Cable Design for Fast Ramped SC Magnets (Cos-θ Design)

Arup Ghosh

Introduction

- Most high-field SC-synchrotron magnets are ramped at low dB/dt, *Tevatron* being one of the highest with *dB/dt* ~ 60-125 *mT/s*.
- There are also several lower field (~2T) synchrotrons which are cycled at much higher ramp-rates ~ 1-4 T/s.
  - With the exception of the *Nuclotron* magnets which are SC, all others are resistive magnets.
- In recent plans for upgrades of accelerator facilities are proposals for higher field rapid cycling SC magnets, in the range of 2T to 6T

2-6T Rapid Cycling Magnets

- New facility approved for GSI
- SIS100 ring cycling to 2T at 4T/s
  - *Nuclotron* Magnet
  - Iron Dominated
- SIS200 ring (200 Tm, original proposal) cycling to 4T at 1T/s
  - GSI-001 *RHIC* style Magnet
  - Coil Dominated
- SIS300 ring (300 Tm, current proposal, from physics) ramped up at 1T/s to 6T

Collaboration

- BNL
  - M. Anerella, G. Ganetis, A. Ghosh, P. Joshi, A. Marone, J. Muratore, J. Schmalzle, R. Soika, R. Thomas and P. Wanderer
- GSI
  - J. Kaugerts, G. Moritz
- Consultants
  - W. Hassenzahl, M. N. Wilson

Rapid Cycling Magnets operated at 4T/s

- Technical Challenge:
  - Minimize losses due to eddy currents
    - In Strand, Cable, Iron, Beam tube
  - Reduce losses due to SC magnetization and the iron
  - *Avoid Ramp rate induced quenching found in some fusion magnets and investigated in detail during the development of magnets for the SSC High Energy Booster*
  - Develop precise magnetic field measurement system for fast-changing magnetic fields

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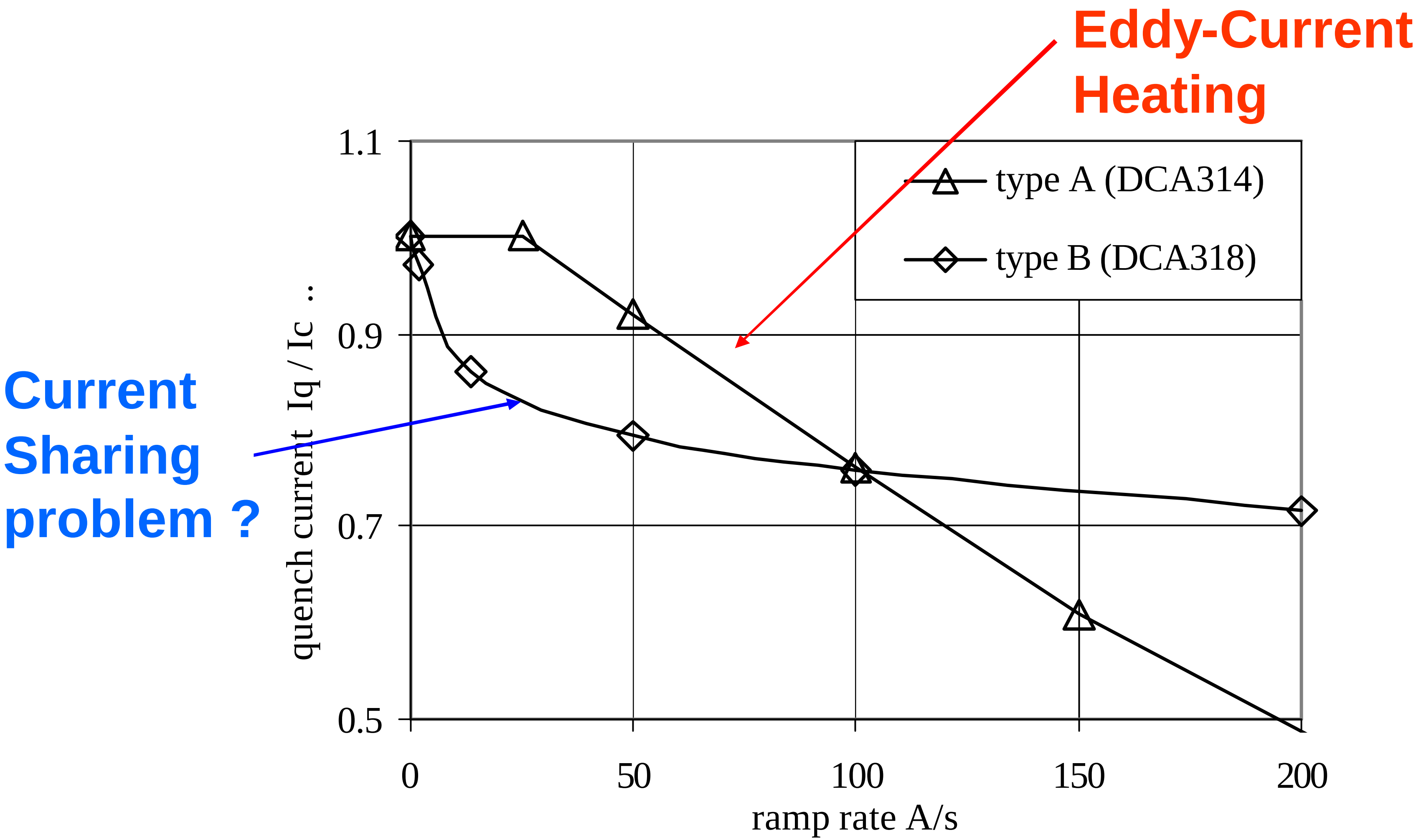
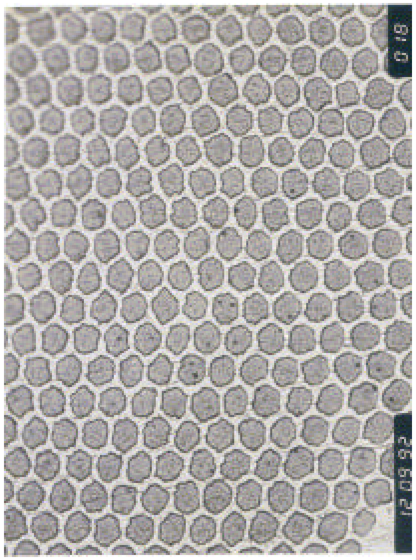
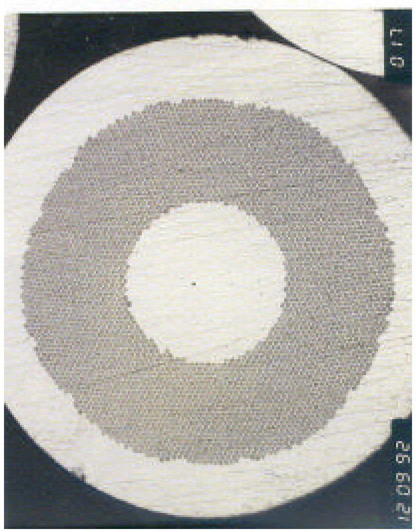
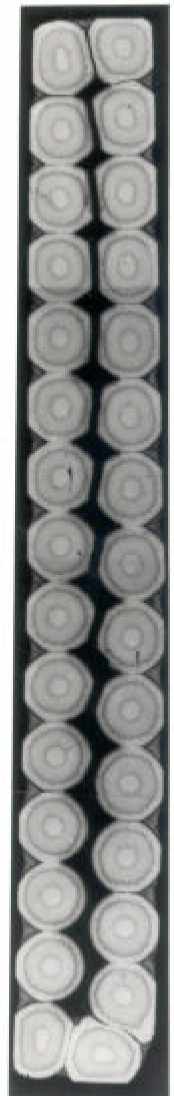
Quench current of SSC magnets as a function of ramp rate



starting point RHIC wire and cable



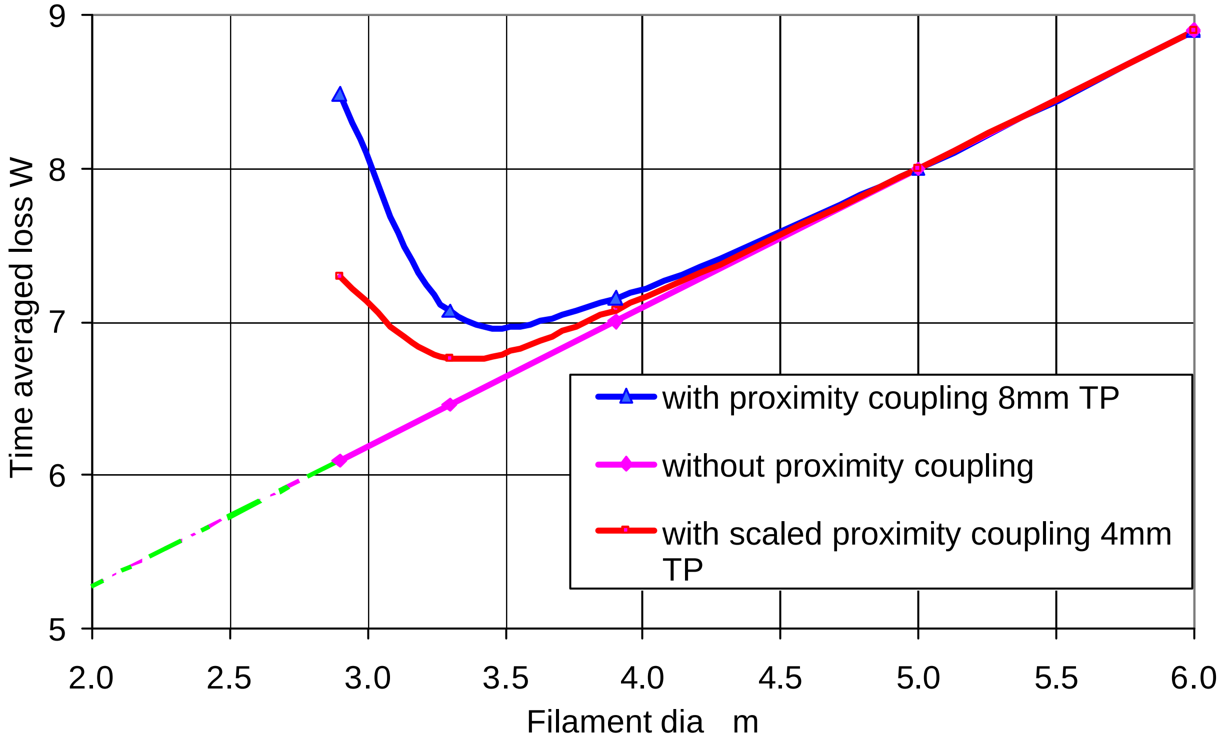




Wire diameter (mm)	0.648
Filament diameter	6
Cu/Sc ratio	2.25
Wire twist pitch (mm)	13
Wire coating	None
No. of strands in cable	30
Cable width (mm)	9.73
Cable mid-thickness	1.166
Cable Keystone angle	1.2
Cable lay pitch (mm)	74

For Cos q Magnet :Strand Design

- Minimize SC magnetization
  - Small filament diameter 2.5 μm
  - suppress “proximity-coupling by using Cu-2.5%Mn matrix.

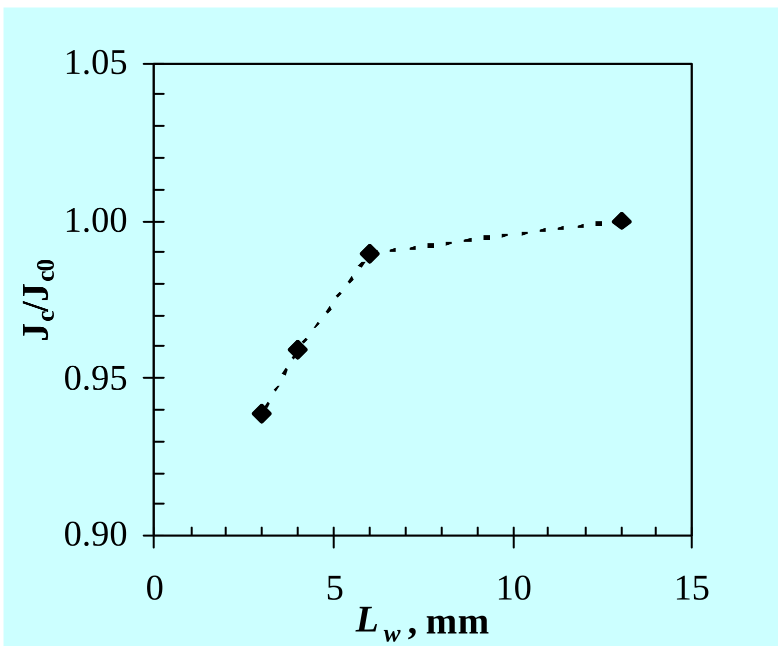


For Cos q Magnet :Strand Design

- Reduce eddy-current magnetization
  - High-resistive matrix, Cu-2.5%Mn
  - Small twist pitch, practical limit 5xd_w
  - Jc > 2500 A/mm^2 at 5T

$$M_e = \frac{2\dot{B}t_f}{m_o}$$

$$t_f = \frac{m_o}{2r_{et}}\left\{\frac{L_w}{2p}\right\}^2$$



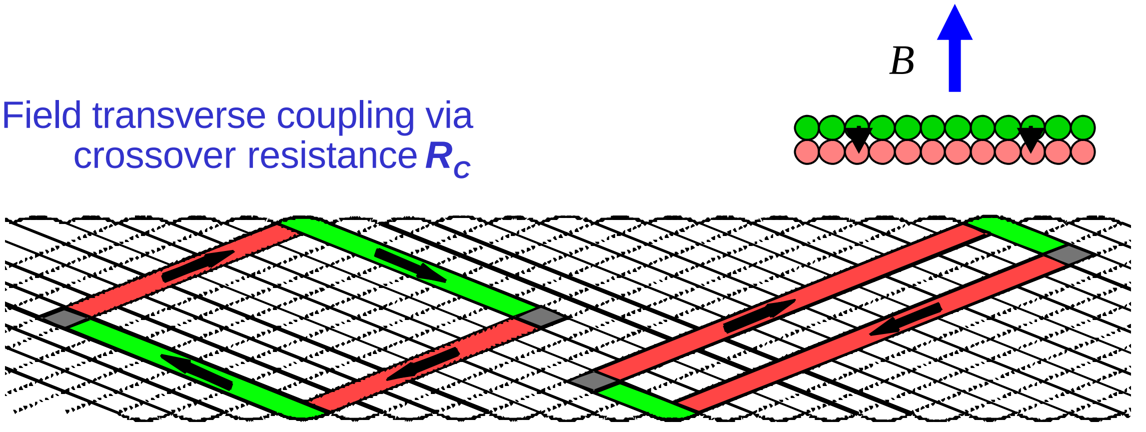
For RHIC wire
$r_{et} = 1.8 \times 10^{-10}$ μΩ–cm.

Use 4mm TP wire in cable

Jc =2780 A/mm^2 @ 5T

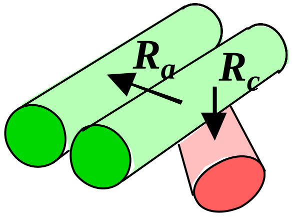
Coupling in Rutherford cables

Field transverse coupling via crossover resistance R_C

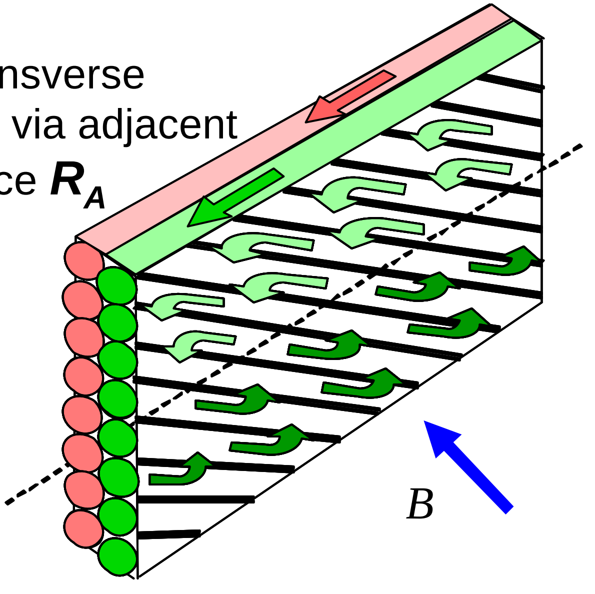


crossover resistance R_C

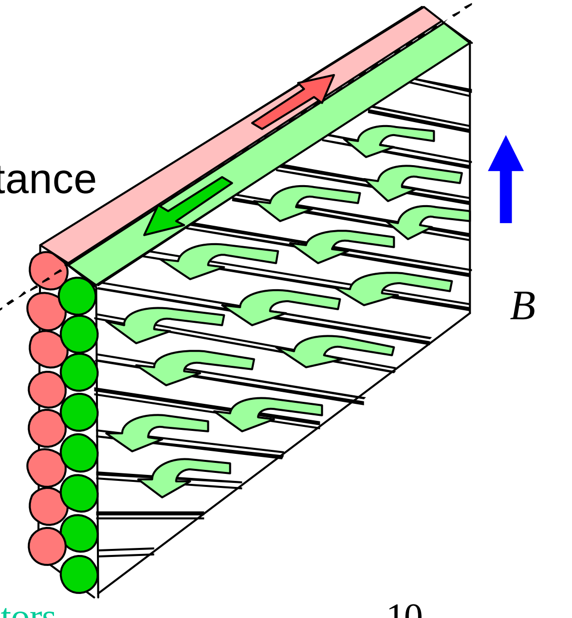
adjacent resistance R_A



Field transverse coupling via adjacent resistance R_A



Field parallel coupling via adjacent resistance R_A



Losses in a Rutherford Cable

Cable coupling via R_c in transverse field

$$M_{tc} = \frac{1}{120}\frac{\dot{B}_t}{R_c}\frac{c}{b}\,p\,N(N-1)$$

Cable coupling via R_a in transverse field

$$M_{ta} = \frac{1}{6}\frac{\dot{B}_t}{R_a}\,p\,\frac{c}{b}$$

Factor of 3 if Ra is much lower at the edge than in st. section.

Cable coupling via Ra in parallel field

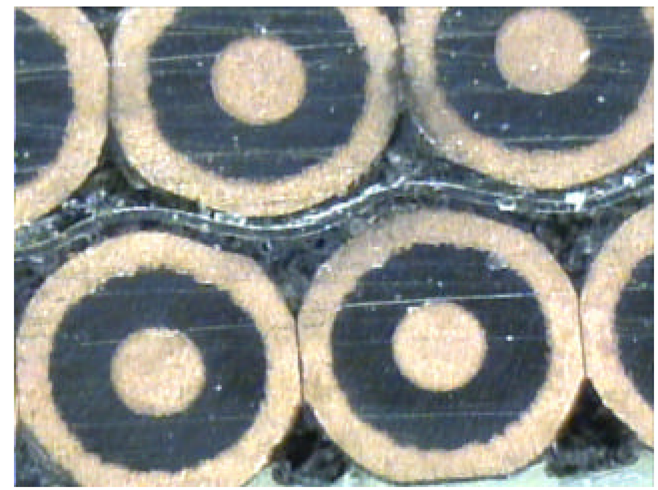
$$M_{pa} = \frac{1}{8}\frac{\dot{B}_p}{R_a}\,p\,\frac{b}{c}$$

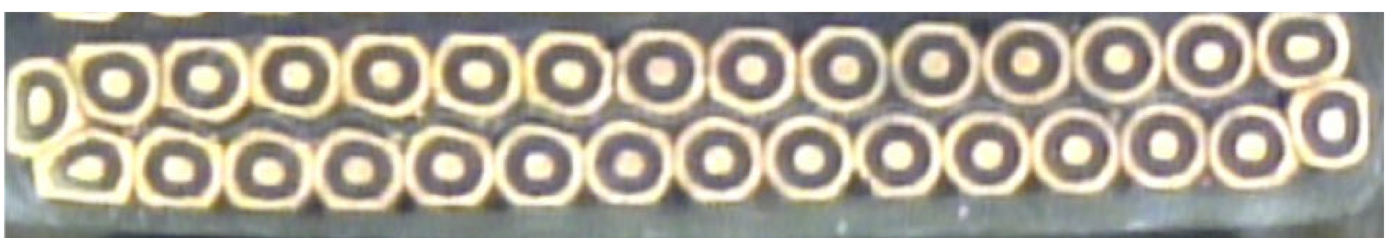
$$\longrightarrow \quad \frac{M_{tc}}{M_{ta}} = \frac{R_a}{R_c}\left\{\frac{N}{20}(N-1)\right\}$$

~ 50

Losses in a Rutherford Cable

- In a typical cable $R_C \sim R_A$
- Resistive coating on strand increases both R_C *and* R_A
- Reduce R_c Loss
    - Resistive core
- Maintain R_A for adequate Current Sharing
- Coat strands with *Sn-4%Ag* to control R_A ~ *50-100 mW*





Cabling experience (limited)

- Using a *hollow* mandrel at New England Wire Technology
  - Tape fed through the cable shaft
  - Main problems
    - Mandrel wear
    - Foil perforation of the stainless steel tape at the minor edge, depends on cable compaction, strand anneal state.
    - Difficult to splice tape.
  - Foil perforation not seen in 50 μm brass tape and by using 2 layers of 25μm SS-tape
- Recent cable made at LBL using a *slotted* mandrel shows that single layer SS-tape cored cable can be made without any perforations.
- Another promising candidate for foil is Cu-30%Ni. This is being evaluated for R_c

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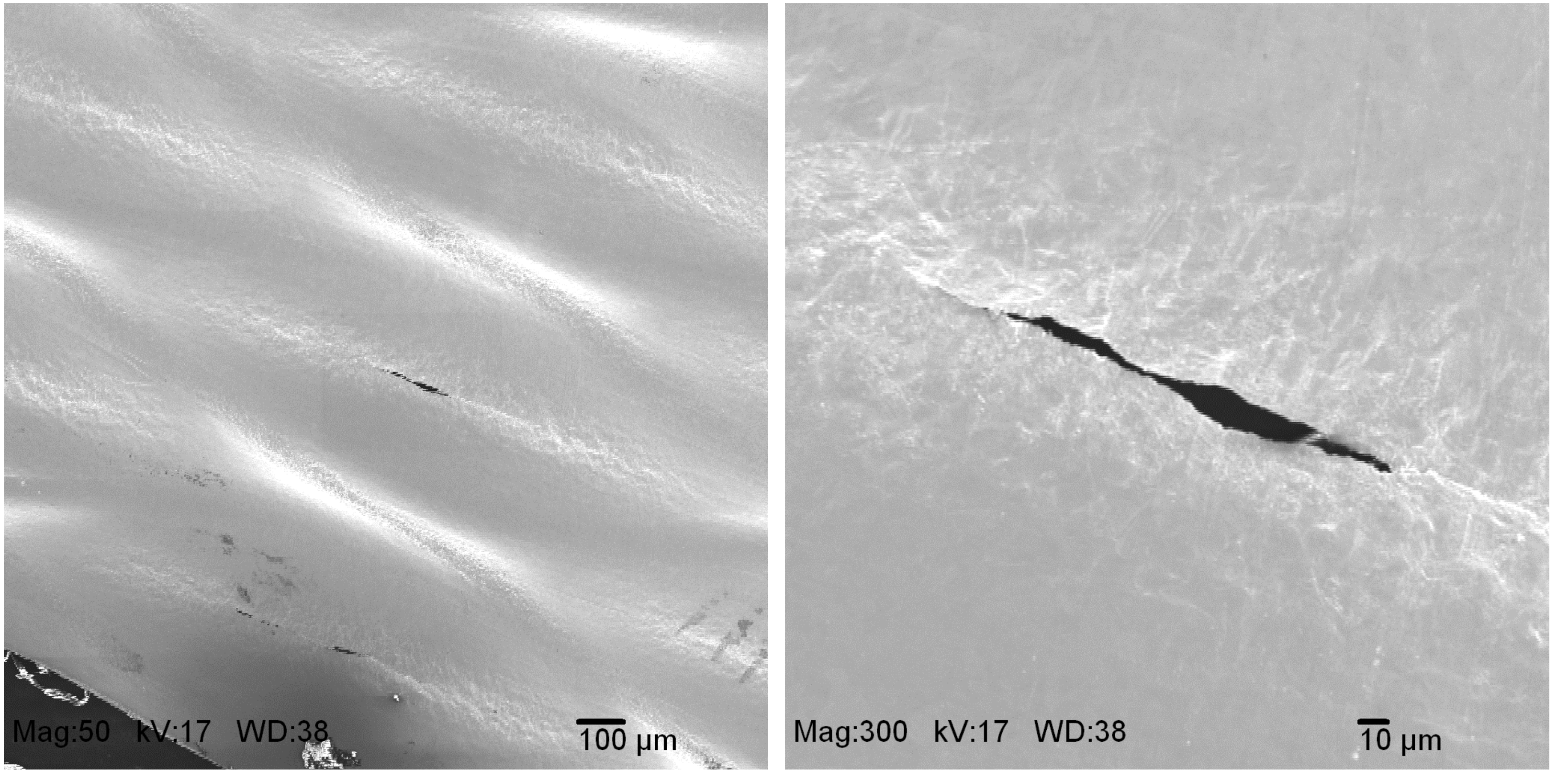
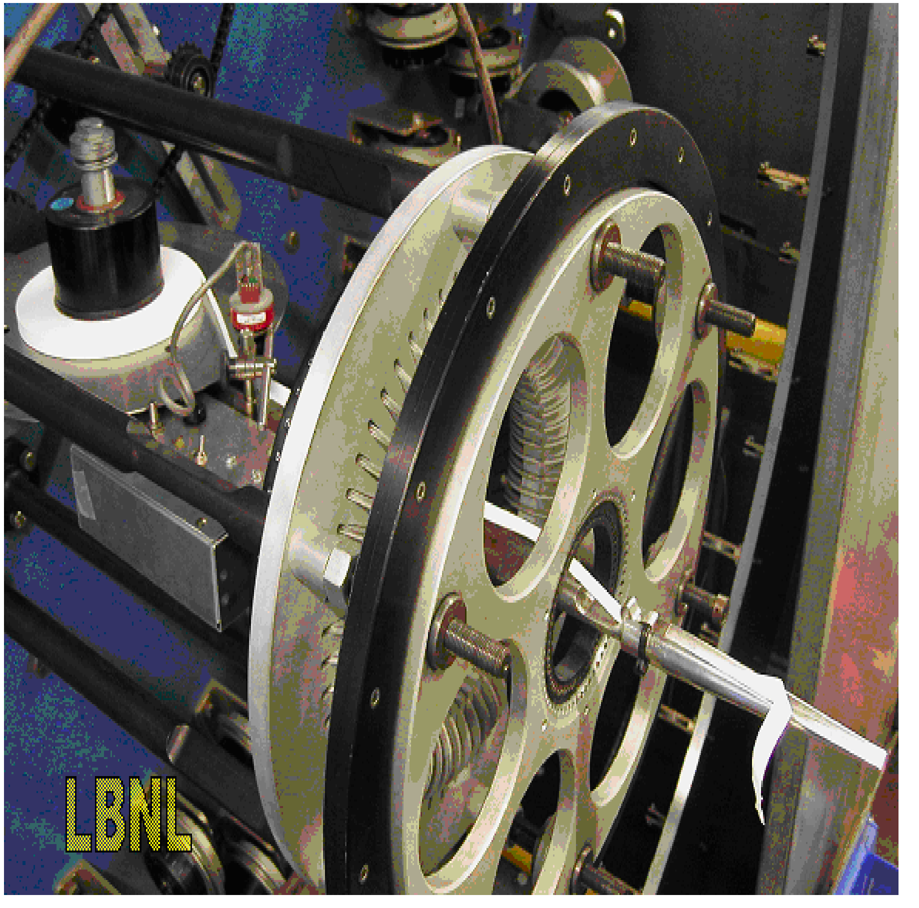
Perforations in the SS-ribbon at the cable minor edge

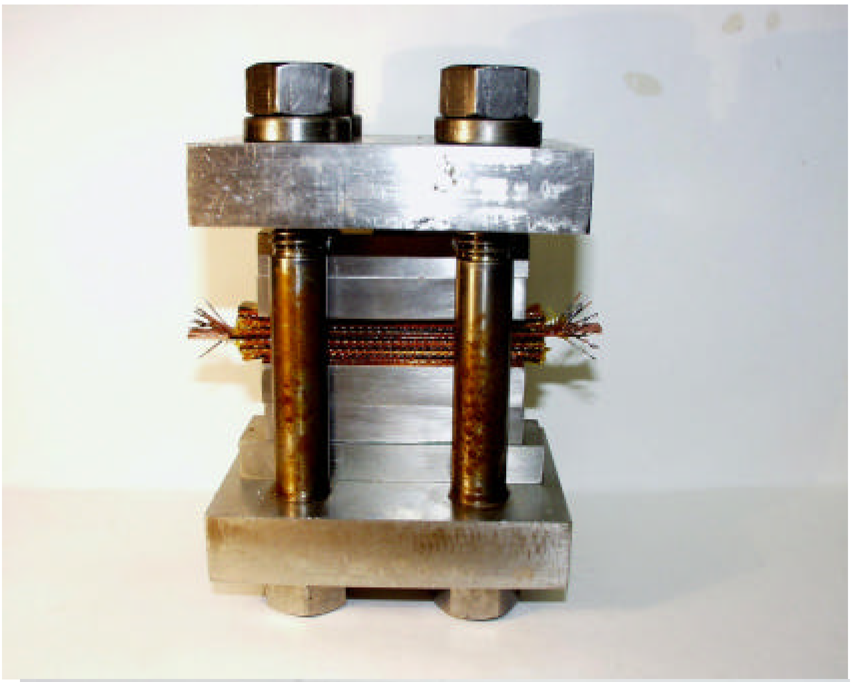


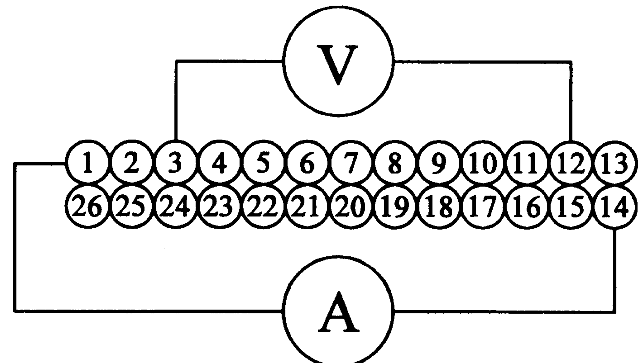
Slotted mandrel at LBL



Contact resistance measurement

R_A and R_C measured by the V-I method.





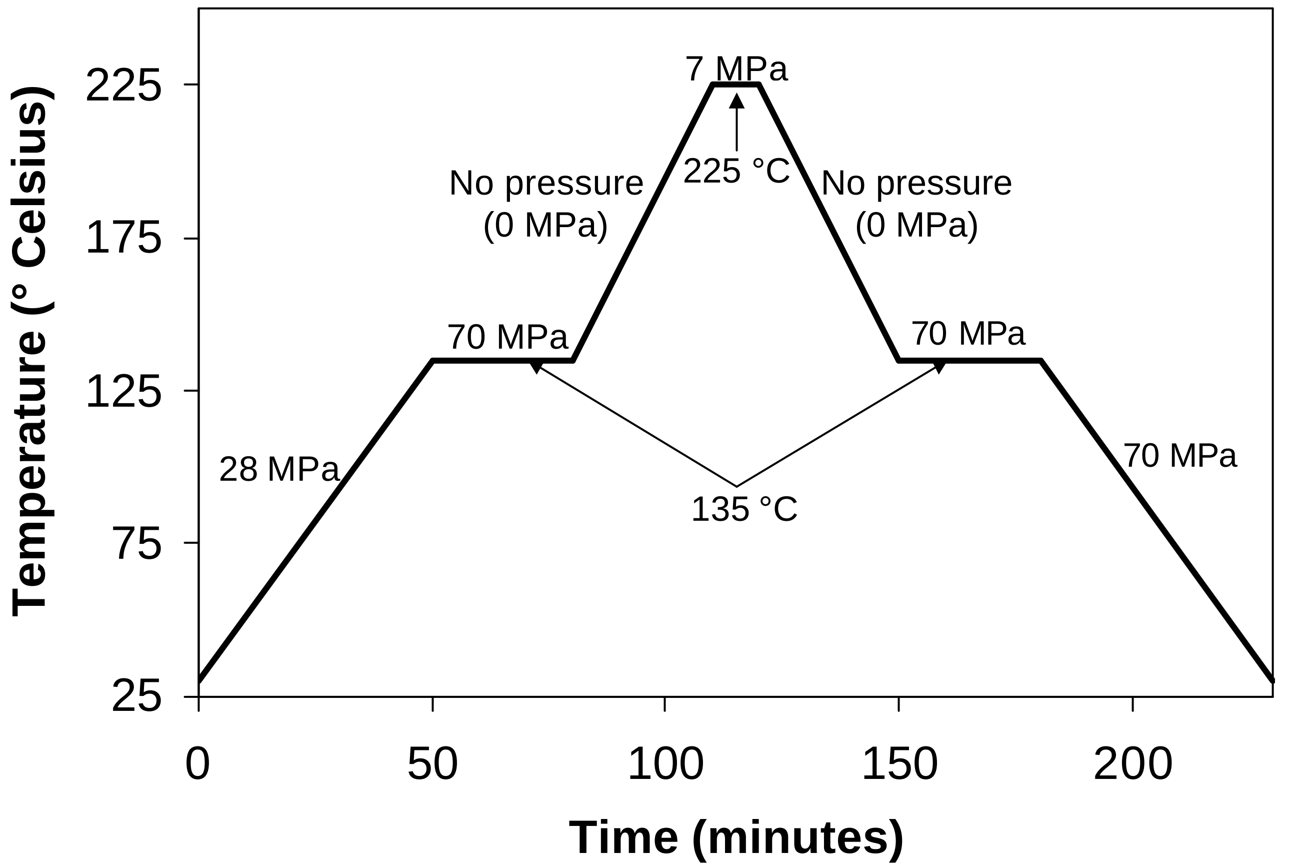
Courtesy A. Verweij

Typically current input in strand #1 and out at strand #16
Voltage measured between #1 and the other strands.

10-Stack sample prepared similar to a magnet coil

Coil curing cycle

R_A and *R_C* varies with pre-annealing and coil curing cycle



R_A and R_C Measurements

Cable	Sn-Ag Coating, µm	Cable Thickness, mm	Foil	Ra (µO) After Cabling	Ra (µO) 6 months later	Rc (mO)
GSI-003-A	0.66	1.138	25 µm SS	**100**	**139**	
GSI-003-B	0.66	1.180	25 µm SS	**72**	**147**	**14**
GSI-003-C	1.04	1.187	25 µm SS	**28**	**80**	
GSI-003-D	1.04	1.202	25 µm SS	**18**		**12.5**
GSI-003-E	1.04	1.173	2·25 µm SS	**21.5**	**25**	**62.5**
GSI-003-F	1.04	1.175	50 µm Brass	**8.5**	**45**	**0.66**
GSI-004-A	1.00	1.164	2·25 µm SS	**55**		
GSI-004-B	1.00	1.174	2·25 µm SS	**74**		

Prototype Magnet used GSI-004

R_C ~ 60 mΩ, R_A=64 µΩ

Prototype Cos q 4T Magnet

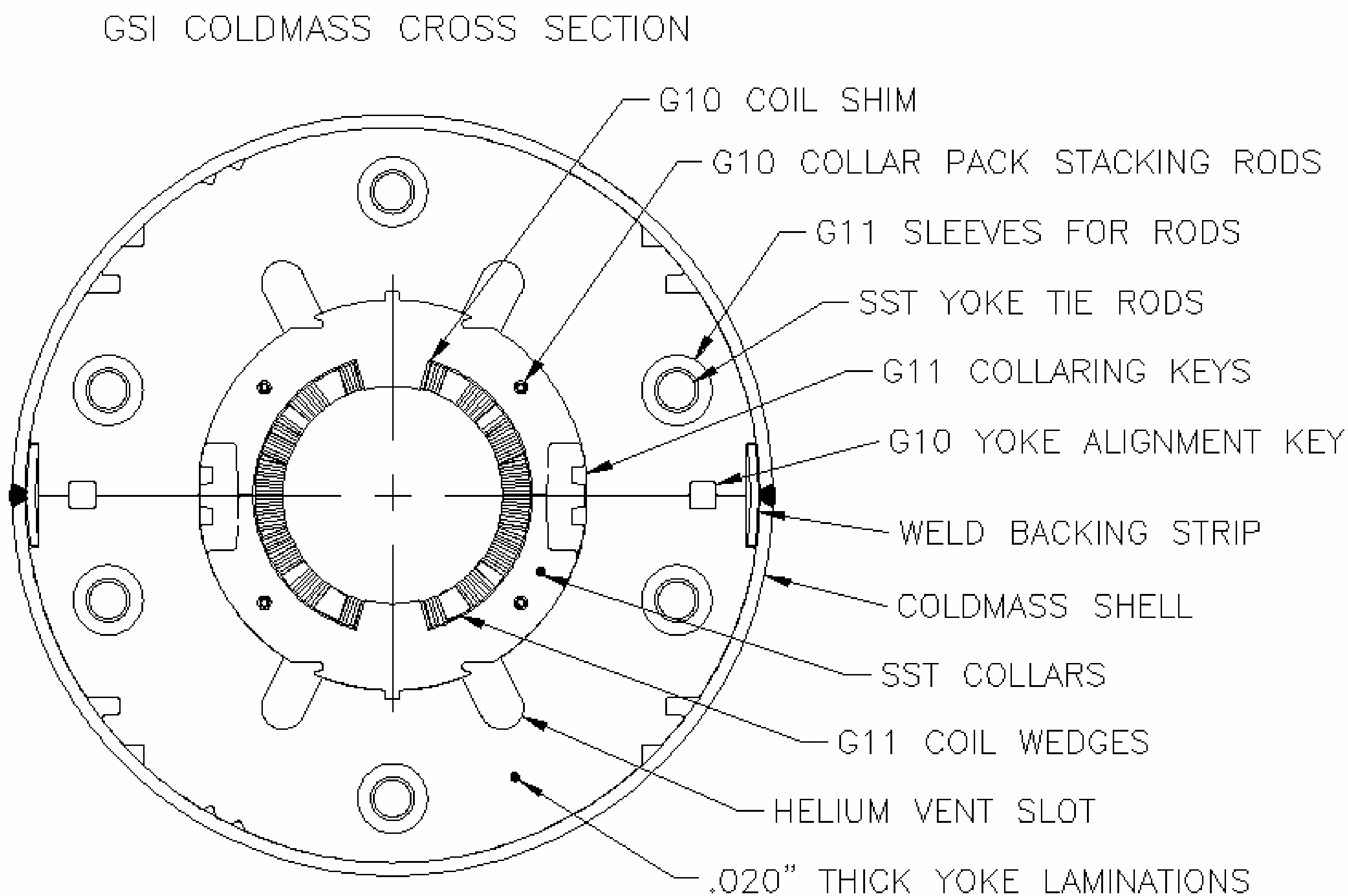
Cable with core

RHIC coil with G11 wedges

SS collars

G11 collar keys

0.5 mm Si-steel yoke lamination

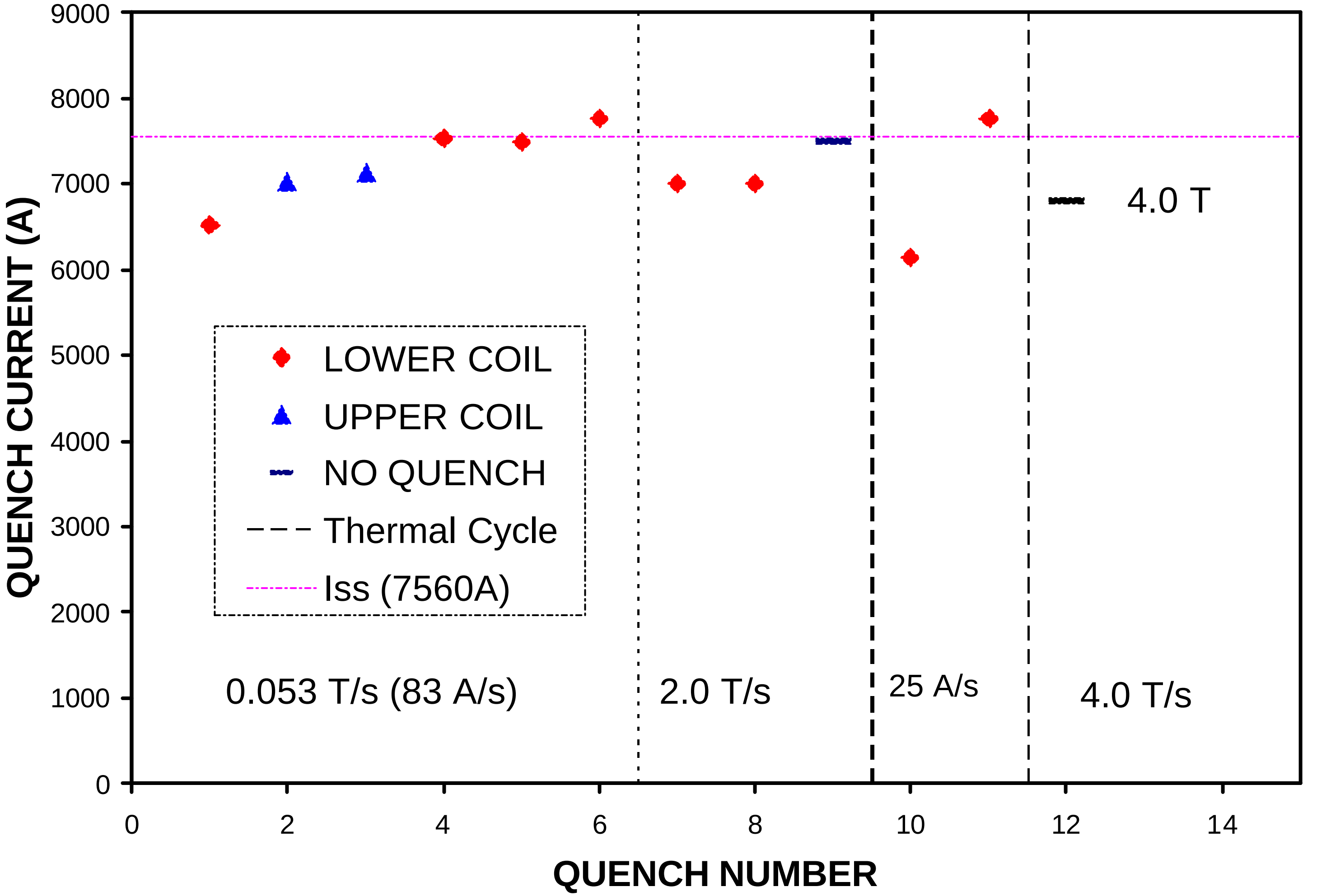


GSI-001 Quench Performance

Ramp to 4T in liquid He without quenching:

4T/s – 3 cycles – 2X

2 T/s – 500 cycles – 40 minutes



GSI Cable Insulation

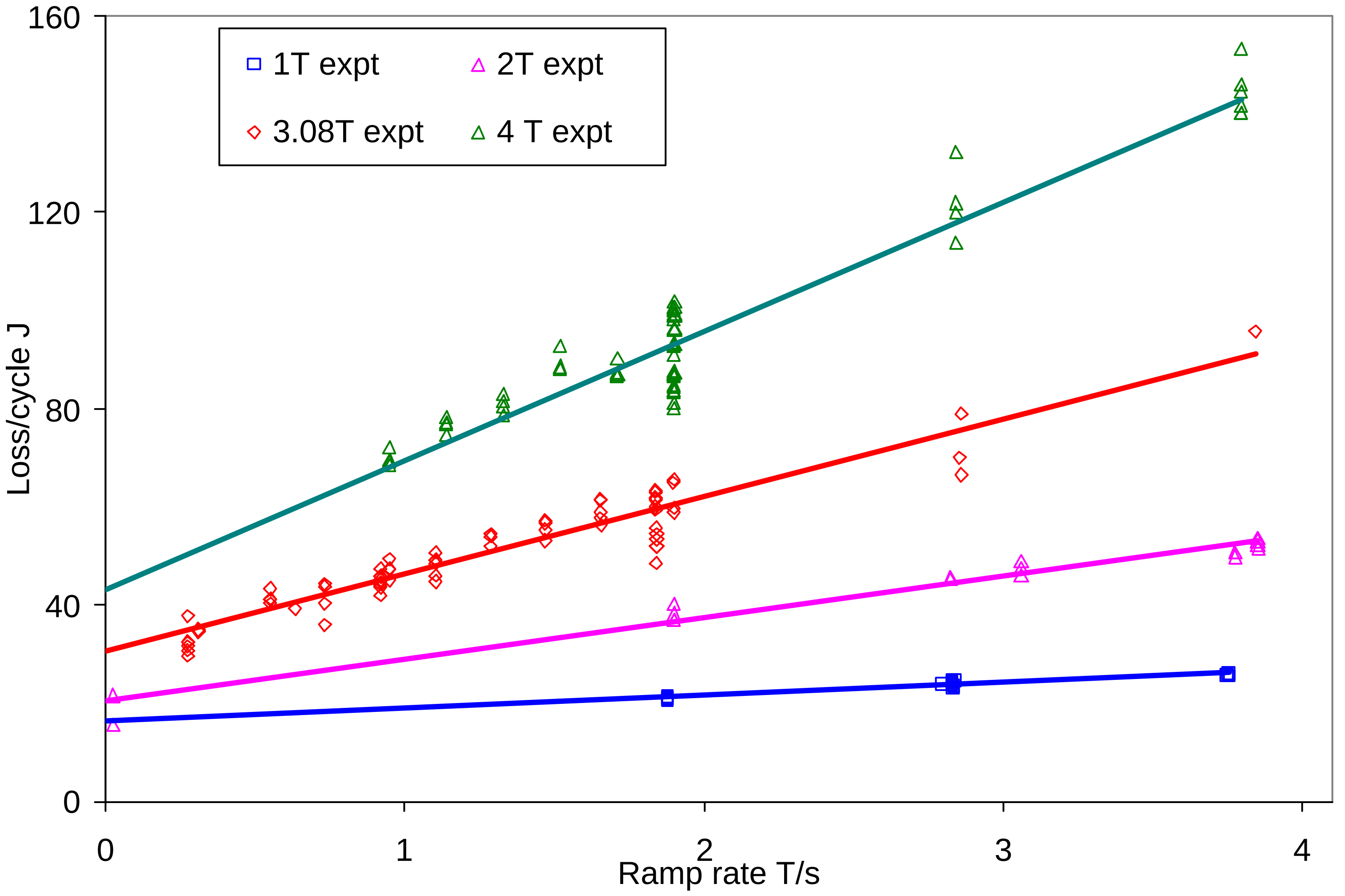
- Laser-cut holes (University of Jena, Germany)
- Keeps strands in intimate contact with helium – better cooling.
- Cable passed 1.1 kV turn to turn, in both the straight-section and the ends.

Loss contributions at 1T/s to 4T for GSI-001 Prototype Magnet

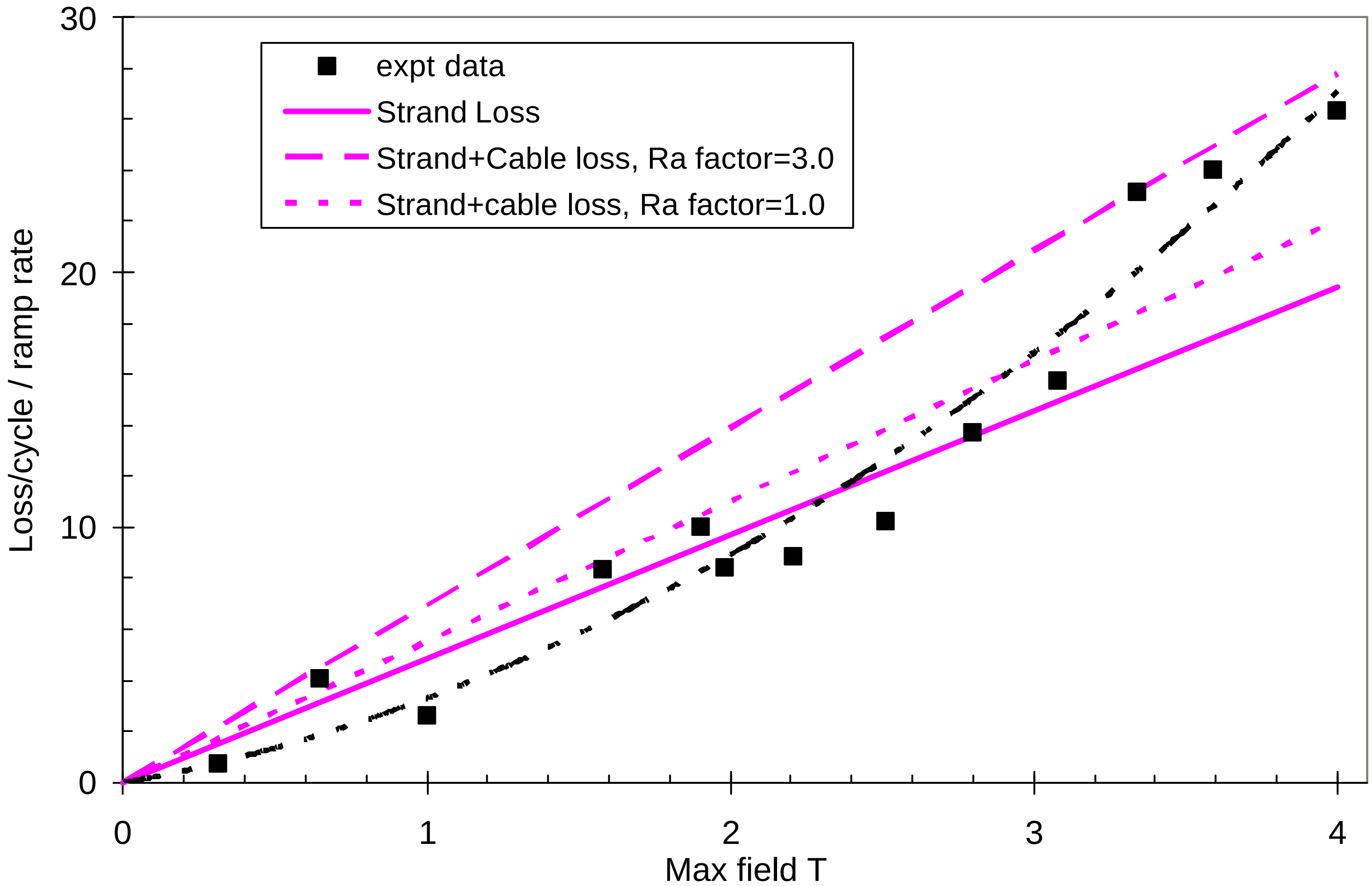
	Uniform R_A	R_A at edge
Transverse crossover loss (R_C)	= 0.2%	0.2%
Transverse adjacent loss (R_A)	= 5.2%	14.2%
Parallel loss (Rc)	= 0.2%	0.2%
Filament coupling loss (Cu-matrix)	= 35.9%	32.5%
Hysteresis loss (d_{fil} 6 μm)	= 58.5%	52.9%

These are based on R_C= 60 mΩ, R_A= 64 μΩ, $\rho_{et}=1.1\text{x}10^{-10}$ Ω-m

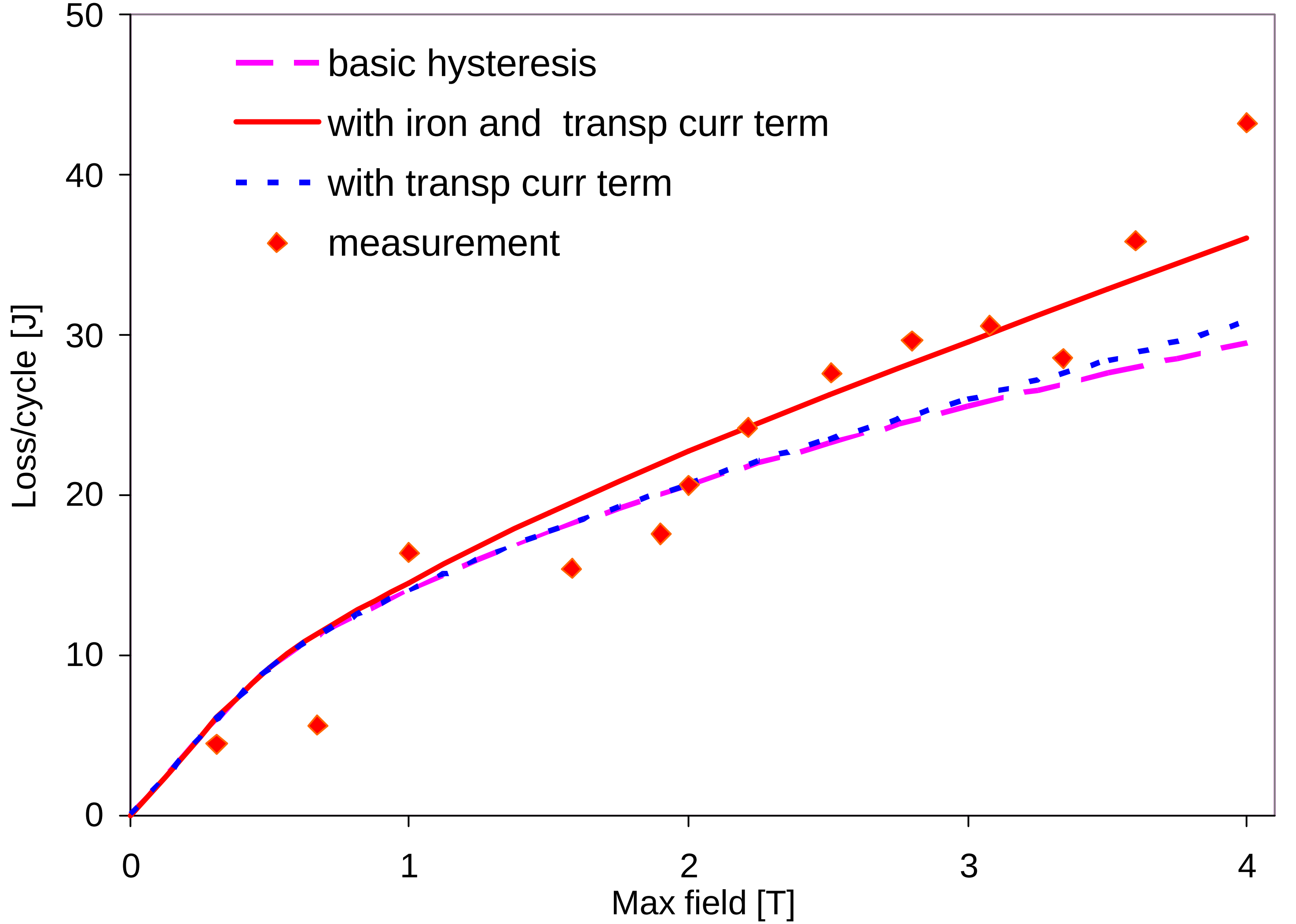
Measured losses



Calculated and measured gradients
(rate dependent or eddy current terms)



Calculated and measured intercepts
(hysteresis term)



Summary

- SC magnets cycling at 1-4T/s are quite feasible.
- Develop strand with smaller filament size 2.5-3.5 μm goal.
- Reduce strand loss by using Cu-0.5%Mn inter-filament matrix ρ_{et} ~ 1-2 x 10^{-8} Ω-m
- Use "cored" cable with a single layer tape for dimensional control. Develop cabling expertise.
- Investigate the limit of higher R_A without compromising current-sharing.
- Magnet data show that the theory works pretty well
- Rate dependent loss show non-linear increase at high field
  - Change in R_A with increasing pressure ?
- Hysteresis losses show anomalous increase at high fields