Prospects for fast ramping superconducting magnets (trans. Lines, FAIR, SPS+, VHE-LHC LER)

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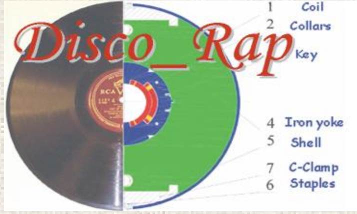
Starting from the development of the fast cycled dipole magnets for FAIR SIS300, some information and considerations for the development of future fast ramped superconducting magnets

This presentation is based on the work of many colleagues of INFN working in the DISCORAP project (Milano LASA and Napoli)



INFN DISCO_RAP project
Development of SIS300 fast cycled and curved magnet

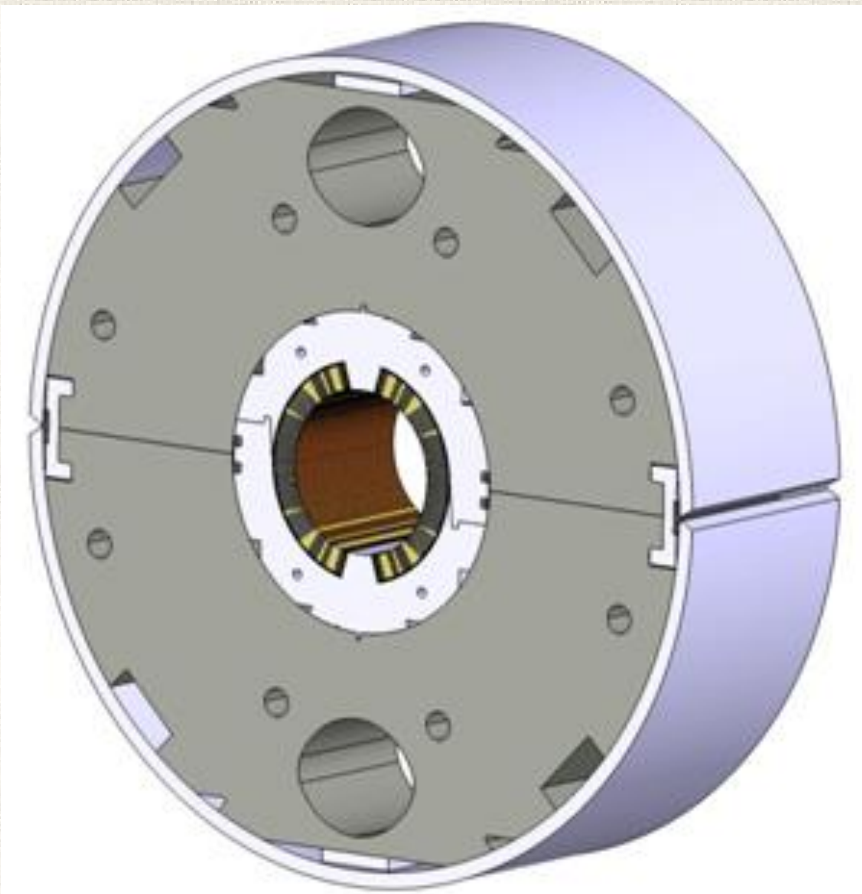


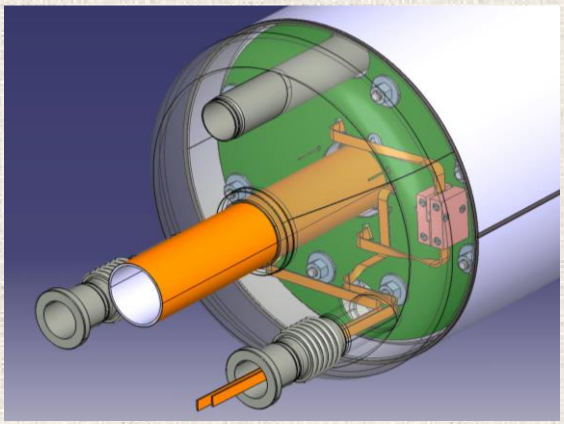
TABLE I MAIN REQUIREMENTS OF SIS300 SHORT DIPOLES

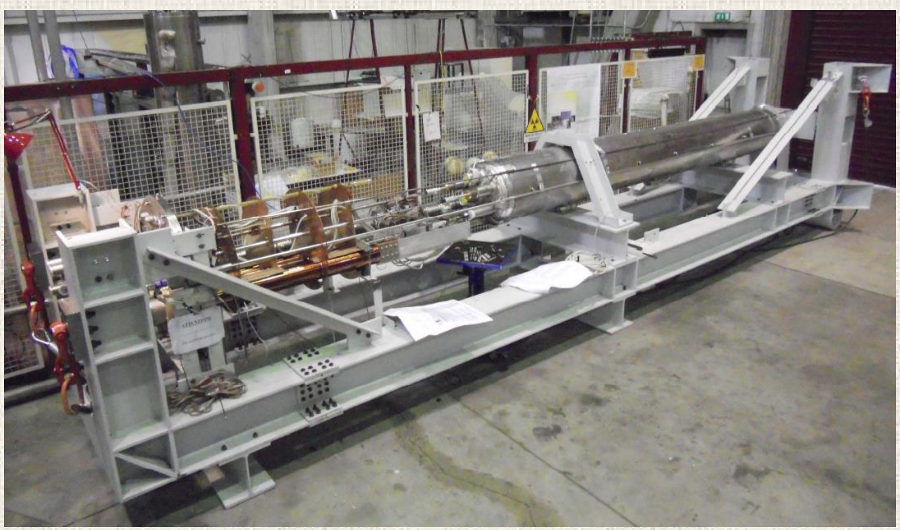
Nominal Field (T) :	4.5
Ramp rate (T/s)	1
Radius of magnet geometrical curvature (m)	66 2/3
Magnetic Length (m)	3.879
Bending angle (deg)	3 1/3
Coil aperture (mm)	100
Max operating temperature (K)	4.7

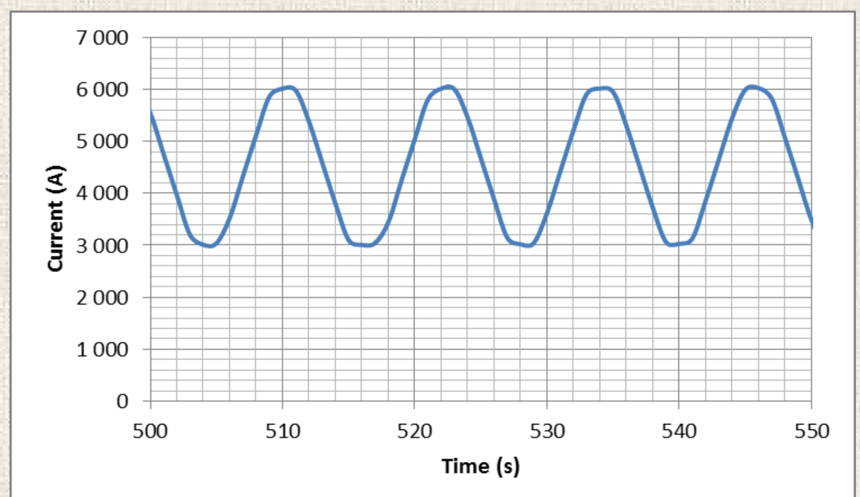
TABLE II MAIN CARACTERISTICS OF THE MODEL MAGNET

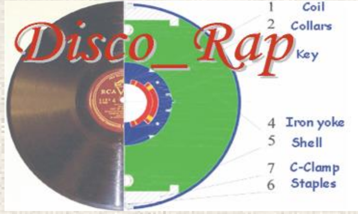
Block number	5
Turn number/quadrant	34 (17+9+4+2+2)
Operating current (A)	8920
Yoke inner radius (mm)	96.85
Yoke outer radius (mm)	240.00
Peak field on conductor (with self field) (T)	4.90
B_{peak} / B_o	1.09
Working point on load line	69%
Current sharing temperature (K)	5.69

A 4 m long model (indeed a prototype) has been designed by INFN, constructed (at ASG Superconductors) and tested at INFN LASA









Criticities of SIS300 dipoles

Requirement 1:	Ramp 1T/s → ac losses
Target :	10 W/m @4.7 K max losses in ramping conditions
Needed R&D:	Development of a low loss conductor
Design issues:	Minimization of eddy currents in structures
	Low magnetic loss yoke

Requirement 2:	10^7 cycles → Fatigue
Consequences:	Mechanical design and materials optimization
Open problems:	Not easy checking the achievement of the requirement

Requirement 3:	Geometrical Curvature R=66.667 m (sagitta 117 mm)
Consequences:	Many design and constructive problems

Results from the R&D and lessons learned

Superconducting wire (INFN-Luvata design)

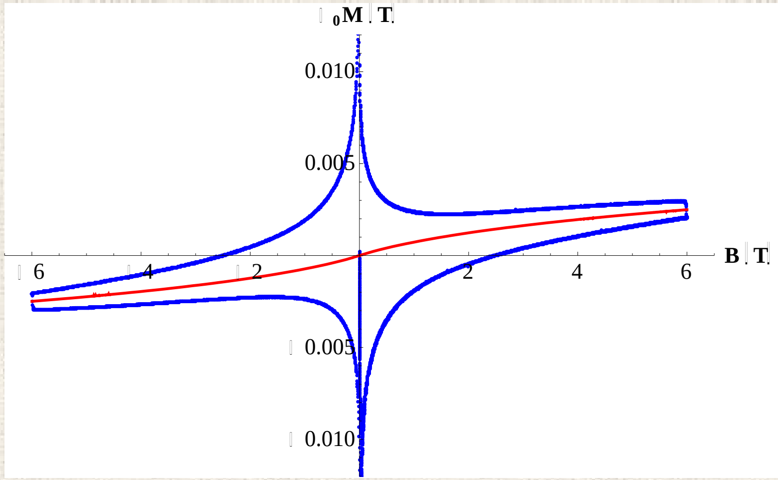
	Specified	Obtained	Comment
Diameter after surface coating (mm)	0.825 ± 0.003	Ok	
Filament twist pitch (mm)	5 +0.5 -0	6.6	5 mm obtainable
Effective filament diameter for 1st generation wire (μm)	3.5	~3.2	Filament deformations
Effective filament diameter for 2nd generation wire(μm)	2.5	~3.2	
I_c @ 5 T, 4.22 K (A)	> 541	470 1st 520 2nd	Breakages during manufacturing in 2nd generation
n-index @ 5 T, 4.22 K	> 30	32	
Stabilization matrix	Pure Cu		
Strand transverse resistivity at 4.22 K (nΩm) (Cu-0.5 wt% Mn involved)	0.43 + 0.09 B [T]	0.3 1st 0.4 2nd	
Cu+CuMn:NbTi ratio (α ratio)	>1.5	ok	
Surface coating material	Staybrite (Sn-5 wt% Ag)	ok	
Surface coating thickness *d*	0.5	ok	

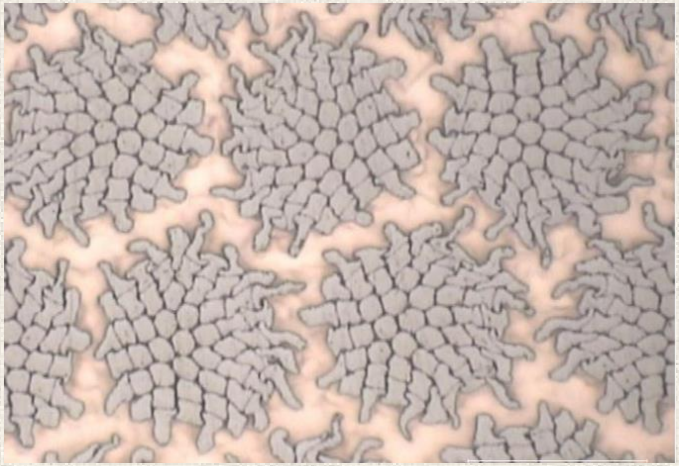
Superconducting cable

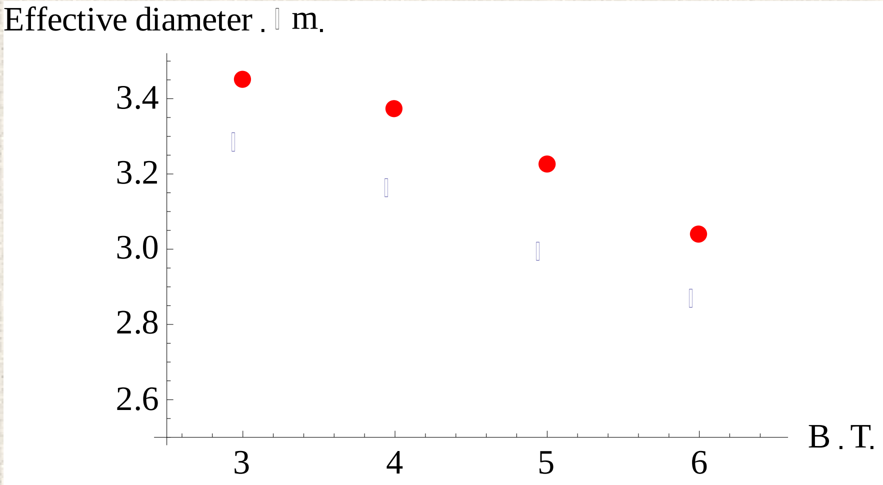
	Specified	Obtained
Strand Number	36	ok
Width	15.10 +0 -0.020	ok
Thickness, thin edge	1.362 ± 0.006	ok
Thickness, thick edge	1.598 ± 0.006	ok
Core material	AISI 316 L stainless steel, annealed	ok
Core width	13	ok
Core thickness	25	ok
I_c @ 5 T, 4.22 K (A)	18450	16000 1st 17600 2nd

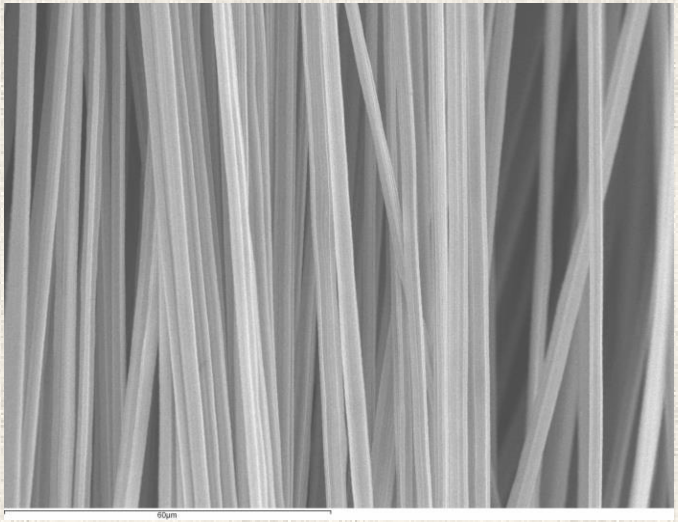
The cable development is not yet finished. New wires and cables are under development. Filament (partly) deformation, critical current and breakages during manufacturing are the main issues. However .. a low loss cable exists till now and can be used for ramped magnets.

Some interesting features about the developed sc wires

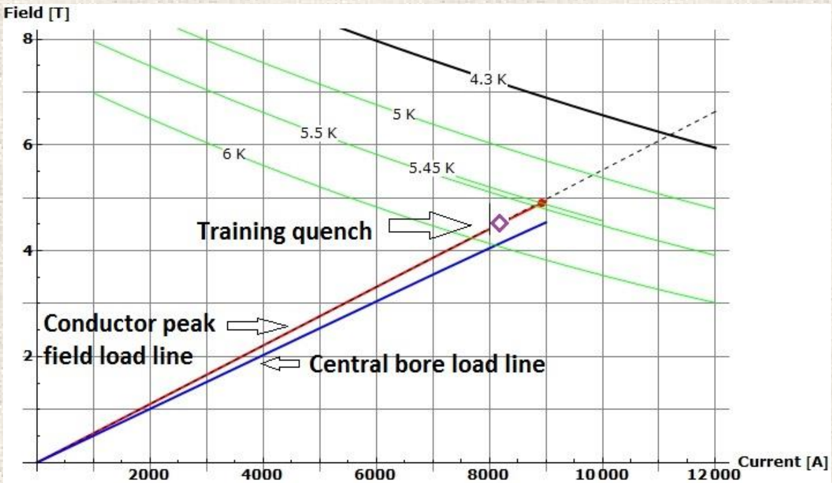


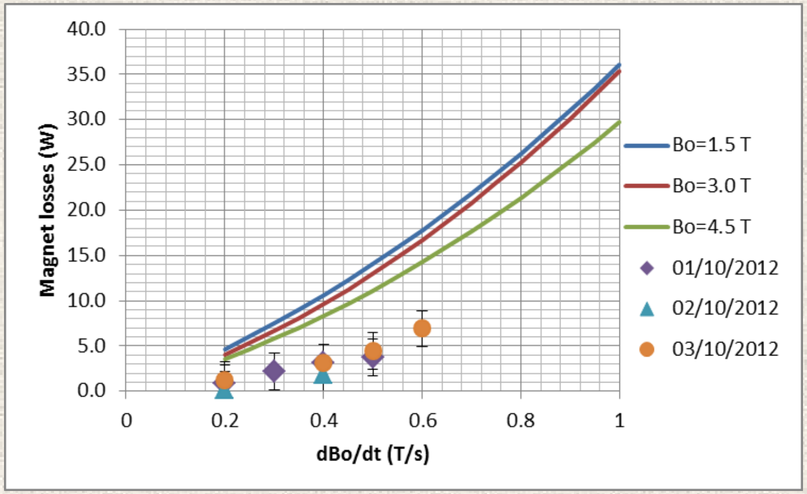






Magnet cold test



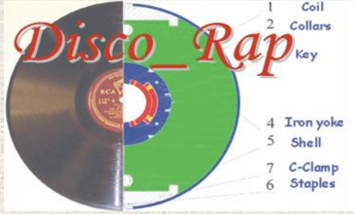


Excellent training

Apparently ac low losses (calorimetric)
From analysis of electrical signal, the losses comparable with expectations

Some problems of premature quench for large field sweep (> 4000 A)

Complete results to be presented at MT-23 Boston by G.Volpini and M.Sorbi



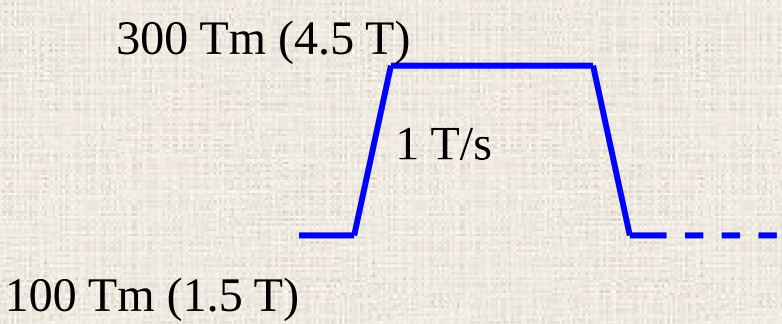
Conclusions on DISCO_RAP R&D

The results of DISCO_RAP project show that a big step has been done towards the developments of fast cycled (and curved) magnets. Though some aspects of the mechanics (related to the geometrical curvature) are not yet fully understood, some problems have been found related to premature quenching when ramping the coil and the conductor could need further developments, the key technologies are almost available <u>at industrial level</u> and we are now ready to move forward

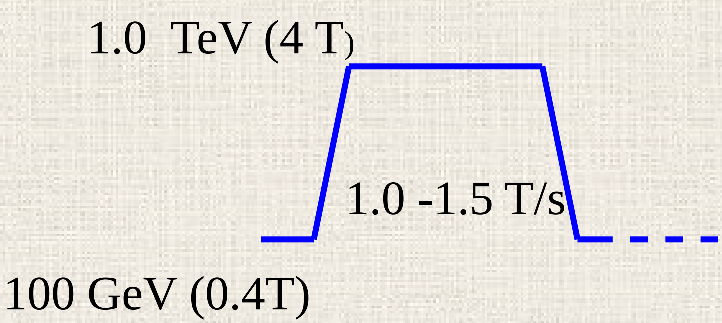
Future
An example: a new injector for HE-LHC

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

For FAIR SIS300, 6s ramps up and down
Duty cycle 50%

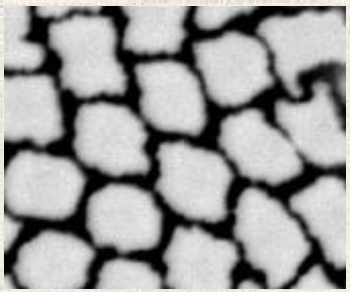


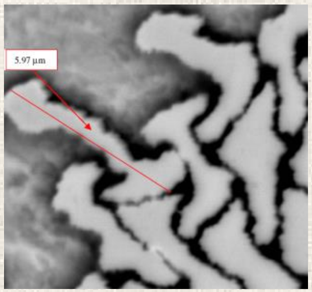
For injector let's consider…
Duty cycle 50%



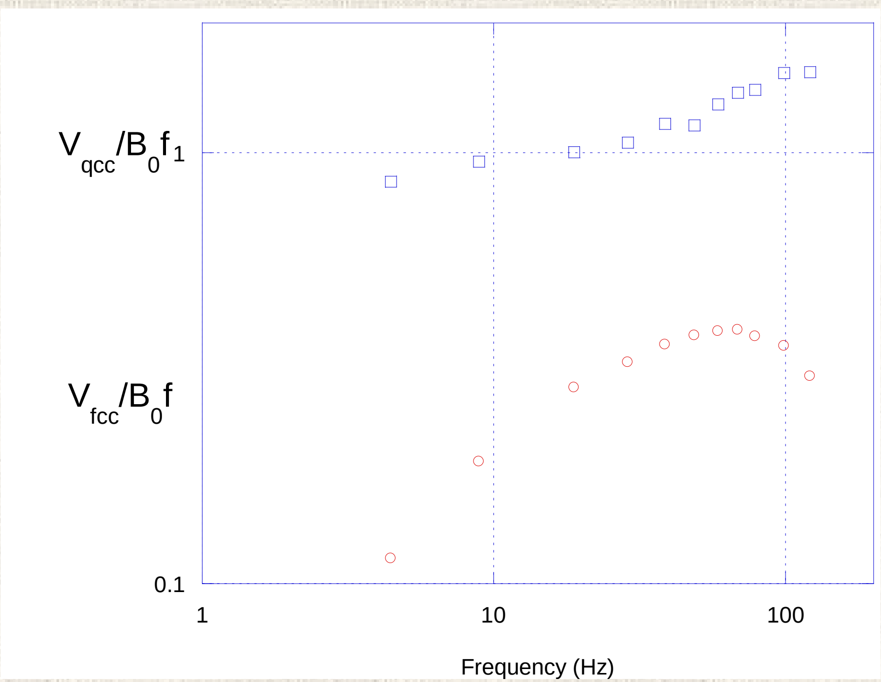
Ac losses in the magnet body (no end coils contribution)	**SIS300 4.5T 100mm bore**		**LHC injector 4T 100mm bore**	
	Total loss when ramping from 1.5T to 4.5T at 1 T/s: **7.7 [W/m]**		Total loss when ramping from 0.4 T to 4.0T at 1 T/s or 1.5 T/s: **8.26 [W/m] - 15.5 [W/m]**	
Hysteresis	30 %	D $_{\text{fil effect}}$ =3.5 µm (2.5 µm geom. 3 µm eff.)	38%	30%
Coupling Strand	9 %	CuMn ρ_t = 0.43 nΩ·m 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 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%

Margins for improvements



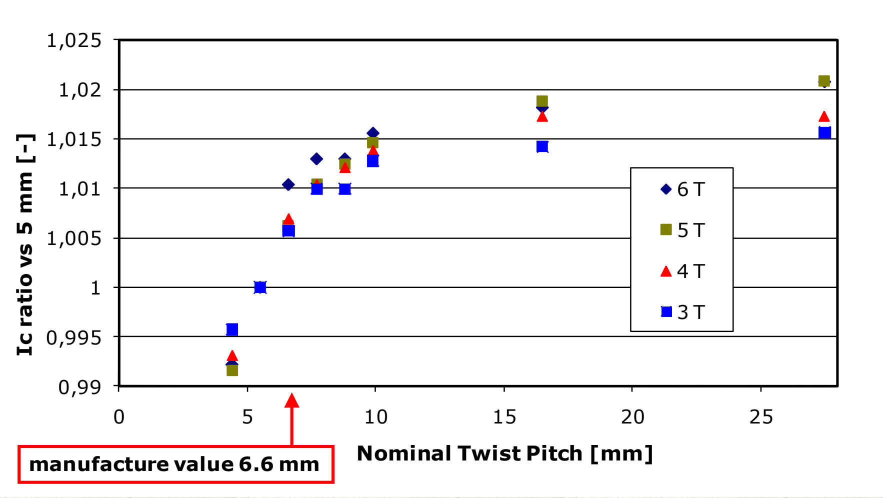


Improve filament quality. Goal Jc(5T,4.22K) =3000 A/mm2 with filaments of effective diameter 2 µm



Better control of the transverse resistivity. Designed 0.44 nΩm, obtained 0.4 nΩm (presumably due to the filament deformation).

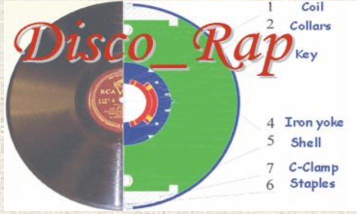
G. Volpini et al., "Low-Loss NbTi Rutherford Cable for Application to the SIS-300 Dipole Magnet Prototype"; IEEE Trans. Appl. Supercond., 18, Issue 2, June 2008 pp 997-1000



Decrease strand twist pitch. Measurements done during the R&D 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 systems collar-keys and yoke-keys

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



Let’s extrapolate (Maybe too futuristic!!)

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 down to 5W/m when ramping.

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

CONCLUSIONS

- The R&D developments for SIS300 dipole at INFN demonstrated the feasibility of superconducting magnets 4.5 T ramped at 1T/s.

- Advanced designs, construction techniques and first low loss conductors were developed.

- We need more information regarding the effects due to mechanical fatigue.

- On the basis of present knowledge some extrapolations can be done for future fast ramped magnet (e.g. 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.

SPARE SLIDES

CRISP WP5

In the frame of the FP7 program CRISP Work Package 5 INFN with GSI and CERN are developing an advanced model of SIS300 involving the cable of the II generation . Presently the collared coil is funded. Deadline: end 2013

Further an improved conductor and the re-design of electrica exits, the coil layout has been optimized for reducing the geometrical harmonics.

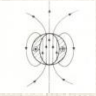
Normal	Units in 10^4	Skew	Units in 10^4
B1	10^4	A1	0.16
B2	0.78	A2	0.82
B3	6.52	A3	-1.32
B4	1.78	A4	-1.57
B5	-3.03	A5	-0.22
B6	0.72	A6	0.31
B7	0.55	A7	0.15

With respect to the first dipole we are trying to reduce B3 and B5

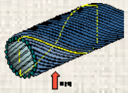
AC losses

1) Ac losses in the superconducting cable

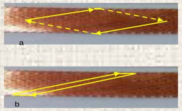
   1.1) Hysteretic losses in the superconductor $Q_{Hysteretic} \propto d_f\, B_e\, J_c$



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

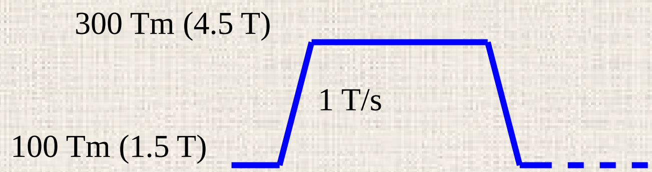


2) Losses in the iron (Irreversible Magnetization, Eddy currents)

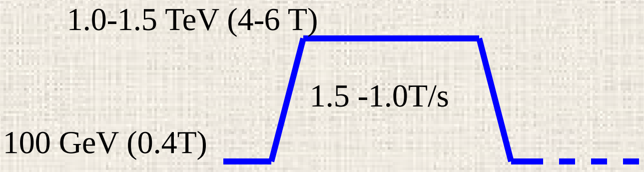
3) Eddy currents in the metallic structure (including beam pipe)

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

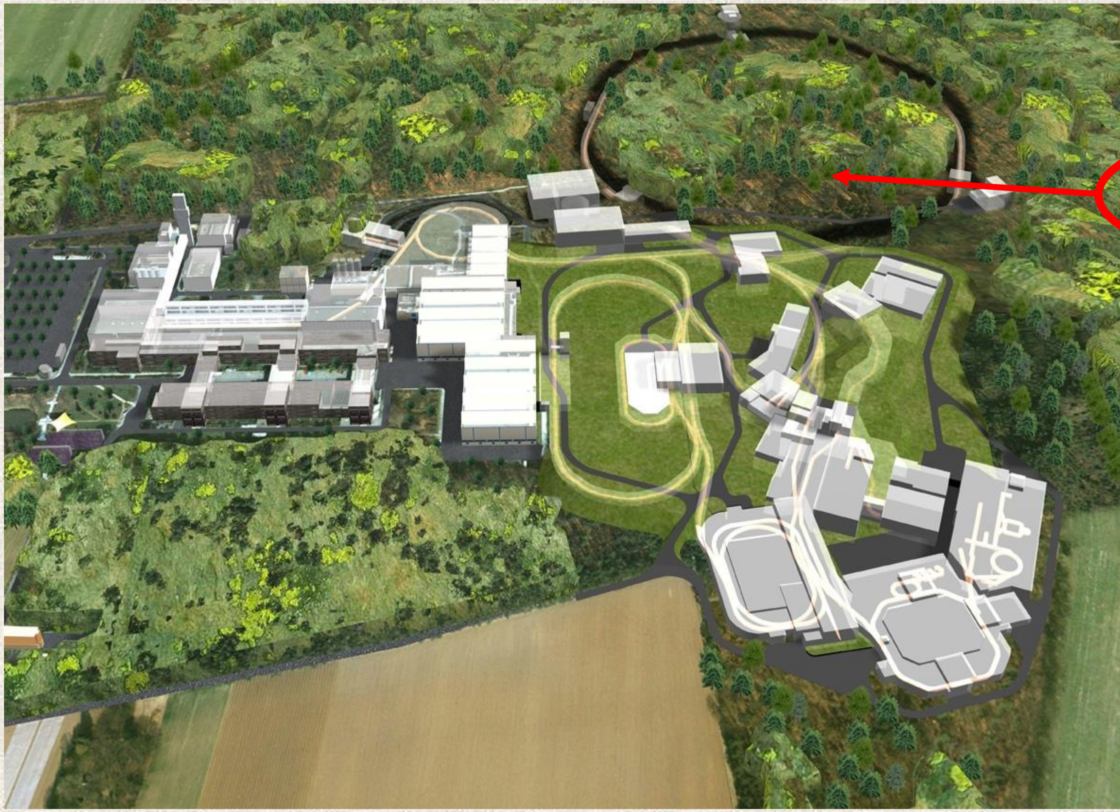
For Discorap 6s ramps up and down
Duty cycle 50%

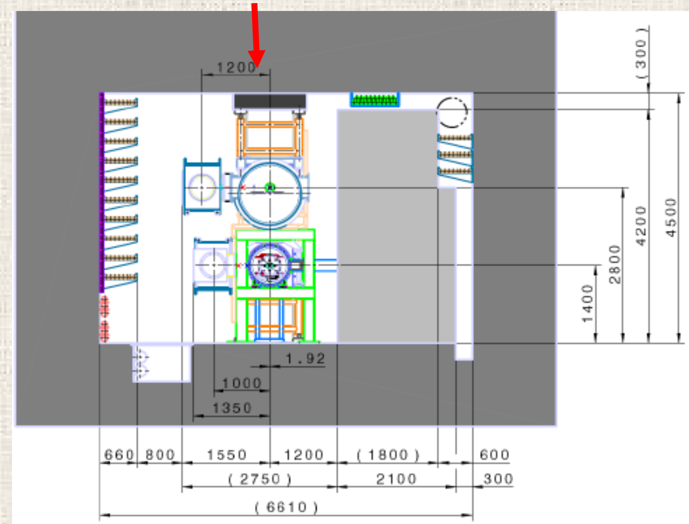


For injector let's consider…
Duty cycle 50%



The facility **FAIR** including the synchrotrons SIS100 and SIS300





- The SIS300 will be installed on top of SIS100 in the same tunnel.
- The maximum magnetic rigidity is 300 Tm
- Curved super conducting cos(θ)-type magnets will be used with a maximum field of 4.5 T in the dipoles, to be ramped at 1T/s : 48 long (7.757 m) 12 short (3.879 m) dipoles

Tool development for curved winding operations:
Curved mandrel and mold, curved winding of a cored cable