# Next Generation of Fast-Cycled Dipoles for SIS300 Synchrotron

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Abstract-The SIS300 is one of the two fast ramped synchrotrons of the future FAIR facility to be built at the site of GSI at Darmstadt, Germany. Planned to be installed during the second phase of FAIR, preliminary R&D work has to be carried out now to be ready to build up the machine later on without delay. Some remarkable results have been achieved over the last years concerning the development of the magnets for this machine, which are of superconducting  $\cos(\theta)$  type. For example a low loss Rutherford cable with stainless steel core and small filament wires has been developed. Also prototype magnets, dipoles as well as quadrupoles, have been manufactured and tested successfully. The experiences with the first curved dipole in the frame of the DISCORAP project showed the need for some changes in the design of the collared coil. Such a new collared coil is under construction now in the frame of the European CRISP project. The presentation will show the lessons learned from the DISCORAP project and the actual status of the CRISP coil.

Index Terms-FAIR, fast cycled dipole magnet, SIS300, Superconductivity.

## I. INTRODUCTION

▶ HE SIS300 is one of the two new heavy ion synchrotrons planned for the future Facility for Antiproton and Ion Research (FAIR) [1] at the site of the existing GSI in Darmstadt, Germany (An overview of the new facility can be found in Fig. 1). The two synchrotrons SIS100 and SIS300 will be placed in the same tunnel, the SIS300 directly above the SIS100, with the magnets of SIS300 arranged in a FODO lattice. Due to limited funding, the building up of SIS300 was shifted to a later date. Nevertheless research and development work had been going on over recent years and is still ongoing on a small scale. Within this time, concerning the magnet development, first quadrupole magnets have been built and tested by IHEP in Protvino, Russia [2], [3]. Regarding the dipoles a first real size short dipole of SIS300 was built by INFN in the

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Fig. 1. Overview of existing GSI and future FAIR facilities.

frame of the DISCORAP project and tested in INFN/LASA in 2012 [4], [5]. From the results of these measurements it became clear that further optimization work on the magnet is necessary to fulfill the requirements needed for FAIR.

# **II. PARAMETERS AND DESIGN PRINCIPLES**

SIS300 is foreseen to be used in 2 different operation modes. The first one is a further acceleration of the ions injected from SIS100 to even higher energies and then to be used in the CBM (Compressed Baryonic Matter) experiment. The second mode is the usage as a storage ring for ions accelerated in SIS100, which then can be delivered to various experiments. For the first kind of operation the magnets are submitted to powering cycles with high current ramp rates. So, the maximum ramp rate of the SIS300 dipole is 1 T/s which is orders of magnitudes higher than for other superconducting accelerators. Since about 10 million cycles are foreseen within the lifetime of the magnets, mechanical issues are crucial for the design. The cycling also leads to AC losses and field errors during ramping due to the magnetization of the superconductor and eddy currents. Therefore special care has been taken on the development of new low loss conductors from the wire as well as from the cable point of view. Furthermore the dipole magnets of SIS300 are curved with a radius of 66.67 m, which also requires special attention during manufacturing. Table I summarizes the main operation parameters of the SIS300.

#### **III. DISCORAP DIPOLE**

The first dipole magnet for SIS300 was built in the frame of the so-called DISCORAP project [6], [7]. For this magnet it was decided to build a full size short dipole of the SIS300. Also

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number of magnets	12 short/ 48 long
maximum magnetic field	4.5 T
Maximum ramp rate	1 T/s
Usable aperture	86 mm
Curvature radius	66.67 m
Effective length	3.897 m/ 7.757 m

TABLE II	
MAIN PARAMETERS OF DISCORAP DIPOLES	

Coil aperture	100 mm
Cold mass outer radius	250 mm
Magnetic length	3879 mm
Number of layers/blocks/turns	1/5/34
Operation current	8920 A
Peak field on coil	4.9 T
Working point on load line	69%
Total ac losses during ramp	<10 W/m



Fig. 2. Slice of the DISCORAP dipole. From the inside to the outside one sees the coil blocks with spacers, the collar, the yoke split in the mid plane and the outer shell.

the magnet was built as a curved one. The coils were wound on a dedicated curved mandrel and the collars were arranged in short blocks of about 30 mm and follow the curvature of the coil with help of calibrated washers added on the convex side. All prestress on the coil in the cross section is exerted only by the collars. The mechanical role of the yoke is only to prevent a deformation of the coil during excitation of the magnet [8], [9]. The yoke was also built in curved blocks and the outer shell comprised of two curved halves. The longitudinal prestress of the coil is achieved during cool down by a larger thermal contraction of the outer shell, which is transferred to the coil ends by bolts. Table II summarizes the main features of the dipole and a 3D view of a part of the magnet can be seen in Fig. 2.

#### A. Conductor Development

The development of a new low loss conductor played a crucial role in the work for DISCORAP [10], [11]. During the ramping of a superconducting magnet, eddy currents, as well as the superconductor's magnetization loop, create heat loads which might even lead to a quench of the magnet. Furthermore, the magnetic field also is changed during ramping, leading

to worse field quality of the magnet [13]. The different loss mechanisms are:

- Hysteresis Losses due to persistent currents (PCs) in the filaments. They depend on the critical current density and the filament diameter but only very weakly on the ramp rate.
- Losses due to coupling currents between the superconducting filaments. These losses depend on the wire twist pitch, the transverse resistivity of the matrix between the filaments, and also on the ramp rate.
- Losses due to coupling currents between neighboring strands. They depend on the contact resistivity between the strands (Ra and Rc) and on the ramp rate.

To reduce the hysteresis losses, therefore, the wire should have small filaments. The coupling currents between the filaments can be reduced by decreasing the twist pitch of the conductor and increasing the transverse resistivity, for example by introducing a high resistive material in between the filaments. This measure also helps to avoid proximity coupling, which can occur when neighboring filaments get too close and start to couple with each other and therefore act as one big filament again. On the other hand, the overall resistance of the wire still has to be low enough to guarantee the stable operation of the superconductor. Also, reducing the twist pitch must not lead to a decrease in critical current. All this requires some optimization work concerning the wire.

For the cable, the same outer dimensions as for the cable of the outer layer of the LHC dipoles were chosen, i.e., a Rutherford type cable out of 36 strands. To reduce the eddy currents between the 2 layers of the cable a stainless steel tape with 25  $\mu$ m thickness was inserted. The eddy current between adjacent strands can be adjusted by coating the wire with a SnAg coating and using an appropriate heat treatment [14]. The resulting resistance, Ra, between adjacent strands still has to be low enough to allow a current sharing between the strands for stability reasons. Table III summarizes the main parameters of the wire and cable produced in the frame of DISCORAP. Two slightly different types of wire had been produced by LUVATA (Pori, Finland) and cabled by New England Wire Technologies (New Hampshire, USA). The DISCORAP coils have been manufactured with the "Generation I" wire, which has bigger filaments and less CuMn than the wire of "Generation II".

## B. Manufacturing and Testing

The manufacturing of the magnet took place at ASG Superconductors, Genova. Fig. 3 shows the 2 DISCORAP coils, one can clearly see the curvature of the coils. The collaring was originally planned to be in a way that should result in a prestress of 50 MPa. Also the design was calculated for this prestress. This value had to be changed during production to a value of 70 MPa. This lead to unwanted deformation of the coil which causes deviations from the calculated field quality. Magnetic measurements in warm condition showed a sextupole component of about 7 units and a decapole component of -3 units (1 unit =  $10^{-4}$  of main field component).

First cold tests of the magnet have been performed at INFN-LASA in 2012 [5], [15], [17]. The magnet reached its nominal

Cable	
Strand Number	36
Width	15.10 +0 -0.020 mm
Thickness, thin edge at 50 MPa	$1.362 \pm 0.006 \text{ mm}$
Thickness, thick edge at 50 MPa	$1.598 \pm 0.006 \text{ mm}$
Core material	AISI 316 L stainless steel, annealed
Core thickness	25 μm
Transposition pitch	$100 \pm 5 \text{ mm}$
Ic @ 5 T, 4.22 K	>18,540 A
Stabilization matrix RRR	>70
Wire	
Diameter after coating	$0.825 \pm 0.003 \text{ mm}$
Filament twist pitch	5 +0.5 -0 mm
Effective Filament Diameter	2.5 – 3.5 mm
Interfilament matrix material	Cu-0.5 wt% Mn
Ic @ 5 T, 4.22 K	> 541 A
n-index @ 5 T, 4.22 K	> 30
Stabilization matrix	Pure Cu
pt at 4.22 K	0.4 + 0.09 B [T] nΩ·m
Cu+CuMn:NbTi ratio (α)	$>1.5\pm0.1$



Fig. 3. Two poles of the DISCORAP magnet. The curvature of the coils can be clearly seen.

current with only one premature quench proving the robustness of the mechanical design. During ramping and loss measurements it turned out that the magnet quenched for field steps of about 2 T regardless of the final value of the magnetic field of the ramp of the magnet. The insertion of the magnet into the test cryostat can be seen in Fig. 4.

## **IV. SECOND GENERATION DIPOLE**

The experience with the DISCORAP dipole shows that there is still work to be done on the way to a SIS300 magnet. The points to be addressed include:

- Enhanced magnetic design adjusted to a pre-stress of 70 MPa on the coil.
- Investigation regarding an enhanced insulation scheme.
- Use of even more advanced low loss conductors.
- Enhanced solutions to construction issues.



Fig. 4. Insertion of the DISCORAP magnet into the vertical test cryostat at INFN-LASA.

The ongoing project is aimed at building, as a first step, a 2nd generation collared coil. It is organized as collaboration between GSI, INFN, CERN and ASG and financed partly by the European CRISP project and partly by contribution from the participating institutes themselves. In the following we will present the status of work concerning the issues mentioned above.

## A. Magnetic Design

It was decided to leave the design of the collars unchanged. Also the number of blocks and turns of the coil remained unchanged. The adjustment of the 2 dimensional field design to the increased pre-stress of 70 MPa was achieved by only changing the arrangement of the coil blocks, leading only to changes of the wedges and shims, not of the collars themself. The collar material is high strength austenitic steel developed by Buderus Edelstahl expressly for the DISCORAP project.

#### B. Insulation Scheme

CERN has developed in recent years a so called enhanced insulation scheme (EI) [18]. The difference to more conventional insulation schemes as used for LHC and DISCORAP is to provide additional channels for the Helium without making the insulation itself thinner. It was investigated whether such an insulation could improve the cooling of the SIS300 dipoles as well. The experiments showed that for the power range of the magnet during operation, the difference between the two insulation schemes is very small, resulting in an increase of the conductor temperature of 0.14 K for the EI and 0.16 for the original DISCORAP insulation. Therefore it was decided to maintain the initial insulation and not to change too many parameters at once.



Fig. 5. Result of first cabling run at CERN with 36 LHC-strands and a 13 mm wide 25  $\mu$ m thick 316L stainless steel sheet.

#### C. Conductor

A superconducting wire has been ordered by INFN with even smaller filaments of 2.2  $\mu$ m. This wire should than have been cabled and insulated at CERN. The cabling machine at CERN has been refurbished to be able to produce cored cable and first trial runs were performed successfully.as can be seen in Fig. 5. Due to technical difficulties the foreseen wire will not arrive before end of 2013. Therefore it was decided to go on with the already existing cable of the Luvata "Generation 2". The existing two cable lengths are just enough to build the coils. This cable is to be insulated at CERN and afterwards the coil winding will start at ASG.

#### D. Construction Solutions

Some updating of the tooling for the magnet construction will also take place. This includes especially the right application of the pre-stress on the coil. For this, in the frame of the ongoing project, a new collaring press will be built at ASG.

## V. CONCLUSION

Over the last years remarkable results have been achieved in the development of magnet components for the future SIS300 synchrotron for FAIR. Two quadrupole magnets as well as the DISCORAP dipole have been built and tested. At the moment only the construction of a collared coil in the frame of the CRISP project is going on, due to the concentration of FAIR on the construction of the components, which are part of the starting version. Even if it is not clear at the moment when exactly SIS300 will be integrated into FAIR, it is aimed to carry on the R&D work on a small scale, not at least to keep alive the know-how gained so far.

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