IEEE/CSC SUPERCONDUCTIVITY NEWS FORUM (global edition) October 2014
Invited Presentation 4LOr2C-02 given at ASC 2014, August 10 - 15, 2014.

Nb_3Sn High Field Magnets for the High Luminosity LHC Upgrade Project

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On behalf of HiLumi-LARP Collaboration for MQXF quadrupole and HiLumi-FNAL Collaboration for 11T dipole

With contributions from:

A. Ballarino, E. Barzi, S. I. Bermudez, B. Bordini, S. Caspi, G. Chlachidze, D. Dietderich, H. Felice, P. Ferracin, A. Ghosh, M. Juchno, M. Karppinen, V. Marinozzi, J.C. Perez, E. Ravaioli, G. L. Sabbi, F. Savary, M. Sorbi, E. Todesco, and A. V. Zlobin

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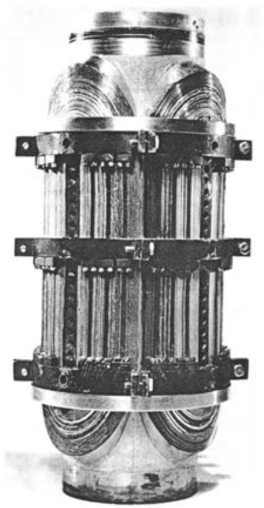
Nb_3Sn magnets: 1960s

- Better performance (~50%) at 4.2 K than NbTi at 1.8 K
- Larger temperature margin
- Development of Nb_3Sn magnets started in the 60's

BNL 76 mm aperture Quad from Nb_3Sn Tape

W. B. Sampson, MT-2 1967



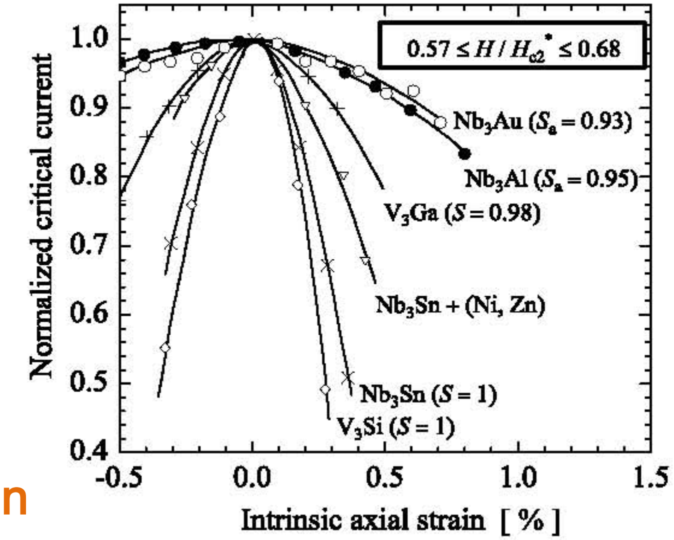
Why not yet?

"Why there is no Nb_3Sn magnet in any High Energy accelerator?"

Because Nb_3Sn is a brittle material

➔ Large degradation vs strain

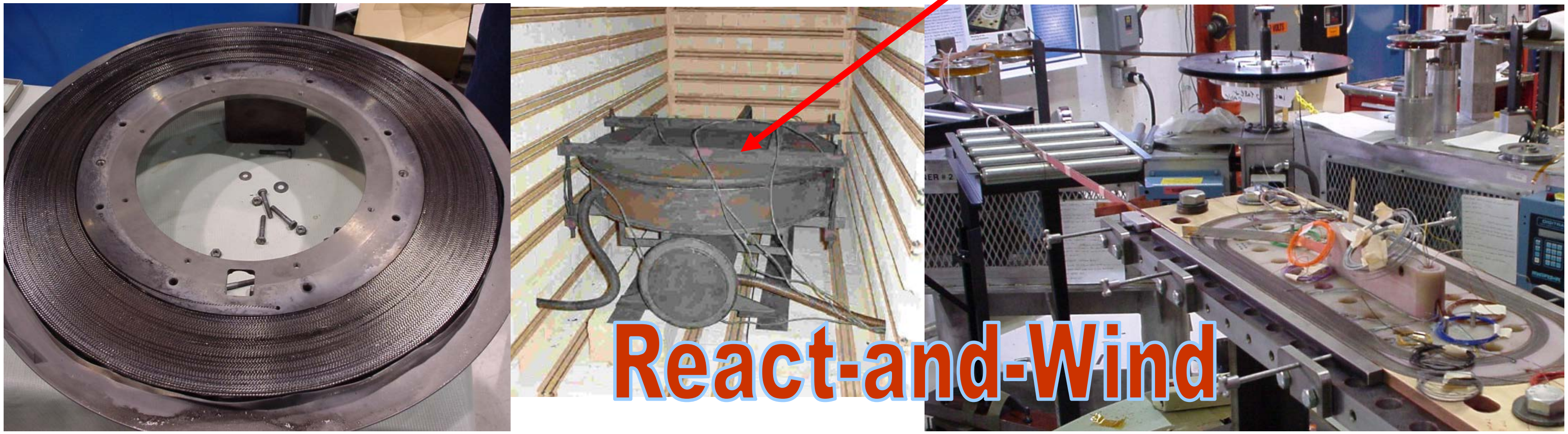
➔ Irreversible degradation at 0 - 0.4% intr. strain



Courtesy of R. Flukiger et al.,

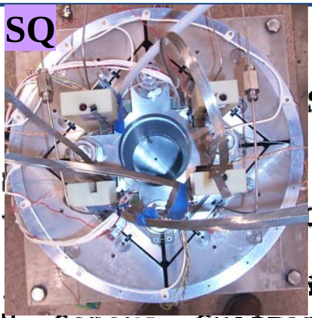
Nb_3Sn Fabrication Technologies

(Nb + Sn) in Cu matrix ➔ Nb_3Sn during heat treatment at 630-700 ^oC



A long way …


SM


SQ

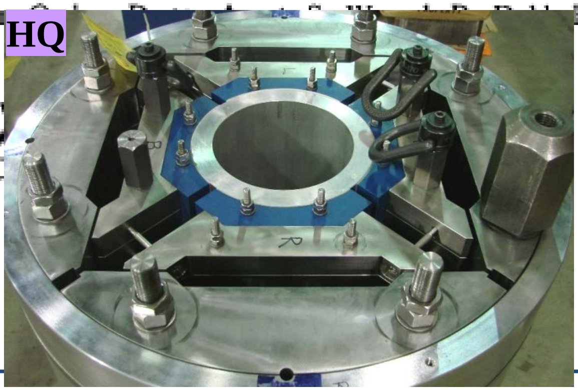

TQS


LQS

CERN, Geneva, Switzerland


LR

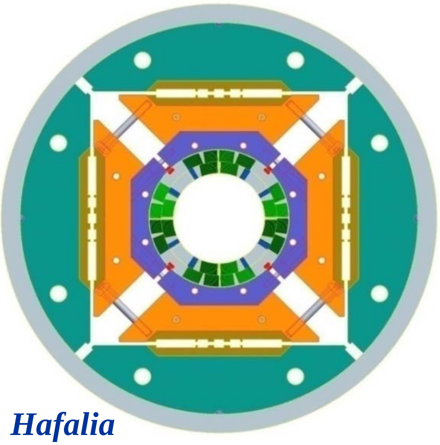

TQC


HQ

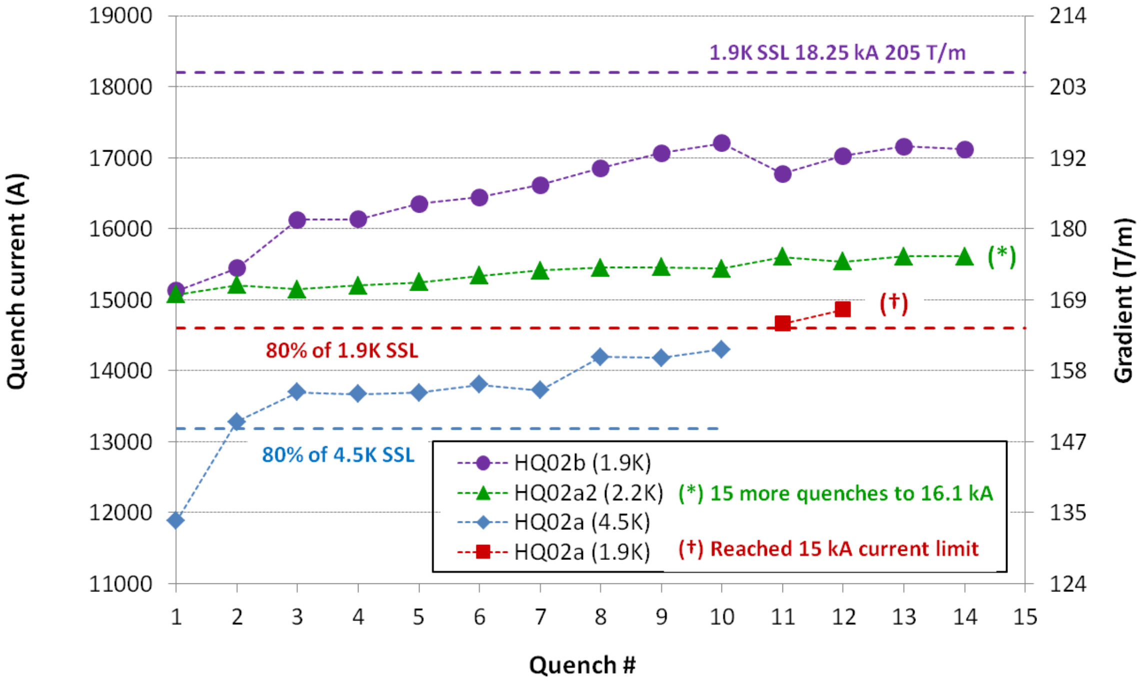
Latest success: LARP HQ02

4LOr2C-06 “Cold Test Results of the LARP HQ02-b magnet at 1.9 K”; *H. Bajas, et al.,*

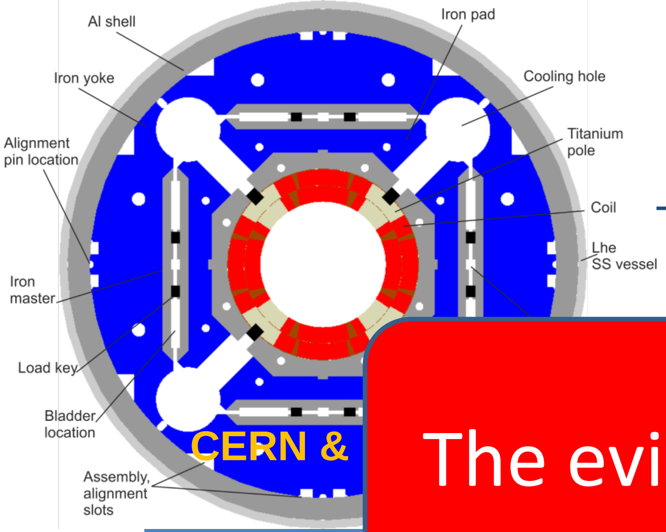
- 90 mm aperture, 1 m long quadrupole
- Tested at FNAL & CERN
- Reached **98% SSL** at 4.5K & **95% SSL** at 1.9K



R. Hafalia



H. Bajas, G. Chlachidze, M. Martchevsky, F.Borgnolutti, D. Cheng, H. Felice, et al.



Nb_3Sn: 2014

Low Beta Quads

The evil is in the details…

N. of poles		4	2
Coil aperture	mm	150	60
Magnetic length	m	2*4/6.8	5.3
N. of layers		2	2
N. of turns per layer		22/28	22/34
Operation temperature	K	1.9	1.9
Nominal gradient/field	T/m - T	140	11.2
Nominal current	kA	17.5	11.85
Peak field at nom. current	T	12.1	11.6
Margin on load line		20%	19%
Stored energy at nom. current	MJ/m	1.3	0.97
Differential induct. at nom. cur.	mH/m	8.2	12
Force on midplane per half coil	MN/m	3.9	1.6

11T table Courtesy of F. Savary

Outline

- **Challenges & Solutions**
  - Conductor
  - Magnetic Design
  - Operational Requirements
  - Coil Fabrication Technology
  - Structure Design & Assembly
  - Quench Protection
- **Status & Plans**

Conductor: Challenges

- **High J_c**: otherwise it is not worth the “pain”
- Sufficiently high **irreversible strain limit**: for handling & operation
  - Optimization of composition, HT temperature, time(?)[†]
- **High RRR** and **small subelements**: for stability
  - Several models
  - Good understanding of strand tests*
  - Cable tests in progress
  - Magnets have shown a more complex behavior

[†] 1MOr1A-01. [Invited] Irreversible Strain Limit of Nb3Sn Wires Made by the Restacked-Rod Process: Review of the Effects of Doping, Heat-Treatment, and Microstructure; *N. Cheggour;*

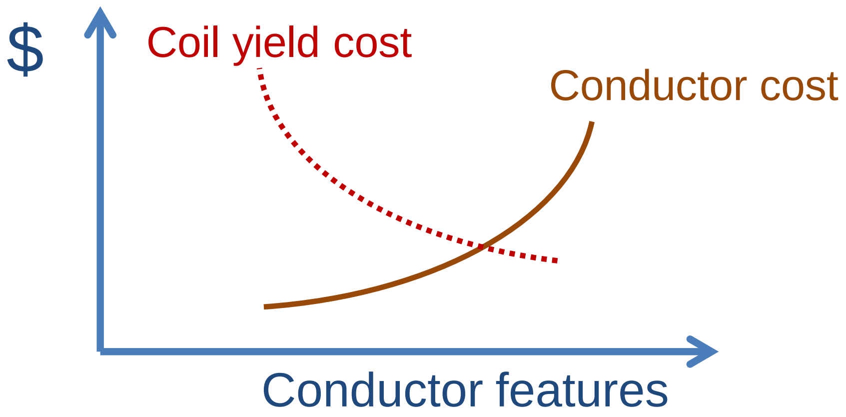
*1LOr2B-06. Magneto-Thermal Stability of the Nb3Sn conductor for the HiLumi Upgrade; *B. Bordini*

Conductor Optimization

- A few examples:
  - – Instability induced in a single coil under tests with higher and higher preload (TQM03[†])
  - – "Enhanced Instability" mechanism in a coil of long quadrupole (LQS02*)

➔Optimization of coil yield vs conductor features

- High RRR
- Small filaments
- "Adequate" J_c



[†] G. Chlachidze, et al., "The Study of Single Nb3Sn Quadrupole Coils Using a Magnetic Mirror Structure", *IEEE Trans. Appl. Supercond*. Vol. 21, No. 3, pp. 1692-1695, 2011

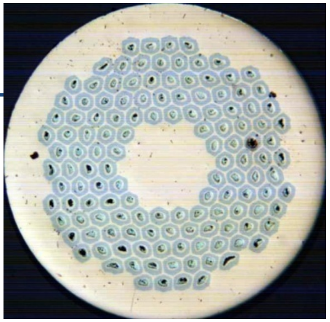
*G. Ambrosio, et al., "Progress in the Long Nb_3Sn Quadrupole R&D by LARP", *TAS* **22** 4003804

Heat treatment can be adjusted to meet all MQXF requirements

Parameter	UNIT	MQXF	11T
Strand diameter	mm	0.85	0.7
Fabrication process		RRP, PIT	RRP, PIT
Number of filaments		132, 192	132, 120
Nominal sub-element diameter	um	<50	<45
RRR after full heat treatment		>150	>100
Cu/non-Cu		1.2	1.15
Minimum Ic (12 T, 4.222 K)†	A		438
Minimum Ic (15 T, 4.222 K)†	A	361	
Number of strands		40	40
Cabling degradation	%	<5	<5
Cable bare width	mm	18.15	14.70
Cable bare mid-thickness	mm	1.525	1.25
Keystone angle	Deg.	0.55	0.79

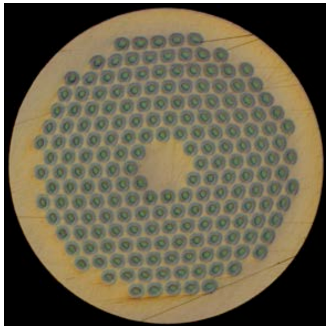
†Without self-field correction

RRP 132/169
by OST



Courtesy of
A. Ghosh

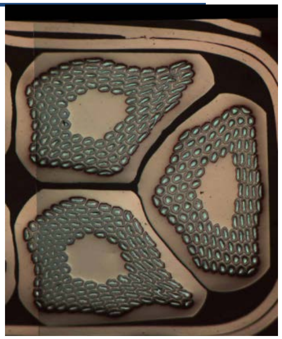
PIT 192
by Bruker-EAS



Courtesy of
A. Ballarino

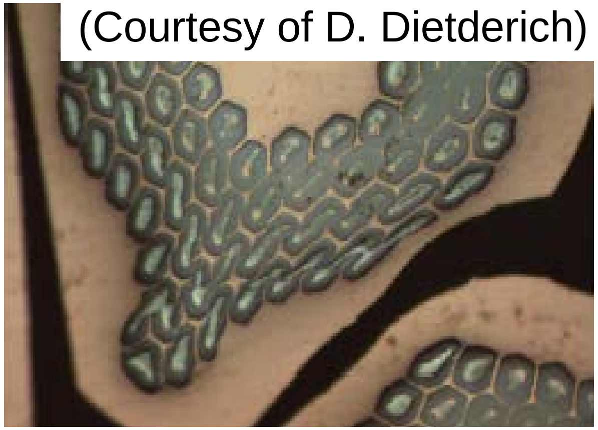
3LPo1E-03: 151. Optimization of Nb_3Sn Cable for the Low-β Quadrupoles for the High Luminosity LHC*; *D. R. Dietderich; A. Godeke; I. Pong; A. K. Ghosh; A. Ballarino; L.-R. Oberli;*

Cable Optimization



- Cable with large number of strands needed for Quench Protection and Stress "Reduction"
  - 40 strands max for CERN cabling machine

➔Trade-off between mechanical stability and strand damage:



(Courtesy of D. Dietderich)

- What is acceptable?
  - LARP: no damaged strands
  - FNAL HFM: < 1 per cable edge
  - QXF: ~2/strand in edge (108/127)
    - Pre-annealed strands
- Exploring testing local RRR for assessing damage
- Techniques for handling cables with limited stability

3LPo1E-03: 151. Optimization of Nb_3Sn Cable for the Low-β Quadrupoles for the High Luminosity LHC*; *D. R. Dietderich; A. Godeke; I. Pong; A. K. Ghosh; A. Ballarino; L.-R. Oberli;*

Magnetic Design: Dynamic effects

- In Nb_3Sn cables the inter-strand contact resistance may vary by order of magnitude after the reaction
  - Impact on harmonics during ramp up
  - Possible quench during ramp down

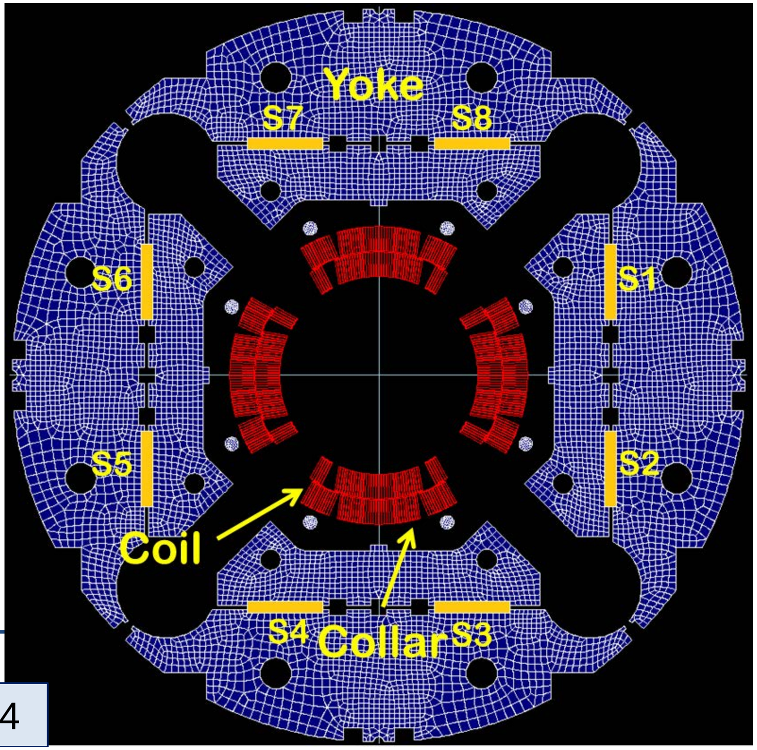
  ➔ 25 um thick stainless steel core
  - 11T: covering almost all internal surface
  - MQXF: covering ~72% of the internal surface
    - Bumps caused by core are under investigation

X. Wang, et al., “Multipoles Induced by Inter-Strand Coupling Currents in LARP Nb3Sn Quadrupoles”, IEEE Trans. Appl. Supercond., **24**, 4002607, June 2014.

Magnetic Design: Reproducibility

- MQXF & 11T models will give us info about harmonics reproducibility in Nb_3Sn magnets
  - MQXF: magnetic shims in bladder slots

Shim combination	Multipoles	Value (units) @ 17.5 kA
S 1,2,3,8	+b3 (+b5)	+3.0 (+0.2)
S 4,5,6,7	-b3 (-b5)	-3.0 (-0.2)
S 1,2,4,7	+b3 +b5	+4.6 (+0.6)
S 3,5,6,8	-b3 -b5	-4.6 (-0.6)
S 1,2,5,6	+b4	+2.8
S 3,4,7,8	-b4	-2.8
S 1,3,4,6	+a3 -a5	+4.6 (-0.6)
S 2,5,7,8	-a3 +a5	-4.6 (+0.6)
S 1,4,5,8	-a4	-0.8
S 2,3,6,7	+a4	+0.8
S 1,6,7,8	-a3 (+a5)	-3.0 (+0.2)
S 2,3,4,5	+a3 (-a5)	+3.0 (-0.2)

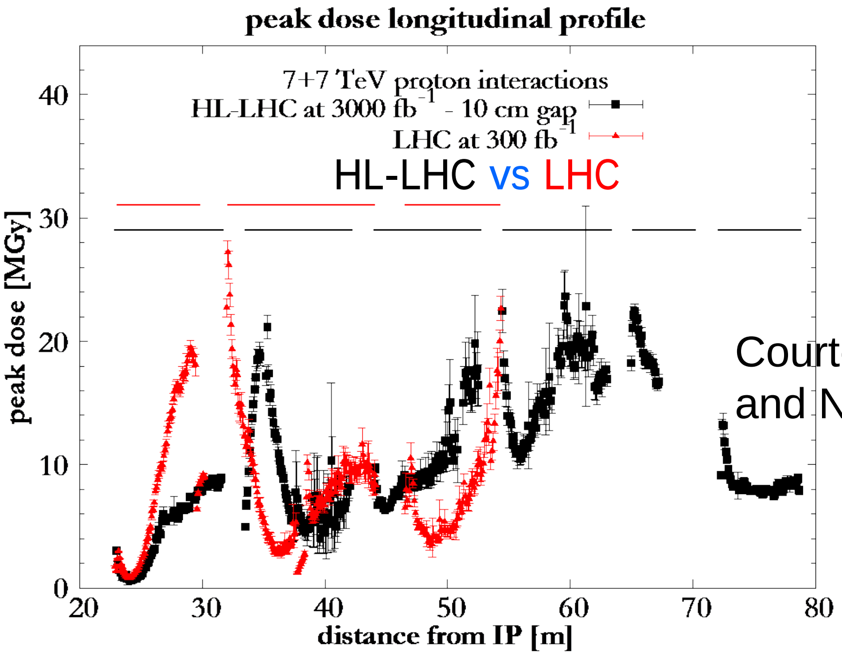


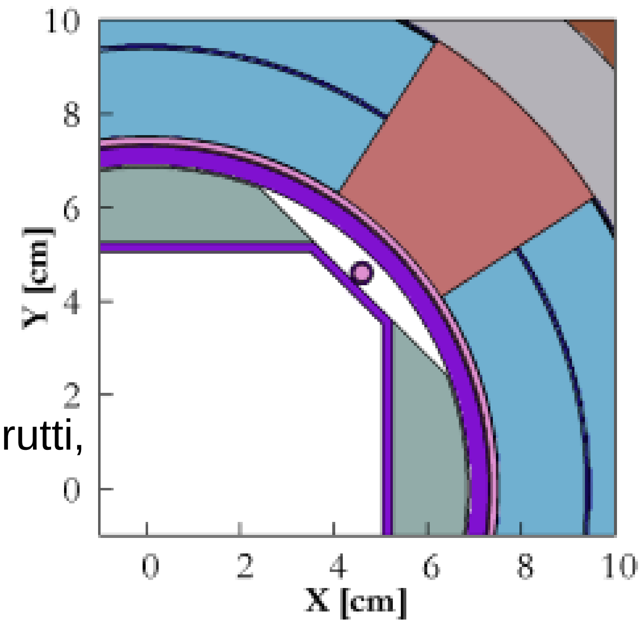
P. Hagen and P. Ferracin, LARP-HiLumi Collab Mtg, 2014

Op. Requirements: Radiation Hardness

- MQXF: higher luminosity ➔ higher dose
- Solution: Tungsten liners
  - 16 mm in Q1; 6 mm in Q2 and Q3

CTD101k: OK at expected Max dose





Courtesy of F. Cerutti, and N. Mokhov

ets in the High Luminosity LHC Insertion
3305, June 2014

Coil Fabrication: Handling

MQXF & 11T:

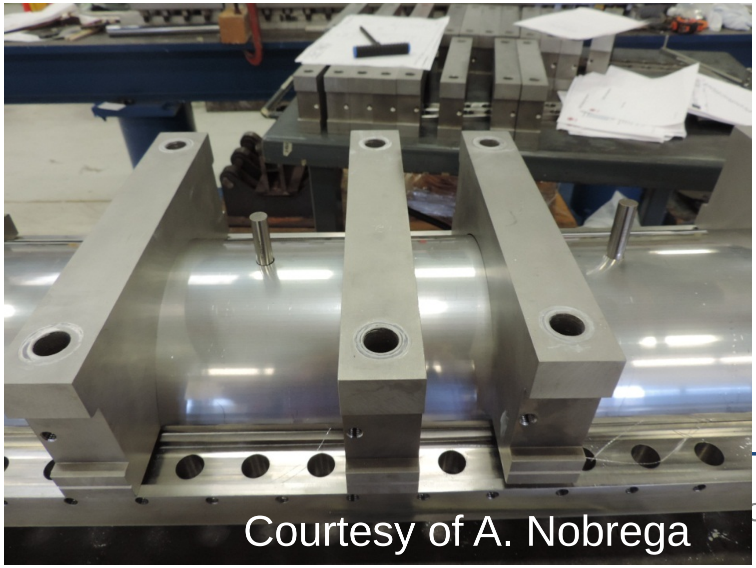
- Double pancake winding
  - ➔ No interlayer splice
- Ceramic binder & Curing
  - ➔ Easier & safer coil handling before potting

Courtesy of M. Yu

Coil Fabrication: Handling

MQXF & 11T:

- Fixtures assembled around coils
  - ➔ Less risk of coil damage
- Potting with epoxy resin
  - ➔ Coil is a solid object and stresses are distributed


Courtesy of A. Nobrega

Ceramic Binder - I

- The ceramic binder keeps the coil glued also after reaction
  - ➔ Easier & safer transition from reaction to potting fixture
- But it makes the fiberglass more fragile after reaction
  - ➔ Is this a concern?
- Fiberglass insulation is acting only as spacer in this phase
- Potting makes the final composite
  - – Binder after reaction is porous to epoxy

Ceramic Binder - II

- The structural properties affecting magnet performance are the properties of the composite after potting
- Several tests of short (1m) and long (3.5m) Nb_3Sn coils & magnets fabricated using this technology gave excellent results
  - Ex: HQ02: **98% SSL** at 4.5K & **95% SSL** at 1.9K

➔ This technology is good enough for MQXF and 11T applications

4LOr2C-06 “Cold Test Results of the LARP HQ02-b magnet at 1.9 K”; *H. Bajas, et al.*,

Cable Insulation

Several different solutions:

- MQXF: S2-glass braided on the cable (145 um)
- 11T - CERN: C-shaped mica foil (80 um) + S2-glass braided on the cable (75 um)
- 11T - FNAL: E-glass tape (75 um) wrapped on the cable with 50% overlap

P. Ferracin, et al., "Magnet Design of the 150 mm Aperture Low-β Quadrupoles for the High Luminosity LHC", *IEEE Trans. Appl. Supercond.*, **24** 4002306.

M. Karppinen, et al., "Design of 11 T Twin-Aperture Nb3Sn Dipole Demonstrator Magnet for LHC Upgrades", *IEEE Trans. Appl. Supercond.*, **22** 4901504.

Winding Marginally-Stable Cables

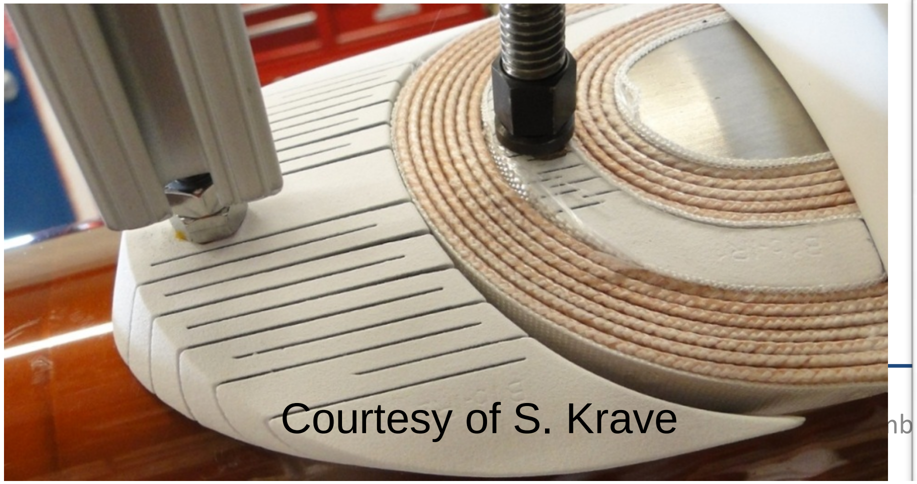
- LARP-HQ (120mm quad): tight-fit tool
- FNAL-11T: binder painted on each turn before end

End Parts

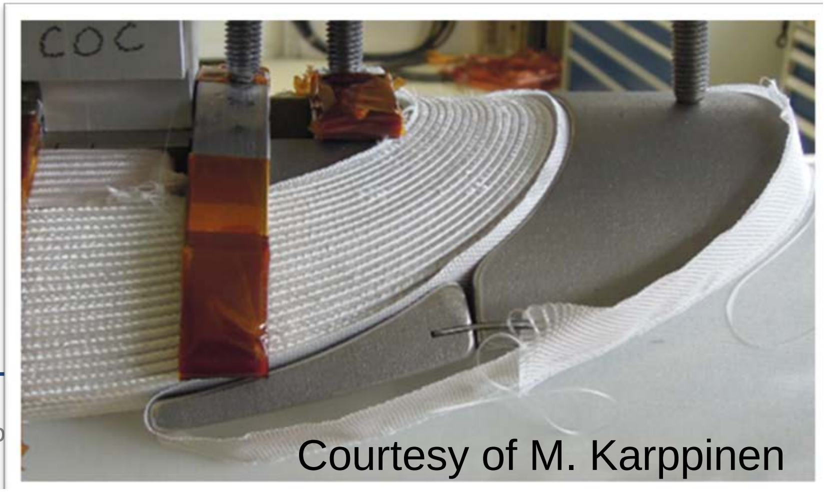
- MQXT & 11T: end parts made of Stainless Steel
- Cables have tendency to separate from mandrel and pole parts during winding; this effect is worse with larger windings

➔MQXF: <u>accordion-style slits</u> in end parts

➔11T: <u>flexible legs</u>



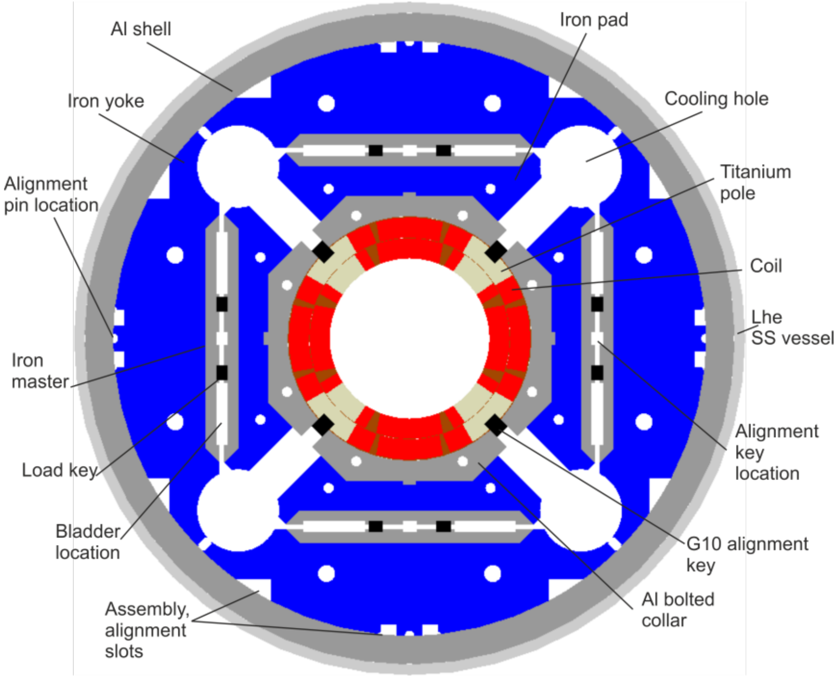
Courtesy of S. Krave



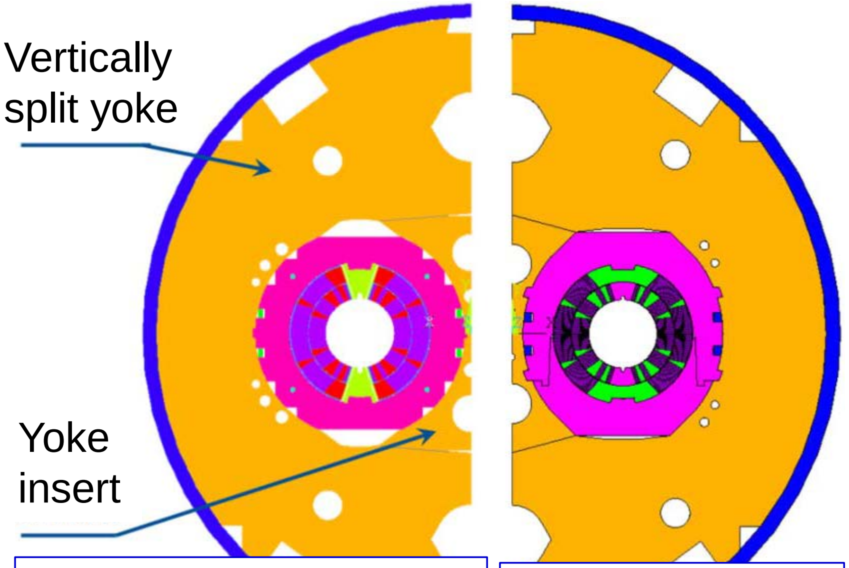
Courtesy of M. Karppinen

Structural Design

MQXF



11T



Vertically split yoke

Yoke insert

Self-standing collars
Pole is not glued to coil

Yoke closes during cooldown

- Bladders & keys: handles well high forces
- Collars: easy scale-up, fit well for 2-in-1 design

2LPo2J-06: 195. Support Structure Design of the Low-β Quadrupoles Short Model for the High Luminosity LHC; *M. Juchno, et al.,*

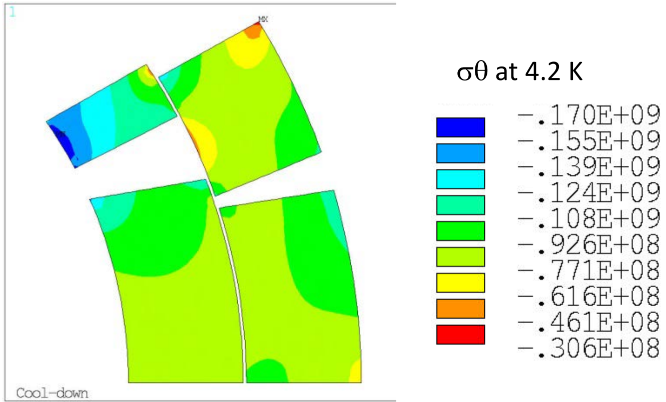
M. Karppinen, et al., “Design of 11 T Twin-Aperture Nb3Sn Dipole Demonstrator Magnet for LHC Upgrades”, *IEEE Trans. Appl. Supercond.*, **22** 4901504.

Structural Design

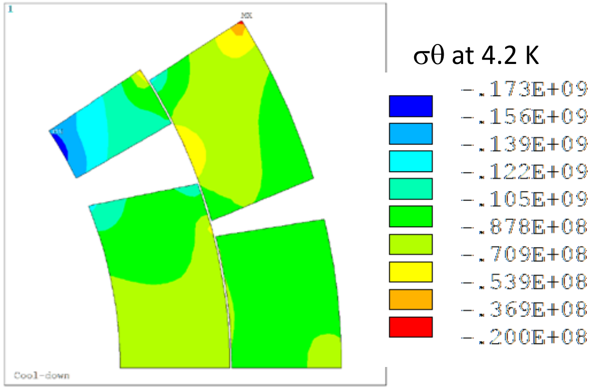
2D max azimuthal stress:

- 11T-CERN, after cold mass assembly: 143 MPa
- 11T-FNAL, during collaring: 148 MPa
- MQXF, after cool-down: 170 MPa

MQXF at nominal current



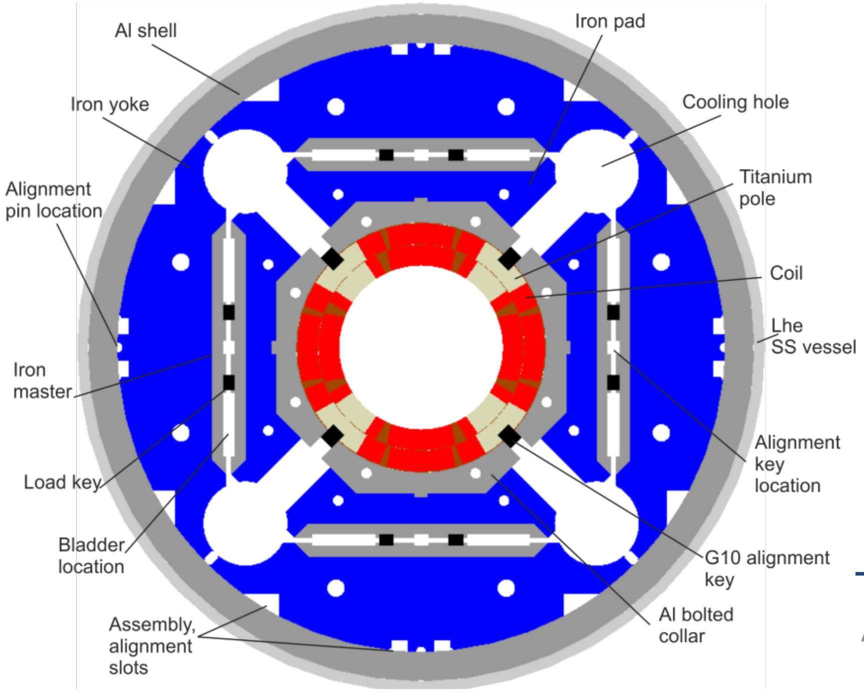
HQ02 at 16.2 kA

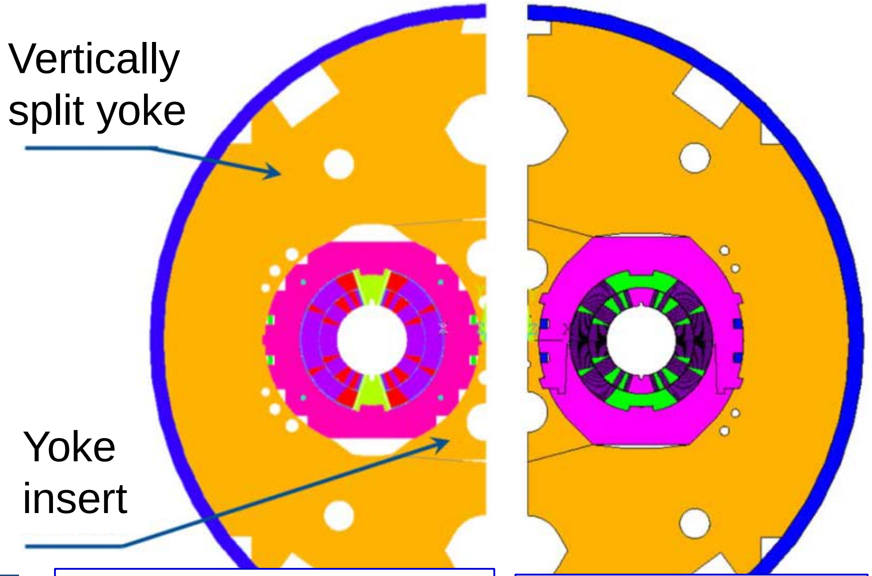


Courtesy H. Felice

Challenges

- MQXF: demonstrate long magnets
  - Tight tolerance and control of preload
- 11T-FNAL: gap control
- 11T-CERN: control of the key-pole interface




Vertically split yoke

Yoke insert

Self-standing collars
Pole is part of collars

Yoke closes
during cooldown

Quench Protection

- MQXF: high energy density = 2 times LHC magnets
- 1st simulation (MT23):
  - Outer layer heaters
  - Energy extraction (2 MQXFs in series)
  - Conservative assumptions

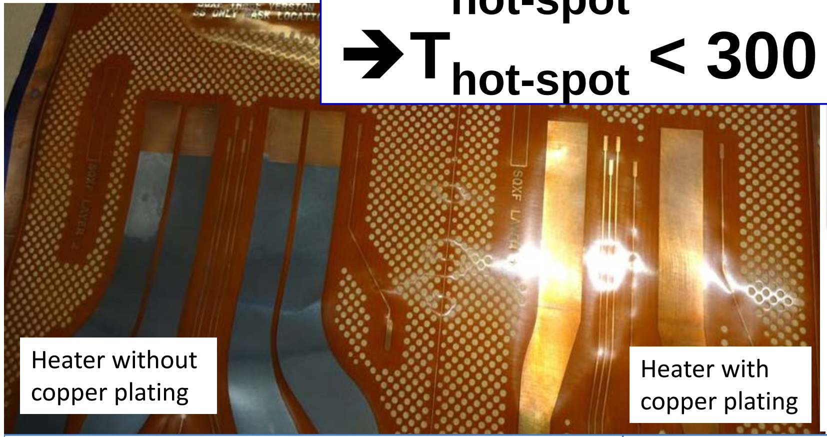
→ $T_{\text{hot-spot}}$ ~ 350 K (without redundancy)

G. Manfreda, et al., "Quench Protection Study of the Nb3Sn Low-beta Quadrupole for the LHC Luminosity Upgrade", *IEEE Trans. Appl. Supercond.*, **23** 4700405.

Quench Protection Improvements

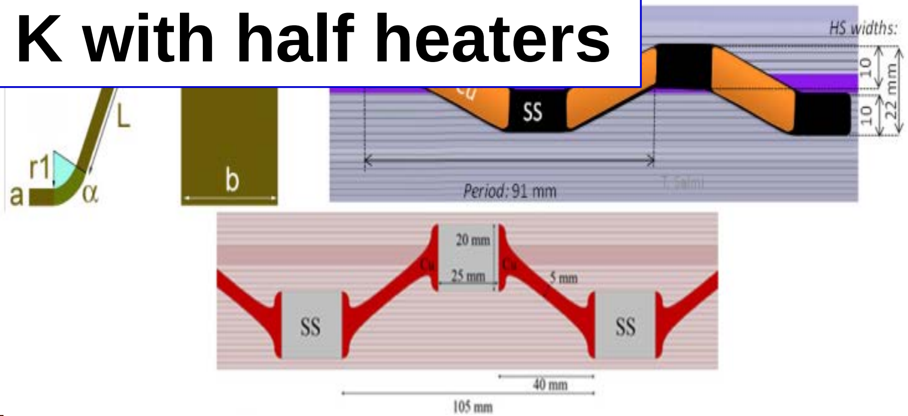
- Understanding "dynamic effects" = energy extraction and quench propagation caused by inter-filament losses
- Development of heaters with copper-cladding
- Development of heaters for inner layer (to be demo.)

➔ $T_{\text{hot-spot}}$ ~ 270 K with all heaters
➔ $T_{\text{hot-spot}}$ < 300 K with half heaters



Heater without copper plating

Heater with copper plating



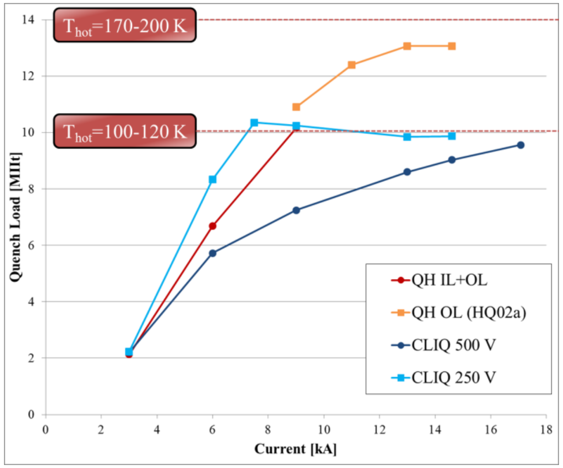
Courtesy J. C. Perez	Courtesy M.Marchevsky, E.Todesco, D.Cheng, T.Salmi

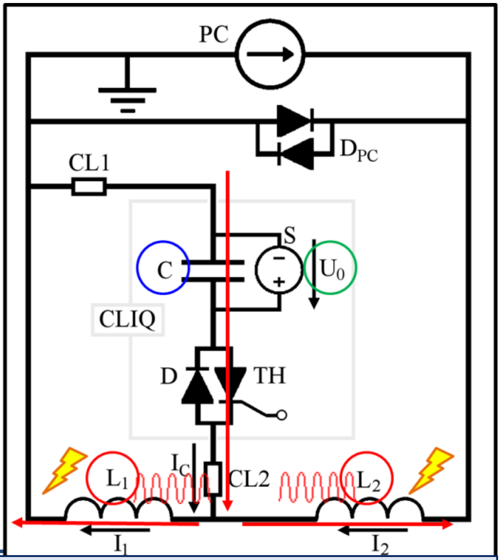
2LPo2K-02: 197. Study of quench protection for the Nb3Sn low-beta quadrupole for the LHC luminosity upgrade (HiLumi-LHC); *Vittorio Marinozzi, et al.,*

CLIQ

- Coupling-Loss Induced Quench System
- Very effective on HQ02 test
- To be demonstrated for long magnets
- Could provide perfect redundancy with heaters on outer layer

Courtesy of E. Ravaioli





1LOr2B-01. First Test of CLIQ, the New Coupling Loss Induced Quench Protection System, on a Nb3Sn Magnet; *E. Ravaioli, et al.,*

Status & Plans

For 11T see next talk

MQXF:

- Making practice coils (LARP & CERN)
- Started real coils
  - One coil for “mirror test” (LARP) → Test 01/15
  - 1st coil for SQXF1 (LARP)
  - SQXF1 shell procured (CERN) → Test 06/15
- Long coils fabrication starts in 2015
  - single coil in “mirror” → Test Spring 2016
  - 1st long prototype → Test Fall 2016

Conclusions

- The development of Nb_3Sn accelerator magnets has reached maturity
  - Nb_3Sn are part of the HL-LHC
- Now it is the time to address remaining challenges and fix all details
- The MQXF and 11T projects are on truck for successful demonstration
- Magnet options for future HEP accelerators are increasing!

THANK YOU ALL!

3rd HiLumi LHC/LARP Annual Meeting
11-15 Nov 13

Back up slides

Magnetic Design: Magnetization

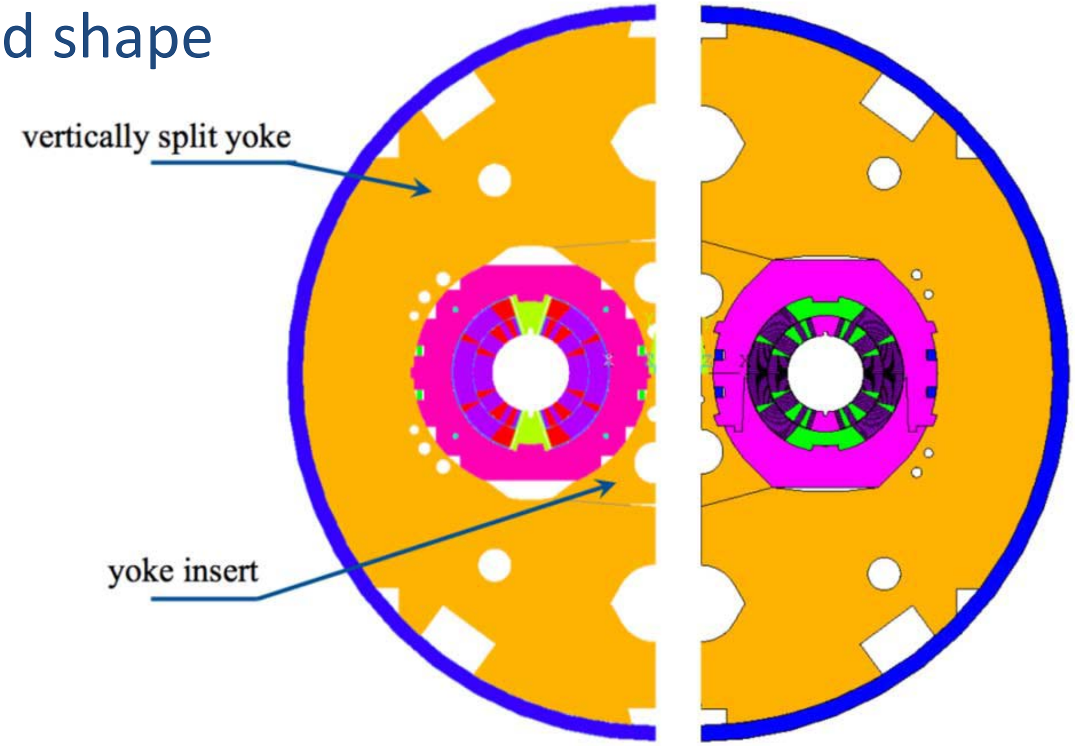
- Large filaments → large magnetization at injection
- 11T strategy*:
  - RRP option was changed from 108/127 to 132/169
  - Minimum current may change from 350 A to 100 A
  - May use passive shims

*M. Karppinen, et al., "Design of 11 T Twin-Aperture Nb3Sn Dipole Demonstrator Magnet for LHC Upgrades", *IEEE Trans. Appl. Supercond.*, **22** 4901504.

4LPo2E-09: 141. Field errors induced by persistent current in high-field superconducting accelerator magnets; *Xiaorong Wang, et al.*

Magnetic Design: Iron Saturation

- In the 11T cross talk between apertures increases at high field
  - Holes in yoke and shape optimization



M. Karppinen, et al., "Design of 11 T Twin-Aperture Nb3Sn Dipole Demonstrator Magnet for LHC Upgrades", *IEEE Trans. Appl. Supercond.*, **22** 4901504.

Op. Requirement: Heat extraction

- MQXF: Tungsten liners keep heat deposition in HL-LHC at present LHC levels
- Heat extraction from epoxy potted coils is OK if:
  - Polyimide coverage of coil inner surface < 50%
  - Holes through pole for heat flow to heat exchangers
    - One hole every 50 mm