

# A Model Dipole for FAIR SIS300: Design of the Mechanical Structure

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**Abstract**—Design activities coupled with conductor R&D and model coil construction are under way for developing a curved fast cycled superconducting dipole suitable for operations of the SIS300 synchrotron at FAIR. The main target is the construction within 2009 of a model magnet (cold mass fully integrated in a horizontal cryostat). This magnet is designed for generating 4.5 T magnetic field in a bore of 100 mm, able to be operated at a field rate of 1 T/s. The magnetic length is 3.8 m with a curvature radius of 66.67 m (the sagitta is 27 mm).

The mechanical structure is based on 3 mm thick laminated stainless steel collars, assembled through keys, and 1 mm thick iron yoke laminations, assembled through large Al alloy C-shaped clamps. A 2D finite element analysis has been performed to evaluate stresses and deformations coming out during assembly, cool-down and energization. Particular emphasis has been given to the possible fatigue problems ensuing from the large operating field rate over a large lifetime cycle number,  $10^7$ . Numerical results are presented and discussed.

**Index Terms**—Collars, finite element analysis, mechanical structure, pulsed dipole.

## I. INTRODUCTION

THE SIS300 synchrotron of the new FAIR facility [1] at GSI (Darmstadt, Germany) calls for the development of fast cycled superconducting dipoles, to be operated at 1 T/s between 1.5 and 4.5 T in a 100 mm bore. They are 7.8 m long and have a curvature radius of 66.67 m, corresponding to a sagitta of 114 mm. In collaboration with GSI, INFN (Genoa, Milan and Frascati laboratory) has undertaken the design and the construction of a 3.8 m long model of one lattice dipole, that will take place at the ASG-Superconductors premises.

The main coil characteristics can be found in details in [2]–[4]. Complete 2D and 3D electromagnetic analyses [5], [6] have been carried out to obtain a cos-theta configuration with good field quality and maximum temperature margin.

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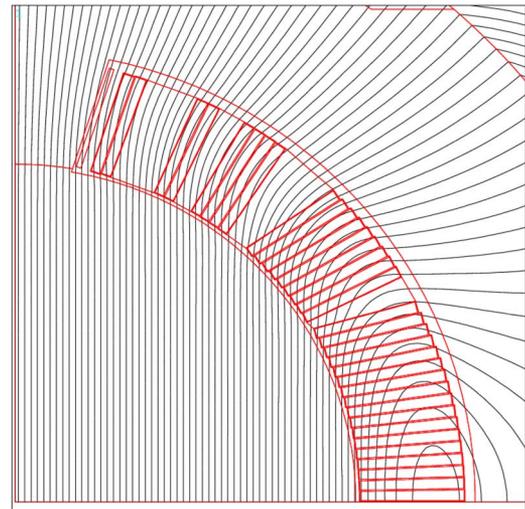


Fig. 1. Coil cross section with equipotential lines.

A solution with 5 blocks per quadrant, shown in Fig. 1, has resulted to be the most reliable and flexible.

Two main aspects have guided the SIS300 dipole mechanical design. First, the fact that the dipole has to be wound curved naturally steered towards the choice of a solution as much simple as possible, namely a single layer coil mechanically supported only by the collars. Actually, the mechanical coupling between a curved collared coil and a curved laminated iron yoke appears to be a critical operation. Unfortunately, as it will be shown in the course of the paper, the collared coil cannot be fully self-sustained, but the iron yoke must have a limited role in reducing the deformation of the coil during the magnetic cycles. The second critical aspect, from a mechanical point of view, is related to the fatigue problems ensuing from the large operating field rate over a large lifetime cycle number, 10 millions. This has large implications both at the design level, urging the minimization of the stress variation during each cycle, and at the material choice level, leading to the selection of fatigue resistant materials.

## II. MATERIAL CHOICE

The choice of the materials to be used in the winding was done trying to limit the ac losses, optimize the field quality and ensure a reliable mechanical behavior.

Particularly, the choice of the material for the collars has been the most demanding. The considerable stress level, overcoming 400 MPa, requires for the collars a high strength material, also in view of the fatigue load. At the same time the relative magnetic permeability has to be less than 1.003, to keep the field quality

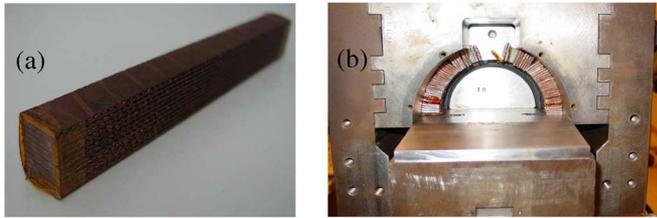


Fig. 2. Stacking sample (a) and arc piled sample (b) for mechanical properties measurements.

TABLE I  
MATERIAL PROPERTIES

Material	Young modulus (GPa)	Thermal contraction coefficient
Conductor	8.0	$5.6 \cdot 10^{-3}$
Wedges (G11)	25.5	$2.5 \cdot 10^{-3}$
Collars (Nitronic40)	192	$2.4 \cdot 10^{-3}$
Iron yoke	200	$1.8 \cdot 10^{-3}$
Kapton	2.5	$9.0 \cdot 10^{-3}$

perturbation within 0.1 units in the field region between 0.5 and 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 from these studies [7] and selected the Nitronic 40, which has a yield stress ranging from 700 MPa at room temperature up to 1400 MPa at 4.2 K.

The coil wedges and the end spacers are in G11, so to cut down the eddy currents during the ramps.

In view of its mechanical function, a high strength iron has been selected for the yoke, the commercial lamination M600-100 A, which has a yield stress ranging from 365 MPa at room temperature up to 700 MPa at 4.2 K.

The conductor is a composite material especially designed for the SIS300 dipole [8]. Qualitatively, it is the same Rutherford cable as the LHC dipole outer layer but with a high resistance metallic core,  $25 \mu\text{m}$  thick, in order to reduce power dissipations in the cycled regime. Mechanical properties of such a conductor cannot be found in literature but have to be measured. We have just started a measurement campaign of short straight samples, both stacked and arc piled, as shown in Fig. 2. First results indicate for the conductor a Young modulus ranging between 8 and 12 GPa.

The properties of the materials involved in the finite element analyses are listed in Table I.

### III. MECHANICAL STRUCTURE OF THE SIS300 DIPOLE

The 2D cross-section of the dipole mechanical structure is shown in Fig. 3. It is based on 3 mm thick laminated stainless steel collars, assembled through stainless steel keys, and 1 mm thick iron laminations, assembled through large Al alloy C-shaped clamps.

The main mechanical function of collars is to give azimuthal pre-stress to the winding. During energization up to 4.5 T, the winding experiences very large Lorentz forces, 0.68 MN/m radially, outward directed, and 0.30 MN/m axially, towards the midplane. The radial component of the Lorentz force is mechanically sustained by collars, the axial component has to be com-

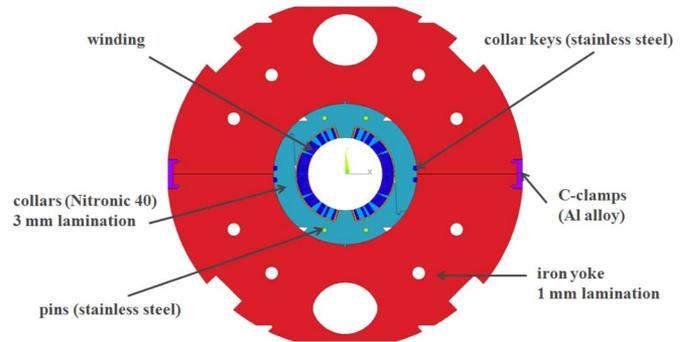


Fig. 3. Cross-section of the SIS300 dipole cold mass.

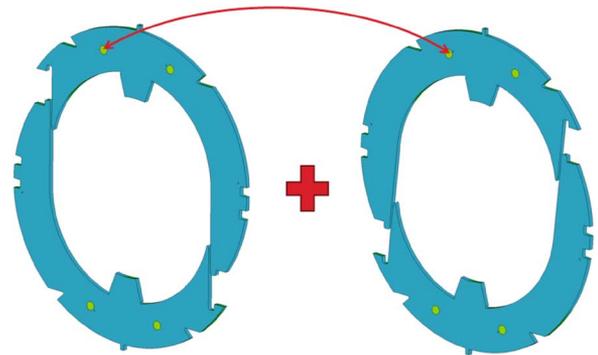


Fig. 4. Collars are assembled in alternate position and kept together through stainless steel pins.

pensated by an adequate axial pre-stress. Its average value is determined requiring continuous contact between the winding pole and the collars even when the winding is fully energized. This corresponds to have an average pre-stress in the winding at the end of the assembly operations of about 70 MPa.

The shape of the collars is very similar to what was designed for SSC [9]. They are parallel packed in alternate position (see Fig. 4) in groups of 10, for a total longitudinal thickness of 30 mm. The curvature is rendered introducing thin spacers ( $\sim 0.1$  mm) on one side only of the midplane, close to the outer radius. The collar width is 30 mm, leading to an inner iron yoke radius of 96.85 mm. That width is the maximum value which allows keeping the current and the temperature margin within safe limits (8920 A and 0.8 K, respectively).

The iron yoke laminations are 1 mm thick and  $\sim 140$  mm wide. The external radius is 240 mm, but the axial dimension has been cut down to 230 mm (see Fig. 3), due to a space limitation in the press already existing at ASG-Superconductors premises. The iron yoke laminations are assembled on a curved template, which gives the right curvature radius (66.67 m). Then, the curvature is retained through the insertion of 0.05 mm thick spacers nearly each 25 laminations. The basic unit of the iron yoke assembly is 1 m long: the laminations are kept together through 4 hollow tie rods per side passing through the small holes visible in Fig. 3. A proper tension applied to these tie rods will also ensure to reach the design packing factor (0.97 on the internal radius). This procedure should ensure a good mechanical coupling between the curved collared coil and the curved iron yoke itself. Finally, the iron yoke has been designed to give no

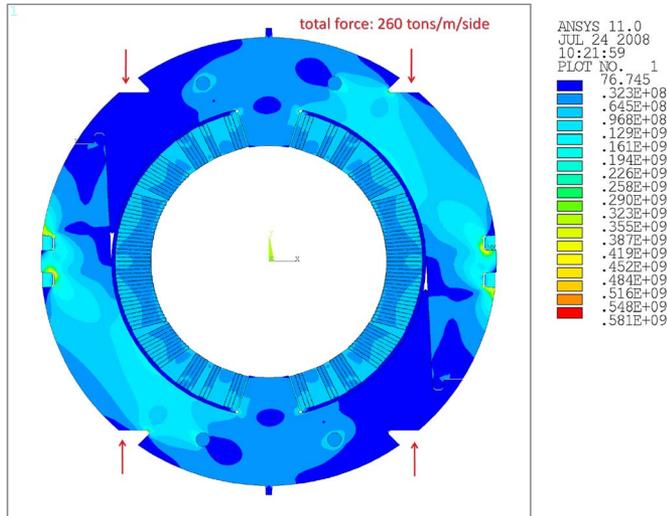


Fig. 5. Von Mises stress (Pa) at the end of the collaring operation.

further pre-stress to the winding but to limit the deformations arising during the magnetic energization.

#### IV. 2D MECHANICAL ANALYSIS

The finite element analyses have been carried out using the commercial code ANSYS. The adopted element is PLANE82, in plane stress configuration with thickness real constant input. Both the back and the front collars shown in Fig. 4 have been modeled: each of them has an equivalent thickness which is half of all the other components, they can slide without friction and are connected through stainless steel pins.

Contact surfaces have been modeled using the ANSYS flexible-to-flexible contact technology, through CONTA172 and TARGE169 elements.

The loads which are subsequently applied are:

- 1(a) Collaring
- 1(b) Fitting of the collars into the iron yoke
- 2) Cool-down
- 3) Energization up to 4.5 T

As stated in the Introduction, we explored the possibility to design completely self-sustained collared coils, without giving the iron yoke any mechanical function. For this reason, in this paper we present cool-down and energization of both collared-only coils (Section IV-B) and collared coils with mechanically functional iron yoke (Section IV-C).

##### A. Collaring

The fitting of the coil into the collars is the first step, common to all the configurations. To perform this operation, we have to press the collars until the holes which will host the keys are perfectly aligned. Once this step is completed, the keys can be easily inserted. The pressing force, whose strength is 260 tons/m/side, is applied in the locations shown in Fig. 5. Once the keys are in the right position, the press can be released. The resulting Von Mises stress at the end of this operation is shown in Fig. 5. The peak value, 581 MPa, is located in the collar near the keys. That region moderately plasticizes, but, in the final design, it will not experience any especially critical

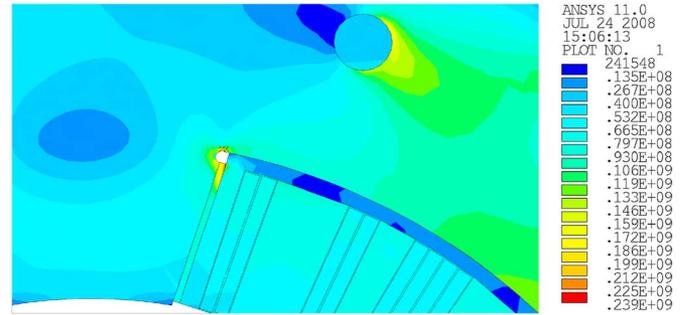


Fig. 6. Von Mises stress (Pa) in pole corner region at the end of the collaring operation.

TABLE II  
VON MISES STRESS OF COLLARED-ONLY COILS

Load	Peak in collars around keys (MPa)	Peak in the pole corner region (MPa)
Collaring	581	239
Cool-down	667	175
Energization @ 1.5 T	672	219
Energization @ 4.5 T	869	579

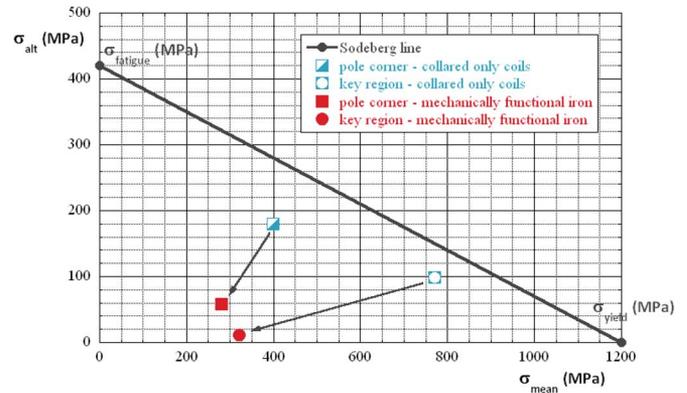


Fig. 7. Soderberg criterion of both collared-only coils (semi hollow symbols) and collared coils with mechanically functional iron yoke (full symbols).

fatigue issue. The real critical point of this design is the pole corner region (Fig. 6), whose shape has already been modeled to minimize its Von Mises peak stress. At the end of the collaring operation, this peak stress is not particularly high, 239 MPa, but it will undergo large variations during the energization cycles, if we do not give the iron yoke any mechanical function, as shown in the next paragraph.

##### B. Cool Down and Energization of Collared-Only Coils Only

The main peak Von Mises stresses after cool-down and energization of the collared-only coils are listed in Table II. The yield stress of Nitronic40 ranging from 700 MPa at room temperature up to 1400 MPa at 4.2 K, those values do not appear to be remarkably critical in absolute, but they need to be further analyzed from the fatigue point of view. The simplest and most conservative fatigue criterion is the Soderberg method, illustrated in Fig. 7. Let's consider a material cycling between a minimum ( $\sigma_{\min}$ ) and a maximum ( $\sigma_{\max}$ ) Von Mises stress. We can define a graph having the mean stress,  $\sigma_{\text{mean}} = (\sigma_{\min} + \sigma_{\max})/2$ ,

TABLE III  
VON MISES STRESS OF COLLARED COILS WITH  
MECHANICALLY FUNCTIONAL IRON YOKE

Load	Peak in collars around keys (MPa)	Peak in the pole corner region (MPa)	Peak in the iron yoke (MPa)
Collaring	581	239	0
Closing of iron yoke	428	180	268
Cool-down	307	206	92
Energization @ 1.5 T	309	222	101
Energization @ 4.5 T	332	338	111

on the x-axis and the oscillation amplitude,  $\sigma_{alt} = (\sigma_{max} - \sigma_{min})/2$ , on the y-axis. A material which is loaded under a purely static load will have  $\sigma_{alt} = 0$  and  $\sigma_{mean} = \sigma_{yield}$ . In Fig. 7,  $\sigma_{yield}$  has been fixed at 1200 MPa, instead of 1400 MPa, in order to keep a safety factor. This is confirmed by a set of measurements that indicate for Nitronic40 a minimum yield strength at 4 K of 1240 MPa [10]. Conversely, a material which is loaded under a purely oscillating load will have  $\sigma_{mean} = 0$  and  $\sigma_{alt} = \sigma_{fatigue}$ . The limit for ten millions cycles under uni-axial load of Nitronic40 is  $\sigma_{fatigue} = 0.35 \cdot \sigma_{yield} = 420$  MPa. This value is compatible with [11], where it has been measured at least 450 MPa for 10 millions cycles. Now, connecting with a straight line these two points, the Sodeberg criterion divides the plane into two halves: the region below the line is safe from fatigue, with potentially infinite life, whilst the region above the line corresponds to a likely fatigue failure. In Fig. 7, the two blue semi-hollow symbols correspond to fatigue status of the collared-only coils between the Von Mises stress limits at 1.5 T and 4.5 T. They are on the safe side of the Sodeberg line, but we evaluated that they are not far enough from it. Actually, the uncertainties on the tolerances and the complexity of the mechanical coupling of the two curved surfaces, windings and packed collars, make necessary to be in a much safer region below the Sodeberg line. For these reasons, we decided to give the iron yoke a very limited mechanical function: it has to contain the radial movement of the winding at the midplane level, which is the main responsible of the peak stresses between cool-down and energization.

### C. Cool Down and Energization of Collared Coils With Mechanically Functional Iron Yoke

The main peak Von Mises stresses after cool-down and energization of the collared coils with mechanically functional iron yoke are listed in Table III. It is clear that both peak values and oscillation amplitudes are greatly reduced. The new fatigue status is represented in Fig. 7 by the full red symbols: the new configuration is deeply inside the safe from fatigue region, making the SIS300 dipoles supposedly free from fatigue issues.

## V. PRELIMINARY 3D MECHANICAL ANALYSIS

A complete 3D finite element analysis is needed to fully understand the mechanical behavior of such a complex structure. Our first approach consists in modeling a straight dipole: only once all the problems related to the straight model are clear, a

TABLE IV  
LORENTZ FORCES IN THE STRAIGHT SECTION (PER QUADRANT)

	Fx (MN/m)	Fy (MN/m)	Fz(MN/m)
2D model	+0.684	-0.301	0
3D model	+0.678	-0.300	0

TABLE V  
LORENTZ FORCES IN THE ENDS (PER OCTANT) BLOCKS ARE  
NUMBERED FROM THE MIDPLANE TO THE POLE

	Fx (kN)	Fy (kN)	Fz (kN)
Block #1a	+ 7.2	- 3.6	+ 1.2
Block #1b	+14.0	-11.3	+ 7.2
Block #2	+17.6	-10.1	+ 8.8
Block #3	+ 7.9	- 2.8	+ 3.5
Block #4	+ 3.9	- 1.0	+ 1.6
Block #5	+ 3.1	- 0.5	+ 1.0
Total	+53.7	-29.3	+23.3

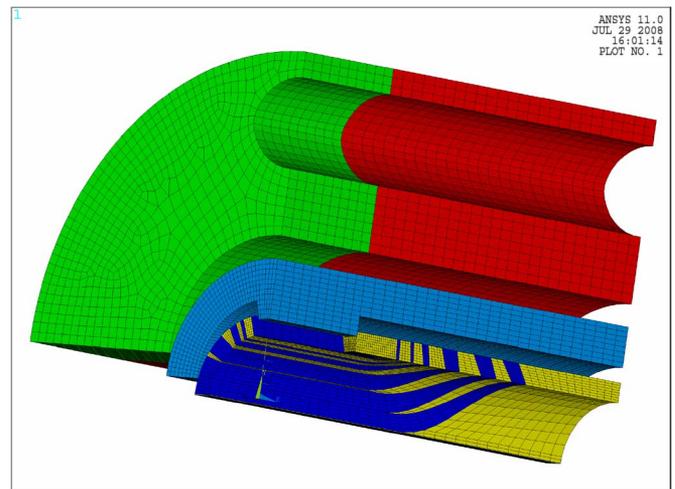


Fig. 8. 3D finite element model of 1 octant for mechanical analysis.

curved model also will be analyzed. Preliminary to a 3D mechanical analysis, a 3D electromagnetic analysis has been carried out to calculate the Lorentz forces. Table IV shows the good agreement between the Lorentz forces in the straight section calculated using the 2D and the 3D model. In Table V the Lorentz forces in the ends on one octant are listed. Note that the first block, the one nearest to the midplane, has been split into two sections. From a mechanical point of view, the most important component is the longitudinal one, as it tends to straighten the windings with nearly 100 kN per end. It will be crucial to evaluate this effect, and, possibly, find a way to strengthen the structure. Finally, Fig. 8 shows the 3D finite element model which is ready for the mechanical analyses.

## VI. CONCLUSION

Very detailed 2D finite element analyses of the SIS300 dipole mechanical structure have been carried out and the cross-section

has been finalized. A self-sustained collared coil design has been abandoned in favor of giving the iron yoke a limited mechanical role. 3D effects still have to be studied and we are ready to adopt possible corrective actions.

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