Conduction Cooled SC Magnet

Vladimir Kashikhin for US-Japan Collaboration

Outline

- Conduction Cooled Splittable Quadrupole
- Quadrupole Fabrication
- Quadrupole Test in the LHe bath at FNAL
- Quadrupole Test at KEK
- Summary

List of Collaborators

- Fermilab: N. Andreev, V. Kashikhin, J. Kerby, M. Tartaglia
- KEK: A. Yamamoto, N. Kimura
- Toshiba: M. Takahashi, T. Tosaka

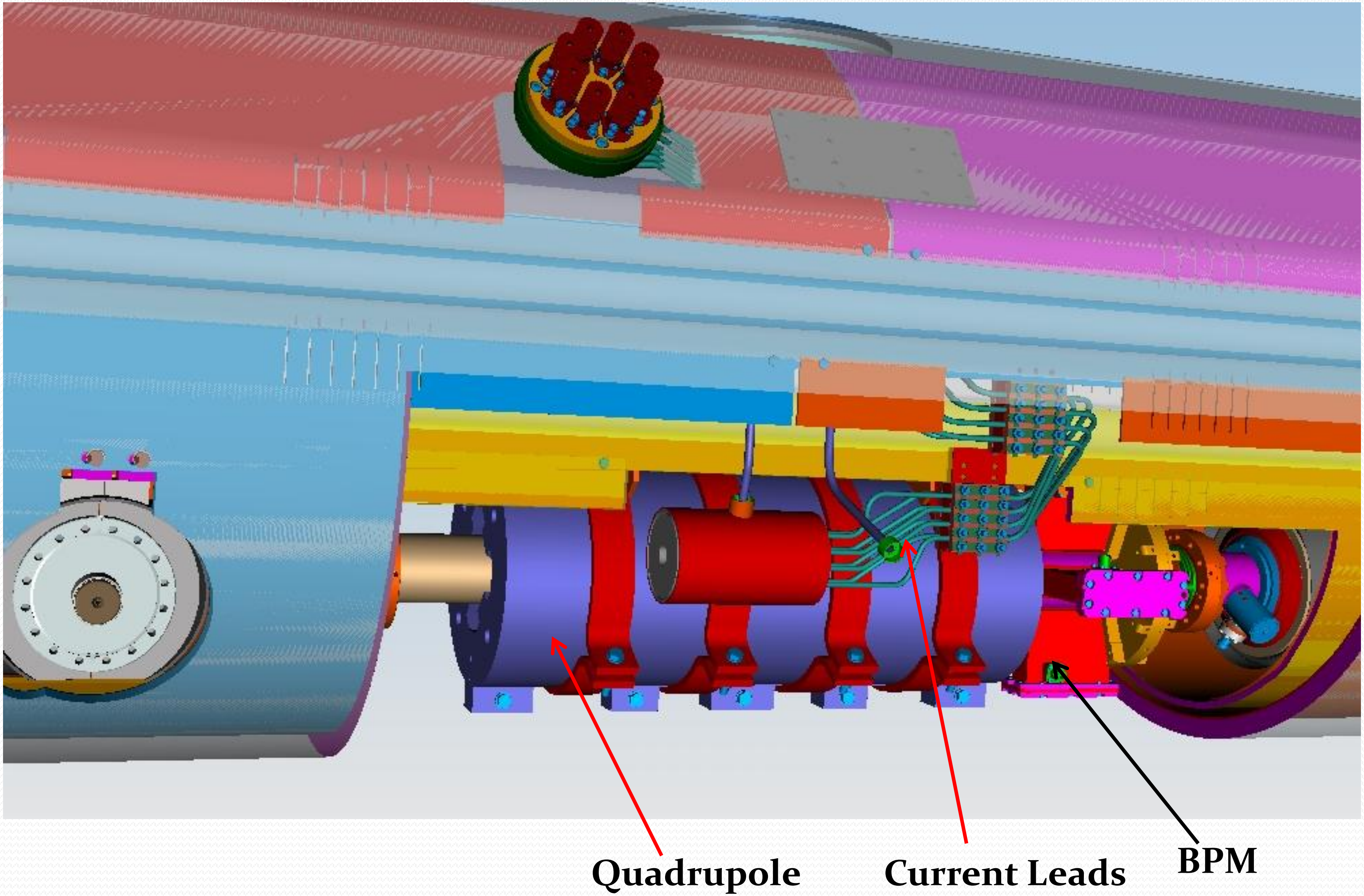
Quadrupole Specification & Superconductor

Integrated gradient, T	36
Aperture, mm	78
Effective length, mm	666
Peak gradient, T/m	54
Peak current, A	100
Field non-linearity at 5 mm radius, %	0.05
Quadrupole strength adjustment for BBA, %	-20
Magnetic center stability at BBA, um	5
Liquid Helium temperature, K	2
Quantity required	560

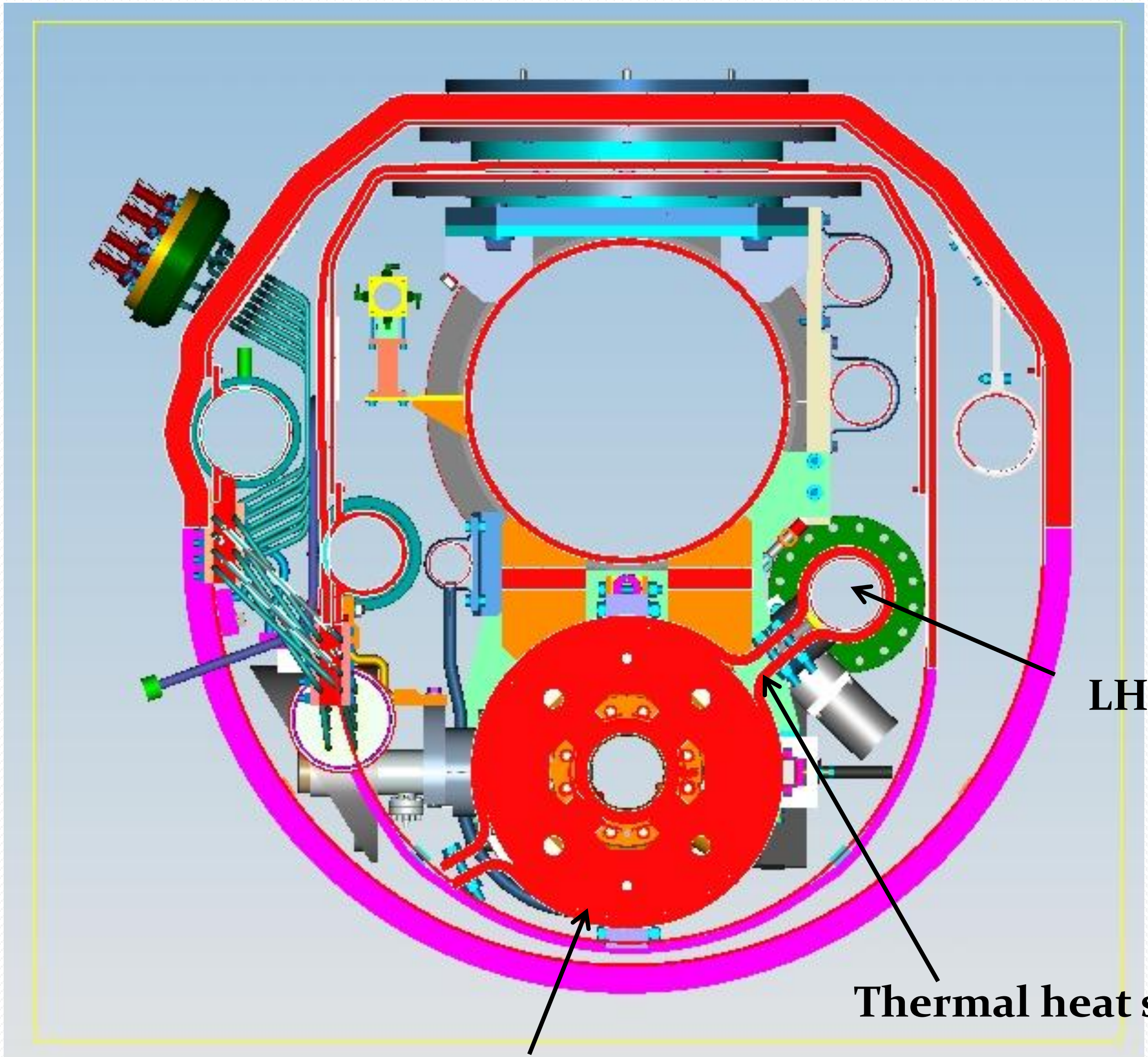
NbTi wire diameter, mm	0.5
Number of filaments	7242
Filament diameter, um	3.7
Copper : Superconductor	1.5
Insulated wire diameter, mm	0.54
Insulation	Formvar
Twist pitch, mm	25
RRR of copper matrix	100
Critical current Ic @ 4.2K, at 5T	204 A

Akira Yamamoto proposed to make the splittable conduction cooled quadrupole to assemble it with the cryomodule cold mass outside the clean room around the beam pipe.

Quadrupole in Cryomodule (1)



Quadrupole in Cryomodule (2)

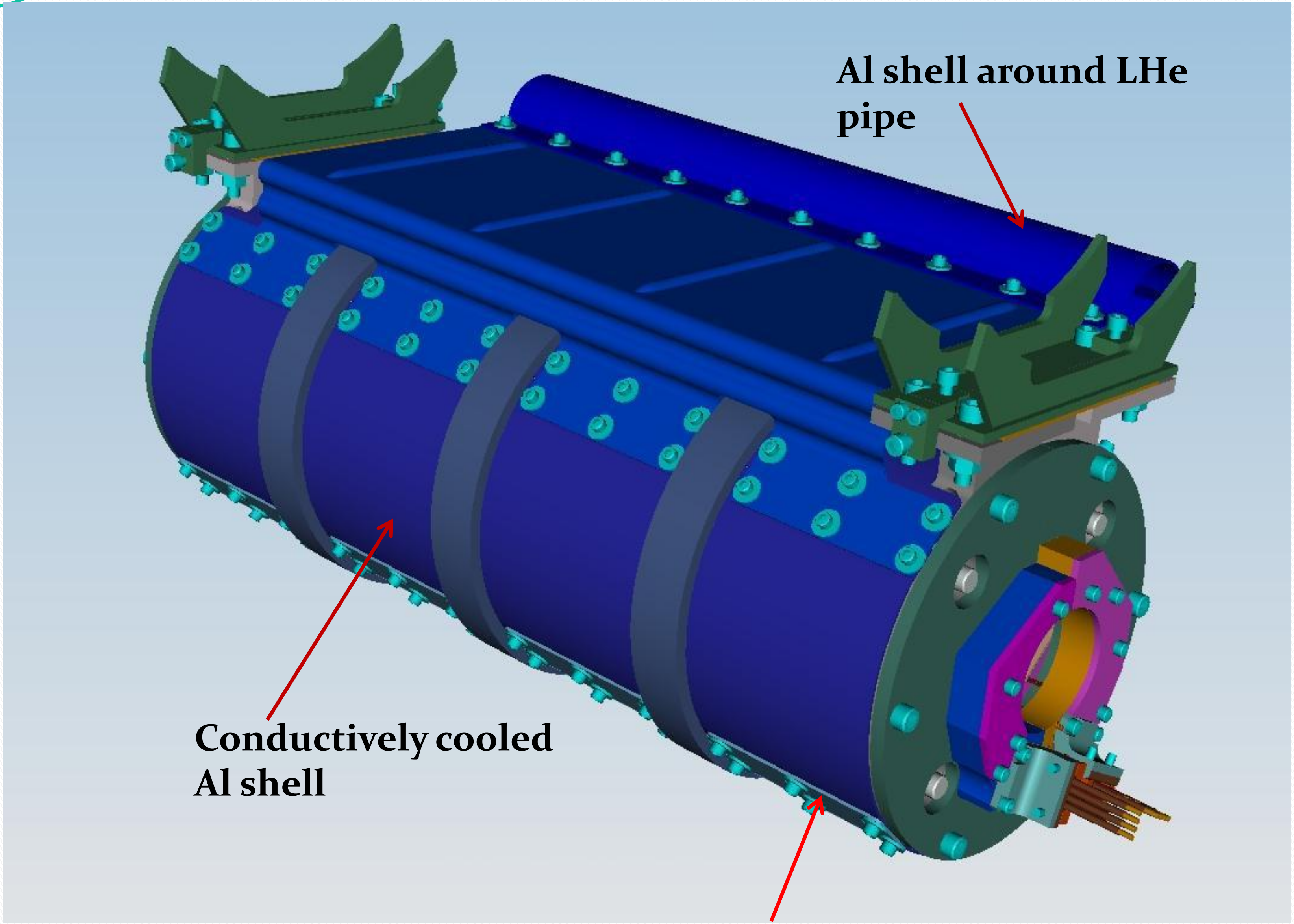


LHe pipe line

Thermal heat sinks

Quadrupole

Quadrupole Cold Mass Assembly

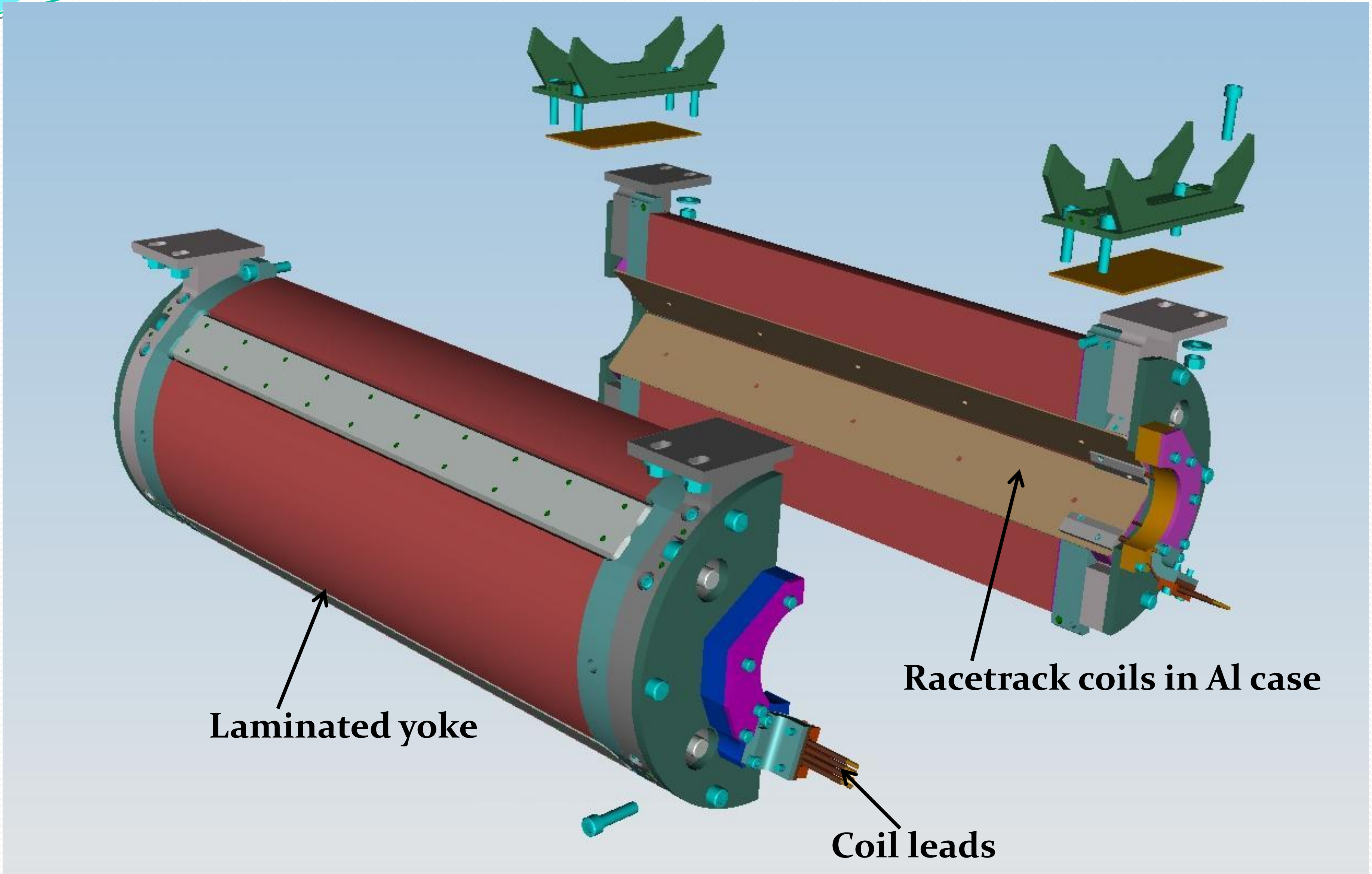


Al shell around LHe pipe

Conductively cooled Al shell

Quadrupole

Two Halves of the Quadrupole

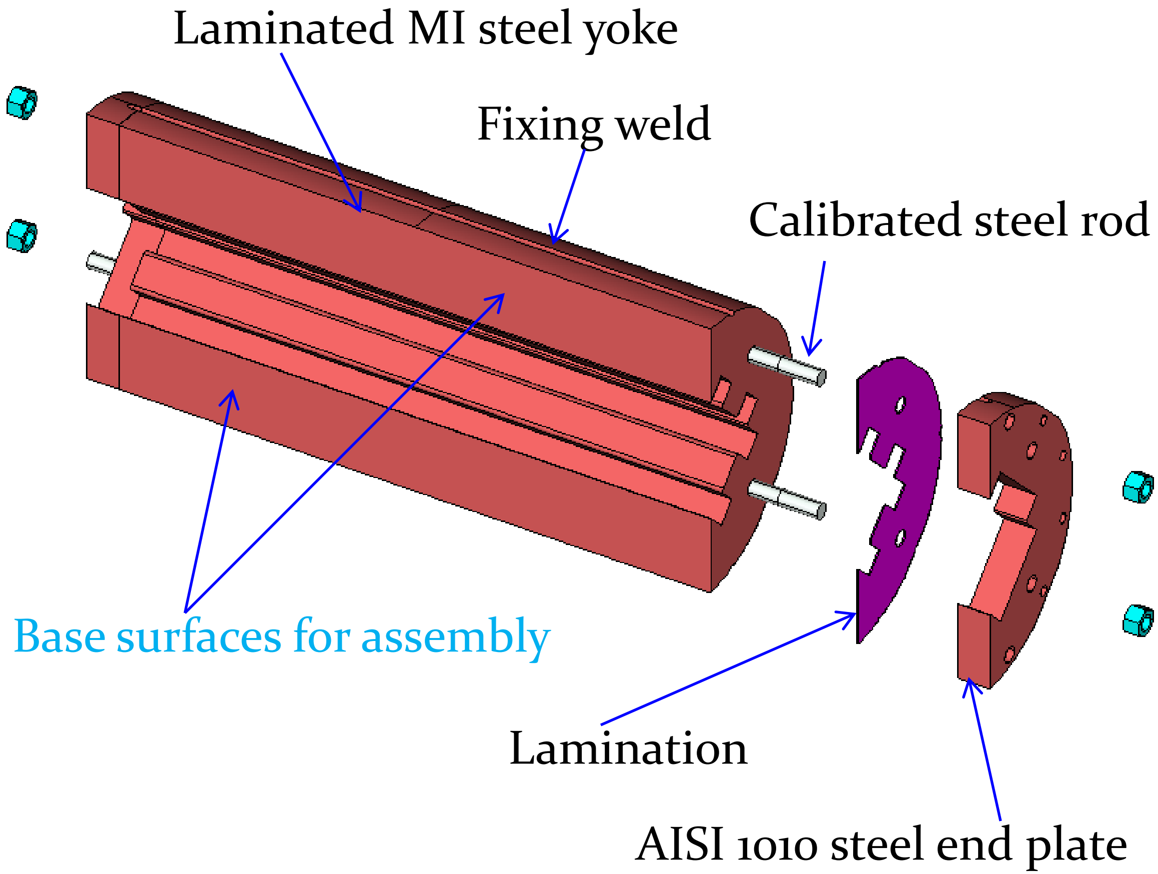


Racetrack coils in Al case

Laminated yoke

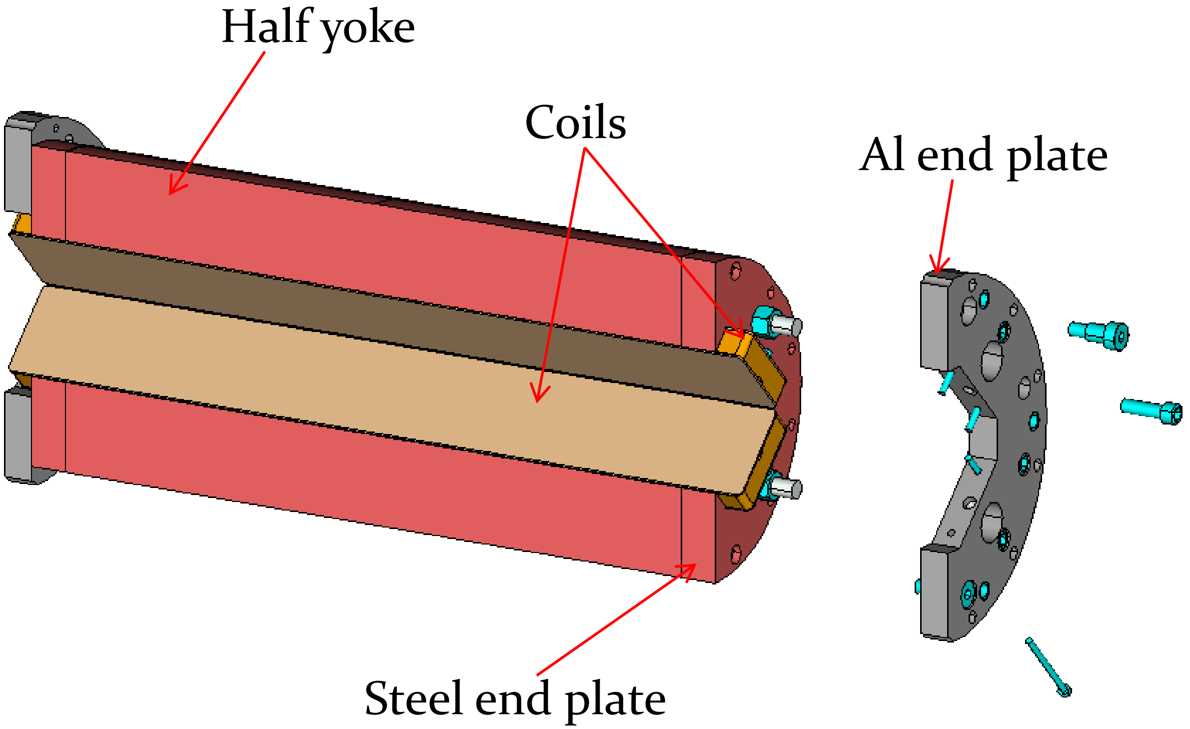
Coil leads

Half of Iron Yoke Assembly



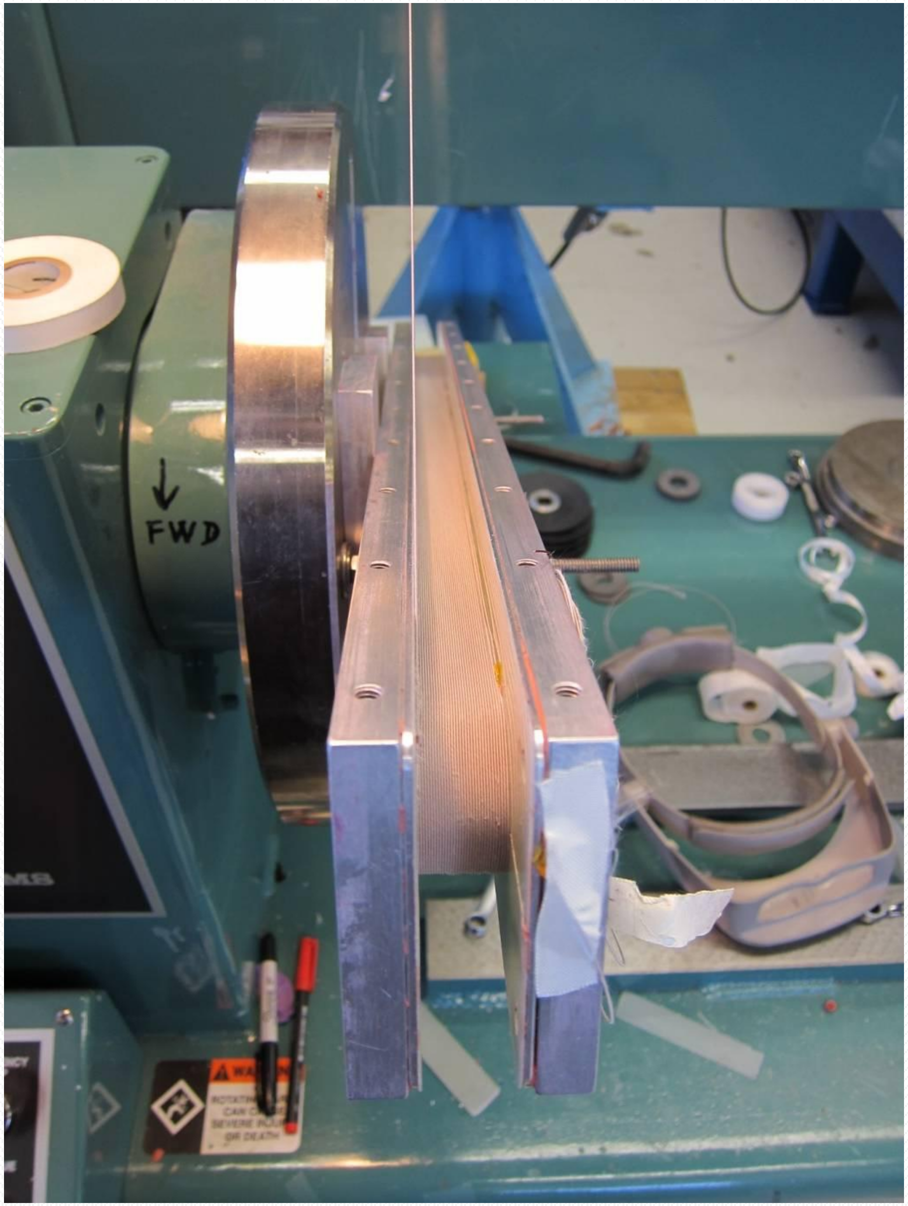
The yoke laminations are laser cut from MI low carbon 1.5 mm thick steel.
The half core is assembled in the FNAL IB2 horizontal press.
Calibrated rods and base surfaces provide package straightness.
Final mechanical rigidity provided by fixing welds.

Half Yoke with Al End Plate

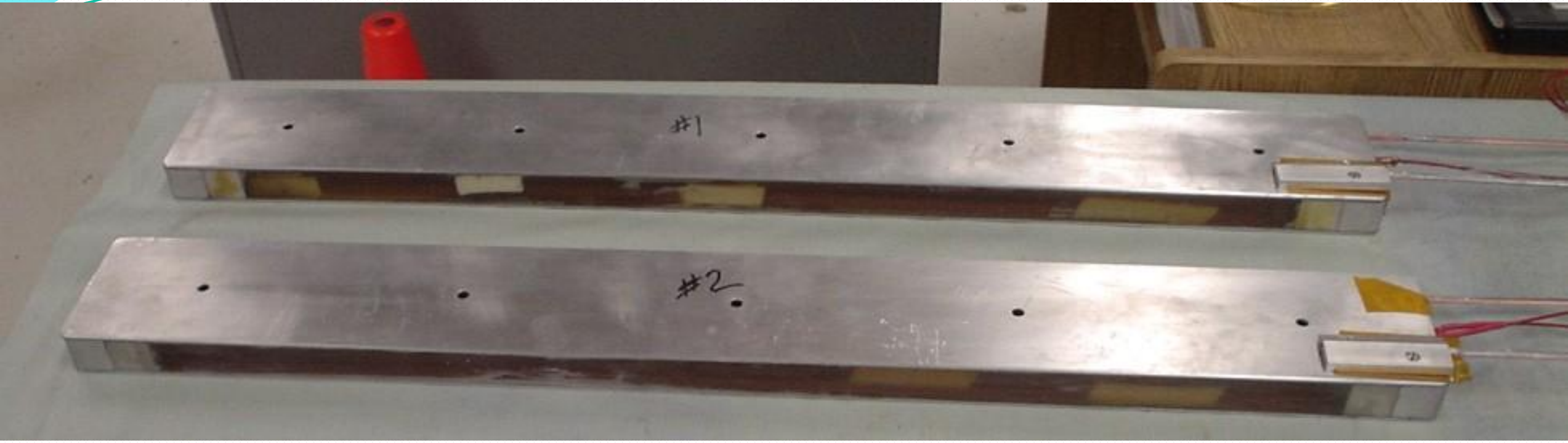


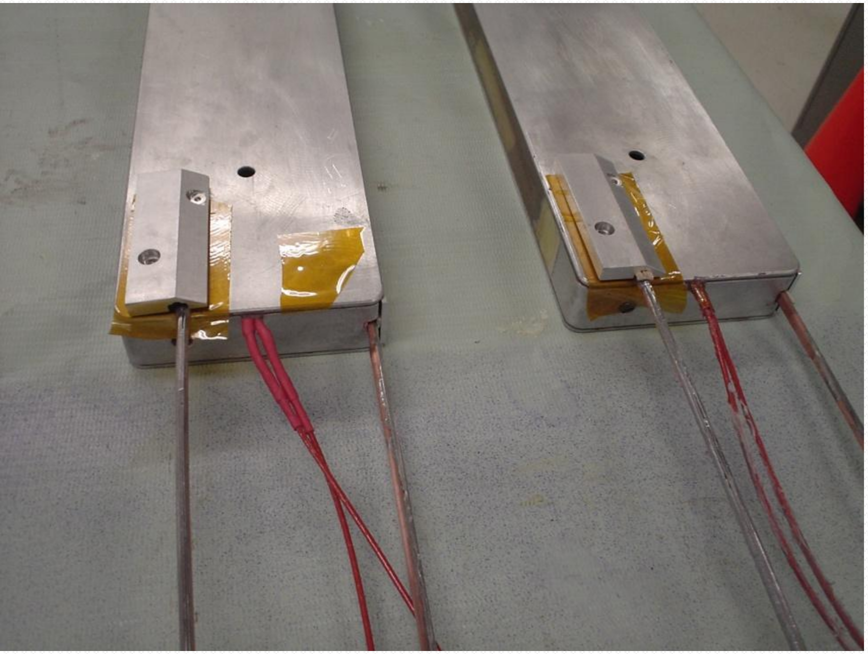
Al end plate mechanically and thermally connected to the coil and outer shell Al collars providing better thermal conductivity between coils and cooling tube.

Coil Winding



Fabricated Quadrupole Coils





Four coils with 910 turns/coil were initially fabricated.

Coil N3 lead was damaged during test setup preparations. One more coil was fabricated to replace the damaged coil.

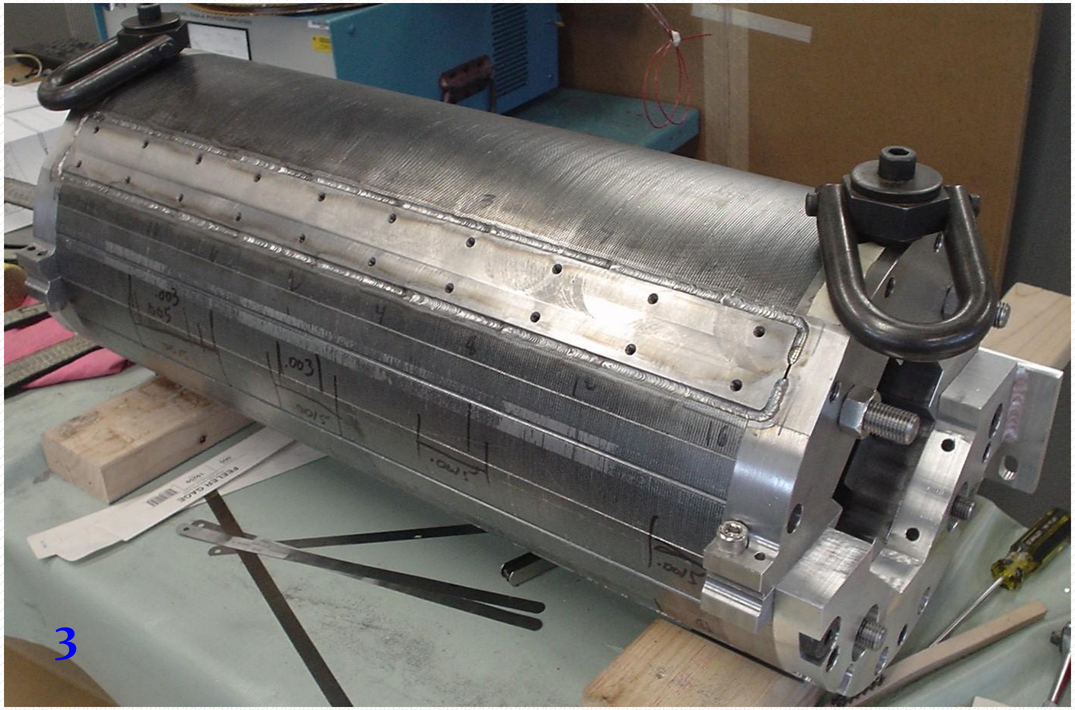
Coils were epoxy-impregnated (CTD-101)

Stainless steel strip heater outside each coil.

Laminated Yoke Assembly


1

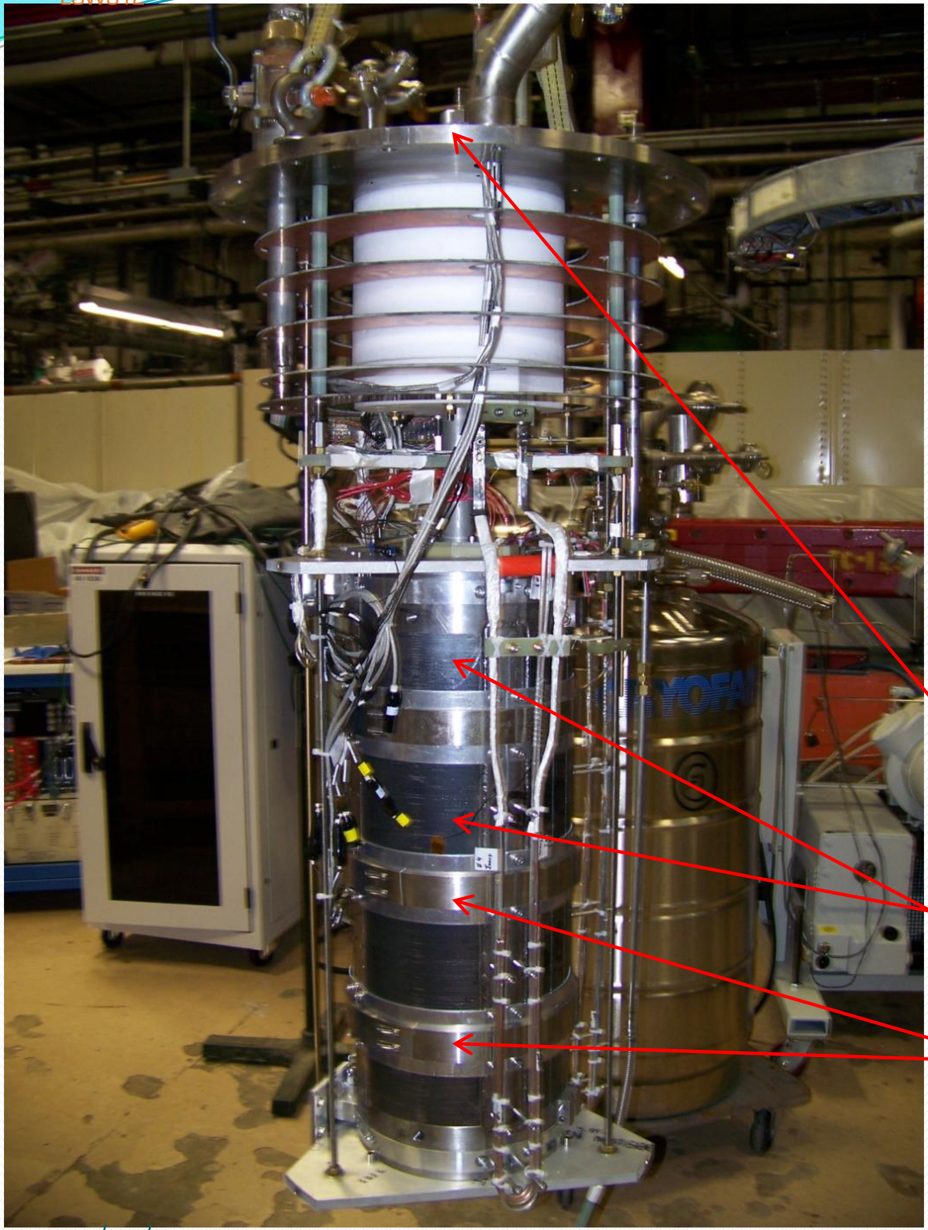

2


3

1. **Half yoke assembly in the press.**
2. **Half yoke final assembly**
3. **Yoke control assembly**

Yoke material – MI low carbon steel, 1.5 mm thick.

Quadrupole with Top Head Assembly



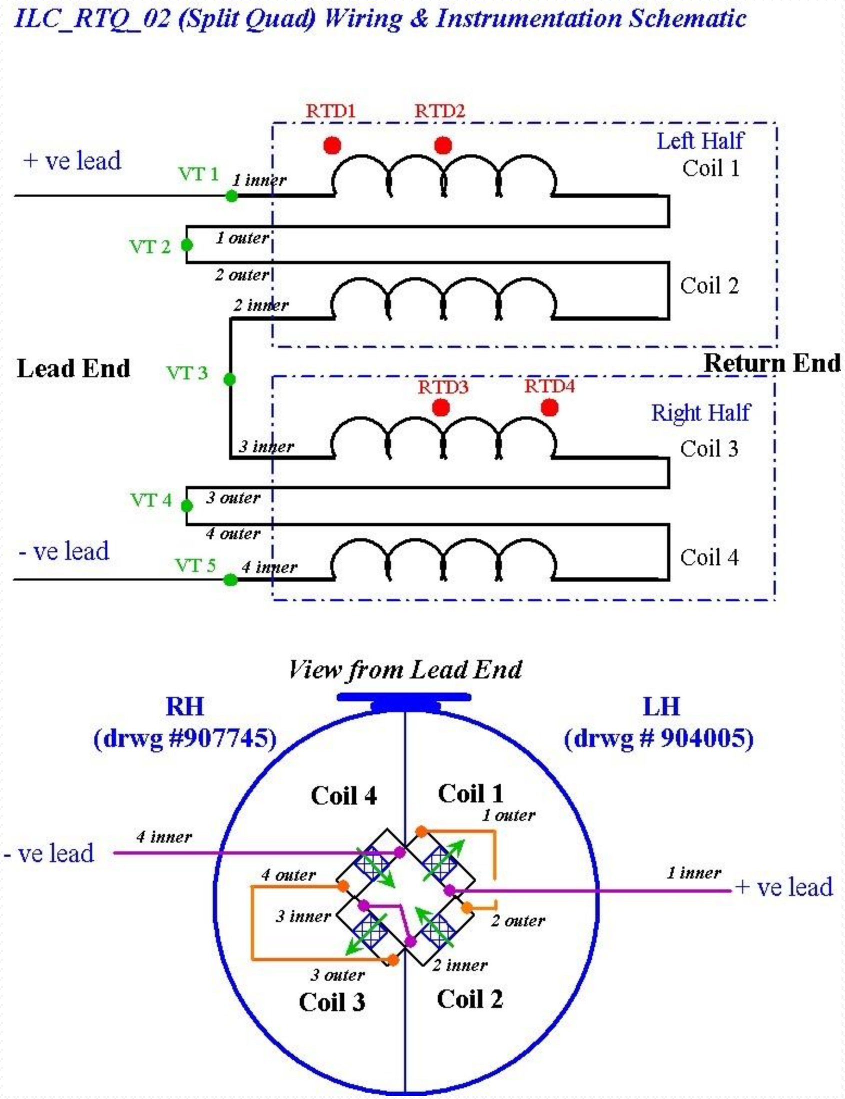
Current leads

Top head

Quadrupole yoke

Two quadrupole halves clamping rings

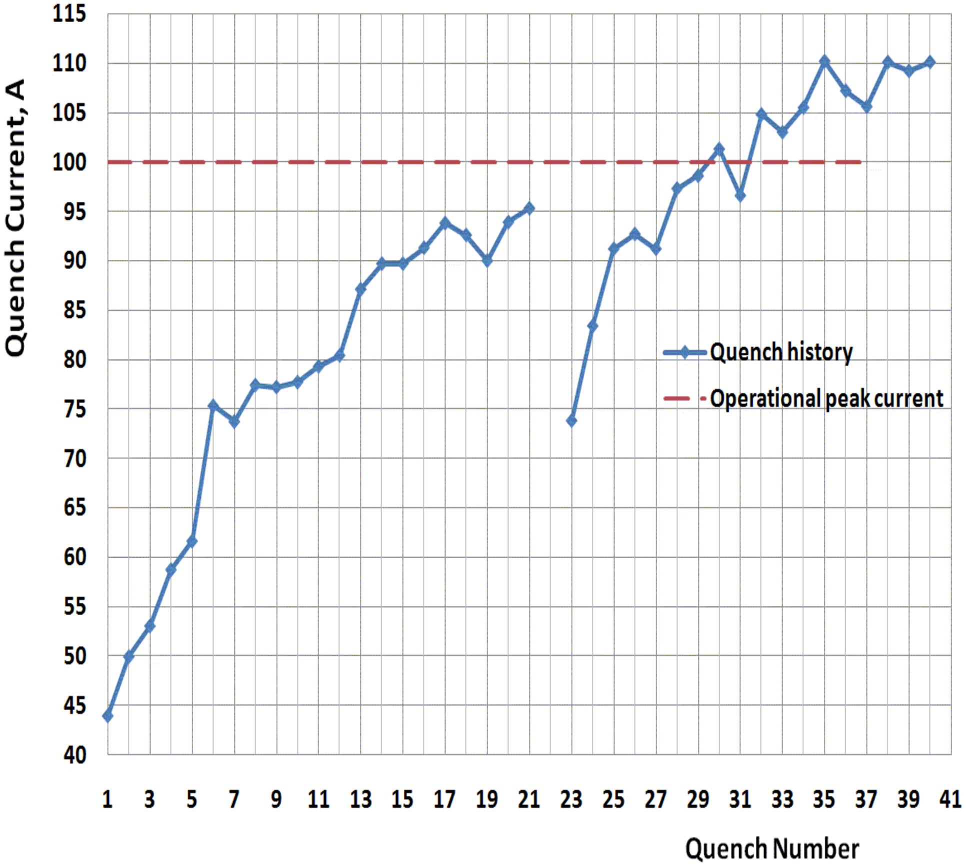
Quadrupole Electrical Scheme



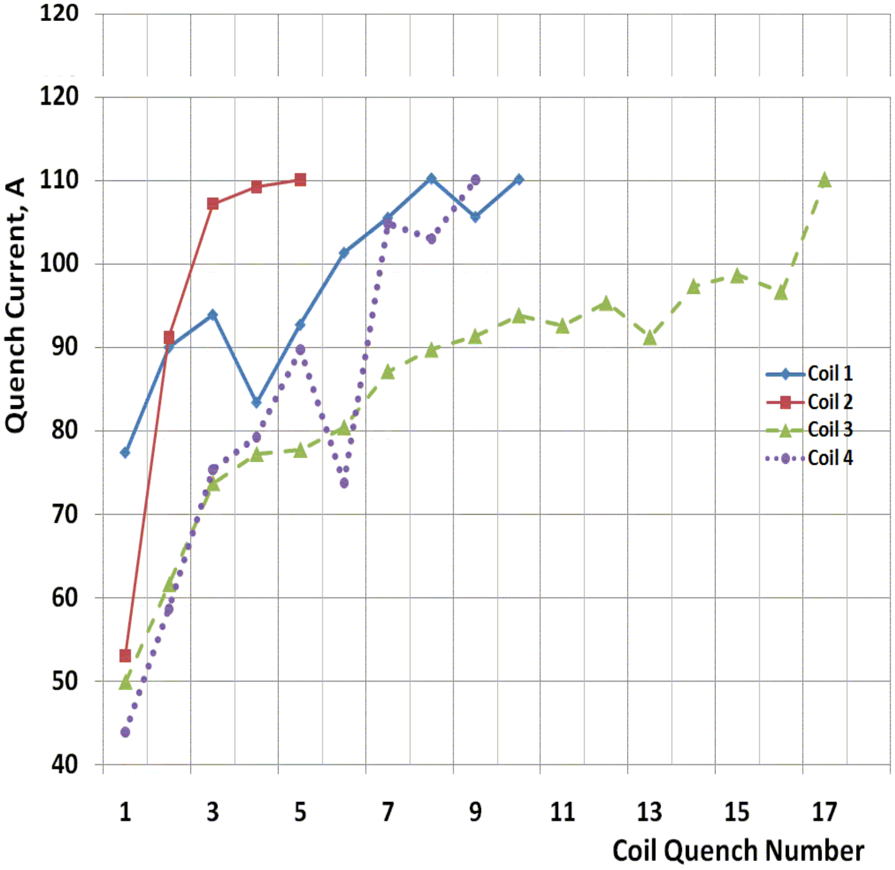
ILC_RTQ_02 (Split Quad) Wiring & Instrumentation Schematic

All coils connected in series.
4 RTD's to monitor the temperature.
5 voltage taps to detect the quench.
4 coil heaters connected in series and fired when the quench event is detected.
Quadrupole is protected with 9 Ohm dump resistor.
The peak voltage is < 1kV.

Quadrupole Training and Quench History



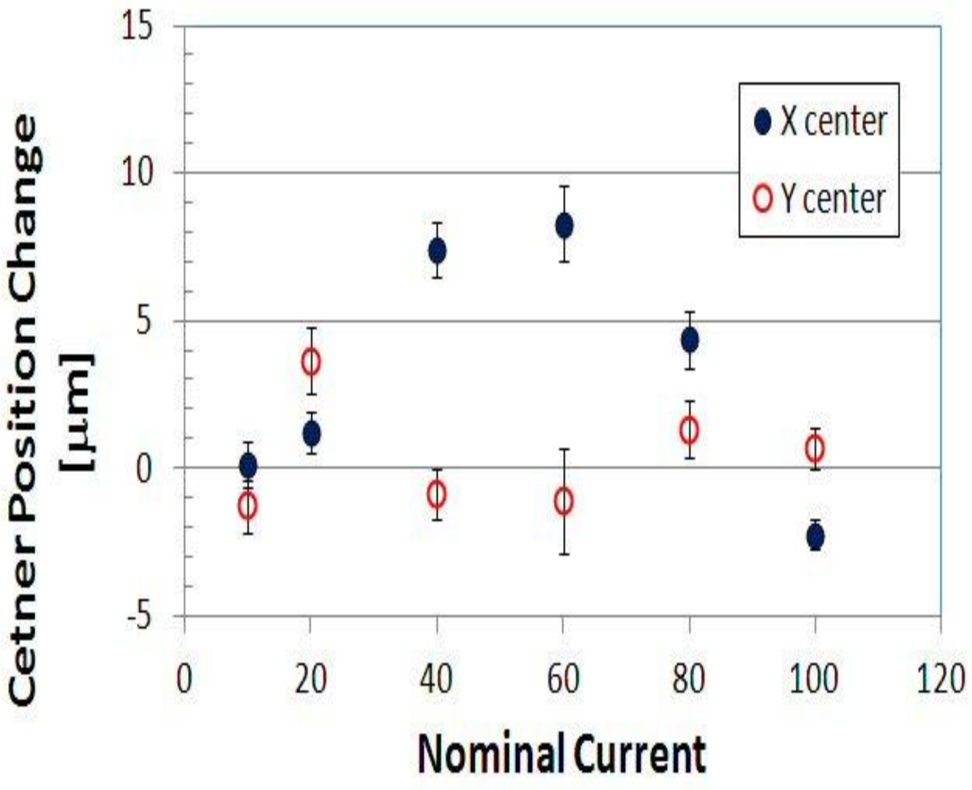
Quench history for two thermal cycles

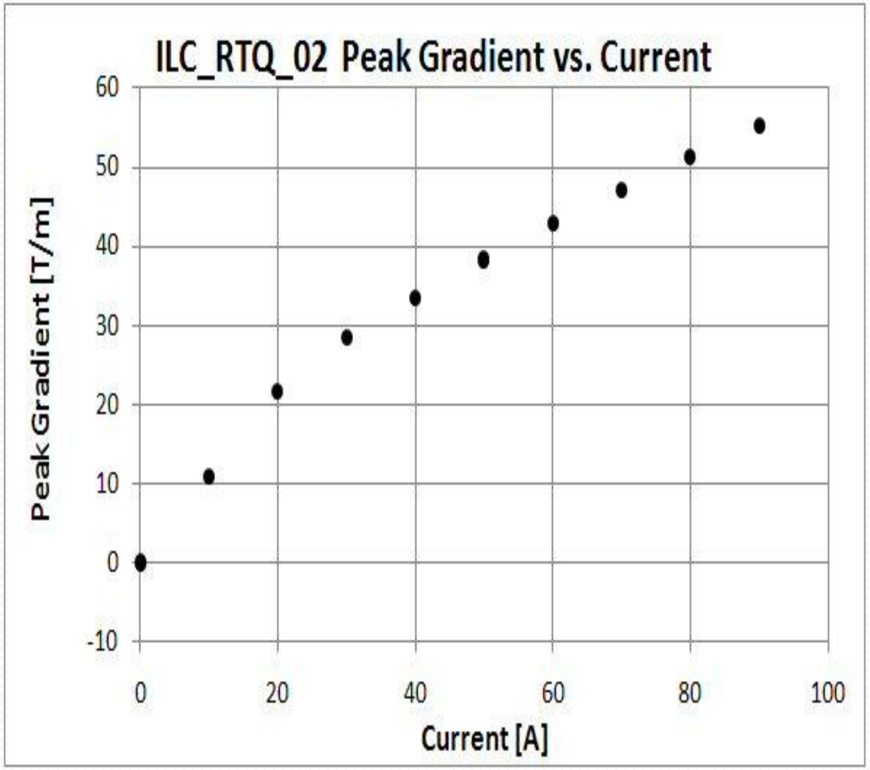


Quench history for each coil

Peak operating current 100 A. Magnet trained up to 110 A – limit for the Stand 3 peak safe pressure during uncontrollable quench.

Magnetic Center and Gradient Measurements



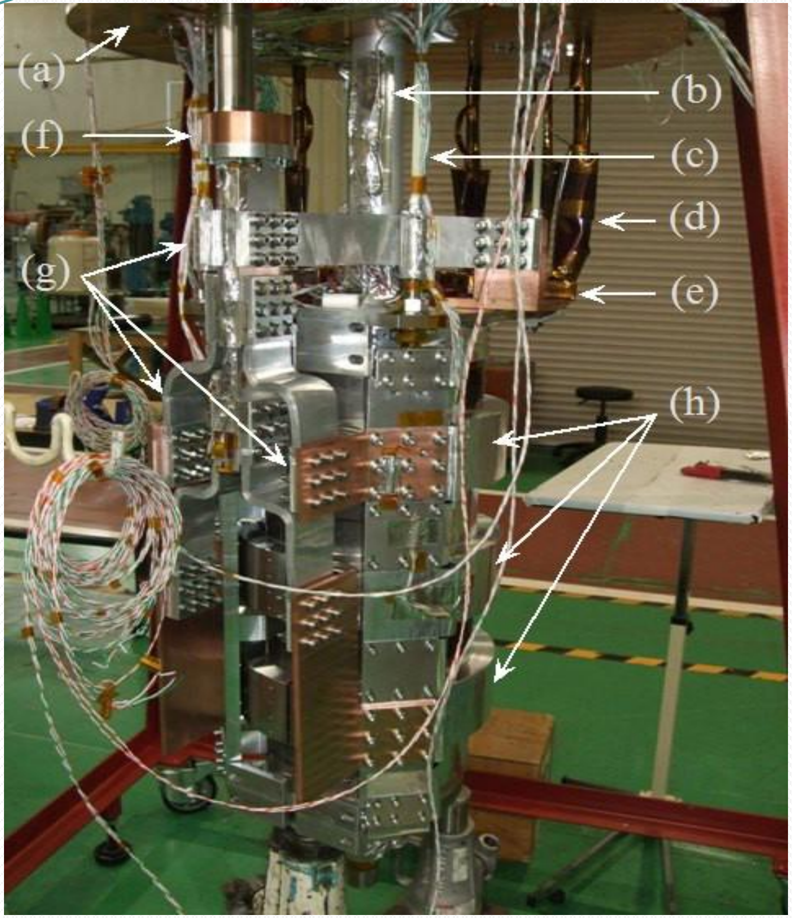


Quadrupole magnetic center shift at -20% current change dx<8um, dy<4 um.

At 90 A current the quadrupole reached the specified peak gradient 54 T/m.

Test results at FNAL cryostat in the LHe bath

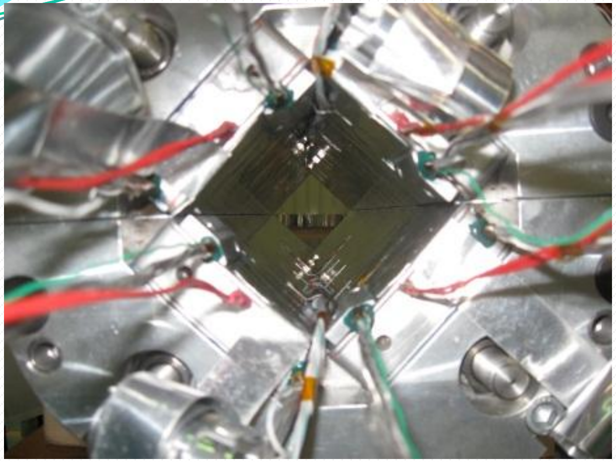
Cold Mass Assembly at Toshiba



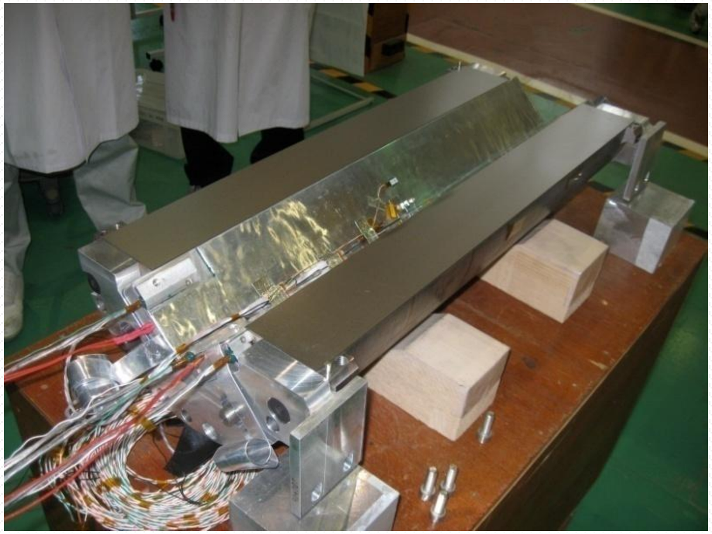
- New cryostat built by Toshiba
    - Sumitomo Pulse-tube Cryo-cooler
        - Efficient pure Al cooling channels, 50K shield
        - Al Strips glued to inner surfaces of (structural) Al coil packages
    - Temperature sensors on all coils, strategic locations
    - HTS power leads at each LTS lead connection (5 total)
        - Allows dipole and/or quadrupole powering options to 150 A
    - Help from Toshiba Corp. with final design, assembly
        - Yoke faces machined flat, shimmed at gap

Conduction cooling test stand during construction: a) top radiation shield, b) warm bore shield, c) vertical magnet support, d) Cu lead below HTS, e) Cu/SC lead thermal anchor, f) PTCC stage 2 cold head, g) pure Al and Cu conduction channels, h) stainless steel clamps around magnet yoke.

Quadrupole Assembly and Test at KEK



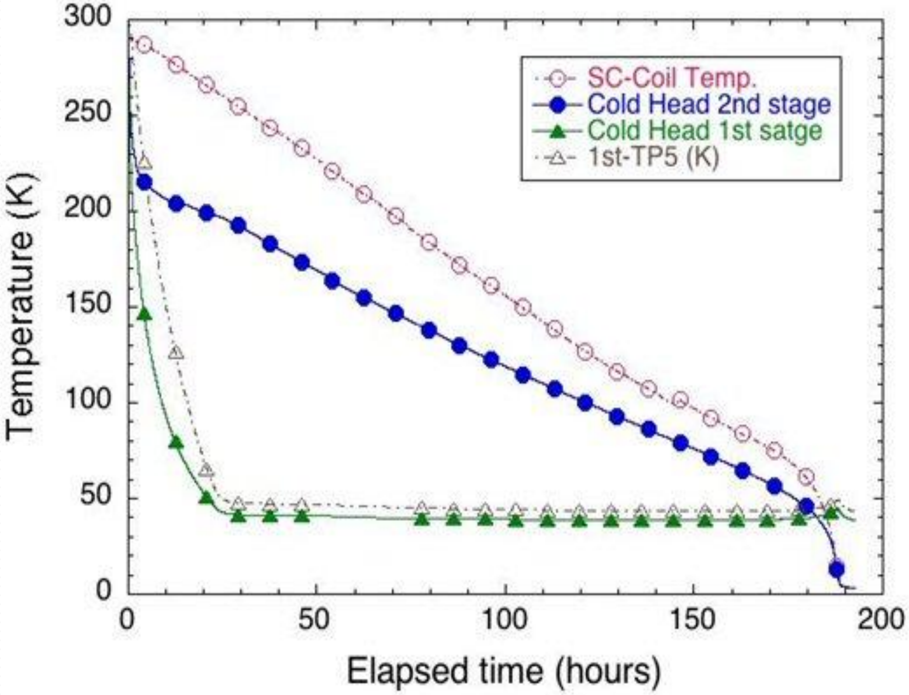
Coils with glued Al foils for better conduction cooling



Quadrupole split plane improving

KEK Test Stand to test the quarupole in the conduction cooling mode

Quadrupole Cooling Down

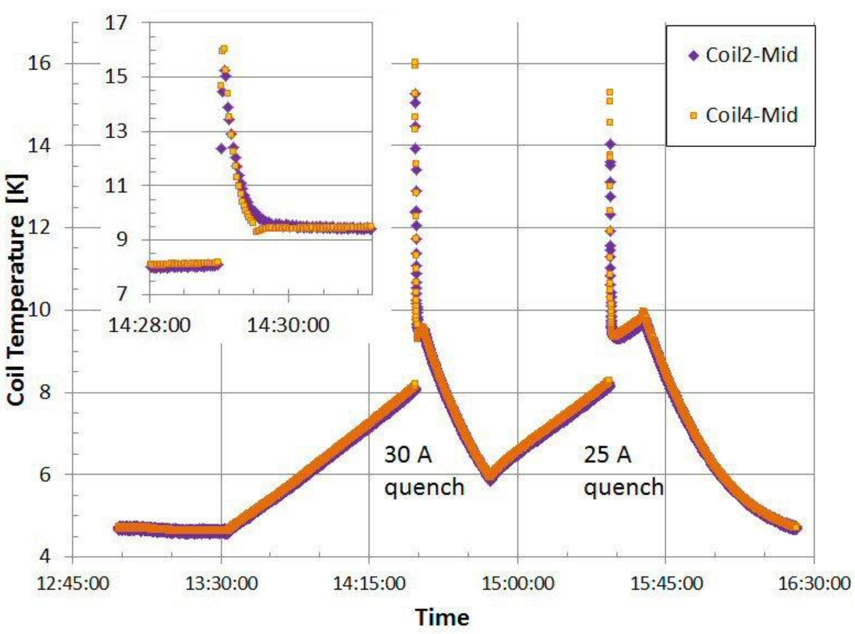


Heat Load Estimates

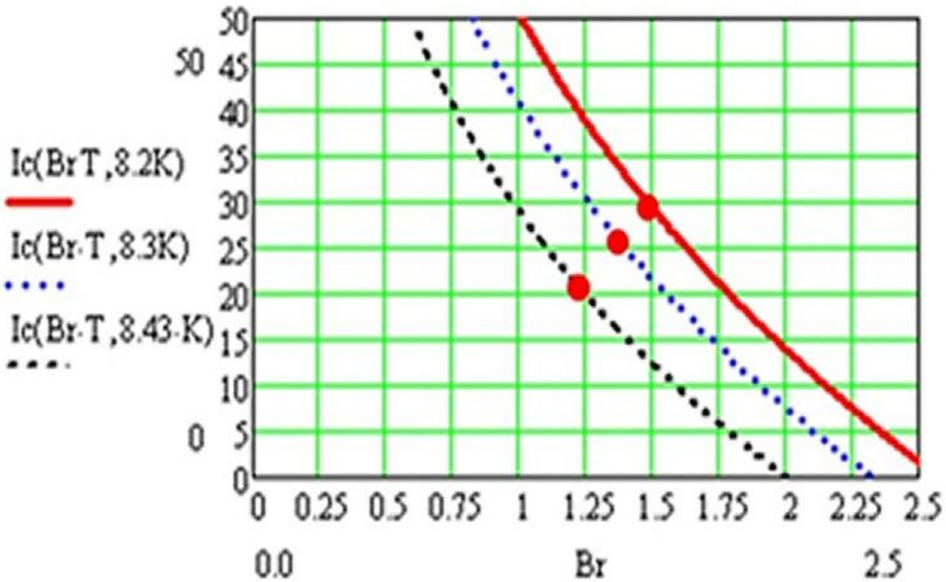
Component/Location	Temp [K]	Est. Heat Load [W]
Assumed 1st Stage Temperature	45	
Current Lead conduction to shield		29.5
300 K Radiation at shield		7.10
Shield Support conduction to shield		3.49
H+V magnet support cond. to shield		1.03
Assumed 2nd Stage Cold Head Temp.	3.5	
Current Lead conduction to anchor		0.4550
Shield radiation (@45 K) to 4 K		0.0463
H+V Support cond. to 4 K magnet		0.0350
Instr. Wires conduction to 4 K		0.0114

The actual cool down to 4 K took only 190 hours (8 days). Figure shows the temperature trend of selected (shield and coil) temperatures during this period. The measured heat loads, calculated from the PTCC load diagram as well as calorimetrically from the rate of temperature rise with PTCC turned off, were 32 W and 0.6 W to the 1st and 2nd stages, respectively.

Conduction Cooling Tests



Coil temperature rise due to background heat load when compressor was turned off with magnet powered at fixed currents.



The superconductor critical current as a function of coil peak field. Dots represent the quench currents (20 A, 25 A, 30 A) at elevated coil temperatures (8.43 K, 8.3 K, 8.2 K).

The magnet cooled by conduction with only a single cryocooler has a large temperature margin (at 30 A current, and 1.5 T, 8.2 K - 4.2 K = 4 K). This is a very promising result because in the cryomodule the quadrupole will be cooled to 2 K by a superfluid LHe supply pipe.

Ramp Rate Study

1. First was a measurement of heating from AC losses while ramping up and down between 0 and 5 A at 0.1 A/s (about 10 times the maximum ramp rate required for ILC operation).
2. To convert the measured equilibrium increase of coil temperatures into a heat load, a calibration was performed by introducing known amounts of power to the quench protection heaters, ranging from 0.05 to 0.26 W.
3. The resulting AC loss at 0.1 A/s was found to be 0.057 W.
4. Subsequent current ramps to 30 A were made at up to 0.4 A/s, to demonstrate that eddy current heating at high ramp rates (40 times the rate needed for ILC beam-based alignment) did not result in a quench.

Summary

1. The splittable quadrupole for ILC-type cryomodules was successfully tested in the conduction cooling mode at KEK using a cryostat built by Toshiba, in which the heat load at 4 K was only 0.6 W.
2. The test demonstrated good performance in the conduction cooling mode of the splittable quadrupole magnet, which showed no re-training and large (4 K) thermal margin consistent with short sample prediction, at currents up to 30 A.
3. Fast ramping at 0.4 A/s did not cause a quench.
4. The magnet with the cryostat will be shipped to FNAL to continue the test to high current (>100 A) and perform high precision magnetic measurements starting in the fall of 2012.
5. In the farther future this facility will be valuable for performance testing of other small magnet styles that require a conduction cooling environment, suitable for cryomodules.