RIA: Rare Isotope Accelerator
FRIB: Facility for Rare Isotope Beams

RIA/FRIB HTS Magnet Program

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HTS Quadrupoles for FRIB/RIA

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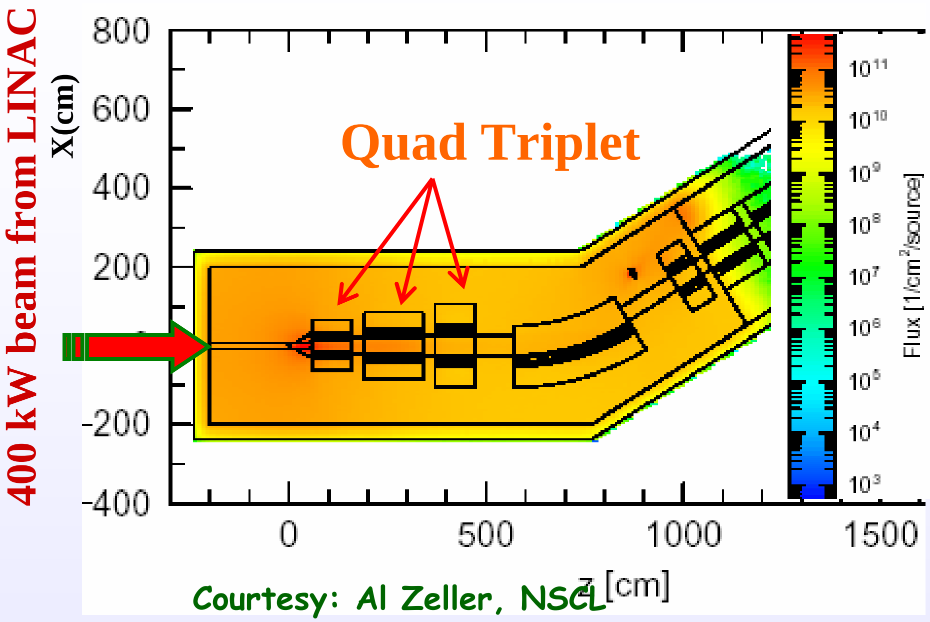


- To create intense beams of rare isotopes, up to 400 kW of beam hits the target before the fragment separator.
- Quadrupole triplet is exposed to very high level of radiation and heat loads (~15 kW in the first quadrupole itself).
- HTS magnets could remove this more efficiently at 30-50 K than LTS at ~4 K.

These quads were identified as one of the most critical components of the machine.

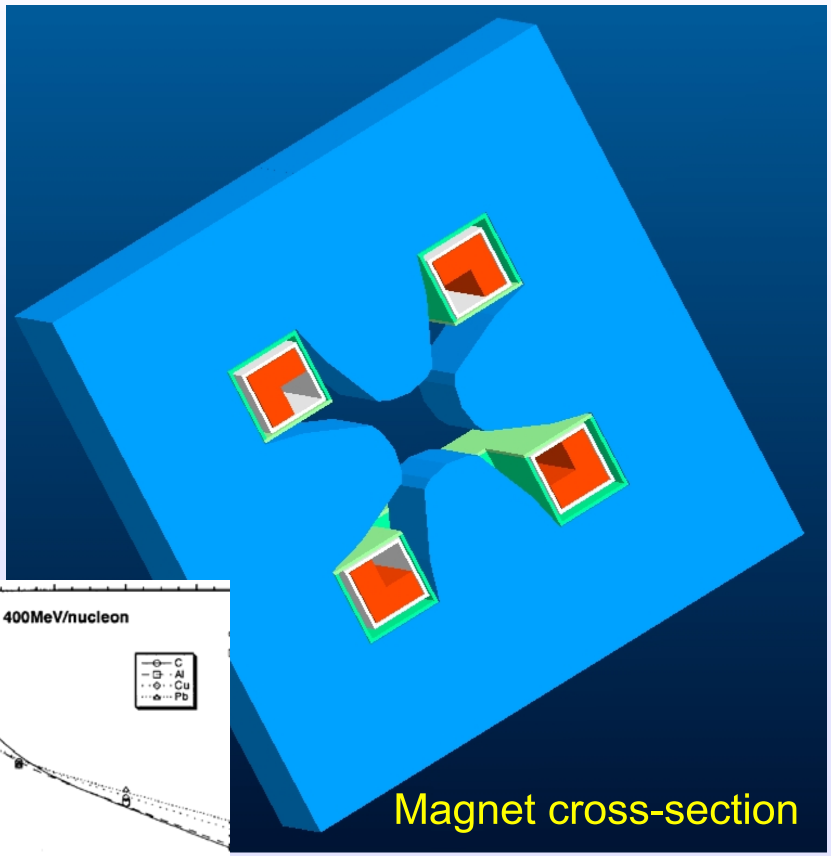
- Can these demanding requirements be met ?
- Is commercially available HTS suitable and ready for magnets ?
- Can HTS magnets be built at a cost that is affordable ?

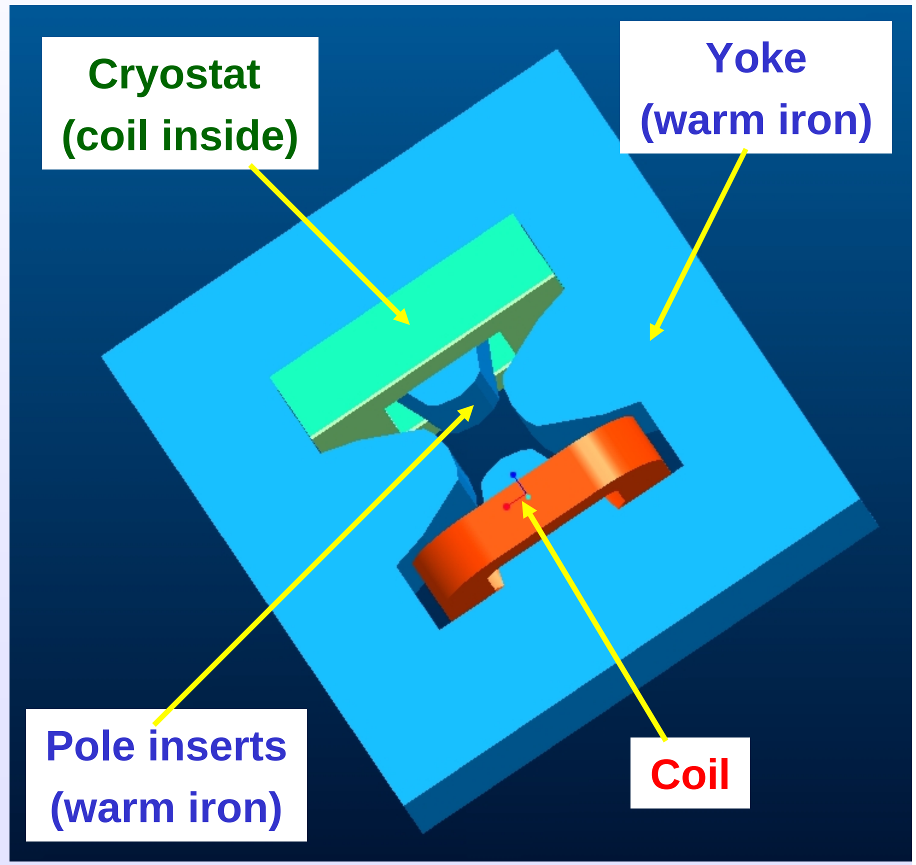
Basic Design of RIA HTS Quadrupole

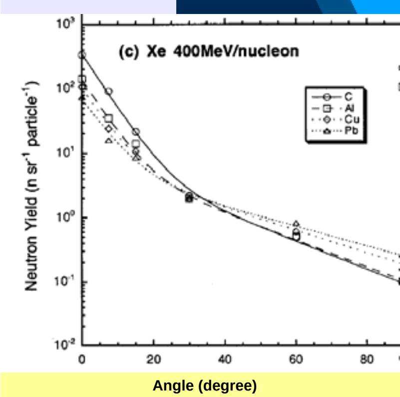
A simple warm iron super-ferric quad design with two racetrack HTS coils

Note that only a small fraction of the mass is cold (see green portion), specially in ends.

Moreover coils are moved to a larger angle where the radiation dose are low.





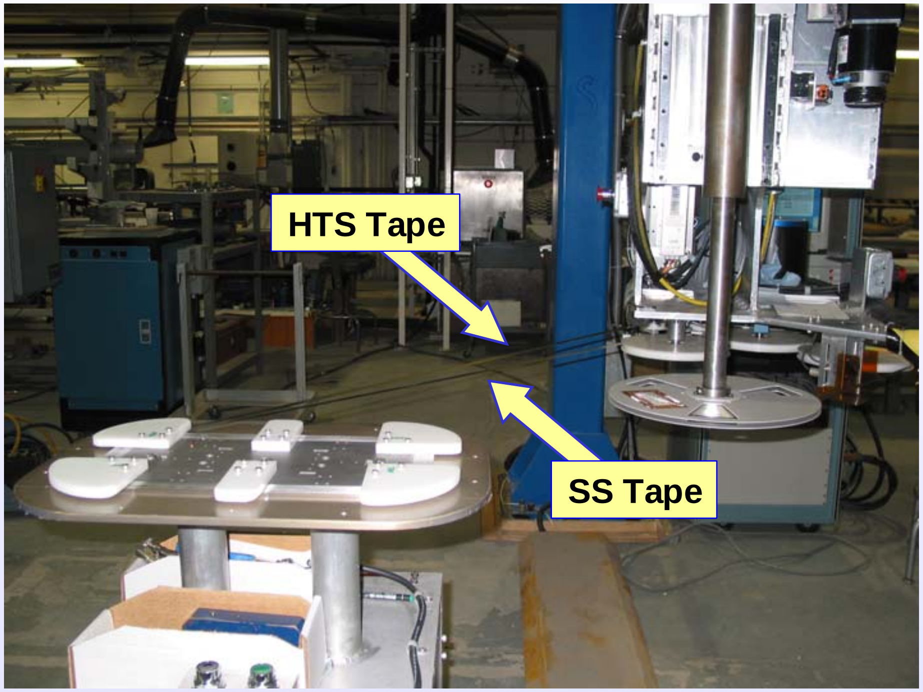


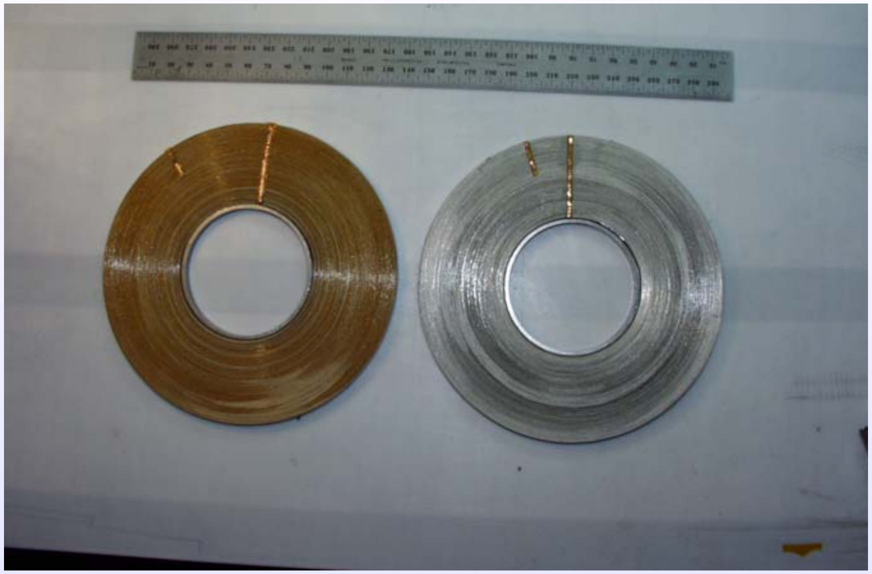
Coils inside the cryostat at the end of the magnet

Stainless Steel Insulation in HTS Coils

Radiation damage to insulation was a major issue for magnets in high radiation area.

Stainless steel tape (highly radiation resistant) serves as turn-to-turn insulator .





Coil-to-coil insulator could be ceramic sheet or anodized sheet of Aluminum.

HTS Coils for RIA/FRIB Model Magnet

- RIA quad is made with 24 coils, each using ~200 meter of HTS.
- This gives a good opportunity to examine the reproducibility in coil performance.

Over 5 km of HTS tape has been purchased for RIA/FRIB

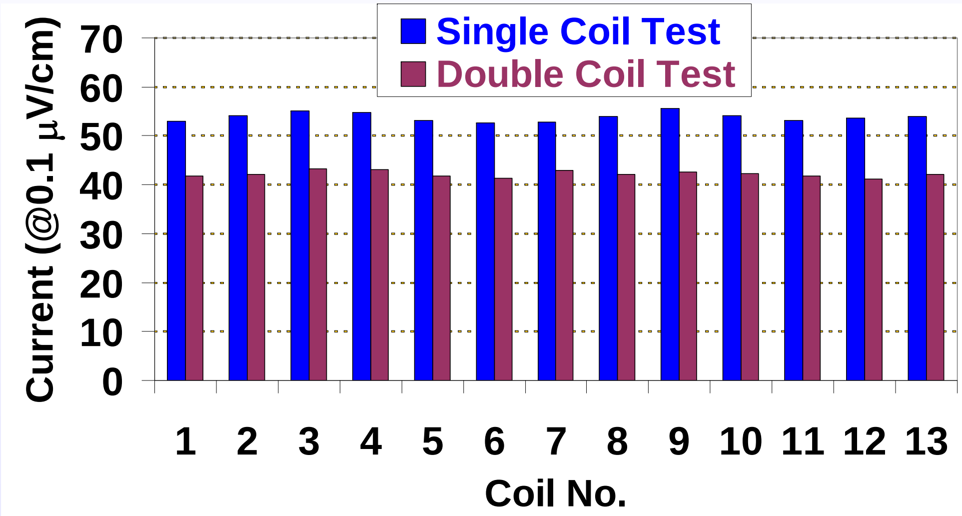
Earlier 1G HTS tape was ~4 mm wide and ~0.4 mm thick with SS enforcement on either side.

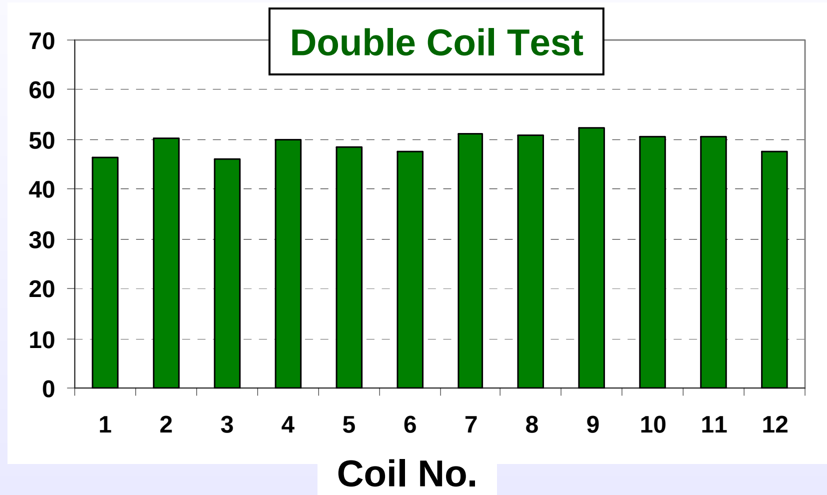
Current 2G HTS is ~4mm or ~12 mm wide and is only ~0.1 mm (SuperPower) or ~0.2 mm (ASC) thick.

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)





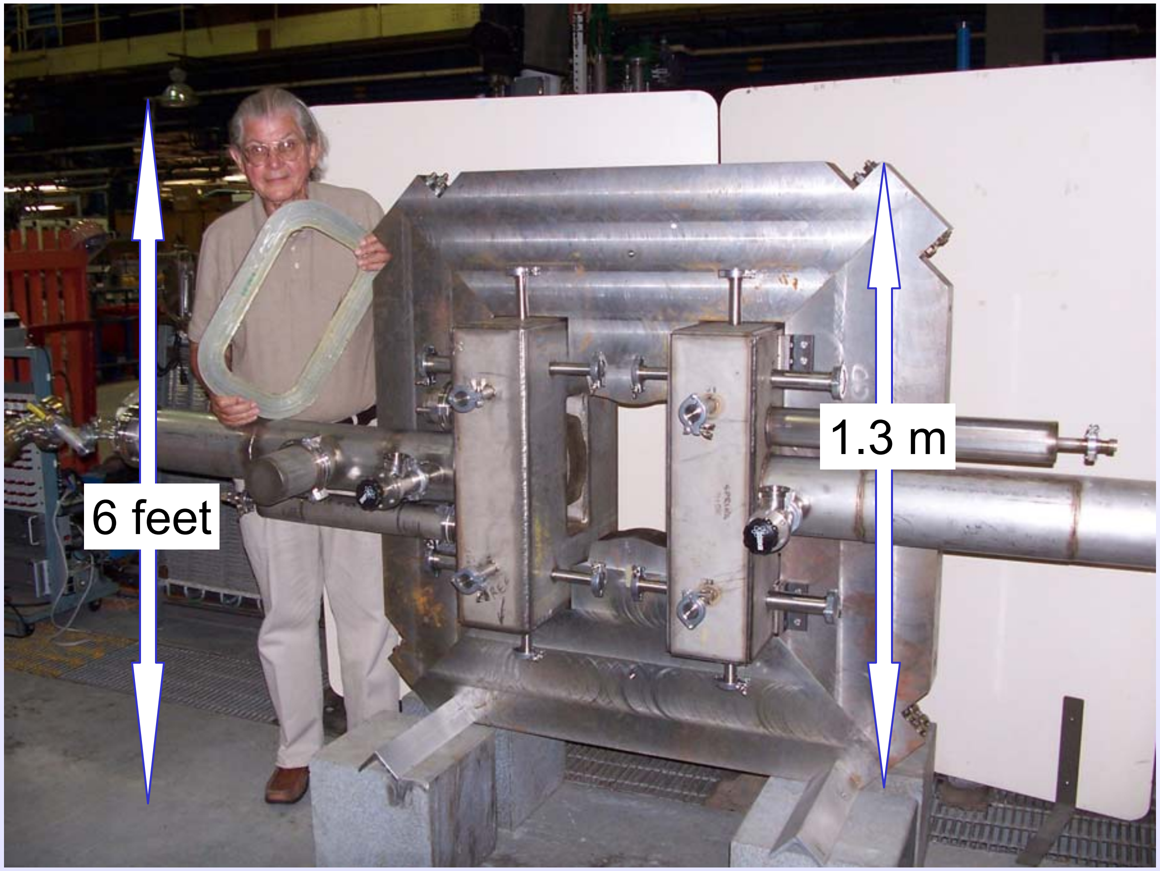
Coil performance generally tracked the conductor performance very well.

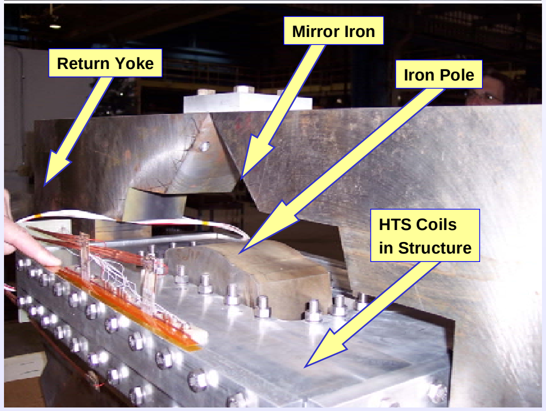
Note: A uniformity in performance of a large number of HTS coils.
It shows that the HTS coil technology is now maturing !

Various Magnet Structures of RIA Quad (a part of step by step R&D program)

Important Features of RIA HTS Quad :

- Large Energy Deposition & Radiation Resistant

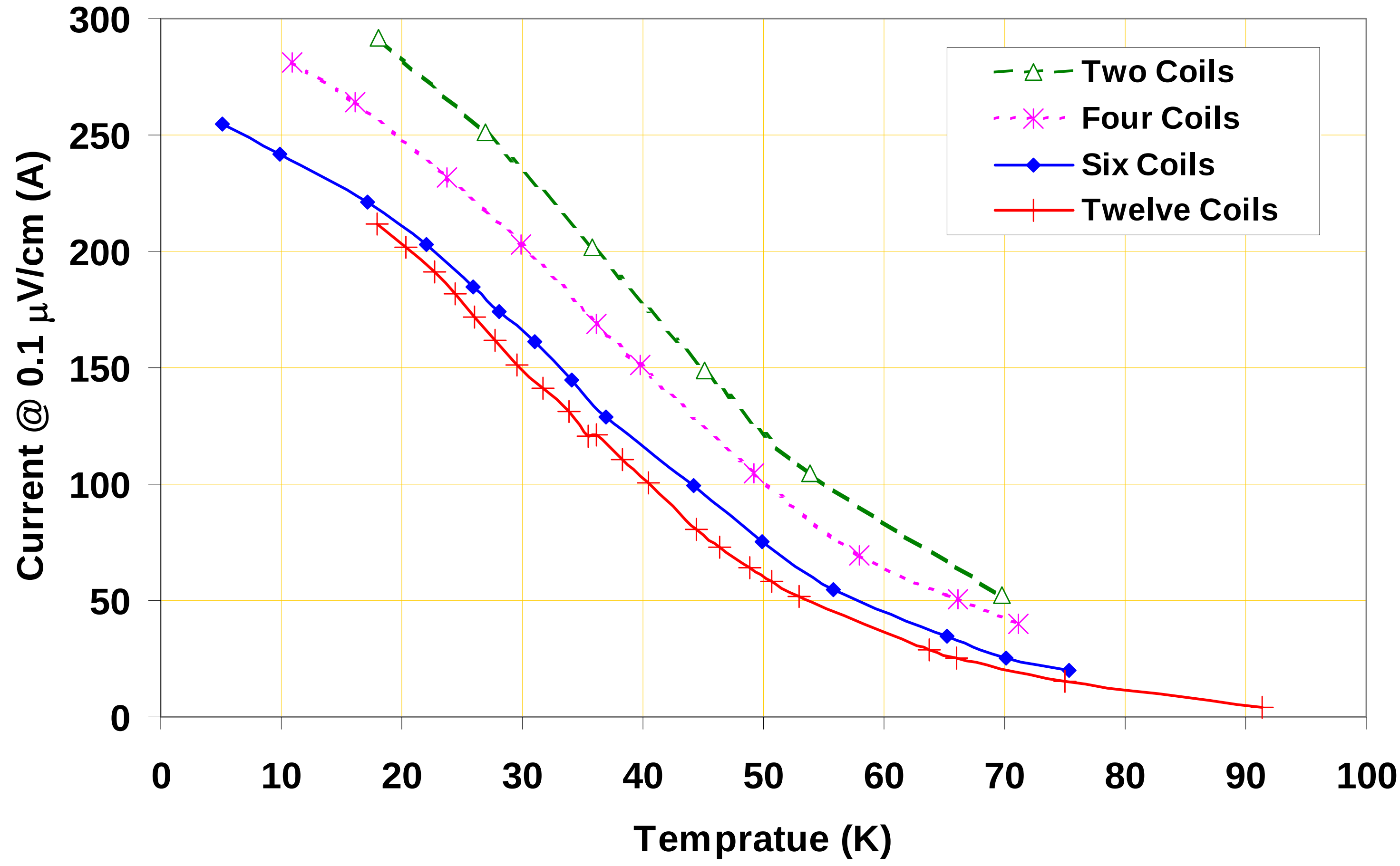




Courtesy/Contributions

Anerella, Dilgen, Ince, Jochen, Kovach, Schmalze

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

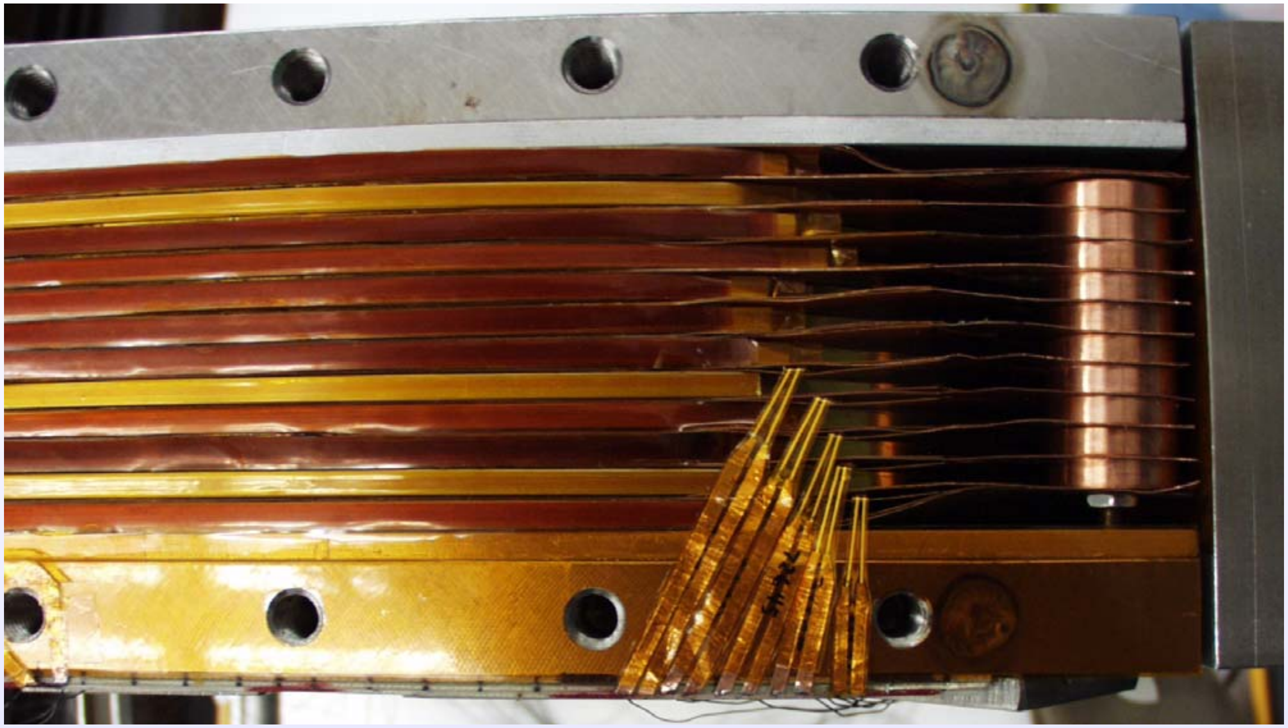


More coils create more field and hence would have lower current carrying capacity

Courtesy/Contributions Sampson

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.

Energy Deposition and Cryogenics Experiments



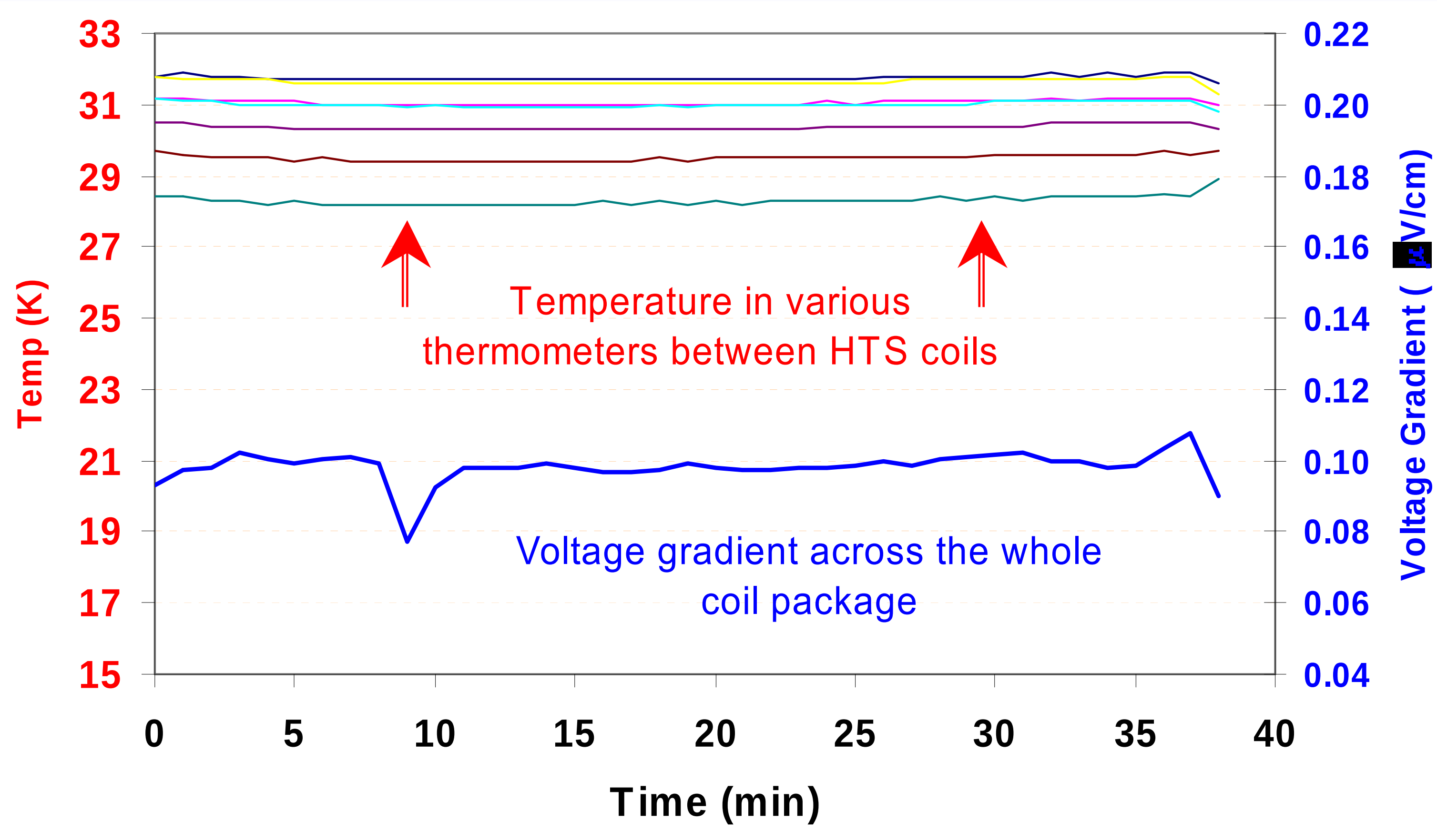
Stainless steel tape heaters for energy deposition experiments

Copper sheets between HTS coils with copper rods and copper washers for conduction cooling

- **In conduction cooling mode, helium flows through top and bottom plates only.**
- **In direct cooling mode, helium goes in all places between the top and bottom plates and comes in direct contact with coils.**
- **Energy deposition in magnet worked well in both cases.**

Large Energy Deposition Experiment

Magnet operated in a stable fashion with large heat loads (25 W, 5kW/m^3) at the design temperature (~30 K) at 140 A (design current is 125 A).



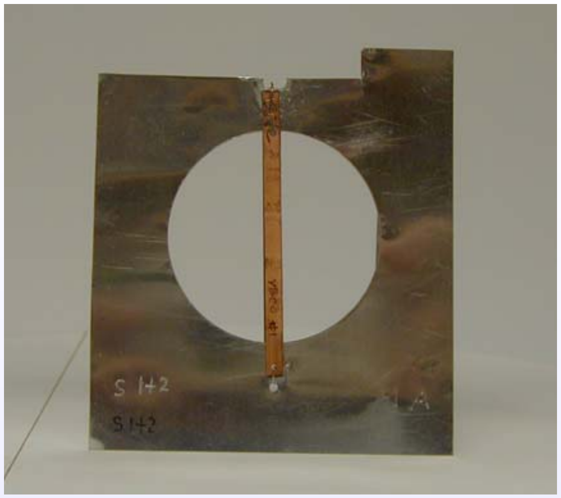
Stable operation for ~40 minutes

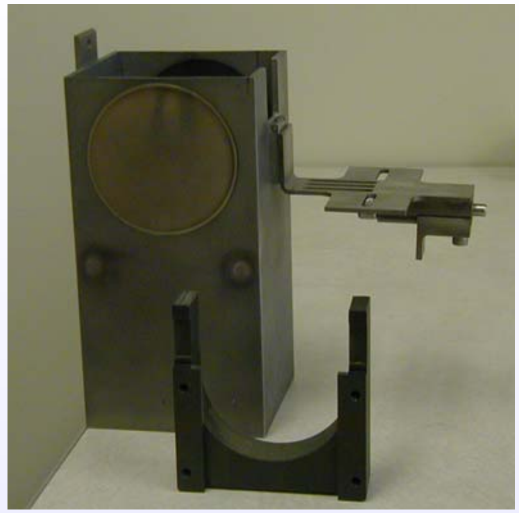
Voltage spikes are related to the noise

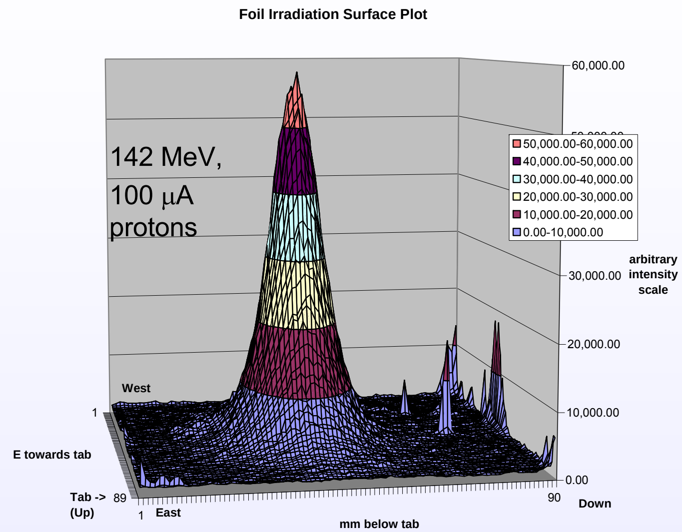
Radiation Damage Studies of HTS (YBCO, Bi2223 and Bi2212)

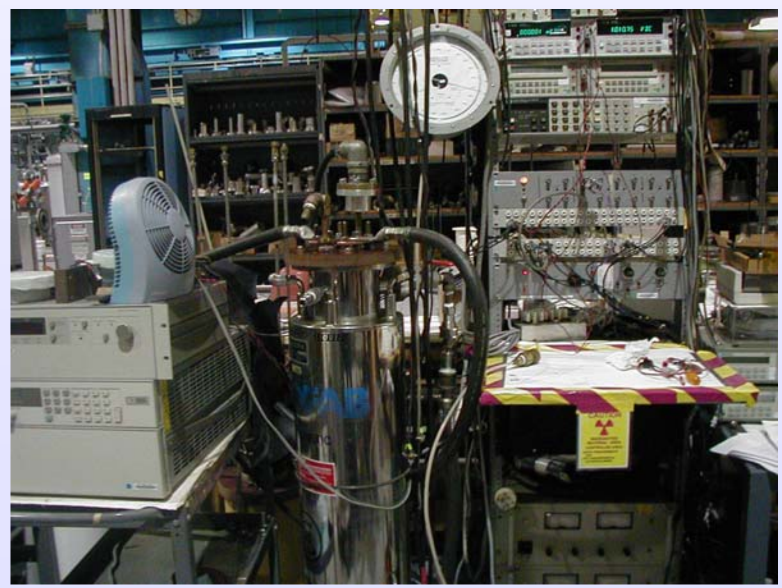
- BNL and NSCL (Zeller) are collaborating in radiation damage studies on HTS and on determining the impact of it in the performance of actual magnets.
- First set of radiation damage studies on Bi2223 was carried out by Al Zeller at LBL Cyclotron.
- More recent studies on YBCO, Bi2223 and Bi2212 are being carried out by George Greene and Bill Sampson at BLIP.
- Test results and analysis of radiation damage on YBCO will be briefly presented here. YBCO samples were provided by SuperPower and American Superconductor Corporation.

Key Steps of Radiation Damage Experiment (Courtesy George Greene and Bill Sampson)









Radiation Damage Studies at BLIP

Figure 2. The BLIP facility.

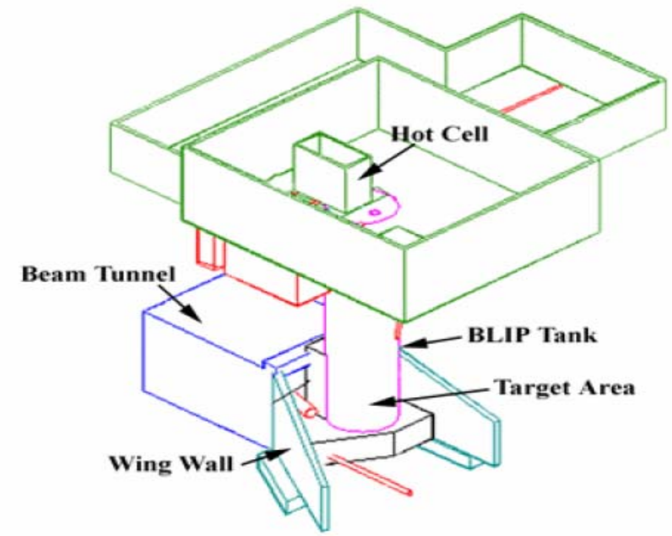


Figure 3. BLIP Beam Tunnel and Target Schematic

From a BNL Report (11/14/01)

The Brookhaven Linac Isotope Producer (BLIP) consists of a linear accelerator, beam line and target area to deliver protons up to 200 MeV energy and 145 μA intensity for isotope production. It generally operates parasitically with the BNL high energy and nuclear physics programs.

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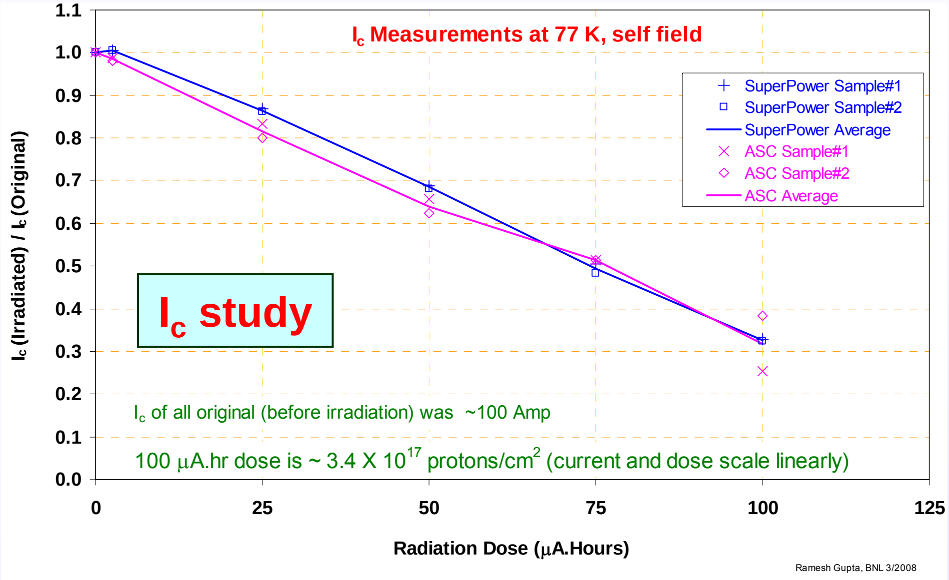
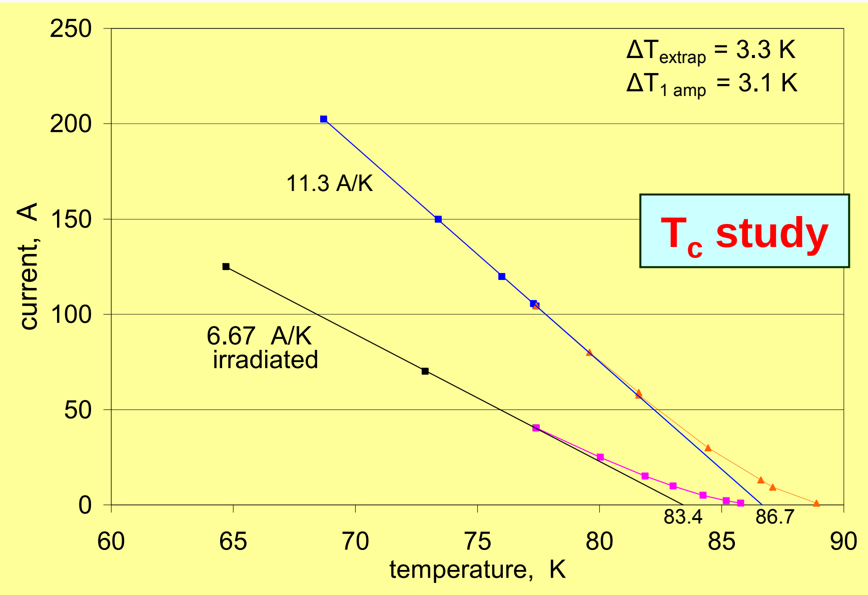
Impact of Large Irradiation on YBCO

Note: The following doses are order of magnitude more than what would be in FRIB

• Radiation damage studies at this level has never been done before !

Courtesy/Contributions: Garber





One way to recover the loss in performance due to radiation damage is to operate magnet at a lower temperature – something that is not possible in conventional LTS magnets.

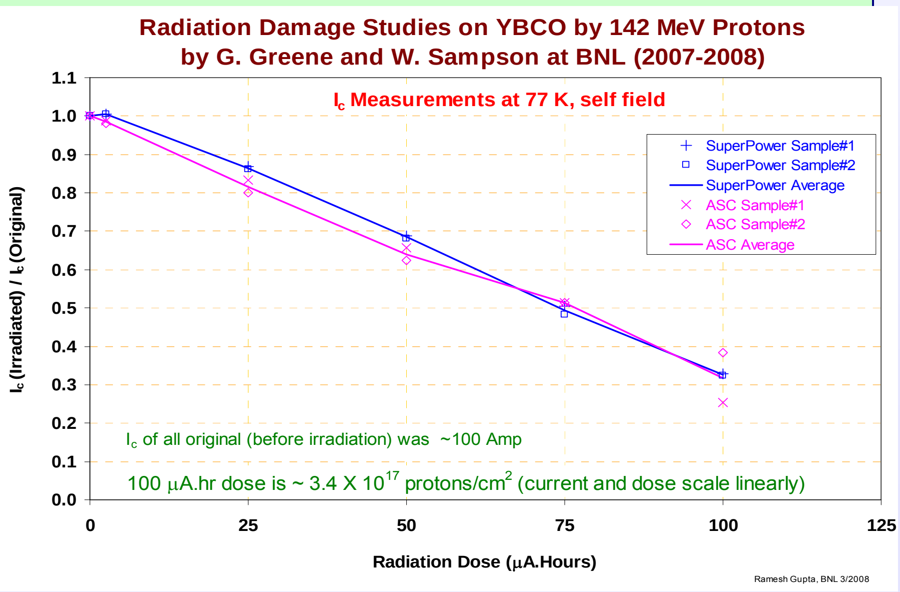
Impact of Irradiation on Magnet

- The maximum dose was 3.4 X 10^{17} proton per sec 100 μA.hr.
- As per Al Zeller, displacement per atom (dpa) per proton is ~9.6 X 10^{-20}.

This gives ~0.033 dpa at 100 μA.hr.

Bottom line:
- **I_c performance of YBCO will drop ~10% after 30 years operation.**
- **This should be acceptable.**
- **Higher, but still acceptable, degradation for 400 MeV instead of 200 MeV proton beam**

- **It appears that YBCO is at least as much radiation tolerant as Nb_3Sn is (Al Zeller).**



Caveat:

Above is based on 77 K, no applied field.

To be completely sure, examine it at 50 K and 3 T (or whatever the operating parameters may be).

FRIB HTS Magnet R&D Program

Summary of Phase I Program

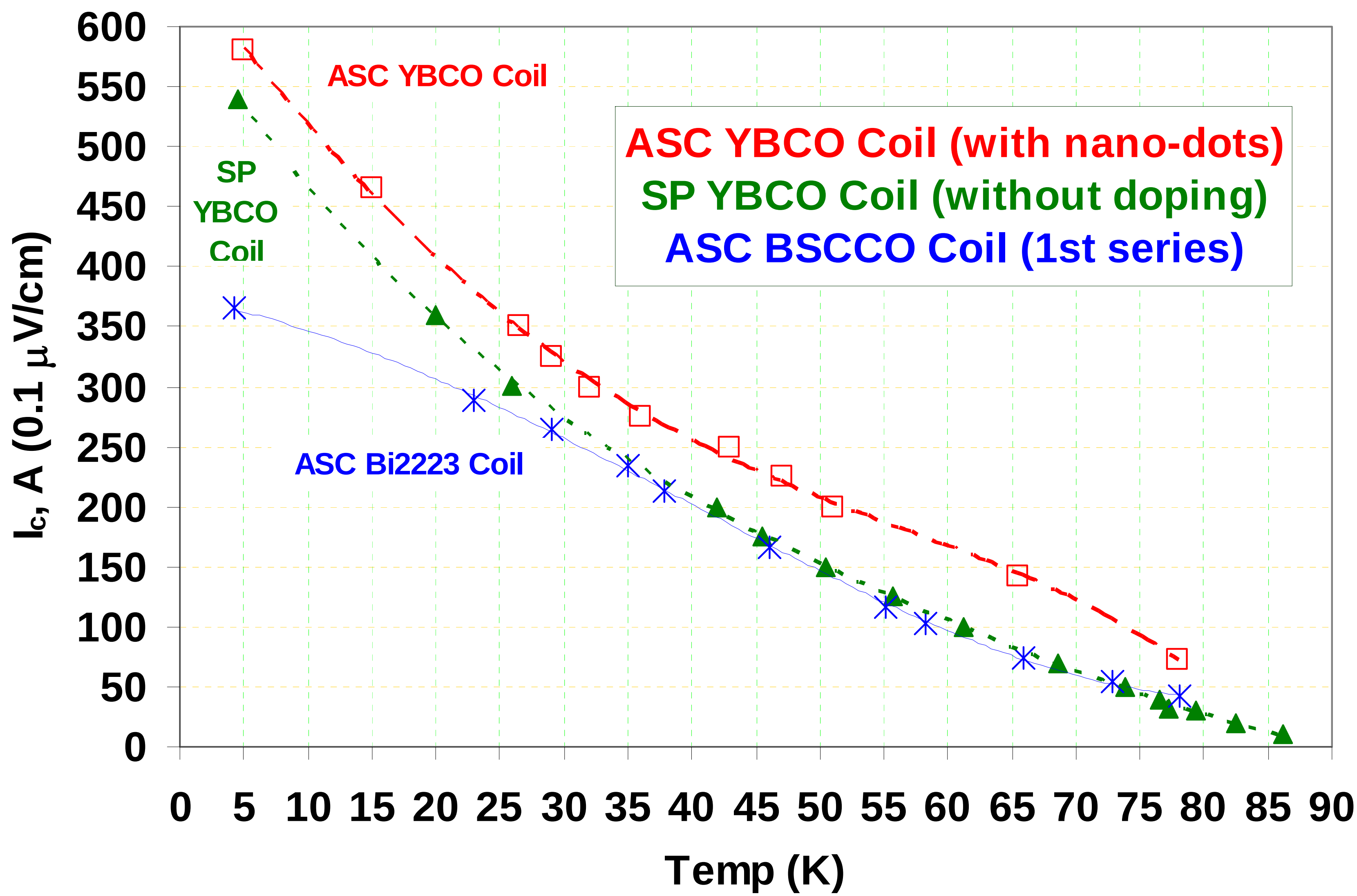
- RIA/FRIB HTS Phase I program has produced a proof-of-principle design and technology and has provided a possible solution to a major technical issue.
- It has shown that R&D magnets with HTS can be built, they can survive the expected radiation doses as expected in FRIB/RIA and can withstand and economically remove large heat loads.

Possible Phase II Program and Future Outlook

- Now we want to carry out R&D for a more ambitious design that could possibly allow the magnets to come closer to the target and have a higher field gradient.
- We have started using the second generation HTS (2G - YBCO) which would allow this large energy to be removed at ~50 K rather than at ~30 K in the first generation or ~4 K in LTS (significant saving due to increased efficiency).
- HTS magnets could be suitable in other places in FRIB beam line; let's investigate.

FRIB HTS Quad Coil Measurements at BNL

I_c (0.1 μV/cm) Vs. Temperature



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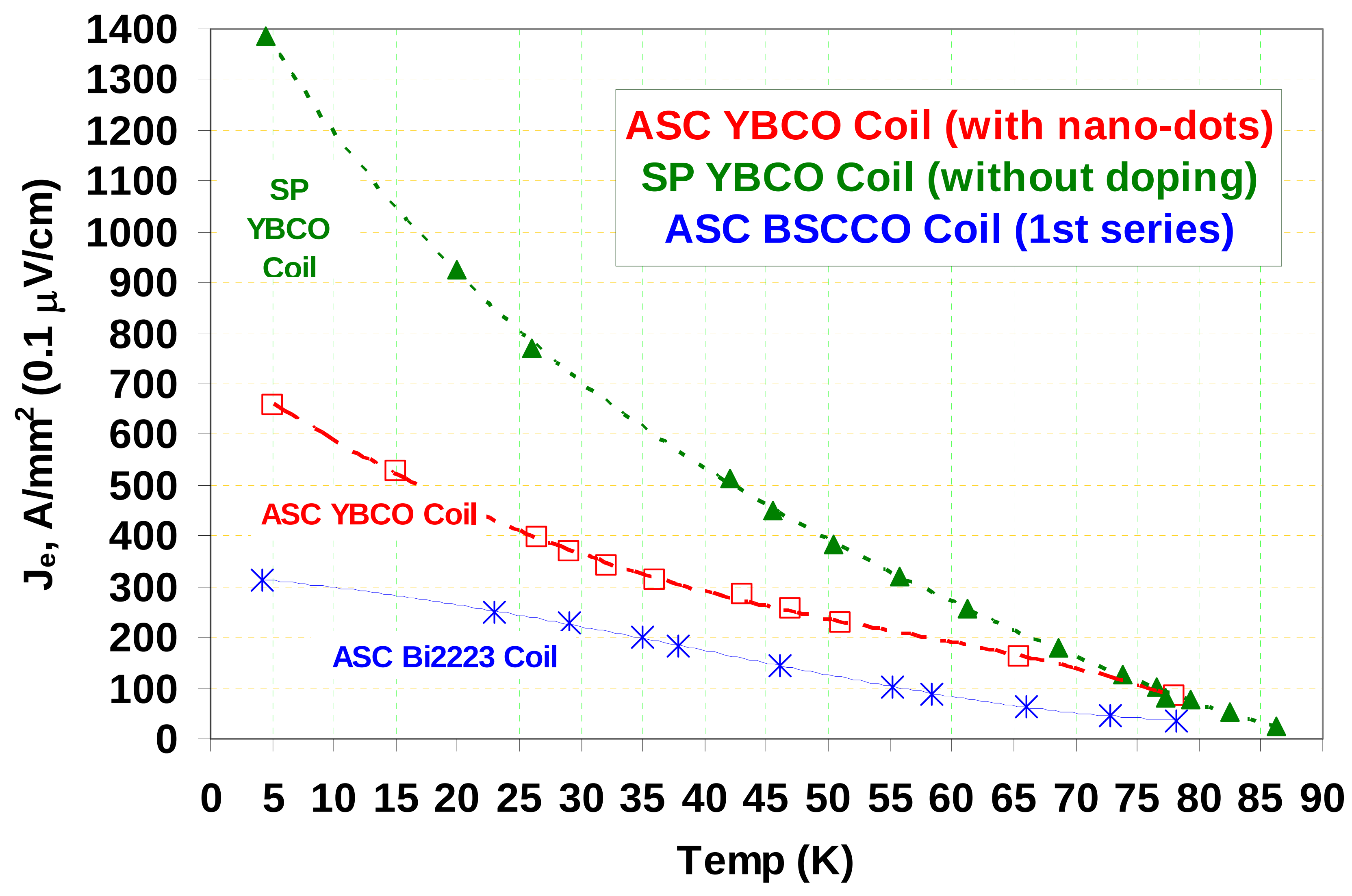
FRIB HTS Quad Coil Measurements at BNL

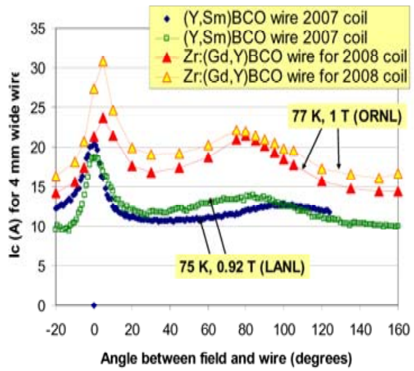
J_e (0.1 μV/cm) Vs. Temperature



Improved Performance of 2G HTS with Doping (or nano-dots)

SuperPower

30% Higher Field Achieved Using 2G with Improved In-field Performance



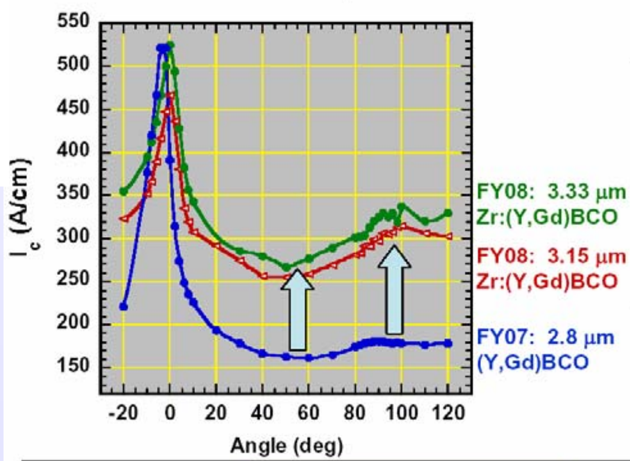
Temperature (K)	Coil current (A)	Max Central Field (T)
77.4	22.7	0.95
70.25	44	1.84
65.8	54	2.26
64.5	57	2.39
63.8	58	2.43

Temperature	2008 coil with Zr-doped (Gd,Y)BCO	2007 coil with (Y,Sm)BCO	Improvement
77 K	0.95 T	0.73 T	30%
65 K	2.39 T		

Note: **65 K**, 3T HTS J_e is already in the same ball-park as **4K**, 3T NbTi J_e used in AGS helical magnet.

SuperPower

Excellent in-field performance at 65 K, 3 T



- Title III Phase 3 program goal is Je without stabilizer of 15,000 A/cm² at 65 K, 3 T
- Minimum Ic = 267 A/cm corresponds to Je of 41,000 A/cm² at 65 K, 3 T
- Ic perpendicular to tape = 340 A/cm corresponds to Je of 52,300 A/cm²

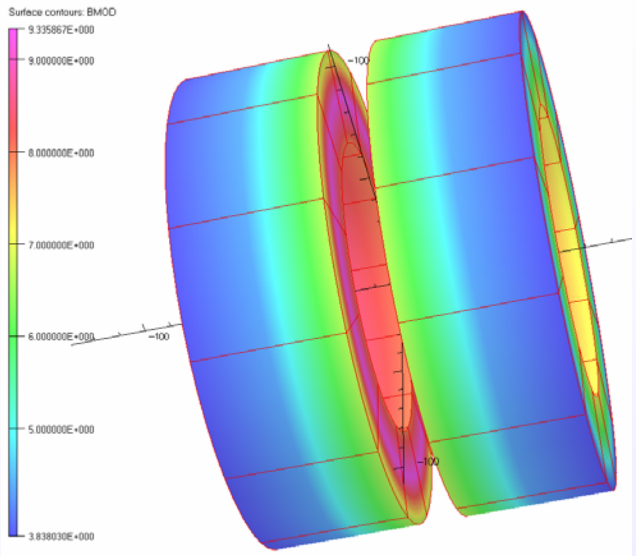
Ic (77 K, 1 T)	FY08 Zr-doped (Gd,Y)BCO	FY07 (Gd,Y)BCO	Improvement
B // c	340 A/cm	181 A/cm	88%
Minimum Ic	267 A/cm	160 A/cm	67%

Data from Y. Zhang, M. Paranthaman, A. Goyal, ORNL

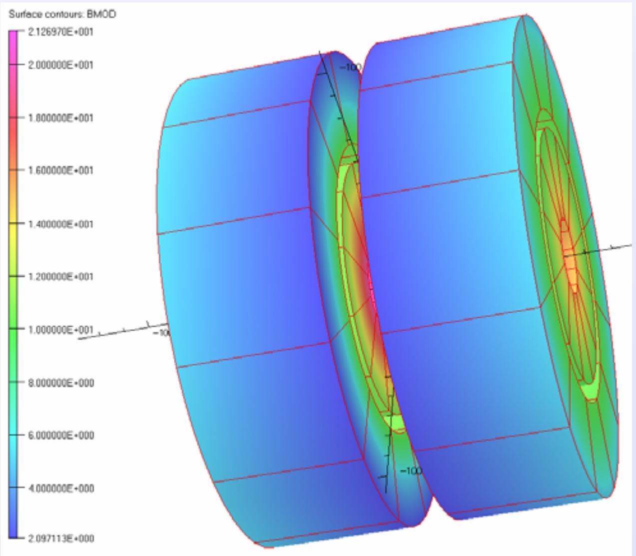
However, measurements at 4 K at several laboratories have shown that this relative gain is mostly at ~4K.

Question is how much it is useful at ~50 K. And how can one optimize the doping at ~5K, ~3 T

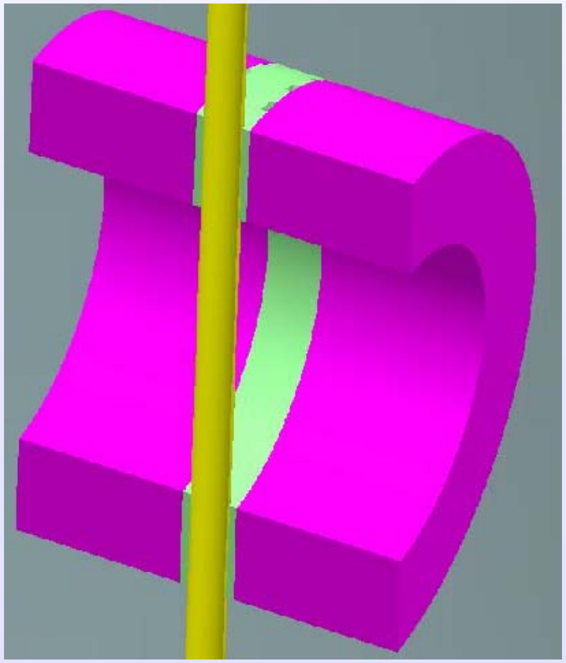
Split-pair HTS Solenoid as a Useful Test Facility



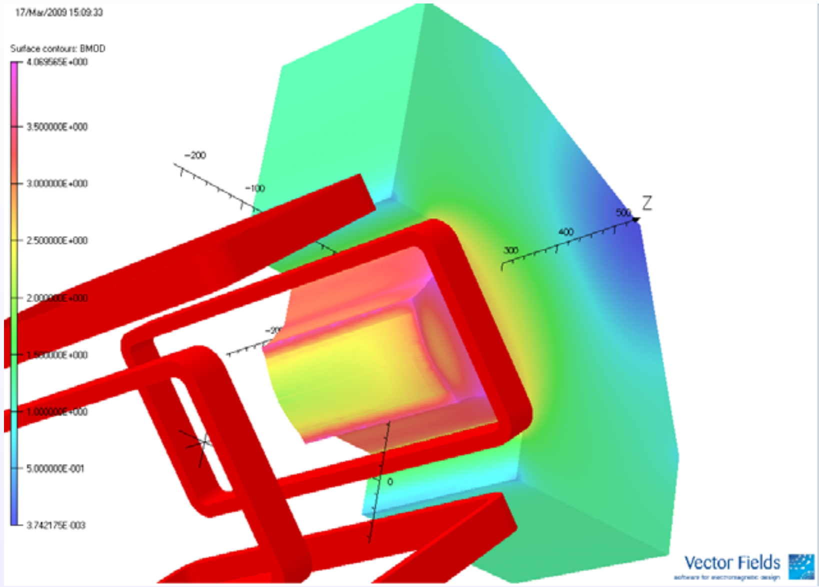
- We are building a ~10 T (@4 K) HTS solenoid as part of an SBIR program. With insert coils this could become a 20+ T.
- The advantage of HTS solenoid is that it can be operated at higher temperature (of course, generating much lower field).
- This could offer a good facility allowing measurements of I_c as a function of both the magnitude and the direction of field.
- This information is useful in optimizing both the conductor and the magnet designs.

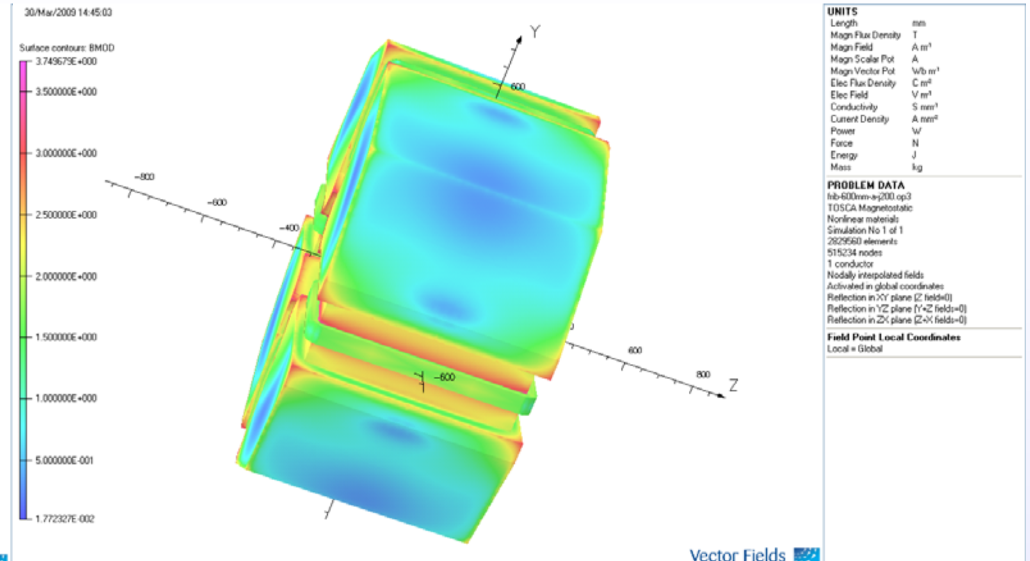


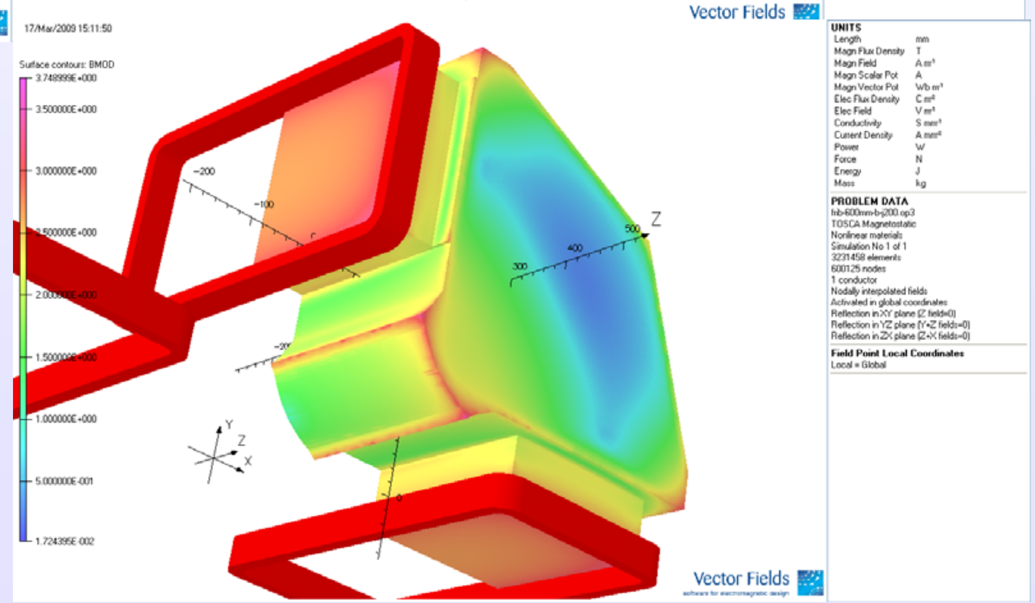
In addition to varying field angle, one may also be able to vary temperature with on-board heaters. This will allow a continuous and systematic 4 K – 80 K measurements as a function of the magnitude and the direction of the field.



Magnetic Design Studies



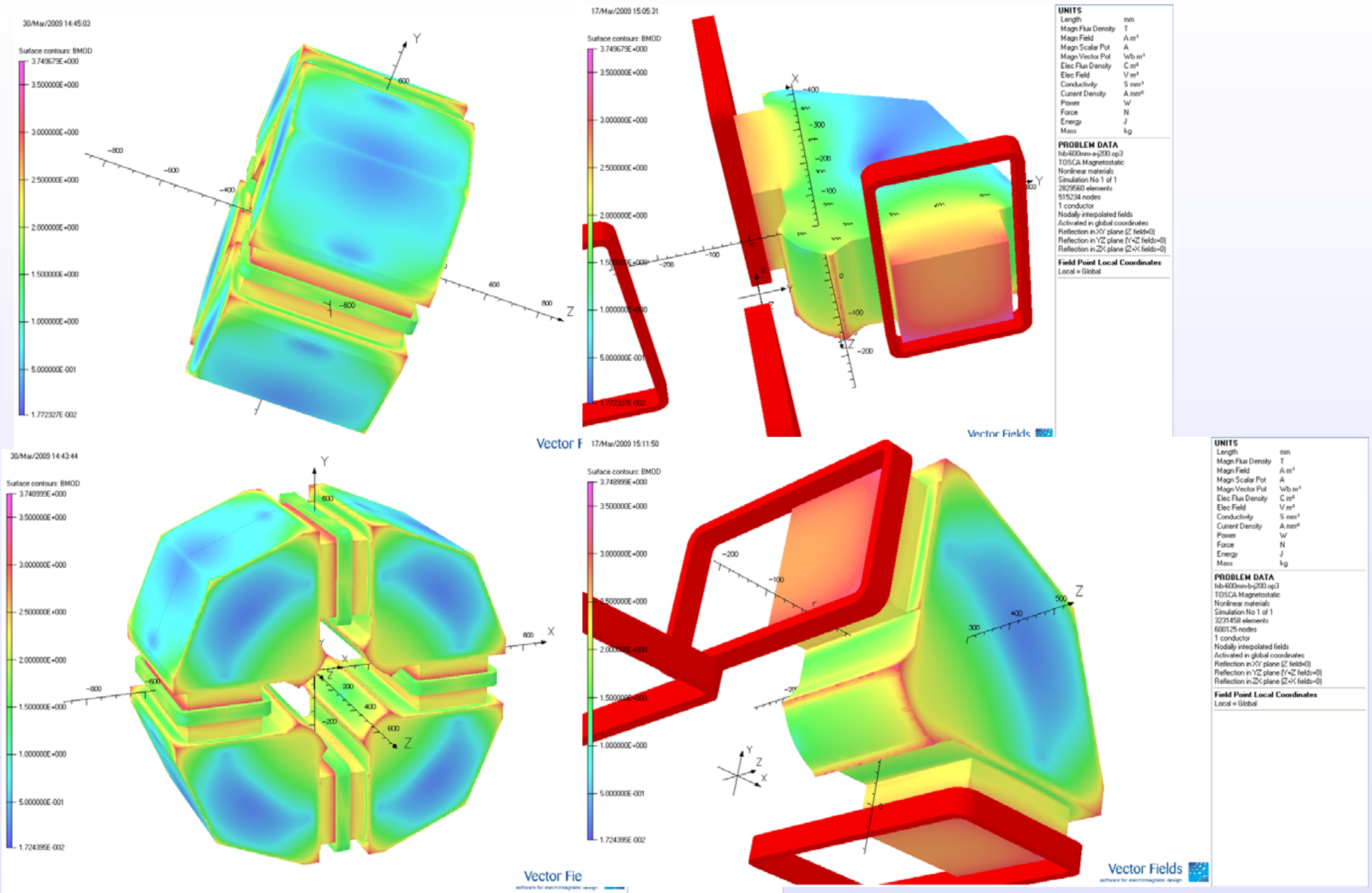




Backleg powered, two coil design is, in principle, highly attractive because it brings magnetic focusing very close to the target and only a smaller fraction of magnet cold-mass is subjected to high radiation.

- **However, such design may not be suitable for high gradient, short magnets.**

Back-leg Powered Design with Cryo-structure Approaching Yoke-length To Bring Focusing As Close As Possible



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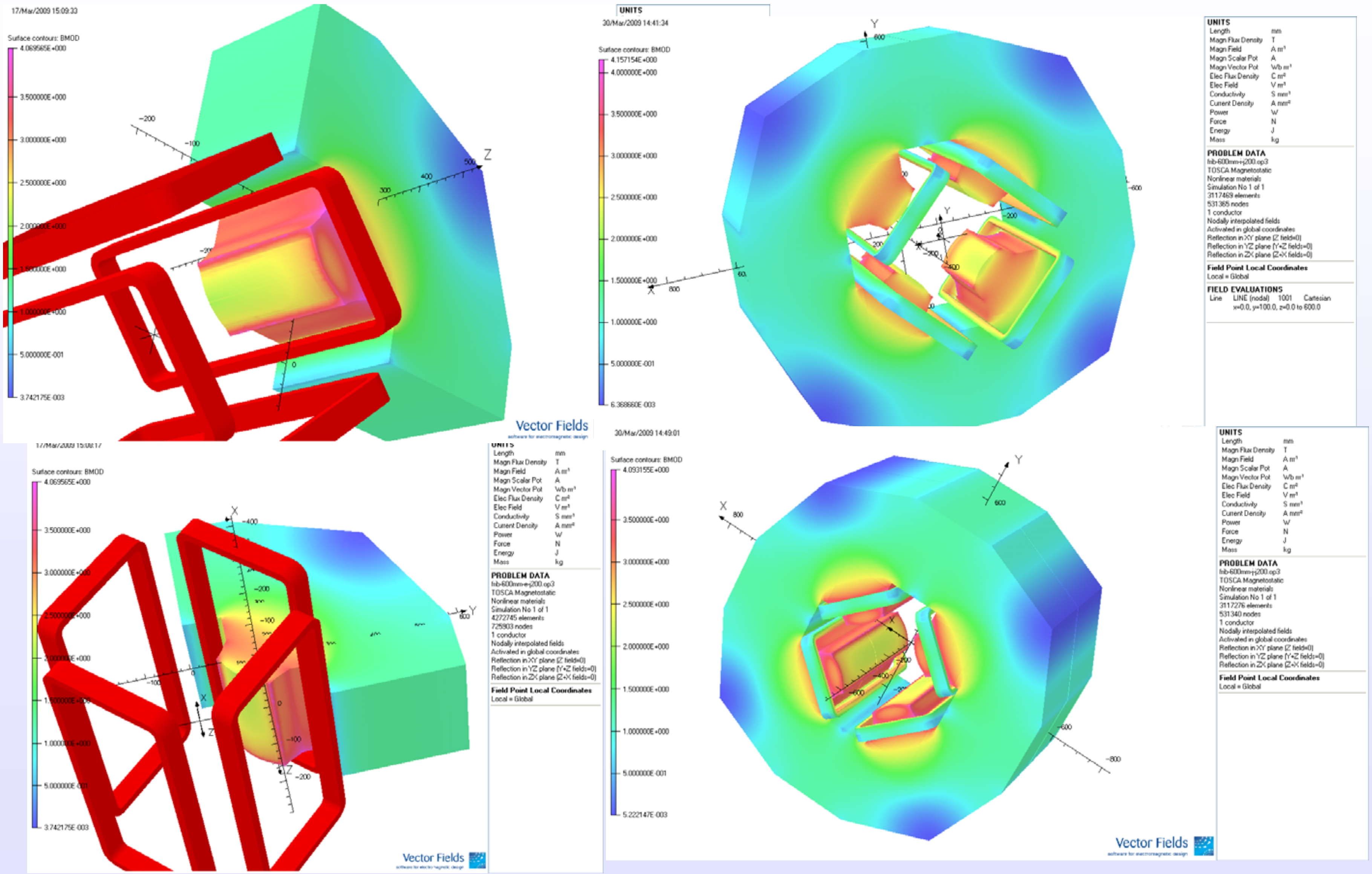
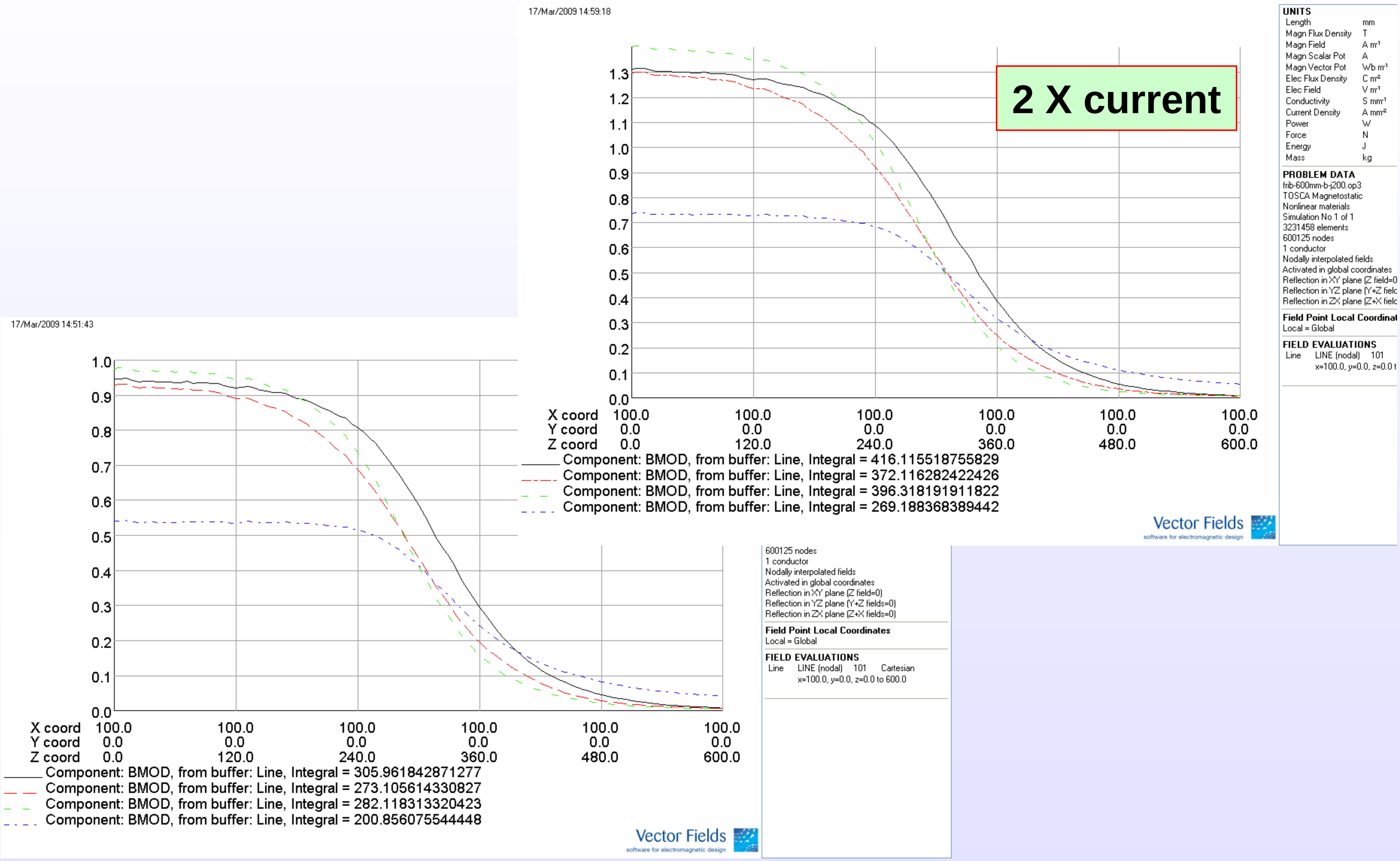
Conventional Super-ferric Magnetic Design (pole-powered, four coils)



Magnet Designs



Magnetic Design Studies

Backleg powered, two coil design is, in principle, highly attractive because it brings magnetic focusing very close to the target and only a smaller fraction of magnet cold-mass is subjected to high radiation.

- Higher gradient (~150 T/meter instead of ~100 T/meter)
- Shorter magnetic length (0.6 meter instead of 1 meter; more in other quad of triplet)

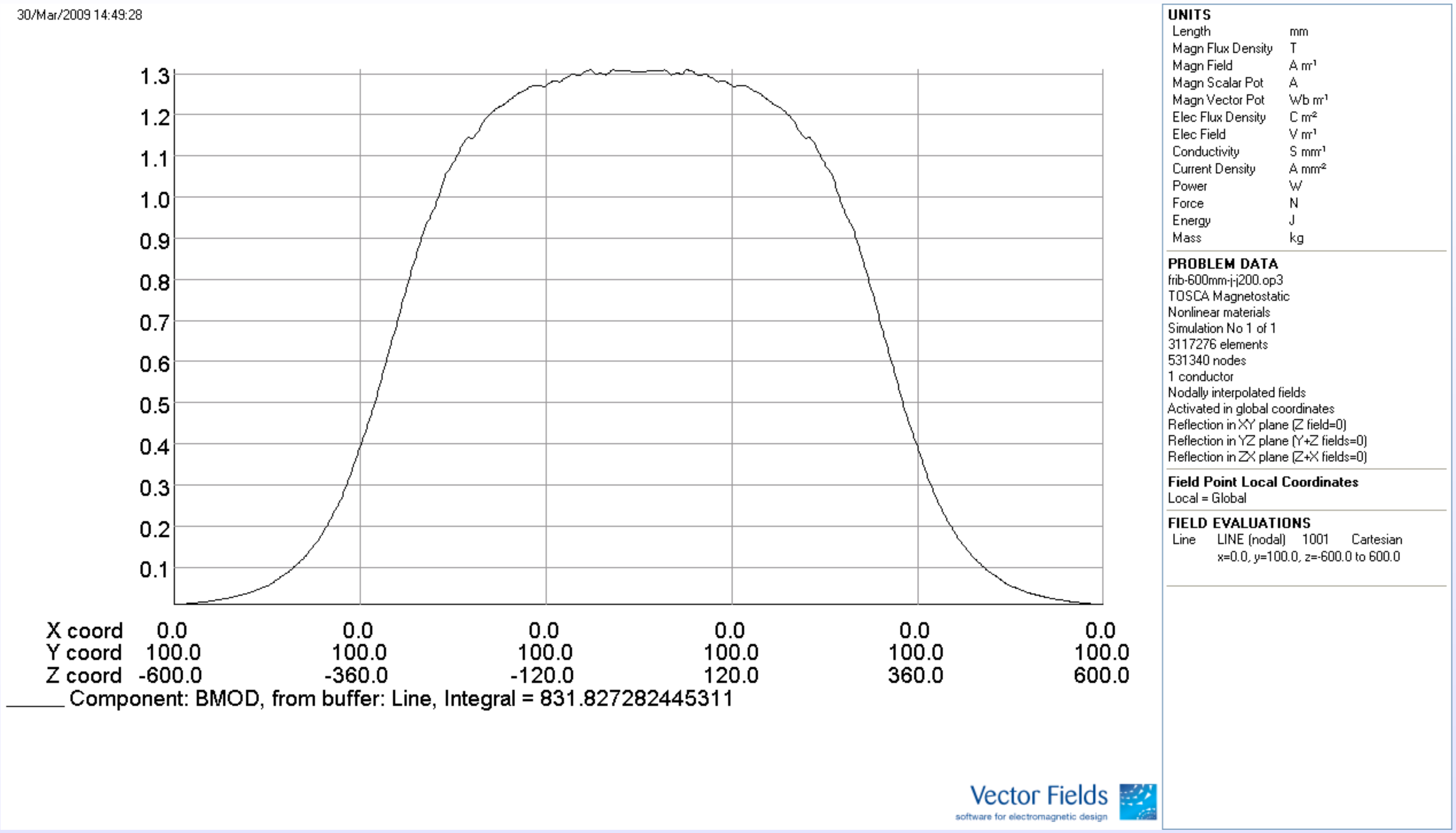
These changes (upgrade) in requirements have significant impact on the magnetic and conceptual design of the quadrupole. They cause significantly, higher saturation.

As saturation becomes large, two coil design shows significant asymmetry at higher fields and hence is no longer suitable.

Backleg-powered design becomes highly in-efficient (not practical) in pumping large amount of flux thru the poles, as needed in high gradient design.

Therefore, we need to move to more conventional design ➔ four coils, pole powered.

Axial Field Profile



Summary

- A step-by-step R&D program was developed to examine a new technology for a key component of FRIB/RIA.
- It proved that a number of HTS coils can be successfully built.
- A number of magnet structures were also built and tested.
- A comprehensive program included *radiation damage* and *energy deposition* studies.
- The first phase of the R&D has proved the most critical features of the technology (no show stoppers) in the magnet.
- Second phase of this program is based on the second generation (2G) HTS (YBCO) that would allow the magnets to be operated at ~50 K, where energy removal is more efficient than at ~30 K with first generation (1G) HTS (BSCCO).
- The new design will have higher field gradient than that in last one.