D1 Design at 150 mm Aperture and Plans

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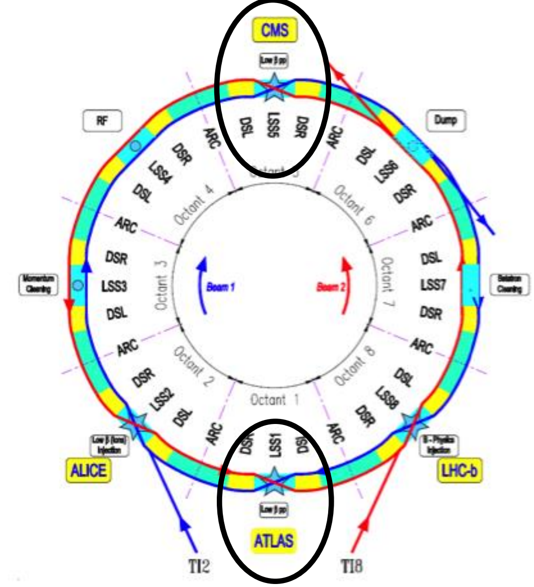
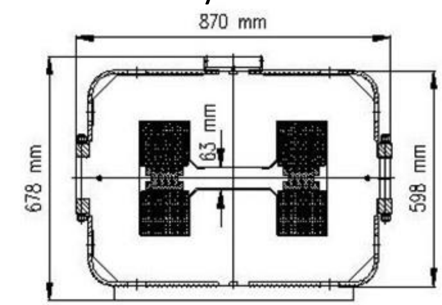
Objective: *New D1*

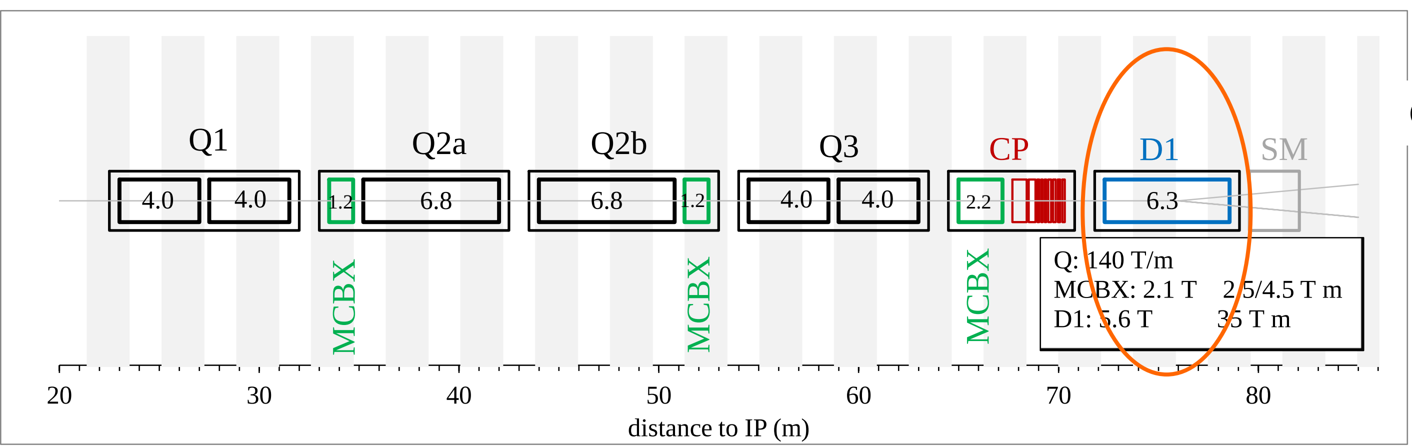
- *For HL-LHC upgrade, needs for new Inner Triplet system at IR1 & IR5.*
  - *Large aperture (150 mm) HF Quadrupoles, corrector package and D1.*
- *New beam separation dipole (D1) should be accommodated with large aperture IT Quads; which will need a large aperture (large beam size) and 50 % increase in original integrated field (distance btw D1-D2 shortened).*



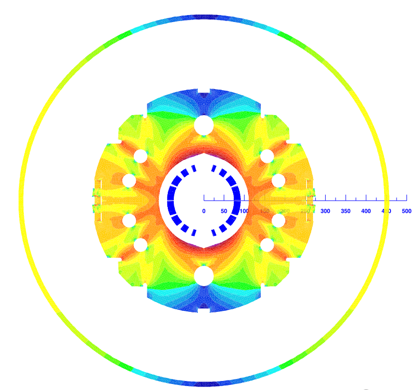
Schematic layout of the LHC



Current D1 (MBXW) at IR1 & IR5



Schematic layout of the IR



New superconducting D1

Design Parameter Change

- Coil aperture of D1 (NbTi) was once set to be 160 (=150+10) mm until April 2013.
  - Extra space (+10mm) reserved for additional thicker beam shielding to suppress heat deposition
- Radiation simulation results for D1
  - First result for D1 with 150 mm aperture with beam shielding of tungsten
    - Peak dose in lifetime: a few 10 MGy
    - Peak heat deposition: 1-2mW/cm^3
      - Additional beam shielding will be unnecessary…

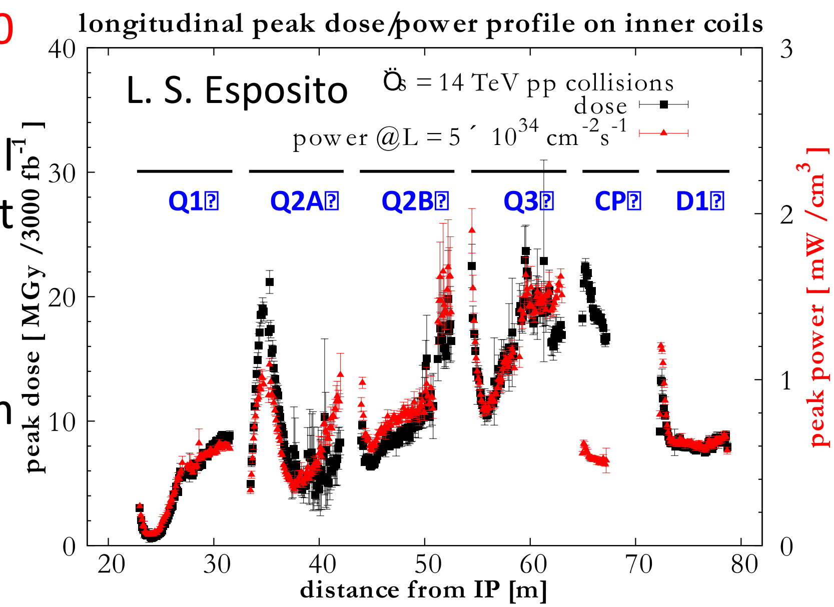
New coil aperture of 150 mm in May 2013

- Requirements for the HeII cooling was relaxed…
  - Free Area 130 cm^2, or
  - Free area 100cm^2 + 2 x ϕ49 mm HX holes

New iron cross section:

Free area >130 cm^2 + 2 x ϕ49 mm HX holes

- Availability: ***NbTi LHC MB outer cable***



R. van Weelderen (March 2013)

	Variant 1	Variant 2	Variant 3/4
Power limit (with max HX holes of 80 mm)	550 W (Q1-D1) vapour velocity constraint	550 W (Q1-D1) vapour velocity constraint	550 W (Q1-Q3) + ~ 160 W (CP-D1) = 710 W Area constraint
Q1-Q3 HXs Q1-Q3 Free Area Q1-Q3 Cryostat Pumping line	2x80 mm holes ~ 150 cm^2 97-100 mm	2x80 mm holes ~ 150 cm^2 97-100 mm	2x80 mm holes ~ 150 cm^2 97-100 mm
CP HXs CP Free Area CP Cryostat Pumping line	none > 300 cm^2 none	2x80 mm holes ~ 150 cm^2 97-100 mm	None or > 2x49-80 mm holes ~ 100 cm^2 none
D1 HXs D1 Free Area D1 Cryostat Pumping line	none > 300 cm^2 none	none ~ 130 cm^2 none	> 2x49-80 mm holes ~ 100 cm^2 ~ X mm
Phase separator & piping entries/exits	1) Q1-end 2) Q3-CP	1) Q1-end 2) CP-D1	1) Q1-end 2) Q3-CP 3) CP-D1 or Q3-CP
QRL-jumpers	Q3-CP SM	CP-D1 SM	Q3-CP SM

Design Variants for D1 150 … ertu …

nted at M …

L_{mech} is longer. Conflict with test cryostat.

Concern about higher local stress in coil and yoke.

	Option A: LL70	Option B: LL80
Bore diameter	150 mm	
# of turns	44 (4 + 8 +13 +19)	
Nominal field (dipole)	**5.22 T**	**5.97 T**
Magnetic length *	**6.7 m**	**5.9 m**
Operating current	**11 kA**	**13 kA**
Injection current	~ 0.7 kA	~ 0.84 kA
Field homogeneity	<0.01% (R_{ref}=50 mm)	<0.01% (R_{ref}=50 mm)
Peak field in the coil (2D)	6.0 T	6.9 T
Load line ratio (2D)	9% @ 1.9 K / 90% @ 4.2 K	80% @ 1.9 K
Inductance (low / nominal field	5.7 / 5.2 mH/m	5.7 / 5.1 mH/m
Stored energy	**294 kJ/m**	**391 kJ/m**
Peak field/central field	1.15	1.16
Lorenz force X/Y (1st quadrant)	**1.3/0.5 MN/m**	**1.7/0.7 MN/m**
Outer dia. of iron yoke	550 mm	550 mm
Inner dia. of iron yoke	222 mm	222 mm
Strand diameter	0.825 mm	0.825 mm
Cu/Non-Cu ratio	1.95	1.95
Cable dimension / insulation	**15.1* 1.48mm^2 /** 0.16 mm (radial) 0.145 (azimuthal)	**15.1* 1.48mm^2 /** 0.16 mm (radial) 0.145 (azimuthal)
No. of strands	36	36
Keystone angle	0.9 °	0.9 °
Superconductor current density	1710 A/mm^2	1954 A/mm^2
Total length of the cable	**618 m (Coil length ~7.1 m)**	**548 m (Coil length ~6.3 m)**

Latest Design Parameters of D1: Option C

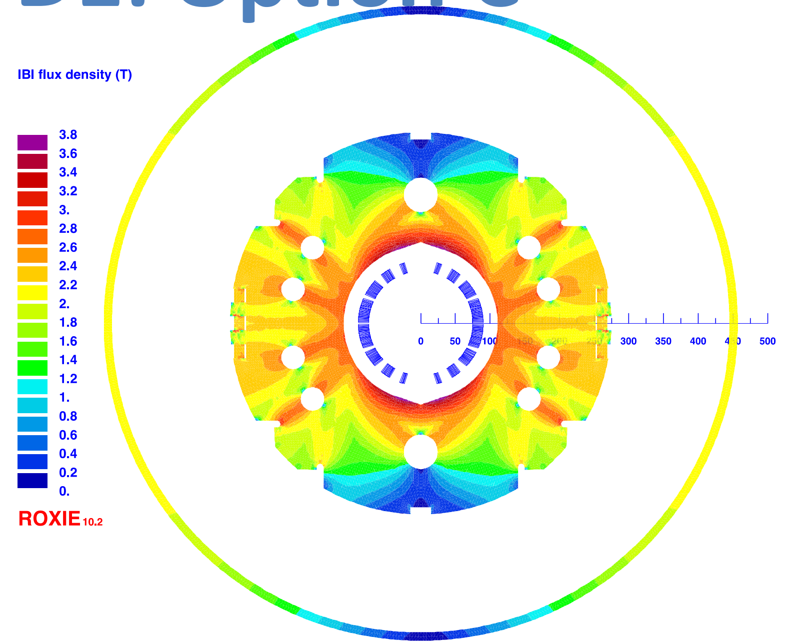
- *Coil ID:* ***150 mm***
- *Integrated field:* ***35 T m*** *(26 Tm at present LHC)*
  - *5.59 T at 12 kA.* L_{coil}*=6.3 m*
- T_{op}: *1.9 K by HeII cooling*
- *Op. point (2D coil):* ***75 %***
- *Coil layout: 1 layer of 15.1 mm cable*
  - *Better cooling. Saving space for iron yoke.*
- *Conductor:* ***Nb-Ti LHC MB outer cable***
- *Structure: Collared yoke structure by keying*
  - *RHIC dipole, LHC MQXA, J-PARC SCFM*
  - *Enhancing iron material for stray field issue*
- *Field quality:* $< 10^{-4}$ *at* R_{ref} *= 50 mm*
- *Cold mass OD: 550 +10 x 2 = 570 mm*
- *Cryostat OD: 914 mm, same as MB cryostat*
- *Radiation, energy deposition:*

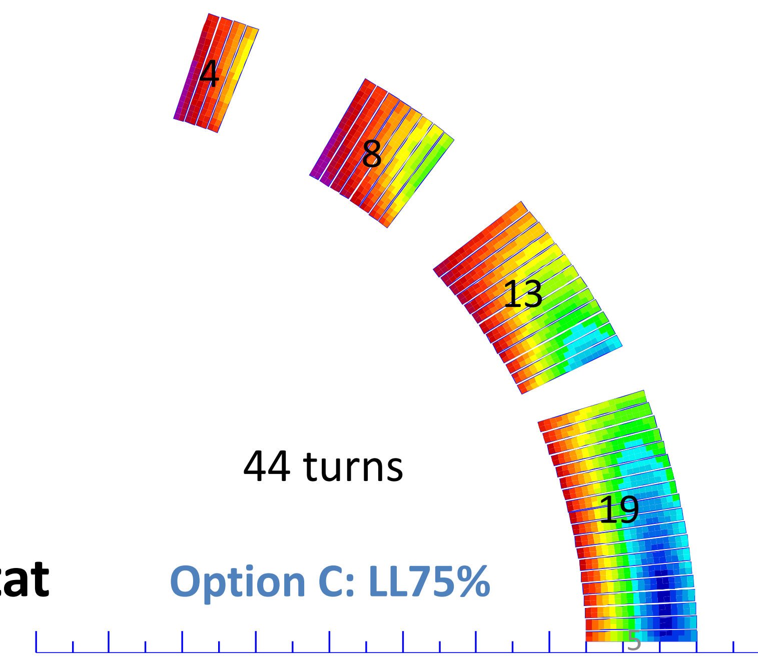
  A few 10 MGy, 1~2 mW/cm³

◆**Stress management**

◆**High saturation, stray field, flux return cryostat**

◆**Radiation resistance, cooling capability**



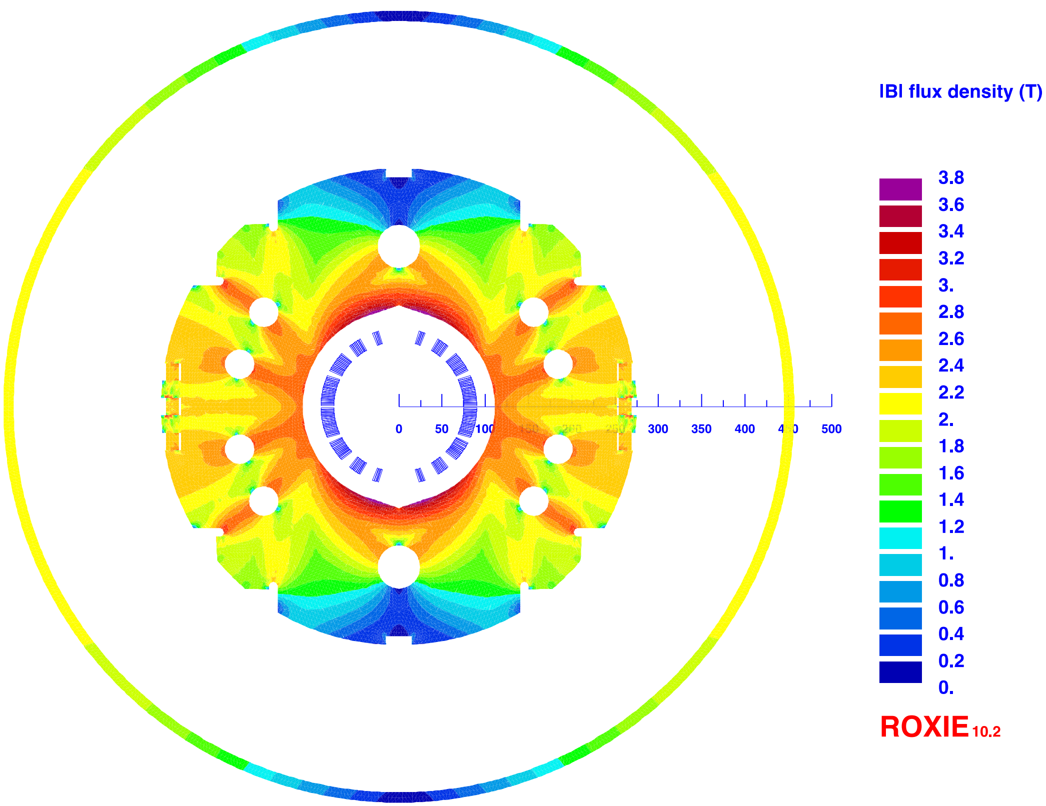


Option C: LL75%

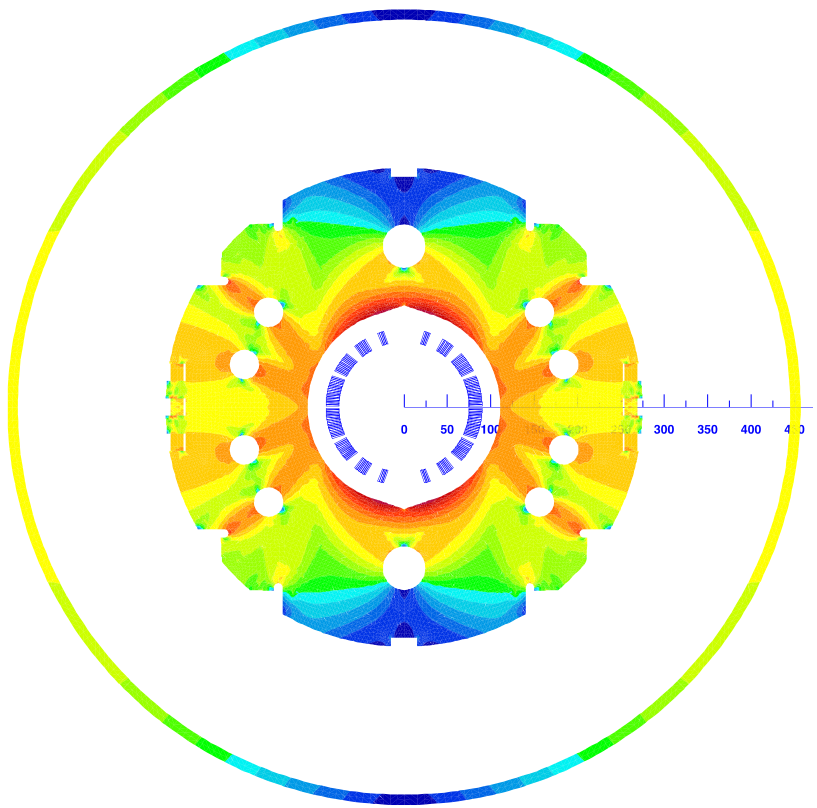
2D Cross Section

- **Same cross section for iron yoke for the Option C and Option A.**
- **The total void area in the iron yoke: 154 cm²**
- **2 x ϕ50 mm holes reserved for HX**

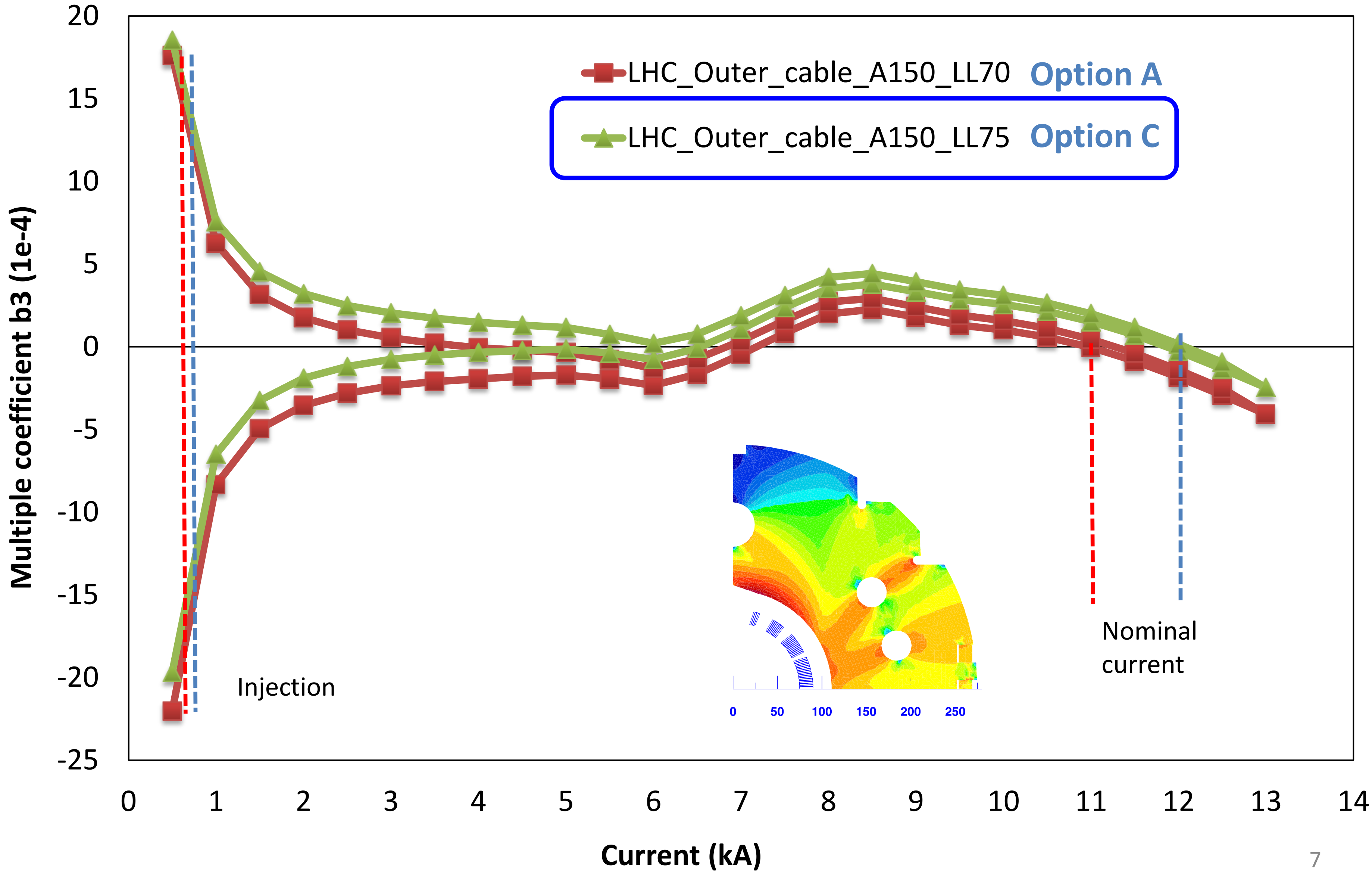
Option C (75% at load line in 2D)



Option A (70 %)

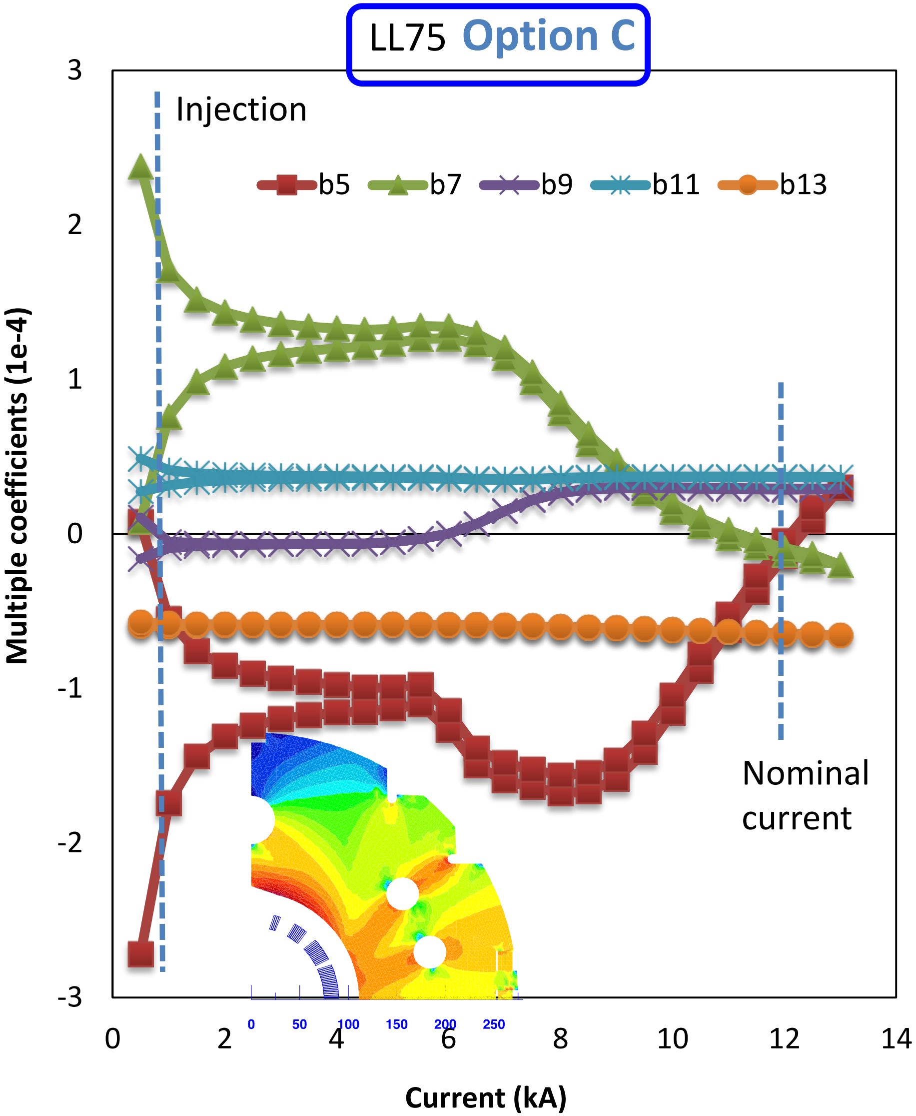


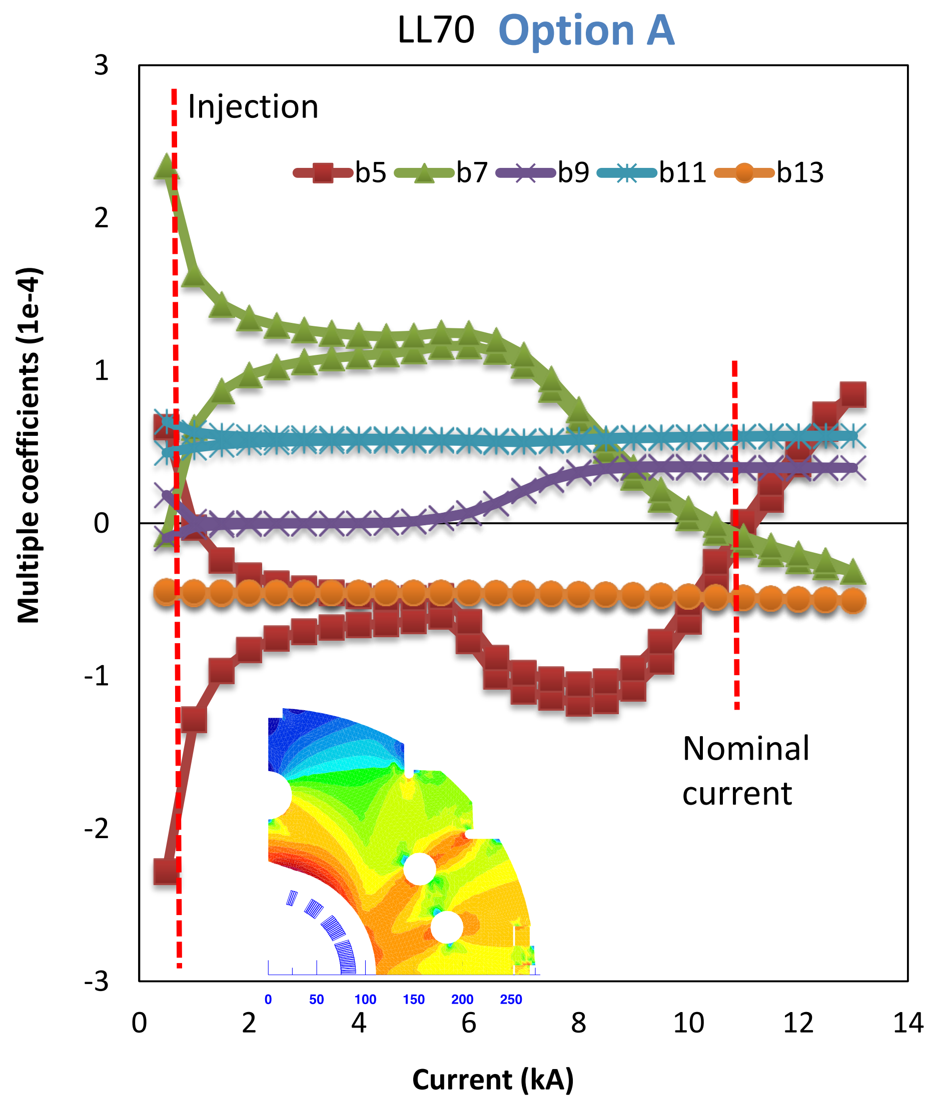
Variation of Multipole Coefficients: b_3 (2D)



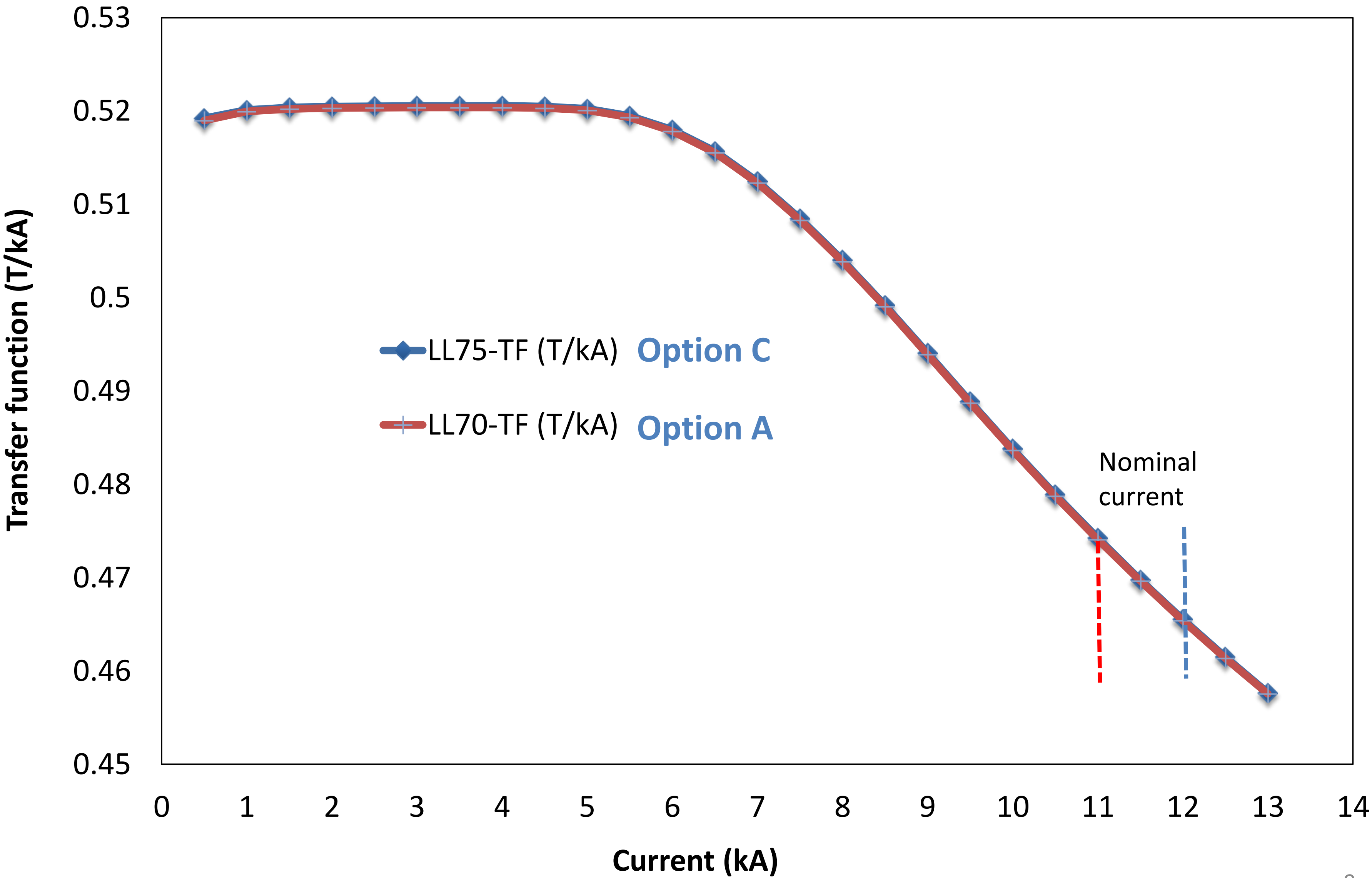
Variation of Multipole Coefficients: b_5 and higher (2D)

- Similar behaviors of Option C and A.
- Both of them look acceptable.



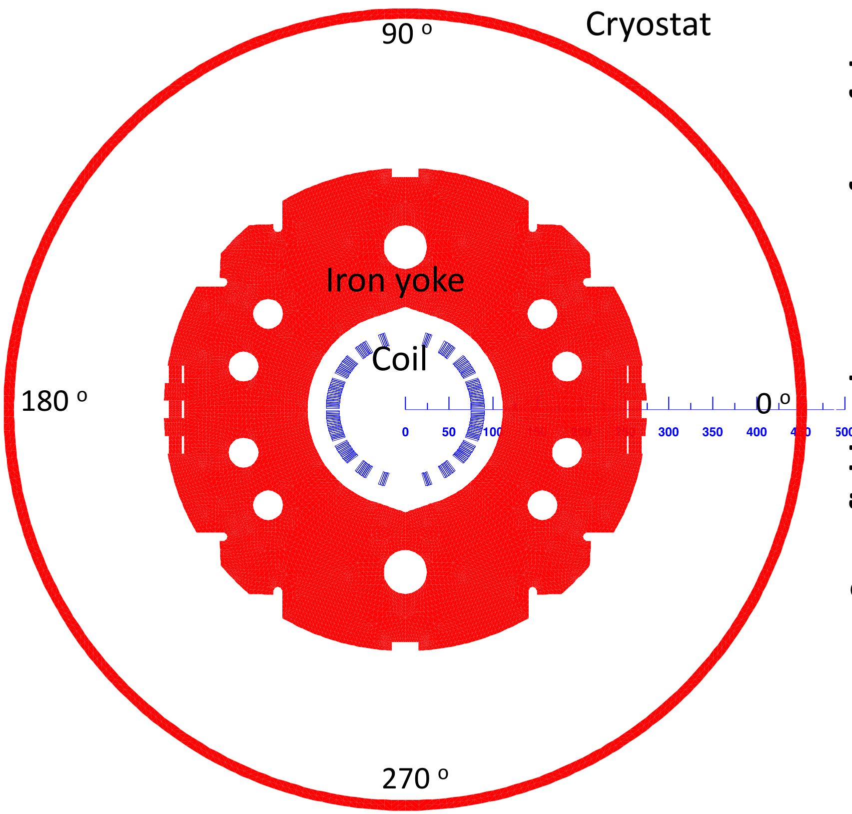


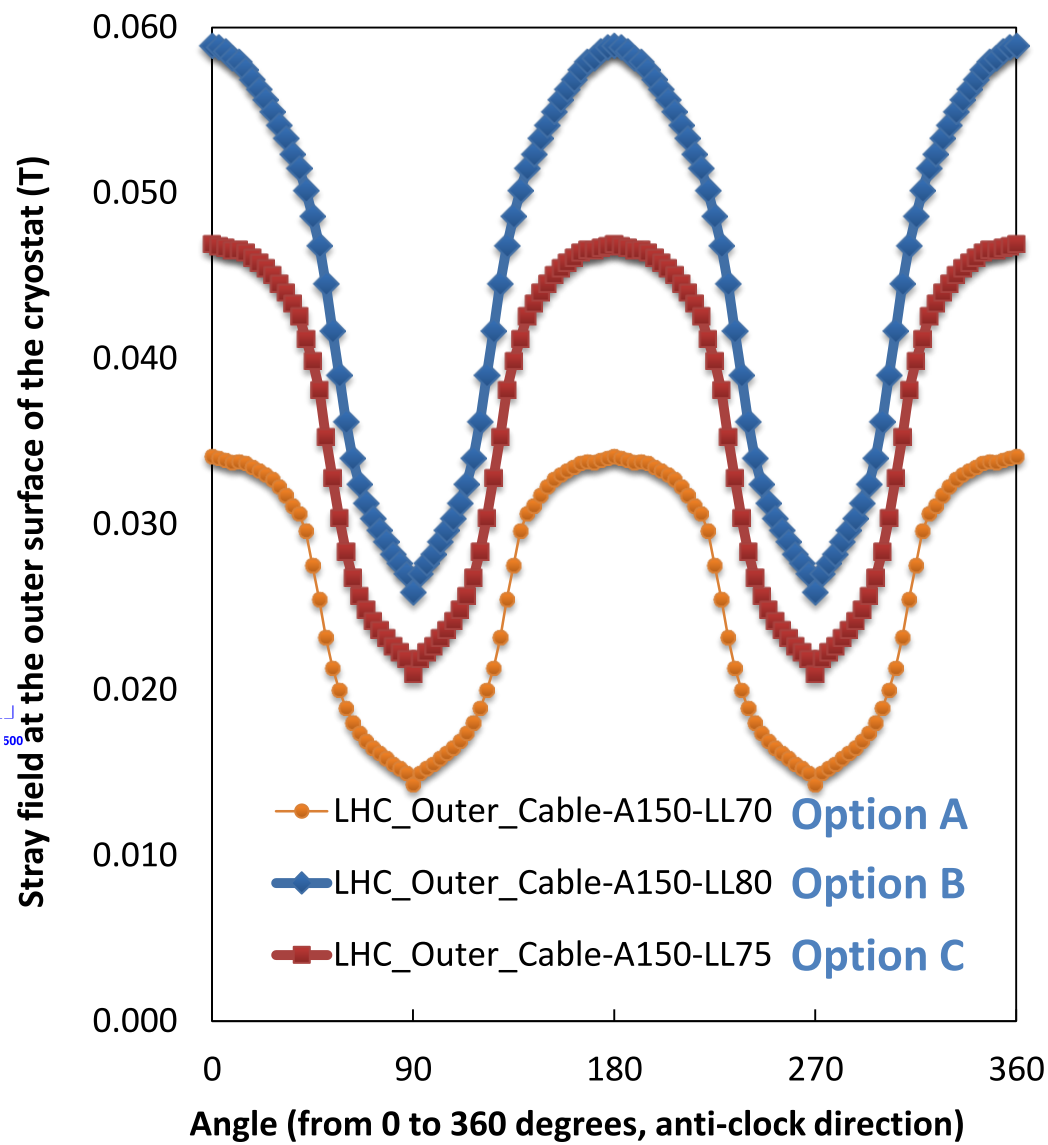
Transfer Function



Stray Field of the Magnet

stray field at the outer surface of the iron cryostat for the two design options with 150 mm aperture.
Cryostat thickness: 12 mm.
Cryostat outer diameter: 914 mm.

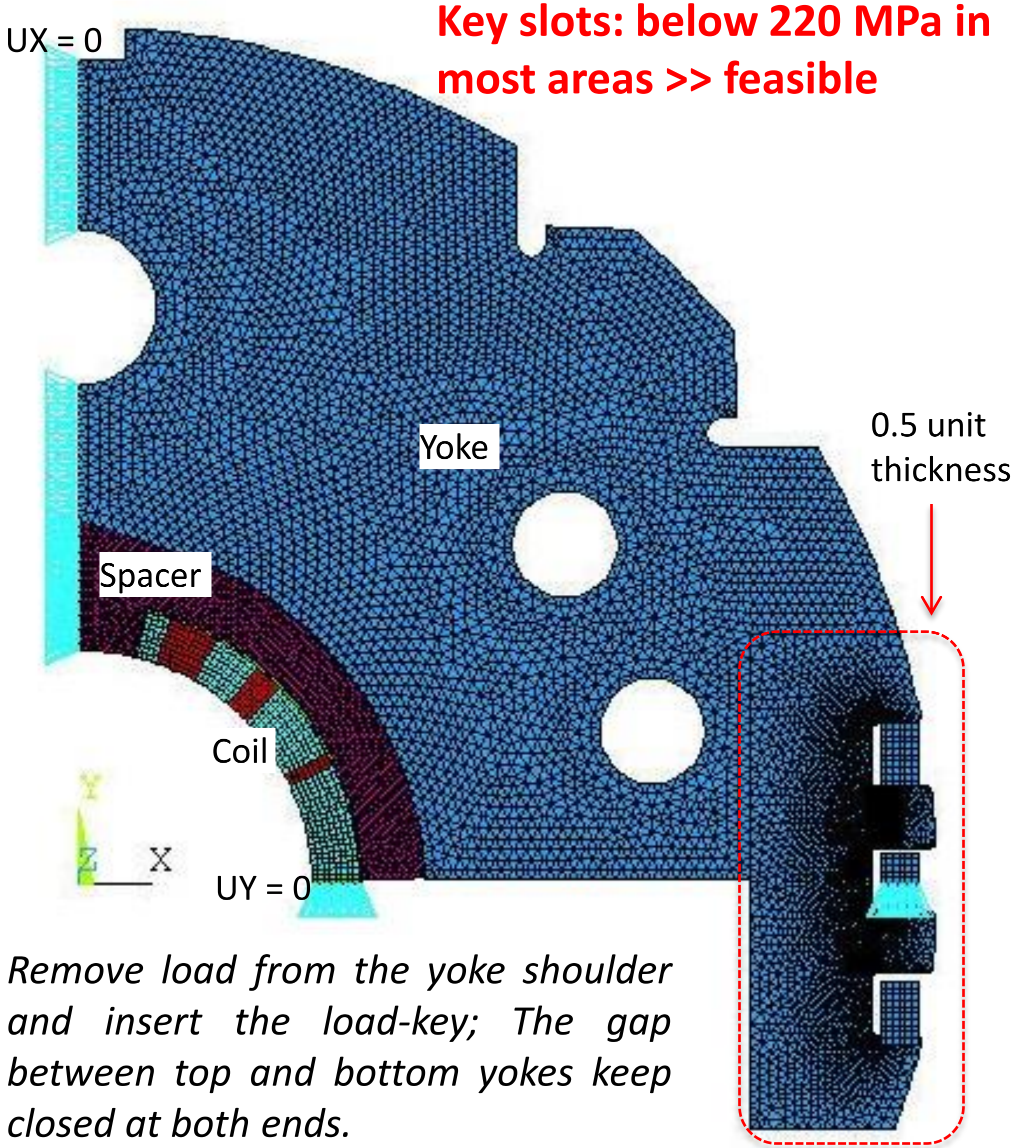




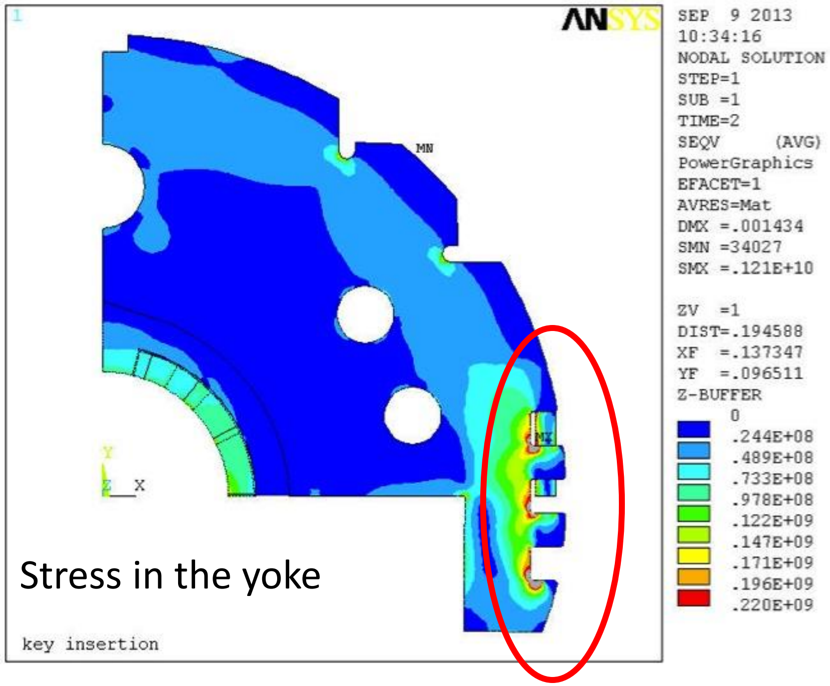
Mechanical Analysis for Option C: Key insertion

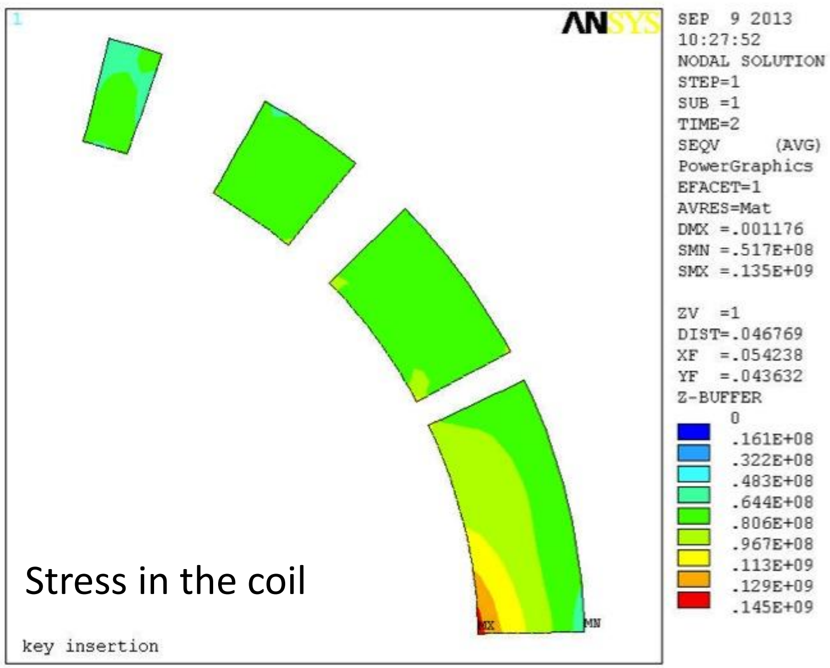
Shear stress in lock-keys is not included

Key slots: below 220 MPa in most areas >> feasible

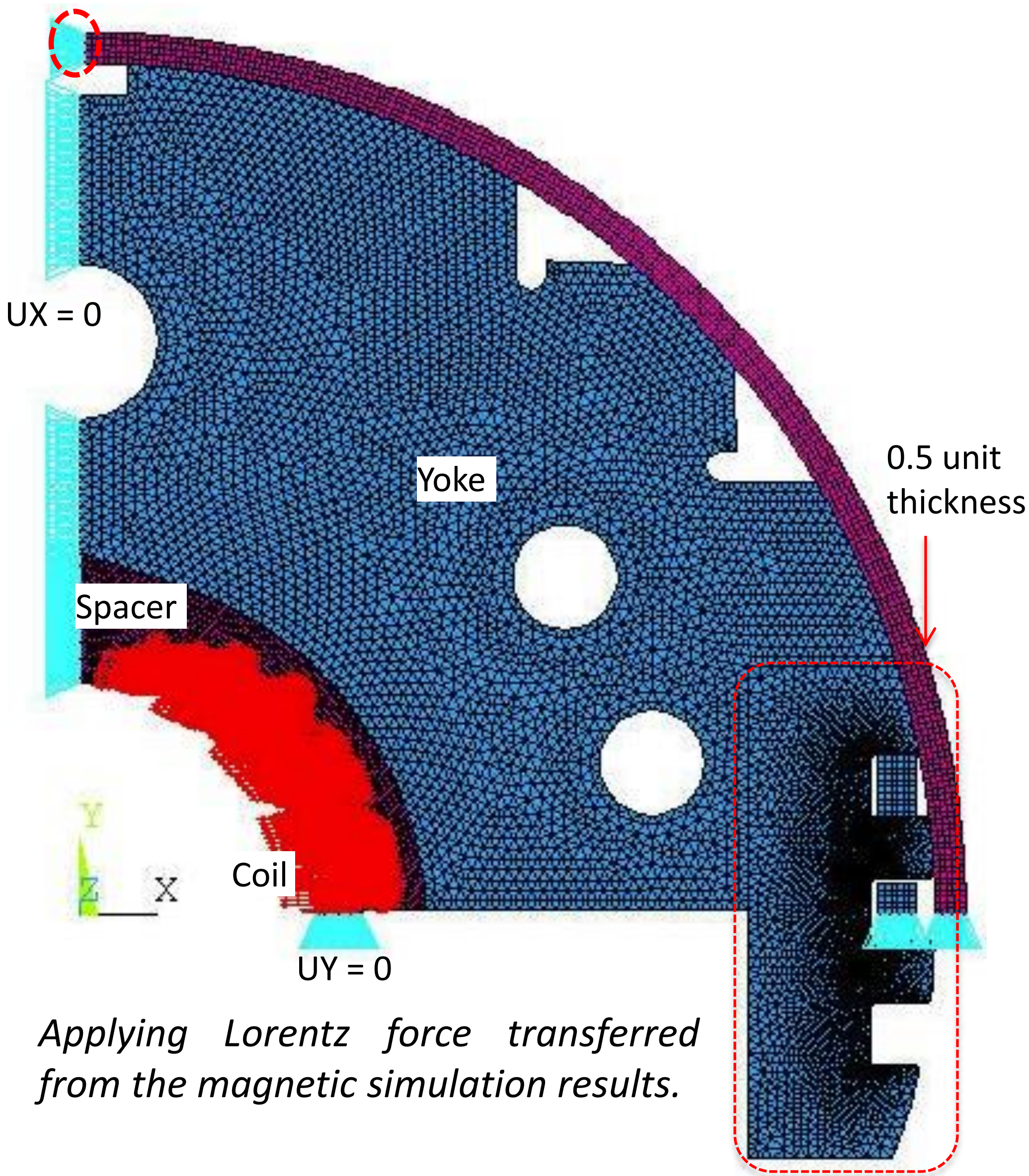


Remove load from the yoke shoulder and insert the load-key; The gap between top and bottom yokes keep closed at both ends.

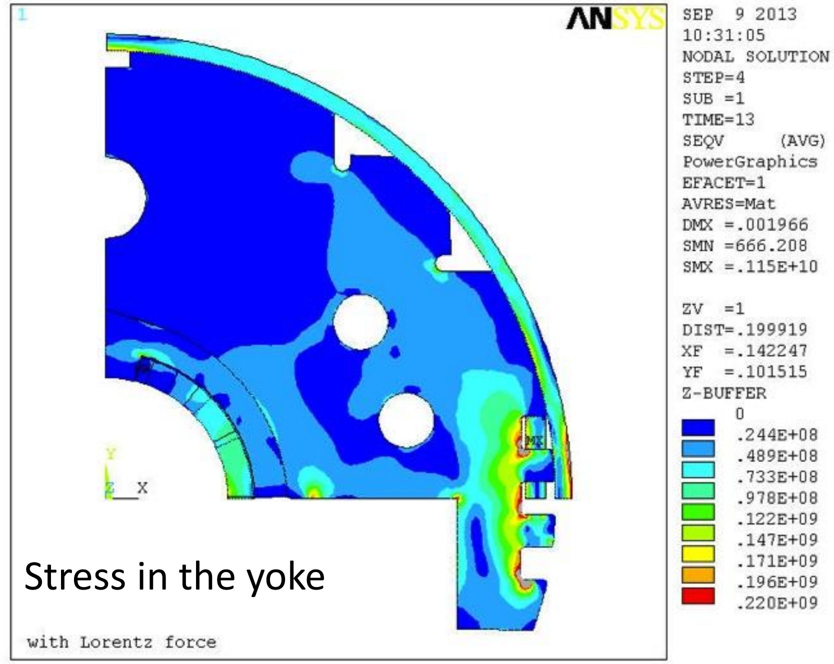


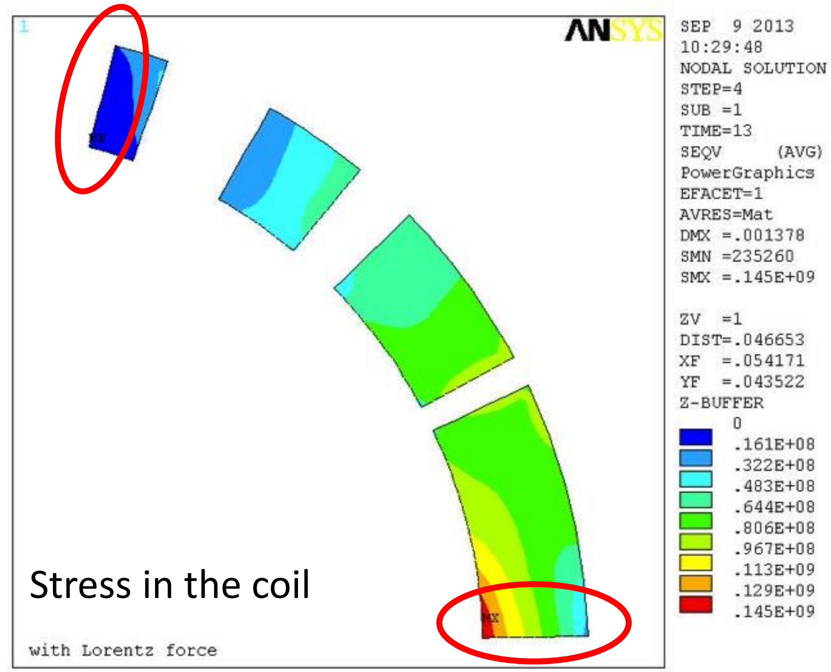


Mechanical Analysis: After excitation (110 % I_{nom})

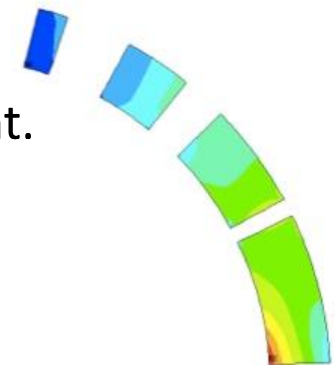


Applying Lorentz force transferred from the magnetic simulation results.

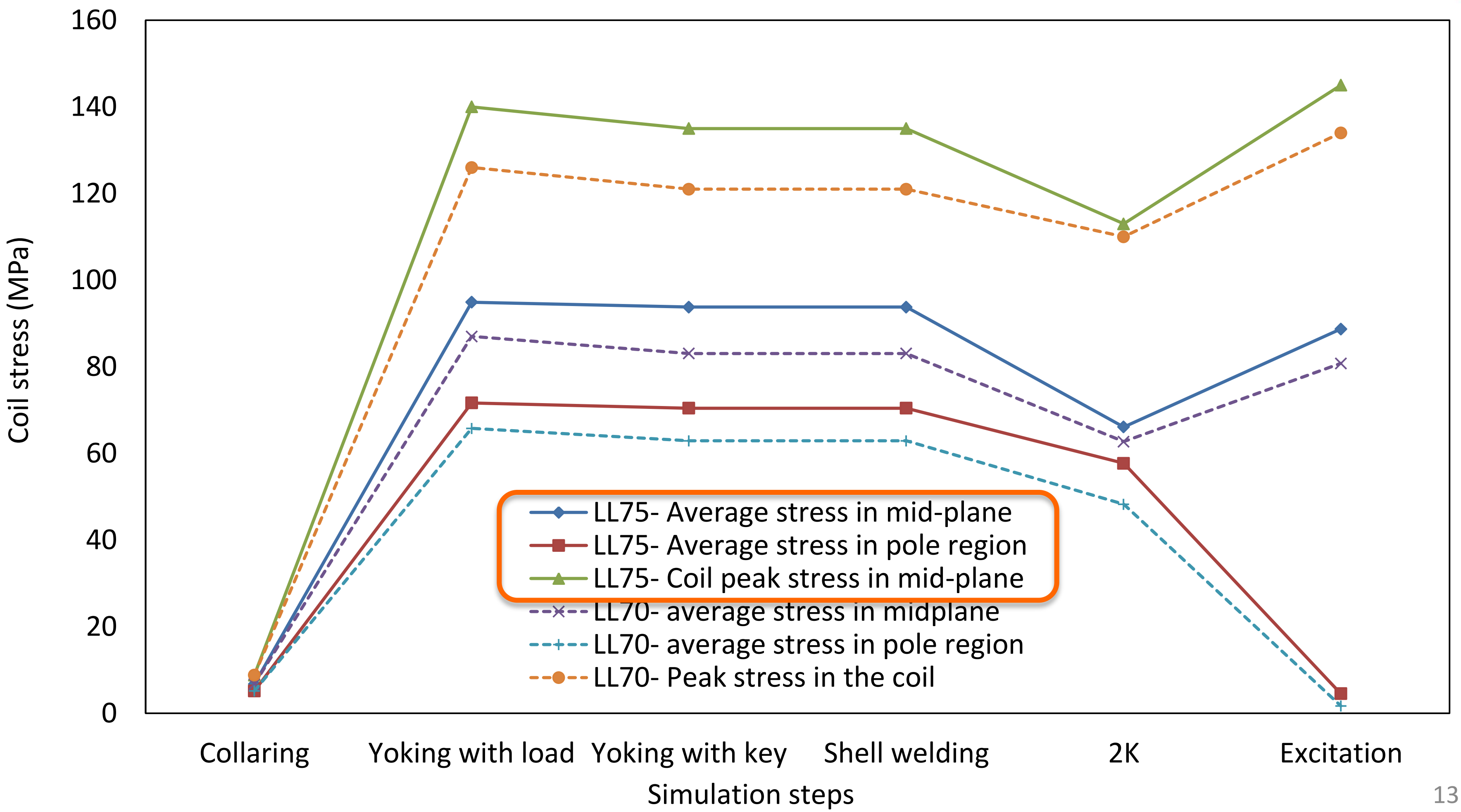




Coil Stress at Each Step



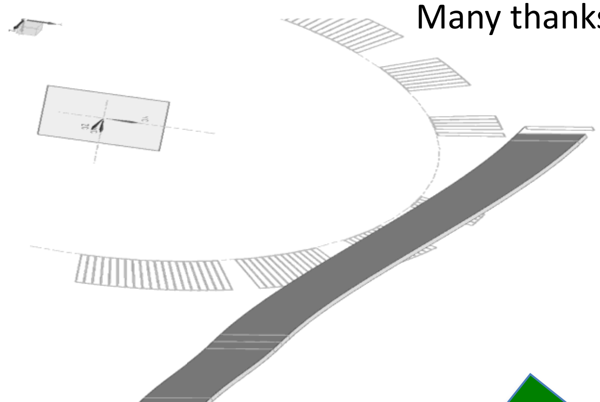
- 150 mm aperture, Option C (LL75) with 110% of the nominal current.
  - At Assembly: $\sigma_{Pole\_Ave.}$ of 70 MPa, $\sigma_{MP\_Ave.}$ of ~95 MPa
  - At excitation: $\sigma_{Pole\_Ave.}$ of ~5 MPa, $\sigma_{MP\_Ave.}$ of 90 MPa
  - Peak stress below 150 MPa



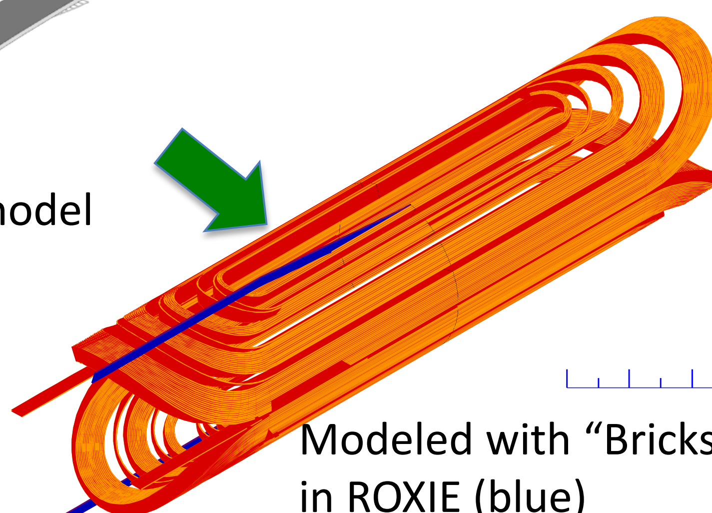
Coil End Design by ROXIE

- **Objectives:**
  - **keep compact coil ends,**
  - **compensation of field integral of multipoles,**
  - **lower peak field.**
- 1 subdivision of CB3 in Return End to reduce peak field: 2 + 6 turn
  - 3 % higher peak field in the end
- Iron covers the whole coil ends.
- Layer jump modeled by CAD >> Simplified “Bricks” model in ROXIE

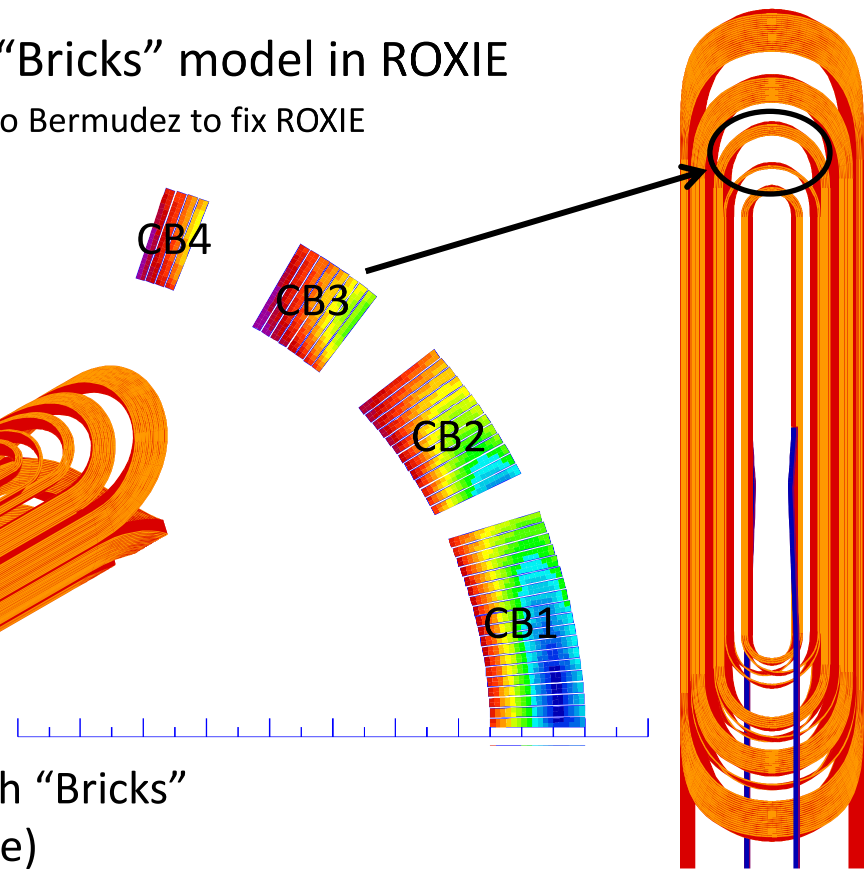
Many thanks to Susana Izquierdo Bermudez to fix ROXIE



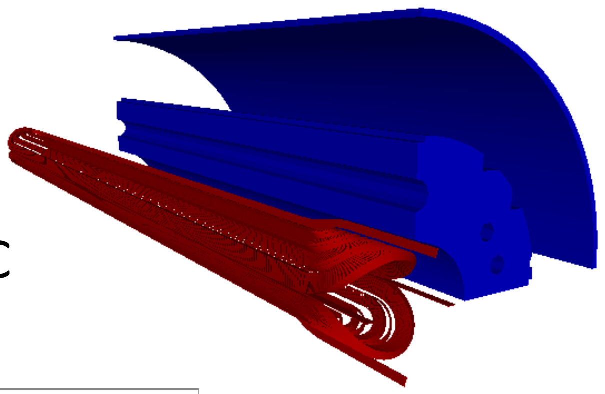
CAD “Layer Jump” model



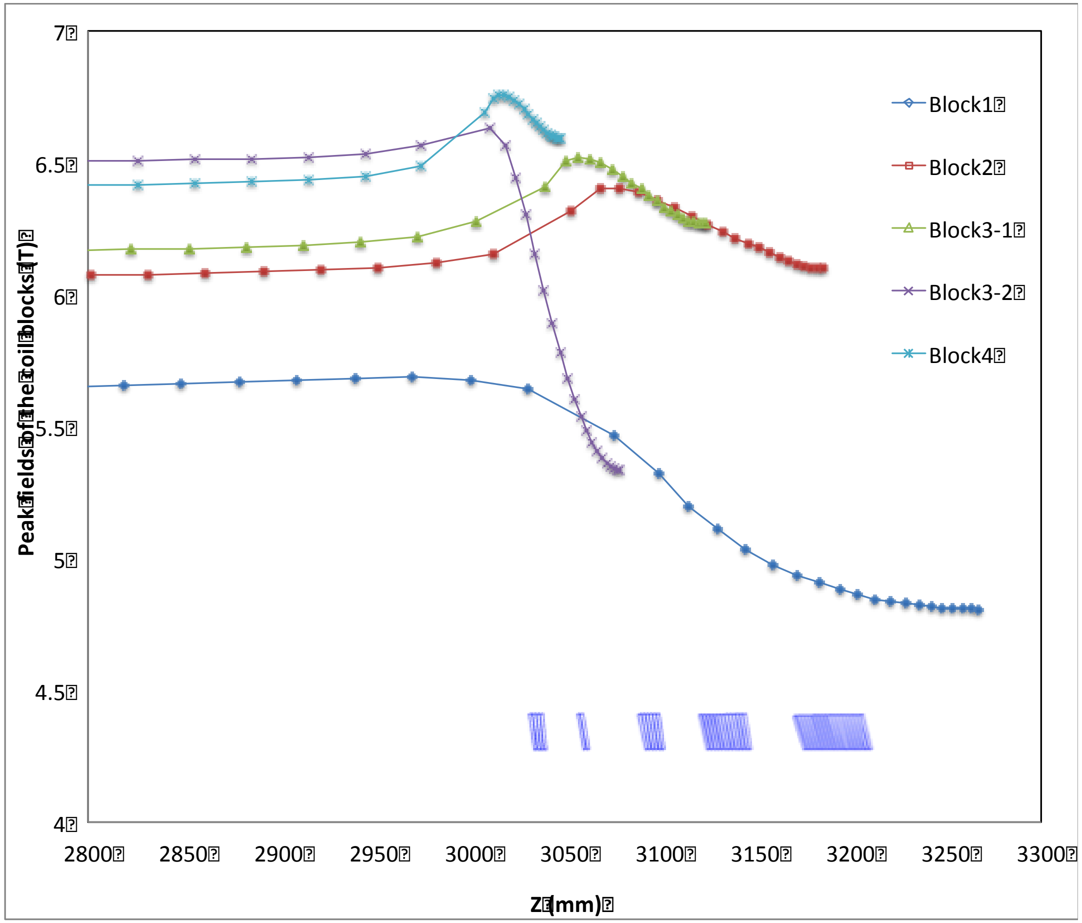
Modeled with “Bricks” in ROXIE (blue)



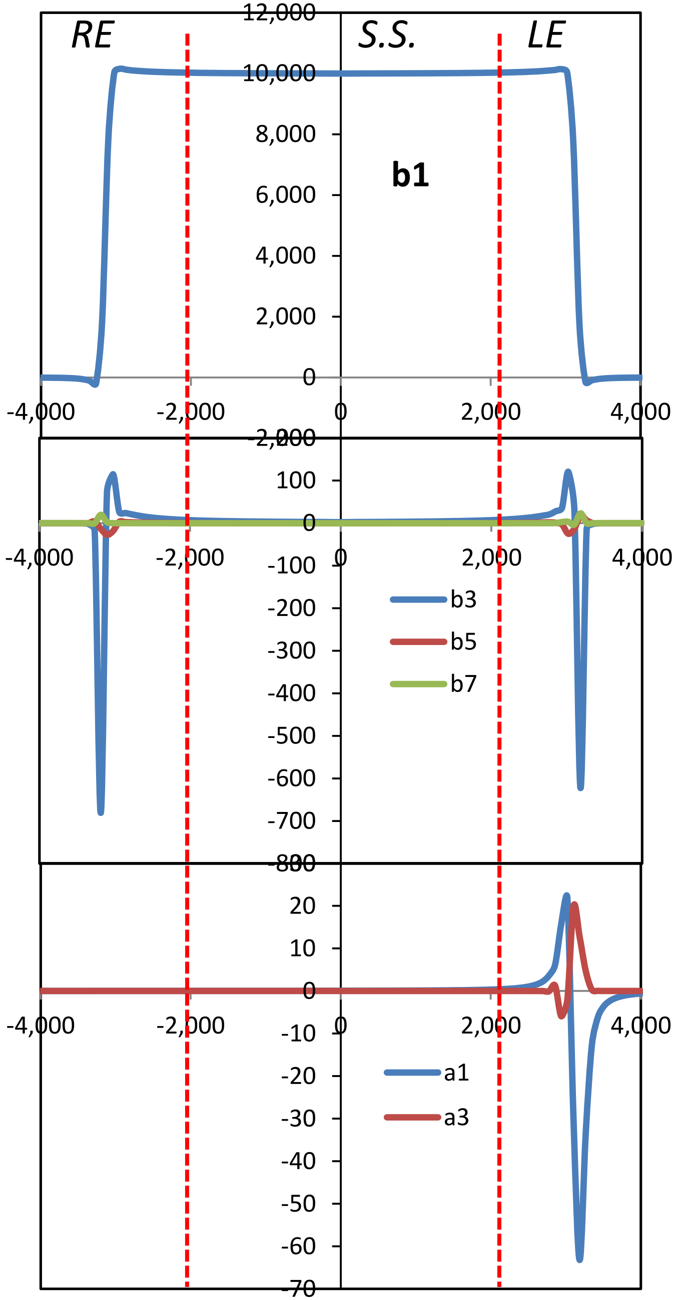
Peak Field in the Coil End



- Peak field moved from Block 3 to Block 1 by subdivision.
- Peak field of 6.75 T >> operating point for Option C is **78 %** (75 % in 2D coil).



Field Integral & Magnet Length: Option C (LL75)



*For Mechanical Coil Length: 6.416 m (-3209 < z < +3207)

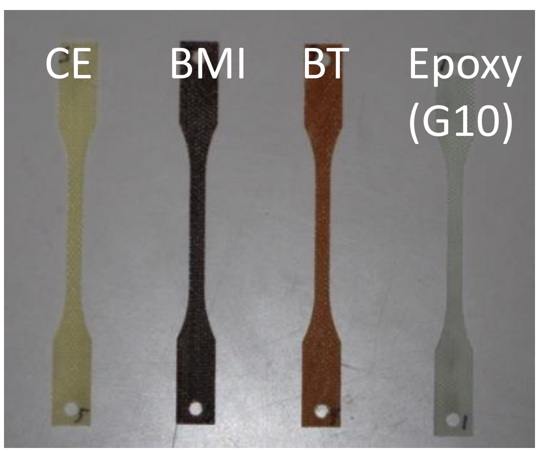
Field Integral	Return End (-4000 < z < -2041)	S.S. (-2041 < z < +2041 mm)	Lead End: (+2041 < z < +4000 mm)	Total (Tm)	Ratio of integral (unit)
B1	6.1715	22.8779	6.1711	35.2204	10000
B3	-0.0156	**0.0090**	-0.0138	-0.0205	**−5.82**
B5	-0.0019	-0.0003	-0.0004	-0.0025	−0.71
B7	0.0009	-0.0005	0.0011	0.0016	0.44
A1	0.0000	0.0002	-0.0046	-0.0044	**−1.26**
A3	0.0000	0.0000	0.0014	0.0014	0.40

- A large B_3 of 0.009 Tm (+4 unit) generated in S.S. due to the end effects while the one in 2D is almost zero.
- The integral of B_3 (-6 unit) could be minimized by adjusting B_3 in S.S. to a certain value.
- Other multipoles less than 1 unit looks acceptable except A_1.
- The whole magnet length estimate: **6.92 m**

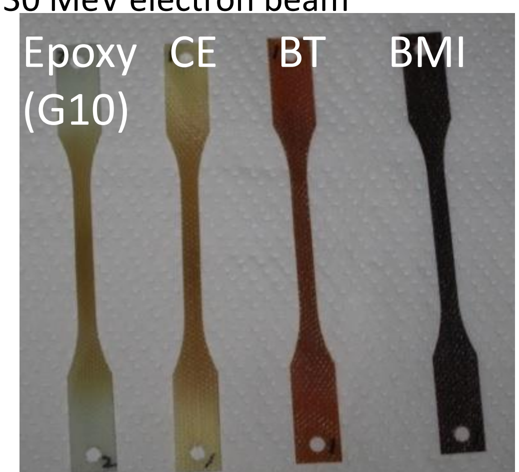
>> Acceptable for the vertical cold test at KEK

Radiation Resistant Materials R&D

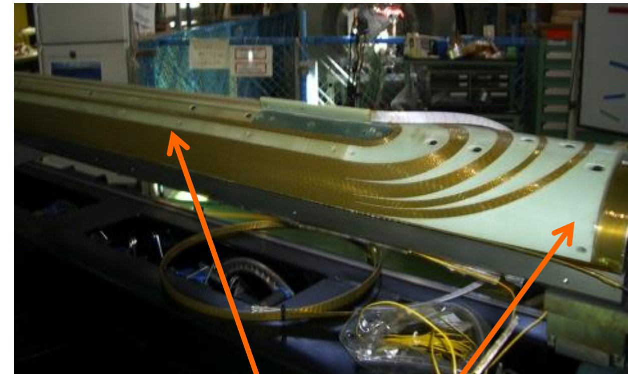
- New radiation resistant GFRPs (w/ S-2 Glass or T-Glass) are baseline for coil wedges, end spacers.
  - Cyanate Ester & Epoxy
  - BT (Bismaleimide Triazine)
  - BMI (Bismaleimide)
- Trial production has been made: prepreg sheets, laminated plates and pipes.
- Backup plan (in case of higher dose) would be metallic parts with Polyimide coating by "Vapor Deposition Polymerization" technology.
- Irradiation test by electron and gamma rays
  - Gamma rays (Co^{60}), 2 MeV electron at JAEA Takasaki
  - 30 MeV electron at KUR

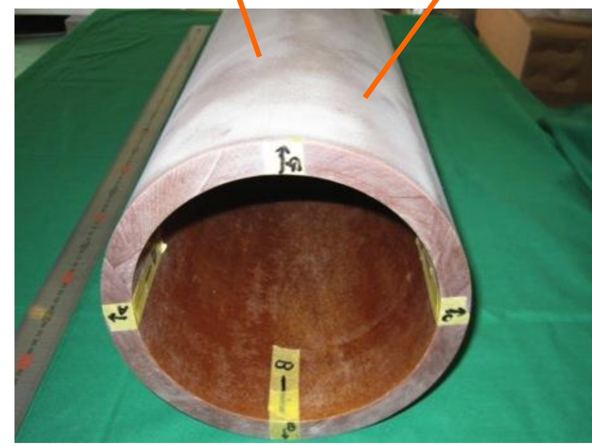


After irradiation of 10MGy with 30 MeV electron beam



Ordinary SC coils (J-PARC SCFM) with G10 (epoxy + E glass) end spacers and wedges.





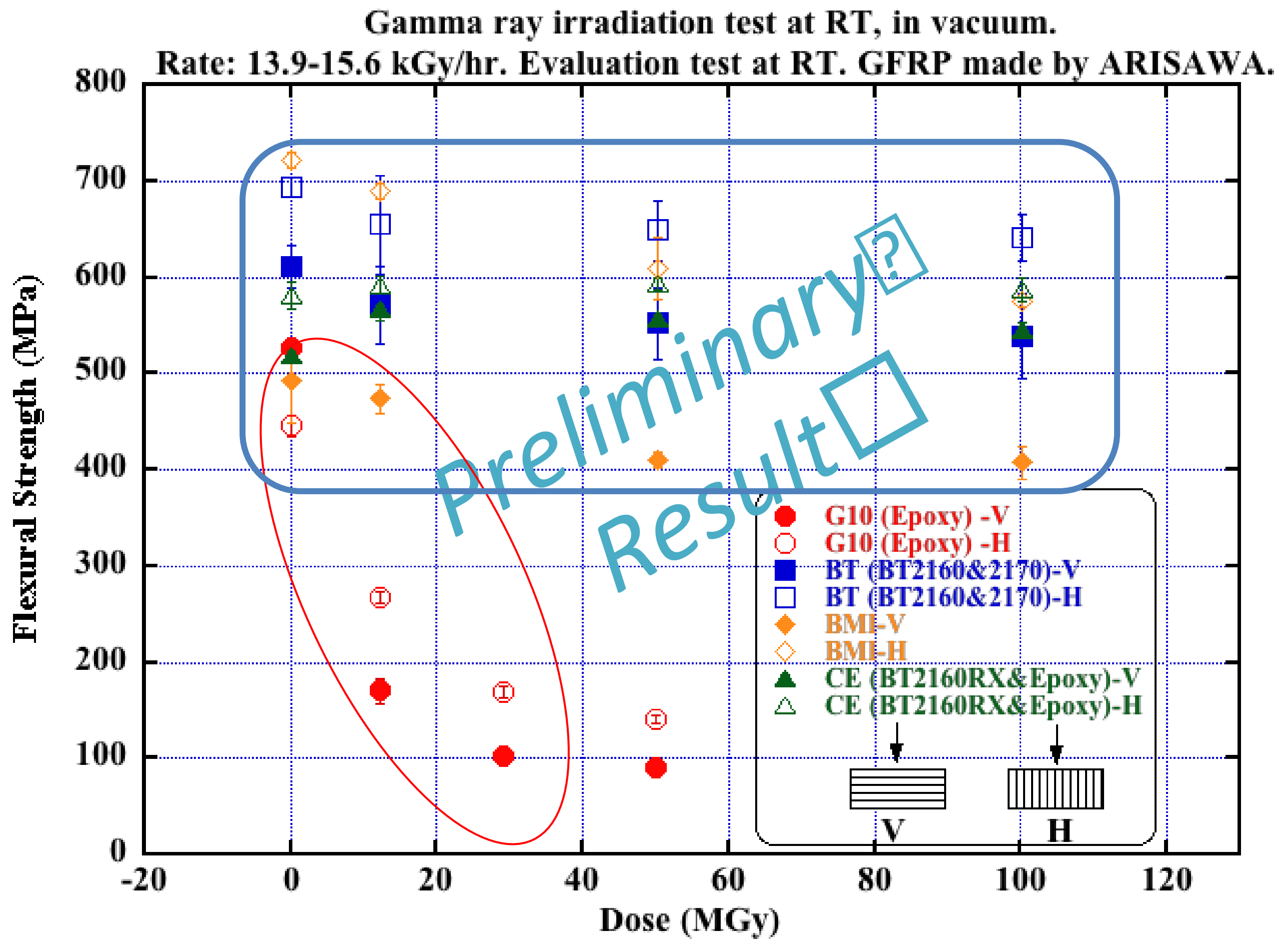
BT-GFRP pipe for end spacers and pipe (ϕ160, L1000)

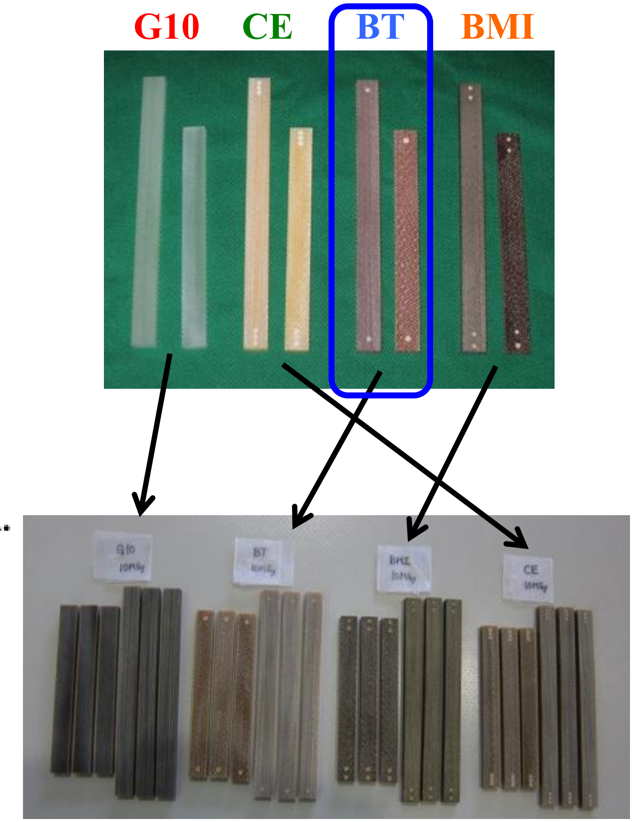
Backup Plan:
Polyimide coating on

RT Gamma-ray Irradiation Tests

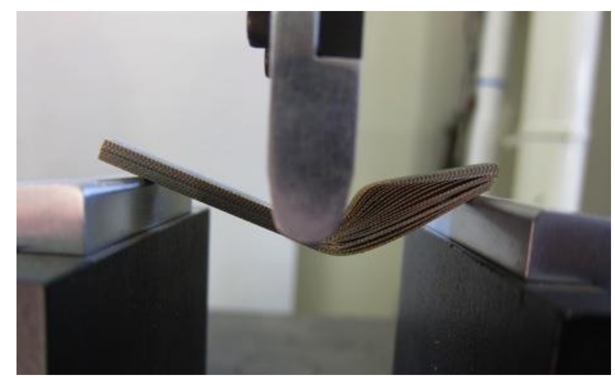
- All new GFRPs (CE&Epoxy, BT, and BMI) shows good radiation resistance up to **100 MGy**.
- Ordinary G10 (MQXA) already showed significant degradation at 10 MGy.

GFRP (S2 glass & BT resin) will be adopted for the new D1





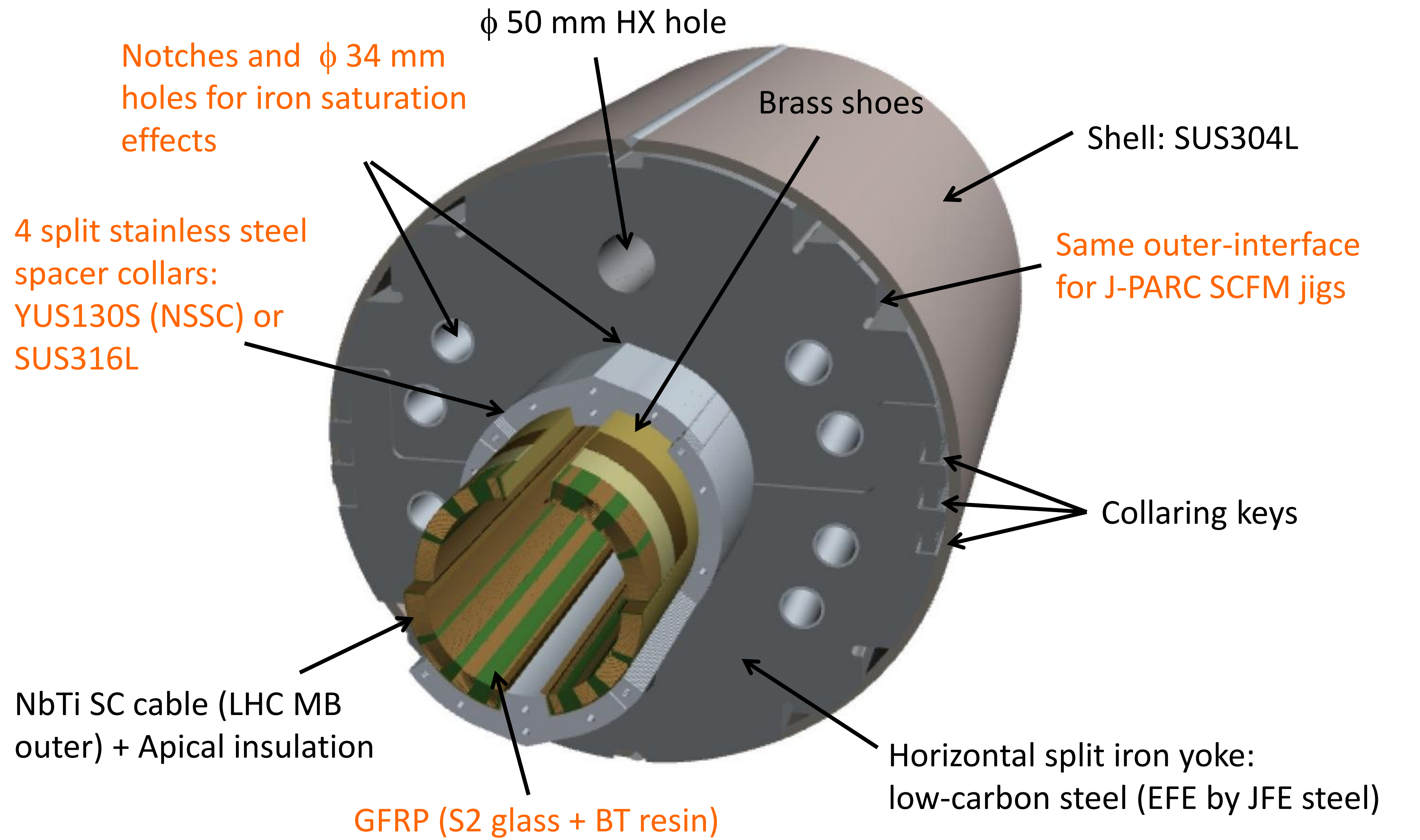
After irradiation of 13 MGy



Flexural strength test（G10, 30MGy）

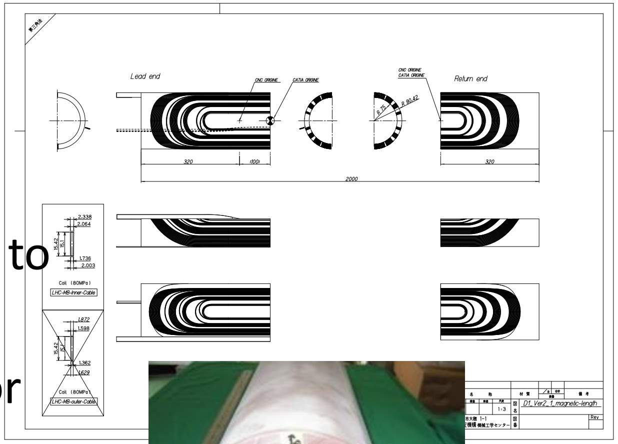
2m-long Model Magnet - Overview

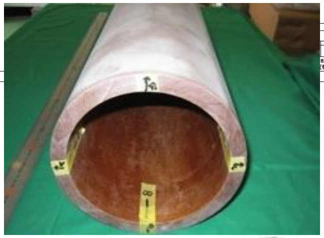
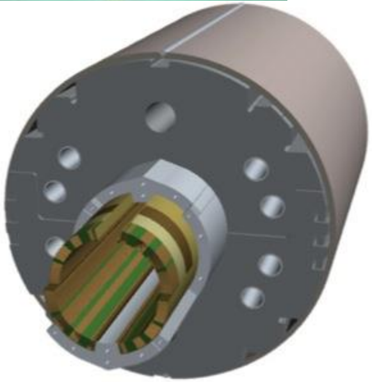
Single-layer coil, 4-split spacer collars, collared yoke by keying



2m-long Model Magnet Development – Status

- Coil design (ϕ150mm, 75%) will be finalized soon.
- Engineering, drawing ongoing.
  - Reuse of available tooling and jigs for J-PARC SCFM.
- NbTi SC cable with standard Apical insulation (220 m x 4) to be delivered from CERN in Jan. 2014.
- Radiation resistant GFRP (plates, pipes) from ARISAWA for wedges and end spacers to be delivered in Jan. 2014.
- Practice coil winding anticipated in March 2014.
- Discussion with vendors, JFE Steel (EFE steel) and Nippon Steel & Sumikin Stainless Steel (YUS130S), started. Supply even for the model magnets.
- Fine blanking for spacer collars and iron yokes will be adopted for the full-scale prototypes and a production.
  - Combination of laser cut and machining will be adopted for the 2m long models.
- Mechanical short model in spring 2014.
- Renovation of development area.
- Modification and consolidation of the vertical cryostat, bus lines, and the 15kA PC.




Plans (or Prospect…)

JFY2013 (until March 2014)

- Practice coil winding. Mechanical short model

JFY2014

- 1st 2m long model magnet. Cold test in vertical cryostat at 1.9K.

Budget supported by ATLAS-Japan

Beyond this, new funding for the construction (including R&D) is necessary.

JFY2015 (*Tentative plan…*)

- 2nd 2m long model magnet, if necessary.
- Major consolidation in cryogenics. New construction of a horizontal cold-test bench. (Otherwise, horizontal cold test at SM18/CERN??)

JFY2016

- One full-scale prototype magnet by a manufacturer

JFY2017

- One full-scale prototype cryostat by a manufacturer

JFY2018

- A series production of the magnets and the cryostats (5 or 6 sets including the spare) to be completed by 2022.

*Presumably, horizontal cold testing at KEK will determine the production rate…

Summary

- Conceptual design study for the new D1 has been made for Option C: ***ϕ150mm, 35 Tm, load line ratio of 75 % in 2D (78 % in total).***
  - Nominal field of 5.59 T at 12 kA, with a peak field of 6.75 T (78% at 1.9K).
  - Field quality in 2D along excitation is acceptable and successfully optimized at nominal current under high saturation effect.
  - Coil end effects are still observed at S.S. of the full-scale model and further optimization on field integral of B_3 would be necessary.
  - The whole magnet length of 6.9 m will fit to the vertical cryostat at KEK.
  - Mechanical analysis: this option is feasible.
  - To be addressed: quench protection studies.

- 2-m long practice coil winding in JFY2013, followed by a 30-cm long mechanical short model.
  - Engineering work underway. Procurement started.
  - New radiation resistant GFRP (S-2 glass & BT resin) adopted for wedges, end spacers.
  - Renovation of development area, consolidation of cold test stand ongoing.
  - Collaboration (support) with CERN: NbTi cable, QPH, fabrication of collar & yoke, etc.

- LHC/ATLAS upgrade review at KEK in this Nov. Funding proposal for construction (+ R&D) starting from JFY2014 will be submitted.