material, by much lighter material. In this case we expect 0.035 pseudo-tracks per event. Similarly, if increasing the rates by 50% in the Second, Third, and BigCal Tracker one would expect 0.00022, 0.013, and 0.063 pseudo-tracks, respectively. One can see that even in such a scenario, the tracking efficiency will be very high.

## 5.3 Background rate and experiment design considerations

The background-induced rate on the detectors could lead to potentially serious problems:

- a) instability of the detector operation, which in principle could be resolved by high segmentation,
- b) low efficiency of the track reconstruction resulting in loss of statistics.

These issues were among the primary factors driving the design of the Super Bigbite Electromagnetic Form Factor (EMFF) experiments. An analysis of the rates in the coordinate detectors led us to select a "vertical" bending configuration for the magnet, in which the beam coordinate is used as a vertex for the momentum analysis, thus eliminating the need for a tracker between the target and the magnet. We selected GEM-based coordinate detectors for the GEP(5) experiment because drift chambers have too low a rate capability and insufficient coordinate resolution. The GEp(5) trackers will be reused in BigBite for the GEn(2) and the GMn experiments, which also require a high spatial resolution and good rate capabilities in their tracking detectors.

Considerations regarding the trigger rates and track reconstruction required the use of segmented calorimeters, whose robust operation in a high-background environment and good coordinate resolution provide the key to such high-luminosity measurements and an efficient event analysis. An analysis of the detector options for the neutron arm led us to modify the original plan for the neutron arm of the GEn(2)/GMn experiments. The high energy of the quasi-elastic neutrons allows an efficient use of the hadron calorimeter, which is a key part of the GEp(5) configuration. That calorimeter allows us to set the threshold 100-300 times higher than in a traditional plastic scintillator neutron detector, which results in a reduction of the calorimeter eliminates the event loss due to front-end dead time and provides a very good coordinate resolution of appr. 2 cm.

In this section we present background-related information: published data for the GEM-based detector rate capability, experimental data for the detector rate in the open-geometry BigBite spectrometer, projections for the background rate in the GEp(5) experiment based on a GEANT calculations, tracking analysis results for the different background rates and conclusions about the background issue.

### 5.3.1 GEM chamber rate capability and long term stability

Extensive studies of GEM-based chambers were performed by the COMPASS collaboration and the LHCb collaboration, as well as by other members of the very active RD51 collaboration [5]. The left panel of Fig. 5.13 shows the excellent gain stability as a function of the rate in the detector up to a very high hit rate. The expected hit rate in the GEM-based trackers for the GEp(5) experiment is three times the one projected for the LHCb muon chambers, but the latter is 100 to 200 times below the level at which the gain test measurements showed any effect.

The long-term stability of a GEM-based detector with a  $CF_4$ -based gas mixture was demonstrated in dedicated tests performed by the LHCb collaboration [23] (see the right panel of Fig. 5.13). The aging was not visible at a fast gas flow rate likely because the fast flow prevents etching of the kapton polymer inside the GEM foil. Similar results were published by COMPASS [24] for Ar-CO<sub>2</sub> gas mixtures. It was found that aging of the GEM-based detector was determined by the integrated charge passing through the last GEM foil. In LHCb the chamber will operate about 10 years at an average rate of 184 kHz/cm<sup>2</sup>. This needs to be compared to the 2-month run of the high-luminosity GEp(5) experiment, during which the chambers will accumulate an integrated charge about 15 times lower than that projected for the LHCb GEM-based chambers.



Figure 5.13: The gain variation in the GEM detector with counting rate (left panel) and the result of the detector aging study (right panel), which shows stable operation when the gas flow is 200 cc/min.

### 5.3.2 Background hit rate in the BigBite experiments

It is possible to use existing data from various BigBite experiments to gain a sense of the accuracy of the simulations we have used to estimate our background rates. The BigBite detector package, constructed for the GEn(1) experiment, includes three multi-plane drift chambers (MWDC). During the 2008 Transversity experiment a 5.9 GeV electron beam was used with the BigBite spectrometer at a central angle of 30° relative to the beam direction. A differential measurement was made with two target configurations: with and without hydrogen gas in the reference target cell. The luminosity with the target filled was  $1.55 \times 10^{36}$  electron-proton cm<sup>-2</sup>/s at beam current of 11.5  $\mu$ A. The difference in the rate in one MWDC plane was observed to be 9.8 MHz. The contribution from the "room

background" (low-energy particles that did not pass through the magnet aperture but traveled around the magnet yoke) was estimated through a serious of measurements, including inserting a 20 cm thick wooden plug into the magnet aperture, which reduced the MWDC rate by 30%, implying that roughly 2/3 of the rate was due to "room background". The experimental configuration of the current Hall A polarized <sup>3</sup>He target, in which the target cell is in a helium-air confinement with several vacuum windows in the beam line, results in nearly 90% of the material in the path of the electron beam being due to something other than target gas.

To make an estimate of the quality of our simulation techniques, we performed a GEANT simulation duplicating roughly the configuration that was used during Transversity. Our simulation included the BigBite magnet and a very simple target comprised of a glass target cell that could be filled (or not filled) with hydrogen. No beam line components were included. We found that the photons going through the BigBite magnet aperture and hitting the MWDC amounted to  $1.1 \times 10^{-5}$  per beam electron. Using a detection efficiency of 0.39%, we found a photon-induced rate difference (with or without hydrogen) of  $3.1\pm0.3$  MHz. The rate of pions and protons was estimated independently to be 1.1 MHz. When the pion and proton rates are taken into account, and importantly, when the room background due to the target gas itself are taken into account, the simulation and the BigBite measurements from Transversity differ by just under a factor of two.

Given the nature of our comparison, we find the above agreement to be quite reasonable. The data used for this estimate came from Transversity runs that were not designed to isolate some of the effects in which we are interested. The manner in which room background comes into the estimate, for example, could completely explain the discrepancy. Even so, it is reasonable to take this discrepancy as a bound on the accuracy of our simulations, and we discuss below how we could make fairly minor changes to accommodate a full factor of two increase in the rates used in our estimates. With this said, we note that such a discrepancy is not surprising due to differences between the GEANT model of the target and the complicated geometry of the polarized target setup, in which the target cell is in a helium-air confinement with several vacuum windows in the beam line. In contrast, the target configuration of the GEp(5) experiment is much simpler: liquid hydrogen in a simple aluminum cell placed in a vacuum chamber with a wide snout instead of the relatively narrow exit beam line used in the transversity experiment. We also note (as we will discuss below) that the GEANT simulation for GEp(5) was considerably more sophisticated than the simple exercise describe above.

### **5.3.3** Background hit rate in the GEp(5) trackers

The open geometry of the SBS, while offering large angular and momentum acceptances, also results in high background rates. In order to minimize this rate, special attention was given to the configuration of the beam line and the shielding. The principal geometry of the SBS equipment for the GEp(5) experiment is shown in Fig. 5.1.

The main hit rate in the Front Tracker is due to the interaction of soft photons from the target (from 100 keV up to few MeV) with the material before and inside the tracking detector. Electrons with an energy as low as 1 keV can also produce hits in the detector sensitive volume, but electrons produced in the target can not reach the detector because of the magnet; however, they can produce photons when interacting with high Z material, such as the iron of the magnet. These photons could contribute to the detector hit rate. However, the fringe field in front of the magnet repels practically all low-energy electrons, thus dramatically reducing this portion of the background. The type of material hit by electrons, and the location of that material (respect to the beam line, the magnet field, and the detector's view) play a key role in the background intensity. If, for example, the scattering chamber

has a thick wall, it becomes a significant source of photons.

### 5.3.4 Tracking analysis results for different background rates

The results of the tracking analysis were used to justify the specific design of the trackers: the number of chambers and the segmentation of the read-out. The design consideration was to have low event losses due to tracking inefficiency at the projected background rates. Table 5.4 shows the probability of event loss in the Front Tracker for several values of the incident background flux (see more in Section 5.2). The top line corresponds to the projected rates. In case the rates are higher than simulated, two improvements in the chamber design are considered. First, one of the two honeycomb plates in each chamber of the Front Tracker can be replaced by lighter material. Second, in addition to the first improvement, the strips of the two middle chambers can be separated into two halves.

Incident photon rate,	Probability loss	Probability loss	Probability loss		
kHz/cm <sup>2</sup>					
chamber type	standard	reduced material	reduced material		
strips divided in	two chambers	two chambers	four chambers		
400	1.65%	0.03%	0.00%		
600	100%	3.52%	0.22%		
800	100%	100%	6.95%		

Table 5.4: Probability of event loss in the **Front Tracker** vs. incident photon flux. The second column corresponds to the present design. The third column represents the version in which the chamber material is reduced by 30%; last column: the strips in the two middle chambers are separated, in addition to those in the rear two chambers.

This analysis allows us to avoid over-designed experimental equipment and at the same time to provide significant insurance in case the background rates are higher than expected.

**GEn(2) experiment background considerations:** The GEn(2) experiment is designed for a luminosity of  $4 \times 10^{37}$  cm<sup>-2</sup>/s, which is close to the maximum expected for a polarized He-3 target. Such a luminosity is about 10 times higher than used in previous polarized target experiments. The expected hit rates in the tracker will be appr. 50 kHz/cm<sup>2</sup>. The GEM-based tracker can easily handle such background rates and provide a three times better coordinate resolution than the existing tracker using drift chambers. This advanced coordinate resolution is crucial for the momentum analysis of the scattered electron and a high efficiency of tracking analysis.

**GEp(5) experiment background considerations:** In the proton arm of GEp(5) we plan to use three GEM-based trackers and an iron-scintillator-sandwich hadron calorimeter. The calculated counting rate in each tracker and the logic of data analysis were presented in Section 5.2. The counting rate of the hadron calorimeter was also calculated using the simulation code and checked directly with the known cross section of hadron electro-production.

The GEp(5) experiment is designed for a luminosity of  $8 \times 10^{38} \text{ cm}^{-2}$ /s with a large acceptance open detector. This results in a very high rate of uncorrelated and correlated events. Because of the two-body final state in elastic electron-proton scattering, the angular correlation between the scattered electron and the recoil proton is exact and a precise measurement of the correlation will select pure

elastic scattering events. The scattered electron has the maximum energy possible for any particle at a given scattering angle, while the energy of the recoil proton is very large in our high momentum transfer kinematics (Feynman variable for the hadron electro-production process  $x_F$  is 0.9 and  $p_{\perp} > 1.5$  GeV/c). These features result in the proposed analysis procedure (see Section 5.2), which effectively divides the large acceptance of the apparatus into a thousand small-aperture spectrometers.

**GMn experiment background configurations:** The detector setup of the GMn experiment and the analysis procedure will be very similar to that in GEn(2); however, the weak coupling of the neutron in the deuteron and its narrow momentum distribution allows much more restrictive cuts on the missing energy and the missing momentum. Such accurate cuts can be applied thanks to the excellent angular resolution of the neutron arm. As a result, the GMn measurement can be carried out at a luminosity several times higher than that of GEn(2).

### 5.3.5 Conclusions

- For the configurations of the EMFF experiments, including GEp(5), the tracking detector rates will be at least 100 times below the experimentally observed rate capability for GEM-based chambers. This conclusion is supported by experimental data obtained during measurements with the BigBite spectrometer.
- The GEANT simulation of the background rate is lower than measurements have shown by a factor of at most two, which provides an upper limit for a possible under-estimate of the background rate in the Super Bigbite trackers.
- The tracking analysis in the Super Bigbite detector provides a close to 99% efficiency at the projected background rate and remains high (above 90%) even for a 50% higher background. If the rates are even higher we have two options planned, each of which need only be implemented in the Front Tracker (the polarimeter tracker rates have very small uncertainties). In the first option we will increase the segmentation in the readout, and in the second we will reduce the amount of material in the GEM chamber.

# Chapter 6

# **Physics Program and Experimental Plans**

The development of an understanding of nucleon structure and the nature of quark confinement is one of the most important endeavors facing physics today. Indeed, among other things, the dynamical generation of mass within the nucleon largely answers one of the great questions facing science: What is the origin of mass? While the Higgs mechanism is often invoked in response to this question, David Gross, in his Nobel Lecture in 2004 stated, "This is incorrect. Most, 99% of the proton mass, is due to the kinetic and potential energy of the massless gluons and the essentially massless quarks, confined within the proton." [26] During his lecture Gross at one point calls the understanding of the non-perturbative region of QCD " ... one of the most important areas of theoretical physics." The structure of the nucleon is to nuclear physics, in the early 21st century, what the structure of hydrogen was to atomic physics during the early 20th century.

While a true solution to QCD in the non-perturbative regime remains elusive, enormous progress has been made. Sophisticated phenomenological models have helped to elucidate the relevant degrees of freedom within the nucleon. Some of these models even come tantalizingly close to something approaching an analytical approach. Perturbative QCD (pQCD), while it cannot be used to calculate such underlying quantities as form factors and structure functions, can predict how these quantities evolve with  $Q^2$ . Theoretical advancements such as the development of Generalized Parton Distributions have even allowed us to understand both structure functions and form factors within a single unifying framework. In addition, lattice QCD, which may ultimately provide arbitrarily accurate numerical solutions to just about any question we may pose, has made stunning progress. Again in his Nobel Lecture, Gross notes the enormous progress in Lattice QCD in " ... achieving now reliable results that fit the low-lying spectrum to a few percent!"

One of the critical factors driving progress in understanding nucleon structure is the availability of precision experimental results at the largest possible  $Q^2$ . The observation of the surprising  $Q^2$ dependence of  $G_E^p/G_M^p$  has generated more theoretical papers than any other result to come out of JLab. Measurements of  $G_E^n/G_M^n$ , both at JLab and at MIT/Bates, were explicitly mentioned in the 2007 NSAC Long Range Plan (LRP), and there is considerable anticipation regarding more recent results that push both  $G_E^p/G_M^p$  and  $G_E^n/G_M^n$  to higher values of  $Q^2$ . Regarding measurements of the groundstate form factors after the CEBAF upgrade, the 2007 LRP states that "Such measurements remain the only source of information about quark distributions at small transverse distance scales." Indeed, most of the current theoretical approaches to understanding nucleon structure, including phenomenological models, analysis based on GPDs and lattice calculations all require input and constraints from formfactor measurements. Furthermore, as we will show in this document, the experimental approach embodied in the Super Bigbite Project is likely to be the only one that will have both the reach in  $Q^2$  and the precision to resolve the most pressing theoretical questions.

### 6.1 Formalism

The most general form for a relativistically covariant hadronic current for a spin-1/2 nucleon that satisfies current conservation is

$$\mathcal{J}^{\mu}_{\text{hadronic}} = e\overline{N}(p') \left[ \gamma^{\mu} F_1(Q^2) + \frac{i\sigma^{\mu\nu}q_{\nu}}{2M} F_2(Q^2) \right] N(p), \tag{6.1}$$

where N(p) and  $\overline{N}(p')$  are the nucleon Dirac spinors for the initial and final momenta p and p', respectively, and  $F_1(Q^2)$  and  $F_2(Q^2)$  are the Dirac and Pauli form factors. It is often convenient to express cross sections and other measurable quantities in terms of the electric and magnetic Sachs form factors which are defined as

$$G_{E} = F_{1} - \tau F_{2} \text{ and } G_{M} = F_{1} + F_{2},$$
 (6.2)

where  $\tau = Q^2/4M_{nucleon}^2$ . In terms of the Sachs form factors, the differential cross section for elastic scattering can be written

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}} \left(G_E^2 + \tau \left[1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right]G_M^2\right) / (1+\tau),\tag{6.3}$$

where  $\theta_e$  is the scattering angle in the lab frame and  $\left(\frac{d\sigma}{d\Omega}\right)_{\text{Mott}}$  is the Mott cross section defined by  $\sigma_{\text{Mott}} = (e^2/2E_{\text{beam}})(\cos^2\frac{\theta_e}{2}/\sin^4\frac{\theta_e}{2})$ . Using Eq. 6.3, it is possible to disentangle the electric and magnetic form factors by performing measurements at a well-chosen set of values of both  $Q^2$  and  $\theta_e$ , a process known as a Rosenbluth separation.

At high  $Q^2$ , there are at least two issues that represent significant challenges when performing Rosenbluth separations. One has long been recognized, that at higher values of  $Q^2$  the term involving  $G_M$  dominates, making it difficult to perform an accurate extraction of  $G_E$ . Another issue that has come to light in recent years, however, is more subtle. The validity of Eq. 6.3 depends on the onephoton or Born approximation. It has now been established that two-photon contributions to the cross section can, at high  $Q^2$ , be sufficiently large that the extraction of the form factors (using a Rosenbluth separation) is severely compromised. This makes it desirable to seek other means for determining form factors.

The double polarization method for the measurement of the  $G_E$  was originally proposed in 1957 [27]. It aimed to improve experimental sensitivity to the spin-flip form factor  $F_2$  at large momentum transfer. A large number of form-factor measurements have been performed in recent years using both versions of this method: one involving a polarized beam and a polarized target, and one involving a polarized beam and a recoil polarimeter. The factors defining the Figure-of-Merit in a double-polarization experiment are the cross section, the detector acceptance, and the asymmetry that results from either the degree of target polarization or the analyzing power and efficiency of the recoil polarimeter.

For the proton form factor the best sensitivity has been achieved using the recoil polarization ratio approach [28]. In the one-photon exchange approximation the scattering of longitudinally polarized electrons from unpolarized hydrogen results in a transfer of polarization to the recoil proton with two components,  $P_t$  perpendicular to, and  $P_\ell$  parallel to the proton momentum in the scattering plane [27, 29]:

$$I_0 P_t = -2\sqrt{\tau \left(1+\tau\right)} G_{\scriptscriptstyle E} G_{\scriptscriptstyle M} \tan \frac{\theta_e}{2} \tag{6.4}$$

$$I_0 P_\ell = \frac{1}{m_p} \left( E_{beam} + E'_e \right) \sqrt{\tau \left( 1 + \tau \right)} G_M^2 \tan^2 \frac{\theta_e}{2}, \tag{6.5}$$

where  $E'_e$  is the final electron energy, and  $I_0 \sim G_E^2 + \frac{\tau}{\epsilon} G_M^2$ . Measuring these two components simultaneously and taking their ratio gives the ratio of the form factors:

$$\frac{G_E}{G_M} = -\frac{P_t}{P_\ell} \frac{(E_e + E'_e)}{2m_p} \tan \frac{\theta_e}{2}$$
(6.6)

Using the polarization technique, the form factor ratio  $G_E/G_M$  at a given  $Q^2$  can be obtained without measuring the absolute cross sections and without change of beam energy or detector angle, thus eliminating important sources of systematic uncertainties. Note that the analyzing power of the polarimeter and the beam polarization that come into an actual measurement of  $P_t$  and  $P_\ell$ , cancel out in Eq. 6.6, and thus do not need to be known particularly well. They do affect the size of the measured asymmetries, however, so they still need to be maximized to increase the experimental Figure-of-Merit.

In Fig. 6.1 we show existing data for  $G_E^p/G_M^p$ , the projected errors for GEp(5), and the results of several theoretical calculations. The figure makes it clear that the only way to achieve clarity in discriminating between theoretical explanations of the  $G_E^p/G_M^p$  data is to measure the proton form factor ratio with considerable precision to high values of  $Q^2$ . For example, three of the predictions shown, the relativistic constituent quark model (RCQM, Miller 2002) [34, 35], the DSE/Faddeev calculation [36, 37], and the refined pQCD calculation ( $F_2/F_1 \propto \ln^2(Q^2/\Lambda^2)/Q^2$ ) [38], all predict  $G_E^p/G_M^p$  to cross zero somewhere in the neighborhood of  $Q^2 \approx 7 \text{ GeV}^2$ . At the same time, the two vector-meson dominance (VMD) models show  $G_E^p/G_M^p$  approaching zero much more gradually [39, 40]. GEp(1) and GEp(2) agree reasonably well with all of these predictions. In contrast, the preliminary GEp(3) data appear to favor the VMD models. A definitive resolution to this issue has profound physical implications, and cannot occur without high-precision data at high  $Q^2$ . We note in passing that the new (near-final) results from GEn(1) tend to favor the DSE/Fadeev and RCQM calculations over the VMD models. Indeed, it appears that form-factor measurements are at the cusp of obtaining crisp answers to the host of questions that were first opened by the work of Jones *et al.* in Ref. [30].

The neutron FF measurements have been performed using both techniques, involving either a polarized target or a recoil polarimeter. Due to recent advances in polarized <sup>3</sup>He target technology (mostly achieved by our collaboration), the Figure-of-Merit of such measurements is about 50 times higher than in recoil-polarimeter experiments (off the deuteron) when at large  $Q^2$ , a fact that is reflected in the projected precision of these two methods as can be seen in Fig. 6.1. The double-polarization asymmetry that occurs when scattering a polarized electron off a polarized nucleon can be written as

$$A = A_{\perp} \sin \theta^* \cos \phi^* + A_{\parallel} \cos \theta^* = \frac{a \cdot (G_E/G_M) \sin \theta^* \cos \phi^*}{(G_E/G_M)^2 + c} + \frac{b \cdot \cos \theta^*}{(G_E/G_M)^2 + c}, \tag{6.7}$$

where,

 $a = -2\sqrt{\tau(1+\tau)}\tan(\theta_e/2), b = 2\sqrt{\tau[1+(1+\tau)\tan^2(\theta_e/2)]}$  and  $c = \tau(1+2(1+\tau)\tan^2(\theta_e/2)).$ Here  $\phi^*$  is the angle that the nucleon scattering plane makes with the scattering plane defined by the electron, and  $\theta^*$  is the angle that the hadron polarization makes with the three-momentum transfer  $\vec{q}$  of



Figure 6.1: Shown are existing data and projected errors for measurements of the ratios of the electric and magnetic form factors of the proton (left panel) and neutron (right panel). The projected errors for the measurements made within the Super Bigbite project are shown by the open red squares. On the left panel are shown the published results of GEp(1) [30], GEp(2) [31], preliminary results from GEp(3) [32] and the projected results of GEp(5) in a 60-day run [6]. The various theoretical curves are discussed in the text. On the right-hand panel, for  $G_E^n/G_M^n$ , we show published data including those due to Madey and co-workers [33], and preliminary results of GEn(1) (E02-013). We also show the projected errors of GEn(2), which is part of the Super Bigbite project, and E12-09-006 with SHMS (open blue points).

the virtual photon. For the case of  $\phi^* = 0$  or  $180^\circ$  and  $\theta^* = 90^\circ$ , the asymmetry  $A = A_{\perp}$ , and is nearly proportional to  $G_E/G_M$ . In fact, even if  $\phi^*$  is close to 0 and  $\theta^*$  is close to  $90^\circ$ , it is quite easy to fit the data to Eq. 6.7.

Whether working with a polarized target or a recoil polarimeter, the double-polarization asymmetry has only a negligible contribution from two-photon effects, and for high  $Q^2$ , it has become the gold standard for any form-factor measurement.

### 6.2 Physics content of form factors

The ground-state elastic form factors of the proton and the neutron encode fundamental information that provides us with considerable insight into nucleon structure. Historically, Hofstadter's measurements of the proton provided us with our first understanding of the proton's finite size. Today, precision measurements of the electric and magnetic form factors have provided unprecedented knowledge of both  $F_1$  and  $F_2$  for both the proton and the neutron. These measurements have both: confirmed scaling expectations for  $F_1$ , and brought surprises for  $F_2$ . Indeed, the high values of  $Q^2$  that can be studied at CEBAF have presented a significant challenge to theory, and as a result, our picture of the nucleon has been profoundly changed. Some of the recent theoretical studies of the ground-state FFs provide new insight into the physical structure of the nucleon, and testing these ideas represents an exciting opportunity to clarify the structure of the nucleon using QCD degrees of freedom.

### pQCD scaling and scaling violations

As was discussed earlier, there exist scaling relations for the form factors  $F_2$  and  $F_1$ , arising essentially from quark counting rules, that were derived some time ago by Brodsky and Farrar [41]. They argued

that at sufficiently high values of  $Q^2$ , the Dirac form factor  $F_1$  should scale like  $1/Q^4$ , and the Pauli form factor  $F_2$  should scale like  $1/Q^6$ . Their reasoning has an appealing simplicity. In elastic scattering, for  $F_1$ , if the three quarks in the final state are to emerge in the ground state, they must exchange gluons in the process. For three quarks, there will be two gluon exchanges, each associated with a factor of  $1/Q^2$ , resulting in scaling that goes like  $1/Q^4$ . For  $F_2$ , assuming the quarks are moving in a collinear fashion (with no relative transverse motion) a spin flip is involved, resulting in an additional factor of  $1/Q^2$ . In Fig. 6.2a, we show early data from SLAC on  $F_1^p$  in which scaling behavior appears to begin at a  $Q^2$  of around  $10 \text{ GeV}^2$ . Accurate high- $Q^2$  data on the ratio  $F_2/F_1$ , which according to the scaling rules of Brodsky and Farrar should scale like  $1/Q^2$ , were not available until JLab came on line. With the publication by Jones *et al.* of Ref. [30], however, it became clear that both  $G_E^p/G_M^p$  and similarly  $F_2^p/F_1^p$  did not behave as expected, and showed no evidence of scaling over the range of  $Q^2$ for which accurate measurements were made. The failure of this scaling, and equivalently the failure of  $G_E^p/G_M^p$  to remain constant, came as a great surprise, and is viewed by many as the most striking result to date to come out of JLab.



Figure 6.2: Shown in (a) are early SLAC data in which  $Q^2 F_1^p$  is plotted versus  $Q^2$ . Scaling is clearly visible above something like 10 GeV<sup>2</sup>. In (b), data on  $Q^2 F_2^p / F_1^p$  are plotted, and scaling is clearly not visible. In both plots, the solid lines represent calculations involving model-independent sum rules of GPDs. In (b), the lines show pQCD calculations by Belitsky, Ji, and Yuan [38] that predict  $Q^2 F_2 / F_1 \propto \ln^2(Q^2/\Lambda^2)$ , where  $\Lambda$  is a non-perturbative mass scale.

Clearly, a more sophisticated description is needed to describe some of the new FF data. One approach involves calculations of the FFs using model-independent sum rules of generalized parton distributions (GPDs). The results of such calculations are shown in both Figs. 6.2a and b with the solid lines. We will discuss this approach further in a subsequent section. Another approach is a pQCD calculation performed by Belitsky, Ji, and Yuan [38]. In their calculation, they relaxed the assumption of Brodsky and Farrar that the quarks were moving collinearly with the proton. They included

components in the light-cone nucleon wave functions with quark orbital angular momentum projection  $L_z = 1$ , equivalent to relaxing hadron helicity conservation, and obtained the scaling relation  $F_2/F_1 \propto \ln^2(Q^2/\Lambda^2)/Q^2$ , with  $\Lambda$  being a non-perturbative mass scale. The resulting expected behavior of  $F_2/F_1$  is shown in Fig. 3 for both  $\Lambda = 200$  MeV and  $\Lambda = 500$  MeV. The agreement up to  $Q^2 = 6$  GeV<sup>2</sup> appears quite good, although the agreement above 6 GeV<sup>2</sup> with the preliminary results of GEp(3) is not as impressive. In retrospect, the failure of  $F_2/F_1$  to follow simple  $1/Q^2$  scaling is not surprising, and the observation has been quite valuable for achieving a better understanding of nucleon structure in terms of pQCD. If the logarithmic scaling of Belitsky *et al* turns out to be correct, the striking implication would be that quark orbital angular momentum is playing an important dynamical role in the  $Q^2$ -evolution of the proton form factors. It is also the case that we would still expect  $F_2/F_1$  to scale like  $1/Q^2$  at sufficiently high values of  $Q^2$ . Finding out where this occurs is important, and will require precise measurements at significantly higher values of  $Q^2$ .

### Dyson-Schwinger Equation (DSE) calculations

For all the insight that we gain from pQCD, we learn rather little about many of the most important issues concerning nucleon structure such as the dynamical generation of mass through Dynamical Chiral Symmetry Breaking (DCSB) and quark confinement. There are, however, analytical techniques that at least in principle appear to have the potential to provide solutions to certain aspects of QCD in the non-perturbative regime with arbitrarily high accuracy. One such technique is based on the infinite tower of Dyson-Schwinger equations (DSEs) that relate the Green's functions of a field theory to each other [42]. In principle, solving the DSEs provides a solution to any field theory. In any practical calculation, however, the DSEs must be truncated, and some Ansätze must be employed to account for the omitted functions. By carefully maintaining certain properties of the theory, however, such as local and global symmetries, considerable progress can be made. Recent calculations, for instance, explicitly describe the dynamic generation of the mass of constituent quarks, and show excellent agreement with the lattice QCD results, presently obtained with somewhat large quark masses. In Fig. 6.3 the dressed-quark mass function M(p) is shown[43] as a function of momentum for a variety of quark flavors.



Figure 6.3: Dressed-quark mass function,  $M(p^2)$ . The solid curves show DSE results and the "data" represent unquenched LQCD calculations which are in good agreement with the DSE results. In this figure one observes the current-quark of perturbative QCD evolving into a constituent quark as its momentum becomes smaller.

Using dressed quarks as the elementary degrees of freedom, one can calculate nucleon form factors

using a Poincaré covariant Faddeev equation, as has been done recently by Cloët *et al.* [37]. These authors also assume that two of the quarks couple into a diquark. While still an approximation, the DSE/Faddeev approach incorporates some features (such as the dressed quarks) that are based closely on the fundamental implications of QCD. Also, it is well constrained by the nucleon's static properties such as mass and magnetic moment. It is limited, however, in that there are precisely three (and for instance, not five) constituent quarks used as an input to the calculation. Even so, as mentioned earlier, it is reasonable to assume dominance of the 3-quark component of the wave function at relatively high values of  $Q^2$ . In fact, as is evident from Fig. 6.1, the DSE/Faddeev calculations provide a remarkably good fit to the available data, something that may indicate important aspects of the nucleon's structure, such as, for instance, the potential relevance of diquarks as a degree of freedom. It is also interesting to note that at high  $Q^2$ -values of around  $10 \text{ GeV}^2$ , for the neutron, the predictions of the DSE calculations differ markedly from those expected from the scaling predictions of Belitsky, Ji, and Yuan [38]. Also, again for the neutron, the DSE calculations make the interesting prediction of a zero in  $G_E^n$  at around  $10 \text{ GeV}^2$ , a prediction that would be tested in the course of the proposed Super Bigbite program.

### Constituent-quark models

Constituent-quark models have a long history of providing physical insights into nucleon structure, and that is certainly true regarding the interpretation of the form-factor measurements that have come out of JLab. In 1996, Frank, Jennings and Miller published a paper [44] that included calculations of form factors using a relativistic constituent-quark model. While it was not the primary focus of their paper, their results predicted a very strong decrease of  $G_E/G_M$  as a function of  $Q^2$ . Following the publishing of the  $G_E^p/G_M^p$  results by Jones *et al.* [30], Miller and Frank published another paper showing that the decrease of  $G_E/G_M$  is associated with a violation of helicity conservation [34] and non-zero quark orbital angular momentum. A subsequent paper by Miller used the so-called "light-front cloudy bag model" to successfully reproduce much of the form-factor data over a broad range of  $Q^2$  [35].

A considerable amount can be learned from the calculations of Miller *et al.* and those that preceded them. When calculating form factors for anything but rather low momentum transfer, it is necessary to work with wave functions that are Poincaré invariant. The most practical way to do this is to work with so-called light-front wave functions. As discussed in Ref. [45], the light-front calculations of a number of authors (including calculations that precede Miller) consistently show a strong decrease of  $G_E/G_M$  as a function of  $Q^2$ . The general success of these calculations can be attributed to the fact that they are *relativistic* constituent-quark models. Once the wave functions are Poincaré invariant, the decrease in  $G_E/G_M$  appears to be more-or-less guaranteed. Again, hindsight is everything. A properly relativistic quark model naturally includes the dynamical importance of quark OAM.

A limitation that is inherent to constituent-quark model calculations is that they do not respect the chiral symmetry of the QCD Lagrangian. An early example of a model that restores chiral symmetry is the cloudy bag model. The breaking of chiral symmetry gives rise to the pions, so by including them, it is possible to restore the symmetry of the theory. The inclusion of the pions then leads to a pion cloud, which in turn governs certain aspects of the low- $Q^2$  behavior of the form factor, as was discussed earlier.

What we learn from all of this is that by constructing a model that approximately obeys both Poincaré invariance and chiral symmetry, we are led to the importance of both quark orbital angular momentum and the pion cloud. These are lessons that presumably have relevance beyond CQM calculations. Finally, we find that a light-front cloudy bag model that does a good job reproducing the proton data also makes definite predictions for  $G_E^n/G_M^n$ . Thus, by measuring both  $G_E^p/G_M^p$  and  $G_E^n/G_M^n$  to high  $Q^2$ , we perform a stringent test of the model and gain considerable insight regarding its validity.

#### Lattice QCD

Using lattice QCD (LQCD), it is possible to perform truly *ab initio* calculations of the nucleon form factors. The accuracy of such calculations, however, is limited by a number of factors, many of which will become less important as computational power steadily increases. Even so, meaningful calculations are now being performed up to values of  $Q^2$  as high as roughly  $4 \text{ GeV}^2$ , which covers the range for which data are presently available for *both* the proton and the neutron. As one of the most fundamental properties of the nucleon, form factors provide a powerful test of LQCD. It has even been suggested that the lattice calculations will soon be approaching the point where they can provide useful guidance for experimental programs[46].

Certain quantities, such as the isovector form factors  $F_1^V$  and  $F_2^V$ , which represent the difference between the proton and the neutron, can be computed more reliably than other quantities. This is because there is a class of disconnected diagrams that drops out when considering the difference. It was also pointed out by Göckeler *et al.* that it might be interesting to consider ratios of form factors in order to reveal deviations from naive scaling assumptions[47]. They calculated the ratio of the flavorseparated form factors  $F_1^d/F_1^u$ . In Fig. 6.4 we show a band representing the range covered by their estimates together with experimental data. The agreement with experiment is quite reasonable, despite the fact that the aforementioned disconnected diagrams were not included in the calculation, and the calculation was performed with quark masses corresponding to a pion mass of 400 MeV. Perhaps it is possible that the good agreement is due partly to cancellations that occur in forming the ratio. While there is clearly much work to be done, Fig. 6.4 illustrates the interesting stage to which LQCD calculations of form factors has advanced.



Figure 6.4: Data for the flavor-separated nucleon form-factor ratio  $F_1^d/F_1^u$  is plotted as a function of  $Q^2$ . The band indicates the range resulting from a lattice QCD calculation using a pseudoscalar mass of 400 MeV. Separation involving the preliminary results of the GEn(1) experiment are shown by the red triangles. Calculations using a GPD model [48] and the DSE approach are shown by the solid and dashed lines, respectively.

It is worth mentioning that a number of techniques are being employed to overcome practical limitations in LQCD calculations. For instance, both  $\chi$ PT and  $\chi$ EFT are sometimes used to extrapolate to the chiral limit. This is particularly important for form-factor calculations because a strong dependence on the pion mass is expected when approaching realistic quark masses.

The interplay between LQCD calculations, other calculational techniques and experiment can be very powerful. While LQCD calculations of form factors clearly have a way to go, they are already providing serious predictions that are often in reasonable agreement with experiment, particularly

under favorable circumstances. Such comparisons facilitate refinement of the LQCD calculations, and the calculations, in turn, provide deeper insight into nucleon structure. Comparison between lattice results and analytical calculations are also tremendously useful, particularly when the lattice calculations provide information on regimes that are experimentally difficult to access. For example, such comparisons can sometimes provide powerful physical insight by helping to clarify whether the degrees of freedom being used in an analytical calculation are indeed appropriate. The fact that the interplay between the lattice, analytical calculations and experiment has now begun to include the study of form factors marks an important milestone.

### Generalized Parton Distributions

As has been extensively discussed elsewhere, Generalized Parton Distributions (GPDs) provide a far more detailed picture of nucleon structure than has ever been the case previously [49, 50]. Among other things, the GPD's provide a unified framework that incorporates both the structure functions that are measured in deep inelastic scattering (DIS) as well as the ground-state electromagnetic form factors. The GPDs tell us about correlations between spatial and momentum degrees of freedom which thus enables the construction of various types of "3-D images" of the nucleon. One example is the *u*quark phase-space charge distributions shown in Fig. 6.5. Here the vertical axis is "z", along the beam, the horizontal axis is "r", a radial coordinate, and the three pictures correspond to Bjorken x of 0.01, 0.4 and 0.7, respectively. Many interesting features emerge from such visualizations. For instance, for the x = 0.01 image the struck quark has very little longitudinal momentum. From the Heisenberg uncertainty relation, we would thus expect it to be relatively "deconfined" in the *z* direction, which is exactly what we see. In contrast, in the image corresponding to x = 0.7 the large longitudinal momentum carried by the struck quark permits a considerable amount of localization, which again is evident from the figure.



Figure 6.5: Phase-space charge distributions for the u quark for a particular GPD model from Ref. [49]. From left to right, the images correspond to x = 0.01, 0.4 and 0.7, respectively. The vertical axis corresponds to z (the beam direction) and the horizontal axis corresponds to the radial coordinate r.

An excellent example of a result to come out of GPDs is the formulation of the "Ji Sum Rule" which relates the total angular momentum of the quarks to sums over some of the GPDs. Since polarized DIS results provide insight into the fraction of the nucleon spin that is carried by the spin of the quarks, the combination of the determination of GPDs together with polarized DIS makes it possible to determine the fraction of the nucleon spin due to quark orbital angular momentum. The Ji Sum Rule provides an

important key to understanding the origin of the spin of the nucleon.

Knowledge of the nucleon elastic form factors is critical to the experimental determination of GPDs. The GPDs H and E are functions of the longitudinal momentum fraction x, a skewness parameter  $\xi$ , and  $Q^2$  (see [49] for details). The first moments of the GPDs are related to the elastic form factors of the nucleon through model-independent sum rules:

$$\int_{-1}^{+1} \mathrm{d}x \, H^q(x,\xi,Q^2) = F_1^q(Q^2) \quad \text{and} \quad \int_{-1}^{+1} \mathrm{d}x \, E^q(x,\xi,Q^2) = F_2^q(Q^2). \tag{6.8}$$

These relations currently provide some of the most important constraints on the forms of the GPDs. Since it is extremely unlikely that the GPDs will be exhaustively mapped out any time soon, even after the JLab upgrade, constraints such as those in Eq. 6.8 will be critical to the practical determination of GPDs. Already the constraints from Eq. 6.8 have played an important role in the first estimates of nucleon quark angular momentum using the Ji Sum Rule. One could argue that constraining GPDs is by itself an excellent reason to experimentally determine the nucleon elastic form factors.

### 6.3 Planned measurements

As discussed earlier, we plan to make three measurements of the ground-state electromagnetic form factors: one of  $G_E^n/G_M^n$ , one of  $G_E^p/G_M^p$ , and one in which we will make a detailed comparison of  $G_M^n$  and  $G_M^p$ . These three measurements, together with a very precise measurement of  $G_M^p$  using the Hall A HRS Spectrometers (not part of the Super Bigbite Program), will collectively provide precise determinations of all four nucleon form factors with unprecedented reach in  $Q^2$ . As discussed earlier, the Figures-of-Merit of these measurements represent an improvement by a factor of between 10 and 50 over all past and proposed competing efforts. Together with small projected systematic errors, the Super Bigbite project will provide unique accuracy in a  $Q^2$  regime with impressive discovery potential.

## Neutron Electromagnetic Form-Factor Ratio $G_E^n/G_M^n$ up to $Q^2 = 10 \text{ GeV}^2$

The GEn(2) experiment (E12-09-016), which was approved in January of 2009 by PAC34, will measure a double-spin asymmetry in quasi-elastic scattering of polarized electrons from a very-highluminosity polarized <sup>3</sup>He target using the reaction  ${}^{3}\overrightarrow{\text{He}}(\overrightarrow{e}, e'n)pp$ . A schematic representation of the experimental setup is shown in Fig. 7. The scattered electron will be detected using a modified version of the BigBite spectrometer, the aforementioned spectrometer that was used during GEn(1). The BigBite detector package, however, will include the GEM tracking system that is being built as part of the Super Bigbite project. More specifically, the GEM trackers in BigBite will be those that will also be used in the GEp(5) recoil-proton polarimeter. The recoil neutron will be detected using a large segmented hadron calorimeter that will also be used in the proton arm of GEp(5). For GEn(2), the Super Bigbite magnet itself will be located between the target and the hadron calorimeter, and will make it straightforward to distinguish between charged and neutral quasi-elastic events.

The physics impact of GEn(2) is illustrated in the right-hand panel of Fig. 6.1 which shows data from existing measurements as well as the projected errors from this and the Hall C  $G_E^n$  measurement (E12-09-006). GEn(2) will make measurements at  $Q^2$ -values of 5.0, 6.8 and 10 GeV<sup>2</sup> and will require approximately 58 days of running. The projected errors for the new GEn(2) points can be seen to be roughly 20% of the often cited Galster parameterization. One should also note that the three highest-value  $Q^2$ -points that currently exist represent the results from GEn(1), an experiment performed by



Figure 6.6: Shown is a schematic but scaled representation of the setup that will be used for both the GEn(2) (E12-09-016) and the Hall A GMn experiments (E12-09-019). While the target will be polarized <sup>3</sup>He for GEn(2) and deuterium for the GMn experiment, most other components are identical.

many of the same people involved in the Super Bigbite project. GEn(2) has a Figure-of-Merit that is a factor of 50 larger than the only competing effort, the Hall C GEn measurement (E12-09-006). This is quite evident in Fig. 1. The highest  $Q^2$ -point proposed as part of E12-09-006 is at 6.9 GeV<sup>2</sup>. GEn(2), which will measure up to  $Q^2 = 10 \text{ GeV}^2$ , has a close-by point at  $6.8 \text{ GeV}^2$ . The projected GEn(2) error at this point is more than four times smaller than the corresponding point in E12-09-006, and will be obtained in one fourth the time.

GEn(2) will require an increase in effective usable luminosity over GEn(1) of more than an order of magnitude. It should also be noted that the effective luminosity of GEn(1), when it was performed, represented more than an order-of-magnitude increase in effective luminosity over earlier experiments to measure  $G_E^n$ . The gains in GEn(1) were due largely to three factors: 1) the use of a highly-optimized polarized <sup>3</sup>He target, 2) the ability to collect excellent statistics using the open-geometry dipole spectrometer BigBite and 3) the use of what was then (and probably still is) the world's largest dedicated neutron detector. The additional gains that will come with GEn(2) result from 1) a further upgraded polarized <sup>3</sup>He target that will be able to tolerate beam currents in excess of 60  $\mu$ A while delivering even higher polarization[51], 2) greatly increased rate-handling capability using GEM technology, 3) the use of the Super Bigbite magnet to greatly simplify the identification of charged events, 4) a neutron detector (using our hadron calorimeter) with suppression of background by more than a factor of 200, and of course, 5) the higher beam energy available from the upgraded CEBAF.

In summary, GEn(2) is, by a wide margin, the only experiment that can provide precise measurements of  $G_E^n$  up to  $Q^2 = 10 \text{ GeV}^2$ , a regime that is critical to understanding  $G_E^n$  in terms of QCD degrees of freedom. In fact, GEn(2) is the only experiment with precision above something like  $5 \text{ GeV}^2$ . The experiment builds on the success of GEn(1), but achieves more than an order of magnitude improvement in the Figure-of-Merit through the innovations mentioned above. GEn(2) will provide unprecedented insight into the ground-state structure of the neutron in the heart of the  $Q^2$ -regime where important discoveries have been made on the proton.

### Proton Form-Factor Ratio Measurements up to 14.5 GeV<sup>2</sup> using Recoil Polarization

GEp(5) (E12-07-109) was approved by PAC32 in August of 2007 and was the experiment that provided the original motivation for the Super Bigbite project. It will measure the ratio  $G_E^p/G_M^p$  using the polarization-transfer method and the reaction  $p(\vec{e}, e'\vec{p})$ . The polarization of the recoil proton will be measured using a large-acceptance spectrometer, based on the Super Bigbite magnet, that will incorporate a double polarimeter instrumented with GEM trackers and a highly-segmented hadron calorimeter. The electron will be detected in coincidence by a large existing electromagnetic calorimeter that is sometimes referred to as "BigCal". The target will be the standard Hall A LH<sub>2</sub> cryotarget. A schematic representation of the experiment is shown in Fig. 8.



Proton form factors ratio, GEp(5) (E12-07-109)

Figure 6.7: Shown is a schematic but scale representation of the setup that will be used for GEp(5) (E12-07-109). The proton arm (set at a central scattering angle of  $12^{\circ}$ ) incorporates a double polarimeter instrumented with GEM trackers and a highly segmented hadron calorimeter. The electron arm uses the existing "BigCal" electromagnetic calorimeter based on lead glass.

For GEp(5), measurements will be made at three values of  $Q^2$ : 5, 10, and 14.5 GeV<sup>2</sup>, thus nearly doubling the maximum value of  $Q^2$  achieved by GEp(3), while achieving an error in the ratio  $G_E^p/G_M^p$  of 0.10. The precision and reach of GEp(5) are illustrated in Fig. 6.1 in which we show results from GEp(1) and GEp(2), preliminary results for GEp(3), and the anticipated errors for GEp(5). The excellent precision that GEp(5) will obtain at 14.5 GeV<sup>2</sup> is clearly evident.

The measurement of the ground-state electromagnetic form factors becomes quite challenging at high momentum transfer because the effective rate drops as roughly  $E_{beam}^2/Q^{16}$ . All other things being equal, the polarization-transfer method also requires very large statistics because of the relatively low analyzing power of the recoil polarimeter. The GEp(5) experiment meets these challenges through a fairly innovative approach. The spectrometer in the proton arm is based on a large open-geometry dipole magnet that is placed quite close to the target, and at a fairly small angle, a configuration that provides large solid angle at kinematics that have favorable statistics. The placement of the dipole is only made possible by incorporating a cut in yoke for the beam line. The spectrometer will also be equipped with a double polarimeter that provides improved efficiency. For the electron arm, an existing electromagnetic calorimeter, "BigCal", will be used. BigCal is large enough to match the acceptance of the proton arm, and will also be equipped with a tracker to further improve position resolution. The GEp(5) experiment will use the 11 GeV polarized electron beam and a 40-cm long liquid hydrogen target.

In contrast to more common approaches in the spectrometers used at JLab, Super Bigbite uses a single dipole for magnetic analysis, has a relatively small field integral, and has an open geometry which means that the detector is in direct view of the target. While this approach has big advantages in terms of statistics, it has the drawback of high background rates. The Super Bigbite project, how-ever, includes novel tracking detectors based on GEM technology, which have excellent rate-handling capacity. In fact the GEMs we will use have been demonstrated at both COMPASS and LHC to be capable of handling more than 50 times higher rate than we expect during the Super Bigbite measurements. Our understanding of these rates is based on our experience during both the GEn(1) and the more recent Transversity experiments (both of which used the BigBite spectrometer) together with GEANT and Monte Carlo studies. Regarding track reconstruction, we handle the high rates, as was also the case with BigBite, by using high redundancy in the number of tracking planes. It is worth noting that the suppression of ambiguity in the track reconstruction is highly nonlinear with the addition of planes, adding one plane of GEMs compensates for a doubling or tripling in rate.

There are several features of the GEp(5) experimental design that are quite favorable from the perspective of controlling systematic errors. The implementation of the polarization-transfer method that we are using involves measuring the ratio of the transverse and longitudinal proton polarizations. This eliminates the systematics coming from the beam polarization and the polarimeter analyzing power. However, the mixing of the polarization projections during spin rotation in the spectrometer's magnetic field has the potential for causing a problem. In GEp(5), where we will be using a simple dipole magnet, it is relatively straightforward to control this issue, particularly since it will be possible to make a very accurate calibration of the deflection angle. Numerically, at a  $Q^2$  of  $14 \,\text{GeV}^2$ , the systematics for determining  $\mu_p G_E^p/G_M^p$  are 100 times larger than the uncertainty in the spin precession angle (in the non-dispersive plane). This means that a 0.001 radian uncertainty contributes  $\pm 0.1$  to the final error budget. For the Super Bigbite measurement GEp(5) the absolute deflection angle provides a calibration of the field integral, so an accuracy for the spin rotation angle of better than 0.1 mrad is achievable ( $\pm 0.01$  to the final error budget).

Another source of systematic uncertainty is coincidences due to inelastic events. Here, the tight angular and momentum correlations between the elastic electron and the recoiling proton allows for a high degree of rejection. We note also that GEM-based trackers also have very good position resolution, which is essential for maintaining sufficiently good momentum resolution with the small field integral of the dipole. In the GEp(5) experiment we will measure the angular correlations to 1 mrad accuracy and according to detailed MC studies the inelastic background will be 3% or less.

In summary, from the perspective of both statistical power as well as the control of systematics, GEp(5) promises excellent accuracy up to a  $Q^2$  of  $14.5 \text{ GeV}^2$ .

## Precision Measurement of the Neutron Magnetic Form Factor up to $Q^2$ = 18 GeV<sup>2</sup>

The Hall A GMn experiment was approved in January of 2009 by PAC34 to make measurements up to a  $Q^2$  of  $13.5 \,\text{GeV}^2$ . It will determine  $G_M^n$  by a detailed comparison of the unpolarized elastic cross sections of the two processes d(e, e'p)n and d(e, e'n)p. It will use essentially the same apparatus as GEn(2), with the exception that the target will be the Hall A liquid deuterium cryotarget. The schematic representation of the experimental setup was given above in Fig. 7.

We note that the GMn proposal actually included measurements up to  $18.0 \,\text{GeV}^2$ , something that, combined with the fully approved Hall A  $G_M^p$  measurement (not part of the Super Bigbite project), would enable the reconstruction of the individual u and d quark distributions with a spatial resolution of 0.05 fm. Our collaboration plans to return to the PAC to request an additional two weeks to push to

this higher  $Q^2$ , as the difference between the u and d quark distributions is an exciting question with implications for our understanding of nucleon structure in terms of QCD degrees of freedom.

Like the other Super Bigbite project form-factor measurements, the  $G_M^n$  measurement in Hall A will provide excellent accuracy and reach in  $Q^2$ , well beyond all competing efforts. Considering only the portion of the experiment that is fully approved, the GMn experiment will require only 14 days of running. The CLAS12  $G_M^n$  experiment, which like the Hall A experiment is approved to make measurements up to 13.5 GeV<sup>2</sup>, will require 56 days of running, and will obtain 5 times less statistics at the highest  $Q^2$ -point. When considering a full set of kinematics, the Hall A  $G_M^n$  experiment has a Figure-of-Merit that is 30 times higher than that of the CLAS12  $G_M^n$  experiment. The existing data for  $G_M^n$ , together with the projected errors for both the Hall A and the CLAS12 experiments, are shown in Fig. 9. While the magnetic FF of the neutron has previously been measured up to 10 GeV<sup>2</sup>, the few data that exist above  $4.5 \text{ GeV}^2$  have uncertainties of about 10-20%. The GMn experiment in Hall A will provide sufficient accuracy to bring new understanding to this subject, including the aforementioned decomposition of the u and d-quark distributions.

The GMn experiment in Hall A will determine  $G_M^n$  by measuring the cross-section ratio for two reactions involving the deuteron: d(e, e'n) and d(e, e'p). This ratio method was proposed 50 years ago by L. Durand [52] and has been used in a number of experiments, including one at JLab in which  $G_M^n$  was determined with good precision up to  $Q^2 = 4.5 \text{ GeV}^2$ . When the recoil nucleon energy is above 2-3 GeV, the detection efficiency for the neutron and the proton are quite similar, so the ratio method becomes almost systematic free. Like GEn(2), the Hall A GMn experiment will utilize the BigBite spectrometer with the caveat that the trackers will be based on GEMs instead of MWDCs. Again like GEn(2), the Super Bigbite magnet itself will be placed in the hadron arm, providing excellent separation between recoil protons and recoil neutrons. The magnet will also be turned on and off to study potential systematics.



Figure 6.8: Published  $G_M^n$  data together with the proposed data points of the CLAS12  $G_M^n$  experiment (E12-07-104), and the proposed data of the Hall A  $G_M^n$  experiment (E12-09-019) that will be performed using the Super Bigbite apparatus.

The excellent statistical power of the Hall A GMn experiment is derived from many of the same factors that make the other Super Bigbite experiments so powerful: very high luminosity, and an open-geometry spectrometer that is close to the target, and very good position resolution that permits strong suppression of accidental coincidences and inelastic events. As mentioned before, the direct comparison of events from recoil protons and from recoil neutrons also greatly minimizes potential systematic effects. And because the physical setup of the experiment is nearly identical to that of GEn(2) (with the exception of the target), there will be large savings in setup and commissioning time.

# Chapter 7

# Collaboration

The core of the collaboration, Thomas Jefferson National Accelerator Facility, the University of Virginia, Carnegie Mellon University, the College of William and Mary, the University of Glasgow (Scotland), Norfolk State University, Rutgers the State University of New Jersey, the National Institute of Nuclear Physics (Italy), and the University of New Hampshire, has recently successfully completed the E04-108 (GEp(3)) and E02-013 (GEn(1)) experiments at JLab. The international part of the Super Bigbite collaboration plays a very important role in the project. It includes the groups from INFN (Italy) and Glasgow (Scotland). Efforts of the INFN group (E. Cisbani *et al.*) are concentrated on development of the GEM-based front tracker and associated electronics, for which INFN approved the full requested funding of 720k Euro. The Glasgow group (directed by Prof. G. Rosner) is collaborating in several Super Bigbite experiments and is in the process of submitting a "12-GeV JLab Upgrade Project" funding request to the UK STFC, which includes a research associate position and around \$200k for equipment for the Super Bigbite Project.

**Hall A sub-group:** The Hall A group will take on the design of the apparatus layout, the modification of the 48D48 magnet and the beam-line vacuum pipe. The group will be responsible for the installation and commissioning of the upgraded infrastructure required for the magnet, the targets, and the beam line.

**CMU sub-group:** The Carnegie Mellon University sub-group will take responsibility for the Hadron Calorimeter (HC). The HCAL will have 250 modules similar to the "COMPASS" type. CMU will begin with an in-beam test of a small subset of modules in Hall A. CMU will then coordinate the final HCAL design, working in collaboration with JINR, Dubna (Russia).

**College W&M sub-group:** The College of William and Mary sub-group will take responsibility for assembling and testing the coordinate detector, which will be used in the electron arm of the GEp(5) experiment. It will require design and construction of a large mechanical frame for the two-plane detector with a one-dimensional readout. This detector will have a simplified version of the polarimeter GEM chambers.

**NSU sub-group:** The Norfolk State University sub-group, in collaboration with the INFN-Rome group, will fabricate, test, and commission the Front-End-Electronics and Data Acquisition electronics

for all GEM-based trackers in this proposal. The total number of analog channels is about 40 thousand. This group will also conduct electronic noise-reduction studies of the prototype chamber and commission the tracker electronics for high-rate operation.

**Rutgers University & UNH sub-group:** The Rutgers University & University of New Hampshire group, in collaboration with Jefferson Laboratory, will take responsibility for developing, assembling and testing the trigger electronics for the Electromagnetic Form Factor (EMFF) experiments. As part of this work Rutgers and UNH will write specialized code for the programmable modules used for identifying coincidences.

**UVa sub-group:** The University of Virginia group, in collaboration with the College of William and Mary and Jefferson Laboratory, will develop and fabricate the GEM-based units with active area  $40 \times 50 \text{ cm}^2$  that will be used for the polarimeter trackers (ST and TT) and the coordinate detector (CD). Following the development work, the UVa group will then construct and test at UVa the production chambers for the ST and the TT. The detector facility at UVa consists of a  $4 \times 4 \text{ m}^2$  clean room that was used for the successful construction of the large area MWDCs for the Bigbite spectrometer. The size of this clean room will be increased by the addition of a new class 10,000 level  $6 \times 4 \text{ m}^2$  clean room adjacent to the original clean room. The clean room will be specially equipped for the construction of the GEM chambers.

# Chapter 8

# **Project Schedule**

The Super Bigbite Project is driven by the 12-GeV CEBAF upgrade and we are convinced that the project represents the optimum way of investigating nucleon elastic form factors at high  $Q^2$ . The relatively modest Hall A upgrade in the scope of the JLab 12-GeV project (the beam-line magnets and polarimeters) means that the physics program in Hall A could start as soon as the first beam from the upgraded CEBAF accelerator is available; according to the current schedule, the first operational beam will be delivered in 2014. All three measurements included in the Super Bigbite Project have been approved by the JLab PAC.

The collaboration has been doing extensive design, development and prototype work on the large GEM trackers and has already performed beam tests of a  $(10 \times 10 \text{ cm}^2)$  prototype of the GEM chambers in Hall A. A full-size ( $40 \times 50 \text{ cm}^2$ ) GEM chamber unit is under development by the collaboration of INFN and the CERN MPGD group. The design of the front-end read-out card is also underway by the Italian group. Assuming DOE funding approval, the Electromagnetic Form Factor (EMFF) collaboration is confident that there is sufficient time to complete the Super Bigbite Project for the first operational beam in Hall A in 2014.

The proposed apparatus is based on detector techniques that are already developed, such as calorimeters and trackers. We plan to construct the GEM-based chambers with relatively small chamber units to ensure the use of well-tested technology. GEM-based chambers presently operate in a number of experiments including COMPASS, LHC-B, PHENIX, CLAS-BONUS, and many smaller setups. The CERN MPGD group and Tech-Etch Inc. [53] in Massachusetts are mastering the production of large-area GEM foils. The CERN MPGD group also has the capacity to produce 2-D read-out-boards (ROBs) in large quantities. We have obtained quotations from CERN and Tech-Etch for GEM foils and from CERN for ROBs, and have discussed with them the production capacity needed for our project. The construction schedule shown below was developed on the basis of this information.

The collaboration members have recent experiences with the construction of large-scale state-ofthe-art detector projects including the MWDC for BigBite, focal plane polarimeters for the HRS in JLab's Hall A and the HMS in JLab's Hall C, the RICH counter for the HRS spectrometer, and the large lead-glass calorimeter BigCal.

The schedule of the project and year-by-year expenditure is presented in Table 8.1. The budget values include the overhead required in the respective institutions.

The project schedule coincides with the Jefferson Lab 12-GeV upgrade schedule, so that the Super Bigbite apparatus will be ready for the nucleon form-factor experiments as soon as the upgraded electron beam is available in Hall A. A construction timetable for the new apparatus and the upgrade of the Hall A infrastructure has been developed based on the April 2014 date, but it should be noted

Institute	FY2010	FY2011	FY2012	FY2013	FY2014	Total
Hall A	75	400	560	200	200	1,435
(Magnet, Target, Beam)						
CMU	50	150	110			310
(Hadron calorimeter)						
UVA	184	386	362	343	65	1,340
(Polarimeter Chambers)						
W&M		25	25	41		91
(BigCal Chamber)						
NSU	120	100	72	100	20	412
(Front-End-Electronics)						
Rutgers&UNH			50	150	27	227
(Trigger)						
Institution, total	354	661	619	634	112	2,380
DOE, total	429	1,061	1,179	834	312	3,815

Table 8.1: Experimental equipment budget (in \$1000) broken down by institute (project) and fiscal year.

that the construction timetable is driven both by the availability of funds as well as by construction completion time. The coil design and fabrication, and the assembly of the magnet, are estimated to take 20-26 months from the beginning of design work through installation and mapping of the magnet. The preparation of trackers and calorimeters will take place in parallel with the magnet assembly.

Č-lt.		2010			2011			2012			2013			2014						
Sub-system	1st 2		3rd	4th	1st	2nd	3rd	4th	1st	2nd	3rd	4th	1st	2nd	3rd	4th	1st	2nd	3rd	4th
48D48 Magnet, JLab						   								   						
Hall A infrasructure, JLab														1						
Polarimeter, UVA&NSU																				
BigCal Chamber, W&M																				
Hadron Calorimeter, CMU														   				1	1	
Trigger, RU&UNH																		1	1	
Front Tracker, INFN						1								1						
12-GeV schedule																				

Figure 8.1: The construction time line. The yellow, red, black, blue, and green lines indicate the periods of design, construction, testing, istallation and final commissioning, respectively. The period of accelerator down time for the upgrade is shown in purple on the botton line.

After the installation of the magnet is completed, the more delicate equipment will be mounted. Four months have been allocated for this installation and other tasks related to pre-beam commissioning of the apparatus. The construction time-line is shown in Fig. 8.1.

In order to maintain this schedule, funding for magnet design and GEM assembling facility must begin in FY2010. The cost spreads in FY2010-14 involve procurement of the GEM chambers and the hadron calorimeter, modification of the magnet and preparation of the infrastructure. In addition to

these funds from DOE the EMFF collaborators from Italy and UK will contribute \$1.1M-\$1.3M over FY2010-FY2014 from their national grants. The funding request broken down by funding source is shown in Table 8.2.

institute	funding source	amount	amount		
Lall A	Conital magazate II al-	1 425	amount		
Hall A	Capital request, JLab	1,435			
(Magnet, Target, Beam)	long term DOE fund				
E. Cisbani et al.	INFN		720k Euro		
(Front Tracker)			approved		
G. Rosner et al.	UK		\$200k		
(Trackers)			requested		
CMU	DOE	310			
(Hadron calorimeter)					
UVA	DOE	1,340			
(Polarimeter Chambers)					
W&M	DOE	91			
(BigCal Chamber)					
NSU	DOE	412			
(Front-End-Electronics)					
Rutgers&UNH	DOE	227			
(Trigger)					
Institution, total		2,380			

Table 8.2: Super Bigbite equipment budget (in \$1000) broken down by the collaborating institutions. These values include the overhead cost required by the corresponding institution.

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# **Appendix A**

# **Polarimeter for the SBS Spectrometer**

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The principal considerations for the proton polarimetry in the GEp(5) experiment [1] are reviewed here briefly. Determination of the proton form factor ratio by the method of polarization transfer requires the measurement of the ratio of two components of the spin polarization. These are the longitudinal component, which is parallel to the momentum of the proton after scattering, and the sideways component, which is transverse to the momentum of the proton in the electron scattering plane. The dipole magnet of the proton arm spectrometer provides rotation of the proton spin around the direction of the magnetic field. In the optimal case the spin rotation angle is larger than the rotation of the proton momentum by  $90^{\circ}$ , so such rotation results in the proton polarization after the magnet being normal to the direction of the proton momentum.

The transverse polarization of the recoil proton will be measured from the azimuthal asymmetry after re-scattering in a thick block of  $CH_2$ . Both the polar- and azimuthal angles of the re-scattered protons will be measured in a set of tracking detectors. To maximize the probability of interaction, *i.e.*, the efficiency of the polarimeter, two analyzer blocks, each followed by a set of tracking detectors, will be built. The feasibility of using such a polarimeter for the planned large momentum of the proton has been experimentally supported by calibration measurements at the Dubna accelerator [2] up to 5.3 GeV/*c* and by the GEp(3) experiment in the Hall C up to 5.4 GeV/*c*.

#### A.1 The form factor ratio from the polarization ratio

An important feature of the polarization transfer method developed in the GEp(1) experiment [3] is the very small systematics uncertainty, because the ratio of the form factors is proportional to the ratio of the longitudinal polarization  $P_{\ell}$  and the transverse polarization  $P_t$ , as it is shown below:

$$I_0 P_t = -2\sqrt{\tau (1+\tau)} G_E G_M \tan \frac{\theta_e}{2}$$
(A.1)

$$I_0 P_\ell = \frac{1}{m_p} \left( E_e + E'_e \right) \sqrt{\tau \left( 1 + \tau \right)} G_M^2 \tan^2 \frac{\theta_e}{2}, \tag{A.2}$$

where  $\tau = Q^2/4m_p^2$ ;  $E_e$ ,  $E'_e$ , and  $\theta_e$  are the initial and final electron energy and scattering angle, and  $I_0 \propto G_E^2 + \frac{\tau}{\epsilon} G_M^2$ . Measuring simultaneously these two components and taking their ratio gives the ratio of the form factors:

$$\frac{G_E}{G_M} = -\frac{P_t}{P_\ell} \frac{(E_e + E'_e)}{2m_p} \tan \frac{\theta_e}{2}$$
(A.3)

Using the polarization technique, the form factor ratio  $G_E/G_M$  at a given  $Q^2$  can be obtained without measuring the absolute cross sections and without change of beam energy or detector angle, thus eliminating important sources of systematic uncertainties.

#### A.2 Analyzing power momentum dependence

The analyzing power,  $A_y$ , of the reaction used to measure the proton polarization decreases as  $1/p_p \sim 1/Q^2$  [2, 5], where  $p_p$  is the proton momentum in the lab frame. This is illustrated in Fig. A.1 for the first two GEp experiments [3, 4]. Seen in Fig. A.1 is that above  $p \sim 2 \text{ GeV}/c$ , the shape of the angular distribution of  $pA_y$  versus  $p_T \sim p \times \tan \theta_{fpp}$ , where p is the proton momentum and  $\theta_{fpp}$  is the polar angle between the incident proton and the secondary charged particle detected in the polarimeter, is nearly momentum independent, and vanishes near 1 GeV/c.

The hadron calorimeter, located downstream from the polarimeter, defines the experimental trigger, together with the electromagnetic calorimeter detecting the electron. The discriminator threshold on the hadron calorimeter will be set to require the secondary particle to have an energy greater than ~ 4 GeV, selecting preferentially the protons; the elastic cross-section is ~ 25% of the total cross section. In contrast, in the GEp experiments done so far at JLab there was no constraint on the secondary particle except that it be charged. This is the case for all the C and CH<sub>2</sub> measurements presented in Fig. A.2, for which the analyzing power is about half the value for the elastic *pp* reaction. We expect that by applying a threshold condition on the secondary particle the analyzing power,  $A_y$ , will increase. At the same time the polarimeter efficiency,  $\varepsilon$ , will decrease, but since the polarimeter FOM is proportional to  $\varepsilon A_y^2$ , the expectation is again in favor of increasing the FOM. A test of this assumption will be performed in the planned calibration in Dubna using 25 hadron calorimeter bars of the COMPASS design.

#### A.3 Design considerations for the polarimeter

In the GEp(5) experiment the maximum usable scattering angle in the polarimeter analyzer will be about 10°; this defines the size of the trackers and the trigger calorimeter. The analyzing power has a maximum at  $P_T \approx 0.4$  GeV/c (Fig. A.1), corresponding to polar angles of 40 - 50 mrad, and then



Figure A.1: Analyzing power times proton momentum,  $A_y P_{Lab}$ , versus secondary particle transverse momentum,  $P_T$ . Left, for  $p + C \rightarrow 1charged + X$  for different proton momenta: black, red, green, blue, yellow, magenta circles – 0.76, 0.99, 1.27, 1.46, 1.65, 1.71 GeV/c; black, read, green triangles – 2.07, 2.36, 2.64 GeV/c. Right, for  $p + CH_2 \rightarrow 1charged + X$  for different proton momenta: black, red, green – 2.92, 3.37, 3.81 GeV/c.

drops rapidly at smaller angles. Thus, for polarimetry it is sufficient to have an angular resolution of about 2 mrad. Multiple scattering angle uncertainties in the analyzer for 8 GeV/c proton will be of 1.5-2 mrad.

Figure 5.1 presents the layout of the proton arm. The dimensions of both  $CH_2$  analyzers will be  $100 \times 200 \text{ cm}^2$ . The same size is used for the reference design of the trackers and the hadron calorimeter. The weight of material in each analyzer is about 1 ton.  $CH_2$  plates will be assembled in steel frames and installed in the detector stack by means of the overhead crane.

As shown in Fig. 5.1 the spectrometer has three trackers, called the First Tracker (FT), the Second Tracker (ST) and the Third Tracker (TT). Because of the high rate of background particles and our plan to use the ST tracker in other experiments with the SBS when high spatial resolution is required, the tracker after the first polarimeter will be constructed with GEM technology. The second polarimeter is followed by the TT which is identical to the ST in construction. Both trackers have an active area of  $50 \times 200 \text{ cm}^2$ .

#### A.4 Program of experimental tests and collaboration

The collaboration of W&M, NSU and Dubna is continuing the study of the analyzing power for proton interaction in the C and  $CH_2$ . There is an active proposal to continue such measurements in Dubna up to 7-7.5 GeV/*c*.



Figure A.2: Maximal value of analyzing power,  $A_y^m ax$ , for the  $p + C/CH_2 \rightarrow 1charged + X$  reactions (blue/red) from [2, 6, 8, 9, 3], and for the elastic pp reaction (magenta) [7] versus the inverse of the proton lab momentum

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# **Appendix B**

# **Front Tracker for the SBS spectrometer**

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This chapter describes the design of the front tracking system of SBS with  $40 \times 150$  cm<sup>2</sup> acceptance, 70  $\mu$ m spatial resolution, 6 GEM 2D readout chambers; The tracker will be primarily installed next to the 3 Tm dipole magnet of the Super-Bigbite Spectrometer (SBS) of the Hall A at Jefferson Lab, expected to start taking commissioning data at the end of 2013. Parts of the same tracker is expected to be used in the BigBite spectrometer as well.

Many of the design solutions as well as the readout electronics will be used also for the SBS polarimeter trackers.

#### **B.1 Requirements**

The main requirements for the SBS tracking system are derived from the needs of the 12GeV-Hall A Form Factor experiments [1] and more generally from the optimal exploitation of the Hall A high luminosity and high energy beam which will be available after the 12 GeV upgrade. They are:

- 1. Ability to sustain a background rate of 500 kHz/cm<sup>2</sup> (due to soft photons mainly).
- 2. Moderately high acceptance ( $40 \times 100 \text{ cm}^2$  at least)
- 3. 0.5% momentum resolution and 0.5 mrad angular resolution at 8 GeV

In addition, the following qualitative functionalities are also considered during the development of the tracking system:

- 4. Ability to be relocated and reconfigured in different positions in the same spectrometer and in the BigBite facility
- 5. Ability to provide performances optimized to the different experiments, with minimum modification (e.g. change in spatial resolution).

Finally, the tracker shall:

- 6. tolerate the residual magnetic field of the dipole at about 110 cm from the dipole center (up to 1k Gauss, TBC)
- 7. be contained within  $\sim 110$  and  $\sim 180$  cm after the dipole magnet, for a total tracker length of  $\sim 70$  cm.

## **B.2** Choice of the technology

The tracking system requires the realization of relatively large detectors (never made this size in existing experiments) with minimum dead area in acceptance and minimum material budget; the required momentum and angular resolutions translate approximately into a single hit spatial resolution  $< 100 \ \mu m$  (see chapter on "Optics of the SBS spectrometer").

The available technologies for a tracking system able to provide the above spatial resolution, basically are: drift chambers, Micro Pattern Gas Detectors [7] (MPGD), silicon tracker.

The drift chambers cannot sustain the expected rate (requirement 1) and are generally more sensible to the magnetic field than the other technologies; the silicon trackers, on the other hand, are more expensive and not available in large area (as single tile); they however, may provide better resolution and sustain larger rates. Use small area silicon planes in front of the dipole is considered as a possibility for extending significantly the tracker length to improve momentum and angular resolution significantly.

GEM [2] and Micromegas [3], among the MPGD, are the most consolidated technologies; relatively inexpensive and able to fulfill the requirements; both involve very similar production technologies and identical readout electronics.

GEM has been preferred here due to the higher flexibility and re-usability (requirements 4 and 5) (e.g. GEM multiplication stage is - to large extend - decoupled from the readout plane) as well as significantly smaller discharge rate.

The coverage of the requirements are summarized in Table B.1 and discussed in more details in the next sections.

#### **B.2.1 GEM (Gas Electron Multiplier)**

The GEM technology [2] has been invented by F. Sauli in the 1990's. It is one of the most successful implementation of Micro Pattern Gas Detectors; the primary ionization, the multiplication and the charge collection (readout) regions are largely independent. (see B.1). The multiplication is provided by one or more GEM foils. A typical GEM foil consists of:

• thin (50  $\mu$ m) kapton foil

Requirement	Fulfilled by		
1) Rate	GEM technology & adequate readout segmentation		
	& readout planes redundancy		
2) Acceptance	Assembly of $40 \times 50 \text{ cm}^2$ GEM modules with 8 mm frames		
3) Resolution	Strip pitch 0.4 mm & analog readout		
4) Reconfiguration	$40 \times 50 \text{ cm}^2 \text{ modules}$		
5) Flexibility	GEM (instead of Micromegas)		
6) Magnetic Field	MPGD tolerate moderate magnetic fields		
7) Length	MPGD compactness		

Table B.1: Summary of requirements and their fulfillment; details are discussed in the text.

- conductive metal ( $\sim 5 \ \mu m$  Cu) on both side of the Kapton which will be at different potentials (typically 500 V difference)
- holes in kapton and metal layers ( $\sim 70 \ \mu m$  diameter) on a regular grid with  $\sim 140 \ \mu m$  spacing.

The large electric field in the holes generated by the potential difference of the metal layers at the two sides of the kapton foil is responsible of the secondary electron multiplication of the foil ( $\approx 20 : 1$ ). Therefore the number of GEM foils determine the overall gain; 3 foils configuration represent the optimal compromise in most of the applications.

The hole are obtained by chemical etching. One of the limiting factors in the production of large area GEM has been the alignment of the mask in the standard double mask foil production: the holes are chemically etched from both sides of the kapton foil at two different times, with the same mask.

Recently, a single mask GEM foil production (etching from a single side only, no need of mask alignment) has been developed and seems to provide good results.

The shape of the holes of the two production techniques are generally different but the performances are similar [12]; besides the single mask technique is not yet fully tested, and quality production is not stable yet.

On the other hand the application of the GEM as tracking device can be considered quite consolidated; there are successful examples of GEM tracking detectors working in real experiments, such as COMPASS [4], which represents our reference model.

## **B.3** Tracking chamber layout

The front tracker for Hall A is based on GEM modules: the tracker consists of 6 GEM chambers grouped by 2 for a total tracker length of about 50 cm. Each chamber will have an active area of  $40 \times 150$  cm<sup>2</sup> (only  $40 \times 100$  will be equipped with readout electronics since the beginning).

According to the common modular scheme presented in chapter on "Experimental equipment", each GEM chamber is the combination of 3 compact modules of  $40 \times 50$  cm<sup>2</sup> area each.

This choice had been driven by the following considerations:

• Consolidated production quality and performance of the standard double mask GEM technology (as mentioned in the previous section)



Figure B.1: GEM schematic layout and operation principle.

- Maximum length of the microstrip in the readout plane; longer microstrips means higher capacitance effects (more noise) and lower segmentation (smaller capability to face the high background)
- High flexibility in tracker geometrical reconfiguration for SBS (applicability of the same module to the first and second trackers of the SBS)

Each module will require  $\sim 10$  cm of space along the direction of the central particle: about 2 cm will be reserved to the modules and the rest for electronics, mechanical supports, gas piping and electronics cabling. The active area is surrounded by 8 mm dead area (mechanical frame), which hides the electronics along the joined sides. Guidelines for the design of the single module are:

- Spatial resolution below 100  $\mu$ m (70  $\mu$ m preferred)
- High rate tolerance (especially in false hit rejection for tracking)
- Minimization of the dead area (frame width mainly).

Each module is derived from the COMPASS design, and basically consists of (see B.3):

- 1. thin mylar foil for gas containment. This is generally obtained by the drift plane glued on a honeycomb structure. However, to minimize material we intend to avoid the honeycomb in front of the module<sup>1</sup>;
- 2. the drift conductive plane;

<sup>&</sup>lt;sup>1</sup>This solution is under testing.

- 3. 3 GEM foils (gain up to 10k)<sup>2</sup>; GEMs gap is 2 mm, and thin support grids are required between them to keep distance and planarity. Each foil measures  $40 \times 50$  cm<sup>2</sup> (same as the FPP GEM based tracker). The HV distribution is segmented in order to reduce the severity of electrical discharges.
- 4. the readout plane with 2D readout a la COMPASS (two conductive layers of microstrip at 90 degree, one on top of the other, with equal charge sharing) [5].
- 5. each readout tile is glued on a honeycomb thin substrate which represents the exit window.
- 6. a gas mixture is flushing inside the chamber. The type of mixture is not defined yet, although we do expect to use standard gas mixtures such as Ar and  $CO_2$  in 70:30 ratio.
- 7. the readout electronics is expected to provide the charge collected by each strip (analog readout).

The high modularity, simplifies an extensive reuse of the chambers; however, it may require some compromises in terms of performances. Technology advances will be monitored: CERN is prototyping  $100 \times 40$  cm<sup>2</sup> single-mask GEM foil; if these larger foils will outcome (in the short period) the performance of the standard double mask foil (also in terms of dead area) and cost, its use will be reconsidered.

The material required to construct the active area of a single chamber is detailed in Table B.2. It is derived from the original COMPASS design and taking into account today technology; further improvement in material budget can be achieved in the detailed design optimization.

An additional 2D small plane of high resolution silicon detector, in front of the dipole, is under investigation to improve the tracking accuracy, thanks to the longer effective length of the tracker, keeping the multiplicity per readout segment constant.

#### **B.3.1** Entrance window and drift foil

The entrance window will be a thin layer of 6  $\mu$ m mylar which will contain the gas in the chamber. The drift foil consists of 50  $\mu$ m foil of kapton (TBC) with 3  $\mu$ m of copper on one side. Thinner foil are under investigation.

#### **B.3.2 GEM foil**

The GEM foil consists of 50  $\mu$ m kapton foil with 3  $\mu$ m of copper layers on both side of the kapton. Schematic (draft) is presented in Fig. B.5. One side of the GEM is a single sector 40 × 50 cm<sup>2</sup>; the opposite side (lower potential) is divided by 20 20 × 5 cm<sup>2</sup> sectors. Each sector is connected to the HV through a protection SMD resistor. All resistors are soldered on the same multi-sector side of the GEM foil, below the frame, along the longest side. The terminal of the HV of the single large sector is on the multi-sector side. It goes to one terminal of the protective resistor. The other terminal of the resistor goes to the single  $40 \times 50$  cm<sup>2</sup> sector on the other side by means of a pass through hole. The terminal of the HV of the multi-sectors lays on the single sector side of the GEM. It runs along the frame and is distributed to the protective resistors by means of pass through holes. The terminals of the GEMS foils and the drift foil are replicated on each GEM foil, in order to use the same drawing. The unused terminals in one foil will be cut on the frame border.

 $<sup>^{2}</sup>$ We intend to use 3 GEM foils in each chamber, however, in order to slightly reduce the overall thickness and complexity, we are planning to test the 2 GEM foils solution.

Table B.2: Material budget of a single tracker chamber; values are extrapolated from the COMPASS design [4] and the recent advances in the GEM technologies [6].  $CO_2$  is considered for estimation only; the actual gas mixture is under investigation.

Part	Material	Quantity	Thickness	Area	$X_0$
			$\mu m$ ( $X_0$ mm)	fraction	%
Window	Mylar	1	10 (287)	1.0	0.003
Drift	Copper	1	3 (14.3)	1.0	0.021
	Kapton	1	50 (286)	1.0	0.017
GEM foil	Copper	6	3	0.8	0.100
	Kapton	3	50	0.8	0.042
Grid Spacer	G10 (?)	3	2000 (194)	0.008	0.025
Readout	Copper (80 $\mu m$ )	1	3	0.2	0.004
board	Copper (350 $\mu m$ )	1	3	0.75	0.016
	Kapton	1	30	0.2	0.002
	G10	1	120	1	0.062
	NoFlu glue	1	60 (200)	1	0.030
Honeycomb	Nomex	1	6000 (13125)	1	0.046
Fiberglass	G10	2	120	1	0.124
Gas	(CO <sub>2</sub> )	1	9000 (18310)	1	0.005
				Total	0.508

#### **B.3.3 2D readout plane**

The readout foil is inspired by the COMPASS 2D readout strips layers. It consists of 2 layers of copper strips (5  $\mu$ m thick each, with 0.2 and 0.75 transparency) separated by prepreg foil with the same transparency 0.2 of the first strip layer. The layer are glued on a G10 120  $\mu$ m plane. Attempt to reduce these thickness is underway. Strips pitch is 0.4 mm. The choice of strips (respect to pads) is a compromise between segmentation, costs and material budget: pad readout is preferable for optimal segmentation but is much more expensive in terms of readout electronics and requires more material in the active area.

In order to fit into the frame width we intend to use the PANASONIC YF31 33 ZIF bins (only 32 used, 1 will be grounded), which will be soldered on the front-end cards (see Fig. B.8). Therefore, the readout strips will end up on a flexible printed circuit (FPC) with 0.3 mm pitch. Note that the FPC is part of the readout foil, neither soldered nor glued part!

We propose the connection scheme shown in Fig. B.2: the front-end cards are distributed along all 4 frame sides, in a sort of interleaved (comb-like) way. These cards are at 90° respect to the readout plane at the joint sides of two modules (visible in the side view of Fig. B.2); the FPCs are therefore bent by 90°, following the frame profile which will be properly machined to avoid sharp edges that may damage the FPC. The comb-like signal fan-out on all 4 sides, is not strictly required by a 90° horizontal/vertical orientation of the strips. However, we intend to develop readout plane with strips orientated at  $\pm 45$  degree respect to the vertical; in this case the comb-like (or similar) approach is expected to be mandatory. This approach has the disadvantage of a "more" delicate readout board due to the bending of the FPC, but also offers few advantages respect to the solution of connectors soldered on the readout foil:



Figure B.2:  $40 \times 50$  cm<sup>2</sup> 2D readout strips fan out in the x/y configuration; also shown is one front-end card and how it is connected to the 128 strips.

- 1. Minimize material in the active area;
- 2. Minimize the width of the front-end cards, which may extend in the empty space between two groups of  $4 \times \text{FPC}$ ;
- 3. No direct soldering in the readout foil

#### **B.3.4** Mechanical structure

The mechanical frame of the single module will be made of good quality insulator such as Permaglas TE630 which has been preferred to Vetronite. The GEM foil and frame mechanical and electrostatic stress has been investigated with a FEM and minimum frame width of 6 mm seems to be safe for maintaining a planar GEM foil ( $\pm 2\%$  of the GEM-GEM gap space), as described in the next subsection. In the GEM design the frame width has been safety fixed to 8 mm.

Frames thickness have been chosen to be 3 mm (Drift-First GEM), 2 mm (GEM-GEM gaps and GEM-readout). The honeycomb frame on the readout side has the same width of the other frames but a thickness of 6 mm.

The honeycomb sandwich will be prepared according to the 'CERN' recipe, as schematically shown in Fig. B.4.

All frames have an additional outer frame (connected to the internal frame by small sticks, as shown in Fig. B.6) for better stiffness during assembling. This service frame will be removed after the assembling. The GEM-GEM frames include internal spacers of 0.5 mm width that guarantee the distance between the GEM foils. The spacers are located at the GEM sectors borders; therefore the spacers divide the internal space of the frame into the same sectors of the GEM.

The modules that form a single chamber as well as all ancillary components (electronics, wires and gas pipes) will be supported by an outer rigid frame which connect to the modules frame by a sort of C-like arms. The design of this outer structure is development.



Figure B.3: Schematic detail of the GEM layout detail; shown is one of the four gas line and one of the HV resistors embedded in the frame, as well as the GEM gap spacer with thin aperture for gas circulation.



Figure B.4: Composition of the CERN made honeycomb plane (thickness will be optimized).



Figure B.5: Preliminary detailed design of the GEM foil, its HV segmented distribution.



Figure B.6: GEM mechanical frames; spacer, thin structural frame and service frame are drawn.

Table B.3: Results of the single foil FEM analysis for the estimation of the minimum frame width.

Frame width	(mm)	5	6	7	8	9	10
Maximum Sag	(µm)	180	24	21	19	16	12



Figure B.7: FEM analysis of single GEM foil with 8 mm frame width.

#### Single foil FEM analysis

A single foil straightforward FEM analysis has been performed to study the effect of the frame width on a module with  $40 \times 50$  cm<sup>2</sup> active area, frame made by Permaglas, 2 mm thick. The GEM foil has been assumed to be perfectly glued on each side of the frame.

The electrostatic field of 5 kV/cm has been increased by a safe factor of 10 which also takes into account local non-homogeneity (caused by the avalanche). The field of 5 kV/cm corresponds to a pressure of 0.1 Pa<sup>3</sup> between two parallel plates which are 2 mm apart. Therefore conservatively 1 Pa uniform electrostatic pressure is assumed on the GEM foil (no spacer have been considered). The GEM foil is stretched by a 30 kg weight before being glued on the frame. A planarity distortion smaller than 40  $\mu$ m (2% of the inter-GEM gap of 2 mm) is assumed to be acceptable. Results are summarized in Table B.3 and pictorially shown in Fig. B.7 for the 8 mm frame width case.

#### **B.4** Performance analysis

We have identified the following major critical aspects of the tracking project, which need to be analyzed in details and have relevant impact on the design solutions:

1. Background conditions compatible with the tracking capability: the expected maximum background rate (see chapter "Detector counting rates") of about 500 kHz/cm<sup>2</sup> may be critical for a satisfactory track reconstruction, in term of ghost hits ambiguity, pile up and spatial resolution.

<sup>&</sup>lt;sup>3</sup>Assuming the GEM foil is a parallel plate of a planar  $A = 40 \times 50 \text{ cm}^2$  capacitor with d = 2 mm gap (and capacity  $C = \epsilon A/d$ , with  $\epsilon = 8.910^{-12}$  F/m in vacuum), the superficial charge density in a field of E = 5 kV/m is  $Q = (CV/A) = \epsilon E \sim 0.2 \text{ C/m}^2$  and therefore the pressure on the foil is P = QE = 0.1 Pa.

Concerning the spatial resolution and better constraint in track reconstruction, the possibility of using a relatively small Silicon 2D detector in front of the dipole magnet is under investigation and its decision will depend on the test of the prototype and the validated Monte Carlo simulation.

2. Moderately large area design: single GEM foils of large area  $(100 \times 40 \text{ cm}^2 \text{ or so})$  are expected to be available before the end of 2008, according to the information coming from CERN, basically the only producer of the GEM foils. This advance in the GEM technology may permit the minimization of dead are, but costs, state of the development, mechanical issues and the fact that the readout plane shall be segmented (existing plane have maximum size of  $50 \times 40 \text{ cm}^2$ ) suggest to use chamber section of  $50 \times 40 \text{ cm}^2$ ; moreover, noise on long strip, ambiguities and pile up, are reduced while the number of readout channels increases.

#### **B.4.1 Readout electronics**

The electronics will be based on the APV25 chip developed by the Imperial College for CMS silicon detectors and first used in a GEM detector by COMPASS<sup>4</sup> and currently adopted by HADES for the readout of the MWPC of its RICH detector (in place of the slower Gassiplex chips). The present idea is to simplify the layout used by COMPASS at the expenses of a limited flexibility; we intend to split the Electronics DAQ System into the following components.

#### Front-end card

The front-end card hosts the APV25, is connected to the readout foil by the above mentioned Panasonic YF31 connectors. During the prototyping phase, several alternatives are considered and implemented on it (see Fig. B.8):

- power on board and external (from connectors);
- analog buffer selectable
- internal or external VREF
- GND.2 from diodes or by a resistance
- I2C level adapter in case of USB external interface
- 1-wire temperature monitor
- one rotary switch for the I2C addressing (only 16 chips addressable instead of 32); only even numbers are selectable in order to get not-delayed output.

The APV25 die will be bounded to the PCB directly avoiding the ceramic pitch adapter used in COMPASS/HADES. At the moment a standard flat cable connector with 20 pins has been adopted with the analog output between two grounded twisted pairs.

The front-end board size is constrained by the available space for each chamber and the choice of the geometric configuration of the readout plane. The optimal size of the board is smaller than

<sup>&</sup>lt;sup>4</sup>The design of the electronics has benefit of the very interesting and helpful discussion with Michael Böhmer (TUM, developer of the HADES-RICH implementation of the APV25) and Igor Koronov (TUM, involved in the COMPASS-GEM implementation of the APV25).



Figure B.8: Layout of the Front-End card components and their relevant size and connection to the 2D readout plane (left) of the GEM module.



Figure B.9: Block diagram of the VME64x ADC/Controller module of the GEM readout electronics.

 $Z \times L = 80 \times 50 \text{ mm}^2$  (with Z along the tracker axis and L along the module side) with a thickness smaller than 6 mm. Length of L up to 100 mm are possible as well as thickness up to 8 mm.

The front-end cards digital signals are connected by a bus like flat cable, while the analog output, properly buffered is sent to the digital conversion unit in the VME64x module (next section).

The first few prototypes of the front-end cards will be delivered the second week of January/2010.

#### VME64x module (ADC/Controller)

A schematic view of the ADC/Controller functionalities is presented in B.9.

The module hosts the signals (including CLOCK generator<sup>5</sup>) transmitter and receiver to/from the APV25 Front-End cards, up to sixteen 40 MHz ADCs (ADS5270, one for each front-end APV25 chip), the control logic, the pedestal compensation and zero suppression logic (using a FPGA).

The module should be in a radiation safe area at a distance from the front-end card smaller than  $10 \text{ m}^6$ .

<sup>&</sup>lt;sup>5</sup>Possibility to use the JLab VME64x extension system CLOCK will be evaluated

<sup>&</sup>lt;sup>6</sup>This limit is imposed by the maximum length of the analog cable connecting the front-end card and the ADC.

The module will be compliant with the JLab/Hall A DAQ standard. In addition, during the prototyping, the VME64x module will host a fast serial link (optical fiber or Copper Wired Ethernet) which will be used for testing purpose. The digital conversion block is designed in such a way to be easily moved out from the module, closer to the front-end cards, becoming an intermediate module between the Front-End and the VME64x

The current FPGA candidates are the Xilinx Virtex5LXT and the Altera Cyclone III. While the latter is significantly cheaper, the former has more built-in functionality and is currently adopted by RD51. In particular the Xilinx already includes the management of the serial link.

## **B.5** Collaboration list

The GEM tracker project is carried on by a collaboration of Italian INFN and University groups from Bari (BA, leader: Prof. R. De Leo), Catania (CT, leader: Prof. E. Bellini), Rome (RM, leader: E. Cisbani), and Genova (GE, leader: M. Battaglieri). Each group has (or shares) responsibility on specific components, according to the Table B.4.

Table B.4: Responsibility of the different INFN groups working on the GEM tracker projects; BA=Bari, CT=Catania, GE=Genova and RM=Rome while R=responsible, C=collaborator

Component	BA	СТ	GE	RM
GEM Chamber Parts				R
GEM Mechanical parts		R		С
Tracker mechanics		R		С
Mechanical Accessories		R		
Gas System	R			
Slow Control HW and SW		R		
Front End Electronics	R		С	
DAQ HW and SW		С	R	С
Detector Simulation				R
Track Reconstruction				R

The project is coordinated by the Rome Group, who is member of the CERN RD51 collaboration, devoted to the development of the MPGD.

It is worth to mention that the tracker is part of the larger SBS project and therefore the INFN collaboration interacts strongly with the other SBS components developers, sharing resources and achievements as long as possible.

## **B.6** Funding

The  $3^{rd}$  commission of INFN has funded the two prototype phases in 2008 and 2009 as well as the first part of the first production (2010) and it is expected to fund the entire project ( $\sim 700$  kEuro) remaining 2 years.

# **B.7** Development plan

The tracking system is expected to be ready for the end of 2012. Installation is planned during the JLab shutdown in 2013. Commissioning of the system is expected starting at the end of 2013. The major phases of the development are defined in the following Tables B.5, B.6, B.7 and B.8.

Phase	(0) Preliminary Studies
Duration	2008 - end 2009
Activities	
	1. Monte Carlo Simulation
	2. Tracking Reconstruction Algorithm implementation
	3. Tracking system design finalization
	4. Small scale GEM ( $10 \times 10 \text{ cm}^2$ ) prototypes for tracking telescope
	5. Background rate measurement in realistic conditions of high luminosity ( $\sim 10^{38} \text{ cm}^{-2} \text{s}^{-1}$ ) electron-proton scattering at few GeV energies.
	6. Identify front-end readout chip
Deliverables	
	1. Conceptual Design (end of 2008)
	2. Small Area Tracking Telescope (mid 2009)
	3. Detailed Design (end of 2009)
Comments	Monte Carlo and Tracking reconstruction will be used to finalize the tracking system design. Prototype will be used to measure the real background in high luminosity electron-proton scattering at forward angle. Moreover, once tested and calibrated, the telescope will be used as test bench tool for the next phases developments. The Gassiplex chips [[11]] already available in the group will be adapted for the small prototype readout.

#### **B.7.1** Prototyping

We developed a first tracking prototype made of 3 small  $10 \times 10$  cm<sup>2</sup> GEM chambers. The tracker is used to measure the background rate expected in Hall A, verify the capability and limits of track reconstruction in such background, tune the Monte Carlo model which is under development. The tracker will then be used as a tool for the development of the second prototype. A second prototype is under construction with a design close to the final modules. It will permit to test the adopted solutions, make corrections and optimization. Also the readout electronics is prototyped toward the final version. The chamber module will be tested and integrated into the first prototype.

First beam test has been performed on the small prototypes in December 2009 at the DESY test

Phase	(1) Full scale prototyping
Duration	2009 - mid 2010
Activities	
	1. Full size $(50 \times 40 \text{ cm}^2)$
	2. Test large prototype
	3. Improve design (if needed)
	4. Electronics design and prototyping
Deliverables	
	1. Full Scale Prototype (first trimester 2010)
	2. Electronics Design and prototyping (first trimester 2010)
	3. Detailed Design Revised (mid 2010)
Comments	A full scale module prototype and relative electronics will be designed, realized and tested. Feedback from test will be used to improve and finalize the design for the modules production, including evaluation of a Silicon detector in front of the dipole magnet. The design will take into account the application requirements, including the constraints which will come from the detailed design of the spectrometer.

## Table B.6: Phase 1: Full scale prototyping

beam; the very first preliminary results are represented by the beam profile shown in Fig. B.10.

Phase	(2) Production and Installation
Duration	Mid 2010 - end 2013
Activities	
	1. Production of the tracking modules
	2. Realization of the readout electronics
	3. Mechanical support of the tracking system
	4. Ancillary components (gas system, HV and LV systems,)
	5. Component Tests
	6. Component Integration
	7. System Test
	8. System Integrated into the Hall A JLab Spectrometer (2013)
Deliverables	
	1. Tracking Modules (end of 2011)
	2. Readout Electronics (end of 2011)
	3. Other components (first trimester 2012)
	4. Integrated system (mid of 2012)
	5. Tested and Integrated system (end of 2012)
Comments	Components production, test and integration will be carried on in this phase. Once the system has been integrated, it will be tested and finally integrated into the new Hall A spectrometer.

#### Table B.7: Phase 2: Production

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Phase	(3) Commissioning and Data Taking
Duration	End of 2013
Activities	
	1. Commissioning of the system in final spectrometer, in real experiment
	2. Data taking
Deliverables	
	1. Fully calibrated and operative tracking system (mid 2013)
	2. Physics Data
Comments	The beginning of this phase depends on JLab12 upgrade plan. Once the tracking system is installed in the new spectrometer, its commissioning will be performed, calibration finalized.



Figure B.10: Very preliminary beam profile (x-top, y-bottom) from the December 2009 DESY Beam Test; baseline is not yet fully compensated and mapping not completed.

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# **Appendix C**

# Large area GEM tracker for the SBS polarimeter

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# C.1 Parameters

Each SBS polarimeter will consist of a 50 cm  $CH_2$  analyzer, followed by a large area tracker. The requirements for the trackers are:

- large acceptance:  $50 \text{ cm} \times 100 \text{ cm}$ .
- moderate position resolution:  $\sim 1.5$  mm.
- ability to operate under high background rates up to  $\sim 150 \text{ kHz/cm}^2$ .

A cost effective solution for large-area tracking in a high-rate environment is provided by the Gas Electron Multiplier (GEM) technology. Each of the two polarimeter trackers (Second Tracker, ST, and Third Tracker, TT) will consist of four GEM chambers. The active area of these trackers will be  $50 \times 200 \text{ cm}^2$ . Each  $50 \times 200 \text{ cm}^2$  GEM chamber of the two trackers will consist of five  $50 \times 40$  modules, as described in Section 2.3 (see Fig. 2.6). The GEM modules used for these chambers will be identical to the GEM modules of the Front Tracker described in Appendix B, and hence will not be described here. The Front-End Electronics (FEE) for ST and TT will also be identical to the FEE of the front tracker. This allows for development and prototyping of chamber modules and readout electronics for all three trackers to be done together.



Figure C.1: The conceptual layout of the SBS double-polarimeter, with the two 50 cm  $CH_2$  analyzers and the three GEM trackers, FT, ST and TT.

The readout-strip pitch of the 2D readout boards will be 400  $\mu$ m as in the Front Tracker. However, only a 1.6 mm readout pitch is required to provide the necessary spatial resolution for the second and third trackers. Thus, every four readout strips will be bridged into a single readout channel to reduce the number of electronics channels. This merging of the readout strips will be at the entrance to the Front-End Electronics board (after the ZIF connector) outside the chamber.

Two of the four chambers of each polarimeter tracker will have X-Y readout ( $0^{\circ}$  and  $90^{\circ}$  with respect to the dispersive direction), while the other pair will have U-V readout ( $45^{\circ}$  and  $-45^{\circ}$  with respect to the dispersive direction). The two X-Y chambers in a tracker will be installed next to each other, while the U-V chamber pair will be located 50 cm up-stream. This chamber configuration has been selected to give the best background rejection capabilities.

## C.2 Manpower and Facilities

The GEM chambers for second and third trackers, as well as GEM modules for the coordinate detector, will be constructed by the University of Virginia group, in collaboration with Jefferson Lab, following the design developed for the front tracker modules by the INFN group. The GEM foil and 2D readout planes for ST and TT and the coordinate detector will be fabricated at CERN along with those for the front tracker.

The detector facility at UVa consists of a 4 m  $\times$  4 m clean room that was used for the successful construction of the large area MWDC for the Bigbite spectrometer. The size of this clean room will be increased by the addition of a new class 10,000 level 6 m  $\times$  4 m clean room next to it. The clean room will be especially equipped for the GEM chamber construction. The size of these Bigbite MWDC constructed at UVa is comparable to the size of the GEM chambers proposed here and the facilities available at UVa, with the addition of the new clean room, are sufficient to handle the construction of the large GEM tracker. The final testing of the GEM chambers and the assembled tracker will take place at Jefferson Lab.

The leader of the large GEM tracker construction group at UVa, Nilanga Liyanage, is an expert in tracking detectors who recently led the successful project to develop and build the large MWDC tracker for the Bigbite spectrometer. As the manager of that 3-year \$443 k project, he supervised a senior post-doctoral associate, 3 graduate students and 10 undergraduate students. In the past Prof. Liyanage has played leadership roles in other large detector construction projects.

A post-doctoral level technical expert will be hired by UVa for the GEM chamber development and construction. She or he will be responsible for: setting up the clean room for GEM chamber construction, for the development of GEM chamber units in collaboration with INFN and Jefferson Lab, and for the construction and assembly of GEM chambers. In addition to this technical expert, 3 graduate student and several undergraduate students will be recruited to the large GEM chamber project.

The UVa group will also invite and sponsor visits by technical experts from CERN and INFN as needed. UVa already sponsored such a visit by a technical expert from CERN last summer.

# C.3 Development Plan, Prototyping, and Time-line

We already constructed two small scale  $(10 \times 10 \text{ cm}^2)$  prototype GEM chambers at JLab last year. These chambers were tested under very high-rate conditions with the beam in Hall A. We are currently assembling a tracking telescope consisting of four  $10 \times 10 \text{ cm}^2$  GEM chambers. In the telescope, the four chambers will be in the X-Y, X-Y, U-V, U-V configuration proposed for ST and TT. This tracker will be tested in beam at Jefferson Lab this spring with prototype APV25 based readout electronics from INFN. Following the development and fabrication of the  $40 \times 50 \text{ cm}^2$  GEM chamber prototype currently underway at INFN, we will assemble a  $40 \times 50 \text{ cm}^2$  prototype at UVa this Summer.

We plan to start production of final GEM modules this fall and to complete the construction of the trackers by the end of 2012. Installation of the trackers in hall A will take place during JLab shutdown of 2013.

#### • Phase 0: Preliminary Studies - 2008 - Mid 2009

- 1. Conceptual design and layout.
- 2. Construct two small scale  $(10 \times 10 \text{ cm}^2)$  prototype GEM chamber; test high-rate capabilities of this chamber in beam.

- 3. Monte-Carlo simulation of tracks and background hits in the chambers.
- 4. Setup and instrument the clean room at UVa for GEM chamber construction.

## • Phase 1: Prototyping and Design - 2009 - Mid 2010

- 1. Construct tracking telescope with four  $10 \times 10$  cm<sup>2</sup> prototype GEM chambers.
- 2. Test the tracking telescope in beam; study tracking algorithms, background levels, and background suppression.
- 3. Construct a full size  $(40 \times 50 \text{ cm}^2)$  prototype module.
- 4. Test the prototype module in beam.

## • Phase 2: Production and Installation - 2010 - end of 2012

- 1. Order chamber components in collaboration with the INFN group.
- 2. Construct large area GEM trackers
- 3. Move each tracker to Jefferson Lab after its completion for testing and integration into the spectrometer.

# • Phase 3: Final Installation and Commissioning 2013

- 1. Final installation of trackers in the spectrometer.
- 2. Tracker commissioning.
- 3. Optimization of tracking software.

# **Appendix D**

# Hadron Calorimeter for the SBS

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# **D.1** Introduction

The Hadron Calorimeter (HCAL) for the Super-Bigbite Spectrometer (SBS) will be used in the Hall A 12 GeV Nucleon Form Factors experiments to detect the recoiling protons in GEp(5) [1], the neutrons and protons in GMn [2], and the neutrons in GEn(2) [3], in the momentum range  $\sim 2.5$  to 10.5 GeV/*c*. HCAL will be also used for the Transversity experiment [4] to detect all types of hadron jets as described in this CDR.

# **D.2** Requirements for the HCAL

The main requirements for HCAL are derived from the needs of the nucleon form factors experiments. In the case of GEp(5), as an example, the electron arm is located at a central angle of 39° and the proton arm is at 12°. The viability of the proton detection system with the associated polarimeter depends upon the quality of the trigger. The overall experiment trigger is a coincidence between a signal from the electromagnetic calorimeter detecting the electron, and a signal from the hadron calorimeter

detecting the proton after its polarization has been measured in a dual polarimeter. The coincidence between elements of the two calorimeters will be organized in such a way that only events with an *ep* angle relation corresponding to elastic scattering will be accepted. This requirement imposes the dimension of the cells of both calorimeters providing good online use of the angular correlations between the proton and the electron. Furthermore, the energy deposited in the hadron calorimeter will have to be above a threshold determined by the proton energy and the resolution of the calorimeter, typically half the proton energy.

Good energy resolution of the electromagnetic calorimeter will allow for the electron arm trigger rate of 60 kHz at the maximum luminosity of  $\mathcal{L}_{max} = 7.5 \times 10^{38} \text{ cm}^{-2}$ /s at 11 GeV with 75  $\mu$ A beam current on a 40 cm long liquid hydrogen target.

The above conditions, primarily for GEp(5), require the following for the HCAL:

- 1. Position resolution of <5 cm will be necessary for HCAL to play a key role in track reconstruction of the recoiling proton.
- 2. Sufficient energy resolution to suppress low-energy signals (<4 GeV) without significant loss for 8 GeV protons. A 5-10% loss of efficiency for the detector due to low-energy background should be acceptable.
- 3. A total time gate width of  $\sim$ 50 ns for online use to create a coincidence time window for the electron arm and the hadron arm will be necessary.

# **D.3** Choice of the Technology

First we review the general characteristics of a calorimeter of the general type iron/scintillator. For the design of HCAL for SBS we do rely on the considerable experience acquired from the many exemplars built recently at high energy laboratories like Fermilab, CERN and BNL. We will present some specifics of the COMPASS calorimeter, *HCAL1*, which is the basis of the hadron calorimeter for SBS. We have developed Monte Carlo simulation programs based on GEANT4 and modeled HCAL in our energy range.

#### D.3.1 General features of a hadron calorimeter

In general, the shower generated by a high energy hadron in matter has two components, a hadronic one containing protons, neutrons and mesons, and an electromagnetic one due to the neutral pions created in the energy loss process, their succeeding decay into photons, which in turn trigger an electromagnetic shower. An important characteristic of shower information is the very large fluctuation, from shower to shower, between its various components, and therefore the very large fluctuation in the fraction of the initial energy deposited in the form of detectable energy (usually energy loss by the charged components in scintillator material).

Unless active stopping material is used, the functions of slowing down the initial shower and detecting its charged component are accomplished in two different materials; for example lead or iron, and scintillating plastic. In addition to the loss of information associated with the neutral component of the shower, an additional hidden energy goes to the breaking of the nuclear binding of the heavy material. So, in general, only a fraction of the total energy of the initial particle will be measured from light emitted in the scintillator component of the detector; and that fraction varies strongly from event to event. Furthermore, and unavoidably, the shower will have an electromagnetic component, and the material used in the calorimeter will more readily absorb the energy in that component than that in the hadronic part. Indeed, in iron the ratio of the nuclear interaction length,  $\lambda_{int}$ , for protons and neutrons, to the radiation length,  $X_0$ , is, 131.9 g/cm<sup>2</sup> (or 16.76 cm) / 13.8 g/cm<sup>2</sup> (or 1.76 cm); *i.e.*, 9.5. The corresponding numbers for lead are 194 g/cm<sup>2</sup> / 6.37 g/cm<sup>2</sup> for a ratio of 30.5.

A typical calorimeter for protons should have a thickness (including iron or lead and scintillator) corresponding to 4-6 nuclear reaction lengths (depending on the energy), and 12-25 radiation lengths. Depending on actual design, the first number determines the fraction of the total energy deposited in the calorimeter as a whole, and the efficiency of response. The second determines the response to the electromagnetic component. Together these numbers determine the e/h ratio, where h is the recoil hadron, which should be kept close to 1 for optimum performance.

An ideal calorimeter will have the same (or a similar) response for electrons and protons, *i.e.*,  $e/p \sim 1$ . It should have a response increasing linearly with the incident energy, be nearly 100% efficient, and have a spatial resolution of order of a few cm. The electromagnetic shower size is determined by the Moliere radius of the material, typically 2 cm for iron and lead. The radial development of the shower plays a role in the fraction of energy leaking out of a calorimeter module. This energy loss affects the energy response but also improves the position resolution if the energy leaking into the neighboring blocks is used to find the entrance point.

The light generated in the scintillating plastic of the calorimeter must be led into a light detection device, typically PMTs or silicon photo-diodes. The coupling between the scintillator and the PMT photo cathode can be accomplished with wavelength-shifting (WLS) plastic light collectors connected to the periphery of the scintillator tiles, or with WLS fibers going through the stack of iron or lead and scintillator tiles (so-called "Shashlik" design).

#### D.3.2 Hadron calorimeter design for Super-Bigbite

The Super-Bigbite hadron calorimeter design is based on the COMPASS hadron calorimeter *HCAL1* [5]. It has a modular structure with 242 blocks arranged in a matrix  $11 \times 22$  (see Fig. D.1. A single module consists of interleaved layers of 40 iron and scintillator plates. (The total number of plates can be reduced from 40 to 30 since our hadron energies are much lower than the ones of COMPASS.) The thickness of the scintillator and iron plates is 5 mm and 20 mm, respectively. The cross sectional area of the plates are  $142 \times 146 \text{ mm}^2$ . Figure D.2 shows the design for a single calorimeter module. The light from the scintillator is collected using a wave shifter. The length of a wave length shifting light guide is 1200 mm with an active length of 1050 mm, and a thickness of 3 mm. The total length of a calorimeter module is 1450 mm, with an active length of 1000 mm (4.8  $\lambda_{int}$ ). One module weighs 150 kg. Figure D.2 shows the design for a single calorimeter with a cover. Both are made of 1.4 mm thick steel sheets.

The main requirements for the scintillating plates are high light yield and uniform light collection over the scintillator surface. High radiation resistance of the scintillator is also important for its long term operation as it will be exposed to high intensity radiation. The light emitted in the scintillator plates is collected by a flat wave length shifting (from 420 nm to 520 nm) light guide attached to their open surfaces. (WLS with a smaller decay time than the green type used in COMPASS is being considered for SBS HCAL.) A FEU-84-3 PMT with venetian blind dynode system with 12 multiplying stages, and a multi-alkali photocathode is used in the COMPASS calorimeter. Its quantum efficiency is maximum at a wavelength of ~460 nm and varies from 0.18 to 0.26 for different specimens. (PMTs with faster time response than that of FEU-84-3 are being considered for SBS HCAL.)



Figure D.1: HCAL for Super-Bigbite with 242 modules of iron/scintillator plates arranged in a matrix 11×22.



Figure D.2: One module of COMPASS HCAL1 hadron calorimeter [5]. All dimensions are in mm.

# **D.4** Performance analysis of hadron calorimeters

The main characteristics of the hadron calorimeter are the linearity of its response as a function of particle energy, e/h ratio, and its energy and spatial resolutions.

#### D.4.1 Performance of COMPASS HCAL1

The response of the COMPASS *HCAL1* hadron calorimeter was measured at CERN using negative hadron and lepton beams (pions, electrons, and muons) with energies in the range of 10-100 GeV. Figure D.3 shows the spectra of energy deposited in calorimeter modules by muon and pion beams with an energy of 10 GeV. Solid lines are the Landau distribution fit for muon spectrum and the Gaussian distribution fit for pion spectrum.



Figure D.3: Spectra of the energy deposited in a *HCAL1* module by (a) muons and (b) pions at a beam energy of 10 GeV [5].

The experimental energy resolution of the calorimeter for hadrons (pions) and electrons were approximated by:

$$\frac{\sigma_{\pi}(E)}{E} = \frac{(59.4 \pm 2.9)}{\sqrt{E}} + (7.6 \pm 0.4)\%$$

and

$$\frac{\sigma_e(E)}{E} = \frac{(24.6 \pm 0.7)}{\sqrt{E}} + (0.7 \pm 0.4)\%,$$

with energy E in units of GeV. The spatial resolution was measured to be  $\sigma_{x,y} = 14 \pm 2$  mm. The average value of the e/h ratio that characterizes the amplitude response of the calorimeter to electrons and hadrons with equal energies is  $1.2 \pm 0.1$  (for an ideal calorimeter the ratio e/h=1).

Figure D.4 shows the COMPASS *HCAL1* energy reconstruction and energy resolution as a function of momentum for identified hadrons.



Figure D.4: COMPASS *HCAL1* (a) energy reconstruction and (b) energy resolution as a function of momentum for identified hadrons (the full symbols denote test beam results) [6].

#### **D.5** Simulations of Super-Bigbite HCAL

A complete GEANT4 simulation [7] code for the Super-Bigbite spectrometer including an array of  $11 \times 22$  HCAL blocks has been written. Muons, pions, protons and neutrons were generated in the simulation. In this section we will focus on protons and neutrons simulation results.

Figures D.5 and D.6 represent the energy deposited by protons and neutrons, respectively, with momenta from 2.6 GeV/c up to 10.5 GeV/c. We notice some similarity of the shapes of the spectra for protons and neutrons although the distributions for neutrons are a bit wider.

Energy resolutions were also extracted and they are shown in Fig. D.7. These good energy resolutions allow high thresholds in the HCAL to eliminate background and lower the experiment trigger rates.

Efficiencies for detection of protons and neutrons of HCAL are also extracted and shown in Fig. D.8. These efficiencies were extracted for thresholds of one-half and one-quarter of the deposited peak energy, respectively.

Spatial resolution (in x or y direction) was also extracted for both protons and neutrons in the



Figure D.5: Energy deposited in a  $3 \times 3$  cluster in the hadron calorimeter corresponding to protons for GMn [2] kinematics. Results are from GEANT4 simulations.



Figure D.6: Energy deposited in a  $3 \times 3$  cluster in the hadron calorimeter corresponding to neutrons for GMn [2] kinematics. Results are from GEANT4 simulations.

momentum range 2.6-10.5 GeV/c and are presented in Fig. D.9. Position is found as the square-root of the energy weighted mean position in a  $3\times3$  array of blocks centered on the block with greatest energy-deposited. These position resolutions allow for a good angular resolution and are needed in all form factor experiments to separate the (quasi-)elastic from the inelastic and especially needed in GEp(5) to help with tracking in a large low-energy background environment.

Timing resolution for the HCAL is currently under study.

# **D.6** Development plans for the HCAL

The development plans for the SBS hadron calorimeter is to construct one that is very similar to the working COMPASS *HCAL1* calorimeter optimized for experiments with the Super-Bigbite apparatus.


Figure D.7: Resolution of the deposited energy in a  $3 \times 3$  cluster in the hadron calorimeter for protons and neutrons for GMn [2] kinematics. Results are from GEANT4 simulations.



Figure D.8: Detection efficiency in a  $3 \times 3$  cluster in the hadron calorimeter for protons and neutrons for GMn [2] kinematics. Results are from GEANT4 simulations.

our experiments. In fact, about 25 modules of the COMPASS calorimeter are in Dubna (JINR) and underwent preliminary testing with a mixed beam of 13.8 GeV <sup>6</sup>Li and 9.2 GeV <sup>4</sup>He ions from the Nuclotron May 2008. Such tests will be continued, in particular in combination with a modified configuration of the polarimeter POMME to test the hypothesis that the analyzing power can be improved by detecting the leading particle with a hadron calorimeter located downstream from the polarimeter.

### **D.7 HCAL Collaboration**

Currently, the hadron calorimeter collaboration consists of members from Carnegie Mellon University in the U.S.A., Laboratory of High Energies, JINR, Dubna, Russia, and University of Glasgow, Glasgow, Scotland. JINR is an integral part of the collaboration and they will facilitate the construction of



Figure D.9: Position resolution for a  $3 \times 3$  cluster in the hadron calorimeter for protons and neutrons for GMn [2] kinematics. Results are from GEANT4 simulations.

the HCAL modules and their prototyping and testing together with the collaborators from the U.S.A. Carnegie Mellon University is taking the leading role in organizing the HCAL design, development, construction, and commissioning of the hadron calorimeter.

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## **Appendix E**

# **Electromagnetic Calorimeter for GEp(5) Experiment**

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#### **E.1** Introduction and requirements

The use of the lead-glass electro-magnetic calorimeter, BigCal, in the GEp(5) experiment [1, 2] has several specific for the experiment purposes. First, the correlation between the positions of the elastic electron hit in the BigCal and the proton hit in the Hadron Calorimeter will be used in the trigger to reduce the rate down to levels (of a few kHz) acceptable for the DAQ. Second, by registering the elastic electron in the EM calorimeter and applying kinematic correlations, one can find in the analyses the region in the SBS front chamber where the elastic proton is expected. This will help to identify the proton track even at very high random hit multiplicity, thus allowing the experiment to run with a luminosity as high as  $10^{39}$  e/cm<sup>2</sup> nucl/s. Finally, the EM calorimeter information combined with the reconstructed proton parameters will be used to identify the elastic reaction suppressing the physical inelastic background down to less than 10% of the elastic events.

To achieve these goals we need an energy resolution better than  $10\%/\sqrt{E}$ . This is dictated by the trigger rate considerations. A coordinate resolution of about 10 mm is essential for the kinematic correlation between the position of the elastic electron, and the proton parameters.

The BigCal detector is operational and has been used already in several experiments in Hall C (Fig. E.1). It is built of two sizes TF1 lead glass with cross-sections  $3.8 \times 3.8$  cm<sup>2</sup> and  $4 \times 4$  cm<sup>2</sup>. In spite of the large number of channels (1744) the failure rate of the detector was acceptable and it was running smoothly. The main problem that appeared during these high luminosity experiments was the radiation damage of the glass which resulted in continuous reduction of the gain and worsening of the resolution. As estimated here, for the GEp(5) experiment we expect about a factor of 10 higher



Figure E.1: BigCal in Hall C with the front opened, February 2008.

background rates. Therefore, here we will discuss in detail the radiation hardness requirements and proposed solutions to the problem.

## **E.2** BigCal performance during GEp experiments in Hall C

The calorimeter was roughly calibrated with cosmic muons before the experiment and then using 1.06 GeV elastic electrons during the commissioning in October 2007. To reduce the radiation damages the calorimeter was equipped with an absorber consisting of four removable Al plates, each one inch thick. Two absorber configurations were used during the calibration, consisting of one and four Al plates, which, in addition to the permanent material in the front (monitoring system and frame) results in thicknesses of 0.43  $X_0$  and 1.29  $X_0$  respectively. The obtained energy resolution together with the expected one from Monte Carlo simulation [3] are shown at Fig. E.2. The experimentally achieved resolution differs by about 1–1.5% from the simulations and is among the best results obtained with this type of calorimeters especially given the additional absorber and the large number of channels. However, due to the darkening of the lead-glass it was gradually increasing and we ended up with  $\sim 24\%/\sqrt{E}$  resolution in June 2008, inspite of the partial UV curing in the middle of the running period.

Figure E.3 demonstrates the problem. The relative gain, normalized to one at the beginning of the experiments, was obtained by averaging the gain of all the channels and applying the following corrections. During the GEp experiments it was a standard procedure to re-calibrate the calorimeter, since the energy of the elastic electron was known from the proton arm. Every time the calorimeter was re-calibrated, corrections to all the channels separately were applied to undo the effect of the HV



Figure E.2: BigCal energy resolution (red solid boxes) obtained during commissioning using 1.06 GeV elastic electrons with two different absorber thicknesses, 0.43  $X_0$  and 1.29  $X_0$ , compared to Monte Carlo simulations for different energies as function of the additional Al absorber thickness.



Figure E.3: Mean gain of BigCal during the GEp(3) experiments in Hall C (October 2007 - May 2008) as a function of the accumulated beam charge in coulombs. Kinematics 1 (red) and 2 (blue) points are fitted with  $ae^{-bC}$  (results given in Table E.2). No data for the week-long WACS experiment (E07-002) is given except the last run (solid magenta triangle) just before the UV curing.

change, so that effective gain comparison can be done for the fixed initial high voltages. There were several kinematics for which it was not practical to re-calibrate, mainly because only a fraction of the calorimeter was used and because of sufficient calorimeter resolution at high electron energies. There was a number of configuration changes during these experiments. The calorimeter was repositioned every time the beam energy changed. In addition the thickness of the absorber in front of the calorimeter was different for the different kinematics. In addition to the obvious gain correction by the electron energy, correction was applied at the beginning of each kinematics to ensure the continuity of the gain before and after the change of the kinematics. Most of the correction is explained by simulations taking into account the fraction of the energy that is deposited in the absorber, which fraction varies with the energy and absorber thickness. Possibly, the reduced transparency in the front of the lead-glass is responsible for the rest of the effect.

Generally, different slopes in Fig. E.3 correspond to different kinematics: different beam energy, angle and distance to the calorimeter. The calorimeter position for the GEp(5) experiment will be fixed:  $39^{\circ}$  at 3 m from the target. To estimate the gain loss due to radiation damages in this future experiment we will analyze two kinematics from the figure, at  $31.4^{\circ}$  (red, kinematics 1) and  $42^{\circ}$  (blue, kinematics 2) both at about 11-12 m from the target. The data points were fitted with exponents:  $ae^{-bC}$ 

kin.	angle	Dist.	Target	E	Gain loss	soft photon
	deg.	m	cm	GeV	rate b	flux J/cm <sup>2</sup> /C
#1	44.9	12	20	2.839	0.14%/C	0.0039
#2	32.0	11.2	20	3.539	0.53%/C	0.013
GEp(5)	37.5	3.5	40	3.539	$\sim 6.7\%/C$	0.17

Table E.1: Gain loss rates b estimated from the Fig. E.3 for kinematics 1 and 2 and predicted for the GEp(5) conditions from the soft photon flux per Coulomb estimated with the Monte Carlo simulations.

and the rate constant b is given in Table E.2. Using GEANT simulations, as explained in Section 5, we have estimated the energy fluxes per Coulomb through the front of the calorimeter in all the cases. As seen from Table E.2, for kinematics 1 and 2, these numbers are roughly proportional to the gain loss rates estimated from Fig. E.3. Thus, for the GEp(5) kinematics, based on the simulations, one can predict that the gain loss will be about 6.7% per Coulumb. The rate increase is mainly due to shorter distance from the target to the calorimeter (factor of 9) and larger target length (factor of 2) however it is partially compensated by the higher beam energy.

### E.3 UV curing

Curing of the glass was performed with a specially constructed UV lamp (Figures E.4, E.5) that covered a quarter of the frontal calorimeter area in the downtime period (February 2008) during the GEp experiments. The lamp was moved at four different positions with an average time of 3 days per position. The effect of the UV curing corresponds to the jump in Fig. E.3 between the red triangle (at 39%) indicating the gain before the curing and the next upper point (at 74%) after the curing. Fit with exponential function gives 1.24% per hour gain increase. Because of concerns about glass heating, there was a gap of 2" between the UV bulbs and the glass. During the curing it turned out that the glass temperature rose by a few degrees. We have chosen also low power bulbs (14W) not to damage the PMTs that were left in place during the curing. After the GEp experiment two UV lamps were built to cure the calorimeter for the SANE experiment with expected total curing time of 60 days per position. Constant check of the PMT performance showed no deviation from the normal gain, except some relaxation time was needed after long (several weeks) period of UV illumination.

For the GEp(5) experiment, assuming a current of 75  $\mu$ A and 50% accelerator efficiency, we expect 0.13 coulombs per hour. This corresponds (Table E.2) to about 0.87% gain loss per hour, to be compared with 1.24% per hour gain increase during the curing.

We intend to build a permanent UV light box in front of the glass. By placing the bulbs right next to the glass and increasing the power and density of the bulbs we expect to increase the UV flux by at least 5 times resulting in a gain increase rate of above 6% per hour. Such a design is possible as evident from the existing light box (Figs. E.4, E.5). During the GEp(5) experiment we propose to use one hour per shift for UV curing, since we expect gain loss for 7 hours to be about 6% as well. Assuming half of the time the curing will overlap with accelerator downtime, we introduce 6% inefficiency due to this procedure.



Figure E.4: UV bulbs (in the middle) mounted in front of the glass blocks (at the top), February 2008. Distance between bulbs and glass was 2".



Figure E.5: Top view of the UV lamp. Bulbs have 14 Watt power and an active length of 11", covering 12.5" wide frontal area of the glass (1/4 of the total area).

### E.4 BigCal upgrade

In order to meet the requirements of the GEp(5) experiment we are going to realize the following upgrade plan:

- Building of a permanent UV light box right in front of the lead glass, as explained above. The proposed method of curing the glass requires prototyping in order to optimize the downtime introduced by this procedure and to make sure that the PMTs are not affected by it. For that we plan to use the existing prototype of the calorimeter consisting of a  $5 \times 5$  block array.
- Replacing the 4" aluminum absorber by 8" Al absorber. We expect (see Fig. E.2) to have an energy resolution of about 15-16% for 1 GeV electrons. We plan to investigate the effect of the absorber with Monte Carlo simulations [3].
- We will upgrade the HV supply system since for the Hall C experiments we have used 640 channels from the G0 HV supply system. It will require 58 LeCroy HV cards (696 channels) in 4 LeCroy HV crates.

### E.5 Comparison with other calorimeters

The overall resolution of BigCal obtained at the beginning of the Hall C experiments with a 0.43  $X_0$  absorber for 1 GeV electrons was 7.0% (Fig. E.2). A resolution of  $5.5\%/\sqrt{E}$  was achieved with exactly the same kind of calorimeter but without absorber at the beginning of the RCS experiment [4] in Hall A. The PRIMEX experiment in Hall B had a calorimeter consisting of two block types: lead-glass bars as in BigCal and RCS calorimeters, and lead-tungstate crystals of  $2\times 2$  cm<sup>2</sup> cross-section. The obtained resolution for 1 GeV photons was 7.7% for the lead-glass and 4.4% for the crystals [5]. The radiation hardness of the the lead-tungstate crystals of the PRIMEX experiment is about 100 times larger than the one of the lead-glass.

Another calorimeter type that is worth considering because of its radiation hardness is the so called Shashlyk calorimeter. The Shashlyk type calorimeter [8] of similar block sizes  $(5.5 \times 5.5 \text{ cm}^2)$  in the HERA-B experiment showed moderate resolution of about  $12\%/\sqrt{E}$ , which is mainly defined by the fraction of the sampling (scintillator) material. However, in the recent years a new-type Shashlyk calorimeter was introduced [6, 7] with a resolution comparable to the one of the glass/crystal type calorimeters. This was achieved by using specially developed scintillator at IHEP (Protvino, Russia), improving optical and mechanical properties, and very importantly, by using Avalanche Photo Diodes with Wave-Form Digitizer readout. A production of calorimeter blocks  $(5.5 \times 5.5 \text{ cm}^2)$  of this type was recently established [9] in IHEP for the PANDA experiment. Presently, the price per one block without the electronics is about \$700 [10].

### E.6 Collaboration list

The following collaborators are participating in the upgrade of the BigCal:

- Jefferson Lab, Newport News, VA: M. Jones, W. Luo, L. Pentchev, B. Wojtsekhowski
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## **Appendix F**

# **Trigger Logic and Electronics for the SBS Spectrometer**

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### F.1 Introduction

For the SBS project, we plan to re-use existing FASTBUS and VME electronics for BigBite and BigCal, whereas new, pipelined electronics will be used for all the GEM chamber read-outs and the hadron calorimeter read-out (when it is in the GEp(5) configuration). The DAQ trigger will have two levels: The first-level trigger will have a relatively short delay,  $\sim 100$  ns, relative to the particle detection. It will be generated by the electron arm. This signal is required for operation of the GEM read-outs; despite their pipelined architecture, the APV25 front-end chips used in the GEMs require a fast trigger for marking "interesting" samples (see Section G.2.2). Such a fast first-level trigger also eliminates the need for long delay lines for the conventional FASTBUS and VME electronics. The second-level trigger will be formed using a relatively complex coincidence logic, described below. It can have a latency of several microseconds. Please see Section G.2.2 for more information on the DAQ.

Here we will discuss here the trigger for the GEp(5) experiment which is a critical part of the experimental design. Achieving a reasonable data rate in this measurement is particularly challenging given the high luminosity of  $8 \times 10^{38}$  cm<sup>-2</sup>/s with open detectors. To address this challenge, the trigger for GEp(5) will have two main features: (1) a high energy threshold in the calorimeters in both arms (3-4 GeV for the proton and 2.5 GeV for the electron); and (2) "smart" coincidence electronics

based on Field-Programmable Gate Arrays (FPGAs) that allow second-level triggering on the spatial correlations of hits in the two detector arms.

### F.2 Expected rates

**Counting rate of the proton arm calorimeter (HCAL)** The amplitude of the signal from the hadron calorimeter is proportional to the hadron energy, so with an energy threshold of 4 GeV, the expected rate is 1.5 MHz for the whole calorimeter, or about 10–20 kHz per module. This rate is mainly due to pions, and was calculated by using an experimental cross section [1] and a photon flux calculated from the approximation of [2]. The large energy of the recoiling proton ( $\sim 8$  GeV) will allow a relatively high threshold in HCAL ( $\sim 4$  GeV).

Counting rate of the electron arm calorimeter (ECAL) The good energy resolution of the electromagnetic calorimeter will allow for an electron arm trigger rate of 60 kHz at the maximum luminosity of  $\mathcal{L}_{max} = 7.5 \times 10^{38} \text{ cm}^{-2}/\text{s}$  at 11 GeV, corresponding to a 75  $\mu$ A beam current on a 40 cm long liquid hydrogen target.

With a coincidence time window of 50 ns, forming a simple coincidence between the two arms would result in a trigger rate of at least 5 kHz, which is too high (or at least close to the limit) for the expected total event size of  $\sim 20$  kB (see Section G.2.2). Noting that, in the GEp(5) experiment, the proton trajectory in Super Bigbite has a very small deflection, it becomes possible to use the angular correlation between the elastic electron and the proton trajectories, at the trigger level, to reduce the coincidence trigger rate further by a factor of five.

### F.3 Electronics for coincidence logic

In designing our second-level triggering system, it is important to note that real (not noise) calorimeter hits always cause several adjacent blocks to fire. We therefore construct what we call "macroblocks", consisting of the sums of the individual signals from several nearby blocks. In HCAL, the size of the macroblocks is  $4 \times 4$  (we call this a "sum-16"), and in the ECAL the size is  $8 \times 4$  ("sum-32"). The different macroblocks overlap each other, such that each individual block contributes to the sums associated with several different (overlapping) macroblocks. In this way, at least one macroblock will always contain a large fraction of the deposited energy associated with a real hit. In the HCAL, we place the macroblock centers on a  $7 \times 17$  grid that is centered in the calorimeter region; hence, 119 "sum-16" sums need to be calculated. Similarly, the ECAL macroblock centers are placed on a  $4 \times 37$ grid, for a total of 148 "sum-32" sums.

To take advantage of the strong kinematic correlation between the electron and the recoil proton at the (second-level) trigger level, we need to quickly establish whether a hit in a given macroblock in one arm corresponds to a hit in a given macroblock in the other arm. For example, a given vertical hit position in the ECAL limits the vertical location of a possible coincidence hit in the HCAL to a relatively small region. This is illustrated in Fig. F.1 in which both HCAL and ECAL are shown, and the hits corresponding to a good coincidence are shown in pink. Another hit in ECAL corresponding to a correlation that is kinematically excluded is shown in green. To quickly establish whether or not to exclude a particular coincidence, the ECAL is sub-divided into four non-overlapping regions of  $4 \times 19 = 76$  macroblocks, and the HCAL is sub-divided into four overlapping regions of  $7 \times 7 = 49$ macroblocks. These regions are also illustrated in Fig. F.1. The coincidence logic can then be realized



Figure F.1: Illustrated is the configuration of the second-level trigger logic for the GEp(5) experiment. The electron arm has 148 "sum-32" signals (each comprised of a group of individual blocks) arranged in a  $7 \times 17$  matrix. The hadron arm has 119 "sum-16" signals arranged in a  $4 \times 37$  matrix. They are divided into four groups each and fed into four FPGA units to form the coincidence signal.

with four FPGA modules with 76 + 49 = 125 input channels each. 128-input FPGAs are readily available commercially.

In practice, the "sum-32" ECAL signals will be formed by first forming sums of  $2 \times 4$  blocks with custom "sum-8" units, which provide amplification by a factor of 5, analog output to ADC, and four copies of the analog sum of the 8 inputs. A LeCroy fan-in unit will then be used to sum the "sum-8" signals to form the "sum-32" signals. These summing modules as well as discriminators for the "sum-32" outputs are already available from previous experiments.

On the HCAL side, we plan to use the 250 MHz 12-bit pipelined flash ADCs ("FADC"), which have recently been developed by the JLab electronics group for GlueX, along with additional custom electronics to do the summing of the signals digitally. The FADCs store 2048 samples (8  $\mu$ s pipeline depth) and have 16 inputs each. The 200 HCAL channels thus require 13 FADC modules, which will fit into one VME crate. The data from these modules will be sent to a custom-built Crate Trigger Processor ("Smart HCAL") for digital summing. Because of bandwidth constraints, each FADC will only send the most significant 8 bits of its data (128 bits total) to the "Smart HCAL" every 16 ns, instead of the full 12 bits at the 4 ns digitization interval. This is still compatible with a 50 ns coincidence window, and the full time and amplitude resolution can be recovered from the FADC data offline. The "Smart HCAL" will then compute the required 119 "sum-16" digital sums and provide logical

outputs for them on external connectors, corresponding to the four  $7 \times 7$  vertical subdivisions shown in Fig. F.1. In this way, the "Smart HCAL" module also handles the signal discrimination (via a programmable software threshold) and fan-out without additional hardware. The latency of this type of trigger formation is expected to be on the order of a microsecond.

The "sum-16" outputs from the "Smart HCAL" processor as well as the discriminated signals from the ECAL "sum-32" units will be sent, appropriately delayed, to the coincidence FPGA units (CAEN v1495, 128 inputs each) to form the coincidence with the hadron arm requiring the geometrical correlation for elastic kinematic. Processing in the FPGAs will add roughly another microsecond to the overall trigger formation time. The total trigger latency will be substantially less than the shortest pipeline lookback time of 4.8  $\mu$ s of the APV25s in the GEM readout. We expect a five-fold reduction of the trigger rate with this scheme.

#### F.4 Collaboration list

The Trigger collaboration currently includes Jefferson Lab, Rutgers University, and the University of New Hampshire. The University of New Hampshire is expected to take the leading role in organizing the design, development, construction, and commissioning of the Trigger in the GEp(5) experiment.

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## Appendix G

# Front-end Electronics and DAQ System for the GEM Trackers

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### G.1 Introduction and requirements

The main challenge for the design of the front-end electronics and DAQ system for the GEM-based trackers of the SBS is to build a system that reads out a large number of channels, distributed over the various detector systems operating at high event rates (see, for example, Table 5.3), and with a deadtime as low as possible. The proposed front-end readout for the GEMs will follow a scheme similar to the one developed for the COMPASS experiment at CERN [1]. The scheme uses customized ASIC chips for the front-end boards and intermediate VME64x modules for buffering of the data.

To cope with the expected high data rates, the readout system has a pipelined architecture and the signals are digitized and concentrated as close to the detectors as possible, which not only simplifies the processing and transport of the detector data, but additionally lowers the readout noise. Most of the data links utilize optical fibers, which provide high data bandwidths, are insensitive to electromagnetic noise, and simplify the electrical grounding of the apparatus. Moreover, the system has a modular design in which the modules, that are connected by a tree-like hierarchical network, merge the digital data streams of the various equipments at different levels.

## G.2 Choice of the technology

#### G.2.1 Front-end electronics for the GEM trackers

The proposed plan for processing the signals from the GEM strips is to store them in an analog pipeline. The best candidate is the APV25 chip [2], currently in use for the GEM trackers at COMPASS and the silicon micro-strip detectors in the CMS tracker at the LHC. The chip samples 128 channels in parallel at 40 MHz and stores 192 analog samples per channel. This allows 4.8  $\mu$ s to make the trigger decision which will use a coincidence between the electron arm and the proton arm for the GEp(5) experiment. Note that the GEM trackers will not be part of the experiment trigger. Once the trigger is made, the one "*most interesting*" single sample of each channel can be read, or possibly an average of three samples around the one corresponding to the trigger time (the multi-mode operation of the chip). This permits extracting accurate timing information of the signal, a feature very important to reduce pileup in high-intensity beams.

Figure G.1 shows a simplified block-diagram of the front-end readout electronics. Details are given in Section B.4.1 of Appendix B.



Figure G.1: Schematic block-diagram of the front-end readout electronics for the SBS GEM trackers.

#### G.2.2 Data acquisition system for the GEM trackers

We plan to use a CODA-type DAQ system [3] with a mix of FASTBUS and VME electronics. Some of the electronics will be pipelined, as described in the previous sections. The non-pipelined modules will be gated on the fast first-level trigger and will use the Fast Clear from the CODA Trigger Supervisor to re-arm if the L2 logical condition is not met. At an expected 60 kHz L1 trigger rate and a  $2-3 \mu s$  L2 trigger latency in GEp(5), dead-time from these subsystems will be less than 20%.

The overall data rate will be driven by the GEM trackers. The Super BigBite Spectrometer will have approximately 76,000 GEM read-out channels, and the Coordinate Detector in the Electron Arm will require an additional 12,000 channels, for a total of almost 90,000 channels. As our Monte Carlo

studies show, the SBS front trackers (approximately 49,000 channels) will have a high occupancy of about 10%, while the occupancy for the remaining detectors is expected to be somewhat less, between 4–8%. At 2 bytes per tracker channel (7 bits address, 9 bits data), this leads to an event size of roughly 15 kB from the trackers alone. If the other detector systems (calorimeters etc.) are included, the total event size will of order 20 kB. A physics trigger rate of 5 kHz then corresponds to a data rate of 100 MB/s. Note that we expect an actual physics trigger rate of 2–3 kHz or less.

This substantial data rate will be manageable with the DAQ upgrades in Hall A that are planned for running at 12 GeV [4]. The upgraded DAQ will employ some of the high-speed pipelined trigger and read-out electronics currently under development for the JLab GlueX/Hall D project as well as the associated CODA 3 data acquisition software. These electronics feature a design 200 kHz L1 trigger rate capability. Front-ends will be housed in VME64x crates operating in 2eVME or 2eSST high-speed read-out mode, which both provide a maximum transfer rate of 200 MB/s. The crates will be uplinked to event builder PCs via Gigabit Ethernet (trunked if necessary). Trigger signals will be distributed from a central Trigger Distribution Crate via optical fiber. Essential for achieving the high-rate capability of the system is the requirement that VME front-end modules be able to buffer up to 200 events in on-board FIFO memory. In this way, data transfers between the crates and the event builder will consist of event blocks that will be transmitted at a reasonable rate of 1 kHz, reducing the overhead associated with VME transfers dramatically.

Although possible in principle and a potential upgrade path, it is not currently foreseen to run the entire Hall A DAQ in pipelined mode, as in Halls B and D. Nevertheless, the electronics for the GEM trackers of this proposal will use pipelining in the chamber read-out boards (APV25 chip). This will eliminate any need for analog delay lines for the GEMs, even with possibly long trigger formation times of several  $\mu$ s, and such a pipelined subsystem will not have any significant read-out dead-time.

The interface between the APV25s and VME will consist of custom VME64x modules. They will handle the JLab-specific trigger and clock signals on the VME backplane, forward the trigger signal with appropriate offset as well as control and programming commands to the APV25 frontends and multiplexers via fiber, and provide on-board trigger and event buffering. Because of the (in comparison to GlueX) relatively low trigger rate of the experiments described here, the event buffer of the GEM VME modules may only be some 10–20 events deep instead of 200. Development of these modules will be primarily done by the INFN group, with support from the JLab Data Acquisition Group. The GEM-to-VME interface module is currently being designed at INFN Genova, with a prototype expected to be ready for testing in early 2010.

Event builder and event recorder computers will be standard Hall A equipment, consisting of highperformance, multi-processor x86-based machines with fast local disk arrays. A disk write rate of 100 MB/s is already easily achieved today. Data will be transferred to the central JLab Mass Storage System via a Gigabit Ethernet for storage on tape. The total data volume coming from Hall A running with SBS will be comparable to that expected from Hall B/CLAS12, roughly 5–7 TB/day.

#### G.3 Collaboration list

Albeit, the GEMs require very sophisticated readout electronics, they are part of a working technology. The APV25 chips are currently in use at CERN. The INFN-Rome group has already developed prototypes of the front-end boards and the ADC/VME controller card and has the technical expertise and support at their home laboratory to implement the chips into the GEM readout system.

The following collaborators are part of the development, testing, and implementation of the SBS trackers' front-end electronics and the DAQ system.

- Norfolk State University, Norfolk, VA: M. Khandaker and V. Punjabi.
- INFN-Rome, Italy: E. Cisbani and the electronics group.
- Jefferson Lab, Newport News, VA: J.-O. Hansen.

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## **Appendix H**

## **Collaboration Resources**

In this section we discuss the planned organization of the work involved for each sub-system of the SBS and the necessary resources:

- Dipole with auxiliary vacuum chambers, shielding, support structure
- First tracker
- Second and third trackers or the first and second polarimeters
- Hadron calorimeter
- Electromagnetic calorimeter and coordinate detector
- Front-end electronics and DAQ
- Trigger electronics

The core of the collaboration is formed by the Thomas Jefferson National Accelerator Facility, the University of Virginia, Carnegie Mellon University, the College of William and Mary, Norfolk State University, Rutgers the State University of New Jersey, the University of New Hampshire, the National Institute of Nuclear Physics (Italy), the University of Glasgow (Scotland), and the Laboratory of High Energies, JINR, (Russia). The international part of the Super Bigbite collaboration plays a very important role in the project. It includes the groups from INFN (Italy), Glasgow (Scotland), and JINR (Russia) Efforts of the INFN group (E. Cisbani *et al.*) are concentrated on development of the GEM-based front tracker and associated electronics, for which INFN approved the full requested funding of 720k Euro. The Glasgow group (directed by Prof. G. Rosner) is collaborating in several Super Bigbite experiments and is in the process of submitting a "12-GeV JLab Upgrade Project" funding request to the UK STFC, which includes a research associate position and around \$200k for equipment for the Super Bigbite Project. The JINR group (I. Savin *et al.*), together with the group from Carnegie Mellon University, is primarily involved in the development of the hadron calorimeter and its associated electronics.

### H.1 Dipole with auxiliary equipment

The project leader for this part is B. Wojsekhowski of Hall A; in addition, the group involves C.W. de Jager, J.-O. Hansen, J.J. LeRose and L. Pentchev, all from JLab. They will design and construct the shielding in the beam hole through the yoke, target vacuum chamber extension, front shielding and magnet support. The group will be responsible for the installation and commissioning of the upgraded infrastructure required for the magnet, the targets, and the beam line.

### H.2 First tracker

Design, construction and financing of the first tracker is the responsibility of the INFN, Rome group with the support of other INFN groups. It is expected that the required detectors, with associated readout chips (and associated electronics), as detailed in this CDR, will be delivered to JLab complete. The group includes E. Cisbani (leader), M. Capogni, D.-M. Castelluccio, F. Garibaldi, S. Frullani, F. Meddi, G. Urciuoli, P. Musico, V. Bellini, F. Noto and R. De Leo; in addition the group has technical support at their home laboratories. The project has long range support, with one year funding already given; remaining funding to follow on a year-by-year basis.

The Glasgow group has provided a number of GEM foils which were included in prototypes currently being tested with beam in Hall A.

## H.3 Second and third trackers

The second and third trackers are the detector components of the first and second polarimeters; they are the responsibilities of groups at UVa (N. Liyanage (leader), G. Cates, V. Nelyubin, K. Paschke, S. Riordan and W.A. Tobias), NSU (V. Punjabi and M. Khandaker) and W&M (C.F. Perdrisat). Other major contributor is J. Annand of University of Glasgow.

The UVa group will develop and fabricate the GEM-based units with active area  $40 \times 50 \text{ cm}^2$  that will be used for the polarimeter trackers (ST and TT) and the coordinate detector (CD). Following the development work, the UVa group will then construct and test at UVa the production chambers for the ST and the TT. The detector facility at UVa consists of a  $4 \times 4 \text{ m}^2$  clean room that was used for the successful construction of the large area MWDCs for the Bigbite spectrometer. The size of this clean room will be increased by the addition of a new class 10,000 level  $6 \times 4 \text{ m}^2$  clean room adjacent to the original clean room. The clean room will be specially equipped for the construction of the GEM chambers.

### H.4 Hadron calorimeter

The Carnegie Mellon University (CMU) group (G.B. Franklin (leader), B. Quinn and F. Benmokhtar) will take responsibility for the Hadron Calorimeter (HC) which is essential for the formation of a trigger. The HC will have 250 modules similar to the COMPASS "*HCAL1*" calorimeter. CMU will begin with an in-beam test of a small subset of modules in Hall A. CMU will then coordinate the final HC design, working in collaboration with JINR, Dubna (Russia) group (I. Savin *et al.*).

### H.5 Electromagnetic calorimeter and coordinate detector

The existing BigCal calorimeter will require modifications to the read-out electronics associated with formation of a trigger signal, as well as for refining the radiation damage healing procedure. Jefferson Lab (L. Pentchev (leader) and M. Jones) and the College of William and Mary (C.F. Perdrisat) will take responsibility for this part of the project. In addition, the group will take on the assembly and testing of the coordinate detector, which will be used in the electron arm of the GEp(5) experiment. It will require design and construction of a large mechanical frame for the two-plane detector with a one-dimensional read-out. This detector will have a simplified version of the polarimeter GEM chambers.

## H.6 Front-end electronics and DAQ

The Norfolk State University group (V. Punjabi and M. Khandaker), in collaboration with the INFN-Rome group, will fabricate, test, and commission the Front-End-Electronics and Data Acquisition electronics for all GEM-based trackers in the SBS project. This group will also conduct electronic noise-reduction studies of the prototype chamber and commission the tracker electronics for high-rate operation.

## H.7 Trigger electronics

The Jefferson Laboratory group together with the groups at Rutgers University (R. Gilman (leader), R. Ransom and L. El Fassi) and at the University of New Hampshire (UNH) (J. Calarco (leader) and K. Slifer), will take responsibility for developing, assembling and testing the trigger electronics for all of the SBS experiments. As part of this work Rutgers and UNH will write specialized code for the programmable modules used for identifying coincidences.

In conclusion, the physicists committed to the realization of the SBS setup have experience in building subsystems of various sizes at JLab, in Hall A and Hall C. Although some of the technology required is new at JLab, it has been developed and has been proven to work at CERN and elsewhere. The team involved will benefit from participation in the RD51 group at CERN, which is dedicated to the development of microgas detectors like GEM and Micromega. There is no showstopper we can think of at this time!