Design, Construction and Test Results of A Warm Iron HTS Quadrupole for the Facility for Rare Isotope Beams

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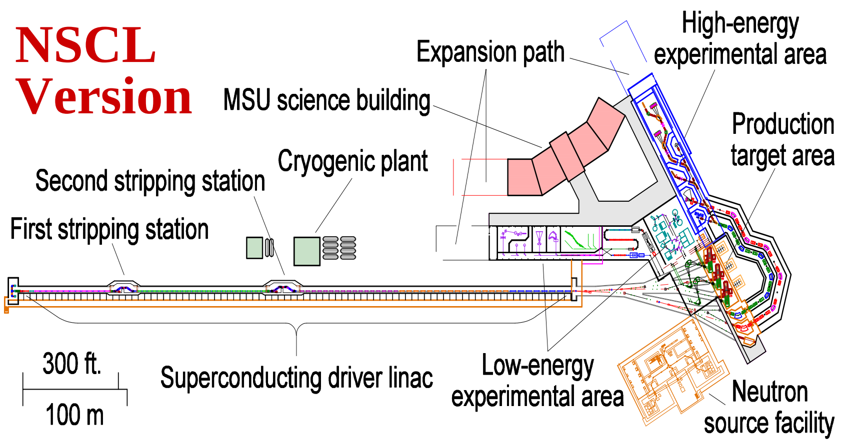
Overview

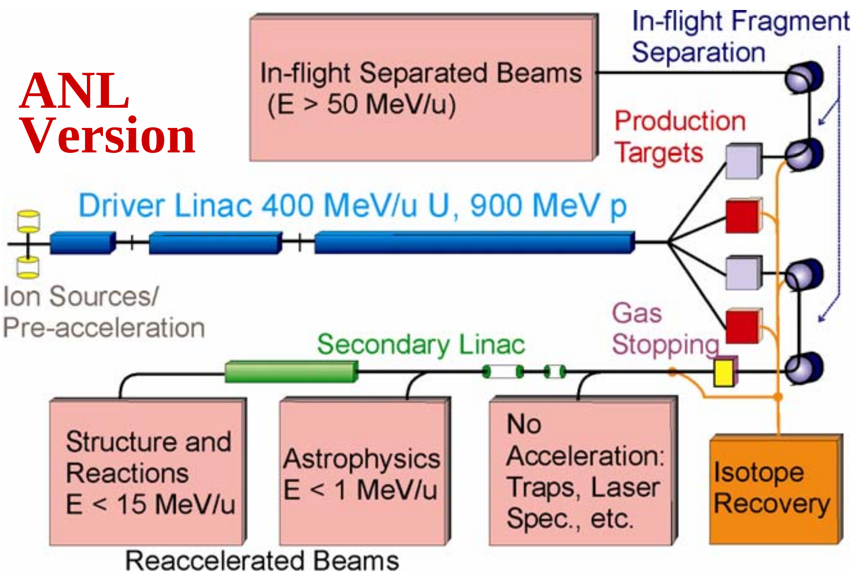
- Challenging Environment of Facility for Rare Isotope Beams
  - Unprecedented energy deposition in the Fragment Separator quadrupoles
  - ~10 kW/m compared to ~0.1 KW/m in the first quad of LHC IR upgrade
- Quadrupole Design
  - A design optimized to minimize radiation and heat loads on cold structure
  - Use HTS coils to withstand and remove these large heat loads economically
- A Step-by-step and Systematic R&D Program
  - Demonstrate that such accelerator/beam-line magnets can be built with the commercially available HTS
- Energy Deposition Experiments
  - The Heart of the Program
- Future Plans
  - Take advantage of YBCO
- Summary and Outlook

RIA and FRIB

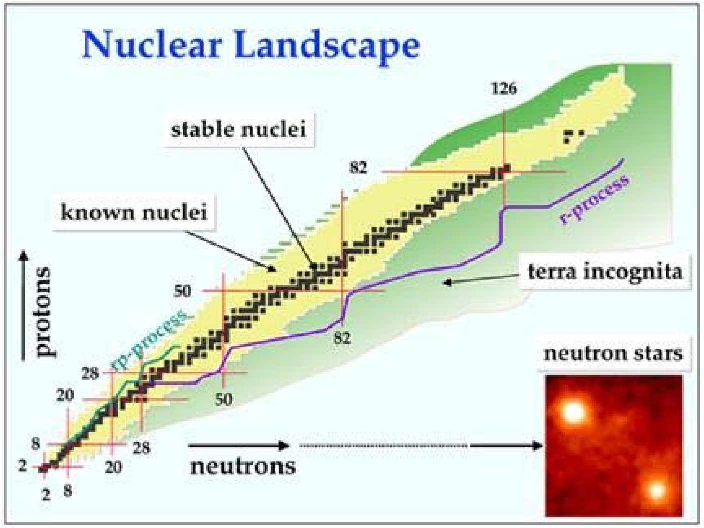
NSCL Version



ANL Version

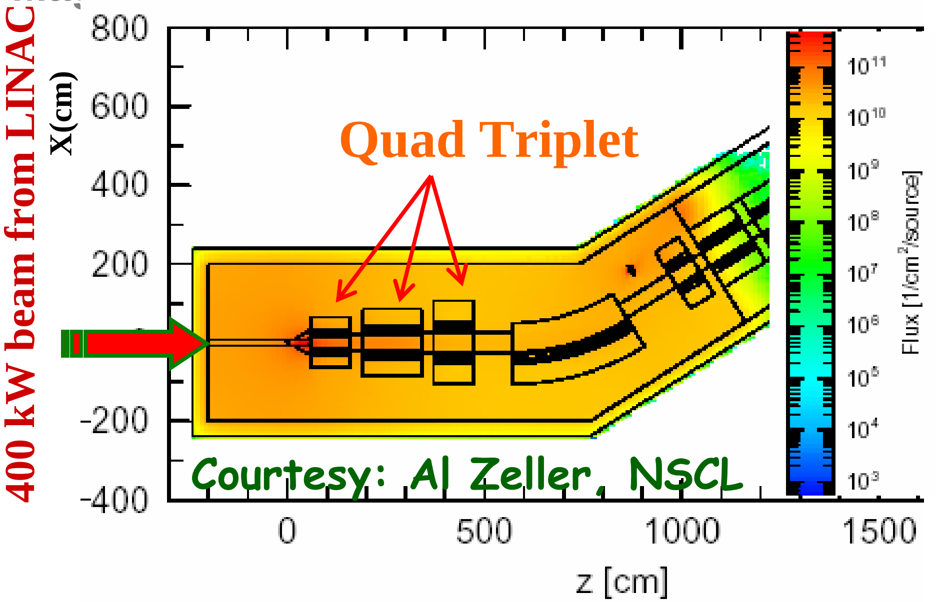


- **Rare Isotope Accelerator (RIA) was proposed to create Rare Isotope Beams that are not available in the sufficient intensity.**
- **Rare Isotope Science Assessment Committee (RISAC) has now recommended the construction of the Facility for Rare Isotope Beams (FRIB), a world-leading facility for the study of nuclear structure, reactions and astrophysics.**



http://www.orau.org/ria/

Fragment Separator



- Up to 400 kW of beam power hits the target producing a variety of isotopes.
- Fragment separator then select one isotope to transport out; but must deal with a large number of unwanted one.
- Quad triplet in the fragment separator is exposed to very high level of radiation and heat loads.
- ~15 kW of the above is deposited in the first quadrupole itself.

Quads in the fragment separator region will live in an environment that was never experienced before by magnets in any accelerator or beam-line.

Water cooled copper magnets produce lower gradient and/or lower aperture, reducing acceptance and making inefficient use of above high beam power.

Also in this case, they were more expensive to build than HTS magnets.

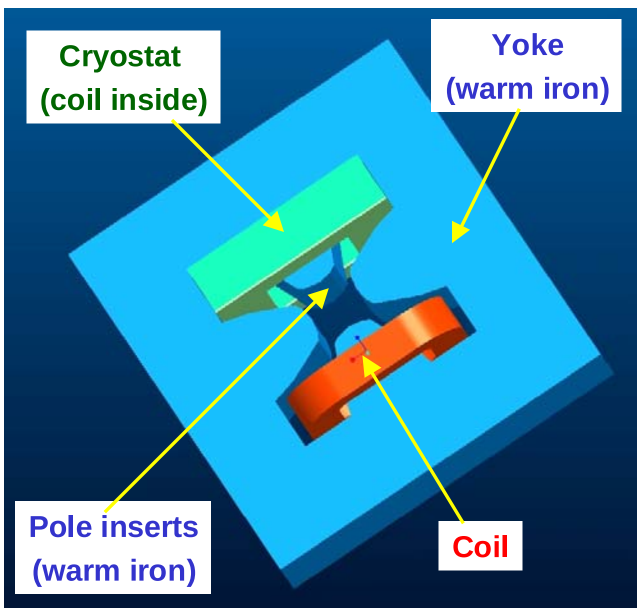
***Basically, we need "Radiation resistant"* super-ferric magnets that can withstand these large radiation and heat loads and can also operate economically.**

Advantages of using HTS in Magnets for Fragment Separator

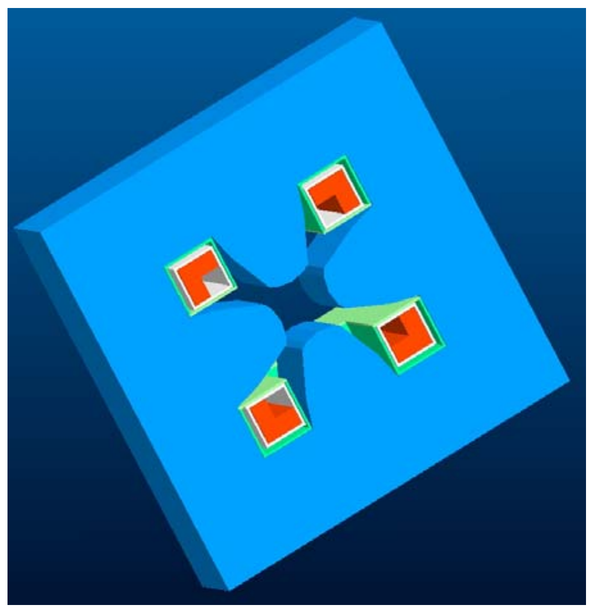
- The magnet system would benefits enormously from the possibility of operating at elevated temperatures (say ~30 K instead of conventional ~4K).
- Removing large heat loads at ~30 K (as in high temperature superconductors) instead of ~4K (as in low temperature superconductors) is over an order of magnitude more efficient.
- HTS can tolerate a large local increase in temperature in superconducting coils caused by the non-uniform energy deposition.
- Moreover, in HTS magnets, the temperature need not be controlled precisely. It can be relaxed by over an order of magnitude as compared to that for the present low temperature superconducting magnets (few kelvin rather than a few tenth of a kelvin). This simplifies the design and reduces cost of the cryogenic system.
- Therefore, HTS would facilitate a magnet system for fragment separator that will be robust and economical to operate.

FRIB Quadrupole Design To Minimize Heat Load

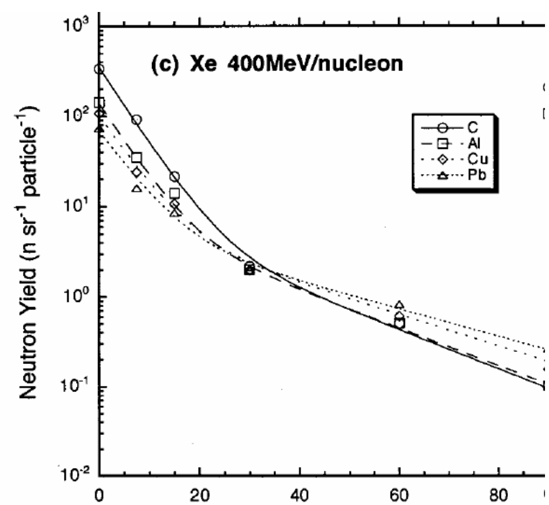
- The magnet is designed with warm iron and a compact cryostat to significantly reduce the amount of cold-mass on which the heat and radiation are deposited.
- Quad is designed with two coils (NOT four) to reduce radiation load in ends.
- Coils are moved further out to reduce radiation dose.
- This design reduces the heat load from ~15 kW to ~0.13 kW on cold structure.



Coils inside the cryostat at the end of the magnet



Cutout at the middle of the magnet



Significantly large neutron yield (radiation load) at small angles

Outline of the Magnet R&D Plan

A Step-by-step R&D Program was envisioned to develop this new design and technology and take full advantage of HTS:

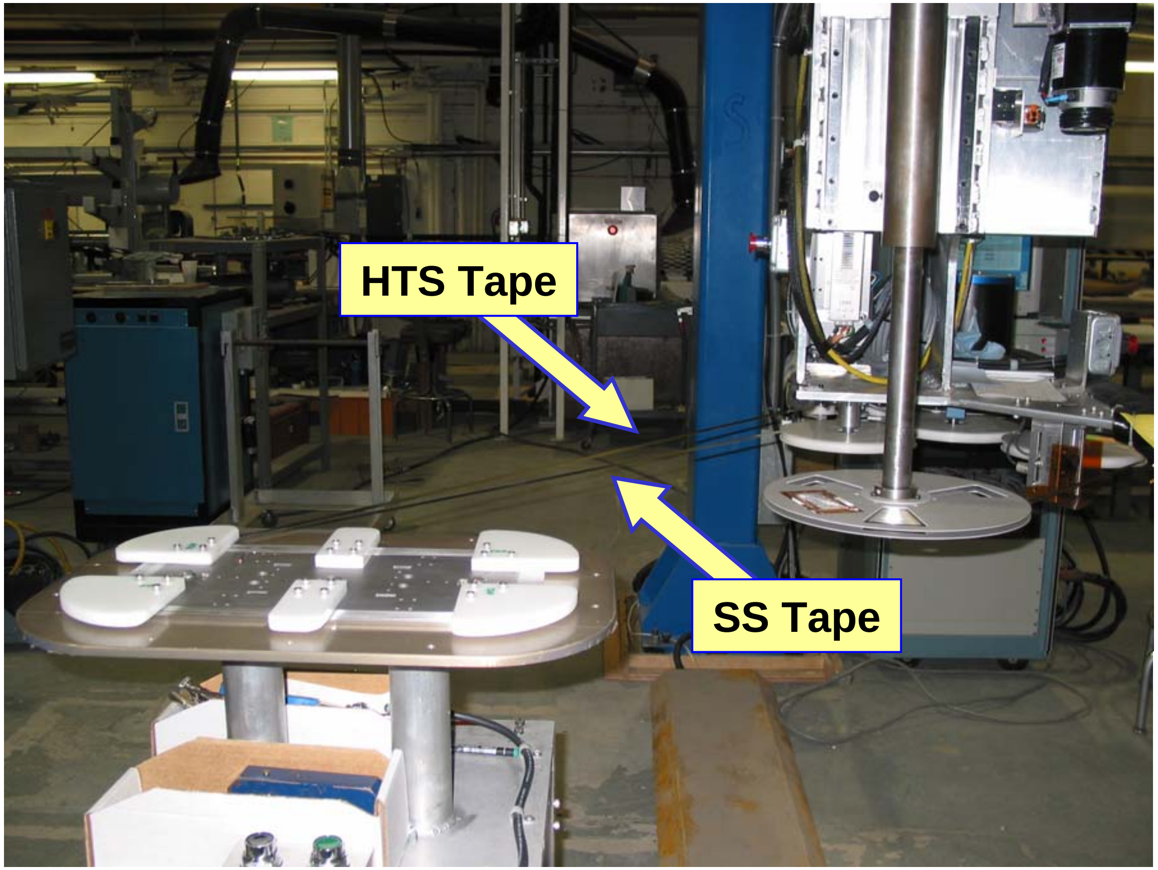
- **Test each coil in liquid nitrogen – cheap and quick QA test - an advantage of HTS**
- **Build initial coils with more manual control and later coil with more computer control**
- **Test pair of coils with splice in liquid nitrogen to iterate on a good splice**
- **Variety of conductor tests over a range of field and temperature**
- **Study coils and magnets as a function of temperature over a large range (4K - 80K)**
- **Perform direct cooling and conduction cooling experiments**
- **Cold iron magnetic mirror configuration of quadrupole with two, four and six coils**
- **Warm iron magnetic mirror configuration with twelve coils (use six coils from above)**
- **Warm iron full magnet with twenty-four coils (use twelve coils from above)**
- **A variety of energy deposition experiments which proves that the design would satisfy the machine requirements and demonstrate the unique advantage of HTS**

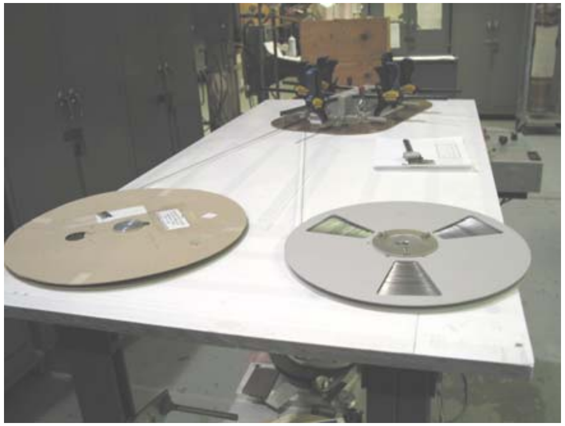
A phased program that was designed to match the expected funding, provide rapid feed back and demonstrate progress along the way.

Design Parameters of R&D and Full-length Quadrupole

Parameter	Value
Aperture	290 mm
Design Gradient	10 T/m
Magnetic Length	425 mm (1 meter full length)
Coil Width	500 mm
Coil Length	300 mm (1125 mm full length)
Coil Cross-section	62 mm X 62 mm (nominal)
Number of Layers	12 per coil
Number of Turns per Coil	175 (nominal)
Conductor (Bi-2223) Size	4.2 mm X 0.3 mm
Stainless Steel Insulation Size	4.4 mm X 0.038 mm
Yoke Cross-section	1.3 meter X 1.3 meter
Minimum Bend Radius for HTS	50. 8 mm
Design Current	160 A (125 A full length)
Operating Temperature	30 K (nominal)
Design Heat Load on HTS coils	5 kW/m^3

HTS Coil Winding

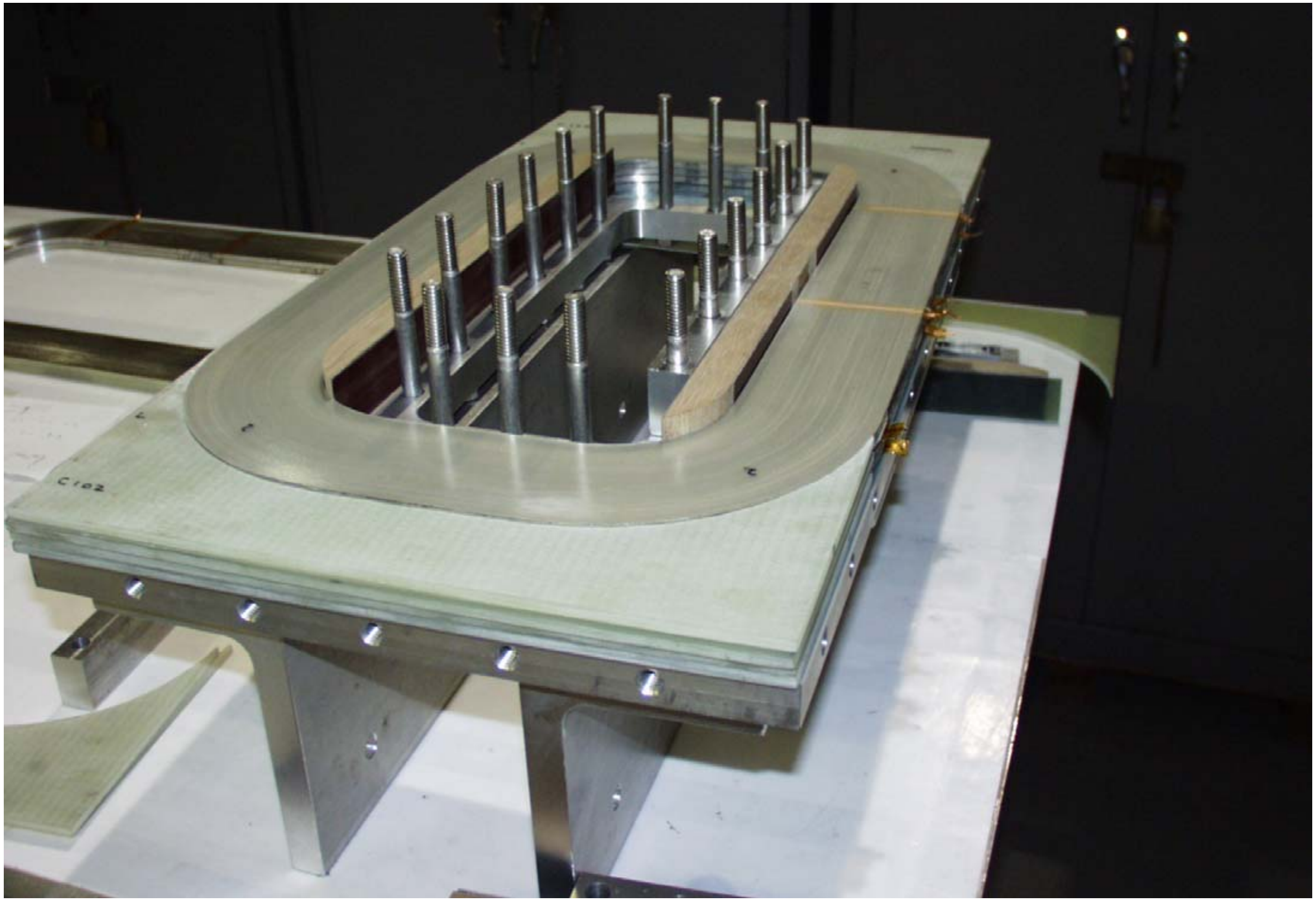




Earlier coils were wound with a machine that has more manual controls.

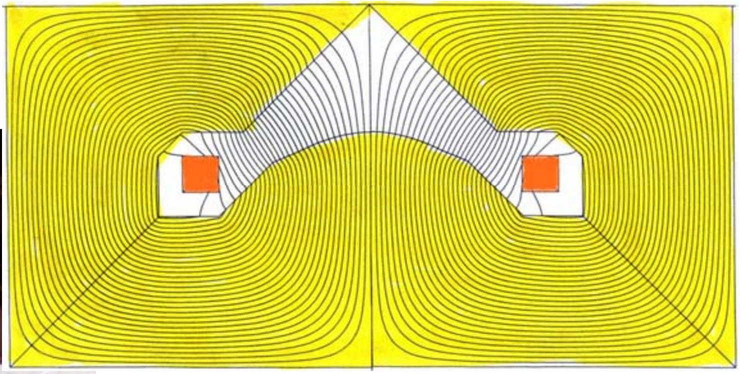
A coil being wound in a computer controlled winding machine.

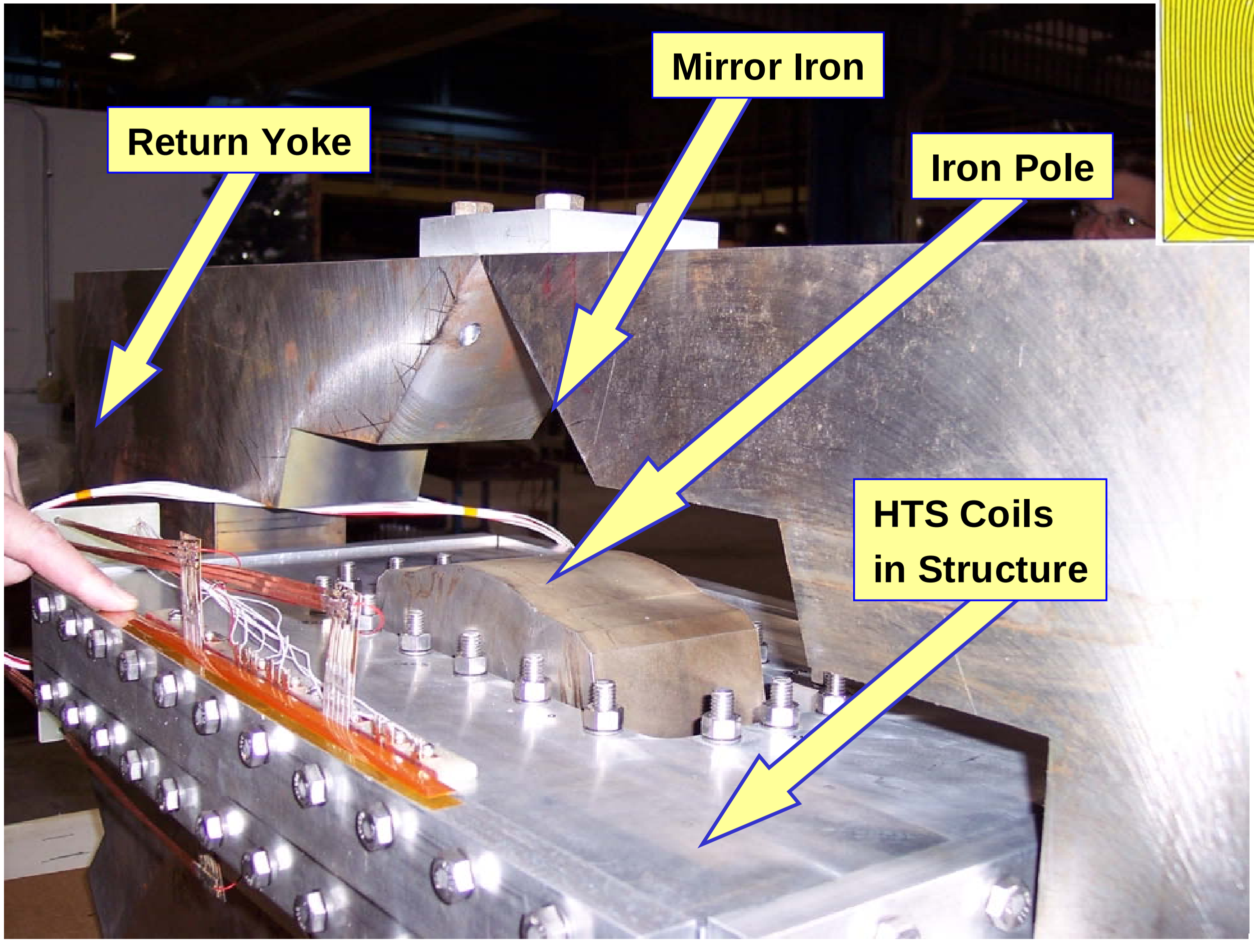
Assembled Coils with Internal Splice



Three pairs of coils during their assembly a support structure.

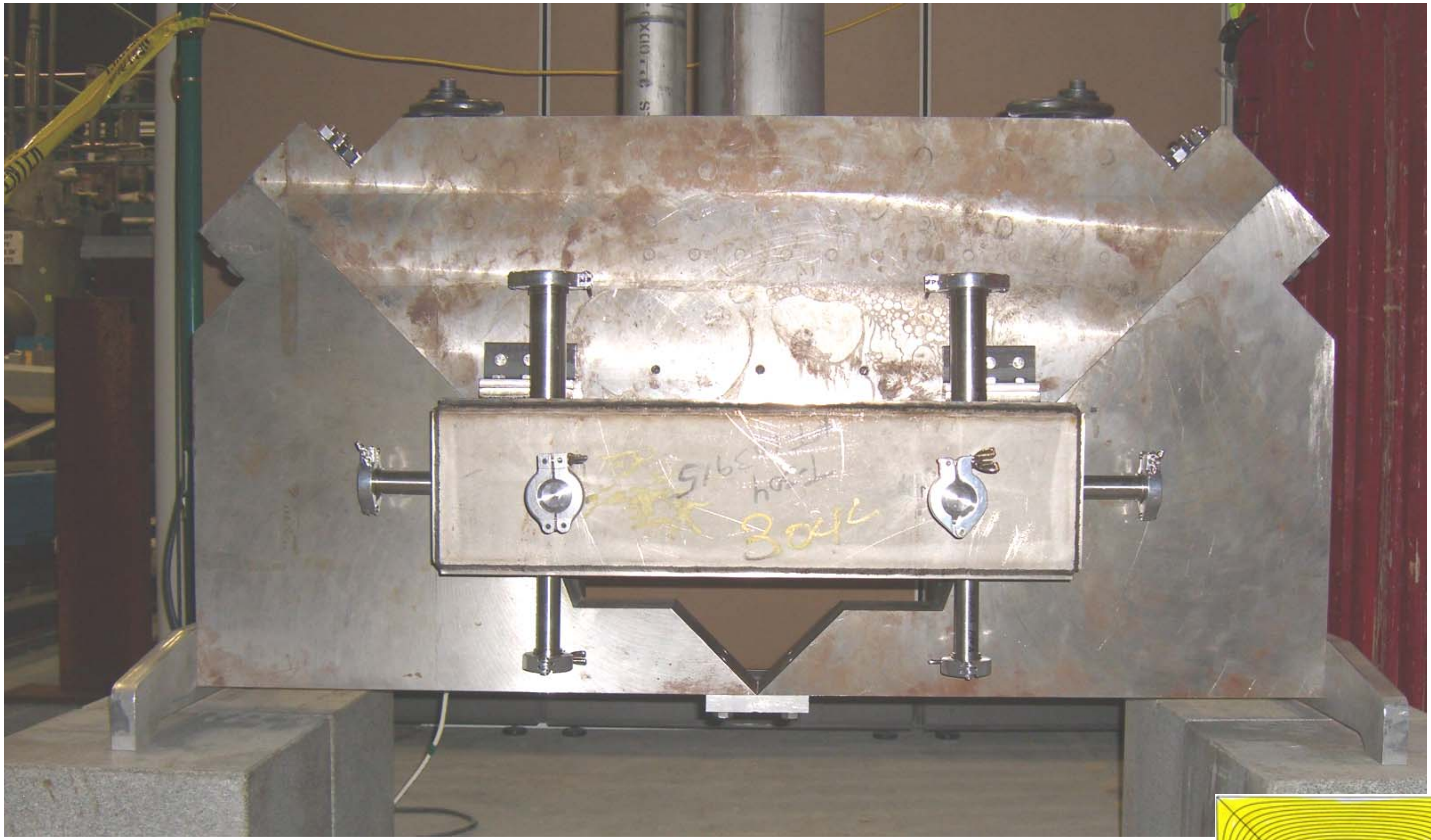
Magnetic Mirror Model (cold iron)

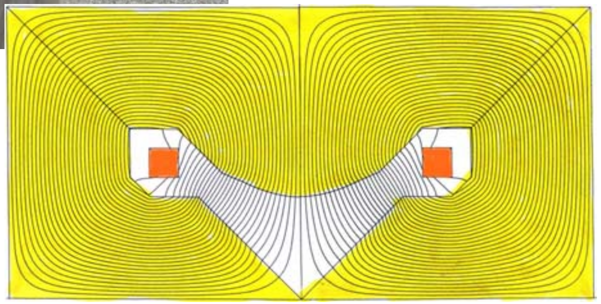




Cold iron magnetic mirror model with six coils in a bolted support structure.

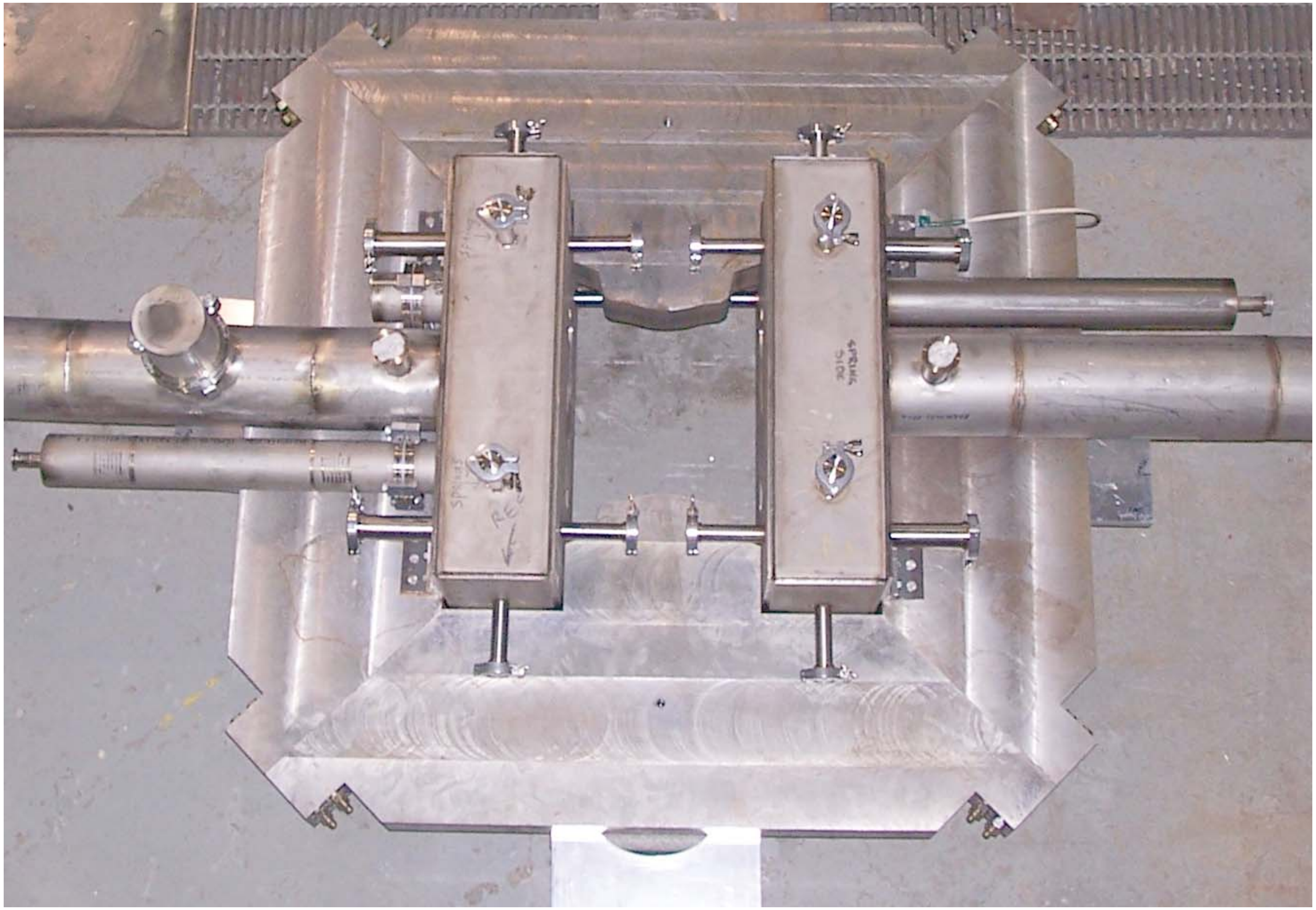
Magnetic Mirror Model (warm iron)





Warm iron magnetic mirror model with twelve coils in its own cryostat

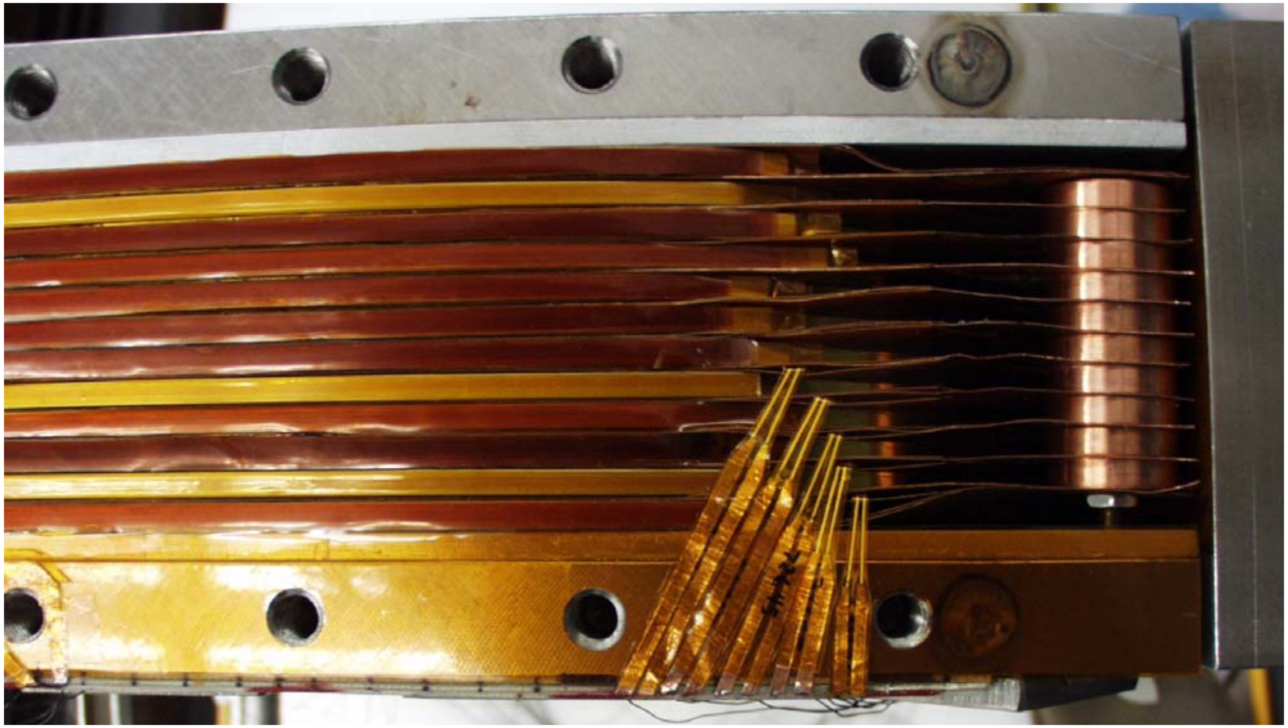
Full HTS Model Quadrupole



Warm iron quadrupole with twenty four coils in two cryostats

Energy Deposition and Cryogenic 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.

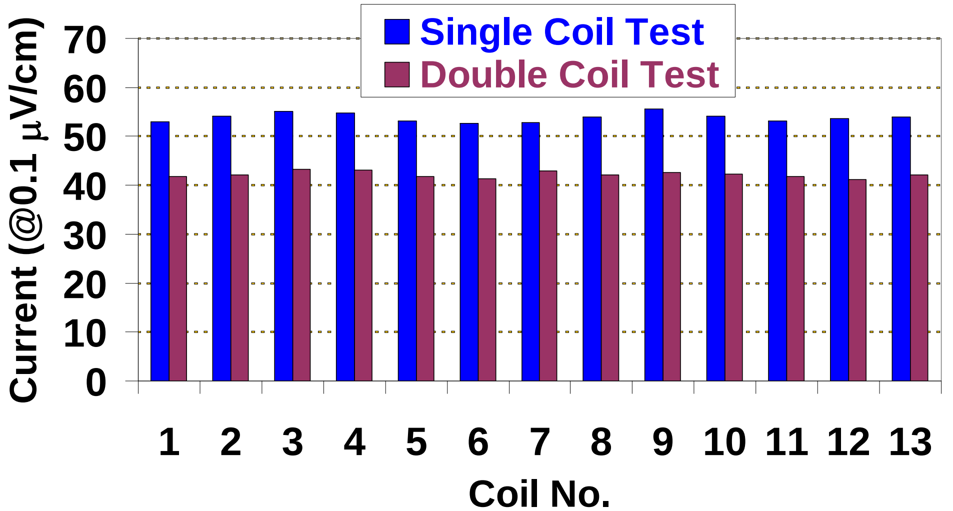
HTS Coil and Magnet Test Results

- Test results of HTS coils
  - A series production of 25 coils made with commercially available superconductor (Bi-2223 from ASC)
- Test results of several HTS magnet configurations over a wide range of temperature (4K – 80 K)
  - Cold iron mirror model with 2, 4 and 6 coils
  - Warm iron mirror model with 12 coils
  - Warm iron full model with 24 coils
- Energy Deposition Experiments

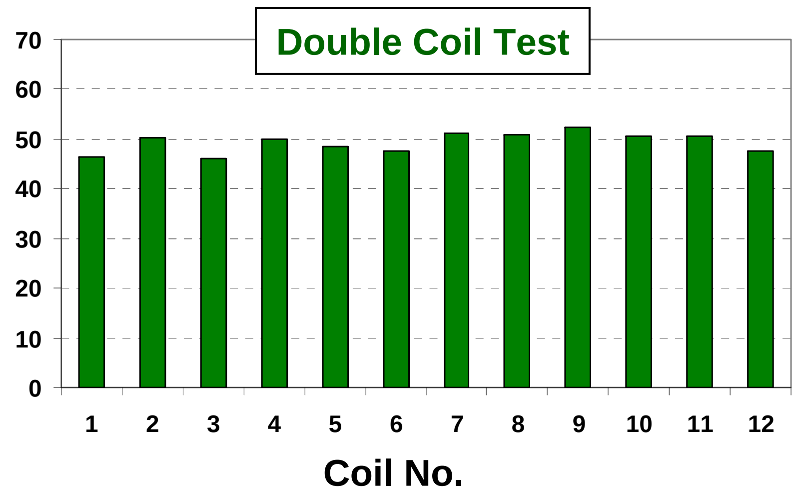
Primary motivation of using HTS is to remove large heat load economically (over a factor of 10 savings)

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)

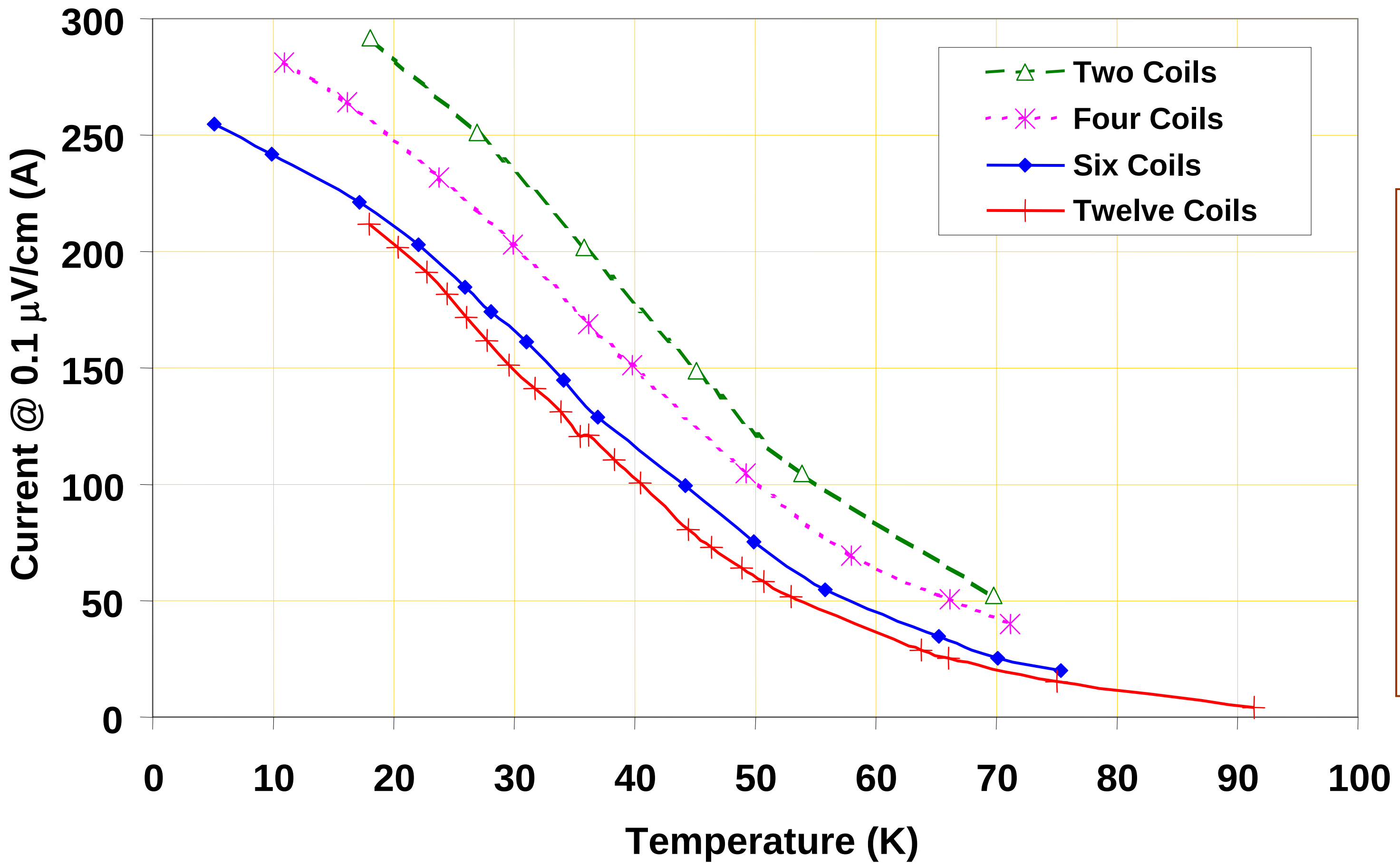


Coil performance generally tracked the conductor performance pretty well.

Note: A uniformity in performance of a large number of HTS coils made with commercially available superconductor (ASC)

– It shows that the HTS technology is now maturing !

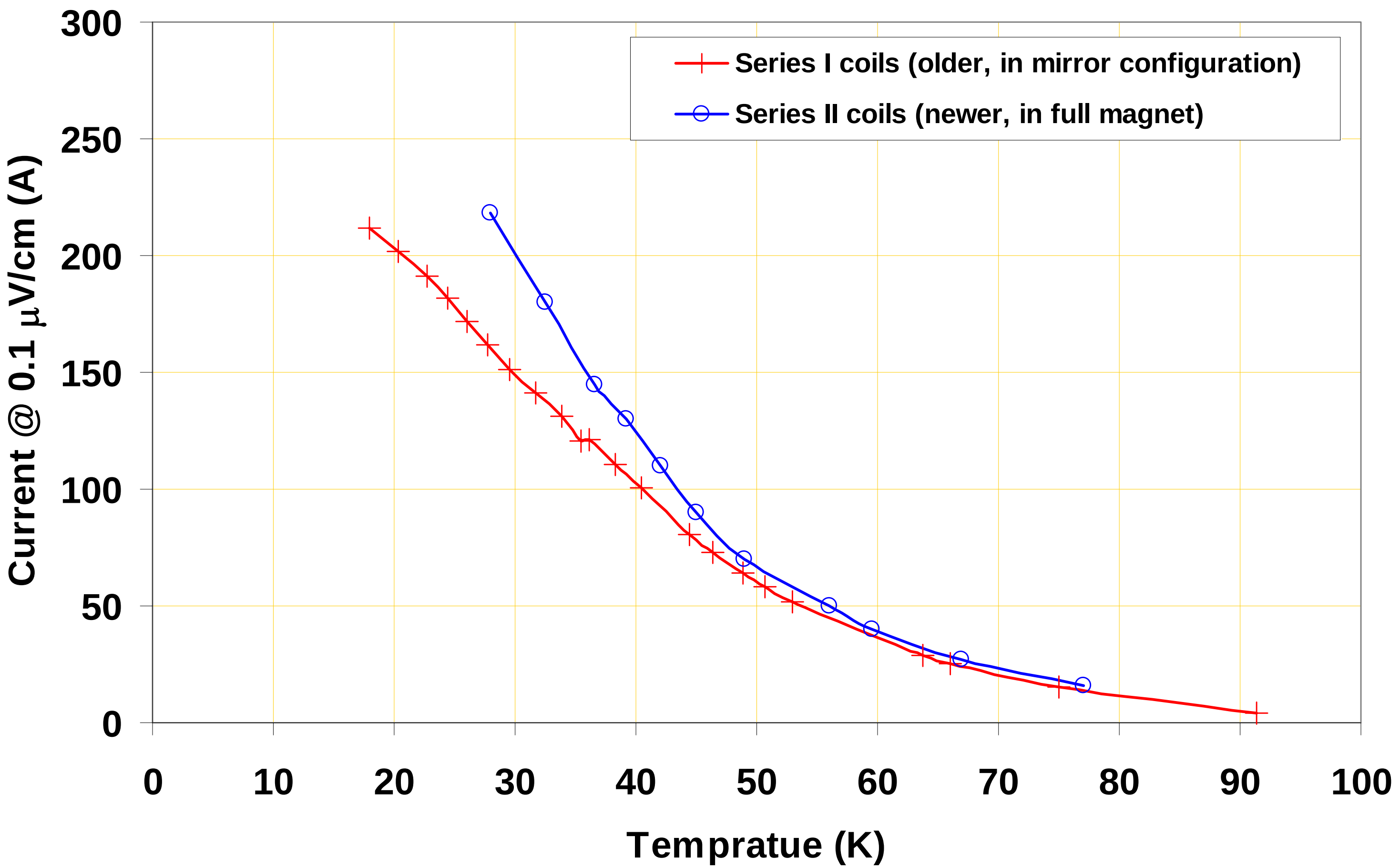
RIA HTS Mirror Model Test Results
(operation over a large temperature range)



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.

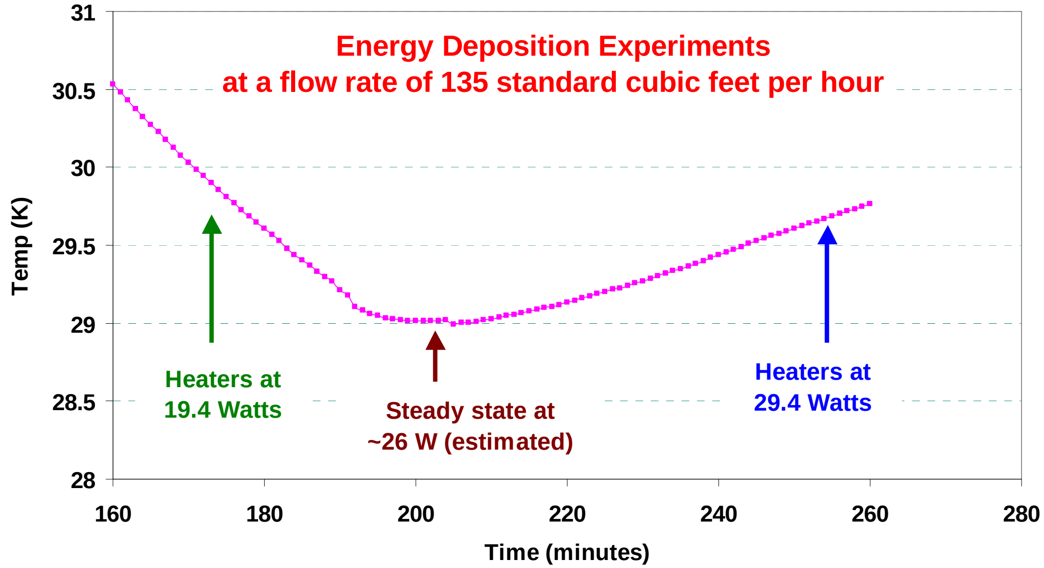
RIA HTS Full Model Test Results (operation over a large temperature range)



Newer (series II) conductor was not only better at 77 K but also had relatively better performance at lower temperature.

Energy Deposition Experiment During Cool-down at a Constant Helium Flow-rate

All heaters between HTS coils were turned on while the magnet was cooling down with a helium flow rate of 135 standard cubic feet (SCF)



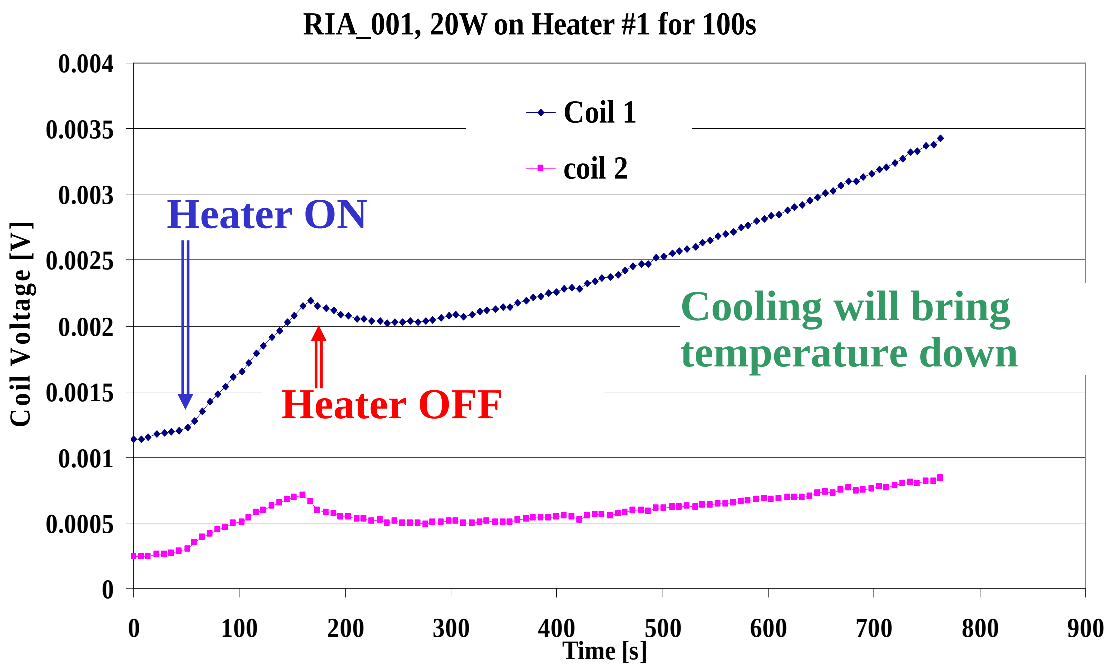
- **Temperature continued to decrease when total power in all heaters was kept at 19.4 W**
- **Temperature started to increase slowly when heater was increased to 29.4 W**
- **Computed heat load for steady state : ~26 Watts**
  - **i.e., expect a constant temperature of 29 K with 26 W at 135 SCF flow rate.**

Note: HTS coil remained superconducting during these tests when operated somewhat below the critical surface.

Energy Deposition Experiment During Natural Warm-up (helium flow stopped)

One of the heater on one side of the HTS coil was turned on briefly (20 W for ~100 sec) when the magnet was warming up naturally and influence on the coil next to it and one after that was observed.

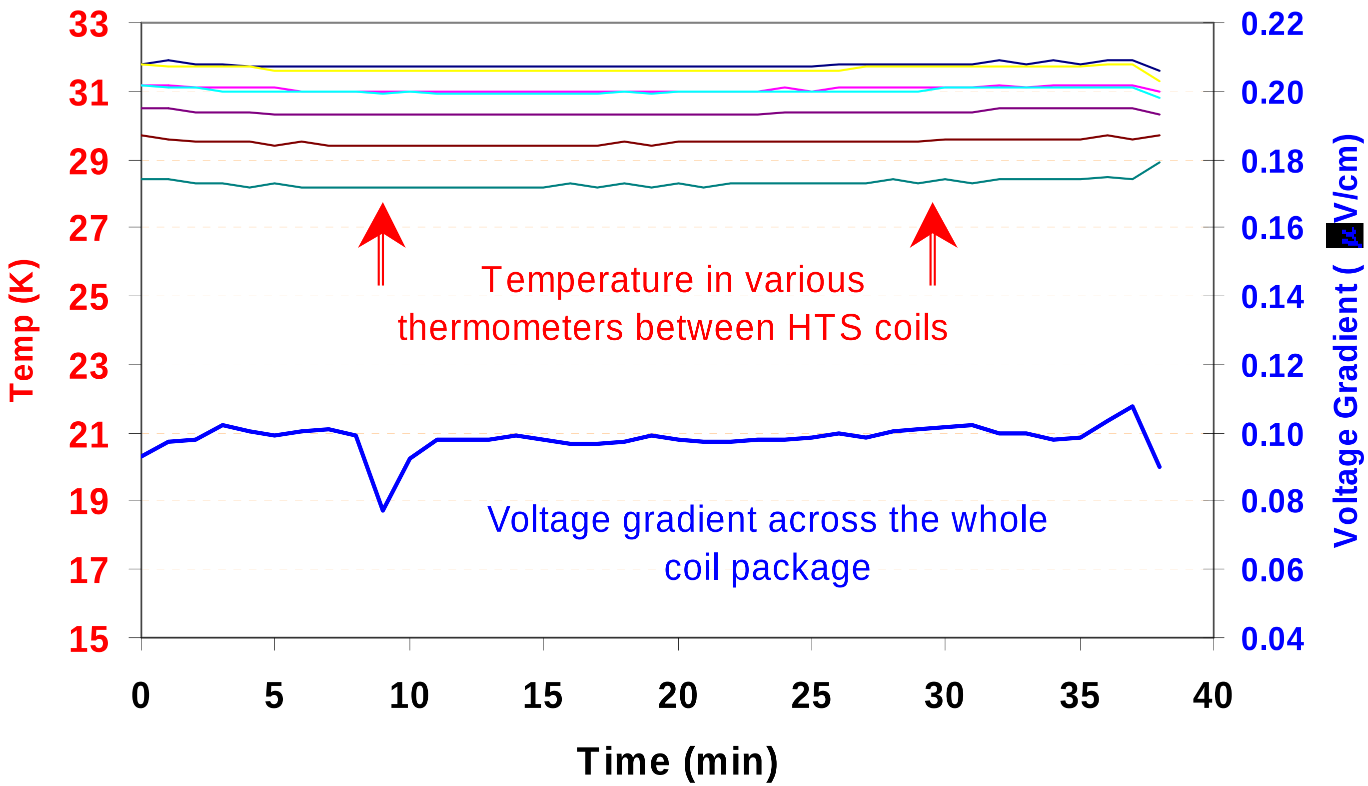
Note that when a coil is near the critical surface, the coil voltage is a very sensitive measure of any small change in temperature (or field and/or current).



- **Turning on heater makes the coil reach critical surface faster.**
- **The coil/magnet can recover during the operation if the source is removed or cooling is increased.**
- **These kinds of measurements (for such time scale and for such a range of temperature) are perhaps only possible in HTS.**

Simulated Energy Deposition Experiment at the Operating Condition (Environment)

Goal is to demonstrate that the magnet can operate in a stable fashion at the expected heat loads (5mW/cm^3 or 5kW/m^3 or 25 W on 12 short HTS coils) at the design temperature (~30 K) with some margin on current (@140 A, design current is 125 A).



Voltage spikes are related to the noise

Stable operation for ~40 minutes

- **We use 0.1 μV/cm as the definition of I_c.**
- **Temperature differences may be partly real and partly calibration mis-match.**
- **As such HTS can tolerate such temp variations with small margin.**

Current and Future Program

The goal is to move to 2nd generation wire because:

- 2G is expected to allow operation at 50 K (or above), which would provide even more saving in operation.
- 2G is expected to be less expensive.

Coil made with 2G

Near Future (04/07-03/08)

- Make 3 coils each with ~100 m of 2nd generation wire
  - Two coils with wire from ASC wire and one from SuperPower
- Continue experimental studies on radiation damage on YBCO and BSCCO to determine if one is significantly better than the other.

Intermediate Future:

- Develop design, build and test full length quad based on whichever conductor is better
- Study other critical magnets

Summary and Outlook

- It has been shown that HTS magnets can be designed, built and operated in presence of a large heat load environment.
- Successful construction and test of a number of coils and various configurations should encourage use of HTS in accelerator magnets.
- We are examining possible use of HTS in several other applications.
- Apart from the use of HTS in special applications (such as high field magnets, magnets that must deal with large energy deposition, etc.), a larger scale application of HTS may lie in the magnets for beam-lines, low energy machines (such as injectors, neutrino factories and synchrotron radiation sources to save operating costs – electricity) and magnets for a number of medical applications.
- Second generation conductor should make HTS magnets much more attractive (lower cost and higher temperature operation).

Extra Slide
Peak Field and Field-gradient Vs. I