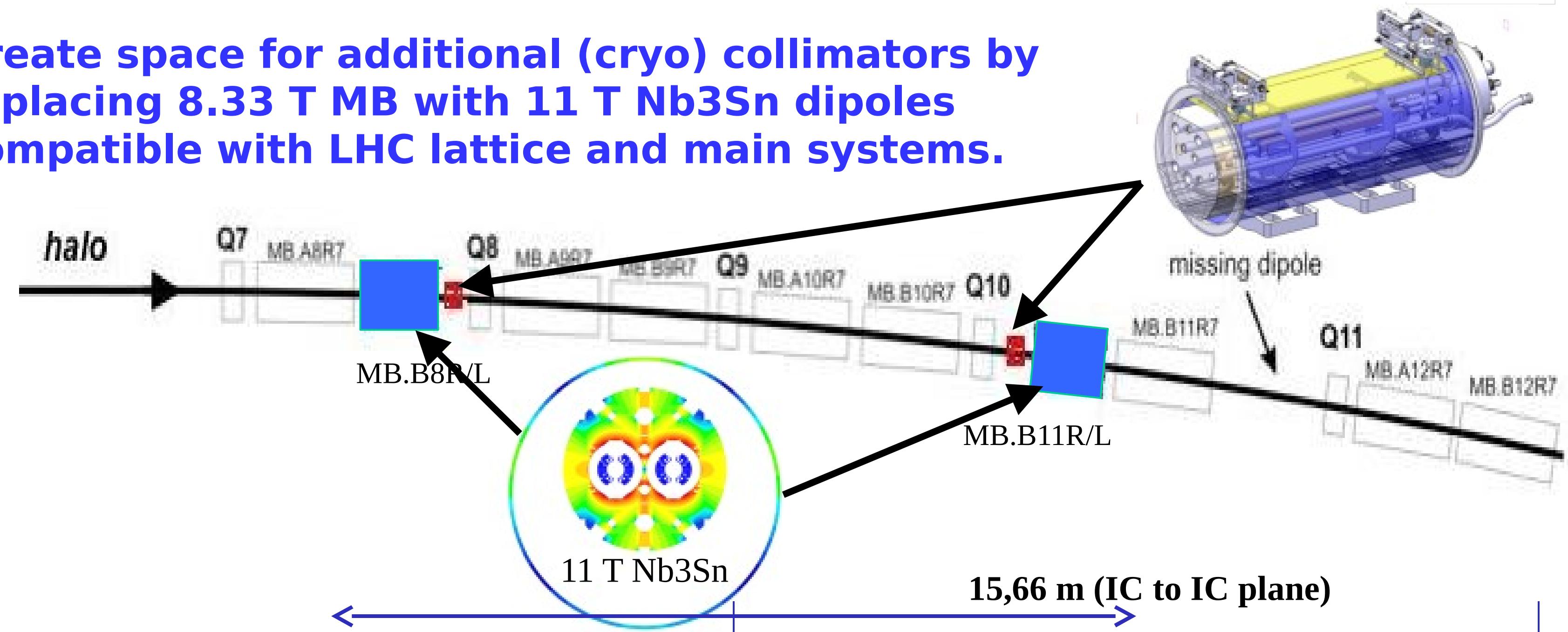
11 T Dipole Status
May 2012

M. Karppinen CERN TE-MSC

On behalf of CERN-FNAL collaboration

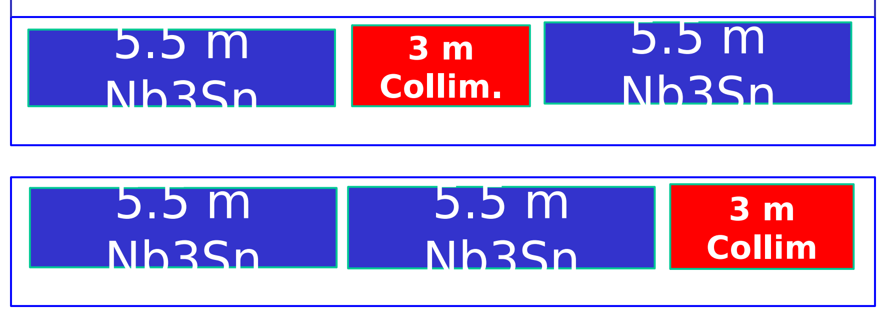
DS Upgrade

- Create space for additional (cryo) collimators by replacing 8.33 T MB with 11 T Nb3Sn dipoles compatible with LHC lattice and main systems.



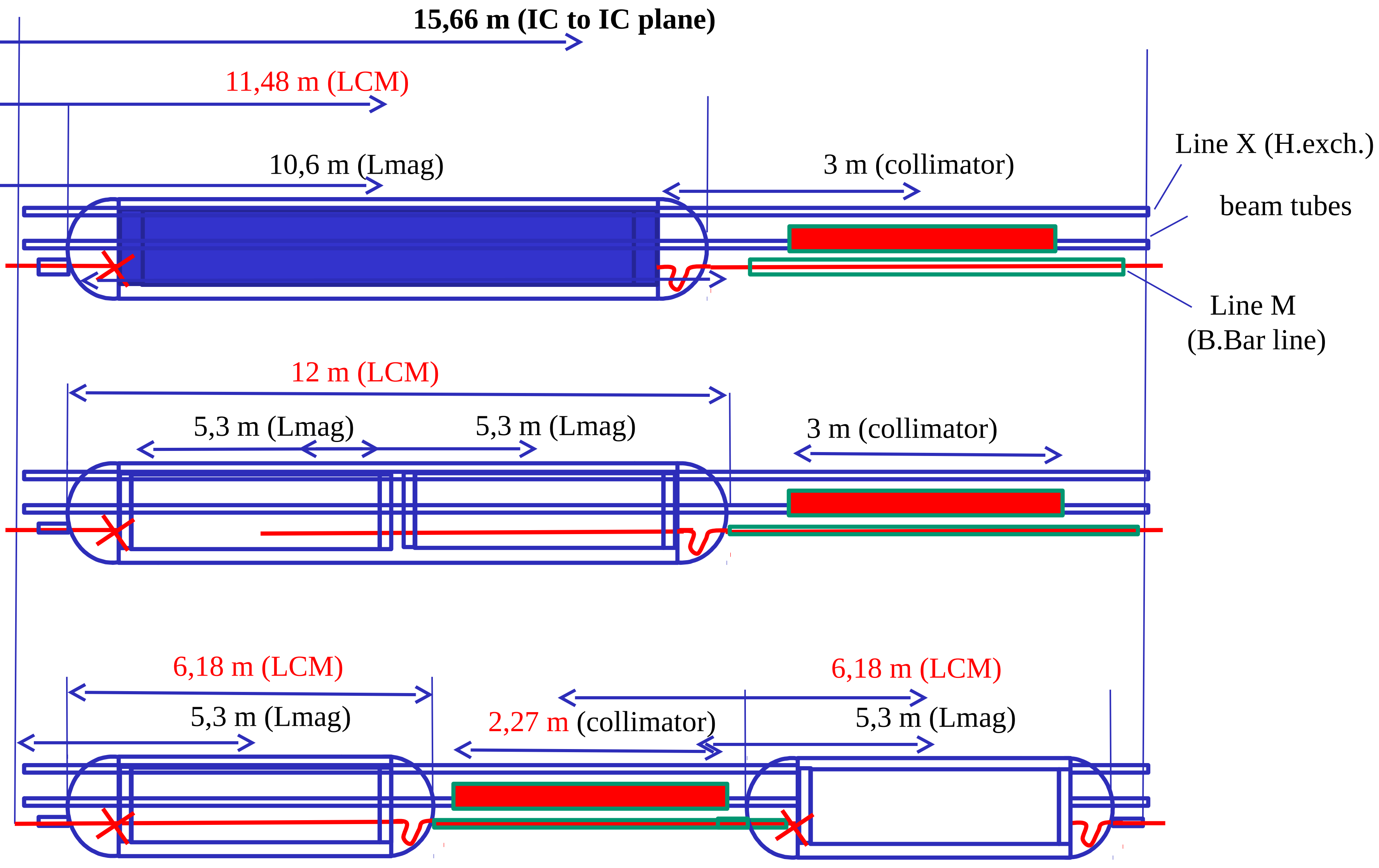
- LS2 2018: IR-2

- LS3 2022: IR-1,5, Point-3,7



- Joint development program between CERN and FNAL underway since Oct-2010 to demonstrate the feasibility of Nb3Sn technology for this upgrade by 2014.

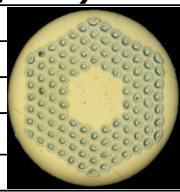
11 T Dipole & Collimator Cryo-Assembly options



11 T Design Challenges

- **Iron saturation effects**
- **Transfer function matching with MB**
- **Coil magnetization effects**
  - **Conductor development**
  - **Cable development**
- **Quench protection**
  - **Heater development**
  - **QPS**
- **Mechanical structure**
  - **Forces almost 2 X MB**
- **Coil fabrication technique**
  - **Reproducibility**
  - **Handling**
- **Thermal**
  - **Resin impregnated coils**
- **Integration**
  - **Optics**
  - **Cold-mass**
  - **Collimator**
  - **Machine systems**

Strand & Cable



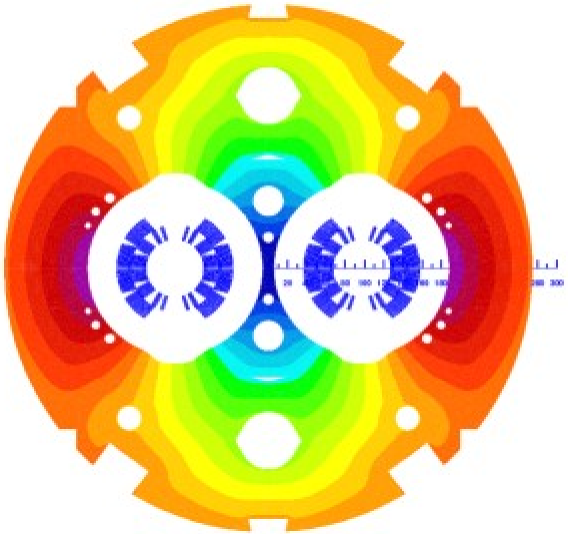
11 T DS Dipole Cable and insulation parameters		unreacted	reacted
Strand (RRP 108/127)			
Strand diameter	(mm)	0.7	*0.711*
Filament diameter	(μm)	46	*46*
Cu/non-Cu		1.1	*1.1*
Jc(4.2K, 12 T)	(A/mm^2)		*2730*
Degradation	(%)		*10*
RRR			*>200*
Cable			
Number of strands		40	*40*
Trasp. Angle	(deg)	14.5	*14.5*
Mid-thickness	(mm)	1.269	***1.307***
Thin edge	(mm)	1.167	***1.202***
Thick edge	(mm)	1.37	***1.411***
Width	(mm)	14.70	***14.847***
Thin edge compaction		0.834	*0.846*
Thick edge compaction		0.979	0.993
Width compaction		1.020	*1.015*
Key-stone angle	(deg)	0.79	*0.81*
Cable Insulation			
Insulation thickness	(mm)	0.150	***0.100***
Insulation material		E-glass	*E-glass*

Cable samples made with and without SS core show Ic-degradation well within the initial goal of 10 %.

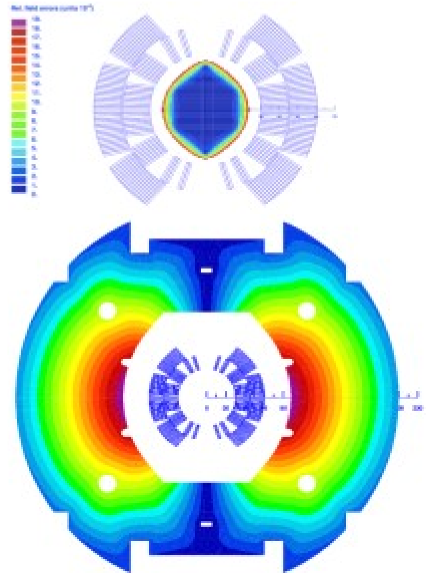
Cored cable with RRP 151/169 being developed at FNAL.

- **Large aspect ratio, low compaction. Presently 20 μm additional compaction**
  - **FNAL roll the cable in two stages with an intermediate anneal**
  - **CERN use single pass process**

11 T Dipole Coil Design



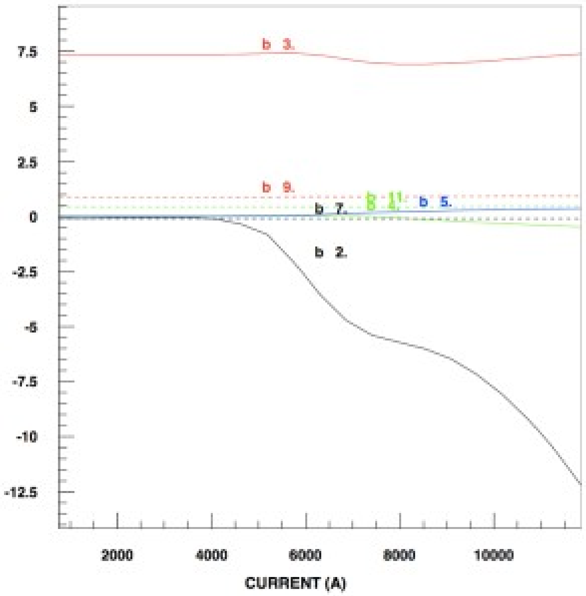
B0(11.85 kA) = 11.21 T

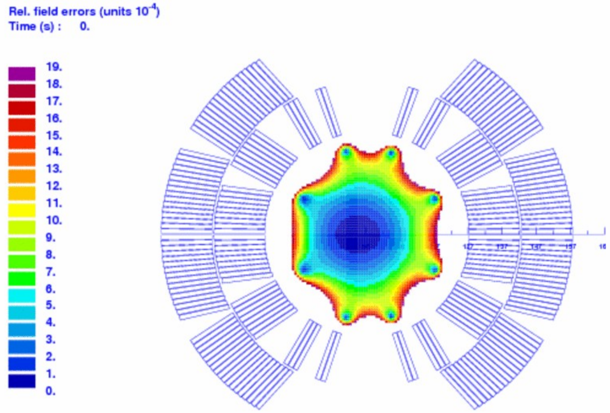


B0(11.85 kA) = 10.86 T

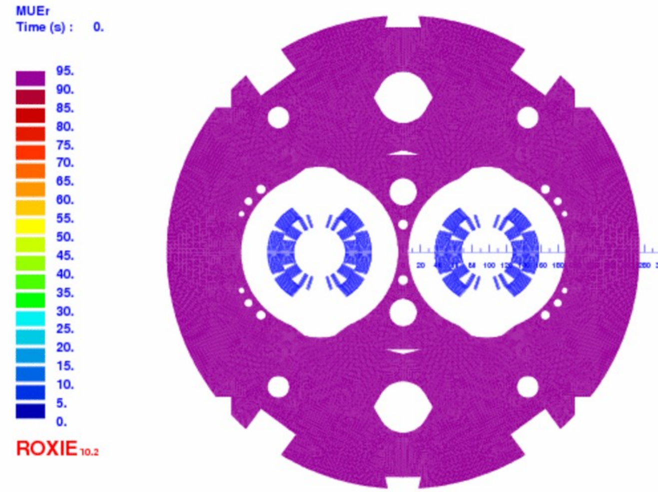
- **Coil optimization**
  - **>11 T at 11.85 kA with 20% margin at 1.9 K**
  - **Field errors below the 10-4 level**
- **6-block design, 56 turns (IL 22, OL 34)**
  - **14.85-mm-wide 40-strand Rutherford cable, no internal splice**
  - **Several X-sections were analyzed with and without core**
  - **Coil ends optimized for low field harmonics and minimum strain in the cable**

Iron Saturation





Relative FQ (units)

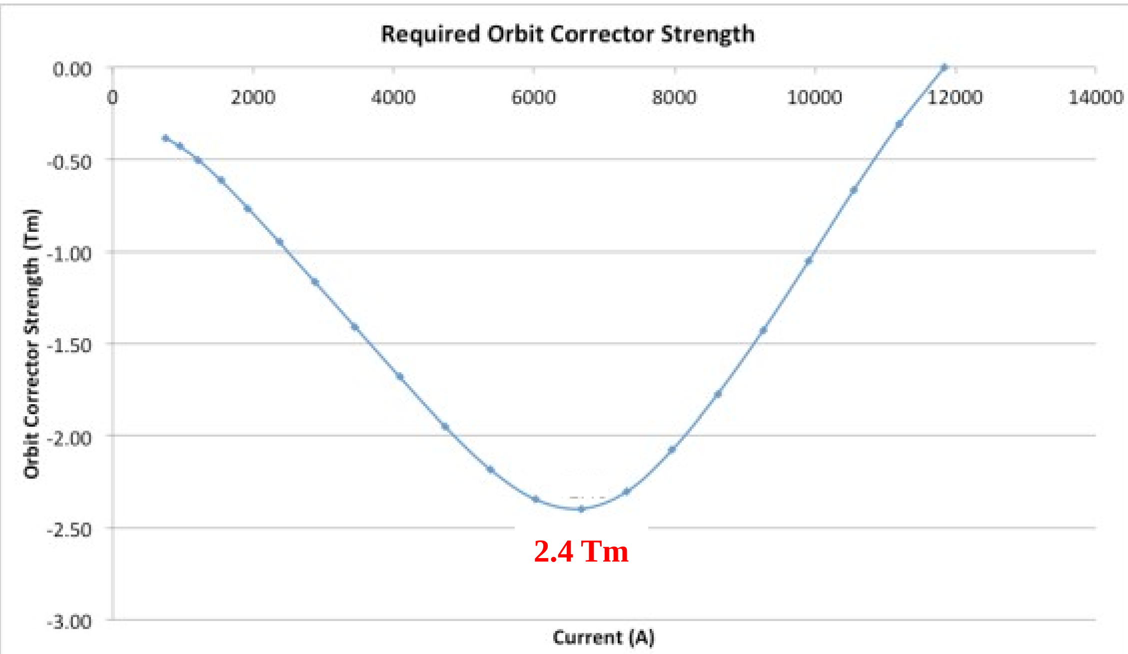


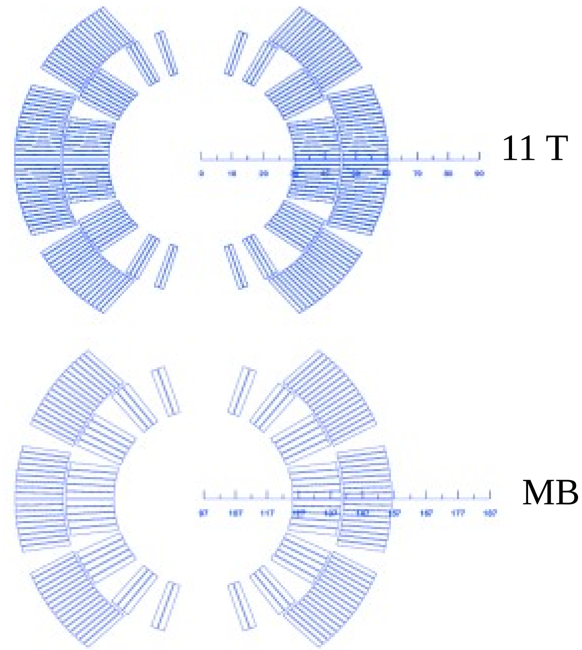
Relative permeability

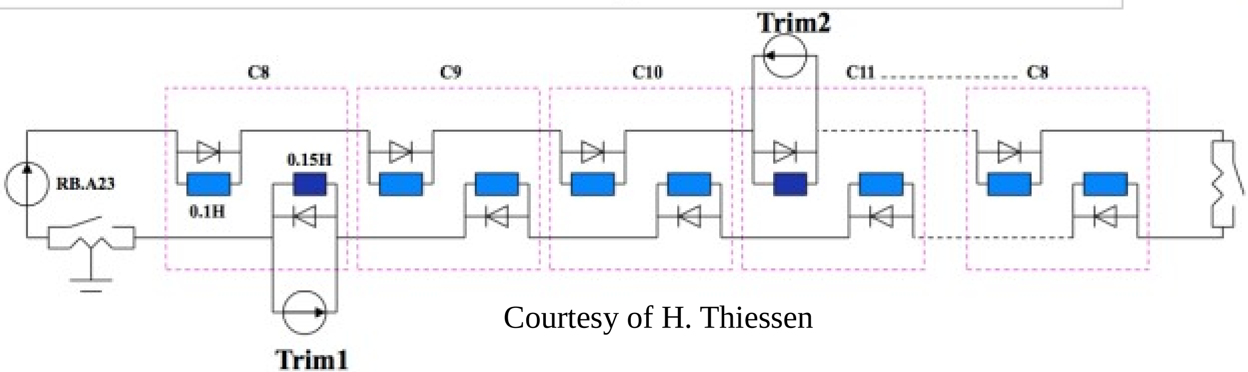
- **Yoke design**
  - **The cut-outs on top of the aperture reduce the *b*3 variation by 4.7 units as compared to a circular shape.**
  - **The holes in the yoke reduce the *b*3 variation by 2.4 units.**
  - **The two holes in the yoke insert reduce the *b*2 variation from 16 to 12 units.**

Transfer Function

- **TF of 11 T dipole is different from MB:**
  - **More turns than MB (56 vs. 40) ⇒ 11 T dipole is stronger at low field.**
  - **More saturation ⇒ reduction of transfer function at high field.**





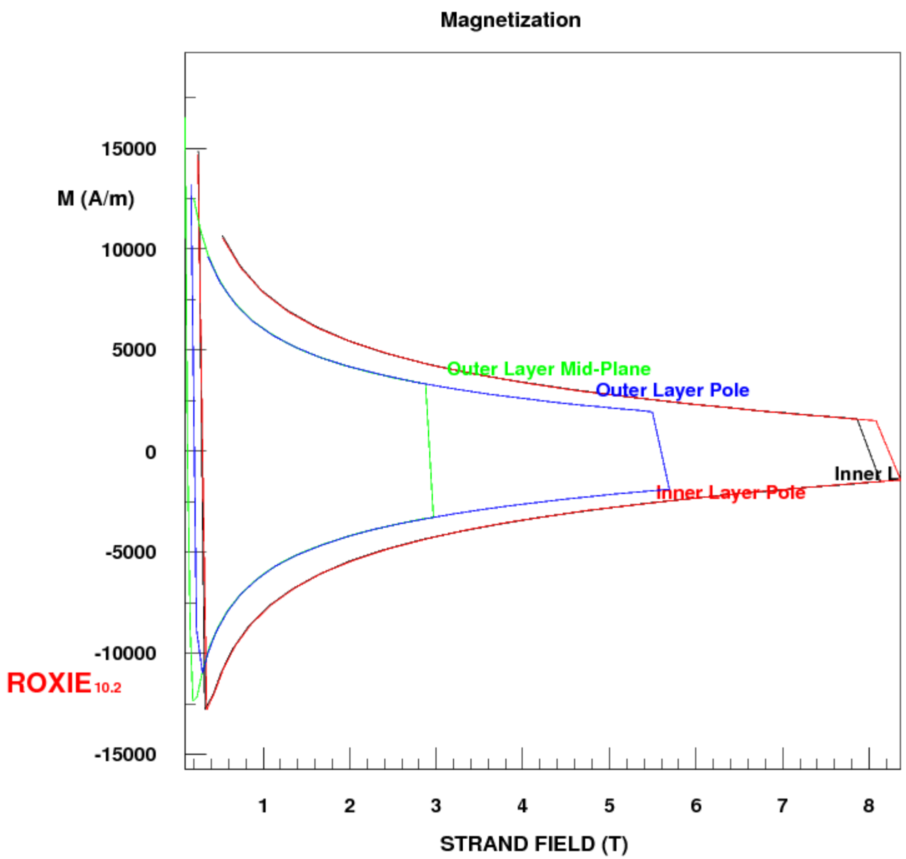


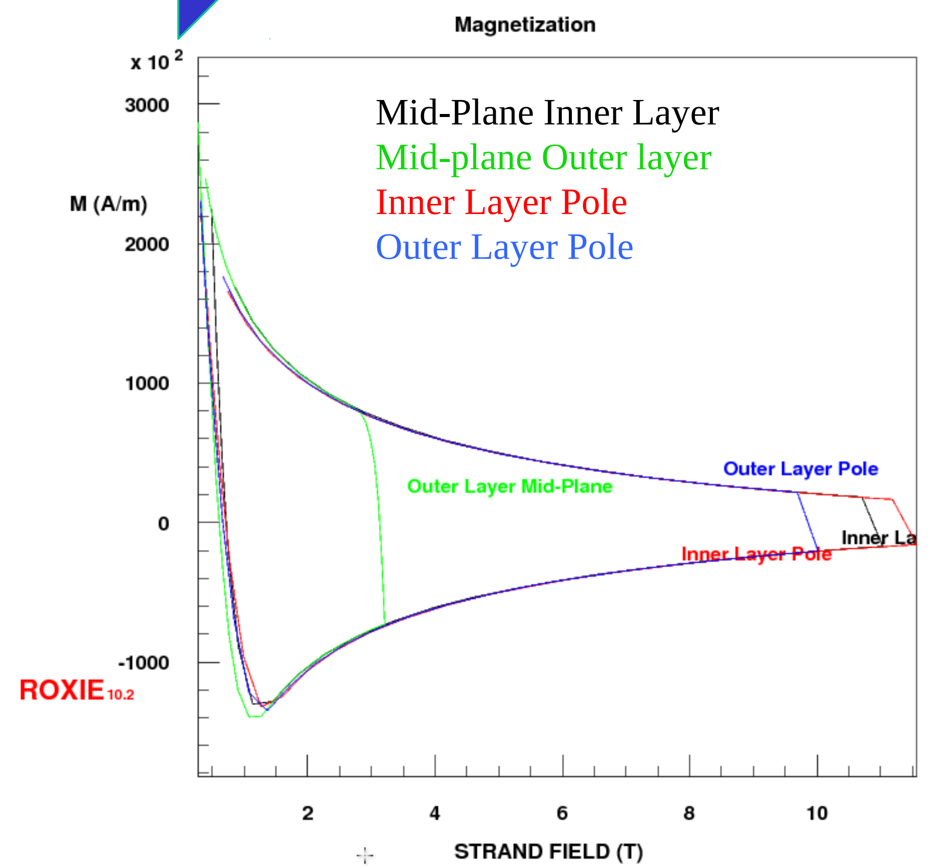
Courtesy of H. Thiessen

300 A Monopolar Trim PC

Coil Magnetization

MB (NbTi) | >10 X | 11 T Dipole Nb3Sn



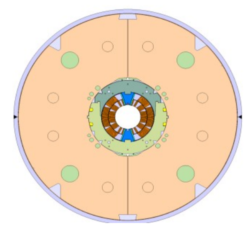
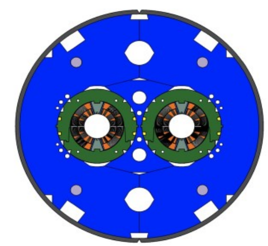


11 T Dipole Model Program

Date	Description	Length	Remarks	Goals
May-12	1-in-1 Demonstrator Magnet	2 m	Construction at FNAL	Cable technology Coil Technology Quench performance Magnetization effects
Mid-2013	2-in-1 Demonstrator Magnet 1	2 m	FNAL collared coils CM-Assembly at CERN	2-in-1 structure Field quality: - iron saturation - cross-talk - Magnetization effects Quench performance Reproducibility
End-2013	2-in-1 Demonstrator Magnet 2	2 m	CERN collared coils CM-Assembly at CERN	
2014	2-in-1 Prototype Cold Mass	5.5 m	Aperture 1 by FNAL Aperture 2 by CERN CM assembly at CERN	Scale-up Long tooling Fabrication of long coils CM assembly Magnetic performance

11 T Model Dipole Parameters

- **FNAL 1-in-1 demonstrator based on existing HFD components. Coils with integrated poles.**
- **CERN 1-in-1 model based on CTF (MB). Coils with non-integrated poles (pole-loading concept).**
- **2 m long 2-in-1 magnets of both concepts.**

Parameter	Single-aperture FNAL	Single-aperture CERN 	Twin-aperture 
Aperture	60 mm		
Yoke outer diameter	400 mm	510 mm	550 mm
Nominal bore field @11.85 kA	10.86 T	11.25 T	11.25 T
Short-sample bore field at 1.9 K	13.6 T	13.9 T	13.9 T
Margin B_{nom}/B_{max} at 1.9 K	0.80	0.81	0.81
Stored energy at 11.85 kA	473 kJ /m	484 kJ /m	969 kJ /m
F_x per quadrant at 11.85 kA	2.89 MN/m	3.16 MN/m	3.16 MN/m
F_y per quadrant at 11.85 kA	-1.57 MN/m	-1.59 MN/m	-1.59 MN/m

1-in-1 Demonstrator Mechanical Concept

Coil mechanical support is provided by stainless collars, vertically split iron yoke, aluminium clamp and welded stainless steel skin.

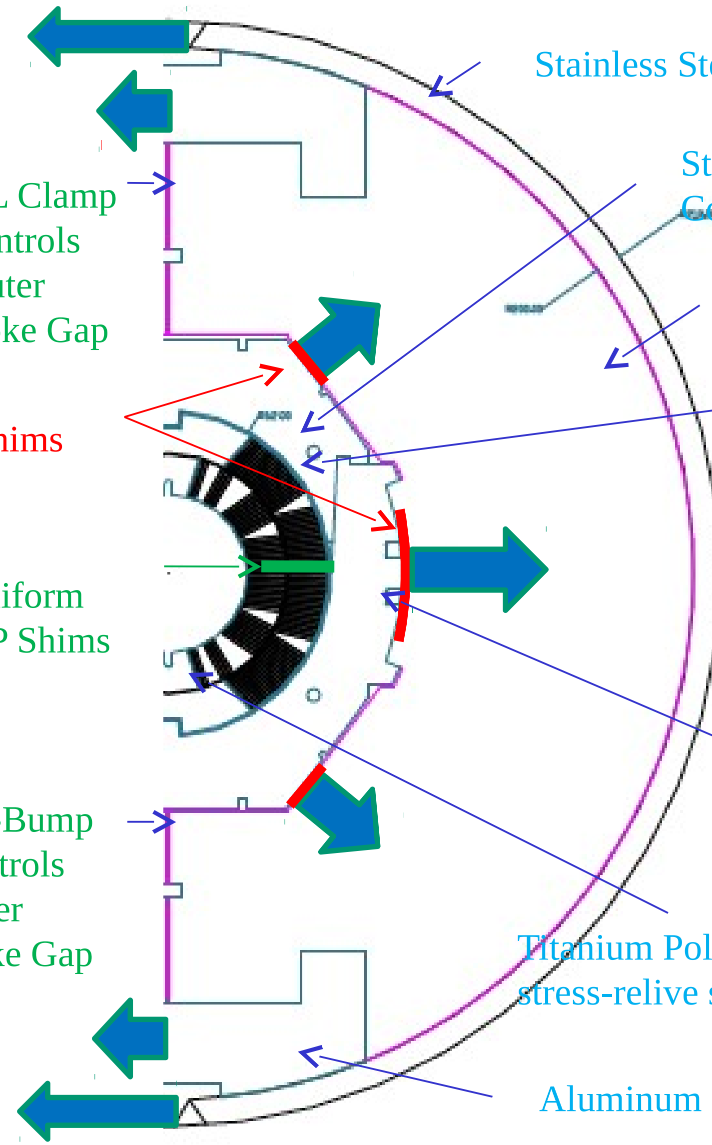
Strong collars and iron yoke create the “rigidity belt” around Nb3Sn coil for conductor protection.

Coil mid-plane and radial shims generate initial coil azimuthal pre-stress at collaring stage.

Skin and clamp tensions deform the iron and produce the desired coil compression. The collar also acts as gap-controller.

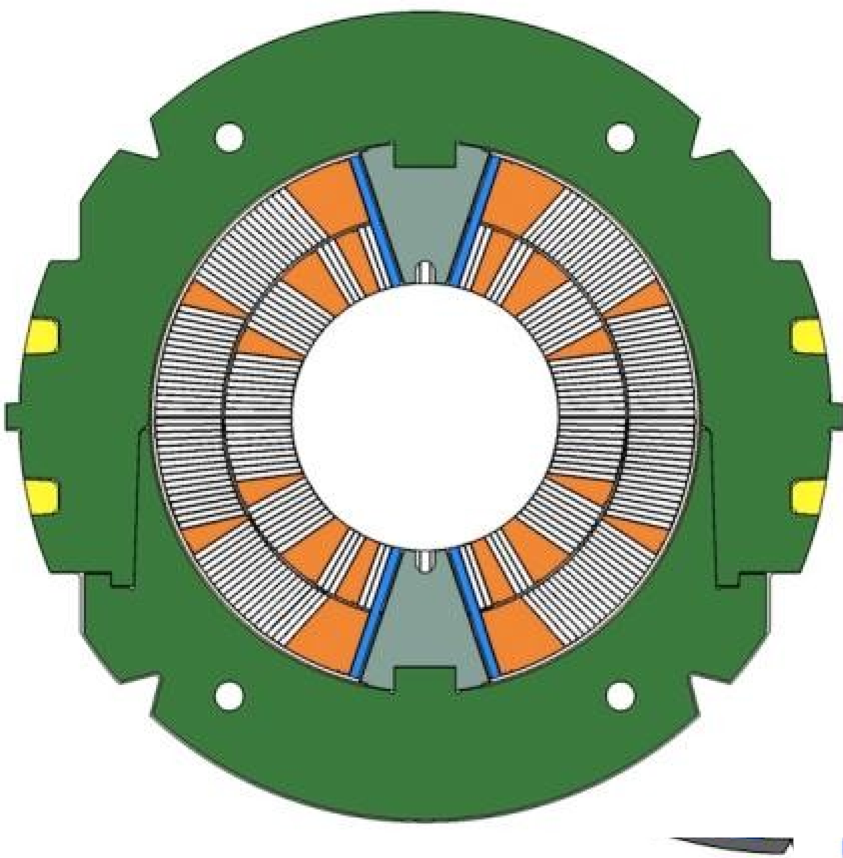
Collar-yoke-clamp-skin interfaces are tuned to sustain the horizontal EM force component.

I. Novitski FNAL

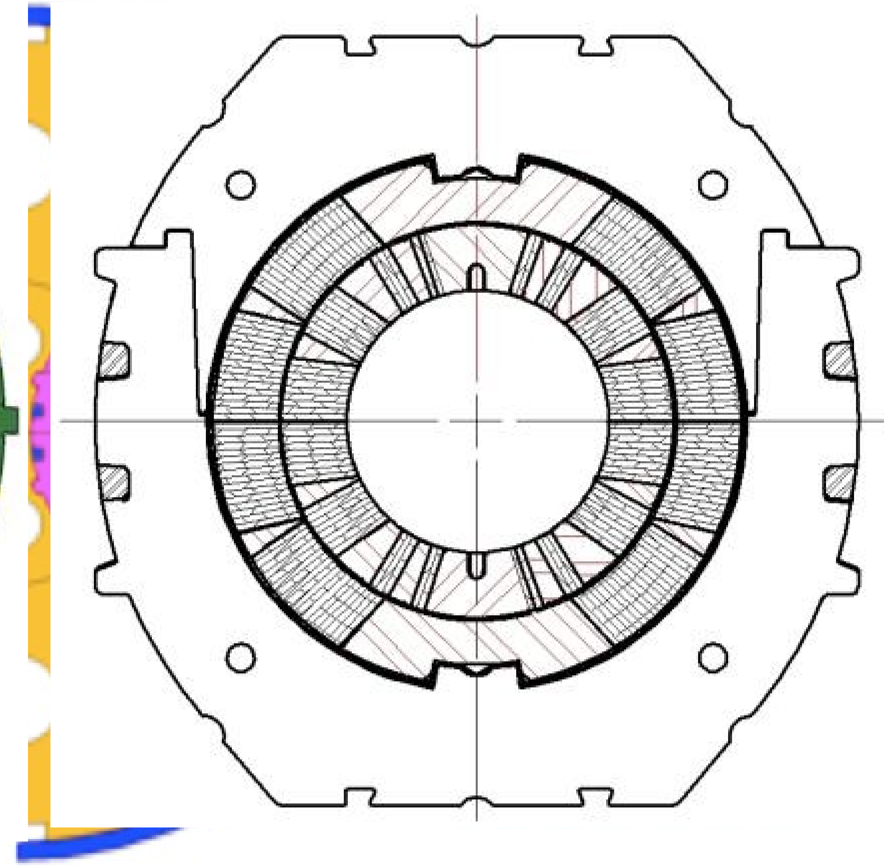


2-in-1 Demonstrator Design

❖ Two alternative design concepts

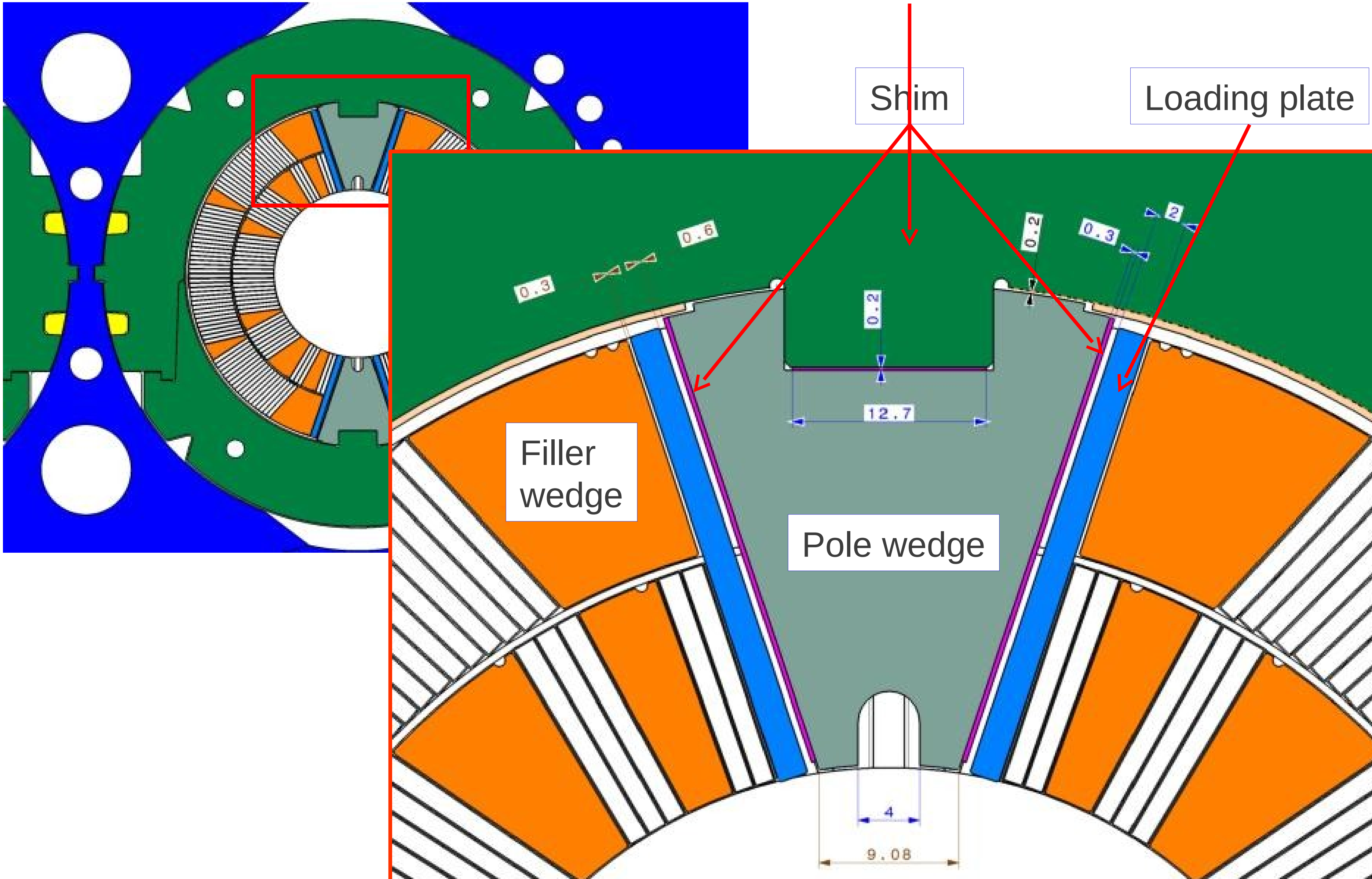


Pole loading design

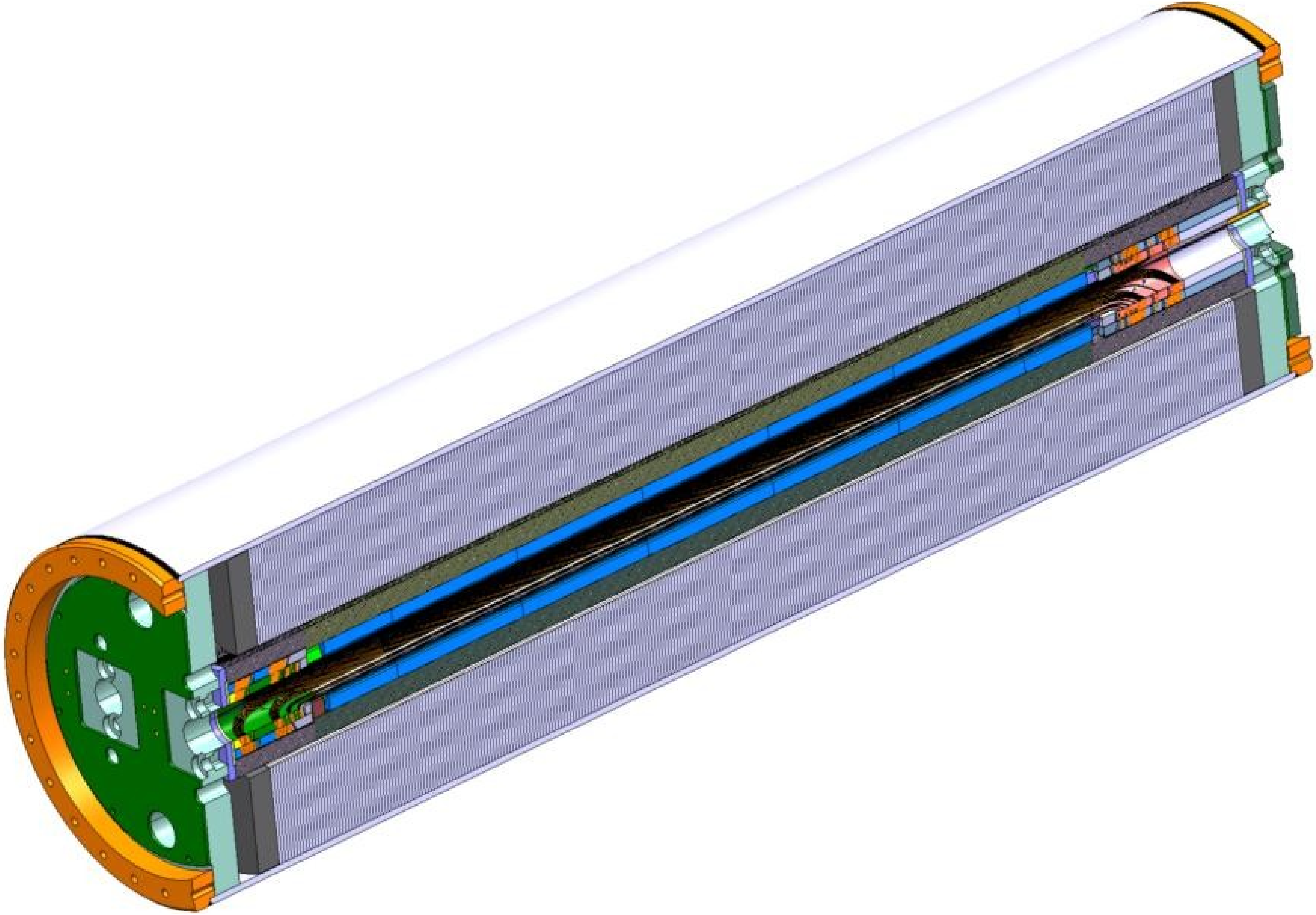


Integrated pole design

Pole Loading Concept



CERN 2-in-1 Model

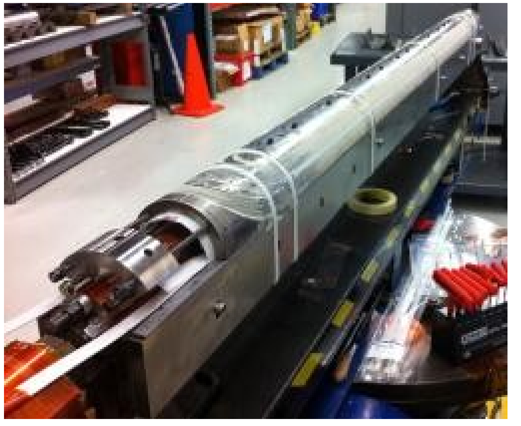


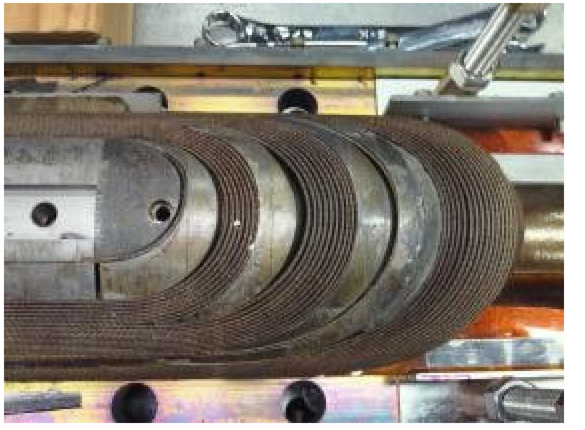
FNAL 1-in-1 Demonstrator Status

- 2 coils completed and fully instrumented with strain gauges and V-taps. CMM revealed dimensional distortions the origin of which is yet to be fully understood. All three coils made so far appear to be similar.
- Spare coil wound from CERN supplied cable has been reacted and is ready for epoxy impregnation.
- Mechanical model of the straight part (about 500 mm) was assembled and used for determining the initial shimming for the Demonstrator.
- Cold mass assembly completed. Electrical connections (splice, instrumentation, heaters) underway
- Magnet test expected as of 4 June.

Coil Fabrication


Wind


Cure

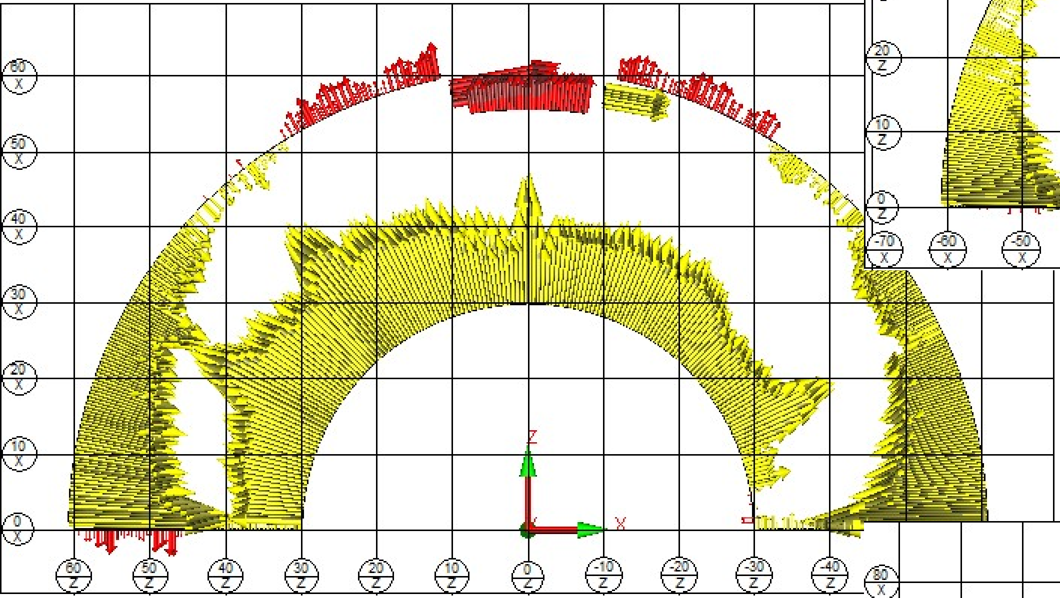

Reaction


Epoxy impregnation

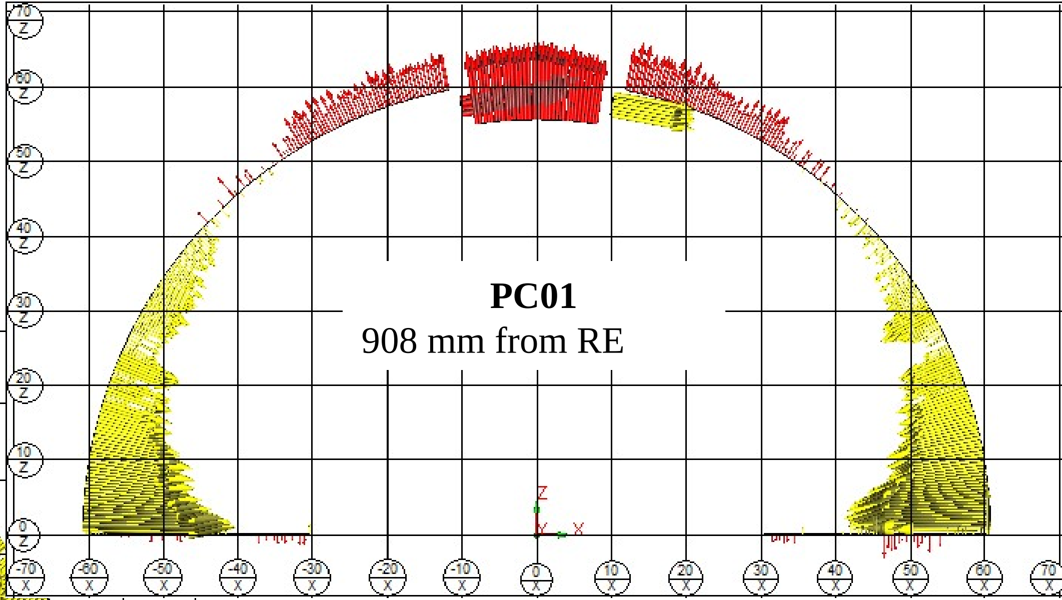

Instrumentation

Coil Dimensions

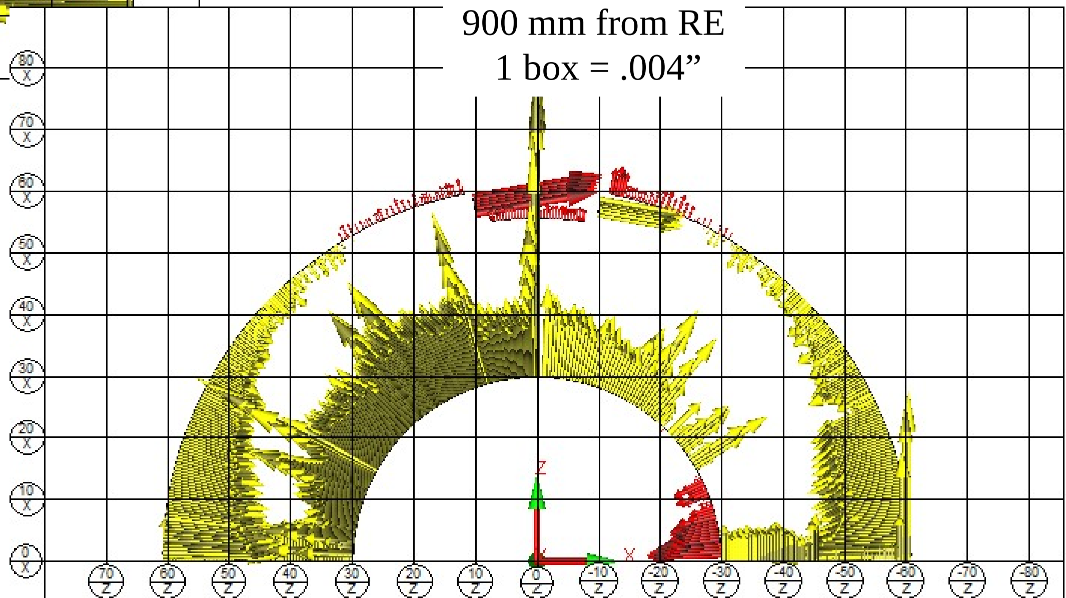
MBH02
900 mm from RE
1 box = .004”



PC01
908 mm from RE

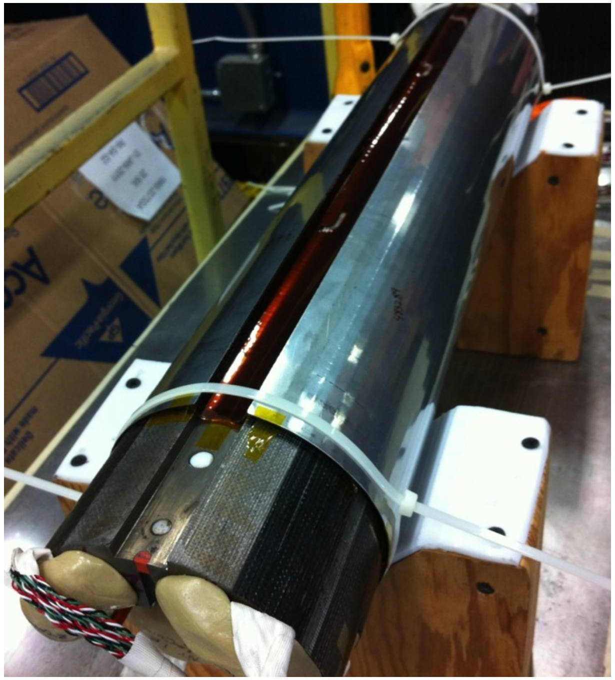


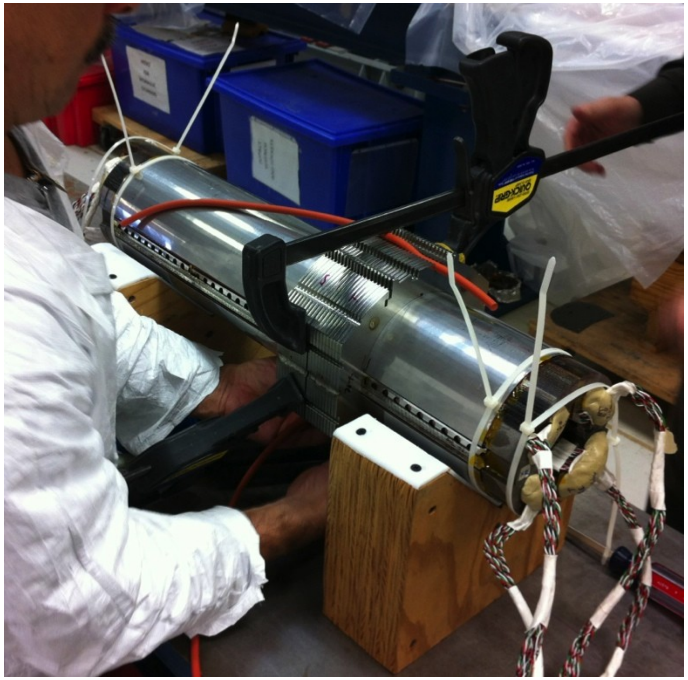
MBH03
900 mm from RE
1 box = .004”



- Reasons for dimensional distortions being investigated.
- All 3 coils appear similar.
- Different from previous coils made at FNAL.
- Post-assembly measurement show smaller (approx. 50 µm) distortions.

Mechanical model 1



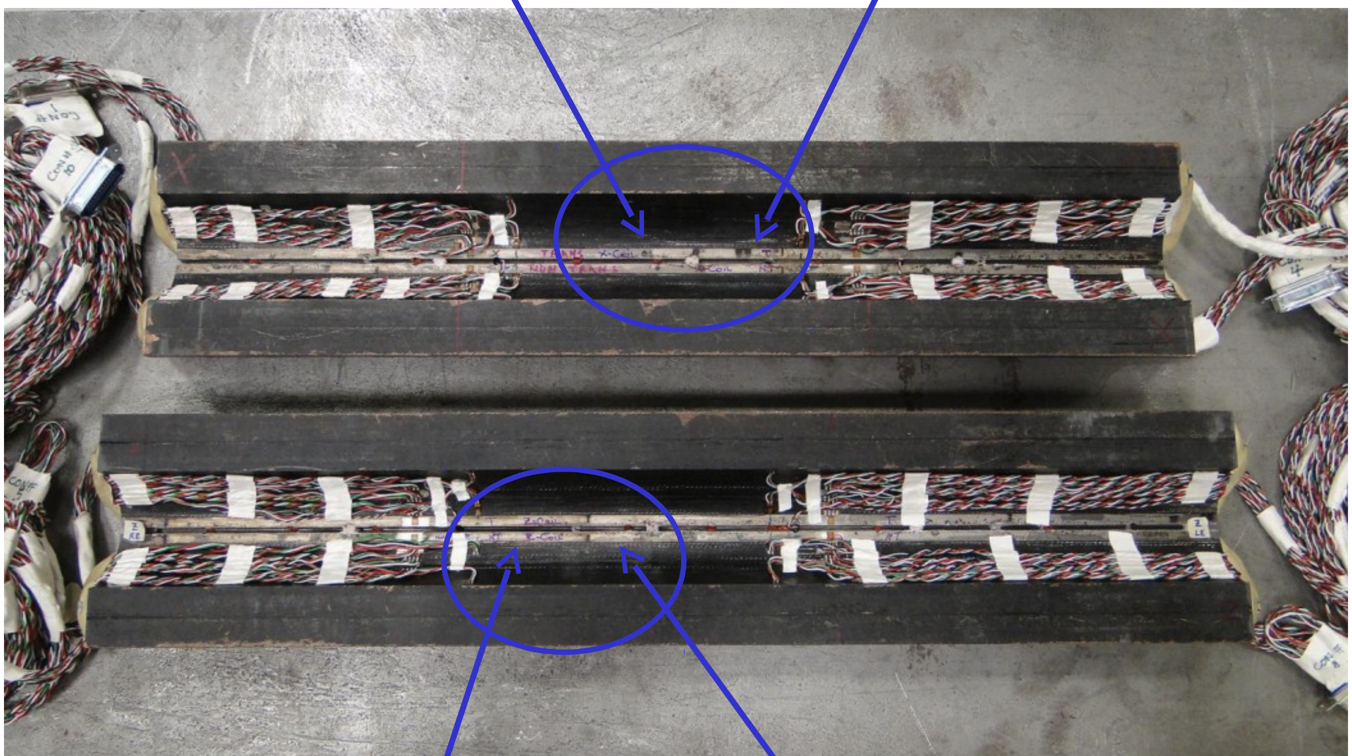


- **Mechanical model based on Nb3Sn practice coil (PC-0) instrumented with strain gauges**
- **Assembly parameters were explored with 5 different sets of shims**
- **Validation of the assembly tooling and procedure**
- **Coil and collared coil dimensional control before and after the assembly**

MM Measurement Locations (4)

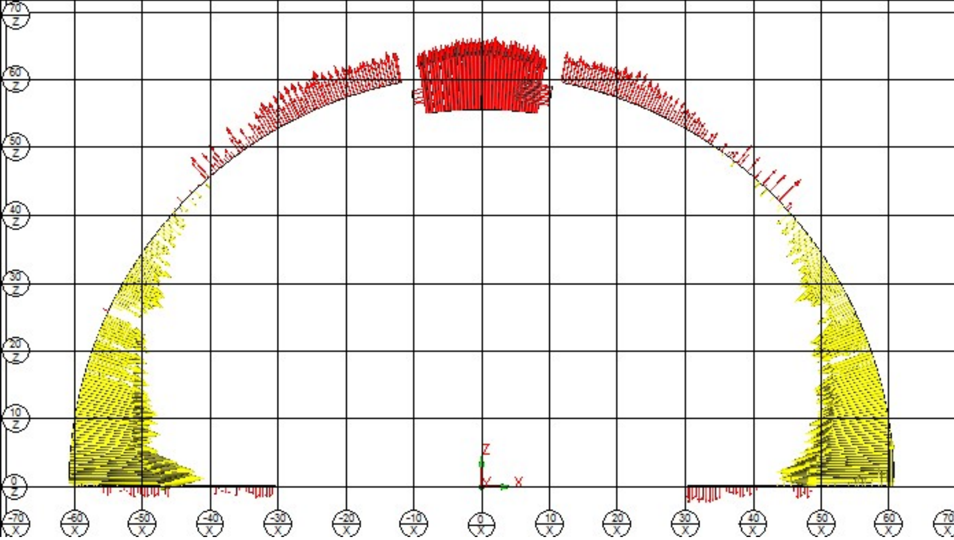
1160 mm from RE

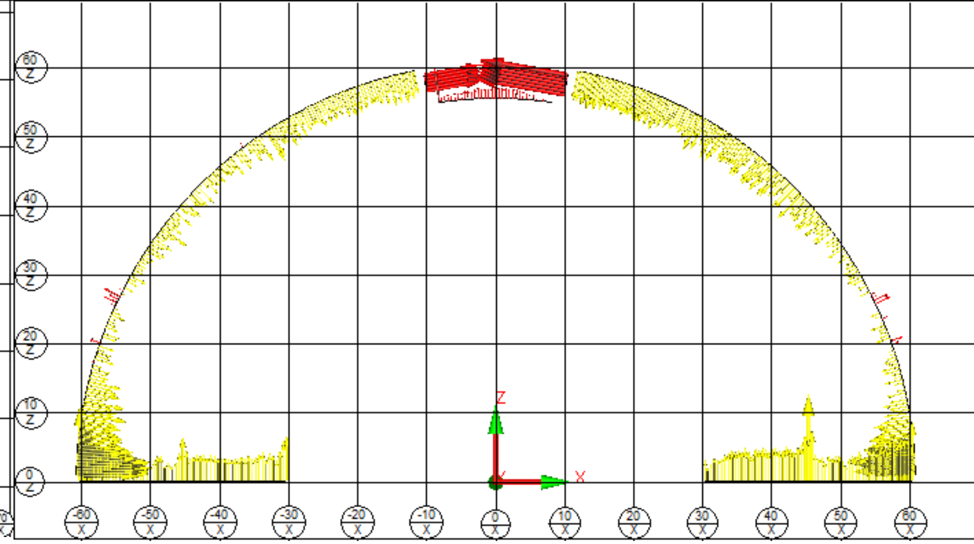
1260 mm from RE



552 mm from RE

652 mm from RE





455 mm from RE

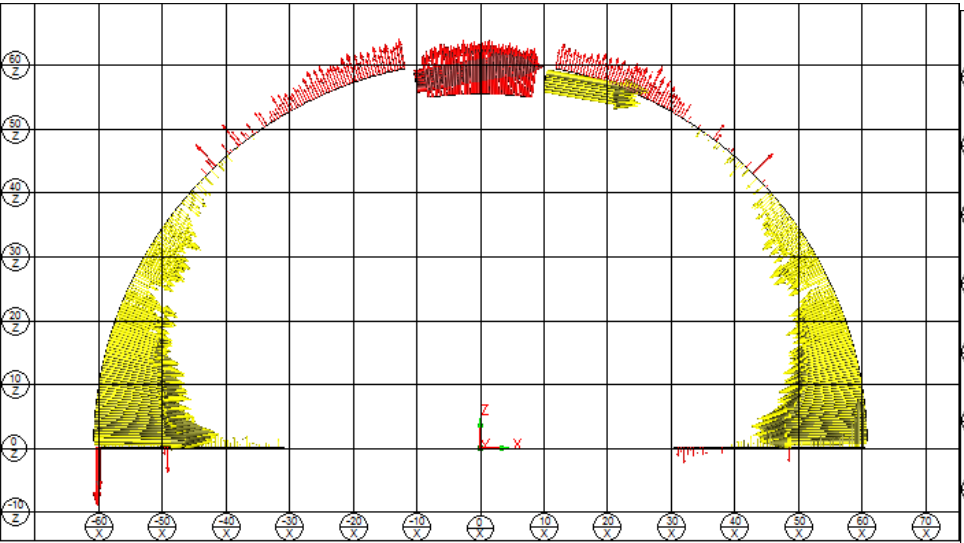
552 mm from RE

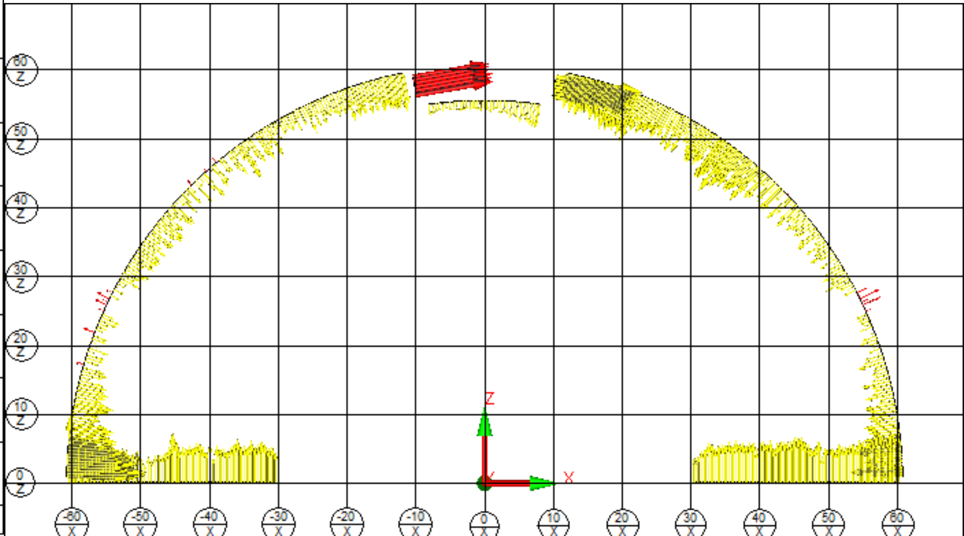
Before MM

After MM

705 mm from RE

652 mm from RE

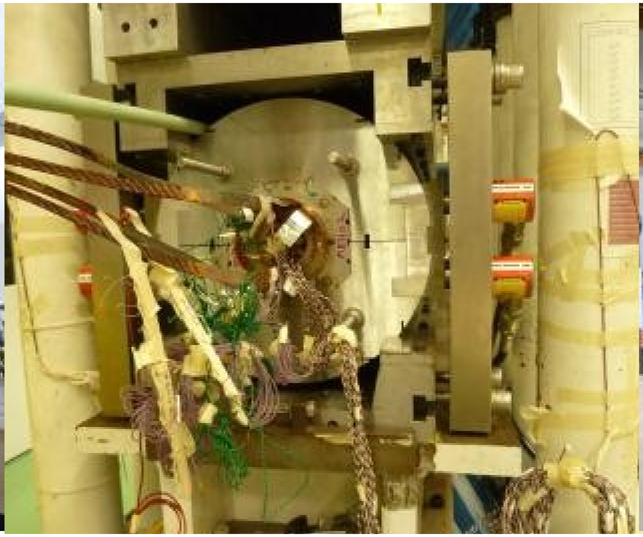


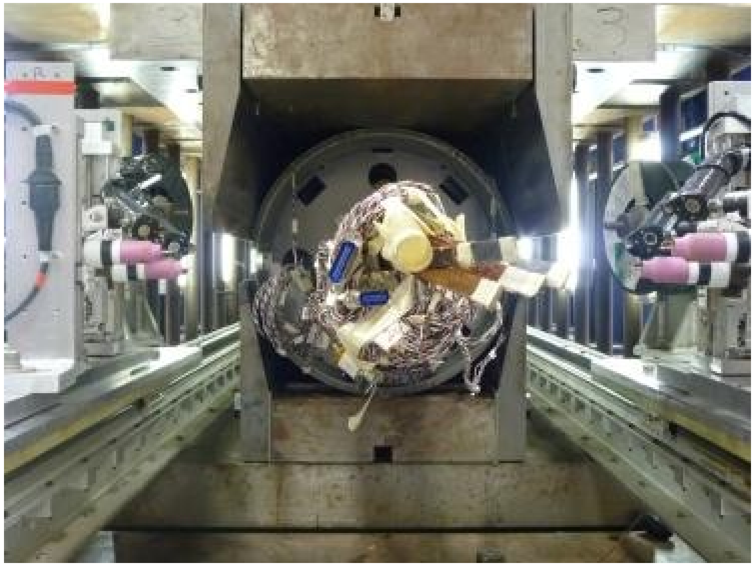


Demonstrator Collaring

- Measured signals from the strain gauges in line with the mechanical model.

Demonstrator Cold-mass Assembly





24/05/2012

FNAL Activities

- Demo test in June
- 2 lengths of cored RRP 151/169 cable available for 1 m coils.
- Cabling trials in progress to validate single pass process (like CERN).
- Design of 5.5 m long coil fabrication tooling in progress.
- Infrastructure for 5.5 m long coils exists (winding, curing, reaction, impregnation, coil assy, collaring).

FNAL Milestones

- 1-in-1 Demonstrator test Jun-12
- 1 m model (cored RRP-151/169)
  - Coil fabrication Jun..Aug-12
  - Cold mass assembly Nov-12
  - Test Dec-12
- 2-in-1 Demonstrator (2 m)
  - Coils for aperture-1 Aug..Oct-12
  - 1-in-1 assembly and test Feb-13
  - Coils for aperture-2 Nov..Feb-13
  - 1-in-1 assembly and test Q2-13
  - 2-in-1 assembly and test (@cern) Q3-13
- 5.5 m prototype magnet
  - Practice coil (Cu) Q2-13
  - Practice coil (Nb3Sn) Q4-13
  - Coils for aperture-1 & mirror tests Q2-14
  - Collared coil Q3-14

CERN Design Effort

- 1-in-1 (2 m) magnet assembly and fabrication drawings being completed.
- 2-in-1 (2 m) magnet assembly in progress.
- Design of 5.5 m long tooling has begun.
- Collaring tooling design complete.
- Conceptual design of coil handling and assembly tooling complete. Fabrication design in progress.

Procurement

- Collar laminations for the mechanical model were delivered and inspected in CERN metrology lab. The order for collars for the aperture #1 was raised. Invitation to tender for the supply of collar laminations for aperture #2 to #5 being launched.
- 1-in-1 yoke laminations ordered.
- Order for the outer shells to raise.
- ODS copper alloy based wedges (Discup C3/30 material) expected in July.

- Winding tooling completed and commissioned.
- Curing tooling delivered.
- Reaction tooling delivered at CERN. Dimensional control underway.
- Reaction furnace commissioning planned for late July.
- Vacuum impregnation tooling order placed (lead-time 18 w)
- Vacuum impregnation tank expected in August.

CERN Milestones

- **Practice coils (2 m)**
  - **Practice coils #1-#2 (Cu) Jun..Aug-12**
  - **Practice coil #3 (ITER Nb3Sn) Aug..Sep-12**
  - **Practice coil #4 (LARP RRP 54/61) Oct..Nov-12**
  - **Mirror test at FNAL Jan-12**
- **2-in-1 Demonstrator (2 m)**
  - **Coils for aperture-1 (RRP 108/127) Jan..Mar-13**
  - **1-in-1 assembly and test Q2-13**
  - **Coils for aperture-2 (PIT) Apr..Jun-13**
  - **1-in-1 assembly and test Q3-13**
  - **2-in-1 assembly and test Q4-13**
- **5.5 m prototype magnet**
  - **Practice coil (Cu) Q1-14**
  - **Practice coil (Nb3Sn) Q2-14**
  - **Coils for aperture-1 & mirror tests Q4-14**
  - **Collared coil Q1-15**
  - **2-in-1 cold-mass and cryo-magnet Q2-15**
  - **Cold test Q3-15**