Fast -Pulsed Superconducting Magnets

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EPAC04, Lucerne

July 5 – 9, 2004

Outline

- Introduction to the planned facility 'FAIR'
- Main R&D topics
- Fast-pulsed superconducting magnets for the synchrotrons of FAIR
- Related R&D activities
- Conclusions

International Facility for Beams of Ions and Antiprotons (FAIR)

W. Henning, TUXCH02, this conf.

SIS100 (Synchrotron 100 Tm):

- „work horse“
- accelerates heavy ions/protons
- fast extraction to SIS 300 or RIB/Antiproton targets

SIS300 (Synchrotron 300 Tm):

- stretcher ring
- accelerates heavy ions to high energies
- slow extraction

SuperFRS (Fragment Separator):

- analyses and separates secondary beams

CR/RESR (Collector Ring complex):

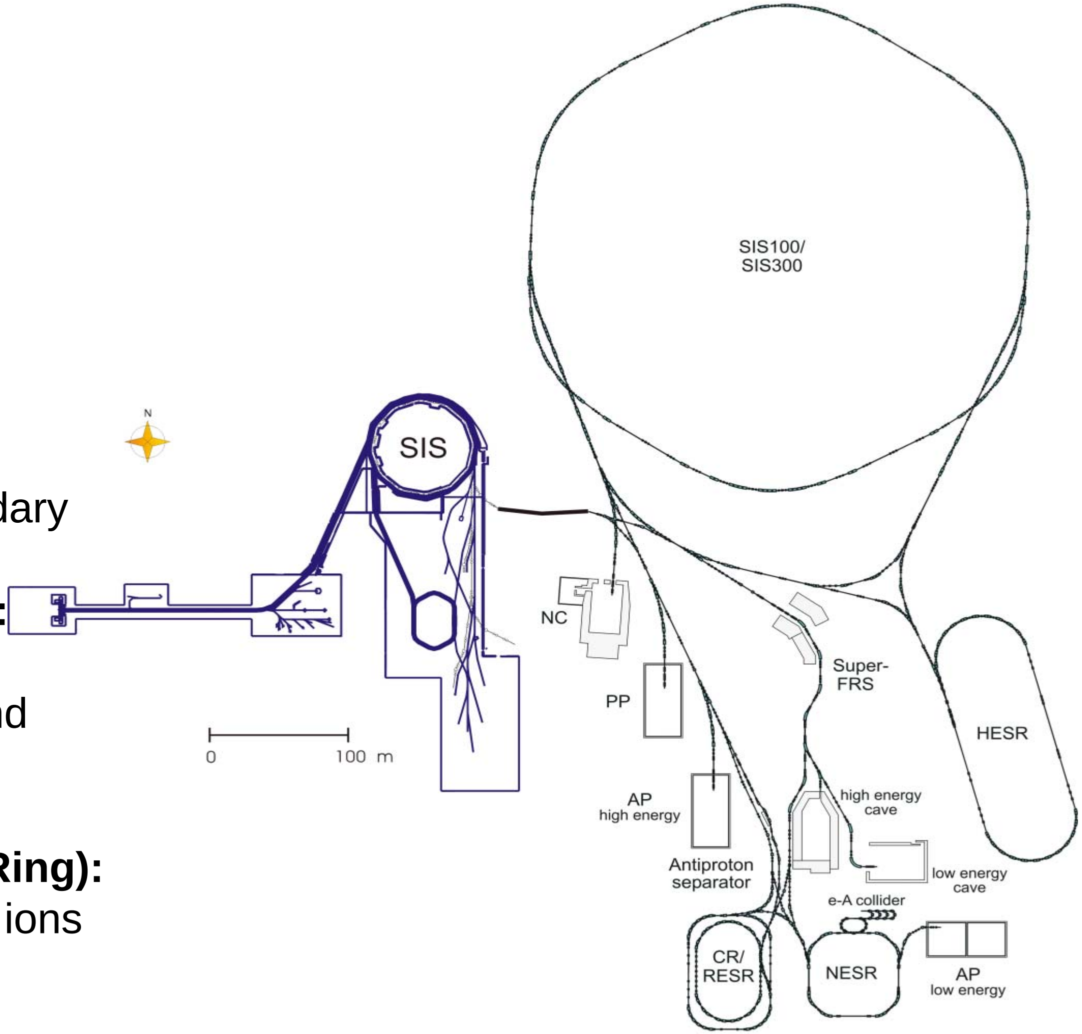
- collects secondary beams
- stochastic precooling of ions and antiprotons
- accumulation of antiprotons

NESR (New Experimental Storage Ring):

- electron cooling and storage of ions
- in-beam experiments with RIB

HESR (High Energy Storage Ring):

- experiments with antiprotons



Key parameters synchrotrons

Gain Factors of FAIR

- Primary beam intensity: factor 100 – 1000
- Secondary beam intensities for radioactive nuclei: up to factor 10000
- Beam energy: Factor 15

Ring	Bending power (Tm)	Circum-ference (m)	Reference energy	Operation modes
SIS 100	100	1080	1.5 GeV/u U^{28+} 29 GeV protons	• acceleration mode: continuous triangular cycle with 1 sec injection time, cycle length 1-2 s
SIS 300	300	1080	34 GeV/u U^{92+} 1 GeV/u U^{28+}	• acceleration mode: continuous triangular cycle with 50% duty cycle, cycle length: 18 s • stretcher mode: DC operated

Magnets for the synchrotrons

	Number of Magnets	Aperture (mm)	Magnet Length (m)	Max. Field / Max.Gradient	Max. Ramprate
SIS100					
Dipoles	120	130 x 65	2.6	2 T	4 T/s
Quadru-poles	162	120 x 63 (pole radius: 40)	0.6 1.0 0.6	34.2 T/m 36.7 T/m 34.2 T/m	73.4 T/m/s
SIS 300					
Dipoles	120	100 (circular)	2.6	6 T	1 T/s
Quadru-poles	132	100 (circular)	0.6 1.0	93 T/m 89 T/m	15.5 T/m/s 14.8 T/m/s

Main R&D Topics for fast-pulsed magnets

Minimization of eddy current and persistent current effects

- affect field quality
  - ➡ correction system
- produce large steady-state AC-losses
  - ➡ appropriate magnet cooling system

Cryogenic system

- heat load is dominated by AC-losses
- heat load varies with cycles

Mechanical structure / lifetime of the magnets

- SIS100 : 200 millions cycles within 20 years
  - ➡ material fatigue, crack propagation

Cryogenic stability

- conservative stability margins

Main R&D Topics for fast-pulsed magnets (continued)

Quench protection of the individual magnets

- high charging voltage

  ⇒ stack of diodes or 'warm bypass'

Iron selection

- search for the best compromise between high saturation flux density and low coercive force / high specific resistivity

(I. Bogdanov, WEPKF061)

Radiation deposition due to primary beam loss affects (in the high intensity synchrotrons)

- heat load of the cryogenic system
- lifetime of components (coil insulation, diodes)
- quench stability

(E. Mustafin, TUPLT112)

R&D policy

- look for existing magnets with similar parameters
- establish collaborations
- start R&D for dipoles, transferring results to quadrupoles...
- build model magnets with existing material and tooling

$\Rightarrow$ saves time and money

Collaborations 2004

SIS 200/300: cosθ magnet

IHEP (RU) 6/2002
BNL (US) 1/2001
Twente University (NL)
Jena University (D)
LBNL (US)
CEA (F)
CERN (CH)
EAS (D)

SIS 100: window-frame magnet

JINR (RU) 2/2000
LBNL (US)
Bochvar Institute (RU)
BINP (RU) 6/2002
Kurchatov Institute (RU)
VNIIKP (RU)
BNN (D)
Accel (D)

Large Aperture Magnets (Storage Rings, SFRS, R3B)

NSCL/MSU (US) 1/2002
CEA (F)

Scientific Coordination
Magnet and Cryogenic Design
Magnet Test Facility
GSI

Magnet Design Software

CERN (CH)
TU Darmstadt (D)

Cryogenics

TU Dresden (D)
ACT Inc. (US)

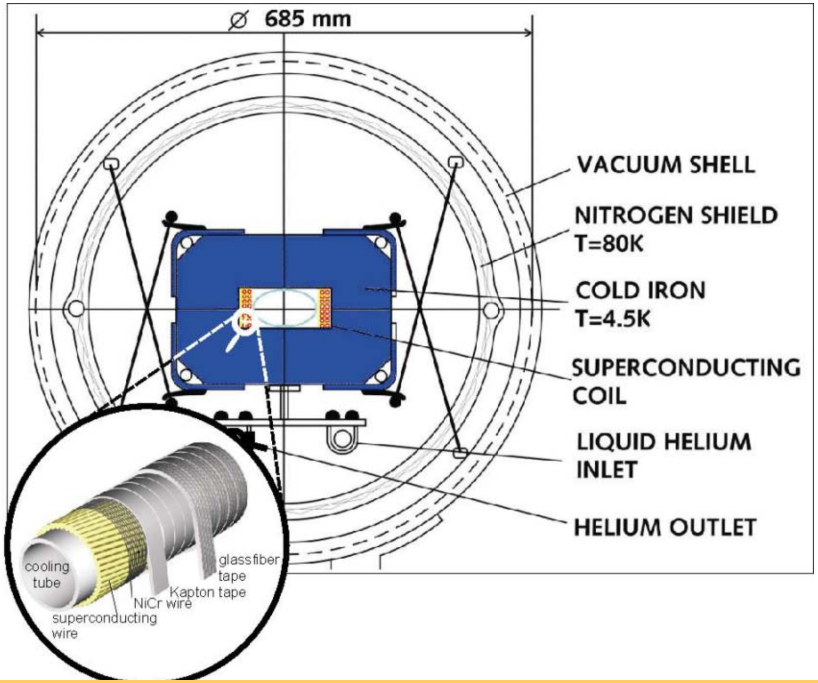
Consulting

CERN (CH) 8/2002
FZ Karlsruhe (D)
DESY (D)
M.N. Wilson (GB)
B. Hassenzahl (US)

Quench Protection

CERN (CH)
Dynex (GB)

Superconducting Magnets for SIS 100

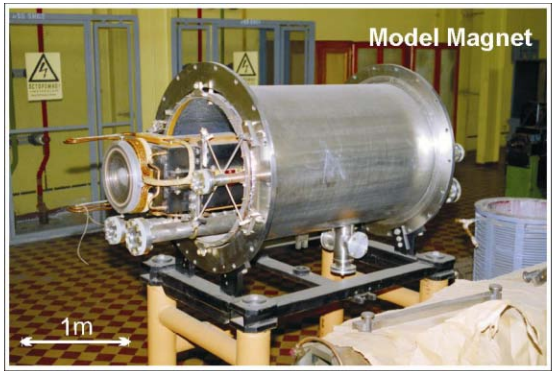


R&D goals

- **Improvement of DC-field quality**
  - 2D / 3D calculations
- **Guarantee of long term mechanical stability** ($\geq 2 \cdot 10^8$ cycles)
  - concern: coil restraint in the gap, fatigue of the conductor
- **Reduction of eddy / persistent current effects (field, losses)**

Nuclotron Dipole

- Collaboration: JINR (Dubna)
- Iron Dominated (window frame type) superferric design
- Maximum magnetic field: 2 T
- Ramp rate: 4 T/s
- Hollow-tube superconducting cable, indirectly cooled
- Two-phase helium cooling

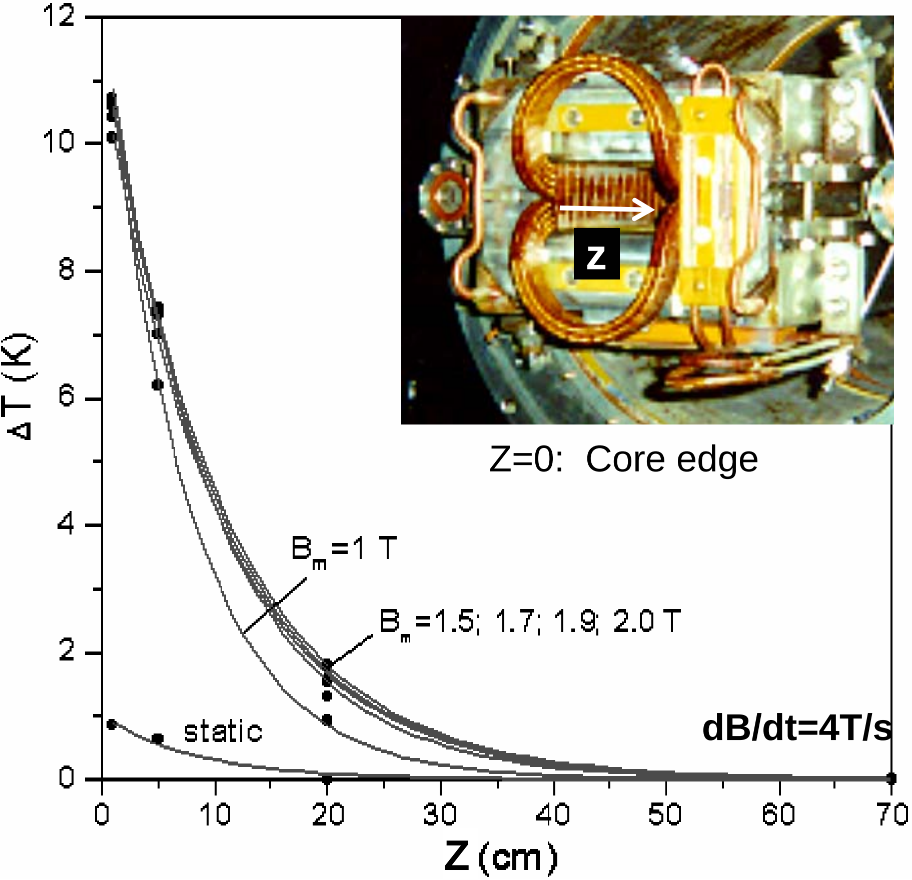


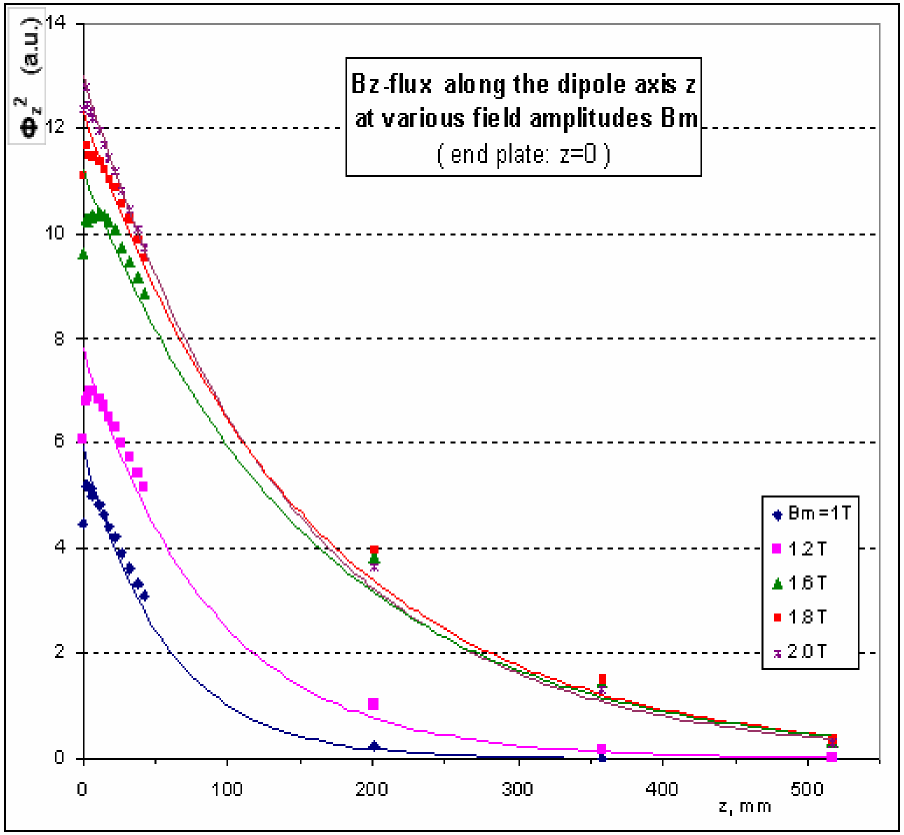
Nuclotron-type Dipole – AC Losses

AC heat load to Helium (4K) triangular cycle: 0-2T, 4 T/s, 1 Hz	Nuclotron-Dipole (1.4 m)	planned prototype (2.6 m)
Total (W/m)	38	
Yoke (W/m)	29	
Coil (W/m)	9	

- **Coil (30%):**
  - main contribution: wire magnetization (74%)
    ⇒ reduction of filament size to 3.5 µm
- **Yoke (70%):**
  - magnetization losses in the central core
  - eddy current losses
    - in structural elements of the central core
    - in the endparts due to longitudinal field components B_z

AC Losses along Magnet axis z

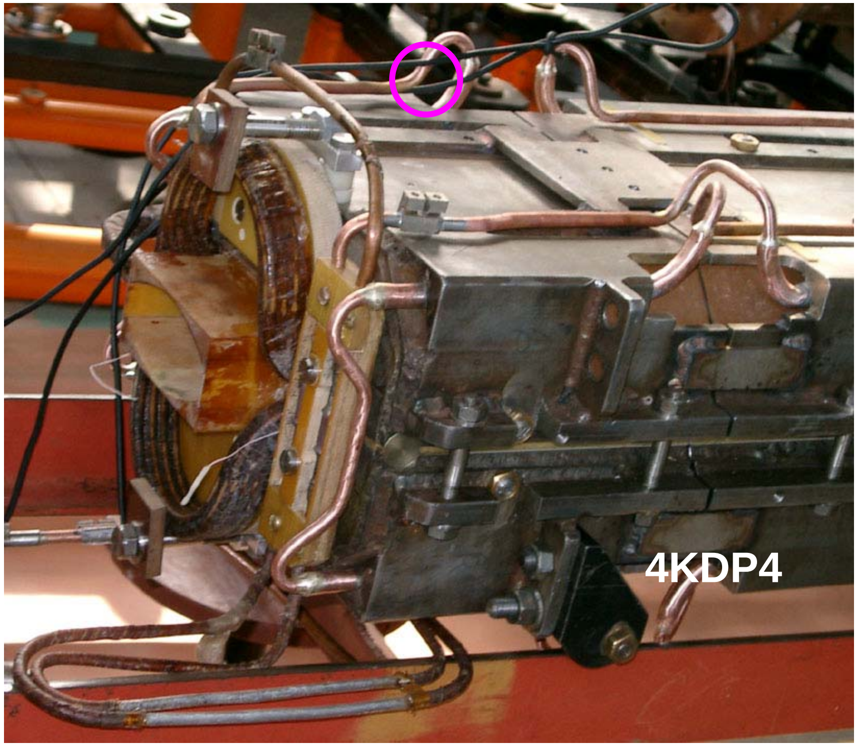


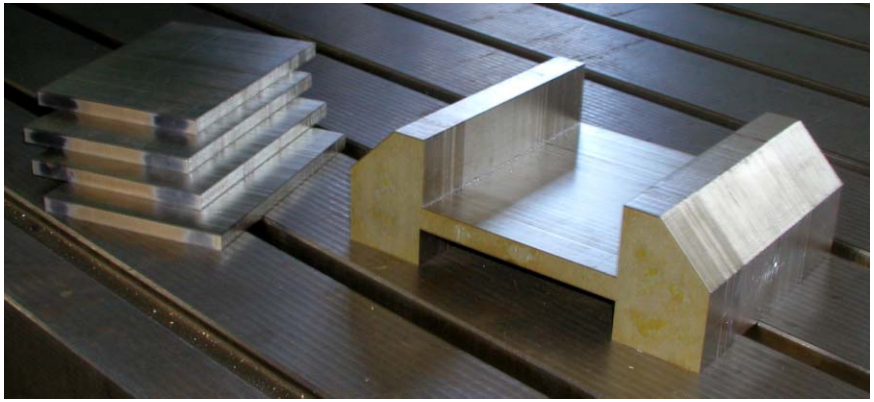


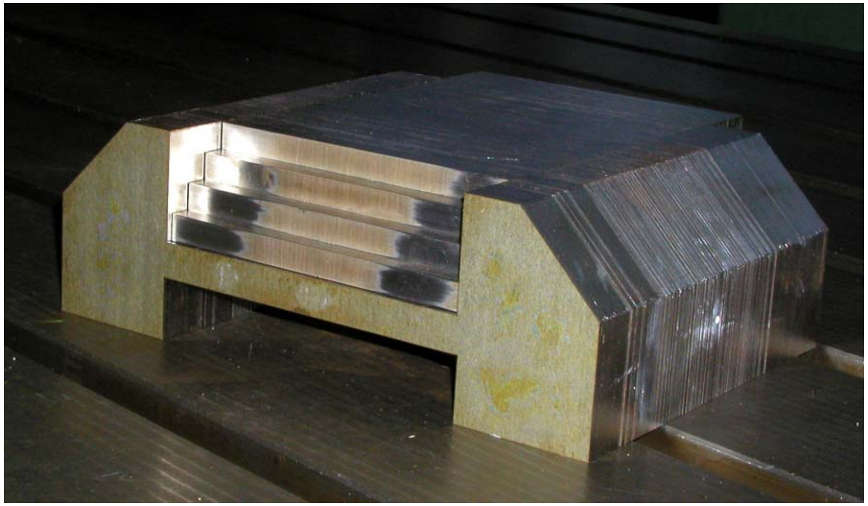
- **Temperature rise in the end part !**

- **OPERA-3D calculations of the integral magnetic flux Φ (z)**

New end blocks







- New 200mm end block

Nuclotron-type Dipole – AC Losses

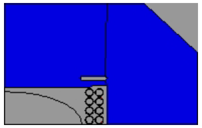
R&D- results

(A. Kovalenko,WEPKF057)

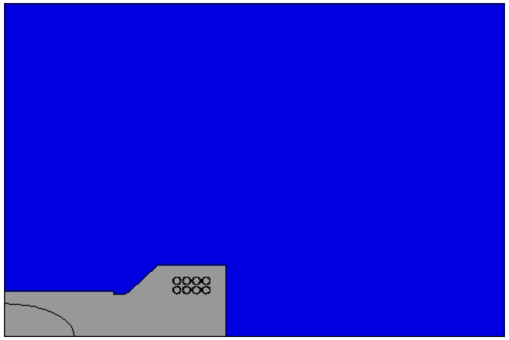
AC heat load to Helium (4K) triangular cycle: 0-2T, 4 T/s, 1 Hz	Nuclotron-Dipole (1.4 m)	planned prototype (2.6 m)
Total (W/m)	38	15
Yoke (W/m)	29	9
Coil (W/m)	9	6

SIS 100 Dipole - Alternatives

Nuclotron Superferric Window-frame Dipole
(cold iron, cold bore, ⇒ cryogenic pumping)



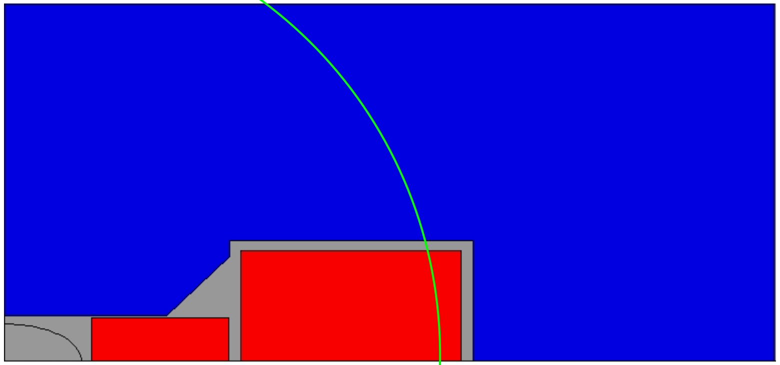
Superferric H-type design
(warm iron, warm bore)



Study at BINP, Russia

Max. Field:	2 T
Max. Ramp Rate:	4 T/s
Field quality:	$\pm 6 \times 10^{-4}$
Aperture:	$110 \times 55 mm^2$

Resistive



Comparison sc and nc 100 Tm dipole

COSTS (M€)	sc	nc
PRODUCTION	36	37
OPERATING	8	45
TOTAL	**44**	**82**

based on:

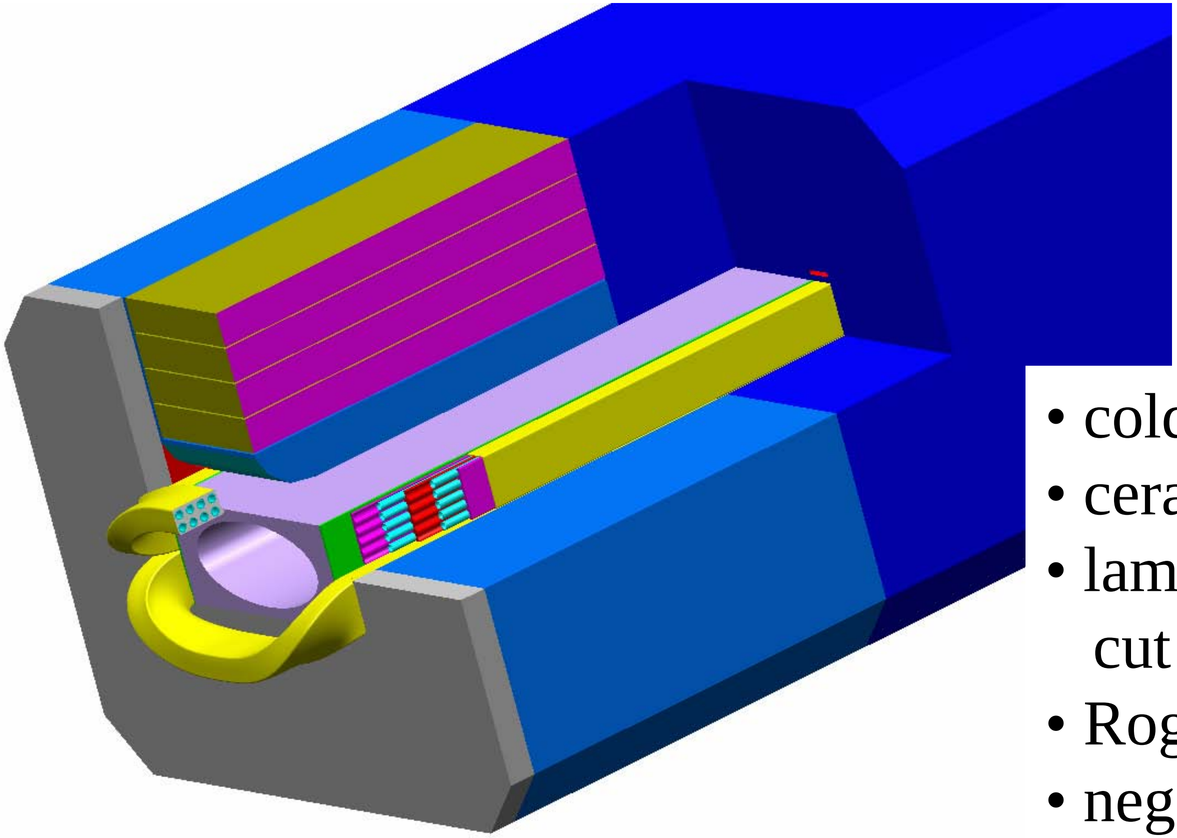
- 248 dipoles (SIS 100 and beamlines)
- 20 years of operation, 6500 h/ y
- present status of the R&D
- aperture (55 mm x 110 mm)
- operation cycles mix
- present electricity costs

includes costs for

- power supplies, quench detection and protection
- cryogenic system
- tests and operation crew

→saves 17 000 t CO_2 / year

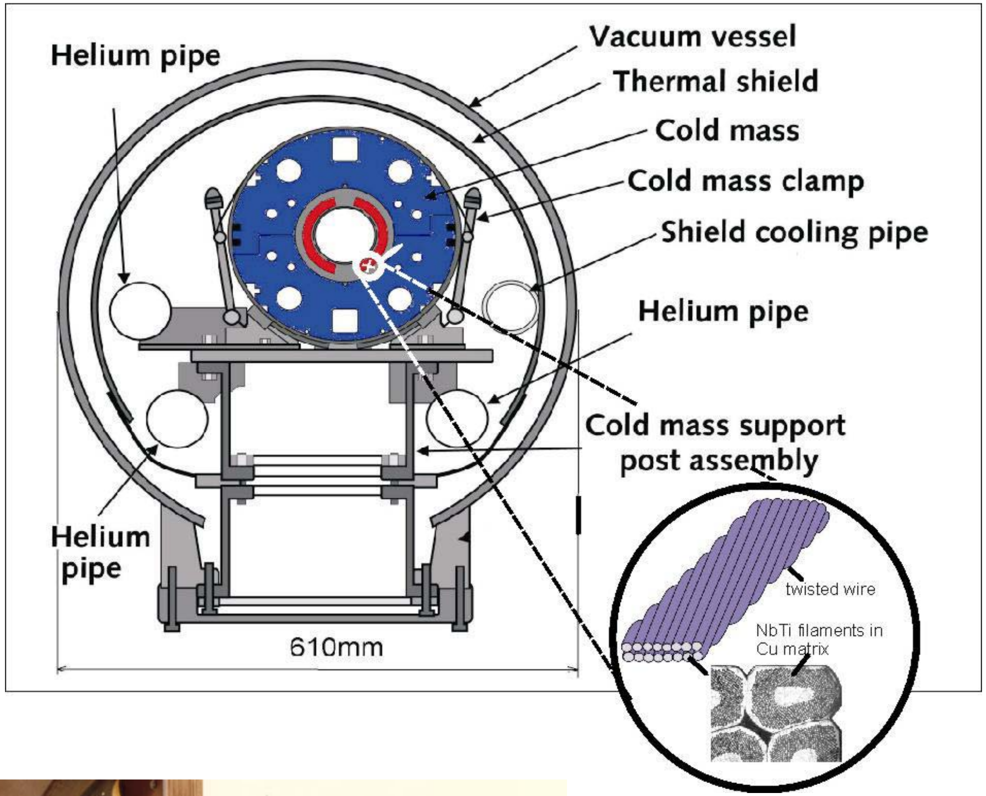
Vision of the final magnet

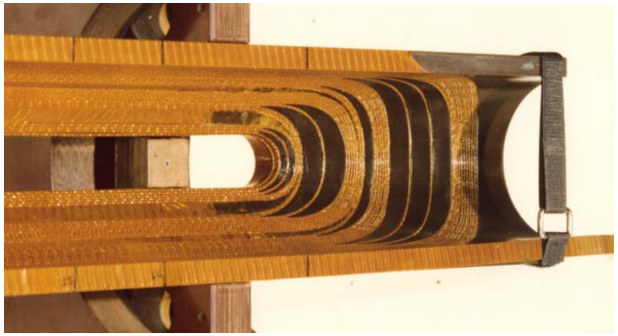


- cold mass: coil + yoke
- ceramic aperture spacer
- laminated and horizontally cut endblocks
- Rogowski end profile
- negative shimming
- homogenisation slits
- more rigid coil structure
- coil ends restrained
- stainless Steel end plates

Superconducting Accelerator Magnets: SIS 200 / 300

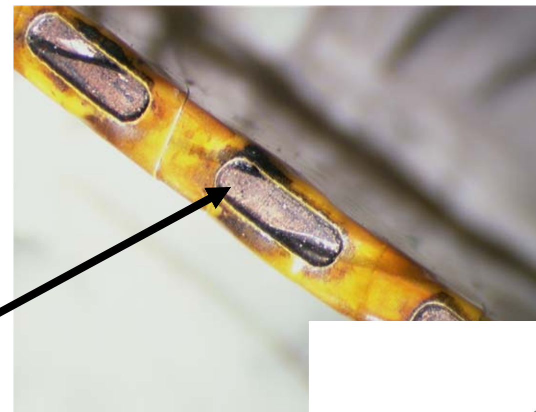
- RHIC dipole
- Collaboration with BNL
- Coil dominated: cosθ
- Maximum field: 3.5 T $\Rightarrow$ 4 T
- Ramp rate: 70 mT/s $\Rightarrow$ 1 T/s !!!
- Supercond. Rutherford cable
- One-phase helium cooling

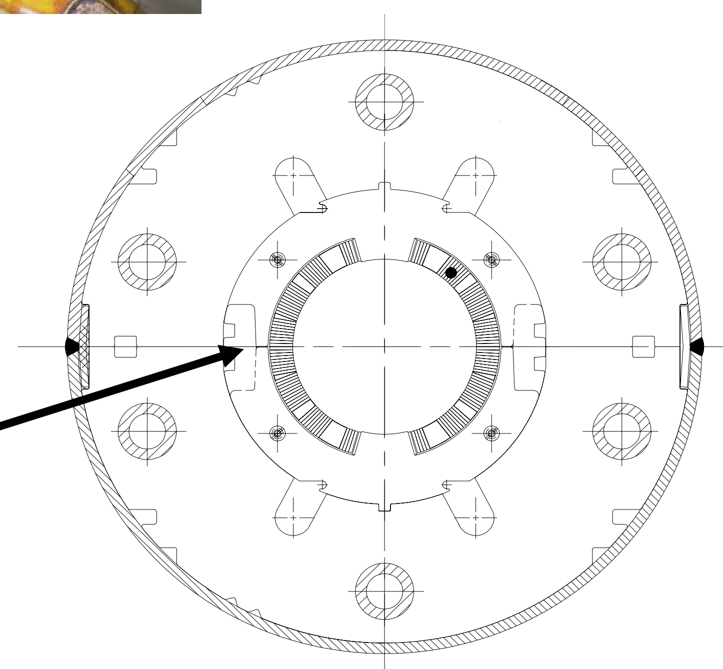




R&D Goals for RHIC type dipole

- Reduce the effects due to the high ramp rate:
  - lower loss in wire, cable and iron
  - better AC field quality
- Improve the cooling of the Rutherford cable
  - open Kapton insulation with laser cut holes
- Use collars to ensure long-term mechanical stability





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

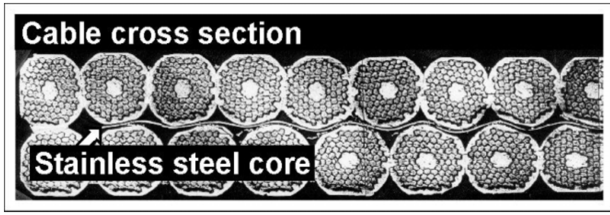
RHIC type dipole GSI 001

Superconducting wire:

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

Rutherford cable

- 2 x 25μm stainless steel core



Coil

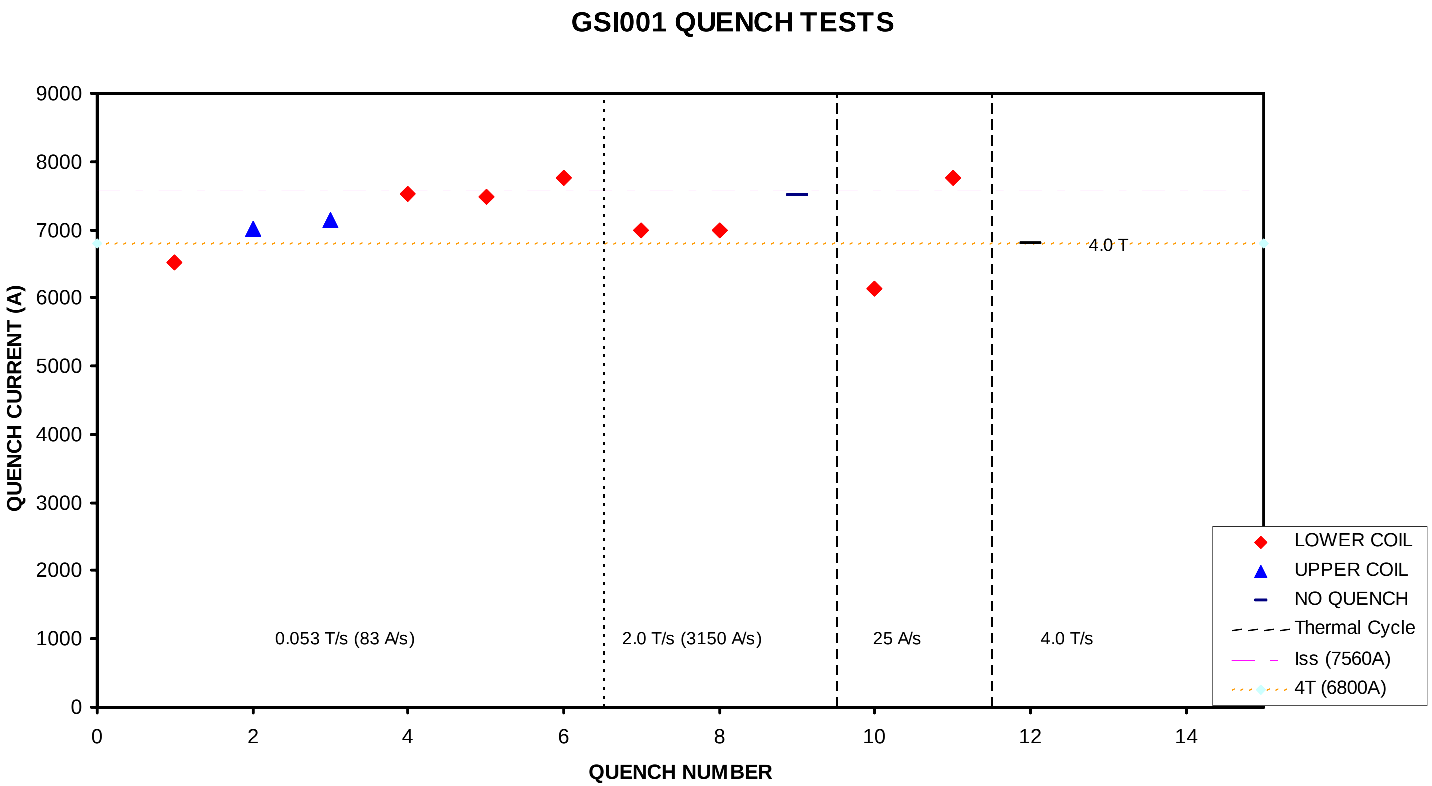
- stainless steel collar (G11 keys)
- G11 wedges

Yoke

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

RAMP RATE TESTS GSI001 (vertical bath)

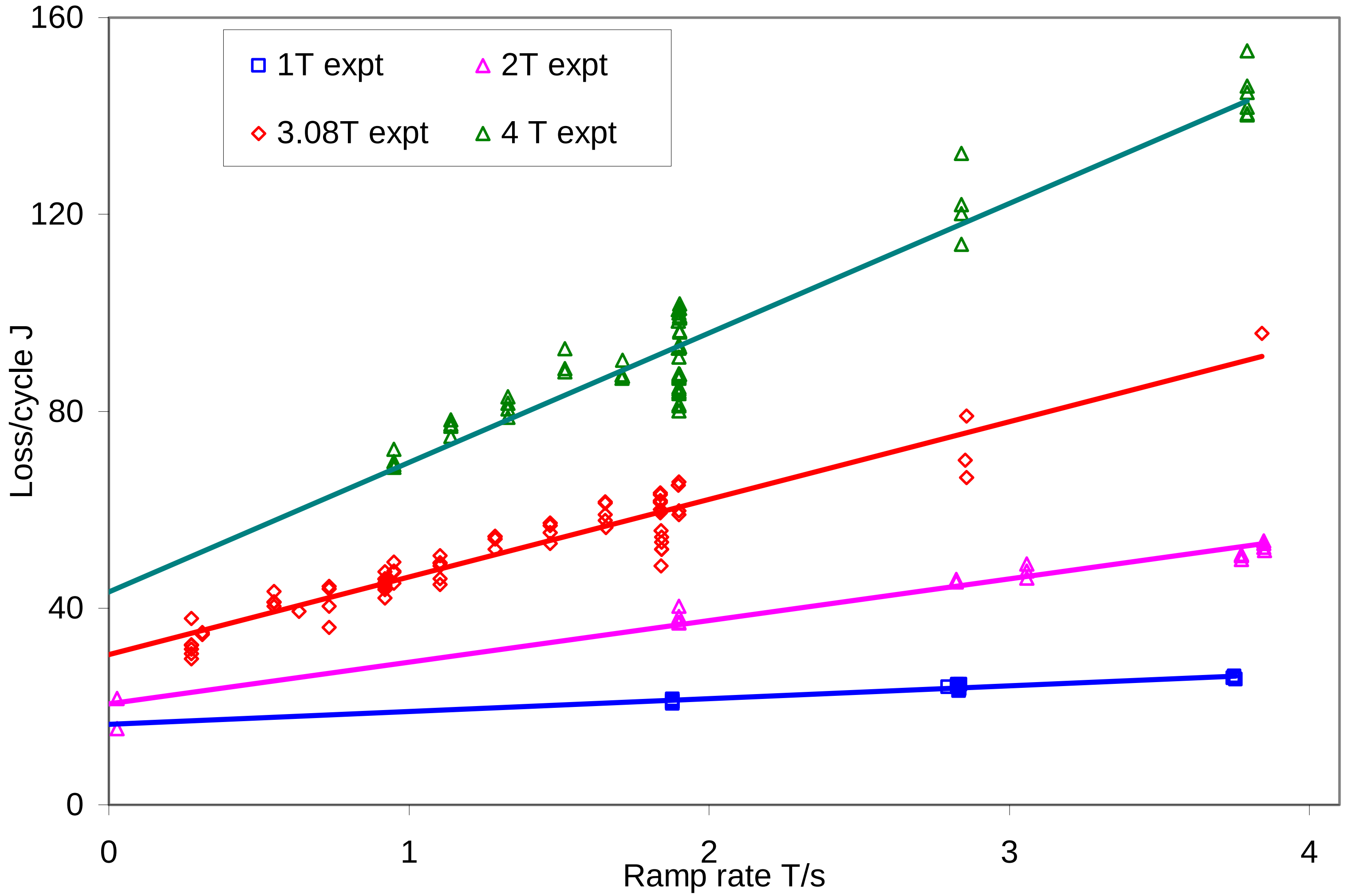
- 4 quenches to short sample limit
- continuous 2T/s operation up to short sample limit
- 3 cycles 4 T/s up to 4T



Thermal time constant ~ 1 min.

by P. Wanderer

Measured total losses for GSI 001

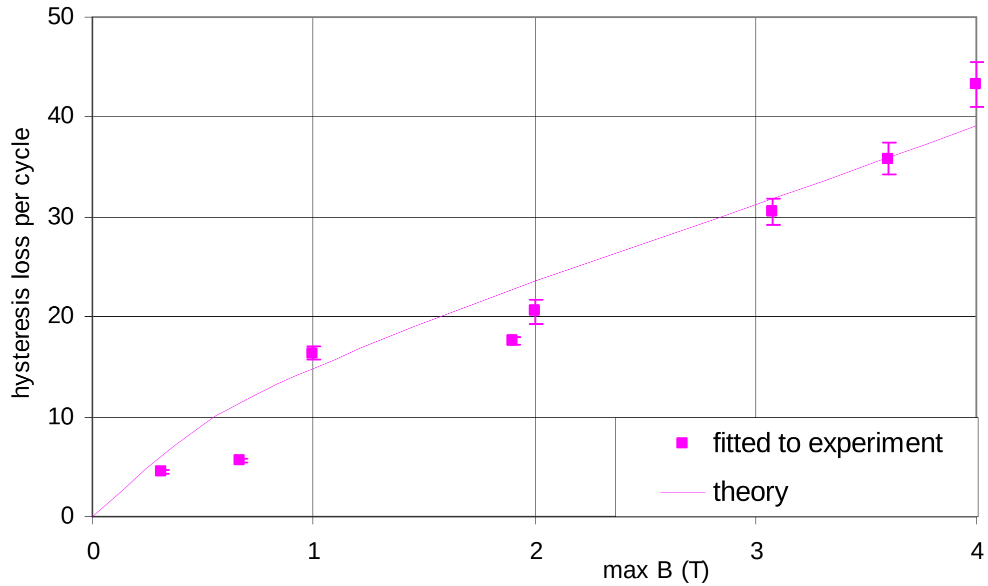


0- 4 T, 1 T/s, triangular cycle: 8.8 W (7.3 W/m)

by A. Ghosh

Calculated and measured losses of GSI001

by M.N. Wilson



Hysteresis part (intercept) (including iron and transport current contribution)

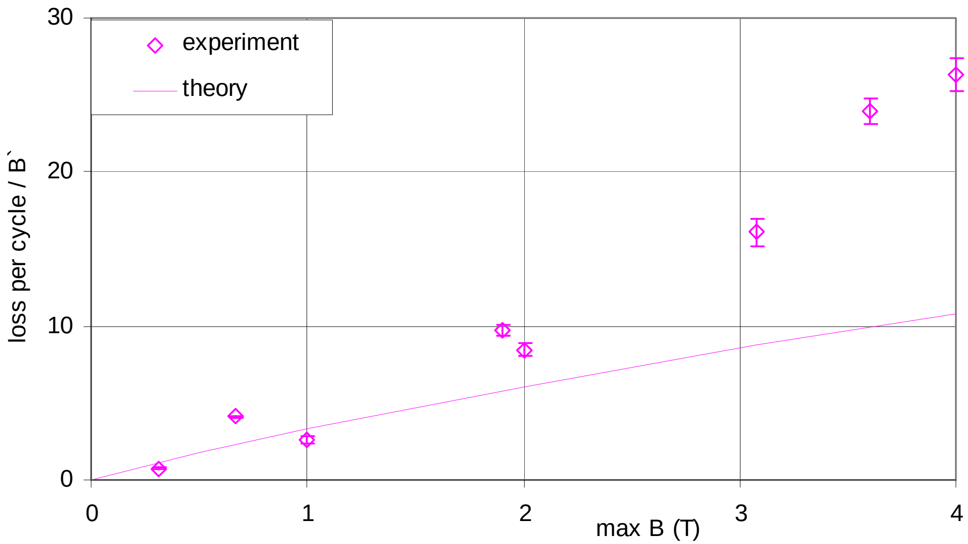
Parameters used for calculation:

$\rho_{et}(B) = 1.24\times10^{-10} + 0.9\times10^{-10}$ B

with ρ_{et} in Ωm and B in Tesla.

R_c = 62.5 m Ω

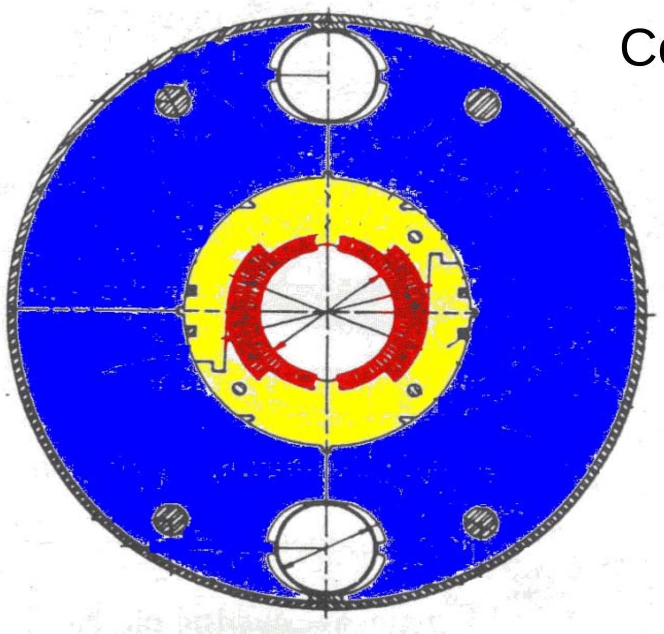
R_a = 64 μΩ



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 (slope)

SIS 300 - Dipole



UNK Dipole

- 2 layer cosθ design
- 80mm bore ⇒ 100 mm
- 5.11 T ⇒ 6 T
- 0.11 T/s ⇒ 1 T/s

Conceptual Design Study by IHEP, Protvino (6/2004)

Main results:

- cooling: one phase Helium 4.4 K
- temperature margin: 1.0 K
- option: lowering Helium-temperature
- collared coil supported by iron shell (taking part of the load)
- strand: diameter: 0.825 mm
filament size: 3.5µm
- Rutherford-cable: 36 strands with core
- quench protection: needs heater, 20 magnets per PS / dump resistor

WEPKF062 (Quench), WEPKF063 (mechanical structure), WEPKF064 (cable losses), WEPKF066 (Stability, margin)

Further work SIS 300 magnets

- GSI001 dipole (BNL / GSI)
  - losses in a bipolar cycle
  - quench current as a function of the ramp rate (RRL)
  - static and dynamic magnetic measurements (harmonics)
  - loss measurement of the collared coil alone
  - horizontal test of the magnet, with one-phase helium cooling in the new test facility at GSI.

- SIS 300 dipole (IHEP / CERN / GSI)
  - technical design
  - construction and testing of two 1 m model dipoles

- SIS 300 quadrupole (CEA Saclay / GSI)
  - parameters, work packages and milestones defined by 08/2004

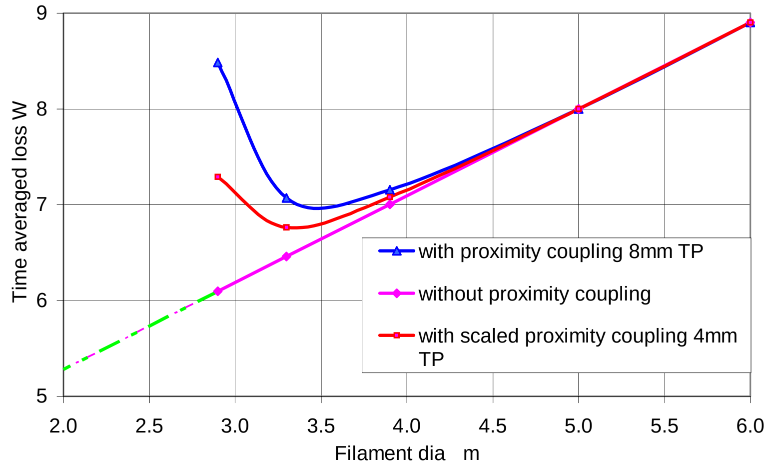
Small filament size wire R&D

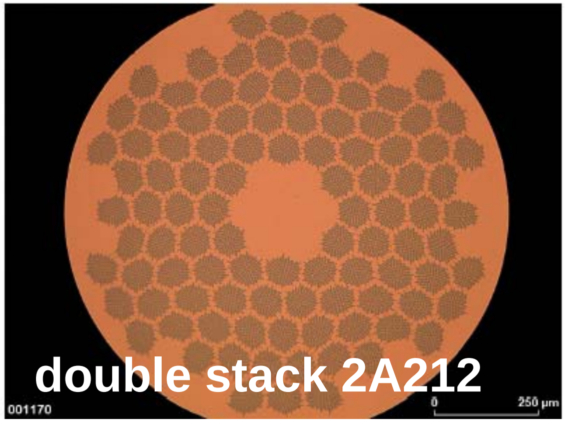
Motivation: 60 -70% of the coil AC- losses

caused by wire magnetization

→ filament size reduction

→ but limit due to 'proximity coupling'
$d_{fil} \geq 3.5 \mu m$ for Copper matrix



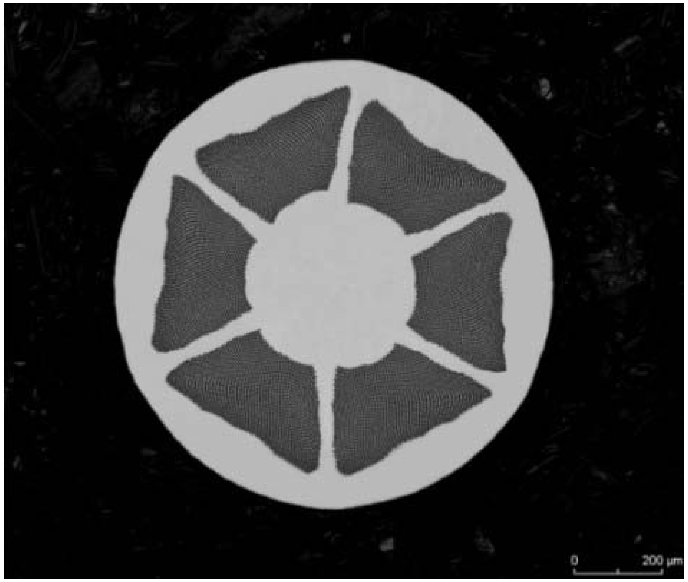


Preliminary tests:

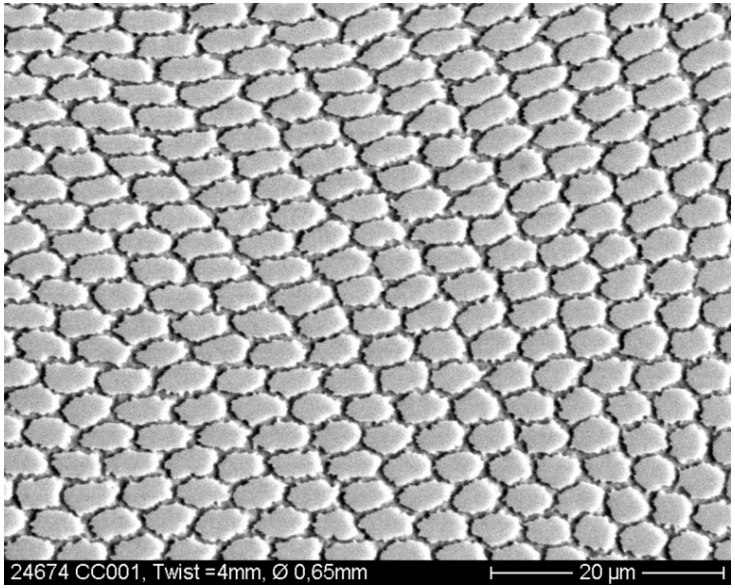
d_{eff} = 3.5 µm, but problems with stacking of 12000 monocores (1.5 mm wide)

d_{eff} = 4.8 µm due to filament distortion (near the copper)

Small filament size wire R&D (continued)



- Modified double stack method:
  - 6 x 2050 filaments
  - 0.65 mm wire diameter
  - 1.80 :1 Cu / NbTi ratio
  - 4 mm twist pitch
  - j_c = 2759 A / mm^2 @ 5T, 4K
  - 3.3 micron NbTi filaments (nominal)
  - full size billet (120kg) is ready for wire production



- Cu-Mn-matrix (2.5 micron NbTi filaments) wire is under investigation !

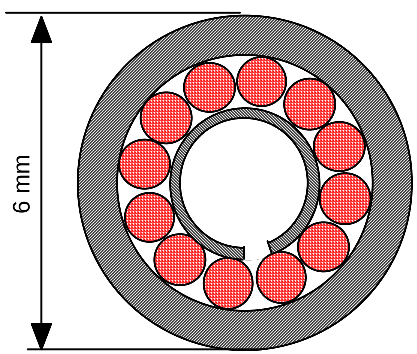
Cable R&D

Rutherford cored cable R&D

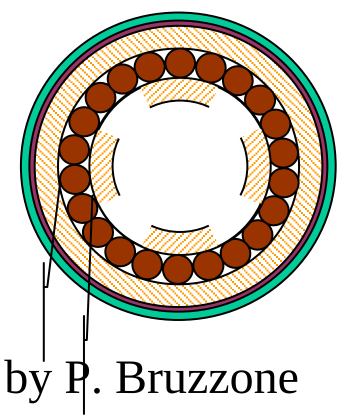
- **different cores (stainless steel, titanium, Cu-Ni, brass, Kapton)**
- **different mandrels (hollow, slotted)**
- **measurement of j_c, R_a, R_c, AC-losses**

➡ **details in A. Ghosh, WAMS-workshop, Archamps, 2004**

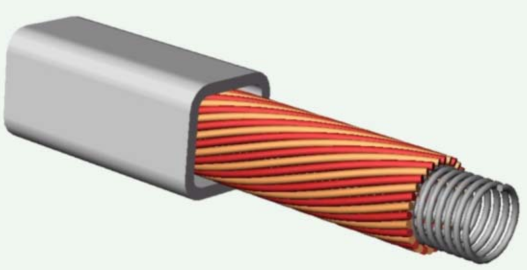
EU INTAS 03-54-4964 : improved N- CICC



by L. Bottura, M.N. Wilson



by P. Bruzzone



by V. Keylin

Summary

- Fast-pulsed sc magnets are foreseen for the synchrotrons of FAIR
- R&D to develop these magnets has started
- First dipole models have been built and tested.
- R&D will continue on quadrupoles and full size magnets.

ACKNOWLEDGEMENTS

I am greatly indebted to all members of the collaborations, to our consultants and to the members of the GSI magnet group for their dedicated work.