Muon Collider 6D Cooling
Model Magnets

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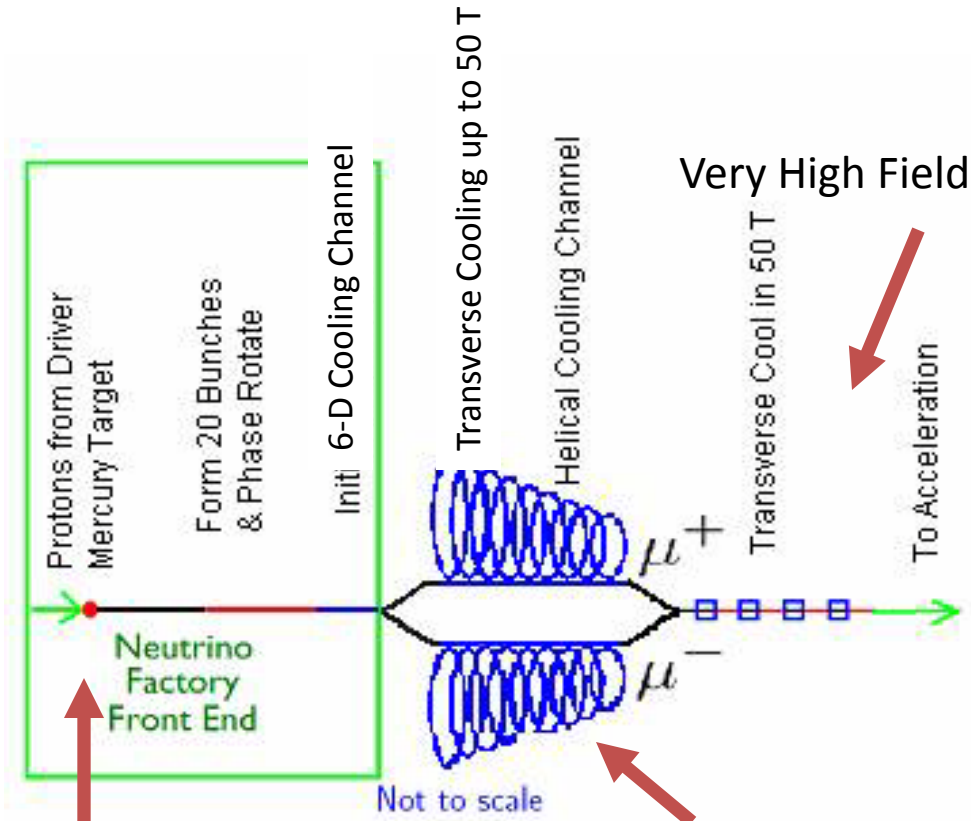
Fermilab

Interesting Magnets in Muon Colliders



Very High Field Solenoids

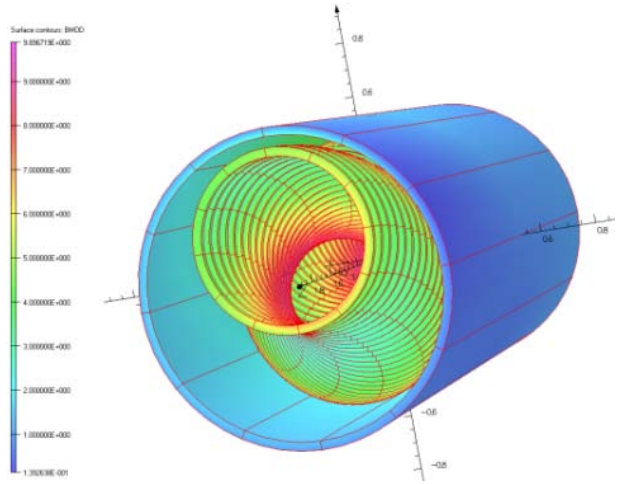
Colliding Ring/IR Magnets ~10 T, wide aperture/ open midplane

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

Wide aperture 20 T solenoids

Helical Cooling Channel

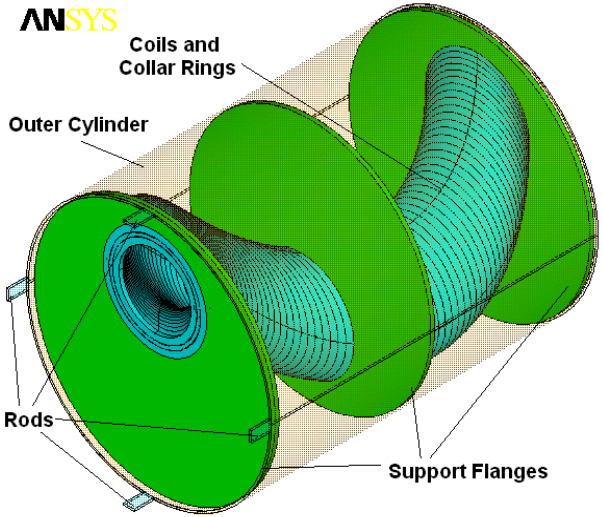
- **The helical solenoid (HS) concept (FNAL/Muons Inc.) :**
  - **Coils follow the helical beam orbit generating solenoidal, helical dipole and helical quadrupole fields**
  - **Multi-section HCC**
- **Would require 160 meters of magnets**
- **Wide range of fields, helical periods, apertures**
  - ➢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



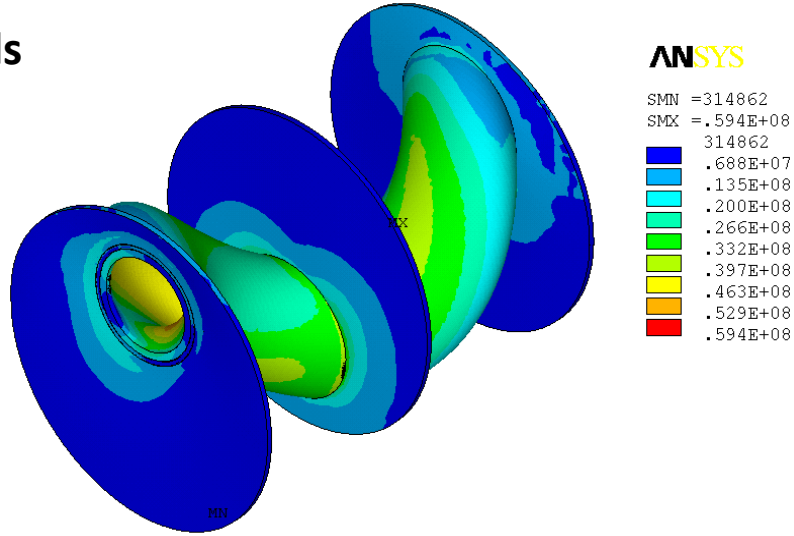
Early Specs, ca. 2006-K. Yonehara, S. Kahn, R. Johnson et al.

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**

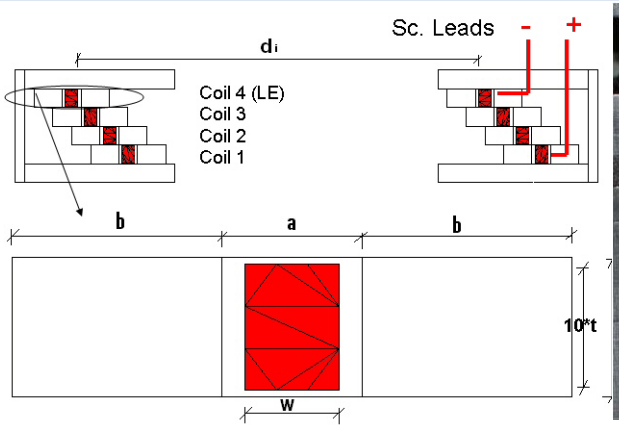
HSM01, HSM02

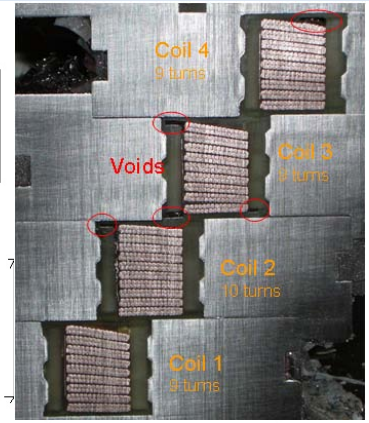
NbTi Model Magnet Design Features

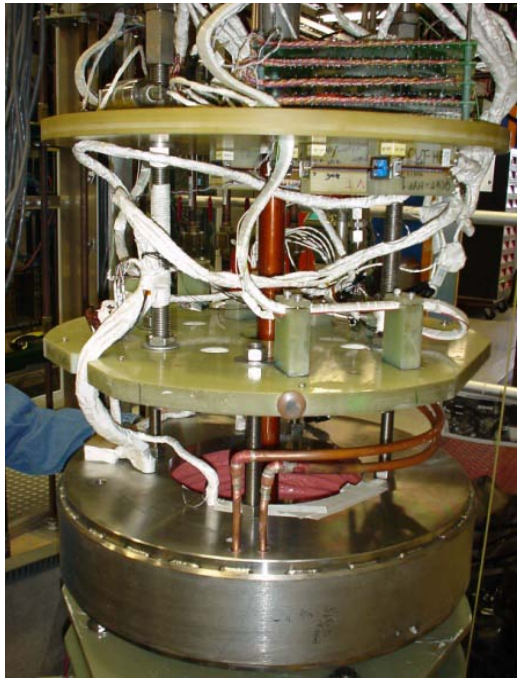
- 4 coil prototype model magnets with large aperture
  - 1st Two models in planned series: Technology Demonstration
    - HSM02 same design with improvements based on HSM01 experience
  - Largest diameter that can be tested in VMTF R&D stand
- "Hard Way Bend" winding of NbTi cable (SSC – not optimized)
  - 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-impregranted 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 conduction motion
    - Next step in the progression will use Al 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 Tests







- **Main Test Goals:**
  - ✓ **Quench Performance**
    - **vs Temperature**
    - **vs Ramp Rate**
  - ✓ **Protection Heater Effic.**
  - ✓ **Magnetic Field Map**
  - ✓ **Meas. Mech. Stresses**
- **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**
  - **2 thermal cycles (quench re-training)**
  - **LN_2 Conduction cooling study**

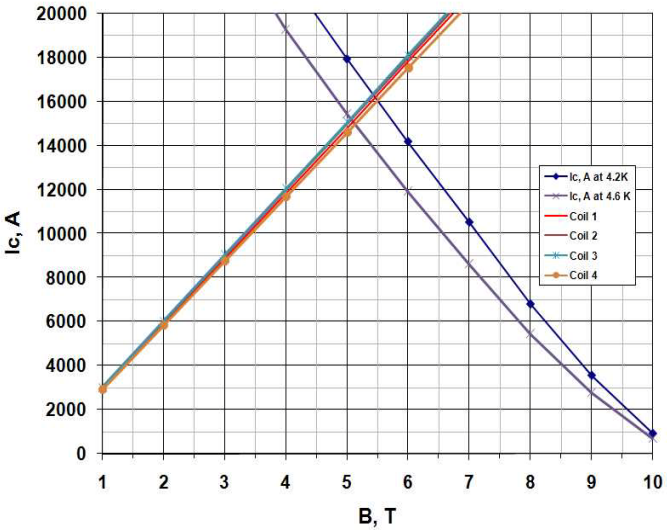
HSM01, HSM02 Test Results

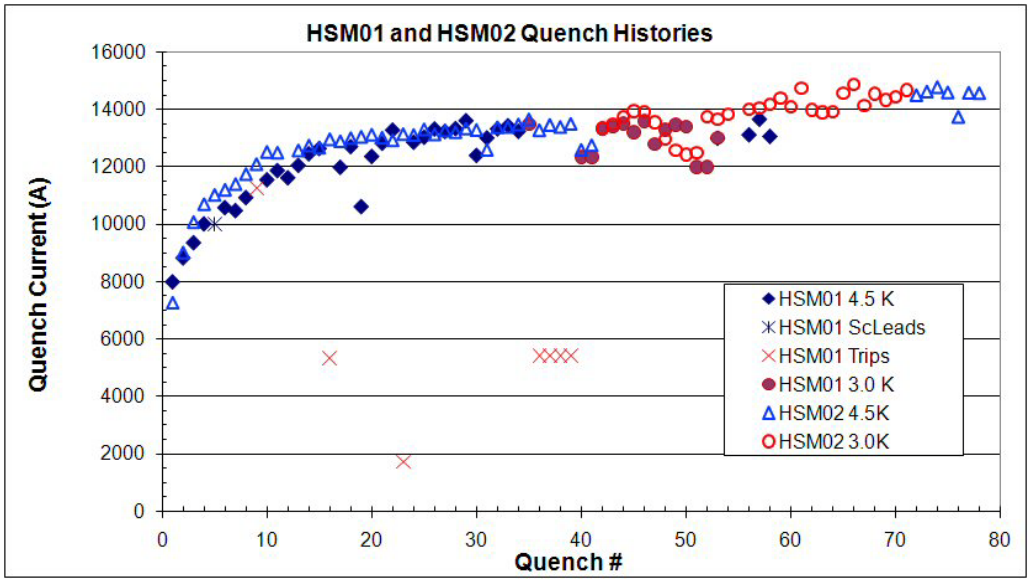
Quench Performance

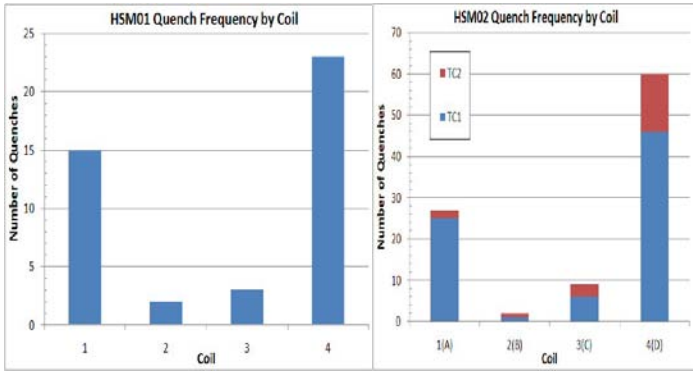
❖ **Quench Prediction: at 4.5 K, HSM01~16 kA, HSM02 ~ 15 kA**

Magnet Load Line crosses Conductor Critical Current (vs T)

Peak field is slightly higher on end coils





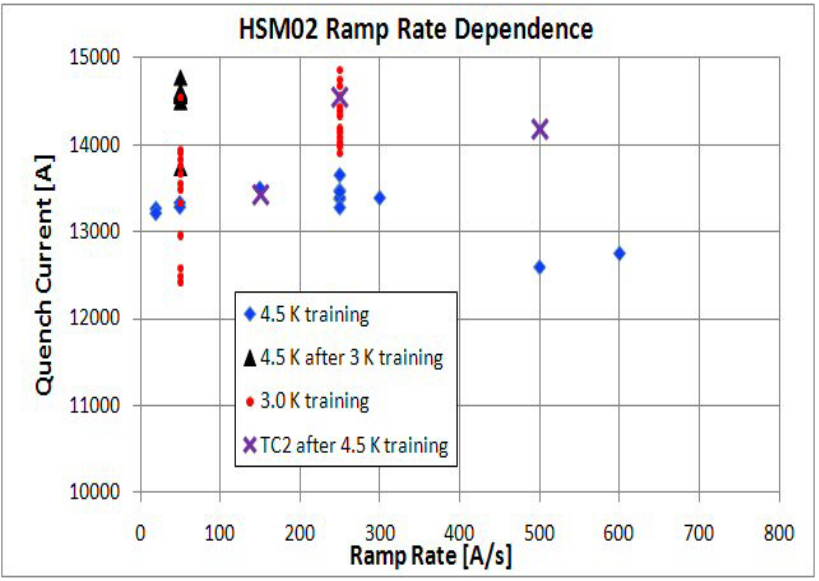


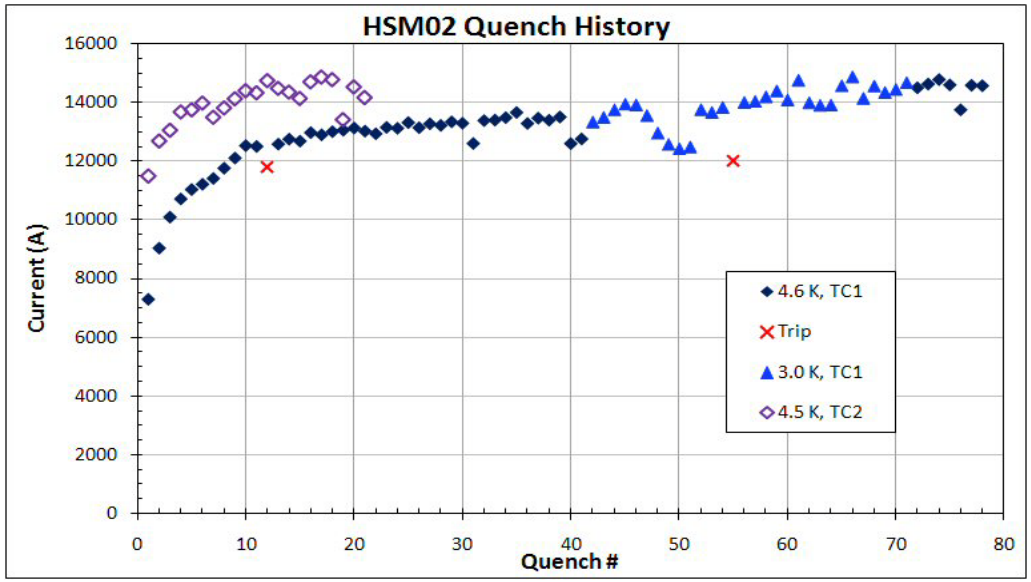
- **Somewhat slow quench training to plateau**
- **HSM01 (HSM02) reached 85% (100%) of Ic**
- **Very similar training curves - slightly erratic**
  (char. of epoxy-impregnated coils)
- **Little temperature dependence of training rate**
  (higher Ic, mechanical limitations)
- **Quenches mostly in end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

HSM01, HSM02 Test Results

Quench Performance

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





- **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

HSM01, HSM02 Test Results

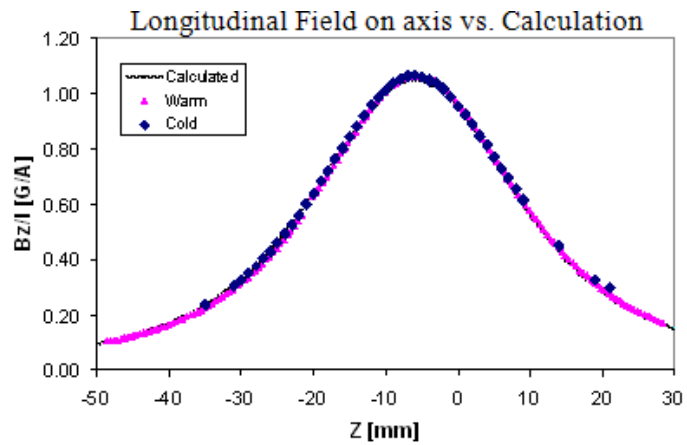
Quench Performance

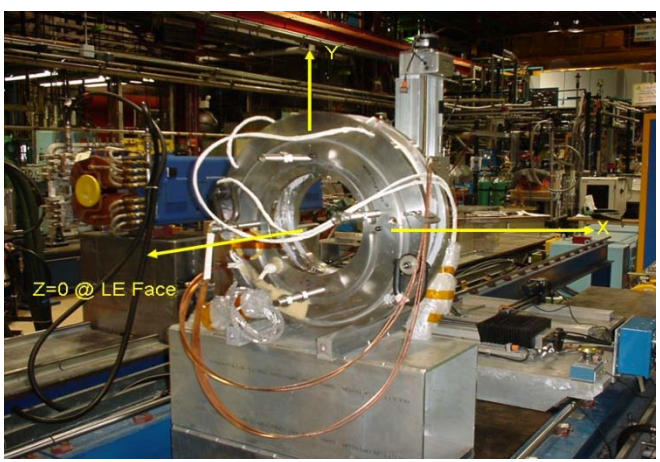
❖ **Magnetic Field Maps: 3D Hall probe scans**

- **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)**

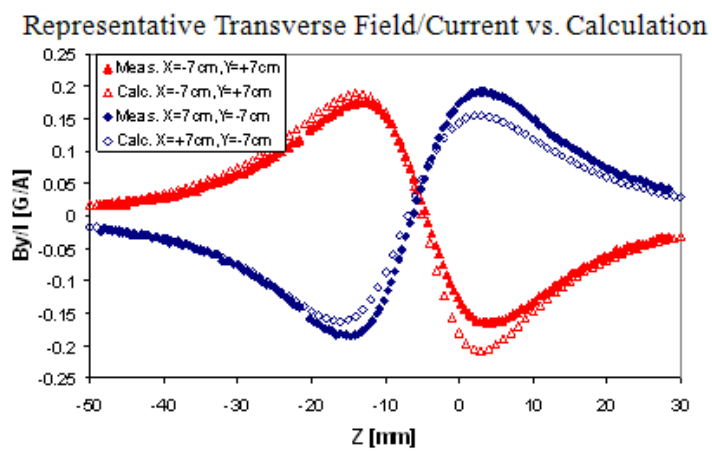
- **There is no central axis (offset rings)**
  - **Mechanical center is well defined**
  - **Fiducial marks allow probe positioning**
  - **Make comparison to 3D Model**

- **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}**

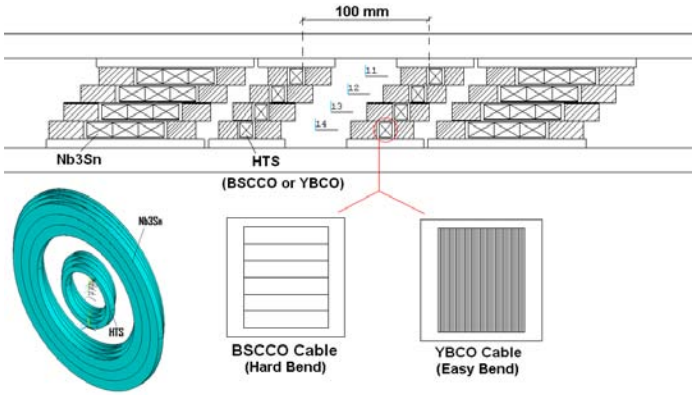
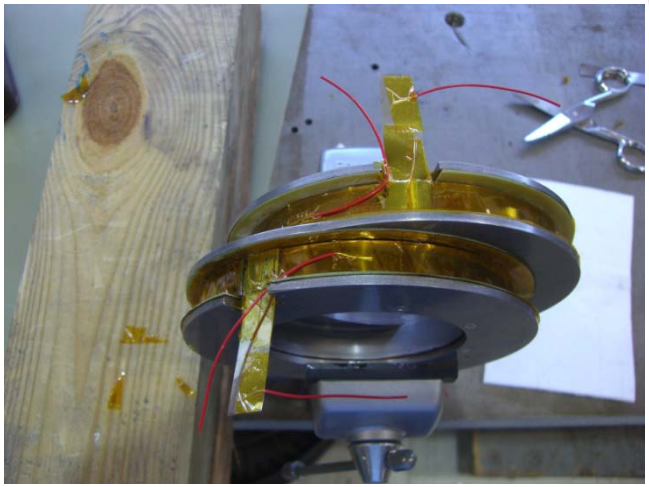
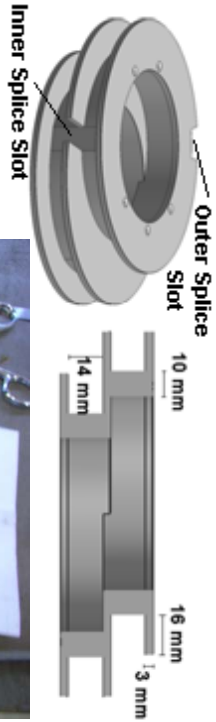




Off-axis:
Relating {magnet, probe, model} Coordinate Systems needs a bit more attention (done in HSM02)



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**
  - **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 !**