HTS Program at BNL Superconducting Magnet Division

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Topics for Discussions

- **Test Results of ASC Wires**
  - **1G and 2G Conductors**
- **Funded Programs**
  - **RIA and ERL**
- **Future Possibilities**
  - **ILC, LHC Upgrade, Neutrino Facilities, NSLS2, Medical Applications**

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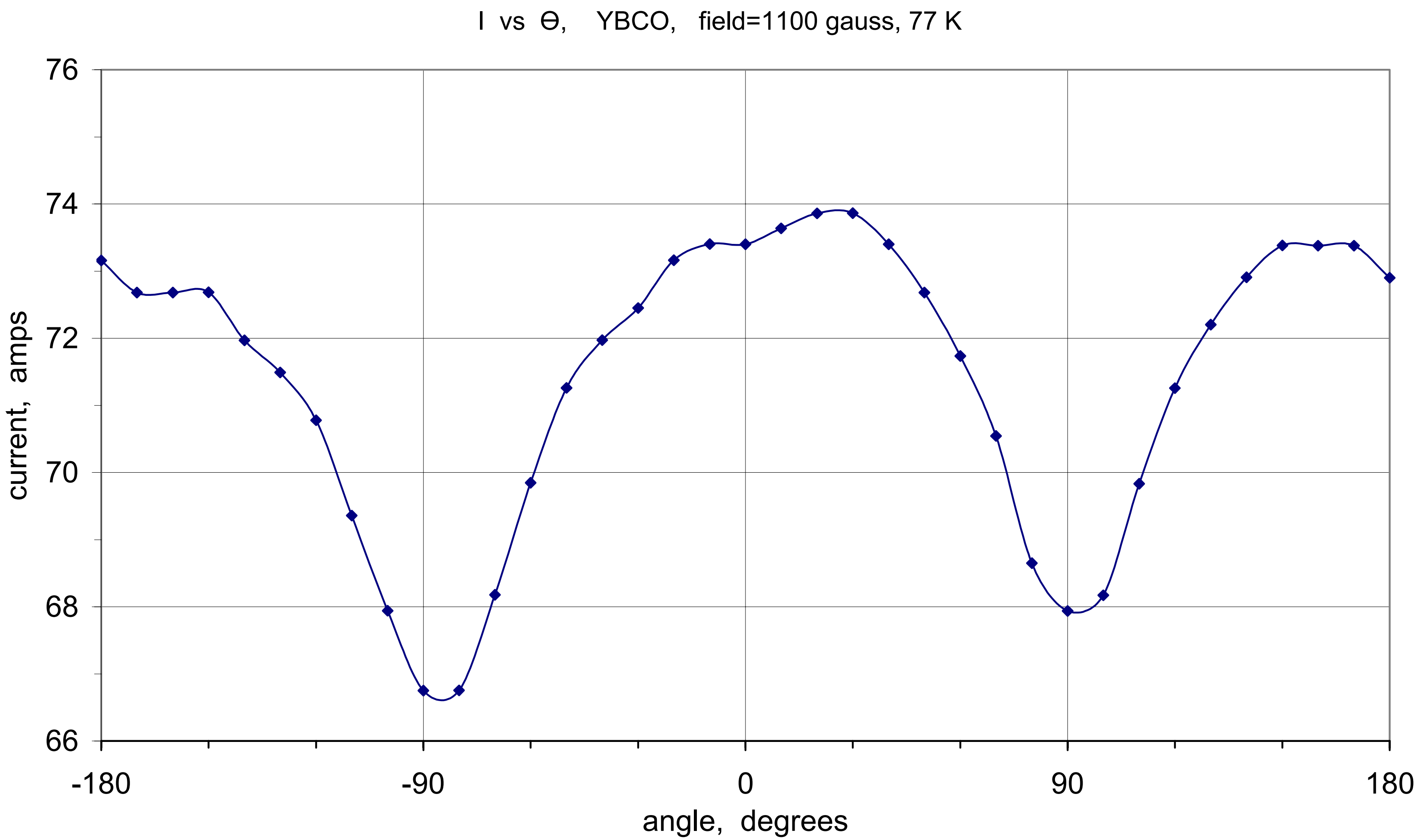
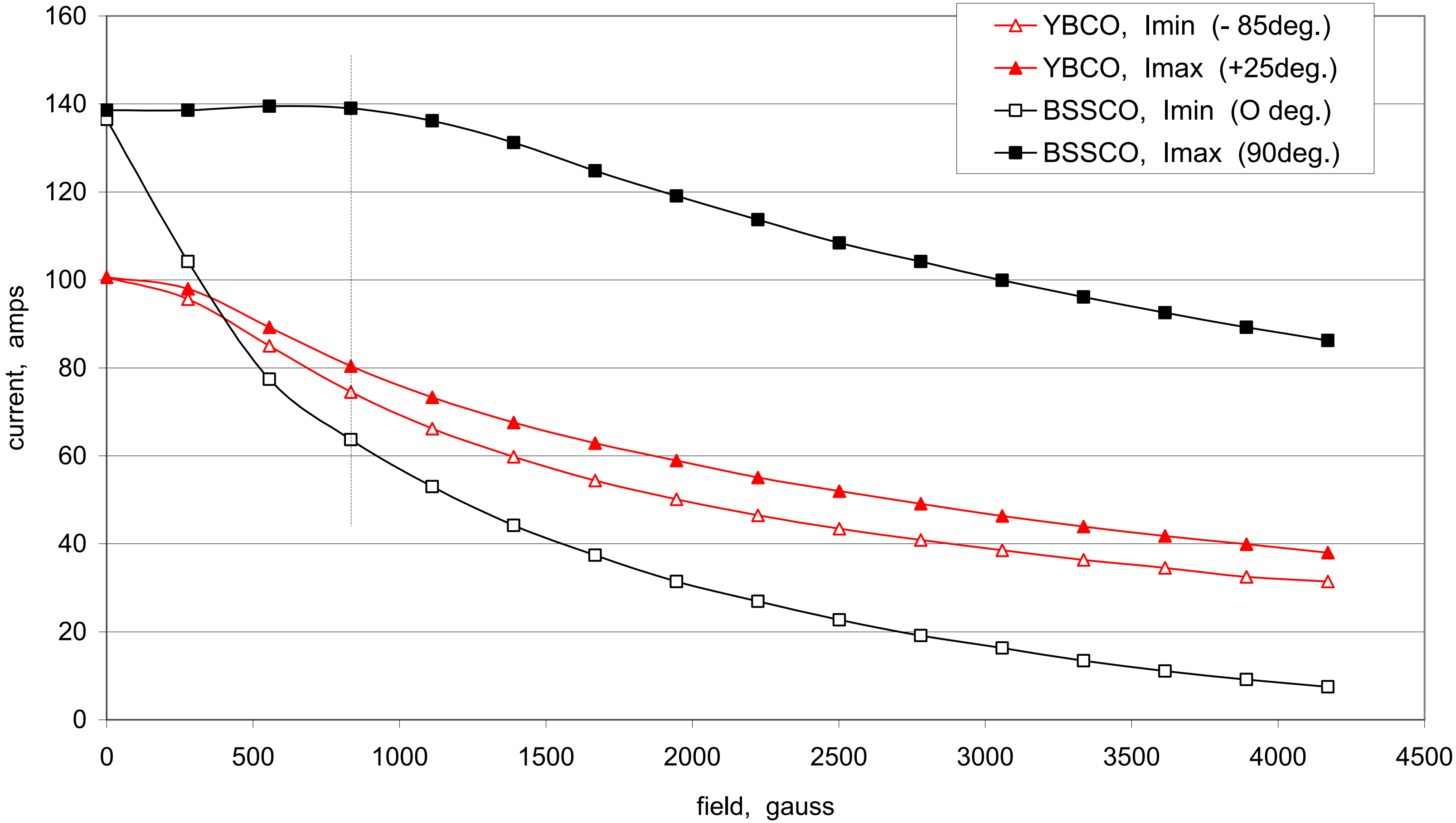
Angular Dependence of YBCO Nanodot Conductor from ASC



This small variation of Ic as a function of field is of great interest in many applications (of course, we would gladly take higher Je any day)

Comparison Between Certain 2G and 1G HTS from ASC



Much smaller current dependence in 2G as compared to 1G.

In this particular case field perpendicular is better than field parallel…

- **How do you do that? Can you control or tune such angular dependence?**

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Future Obviously Belongs to the 2nd Generation Wire

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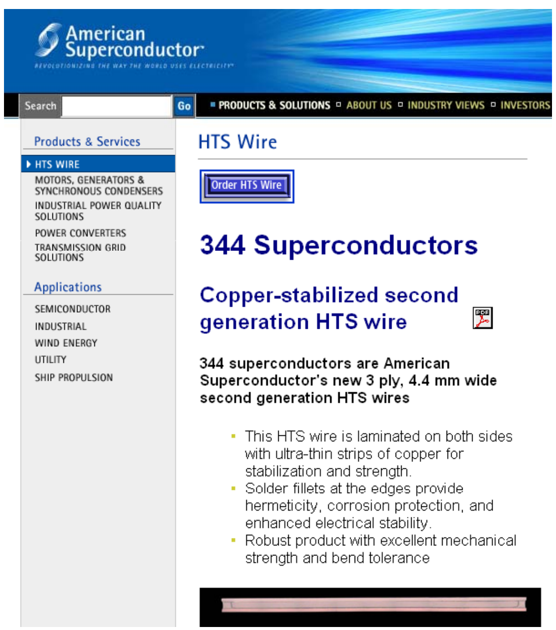
Status of 2nd Generation HTS

- 2nd generation HTS are becoming available in longer lengths.
- 2nd generation HTS are available from multiple vendors. We are placing purchase order from two US vendors for several hundred meters of conductor with I_c(77K)>90 A (quotations for 100 m and 100 m long wires)
- 2nd generation HTS cost is decreasing rapidly - they are projected to become cost competitive to 1st generation HTS within two years.



2G Wire Price is dropping rapidly!

SuperPower

Longer piece lengths, Higher throughput, Higher Ic,

Higher yield, Lower raw material cost

– all in the last few months have resulted in lower 2G production cost

SCS4050	$ /m	Ic (A) 4 mm wide 77 K, self field	$/kA-m
2006	100	80	1250
2007	65	100	650

4 mm wide with copper stabilizer

SF12050	$ /m	Ic (A) 12 mm wide 77 K, self field	$/kA-m
2006	150	240	625
2007	90	300	300

12 mm wide without copper stabilizer

In addition to all other benefits over 1G, 2G can be cost-competitive with 1G by the end of 2008

2007 DOE Wire & Applications Workshop – 29 –

Possible Future Applications

- **Two line of applications**
  - ➢ **Very high fields (special applications)**
  - ➢ **Medium field, operating at as high temperature as 65 K.**

    Development of such a technology may have multi-platform and potentially larger volume applications (for example, beam line magnets, medical applications, etc.)

In addition, the ability of HTS to withstand and economically remove large amount of deposited energy offers a unique advantage in several accelerator applications such as RIA, LHC and ILC, etc.

Funded Programs

RIA – Rare Isotope Accelerator

- We have obtained ~1.3 million dollars
- We have built and tested 25 coils with 1G conductor from American Superconductor
- We have built and tested three magnet configurations
  - o Cold iron mirror configuration with six coils
  - o Warm iron mirror configuration with twelve coils
  - o Warm iron full magnet with twenty four coils
- In addition, we have done important energy deposition experiments
- RIA now has a new name with reduced scope to meet budget guidlines:
  - ⇒ Facility for Rare Isotope Beams (FRIB) or Rare Isotope Beam Facilities
- Next stage of program for us is to evaluate the benefits of using 2G conductor which could allow the magnet to operate at ~50 K rather than ~30 K

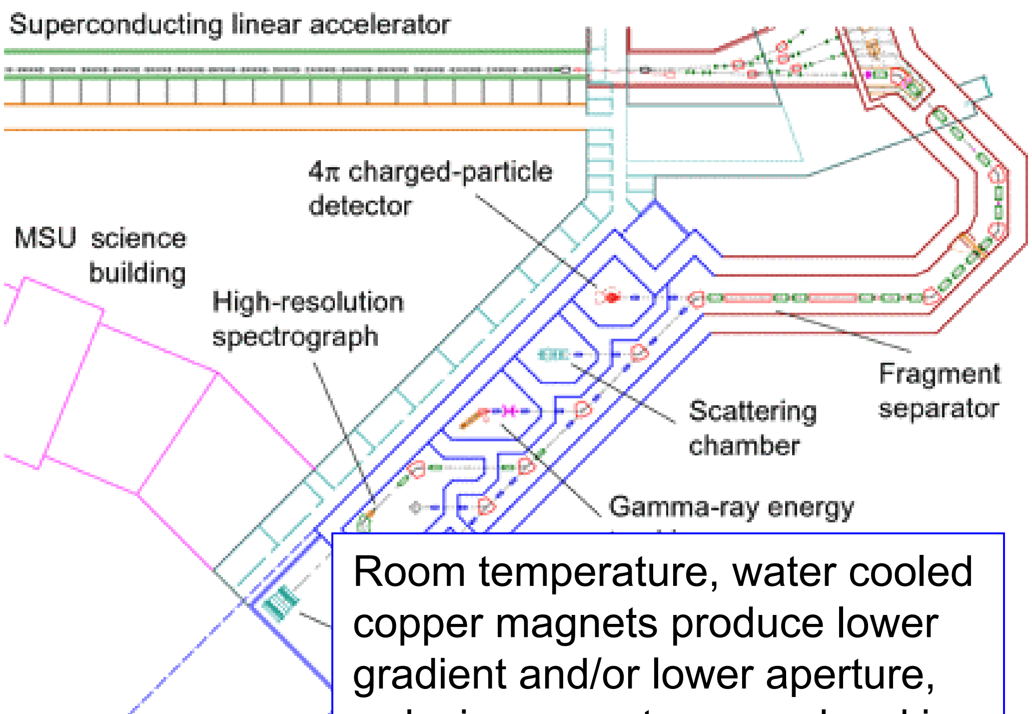
ERL – Energy Recovery Linac

(parameters matches with another important application)

- HTS Solenoid
- Coils have been built and tested

Fragment Separator Region of RIA

Magnetic elements (quads) in the fragment separator region will live in a very hostile environment with a level of radiation and energy deposition never experienced by any magnet system before.



Room temperature, water cooled copper magnets produce lower gradient and/or lower aperture, reducing acceptance and making inefficient use of beam intensity.

- 400 kW beam power.
- ~15 kW in first quad.
- Special design reduces this to ~130 W in cold structure.
- Still a large amount heat to be removed at cold temperature
- Heat removal at ~30 K is order of magnitude more efficient than at ~4K
- Situation will be even better if it is removed at ~50 K with 2G conductor.
- Radiation damage studies for both 1G and 2G is part of the proposal.

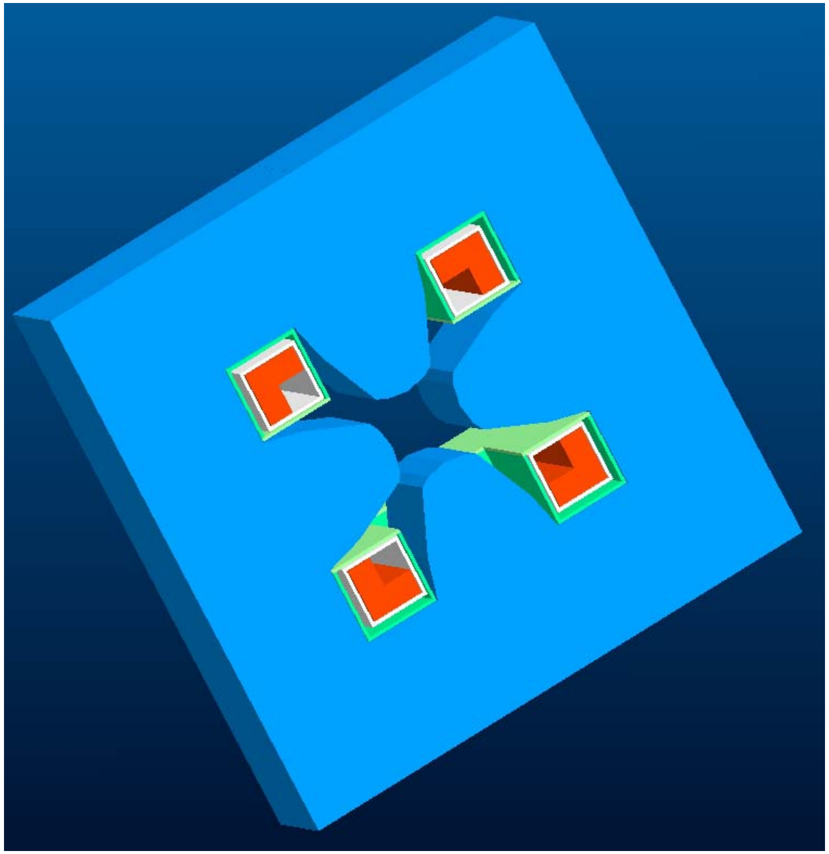
Need "Radiation resistant" super-ferric quads that can stand these large heat loads.

Basic Design of RIA HTS Quadrupole

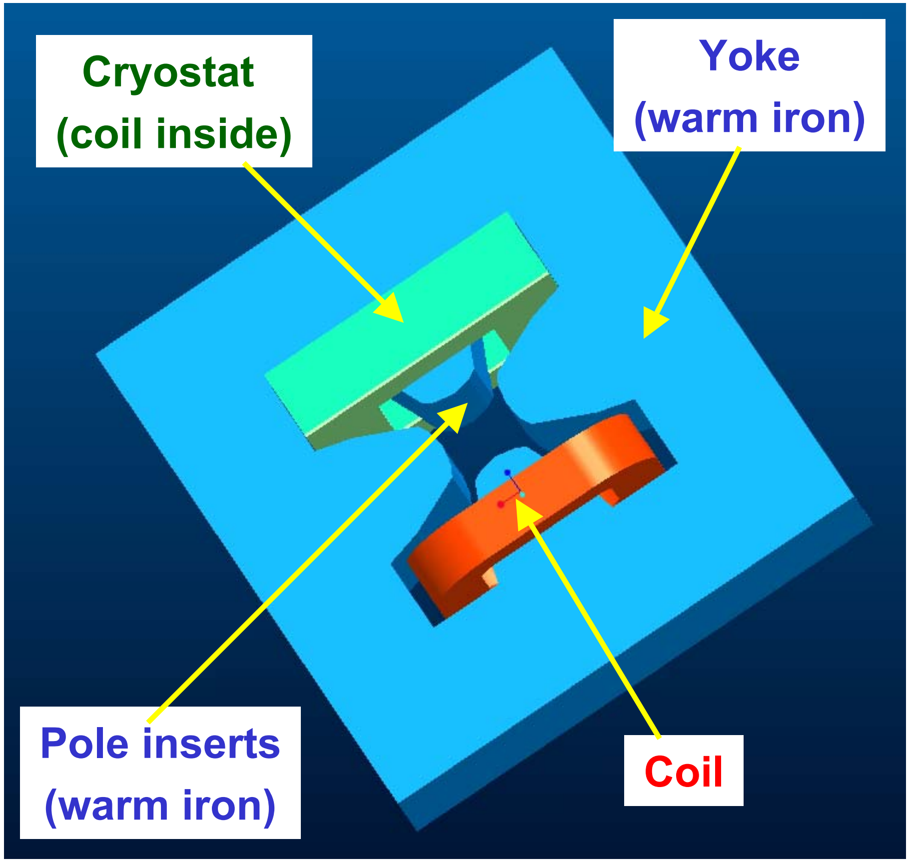
A simple warm iron super-ferric quad design with two racetrack HTS coils

Note that only a small fraction of the mass is cold (see green portion), and also that it is at a large solid angle from the target .

Also two (NOT four) coils means lower heat and radiation load at the ends.



Cutout at the middle of the magnet

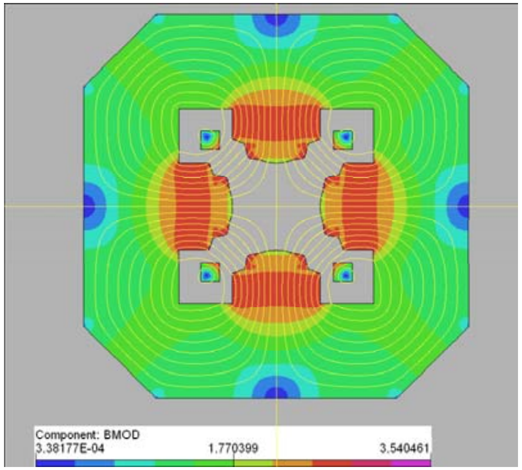


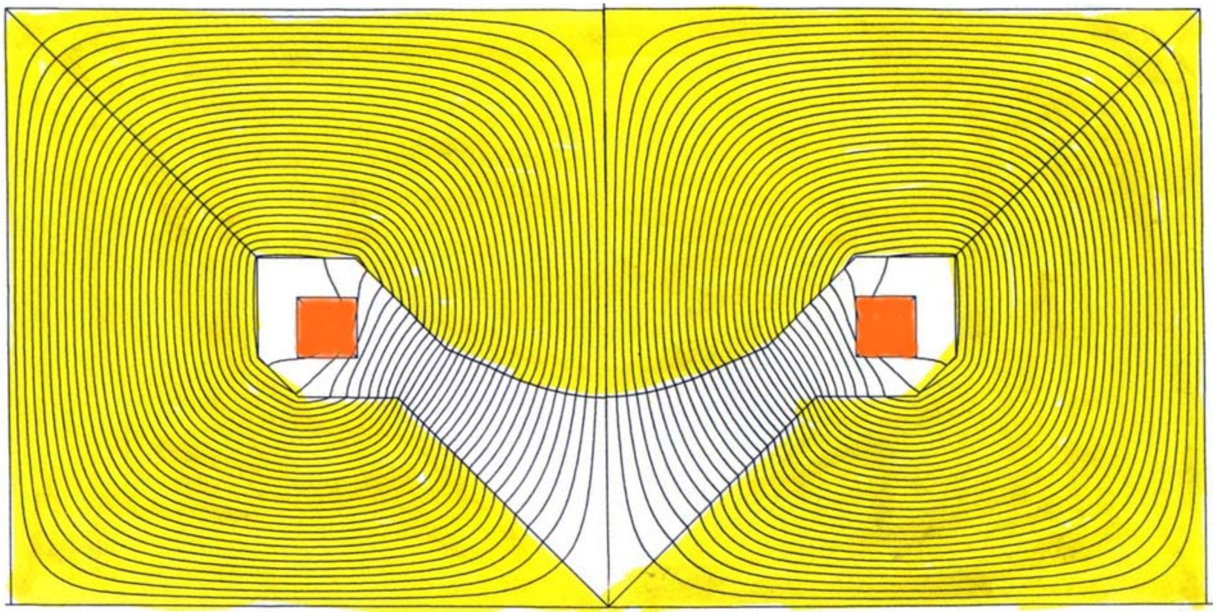
Coils inside the cryostat at the end of the magnet

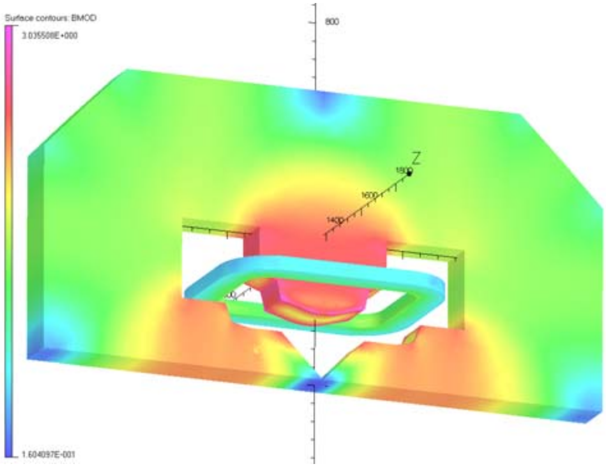
Magnetic Mirror Model of RIA HTS Quadrupole magnet

A phased program was developed in response to expected funding schedule which allowed us to demonstrate key technical issues along the way.

- **Cold iron mirror configuration with six coils**
- **Warm iron mirror configuration with twelve coils**
- **Warm iron full magnet with twenty four coils**

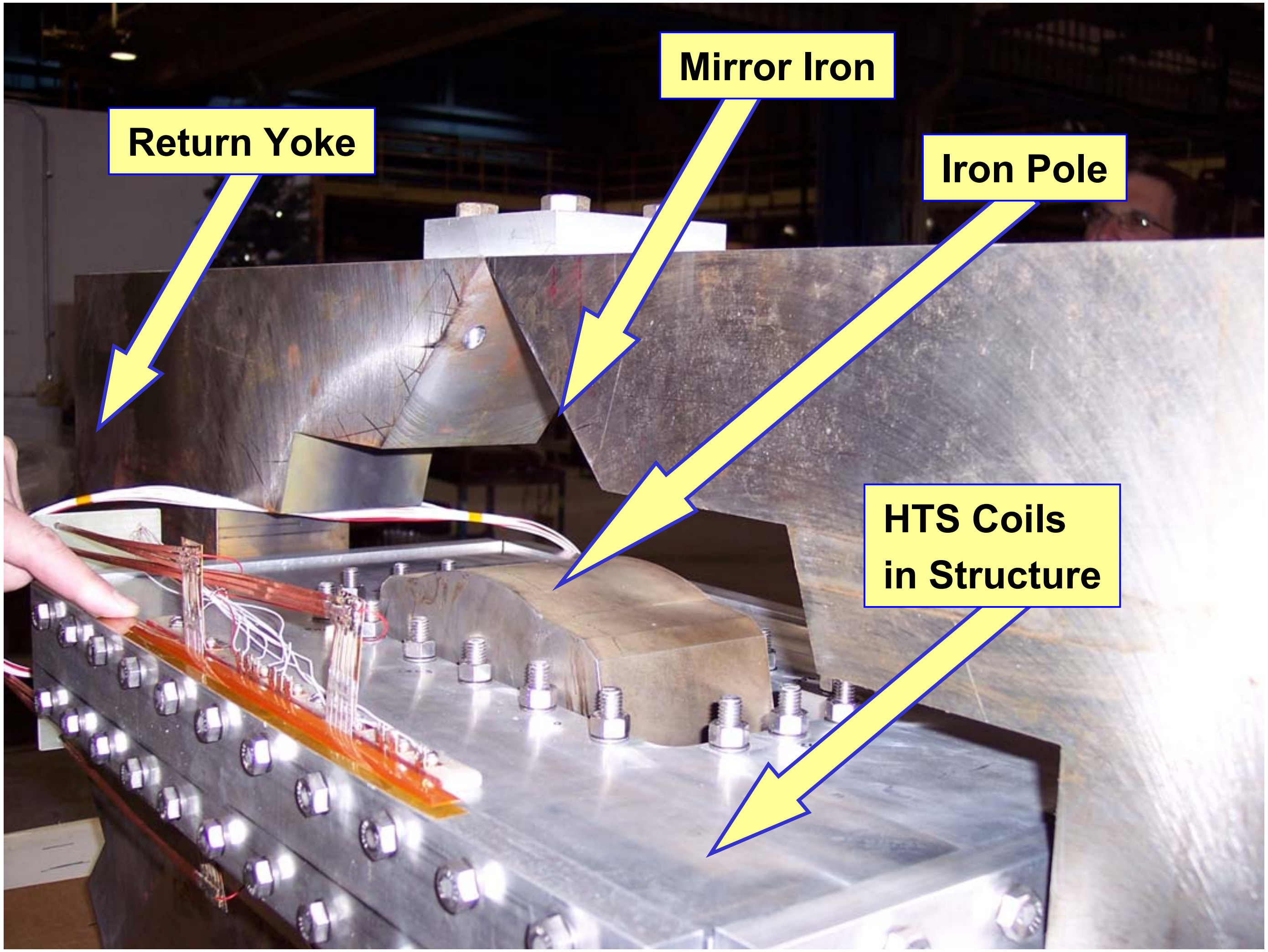






Magnetic Mirror model is cheaper as it requires ¼ number (six layers) of HTS coils.

Magnetic Mirror Model



Coils in their bolted support structure, with the pole iron (in the middle, inside the structure), magnetic mirrors (two on the upper side with 45 degree angles on either side of the vertical axis) and iron return yoke.

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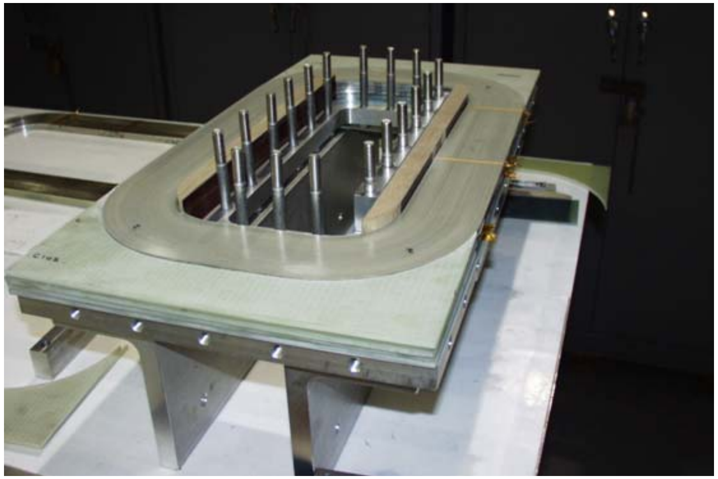
RIA HTS Quadrupole At Various Stages of Construction and Testing

HTS coil winding with SS tape insulator

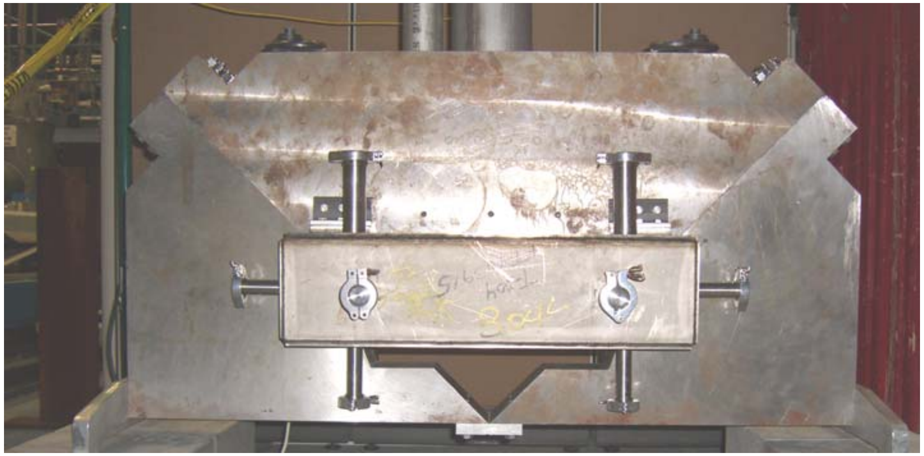
The RIA HTS model magnet has been successfully built and tested.

Experiments of magnet operating with large energy depositions (tens of watts in 0.3 meter long magnet) have been also carried out.

Cold iron magnetic mirror test with six coils



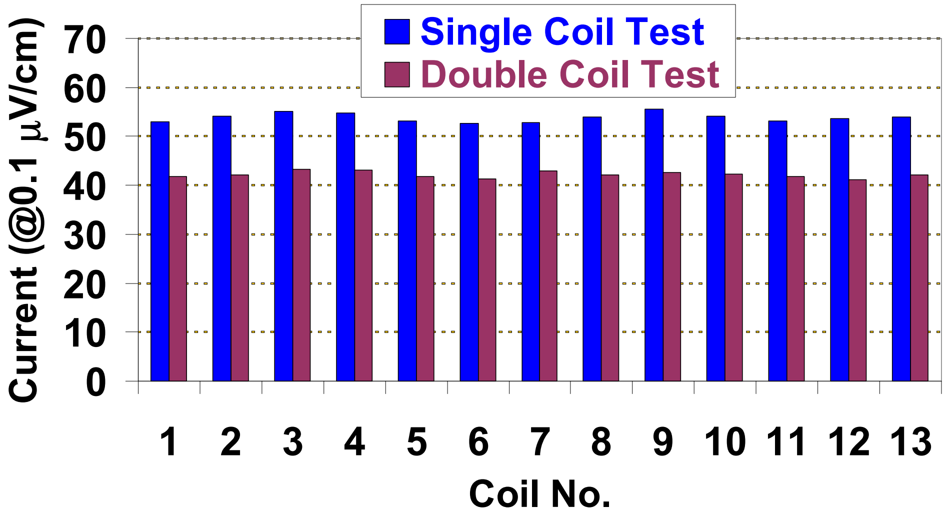
HTS coils during magnet assembly



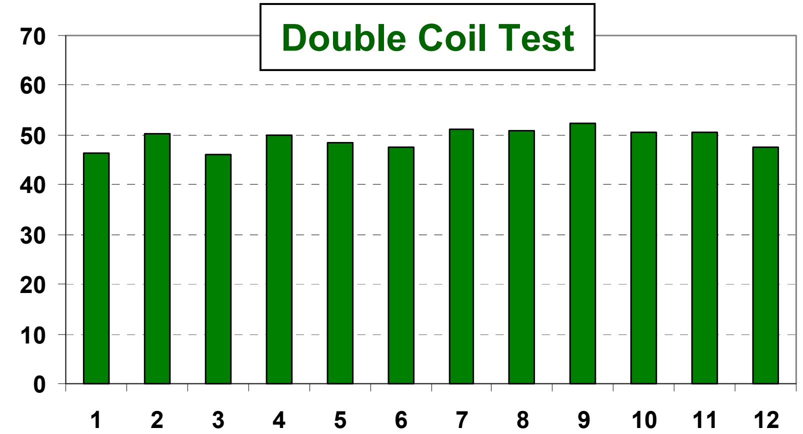
Warm iron magnetic mirror test with twelve coils

LN_2 (77 K) Test of 25 BSCCO 2223 Coils

13 Coils made earlier tape (Nominal 175 turns with 220 meters)



12 Coils made with newer tape (150 turns with 180 meters)



Note the uniformity in performance of coils made with commercially available HTS.

Coil performance generally tracked the tape performance pretty well.

Above coils were also tested at lower temperatures in conduction-cooled and direct-cooled (dunked in liquid helium) modes.

All HTS tapes were purchased from ASC

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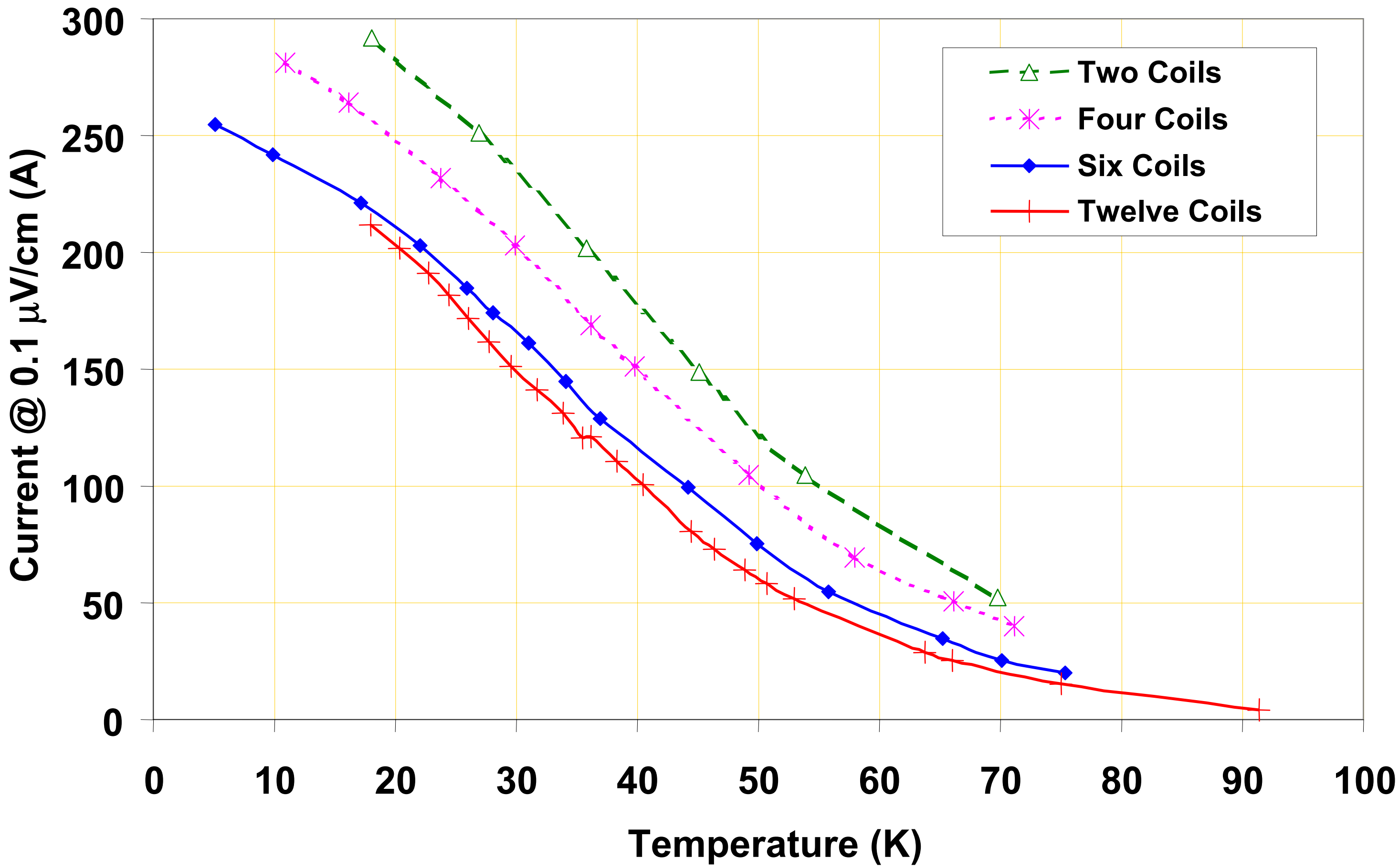
RIA HTS Mirror Model Test Results (operation over a large temperature range)

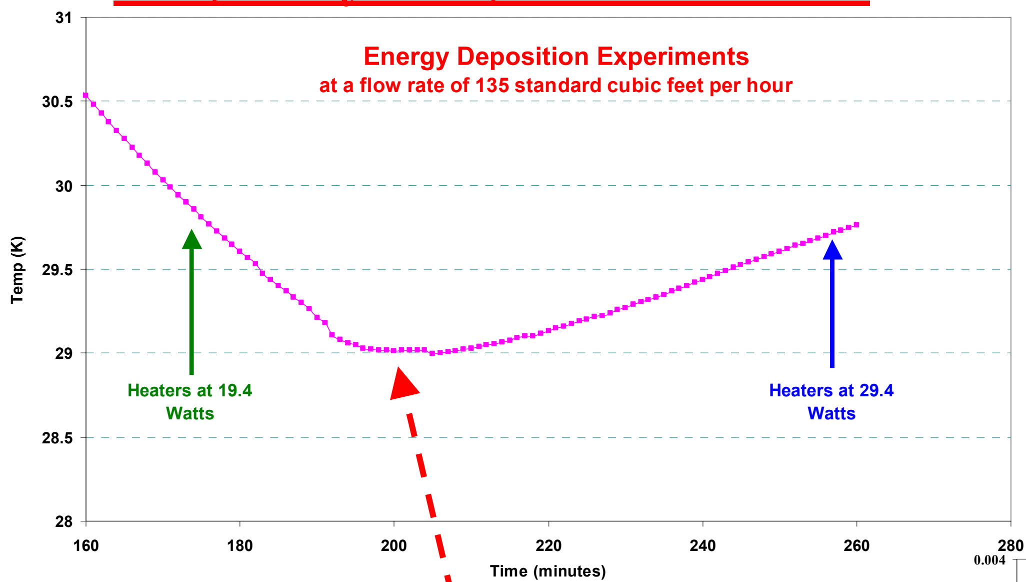


More coils create more field and hence would have lower current carrying capacity

A summary of the temperature dependence of the current in two, four, six and twelve coils in the magnetic mirror model. In each case voltage first appears on the coil that is closest to the pole tip. Magnetic field is approximately three times as great for six coils as it is for two coils.

Large Energy Deposition Experiments In RIA Coils In Mirror Model Magnet

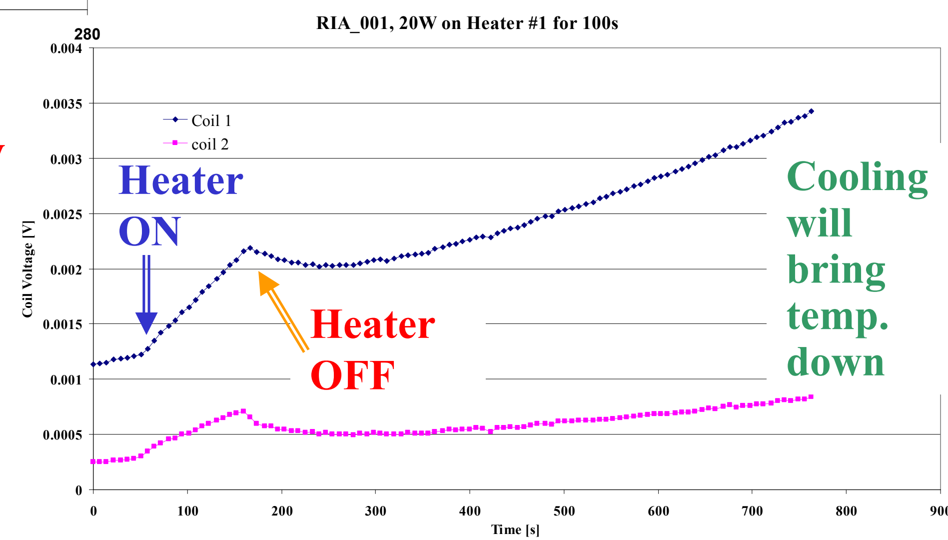
DC (steady state) Heat Load Test



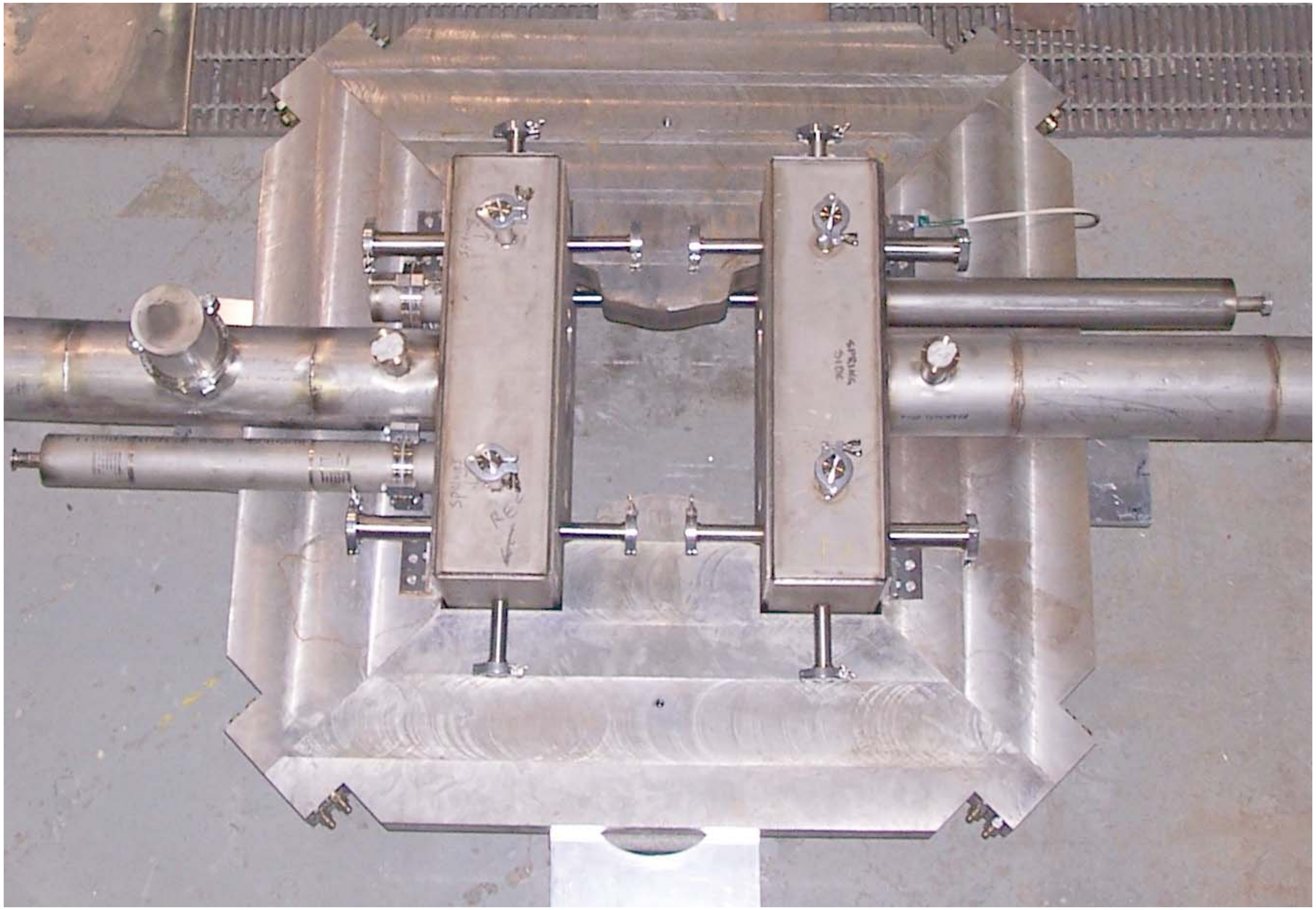
- Current in heaters changed to change steady state heat load from 19.4 Watts to 29.4 Watts.
- Computed steady state value is ~26 Watts.
- 0.3 m long HTS coil, remains Superconducting during these tests.

Impulse Heat Load Test

A heat pulse of "20 W for 100 sec" is given and then coil resistance (voltage) is observed.



Full HTS Model Quadrupole For RIA



The test also involved a 40^{+} minutes of stable operation at 30 K with a huge 25 W ($5mW/cm^3$ or $5kW/m^3$) heat load on coils.

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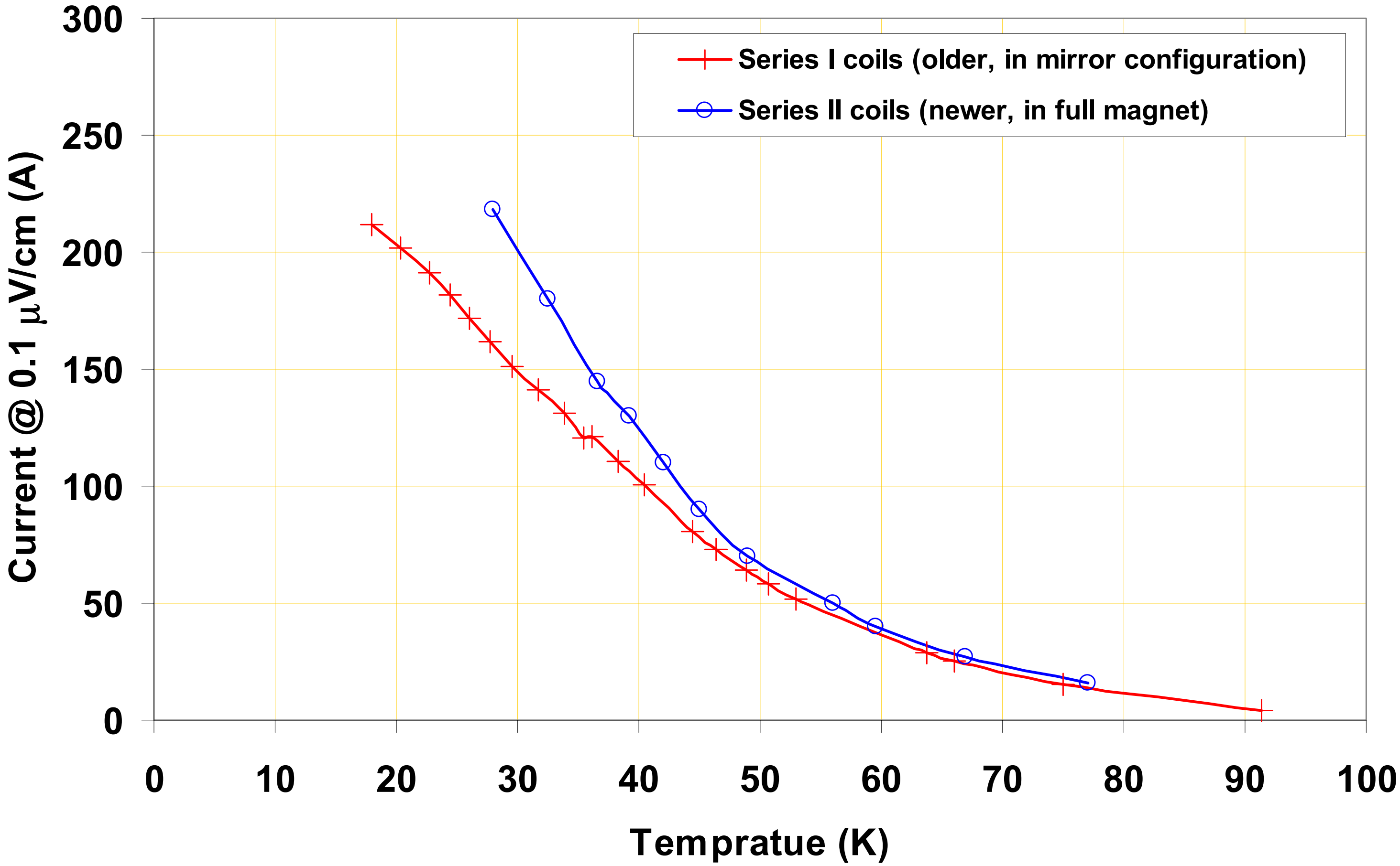
RIA HTS Full Model Test Results
(operation over a large temperature range)

Comparison between performance in a set 12 coils made with previous conductor (mirror model) and newer conductor (full model):



Newer is better. Temperature dependence in performance is being examined.

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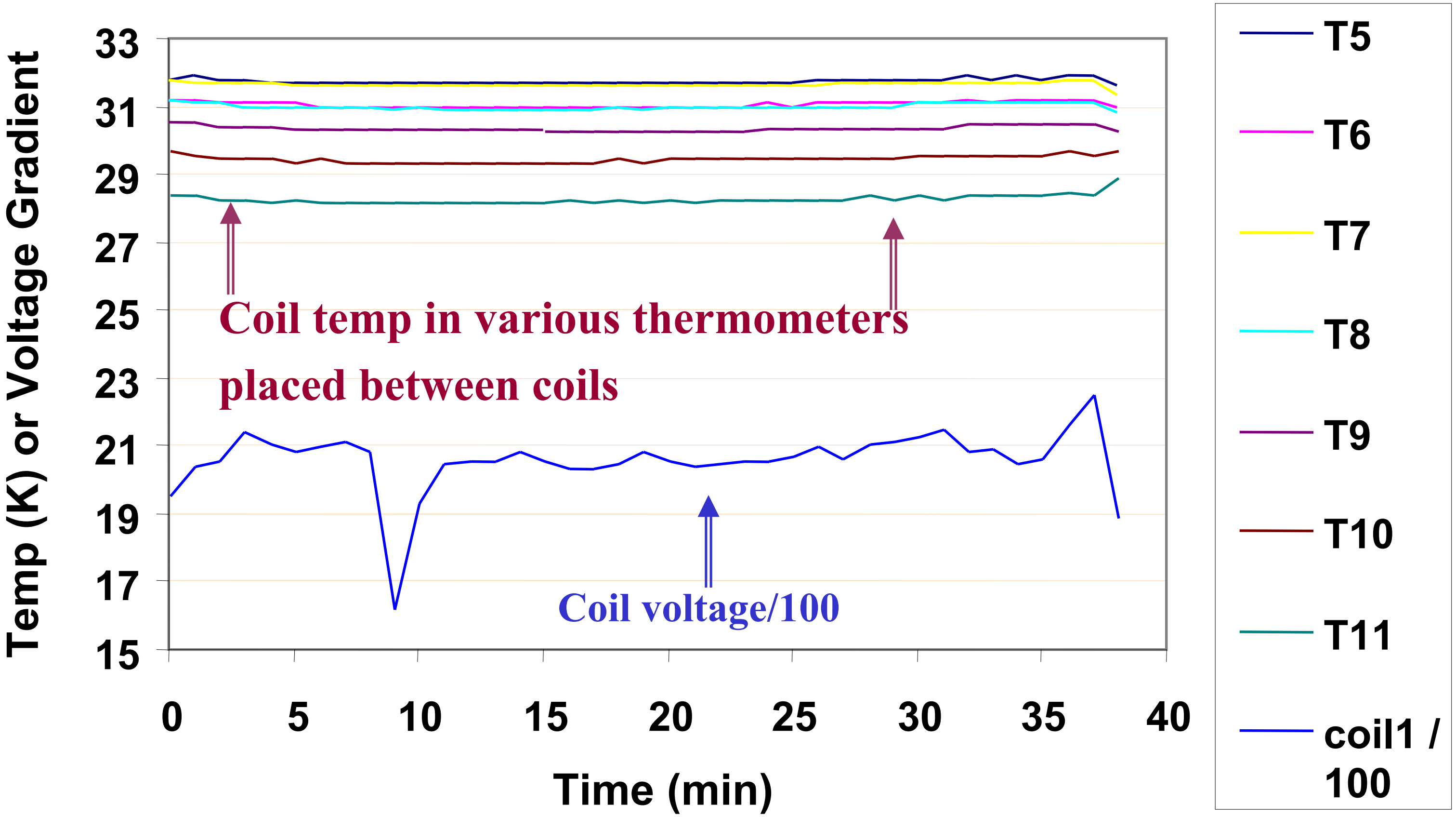
Large Energy Deposition Experiments In RIA Coils In Full Model Magnet

Stable operation at 30 K of HTS model magnet with a 25 W (5mW/cm^3) DC (steady state) heat load on coils.

- **A critical demonstration for RIA.**



T5 to T11 show tempe-ratures at different thermo-meters placed between the coils

- **Stable/Flat operation; spikes in coil voltage are related to noise!**

RIA HTS Quad Plans and Forecast for Near Future

The present goal is to move to 2nd Generation wire

FY 2007:

- **Make 3 coils each using 100 meters of 2nd generation wire**
- **It is important to use wire that has "good in-field performance"**
- **Make 2 coils with wire from ASC wire and one from SuperPower**
- **Study Ic in coil as a function of Temperature**
- **Determine the improvement in performance needed to obtain desired field gradient in at 50-60 K.**

FY 2008:

- **If we are within a factor of two (or projected to be within the fiscal year), scale-up the program similar to that done with BSCCO-2223. We are optimistic.**
- **Continue experimental studies on radiation damage on YBCO and BSCCO to determine if one is significantly better than other.**

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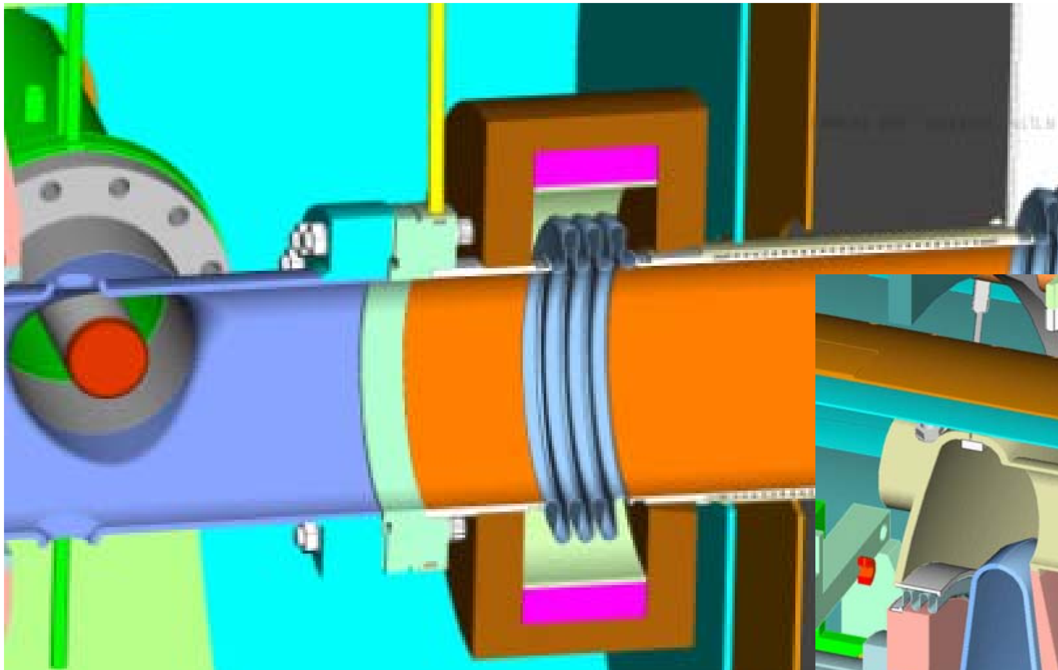
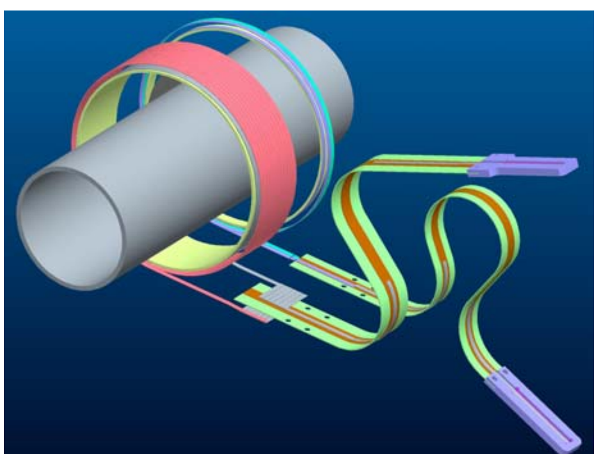
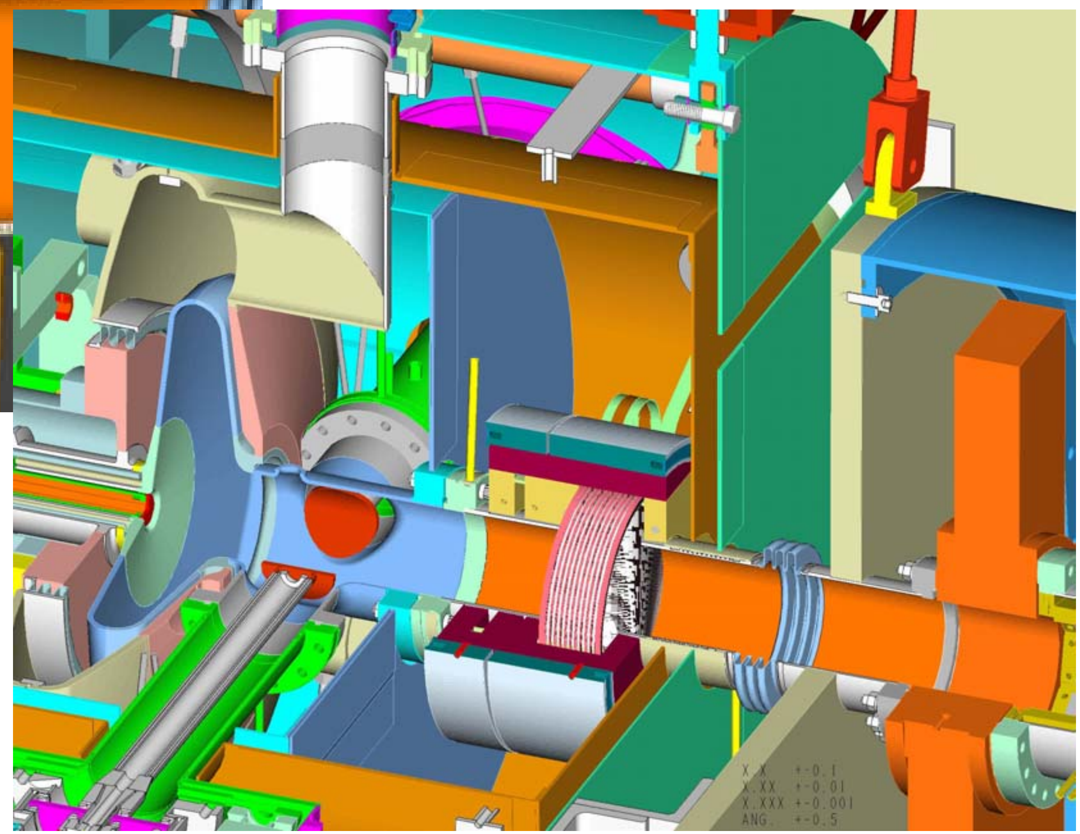
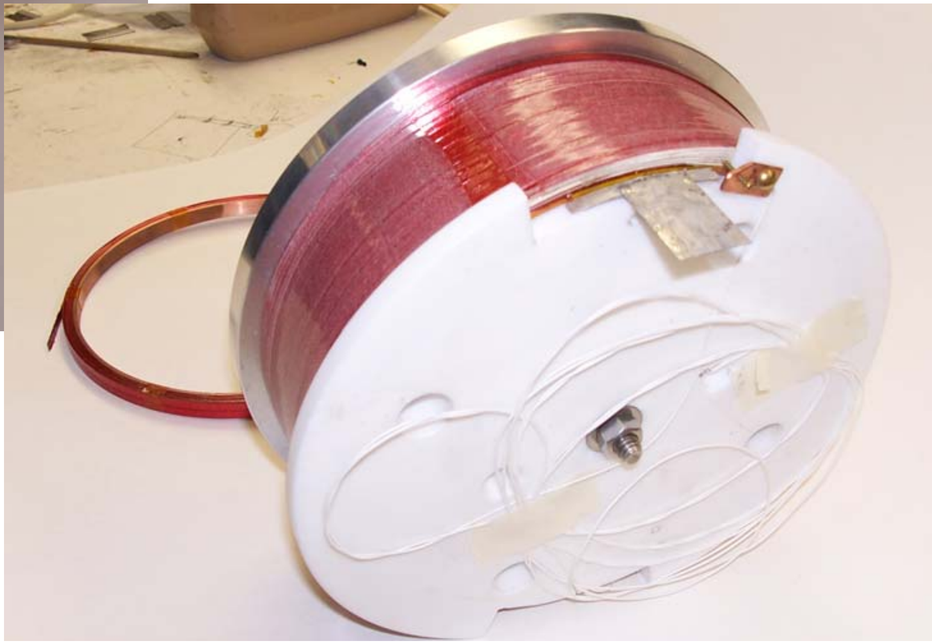
HTS Solenoid for Energy Recovery LINAC (ERL)





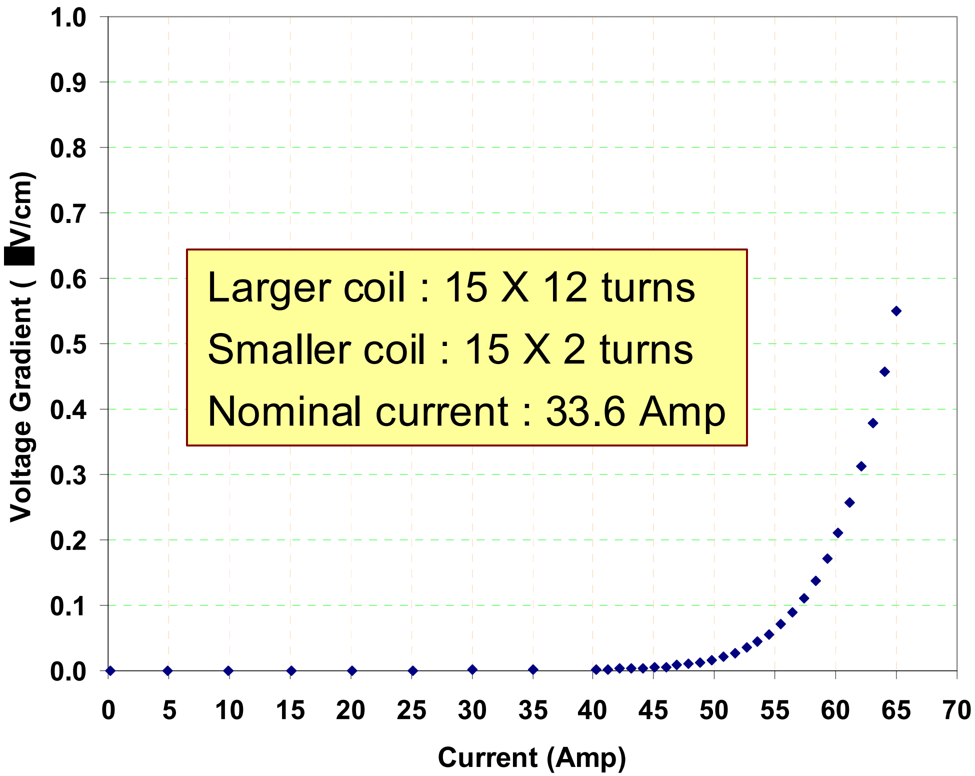


HTS Solenoid Coils



Performance of Solenoid Coils (at 77 K in the absence of yoke)

Test results of larger coil



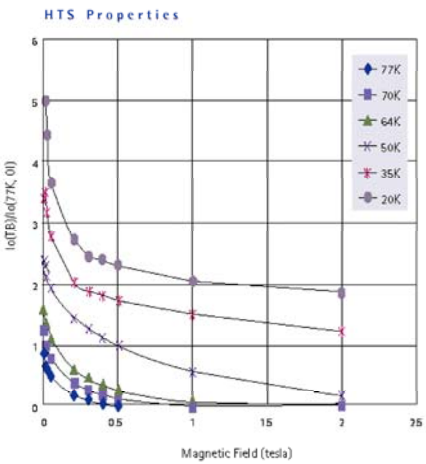
Design current ~34 A @ 0.1 µV/cm (industry spec more liberal: @ 1 µV/cm)

- **Larger coil was successfully operated well above the design current (~34 Amps) even at 77 K (higher value expected at 5-10 K), and without yoke (higher value expected with yoke).**
- **Smaller coil was also recently tested and it successfully operated at ~80 Amps in similar conditions.**
- **These test should be considered as certification of HTS solenoid for its ability to reach design current.**
- **These tests do not address the field issue (fringe field, etc.).**

Possible Future Projects

Future of Medium Field HTS Magnets in Accelerators and Beam Lines

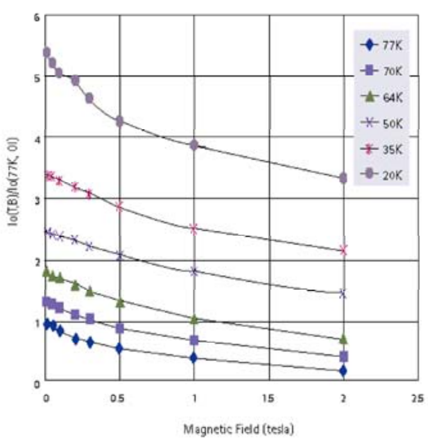
Ic Vs. B at different operating temperature in the first generation wire



Field Perpendicular

Bi-2223 performance at different temperatures and fields compared to the performance at 77K for field perpendicular to the tape surface.

Field Parallel



Bi-2223 performance at different temperatures and fields compared to the performance at 77K for field parallel to the tape surface.

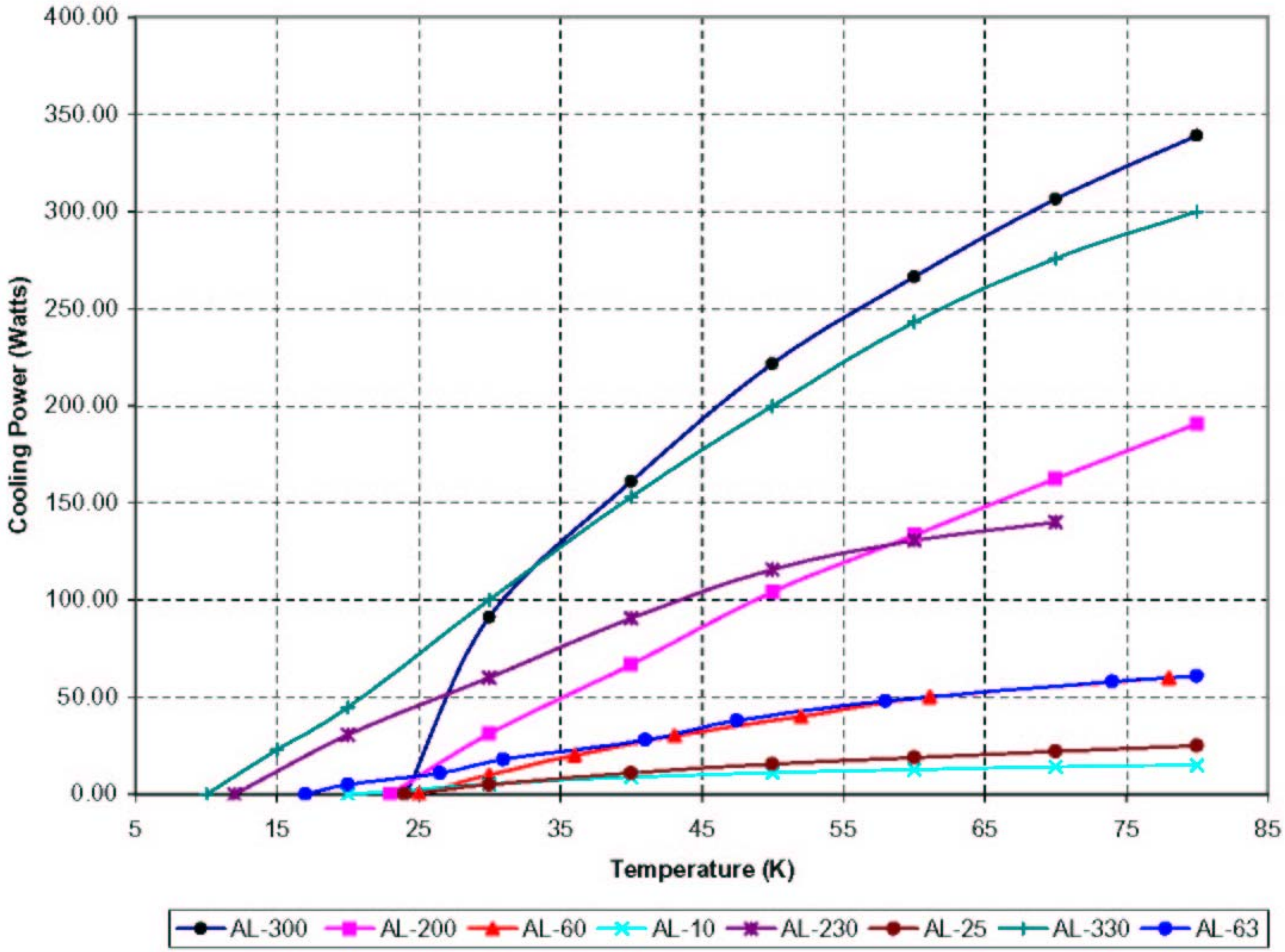
- Medium field (1-3 Tesla) HTS super-ferric magnets operating at ~35K (or even higher temperatures) are an interesting possibility for future beam line and accelerator magnets.
- A ~60 K operation with second generation superconductor may become even more attractive option.

A million dollar question?

Can future HTS magnets compete with water cooled copper (room temperature) magnets in terms of the cost of ownership (capital + operation) in a number of years?

Capacity of Cryo-coolers as a Function of Temperature

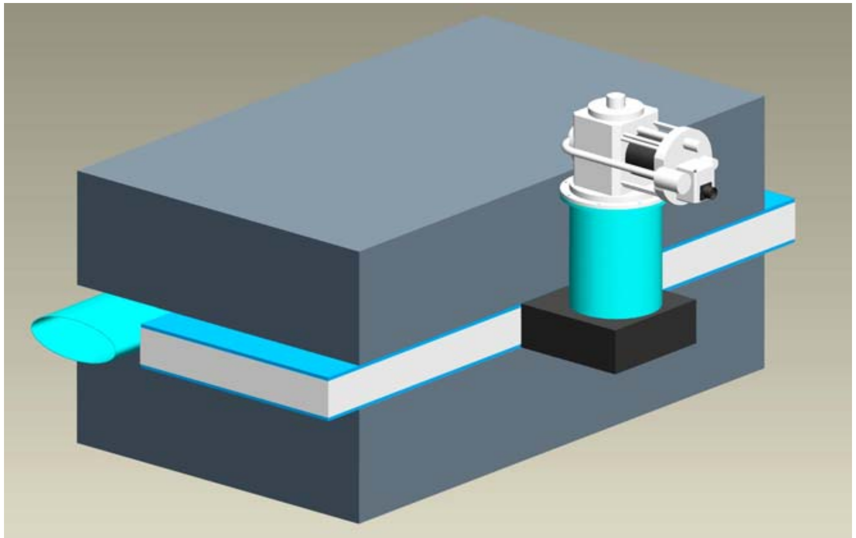
Performance curve of some cryo-coolers from CRYOMECH

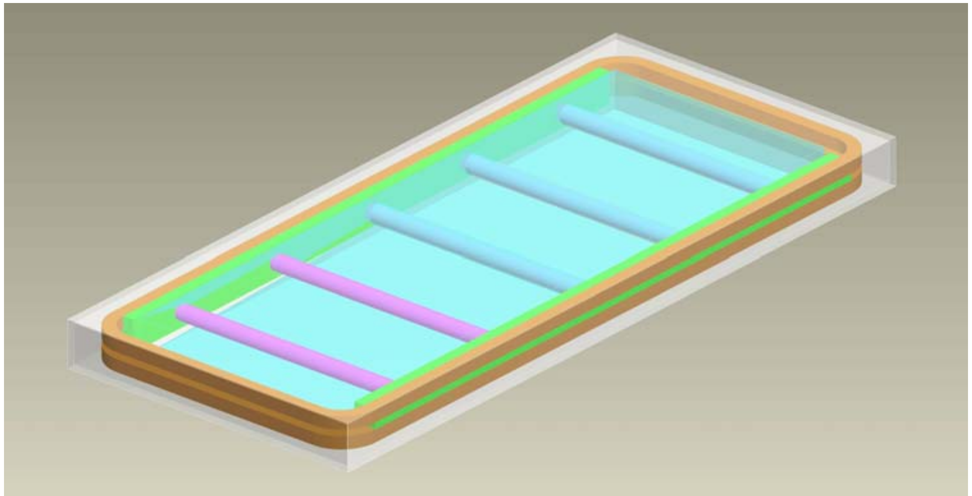


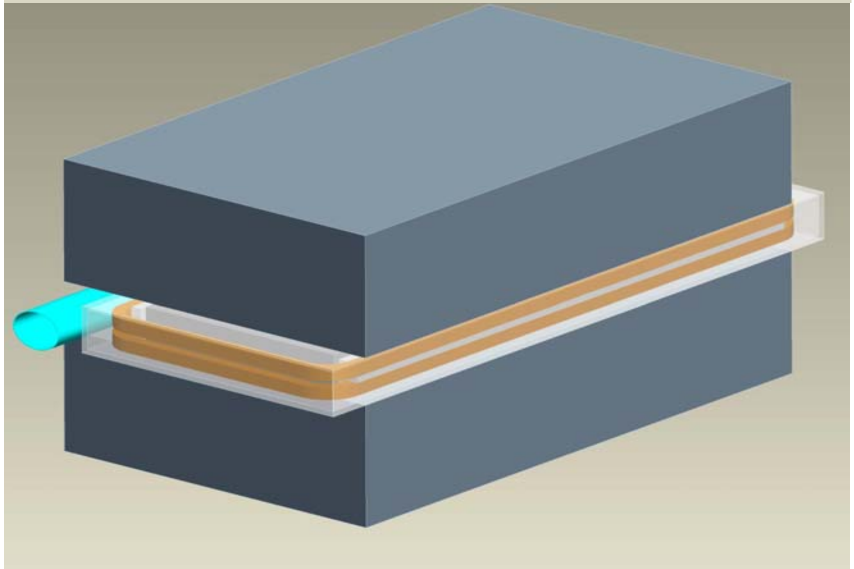
In certain applications, one can consider 60 K operation that is driven by pumped nitrogen.

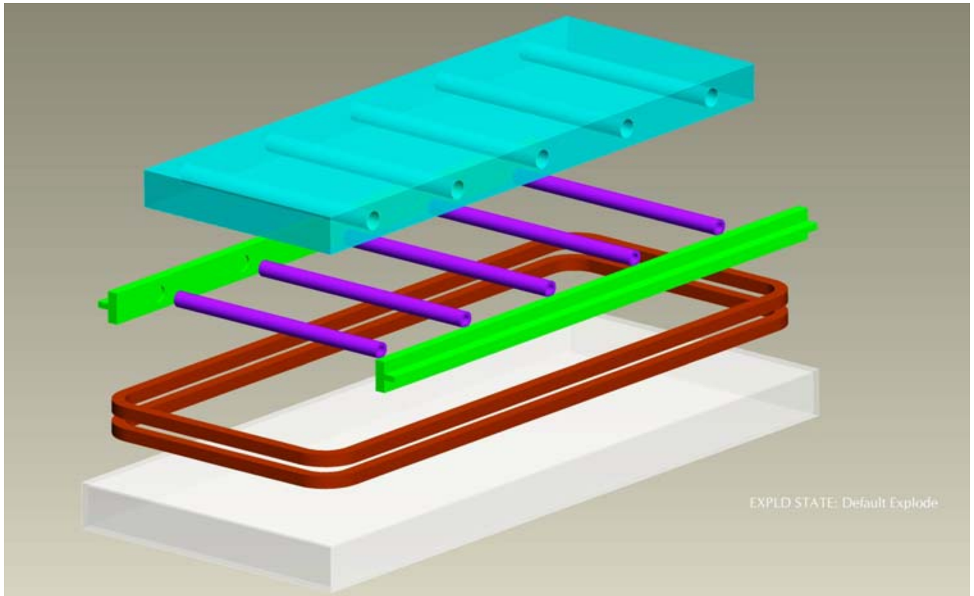
In certain other applications, even 77 K option may be interesting.

Concepts for A Neutrino Facility Magnet









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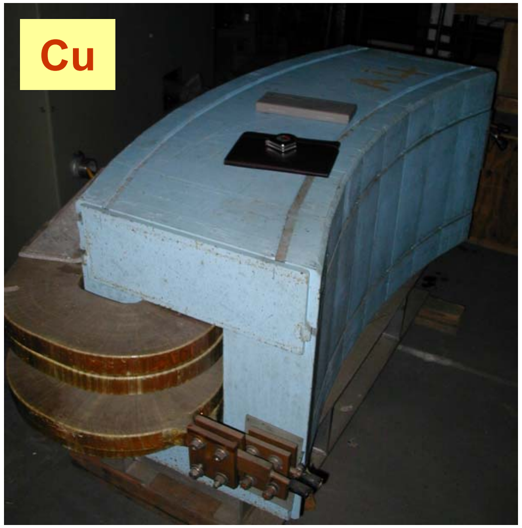
A Case Study for Cost Comparison of Copper and HTS Dipole for Neutrino Facility (This is NOT LS2)

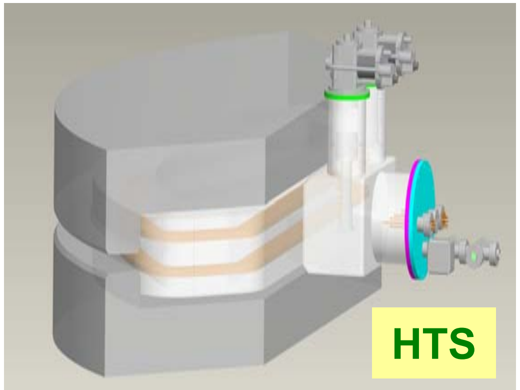
Design Parameters:

- B = 1.55 T
- L = 3.73 m
- Pole width = 153 mm
- Pole gap = 76 mm

Copper Magnets:

- Better known costs (estimated : ~150k$ each for this magnet)
- Cost of individual components like coil, yoke, etc., is well understood
- High operating costs (estimated ~3 MW total)
- Low conductivity water cooling plan
- Higher current (a few kA) power supply (higher cost)
- Maintenance issues (cost, downtime): water leak etc.





Desired cost of support structure and cryostat in this HTS magnet: < 20 K$

HTS Magnets:

- Develop designs to reduce cost (goal : ~150k$/magnet for equivalent integral field)
- Cost of HTS as per present price: ~35 k$ (only ~1/4, lower in future)
- Need to include cost of other components like iron (low and well understood), support structure, cryostat (major driver unless better designs developed)
- Lower operating costs (wall power of cryo-cooler?)
- Cost of cryo-coolers (compare with infrastructure cost of Low Conductivity Power Plant)
- Lower current (a few hundred Amp) power supply (cheaper)
- Maintenance issues (cost, downtime): cryo-coolers

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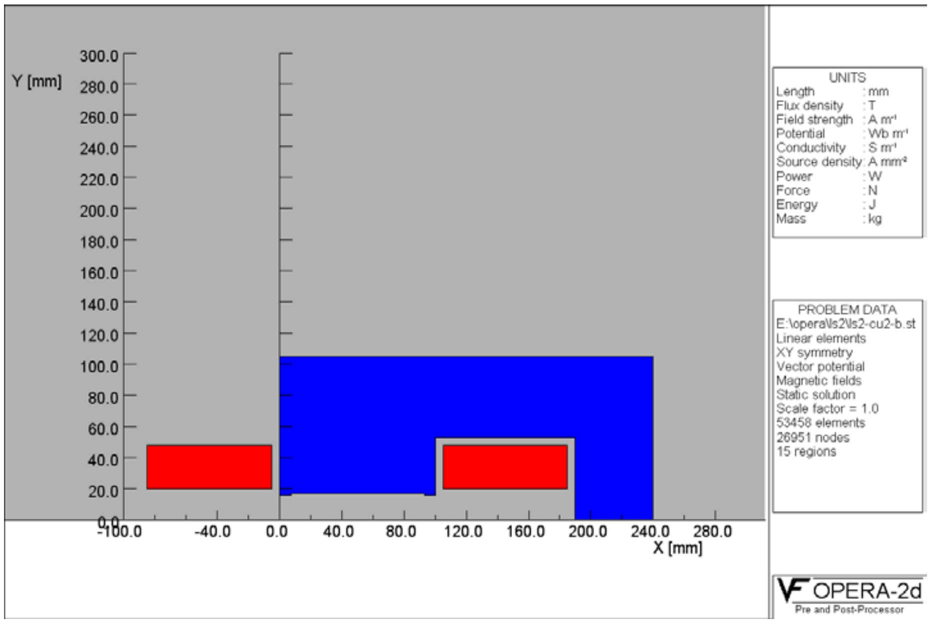
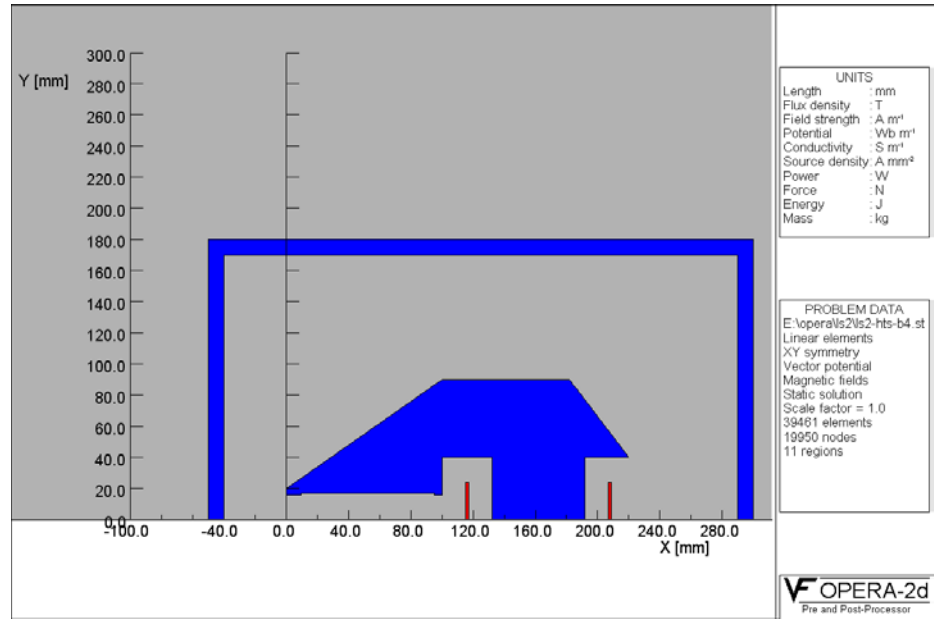
Magnetic Models of 3 kG Magnet Designs for Light Source 2 (LS2)

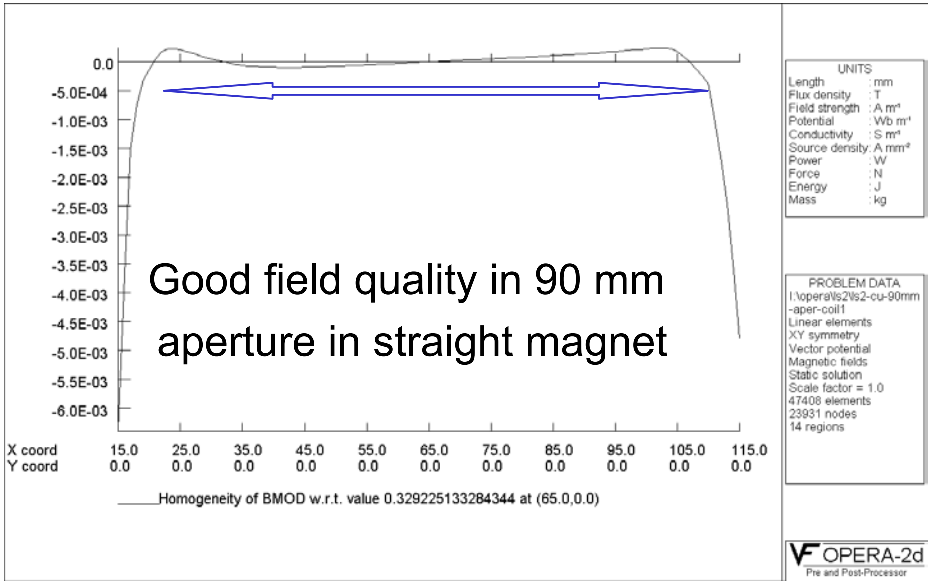


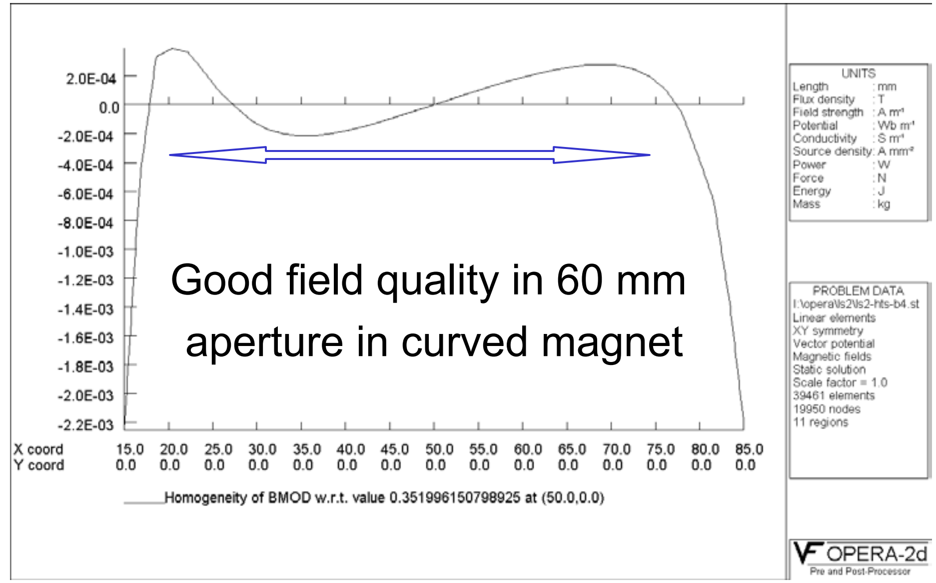


Water-cooled copper magnet
(Pole powered)
Current Density = 2 A/mm^2

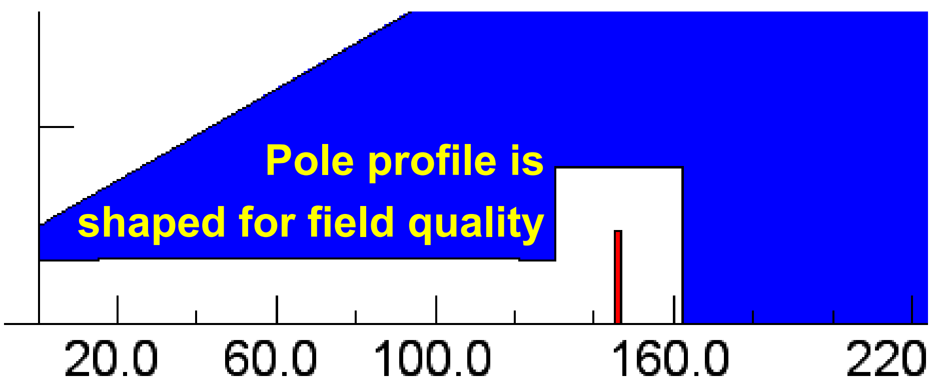
HTS magnet with shield
(Back-leg powered)
Current Density = 50-100 A/mm^2

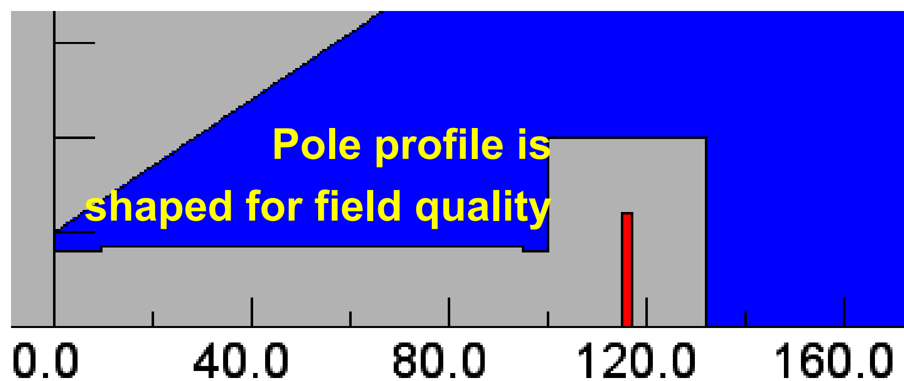
Field Quality



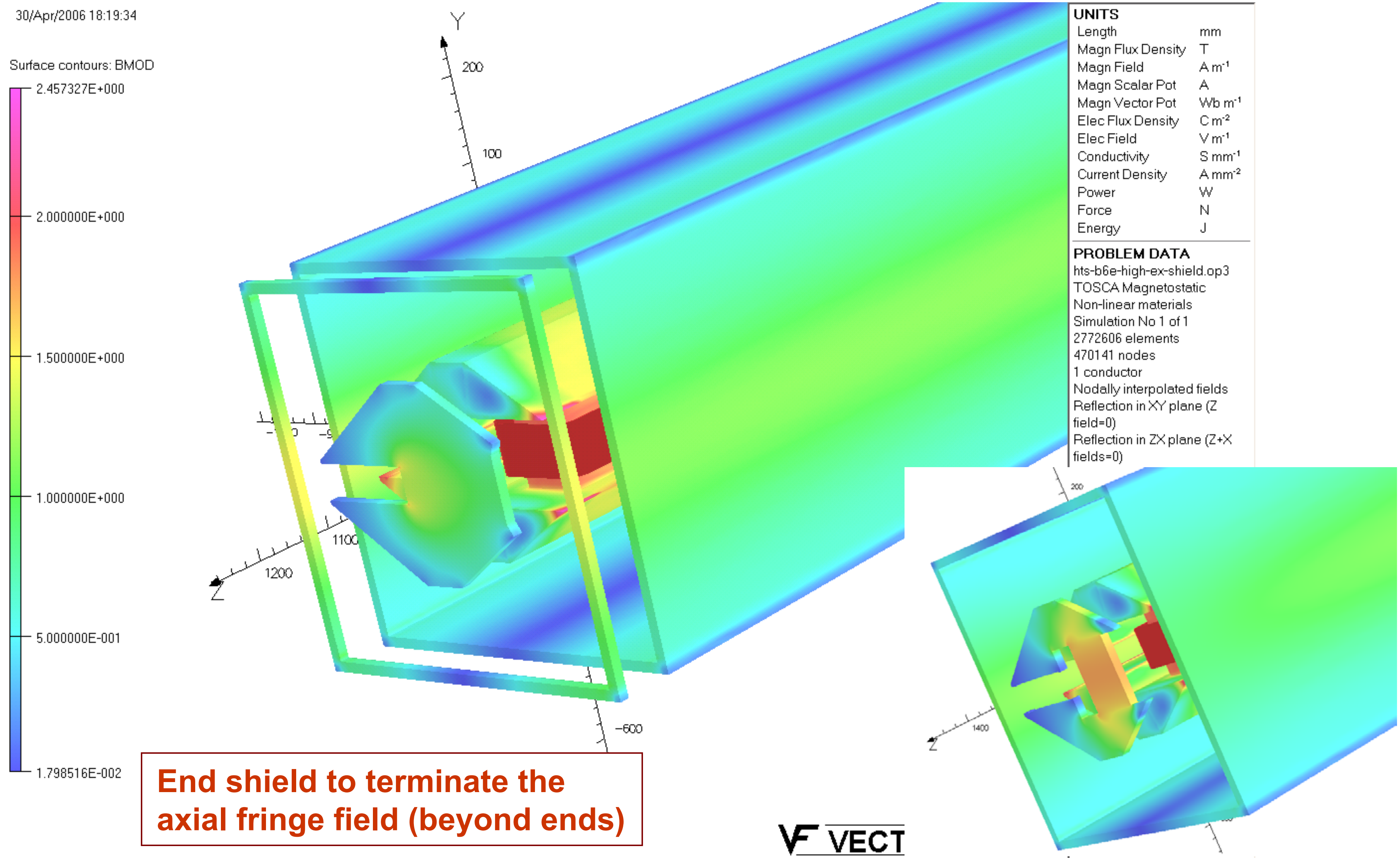


The field quality requirements of a few parts in 10^{-4} are met.



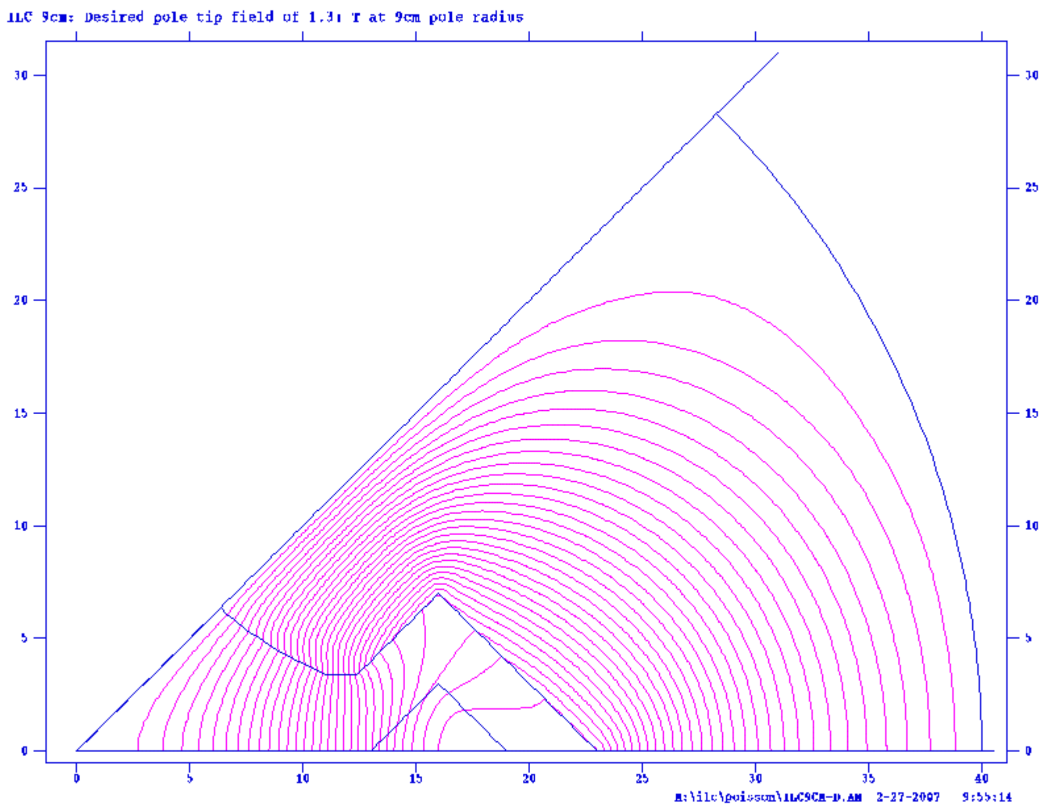


HTS Back-leg Powered Magnet (With End Shields)



End shield to terminate the axial fringe field (beyond ends)

Preliminary Investigation of HTS Quadrupole for ILC (QFEX4B-4E)



Design goals of this investigation:

- Use 2nd generation HTS (YBCO).
- Operate at 65 K or above (use sub-cool nitrogen or cryo-coolers).
- Design with the conductor available today (improved performance would reduce conductor cost and coil size).
- Warm iron compact design with low fringe field (seems to meet ILC spec).

HTS magnets would be more compact plus energy efficient as compared to water cooled magnets; and would allow larger temperature excursions as compared to LTS magnets.

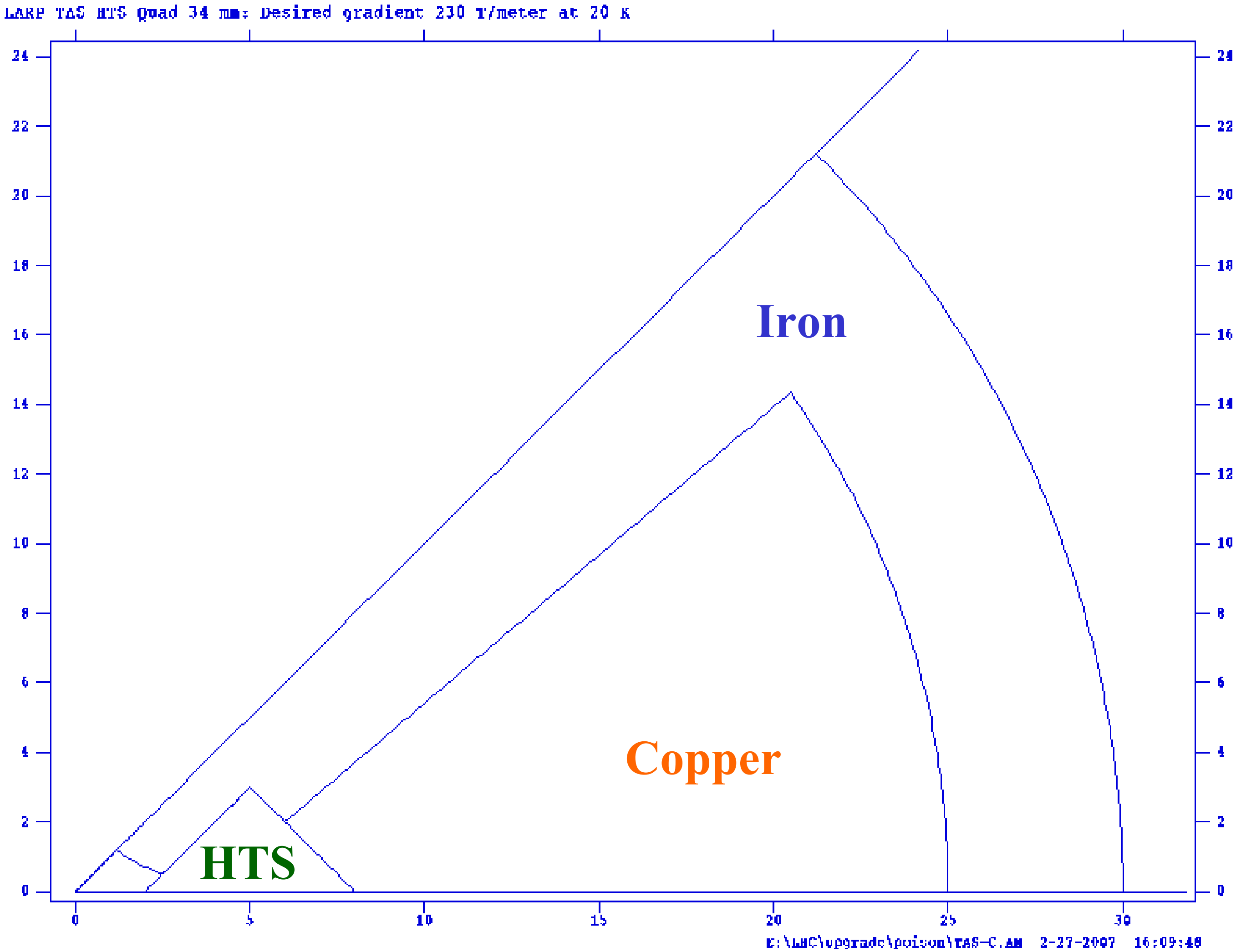
Basic design parameters (as per slac-pub-1159, updated by C. Spencer):

Good field radius = 85 mm; Gradient ~11.8 T/m

Above quad is designed for a minimum pole radius = 90 mm; Gradient = 13^{+} T/m

HTS Quad Embedded in TAS in a LHC Interaction Region Upgrade Scenario

HTS coils remove a large amount of heat at 20 K



1/8 Model of the HTS Quad Embedded in TAS

HTS as High Field Superconductor for Applications in Future High Performance Interaction Region Magnets

These are special few magnets, where conductor performance and not the conductor cost should be the driver.

- **Look for ring magnets for selling a large volume of conductor.**

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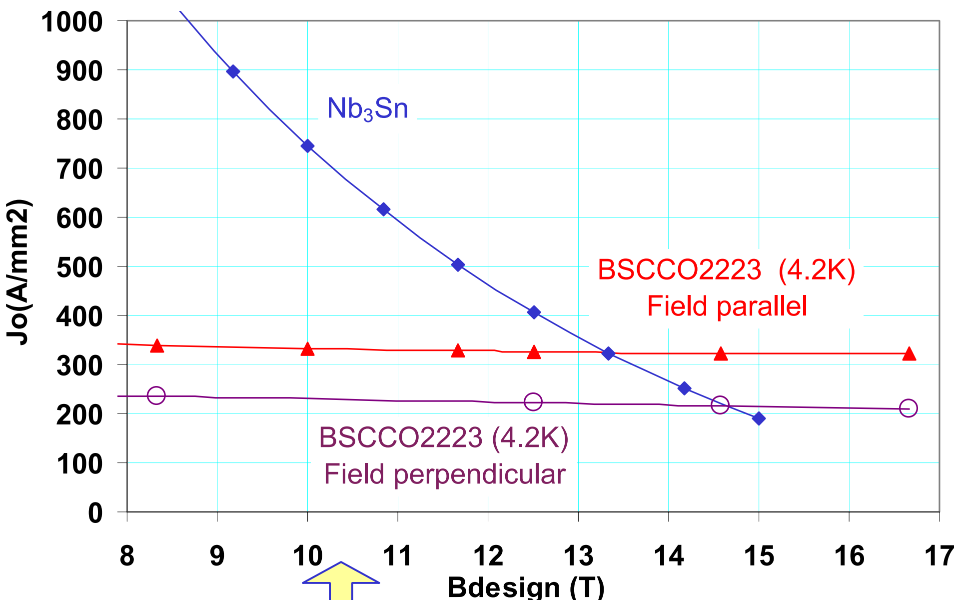
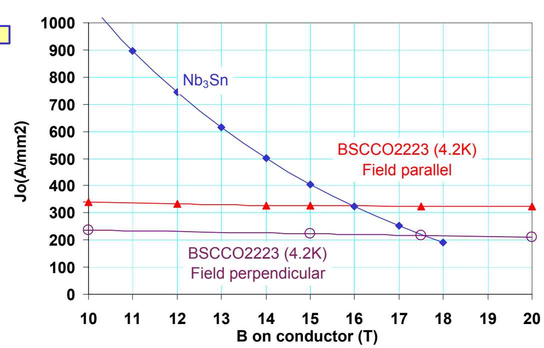
Superconducting Magnet Division

Overall Current Density in Commercially Available High Field Superconductors

Overall current density as a function of design field in commercial high field superconductors





Design operating field is generally 20% over the conductor field due to peak field and margin.

Commercially available HTS now offer more current density than Nb_3Sn to design magnets at an operating field over 13.5 T to 14.5 T.

HTS should now be considered in those high field magnet applications where the performance and not the cost is the driver.

Data used in making plots (details)

Nb_3Sn: Wire/cable specified for present LARP Quad (Jc@12T=2400A/mm2, Cu/Sc=1.0, insulation 250 micron per turn)

HTS: 155A at 77K – can be ordered today from ASC Website. Scaling used for 77 K to 4K. Kapton/SS tape for insulation.

Superior Mechanical Properties of HTS in High Field Magnet Applications

HTS High Strength Plus Wire

- Designed for applications where the wire must be mechanically strong and have high current density, such as many coil and magnet applications
- Tolerant to small winding diameters or bend radii
- High tensile strength
- High engineering current density

American Superconductor

Bismuth based, multi-filamentary, high temperature superconductor wire encased in a silver alloy matrix with a thin stainless steel lamination.

Average thickness:	0.255 - 0.285 mm
Minimum width:	4.2 mm
Maximum width:	4.4 mm
Min. double bend diameter (RT):	38 mm[i]
Max. Rated tensile stress (RT):	200 MPa[i]
Max. Rated wire tension (RT):	21 kg
Max Rated tensile stress (77K)	250 MPa[i, ii]
Max. Rated tensile strain:	0.4%[i, ii]

Customer Options:

Minimum amperage (Ic)	Average engineering Current density (Je)[iii]
125 A[ii]	10,700 A/cm²[ii]
135 A[ii]	11,600 A/cm²[ii]
145 A[ii]	12,500 A/cm²[ii]
155 A[ii]	13,300 A/cm²[ii]

Continuous piece length: 100 to 400m[iv]
Insulation options: PTFE or Kapton wrap
Splice options: spliced wire available in longer lengths

[i] Greater than 95% Ic retention
[ii] 77K, self-field, 1μV/cm
[iii] Je is a calculated value based upon average thickness and width
[iv] Longer continuous lengths available upon request

1st generation wire

- **HTS can tolerate large stress (250 MPa rather than 150 MPa or so for Nb_3Sn). This value can be further increased with more SS enforcement.**
- **HTS bend radius in R&W magnets can be much smaller (19 mm rather than 70 mm to 100 mm in Nb_3Sn).**

Second Generation Superconductor in Accelerator Magnets

American Superconductor (with BNL as a partner) has submitted a SBIR/STTR application.

This will not be discussed here.

SUMMARY

- Successful construction and test of RIA HTS quadrupole should serve as a good demonstration model for using HTS in accelerator magnets.
- We are examining possible use of HTS in several other applications.
- An improvement in the cost and performance of the second generation conductor should make HTS magnet much more attractive.
- The cost of ownership of HTS magnets is being studied in comparison to large water-cooled magnets and to conventional LTS magnets.
- A larger scale application of HTS may lie in magnets for beamline, injector and medical applications.
- New creative designs and overall magnet technology may make a significant difference. So keep trying!