Magnet design issues & concepts for (very) pulsed dipoles

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Starting from the development of a fast cycled superconducting dipole magnet for SIS300, some information and considerations for the development of muon collider

This presentation is based on the work of many colleagues of INFN DISCORAP project, INFN-Genova, INFN-Salerno and INFN-LASA

SIS300 dipoles: fast cycled and curved magnet

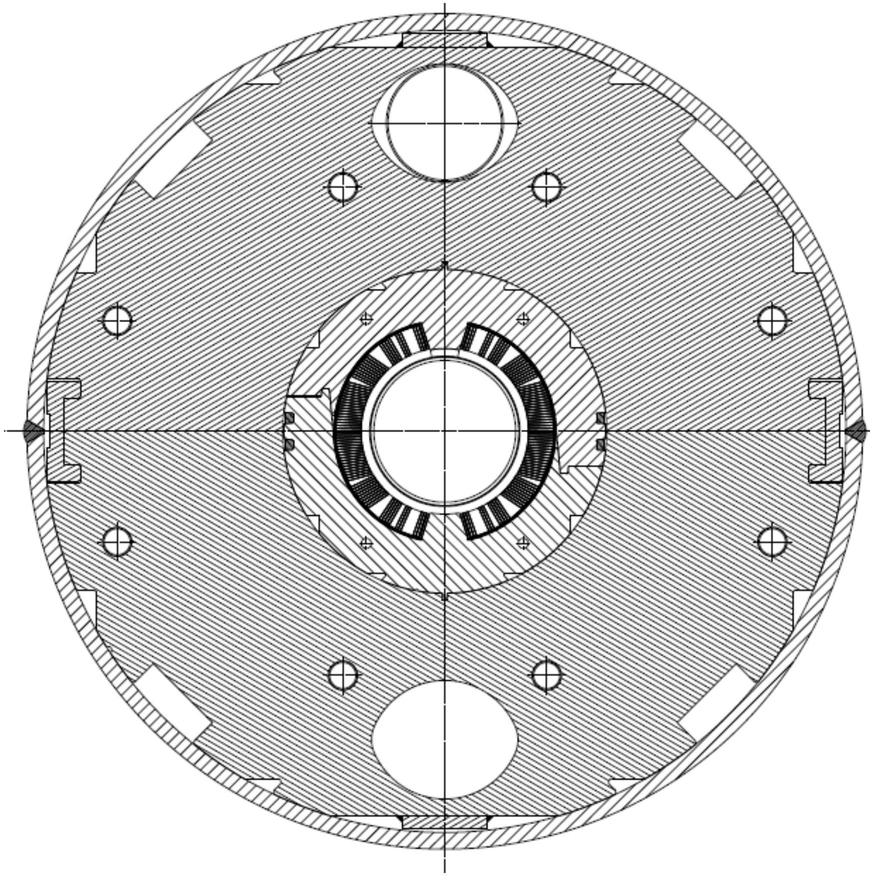


TABLE I MAIN REQUIREMENTS OF SIS300 SHORT DIPOLES

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)	P (W/m)
LHC	53	8.34	0.008	0.18
RHIC	80	3.5	0.06	0.35
SIS300	**100**	4.5	**1**	**<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)

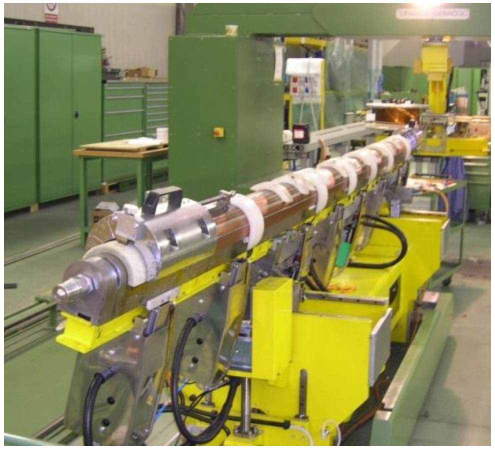
Low ac losses→ Cored conductor→ Constructive problems

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*



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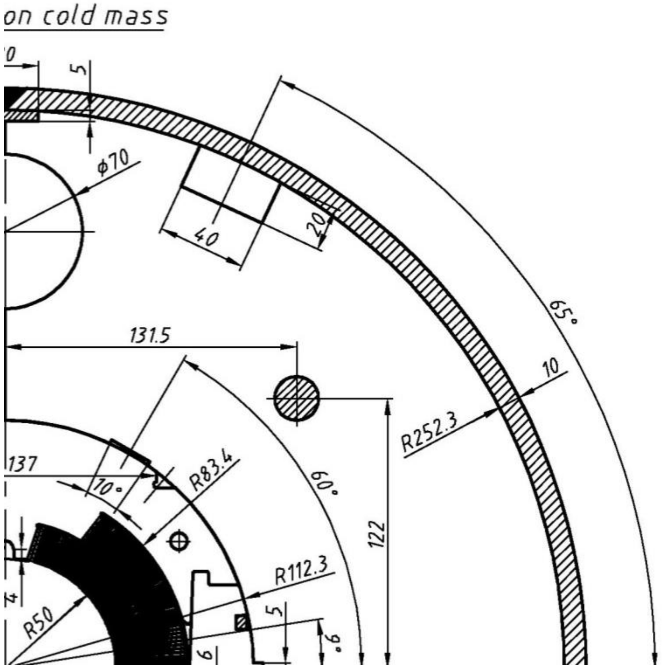
SIS 300 Dipole Model

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



[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

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

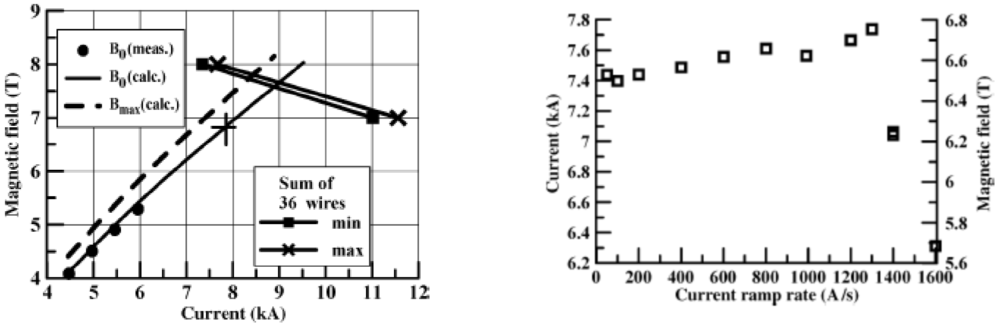


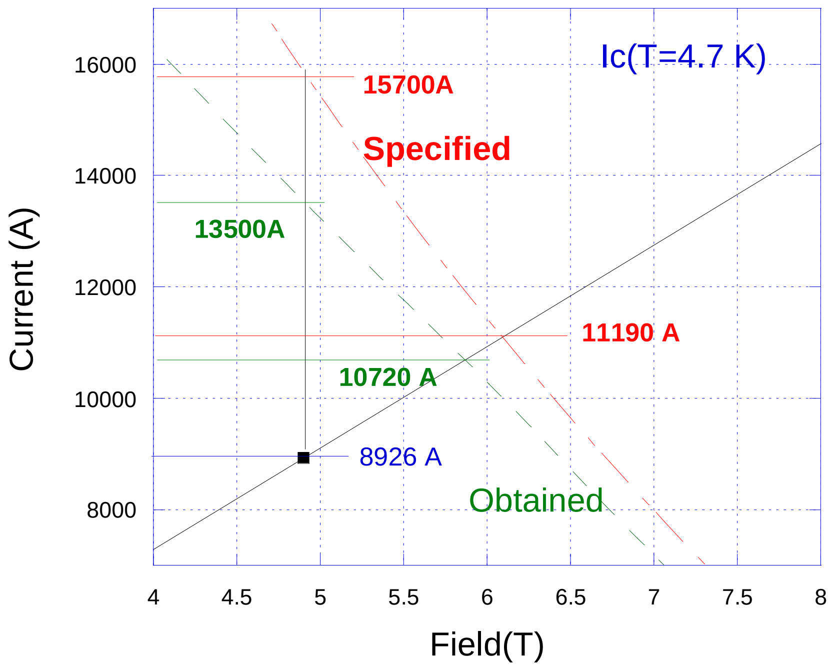
Fig. 6. Calculated dependences of the dipole magnetic field on operating current and cable critical current on magnetic field.

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

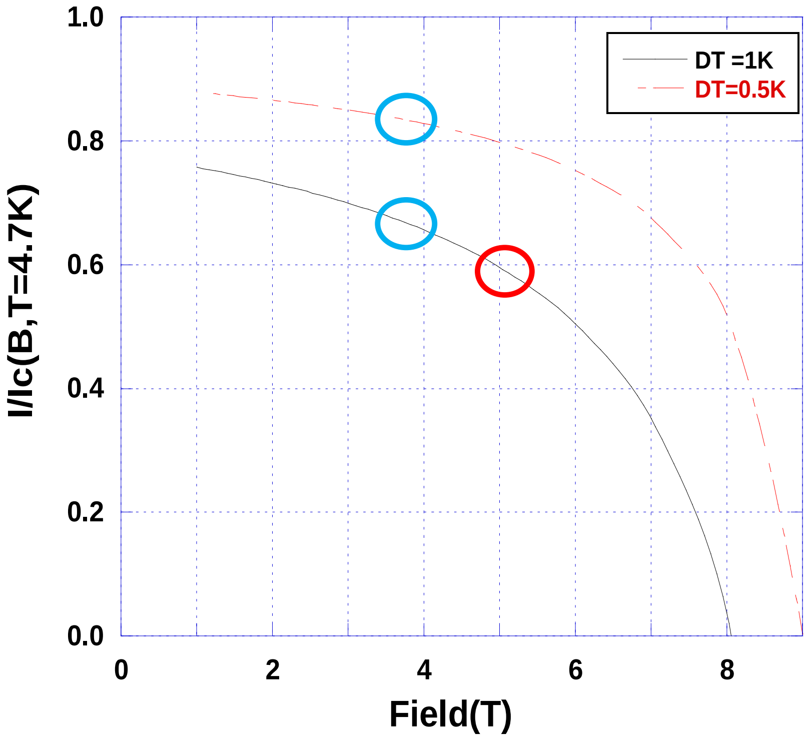
Magnet operating in supercritical He Parameter	SIS300 dipole	Muon collider 27 km
Injection/maximum magnetic field [T]	1.5 / 4.5	0.2/3.5
Peak magnetic field [T]	4.9	3.8
Temperature Margin (K)	0.97	~0.5
Ramp rate [T/s]	1	35
AC losses in the superconductor during ramp [W/m]	3.5	??
AC losses in the structures during ramp (eddy currents and magnetization) [W/m]	4.2	??

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)



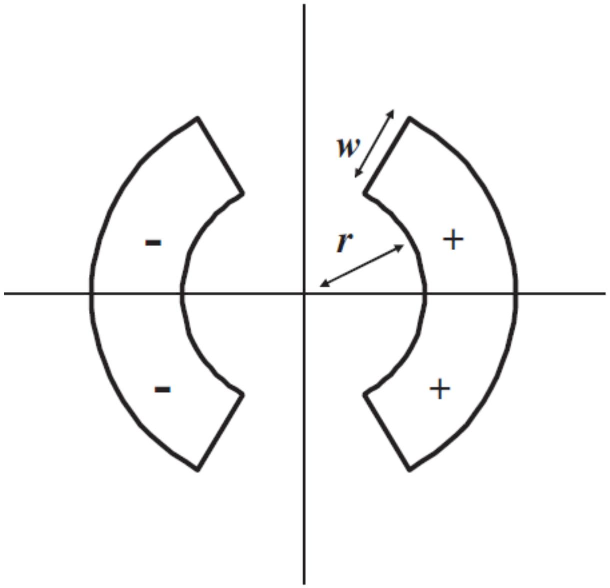
For Discorap the designed margin was 0.97 K
(In reality after cable production it is 0.76 K)



At 3.5 T → Peak 3.8 T, the 1K margin requires I/I_c=0.65; the 0.5 K margin I/I_c=0.83

THE TEMPERATURE MARGIN AFFECTS THE COIL LAYOUT

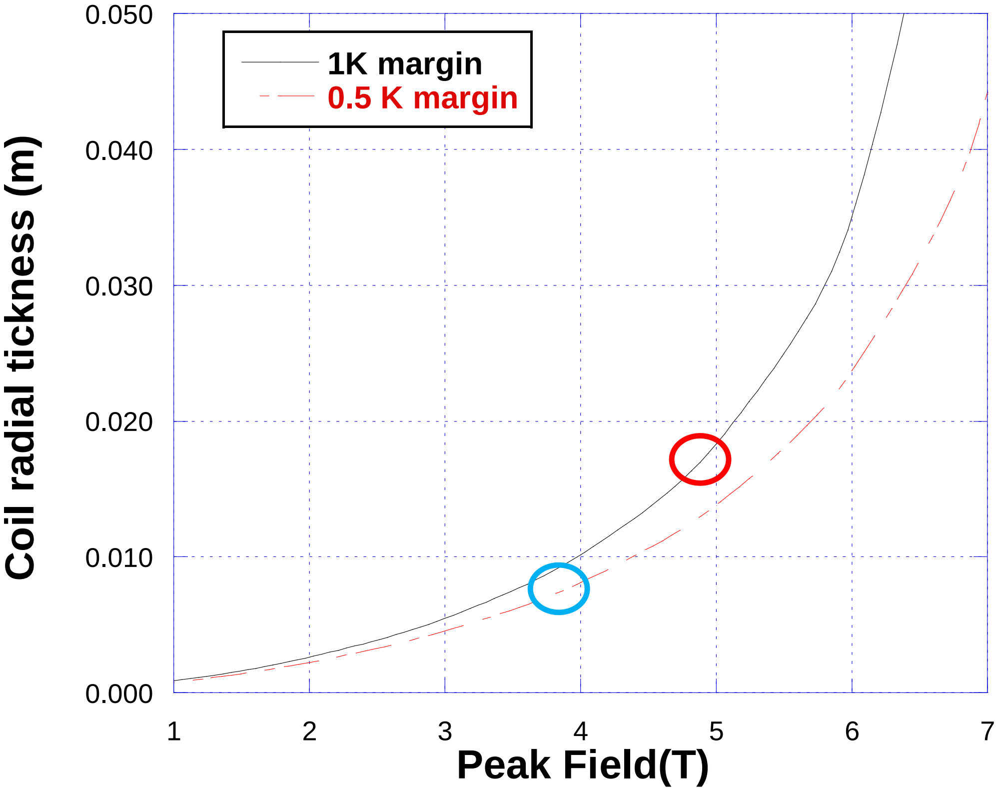
Let’s consider simple sector coil *



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

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

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



At 3.5 T → Peak 3.8 T the 1K margin requires ~9 mm thick conductors; the 0.5 K margin, ~ 7 mm radial thick conductors (22% less)

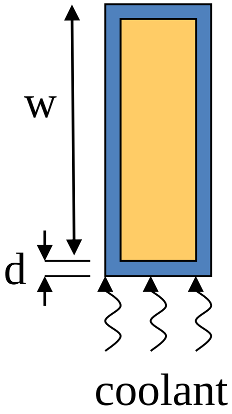
*L.Rossi and E.Todesco *Physical Rev. Spec. Topics – Accelerators and beams* 10, 112401 2007

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

Cooling of conductor only from <u>inner short side</u>: ***gradient δT in the insulation***

• 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)	p= 1300	W/m^3

$$\delta T = \frac{d \cdot w}{k} p$$ (it scales with ***w*** i.e. conductor volume)



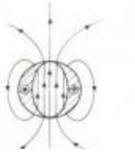
Much more refined models and measurements in

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).

AC losses

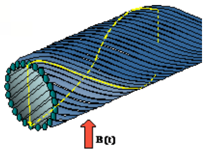
1) Ac losses in the superconducting cable

$$P_{Hysteretic} \propto d_f \, \dot{B}_e \, J_c$$

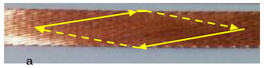


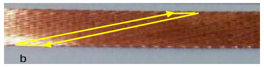
1.1) Hysteretic losses in the superconductor

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 $P_{is} \propto \frac{\dot{B}_i^2}{R_a} \; ; \; \frac{\dot{B}_i^2}{R_c}$



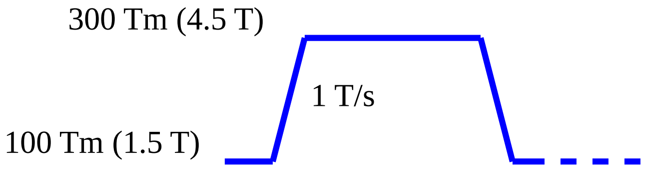


2) Losses in the iron (Irreversible Magnetization, Eddy currents)

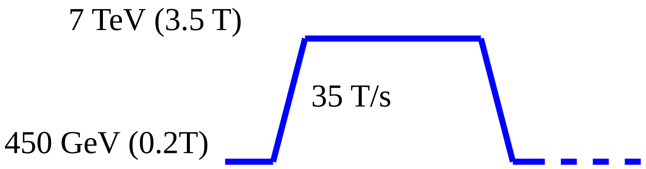
3) Eddy currents in the metallic structure (including beam pipe)

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

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



For muon collider let's consider…
Duty cycle 50%



Ac losses in the magnet body [W/m]	**Bore aperture 100 mm**	**SIS300 4.5T**	**Muon collider in LHC**
		Total loss when ramping from 1.5T to 4.5T at 1 T/s	Total loss when ramping from 0.2 T to 3.5T at **35 T/s**
Hysteresis	D $_{\text{fil effect}}$ =3.5 µm (2.5 µm geom. 3 µm eff.)	2.3	40
Coupling inside the strand	CuMn ρ_t = 0.43 nΩ·m (0.3 nΩ·m) lp 5 mm (6.7 mm)	0.7	424
Interstrand Ra+Rc	Cored cable	0.5	306
Total conductor		3.5	770
Collars+Yoke eddy + Prot. sheets	Collar 3 mm tick Iron 1 mm tick	0.46	400
Yoke magn	H_c (A/m)=35	1.9	50
Beam pipe	$\frac{\pi}{\rho_0} \dot{B}_0^2 \cdot r_{av}^3 \cdot \Delta r$	1.1	1350
Collar-Keys-Pins		0.6	700
Yoke-Keys-Pins		0.2	200
TOTAL LOSSES		**7.7**	**~3500**

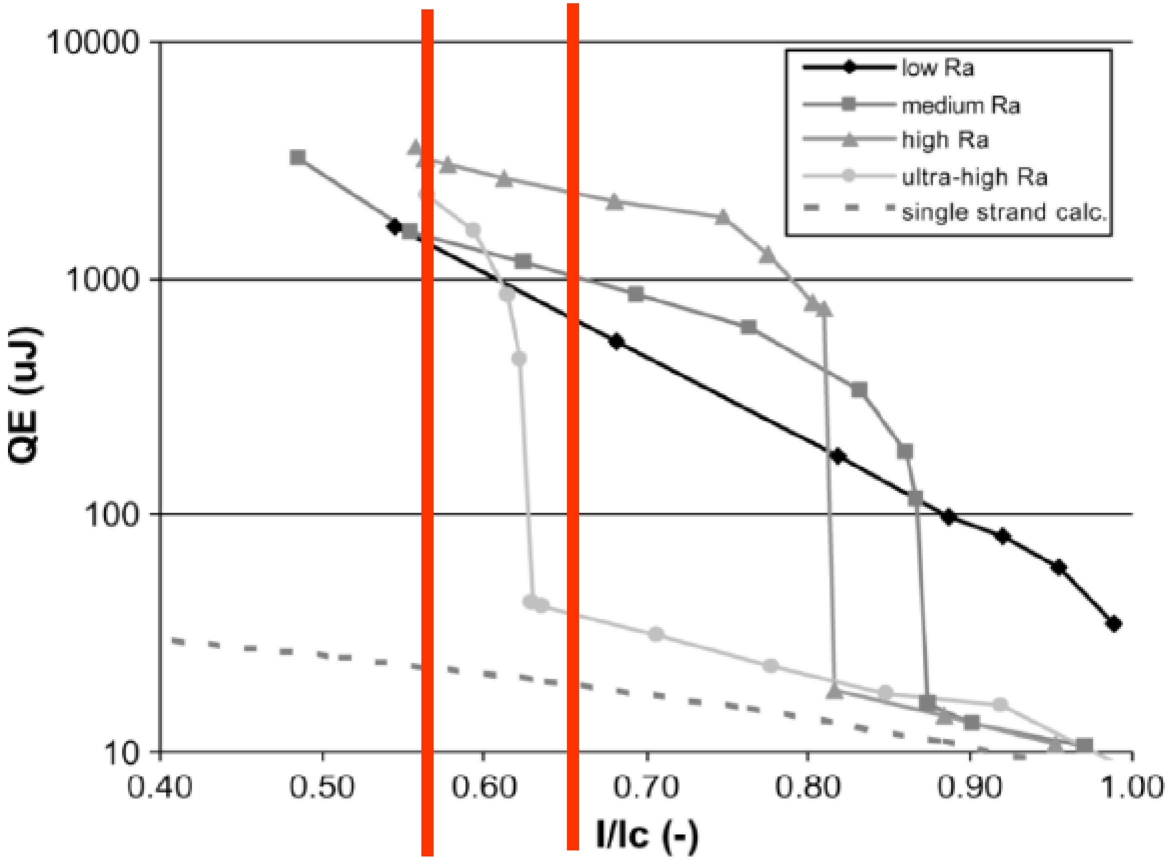
In conclusion if the ramp rate becomes so large, the power depending on [dB/dt]^2 explode. Become dominant eddy current losses respect to hysteresis losses

To reduce them in coils it is necessary to reduce the resistance between filament and the inter-strand in the cable.

This is not trivial, because it is paid by the stability of the conductor respect to quench…

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

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



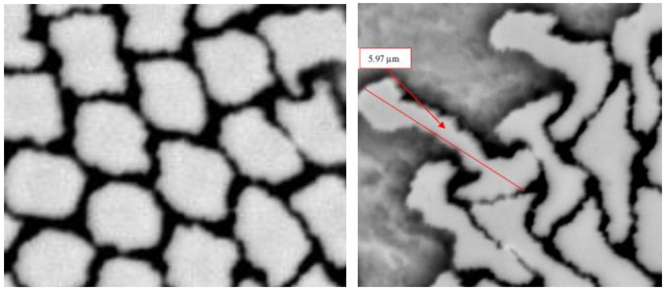
Disco_Rap design (57%) and effective (66%) working points

Let’s extrapolate!

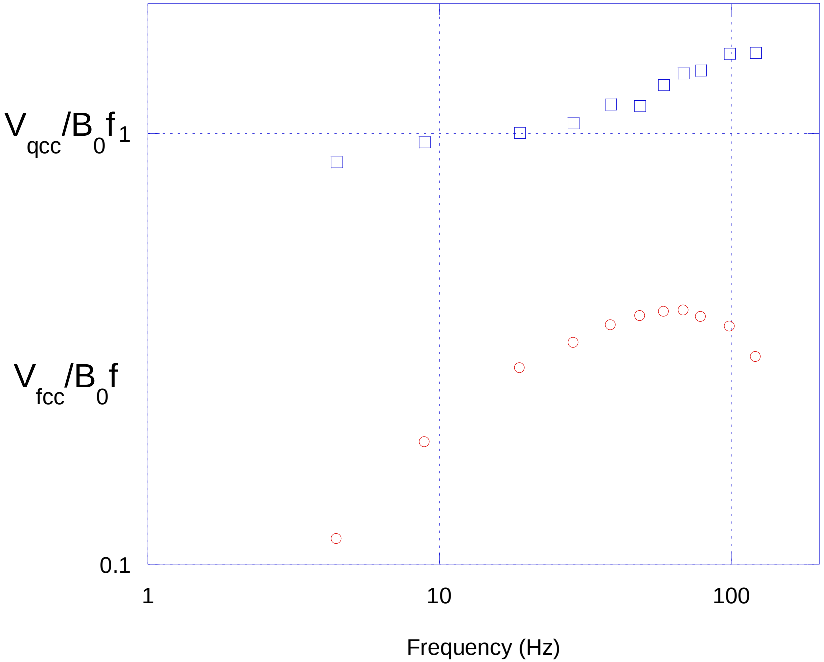
Further reduction of ac losses requires drastic measures:

1) Warm iron (a re-design is necessary)
2) Ceramic beam pipe?
3) NbTi filament smaller (1 μm) but good Jc
4) Larger resistance for inter strand and for stabilizing material in conductor (compromise with stability)
5) Large and creative optimization for the mechanics…

Margins for improvements

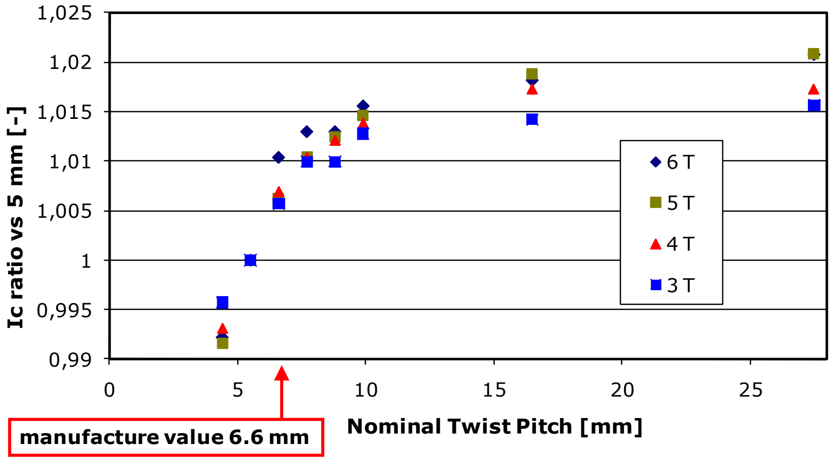


Improve filament quality. Goal Jc(5T,4.22K) =3000 A/mm2 with filaments of effective diameter 1 µm



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



manufacture value 6.6 mm

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)

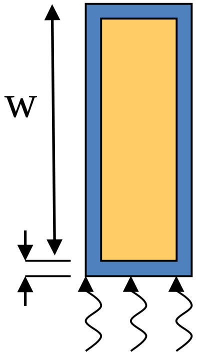
- Use of electrical steel with lower coercitive field (30 A/m)
- Coil protection sheets in insulating material
- Decrease as possible eddy currents in the system collar-keys and yoke-keys

Ac losses in the cold mass [W/m]	**Bore aperture 100 mm**	**Muon collider in LHC**	**Muon collider in LHC**
		Total loss when ramping from 0.2 T to 3.5T at **35 T/s**	“Possible” improvements from 0.2 T to 3.5T at **35 T/s**
Hysteresis	Reduce $D_{\text{fil effect}}$ from 3.5μm to 1 μm	40	10
Coupling inside the strand	Increase the matrix resistance and twist-pitch (factor 10)	424	42
Interstrand Ra+Rc	Increase the resistance	306	31
Total conductor		770	83
Collars	Reduce collar thickness	400	20
Yoke	“warm” yoke	50	-
Beam pipe	Ceramic material	1350	~5
Collar-Keys-Pins	Increase the resistance	700	10
Yoke-Keys-Pins	“warm” yoke	200	-
TOTAL LOSSES		**~3500**	**~120**

Magnet operating in supercritical He Parameter	SIS300 dipole	Muon collider 27 km
Injection/maximum magnetic field [T]	1.5 / 4.5	0.2/3.5
Peak magnetic field [T]	4.9	3.8
Temperature Margin (K)	0.97	0.5
Ramp rate [T/s]	1	35
AC losses in the superconductor during ramp [W/m]	3.5	83
Other AC losses in the "cold" structures during ramp (eddy currents) [W/m]	4.2	35

- 80 W/m in conductor means new concept to evacuate the power: to keep δT ≈ 0.5 K necessary to increase the conductivity through the insulation.

$$\delta T = \frac{d \cdot w}{k} p \quad = 0.5\ \mathrm{K}$$



from standard Kapton thermal conductivity
k = 1.1 E-5 W/(K*mm) pass to high conducting material (with electrical insulation) a factor 20 larger

Other problems

Still large losses:

- A large cooling system necessary

- 120 W/m * 20 km = **2.4 MW at 4.5 K** (when pulsed, 0.1s in a total period of 3-6 s)

(To be compared with the static 13 kW at 1.9 K for LHC: a factor 200 larger)

- The power is requested during the running of magnet: a system to store and release the energy when needed.

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.
- On the basis of present knowledge some extrapolations can be done for HE LHC injector magnets: one can get ac losses as low as 10W/m when ramping the magnet to 2-3 T/s (5W/m as minimum limit).
- For a muon collider with ramping rate in range of 35 T/s, losses are much larger: creative solution must be searched (new material for stabilizing conductor, for insulation, for beam tube, etc.)
- Large power consumption, which requires attention in the feasibility study.