HTS Magnets for eRHIC

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9/26/14

Outline

- Benefits of HTS Magnetic Design
- Mechanical Design
- Prototype / Next Steps
- BNL HTS Background & Capabilities
- Summary

Benefits of HTS Magnets

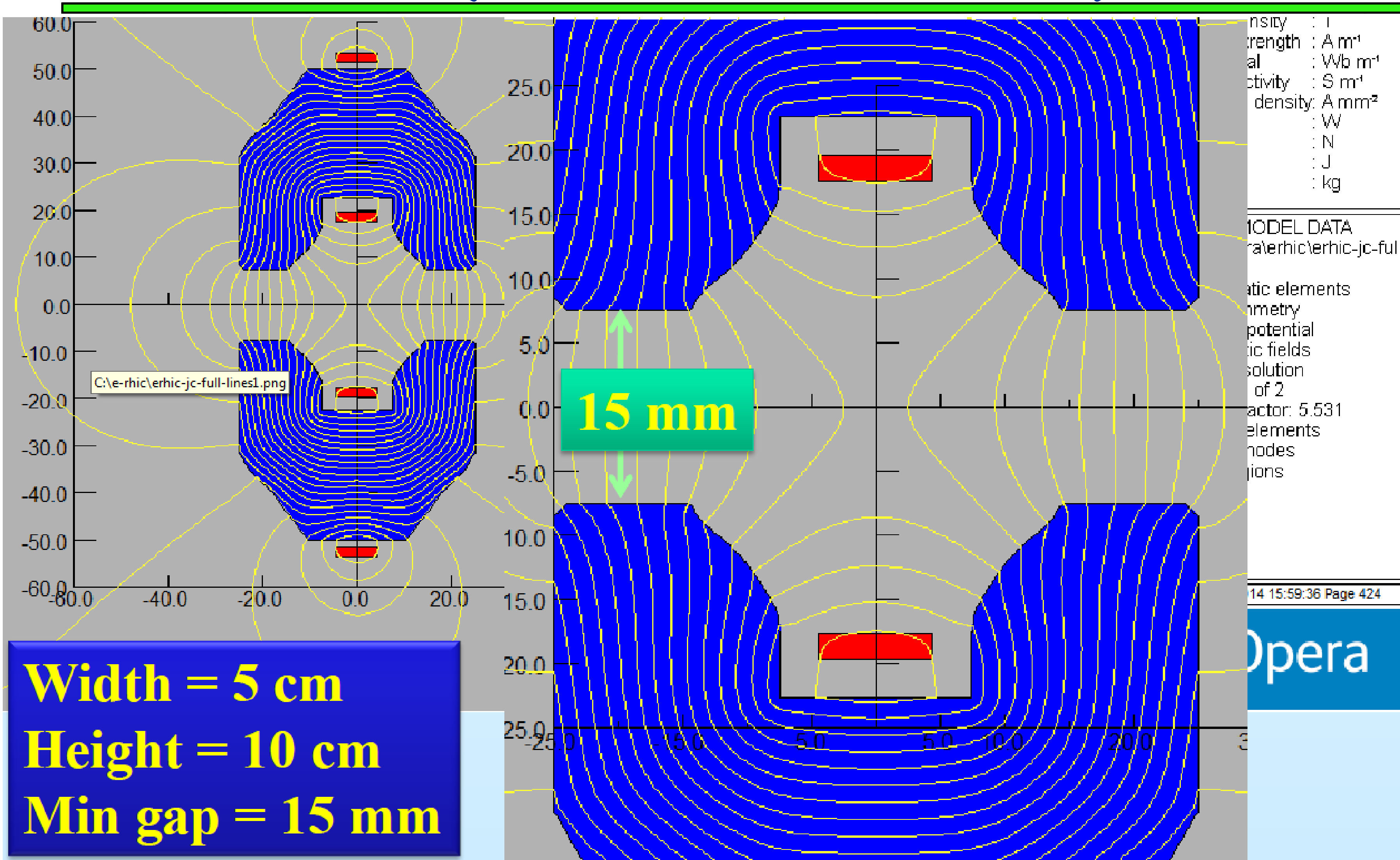
- As compared to the conventional Low Temperature Superconductor (LTS), HTS magnets can operate at elevated temperatures (instead of ~4 K – at 40-80 K)
- Temperature need not be controlled precisely (instead of a few tenth of K, the variation can be as much as 10 K)
- Cryo-mechanical structure can be simple, forgiving and cheap
- The magnet size can be significantly small as compared to the size of room temperature magnets or permanent magnets
- Power consumption – operating cost - is significantly less than room temperature magnets
- Because of a unique situation at BNL, the cryogenic infrastructure is already present in the tunnel (RHIC)
- BNL has a unique experience with HTS magnets (has several ongoing HTS magnet programs, has used an order of magnitude more HTS than any other lab and has achieved record fields, …)

Project Goal

To make a reliable, robust and inexpensive HTS magnet with material and overall cost similar or less than that in other options.

Magnetic Design

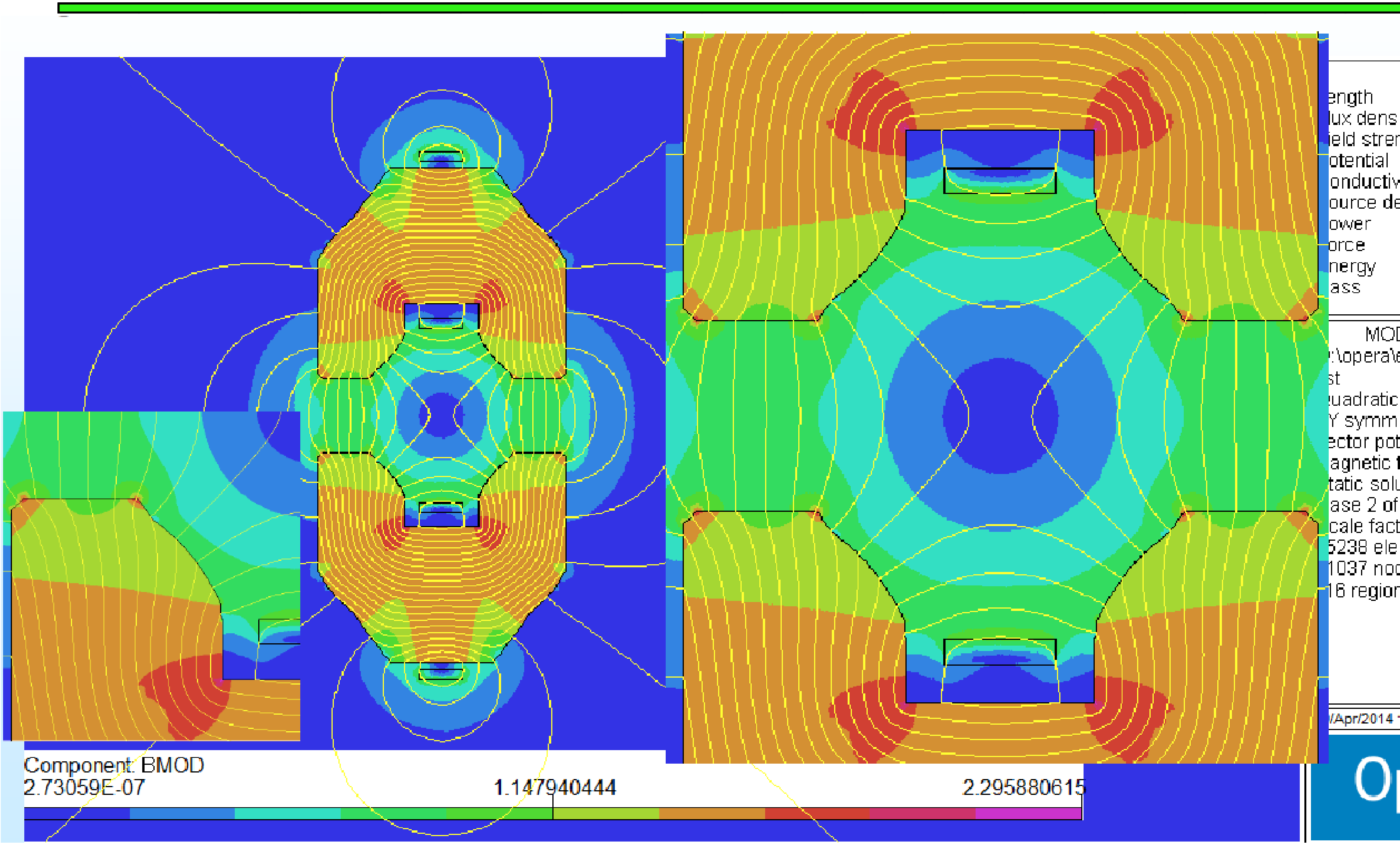
Early work - Initial Model (blue = iron, red = HTS)



Width = 5 cm
Height = 10 cm
Min gap = 15 mm

Superconducting
Magnet Division

Field and Field Lines @ 50 T/m



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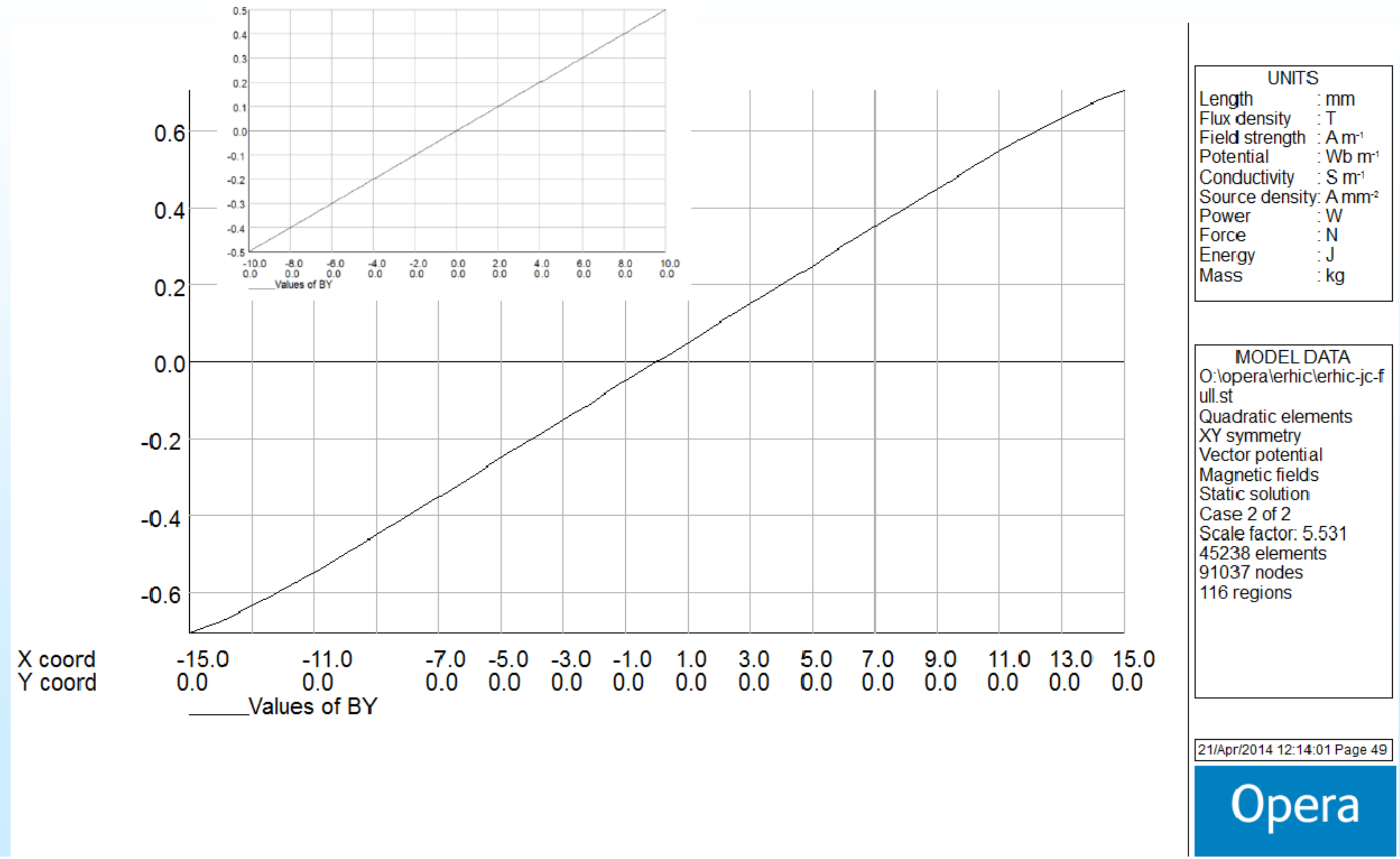
Vertical Field on X-axis



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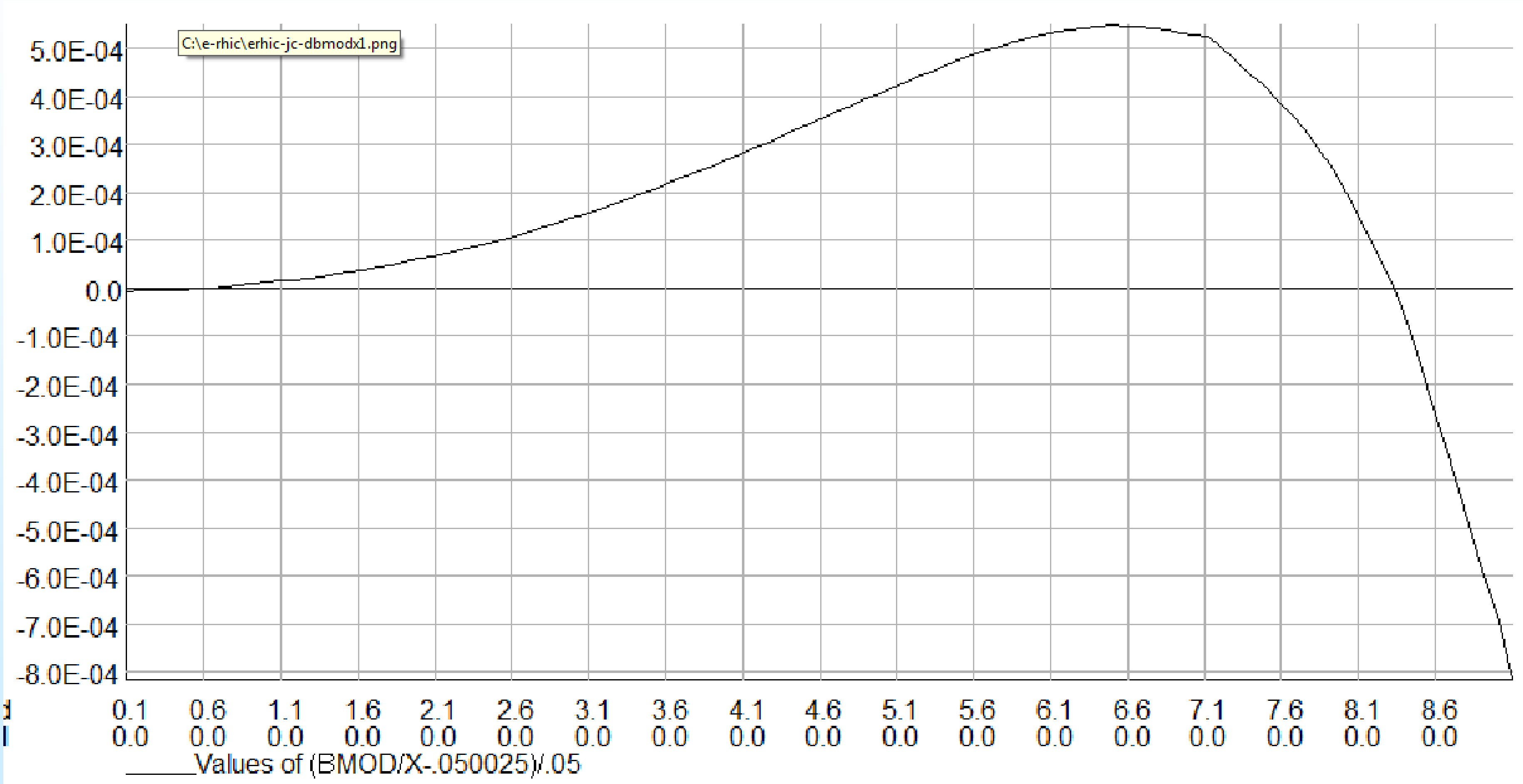
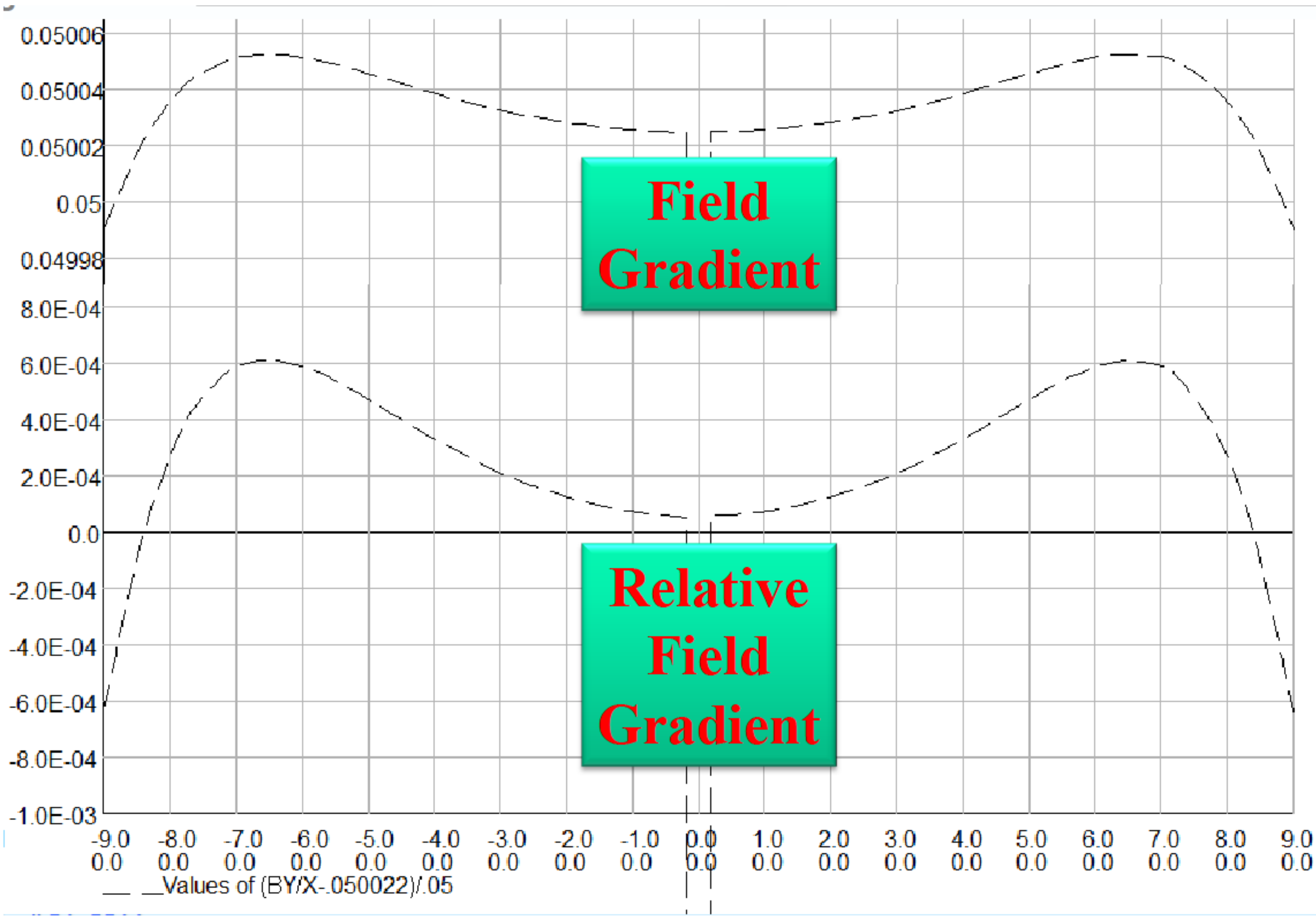
Field Uniformity on Horizontal Axis at 50 T/m



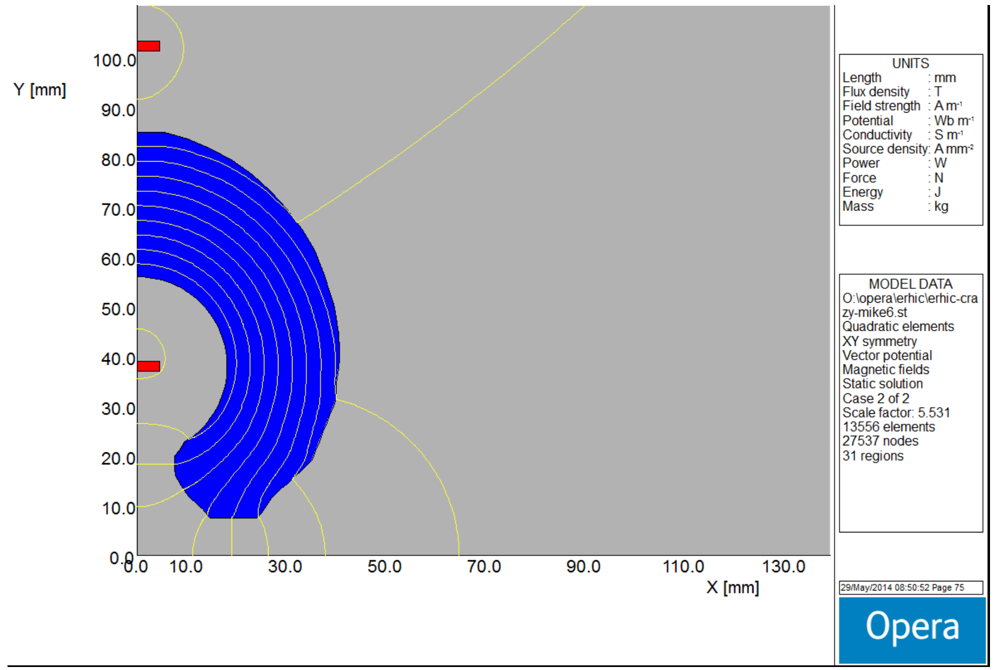
Field Uniformity on Full Horizontal Axis at 50 T/m



Circular 50T/m version

Goal: Exercise in Cost Optimization

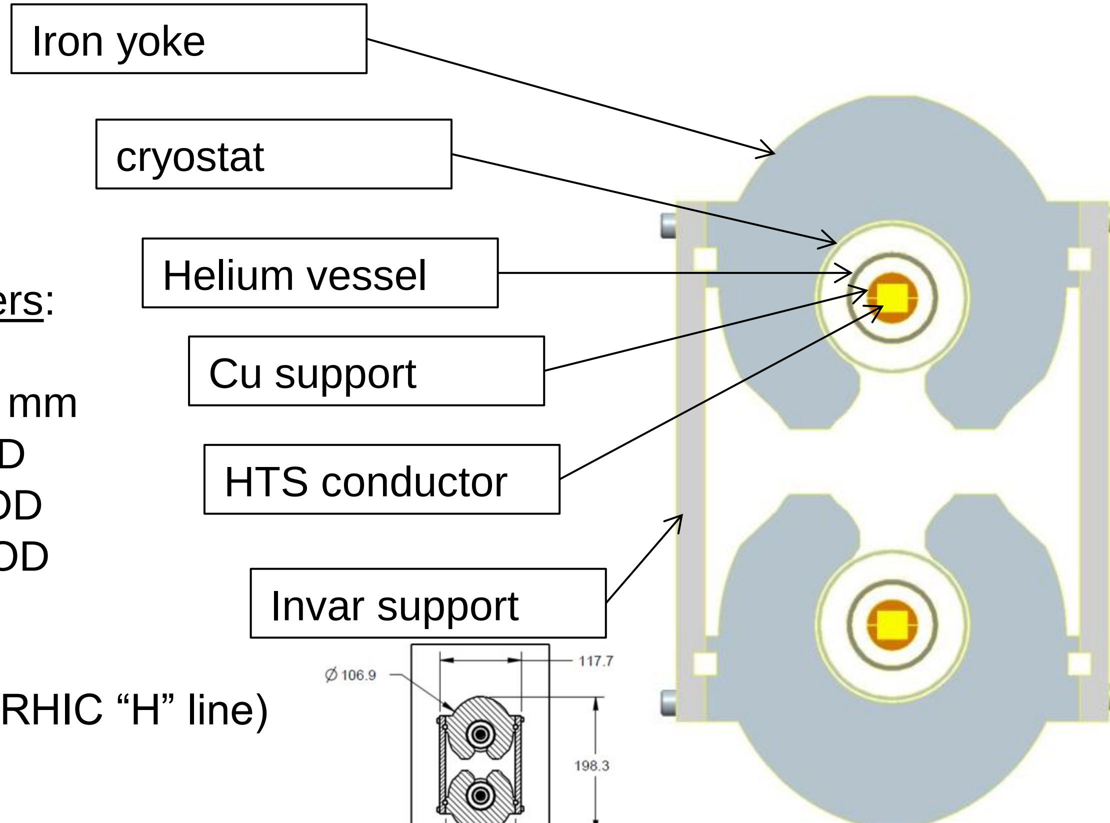
- Cheaper round components
- Easier to fabricate
- Well accepted criteria for helium pressure, insulating vacuum
- Potential for commercial participation



Mechanical Design

Present (still developing) 2-D Design

Based on Jan 2014 lattice



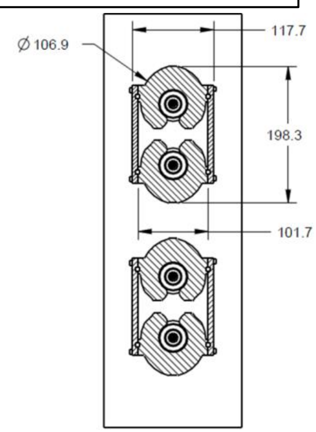
50T/m Working design parameters:

Conductor	50 layers, 8 mm
Helium vessel	Ø 29 mm OD
Cryostat	Ø 41* mm OD
Yoke	Ø 107 mm OD

Helium:

Temperature	45K – 60K (RHIC "H" line)
Pressure	13atm – 11atm
Flow (half ring)	15g/s x 4

Est. Heat Load: 6,600 W

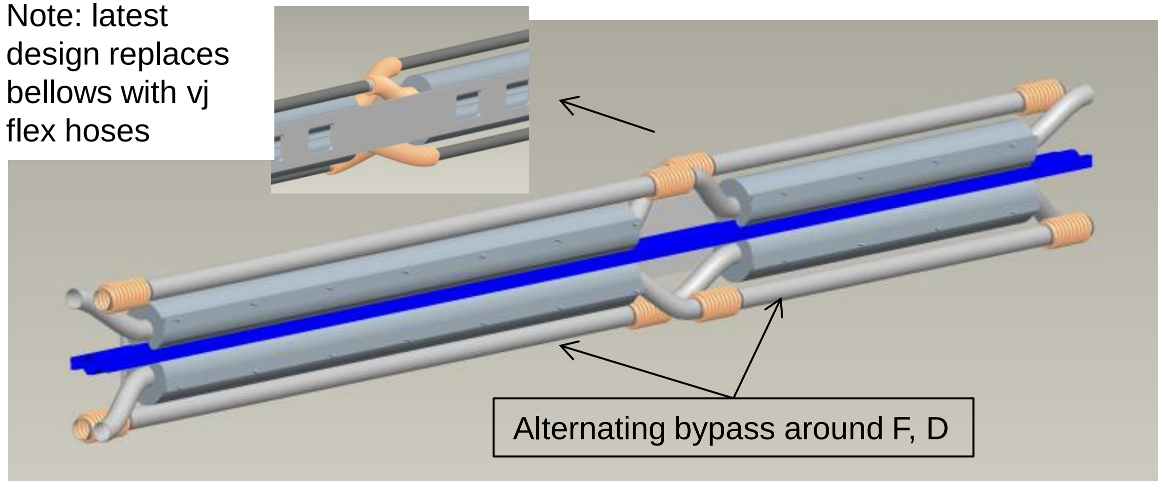


A small, simple, cheap (2-D) magnet

* Magnetic design = 36 mm

3-D Design Considerations (1)

Schematic Courtesy of Peter Theiberger



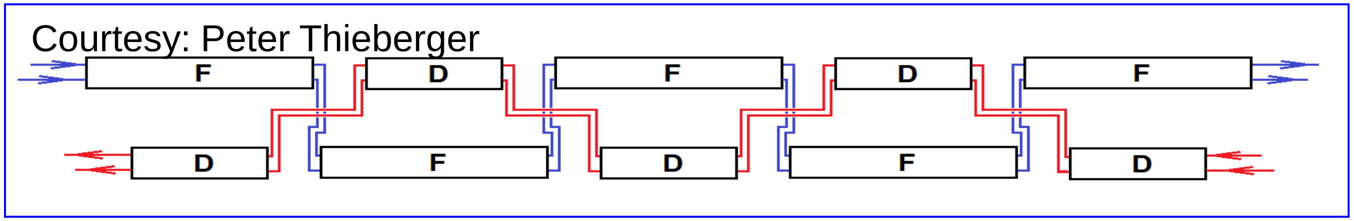
…but racetrack coils have ends

→ Magnet ends are expensive
→ Compact cryostat is complicated if not defeated

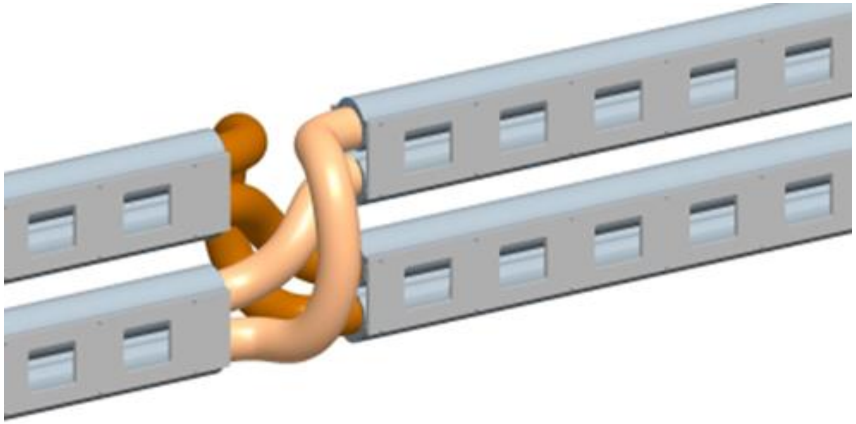
Solution: no coil ends
Build “Pipetron” style magnets
→ Lengths determined by available HTS lengths, shipping considerations, etc.

3-D Design Considerations (2)

Try to implement Theiberger "complicated" connection plan:



- Saves 50% of HTS, cryostat component cost
- Reduces helium cooling requirements



Prototype / Next Steps

Next steps #1 – optimize design, cost

- Update magnetic design (30T/m doublet?)
- Optimize design:
    - Cryo vs. yoke tradeoffs, etc.
    - Engage commercial companies as much as possible
- Complete cost estimate
- Submit as alternate design proposal for eRHIC FFAG

HTS in helium vessel & cryostat; $500-$1,000/m?

HV Wooding

QUOTATION	
HVW Quotation Number	Q-12623
Your Reference	
Date	29/08/2014
Attention	John Cozzolino
Page Number	1 of 2

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Dear John

Thank you for your recent enquiry. We have pleasure in quoting the following prices; please ensure you read the accompanying notes. If anything is unclear please give us a call:

For Delivery to: Receiving - Building 98,
Upton, New York, USA, 11973, U STATES OF AMERICA

Part Number	Issue	Annual Qty	Order Qty	Delv. Qty	Material / Finish	Price Ex. VAT USD	UOM	Weeks Lead Time (FRO)	Tooling
BR900-001	03/06/2014	6,000,000	500,000	500,000	1.52mm CR4 pressed	$13.76	100	TBA	$68,849
Deviation:	This price is based on conventional blanking, with no finishing. Technical discussions needed prior to order placement. This price is Exworks. Prices are ball park. Exchange rate=1.66								

By placing an order against our quotation you hereby agree to the Terms of this quotation as follows:

1. Lead-time is negotiable based upon receipt of Drawings, CAD Data, Technical Specifications and Capacity at time of order. We reserve the right to amend our proposal based upon further information being provided.
2. Unless requested at quotation stage, prices do not include Quality Information, i.e. PPAP, FAIR, etc.
3. Prices are subject to material prices at the time of order
4. All products and services are subject to our standard terms and conditions of supply, a copy of which is available on request.
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7. **Please send any orders to the address/fax/email at the bottom of this quote.**

If you would like to discuss any aspect of this quotation please do not hesitate to contact me directly by telephone or email.

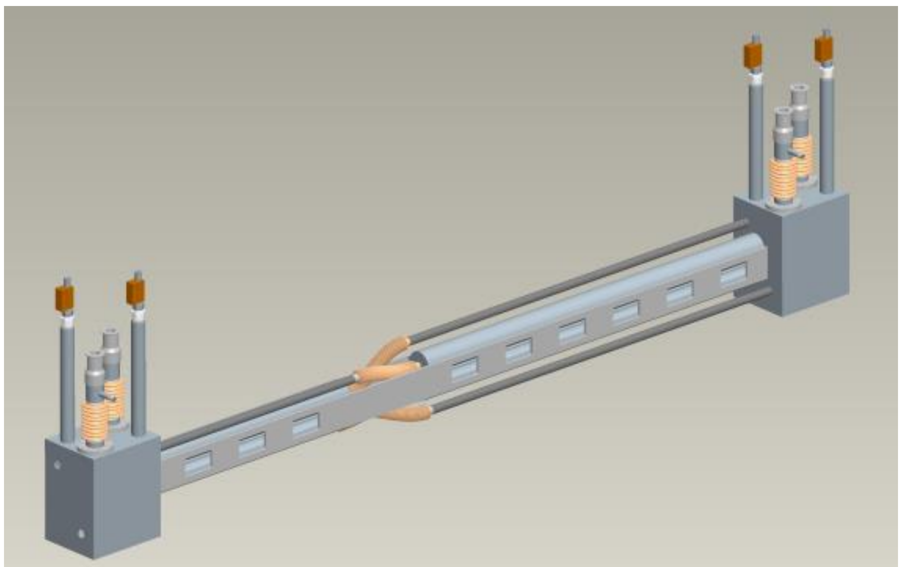
I look forward to speaking to you in the near future.

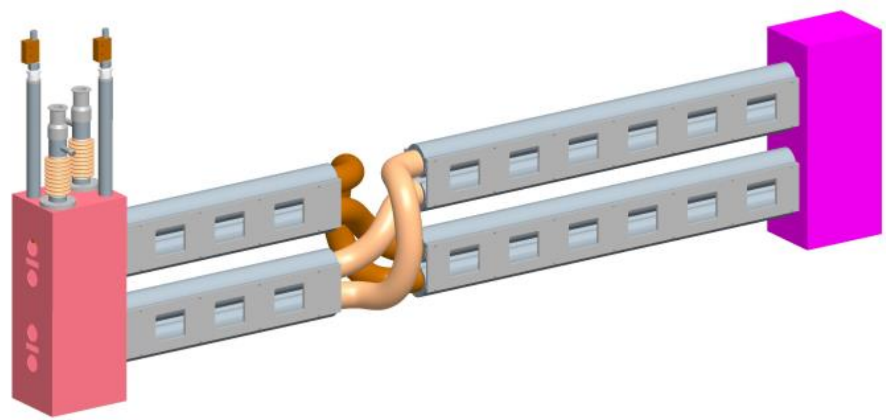
Yours sincerely,

$0.14 per (1.5 mm) yoke lamination inc. material

Next steps #2 - prototype

- Optimize design (30T/m doublet?)
- Design, build and test prototype high field / low field 1 or 2 cell "girder" assembly





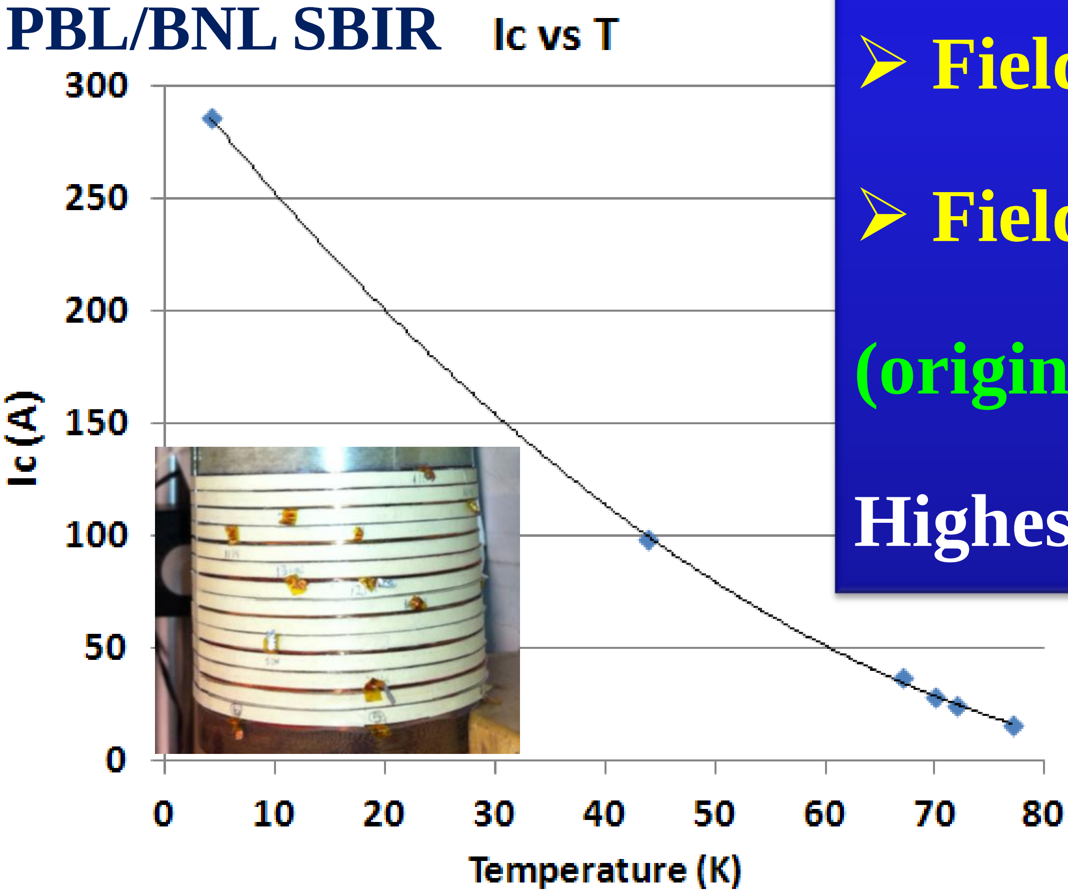
HTS Magnet Program at BNL

HTS Magnet Program at BNL

- HTS magnet R&D over a wide range:
  - High field, Medium field and low field (high temperature)
  - Many geometries – racetrack, cosine theta, solenoid
- Number of HTS coils/magnets designed built & tested:
  - Well over 100 HTS coils and well over 10 HTS magnets
- Type of HTS used:
  - Bi2223, Bi2212, ReBCO, MgB_2 – wire, cable, tape
- Amount of HTS acquired:
  - ~50 km (4 mm tape equivalent)
- Our recent activities have been largely on magnets with ReBCO
  - (yet one Bi2223 and one MgB_2 magnet is ready for testing)

High Field (16T) Demo of HTS Magnet

PBL/BNL SBIR



- **Field on axis: 15.7 T**
- **Field on coil : 16.2 T**

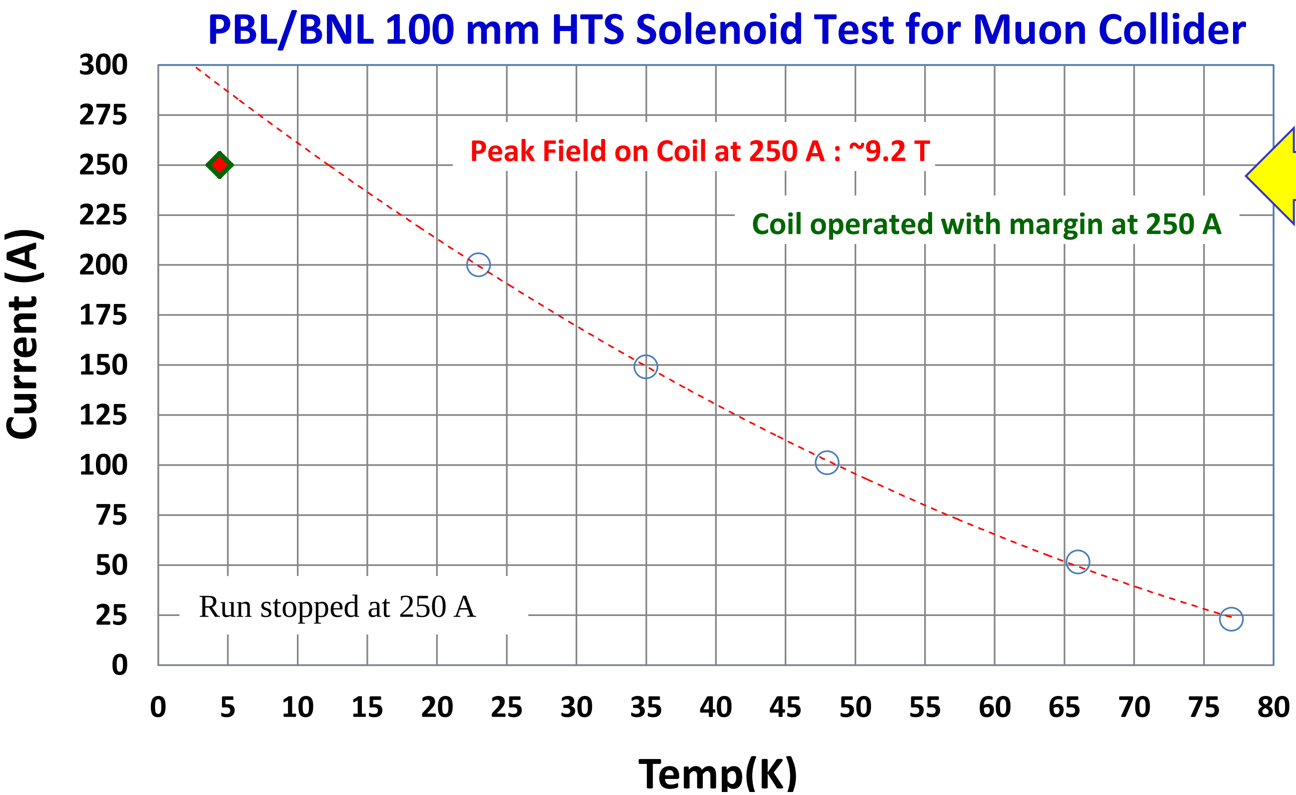
(original target: 10-12T)

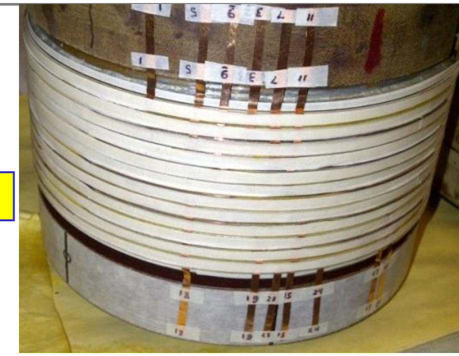
Highest field all HTS solenoid

Overall J_o in coil:
>500 A/mm^2 @16 T

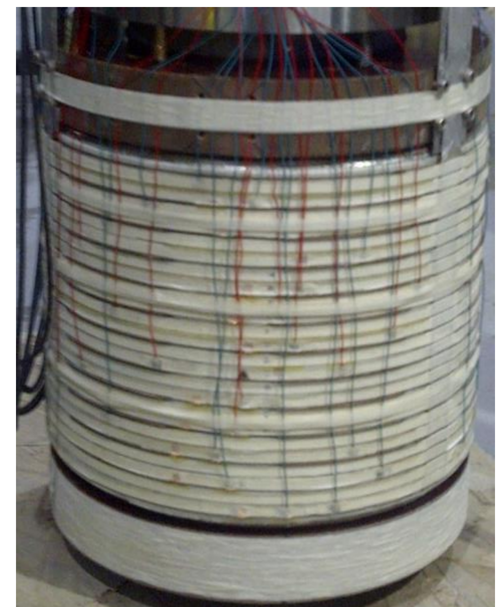
Insert solenoid: 14 pancakes, 25 mm aperture

Large Aperture High Field HTS Magnet





Half midsert (12 pancakes)



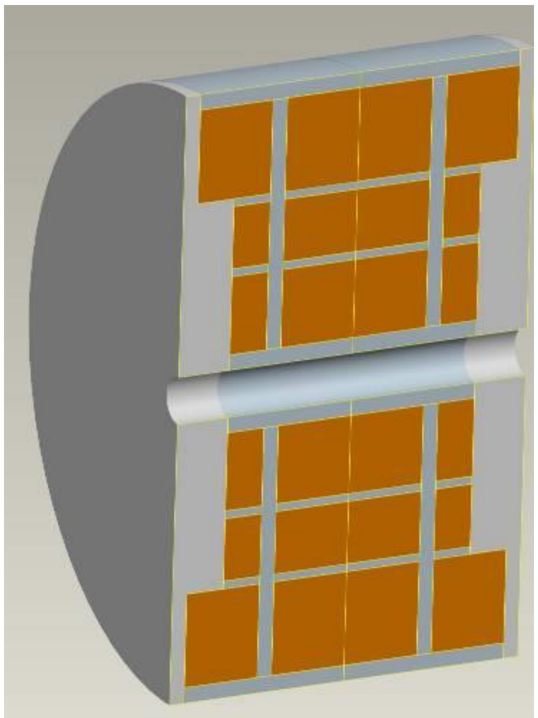
Full midsert (24 pancakes)

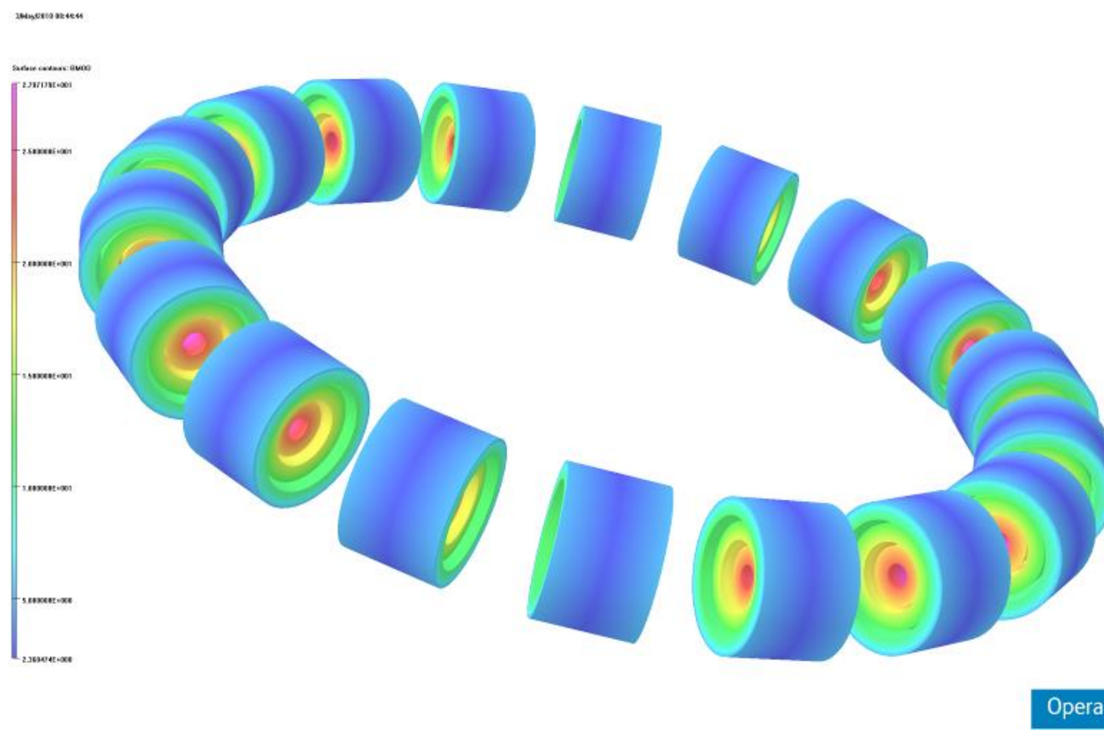
- Half midsert operated at 250 A @4 K
  (6.4 T field on axis, 9.2 T peak field on coil
- Design value for full midsert: 220 A for 10 T

Superconducting Magnetic Energy Storage (SMES)

Key Target Parameters: 25T, 100mm, 1.7MJ, 12mm ReBCO

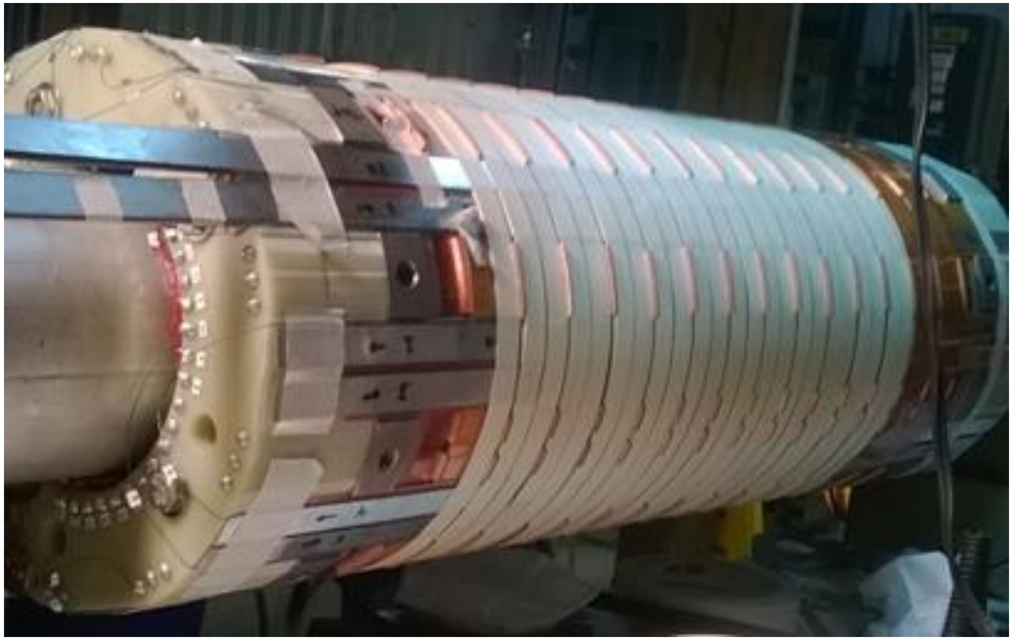
High field large aperture HTS solenoid with huge stresses



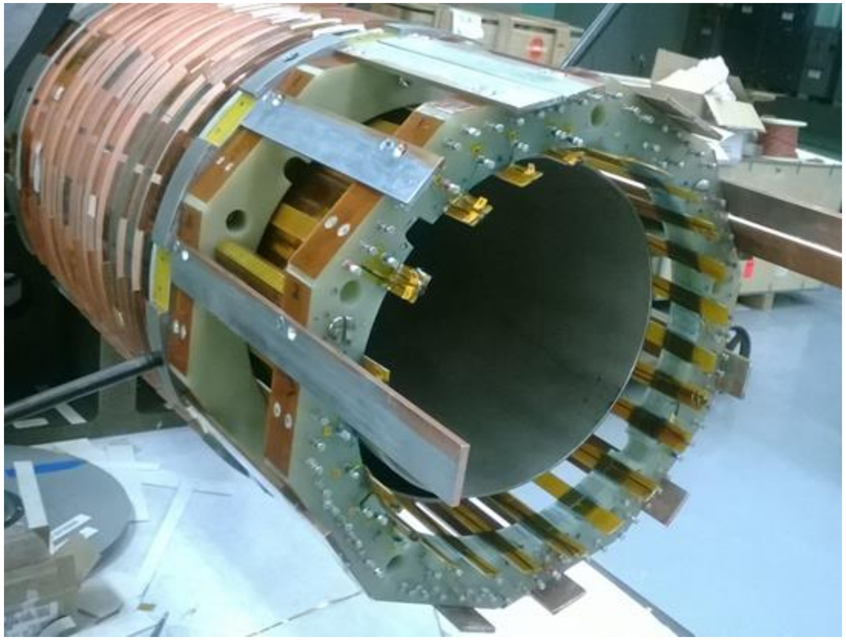


- **Funded by arpa-e as a "high risk, high reward" project**

SMES Magnet



Inner Coil
(28 pancakes)



Outer Coil
(16 pancakes)

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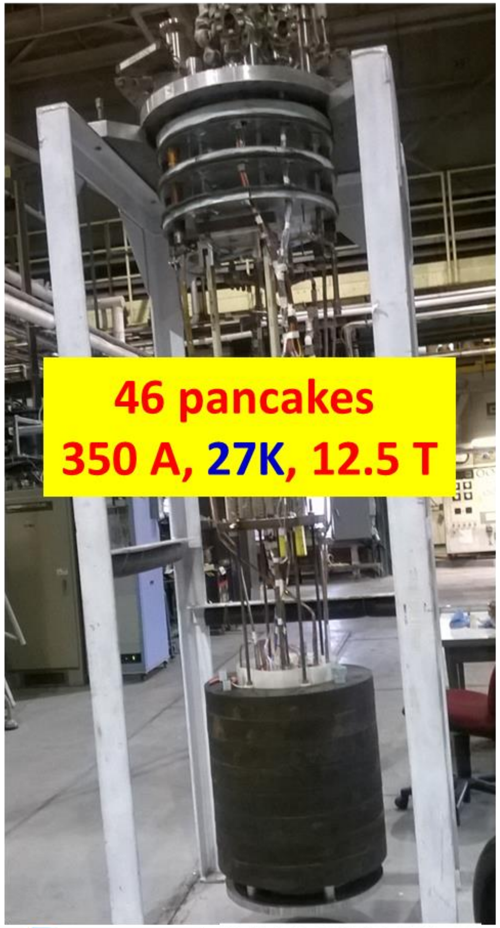
Superconducting
Magnet Division

HTS SMES Magnet Test Results
100 mm bore ReBCO SMES Coil



Peak fields higher

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August 2013

Massive Energy Storage in Superconductors (SMES)

Novel high temperature superconductor magnet technology charts new territory.

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The Office of Nuclear Physics funds a community of scientists to do basic nuclear physics research that seeks to uncover the fundamental nature of matter. As a consequence of this basic research, many ideas and instruments (funded through various sources) have found their way into many different areas in public life as well as in other government programs. This highlight is an example of such a "spinoff".

Enlarge Photo

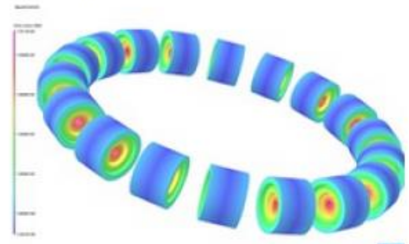

Image courtesy of Brookhaven National Laboratory

A toroid SMES system consisting of a number of high field coils made with the High Temperature Superconductors (HTS).

The Science

Batteries store energy in chemicals: similarly, superconducting coils store energy in magnets with low loss. Researchers at Brookhaven National Laboratory have demonstrated high temperature superconductors (HTS) for energy storage applications at elevated temperatures and/or in extremely high densities that were not feasible before.

HTS Quadrupole for FRIB

(now part of baseline design)

FRIB: Facility for Rare Isotope Beams, now under construction at MSU, USA.

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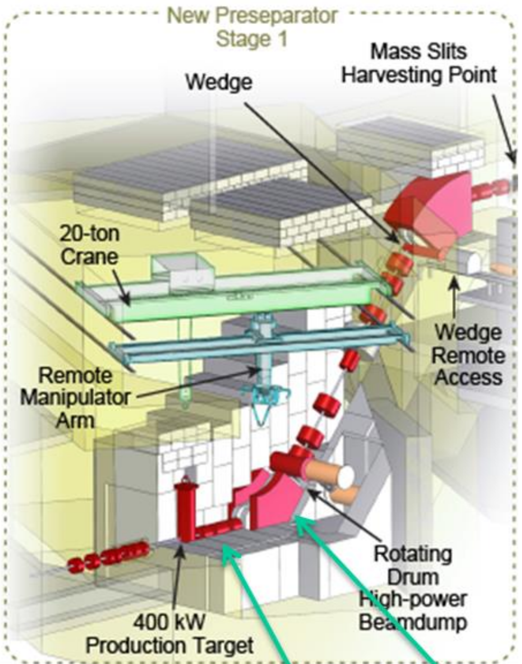
Superconducting Magnet Division

Radiation Tolerant HTS Quad for the Fragment Separator Region of FRIB

To create intense rare isotopes, 400 kW beam hits the production target.

Magnets in the fragment separator region are exposed to unprecedented radiation and heat loads. HTS can efficiently remove that at elevated temperatures.

Courtesy: Al Zeller, FRIB/MSU

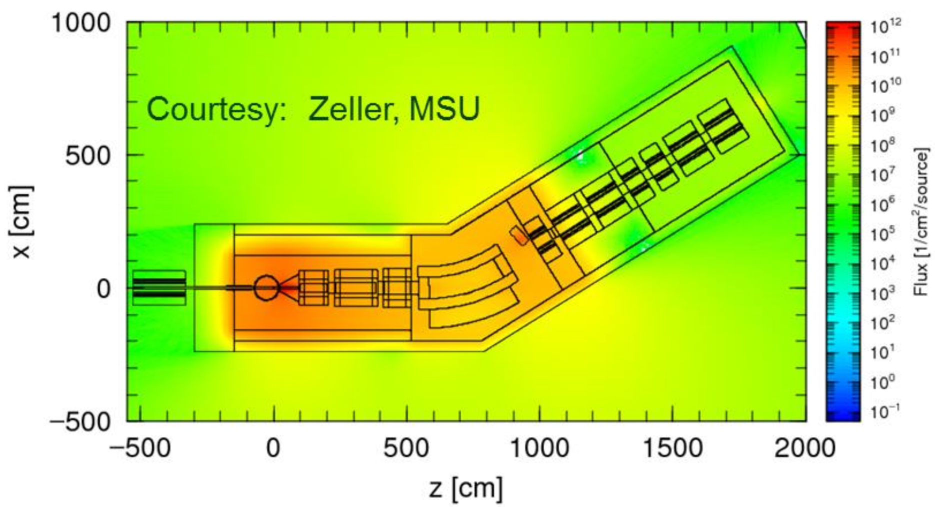


Radiation resistant

Pre-separator quads and dipole

Exposure in the first magnet itself:

- **Head Load : ~10 kW/m, 15 kW**
- **Fluence : 2.5 x10^{15} n/cm^2 per year**
- **Radiation : ~10 MGy/year**



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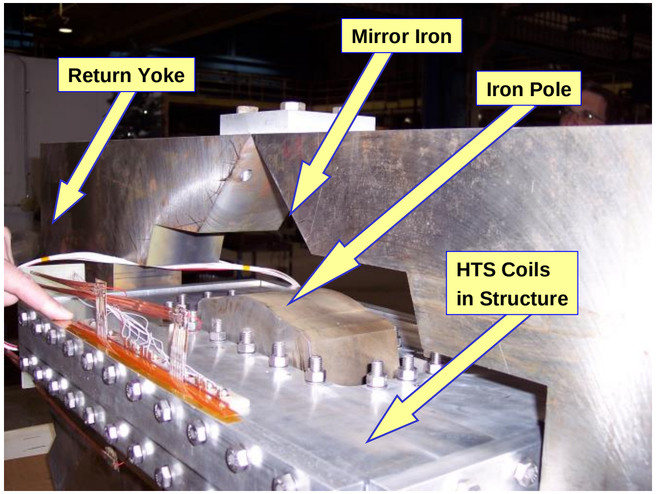
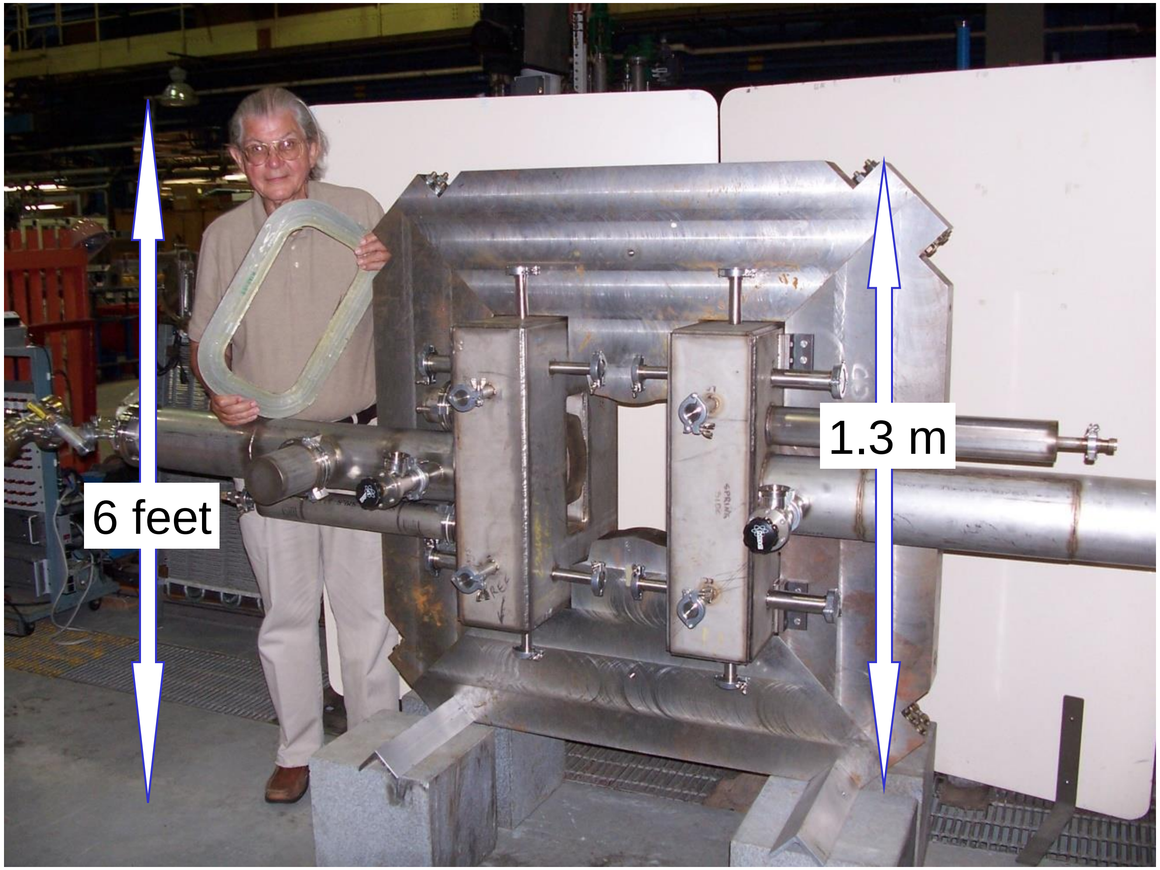
First Generation HTS Quad for FRIB



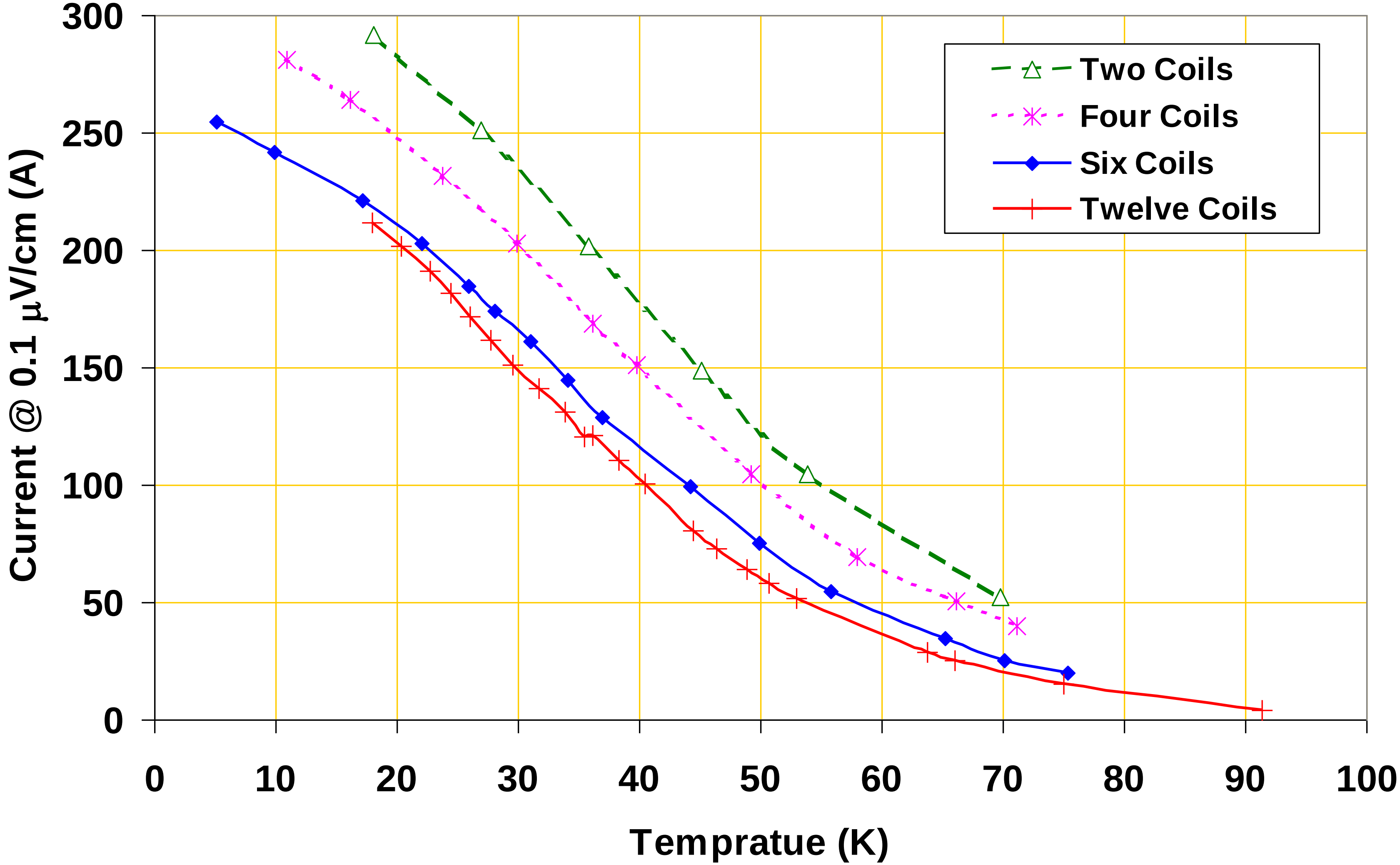
Mirror cold iron

Warm Iron Design with Bi2223 HTS

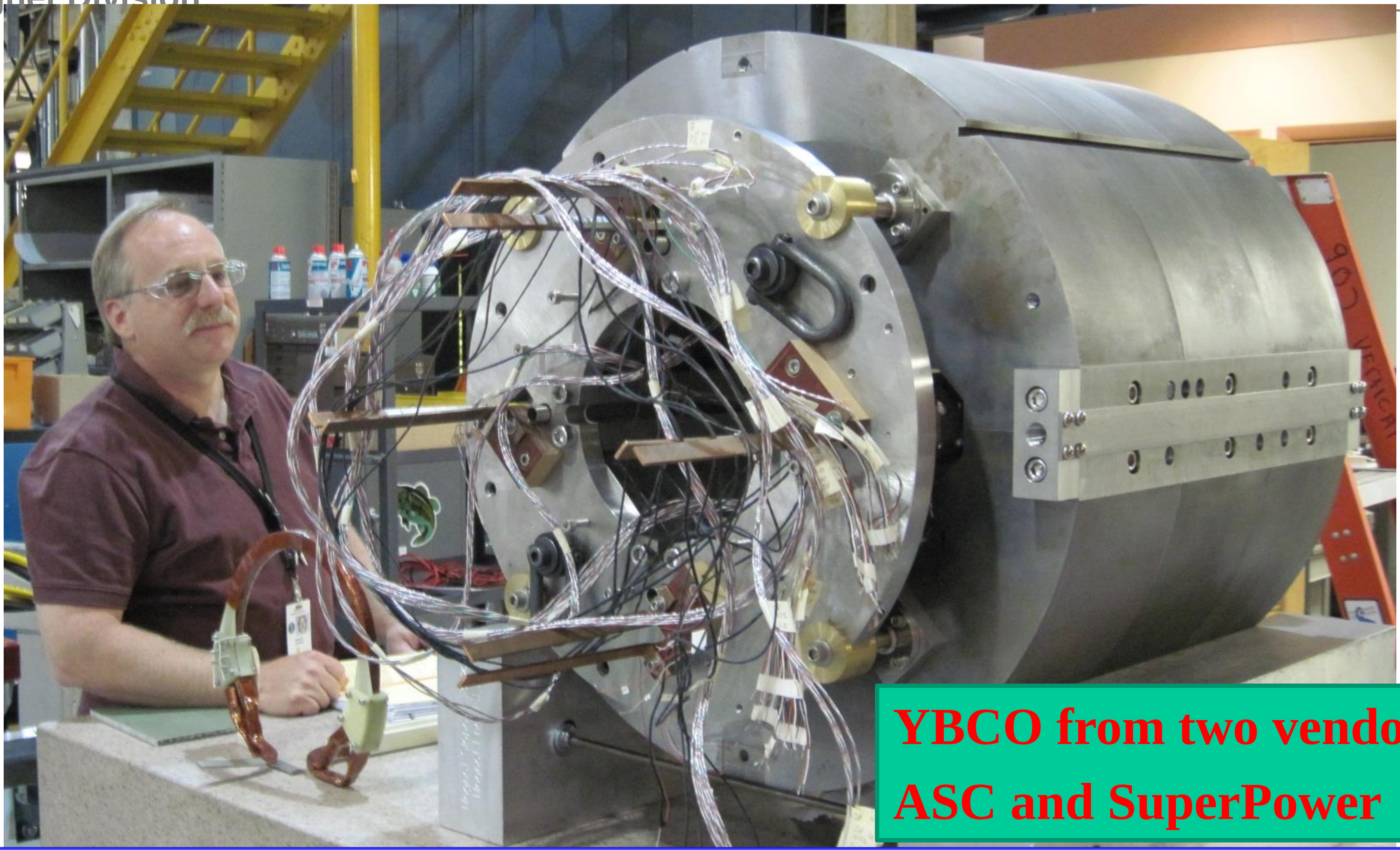


Mirror warm iron

First Generation HTS Quad Test (operation over a large temperature range)



Second Generation HTS Quad for FRIB Fragment Separator Region

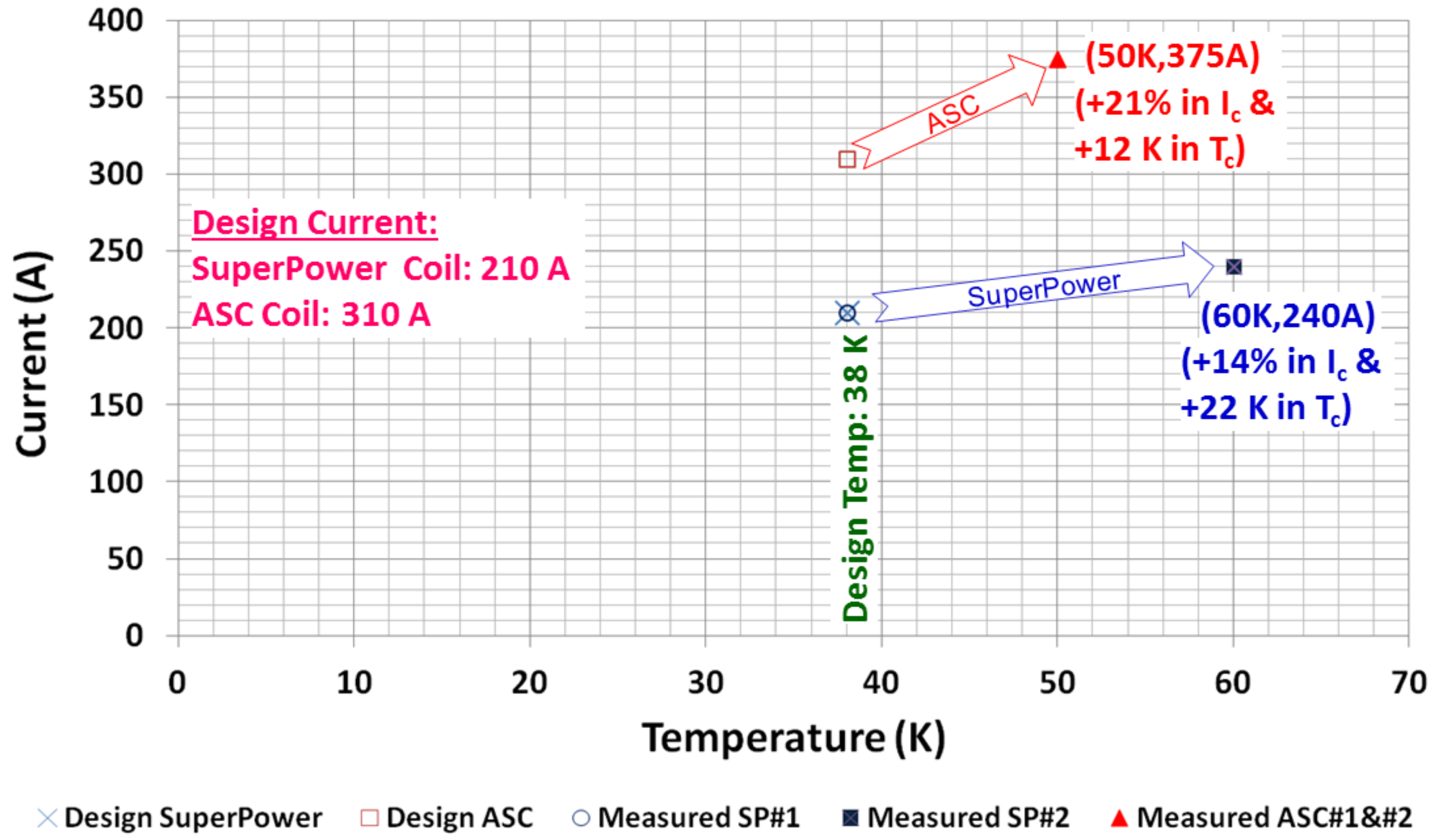


YBCO from two vendors
ASC and SuperPower

Important: Magnet for a real machine- baseline design of FRIB

Winding of Second Generation HTS Racetrack Coil for FRIB

Large Temperature Margins (only possible with HTS)

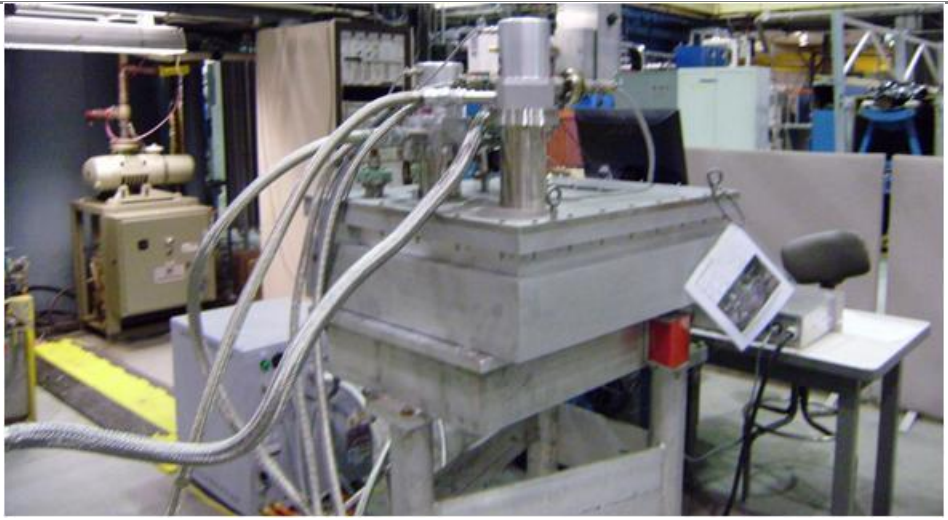


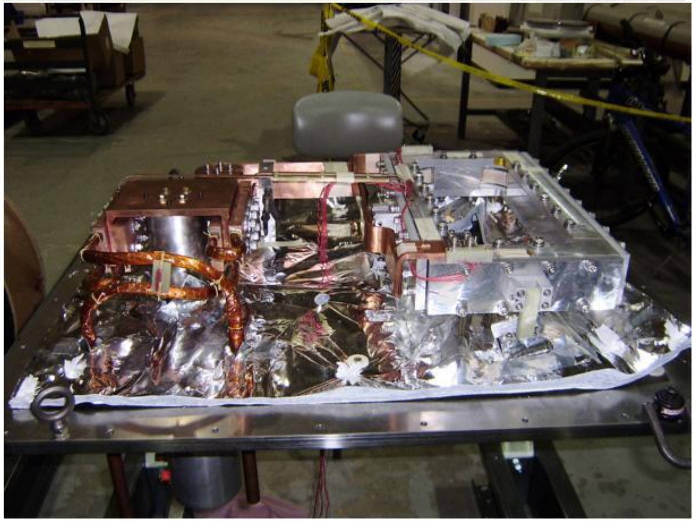
HTS provides robust operation against local and global heat loads

Advanced Quench Protection Electronics

Detects onset of pre-quench voltage at < 1mV and with isolation voltage > 1kV allows fast energy extraction

A Warm bore Cryo-cooled Magnet with 6 HTS coils





Evening: Switch ON

Morning: Fully COLD for operation

- **No Helium needed**

Low Magnetic Field Application
HTS Solenoid with Superconducting Cavity for the Energy Recovery Linac (ERL) at BNL

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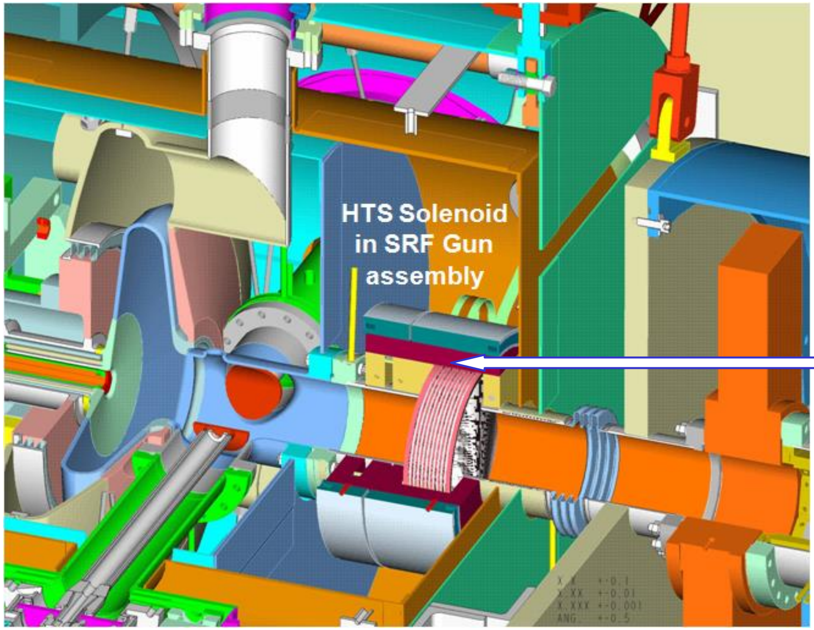
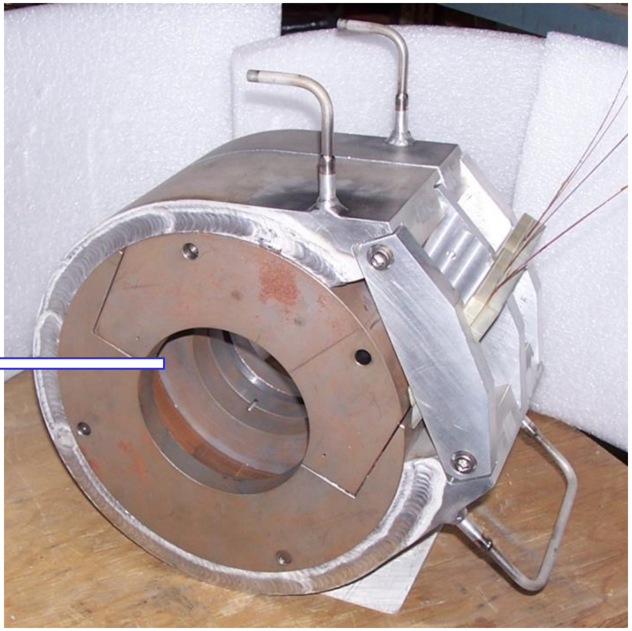
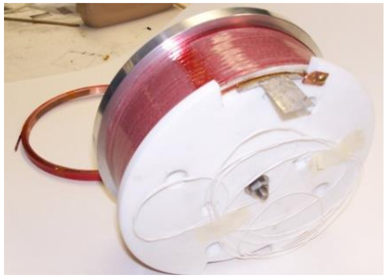
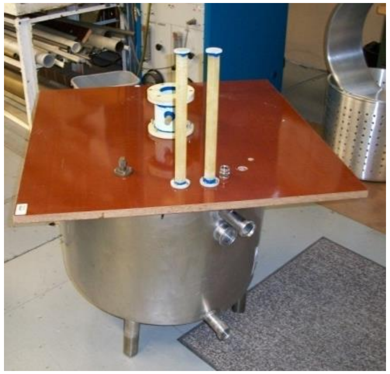
Superconducting Magnet Division









HTS solenoid is placed in cold to warm transition region after the superconducting cavity where neither LTS or copper solenoid would work

Early focusing provides a unique and better technical solution

Summary

- HTS is a good technical solution for FFAG eRHIC
- Work remains to be done to be cost competitive
- BNL SMD has a strong history of successfully designing, building and testing unique and challenging HTS magnets and welcomes the opportunity to contribute to eRHIC