# 11 T Dipole Some Background on the Design Choices

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***On behalf of CERN-FNAL collaboration***

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***"Demonstrate the feasibility of an accelerator quality 2-m-long 2-in-1 dipole providing > 11 T with an adequate margin and being scalable up to 5.5 m"***

# *Outline*

- Project goals and plans
- Magnetic design
- FNAL Demonstrator design and  & coil technology
- CERN mechanical design
- Short model program milestones
- CERN R&D topics
- LARP and US Core Programs & 11 T Project
- Conclusions

# *11 T Dipole Design*

## Summary of the First Technical Discussions
## FNAL 24 Sep 2010

**M. Karppinen CERN TE-MSC-ML**

# Superconductor

- **ø0.7 mm OST 108/127 strand**
- **Rutherford cable**
  - **40 strands (limit of CERN cabling machine)**
  - **Transposition angle 14.5 degrees**
  - **Key-stone angle 0.9 degrees**
  - **Width 14.5 mm (+1.5% post-reaction)**
  - **Thick/Narrow edge 1.182 mm / 1.284 mm (+2% post-reaction)**
  - **25 µm stainless steel core**

***OST 0.7 mm strand was the only available choice***
***Cu/non-Cu ratio fixed (protection)***

# Insulation and Resin

- **S2/E-glass tape, 2 layers of 75 µm**
- **˜150 µm S2/E-glass sleeve braided on the cable. (Inorganic ceramic sizing)**
- **Resin:**
  - **CTD-101K (FNAL standard epoxy)**
  - **MY740/HY906/DY073-1 (100:8:1 pbw)**
  - **RAL epoxy resin system (tough at low-T)**
  - **Cyanate-esther blend**
  - **Polyimide (Matrimid)**

# Coil Design

- **Two layers, 6/7-block configuration, high outer layer pole angle (top turns of inner and outer layer either aligned or with a clear off-set)**
- **No grading**
- **Integrated pole (Ti-alloy, St.steel, or Bronze)**
- **Drawn bronze-wedges (Cu?). Tool $10k/6 weeks**
- **End spacers of the same material as the pole, design and procurement by CERN**
- **Quench heater only on the outer layer (quench analysis FNAL & CERN)**

# Model Length

- **The iron length shall be chosen to have similar saturation effects in 2-in-1 configuration to the long magnet**
- **To be confirmed with a 3D magnetic analysis**
- **Model length in the range of 1.2 to 1.5 m**
- **3.5 m model to would address the scale-up, but would use up the conductor stock**

# Collar

- **Round stainless steel collars with appropriate features for the alignment of the coils relative to the yoke**
- **Demonstrator collar as robust as possible with the goal of reaching min 11 T**
- **Final collar design requires magnetic and mechanical optimization of the 2-in-1 structure**
- **For 1.5 mm 316 LN, press tool ~$30k/2 months. FNAL will procure collars for all model magnets**
- **3 mm high-Mn steel for the series?**

# Yoke

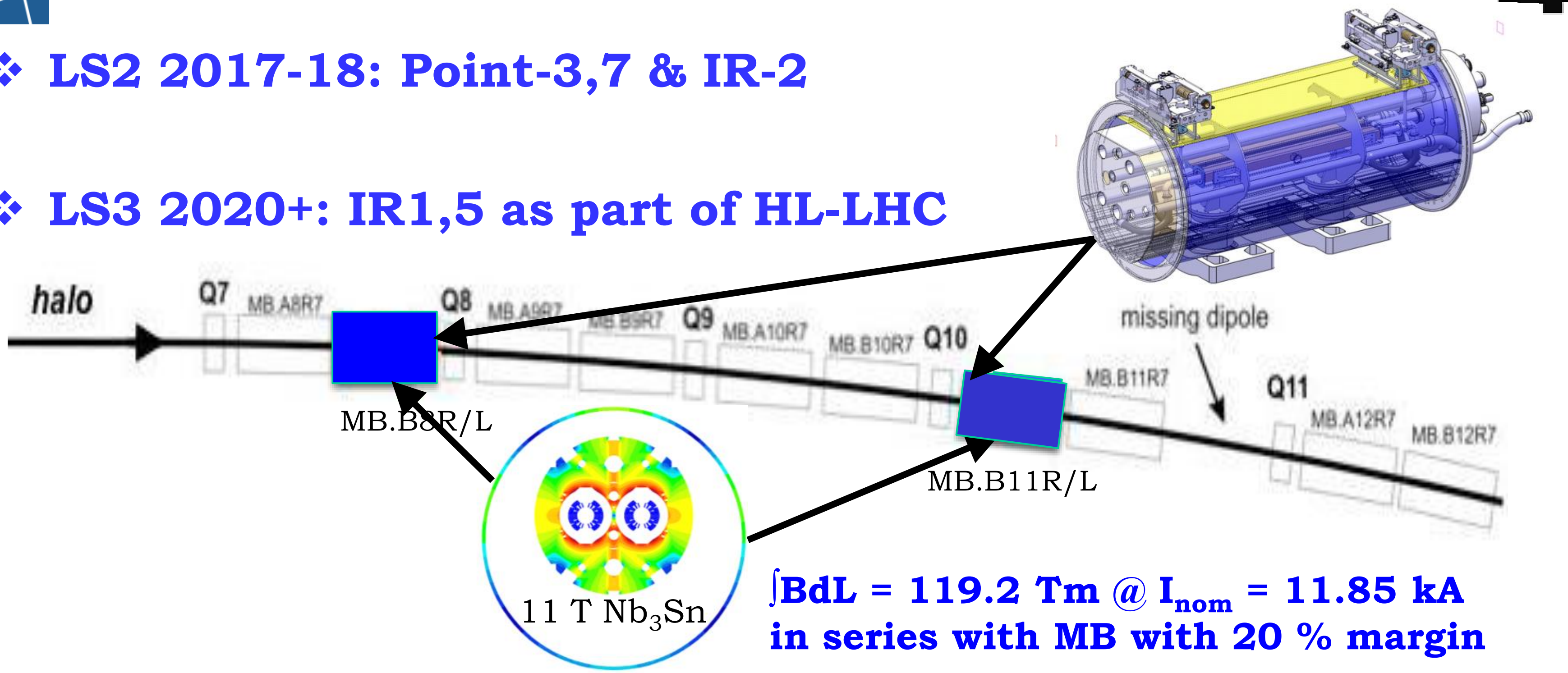
- **Structural element (collar-yoke interface, vert./hor. split, open/closed gap at RT, gap controllers etc.)**
- **FNAL tooling limited to ø400 mm OD**
- **Demonstrator: modify the existing yoke, order new bolt-on skin**
- **Single aperture: CERN CTF-like structure, bolted skin (3.5 m welded)**
- **2-in-1: MFISC-like design, welded skin**

# Tooling

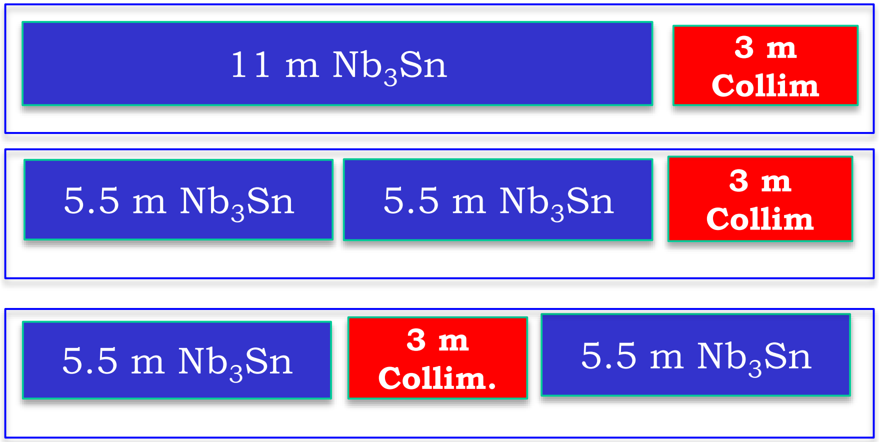
- **FNAL design the coil fabrication tooling**
- **CERN procures an additional set based on FNAL dwg (winding trials, 2nd coil production line)**
- **FNAL 2 m collaring press ok for ~130 MPa**
- **CERN can very rapidly wind, cure, vacuum-impregnate, and collar coils. Reaction will only be possible in the end of 2011.**
- **Coils wound at CERN can be reacted elsewhere in Europe or at FNAL**

# DS Upgrade

- **LS2 2017-18: Point-3,7 & IR-2**
- **LS3 2020+: IR1,5 as part of HL-LHC**



**$\int BdL = 119.2$ Tm @ $I_{nom} = 11.85$ kA**
**in series with MB with 20 % margin**



11 m $Nb_3Sn$ | **3 m Collim**

5.5 m $Nb_3Sn$ | 5.5 m $Nb_3Sn$ | **3 m Collim**

5.5 m $Nb_3Sn$ | **3 m Collim.** | 5.5 m $Nb_3Sn$

**LS2: 12 coldmass + 2 spares = 14 CM**
**LS3: 8 coldmass + 2 spares = 10 CM**
**Total 24 CM**

**LS2: 24 coldmass + 4 spares = 28 CM**
**LS3: 16 coldmass + 4 spares = 20 CM**
**Total 48 CM**

# 11 T Dipole Cold Mass

- **Cold mass length 5.5 m:**
  - **FNAL have coil fabrication and collaring tooling up to 6 m**
  - **Handling of 11 m coils is risky (250 kCHF of cable)**
  - **11-m-long coils require cable unit length of 1200 m**
- **Sagitta: 11 m – 5.0 mm, 5.5 m – 1.3 mm**
  - **Ø60 mm aperture and straight cold mass**
- **Integration in the LHC**
  - **2-in-1 design, intra-beam distance 194 mm**
  - **Bus-bar routing and heat exchanger location as MB**
- **Schedule and cost**
  - **Make use of existing tooling and infrastructure**
  - **Parallel production lines at CERN and FNAL**

# *11 T Model Program*

| Date | Description | Length | Remarks | Goals |
|---|---|---|---|---|
| End-2011 | 1-in-1 Demonstrator Magnet | 2 m | Construction at FNAL | Cable technology<br>Coil Technology<br>Quench performance<br>Magnetization effects |
| End-2012 | 2-in-1 Demonstrator Magnet 1 | 2 m | FNAL collared coils<br>CM-Assembly at CERN | 2-in-1 structure<br>Field quality:<br>- iron saturation<br>- cross-talk<br>- Magnetization effects<br>Quench performance<br>Reproducibility |
| Mid-2013 | 2-in-1 Demonstrator Magnet 2 | 2 m | CERN collared coils<br>CM-Assembly at CERN | |
| End-2014 | 2-in-1 Prototype Cold Mass | 5.5 m | Aperture 1 by FNAL<br>Aperture 2 by CERN<br>CM assembly at CERN | Scale-up<br>Long tooling<br>Fabrication of long coils<br>CM assembly<br>Magnetic performance |

# *11 T $Nb_3Sn$ Dipole Project*

## Short model program

- Magnetic and mechanical design validation
- Conductor development
- Magnet protection
- Material choices
- Fabrication process validation

## Scale-up

- Coil fabrication (winding, curing, reaction, impregnation)
- Handling
- Cold mass integration (collaring, yoke assembly)

## Cold mass integration

- Cold bore tube
- Bus-bar routing
- Interconnects
- Spool correctors
- Heat exchanger
- Instrumentation
- Alignment

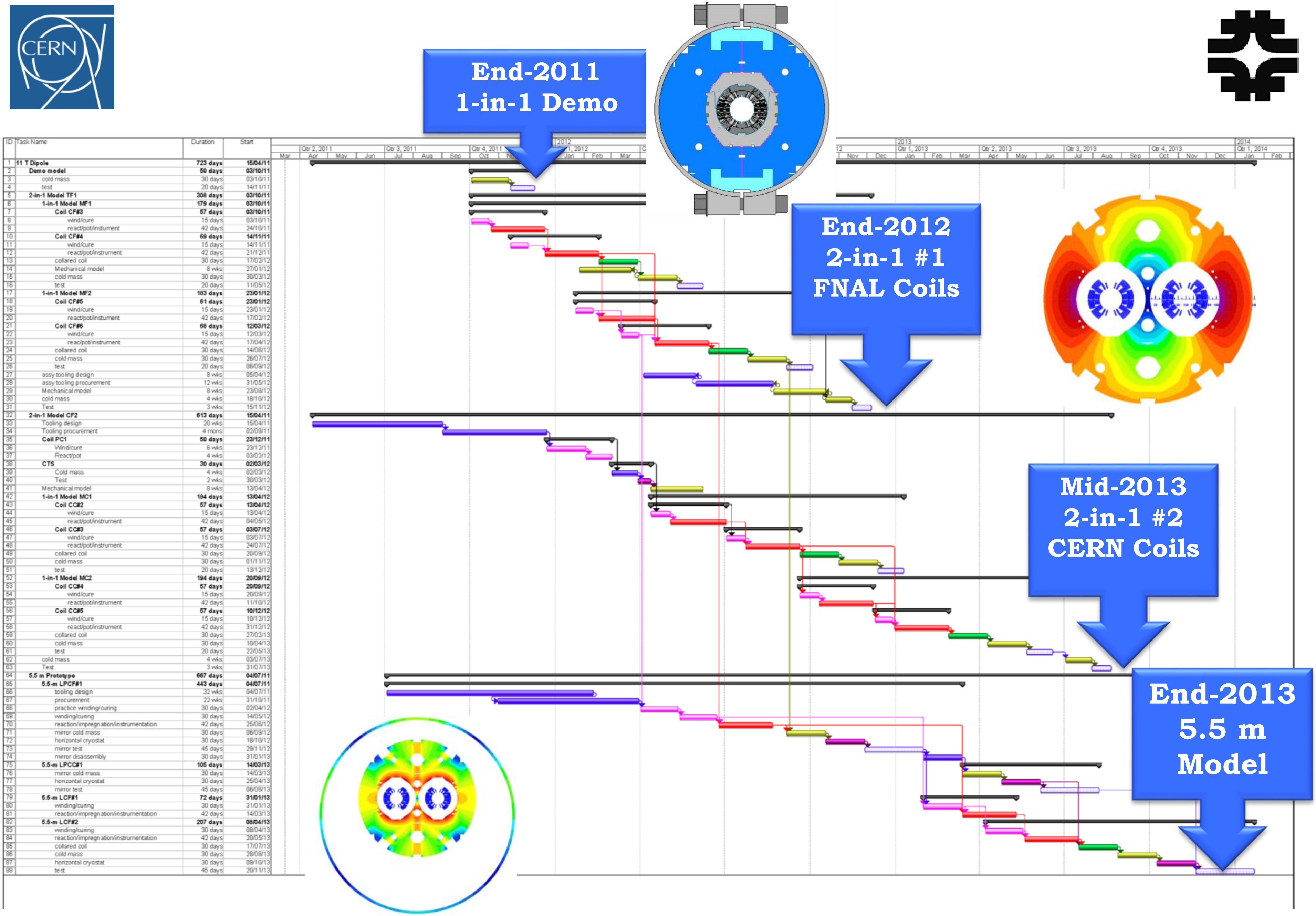
## Cryo-assembly (5.5 m)

- Cold-test in SM18

## Collimator integration

- Collimator dimensions
- Interfaces (powering, instrumentation, vacuum, cryogenics, …)
- Cryostat design
- QC and testing

## Transport & handling



**End-2011**
**1-in-1 Demo**

**End-2012**
**2-in-1 #1**
**FNAL Coils**

**Mid-2013**
**2-in-1 #2**
**CERN Coils**

**End-2013**
**5.5 m**
**Model**

| ID | Task Name | Duration | Start |
|---|---|---|---|
| 1 | **11 T Dipole** | **723 days** | **15/04/11** |
| 2 | **Demo model** | **50 days** | **03/10/11** |
| 3 | cold mass | 30 days | 03/10/11 |
| 4 | test | 20 days | 14/11/11 |
| 5 | **2-in-1 Model TF1** | **308 days** | **03/10/11** |
| 6 | **1-in-1 Model MF1** | **179 days** | **03/10/11** |
| 7 | **Coil CF#3** | **57 days** | **03/10/11** |
| 8 | wind/cure | 15 days | 03/10/11 |
| 9 | react/pot/instument | 42 days | 24/10/11 |
| 10 | **Coil CF#4** | **69 days** | **14/11/11** |
| 11 | wind/cure | 15 days | 14/11/11 |
| 12 | react/pot/instrument | 42 days | 21/12/11 |
| 13 | collared coil | 30 days | 17/02/12 |
| 14 | Mechanical model | 8 wks | 27/01/12 |
| 15 | cold mass | 30 days | 30/03/12 |
| 16 | test | 20 days | 11/05/12 |
| 17 | **1-in-1 Model MF2** | **183 days** | **23/01/12** |
| 18 | **Coil CF#5** | **61 days** | **23/01/12** |
| 19 | wind/cure | 15 days | 23/01/12 |
| 20 | react/pot/instument | 42 days | 17/02/12 |
| 21 | **Coil CF#6** | **68 days** | **12/03/12** |
| 22 | wind/cure | 15 days | 12/03/12 |
| 23 | reac/pot/instrument | 42 days | 17/04/12 |
| 24 | collared coil | 30 days | 14/06/12 |
| 25 | cold mass | 30 days | 26/07/12 |
| 26 | test | 20 days | 06/09/12 |
| 27 | assy tooling design | 8 wks | 05/04/12 |
| 28 | assy tooling procurement | 12 wks | 31/05/12 |
| 29 | Mechanical model | 8 wks | 23/08/12 |
| 30 | cold mass | 4 wks | 18/10/12 |
| 31 | Test | 3 wks | 15/11/12 |
| 32 | **2-in-1 Model CF2** | **613 days** | **15/04/11** |
| 33 | Tooling design | 20 wks | 15/04/11 |
| 34 | Tooling procurement | 4 mons | 02/09/11 |
| 35 | **Coil PC1** | **50 days** | **23/12/11** |
| 36 | Wind/cure | 6 wks | 23/12/11 |
| 37 | React/pot | 4 wks | 03/02/12 |
| 38 | **CTS** | **30 days** | **02/03/12** |
| 39 | Cold mass | 4 wks | 02/03/12 |
| 40 | Test | 2 wks | 30/03/12 |
| 41 | Mechanical model | 8 wks | 13/04/12 |
| 42 | **1-in-1 Model MC1** | **194 days** | **13/04/12** |
| 43 | **Coil CC#2** | **57 days** | **13/04/12** |
| 44 | wind/cure | 15 days | 13/04/12 |
| 45 | react/pot/instrument | 42 days | 04/05/12 |
| 46 | **Coil CC#3** | **57 days** | **03/07/12** |
| 47 | wind/cure | 15 days | 03/07/12 |
| 48 | react/pot/instrument | 42 days | 24/07/12 |
| 49 | collared coil | 30 days | 20/09/12 |
| 50 | cold mass | 30 days | 01/11/12 |
| 51 | test | 20 days | 13/12/12 |
| 52 | **1-in-1 Model MC2** | **194 days** | **20/09/12** |
| 53 | **Coil CC#4** | **57 days** | **20/09/12** |
| 54 | wind/cure | 15 days | 20/09/12 |
| 55 | react/pot/instrument | 42 days | 11/10/12 |
| 56 | **Coil CC#5** | **57 days** | **10/12/12** |
| 57 | wind/cure | 15 days | 10/12/12 |
| 58 | react/pot/instrument | 42 days | 31/12/12 |
| 59 | collared coil | 30 days | 27/02/13 |
| 60 | cold mass | 30 days | 10/04/13 |
| 61 | test | 20 days | 22/05/13 |
| 62 | cold mass | 4 wks | 03/07/13 |
| 63 | Test | 3 wks | 31/07/13 |
| 64 | **5.5 m Prototype** | **667 days** | **04/07/11** |
| 65 | **5.5-m LPCF#1** | **443 days** | **04/07/11** |
| 66 | tooling design | 32 wks | 04/07/11 |
| 67 | procurement | 22 wks | 31/10/11 |
| 68 | practice winding/curing | 30 days | 02/04/12 |
| 69 | winding/curing | 30 days | 14/05/12 |
| 70 | reaction/impregnation/instrumentation | 42 days | 25/06/12 |
| 71 | mirror cold mass | 30 days | 06/09/12 |
| 72 | horizontal cryostat | 30 days | 18/10/12 |
| 73 | mirror test | 45 days | 29/11/12 |
| 74 | mirror disassembly | 30 days | 31/01/13 |
| 75 | **5.5-m LPCC#1** | **105 days** | **14/03/13** |
| 76 | mirror cold mass | 30 days | 14/03/13 |
| 77 | horizontal cryostat | 30 days | 25/04/13 |
| 78 | mirror test | 45 days | 06/06/13 |
| 79 | **5.5-m LCF#1** | **72 days** | **31/01/13** |
| 80 | winding/curing | 30 days | 31/01/13 |
| 81 | reaction/impregnation/instrumentation | 42 days | 14/03/13 |
| 82 | **5.5-m LCF#2** | **207 days** | **08/04/13** |
| 83 | winding/curing | 30 days | 08/04/13 |
| 84 | reaction/impregnation/instrumentation | 42 days | 20/05/13 |
| 85 | collared coil | 30 days | 17/07/13 |
| 86 | cold mass | 30 days | 28/08/13 |
| 87 | horizontal cryostat | 30 days | 09/10/13 |
| 88 | test | 45 days | 20/11/13 |

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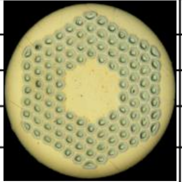
# Strand & Cable

| **11 T DS Dipole**<br>**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 stability!**

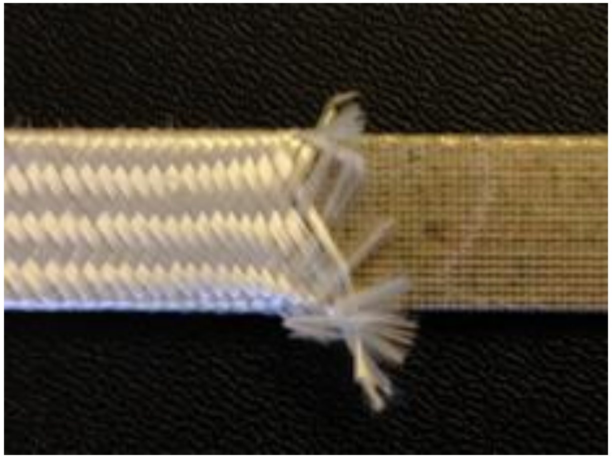
**Cable samples made with and without SS core show $I_c$-degradation well within the initial goal of 10 %.**

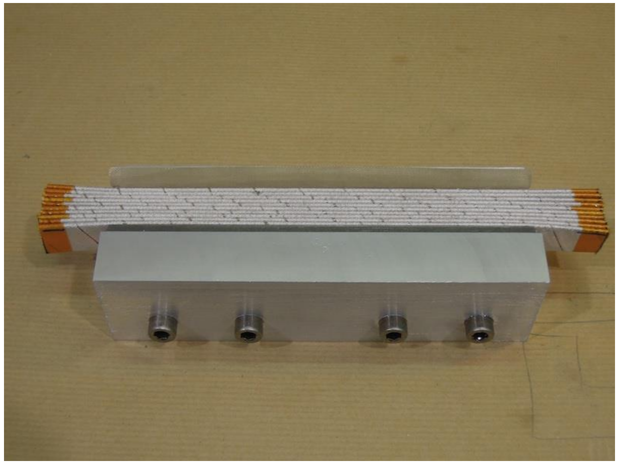
**Cored cable with RRP 151/169 being developed at FNAL.**

- **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**

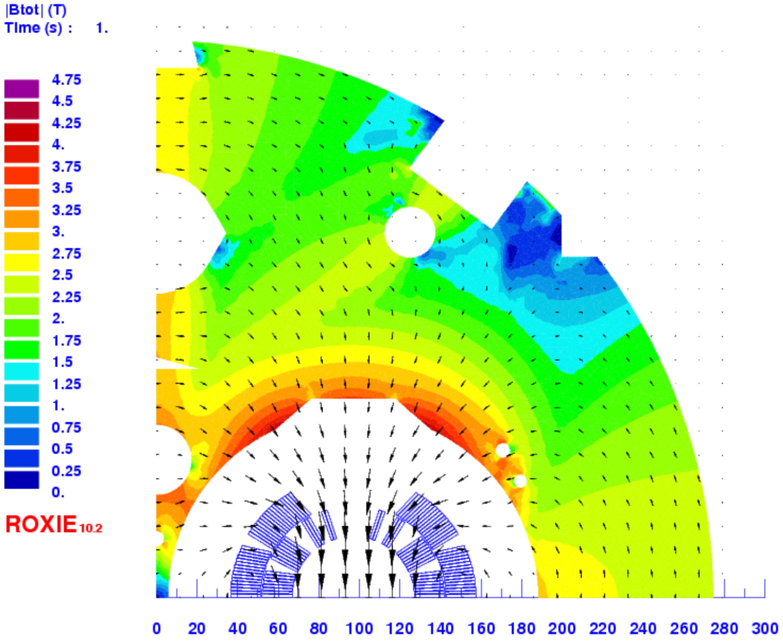
# *Cable Insulation*

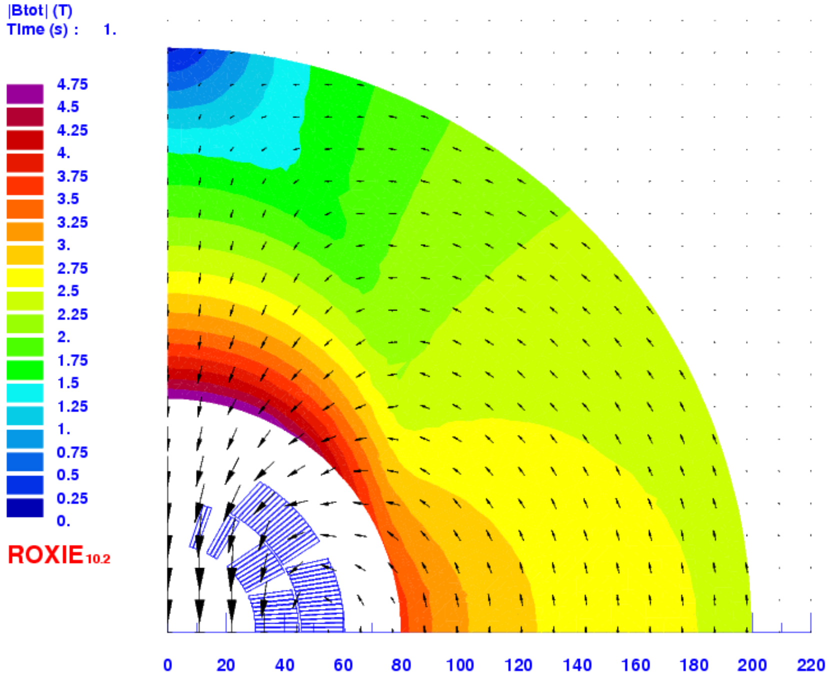
- **Base-line:**
  - **E-Glass thickness – 0.150, 0.075 mm x 12.7-mm wide E-glass 50% overlap.**
- **Alternative insulation methods:**
  - **S2-glass tape**
  - **S2-glass sleeve (LARP)**
  - **S2-glass braiding directly on the cable**
  - **90 μm Mica with E/S-glass tape**
  - **90 μm Mica with E/S-glass braiding (?)**





# 2D-Models used for Coil Optimization

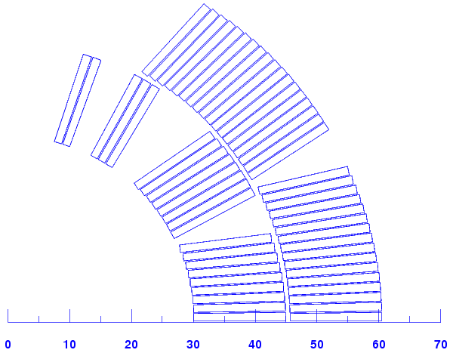




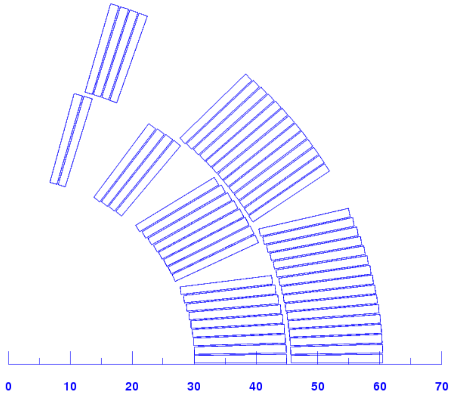
- **The coil optimization was done with non-optimized iron to rapidly launch the coil fabrication for the demonstrator.**
- **The plan was to tune the field quality after magnetic meas. of the model magnets**

| **1-in-1 Yoke ID/OD** | **130/400** | **160/400** | **200/400** | **200/550** | **160/550** |
|---|---|---|---|---|---|
| $B_0$(T) | 11.66 | 11.22 | 10.76 | 11.20 | 11.67 |

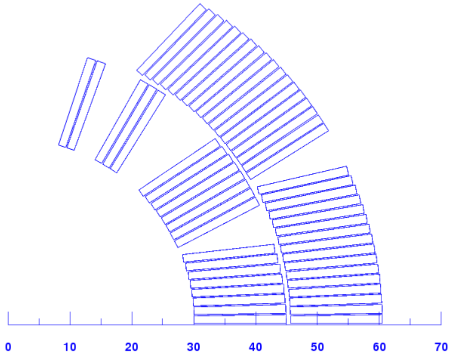
# *Possible Coil X-Sections*



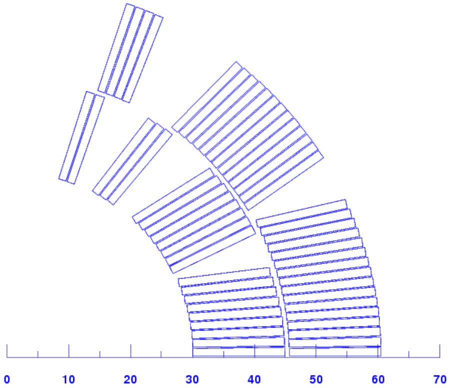
**6 Blocks**
**56 turns**



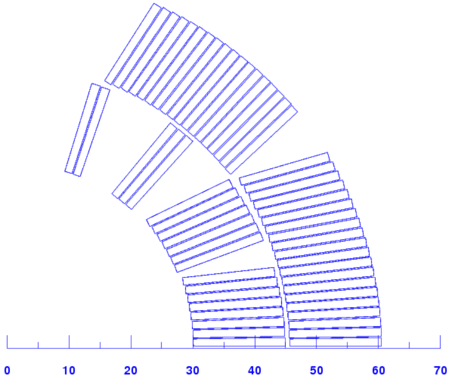
7 Blocks
56 turns



6 Blocks SS Core
55 turns



7 Block SS Core
55 turns



6 Block SS Core
58 turns

# Parameters of Coil X-Sections

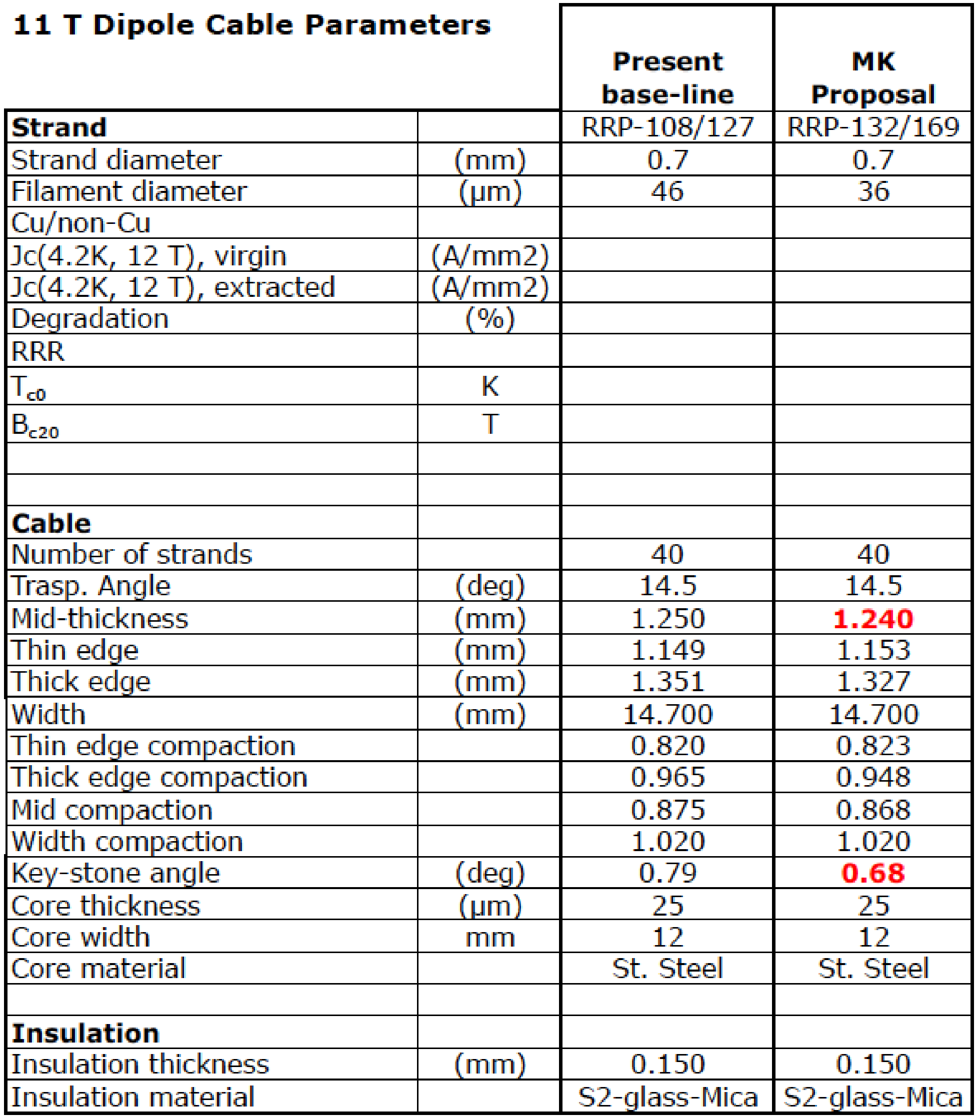
| Parameters | 6-Block | | | | | | 7-Block | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1-in-1 | 2-in-1 | 1-in-1 | 2-in-1 | 1-in-1 | 2-in-1 | 1-in-1 | 2-in-1 | 1-in-1 | 2-in-1 |
| Coil aperture, mm | 60 | | | | | | | | | |
| Nominal current, A | 11850 | | | | | | | | | |
| Cable core | N | | Y | | Y | | N | | Y | |
| Nominal field, T | 11.22 | 11.21 | 11.01 | 10.98 | 11.23 | 11.23 | 11.13 | 11.10 | 10.97 | 10.94 |
| Margin (load-line), % | 19.0 | 19.1 | 20.0 | 20.3 | 19.1 | 19.2 | 19.6 | 19.8 | 20.4 | 20.6 |
| Magnetic length, m | 10.62 | 10.62 | 10.82 | 10.85 | 10.60 | 10.61 | 10.71 | 10.73 | 10.85 | 10.89 |
| Peak field, T | 11.60 | 11.56 | 11.40 | 11.36 | 11.58 | 11.56 | 11.47 | 11.44 | 11.34 | 11.29 |
| Peak/Central field | 1.03 | 1.03 | 1.04 | 1.03 | 1.03 | 1.03 | 1.03 | 1.03 | 1.03 | 1.03 |
| Inductance, mH | 70.6 | 141.1 | 69.6 | 138.0 | 72.4 | 144.7 | 68.6 | 137.1 | 67.9 | 135.7 |
| Differ. inductance, mH | 58.8 | 127.0 | 57.8 | 124.1 | 60.3 | 130.1 | 57.1 | 123.5 | 56.4 | 122.2 |
| Stored energy, MJ | 5.3 | 10.1 | 5.2 | 10.0 | 5.5 | 10.5 | 5.2 | 9.9 | 5.1 | 9.8 |
| Number of turns/pole | 56 | 56 | 55 | 55 | 58 | 58 | 56 | 56 | 55 | 55 |
| Inner layer | 22 | 22 | 21 | 21 | 20 | 20 | 23 | 23 | 22 | 22 |
| Outer layer | 34 | 34 | 34 | 34 | 38 | 38 | 33 | 33 | 33 | 33 |

- **56 turns is the sweet spot with 22 turn on the IL**
- **Fitting 22 turns on the IL tight and only allows for very small increase of the thin edge thickness (key stone angle/compaction)**
- **Any change in cable dimension meant re-optimization of the X-section**

# Cable Parameters & Stability

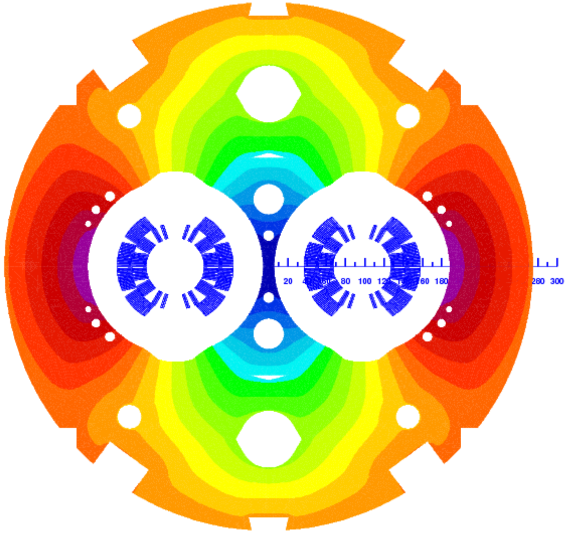
- **Improve cable mechanical stability**
  - **Compact more on outer edge**
- **Minimise Jc degradation**
  - **Compact less on the inner edge**
- **Fit 22 turns on IL**
- **Use existing wedges and end parts**

- **Keystone angle 0.79 => 0.68 deg**
- **Mid-thickness 1.250 => 1.240 mm**

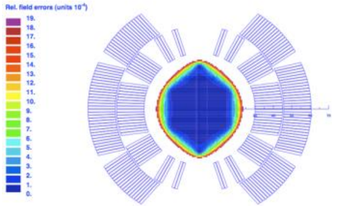


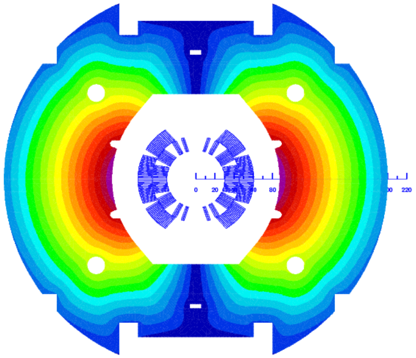
| **11 T Dipole Cable Parameters** | | **Present base-line** | **MK Proposal** |
|---|---|---|---|
| **Strand** | | RRP-108/127 | RRP-132/169 |
| Strand diameter | (mm) | 0.7 | 0.7 |
| Filament diameter | (µm) | 46 | 36 |
| Cu/non-Cu | | | |
| Jc(4.2K, 12 T), virgin | (A/mm2) | | |
| Jc(4.2K, 12 T), extracted | (A/mm2) | | |
| Degradation | (%) | | |
| RRR | | | |
| $T_{c0}$ | K | | |
| $B_{c20}$ | T | | |
| | | | |
| | | | |
| **Cable** | | | |
| Number of strands | | 40 | 40 |
| Trasp. Angle | (deg) | 14.5 | 14.5 |
| Mid-thickness | (mm) | 1.250 | **1.240** |
| Thin edge | (mm) | 1.149 | 1.153 |
| Thick edge | (mm) | 1.351 | 1.327 |
| Width | (mm) | 14.700 | 14.700 |
| Thin edge compaction | | 0.820 | 0.823 |
| Thick edge compaction | | 0.965 | 0.948 |
| Mid compaction | | 0.875 | 0.868 |
| Width compaction | | 1.020 | 1.020 |
| Key-stone angle | (deg) | 0.79 | **0.68** |
| Core thickness | (µm) | 25 | 25 |
| Core width | mm | 12 | 12 |
| Core material | | St. Steel | St. Steel |
| | | | |
| **Insulation** | | | |
| Insulation thickness | (mm) | 0.150 | 0.150 |
| Insulation material | | S2-glass-Mica | S2-glass-Mica |

# Coil Design

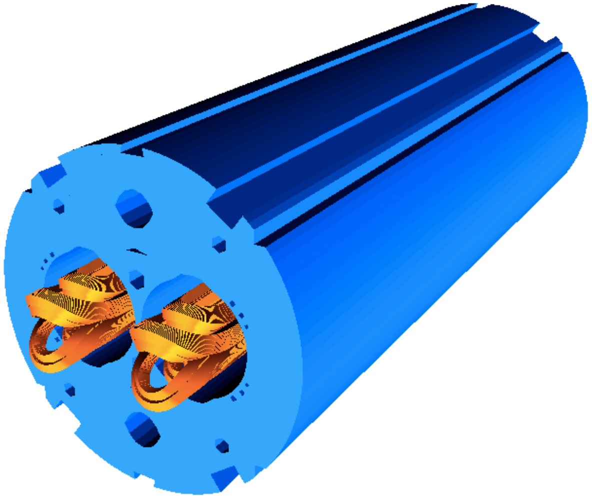


$B_0$(11.85 kA) = 11.21 T



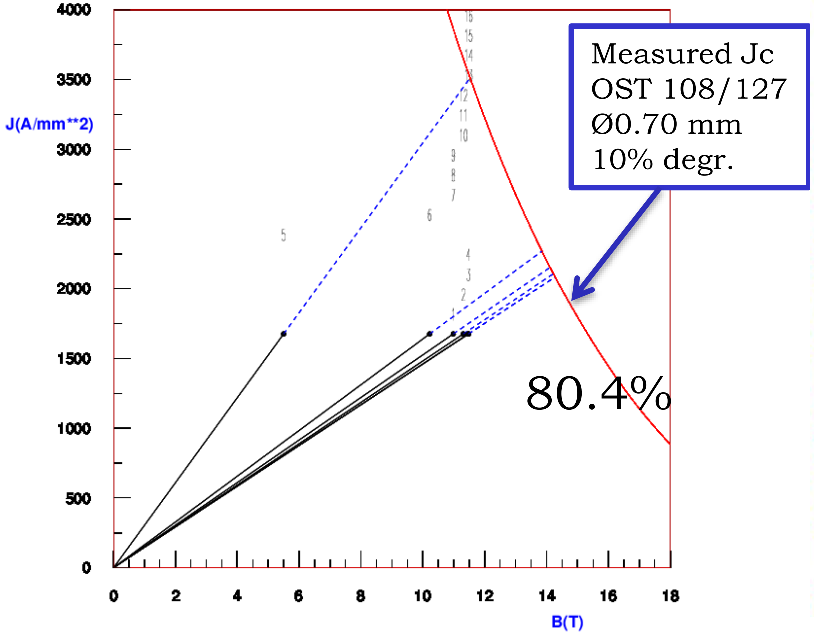


$B_0$(11.85 kA) = 10.86 T

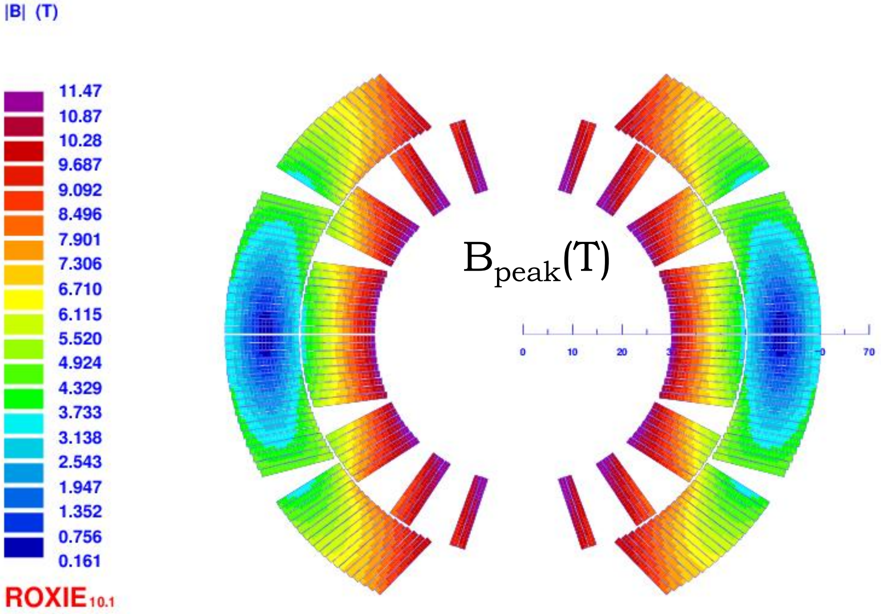


- **Coil optimization**
  - >11 T at 11.85 kA with 20% margin at 1.9 K
  - Field errors below the $10^{-4}$ level
- **6-block design, 56 turns (IL 22, OL 34)**
  - 14.85-mm-wide 40-strand Rutherford cable, no internal splice
  - Several X-sections were analyzed with and without core
  - Coil ends optimized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

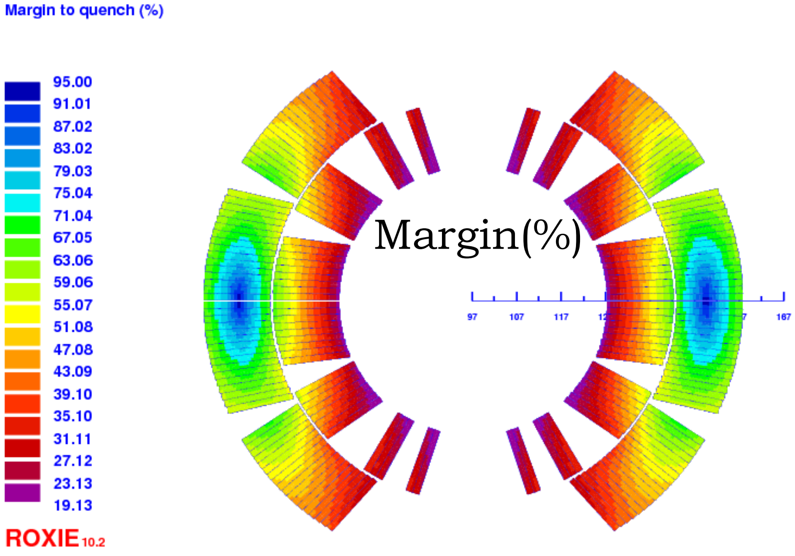
# *Working point & Margins*



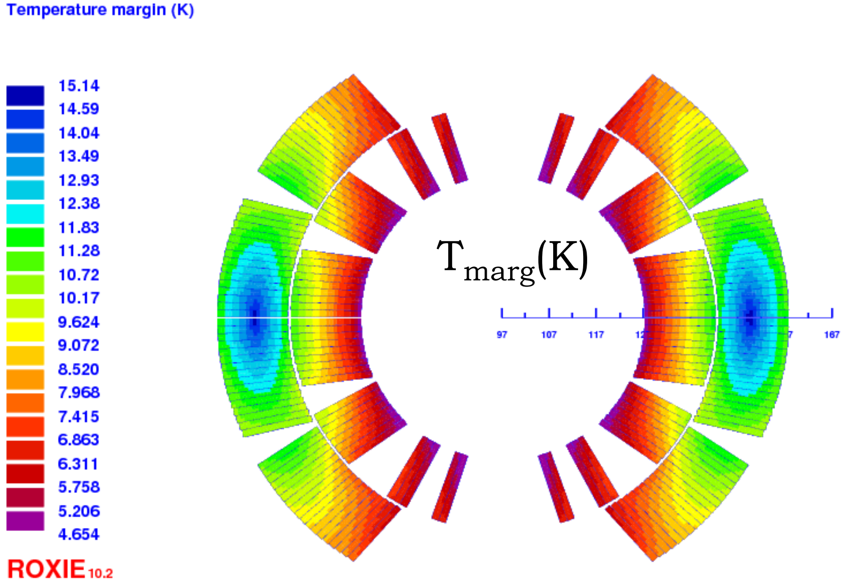
Measured Jc
OST 108/127
Ø0.70 mm
10% degr.



$B_{peak}$(T)



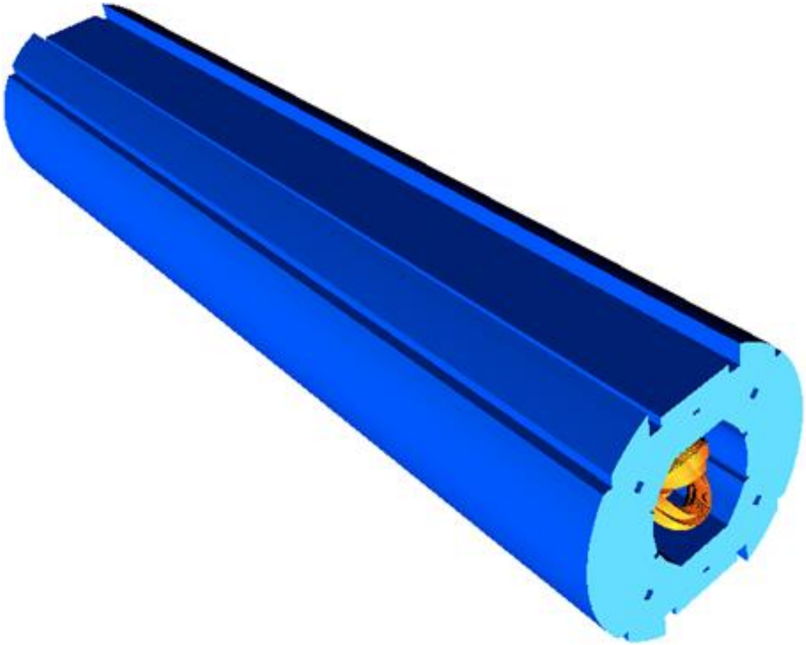
Margin(%)



$T_{marg}$(K)

# *3D Models*

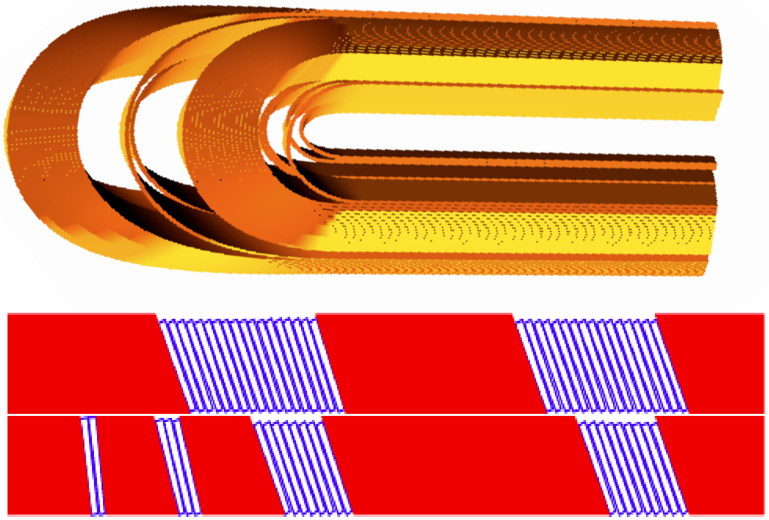
**Yoke cut-back determined such that the Bp is in the straight section**



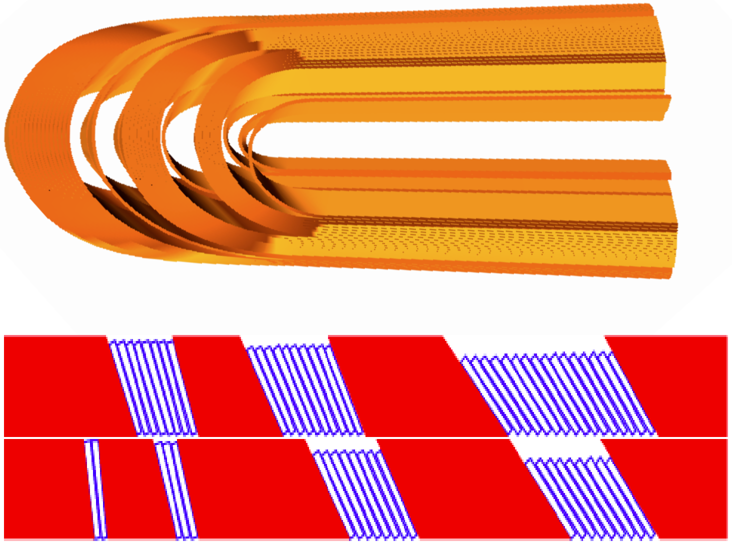
**1-in-1 Demonstrator Dipole**
**Yoke covers the ends.**
**=> Bp = +0.25 T**

# End Design

## Up-right End



## Minimum Strain End



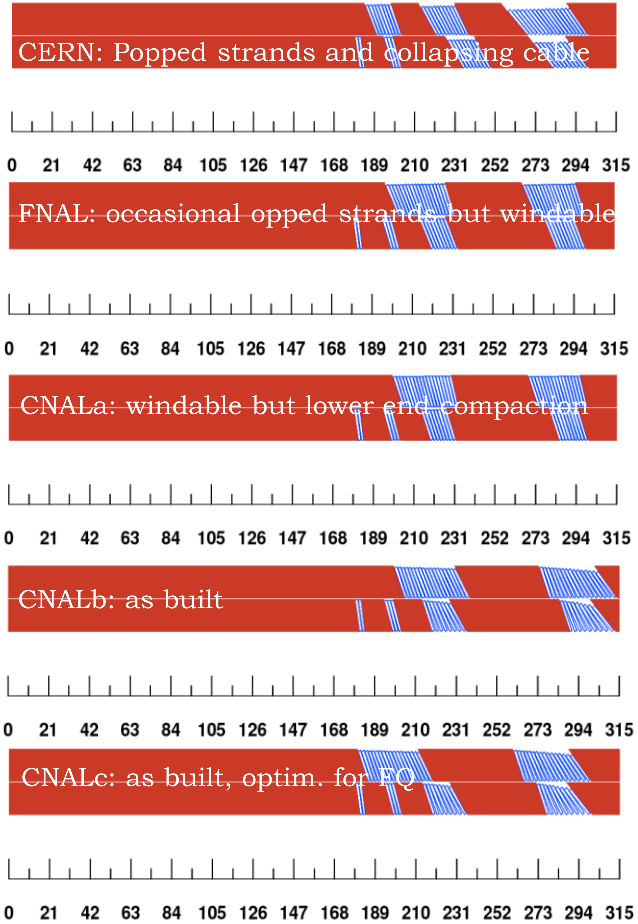
- Based on FNAL experience
- Smaller voids to fill on yz-plane
- More hard-way strain during winding
- 2 winding blocks on the outer layer ends

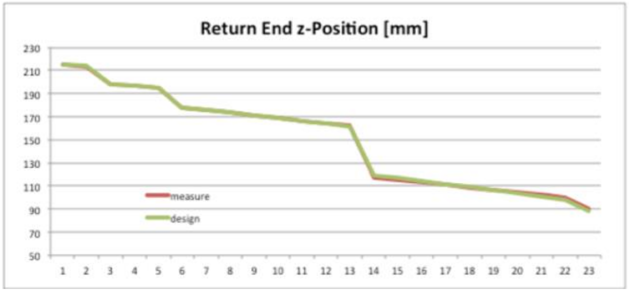
- Based on CERN experience
- Larger voids to fill on yz-plane
- Minimum hard-way strain during winding
- 3 winding blocks on the outer layer ends

**Balance between torsion, strain, and bending**

# Evolution of Coil Ends

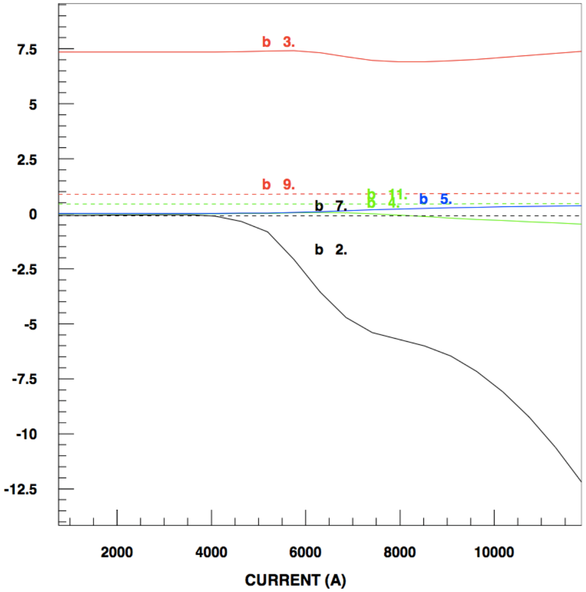
- **Five design iterations:**
  - **CERN: minimize hardway bend**
  - **FNAL: minimize upper gap**
  - **CNALa: minimize torsion**
  - **CNALb: as built (FNAL Coils)**
  - **CNALc: as built with FQ optim. (CERN coils)**
- **Turn-by-turn winding follow-up to enhance reproducibility.**

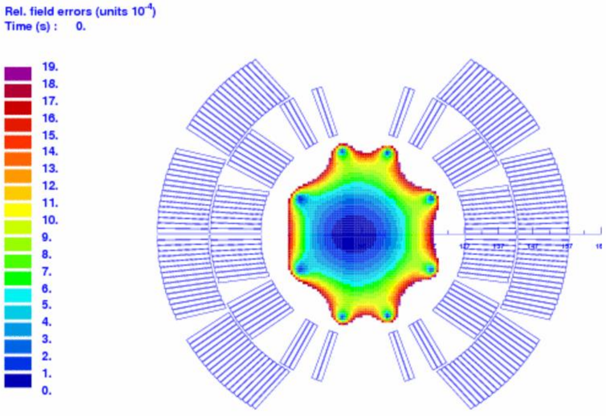




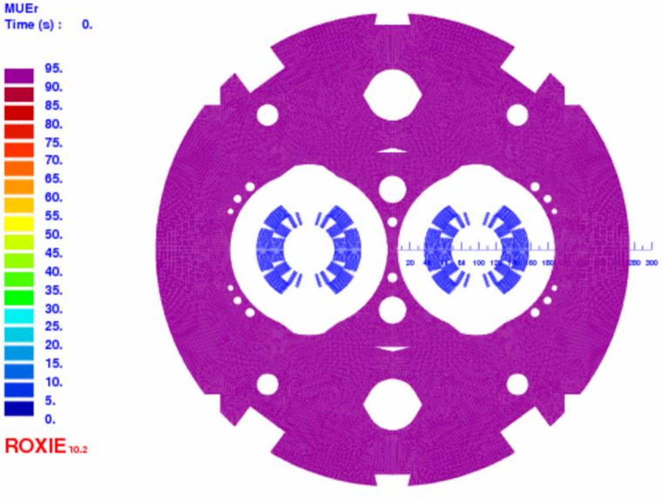
| | CERN | | FNAL | | CNAL | |
|---|---|---|---|---|---|---|
| **Block** | Torsion | Hard-way | Torsion | Hard-way | Torsion | Hard-way |
| **1** | 43 | 8 | 29 | 28 | 29 | 31 |
| **2** | 46 | 9 | 37 | 20 | 33 | 29 |
| **3** | 35 | 7 | 35 | 7 | 32 | 9 |
| **4** | 32 | 11 | 32 | 11 | 32 | 11 |
| **5** | 25 | 8 | 21 | 21 | 18 | 25 |
| **6** | 25 | 7 | 37 | 24 | 27 | 40 |
| **7** | 34 | 9 | n/a | n/a | n/a | n/a |

# *Iron Saturation*





Relative FQ (units)



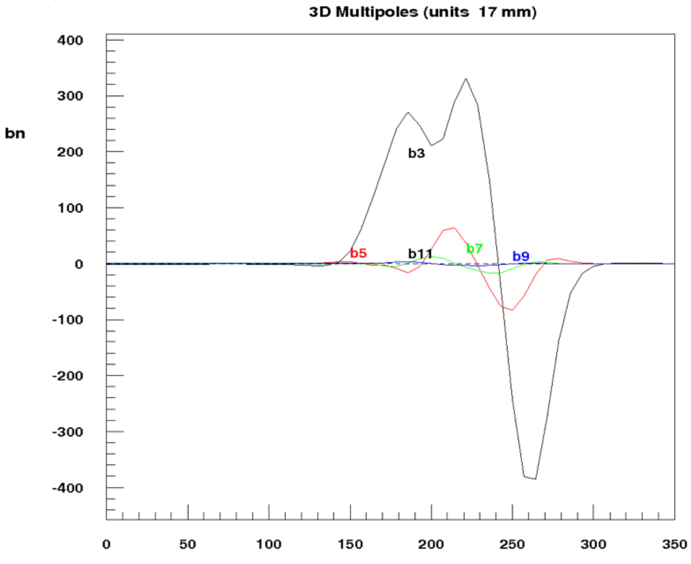
Relative permeability

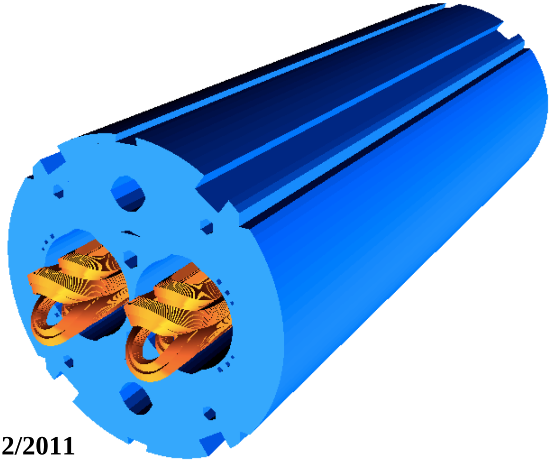
- **Yoke design**
  - **The cut-outs on top of the aperture reduce the $b_3$ variation by 4.7 units as compared to a circular shape.**
  - **The holes in the yoke reduce the $b_3$ variation by 2.4 units.**
  - **The two holes in the yoke insert reduce the $b_2$ variation from 16 to 12 units.**
  - **Systematic b3 offset was to be addressed after model magnet results**

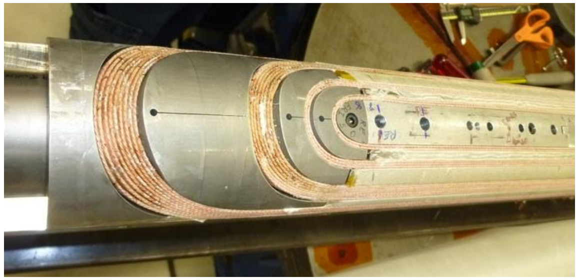
# 3-D Field Quality

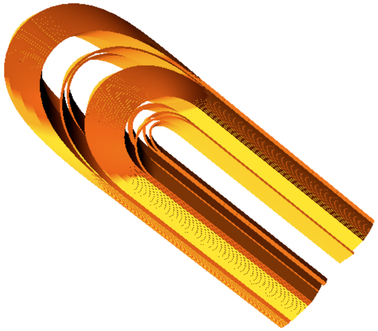
- **3-D integrated harmonics vs. 2-D harmonics @ $I_{nom}$**
  - **Optimized 3-D coil design.**
  - **Cross-talk in the ends ➔ increase in $b_2$.**
  - **Need to control winding accuracy.**

| | **2-D** | **3-D** |
|---|---|---|
| **$b_2$** | **-12.5** | **-15.8** |
| $b_3$ | 7.4 | 7.4 |
| $b_5$ | 0.4 | 0.6 |
| $b_7$ | -0.1 | -0.2 |
| $b_9$ | 0.9 | 0.8 |

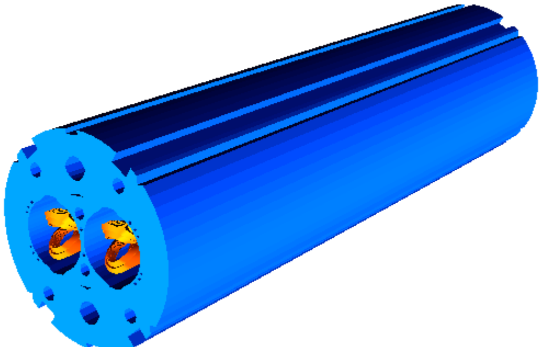


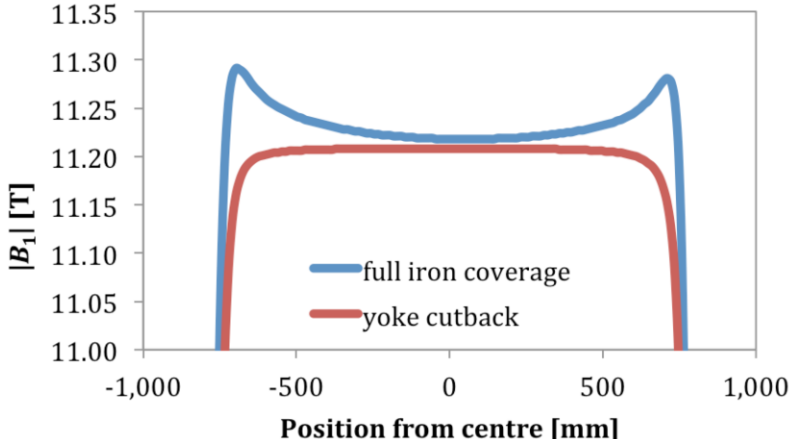


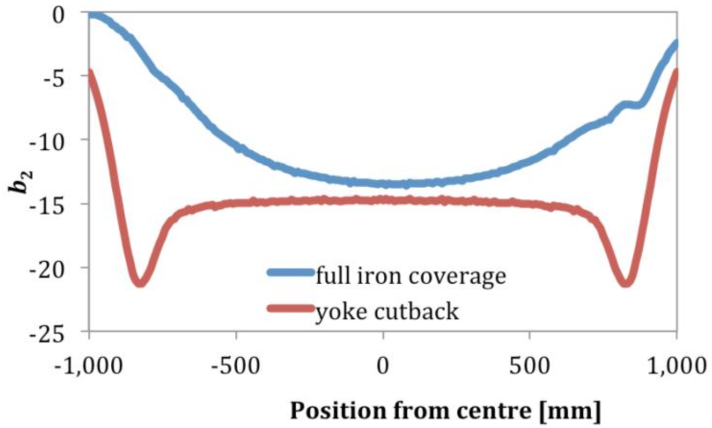


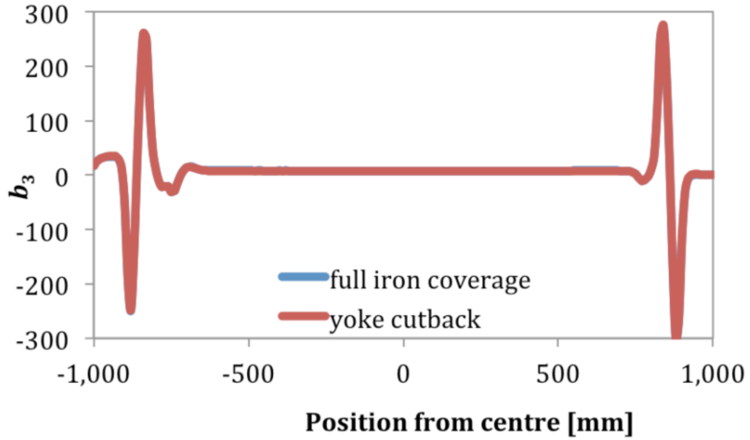


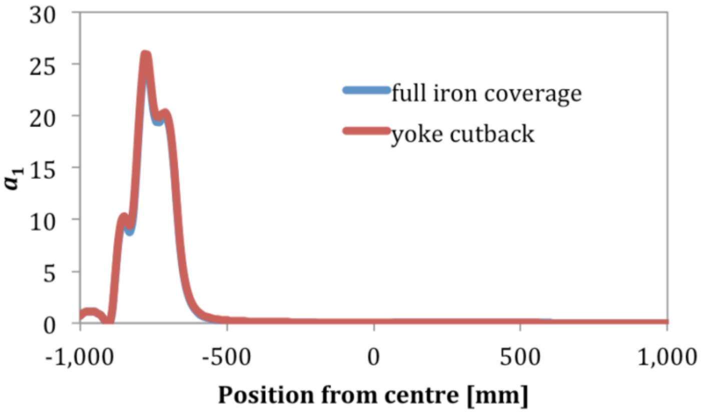
# Yoke Cut-Back Impact on Field Quality







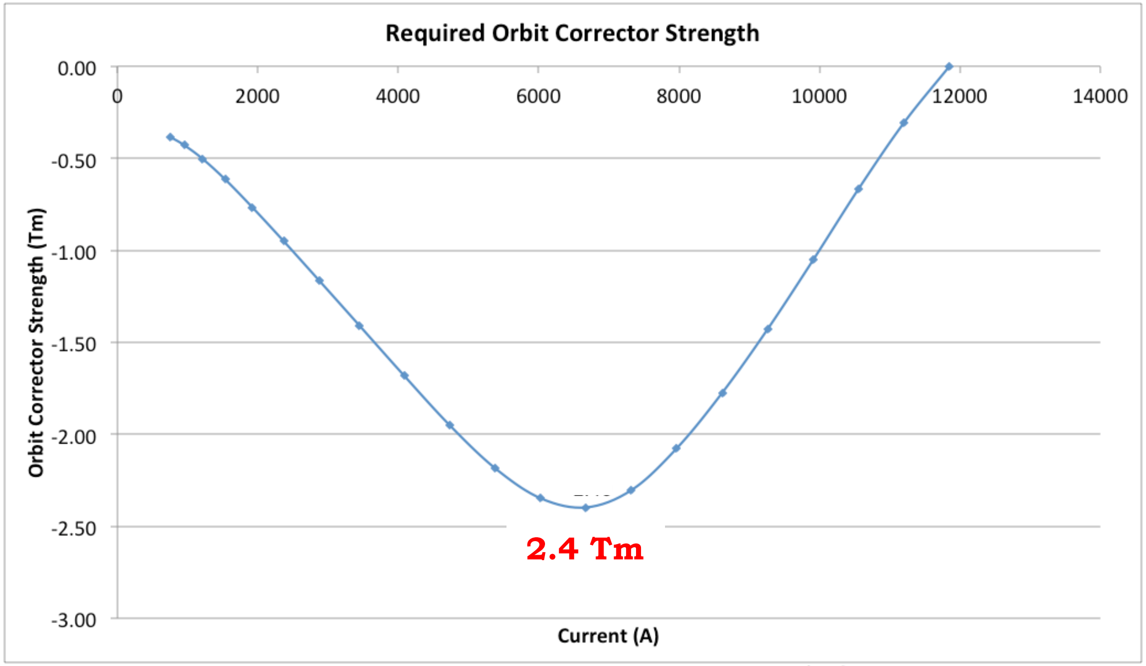




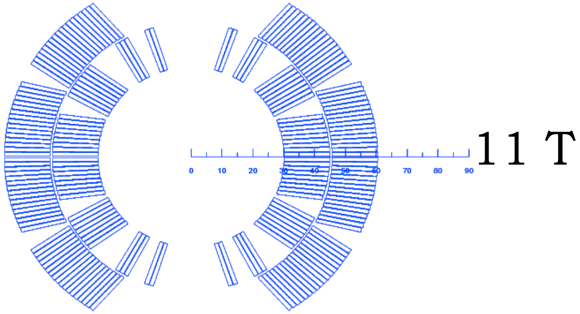
# Transfer Function

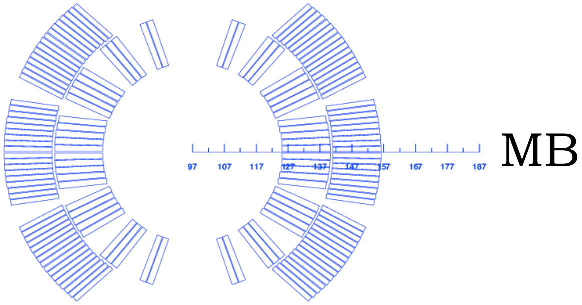
## ❖ TF of 11 T dipole is different from MB:

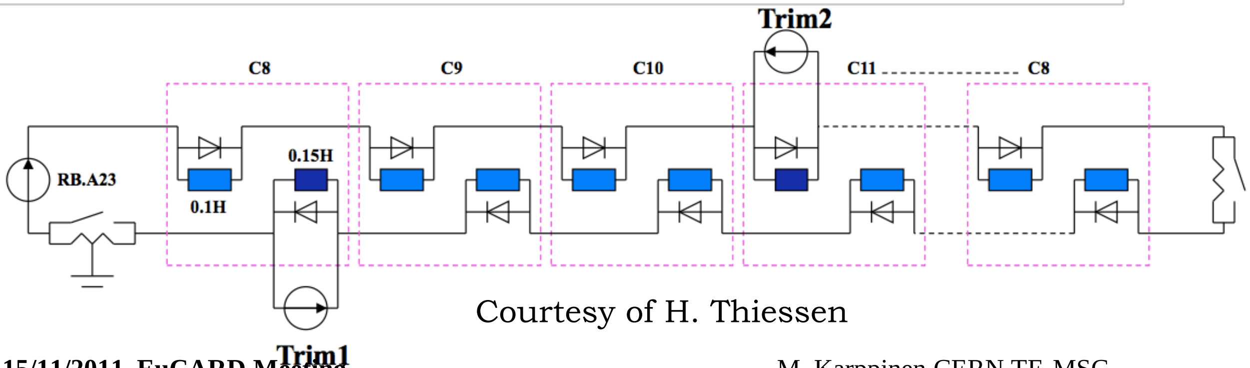
- More turns than MB (56 vs. 40) ➔ 11 T dipole is stronger low field.
- More saturation ➔ reduction of transfer function at high field.



2.4 Tm







Courtesy of H. Thiessen

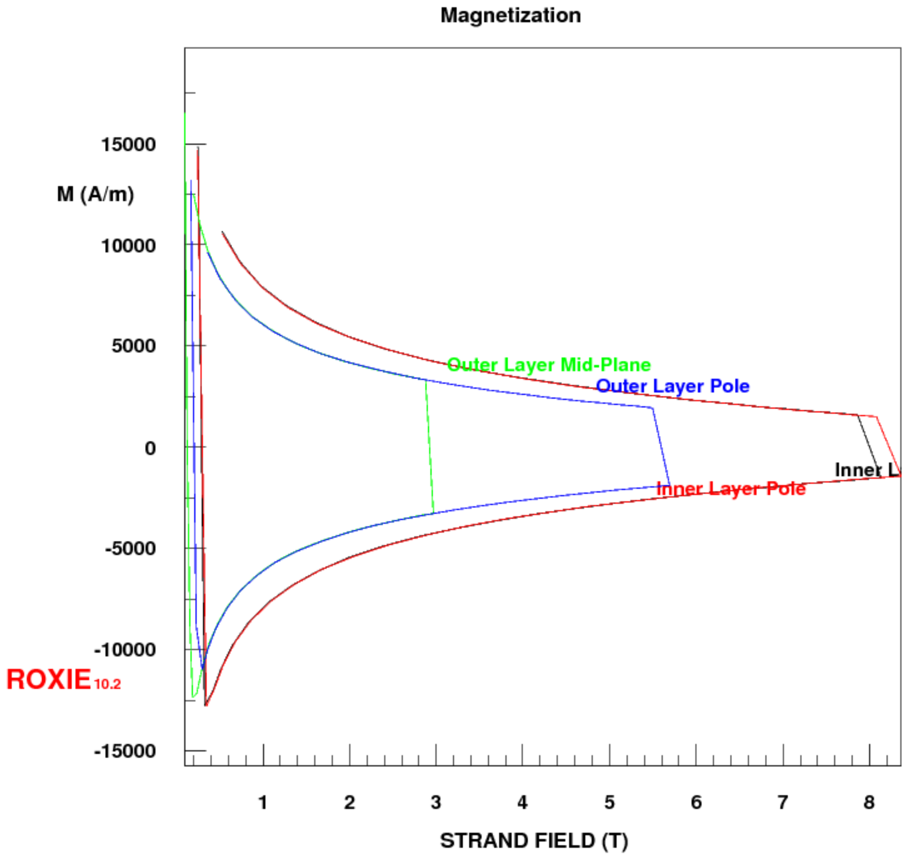
300 A Monopolar Trim PC

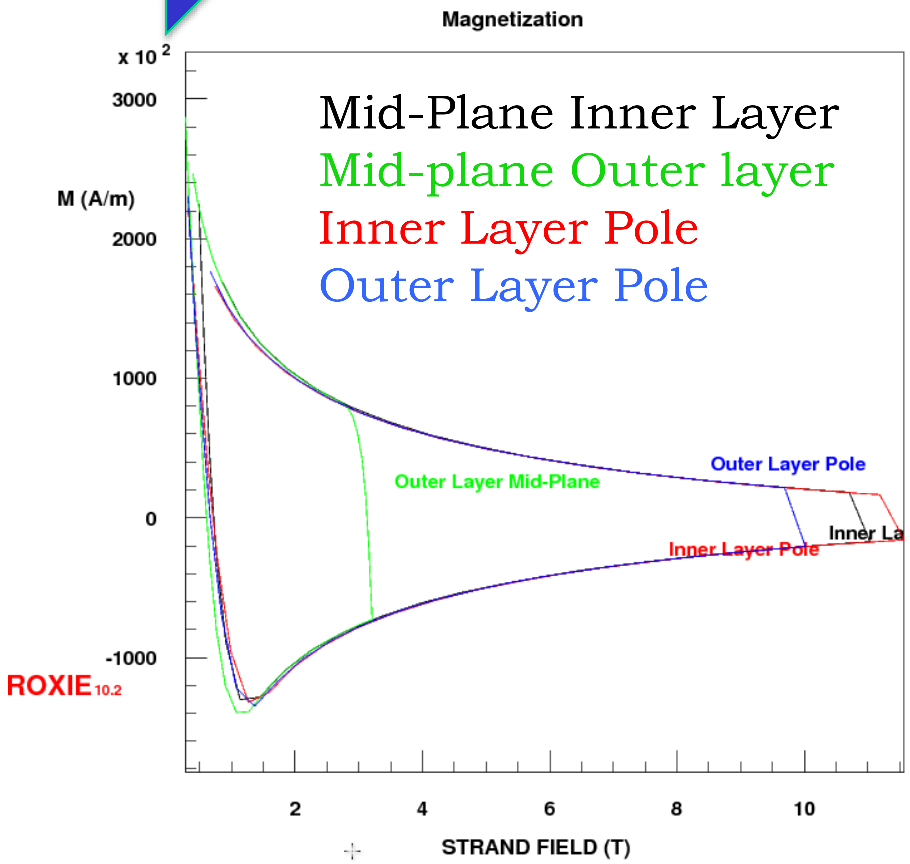
# Coil Magnetization

**MB (NbTi)**

>10 X

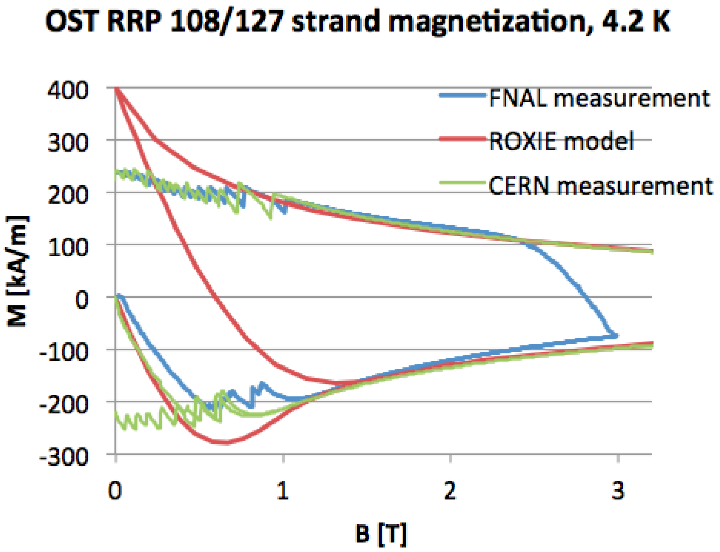
**11 T Dipole Nb3Sn**



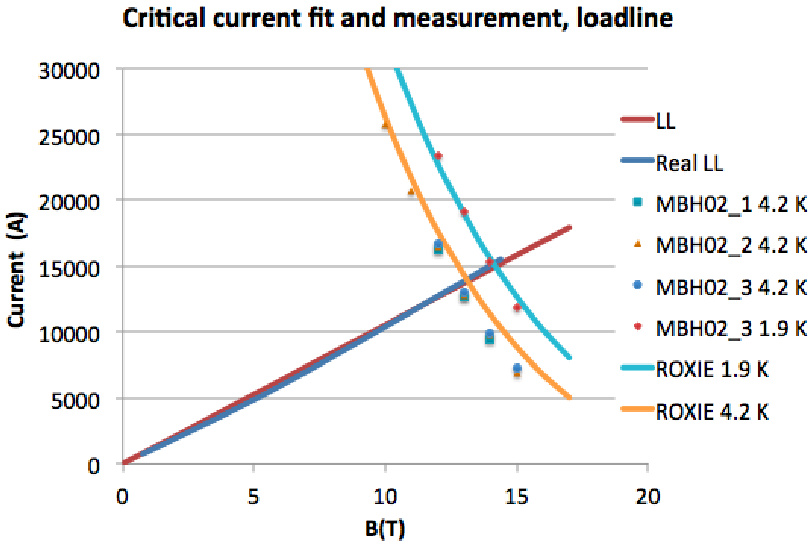


# *Strand magnetization model*

- **ROXIE magnetization model**
  - **Summers fit,**
  - **Deff = 55 µm,**
  - **Aleksa/Russenschuck/Völlinger scalar model.**



OST RRP 108/127 strand magnetization, 4.2 K



Critical current fit and measurement, loadline

measured data courtesy E. Barzi

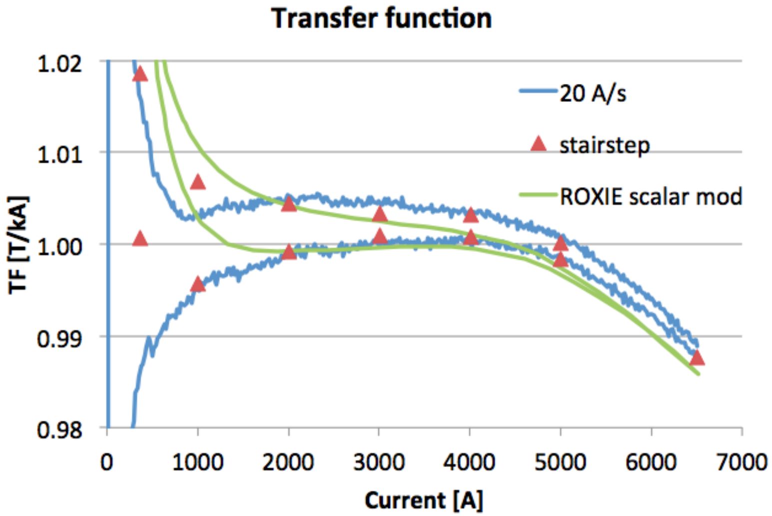
- **Magnetization measurement references**

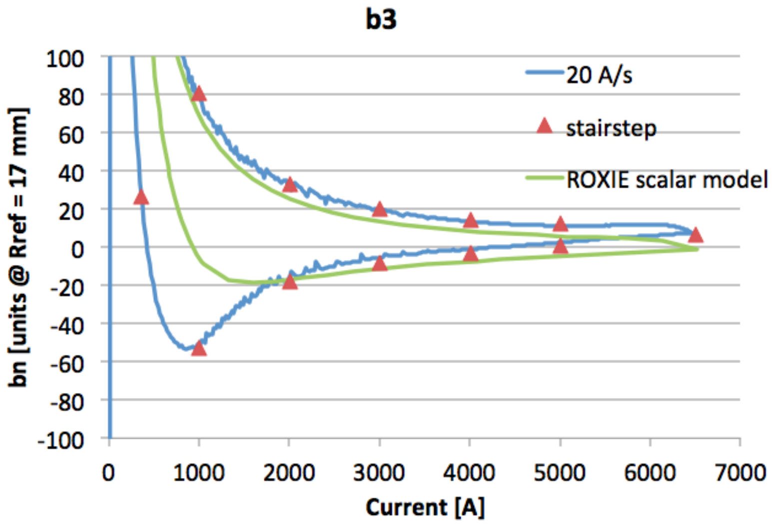
  **FNAL:** ***E. Barzi et al., "Studies of $Nb_3Sn$ Strands based on the Restacked-Rod Process for High Field Accelerator Magnets", IEEE Trans. Appl. Sup., Vol. 22(3), June 2012.***
  **CERN:** ***B. Bordini et al., to be presented at ASC 2012, Portland, USA***

- **Strand magnetization model consistent with measurements at CERN and FNAL.**

# *Persistent current effects TF, b3*

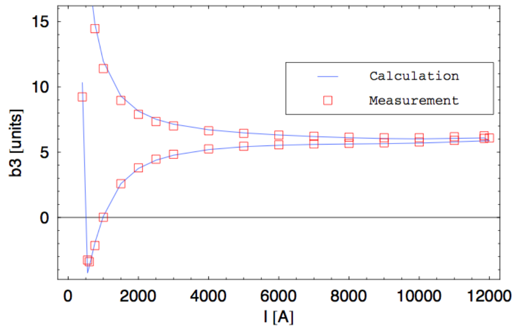
## ❖ Scalar persistent current model vs. measurement (MBHSP01)





## ❖ b3 around injection (~760 A)

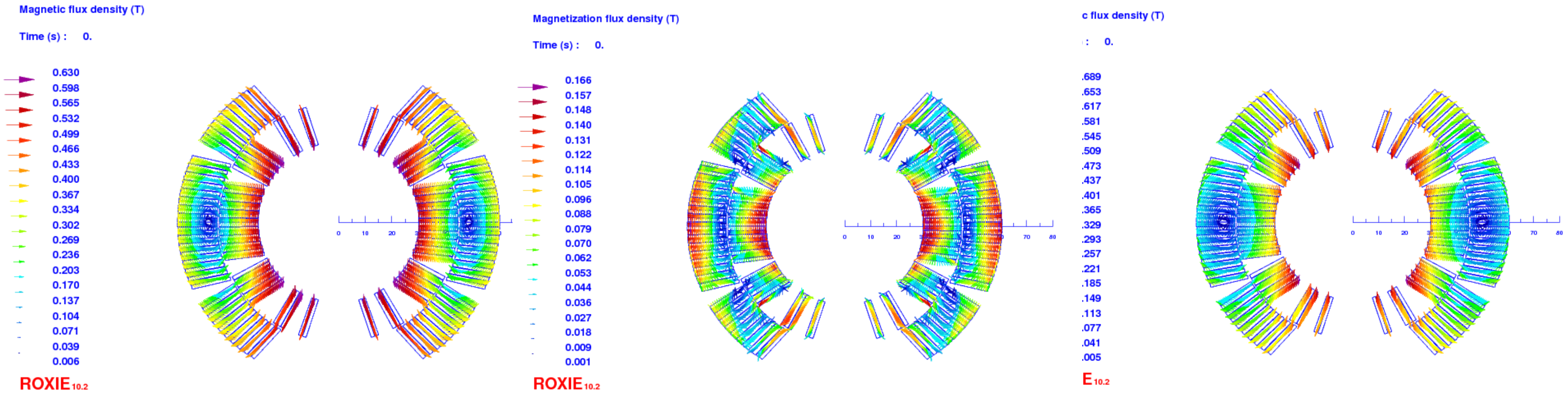
- The scalar model does not capture the low-field coil re-magnetization properly.
- Monotonous b3 curve with minimum around injection level should be amenable to passive shimming.



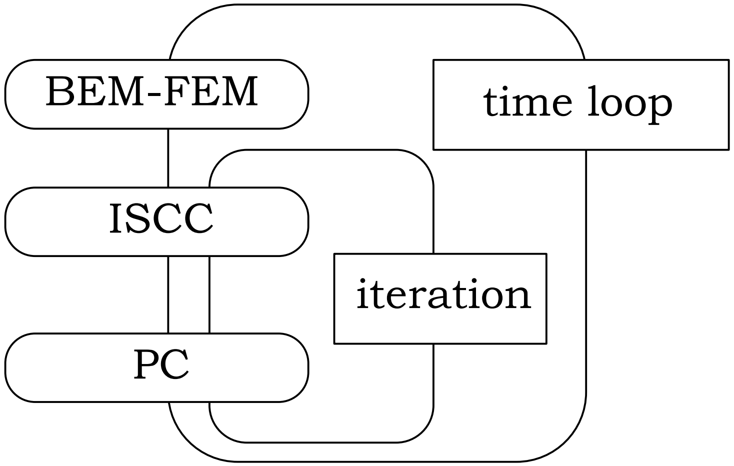
MB simulation, courtesy N. Schwerg

# *Coil re-magnetization at low currents*

- **Transport current field + PC field = total field (at 760 A).**



- **Vectorial model required.**
- **Iteration scheme required.**



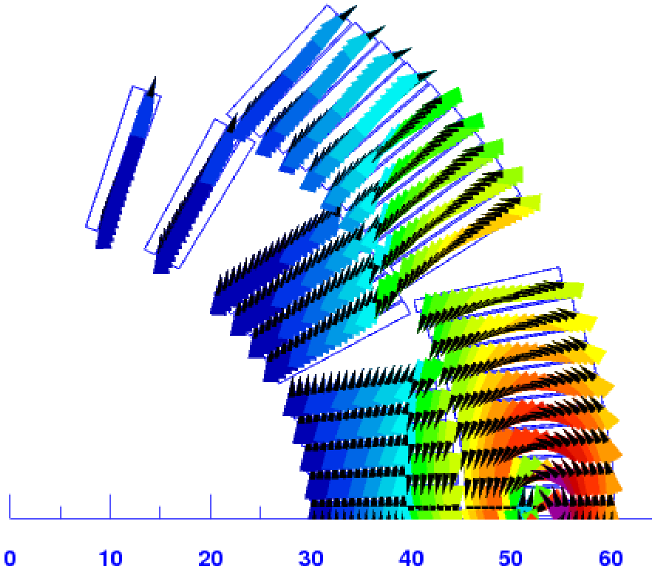
BEM-FEM

time loop

ISCC

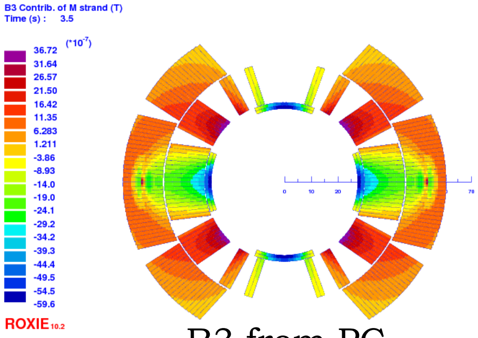
iteration

PC

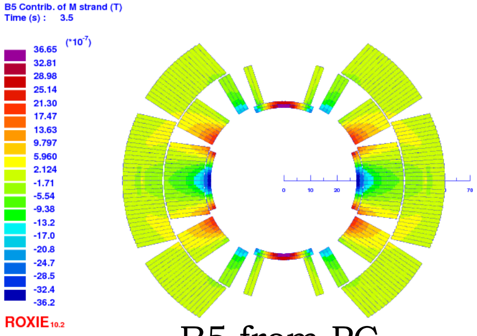


# *Mitigating the persistent-current induced sextupole*

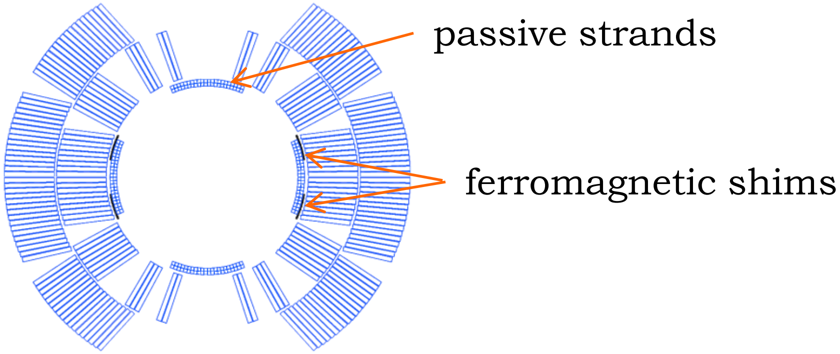
- **Passive compensation: ferromagnetic, passive strands**
  - **Superconducting strands between cold bore and coil. Might reduce aperture by as much as 4 mm in diam.**

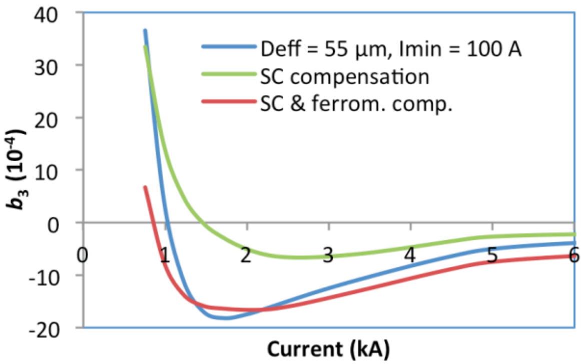


B3 from PC



B5 from PC

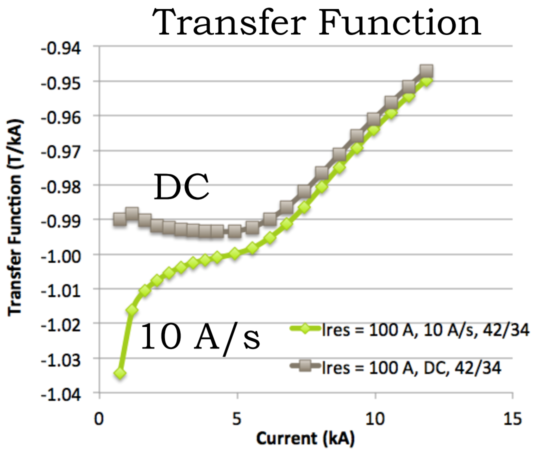


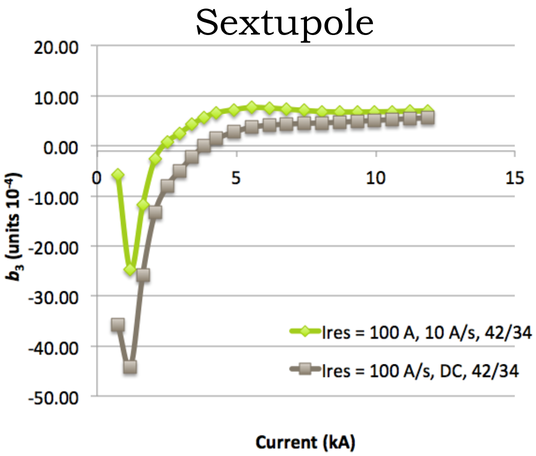


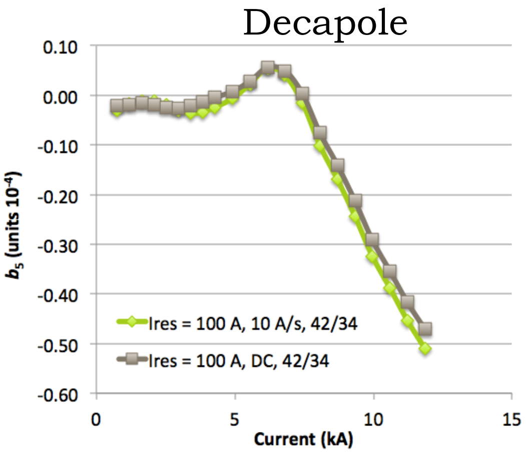
- **However, the model cannot be used to predict effectiveness.**
- **Design and construction should start now for test in the next magnet.**

# Cable Eddy Currents

- **ISCCs in 11 T magnet**
  - o **Based on $R_c$ = 0.4 μΩ we give presumably worst-case field quality for the 11-T dipole. (MSUT ≈ 1.2 μΩ)**
  - o **"Field advance" of ~ 4% due to ISCCs clearly visible in transfer function.**


Transfer Function


Sextupole


Decapole

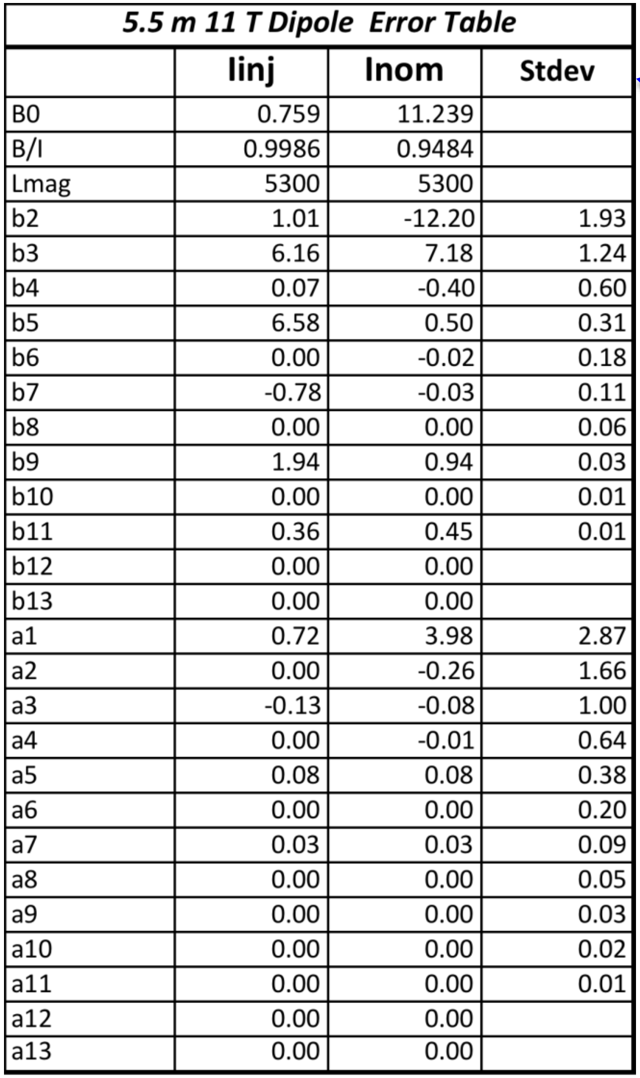
- **Probably need a cored cable to increase $R_c$.**
- **Need to measure snap-back at injection with and without cored cable.**

# Field Quality Requirements

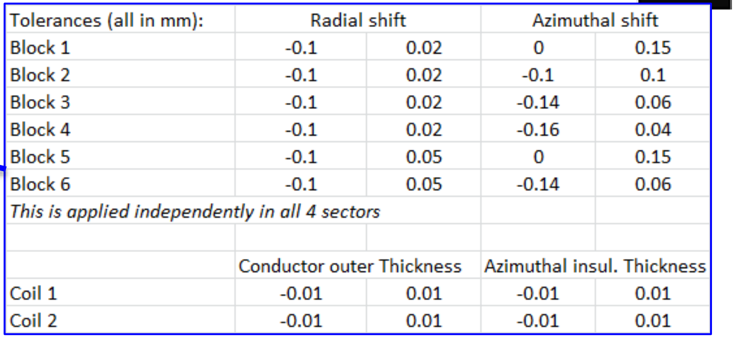
- **Present beam-dynamics requirements (B. Holzer):**
  - $B_1$ **matches MB.**
  - $|b_3|$ **below 20 units.**
  - $|b_2|$ **below 16 units.**
  - $|b_5|$ **below 5 units.**
  - **…**

- **Can be met by:**
  - **trim power converter,**
  - **part-compensation in coil geometry,**
  - **passive persistent-current compensation,**
  - **adapted precycle (trim power converter),**
  - **cored cable.**

# Error Table Nov-13



| 5.5 m 11 T Dipole Error Table | | | |
|---|---|---|---|
| | Iinj | Inom | Stdev |
| B0 | 0.759 | 11.239 | |
| B/I | 0.9986 | 0.9484 | |
| Lmag | 5300 | 5300 | |
| b2 | 1.01 | -12.20 | 1.93 |
| b3 | 6.16 | 7.18 | 1.24 |
| b4 | 0.07 | -0.40 | 0.60 |
| b5 | 6.58 | 0.50 | 0.31 |
| b6 | 0.00 | -0.02 | 0.18 |
| b7 | -0.78 | -0.03 | 0.11 |
| b8 | 0.00 | 0.00 | 0.06 |
| b9 | 1.94 | 0.94 | 0.03 |
| b10 | 0.00 | 0.00 | 0.01 |
| b11 | 0.36 | 0.45 | 0.01 |
| b12 | 0.00 | 0.00 | |
| b13 | 0.00 | 0.00 | |
| a1 | 0.72 | 3.98 | 2.87 |
| a2 | 0.00 | -0.26 | 1.66 |
| a3 | -0.13 | -0.08 | 1.00 |
| a4 | 0.00 | -0.01 | 0.64 |
| a5 | 0.08 | 0.08 | 0.38 |
| a6 | 0.00 | 0.00 | 0.20 |
| a7 | 0.03 | 0.03 | 0.09 |
| a8 | 0.00 | 0.00 | 0.05 |
| a9 | 0.00 | 0.00 | 0.03 |
| a10 | 0.00 | 0.00 | 0.02 |
| a11 | 0.00 | 0.00 | 0.01 |
| a12 | 0.00 | 0.00 | |
| a13 | 0.00 | 0.00 | |

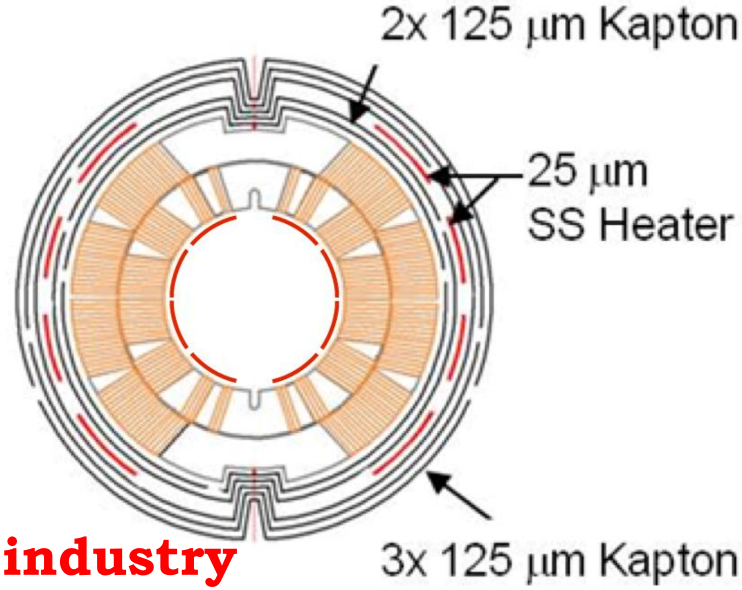


| Tolerances (all in mm): | Radial shift | | Azimuthal shift | |
|---|---|---|---|---|
| Block 1 | -0.1 | 0.02 | 0 | 0.15 |
| Block 2 | -0.1 | 0.02 | -0.1 | 0.1 |
| Block 3 | -0.1 | 0.02 | -0.14 | 0.06 |
| Block 4 | -0.1 | 0.02 | -0.16 | 0.04 |
| Block 5 | -0.1 | 0.05 | 0 | 0.15 |
| Block 6 | -0.1 | 0.05 | -0.14 | 0.06 |
| *This is applied independently in all 4 sectors* | | | | |
| | | | | |
| | Conductor outer Thickness | | Azimuthal insul. Thickness | |
| Coil 1 | -0.01 | 0.01 | -0.01 | 0.01 |
| Coil 2 | -0.01 | 0.01 | -0.01 | 0.01 |

- **b3**
  - **minimum at around 1200 A**
  - **steep gradient at 760 A**
  - **re-optimise coil to suppress systematic error**
  - **snap-back & decay not included in this table**
  - **Roxie scalar model appears to work better for the cored cable**
- **reproducibility of magnetization to clarify (b3 min current/initial slope , skew multipoles from top-down asymmetry etc.)**
- **Cable testing to validate Rc/Ra for cored Nb3Sn cables**

# Magnet Protection

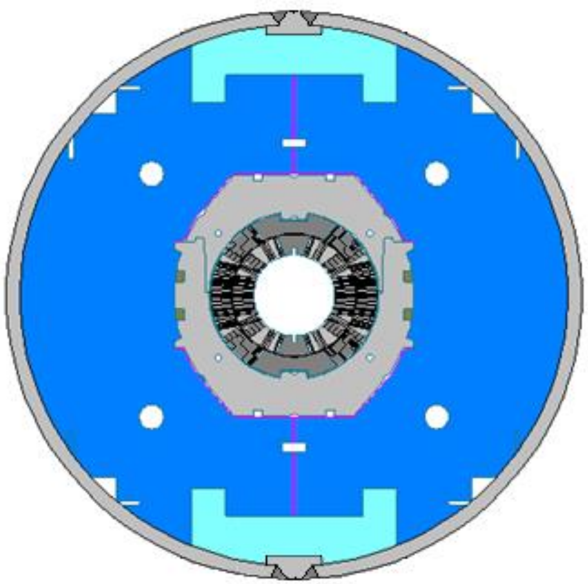
- **Simulation results (25 ms from quench to full heater efficiency, RRR = 200):**
  - $T_{peak}$ = 480 K for outer-layer (OL) low-field heaters.
  - $T_{peak}$ = 360 K for OL high-field heaters.
  - $T_{peak}$ = 450 K for OL low-field heaters with quench-back.
  - $T_{peak}$ = 300 K for intra-layer low-field heaters.
- **Single-aperture demonstrator will provide experimental data to validate the model:**
  - Extraction and heater delays
  - Heater efficiency and required coverage
  - Quench propagation
  - Quench-back
- **Inter-layer heater development:**
  - Mica-stainless steel-ceramic sandwich?
  - Can be tested in SMC
    - **Can be produced up to 5.5 m in industry**

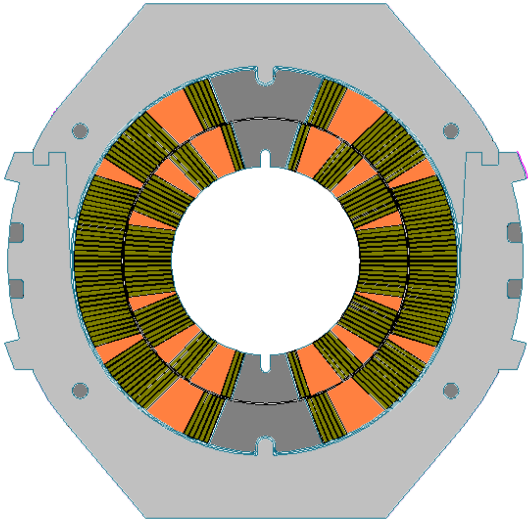


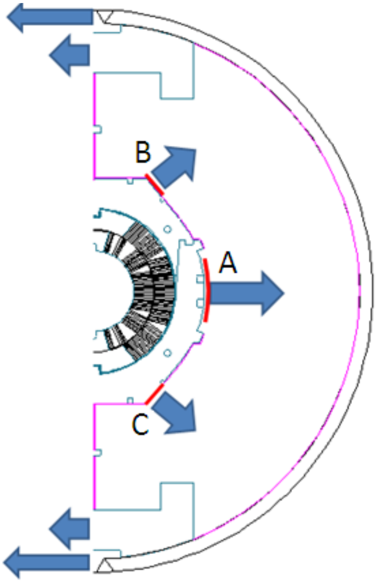
# *Outline*

- Project goals and plans
- Magnetic design
- **FNAL Demonstrator design and  & coil technology**
- CERN mechanical design
- Short model program milestones
- CERN R&D topics
- LARP and US Core Programs & 11 T Project
- Conclusions

# 1-in-1 Demonstrator Mechanical Structure

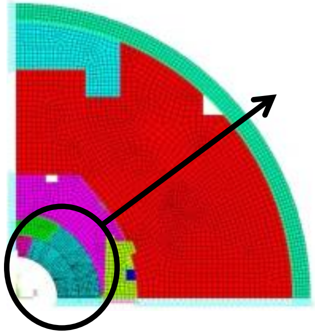




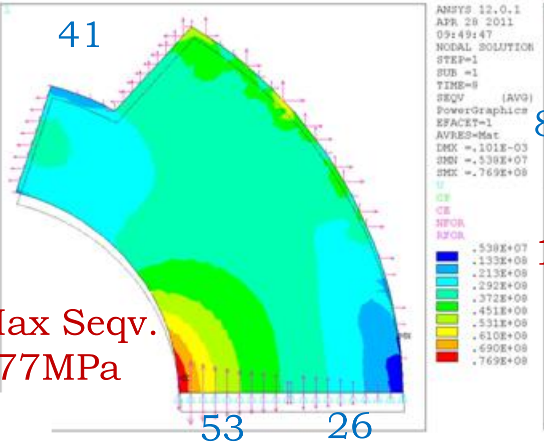


- Slightly elliptical stainless steel collar, 25-mm wide near mid-plane.
- The vertically split iron yoke clamped with Al clamps.
- The 12-mm stainless steel skin.
- Two 50-mm thick end plates.
- Maximum stress during assembly ~130 MPa to keep coil under compression up to 12 T bore field.
- The mechanical structure is optimized to maintain the coil stress below 165 MPa - safe level for brittle Nb3Sn coils

# *1-in-1 Demonstrator FEA*



After Collaring



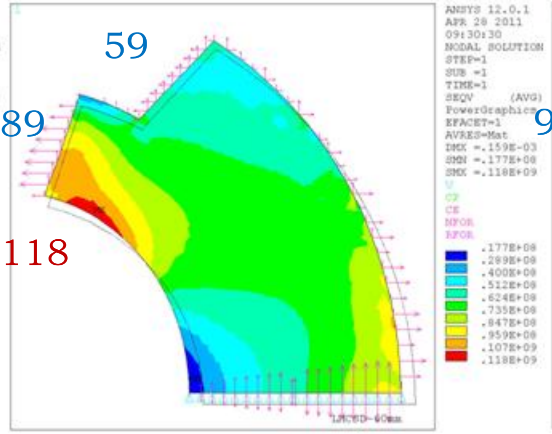
41

Avg.=28MPa

Max Seqv.
=77MPa

53 26

After Skin Welding



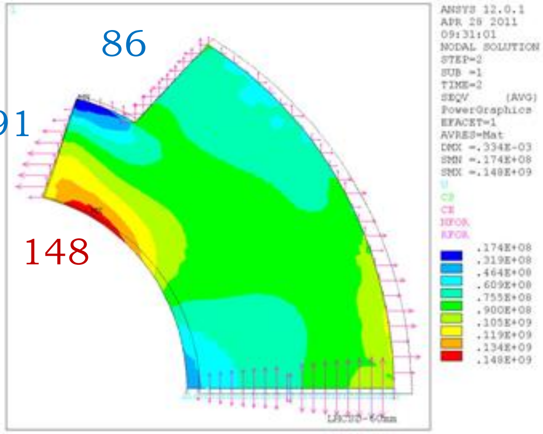
59

89

118

49 85

After Cooling Down, 300-2K



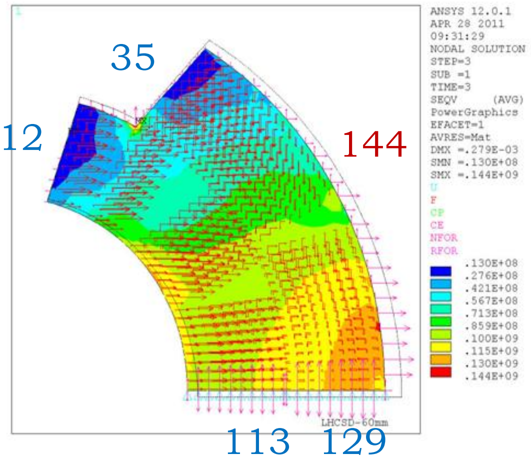
86

91

148

66 99

11T, 2K



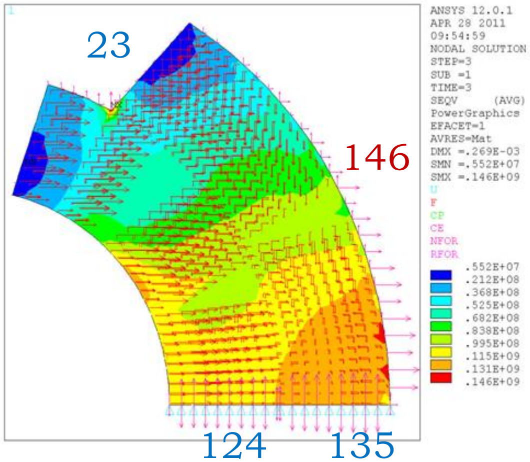
35

12

144

113 129

12T, 2K



23

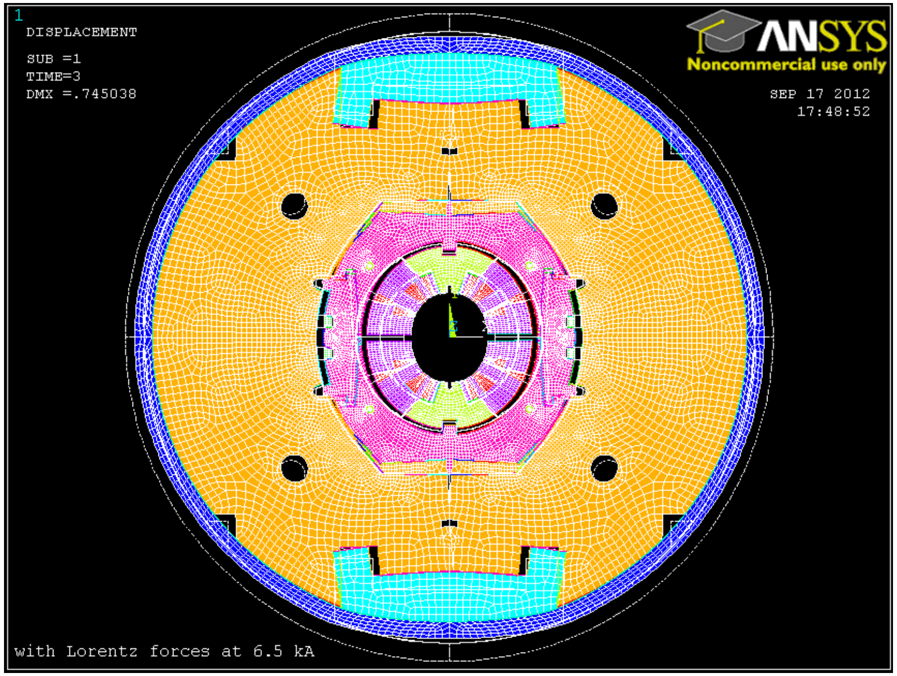
2

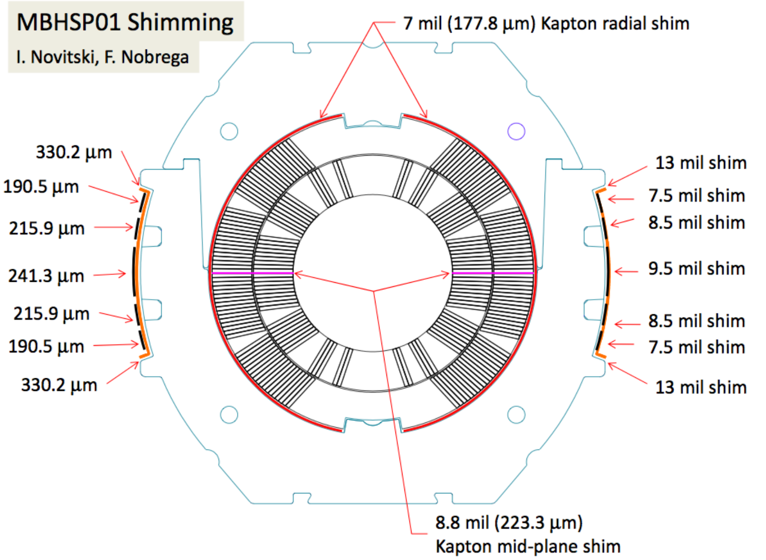
146

124 135

# *ANSYS/ROXIE interface*

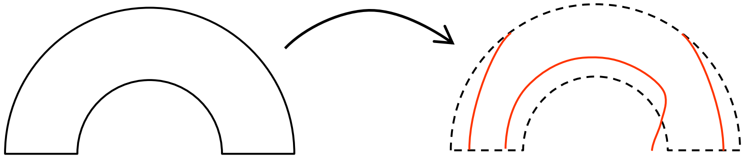
- **ANSYS model includes**
  - **shimming,**
  - **cool-down,**
  - **Lorentz forces.**
- **Full asymmetric model.**

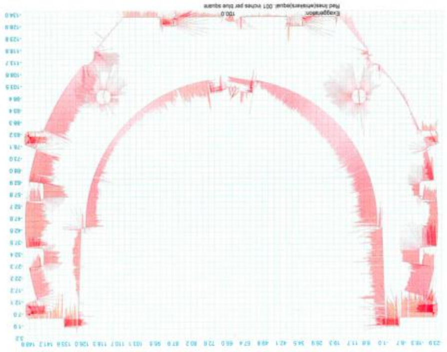


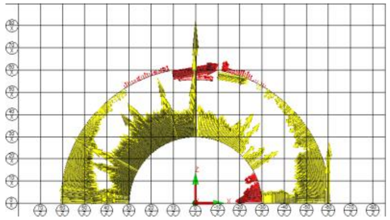


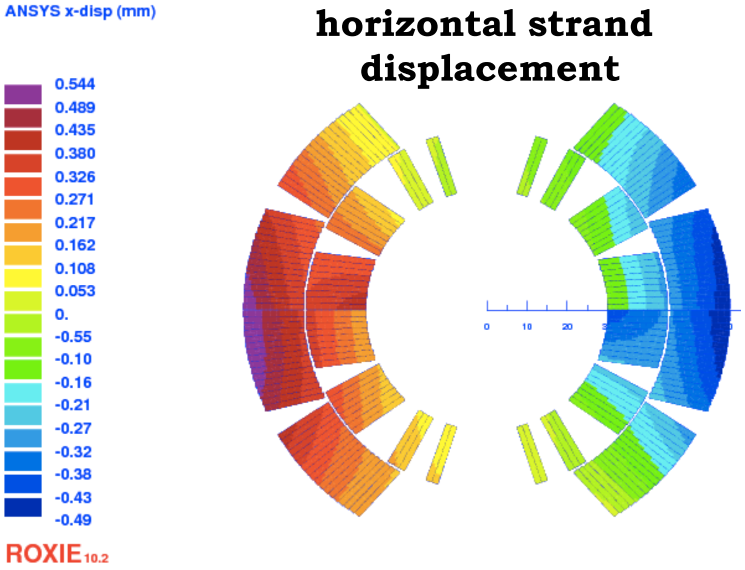
# *Including inspection data*

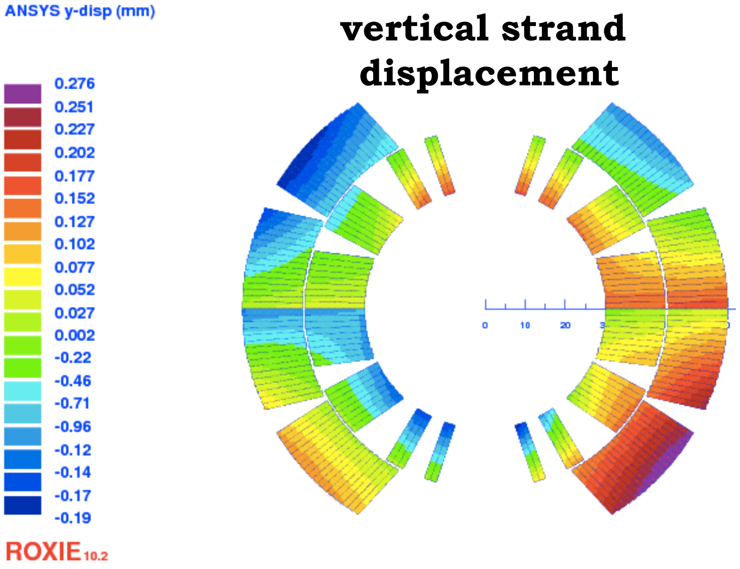
- **Collar inspection reports**
  - **contacts (gaps/interferences).**
- **Coil inspection reports**
  - **node-by-node transformation:**



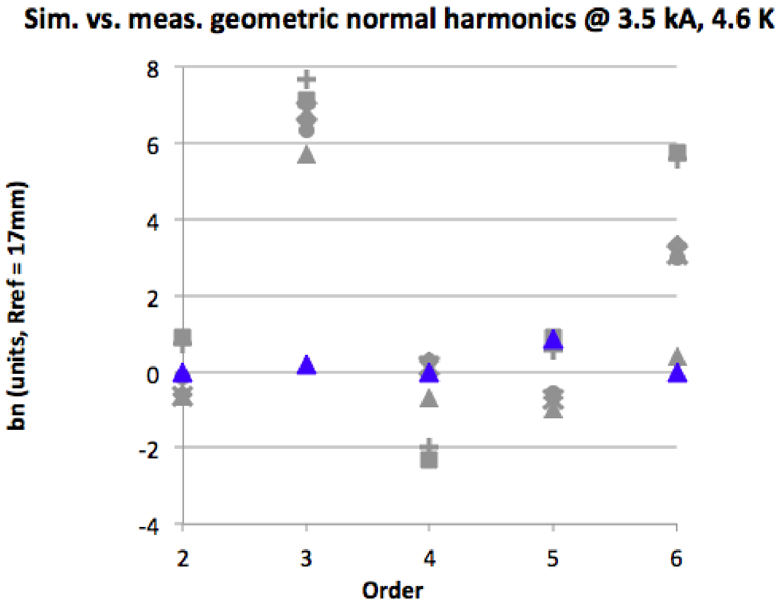


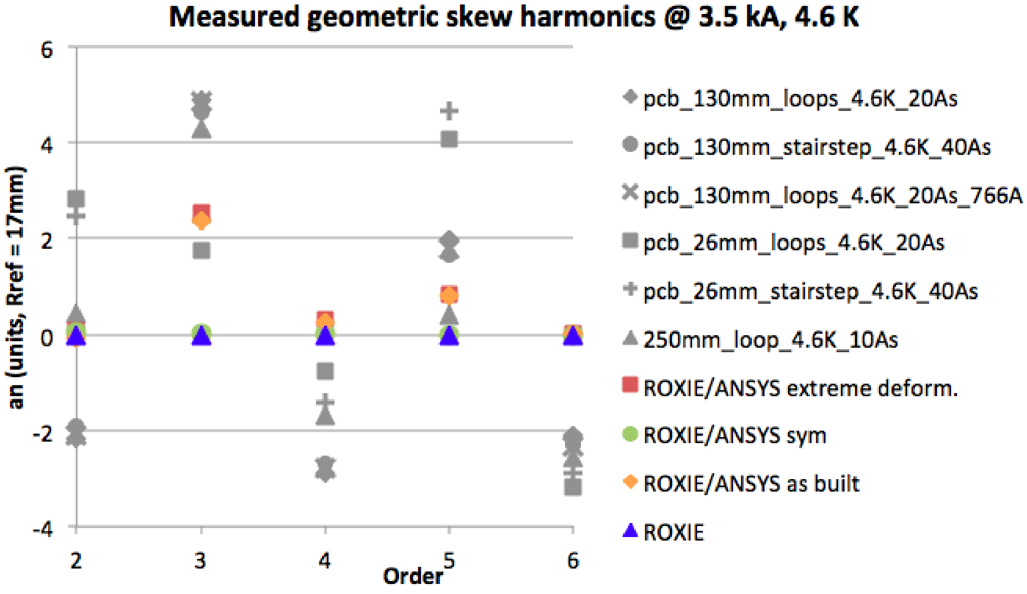



**horizontal strand displacement**

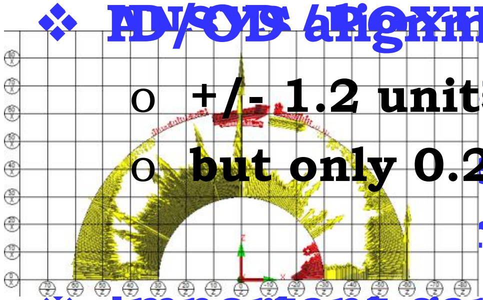

**vertical strand displacement**

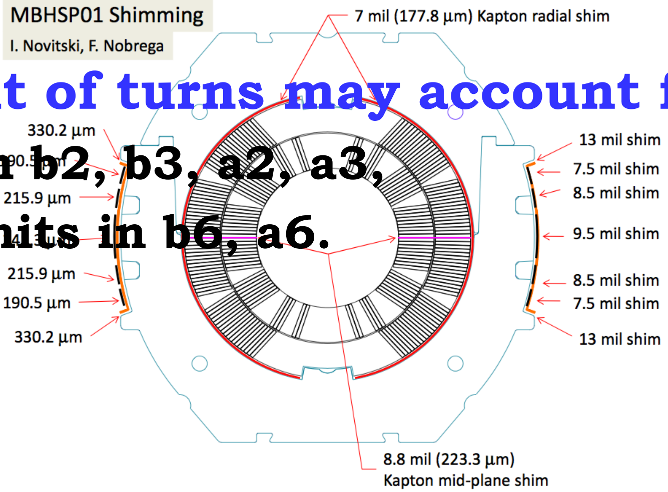
# *Geometric harmonics vs. predicted*



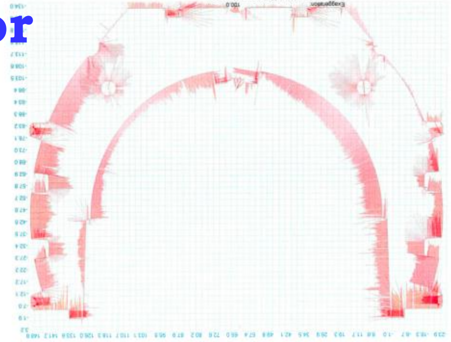


- ANSYS / ROXIE
- ID/OD alignment of turns may account for
  - o +/- 1.2 units in b2, b3, a2, a3,
  - o but only 0.2 units in b6, a6.
- Important gap o
- Autopsy data m

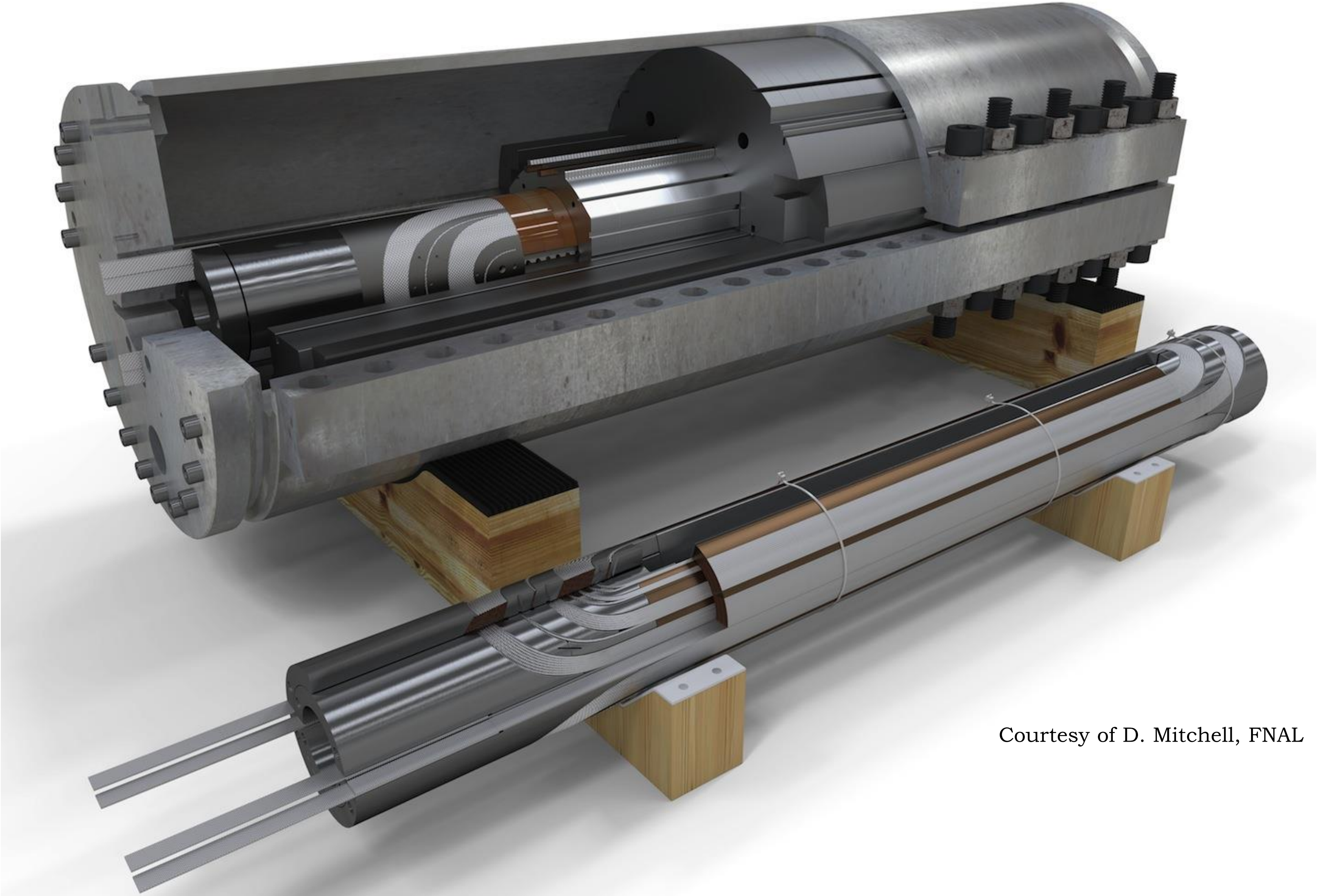



MBHSP01 Shimming

I. Novitski, F. Nobrega

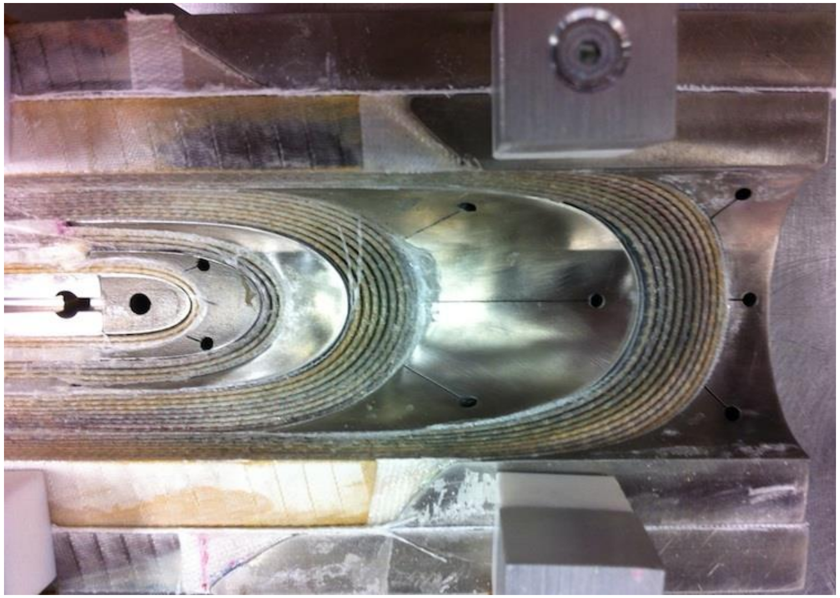


# FNAL 1-in-1 Model Magnet (1m) & CERN Coils

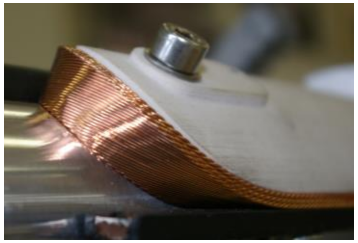


Courtesy of D. Mitchell, FNAL

# Demo Coil #1

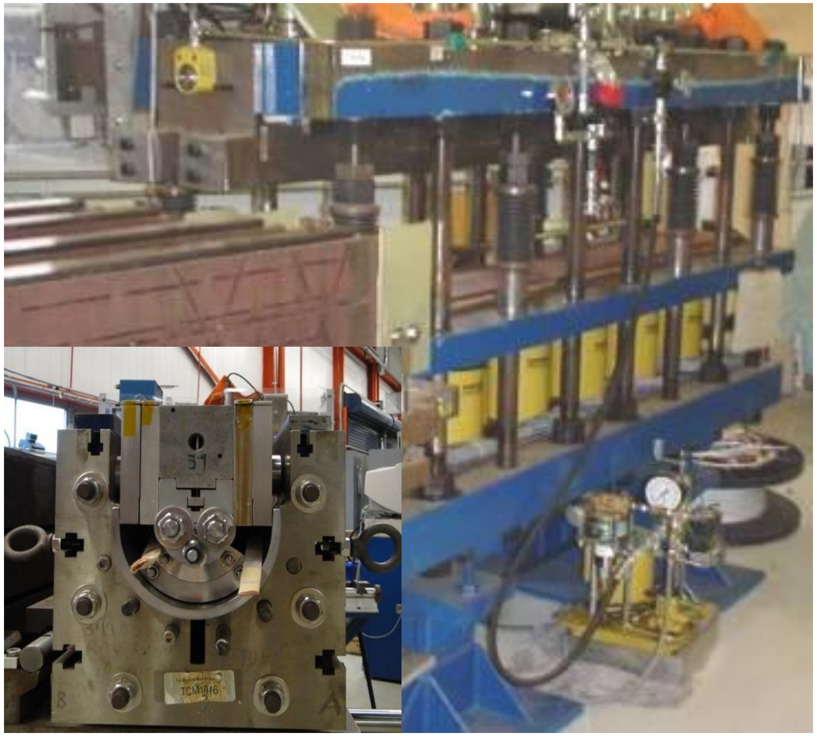


# Coil Fabrication



- Coil technology developed at FNAL
- **FNAL coils:** E-glass wrap, integrated Ti-poles, laser sintered st. steel end parts, and bar milled st. steel wedges (x4)
- **CERN coils:** S2-braid-Mica, removable Ti-poles, st. steel loading plates, laser sintered st. steel end parts, and extruded ODS wedges (x5)

# Curing & Reaction

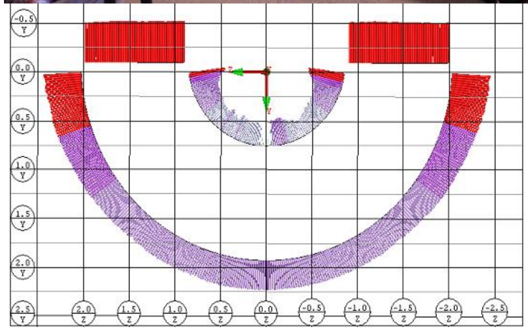


| Step # | Type | Start | Rate/time |
|---|---|---|---|
| 1 | Ramp | 20C | 25C/hour |
| 2 | Soak | 210C | 72 hours |
| 3 | Ramp | 210C | 25C/hour |
| 4 | Soak | 400C | 48 hours |
| 5 | Ramp | 400C | 50C/hr |
| 6 | Soak | 640C | 48 hours |
| 7 | Ramp | 640C | -100C/hr |

- After winding of each layer, cable insulation is injected with ceramic binder CTD-1202.
- Coils are cured at 150° C for 30 minutes in a closed cavity mold.
- Azimuthal coil pressure is approximately 27 Mpa.

- Closed cavity mold defines the coil size precisely.
- Tooling is modular, the process can be easily adapted to long magnets.
- Reaction with positive argon pressure in the tooling.

# Impregnation and Metrology



- Impregnation with CTD101K at 0.04..0.07 mbar & 60° C.
- Curing at 110° C for 5 hrs, post-cure at 125° C for 16 hrs.

- Coil X-section uniformity and azimuthal size measured with CMM to help determine the shimming for coil pre-load.

# *Outline*

- Project goals and plans
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- **CERN mechanical design**
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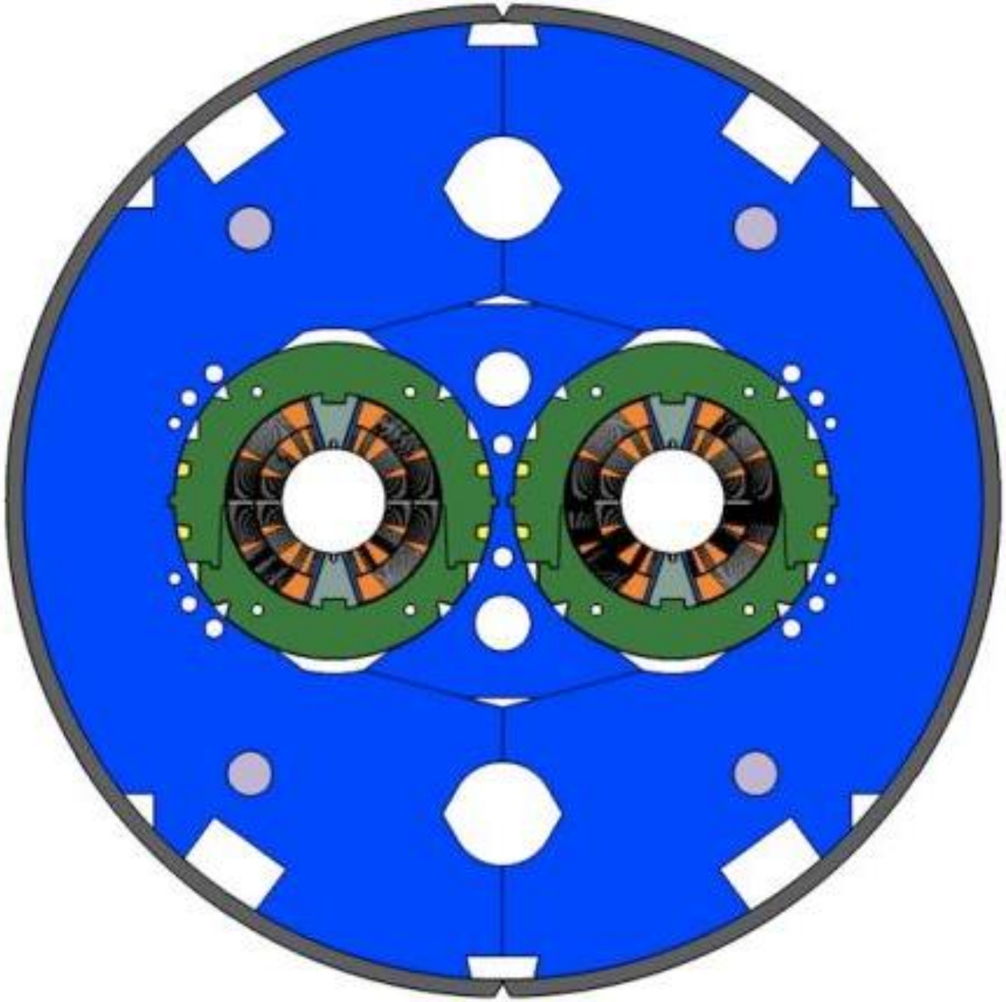
- Conclusions

# Mechanical Design Features



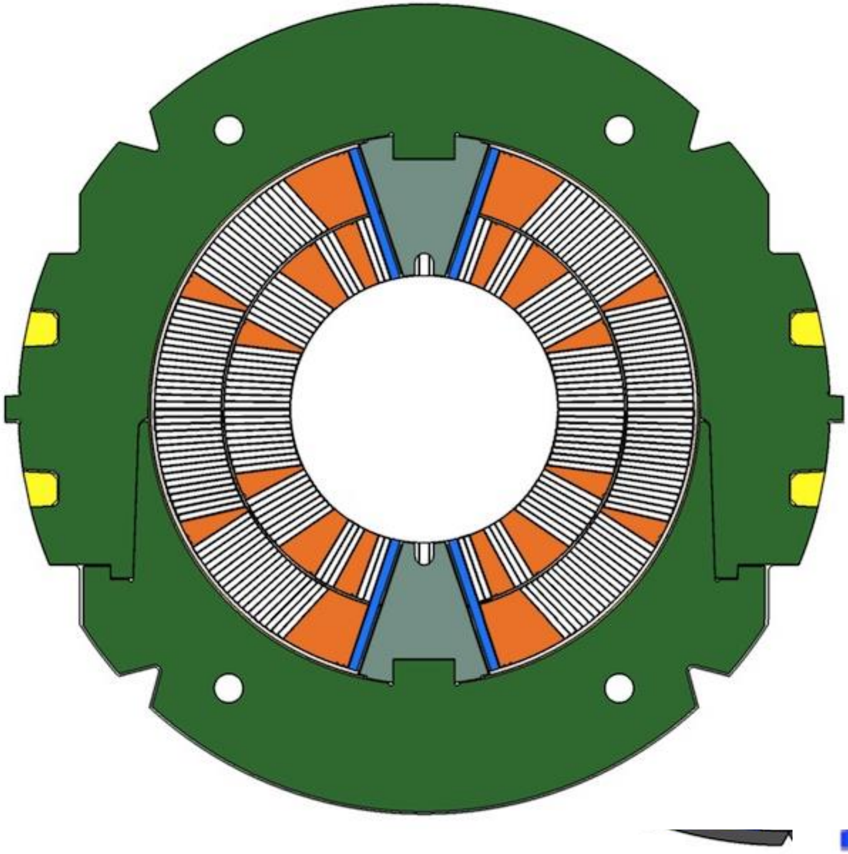
- **Separate collared coils**
  - **Most of the coil pre-stress obtained by collaring**
  - **Symmetric loading**
  - **Better control of pre-stress**
  - **Testing of collared coils in 1-in-1 structure**
- **Vertically split yoke**
  - **Assembly process less influenced by friction (vs. horizontal split)**
  - **Closed gap at RT and up to 12 T to provide rigid support for the collared coil**
  - **Better controlled (collared) coil deformation**
- **Welded stainless steel skin**

# 2-in-1 Demonstrator Parameters

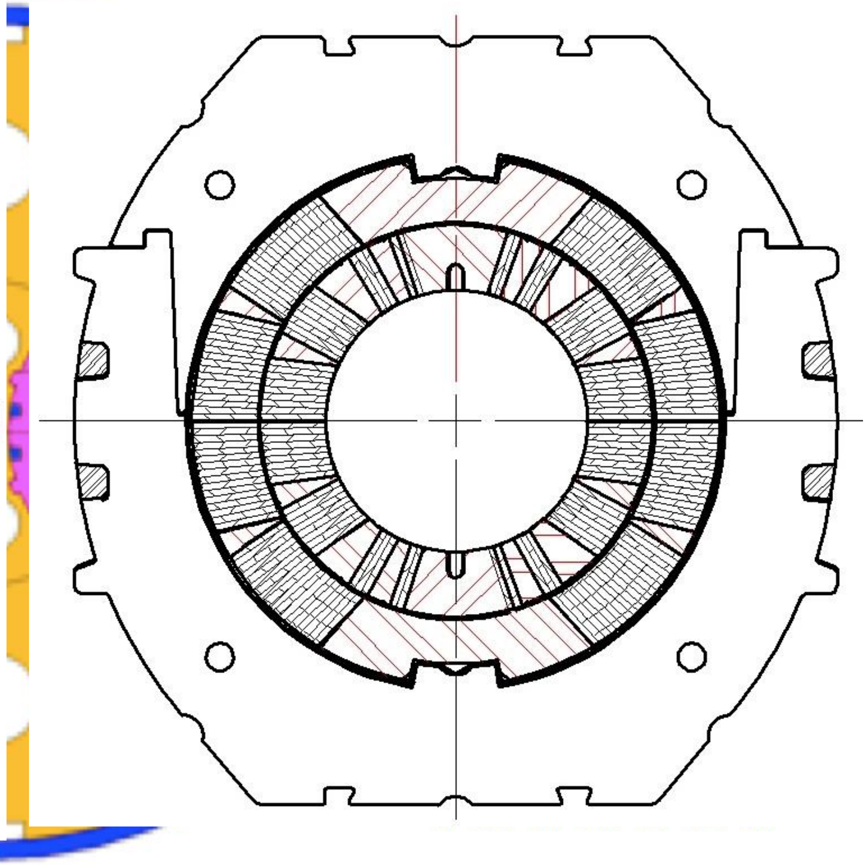
| **Parameter** | **Unit** | **Removable Pole Design** | **Integrated Pole Design** |
|---|---|---|---|
| Nominal current $I_{nom}$ | kA | 11.85 | 11.85 |
| Nominal bore field | T | 11.23 | 11.25 |
| Maximum coil field | T | 11.59 | 11.6 |
| Magnetic length | mm | 1.537 | 1.54 |
| Working point on the load-line at $I_{nom}$ | | 81% | 81% |
| Ultimate design field | T | 12 | 12 |
| Inductance at $I_{nom}$ | mH/m | 11.97 | 11.98 |
| Stored energy at $I_{nom}$ | kJ/m | 966.3 | 968.6 |
| $F_x$ per quadrant at $I_{nom}$ | MN/m | 3.15 | 3.16 |
| $F_y$ per quadrant at $I_{nom}$ | MN/m | -1.58 | -1.59 |
| $F_z$ per aperture | kN | 430 | 430 |
| Overall length | mm | 1960 | 1960 |
| Coil overall length | mm | 1760 | 1760 |
| Yoke outer diameter | mm | 550 | 550 |
| Outer shell thickness | mm | 15 | 15 |
| Mass | kg | ~2600 | ~2600 |

# *2-in-1 Demonstrator Design*

- **Two alternative design concepts**

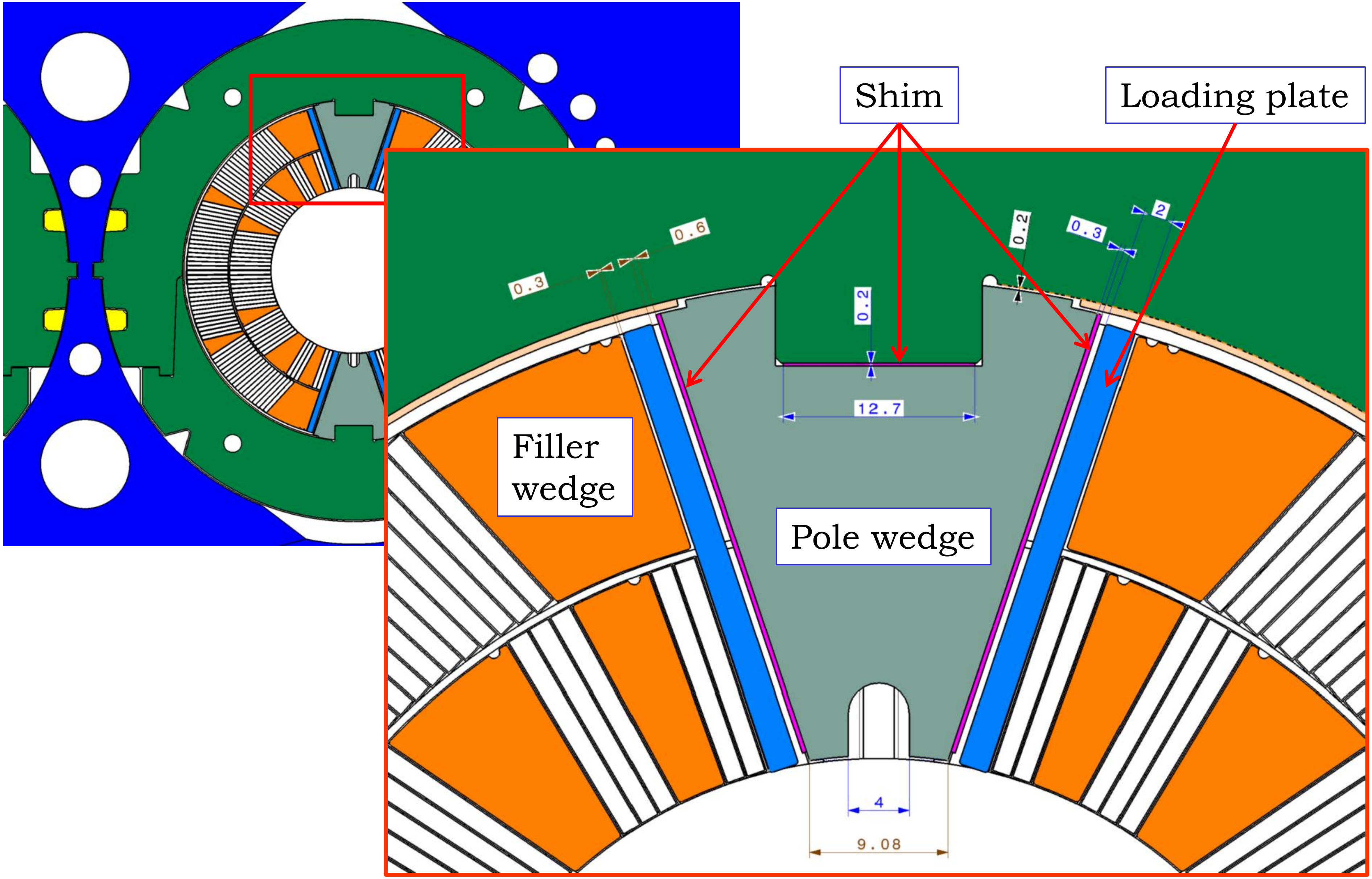


Pole loading design



Integrated pole design

# Pole Loading Concept



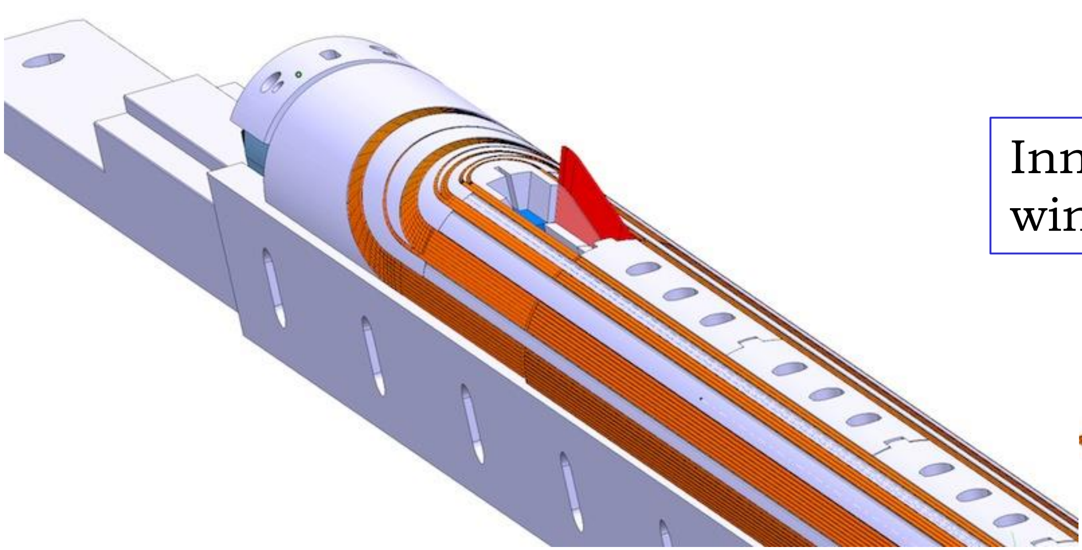
Shim

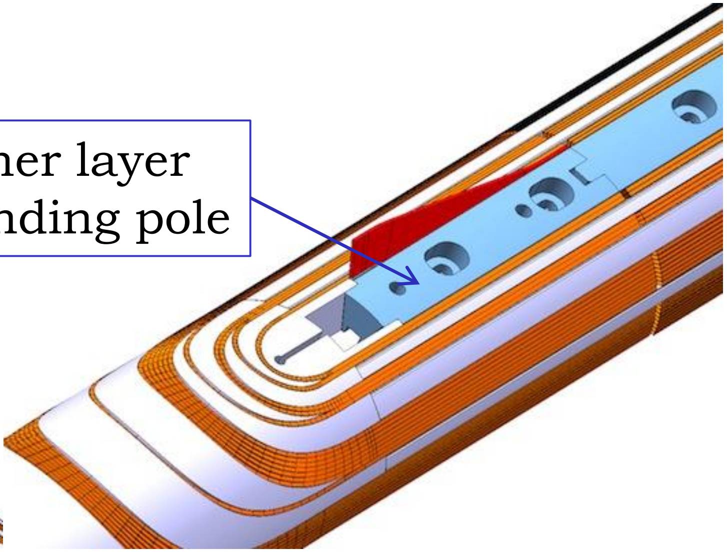
Loading plate

Filler wedge

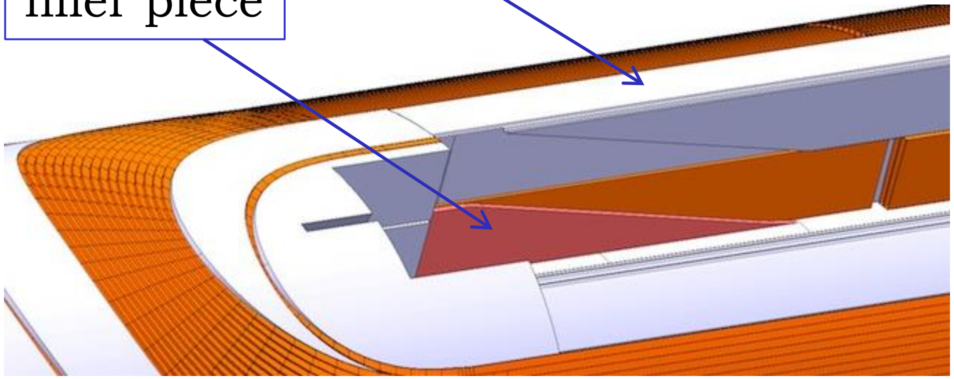
Pole wedge

# Pole Loading Concept: Lead End Winding





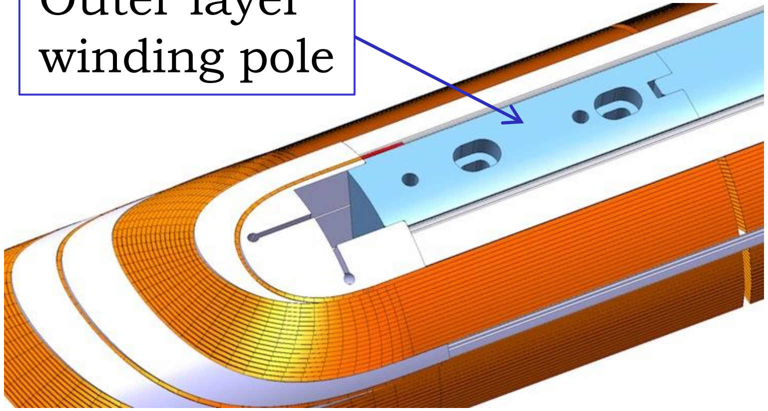
Inner layer winding pole



Ceramic filler piece

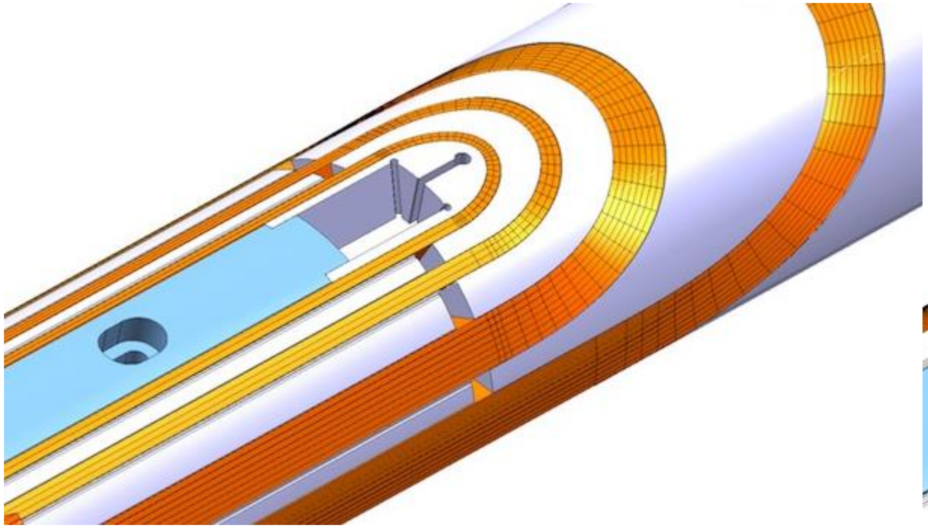
Filler wedge

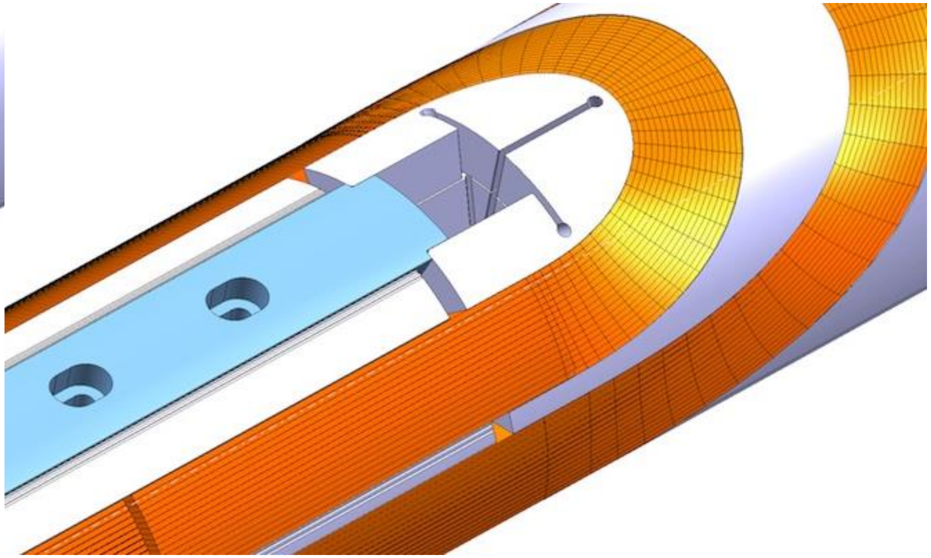
Layer-jump region with cable removed



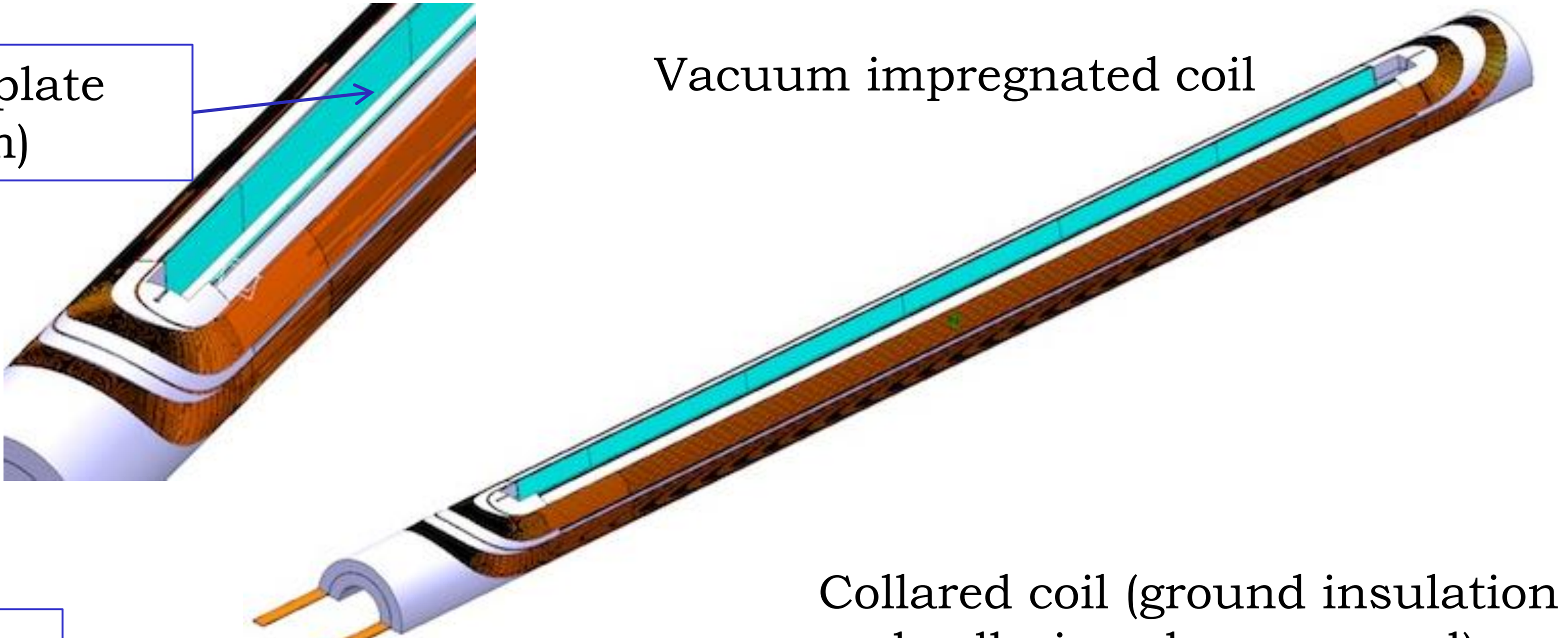
Outer layer winding pole

# Pole Loading Concept: Return End Winding



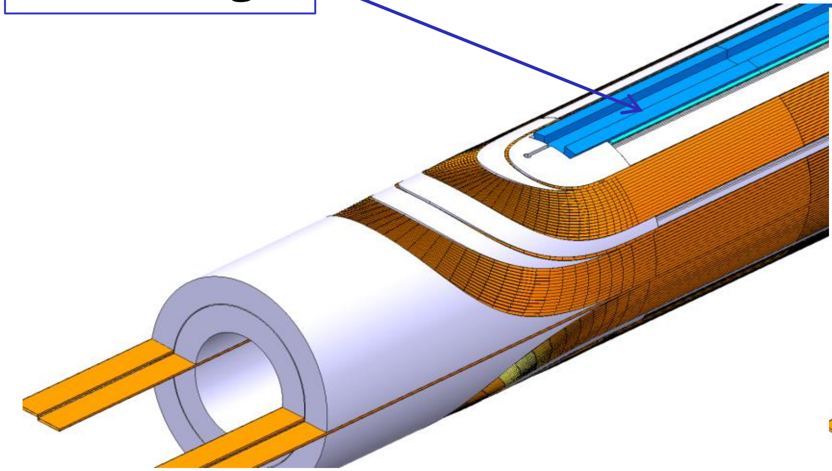


# Pole Loading Concept: Coil & Collar Assembly

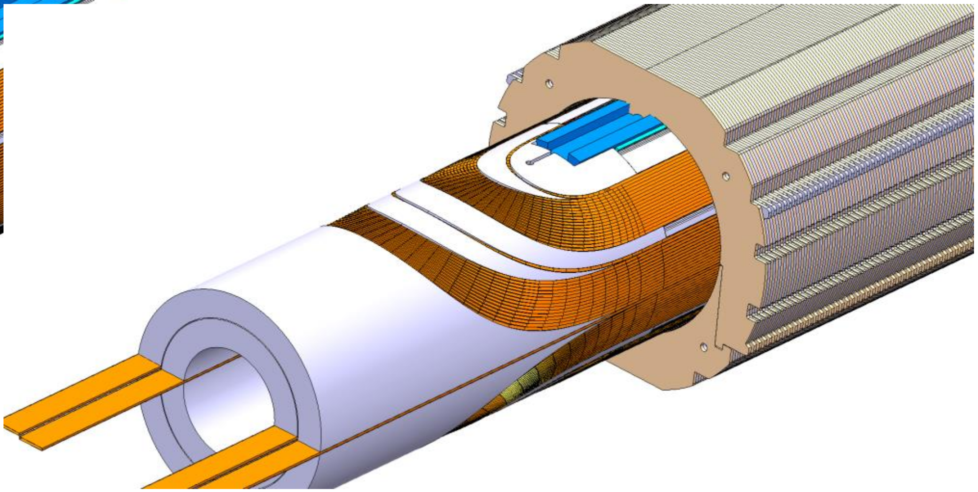


Loading plate
(t = 2 mm)

Vacuum impregnated coil

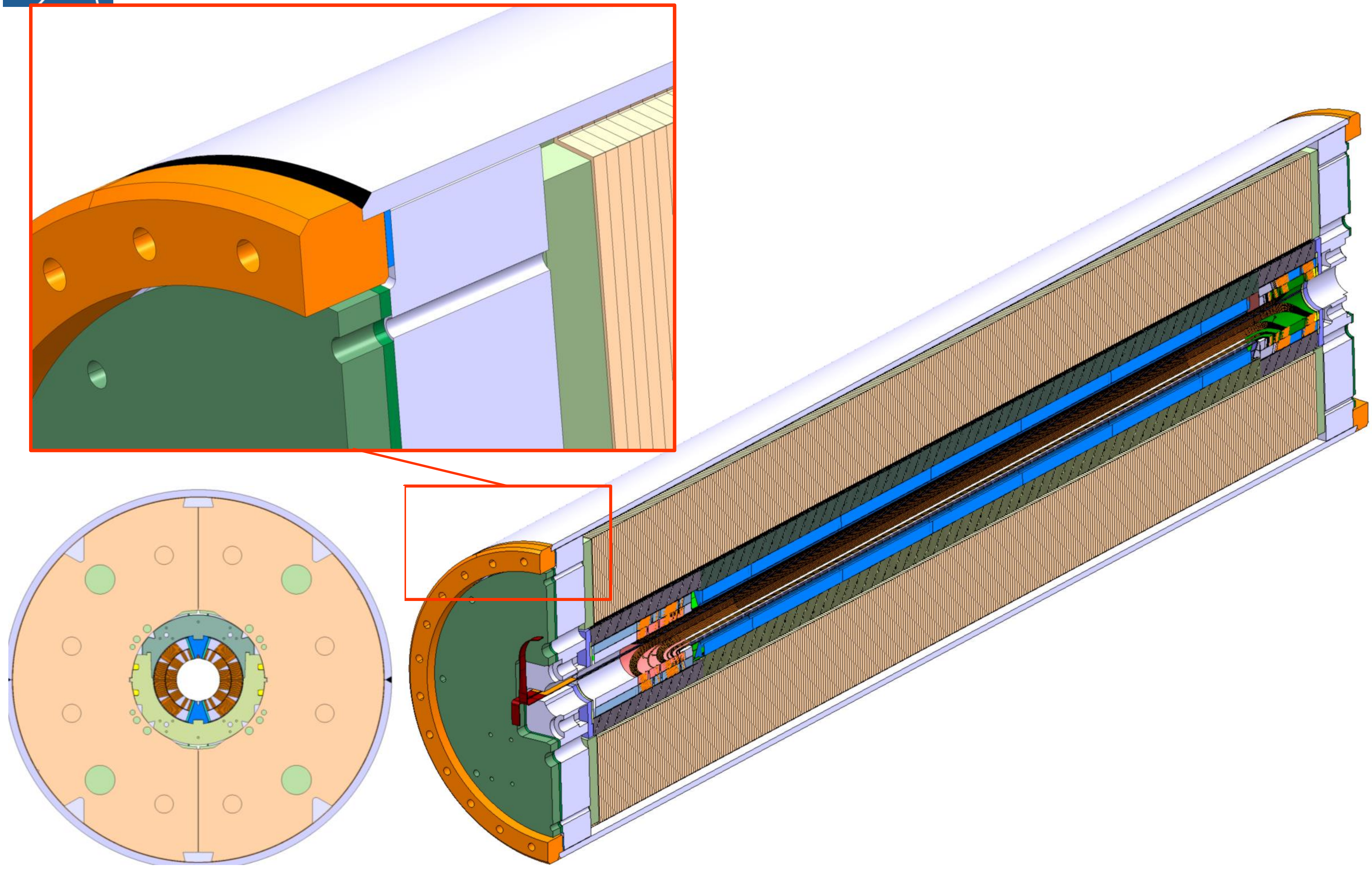


Pole wedge

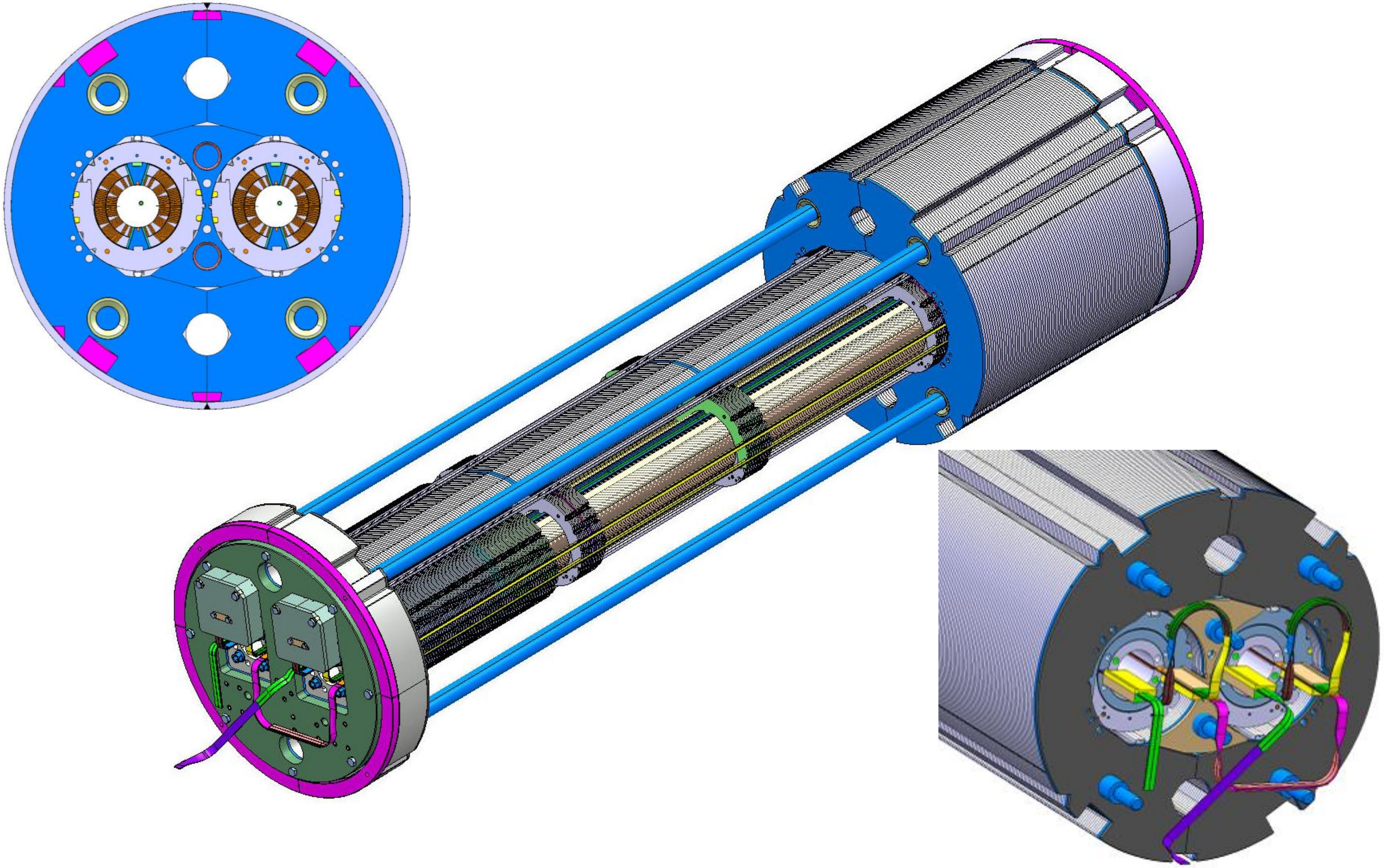


Collared coil (ground insulation and collaring shoe removed)

# *CERN 1-in-1 Cold-mass*

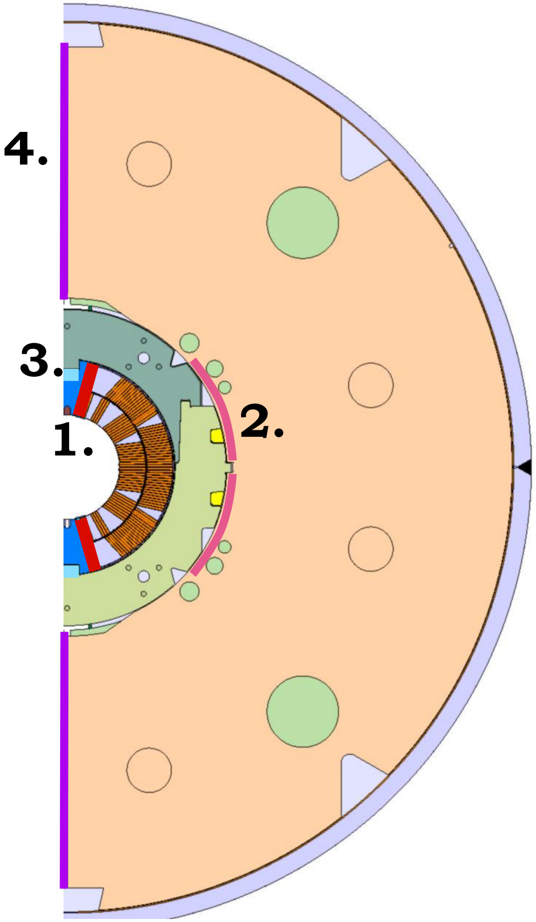


# CERN 2-in-1 Cold-mass



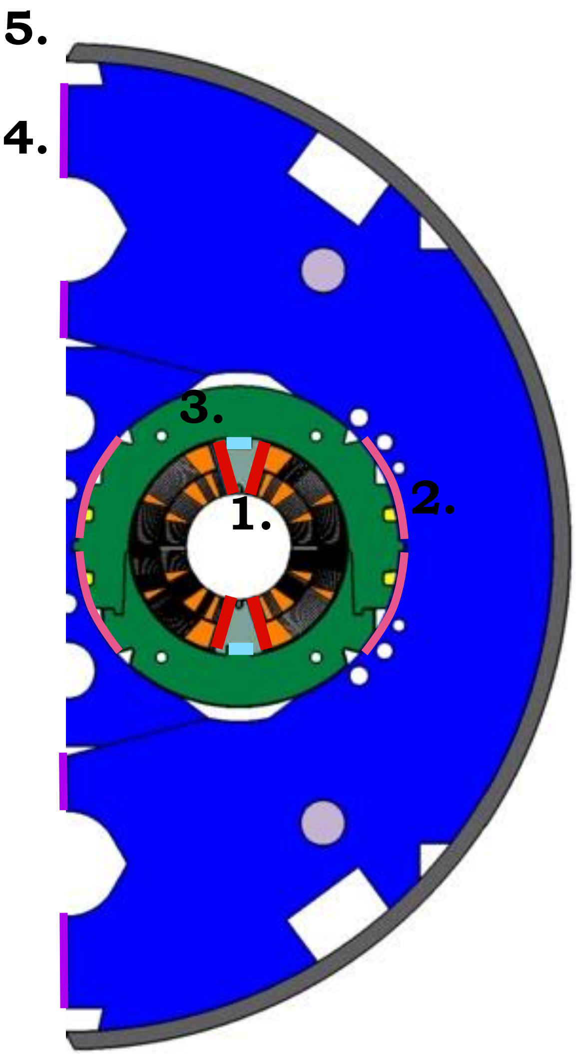
# *1-in-1 with Pole-Loading*

- **Design features:**
  1. **Pole shim**
  2. **Collar/yoke shim**
  3. **Pole adjustment shim**
  4. **Gap closing @ room temperature remaining closed to 12 T.**
  5. **Stainless-steel shell**
- **(3) is an optional knob.**
- **(2) and (4) must be controlled in order to close gap at RT.**

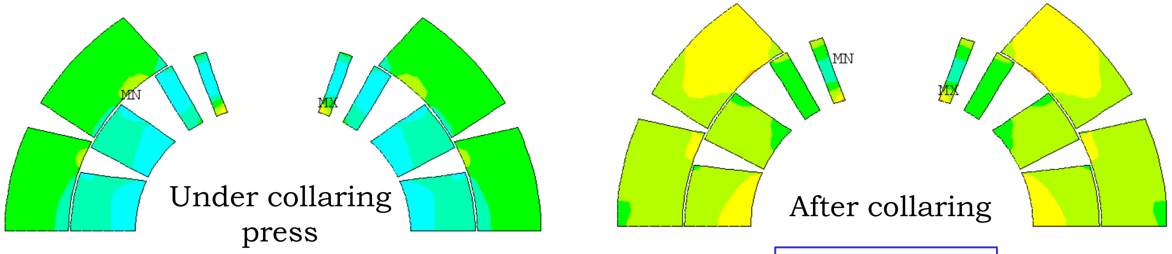


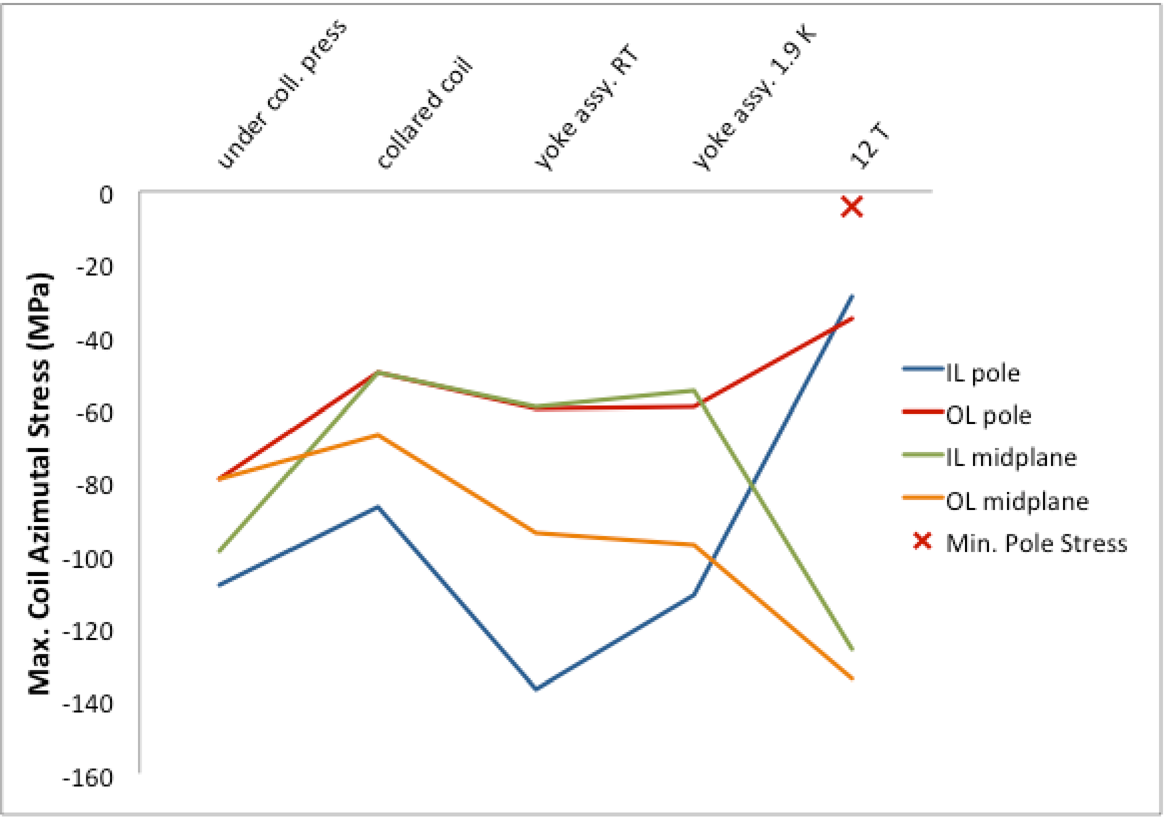
# 2-in-1 with Pole-Loading

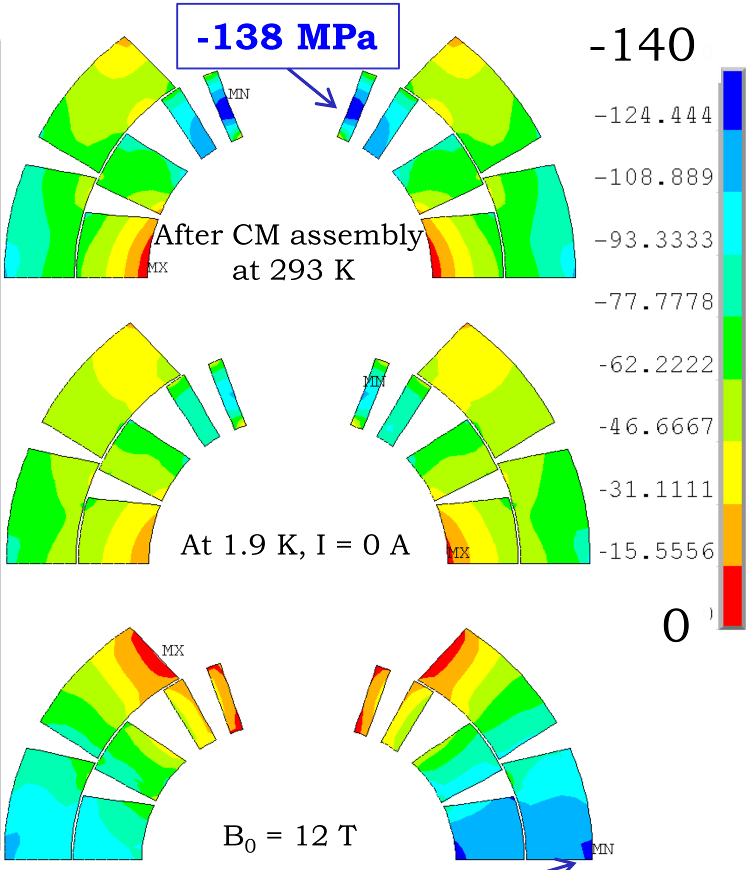
- **Design features:**
  1. **Pole shim**
  2. **Collar/yoke shim**
  3. **Pole adjustment shim**
  4. **Gap closing @ room temperature remaining closed to 12 T.**
  5. **Stainless-steel shell**
- **(3) is an optional knob.**
- **(2) and (4) must be controlled in order to close gap at RT.**



# Pole Loading Concept: 2-in-1 FEA



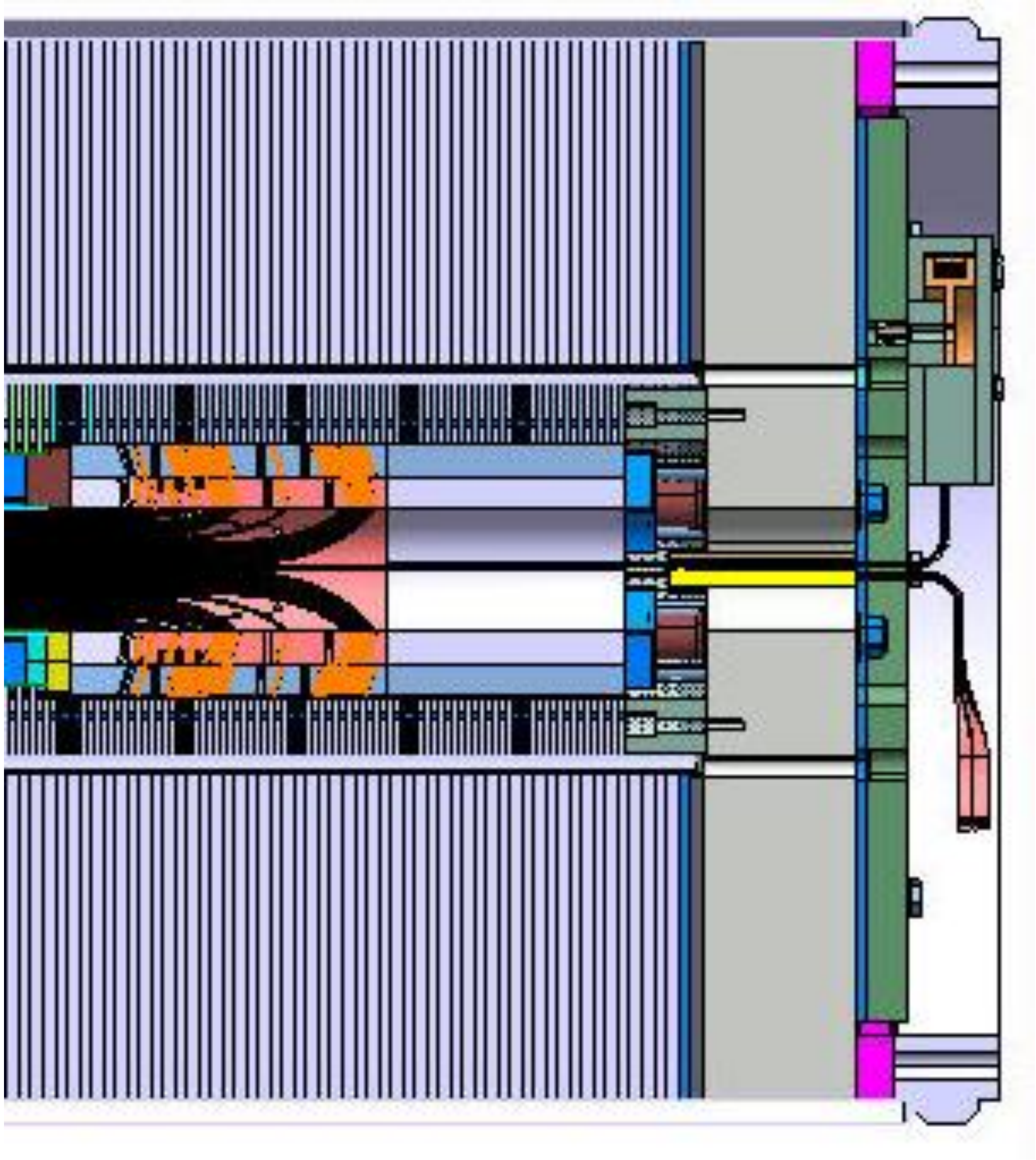


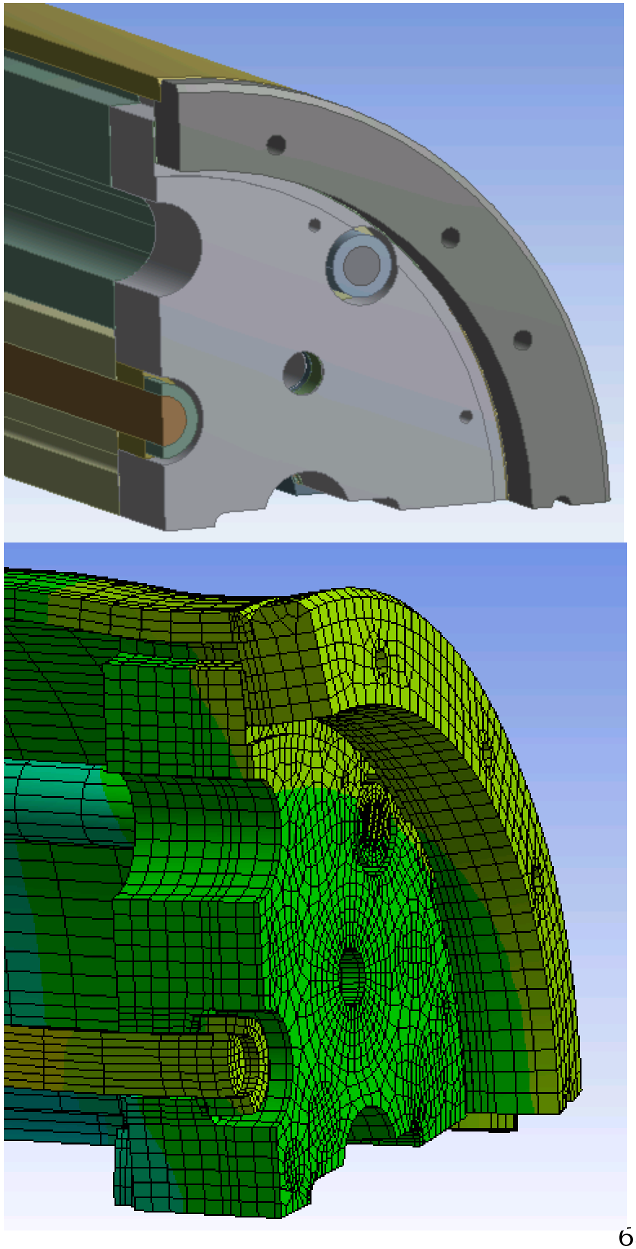


**-138 MPa**

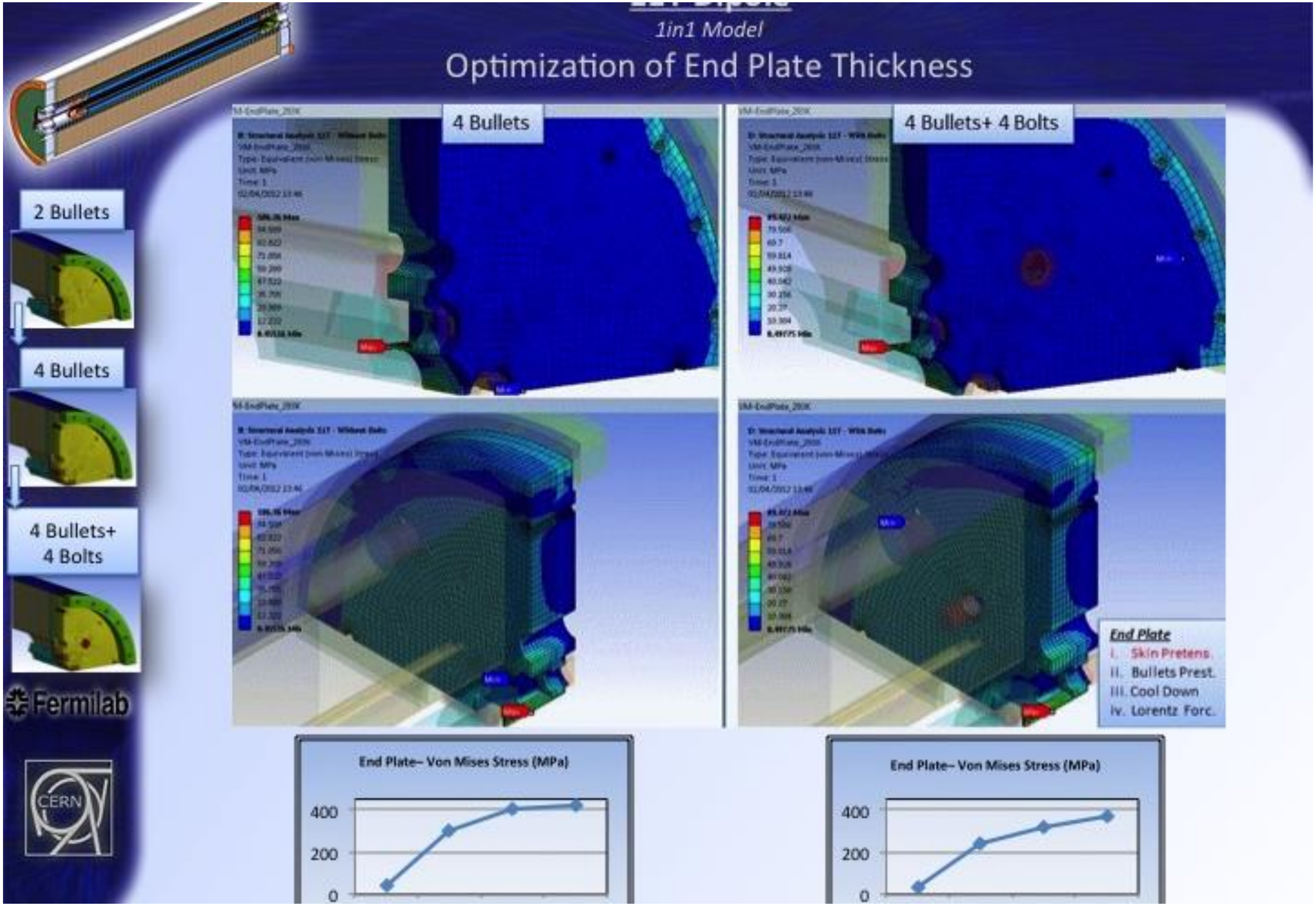
**-138 MPa**

# CERN 2-in-1 End Support





# Structural Analysis of End Region



*1in1 Model*

Optimization of End Plate Thickness

2 Bullets

4 Bullets

4 Bullets+ 4 Bolts

4 Bullets

4 Bullets+ 4 Bolts

***End Plate***

i. Skin Pretens.

ii. Bullets Prest.

iii. Cool Down

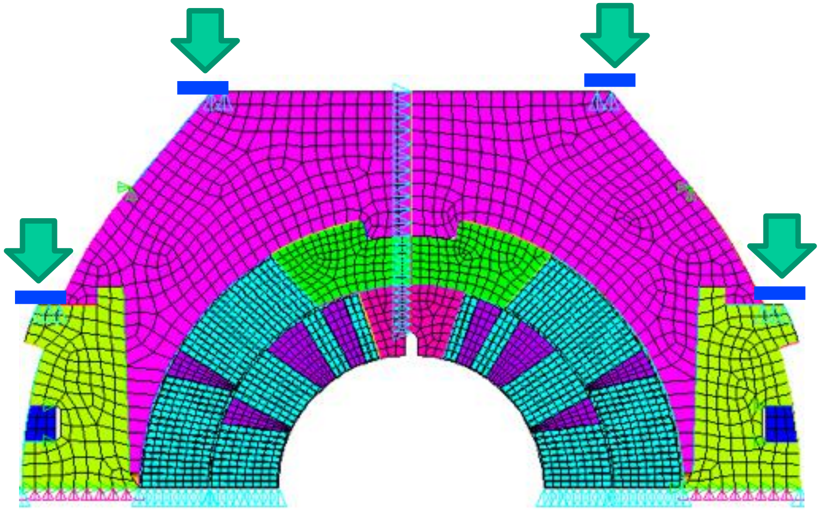
iv. Lorentz Forc.

End Plate– Von Mises Stress (MPa)

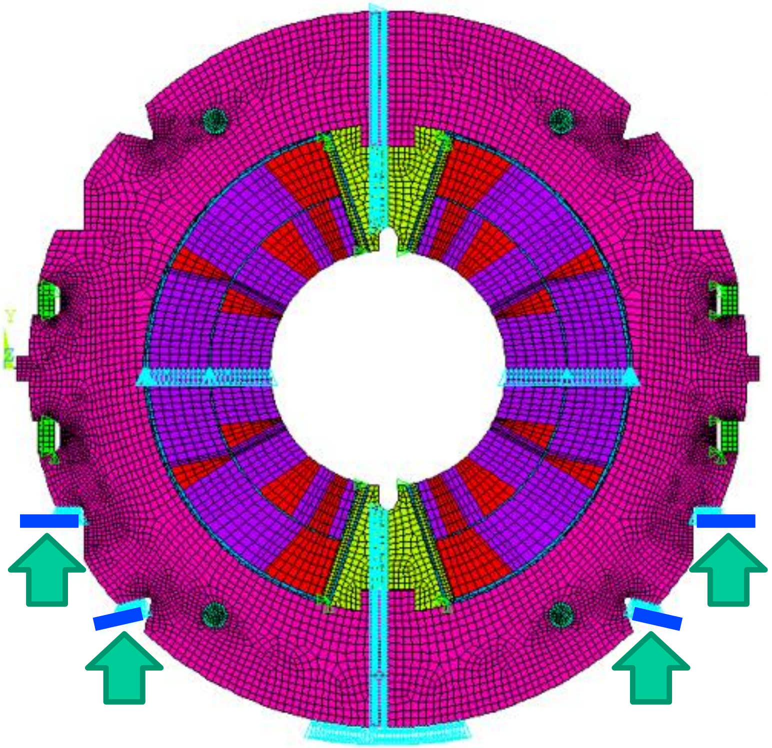
End Plate– Von Mises Stress (MPa)

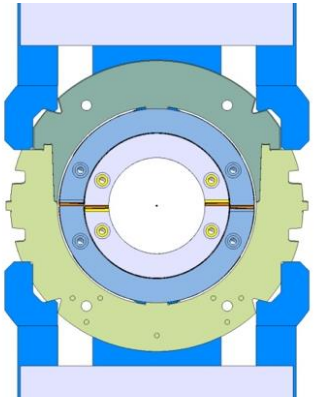
# FEA Model Under the Collaring Press

## Integrated pole concept



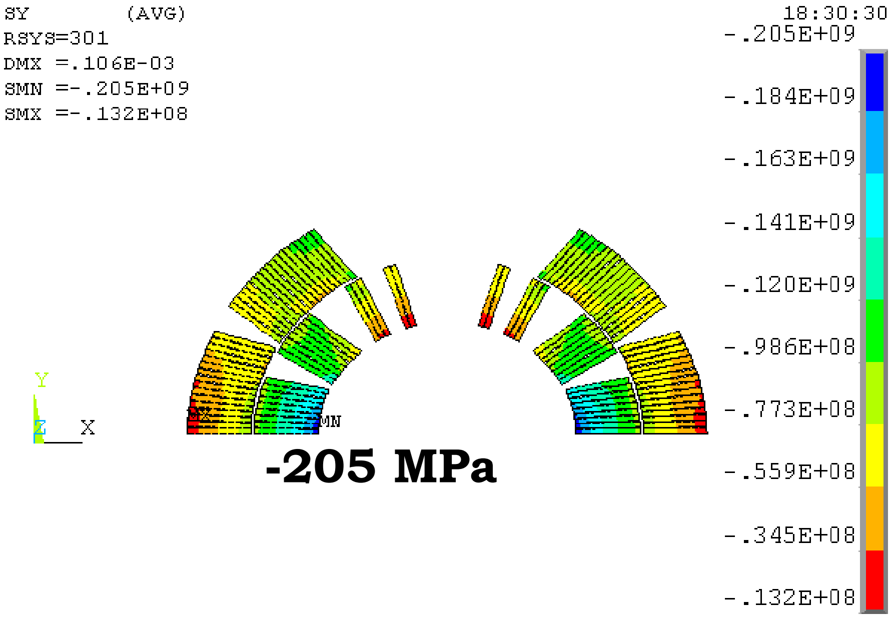
## Pole-loading concept

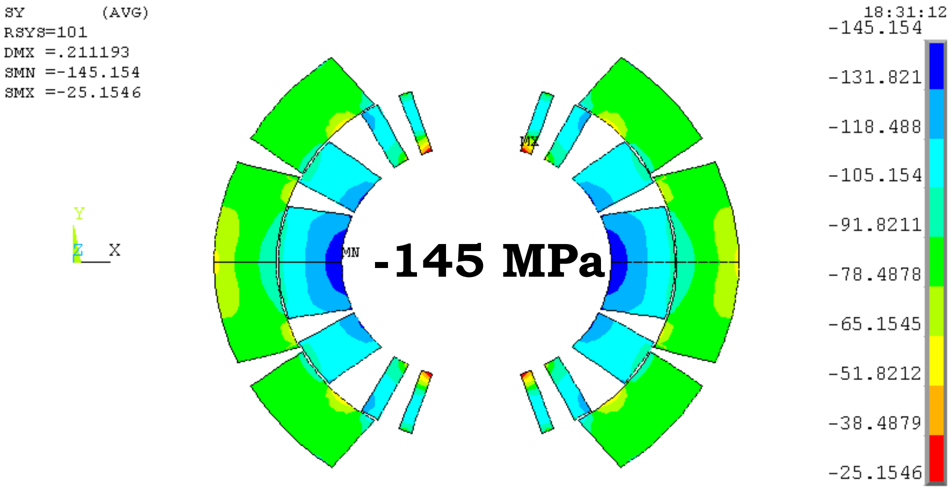




# Impact of Over-Compression

- **Check impact of over-compression by additional 0.05 mm collar press displacement.**

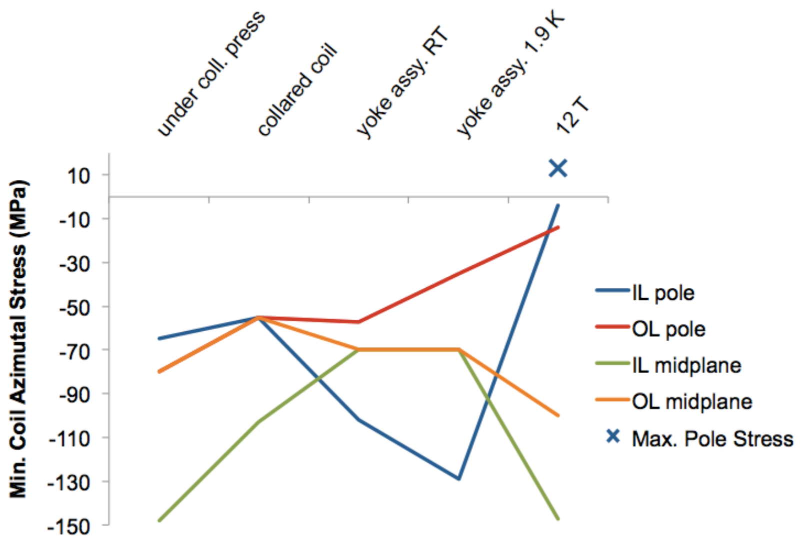


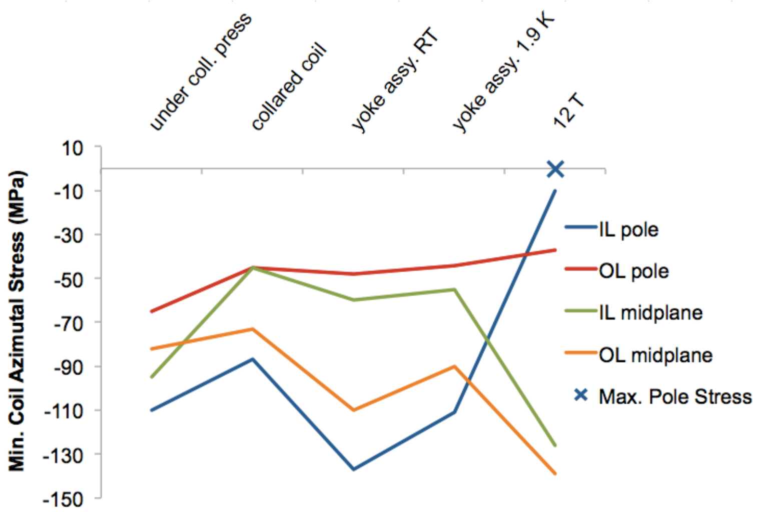


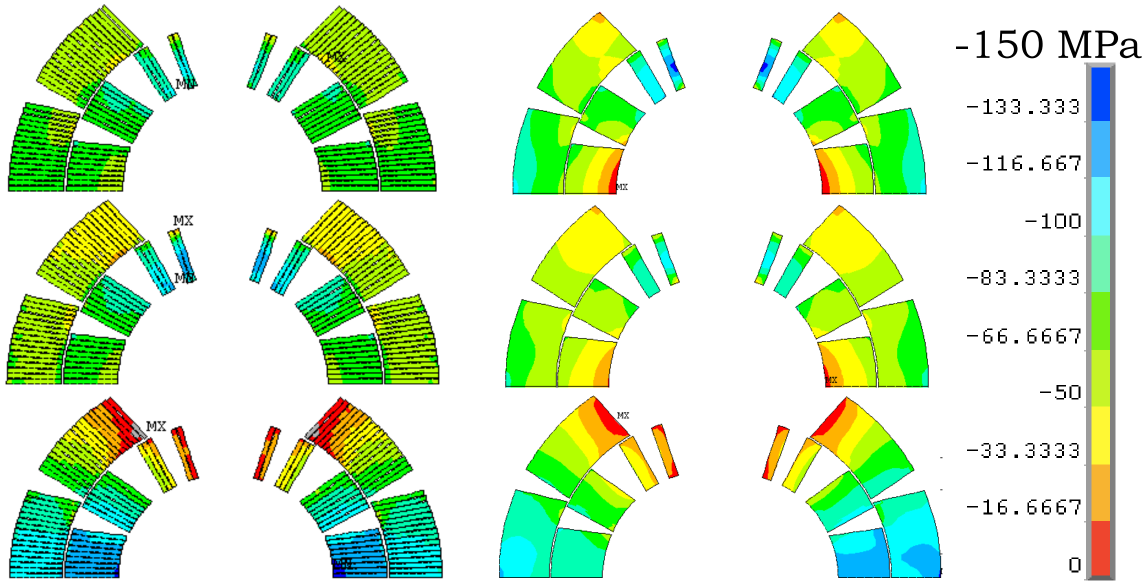
## Values for default displacement

| | **Integrated pole** | | | **Pole loading** | | | |
|---|---|---|---|---|---|---|---|
| | **P1** | **P2** | **M1** | **P1** | **P2** | **M1** | **M2** |
| **Under press** | -65 | -80 | -148 | -110 | -65 | -95 | -82 |

# Coil Stress Evolution 1/2







**Yoke assembly @ room temp.**

**Cryogenic temp.**

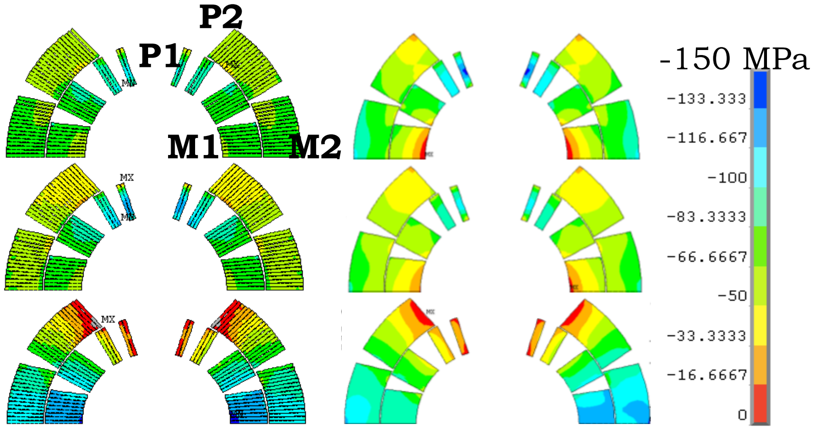
**12 T**

# Coil Stress Evolution 2/2

- **Minimal azimuthal coil stress:**

| | Integrated pole | | | | Pole loading | | | |
|---|---|---|---|---|---|---|---|---|
| | **P1** | **P2** | **M1** | **M2** | **P1** | **P2** | **M1** | **M2** |
| **Under press** | -65 | -80 | -148 | -80 | -110 | -65 | -95 | -82 |
| **Spring-back** | -55 | -55 | -103 | -55 | -87 | -45 | -45 | -73 |
| **Yoke assy.** | -102 | -57 | -70 | -70 | -137 | -48 | -60 | -110 |
| **Cool down** | -129 | -35 | -70 | -70 | -111 | -44 | -55 | -90 |
| **12 T** | -4 | -14 | -147 | -100 | -10 | -37 | -126 | -139 |

- **FEA shows that both designs allow for +/- 0.05 mm adjustment of the collar size.**

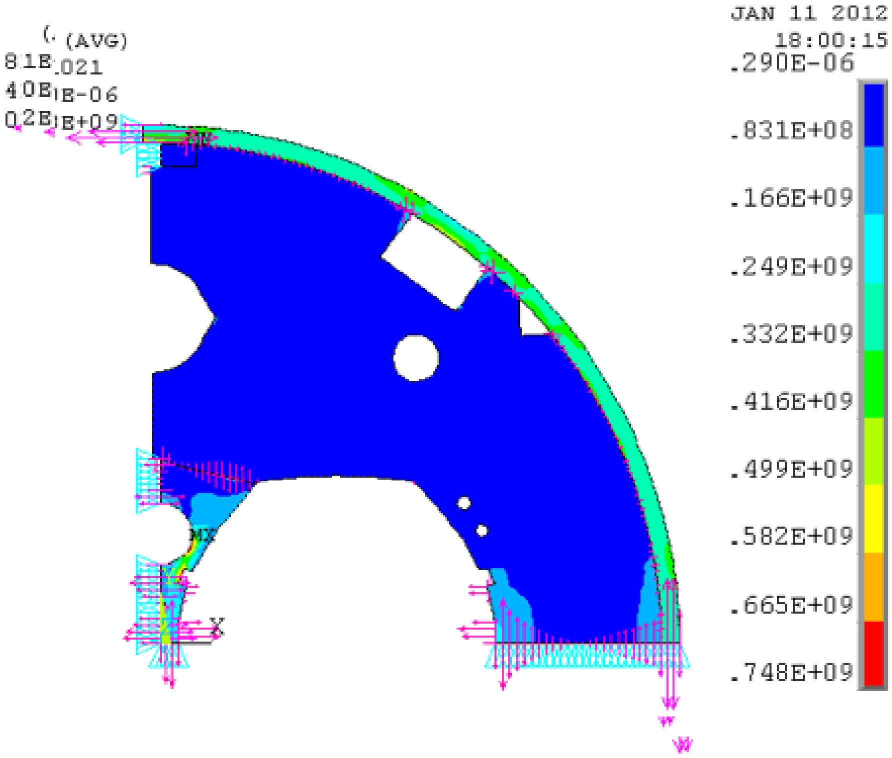


# *Shell Stress, Yoke Gap*

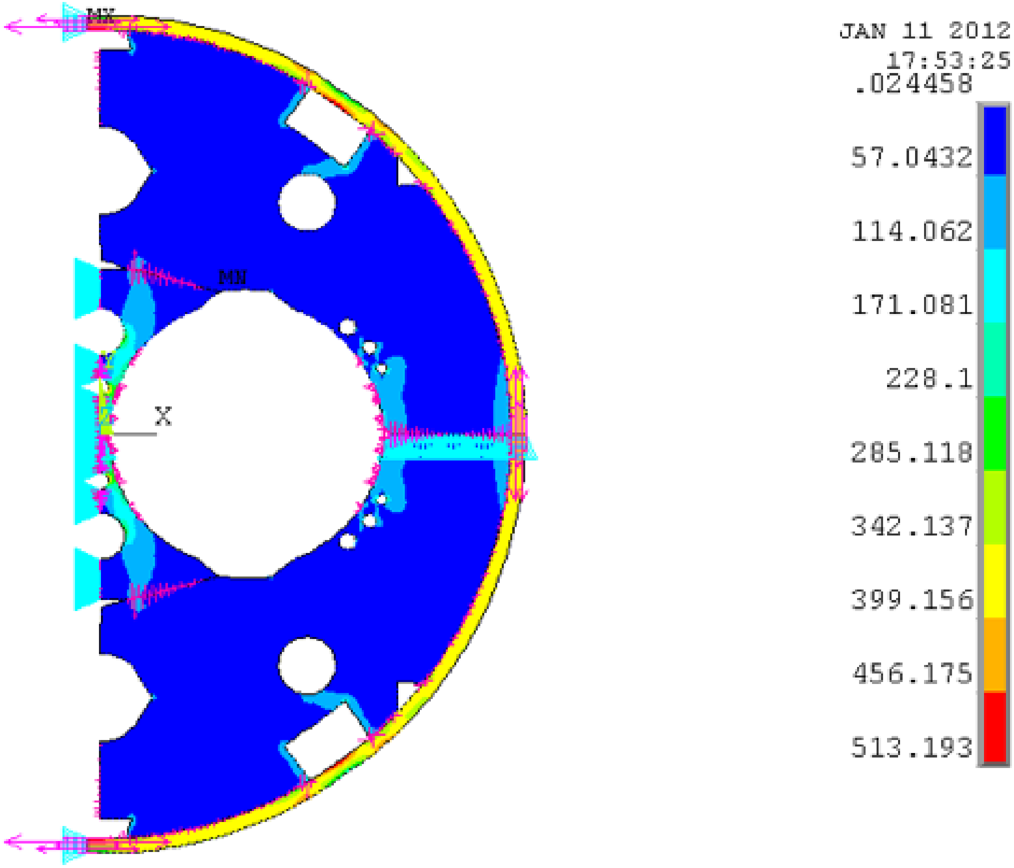
**Cryogenic 12 T**

**Room temp.**

shell thickness 10 mm



shell thickness 10 mm



# Structural Analysis Status

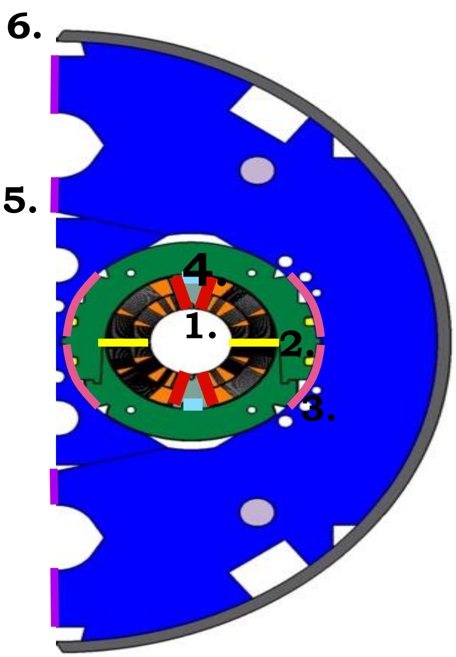
- **Optimisation of Case #1 (CERN coil & CM) and #2 (FNAL coil & CERN CM) completed**

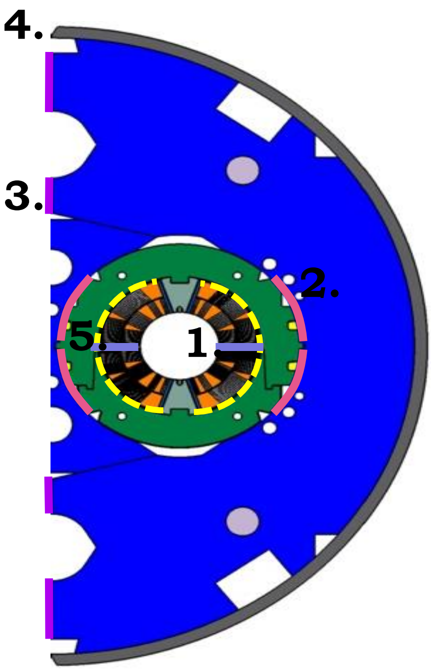
**Case #1 design features:**

1. Pole shim
2. Mid-Plane Shim
3. Collar/yoke shim
4. Pole adjustment shim
5. Gap closing @ room temperature remaining closed to 12 T.
6. Stainless-steel shell

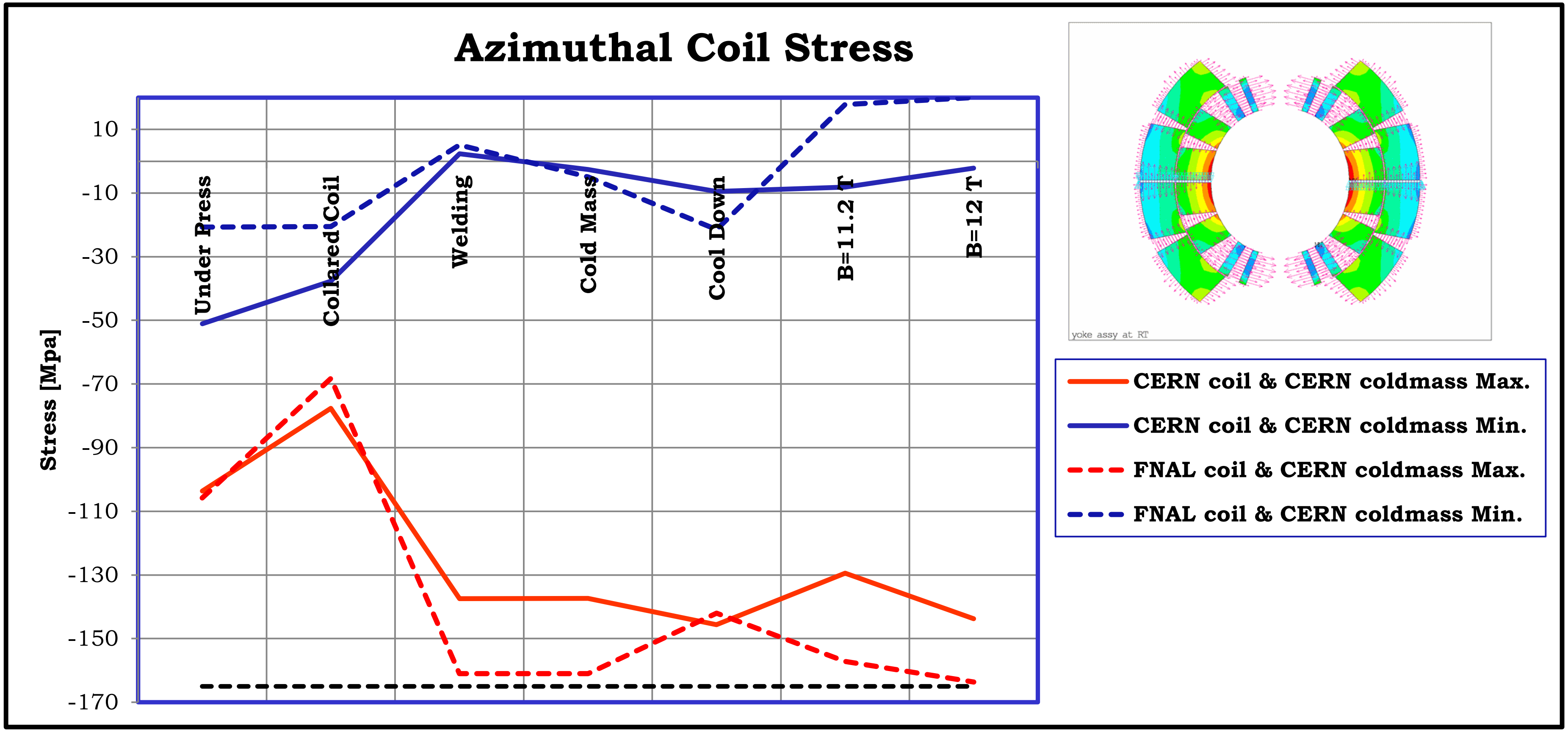
**Case #2 design features:**

1. Mid-Plane Shim
2. Collar/yoke shim
3. Gap closing @ room temperature remaining closed to 12 T.
4. Stainless-steel shell
5. Coil/Collar Radial Shim





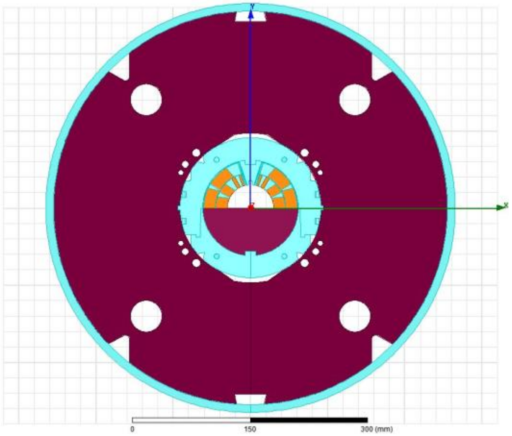
# FEA: Case #1 & # Summary

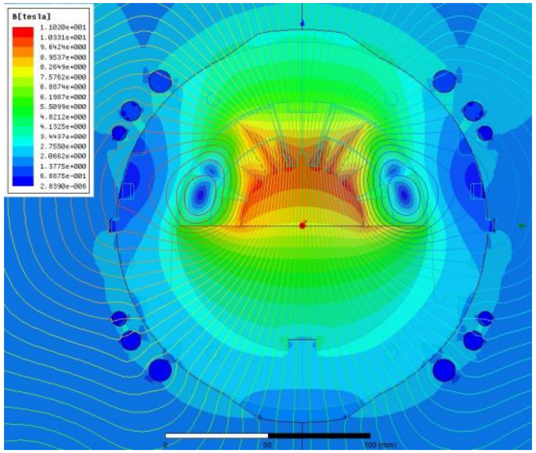


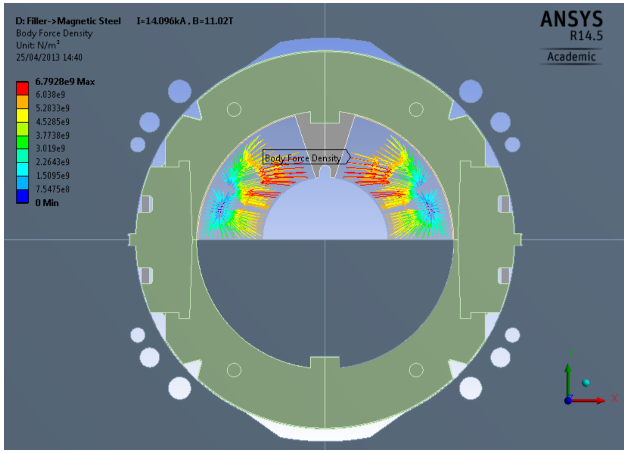
- **Acceptable solution with both configurations**
- The maximum coil stress is lower with CERN coils
- Yoke gap with CERN coils is closed at RT with all parameter sets, while in the FNAL coil & CERN cold mass scenario, it's quite challenging.
- The FNAL coil in CERN cold mass requires radial shimming in the Collar/Coil interface, the mid-plane shim is not required.

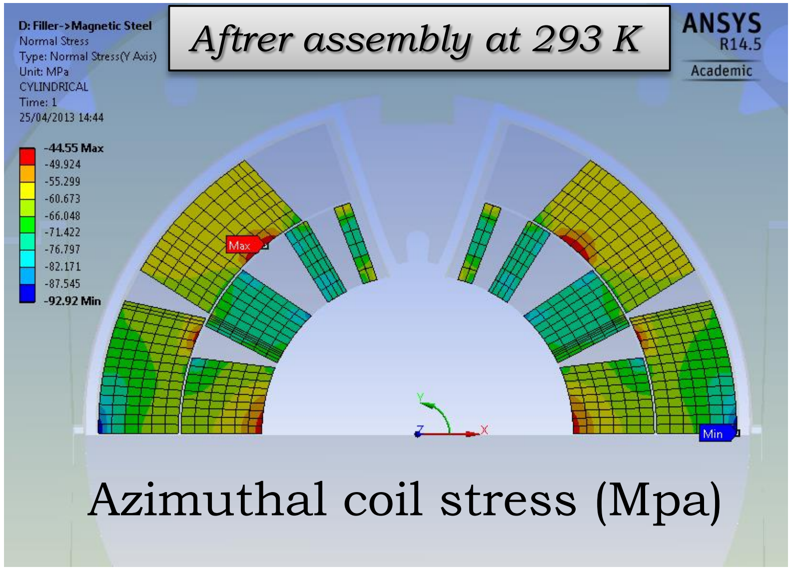
# CERN Single Coil Assembly

Courtesy of C. Kokkinos & T. Lyon CERN TE-MCS



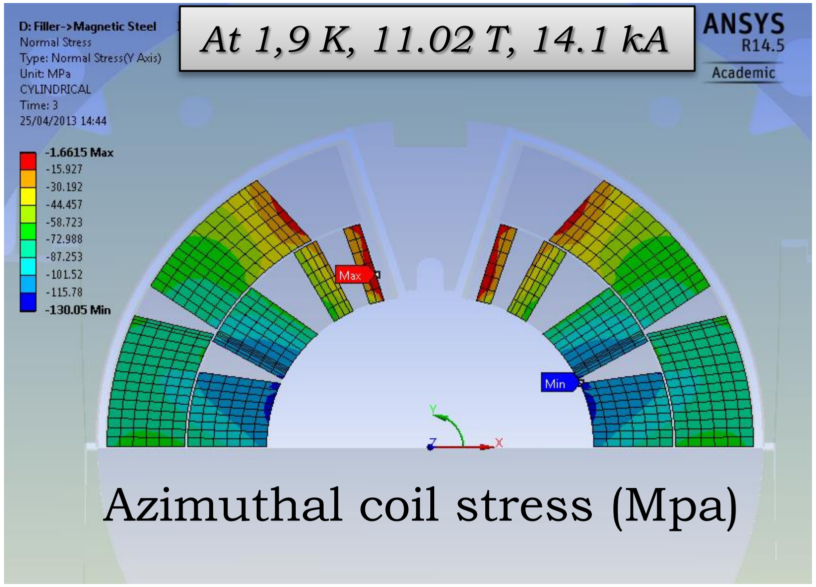






*Aftrer assembly at 293 K*

Azimuthal coil stress (Mpa)



*At 1,9 K, 11.02 T, 14.1 kA*

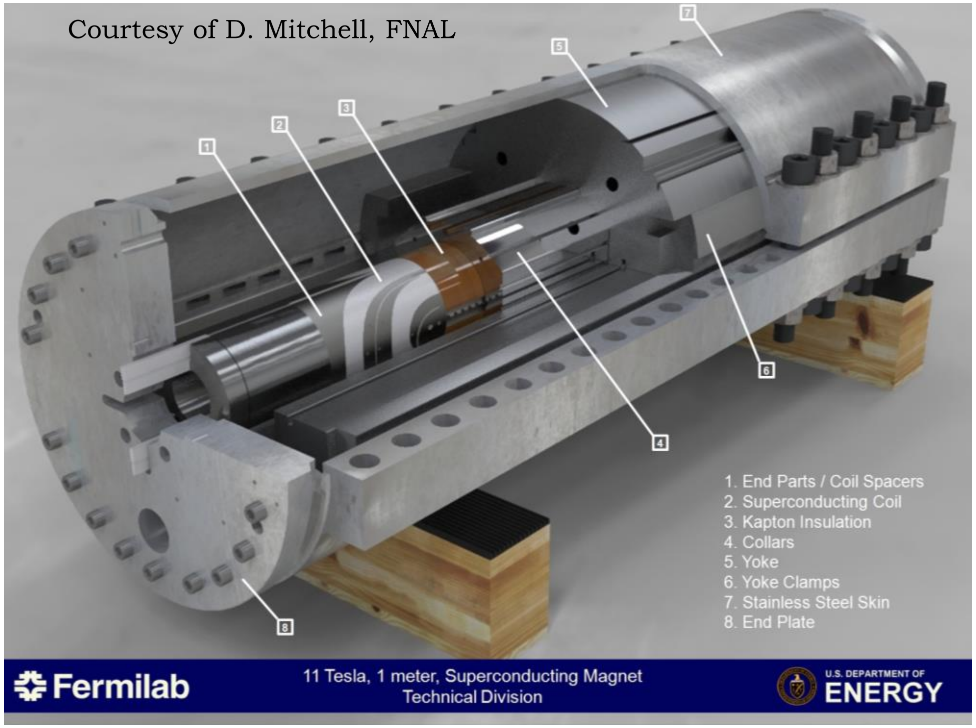
Azimuthal coil stress (Mpa)

# *Outline*

- **Project goals and plans**
- **Magnetic design**
- **FNAL Demonstrator design and & coil technology**
- **CERN mechanical design**
- **Short model program milestones**
- **CERN R&D topics**
- **LARP and US Core Programs & 11 T Project**
- **Conclusions**

# *FNAL Short Model Program*

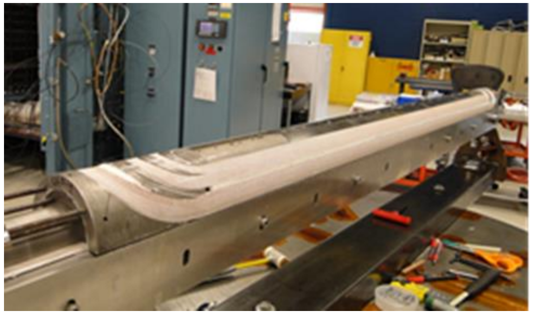
- **MBHSP01 (2 m) and MBHSP02 (1 m) have been tested.**
- **Coil #9 (being reacted) will be tested in Mirror, MBHM01.**
- **Assemble and test MBHSP03 (1 m, 1-in-1) using coils #9-10**
- **Assemble and test the MBHDP01 (1 m, 2-in-1) using collared coils from MBHSP02 and MBHSP03**
- **Assemble and test MBHSP04 (1 m, 1-in-1) using coils #11-12**
- **Assemble and test MBHSP05 (1 m, 1-in-1) using coils #13-14**
- **Assemble and test MBHDP02 (1 m, 2-in-1) using collared coils from MBHSP04 and MBHSP05**


Courtesy of D. Mitchell, FNAL

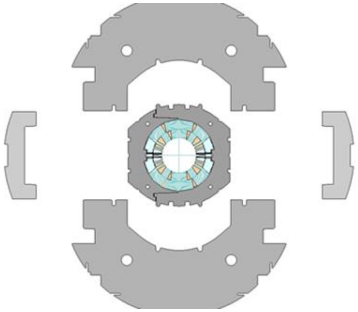
# MBHSP01 – 1-in-1 Demonstrator (2 m)


OST RRP-108/127


40-strand cable produced with FNAL cabling machine


Coil fabrication


Collared coil assembly


Cold mass assembly

**Magnet development and fabrication was done in record time – 18 month!**

# *CERN Short (2 m) Model Program*

- **Assemble and test the RRP-54/61 coil (reacted) as single coil assembly (MBHSS101) using existing collars, yoke, welded outer shell, and end plates Sep -13 => Jan -14**
- **Two RRP-108/127 coils to assemble and test the 1st 1-in-1 model (MBHSP101) Nov-13 => Dec -14**
- **Two RRP-132/169 coils to assemble and test the 2nd 1-in-1 model (MBHSP102) Feb-14 => Jul-15**
- **Collared coils from MBHSP101 & 102 to assemble and test the 1st 2-in-1 model (MBHDP101) May -14**
- **Idem for PIT-cable: 2 x 1-in-1 model (MBHSP103-4) to have tested collared coils for the 2nd 2-in-1 model (MBHDP102). Jun -15**
- ***Will be conflicting with MQXF and other magnet projects in terms of human resources and infrastructure***

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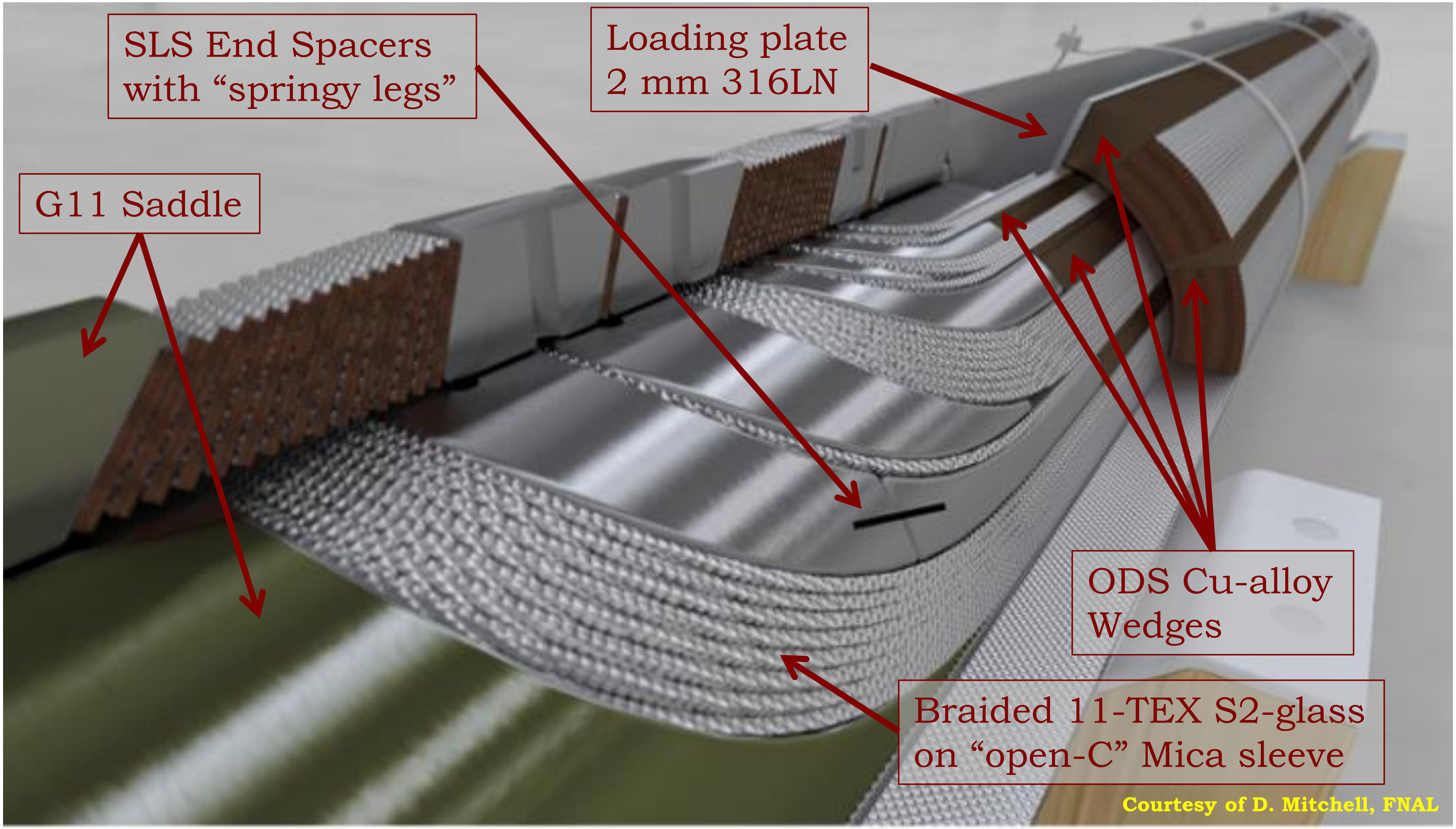
# CERN R&D Topics

- **Pole loading concept (discussed above)**
- **Cable insulation: S2-glass braided over open-C Mica**
  - **Improve electrical integrity**
  - **With ceramic binder the glass (E & S2) turn into powder**
- **ODS wedges**
  - **Minimize plastic deformation of the coils whilst having elastic, electrical, and thermal properties of Cu**
- **Springy legs**
  - **Minimize cable insulation damage during widning**
- **G11 end saddle**
  - **Minimize risk of insulation damage and over-compression of the tails**
  - **Better match the elastic properties of the straight section (G11 cylinder vs. Stainless steel cylinder)**
  - **Better distribution of the end forces on the coil**
- **Inter-layer protection heater**
  - **Very efficient and can be made up to 5.5 m length**

# CERN 11 T Dipole Coil



SLS End Spacers with “springy legs”

Loading plate 2 mm 316LN

G11 Saddle

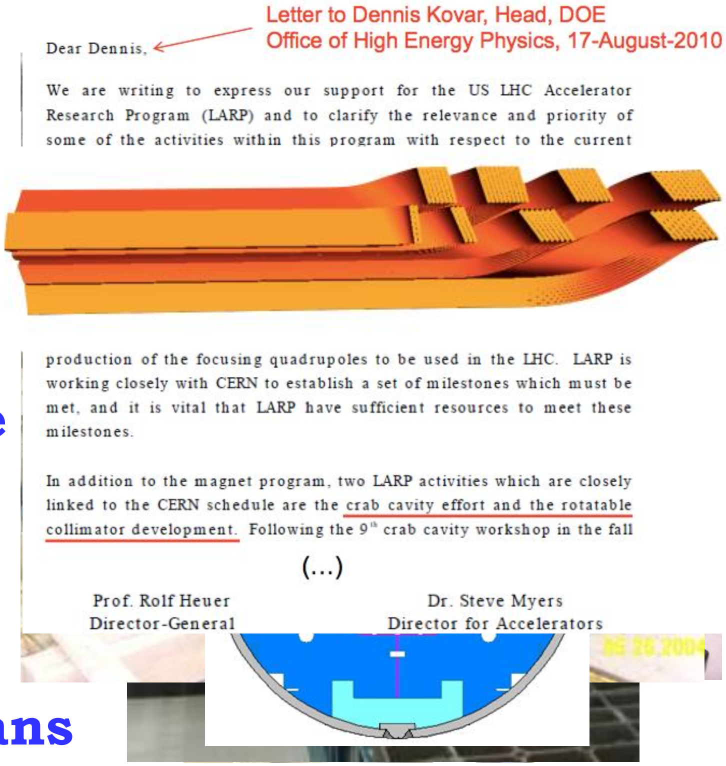
ODS Cu-alloy Wedges

Braided 11-TEX S2-glass on “open-C” Mica sleeve

**Courtesy of D. Mitchell, FNAL**

# LARP and US Core Programs' Technology used for 11-T

- ❖ Conductor
- ❖ Baseline insulation
- ❖ Pole pieces, metallic spacers
- ❖ Ceramic binder/curing matrix
- ❖ End design experience
- ❖ Winding/curing tooling + procedure
- ❖ Handling tooling
- ❖ Reaction tooling + procedure
- ❖ Impregnation tooling + procedure
- ❖ Experience transferred by technicians
- ❖ Mechanical structure experience
- ❖ Length scale-up
- ❖ Lab infrastructure for 2 parallel production lines
- ❖ Credibility for Nb3Sn accelerator magnet projects



Letter to Dennis Kovar, Head, DOE Office of High Energy Physics, 17-August-2010

Dear Dennis,

We are writing to express our support for the US LHC Accelerator Research Program (LARP) and to clarify the relevance and priority of some of the activities within this program with respect to the current

production of the focusing quadrupoles to be used in the LHC. LARP is working closely with CERN to establish a set of milestones which must be met, and it is vital that LARP have sufficient resources to meet these milestones.

In addition to the magnet program, two LARP activities which are closely linked to the CERN schedule are the crab cavity effort and the rotatable collimator development. Following the 9th crab cavity workshop in the fall

(...)

Prof. Rolf Heuer
Director-General

Dr. Steve Myers
Director for Accelerators

# Conclusions

- **11 T Project was an example of very good collaboration between FNAL and CERN.**
- **The coil fabrication process and tooling was developed at Fermilab and transferring this to CERN gave us a real jump start into Nb3Sn technology.**
- **The continuous exchange of experience during the parallel development work in both labs helped us to refine the process and avoid potential performance limitations.**

- **I am very pleased to see that our efforts to improve the robustness in view of accelerator operation and industrial production seem to have paid off (MBHSP102 test July 2015)**