Magnet Design of the 150 mm Aperture Low-β Quadrupoles for the High Luminosity LHC

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23rd International Conference on Magnet Technology
Boston, MA
14-19 July, 2013

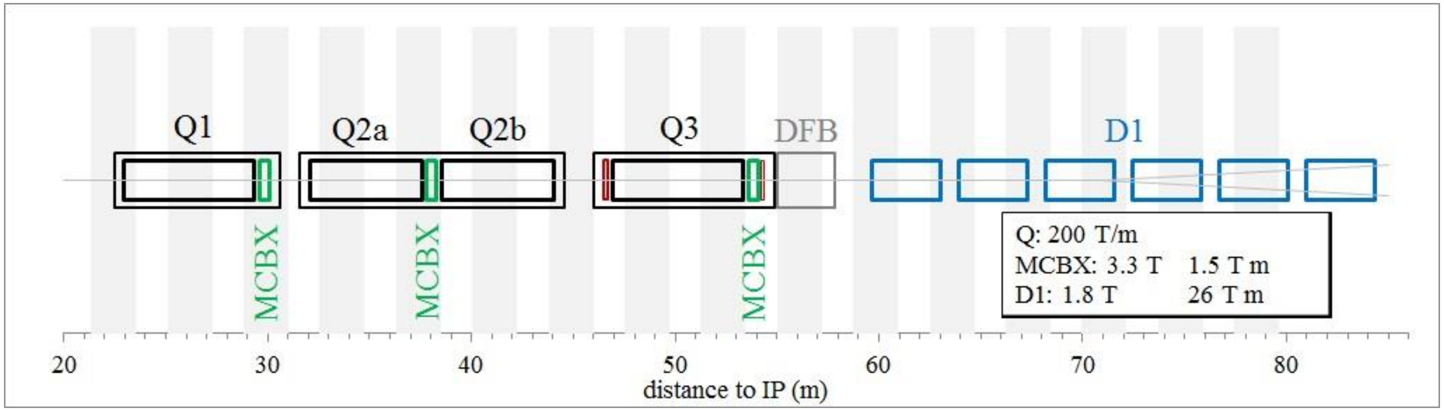
High Luminosity LHC

U.S. LARP

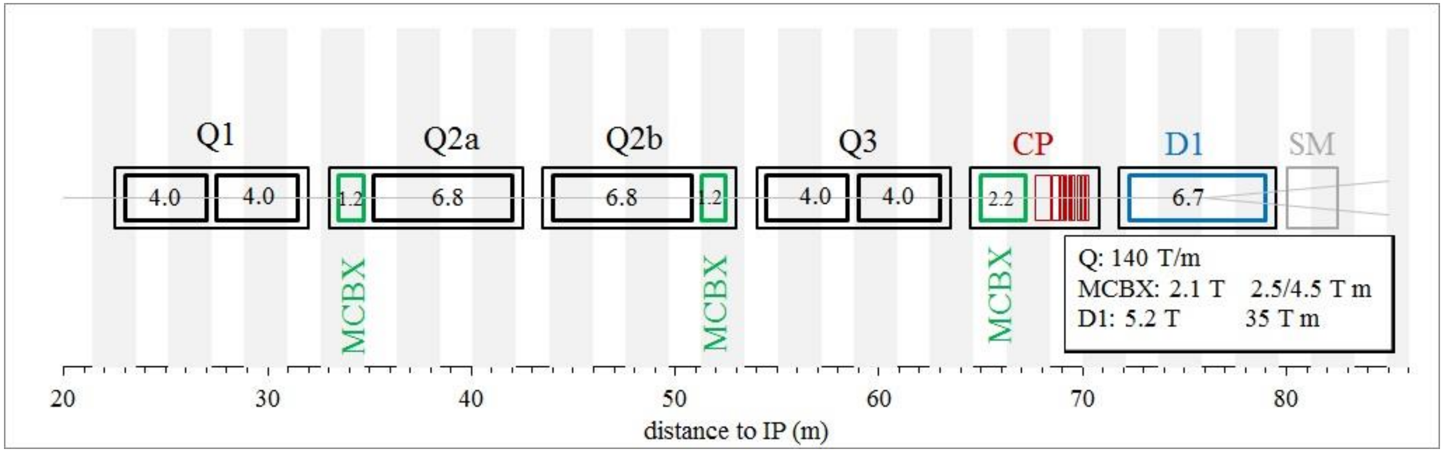
Introduction

(…from previous talk by E. Todesco, 3OrCC-01)

- IR in the present LHC

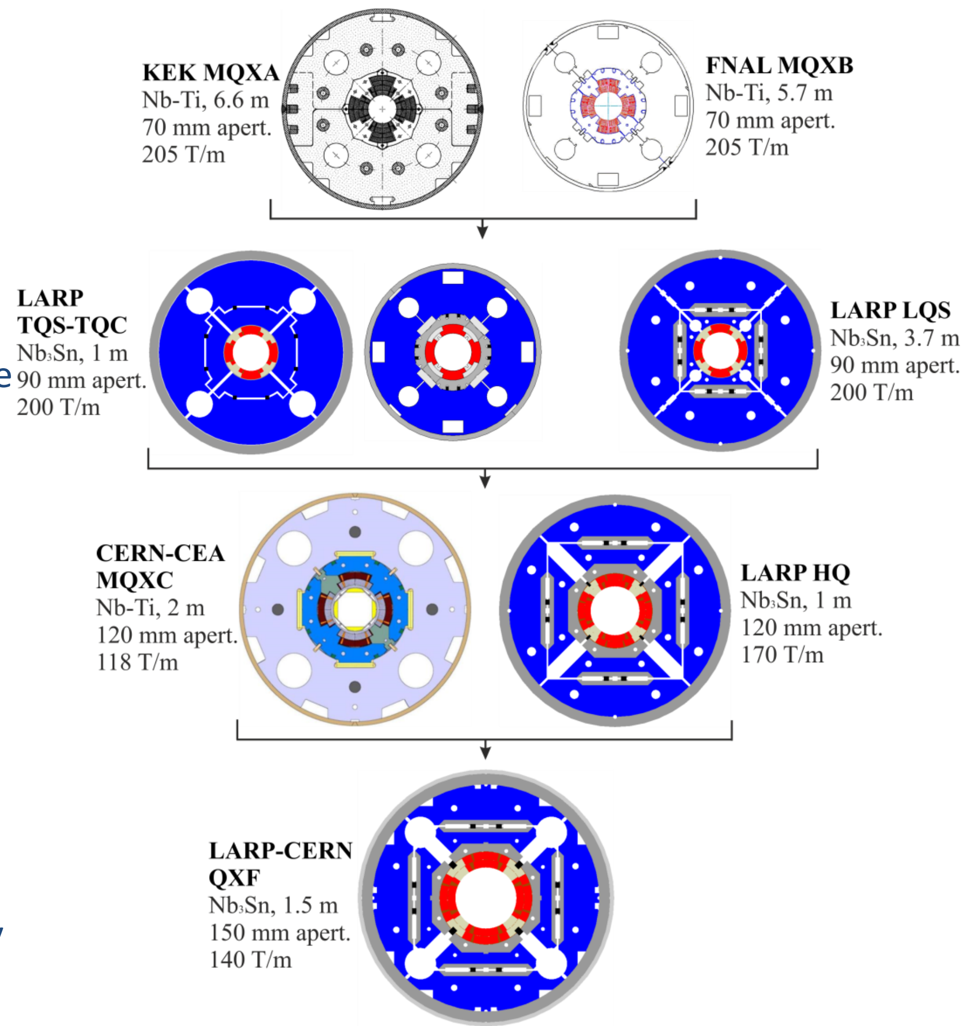


- IR in the HiLumi LHC



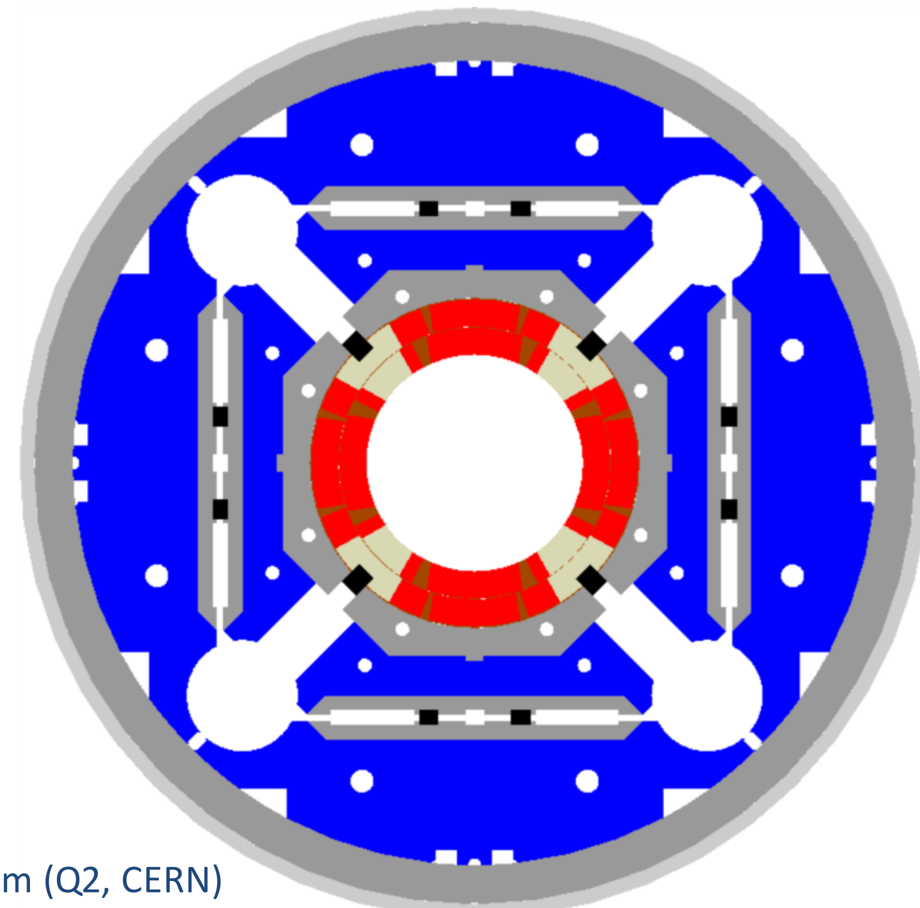
Introduction
LHC low-β quadrupole overview

- Present Nb-Ti low-β quadrupole
  - Nominal luminosity
    - $L_0 = 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
  - Integrated luminosity
    - ~300–500 fb^{-1} by 2021
- 2004, start of LARP Nb_3Sn program
  - Same gradient in larger aperture for ultimate luminosity (2-3 · L_0)
- 2008, two-phase upgrade
  - Phase-I, NbTi for ultimate
  - Phase-II, Nb_3Sn for higher L
- 2012, large aperture Nb_3Sn design
  - Increase the peak luminosity by a factor of 5 and reach 3000 fb^{-1} of integrated luminosity



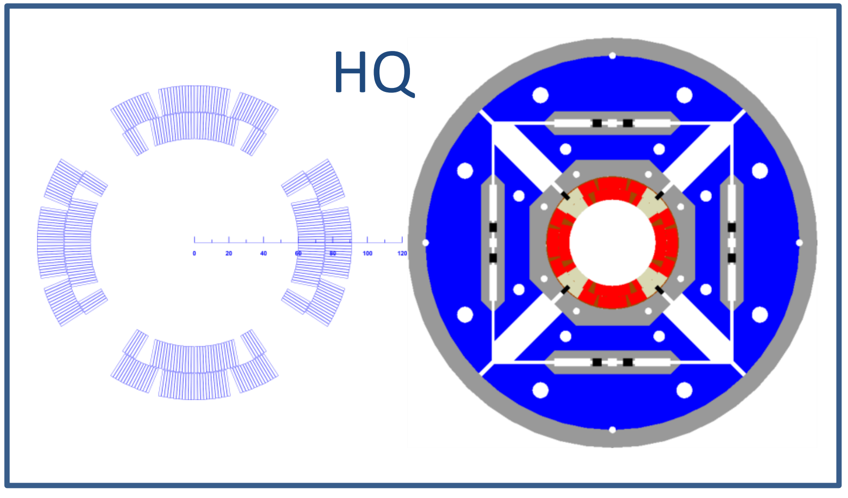
QXF magnet design

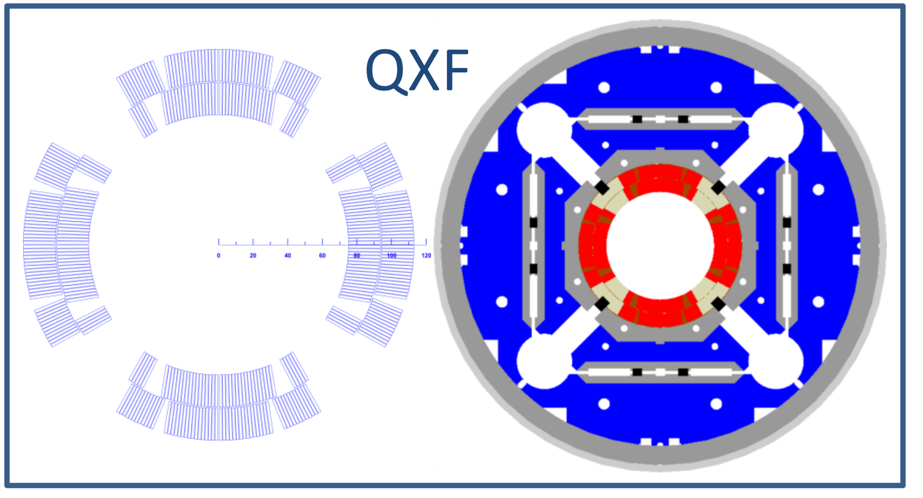
- Target: 140 T/m in 150 mm coil aperture
- OD: 630 m
- SS shell, 10 mm for LHe containment
- Al shell, 27 mm thick
- Iron yoke
  - Cooling holes
  - Slots of assembly/alignment
- Master plates
  - 58 mm wide bladder and key pre-load
  - Alignment
- Iron pad
  - Space for axial rods
- Aluminum bolted collars
  - Coil alignment with G10 pole key
- Ti alloy poles
- Magnetic lengths
  - Short model: 1.1 m
  - Long magnet: 4 m (Q1-Q3, LARP) and 6.8 m (Q2, CERN)



From HQ to QXF

- Similar coil lay-out
  - 4-blocks, 2-layer with same angle
  - Wider cable (from 15 to 18 mm), same stress with +30% forces
- Same structure concept with additional accelerator features
  - Pre-load capabilities of HQ design qualified and successfully tested
    - *See G. Chlachidze, 3OrCC-05*
  - Larger pole key for cooling holes, cooling channels, alignment – assembly - handling slots, LHe vessel

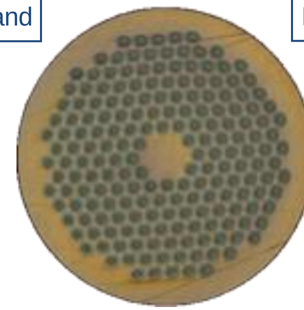




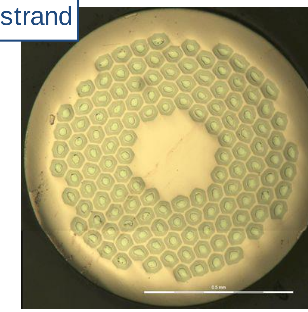
Conductor and cable parameters

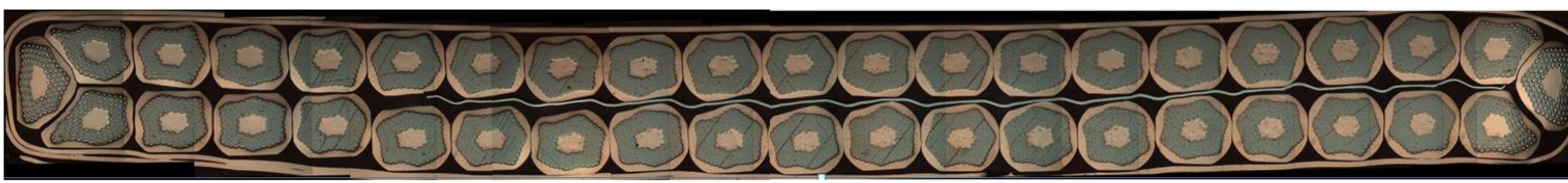
- 0.85 mm strand
  - OST RRP (108/127, 132/169 and 144/169)
  - Bruker PIT (192)
  - Cu/Sc: 1.2 → 55% Cu
- 40-strand cable
  - Bare width X thickness after cabling: 18.150 X 1.525 mm
  - SS core 12.7 mm wide and 25 μm thick
- R&D in progress to meet target criteria
  - Mechanical stability and no sheared filaments
  - $I_s \geq 3^*I_{op}$ *and* RRR after cabling > 150
- +4.5% in thickness and +2% in width after HT
- Braided insulation: 0.150 mm (S2 glass)

PIT strand

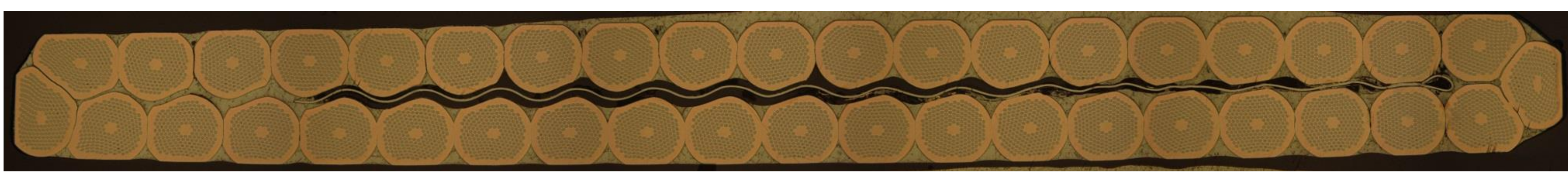


RRP strand





RRP cable



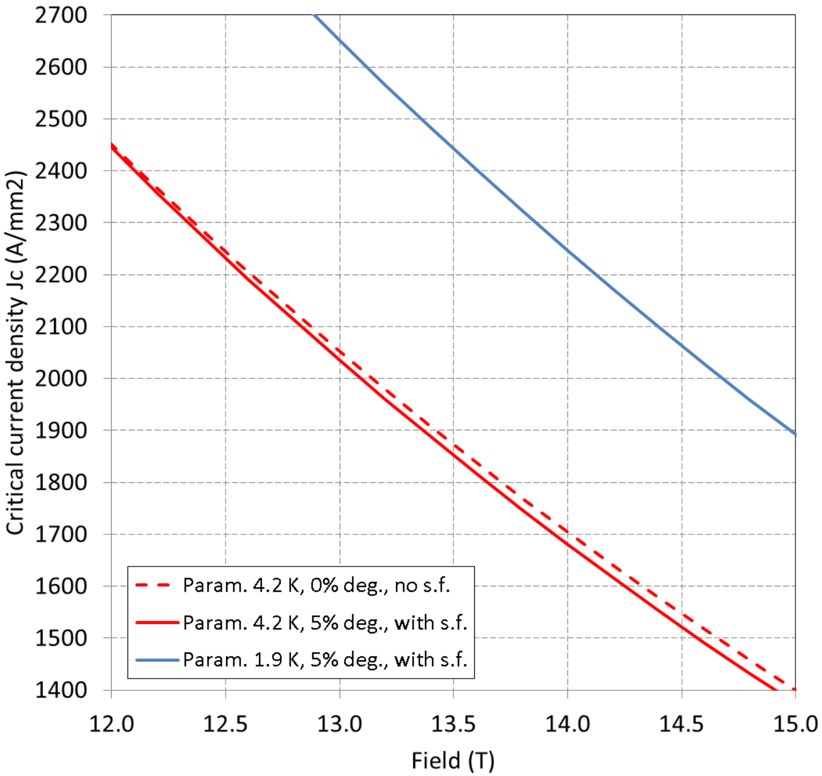
PIT cable

Superconductor properties

- Non-Cu J_c of virgin strand (4.2 K) without self field (s.f.) correction
  - 2450 A/mm^2 at 12 T applied field
  - 1400 A/mm^2 at 15 T applied field

- Self field corr. for ITER barrel
  - 0.429 T/kA
- 5% cabling degradation
- LARP parameterization

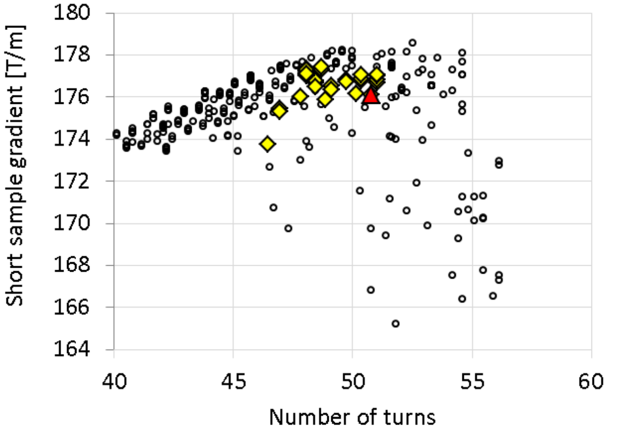
- Resulting J_c for comp.
  - 2440 A/mm^2 at 12 T total field
  - 1370 A/mm^2 at 15 T total field

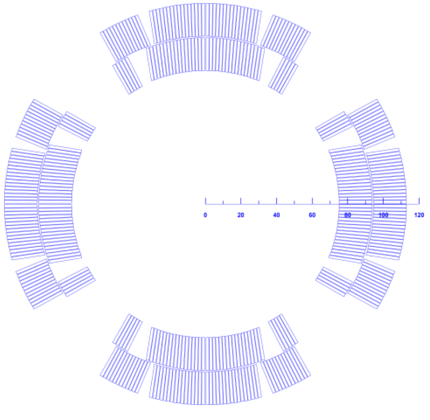


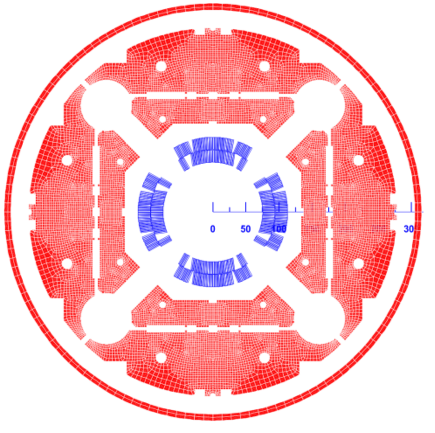
2D magnetic design

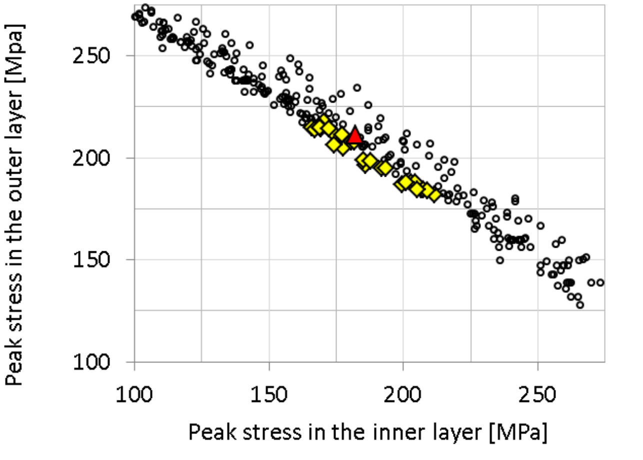
(By F. Borgnolutti, 1PoAN-04)

- Two-layer – four-block design
- Analytical model with sector coil (radial blocks)
  - 6 angles to optimize for field quality
  - 300 cross-sections identified
- Criteria for the selection
  - Maximize gradient and # of turns (protection)
  - Distribute e.m. forces in 2 layers and minimize stress
- Result: 22+28 = 50 turns
  - Close to maximum gradient and distributed stress
- All harmonics below 1 units at R_{ref} = 50 mm
- 9% reduction of TF for saturation



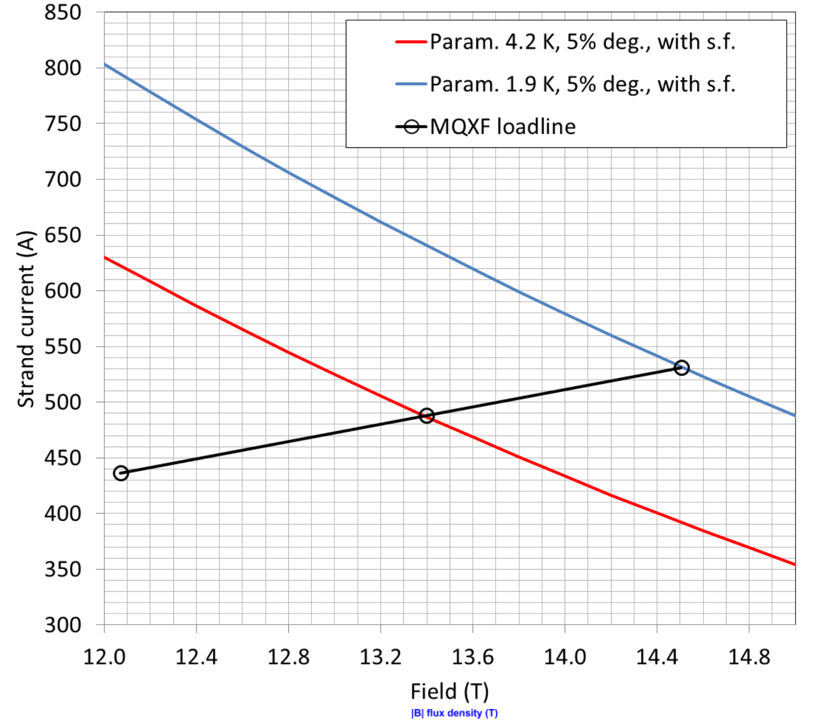


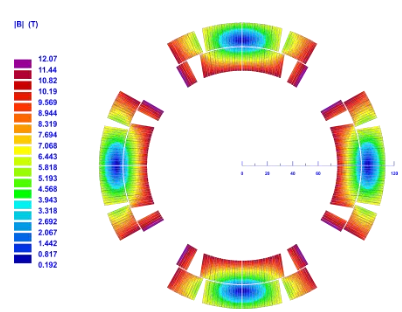


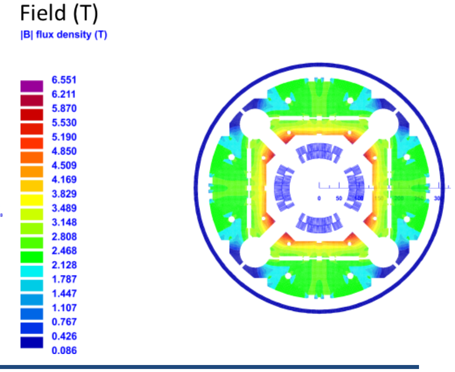


Magnet parameters

- Operational conditions: 140 T/m
  - I_{op}: 17.5 kA
  - B_{peak_op}: 12.1 T
    - 82% of I_{ss} at 1.9 K
    - G_{ss}: 168 T/m
    - I_{ss}: 21.2 kA
    - B_{peak_ss}: 14.5 T
- Stored energy: 1.3 MJ/m
- Inductance: 8.2 mH/m



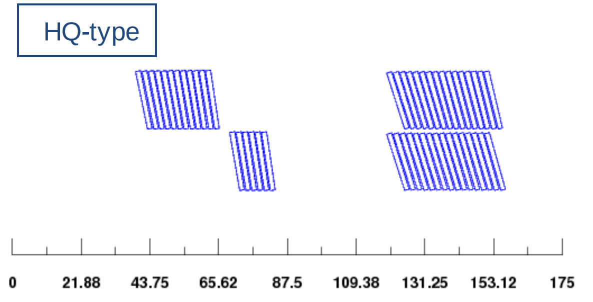


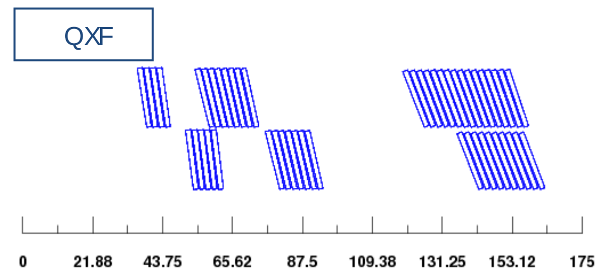


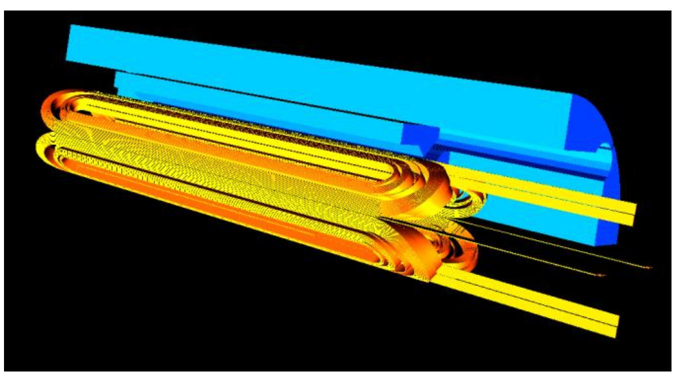
3D magnetic design

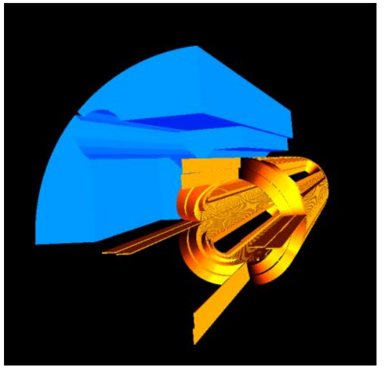
(*By S. Izquierdo Bermudez, 1PoAN-04*)

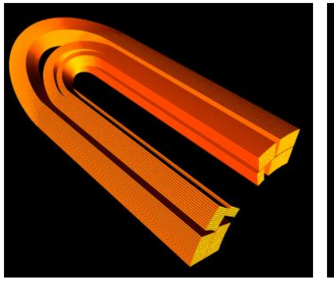
- From 4 (HQ) to 6 blocks in the ends
  - Impact on field quality: $b_6 < 1.1$ unit and $b_{10} < 0.2$ unit
- Iron pad removed with reduced length
- 1% peak field margin in the end
- Short model
  - Magnetic length 1.2 m
  - Coil length: 1.5 m
  - Good field quality region: 0.5 m

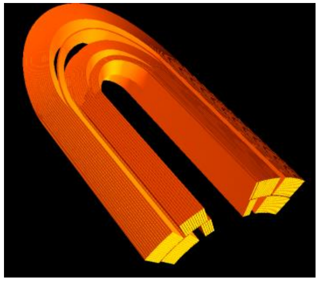










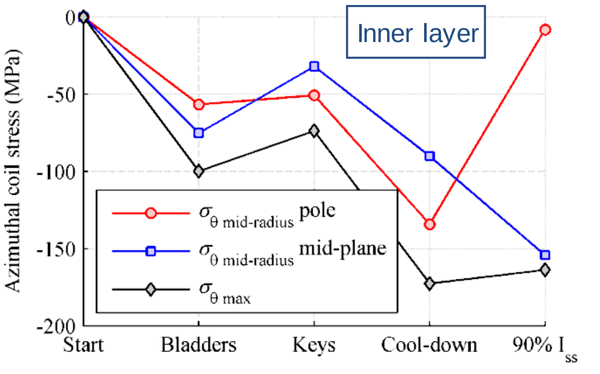


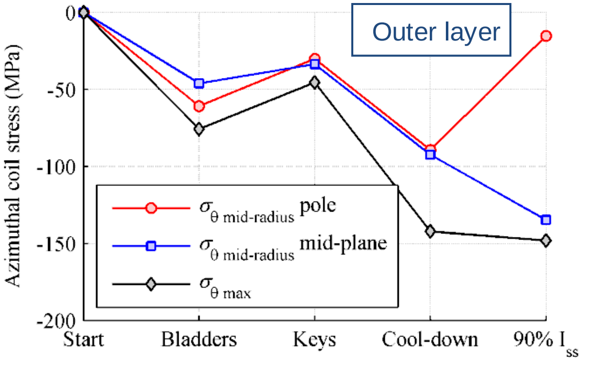
Mechanical analysis

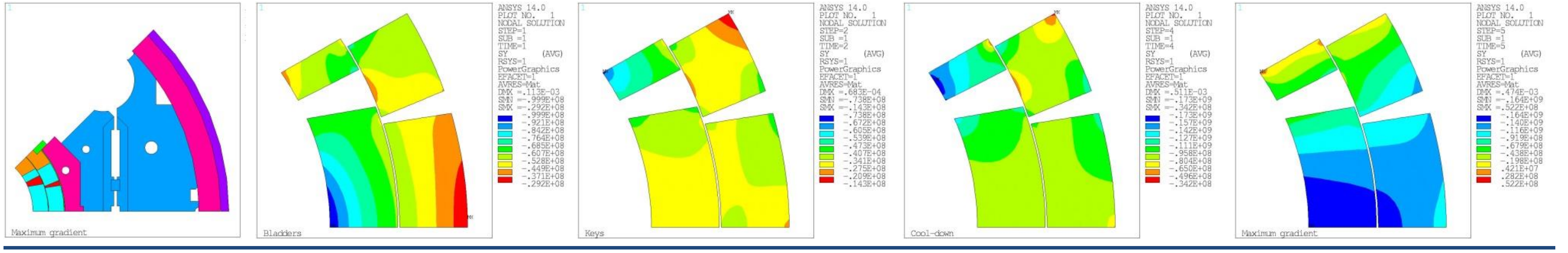
(by M. Juchno)

- Optimization of dimensions and locations of new features
- ≥2 MPa of contact pressure at up to 155 T/m (~90% of I_{ss})

- Peak coil stress: 175 MPa
- Coil displ. from start to nominal grad.
  - Radial: -0.3 to -0.4 mm
  - Azimuthal: -0.04 to -0.05 mm.
- Effect on field quality: 0.75 units of b_6



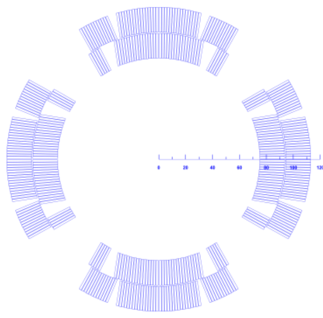


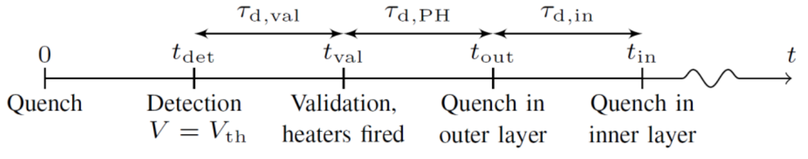


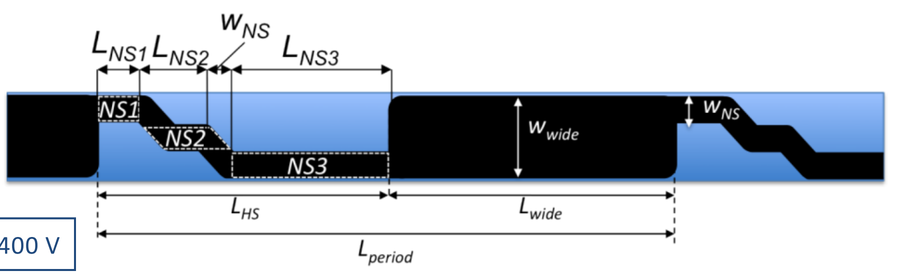
Quench protection

(*see T. Salmi, 2PoCC-03, and G. Manfreda, et al., 2PoCC-05*)

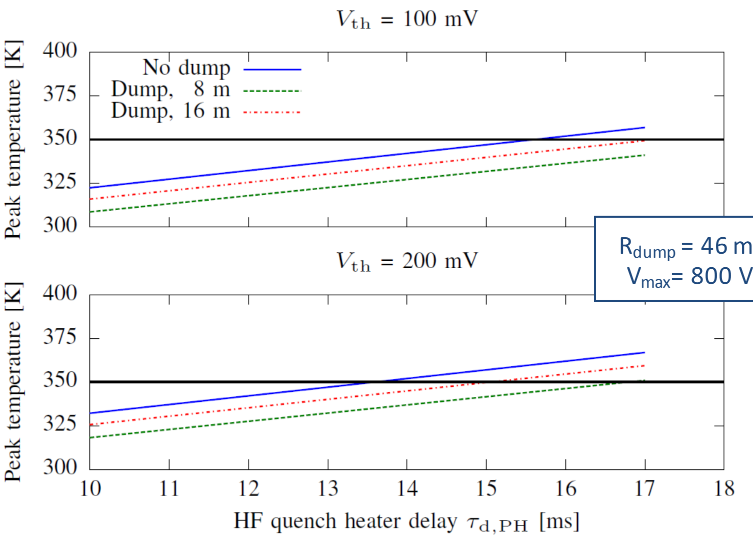
- Trace with 4 heaters strips per coil, with 50 µm polyimide insulation
  - Heating stations in outer layer only
  - Heater delay of about 17 ms
- Before, 10 ms of validation and, after, 20 ms of outer-to-inner delay
- Hot spot T of 350 K (34 MIITS) hardly achieved with no margin
- Under study
  - Modelling of material properties (bronze) and quench-back + *dI/dt* effects (observed in LQ/HQ)
  - Reduced heater delay (25 µm polyimide?)
  - Reduced inner layer quench delay
    - Faster propagation outer to inner
    - Inter-layer heaters?







V_{max}= 400 V



R_{dump} = 46 mΩ
V_{max}= 800 V

Conclusions

- Design of QXF, a Nb_3Sn low-b quadrupole for the HL-LHC, finalized
  - 150 mm aperture with an operating gradient of 140 T/m (82% of I_{ss})
  - Evolution of LARP HQ design with additional accelerator features
- New cable dimension defined (first iteration)
  - R&D in progress to improve mechanical stability a minimize degradation
- Coil optimized to maximize gradient and distribute stress
  - Improved end design to reduce impact on field quality
- Shell based structure capable to support up to 90% of I_{ss}
  - Coil peak stress of 175 MPa
- Challenging quench protection under investigation
- Plans
  - 3D design of the structure and design of LHe containment
  - Fabrication of coils for short model and mirror test in 2014
  - First short model test in 2015
  - Then, long models development and production for installation in 2022