HCC Magnet Studies

Outline

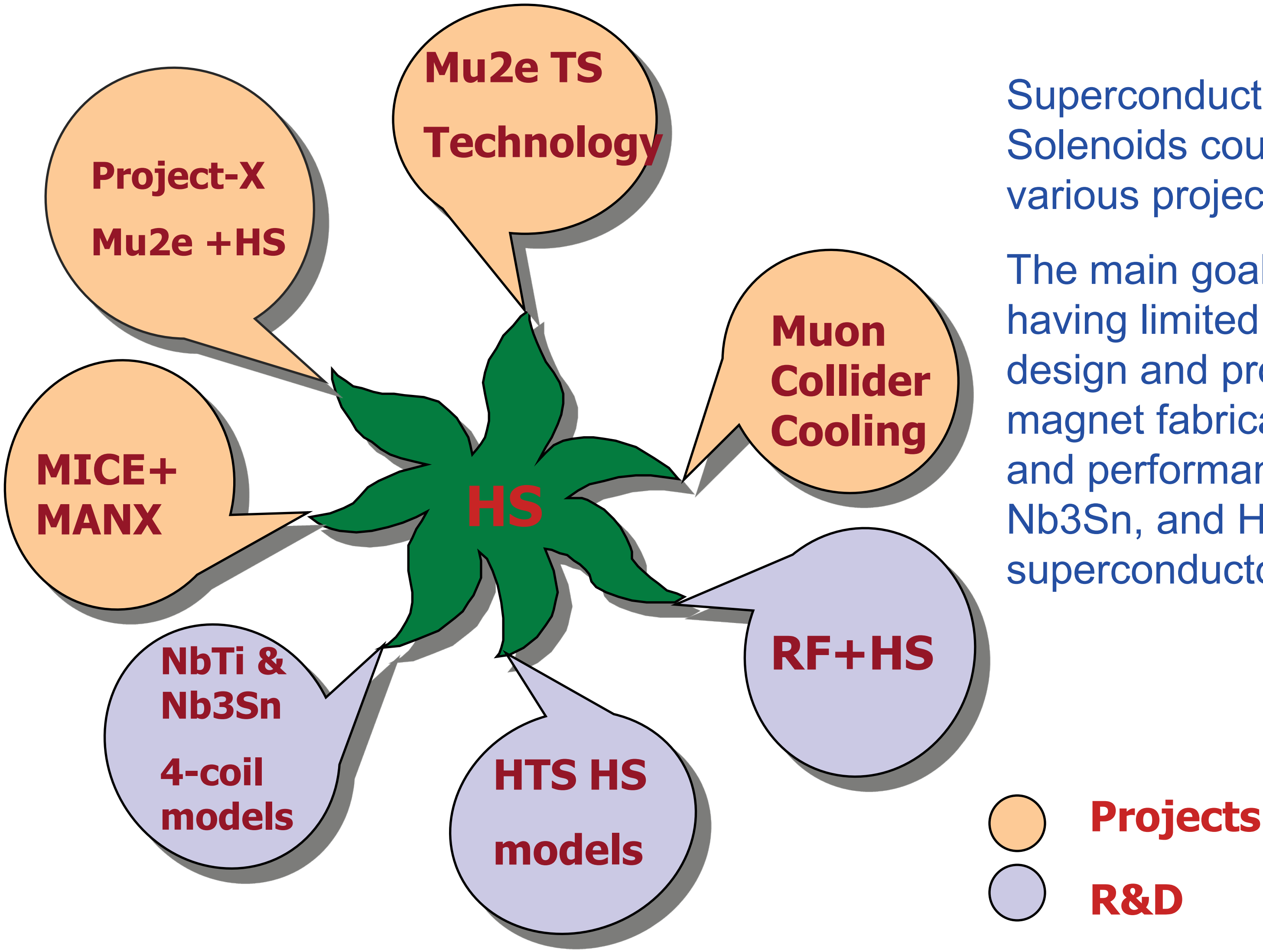
- Helical Cooling Channel
- Helical Solenoids and possible applications
- Helical Solenoids configurations, beam matching, magnetic, and mechanic designs
- High Field Helical Solenoids
- Helical Solenoid 4-Coil models and test results
- Summary

Helical Cooling Channel

- Helical Cooling Channel (HCC) is a Superconducting Helical Muon Beam Transport Solenoid (HS) integrated with RF acceleration system.
- The following steps should be performed during design studies and R&D before final systems integration and prototyping:

  - Define RF outer dimensions, space for power wave guides, external power losses and cryoloads, system weight, etc… ;
  - Define the High Pressure gas (absorber) vessel parameters;
  - HS magnetic and mechanical design;
  - HS manufacturing technology;
  - HS models tests;
  - HS unit design with space for RF system;
  - HS prototype unit fabrication and tests w/o RF;
  - HS fabrication and tests with RF.

Helical Solenoid Applications



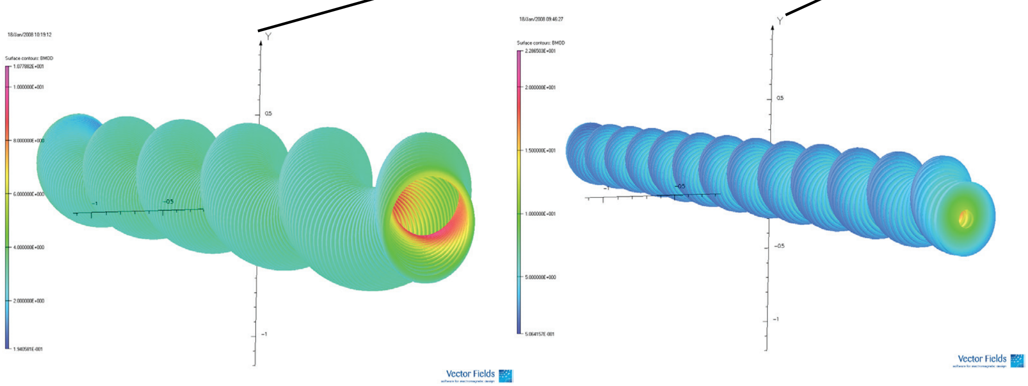
Superconducting Helical Solenoids could be used for various projects.

The main goal at that time, having limited resources, to design and proof the helical magnet fabrication technology and performance for NbTi, Nb3Sn, and HTS superconductors.

HCC Magnet System Studies (EPAC08)

Specs in 2006

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



- The helical solenoid concept .
- Coils follow the helical beam orbit generating solenoidal, helical dipole and helical quadrupole fields
- Multisection HCC
  - 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
  - Straight solenoid concept does not work for high-field/small-aperture sections

Helical Solenoid Configurations (EPAC08)

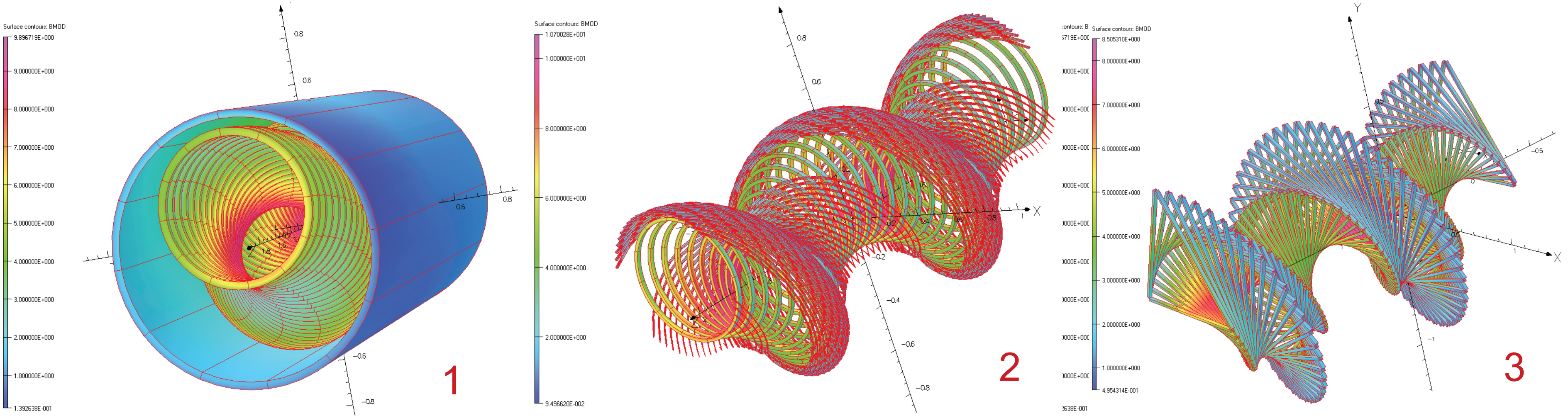
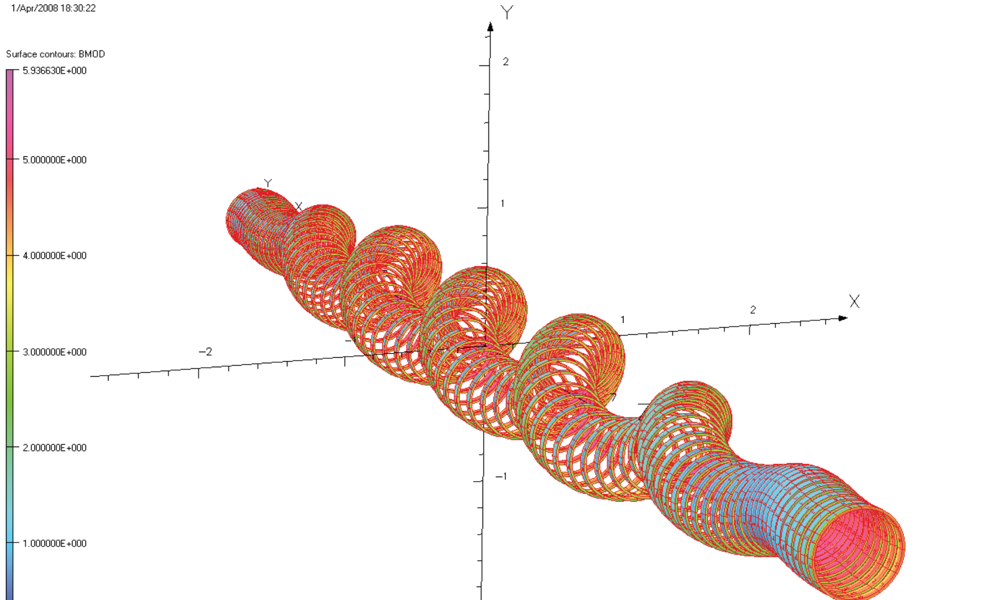


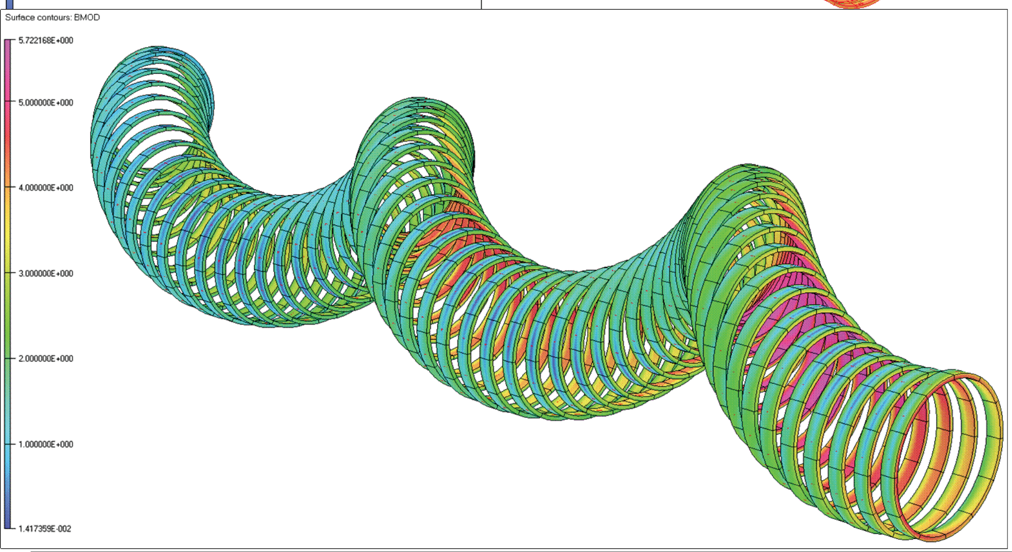
Table 1: Helical Solenoid Parameters

Parameter	Units	Value
Coil inner diameter	mm	550
Helical reference beam orbit radius	mm	159.2
Helix period	m	1.0
Transverse field Bt on the reference orbit	T	1.64
Bz - field on the reference orbit	T	-5.35
Gradient dBz/dr on the reference orbit	T/m	9.4
Bzo – field in the magnet system center	T	-6.99
Bz = Bz/Bzo – on the reference orbit		0.765
Bt/Bz – on the beam reference orbit		0.307

- Helical Solenoids capable to generate fields required for the optimal muon cooling even at different helix periods.
- Large bore straight solenoids (1), helical multipole windings (2) or trapezoidal coils (3) could be used for eliminating of the misbalance between transverse and longitudinal fields.
- Demonstration models could use helical multipole windings for greater flexibility. The final design will be more efficient with non-circular shape coils.

HS and Beam Matching (EPAC08)

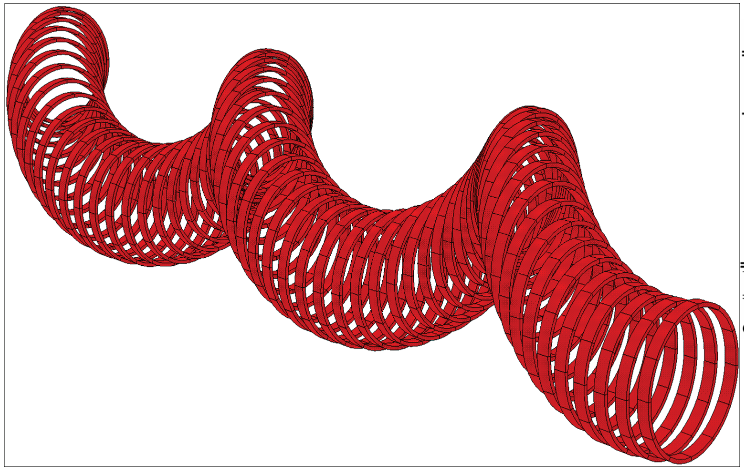




- HS with helical matching sections of 3 m long at front and far ends.

- HS design could be used in combination with tangential muon beam injection to the helical orbit. This magnet system will be cheaper for short HS channels.

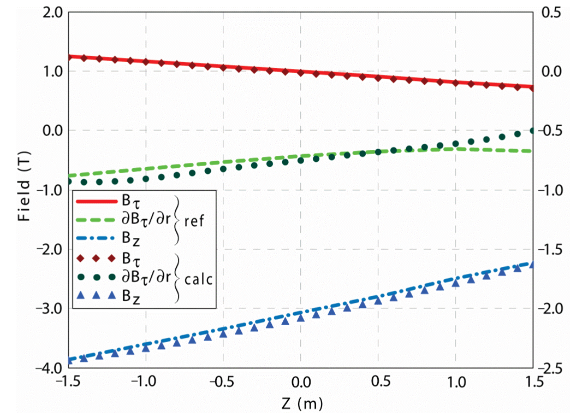
HS Magnetic Concept for MANX (PAC07)

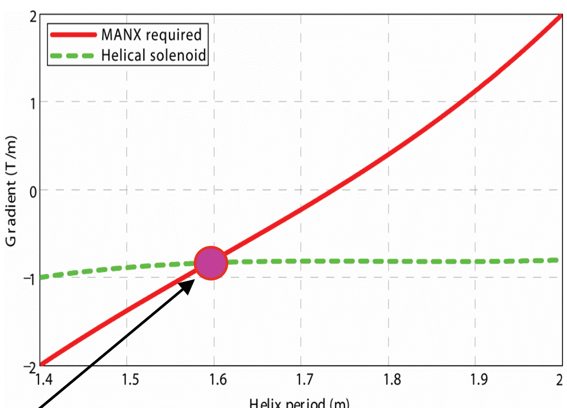


Parameters of Small Bore Cooling Channel

Parameter	Unit	Value
Inner radius	m	0.28
Radial thickness	mm	15.00
Operating current density†	A/mm^2	346.4
Operating peak field	T	5.72
Quench peak field‡ at 4.2 K	T	7.38
Operating stored energy	MJ	4.42

†Calculated as the total current over the total conductor cross-section.
‡Calculated assuming that the non-Cu fraction of superconductor spans 30% of the total conductor area.





One could see that the optimum gradient for the helical solenoid is -0.8 T/m, corresponding to a period of 1.6 m.

- The solenoid consists of a number of ring coils shifted in the transverse plane such that the coil centers follow the helical beam orbit.
- HS with RF has the same curent in each coil.
- The current in the coils could be chaned along the HS to obtain the longitudinal field gradients.
- The magnet system has a fixed relation between all components for a given set of geometrical constraints.
- Thus, to obtain the necessary cooling effect, the coil should be optimized together with the beam parameters.

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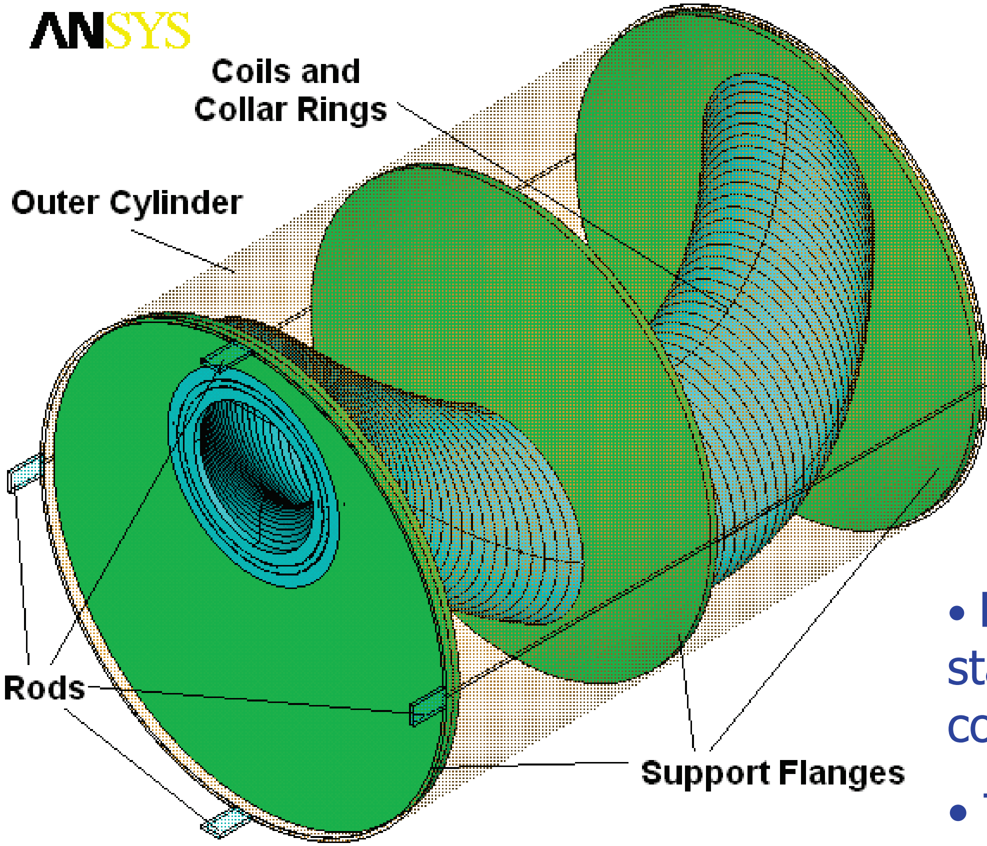
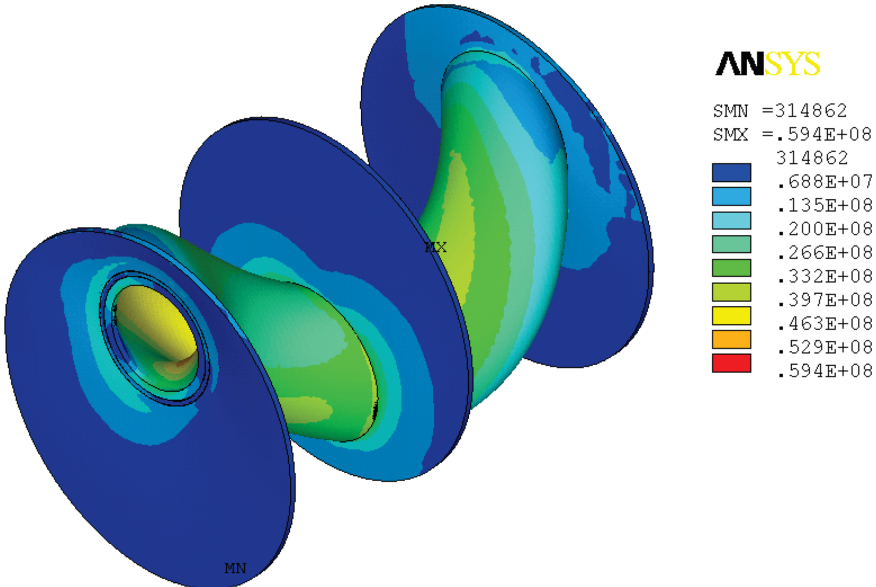
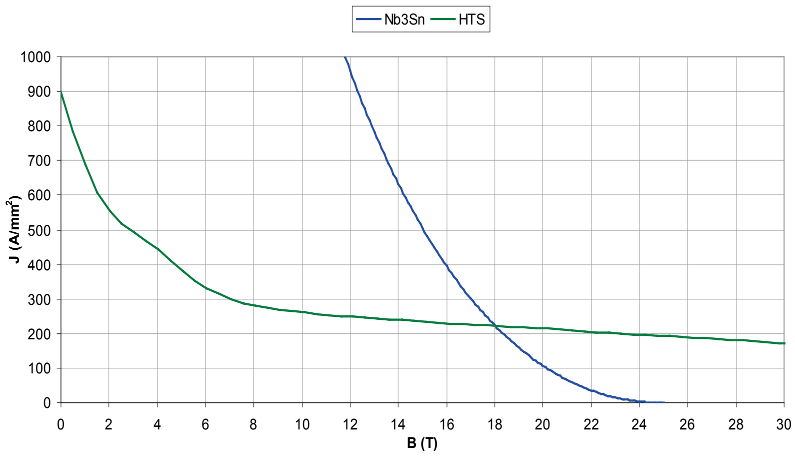
Long HS Mechanical Concept in 2008

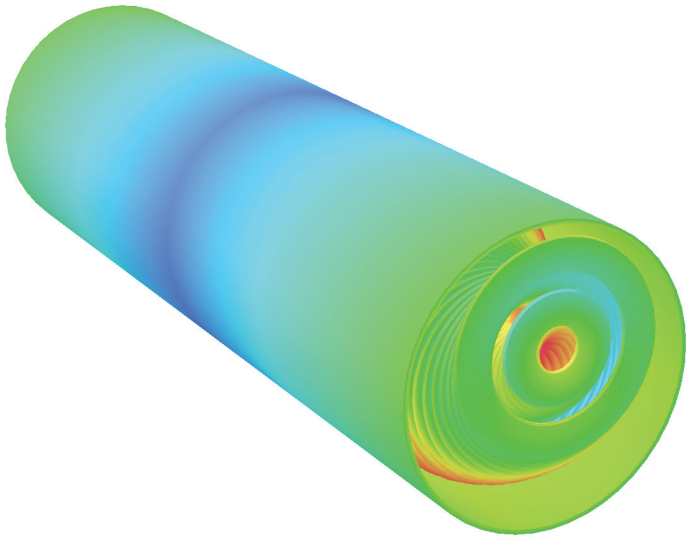


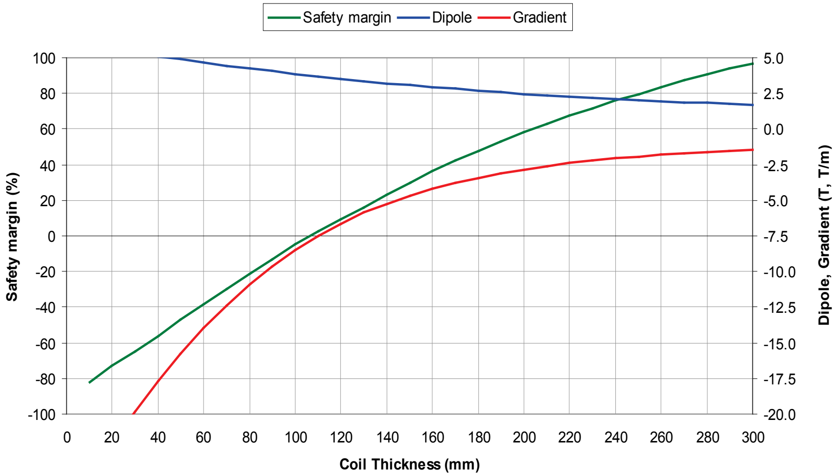


- Hoop Lorentz forces intercepted by stainless steel bandage rings around the coils
- Transverse Lorentz forces intercepted by support flanges
- Outer LHe vessel cylinder provide mechanical rigidity to the structure
- The peak stress is ~60 MPa

Hybrid High Field HS at Far End in 2008

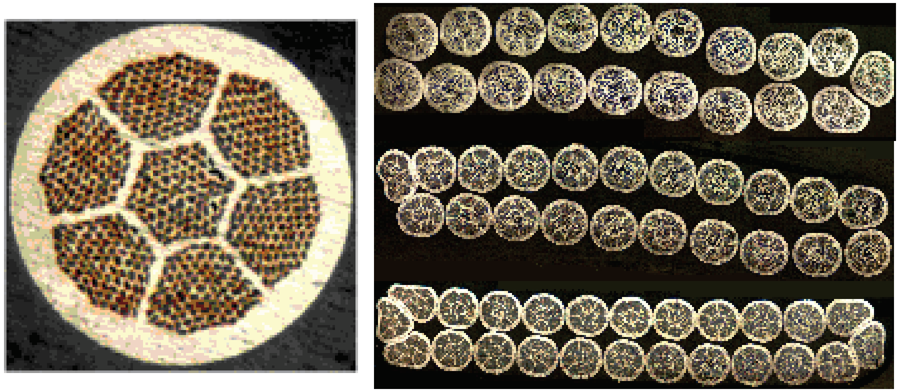




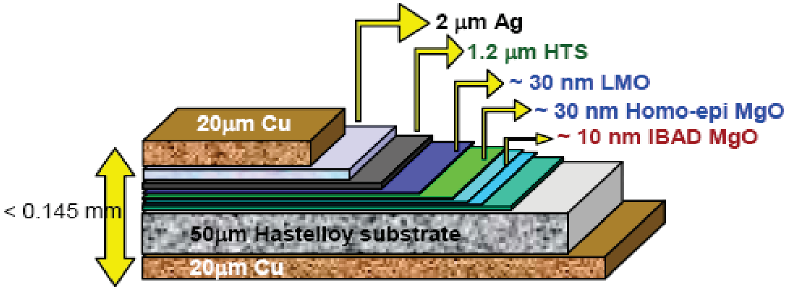


- Objectives:
- Superconductor choice – LTS, HTS, hybrid, conductor grading
- Field components for given geometry
- Operation margin
- Work in progress

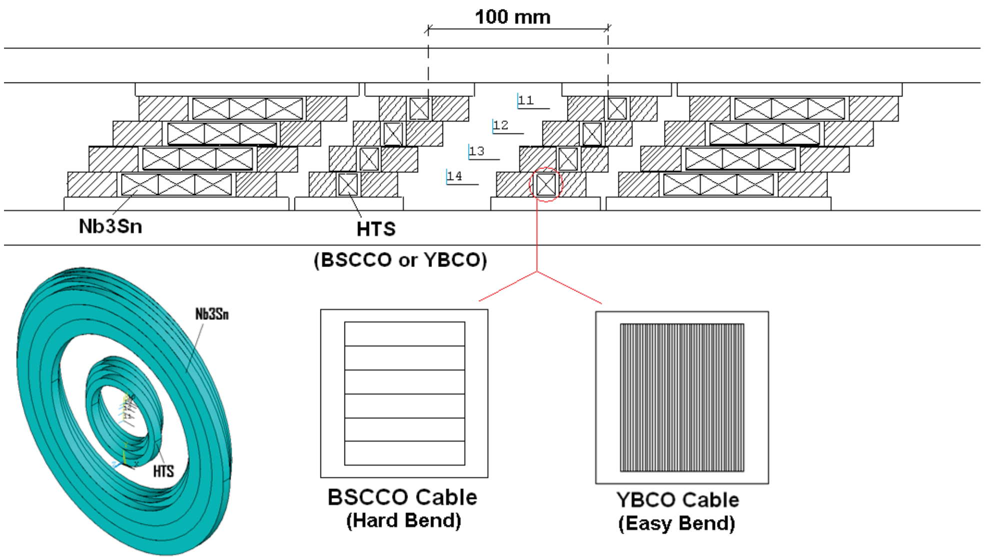
Hybrid HS Model in 2008



HTS: Bi-2212 strand and cable



HTS: YBCO tape

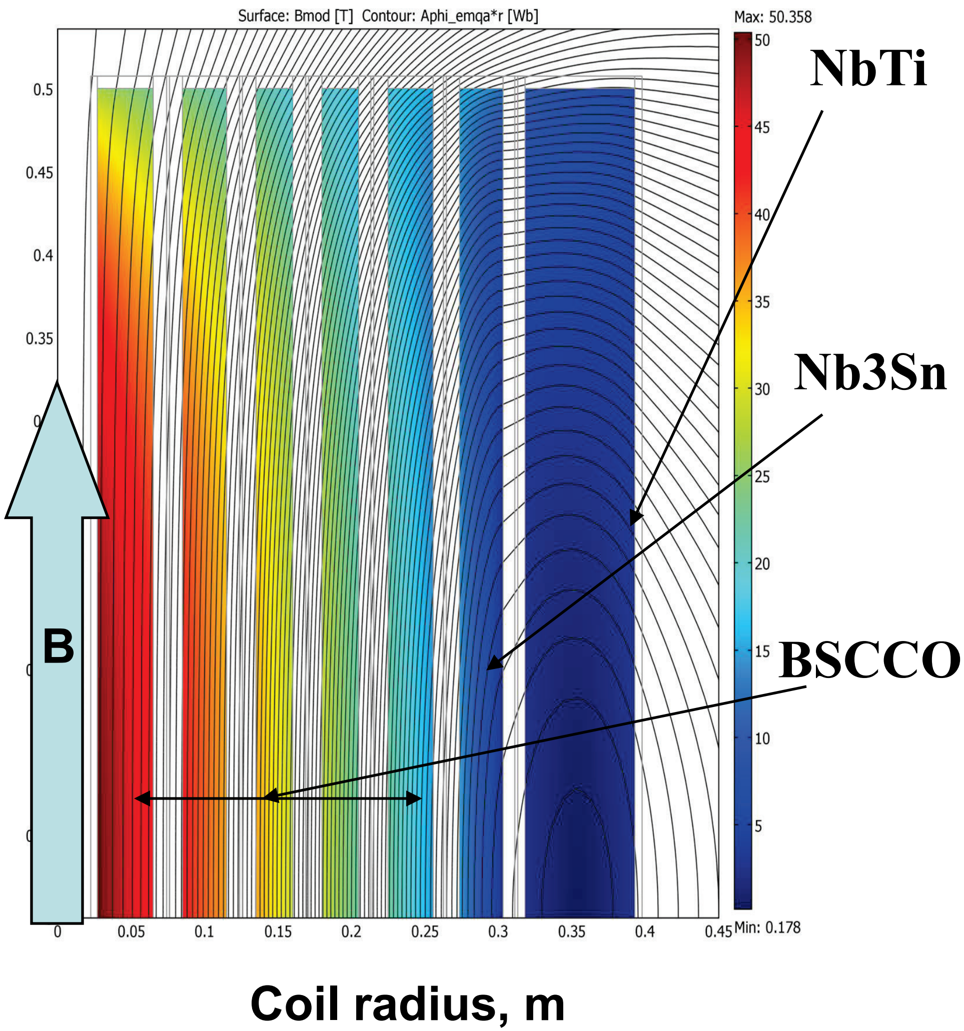


- Conceptual design of Hybrid HS model
- Develop the technology for mechanical design, fabrication and assembly
- Develop the technology for quench protection

50 T Solenoid Technology R&D

- Build and test smaller HTS and HTS/Nb_3Sn hybrid solenoid models
  - Field range: up to 20-25 T
  - Emphasis on HTS strands, tapes and cables
    - Nb_3Sn and Nb_3Al strand and cable R&D is supported by other programs (DOE, LARP, NIMS/FNAL/KEK, CARE, etc.),
    - See Alvin Tollestrup talk this Meeting.
  - HTS material: BSCCO (G1) or YBCO (G2)
  - Conductor type: round strands, cables or tapes
  - Technologies: react-&-wind or wind-&-react

50 T Solenoid Conceptual Design (ASC 2008)



- **Basic Parameters**
  - **Inner bore diameter 50 mm**
  - **Length 1 meter**
  - **Fields 30 T or higher ➔**
    - **HTS materials**
- **Key design issues:**
- **superconductor Jc**
- **effect of field direction on Ic in case of HTS tapes**
- **stress management**
- **quench protection**
- **cost**
- **Conceptual design:**
- **hybrid coil design**
- **coil sections**
- **Work in progress:**
- **Conductor**
- **Quench protection**

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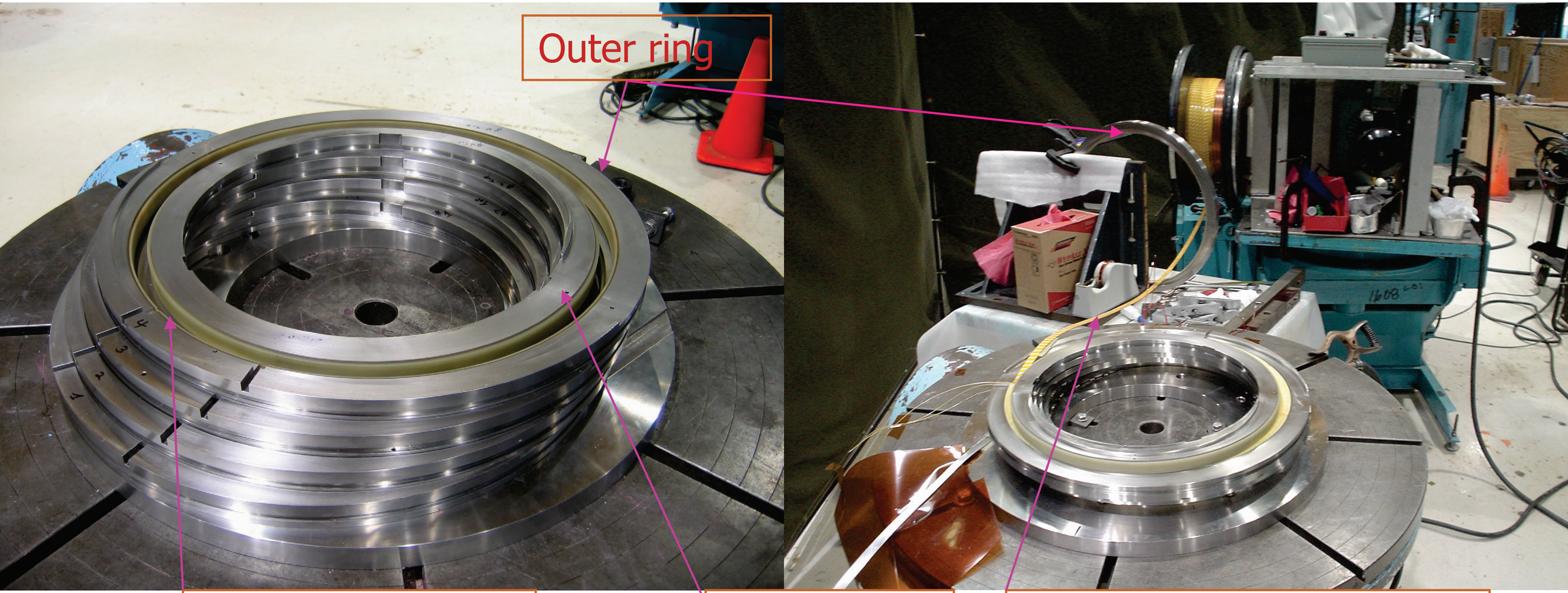
4-Coil NbTi Model Fabrication in 2008

Muons, Inc.
Innovation in Research



Bandage rings control assembly

Winding process

The Model was built using funds from MCTF and SBIR with Muons Inc. during FNAL very limited funding in FY2008.

4-Coil Warm Magnetic Measurements in 2008

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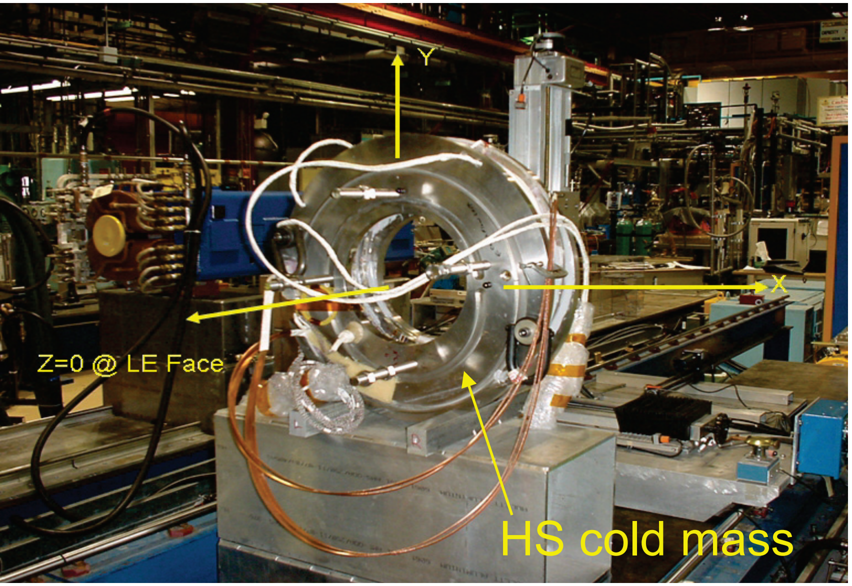
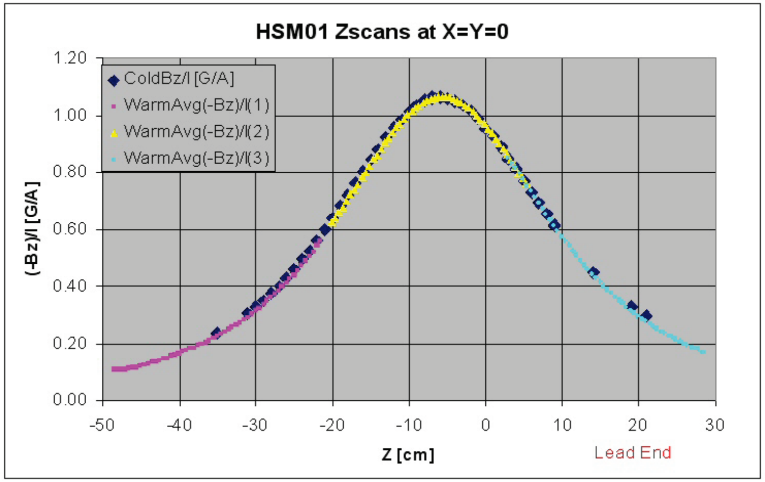
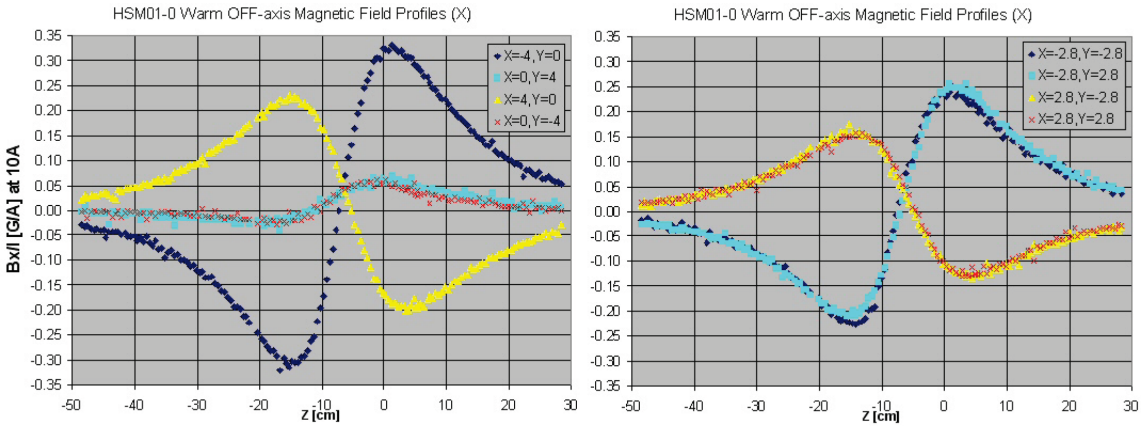




Bz vs Z at central axis X=Y=0

Warm magnetic measurements

Have a good agreement with the field simulations



Warm transfer function Bx/I vs Z at 4 inch radius on X and Y axes (left) and along 45º diagonals (right).

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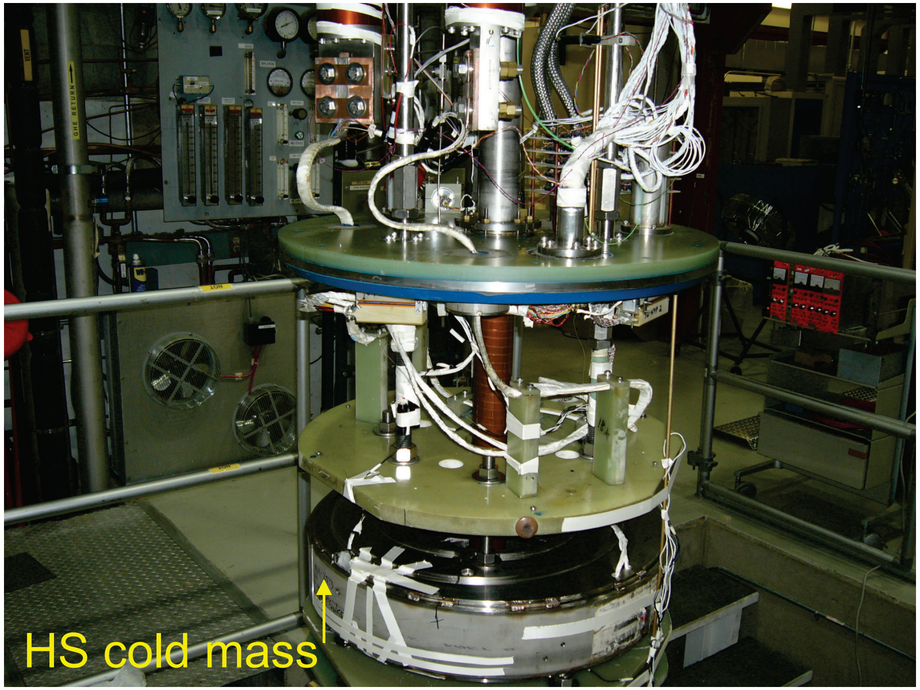
4-Coil Model Cold Test in 2008



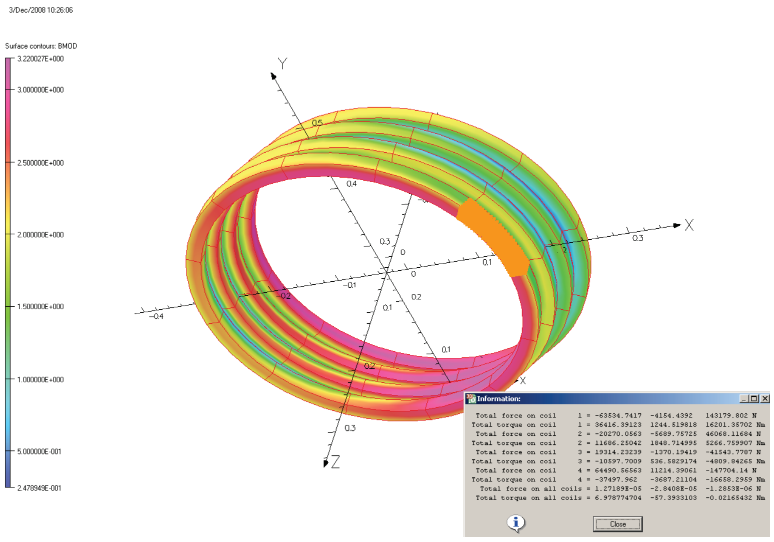
HS cold mass with top plate assembly

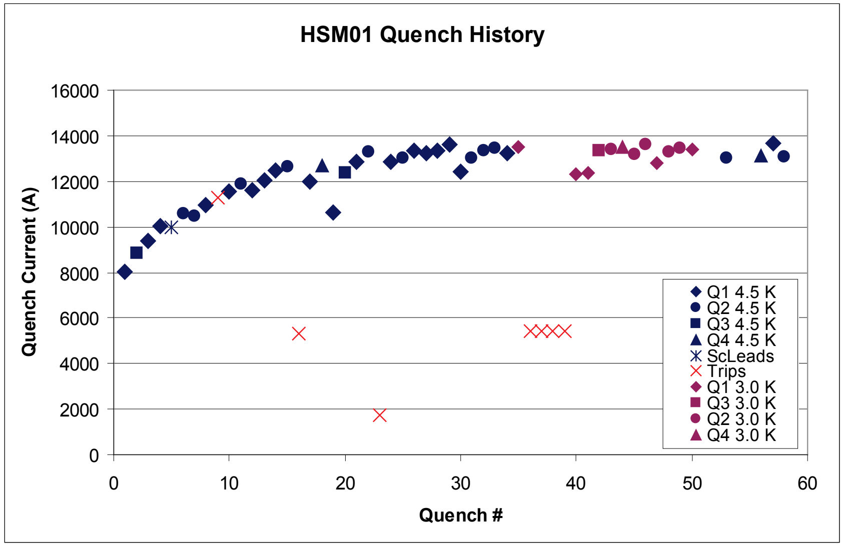
before mounting inside cryostat.

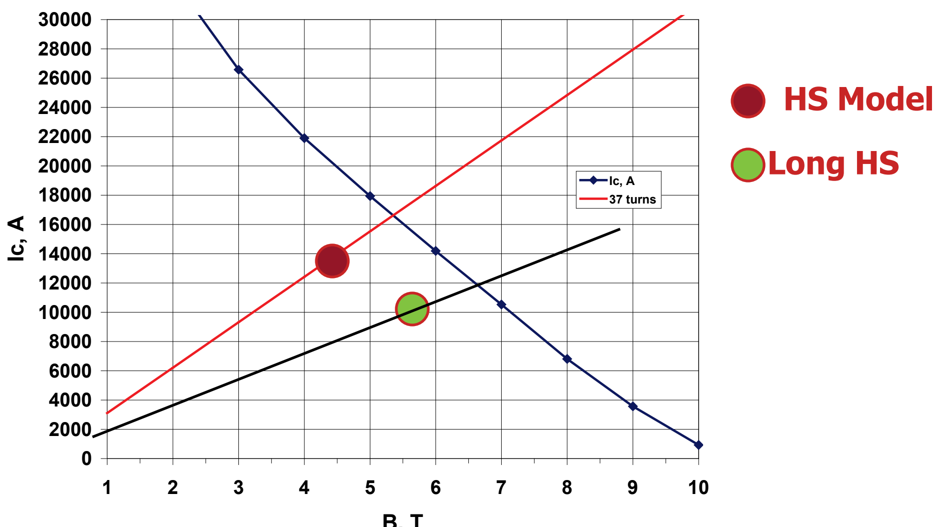
Parameter	Short HS nominal	Short HS Max	Long HS	HS Test Results
Peak superconductor field, T	3.3	4.84	5.7	4.38
Current, kA	9.6	14	9.6	13.6
Coil inner diameter, mm	420	420	510	420
Number of turns/section	10	10	10	3x9+10
Fx force/section, kN	70	149	160	119
Fy force/section, kN	12	25	60	21
Fxy force/section, kN	71	151	171	121
Fz force/section, kN	157	337	299	273

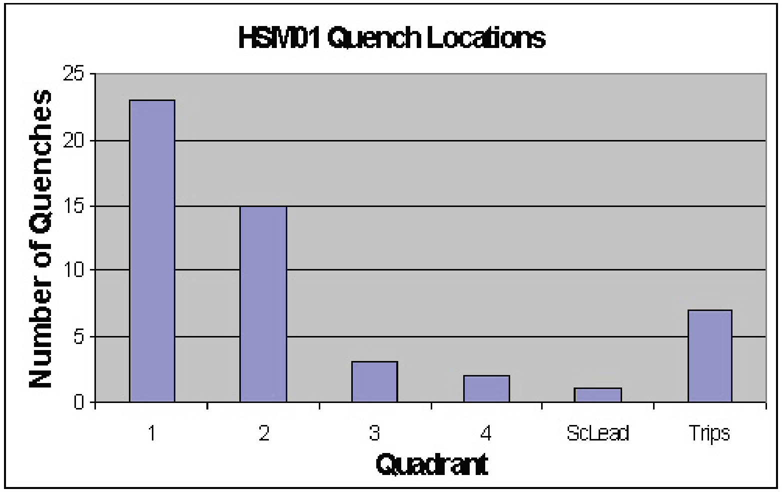
During test model current reached 13.6 kA and had close to the long HS mechanical load.

4-Coil Model 1 Test Results

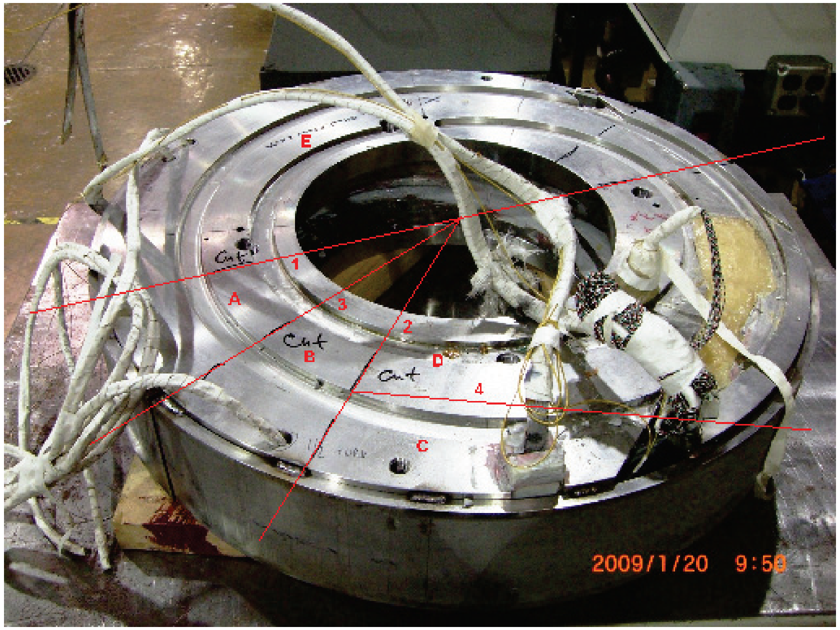


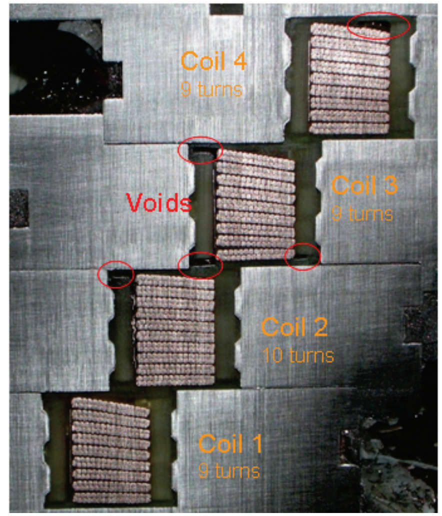


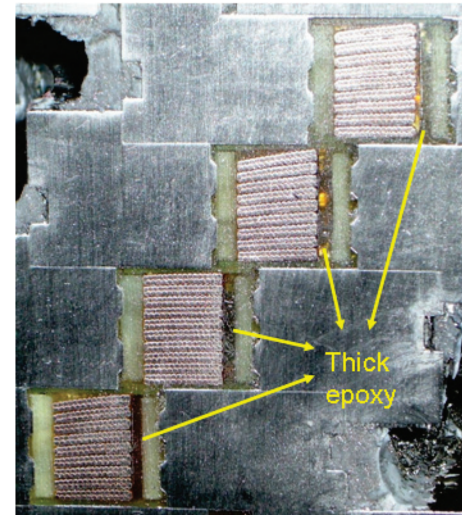




4-Coil Model 1 Autopsy in 2009







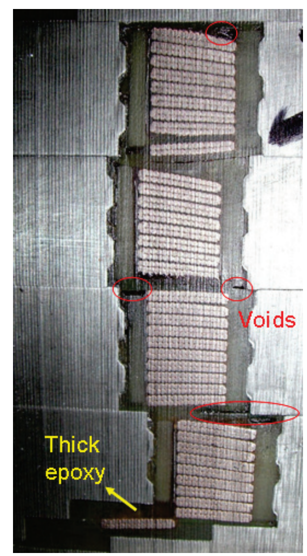
The cold mass autopsy showed the places for improvements:

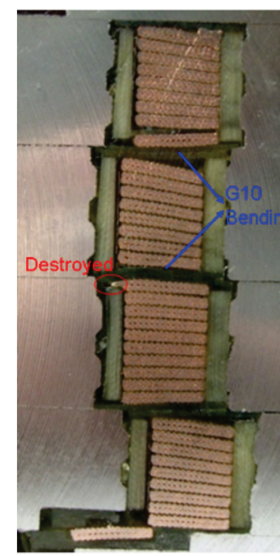
- Coil geometry with 9 turns worse than with 10 turns;

- Large voids in space between coils;

- G10 spacers bending;

- Too thick epoxy areas;





HS NbTi Model 2 in 2009

The main goal of building the second model is to improve the solenoid manufacturing technology and as a result to improve the magnet performance.

- The second HS Model will have in general the same design as Model 1;
- Outer stainless steel support rings will be replaced by Aluminum rings. It will provide the coil prestress after cooling down and will improve the solenoid performance;
- Will be used two stages of epoxy impregnation: the first is with conventional for SC magnets epoxy resin and the second with the epoxy filler (Cab-o-Sil). During second stage the epoxy will fill all large area which had voids. Such process will help to avoid number of epoxy cracks during magnet training;
- The SSC superconducting cable will be dekeystoned to the rectangular cross-section to improve winding process.

Summary

- Muon magnet program is making progress in all key directions:
  - Magnet design studies;
  - Technology development;
  - HTS material R&D.
- We collaborate with DOE Labs, industry and Universities through National HTS Conductor program and Muons. Inc. SBIR programs;
- Results published at EPAC08 and ASC08. New results will be reported in several papers at PAC09, CEC/ICMC'09 and MT-21;
- Stable funding and manpower resources are critical to accomplish the 5-year Muon magnet R&D plan.