

# Development of a Curved Fast Ramped Dipole for FAIR SIS300

P.Fabbricatore, F. Alessandria, G. Bellomo, S. Farinon, U. Gambardella, J.Kaugerts, R.Marabotto, R.Musenich, G.Moritz, M. Sorbi, and G. Volpini

**Abstract**— At present, one of the main options for beam bending dipoles of the SIS 300 synchrotron, under design for the FAIR facility at GSI, is a single layer magnet, 7.8 m long, 100 mm coil inner diameter, generating 4.5 T. This coil has two main features: it is curved, with a curvature radius of 66.67 m, and shall be ramped at 1 T/s. Both these characteristics demand challenging R&D, aimed at the development of the required conductor and winding technology. The paper discusses both these aspects, in the framework of a general ongoing R&D program at INFN, under the name DISCORAP. Its goal is the construction of a half-length prototype (3.8 m) dipole, fully integrated into its horizontal cryostat, within three years. The R&D program includes: 1) the activities required to develop low loss superconducting wires and cable; 2) the technological developments (at the industrial level) for defining and optimizing the dipole construction methods; 3) the construction of curved dipole coil winding models; 4) the construction of the complete curved dipole; 5) the test of the curved dipole in a vertical cryostat; 6) the integration of the curved dipole into a horizontal cryostat, for the final test at GSI.

**Index Terms** — Superconducting dipoles, fast ramped magnets.

## I. INTRODUCTION

In the framework of a large international collaboration it is planned to construct a new accelerator complex FAIR [1], which will be integrated into the existing GSI facility in Darmstadt and will provide high intensity primary and secondary beams of ions and antiprotons for experiments in nuclear, atomic and plasma physics. The heart of the FAIR facility is the synchrotron SIS100 (100 Tm rigidity), which will accelerate ions and protons at a high repetition rate and send them to either the targets for Radioactive Ion Beam (RIB) or Antiproton Beam production or the SIS300 (300 Tm rigidity) synchrotron, for further acceleration to higher energies (90 GeV protons). In order to reach the required high intensities, the magnets of the synchrotrons [2] have to be rapidly pulsed at a high repetition frequency. The required dipole ramp rate is 4 T/s for SIS100 at about 1 Hz and 1 T/s for SIS300, with a duty cycle of 50%. This paper deals with R&D activities aimed at developing the high field rapidly-cycling super-conducting dipoles needed for SIS300. At an early stage of the FAIR facility design, the

beam rigidity of the synchrotron placed after the SIS100 was 200 Tm. This rigidity was obtained through superconducting dipoles, generating a 4 T field in a 80 mm coil aperture. During the R&D phase, it was decided to increase the beam rigidity of this second synchrotron to 300 Tm, the dipole aperture field to 6 T, and in addition the inner coil diameter to 100 mm. IHEP, Protvino, prepared a Conceptual Design Report for this dipole, based on the UNK dipole [3]. The two layer coil (based on LHC dipole outer layer cable with stainless steel core) was designed to be cooled with supercritical helium and re-cooled by two-phase helium flow within the magnet yoke. In a later stage of the SIS300 design, the importance of enlarging the acceptance, with a minimum field volume, was stressed. Consequently, a curved design with a radius of 66.67 m was proposed. Its parameters are given in Table I. This coil has two main features: it is curved (the corresponding sagitta is 114 mm), and shall be ramped at 1 T/s. Both of these characteristics demanded challenging R&D, aimed at the development of the required low loss conductor and a suitable winding technology. As a first step, in order to check if show stoppers could arise during the construction stage, technical feasibility studies, involving experienced companies, were performed. The positive answer coming from these studies, together with the promising result of the cost estimates (potential cost saving with respect to the 6 T straight magnet), gave a 'green light' for further design work by the Italian National Institute of Nuclear Physics (INFN) in the framework of a project called DISCORAP ("Dipoli SuperCONDuttori RAPidamente Pulsati"), started in 2006. The geometry of the Rutherford cable for this magnet is the same as that used for the 6 T straight magnet. Coil winding models, using a curved mandrel, will be built. A half-length magnet will be ready for testing in 2009. The present paper discusses mainly the design choices, which provided the guidelines for the development of the curved fast ramped superconducting dipole presently under way. The status of the design activities is discussed as well, stressing the aspects related to the ac losses, the thermal stability, the mechanical aspects involved in a magnet to be cycled  $10^6$  times, and the manufacturing problems to be faced.

TABLE I  
MAIN PARAMETERS OF THE CURVED DIPOLE OPTION FOR SIS300

Magnetic Field	4.5 T
Magnetic length	7757 mm
Bending angle	6° 2/3
Bending radius	66.667 m
Free aperture (ID of the beam pipe)	86 mm
Coil inner diameter	100 mm
Field quality at radius R=35 mm	2 (in $10^{-4}$ units)
Ramp rate	1 T/s

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P. Fabbricatore and S. Farinon are with INFN Sez. di Genova, via Dodecaneso 33, 16146 Genova, Italy (e-mail [pasquale.fabbricatore@ge.infn.it](mailto:pasquale.fabbricatore@ge.infn.it)), tel +390103536340, fax +390103536573

U. Gambardella is with INFN L.N.F., via Fermi 40, Frascati, Italy.

F. Alessandria, G. Bellomo, M. Sorbi and G. Volpini are with INFN-LASA and Milan University, Physics Department, Italy

J.Kaugerts and G.Moritz are with GSI (D)

R.Marabotto is with ASG Superconductors, Corso Perrone, Genova (I)

## II. BASIC DESIGN CHOICES

Since the beginning of the R&D activity, prior to the engineering design, it was clear that one of the main problems to be solved was the technical feasibility of a cos-theta curved magnet. In this framework, two interconnected aspects were relevant: a) the definition of a credible and robust manufacturing method for a curved magnet; b) the development of a magnet design which minimized the manufacturing difficulties. These two aspects were investigated in parallel by developing a preliminary design, which provided the suitable input to experienced companies, asked to study the possible manufacturing methods.

This process was quite complex, with many feedbacks between design and feasibility analyses. Here, we summarise the main results, in terms of coil layout and preferential manufacturing method. The preliminary design activities had to face two other very important aspects. The first one is of a mechanical nature, since the magnet has to survive  $10^6$  magnetic cycles. The second one is related to the need to limit coil heating and remove the heat dissipation efficiently. While the mechanical and the heat removal problems are related to the winding, and consequently are discussed in detail here, the heat dissipation aspects are more related to conductor design and are only briefly discussed, referring to other papers dedicated to this topic [4,5].

### A. Basic coil layout

Our starting assumption was that the coil should be wound curved because: 1) This solutions allows the definition of the geometrical dimensions of a curved stress-free coil with certainty; 2) Once cured, the coil can be handled in a simple and safe way for the subsequent manufacturing operations (collaring, insertion into the iron yoke, ...).

A different solution, involving the bending of a straight coil, faces the problem of spring back effects during all manufacturing stages and coil operation. In fact, considering a coil outer radius around 65.4 mm (50 mm inner radius + 15.4 mm of conductor and insulation radial thickness), the bending strain for obtaining a curvature of 66.67 m is about  $10^{-3}$ . This value is too high when considering both the control of the coil geometry during the collaring and possible shear failures of cable-to-cable insulation.

The choice of a curved winding led naturally to the choice of a single layer coil with self-supporting collars. These important choices ( curved coil, self-supporting collars) are based on the reasoning that good mechanical coupling between two curved layers or between a curved collared coil and a curved yoke appeared to be challenging operations, which could be attempted only once the simplest curved layout (single layer self-supporting collared coil) had been thoroughly investigated. We were helped in moving in this direction by the relatively low value of the field (4.5 T), obtainable with a one layer coil. Furthermore, the magnetic forces are not high enough to require a mechanical support role for the yoke. Had the field been a little higher (5 T), this design path would not have been possible.

### B. Goals of the R&D program

Given the goal of developing a robust single layer curved dipole coil design for the SIS300, the objectives of the dedicated R&D program DISCORAP were defined as: 1) Development of a low loss conductor using a staged approach, enabling the availability of some lengths of cored dummy cable for winding tests in a very short time period, the availability of a cable with minimal required characteristics in a relatively longer time, and later on a cable with optimal ac loss properties [5]; 2) Study and development of the winding technologies for curved cos-theta dipoles, to be assessed by the construction of model coils (foreseen to be completed at beginning of 2008) using dummy cable; 3) Construction of the cold mass (collared coil plus yoke) of a short prototype (3878.5 mm), to be tested in a vertical LHe bath cryostat; 4) Integration of the cold mass into a horizontal cryostat in 2009; 5) Test of the prototype at GSI. In fact, the choice to construct a prototype having half magnetic length is not only due to the need to reduce the risk of the R&D activities, but also due to the fact that the SIS300 FODO lattice includes half length magnets. So in principle, the prototype under development is in fact a magnet of the synchrotron.

### C. The Conductor

The conductor under development [5] is based on a cored Rutherford cable with 36 strands (similar to the LHC dipole outer layer), whose main characteristics are shown in Table II. This conductor is characterized by having several components designed for low ac losses: 1) The filaments are fine (down to 2.5  $\mu\text{m}$ ) for minimizing the hysteretic losses; 2) The part of the matrix surrounding the filaments is made of CuMn, for electromagnetic decoupling of the filaments and for increasing the transverse resistivity; 3) The cable is cored, using a central thin stainless steel foil (25  $\mu\text{m}$ ) for cutting down the inter-strand coupling currents. The contribution to ac losses in the magnet during ramping conditions (due to the conductor) ranges from 4.4 W/m (power per magnet unit length) at 1.5 T, to 2.7 W/m at 4.5 T [6]. This conductor is basically the one already defined as target for the 6T straight magnet option. We started the design of our curved dipole using the same conductor, mainly to minimize the costs of the conductor R&D. After some magnetic, mechanical and thermal analyses, we confirmed this choice. According to the developed lay-out, the peak field in the winding is 4.9 T and the magnet is working at 69% of the critical current, along the load line. The corresponding current sharing temperature is 5.69 K, which is about 1 K higher than the maximum temperature of the supercritical helium, cooling the magnet (4.7 K).

TABLE II  
MAIN PARAMETERS OF THE SUPERCONDUCTING CABLE

Strand characteristics :	
Filament diameter	2.5 to 3.5 $\mu\text{m}$
Strand Diameter	0.825 mm
Twist Pitch	5 mm
Cable characteristics :	
Number of strands	36
Width	15.1 mm
Thickness: Thin/Thick edges	1.362 mm/ 1.598 mm
Core material/thickness	AISI 316L/ 25 $\mu\text{m}$
Critical Current @5T , 4.22K	>18540 A

We considered this margin a good starting point, to be confirmed later by thermal heat exchange analyses. At the same time, we verified that a higher temperature margin would require either a greater number of strands in the cable or the switching to a two layer solution. Both of these consequences were considered unacceptable because the two layer option had already been discarded for manufacturing reasons, while a larger (radially) conductor was considered risky due to possible mechanical instability during coil winding. However, a 40 strand cable with the same wire only increases the margin by 0.1 K.

### III. MAIN DESIGN ISSUES

#### A. Magnetic layout and field quality

Based on the guidelines described in the previous section, an extensive analysis and optimization activity has been carried out, to obtain a magnet configuration with good field quality and maximum temperature margin [6]. A solution with 5 blocks has resulted from these studies, with parameters reported in Table III. The cross section of the coil with the magnetic field distribution for a central field of 4.5 T is shown in Fig.1. The magnet is not yet fully optimized with respect to field quality because the saturation effects of the iron yoke are still missing. However, the most important effects on field quality (namely the sextupole and decapole field harmonics), due the ac operation, were studied in many details. There is a contribution to the sextupole coming from the persistent current in the superconducting filament, which is by far the most important: it ranges from -3.65 units ( in  $10^{-4}$  parts of the central field) at 0.5 T down to 0.13 units at full field. The decapole is one order of magnitude lower. The inter-filament and inter-strand coupling currents also have a small effect on the field quality (order of tenth of unit).

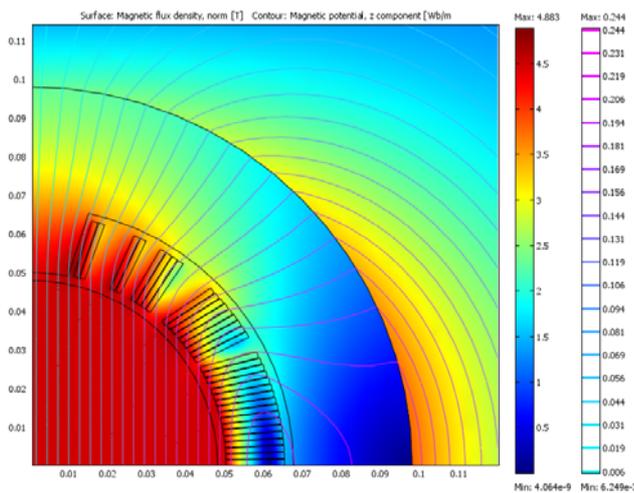


Fig.1 Coil cross section with field distribution and equipotential lines at peak current (Comsol<sup>®</sup> output)

TABLE III

MAIN PARAMETERS OF THE OPTIMIZED SOLUTION ( $\mu$  IRON- =  $\infty$ )

Block number	5
Turn number/quadrant	34 (17+9+4+2+2)
Operating current	8924 A
Yoke inner radius	98 mm
Peak field on conductor (with self field)	4.90 T
B <sub>peak</sub> / B <sub>o</sub>	1.09
Working point on load line	69%
Current sharing temperature	5.69 K

#### B. Materials and Components

The choice of the materials to be used in constructing the magnet was also made with a view to limit the ac losses and to optimize the field quality.

The coil wedges and the end spacers will be made from G11-CR, to cut down eddy currents during the ramps. Ceramic materials were also considered as a potentially interesting solution, but the worry about possible conductor damage (ceramic materials are generally hard and brittle) led to a decision to discard this option now, to be considered in future developments. Some reservations are related to radiation hardness. At present the available information about the radiation load in the dipole volume seems confirming that G11-CR could be acceptable from this point of view.

The collar material was chosen on the basis of the required mechanical and magnetic properties. The preliminary mechanical analysis showed that during the field ramp the peak Von Mises stress in the collar could be as high as 400 MPa. This stress level requires a high strength material, also in view of the fatigue load. At the same time, the relative magnetic permeability is required to be less than 1.003 to keep the field quality perturbation at the level of 0.1 units in the field region from 0.5 T (stretcher mode) to 4.5 T. Several austenitic steels with a significant Mn content were investigated in the past by laboratories developing accelerator dipole magnets. We took advantages of these studies [7] and selected Nitronic 40, which has a yield stress  $R_{0.2}$  ranging from 700 MPa at room temperature up to 1400 MPa at 4.2 K. The thermal contraction of this alloy is 2.3%, which, although far from the contraction of the coil winding in the azimuthal direction (around 6 ‰), is still compatible with an acceptable level of the required pre-stress during collaring (70 MPa), for having a coil with a residual pre-stress of 50 MPa at operating conditions ( See Fig. 2). The radial thickness of the collars has not yet been frozen. All calculations reported in this paper are based on a collar thickness of 30 mm. We are considering a reduction down to 25 mm (compatible with mechanical requirements) for enhancing the role of the magnetic yoke and so decreasing the required magnet current, with the consequence of increasing the stability margin. The collars will be made from 3 mm thick laminations. In fact, the collar ac loss due to eddy currents would allow a larger lamination thickness, but the envisaged construction method (punching of thin sheets) puts a limit on the allowed sheet thickness.

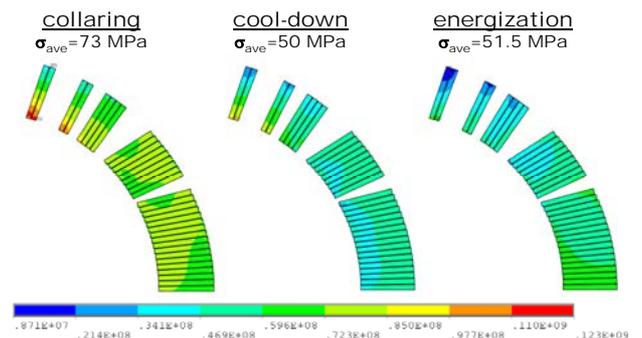


Fig.2 Stress distribution in the winding from collaring to operating conditions (Ansys<sup>®</sup> outputs)

The cable insulation consists of three polyimide layers, forming a total insulation thickness, after curing and under 50 MPa stress, of 98  $\mu\text{m}$ . Since the cooling of the coil is done with supercritical helium in contact with the coil inner surface, the temperature of the cable is greatly determined by the balance between the heat dissipation and the heat removal through this thin insulation layer.

A steady state thermal analysis demonstrated that the temperature in the winding can increase up to 0.3 K with respect to the coolant temperature. Computations under more realistic assumptions (transient conditions) have shown that the temperature increase could be lower (0.2 K). This study has not been completed yet because the heat ex-change conditions have not been completely integrated into the simulation. This point will need future efforts, not only in simulations but also through experimental activities. We remind the reader that the excellent results obtained on the first and unique prototype of SIS200 [8] (GSI001, which was a model coil for ac studies, operated up to 4 T/s), might be due to the cooling holes on the thin edge of the cable insulation, ensuring optimum cooling. Since we do not intend to adopt this solution, for the risks connected with arcing during quenches, the limitation on heat removal with solid insulation shall be better understood.

The material for yoke laminations has been investigated with the main aim of having low ac losses, coming from three contributions: hysteretic, eddy currents, and anomalous losses. At the same time, commercially available steels were investigated. In this context, only electrical steels with silicon can be considered. It can be easily verified that at our 1 T/s ramp rate the main contribution to the losses comes from magnetic hysteresis. Therefore, we looked for silicon steel having a coercive field as low as possible. Since the coercive field is a decreasing function of the Si content, one should use a high Si content alloy. Unfortunately, the brittleness also increases with Si content. A good compromise was found for a Si content of 3.5%, giving a coercive field of 35 A/m. We identified the commercial lamination as M600-100A, according the EN 10106 code (1995). The calculated losses in the magnet, using this material, are 1.3 W/m.

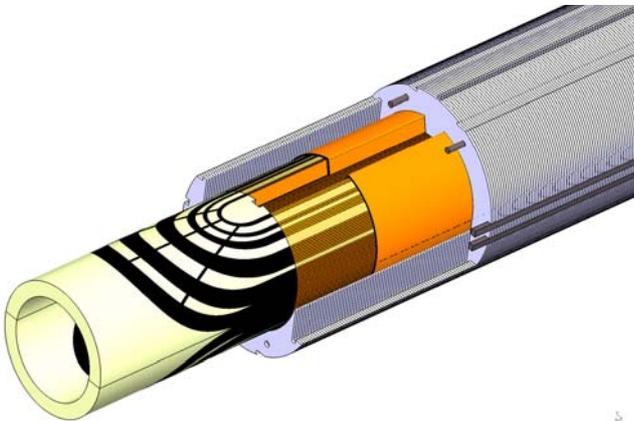


Fig.3 Detail of the present coil end design. Coil ground insulation and collar structure is also shown.

#### IV. 3D LAYOUT

At present, a first 3D-layout has been developed, including the coil ends. Fig.3 shows how the coil should appear. It can be noticed that the collars under design are very similar to the ones involved in the SSC main dipoles. Though many collar details are not visible, the collar laminations are parallel and packed in groups of 16 (for a total axial thickness of 50 mm), placed in a way to follow the coil curvature, through the introduction of thin spacers (0.8 mm) placed only on one side of the mid-plane (the one corresponding to the convex part). The ground insulation has been sized following LHC main dipole design. It includes channels for supercritical He, providing some additional cooling (other than the cooling on the inner coil surface) and (possibly) quench heaters. These choices are not yet frozen, given that a series of 3D magnetic, mechanical and thermal analyses are still under way.

#### V. CONCLUSIONS

Design activities, coupled with conductor and model coil developments, are under way for developing a curved, fast cycled superconducting dipole suitable for operation in the SIS300 synchrotron at FAIR. The main goal is the construction by 2009 of a prototype magnet (cold mass fully integrated in a horizontal cryostat), which will be tested at GSI. An important intermediate milestone is the industrial assessment of the winding technology for a curved cos-theta dipole, through the construction of cured curved half-coils by February 2008. The need of using non non-conventional makes the achievement of this goal critical. Other crucial aspects of the R&D are related to the development of a low loss conductor, generating about 3.5 W/m, and to the demonstration that the heat dissipated in the winding can be efficiently removed through the cooling of the dipole inner surface.

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