Once upon a time, there were Three Splittable Quads…

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Representing many collaborators from U.S. and Japan

esp. Vl.Kashikhin, N. Andreev, T. Wokas; C. Ginsburg,

H. Hayano, A. Yamamoto, N. Kimura; Toshiba Corp.

A Little History…

Ongoing U.S.-Japan Collaborative Development

(since ASC 2008)

Focusing elements for Linac SRF Cryomodules

(esp. ILC; ASTA)

ILC Challenges: one magnet for 15-250 GeV range

Strict magnetic center stability (5 µm/20% ΔB/B)

“Splittable” to address ass’y in ultra-clean SRF space

➔ Conduction Cooling

Program Trajectory and Goals

- ***Spl. Quad # 1:*** ILC_RTQ_02 (split version of _01, without dipole correctors: Axis = *f*(history)
  - l=740 mm, r=39 mm; g_{max}=56 T/m; I_{max}=90A; $g\ell$eff=36T
  - 4 racetrack coils in split core, N_{turns}=910; $\mathcal{L}$=10.4$\mathcal{H}$
  - 0.5 mm (1.5:1) Cu/NbTi strand; Outer S.S. Strip Htr
  - Epoxy-potted in 6061-T Al structural coil pkg
  - Coil #3 broken lead - extracted, replaced by new coil
  - Tested 2011 in 4.5 K LHe bath (FNAL MTF St3)
  - Tested 2012 at KEK, 2013 at FNAL, Cryo-cooler Stand **Quench Training, Quench Protection (Heater, Rdump) Magnetic Performance (harmonics, axis stability)**

Program Trajectory and Goals

- ***Spl. Quad # 2:*** Short version of ILC_RTQ_02, with dipole correctors
- Based on Split Doublet Quad design for ASTA
  - L=295 mm, r=39 mm; g_{max}=18.7 T/m; I_{max}=33.3A; $g\ell_{eff}$=3.5T
  - 4 racetrack coils in split core, Quad+2Dipole windings
    - Quad N_{turns}=450; $\mathcal{L}$=0.120$\mathcal{H}$
    - Dipoles (H,V) N_{turns}=44; $\mathcal{L}$=0.002$\mathcal{H}$
  - 0.5 mm (1.5:1) Cu/NbTi strand; Outer S.S. Strip Htr
  - Epoxy-potted in 6061-T Al structural coil pkg
  - Cernox RTDs within the coil packages
  - **Not yet tested – will be commissioned in-situ:**
  - **Features for KEK Cryomodule installation**

Program Trajectory and Goals

- ***Spl. Quad # 3:*** Second (Identical) Short Split Quad with dipole correctors
- Based on Split Doublet Quad design for ASTA
  - L=295 mm, r=39 mm; g_{max}=18.7 T/m; I_{max}=33.3A; $g\ell_{eff}$=3.5T
  - 4 racetrack coils in split core, Quad+2Dipole windings
  - Cernox RTDs within the coil package
  - **Under Construction (completion in December 2013)**
  - Features for testing in Cryo-cooled test stand

Quench Training, Quench Protection, Magnetic Performance (Ref. absolute axis & magnetic axis stability)

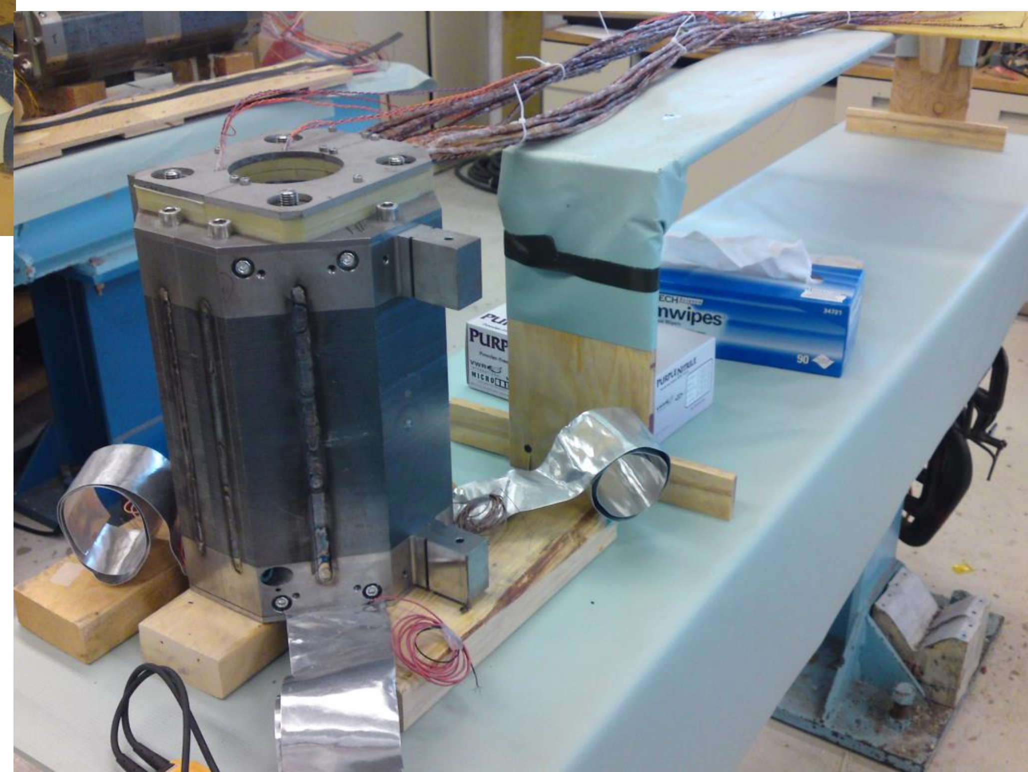
Program Trajectory and Goals

- ***Split Quad # 1:***
  - Full length ILC prototype, quad only
    - 4K bath tested; modified, many tests completed in conduction cooling mode
    - Preliminary result: meets ILC requirements
- ***Split Quad #2:***
  - ~half ILC quad length, quad+2 dipoles
    - Just installed in 1st KEK ILC Cryomodule (2014 beam tests)
    - Lead, instrumentation wire final details to be completed
- ***Split Quad #3:***
  - Identical to #2, under construction (nearly done)
    - To replace #1 in KEK/Toshiba/FNAL conduction-cooled test stand (a new procedure, some modifications required)
    - 2014 performance tests

Split Quad #2 Assembly @FNAL

Fully assembled, with 5N purity
5N pure Al strips for coil cooling
Cu stabilized leads
Multi-pass welds of laminations to prevent warp, distorting gap at split yoke faces

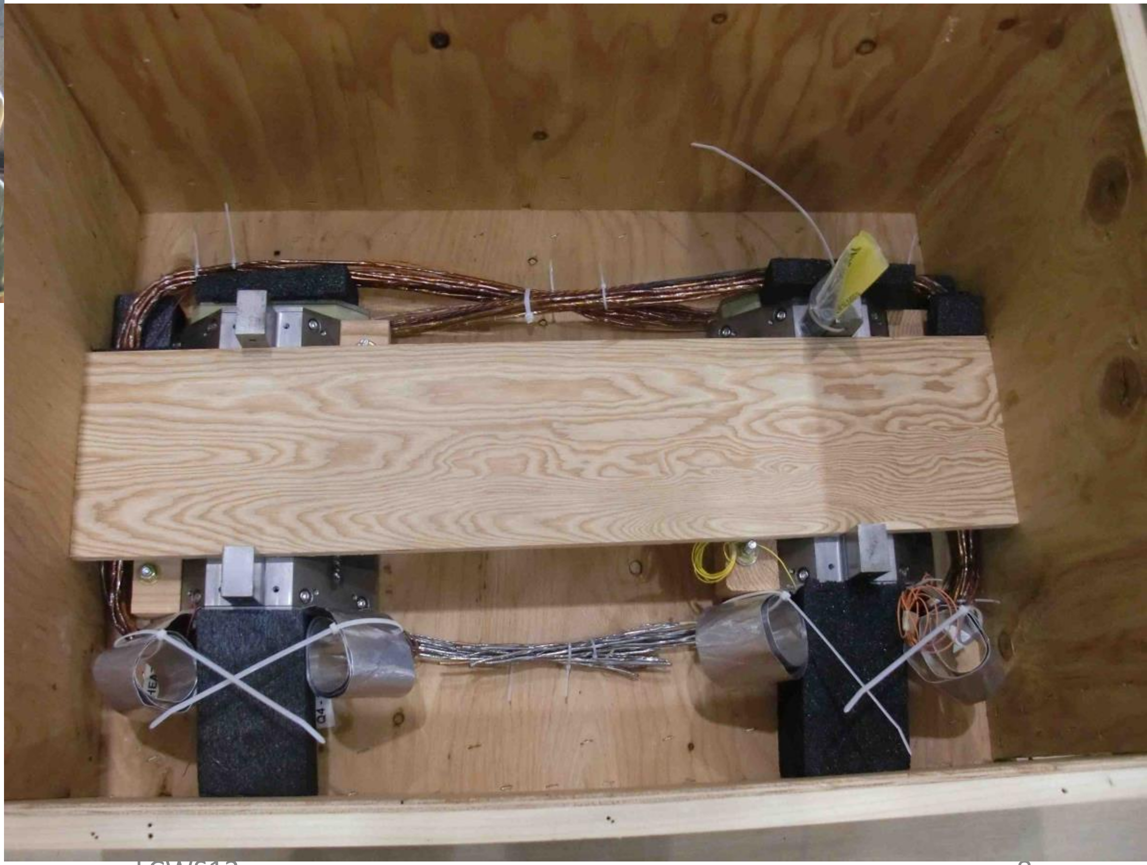
Four completed coils



Note: our lead technician, Tom, is retiring in January; he has an apprentice and is capturing process steps in procedure and draft Traveler

Split Quad #2 Shipping to KEK

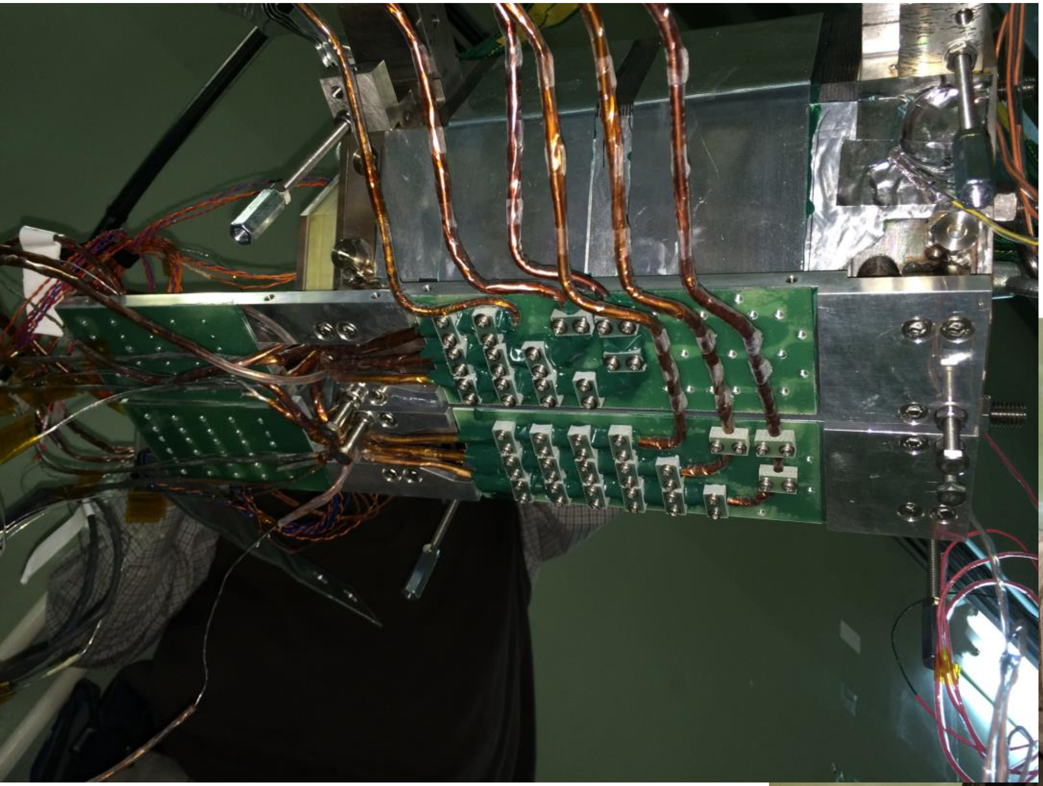
Received 9/20/13



Split Quad #2 Preparation to Install

- Start Fabrication (w/ some design modifications): 3/1/13
- Shipped to/Received at KEK: 9/20/13
- Incoming Electrical Inspection (coil resistances, hipot)
- Parts for lead splicing, routing, cooling
- Parts, tooling for mechanical installation
- Practice mechanical installation sequence
- Final electrical inspection
- Verify correct Quad, H-, V-Dipole field polarities (0.1A~0.5G)
- Execute mechanical installation sequence (11/12/13)
  - About 1.5 hours to complete the mechanical work

Split Quad #2 Final Inspection



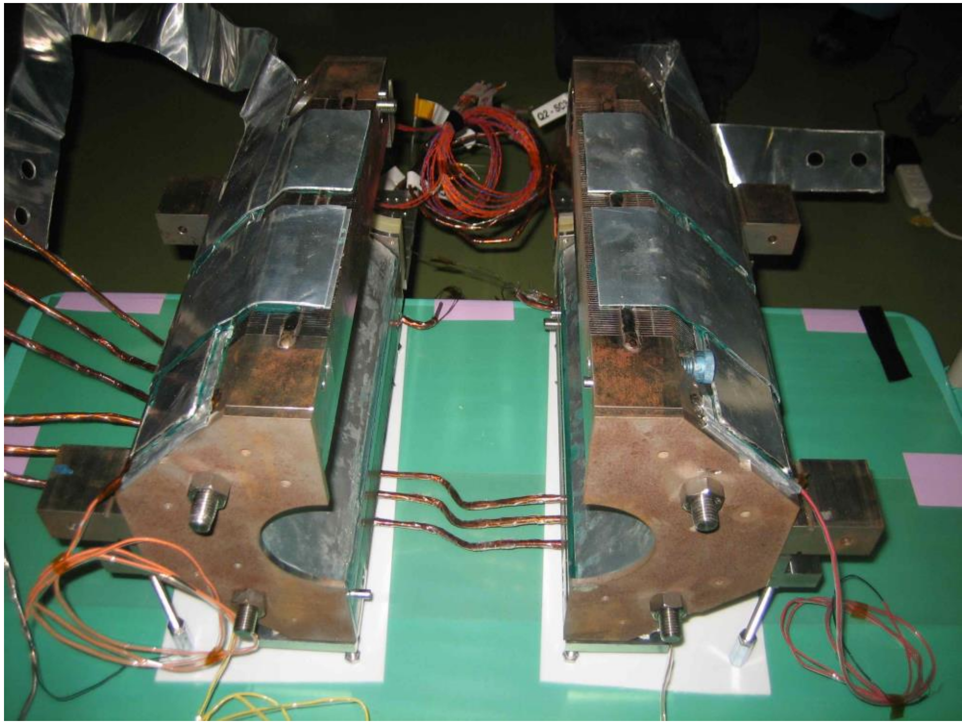
Checking field polarities with Hall probe

Lead and Splice routing below Magnet support plate

Step by Step Mechanical Installation

1.

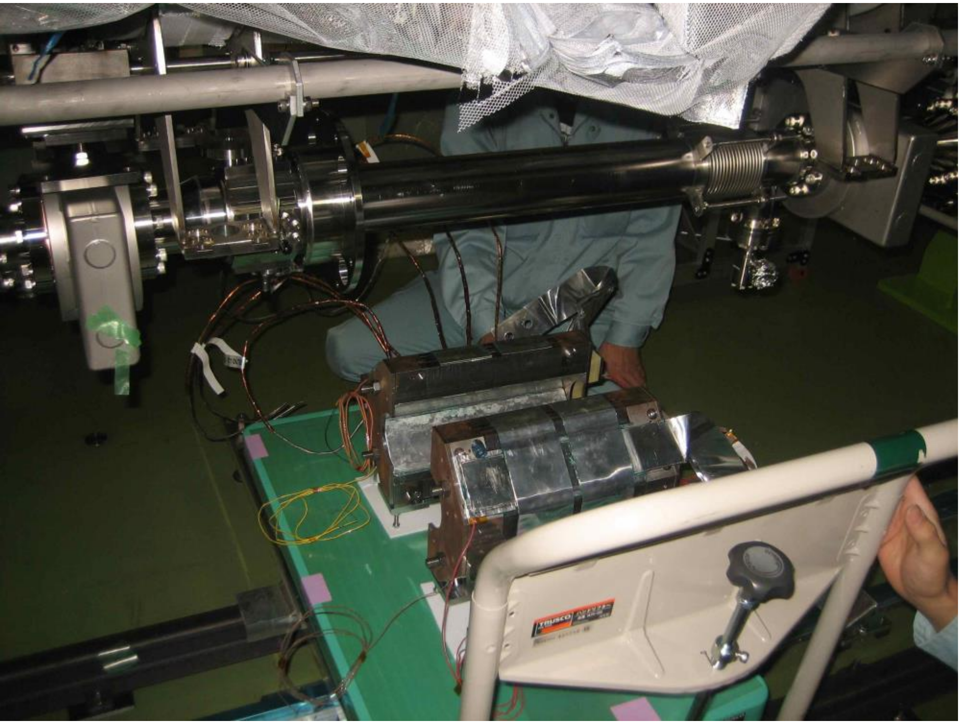
2.



1. Lay a pair of guide rails under setup position, and put a cart equipped with lifting table on the rail.
2. Set the magnet on the table, and separate iron yokes.

Step by Step Mechanical Installation

3.



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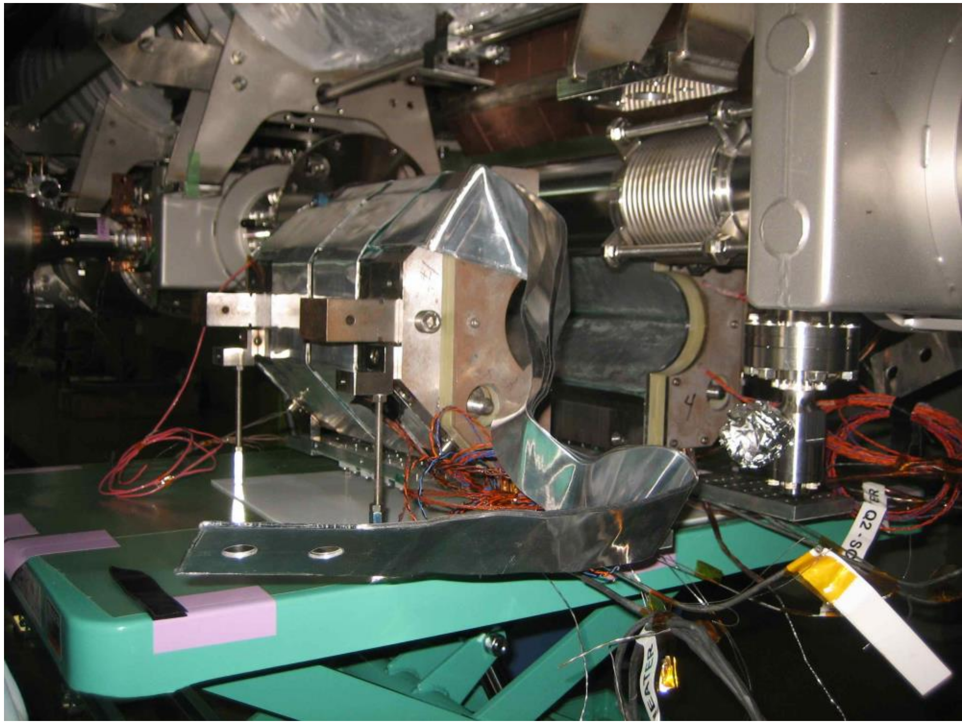
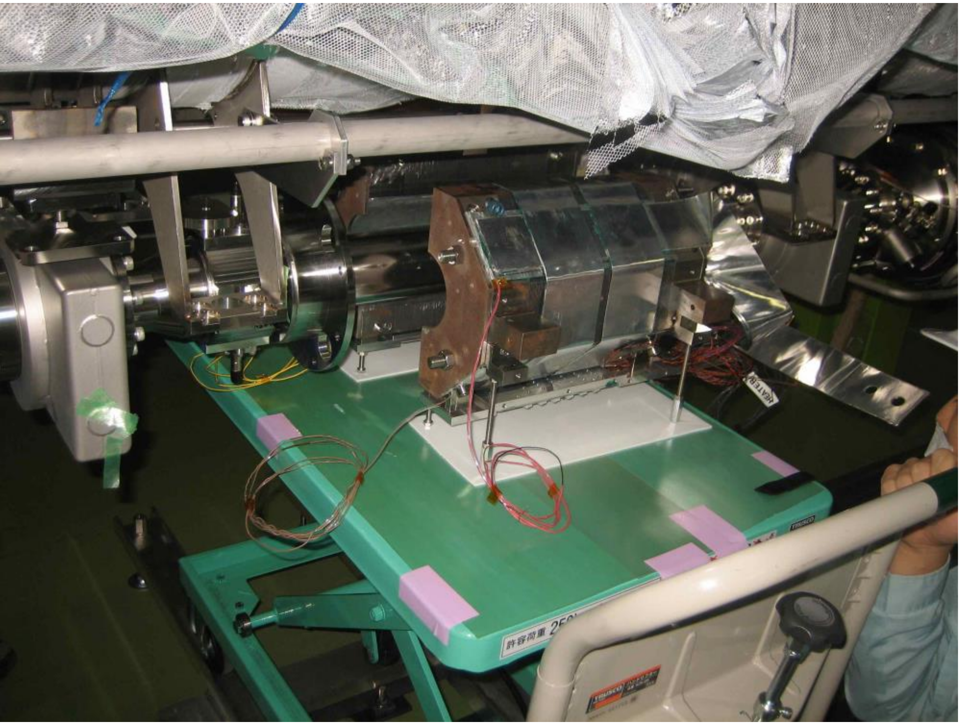


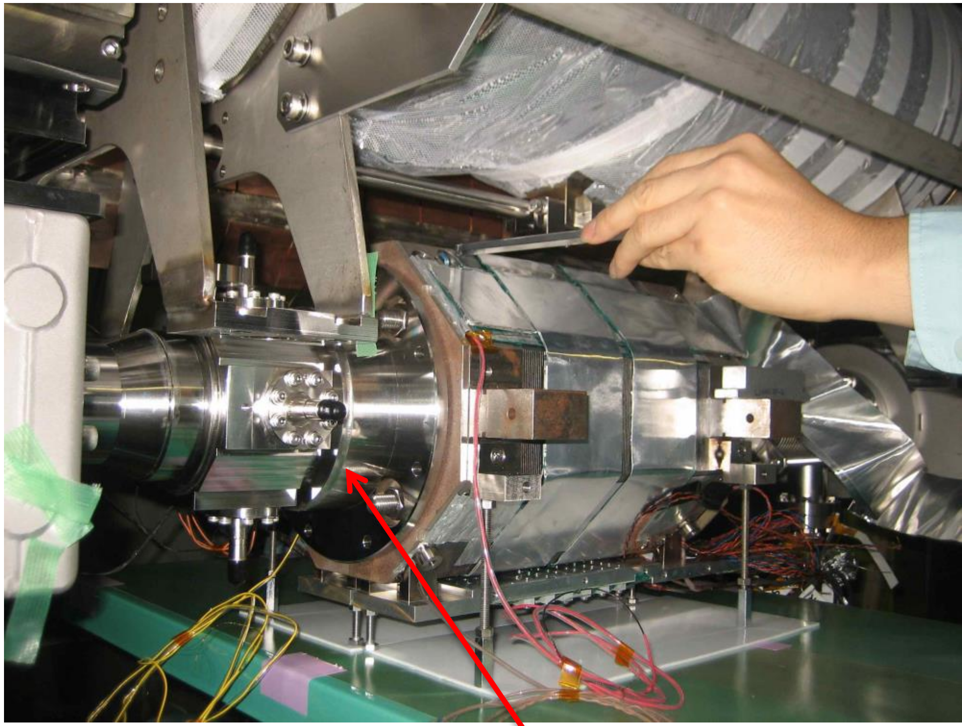
3. Move the cart under setup position.
4. Lift up the magnet by the table.

Step by Step Mechanical Installation

5.



6.



5. Lift up the magnet to right position.
6. Align the iron yoke halves, and couple them.

Step by Step Mechanical Installation

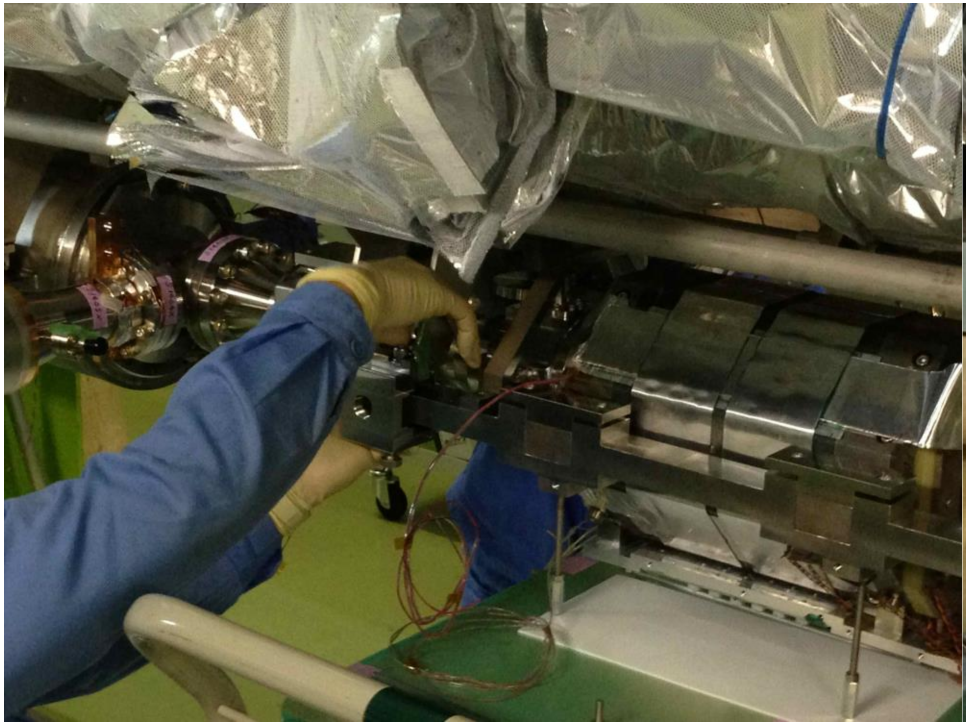
7.

8.

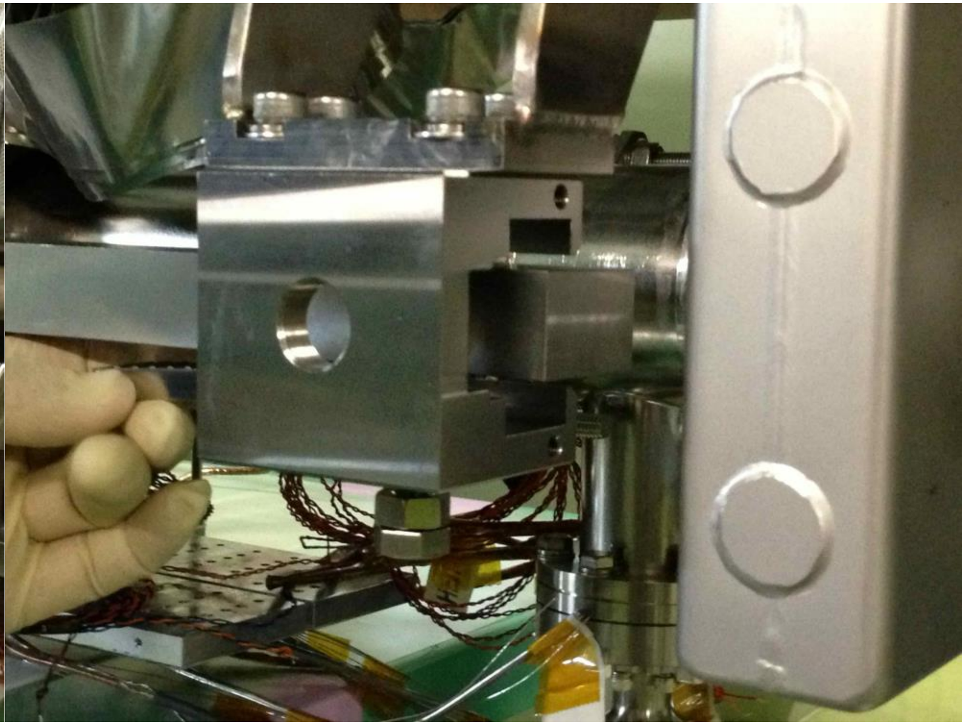
7. Align the magnet again.
8. Install stainless support bar on both sides of the magnet.

Step by Step Mechanical Installation

9.



10.

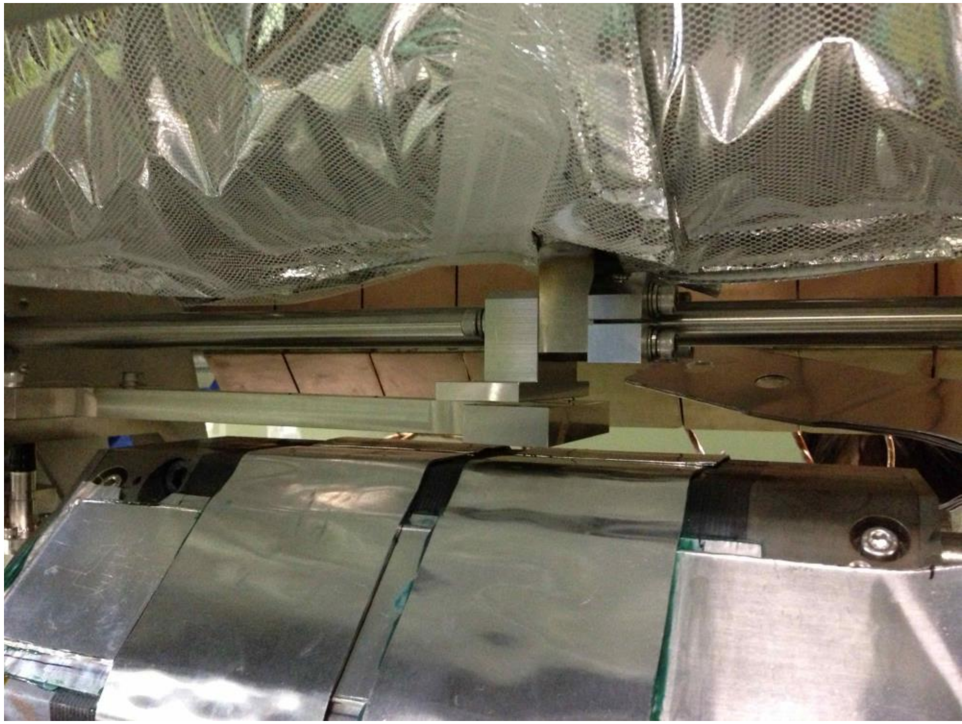


9. Install C-style holding clamps at both end of stainless supports.
10. Install bearings and fixing bolts between the stainless bar and the C-style holding clamp.

Step by Step Mechanical Installation

11.

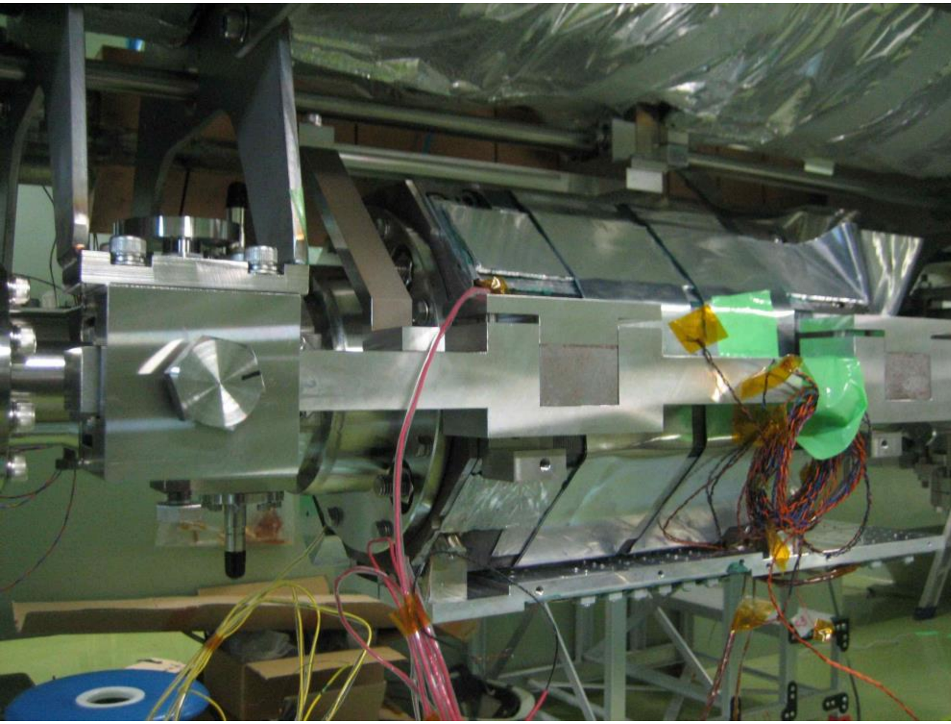
12.



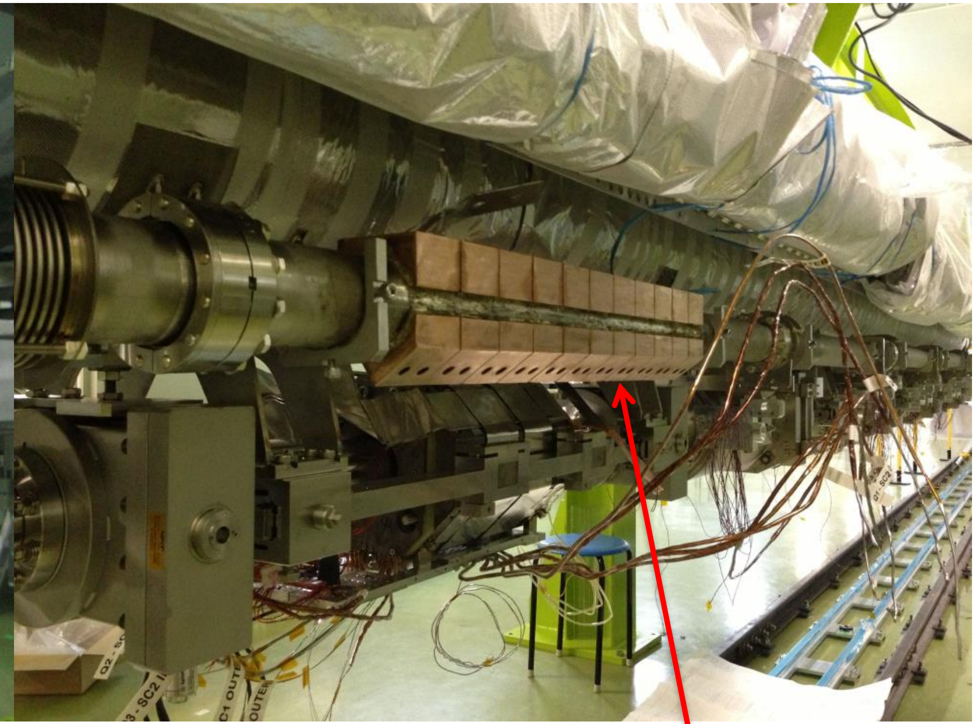
11. Align horizontal and vertical position of the magnet again; Couple the magnet and BPM.
12. Couple the stainless bar and Invar bar (which is the fixed mounting point).

Step by Step Mechanical Installation

13.



14.



13&14. After completing the magnet mechanical installation work.

2K He pipe, brazed Cu blocks For lead & coil conduction cooling

Next Steps

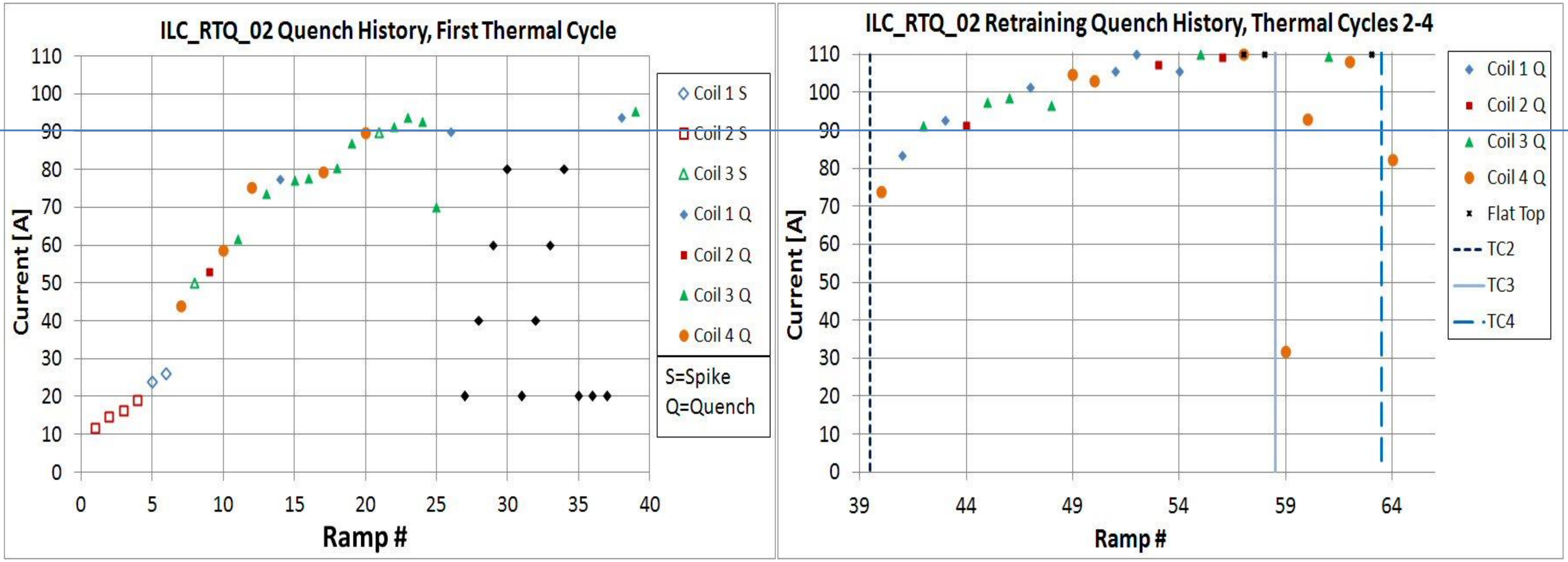
- Make Al. cooling channel & lead connections to 2K pipe
  - Aluminum Nitride thermal conductor, electrical insulator
- Splice bronze leads
- Install thermal, magnetic shields
- Insert cryo assembly into vacuum vessel
- Make lead and instrumentation feed-through connections
- Develop the magnet commissioning plan
- Time scale ~ 2-3 months(?)

Split Quad #1: ILC_RTQ_02

Tested at Fermilab MTF Stand 3 (4.5K He bath) 6/2011 (pub MT-22)

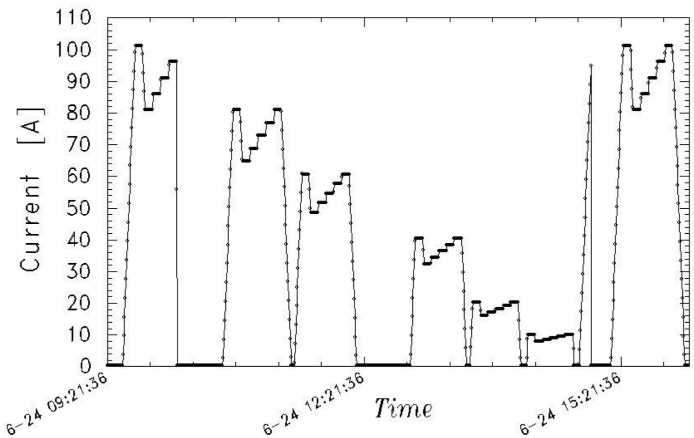
Slow, steady quench (some re-training) in 4 TC's

(4 racetrack coils, 0.5mm strand, 910 turns/impreg)



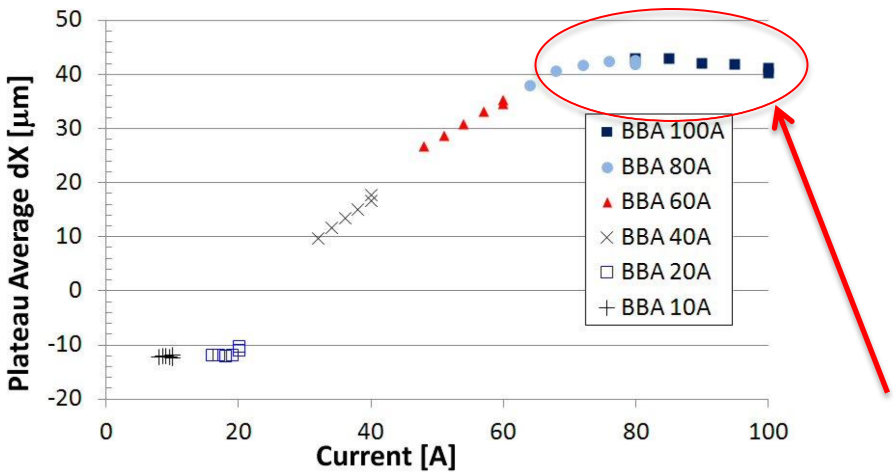
Brief History of ILC_RTQ_02

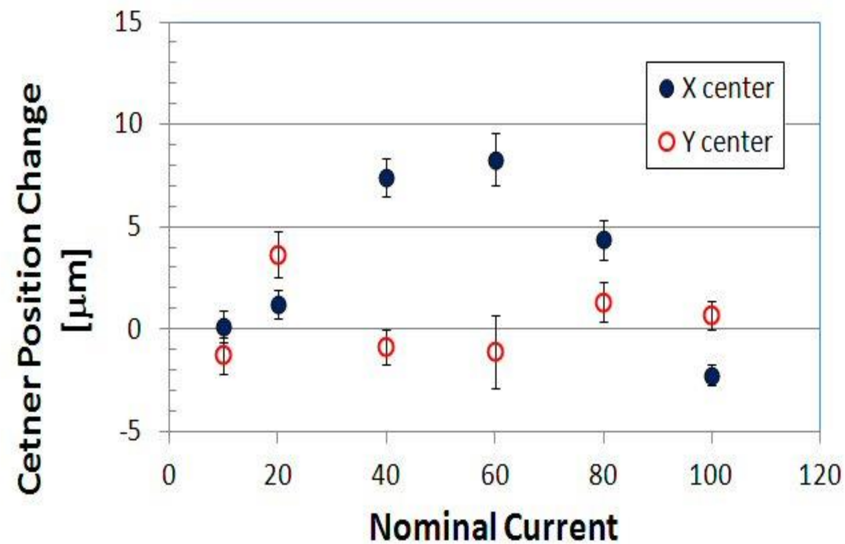
Stand 3 Magnetic Center Stability



8-10 μm (goal=5)

Beam- Based Alignment (BBA) current profiles





dX *vs* $I = f$(axial position); dY ~ constant

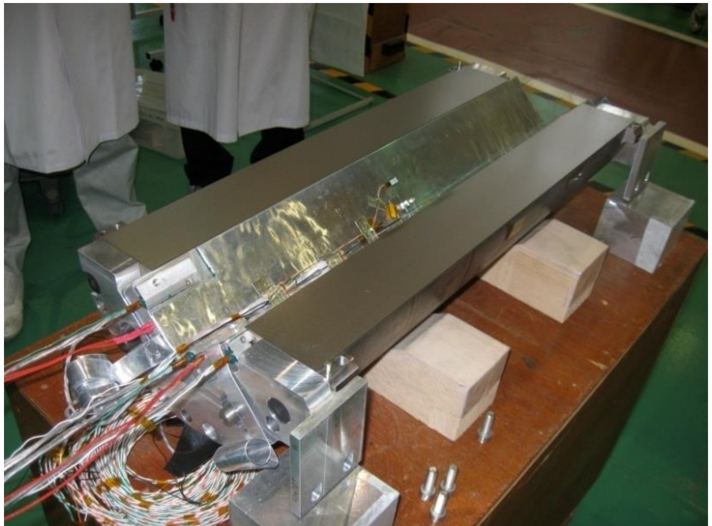
Brief History of ILC_RTQ_02

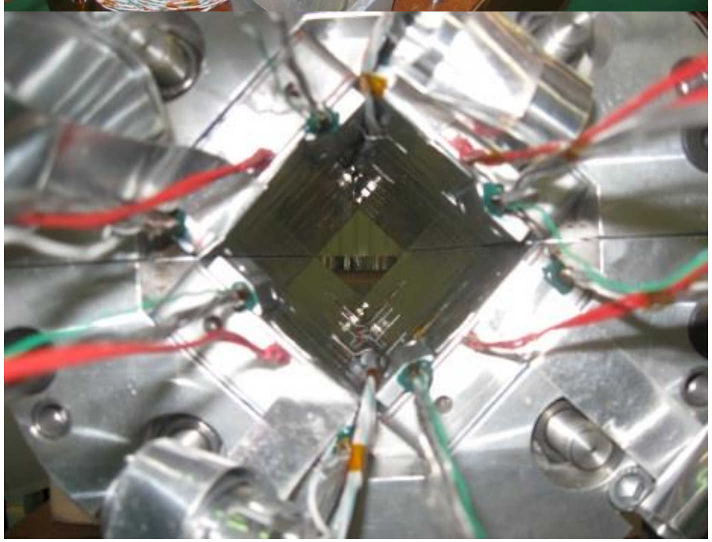
Conjecture: uneven gap along split yoke length

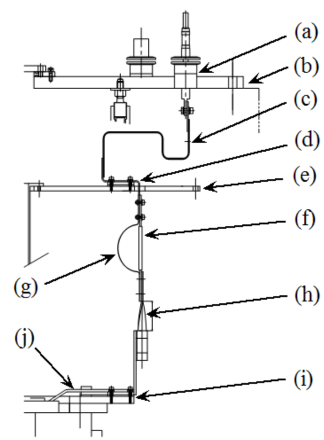
Collaboration with KEK & Toshiba Corp:

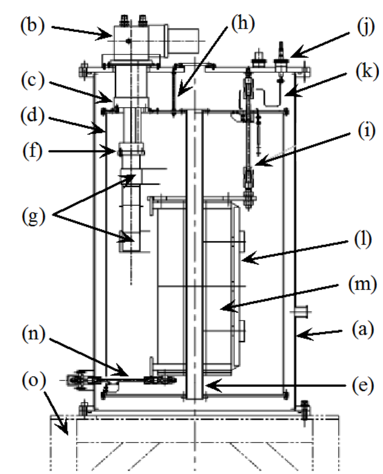
- Ship magnet to KEK (Dec. 2011)
- New Conduction-cooled cryostat design & fabrication (1W cryo-cooled vac vessel; HTS leads; warm bore)
- Machine yoke faces flat, add 0.5 mm iron shim)
- Glue 5N purity Al cooling strips to coil faces
- Assemble into (1W@4K) cryostat (June 2012)
- Thermal, Quench Tests at KEK, to 30 A, (Sep. 2012)
- Report Test Results, (Oct. 2012, ASC)

Splittable Quad, KEK/Toshiba Cryostat









Recent History of ILC_RTQ_02

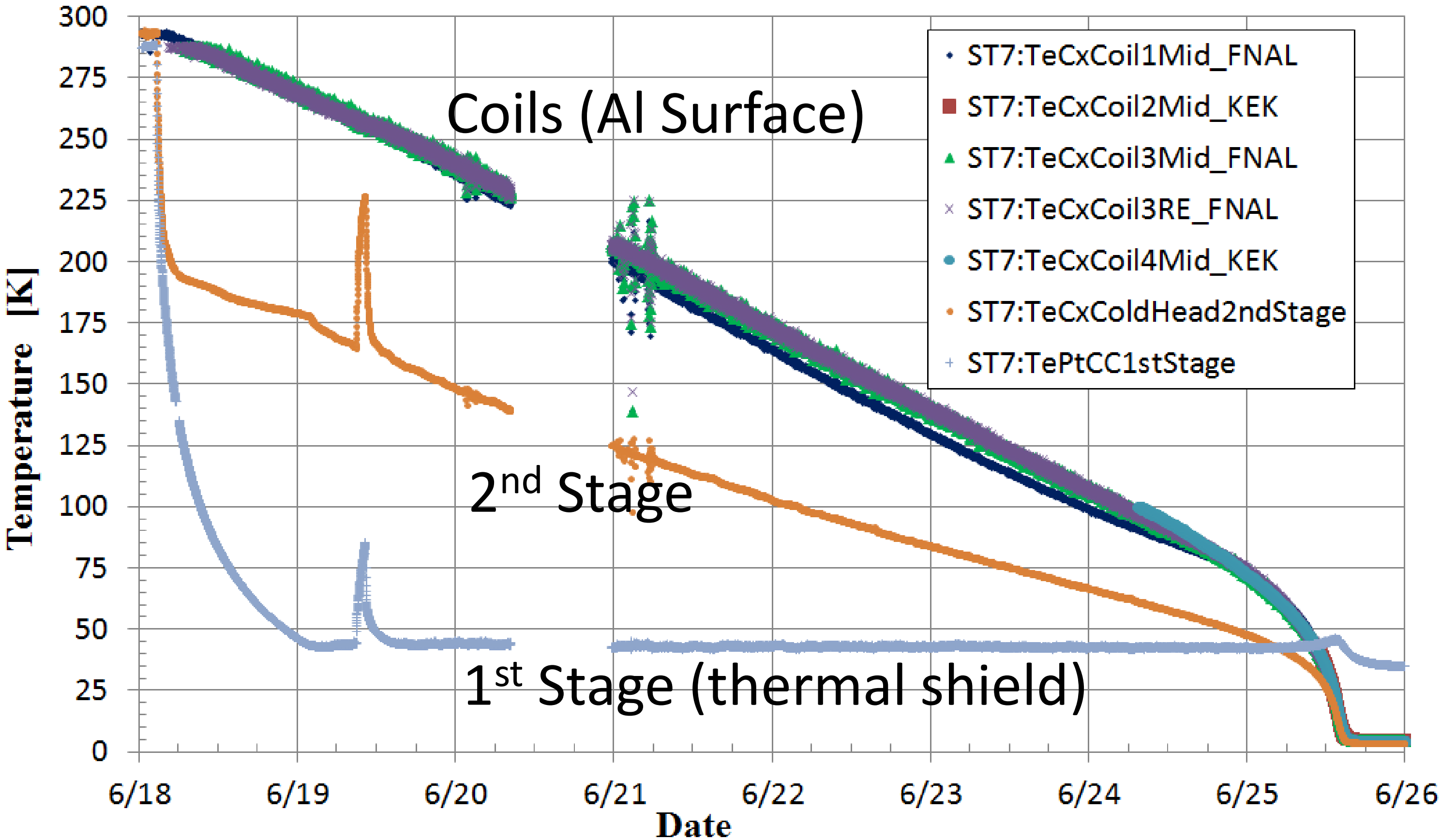
- Ass'y and Compressor Ship to FNAL (Oct. 2012)
- Unpack and check out (No Problems!)
- New Test Stand 7 Configured in MTF Dewar Pit
- Begin 8 day Cool Down 6/18/2013-6/26/2013
- Magnetic Measurements, Thermal, Quench Tests
- Report Test Results, (<u>7/15/2013, MT-23</u>)
  - VERY PRELIMINARY !
    - "Online" Results; Offline Analysis In Progress

New MTF Test Stand 7 ("PJL TF")

Results: First Cool Down

First Cool Down to 4K: **8 days, same as at KEK**

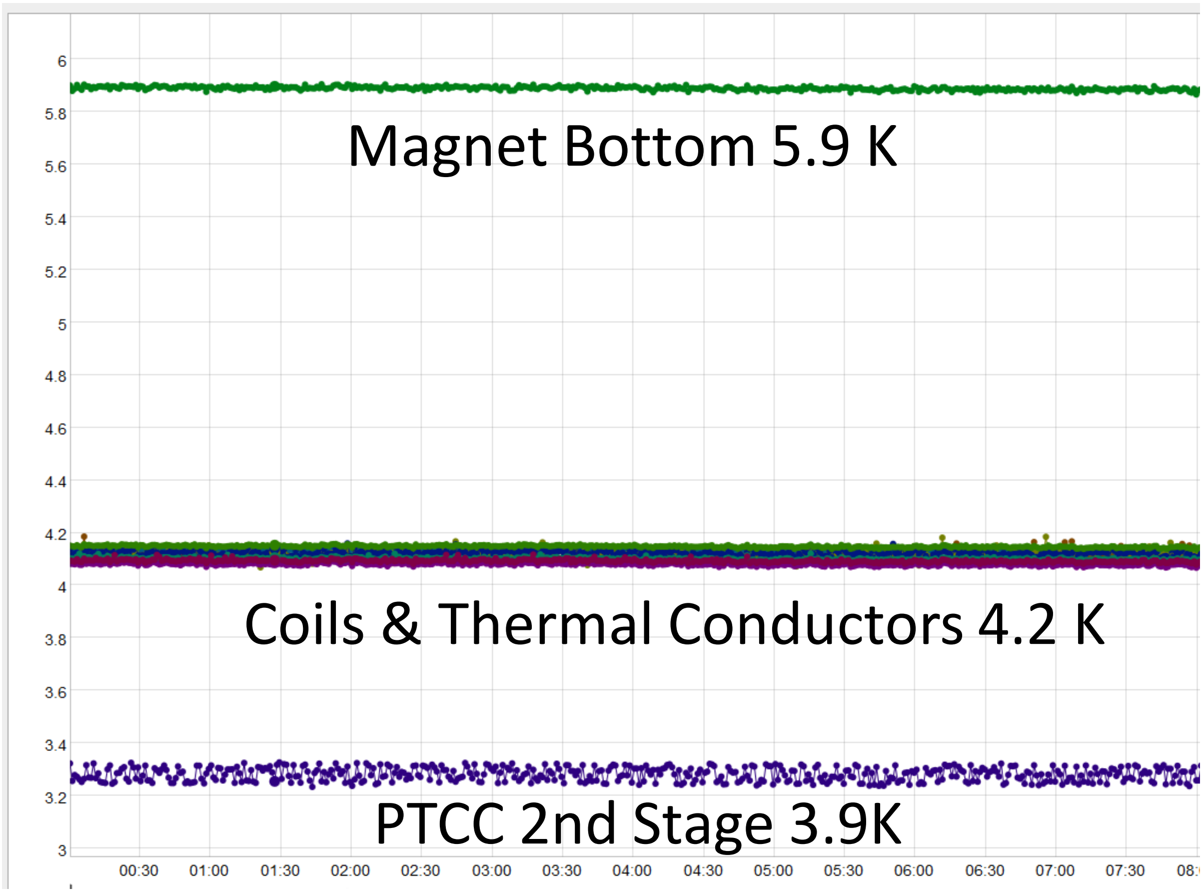
1st Operation Features: chiller trip (too hot); PC in "sleep" mode; noise from welding in MTF

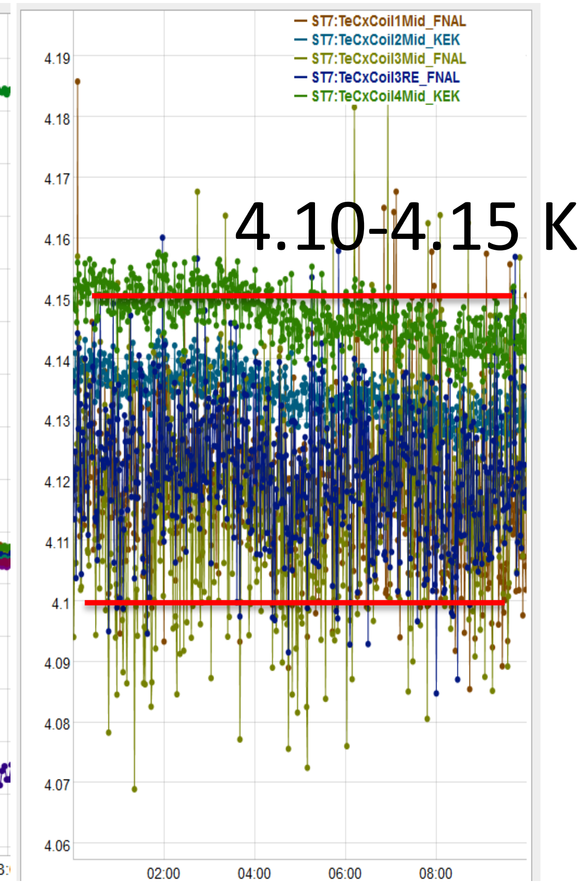


System Temperatures

Very Steady (0:00 to 08:00)

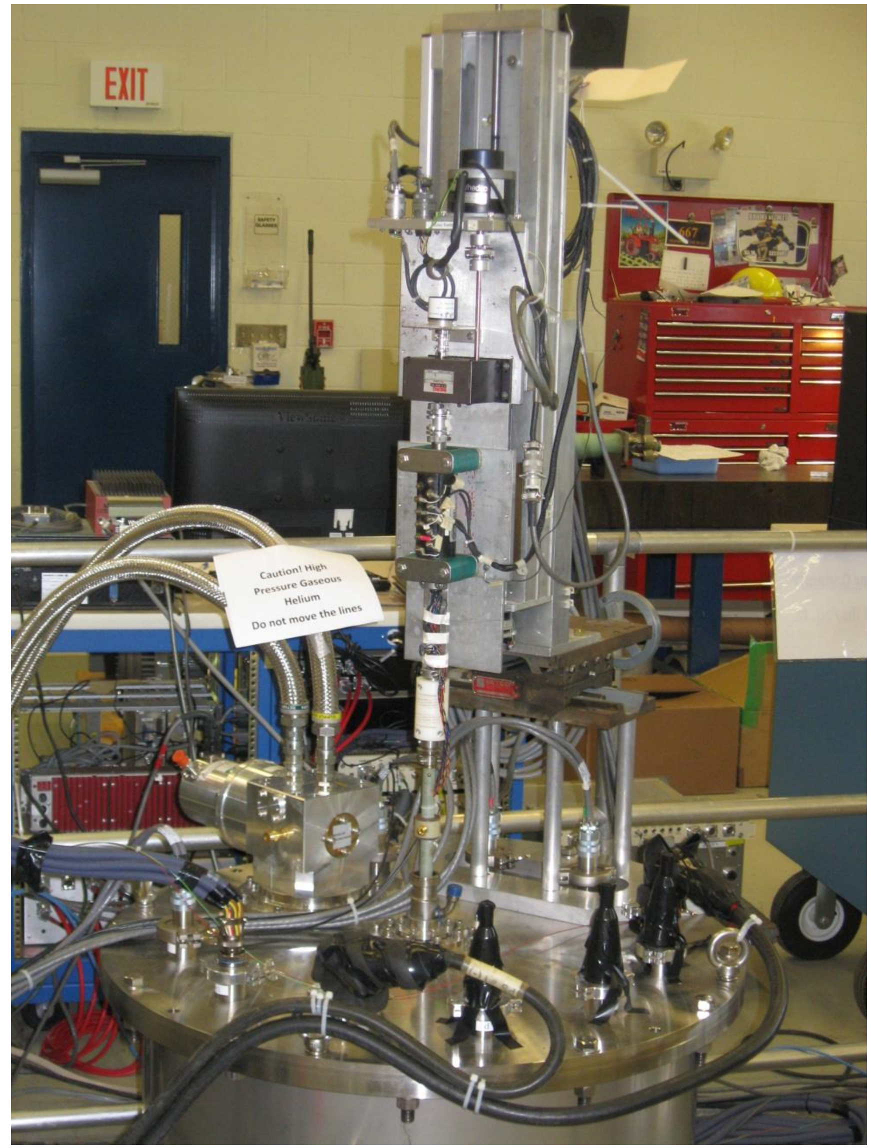
5 Coil (Surface) Temperatures



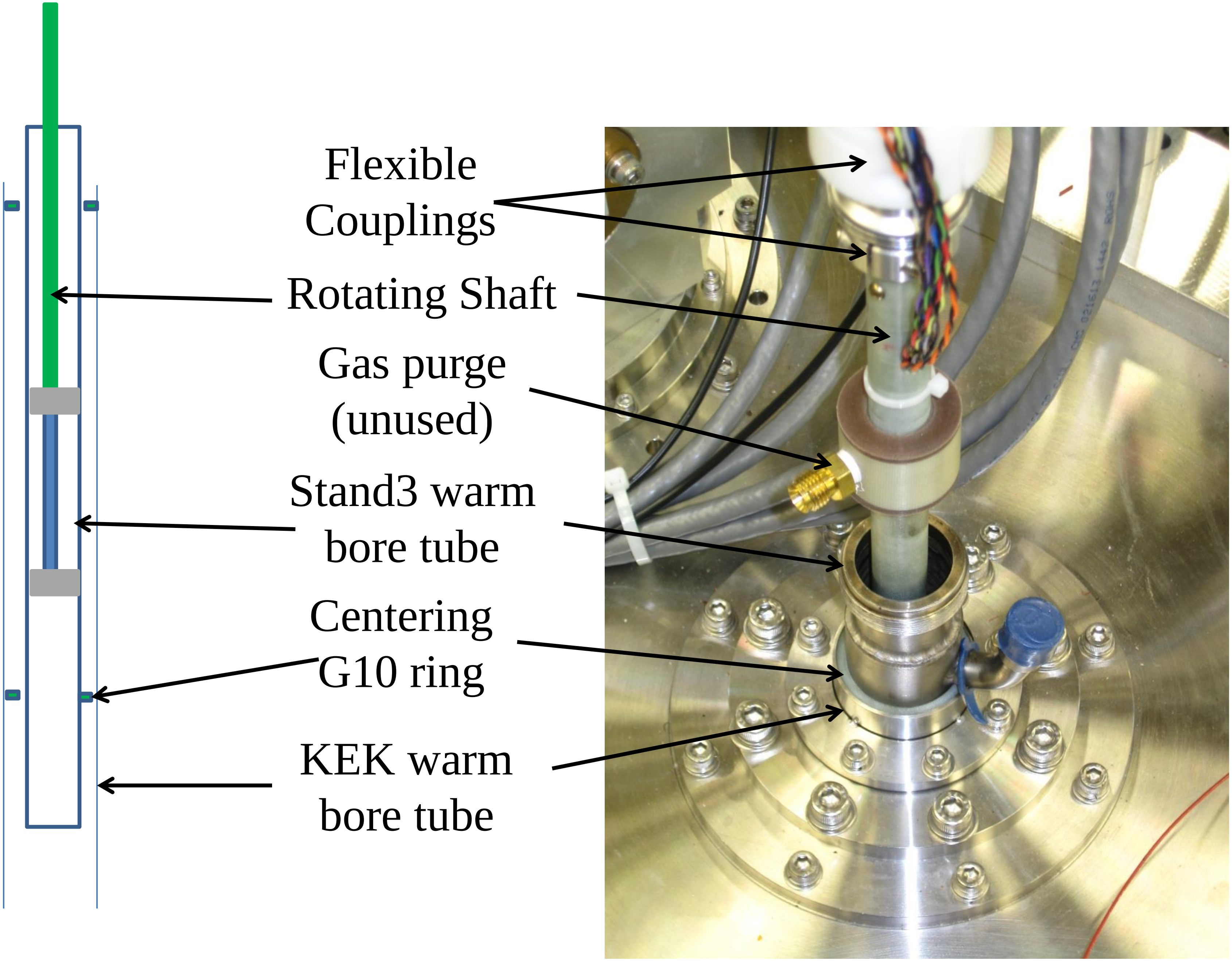


Magnetic Measurements

ADC/DSP measurement cart



Drive system (stand3 bore within KEK bore)



stand3 warm bore within KEK bore

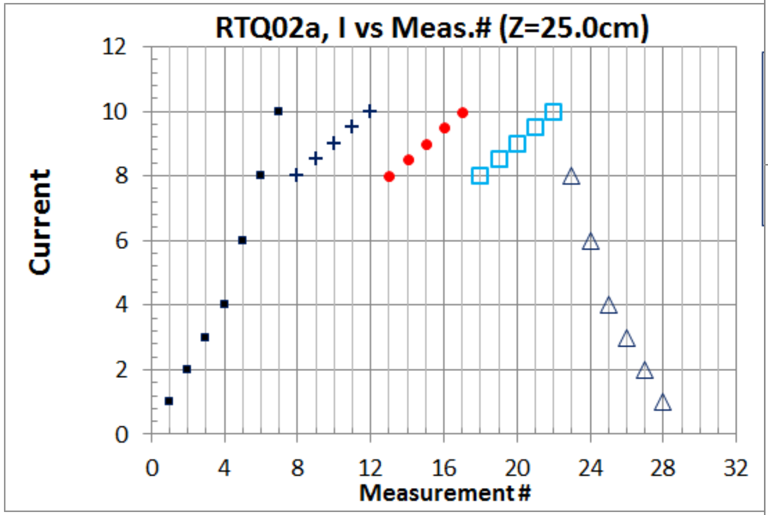
Magnetic Measurements

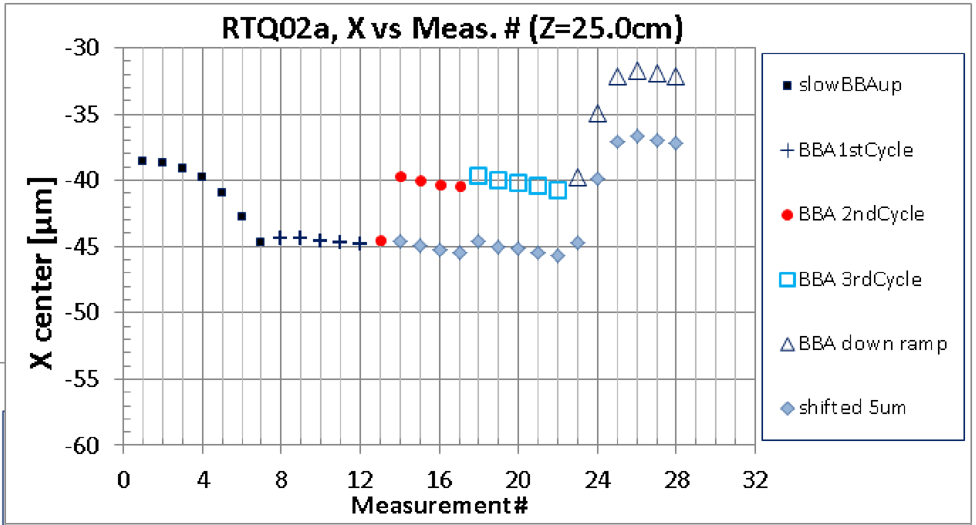
- First priority, first power tests
- Find Lead End/Body position
- Measure in mid body (location) "Z=25.0 cm"
- Strength vs Current:
  - agrees with previous test in stand 3
- Harmonics indicate field quality is good
  - (easily meets 5% uniformity at 5 mm radius)
- Focus on center position stability, especially X
  - Performed many BBA and Stair step profiles
  - From Low (10A) to high current (100A)
  - **No re-training quench until 95.9 A !! (2nd at 97.1 A)**

Magnetic Measurements *(online results)*

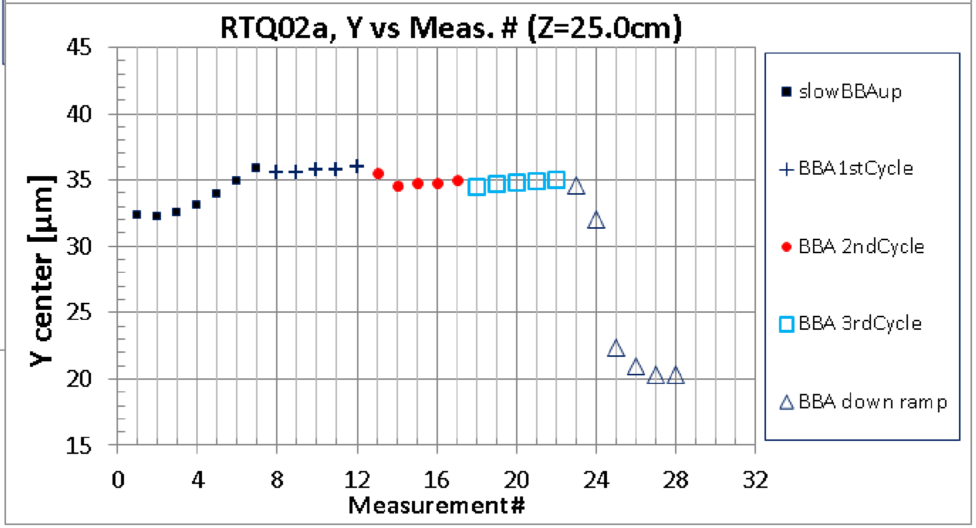
- Generally, meets requirements in X,Y stability over the full field range
- Occasional (random?) 5-10 μm SHIFTS seen, in X and/or Y

EXAMPLE:
10A BBA Profile
3 repeated cycles
(10_8_8.5_9_9.5_10)





X



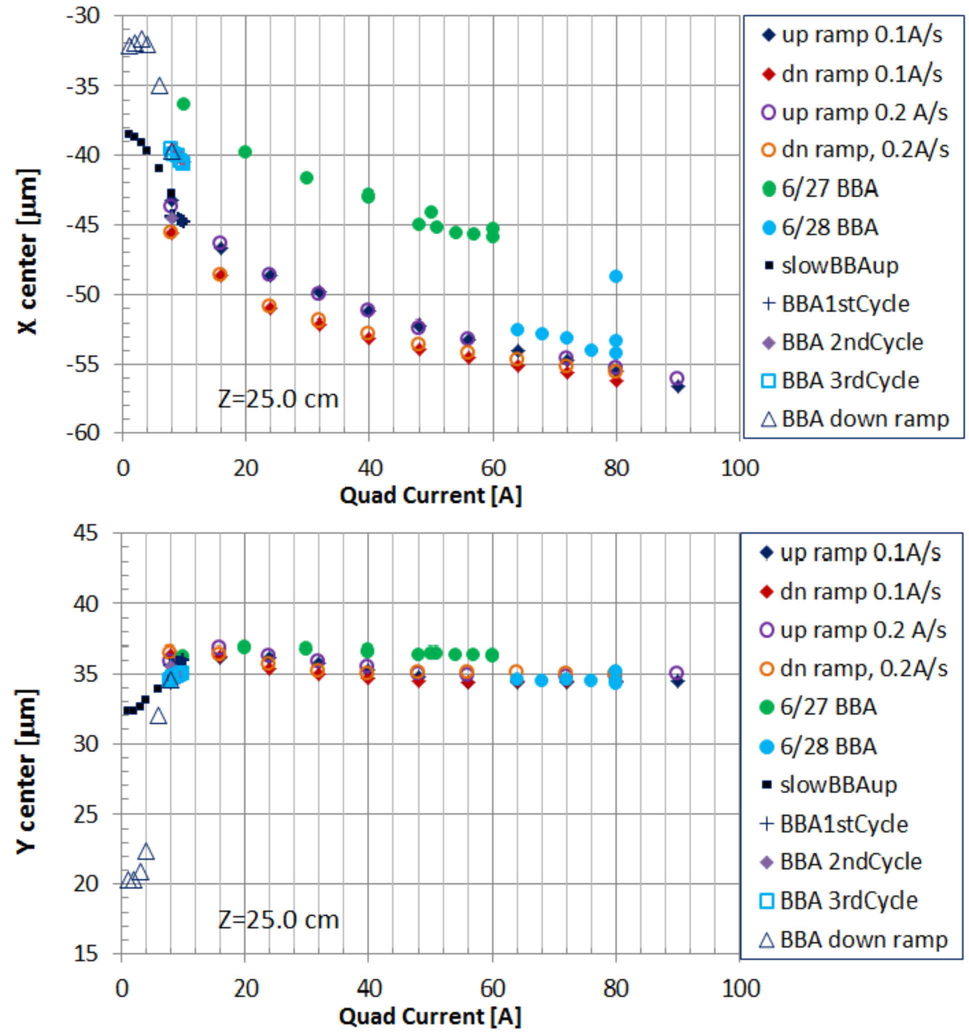
Y

Magnetic Measurements

- Conclusion: more investigation is needed

Overlay of many profiles, BBA & stair steps up to 90A

- Some shifts and hysteresis (OK)
- *Probe/Bore tube mechanical stability?*
- *Online vs offline analysis/corrections?*
- *Amplifier stability?*
- *Electro-Magnetic influences (chiller on/off) ?*
- *Small Coil motion ?*



X

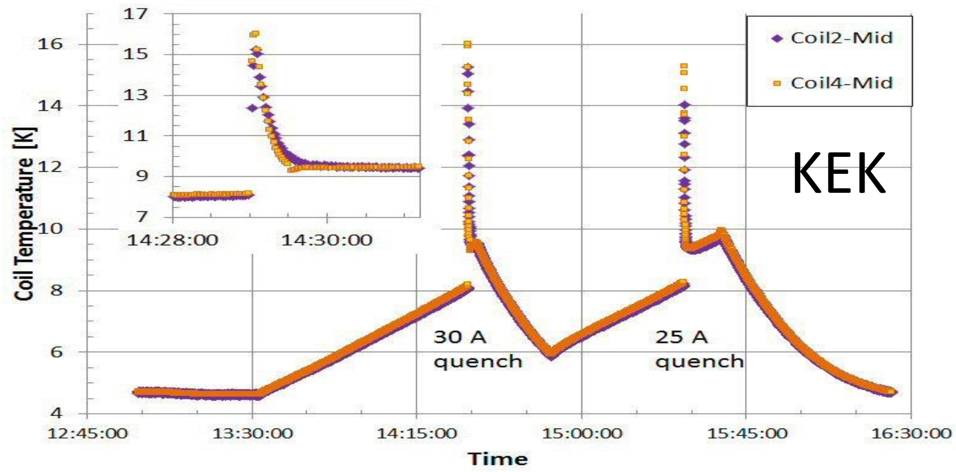
Y

Quench & Thermal Tests

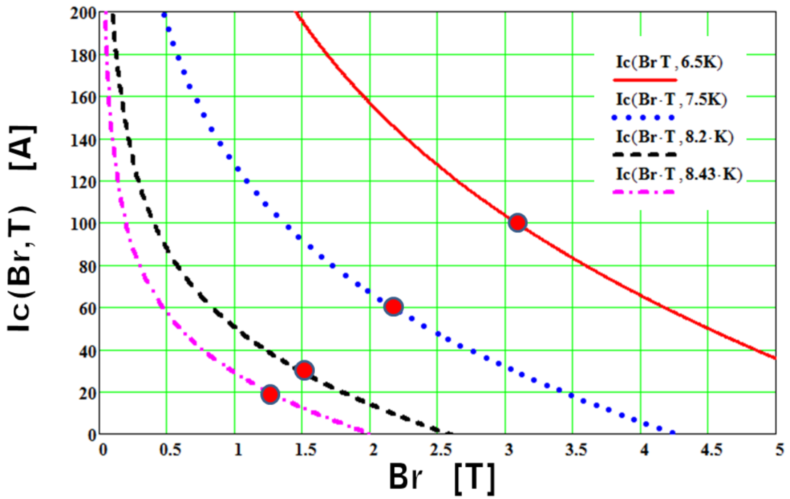
- Re-Training
  - 2 quenches: 95.9A (coil 1), 97.1A (coil 4)
  - No other spontaneous quenches with many ramps, up to 100 A: **very encouraging result**
- T(FNAL) – T(KEK) = 0.2 K (small systematic shift)
  - Difference in how calibrations are applied?
  - Polarity reversal vs non-reversal (thermal emfs)
- Repeat Critical Temperature Measurements
  - Ramp to current plateau {30, 60, 100 A}
  - Turn off compressor, isothermal T rise to quench

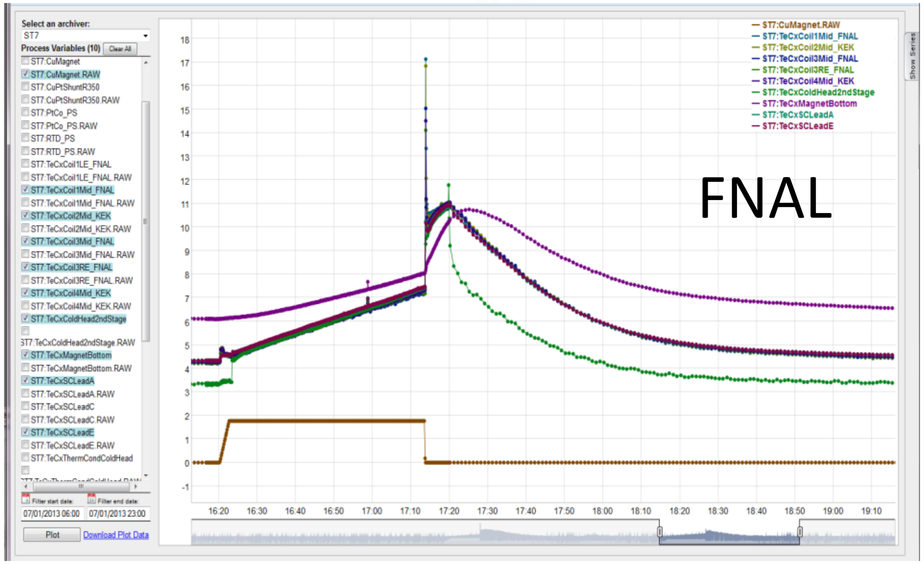
Quench & Thermal Tests

- Critical Temperature Test



MODEL and Data points





- KEK data agree to 0.2K
- Coils (SC) probably slightly above pure aluminum surface temperature
- to study with FEA model

Quench Protection & Thermal Tests

- Heater-induced quenches (baseline protection studies)
  - ✧Explore heater powered by parallel dump+heater circuit
  - Use current limiting resistor on heater branch
- Look for evidence of "Quench-back" (self-protecting?)
  - ✧Due to large eddy current heating with rapid dI/dt during discharge into dump resistor, enough heat to quench coil(s)
  - ✧Manual system trips (not quench) at low current (30A)
    - Done at both FNAL and KEK; comparison to be completed
    - w/o heater vs w/ heater (at FNAL)
  - ✧Look for evidence of resistive voltage growth
    - ✧ Coils are not identical – coil 1 always quenches first, 3 last
    - ✧ Subtract inductive voltage from another coil (coil 3)
  - ✧Compare current profiles versus current
    - 2 FNAL dump circuits (one similar to KEK)
    - Result in very different dI/dt profiles
- Temperature rise, energy balance also still to be studied

LOTS OF DATA TO BE ANALYZED; PRELIM. RESULTS SO FAR

Conclusion

- Successful transfer of cryo-cooled magnet ass'y from KEK to FNAL
- Preliminary results following recent operation of new test stand at FNAL published at MT23
- Further magnetic measurement plans:
  - Complete offline data analysis of existing data sets
  - Investigated other possible effects (so far no clues)
  - PCB probe with bearings matched to KEK warm bore
- Further study of many data sets
  - Quench-back, energy balance, recovery time
  - Thermal resistance calculations
- Replace Spl. Q #1 with new Spl. Q #2 and test it
  - Learn a new procedure
  - May use SSW system for axis measurements

References

[1] "International Linear Collider Reference Design Report," http://www.linearcollider.org/cms/?pid=1000025.

[2] V.S. Kashikhin *et al.*, "Design and Manufacturing Main Linac Superconducting Quadrupole for ILC at FERMILAB," *IEEE Transactions on Applied Superconductivity*, vol. 18, No. 2, June 2008, pp. 155-158.

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[4] V.S. Kashikhin, *et al.*, "Superconducting Magnets for SCRF Cryomodules at Front End of Linear Accelerators," Proceedings of IPAC'10, Kyoto, Japan, 2010, pp. 379-381.

[5] G.V. Velev *et al.*, "A Fast Continuous Magnetic Field Measurement System Based on Digital Signal Processors," IEEE Trans. of Applied Superconductivity, Vol. 16, No. 2, June 2006, pp. 1374-1377.

[6] V.S. Kashikhin, *et al.*, "Superconducting Splittable Quadrupole Magnet for Linear accelerators," *IEEE Transactions on Applied Superconductivity*, vol. 22, Issue 3, Part 2, 2012, Article#: 4002904.

[7] N. Andreev, *et al.*, "Conduction Cooling Test of a Splittable Quadrupole for ILC Cryomodules," *IEEE Transactions on Applied Superconductivity*, vol. 23, Issue 3, Part 2, 2013, Article#: 3500305.

[8] N. Kimura, et al, "Cryogenic Performance of a Conduction Cooling Splittable Quadrupole Magnet for ILC Cryomodules," submitted to the 2013 CEC/ICMC conference.

[9] R. Carcagno, *et al.*, "Magnetic and Thermal Performance of a Conduction-Cooled Splittable Quadrupole," *IEEE Transactions on Applied Superconductivity*, vol. 24, Issue 3, 2014, Article#: 4001604.