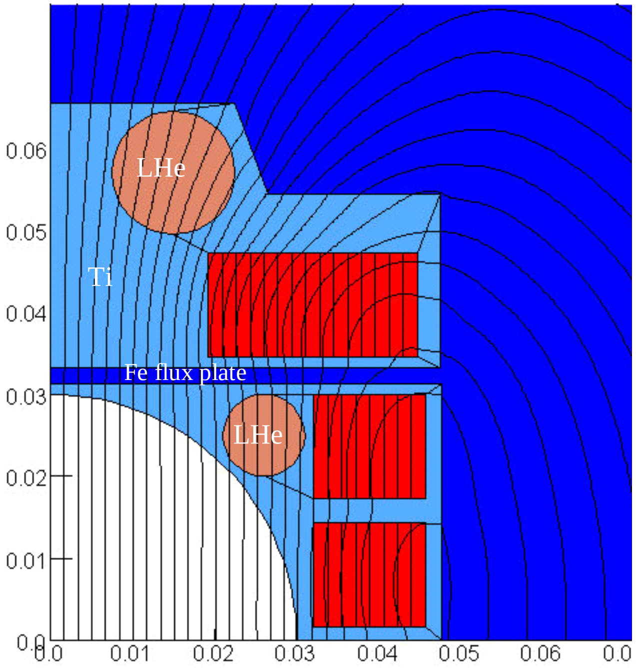
Rapid-Cycling Dipole using Block-Coil Geometry and Bronze-Process Nb_3Sn Superconductor



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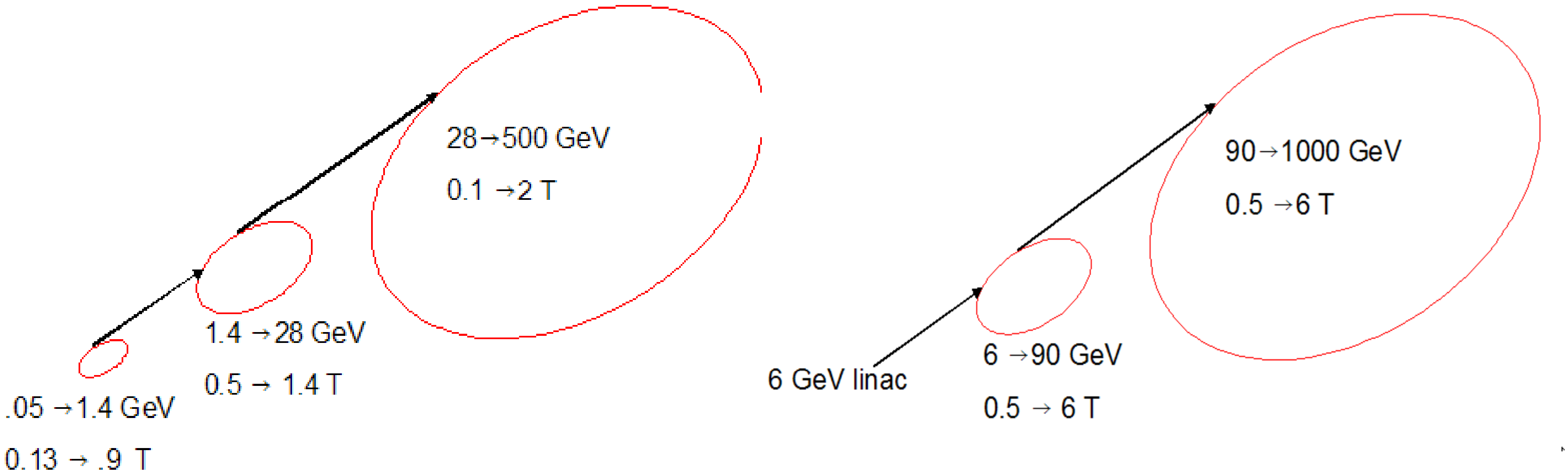
LHC Luminosity Upgrade: Inject from Super-SPS

- Replace SPS and PS with a rapid-cycling superconducting injector chain
- 1 TeV in SPS tunnel: stack at injection to LHC
- Super SPS needs 5 T field, ~1 s cycle time



.05 →1.4 GeV

0.13 → .9 T

1.4 →28 GeV

0.5 → 1.4 T

28→500 GeV

0.1 →2 T

6 GeV linac

6 →90 GeV

0.5 → 6 T

90→1000 GeV

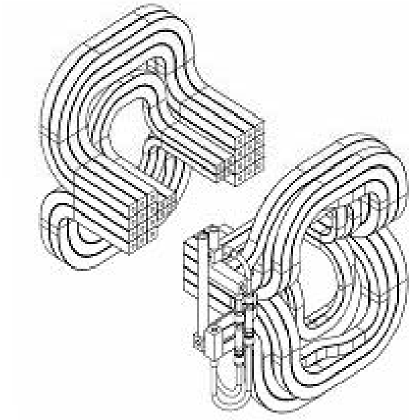
0.5 →6 T

Requirements for SuperSPS

- PS and SPS will require pulsed magnets with a ramp rate 1.5-2T/sec, the magnet for SPS has to be superconducting
- Development of 2-3μm size filament superconducting strands
- Magnet losses have to be contained at 10W/m peak
- Optimized design for good quench/ magnetic field performance
- Design with Minimum amount of superconductor
- Optimized for series production

One approach to rapid cycling

Schematic view of the
ends of one of 744
water-cooled OFHC
copper dipoles of SPS



Peak Field: 2.02 T @
5750 A (450GeV/c)

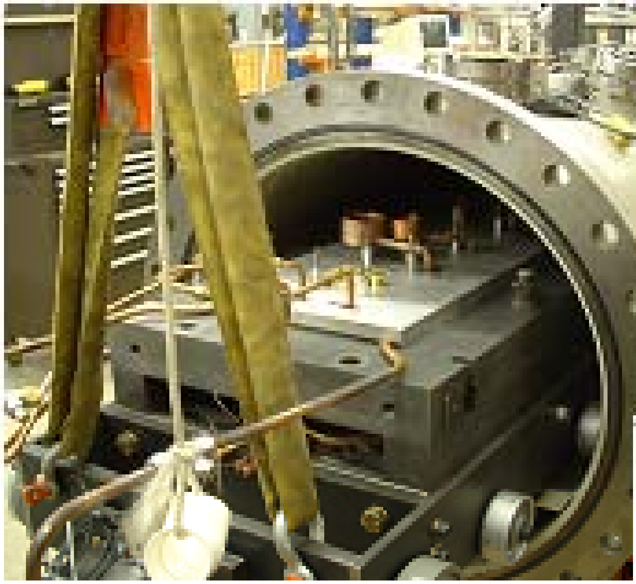
→

CosΘ geometry as upgrade option.
RHIC type dipole.
Cross section and ends

- Coil dominated: cosθ
- Maximum field: 3.5 T -> 4 T
- Ramp rate: 70 mT/s -> 1 T/s !!!

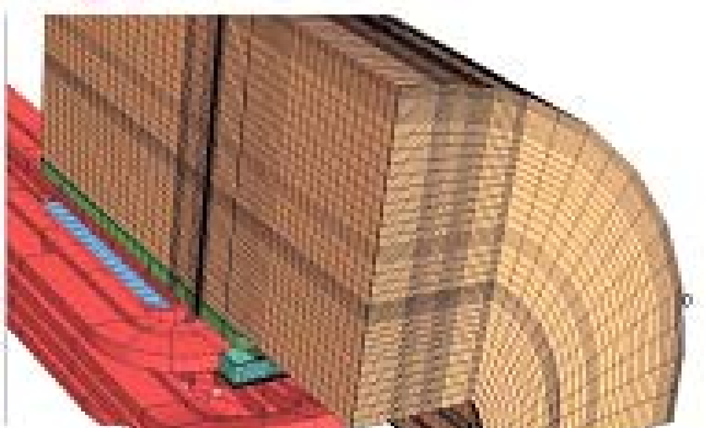
We think there may be a better way…

The Texas group is developing high-field dipoles to triple LHC energy



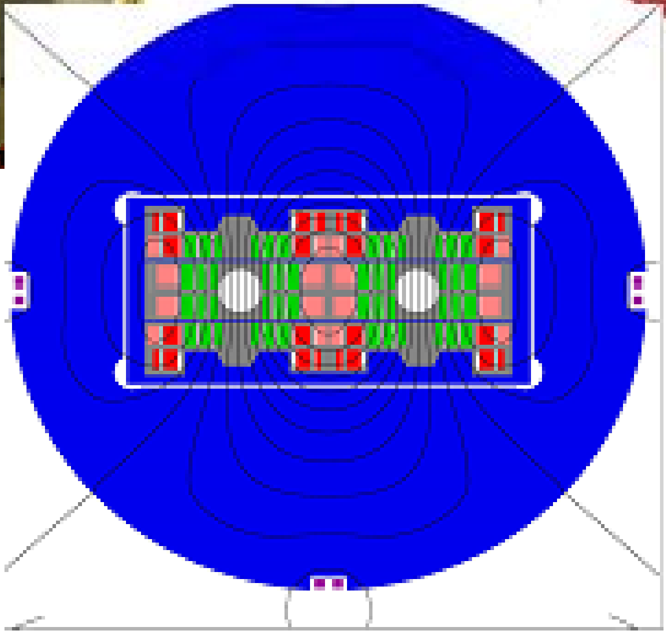
TAMU2: 7 Tesla

Single-layer coil with ITER cable



TAMU4: 16 Tesla

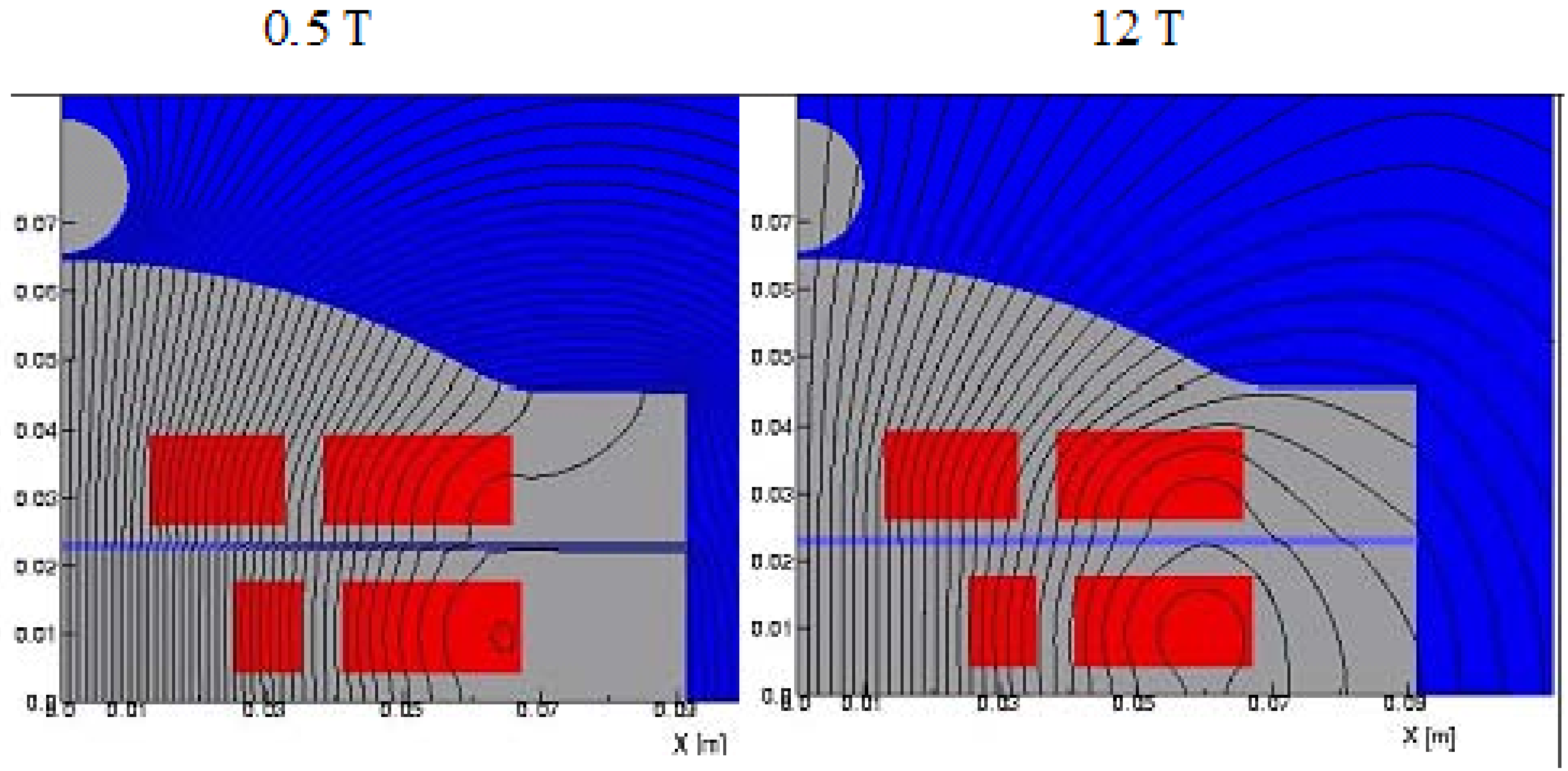
4-layer



LHC-T: 25 Tesla

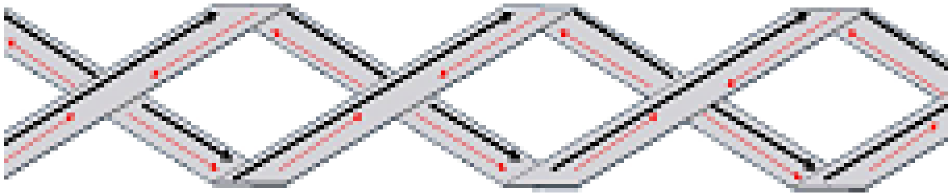
Nb_3Sn-Bi-2212 hybrid

Flux plate redistributes flux to suppresses multipoles

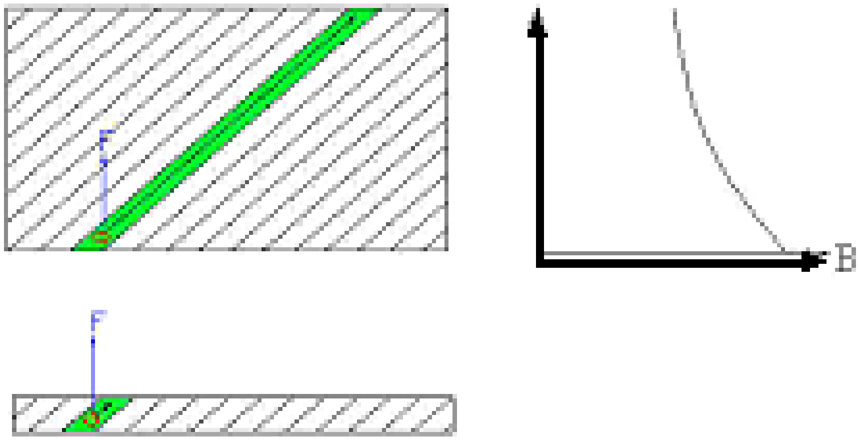


Super-SPS: suppress PC multipoles during rapid cycling

Cable orientation suppresses source term for snap-back



Induced coupling currents between adjacent strands in cable when it is oriented face on to time-changing flux.



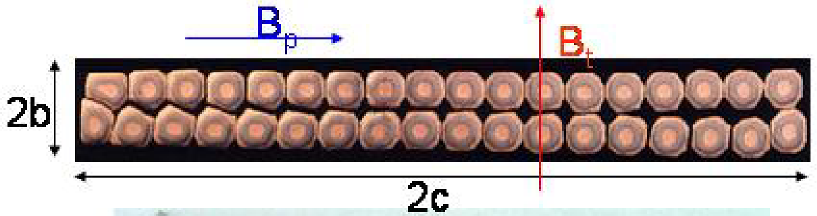
Gradient force acting on a magnetization current loop (red) in a sub-element of a) a face-on cable in a $\cos\theta$ or common-coil dipole; b) an edge-on cable in a block-coil dipole.

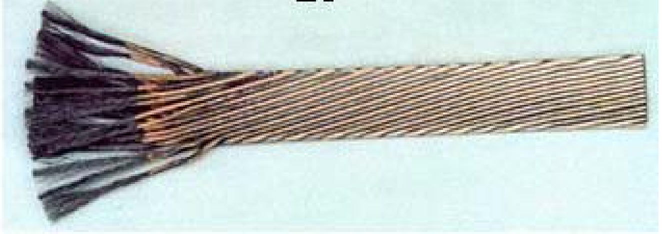
Coupling currents can be controlled by orienting cable || field, coring cable

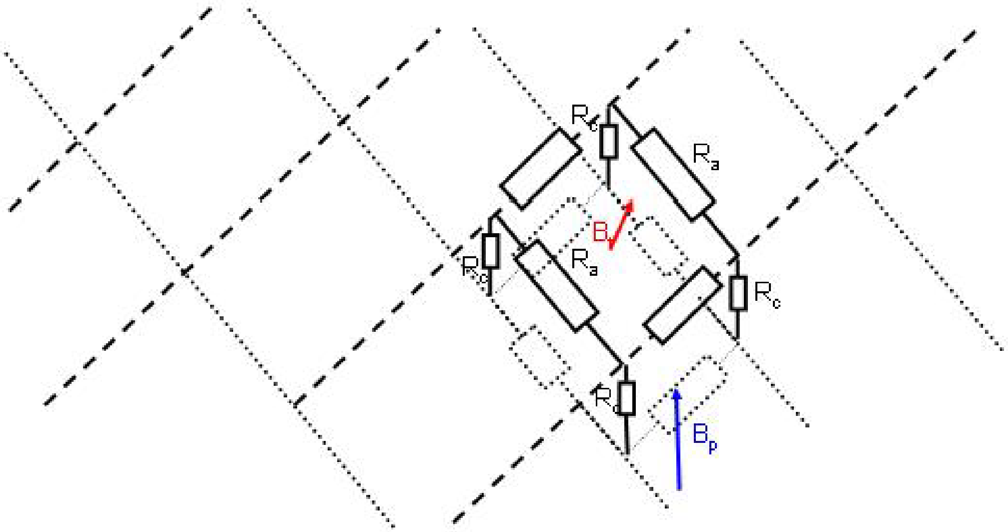
$$P_{tc} = \frac{N(N-1)}{120R_c} \cdot \dot{B}_t^2 \cdot p \cdot \frac{c}{b}$$

$$P_{pa} = \frac{1}{8R_a} \cdot \dot{B}_p^2 \cdot p \cdot \frac{b}{c}$$

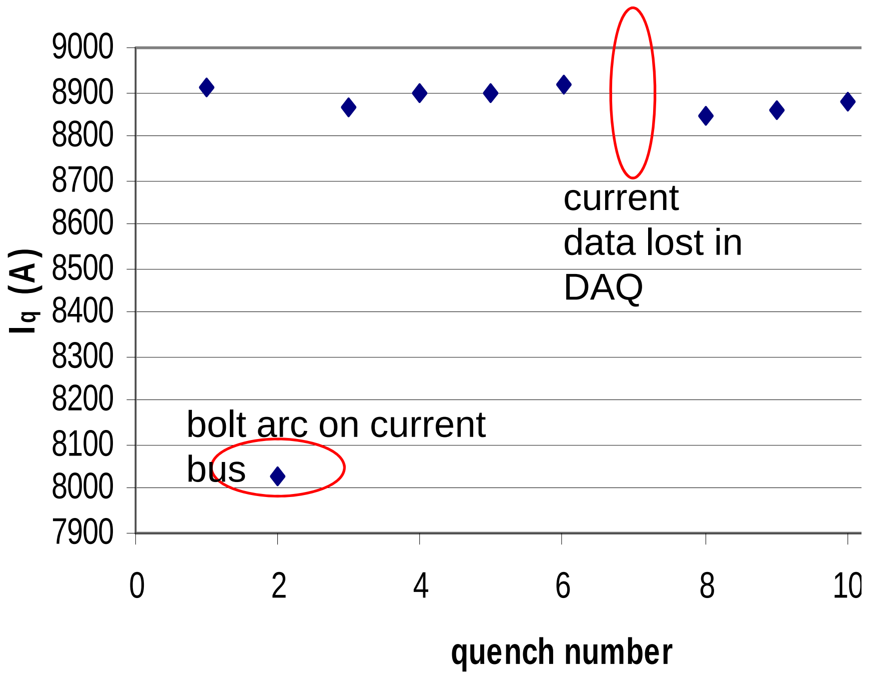
$$P_{ta} = \frac{1}{6R_a} \cdot \dot{B}_t^2 \cdot p \cdot \frac{c}{b}$$

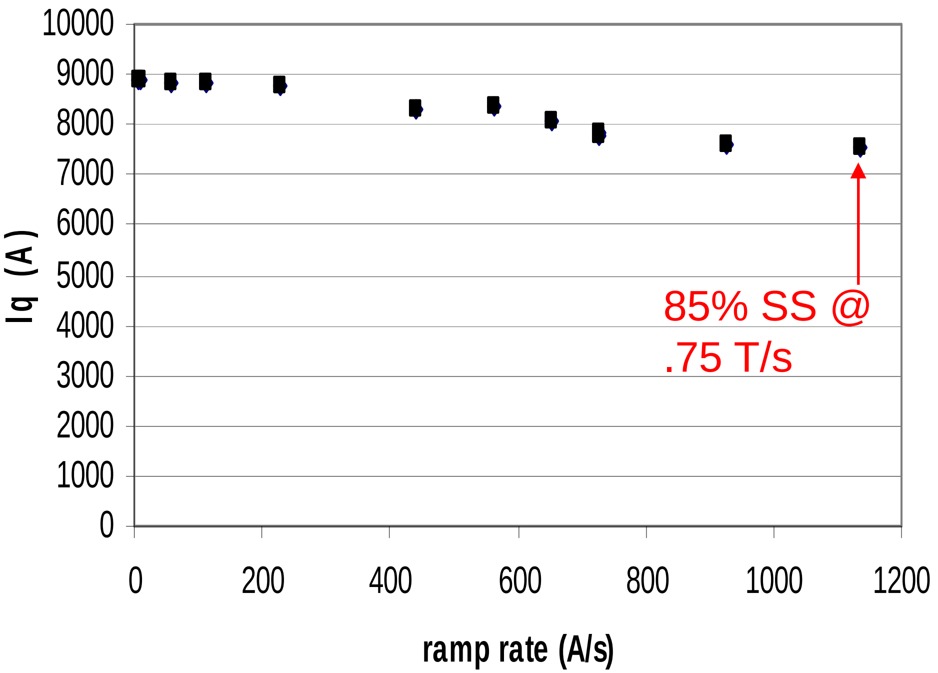






A first taste of the benefits: TAMU2 ramped to 0.75 T/s





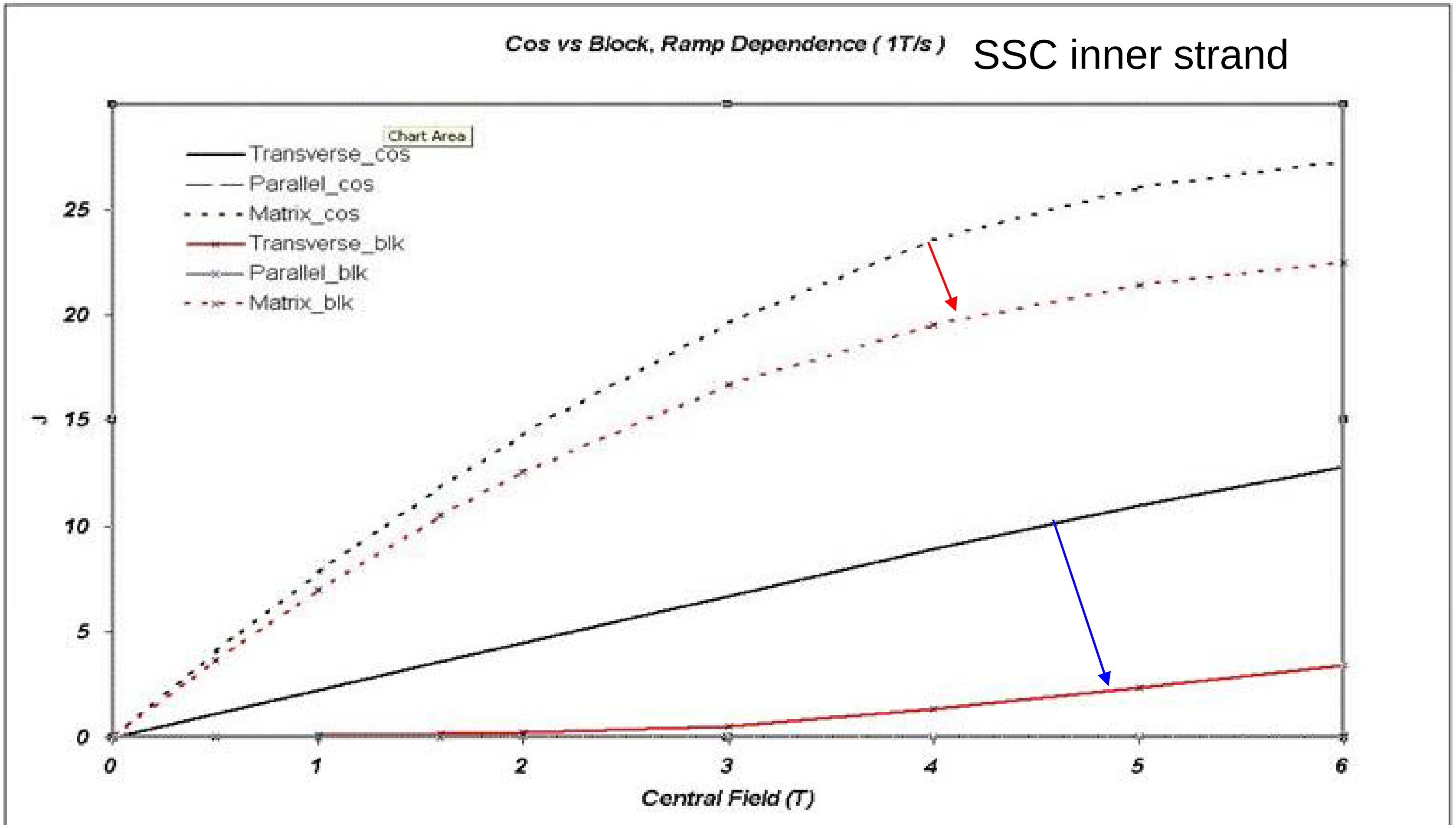
Conductor, cabling not optimized to minimize ac losses… or was it?

Let’s see what could be done to optimize for rapid cycling.

AC losses arise from several sources

- Coupling currents between strands in cable
  - *Block-coil configuration + cored cable can control coupling currents between strands*
- Hysteresis within subelements:
  - *need small subelement size*
- Coupling between subelements:
  - *need optimum matrix resistance*

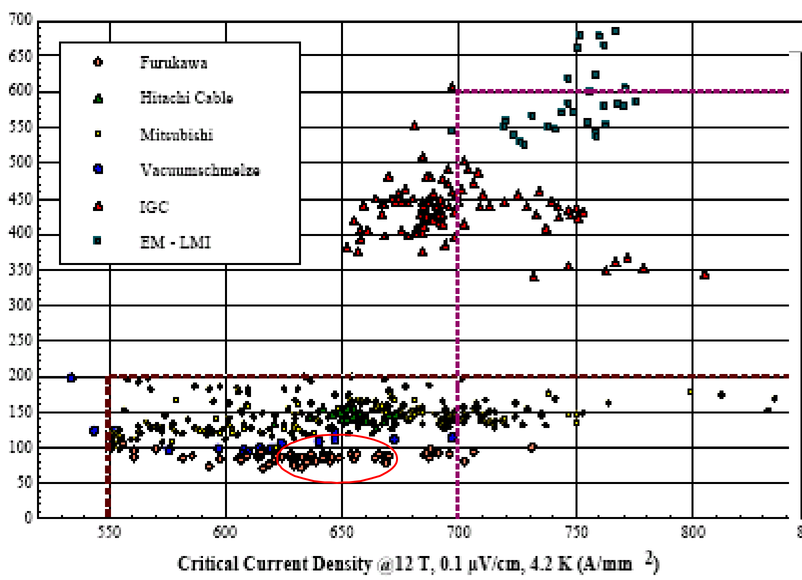
Calculate losses from each mechanism: matrix, hysteresis, para/trans coupling

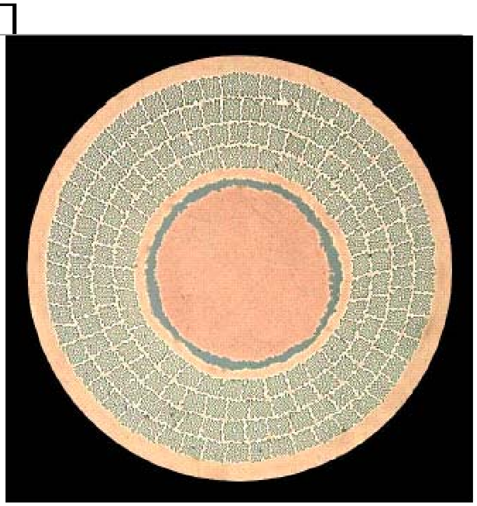


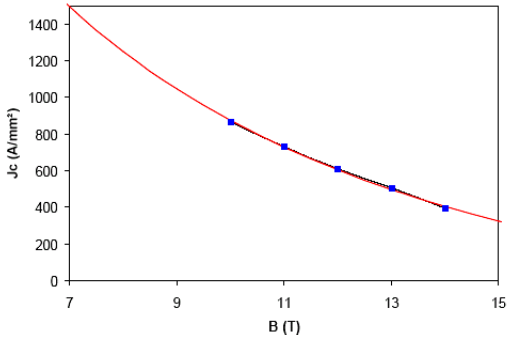
Matrix > Coupling > Hysteresis

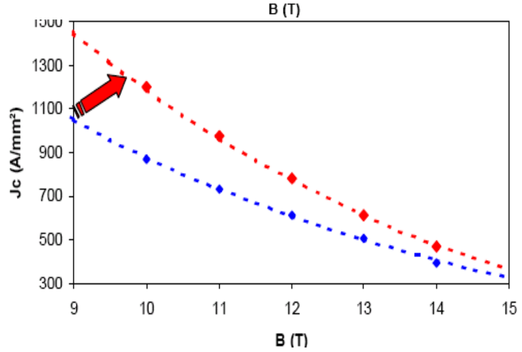
Nb_3Sn Bronze Process: Ultimate in filament size, Optimum matrix resistivity

Payoff from ITER:









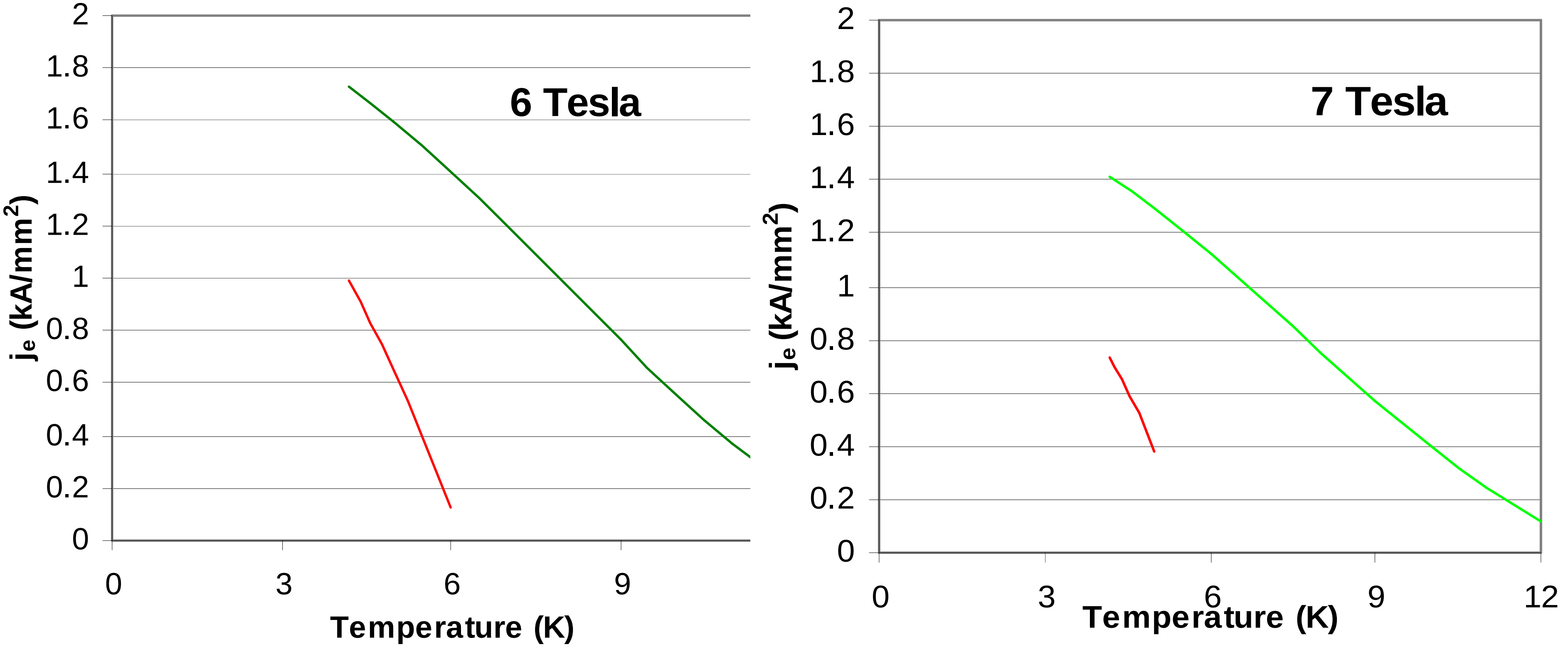
Fine-filament bronze-process Nb3Sn strand from Furukawa: 9800 filaments, 0.8 mm diameter filaments, Cu:SC = 0.2 :

- **strand cross-section;**
- **j_{sc} *vs*. B for nominal heat treat;**
- **optimization of heat treat for high current density.**

Comparison of losses – 1 T/s

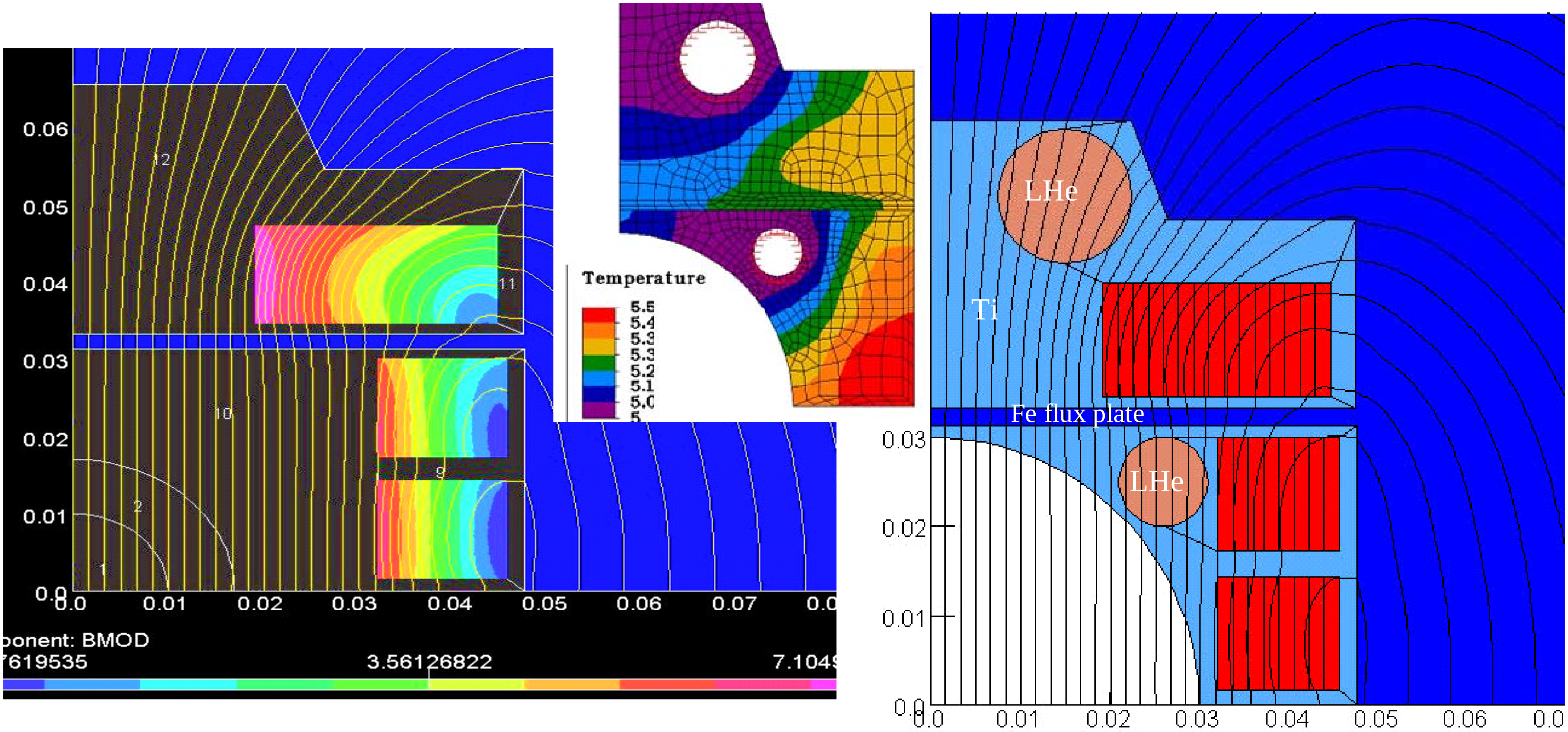
Dipole design	B_{max} (T)	A_{sc} (cm^2)	Bore dia. (mm)	AC loss (J/m/cycle
RHIC-type cos θ	4	13	80	58
Tkachenko cos θ	6	55	100	58
Simple block-coil	6	43	100	40
TAMU block-coil				
- SSC NbTi	6	19	60	34
- bronze Nb_3Sn	6	16	60	20

Payoff in refrigeration



Nb_3Sn: can use 5→6 K supercritical cycle, twice as efficient refrigeration, larger ΔT for heat transport, twice the heat capacity

Optimum design using block-coil Nb_3Sn bronze supercritical He cooling channels

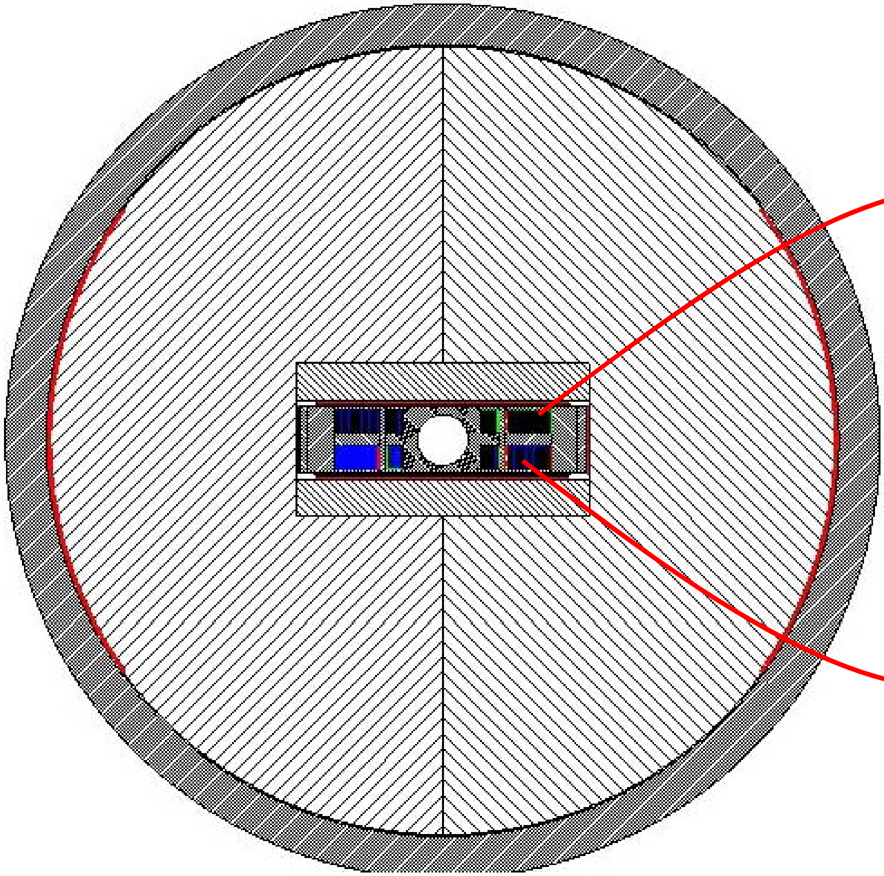


6 T NbTi

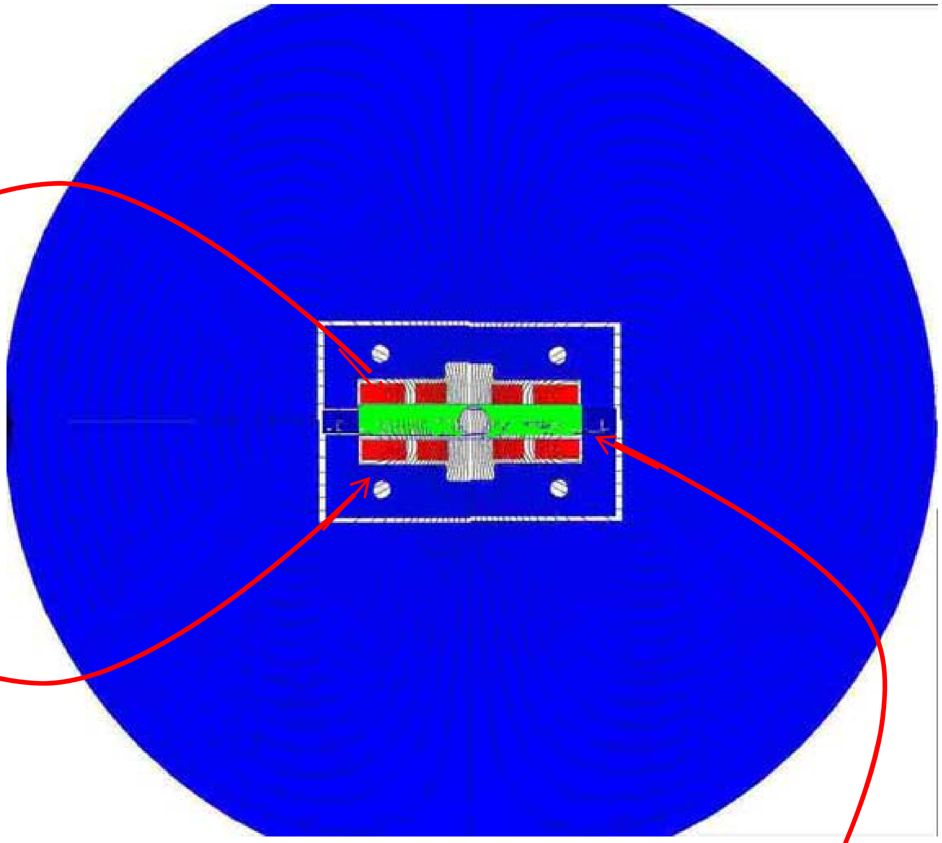
60 mm bore diam.

7.6 T/s with ΔT = 0.5 K, 48 W/m

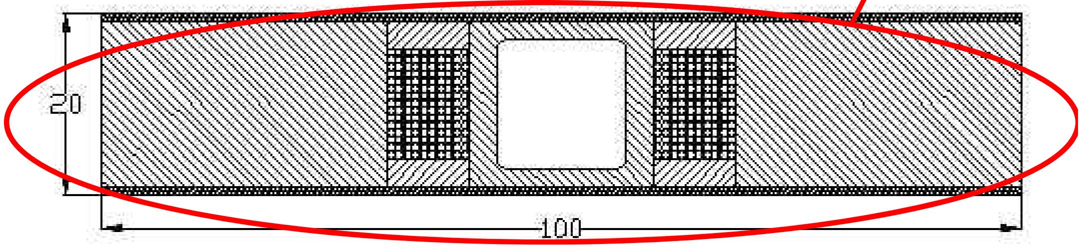
Plans for first tests



TAMU3: 14 T dipole: IT Nb_3Sn



TAMU4: 12 T background field, insert test winding for ramp rate studies.



Conclusions

- Block-coil configuration suppresses coupling losses
- Flux plate suppresses ramp-induced persistent current multipoles
- ITER bronze strand suppresses matrix and hysteresis losses
- Nb_3Sn gives x2 improvements in
  - ac losses
  - heat capacity
  - heat transport
  - refrigeration efficiency

- *We hope to show that bronze-process block coil dipole could win the race!*