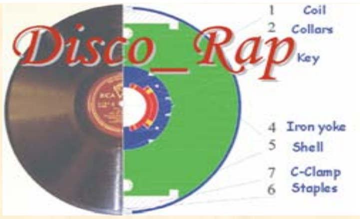


# Magnet design issues & concepts for the new injector

**P.Fabbricatore**

**INFN-Genova, Italy**

**Starting from the development of the fast cycled dipole magnets for SIS300 some information and considerations for the development of future high field injector**

**This presentation is based on the work of many colleagues of INFN DISCORAP project**

# SIS300 dipoles: fast cycled and curved magnet

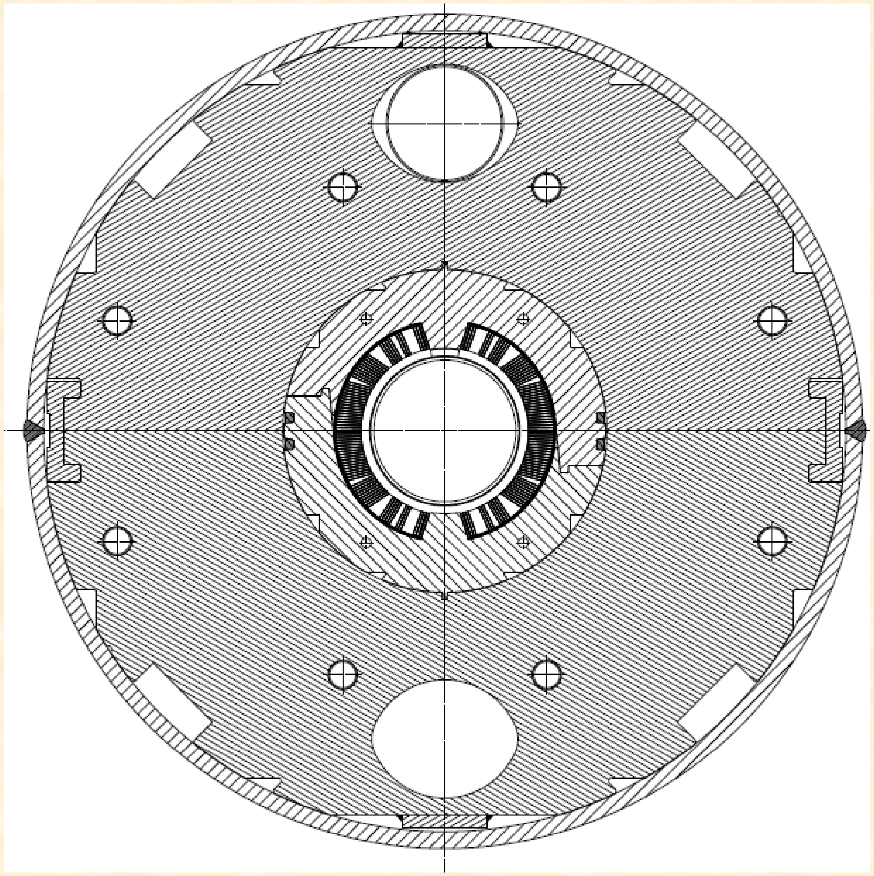
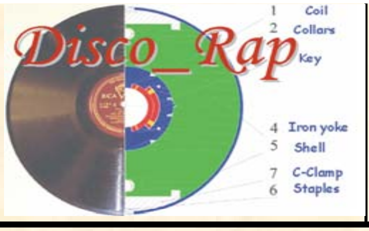


TABLE I MAIN REQUIREMENTS OF SIS300 SHORT DIPOLES

| | |
|---|---|
| Nominal Field (T) : | 4.5 |
| Ramp rate (T/s) | 1 |
| Radius of magnet geometrical curvature (m) | 66 2/3 |
| Magnetic Length (m) | 3.879 |
| Bending angle (deg) | 3 1/3 |
| Coil aperture (mm) | 100 |
| Max operating temperature (K) | 4.7 |

TABLE II MAIN CARACTERISTICS OF THE MODEL MAGNET

| | |
|---|---|
| Block number | 5 |
| Turn number/quadrant | 34 (17+9+4+2+2) |
| Operating current (A) | 8920 |
| Yoke inner radius (mm) | 96.85 |
| Yoke outer radius (mm) | 240.00 |
| Peak field on conductor (with self field) (T) | 4.90 |
| $B_{peak} / B_o$ | 1.09 |
| Working point on load line | 69% |
| Current sharing temperature (K) | 5.69 |



# Criticities of SIS300 dipoles

| | Aperture (mm) | B (T) | dB/dt (T/s) | Π (T$^2$/s) | Q (W/m) |
|---|---|---|---|---|---|
| LHC | 53 | 8.34 | 0.008 | 0.067 | 0.18 |
| RHIC | 80 | 3.5 | 0.06 | 0.21 | 0.35 |
| SIS300 | **100** | 4.5 | **1** | **4.5** | **<10** |

Ramp 1T/s → ac losses → Limited performances
→ Costs of Cryogenics

Hence: Development of a low loss conductor
Design with loss minimization (taking care of eddy currents in structures)

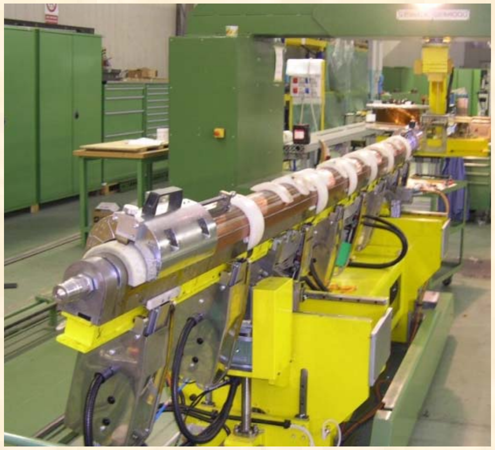
Low ac losses→ Cored conductor→ Constructive problems

Curvature R=66.667 m (sagitta 117 mm ) → Design and constructive problems

$10^7$ cycles → Fatigue → Mechanical design and materials optimization

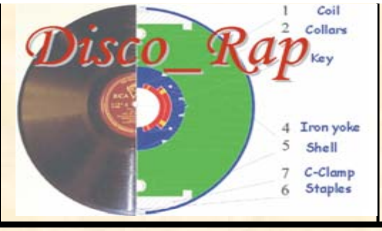
# Our concern: how to couple (perfectly ?) curved objects

At the end of the construction, we can say that *many constructive problems to be faced were mainly coming from the geometrical curvature, which also had forced specific design choices: one layer, mechanical strength provided by collars only, mid-plane gap in iron yoke, longitudinal pre-stress achieved after cool-down*



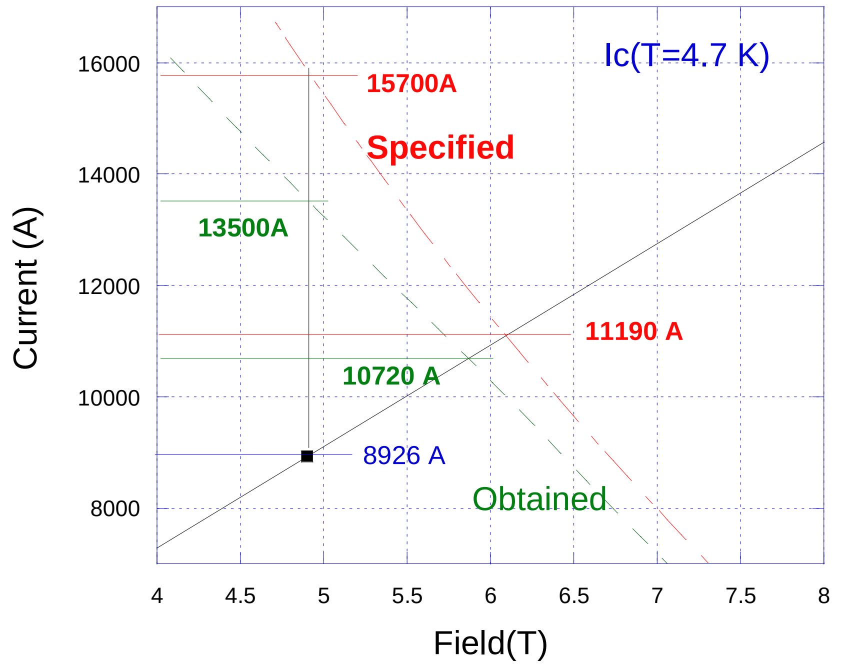
# MAIN CHARACTERISTICS

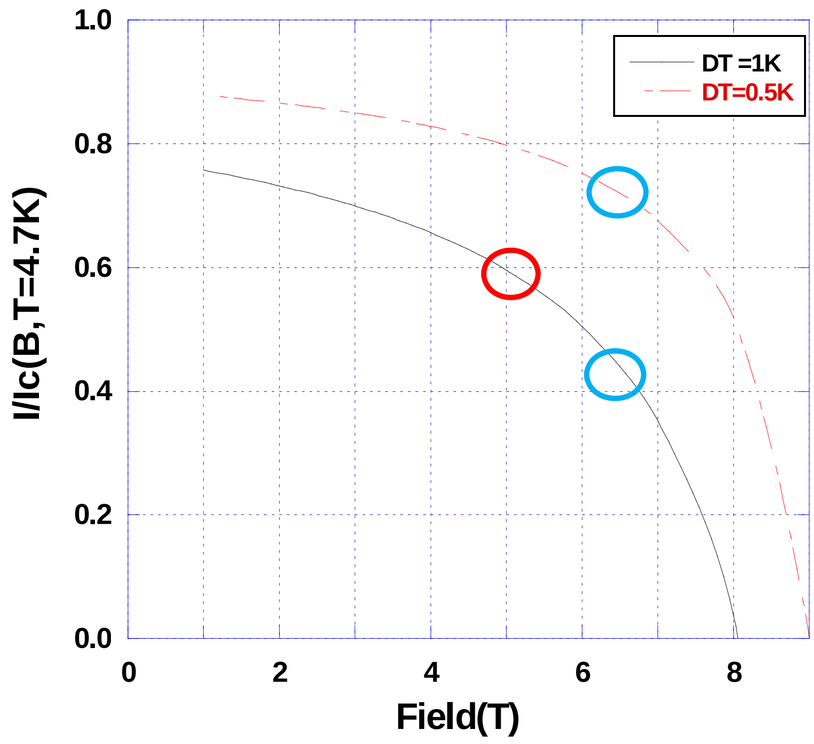
| **Magnet operating in supercritical He**<br>**Parameter** | **SIS300 dipole** | **Injector 4T 100mm 1.5T/s** | **Injector 6T 100mm 1.0T/s** |
|---|---|---|---|
| Injection magnetic field [T] and $b_3$ | 1.5 / -0.75 | 0.4/ | 0.4/ |
| Maximum/ Peak magnetic field [T] | 4.5/4.9 | | |
| Temperature Margin (K) | 0.97 | | |
| AC losses in the superconductor during ramp [W/m] | 3.5 | | |
| AC losses in the structures during ramp (eddy currents and magnetization) [W/m] | 4.2 | | |
| Weight [T/m] | 1.28 | | |
| Cost of cryostated magnet [€/m] | 60-70 | | |



# A KEY PARAMETER: THE TEMPERATURE MARGIN

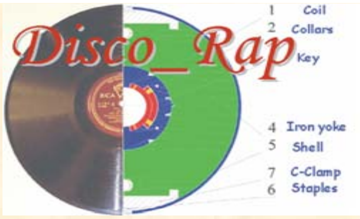
**Current margin current along the load line: 79% (design); 83% (effective)**
**Current margin at constant magnetic field: 57% (design); 66% (effective)**





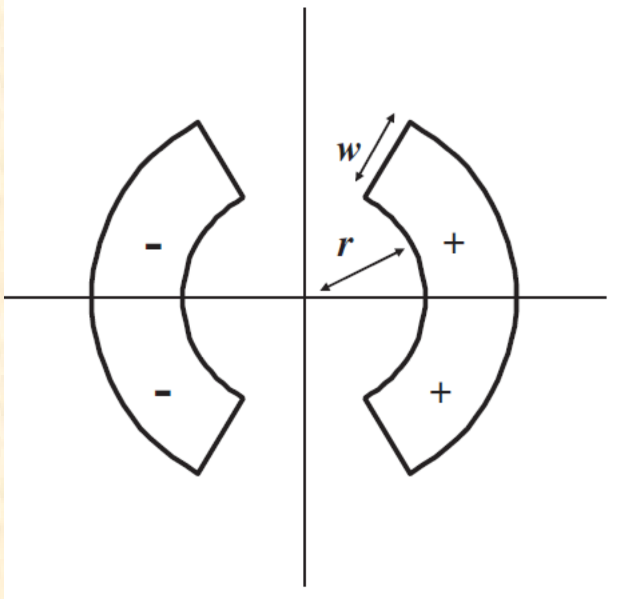
For Discorap the designed margin was 0.97 K
In facts (after cable production) it is 0.76 K

At increasing fields (6 T → Peak 6.42 T)
The 1K margin requires $I/I_c=0.45$; the 0.5 K margin $I/I_c=0.72$



# THE TEMPERATURE MARGIN AFFECTS THE COIL LAYOUT

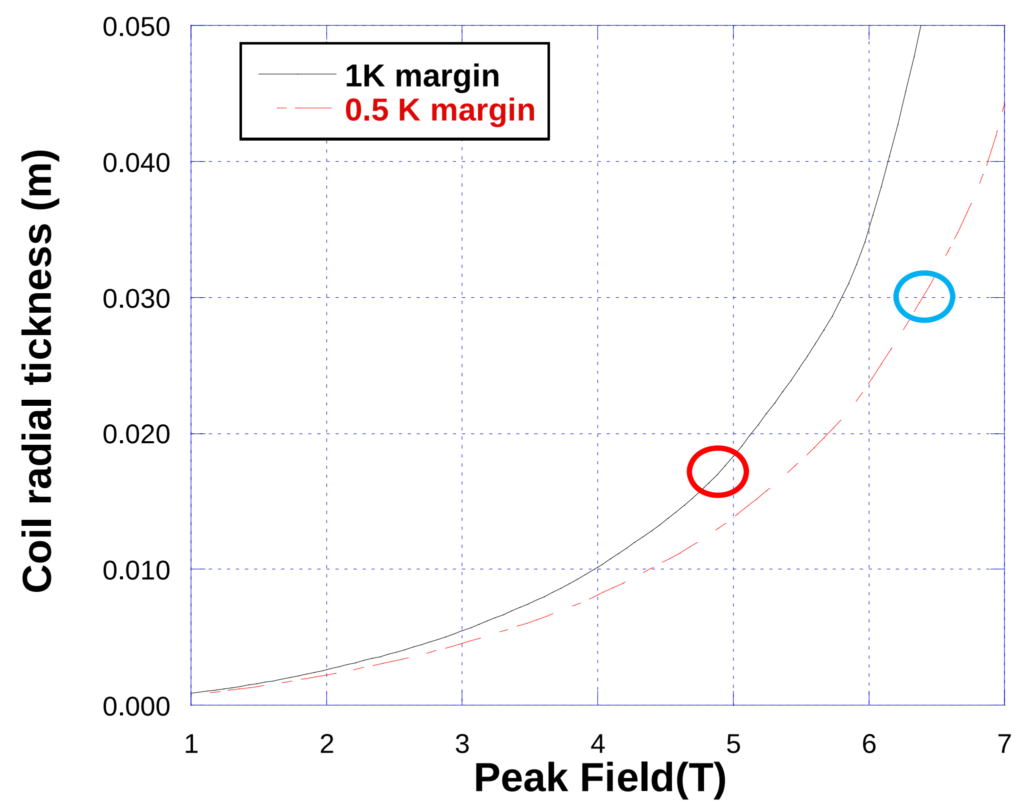
Let’s consider simple sector coil *



$$B = \frac{\mu_0}{\pi}\sqrt{3}J_{ov}w \qquad B_{peak} = \gamma\, B$$

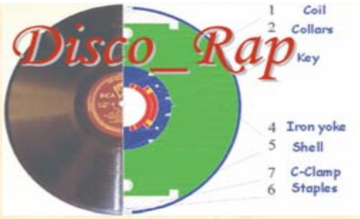
$$J_{ov} = f\, J_{cov}(B_{peak}, T_0) = fJ_c(B_{peak}, T_0)\xi$$

$$DISCORAP\ \ \xi = 0.283,\ \ \gamma = 1.09$$



At 6 T → Peak 6.42 T The 1K margin requires too thick conductors; the 0.5 K margin 2 layers 15 mm radial thick conductors

*L.Rossi and E.Todesco *Physical Rev. Spec. Topics – Accelerators and beams* 10, 112401 2007



# Magnet design issues & concepts for the new injector

P.Fabbricatore INFN-Genova

200 IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 20, NO. 3, JUNE 2010

## SIS 300 Dipole Model

S. Kozub, I. Bogdanov, V. Pokrovsky, A. Seletsky, P. Shcherbakov, L. Shirshov, V. Smirnov, V. Sytnik, L. Tkachenko, V. Zubko, E. Floch, G. Moritz, and H. Mueller

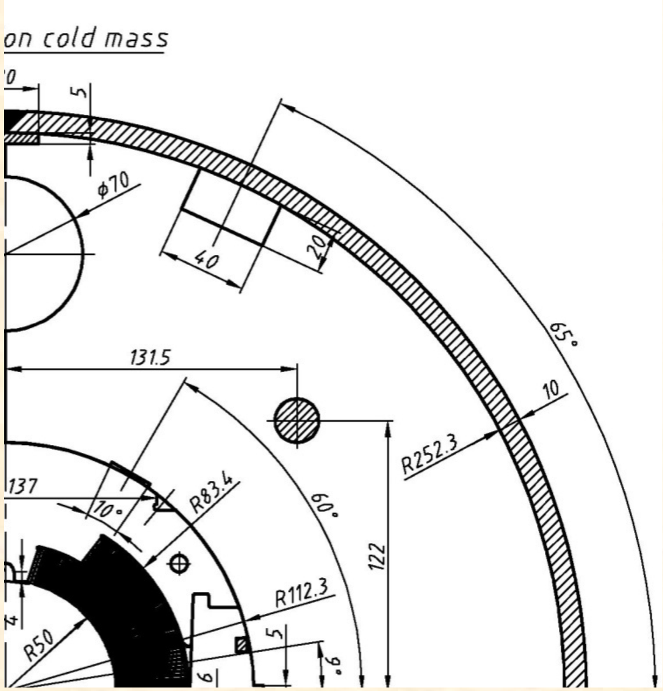


TABLE I
MAIN CHARACTERISTICS OF DIPOLE

| | |
|---|---|
| Central magnetic field, T | 6 |
| Magnetic field ramp rate, T/s | 1 |
| Operating current, A | 6720 |
| Stored energy, kJ | 260 |
| Inductance, mH | 11.7 |
| Number of layers | 2 |
| Inner layer turn number | 64 |
| Outer layer turn number | 76 |
| Coil inner diameter, mm | 100 |
| Length of coil straight part, mm | 580 |
| Coil length, mm | 1020 |
| Collar thickness, mm | 30 |
| Thickness of iron yoke, mm | 140 |
| Thickness of outer cylinder, mm | 10 |
| Outer diameter of outer cylinder, mm | 520 |
| Length of outer cylinder, mm | 1292 |
| Weight of dipole cold mass, kg | 1800 |

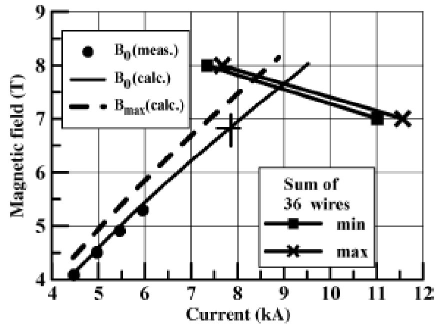
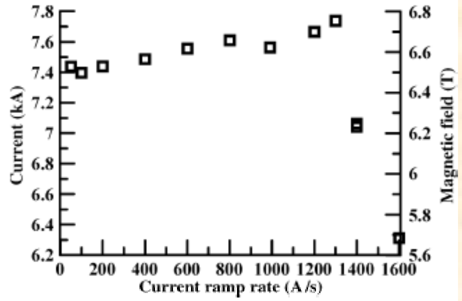


Fig. 6. Calculated dependences of the dipole magnetic field on operating current and cable critical current on magnetic field.



[2]. The bare cable has the following dimensions: 1.362 mm thin edge thickness, 1.598 mm thick edge thickness, 1.480 mm mean thickness, 0.90 keystone angle, and 15.1 mm width. The cable

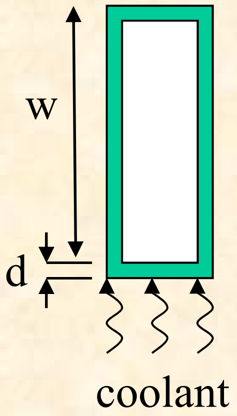
The magnet was tested at 4.3 K getting 6.8 T at 1T/s; the temperature margin is 1.0

# What temperature margin do we really need considering the ac losses?

*Cooling of conductor only from inner short side.*

| | | |
|---|---|---|
| • Kapton thermal conductivity | $k = 1.1$ E-5 | W/(K*mm) |
| • Insulation thickness | d = 0.125 | mm |
| • Conductor width | w = 15.1 | mm |
| • Average power density (ramp) | 1300 | W/m$^3$ |

$$\delta T = \frac{d \cdot w}{k} p \quad = 0.25 \text{ K}$$

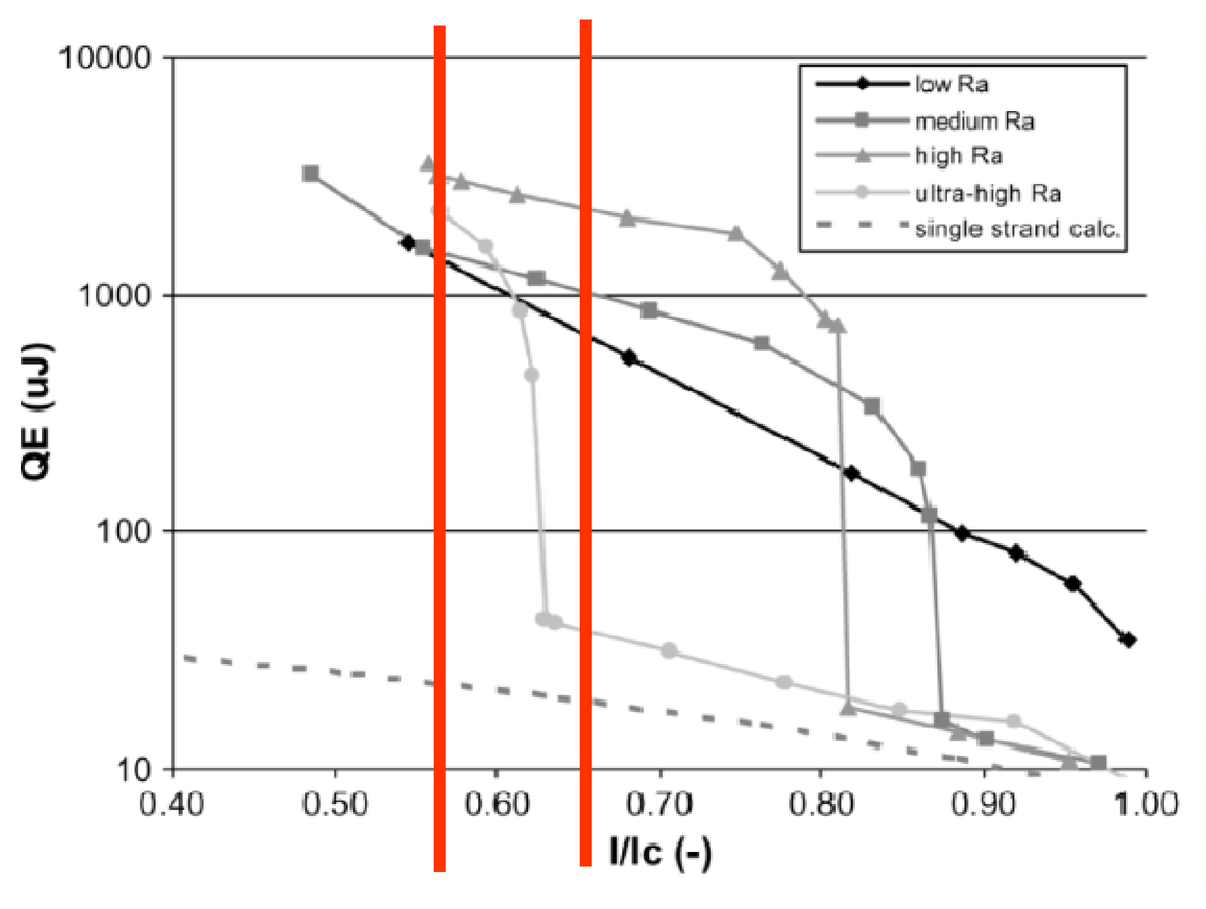


Much more refined models and measurements in

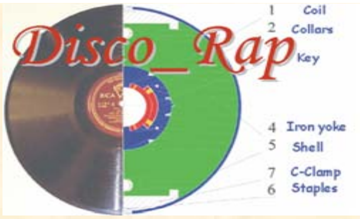
**Thermal Analysis of the Fair SIS300 Model Dipole**
M.Sorbi et al in TRANSACTIONS OF THE CRYOGENIC ENGINEERING CONFERENCE-CEC: Advances in Cryogenic Engineering. AIP Conference Proceedings, Volume 1218, pp. 981-988 (2010).

WILLERING *et al.*: STABILITY OF Nb-Ti RUTHERFORD CABLES WITH DIFFERENT CONTACT RESISTANCES

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 18, NO. 2, JUNE 2008



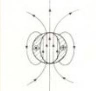
Disco_Rap design (57%) and effective (66%) working points



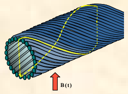
# AC losses

1) Ac losses in the superconducting cable

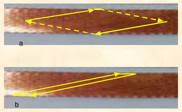
1.1) Hysteretic losses in the superconductor $Q_{Hysteretic} \propto d_f \, B_e \, J_c$



1.2) Coupling losses in the strand multifilamentary structure $P_{if} = \frac{\dot{B}_i^2}{\rho_t}\left(\frac{L_p}{2\pi}\right)^2$



1.3) Losses due to coupling currents between strands $P_{is} \propto \frac{\dot{B}_i^2}{R_a} \; ; \; \frac{\dot{B}_i^2}{R_c}$

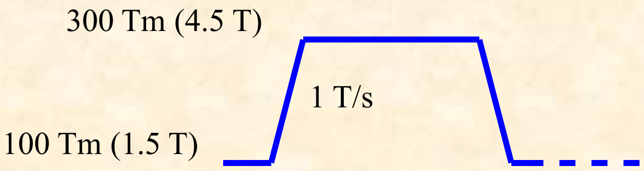


2) Losses in the iron (Irreversible Magnetization, Eddy currents)

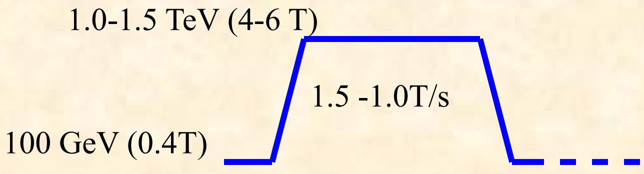
3) Eddy currents in the metallic structure (including beam pipe)

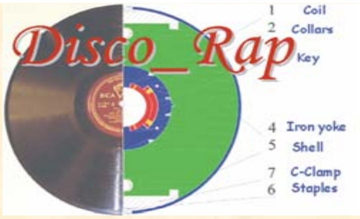
Any discussion about the ac losses should start from the field cycle

For Discorap 6s ramps up and down
Duty cycle 50%



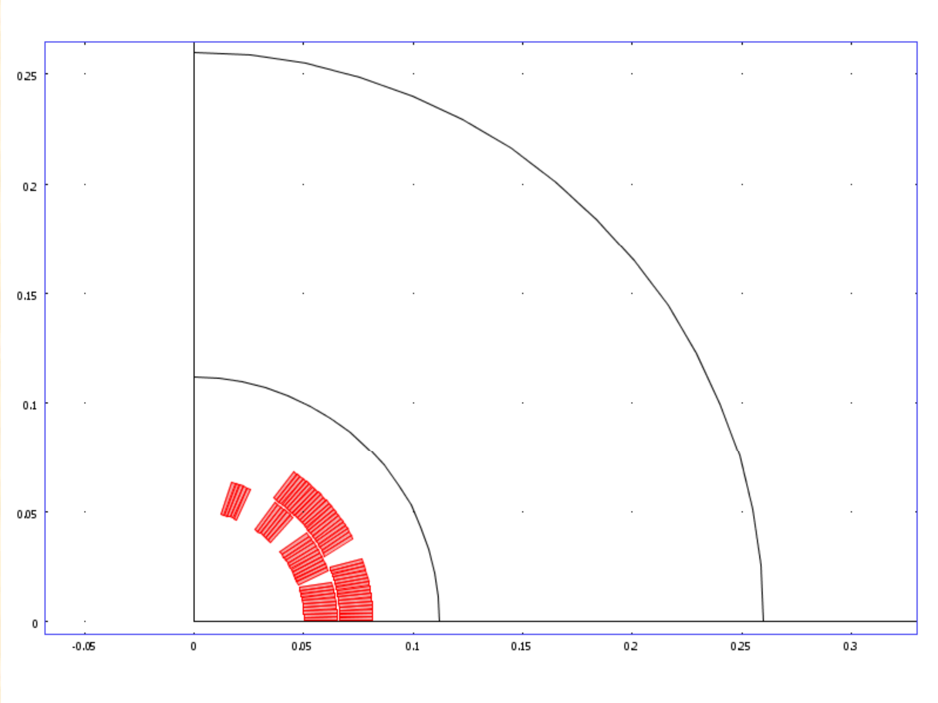
For injector let's consider…
Duty cycle 50%

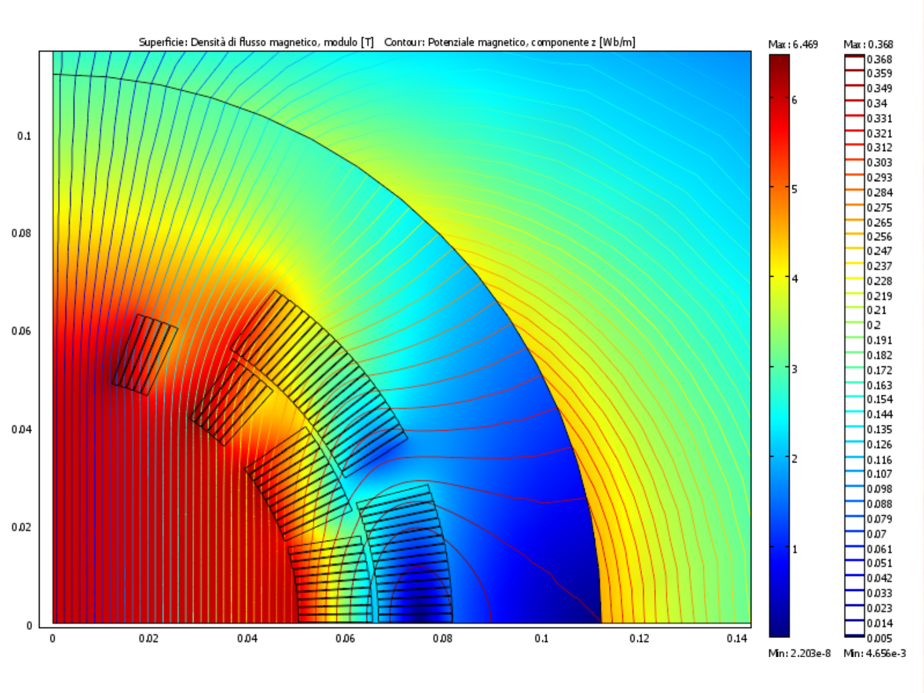




| **Ac losses in the magnet body**<br>**(no end coils contribution)** | **SIS300 4.5T 100mm bore** | | **LHC injector 4T 100mm bore** | |
|---|---|---|---|---|
| | Total loss when ramping from 1.5T to 4.5T at 1 T/s: **7.7 [W/m]** | | Total loss when ramping from 0.4 T to 4.0T at 1 or 1.5 T/s: **8.26 [W/m] - 15.5 [W/m]** | |
| Hysteresis | 30 % | D $_{\text{fil effect}}$=3.5 μm<br>(2.5 μm geom. 3 μm eff.) | 38% | 30% |
| Coupling Strand | 9 % | CuMn $\rho_t = 0.43$ nΩ·m<br>(0.3 nΩ·m )<br>lp 5 mm (6.7 mm ) | 9% | 11% |
| Interstrand Ra+Rc | 6 % | Cored cable | 6% | 7% |
| **Total conductor** | **(45 %)** | | **(53%)** | **(48%)** |
| | | | | |
| Collars + Yoke eddy + Prot. sheets | 6 % | Collar 3 mm tick<br>Iron 1 mm tick | 6% | 7% |
| Yoke magn | 24% | $H_c$ (A/m)=35 | 19% | 17% |
| Beam pipe | 14 % | $\frac{\pi}{\rho_0} \dot{B}_0^2 \cdot r_{av}^3 \cdot \Delta r$ | 11% | 14% |
| Collar-Keys-Pins | 8 % | | 8% | 10% |
| Yoke-Keys-Pins | 3 % | | 3% | 4% |

# Cosθ 6T dipole 100 mm bore

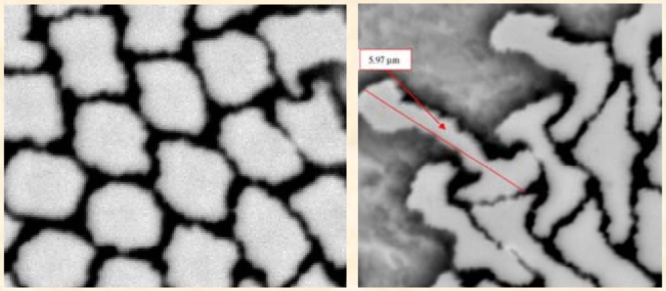




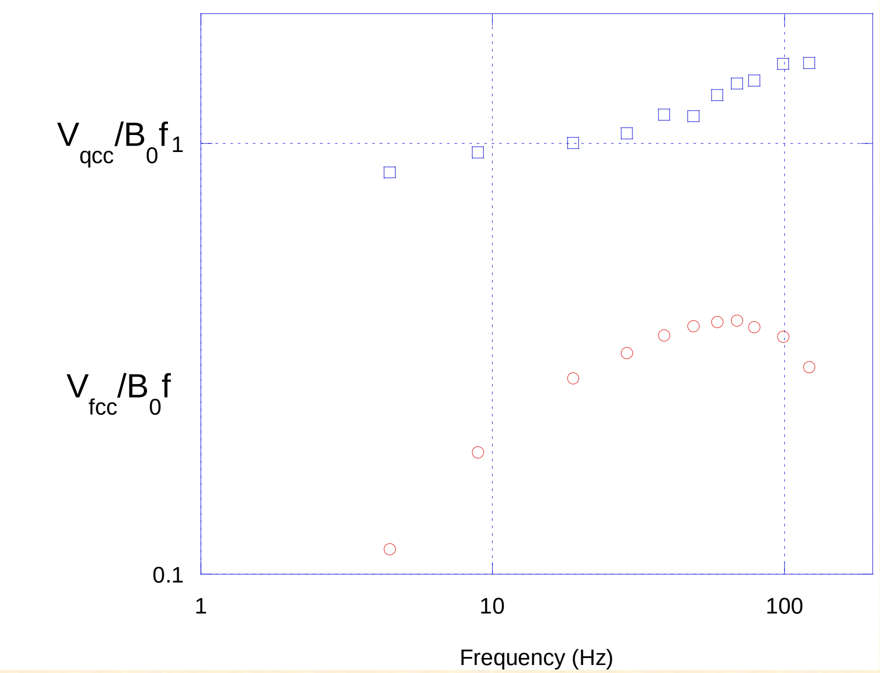
Peak Field 6.42 T; Temperature margin 0.65 K;
Operating at 65% of short sample and 89% along the load line
(with respect to an *ideal* conductor)

| | **Injector 6T 100mm bore** | |
|---|---|---|
| | Total loss when ramping from 0.4 to 6 T at 1 T/s:<br>**13.5 [W/m]** | |
| Hysteresis | 40 % | $D_{\text{fil effect}}$=3.5 μm |
| Coupling Strand | 9 % | CuMn $\rho_t = 0.43$ nΩ·m<br>lp 5 mm |
| Interstrand Ra+Rc | 9 % | Cored cable |
| **Total conductor** | **(58 %)** | |
| | | |
| Collars + Yoke eddy + Prot.sheets | 1.1 % | Collar 3 mm tick<br>Iron 1 mm tick |
| Yoke magn | 23% | $H_c$ (A/m)=35 |
| Beam pipe | 8 % | |
| Collar-Keys-Pins | 5 % | |
| Yoke-Keys-Pins | 2 % | |

# Margins for improvements

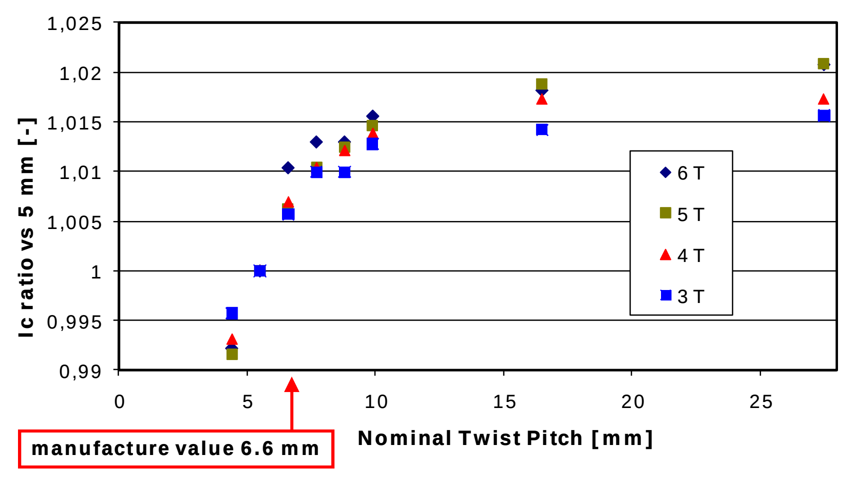


Improve filament quality. Goal Jc(5T,4.22K) =3000 A/mm2 with filaments of effective diameter 2 μm



Better control of the transverse resistivity. Designed 0.44 nΩm, obtained 0.3 nΩm (presumably due to the filament deformation).

G. Volpini et al., “Low-Loss NbTi Rutherford Cable for Application to the SIS-300 Dipole Magnet Prototype”; IEEE Trans. Appl. Supercond., 18, Issue 2, June 2008 pp 997-1000



Decrease strand twist pitch. The measurements done during the development demonstrated that we can get values as low as 5 mm or less (4 mm)

- Use of electrical steel with lower coercitive field (30 A/m)
- Coil protection sheets in insulating material
- Decrease as possible eddy currents in the system collar-keys and yoke-keys

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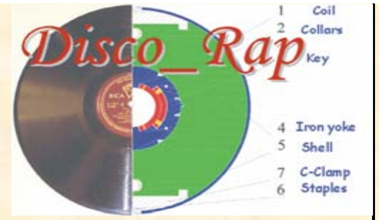


# Magnet design issues & concepts for the new injector

P.Fabbricatore INFN-Genova

| Pushing forward both design and technology | **LHC injector 4T 100mm bore** | | **LHC injector 6T 100mm bore** |
|---|---|---|---|
| | Total loss when ramping from 0.4 T to 4.0T at 1.5 T/s: **11.5 [W/m]** | | Total loss when ramping from 0.4 T to 6.0T at 1.0 T/s: **10.6 [W/m]** |
| Hysteresis | 34 % | D $_{\text{fil effect}}$ =2µm | 40 % |
| Coupling Strand | 7 % | CuMn $\rho_t = 0.43$ nΩ·m<br>lp =4 mm | 11 % |
| Interstrand Ra+Rc | 8 % | Cored cable | 8 % |
| **Total conductor** | **(49 %)** | | **(59%)** |
| | | | |
| Collars + Yoke eddy + Prot. sheets | 1 % | Insulated<br>Prot. sheets | 1 % |
| Yoke magn | 20 % | $H_c$ (A/m)=30 | 25 % |
| Beam pipe | 19 % | - | 10 % |
| Collar-Keys-Pins | 8 % | Reduced of 50% | 3 % |
| Yoke-Keys-Pins | 3 % | Reduced of 50% | 2 % |

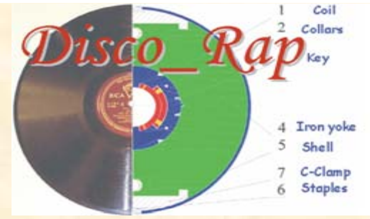
# Let’s extrapolate!

Further reduction of ac losses requires drastic measures:

1) Warm iron (a re-design is necessary)
2) Ceramic beam pipe?
3) NbTi filament even smaller (1 μm) but good Jc

Under these conditions the ac losses could be reduced to 5W/m when ramping.

| Parameters | SIS300 dipole | Injector 4T 100mm 1.5T/s | Injector 6T 100mm 1.0T/s |
|---|---|---|---|
| Injection magnetic field [T] and $b_3$ | 1.5/ -0.75 | 0.4/ -4.5 | 0.4/-5.9 |
| Maximum/ Peak magnetic field [T] | 4.5/4.9 | 4.0/4.4 | 6/6.42 |
| Temperature Margin (K) | 0.97 | 1.46 | 0.65 |
| AC losses in the superconducting cable during ramp [W/m] | 3.5 | 5.6 | 6.3 |
| AC losses in the structures during ramp (eddy currents and magnetization) [W/m] | 3.5 | 5.9 | 4.3 |
| Weight [T/m] | 1.28 | 1.28 | 1.68 |
| Const. Cost [K€/m] evaluated on 60 magnets | 60-70 | 60-70 | 80-90 |



# CONCLUSIONS

- The R&D developments for SIS300 dipoles both at INFN and at IHEP in collaboration with GSI are setting the basis for demonstrating the feasibility of superconducting magnets 4.5-6 T ramped at 1T/s.
- Advanced designs, construction techniques and first low loss conductors were developed.
- More conclusive condiderations next year after testing the model magnets at operating temperatures at GSI.
- We need more information regarding the effects due to mechanical fatigue.
- On the basis of present knowledge some extrapolations can be done for HE LHC injector magnets.
- In particular it appear one can get ac losses as low as 10W/m when ramping the magnet (5W/m as minimum limit). The field quality at injection energy could be an issue.