Muon Collider 6D Cooling
Model Magnets

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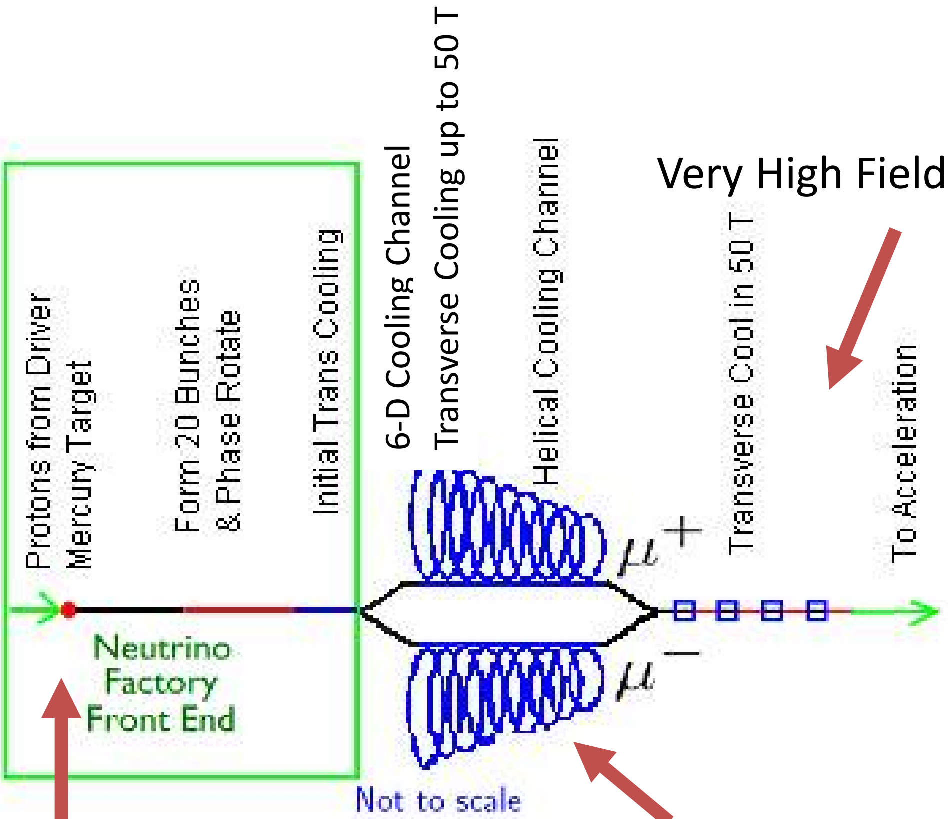
Interesting Magnets in Muon Colliders



Very High Field Solenoids

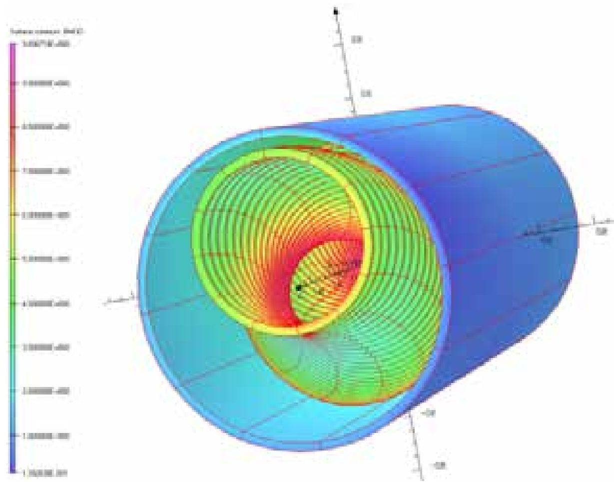
Colliding Ring/IR Magnets ~10 T, wide aperture/ open midplane

HCC solenoid rings up to 20 T (**one of many options-most challenging magnet-wise**)

Wide aperture 20 T solenoids

Helical Cooling Channel

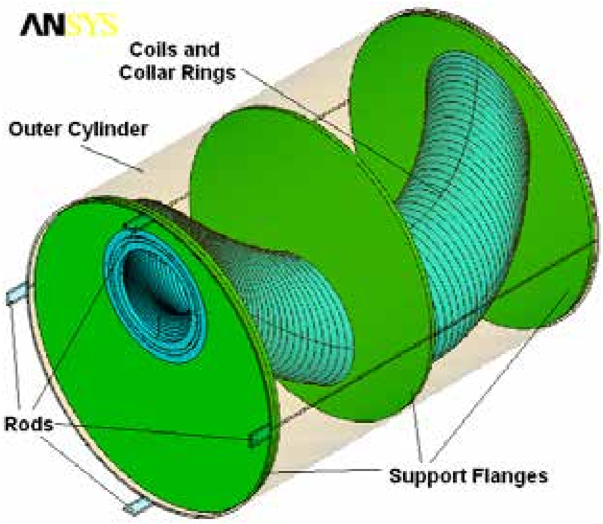
- The helical solenoid (HS) concept (FNAL/Muons Inc.) :
  - Coils follow the helical beam orbit generating solenoidal, helical dipole and helical quadrupole fields
  - Multi-section HCC
- Would require 160 meters of magnets
- Wide range of fields, helical periods, apertures
  - ➢ Room for RF system
- Field tuning is more complicated at high fields
  - ➢ NbTi, Nb3Sn/Nb3Al and HTS in final stage (progression of models)



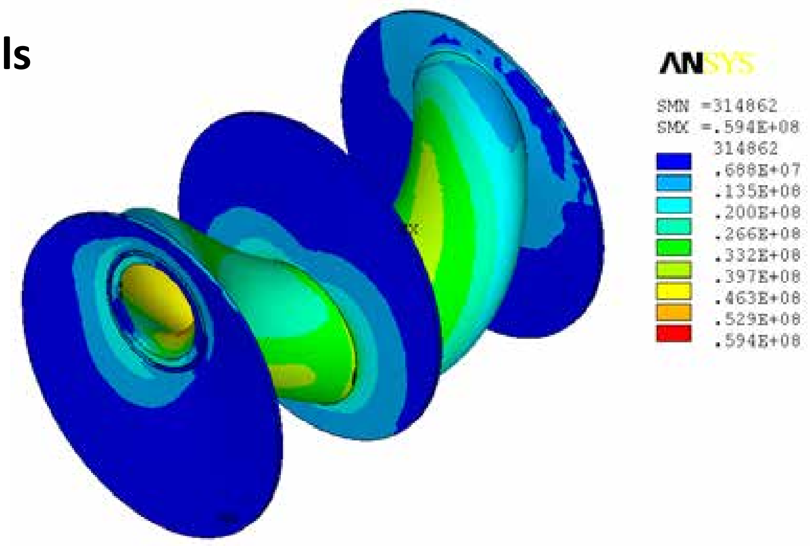
Early Specs, ca. 2006-K. Yonehara, S. Kahn, R. Johnson et al.

Parameter			Section			
			1st	2nd	3rd	4th
Total length		m	50	40	30	40
Period		mm	1000	800	600	400
Orbit radius		mm	159	127	95	64
Solenoidal field	B_z	T	-6.95	-8.69	-11.6	-17.3
Helical dipole	B_t	T	1.62	2.03	2.71	4.06
Helical gradient	G	T/m	-0.7	-1.1	-2	-4.5

HS Mechanical Concept
(FNAL)



Two short models built and tested successfully



- **Hoop Lorentz forces intercepted by stainless steel rings around the coils**
- **Transverse Lorentz forces intercepted by support flanges**
- **Outer LHe vessel shell provides mechanical rigidity to the structure**
- **The peak stress is ~60 MPa**

HSM01, HSM02

NbTi Model Magnet Design & Documentation

Design, Fabrication, Testing	Primary Responsibility
• Program Oversight	Mike Lamm Sasha Zlobin, John Tompkins
• Magnetic Design	Vladimir Kashikhin
• Mechanical Design & Fabrication	Sasha Makarov Nikolai Andreev, Miao Yu
• Testing & Analysis	Mike Tartaglia Guram Chlachidze, MTF !

- **Documents**
  - Tiweb.fnal.gov — Magnet Description Documents
  - TD-09-011 — Test of Four Coil Helical Solenoid Magnet HSM01
  - PAC'09 — Four Coil Superconducting Helical Solenoid For MANX
  - TD-11-012 — HSM02 Magnet Fabrication and Test Summary
  - MT-22 — Model NbTi Helical Solenoid Fabrication and Test Results

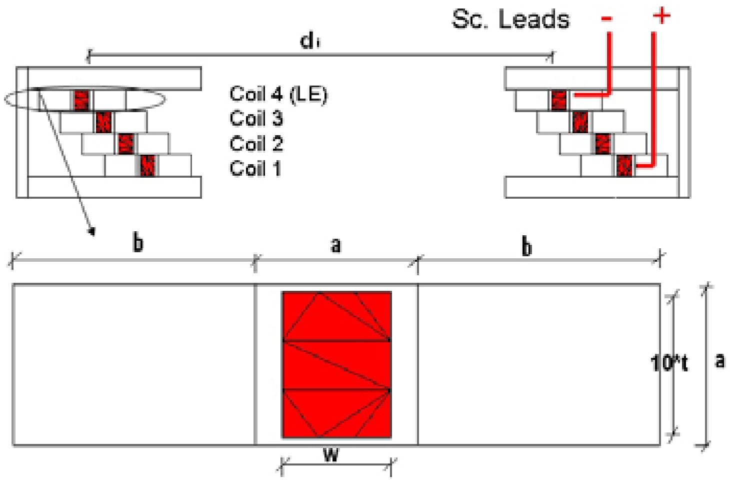
HSM01, HSM02

NbTi Model Magnet Design Features

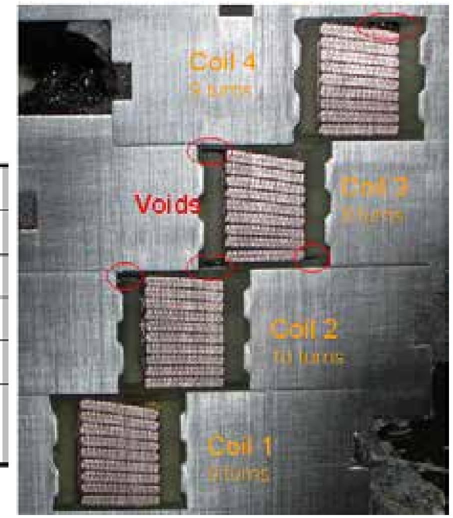
- 4 coil prototype model magnets with large aperture
  - 1st Two models in planned series: Technology Demonstration
    - HSM02 same design with improvements based on HSM01 experience
  - Largest diameter that can be tested in VMTF R&D stand (OD ~ 25")
- "Hard Way Bend" winding of NbTi cable (LHC quad – not optimized)
  - Smooth transition without splices between 4 offset coils
  - "keystoned" cable hard to wind with high packing factor
    - HSM02 cable flattened, improved winding
  - Embedded quench protection strip heaters
- Epoxy-impregnated coil package
  - Stainless steel rings control hoop Lorentz stresses
    - Sharp edges require care with insulation scheme
  - but provide no pre-stress on coils to constrain conductor motion
    - Next step in the progression will use Aluminum outer rings
- No Iron Flux Return
  - Large stray field, forces on SC leads
    - SC Lead motion in HSM01 led to some quenches, ground fault

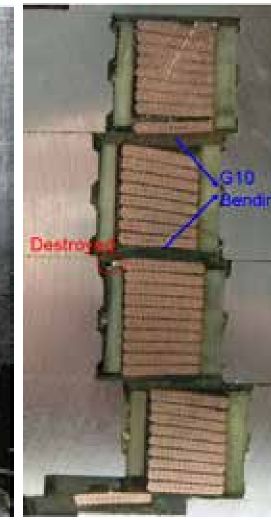
HSM01, HSM02

NbTi Model Magnet Design

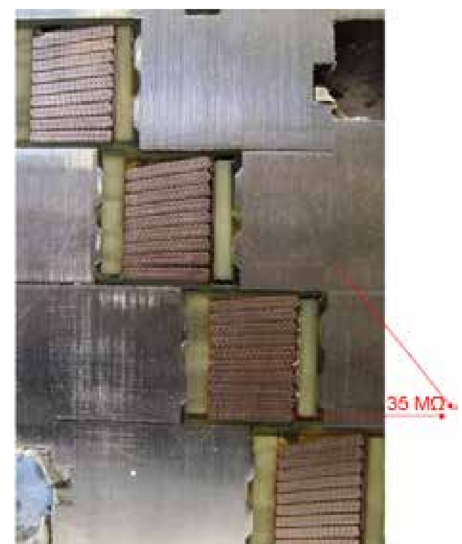


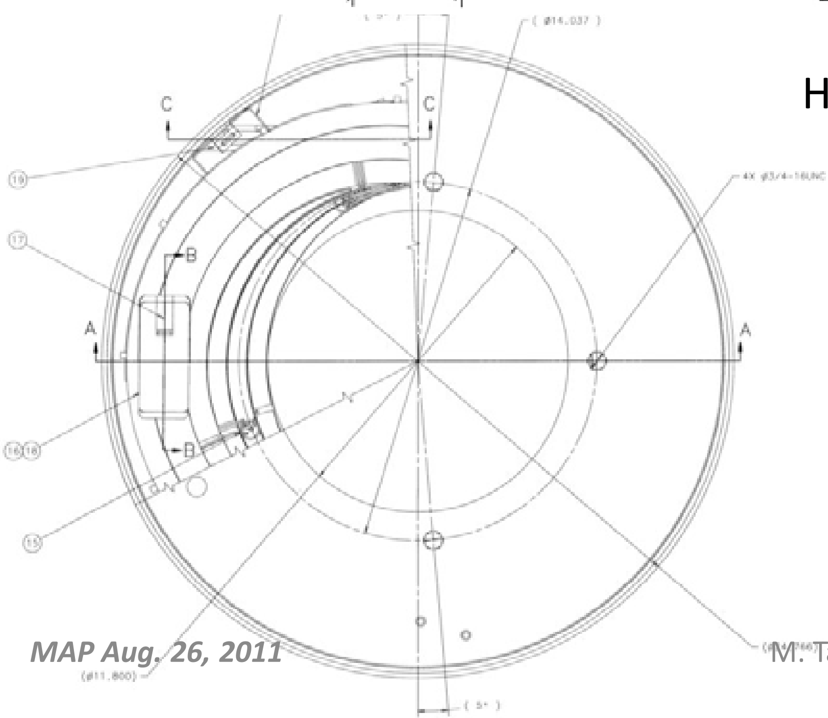
dᵢ (mm)	426.5
w (mm)	13.5
t (mm)	1.8
a (mm)	20
b (mm)	30
No. turns (turns/coil)	9 or 10

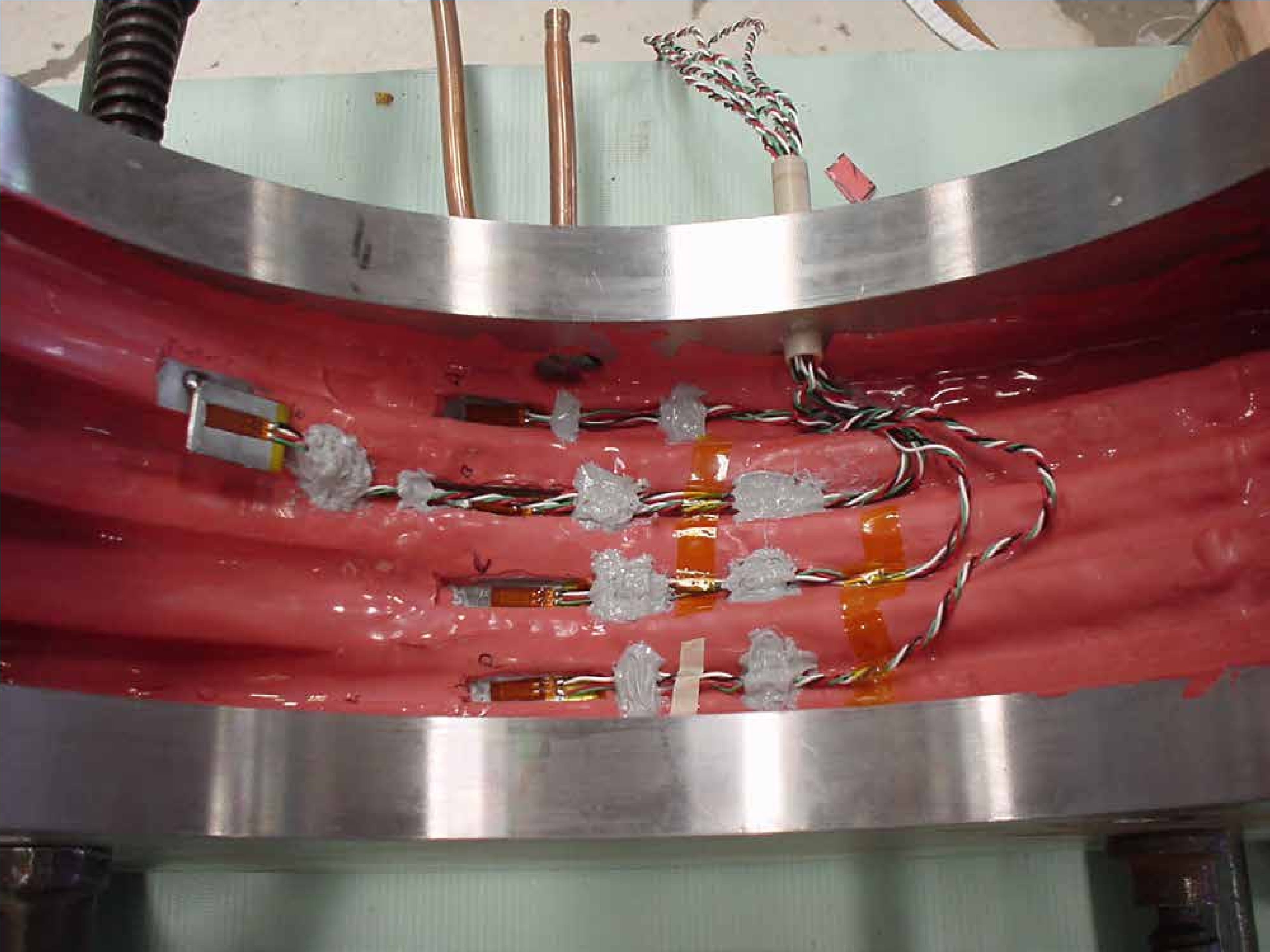




HSM01 Dissection After Testing

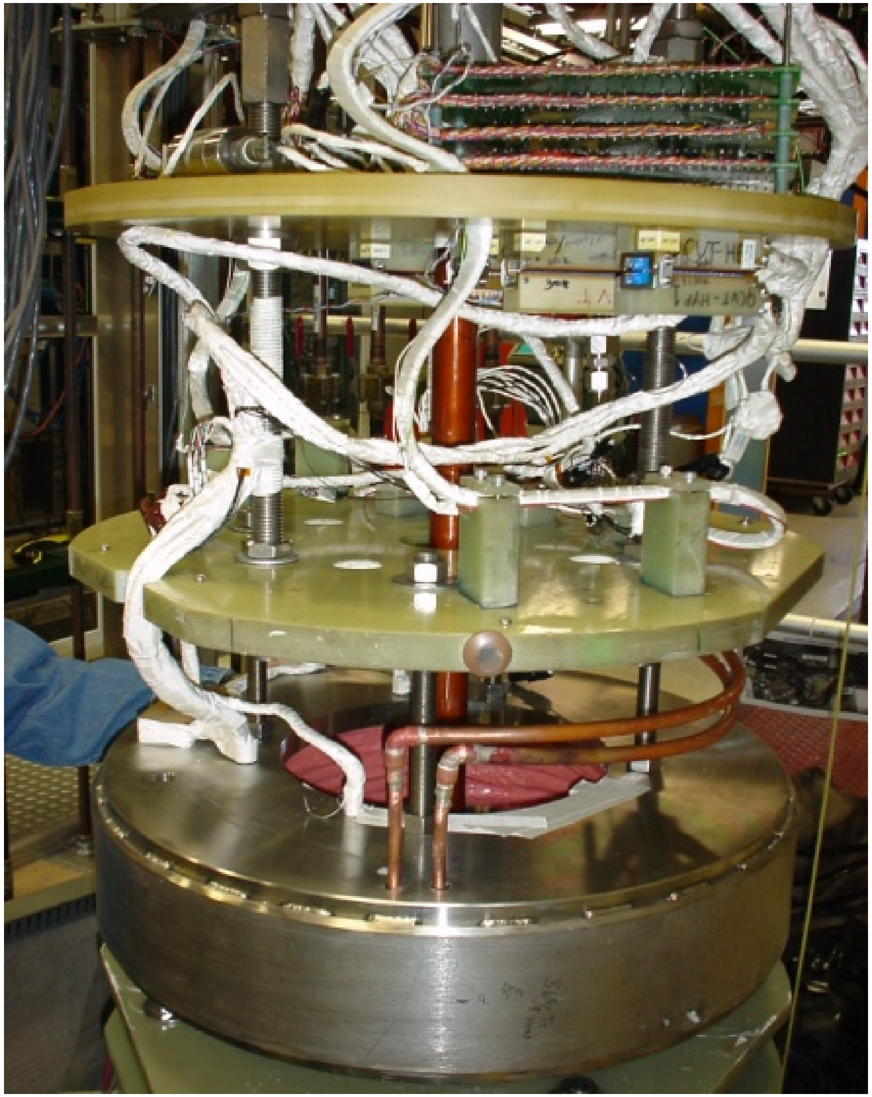






HSM01, HSM02

NbTi Model Magnet Tests



- **Main Test Goals:**
  - ✓ **Measure Mech. Stresses**
  - ✓ **Quench Performance**
    - **vs Temperature**
    - **vs Ramp Rate**
  - ✓ **Protection Heater Effic.**
  - ✓ **Magnetic Field Map**
- **HSM01 tested in Nov/Dec 2008**
  TD-09-011, PAC'09
  - **Ground Insulation issues**
  - **Epoxy voids, packing factor**
  - **SC lead support**
  - **Coordinate System**
- **HSM02 tested in Nov/Dec 2010**
  TD-11-012, MT-22
  - **2 thermal cycles (quench re-training)**
  - **LN_2 Conduction cooling study**

HSM01, HSM02

NbTi Model Mechanical Stress

- **Detailed HSM01 mechanical stress analysis made in TD-09-011**
  - **FEM analysis of Cool down (.2-.3%); Lorentz Force <.007%) stresses**
  - **Transverse (radial), Azimuthal, Longitudinal , compensating (T,B) gauges on coils**
    - **Predicted Max On Coils: 13 MPa (T), 10.5 MPa (A), 34.5 MPa (L)**
    - **Predicted Max On Links: 116 (T), 101 (A) , 306 (L)**
    - **"Acceptable" for 304 S.S., "designed far beyond required even for Nb3Sn"**
  - **Hard to measure with any confidence**
    - **Imperfect compensation, gauge calibrations? Debonding from surface**
    - **measured stresses were < or ~ consistent with calculated**
- **HSM02 has same mechanics**
  - **Instrumented with fewer gauges (4 Azimuthal + 1 comp.)**
  - **Cool down stress analysis not completed –**
    - **inconsistent gauge data (warm/cold) suggests debonding**
    - **Lorentz force stresses were <~0.008%**

HSM01, HSM02 Test Results

Quench Studies

❖ **Quench Protection**

❖ **MIITS calculation (local heat balance), Peak Temperature Rise**

- **LHC Outer cable (30 0.8mm strand NbTi) max. 11 MIITS; data ~3-4**
- **Conductor RRR – Copper stabilizer resistance (higher RRR is better)**
- **HSM01 ~140-155 (same as LQXB) HSM02 ~102 (rather low; why?)**

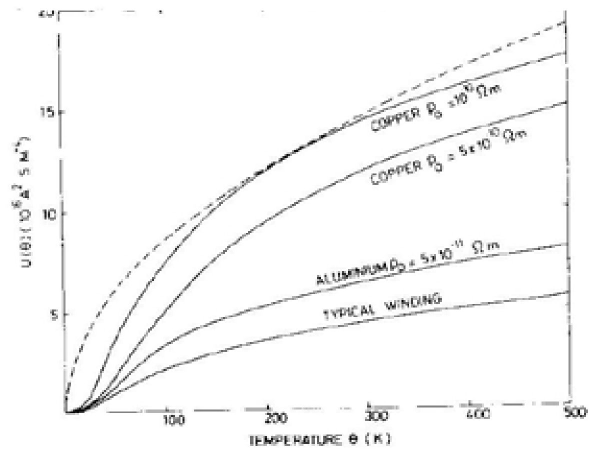
❖ **Magnet Description Document**

- **Low Inductance ~200 μΩ, E_{stored}(16kA)~26 kJ**
- **Dump Resistor energy extraction**
  - **(t~L/$R_{bus+mag}$, Vmax=IR_{dump})**
- **R_d HSM01 = 10 mΩ, HSM02 = 60 mΩ**

❖ **Protection Strip Heaters**

- **Study of inducing quenches (for long magnets)**

$$\int_0^\infty J^2(T)\,dT = J_0^2 T_d = \int_{\theta_0}^{\theta_m} \frac{\gamma C(\theta)}{\rho(\theta)}\,d\theta = U(\theta_m).$$



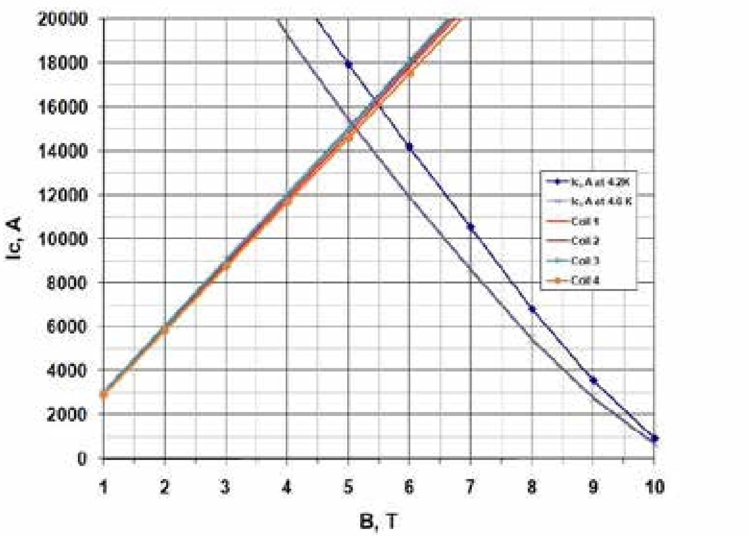
HSM01, HSM02 Test Results

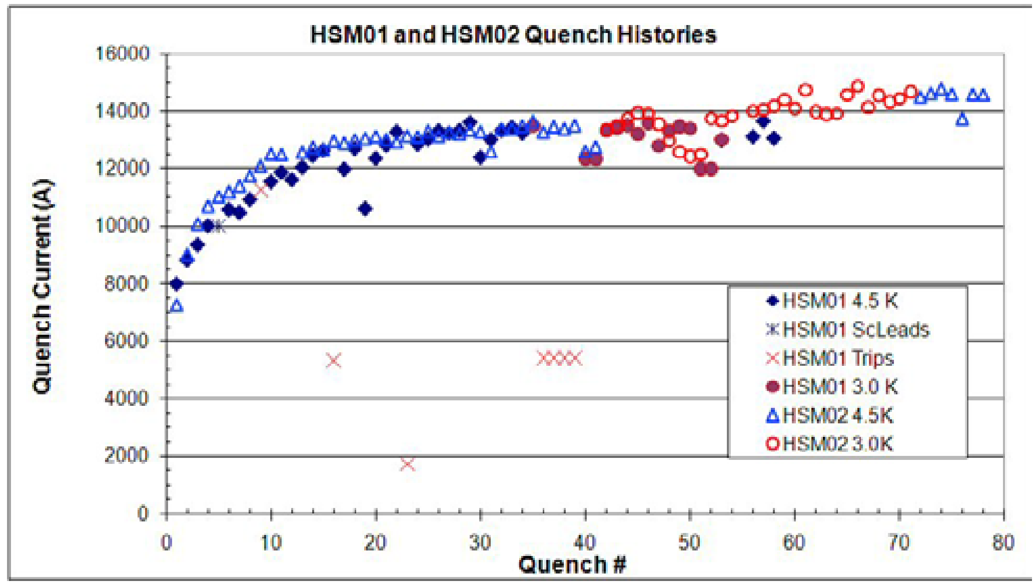
Quench Performance

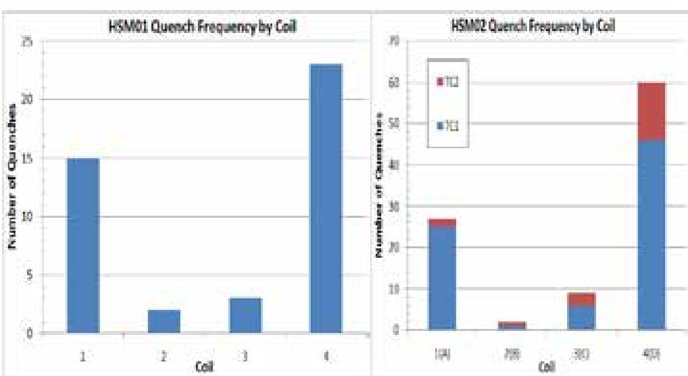
❖ **Quench Prediction: at 4.5 K, HSM01~16 kA, HSM02 ~ 15 kA**

Magnet Load Line crosses Conductor Critical Current (vs T)

Peak field is slightly higher on end coils







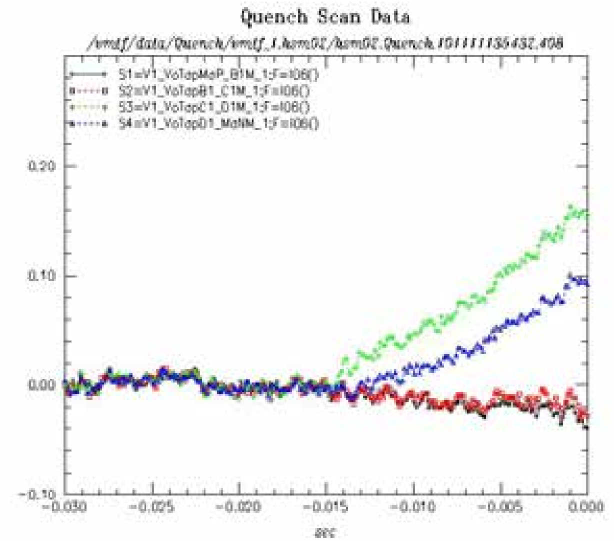
- **Somewhat slow quench training to plateau**
- **HSM01 (HSM02) reached 85% (100%) of I_c**
- **Very similar training curves - slightly erratic (char. of epoxy-impregnated coils)**
- **Little temperature dependence of training rate (higher Ic, mechanical limitations)**
- **Quenches mostly in end coils for both**

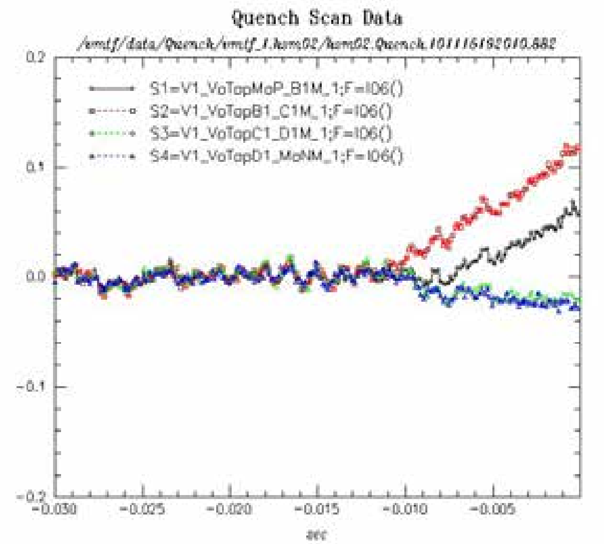
HSM01, HSM02 Test Results

Quench Performance

❖ **Quench Locations**

- **Generally only know which coil quenched (one voltage segment across each coil)**
  - **There has been no detailed analysis of quench velocity**
- **HSM02: Two quenches developed ~ simultaneously in adjacent coils presumably originating in transition region between coils**

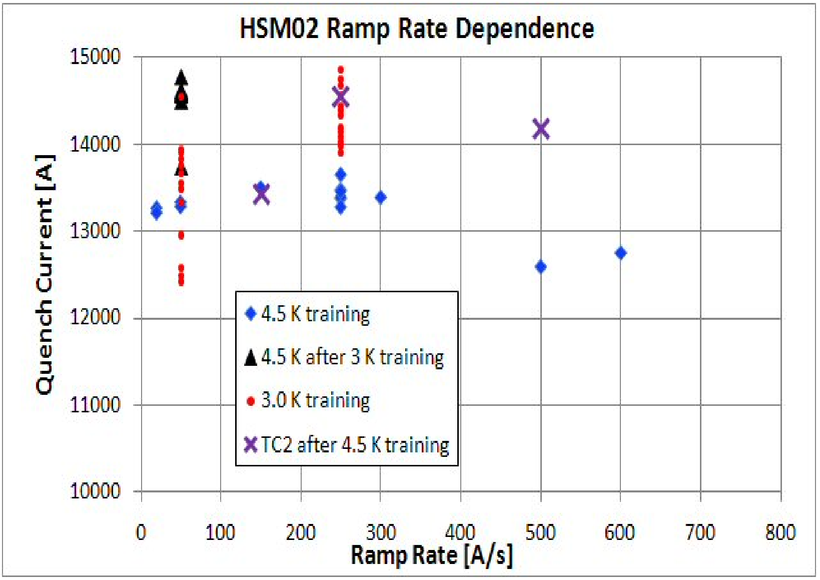


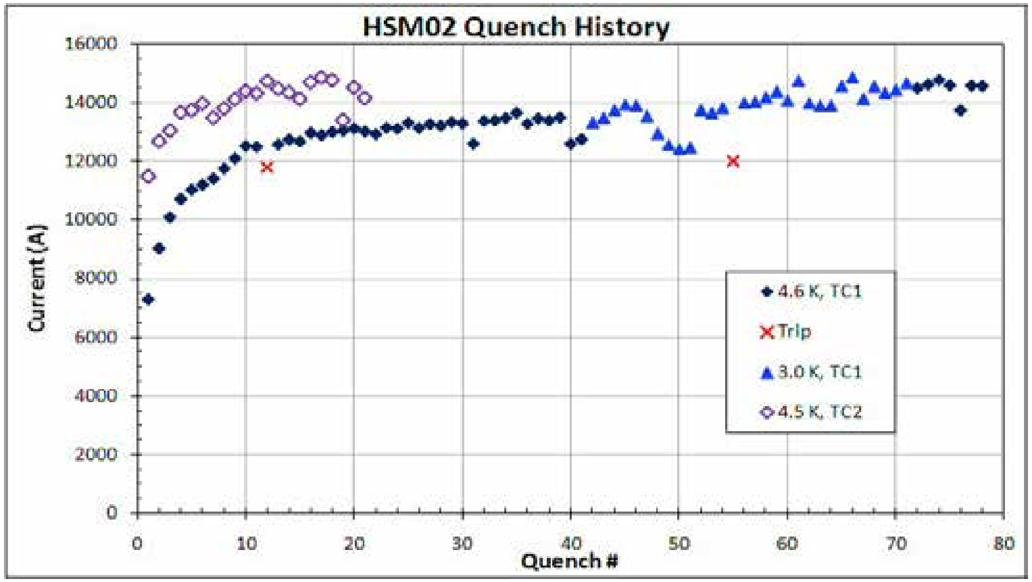


HSM01, HSM02 Test Results

Quench Performance

❖ **Quench Prediction: at 4.5 K, HSM01~16 kA, HSM02 ~ 15 kA**
- **Design would allow at least 15 % current operating margin**





- **Plateau is "remembered" at 4.5 K after reaching highest current at 3.0 K**
- **Fast Re-training of HSM02 after 300K T-cycle**
- **Virtually no ramp rate dependence (both magnets) to quite high ramp rates (600 A/s) …** as expected

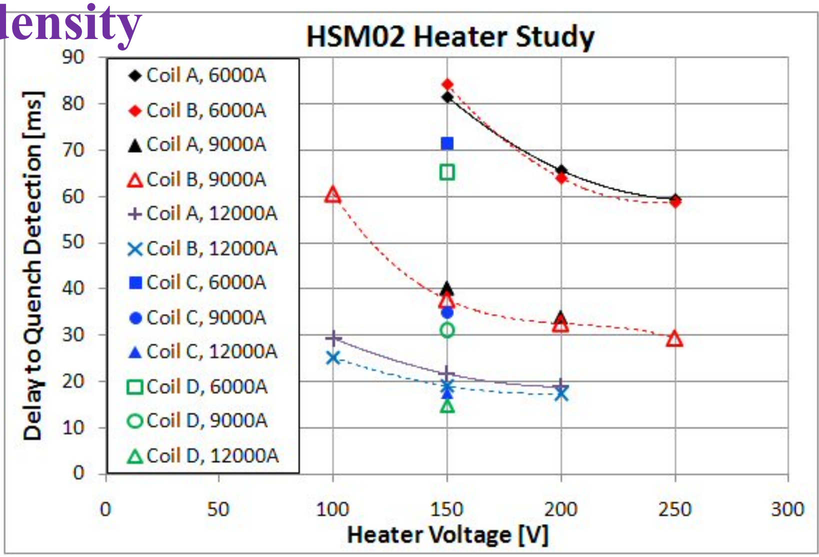
Quenches 46-51 Dip at 3K: Allowed 30 minutes recovery between quenches
Quench 52: waited 1 hour

HSM01, HSM02 Test Results

Quench Heater Performance

❖ **Quench Protection Heaters**

- **HSM01 had S.S. strip heaters on *Outer Layer* of each Coil**
  - **Three were full length, one 6-inch "spot" heater**
  - **Time did not allow exploration of heater parameters**
    - **only one quench induced, at low heater voltage**
- **HSM02 S.S. strip heaters on mandrel prior to winding of each Coil**
  - **All in parallel, with 4W external resistor ; fixed HFU capacitance (to increase range of parameters given heater voltage limits)**
  - **Mapped out Time (heater fired to quench detected) vs {I, Vhfu}**
  - **Still needed: calculate heater power density**

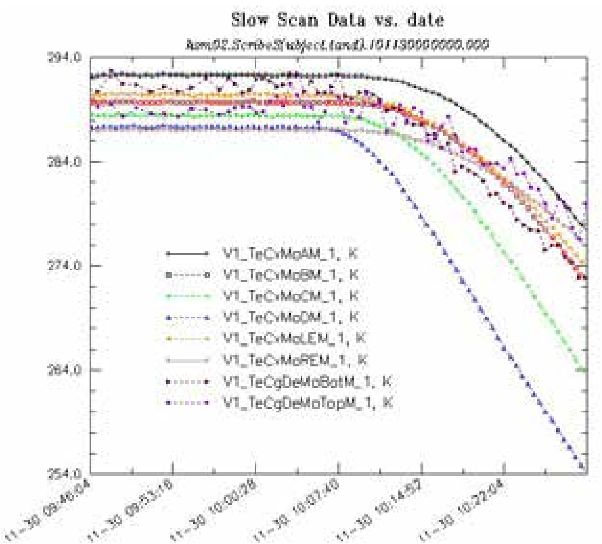


HSM01, HSM02 Test Results

Quench Heater Performance

❖ **Conduction Cooling Study**

- **We do not have the facilities to test indirectly cooled magnets**
  - **Need vacuum vessel for insulation**
    - **VMTF is not a good vac. Vessel**
  - **No helium supply to cooling tubes**
  - **Helium vapor-cooled leads for power testing**



- **We tried a simple thermal test**
  - **Pump out VMTF helium space; we achieved <0.1 Torr**
  - **Connect LN2 to cooling tubing**
  - **Measure T vs time on all four coils with 1 RTD/coil +top, bottom**
    - **Not so great: RTD calibrations are sparse at high T (300, 80K)**
    - **No one has had time to model expectations, compare with data**

HSM01, HSM02 Test Results

Quench Heater Performance

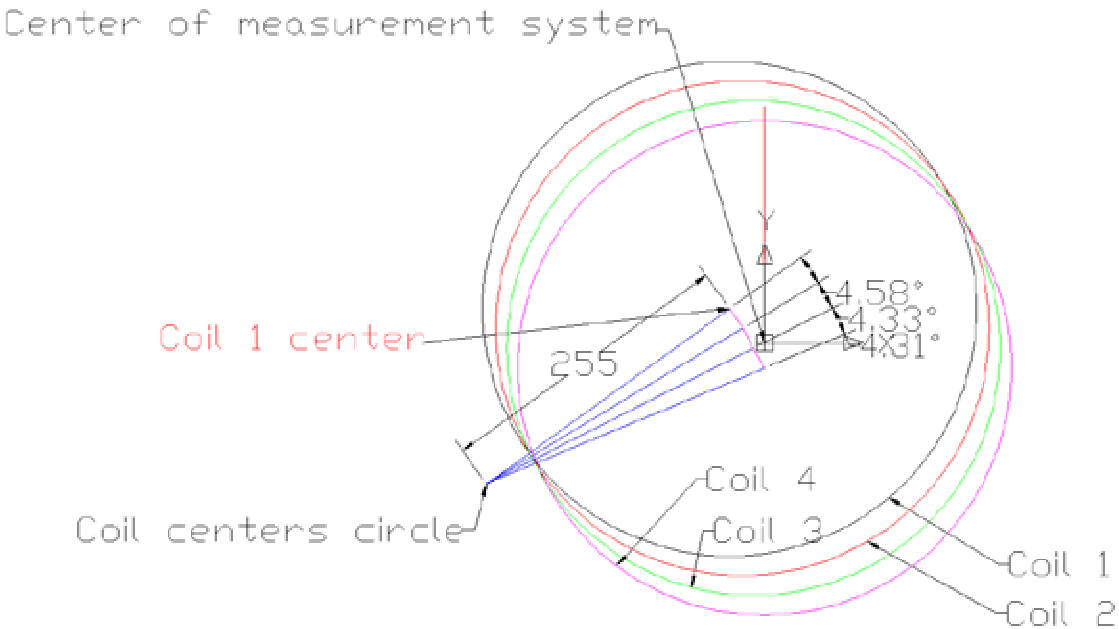
❖ **Conduction Cooling Study**

- **We learned one very important Lesson**
  - **Copper tubing wrapped around each coil**
  - **Makes a beautiful 10:1 transformer!**
  - **This is not the right way to design the cooling tube layout**

HSM01, HSM02 Test Results

Magnetic Field

❖ **Magnetic Field Maps: 3D Hall probe scans, vs 3D model prediction**



What are the tolerances
On "field quality"
On ring positions ?

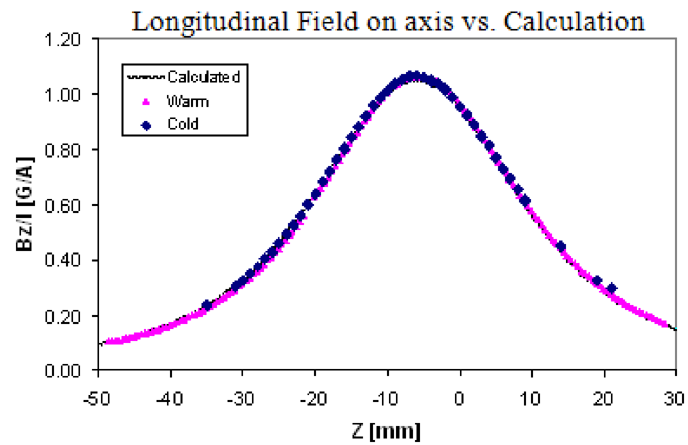
These will be measured
Carefully in HSM02
(better attention to
alignment/survey features,
Coordinate systems)

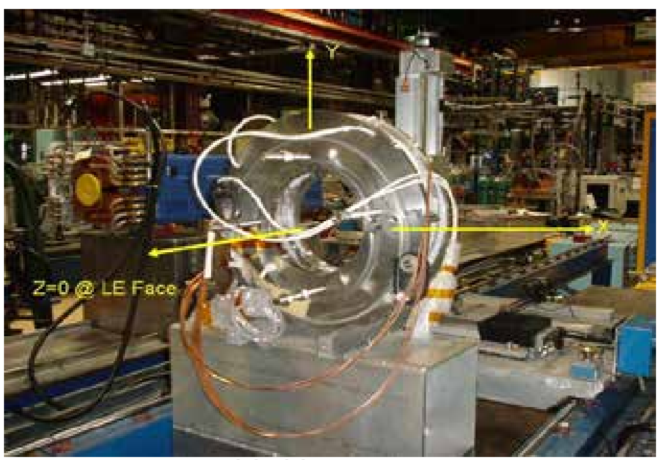
HSM01, HSM02 Test Results
Magnetic Field

❖ **Magnetic Field Maps: 3D Hall probe scans**
- **HSM01 ±10A at 300 K, 2 kA at 4.5 K (in 1.75" warm bore tube)**
- **HSM02 5 kA at 4.5 K (warm planned)**

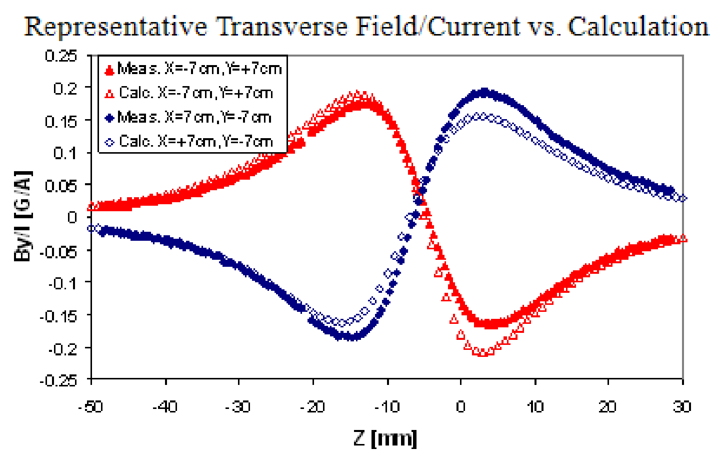
- **There is no central axis (offset rings)**
  - **Mechanical center is well defined**
  - **Fiducial marks allow probe positioning**
  - **Make comparison to 3D Model**

- **Cold measurements along a central line**
  no surprises – Bz/I agrees with warm
- **Warm measuments**
  - **central line along Z (solenoid dir.)**
  - **Along Z at {R=4cm, θ}**





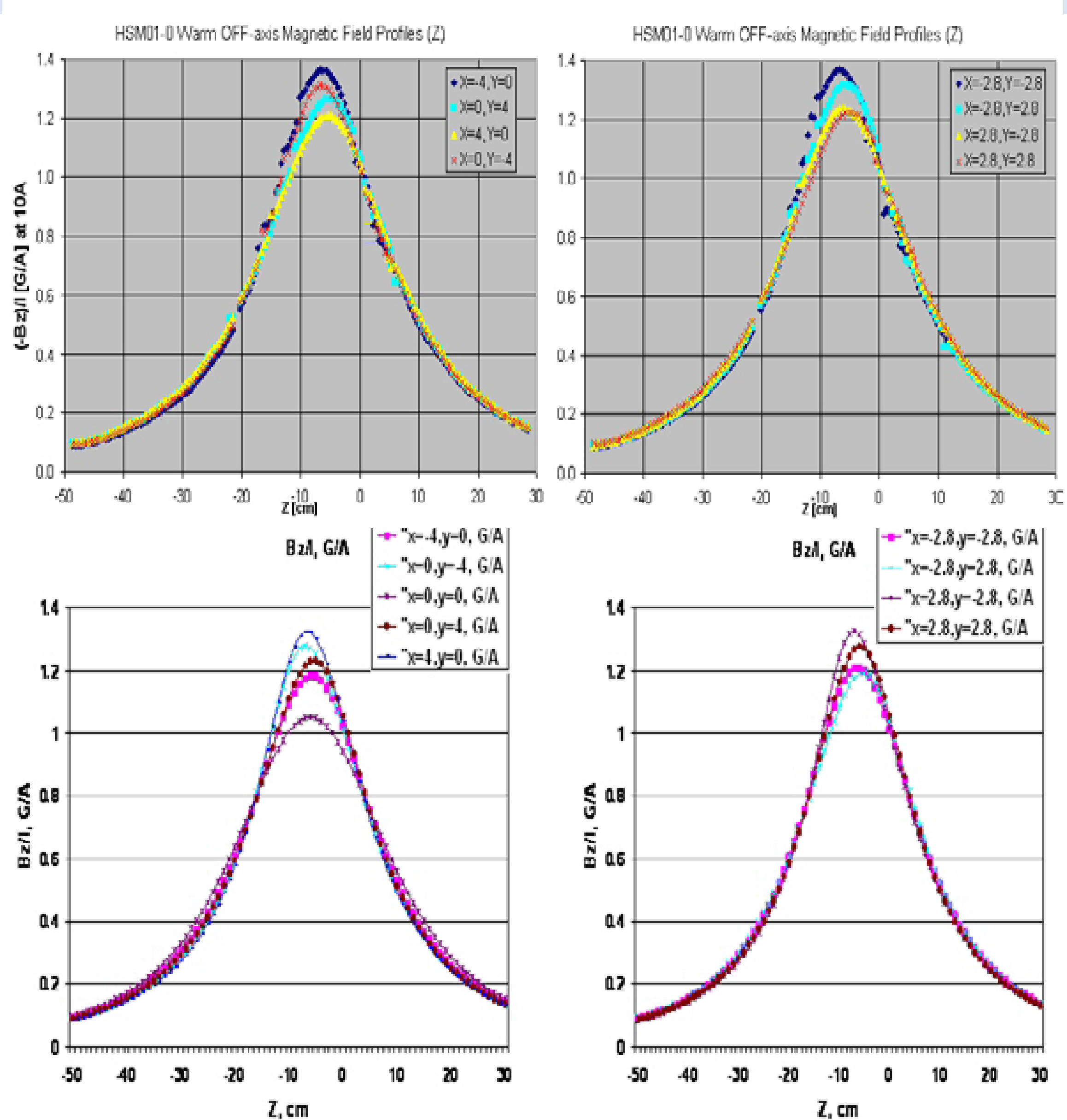
Off-axis:
Relating {magnet, probe, model} Coordinate Systems needs a bit more attention (done in HSM02)



HSM01, HSM02 Test Results

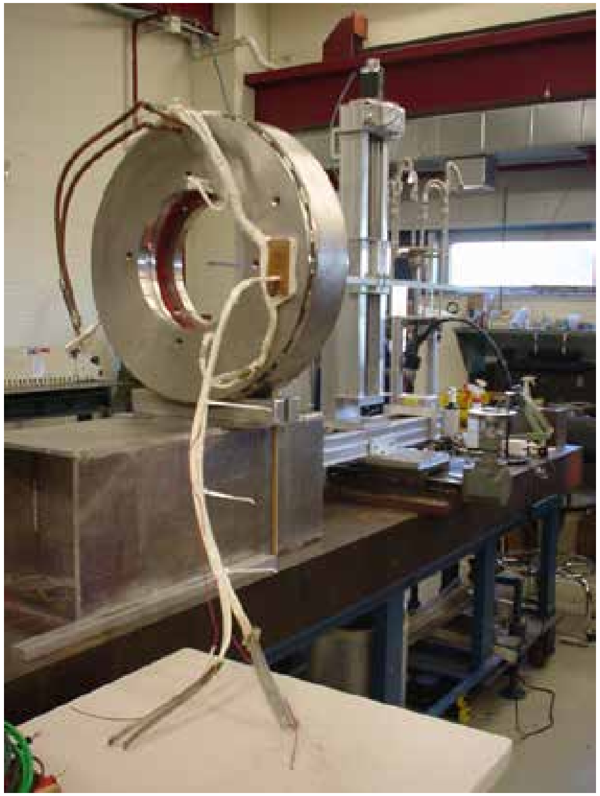
Magnetic Field

- **HSM01**



HSM01, HSM02 Test Results
Magnetic Field

❖ **HSM02: Still setting up to do warm measurements at ±10A**
- **Conventional Test Stand B tied up with Accelerator Support projects**
- **New system development, new 3D Senis Hall probe (vs 3 1D probes)**
- **Minor complication: steel table (mounted high on Al beam)**



HSM Next Steps

Other models in progress, planned

- **HSM03 – same design but with Aluminum rings for coil pre-stress**
- **HSM04 – Nb_3Sn design**
  - **Needed for inserts in higher field cooling regions**
  - **Very different technology (small part of larger High Field magnet program)**
- **Helical solenoids using HTS (BSSCO wire or YBCO tape) conductor**
  - **Also needed for inserts in higher field regions**
  - **New, very different technology –**
    - **collaboration with Muons, Inc. to design, build, test first model**
    - **First YBCO model has been built and tested –**
      - **results for another talk !**