Rapidly-cycling superconducting accelerator magnets

for FAIR at GSI

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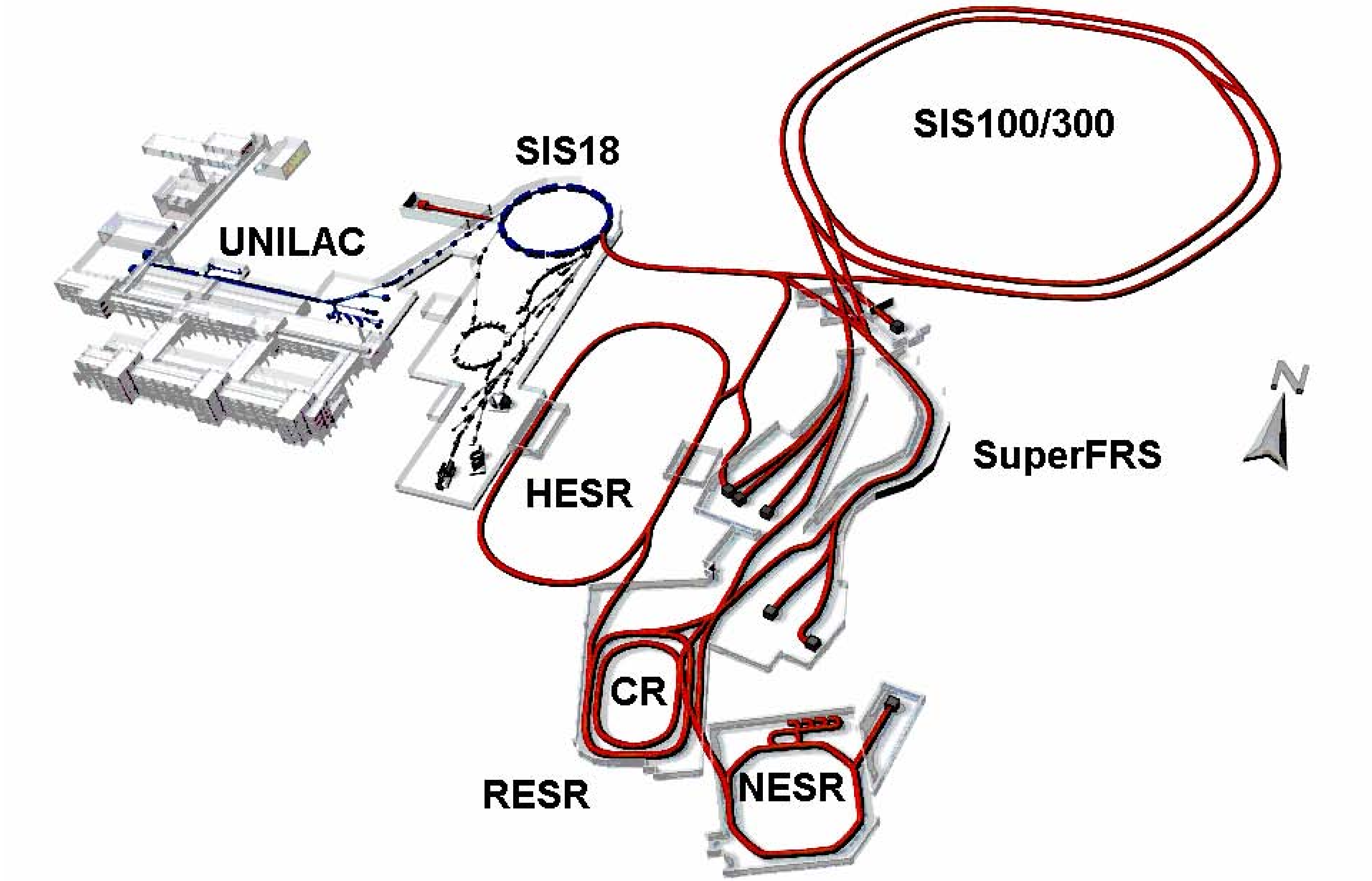
on behalf of the FAIR Magnet Technology group

PAC 07, Albuquerque, June 29 2007

Outline

- Introduction to FAIR synchrotrons
- Motivation – load to the cryogenic system
- R&D
  - Basics / Goals
  - Development of low loss conductor
  - SIS 100 synchrotron magnets
  - SIS 300 synchrotron magnets
- Summary

FAIR schematic topology



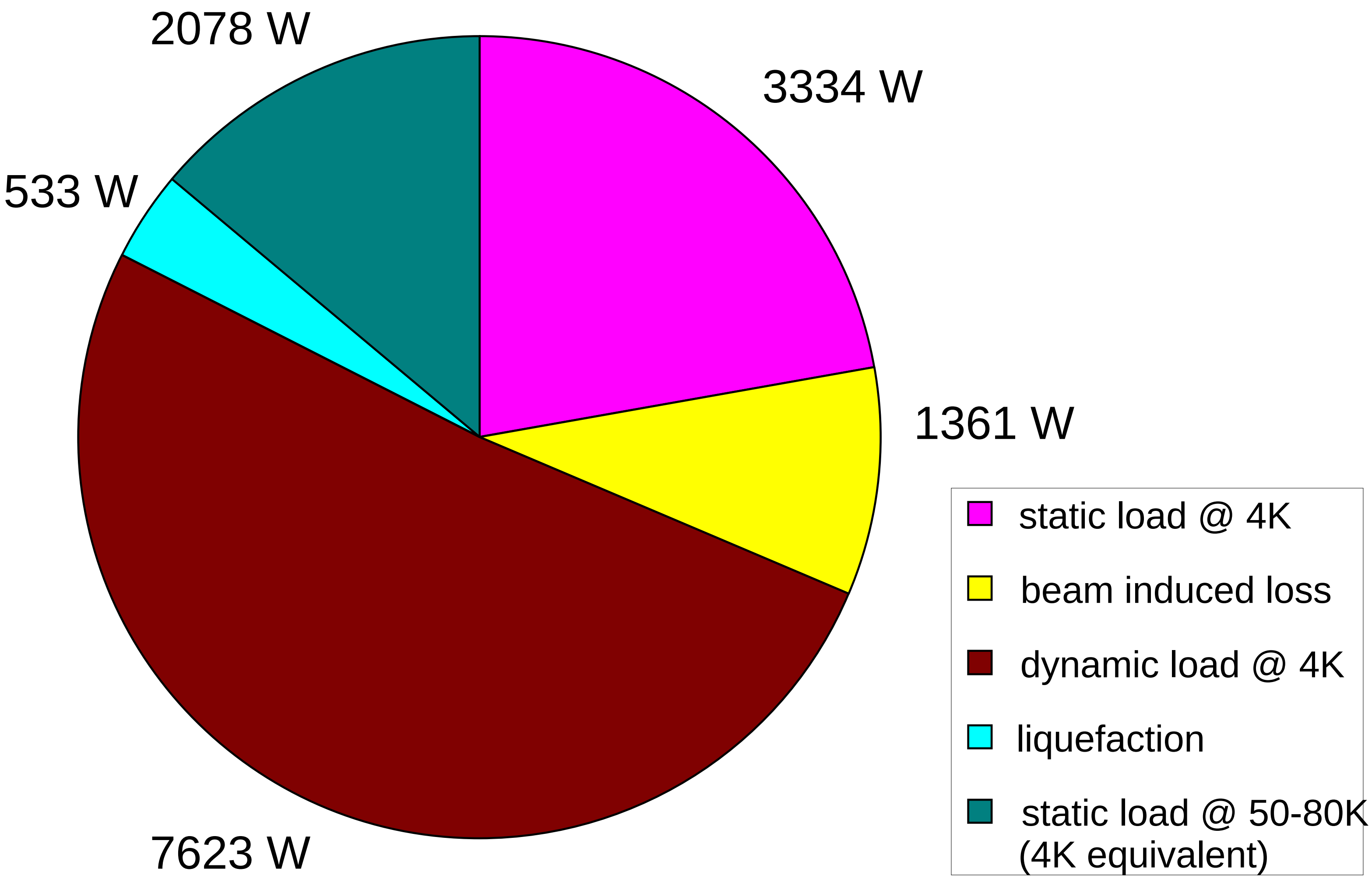
D. Kraemer, 'Current Status of the FAIR-project', THXAB02

P. Spiller, 'Status of the FAIR SIS 100/300 Synchrotrons Design', TUPAN014

Main sc magnets of the synchrotrons

	Number of Magnets	**Usable Aperture (mm)**	**Eff. Magnet Length (m)**	**Max. Field / Max.Gradient**	**Max. Ramprate**
SIS100					
Dipoles (curved, R= 52.6 m)	108	115 x 60 (gap height: 68)	3.062	1.9 T	4 T/s (0.5-1 Hz)
Quadrupoles	168	135 x 65 (pole radius: 50)	1.3	27.0T/m	57 T/m/s
SIS 300					
Dipoles (curved, R= 66.7 m)	48/12	86 (circular) (coil inner diameter: 100mm)	7.757 / 3.879	4.5 T	1 T/s
Quadrupoles	84	105 (circular) (coil inner diameter: 120)	1.0	45 T/m	10 T/m/s

Example: Cryogenic load distribution of the Synchrotrons SIS 100/200 (maximum load)



AC loss contributions (dynamic heat load)

- Magnet iron yoke (hysteresis loss)
- Structural elements (hysteresis and eddy current loss)
- Beam pipe (eddy current loss)
- Conductor (hysteresis and eddy current loss)

Main R&D Topics for rapidly-cycling magnets (Hz-range)

Eddy and persistent currents

- affect field quality
- produce large steady-state AC-losses in coil, yoke, structural elements, beam pipe

→ minimization of these effects

→ good heat removal

Mechanical structure / lifetime of the magnets

- SIS100 : 200 millions cycles within 20 years
- SIS 300: 1 million cycles within 20 years

→ minimization of movement of any part

→ R&D on material fatigue, crack propagation

Other specific R&D topics for rapidly-cycling magnets (Hz-range)

- **Iron selection**
  - search for the best compromise between high saturation flux density and low coercive force
- **Quench protection of the individual magnets of a string**
  - fast dump of the magnet string without 'bypass' (SIS 100)
  - protection of the individual magnet by cold diode bypass (SIS 300)
    - due to high charging voltage: one needs a stack of diodes (radiation sensitive)
- **Magnetic measurements**
  - harmonic analysis at high ramp rates
- **Stability of the cryogenic system against variation of the AC loads**

AC loss contributions of the conductor (persistent / eddy currents)

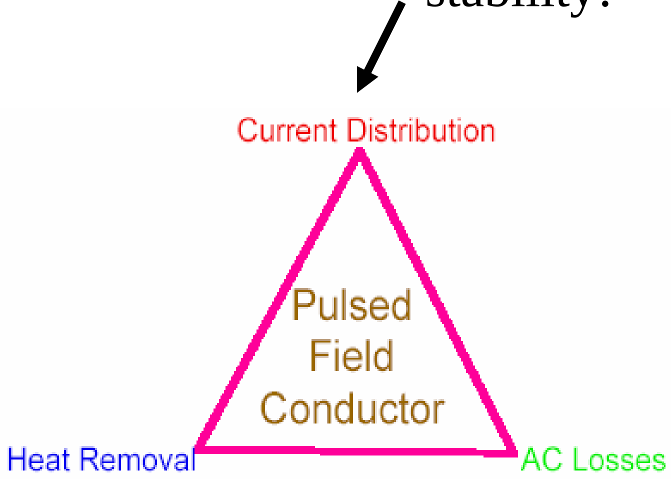
Strand

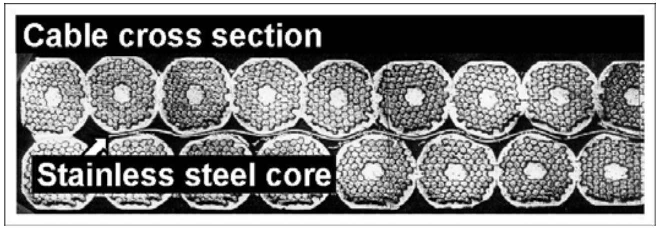
- hysteresis loss ~ filament diameter d
  - reduce filament size
- filament coupling loss ~ t_p^2/ρ_{et}
  - reduce twist pitch, increase matrix resistivity

Cable (Rutherford or similar)

- strand coupling loss due to R_a
- strand coupling loss due to R_c
  - increase R_c (cored cable) and R_a (coating)

preserve conductor stability!





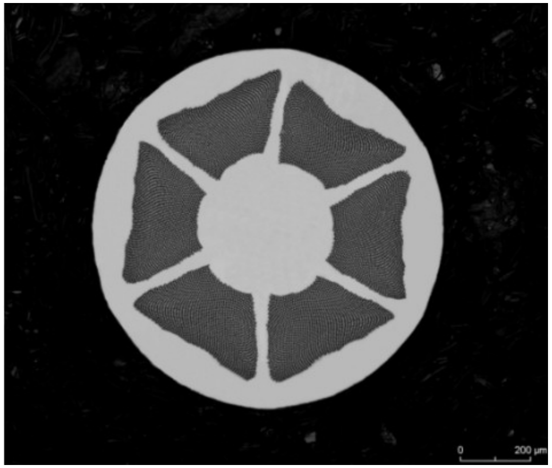
courtesy of P. Bruzzone

Low loss wire R&D (Cu-matrix)

'effective' filament size limited to 3.5 µm by

- proximity coupling
- filament distortion

'Modified' double stack method:



wire (size as for RHIC dipole)

- 0.648 mm wire diameter
- 6 x 2050 filaments
- 4 mm twist pitch
- jc = 2759 A / mm2 @ 5T, 4K
- 3.5 µm nominal filament size
- 4.1 µm measured filament size

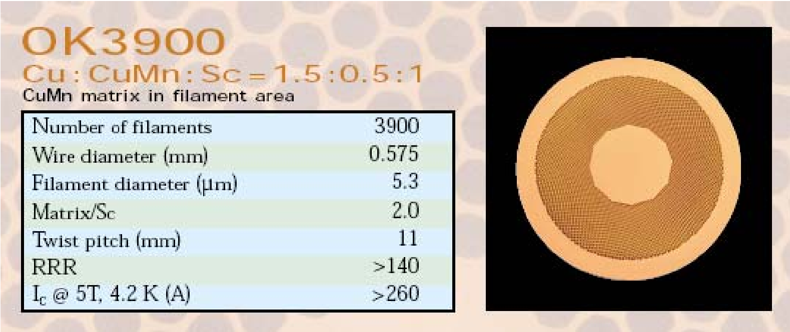
Low loss wire R&D: CuMn-matrix (INFN/ GSI)

larger wire size (0.825 mm) → larger twist pitch
→ higher filament coupling losses

to compensate:

use Cu- 0.5% Mn as interfilamentary matrix

- increases matrix resistivity by up to two orders
- in addition: allows lower filament size



OK3900

Cu : CuMn : Sc = 1.5 : 0.5 : 1

CuMn matrix in filament area

Number of filaments	3900
Wire diameter (mm)	0.575
Filament diameter (µm)	5.3
Matrix/Sc	2.0
Twist pitch (mm)	11
RRR	>140
I_c @ 5T, 4.2 K (A)	>260

courtesy of G. Volpini

R&D program with industry, based on Cu-0.5%Mn matrix, was initiated

- specification was sent to manufacturers (2.5-3.0 µm filament size)
- 'pilot' wire was delivered by Luvata, Italy
- INTAS project 8865 started

Rutherford Cable R&D

Rutherford cored cable R&D

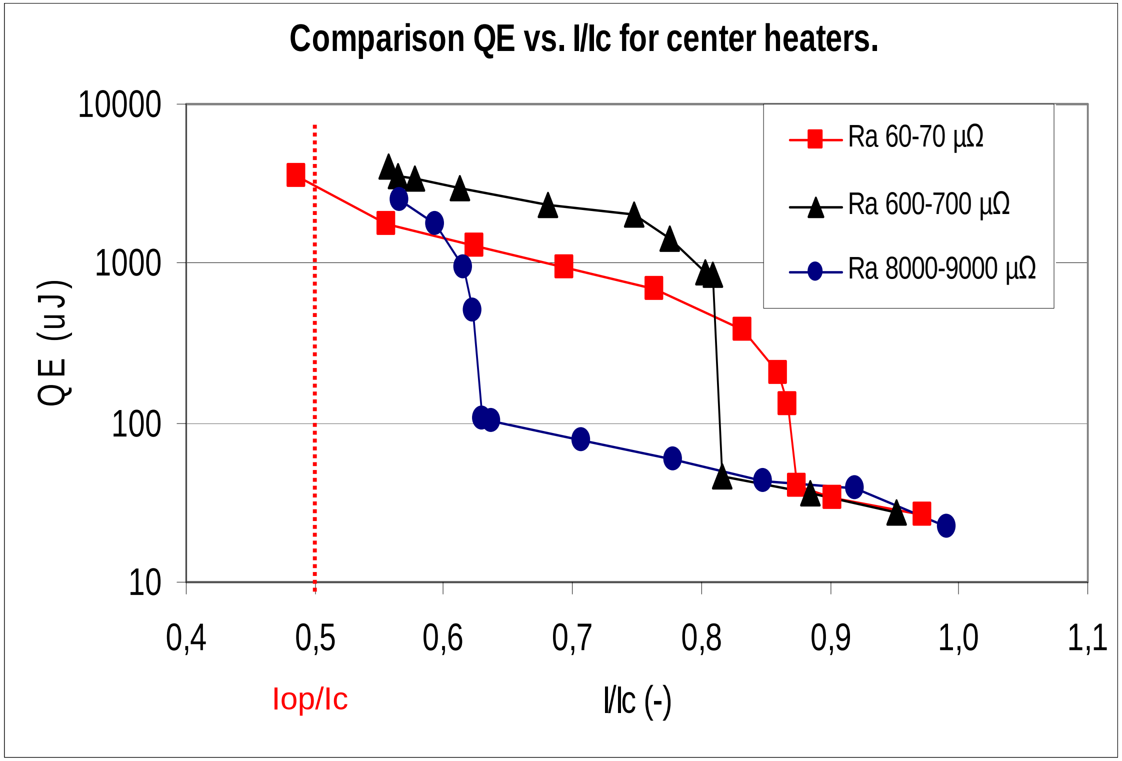
- RHIC-type cable
  - different cores (stainless steel, titanium, Cu-Ni, brass, Kapton)
  - different mandrels (hollow, slotted)
  - measurement of j_c, R_a, R_c, AC-losses
    - details in A. Ghosh, WAMS-workshop, Archamps, 2004
- LHC-type cable (dipole outer layer)
  - same program as above, recipe for R_a completed

ongoing/ planned R&D

- R_a dependence on pressure (field), coating thickness
- Reproducibility of R_a
- Heat transfer measurement in supercritical helium
- Quench Energy (QE) measurements for different Ra

QE tests of a Rutherford cable with core for different values of Ra (low, medium, high)

- 4.3 K (2-phase), external field of 6 T, inductive heater, heat deposited in one strand



Conclusions:

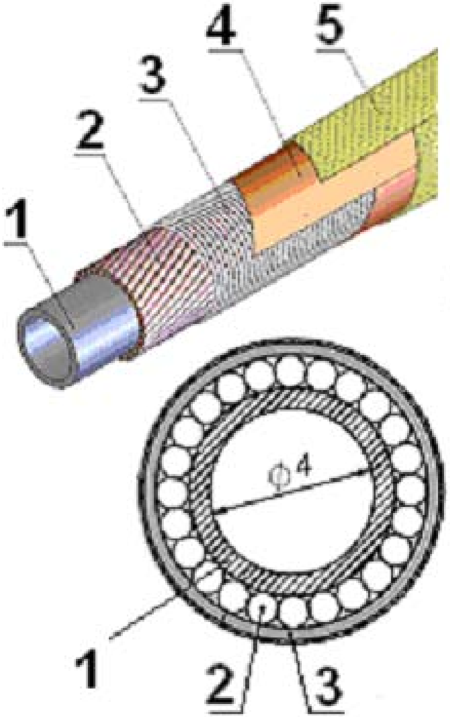
Courtesy of A. Verweij,
G. Willering

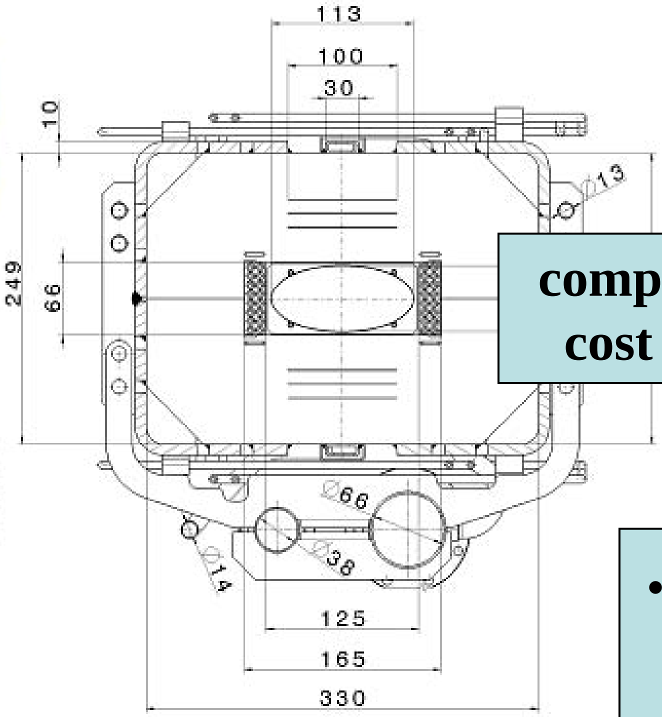
- we stay left of the knee → Ra = 200-300µOhm
- stainless steel core needed → Rc = 60 mOhm

SIS 100 superferric dipole

based on Nuclotron dipole

Collaboration: JINR (Dubna)

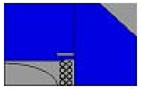


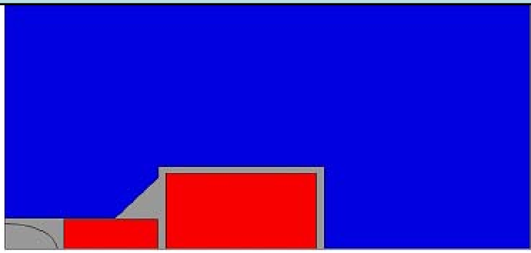


1- cooling tube, 3 - Superconducting wire, 3 - NiCr wire, 4 - Kapton tape, 5 – adhesive Kapton tape

- iron-dominated superferric design (window frame type)
- cold iron
- maximum field: 1.9 T
- ramp rate: 4 T/s

compact, low cost design





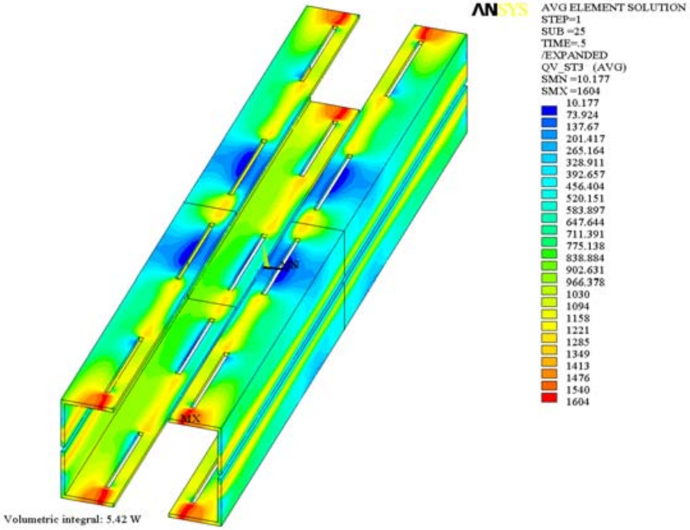
- hollow-tube superconducting cable with low hydraulic resistance
- two-phase helium cooling
- strands indirectly cooled

AC loss reduction (model magnets / FEM-calculations)

70% of the Nuclotron dipole losses are in the yoke!!!

Experimental studies on model magnets

Theoretical ANSYS calculations

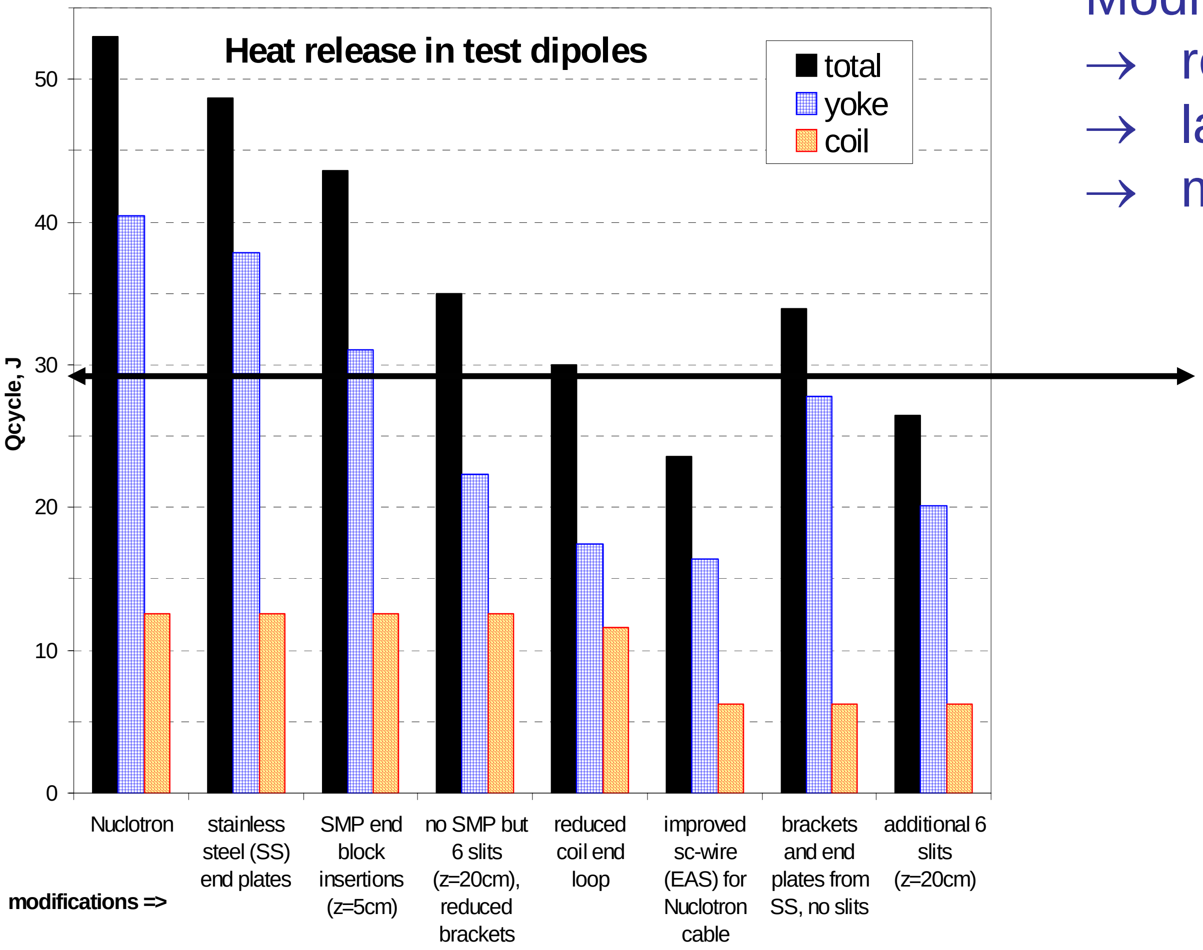


example: loss reduction by slitting the pole and reduce brackets material

example: calculation of hysteresis loss in the brackets

R & D Results: AC loss reduction @ 4 K

Loss (J) per cycle (0-2T, 4T/s), 1.4 m long test dipoles



Modifications:

→ removed brackets

→ laser cut lamination slits

→ minimized coil ends

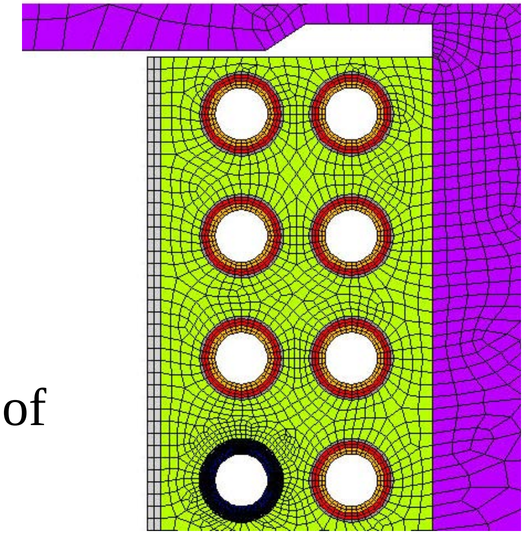
assumption for 20years operation costs comparison study:

nc version: 26M€

sc version: 2.6 M€

SIS100 dipole coil design

Coil support structure



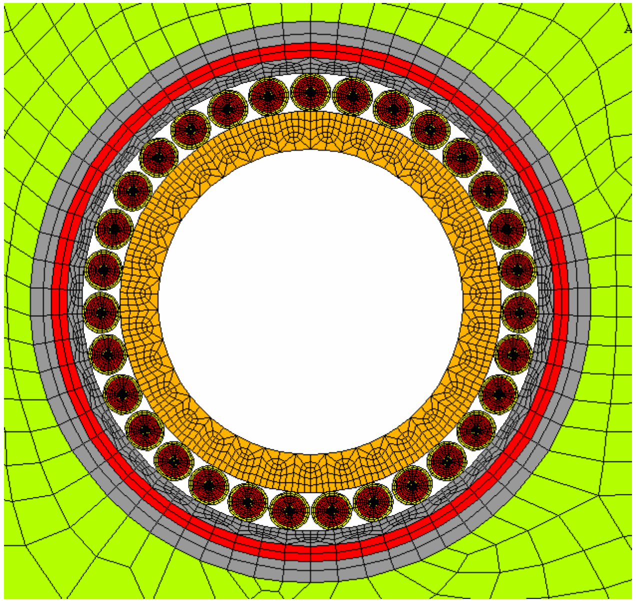
Goal:

- accurate positioning
- reduction of point load

Status:

- mockups were produced
- mechanical properties tested at 77K

Fatigue /crack propagation of the Cu-Ni- tube



detailed ANSYS model of the coil / conductor (Courtesy of E. Bobrov)

Result: tube will survive 20 years of operation!

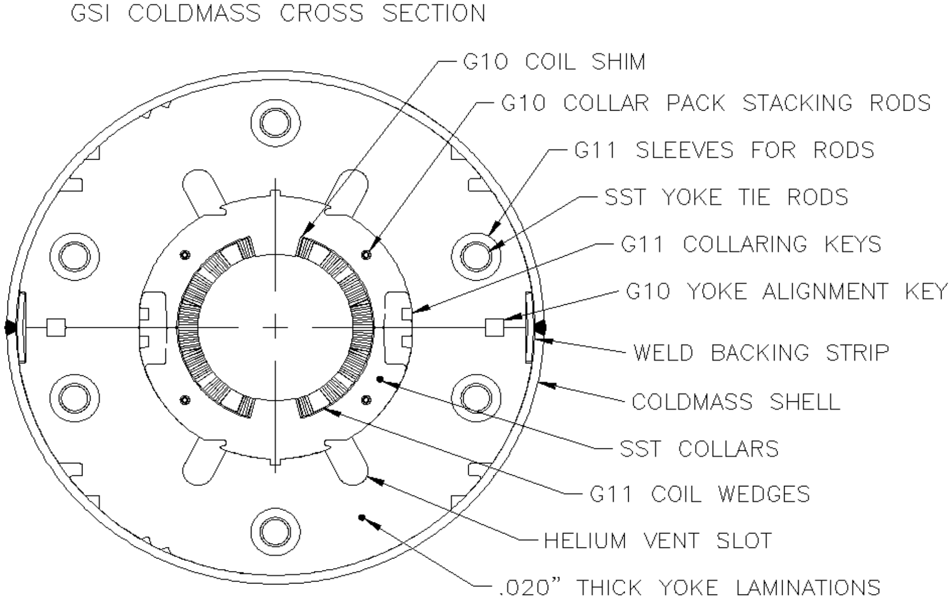
Superconducting Accelerator Magnets: SIS 200 / 300

Construction of model dipole GSI001

based on RHIC dipole

collaboration with BNL

- Coil dominated: cosθ
- Maximum field: 3.5 T ⇒ 4 T
- Ramp rate: 70 mT/s ⇒ 1 T/s !!!
- Supercond. Rutherford cable
- One-phase helium cooling



goal:

- to demonstrate the feasibility of a rapidly-cycling dipole
- to understand the mechanism (loss, AC- field quality)

Dipole Parameters

RHIC dipole

Superconducting wire:

- NbTi-Cu (1:2.25)
- filament diameter 6 μm
- twist pitch 13 mm
- no coating

Rutherford cable

- no core

Coil

- phenolic spacer
- Cu wedges

Yoke

- H_c= 145 A/m
- 6.35 mm laminations

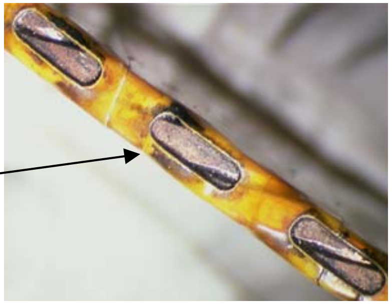
RHIC type dipole GSI 001

Superconducting wire:

- NbTi-Cu (1:2.25)
- filament diameter 6 μm
- twist pitch 4 mm
- Stabrite coating

Rutherford cable

- stainless steel core
- open insulation



Coil

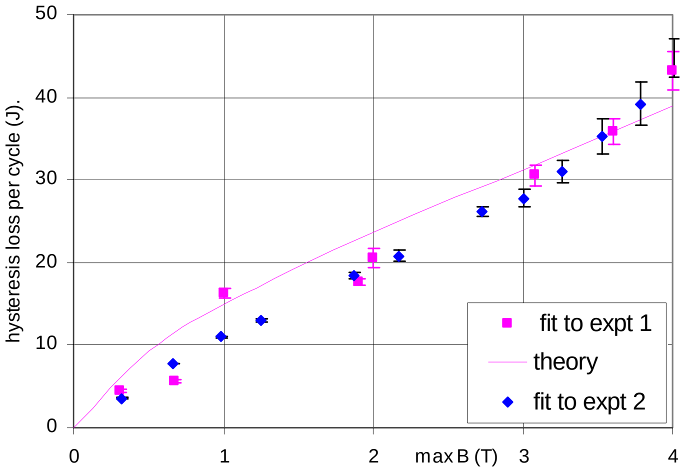
- stainless steel collar
- G11 wedges

Yoke

- H_c= 33 A/m, 3.5% Silicon
- 0.5 mm laminations, glued

red: loss reduction, blue: improved cooling, green: increase mechanical stability

Losses of GSI001 measured (electric method) in vertical bath at BNL, calculated by M.N. Wilson



Hysteresis part (including iron and transport current contribution)

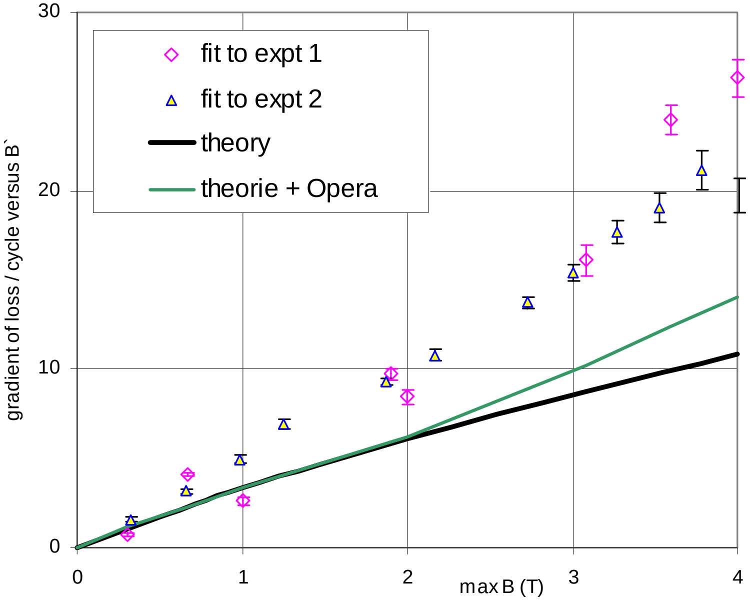
measured (short samples) parameters used for calculation:

$\rho_{et}(B) = 1.24\times10^{-10} + 0.9\times10^{-10}\,B$ with ρ_{et} in Ωm and B in Tesla.

$R_c = 62.5\ \mathrm{m}\Omega$

$R_a = 64\ \mu\Omega$

Coil loss	[%]
Transverse crossover loss (R_c)	0.2
Transverse adjacent loss (R_a)	12.0
Parallel loss (R_a)	0.2
Filament coupling loss (Cu-matrix)	11.9
Hysteresis loss (d_{fil} = 6 μm)	69.7

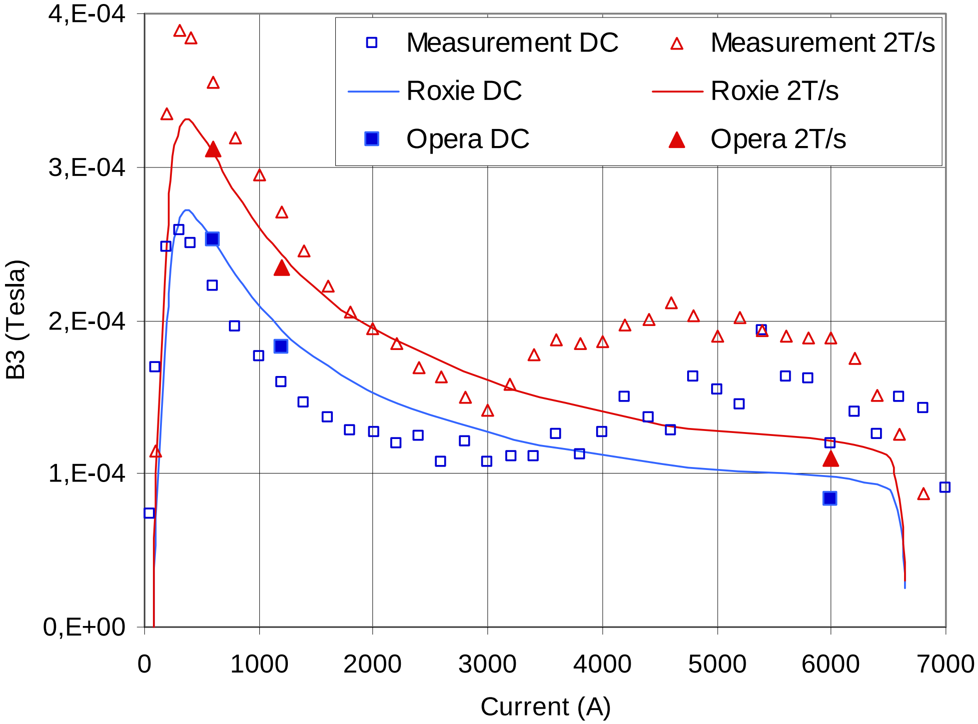


Eddy current part

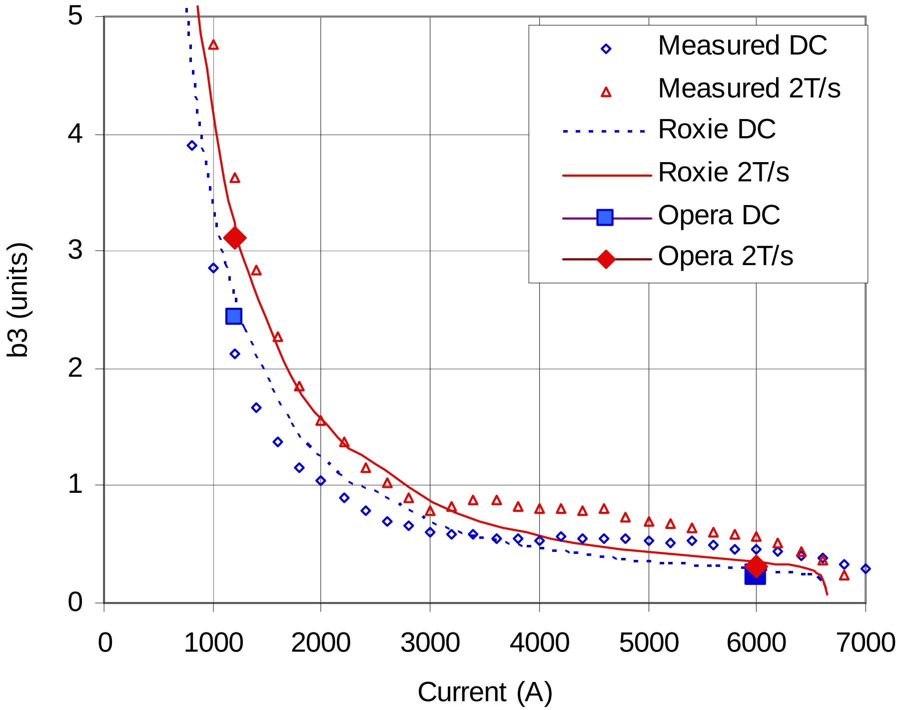
2D Field Quality: B3 and b3

sextupole B3 / b3 (half difference between up and down)

in Tesla @ 25 mm radius



in units @ 25 mm radius (1 unit= 10^{-4})



- both codes (Opera and Roxie) agree well, with the experiment
- < 4 units at stretcher mode injection,
- < 1 unit at pulsed mode injection (1 T/s)

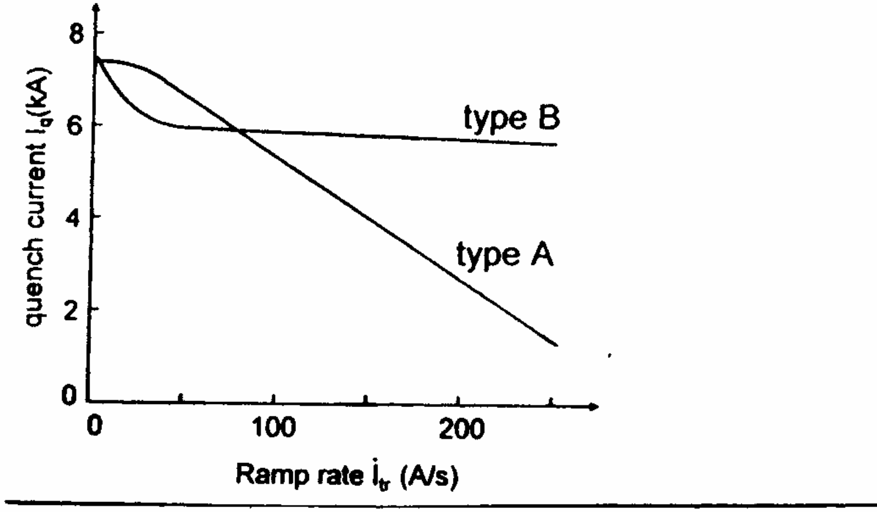
stretcher mode injection

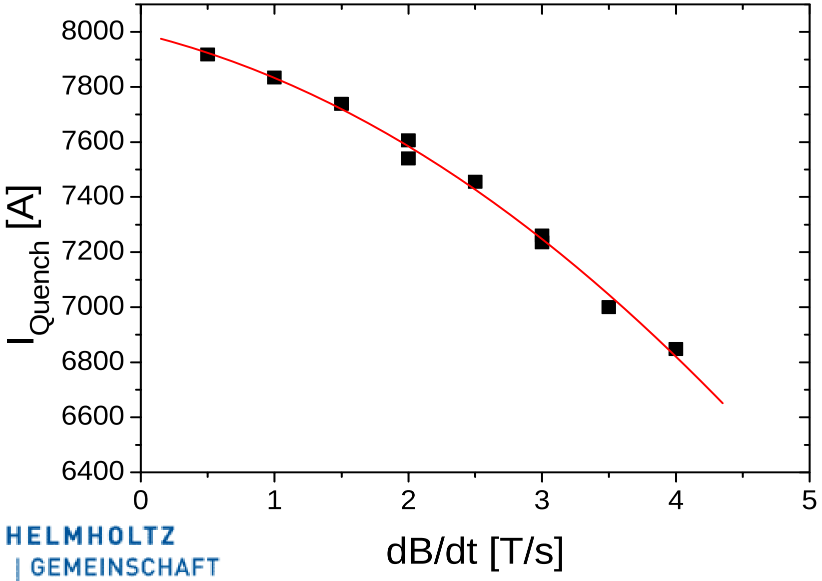
pulsed mode injection

courtesy of M. Wilson, B. Auchmann, S. Russenschuck

Quench current Ramp Rate Limitation (RRL)

- type 'A' behavior: quench current reduced by AC- conductor heating
- type 'B' behavior: quench current reduced due to unequal current distribution between strands- unwanted!





Conclusion: type 'A', but small degradation only in the region of interest due to moderate AC-heating and good cooling; small Ra allows current redistribution.

Additional tests at GSI test facility (supercritical helium)

- continuous ramping (0-4T, 1 T/s) for more than 36 hours
- electrical (V-I-method) and calorimetric measurement of the losses, upper and lower coil half separately (data to be evaluated)

Summary of test results GSI 001

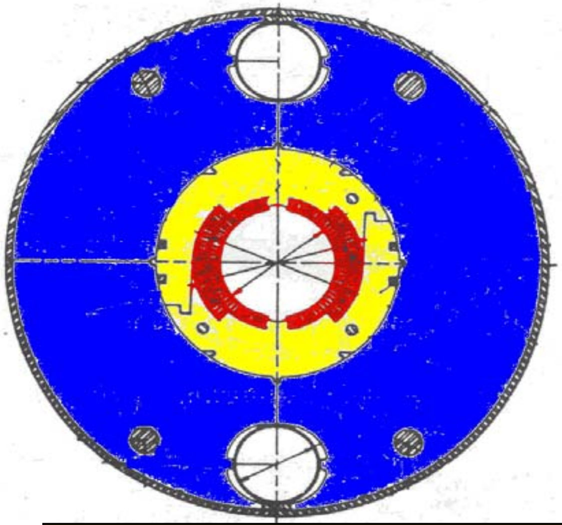
Purpose of this work was to investigate the influence of persistent and coupling currents on

- quench behavior
- cryogenic losses
- field quality

Conclusions:

- **magnet looks suitable for the use in a synchrotron**
- **quench behavior is dominated by Joule heating**
- **cryogenic losses are tolerable**
- **"AC" field quality (allowed harmonics) is mostly predictable and acceptable**

SIS 300 – Dipole (6T, straight)



based on UNK Dipole
Collaboration with IHEP, Protvino

- 2 layer cos θ design
- 80 mm coil ID ⇒ 100 mm
- 5.11 T ⇒ 6 T
- 0.11 T/s ⇒ 1 T/s

Conceptual Design Study by IHEP (6/2004)

Main parameter / results:

- cooling: one phase Helium 4.4 K, internal recooling
- AC temperature margin: 1.0 K
- collared coil supported by iron shell (taking part of the load)
- Rutherford-cable: 36 strands with core (LHC outer layer)
- quench protection: needs heater
- besides: same design principles as GSI001

Technical Design Study by IHEP / CERN (3/2006)

Status:

- Technical design finished
- Tooling design / production started
- Winding of model coil in preparation
- Construction and testing of 1 m model dipole in 2007/2008

SIS 300: larger acceptance needed → curved long dipole

bending radius	66.6 m
coil inner diameter	100 mm
eff. length	7.757 m
central field	4.5 T

Study on mechanical feasibility/ costs by

- GSI / BNG
- INFN / ASG

- technically feasible
- production costs comparable with straight version

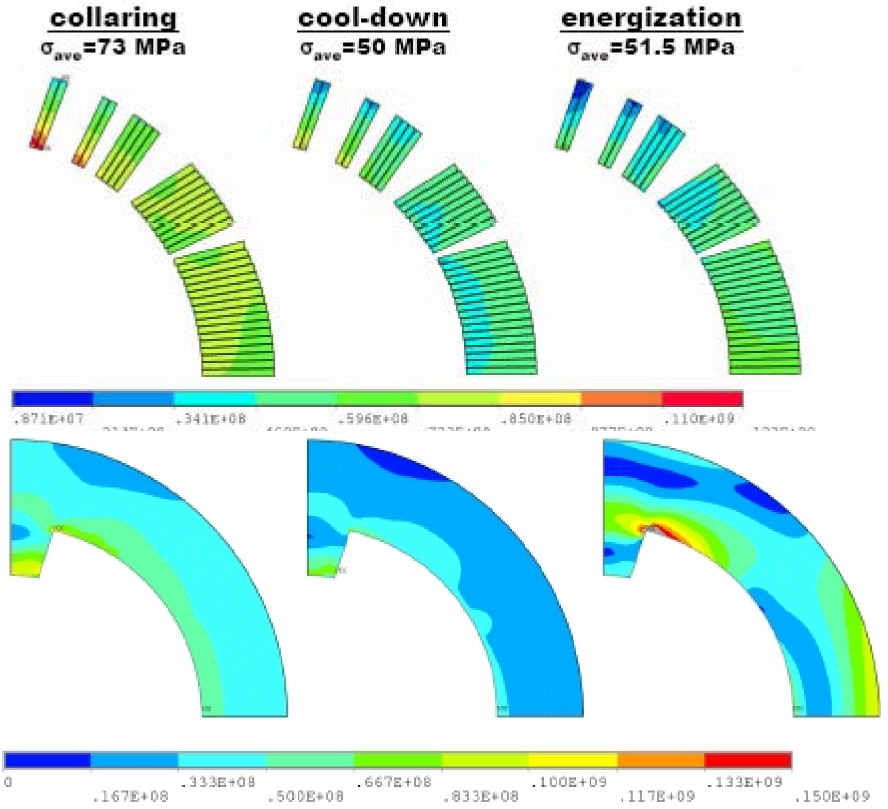
pros	cons
same bore diameter, but higher acceptance due to sagitta	curved winding, ...
costs comparable (7.8 m, one layer coil !)	2 versions: long and short
less magnets → reduced costs for assembly, cold tests	cryostats more complicated
6T ⟶ 4.5 T: lower forces, stresses: free standing collar	MM more complicated
6T ⟶ 4.5 T: reduced stored energy	

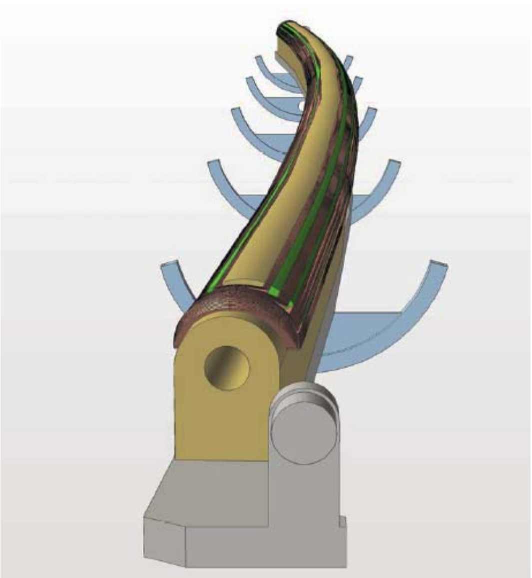
Preliminary design (INFN)

Project: DISCO_RAP (Dipoli SuperCOnduttori RApidamente Pulsati)

- same design principles as GSI001 and 6T dipole
- LHC outer layer cable with stainless steel core
- wire based on Cu-Mn-matrix

Number of turns	34
Peak field/Central field	1.09
Current	8924 A
Collar thickness	30 mm
AC losses in the windings for a closed cycle 1.5T-4.5 T at 1T/s	20.7 J/m





magnet ready for testing in 2009 !

courtesy of P. Fabbricatore / S. Farinon

Summary

SIS 100

- Cryogenic losses reduced, coil structure improved, full length dipoles under construction

SIS 300

- RHIC type model dipole GSI001 tested and behavior understood
- Technical design of 6 T model finished, tooling and magnet production on its way.
- Feasibility of curved long 4.5 T dipole investigated, design of long magnet has started.

Conductor

- wire: Cu matrix, 4.1 µm filament size reached
    - goal: Cu-Mn-matrix, 2.5 -3.0 µm filament size
- cable: cored cable produced, 'recipe' for chosen Ra=200µOhm known, R&D on reproducibility

Acknowledgements

I am greatly indebted to all colleagues of the collaborations with BNL, IHEP, INFN, JINR, to our consultants, to helpful colleagues in many other laboratories and to the members of the GSI magnet group for their dedicated work.