Fermilab

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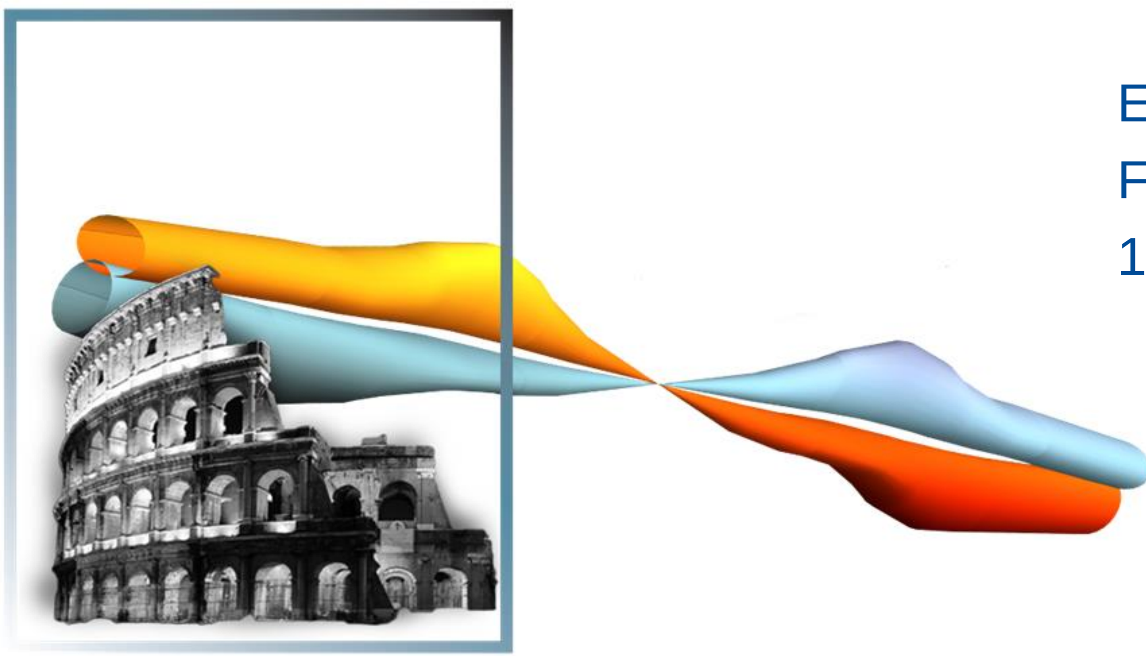
# Development of 60-mm aperture 15-16 T $Nb_3Sn$ dipole at Fermilab



E. Barzi, A.V. Zlobin

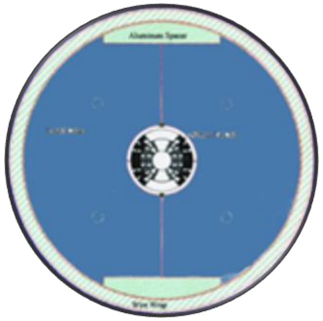
FCC meeting in Rome

11-15 April 2016

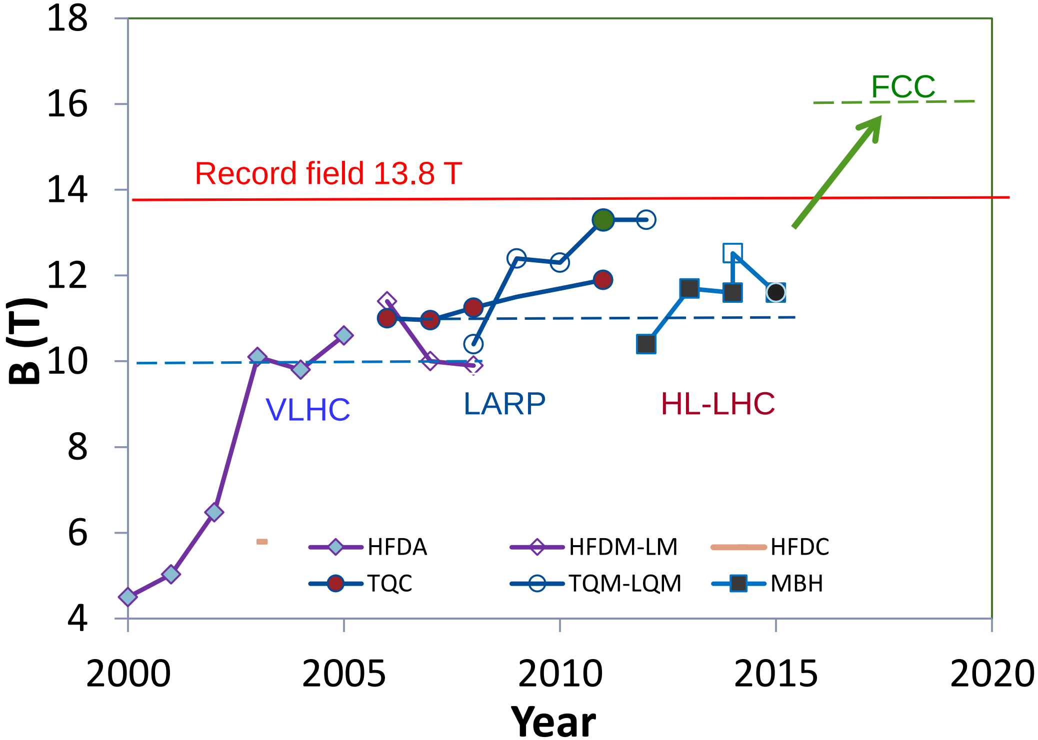
# Premise

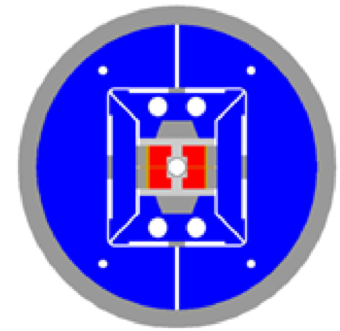
- In the plenary talk «The Steps Towards 16 T FCC Magnets» we heard two contrasting messages: on one hand, the speaker stressed how complex of a technology Nb3Sn is, on the other flat coils without aperture producing 16 T on the conductor were considered representative of the technology.
- In accordance to the clear concept presented by Fabiola Gianotti in her plenary talk, we should focus in developing/producing systems ready for implementation and operation ➔ i.e. A  magnet is a system for beam bending/focusing and of course should have (at least) one aperture.
- The present magnet statistics show that Bruce is right when he speaks of a «14 T brick wall» for Nb3Sn magnets.

# Program Timeline

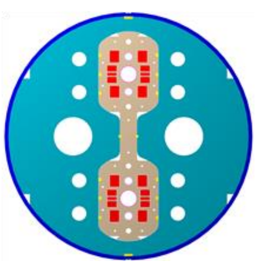


D20 (LBNL)
50 mm dipole
**13.5 T (1997)**

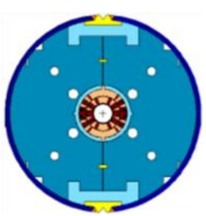


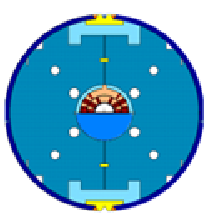
HD2 (LBNL)
35 mm dipole
**13.8 T (2008)**



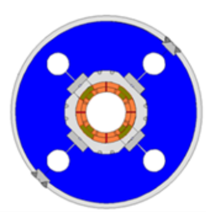
**HFDC (R&W)**
**40 mm 10 T dipole**



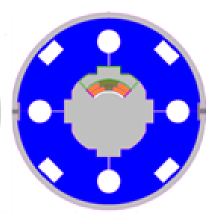
**HFDA**
**43.5 mm**
**10 T dipole**



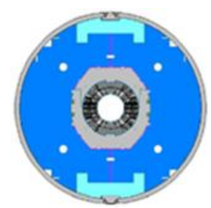
**HFDM-LM**
**Dipole mirror**



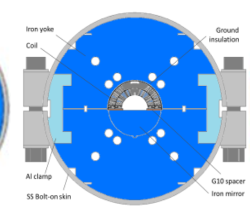
**TQC**
**90 mm 200 T/m**
**quadrupole**



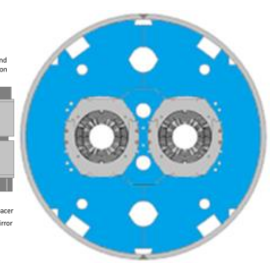
**TQM-LQM**
**Quadrupole**
**mirror**



**MBHSP**
**60 mm 11 T dipole**



**MBHSM**
**Dipole mirror**

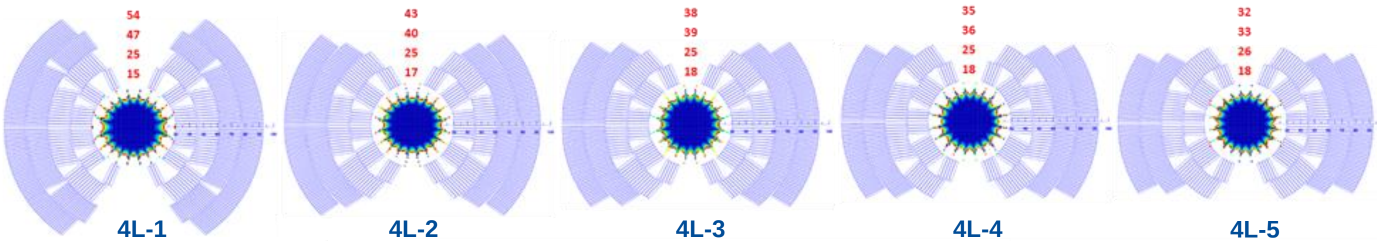


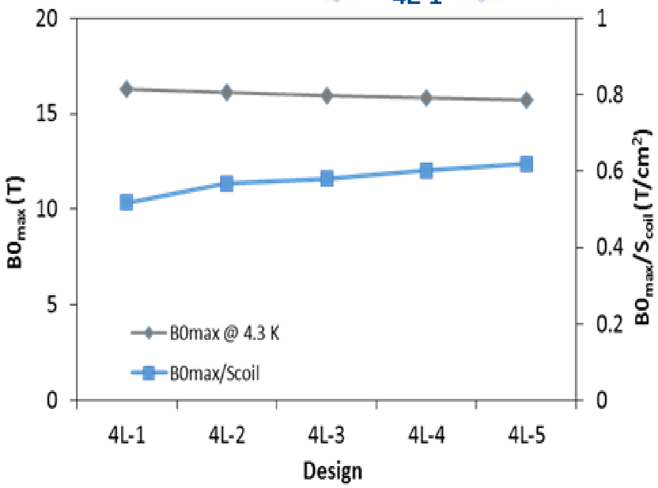
**MBHDP**
**60 mm 11 T dipole**

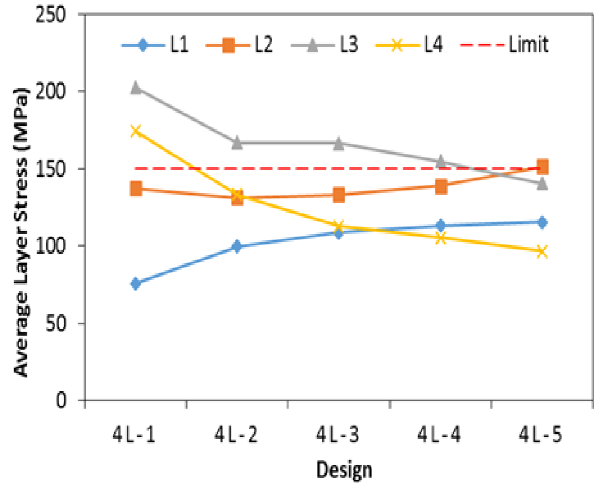
# Current HFM R&D Program

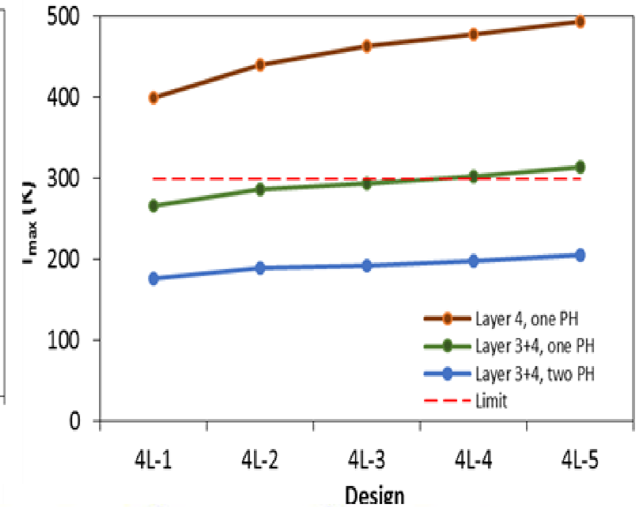
- As a part of the National HFM collaboration develop *accelerator magnets* with *world record* parameters
  - Small-aperture 15-16 T $Nb_3Sn$ dipole suitable for VHEppC (phase I)
    - background field for small 1-2 T HTS inserts
  - Large-aperture 15 T $Nb_3Sn$ dipole with stress management (phase II)
    - background field for 5+ T HTS inserts
- Magnet cost optimization
- Superconductor and structural material R&D for 15-20 T accelerator magnets
  - $Nb_3Sn$ composite wires
  - Large Rutherford cables

# Coil Design Study

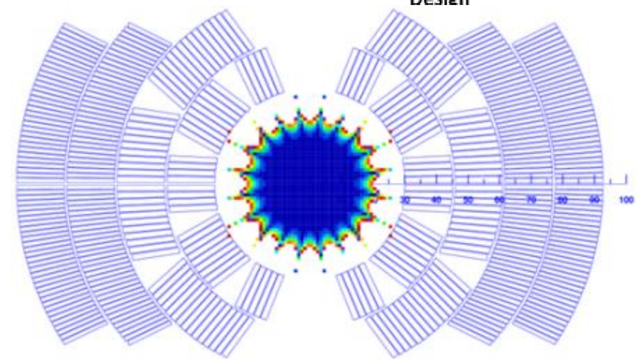



- Coil aperture: 60 mm
- Coil cross-section: modified cosθ,4 layers, graded
- Design parameters: $B_{max}$, field quality, coil volume, azimuthal stress, quench protection
- Design choice: 4L-5



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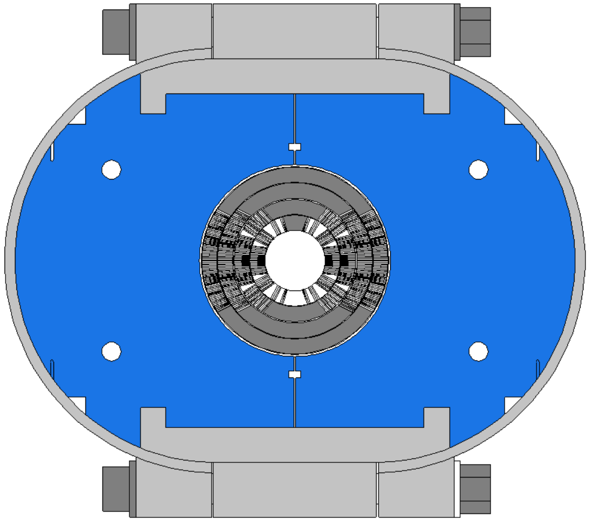
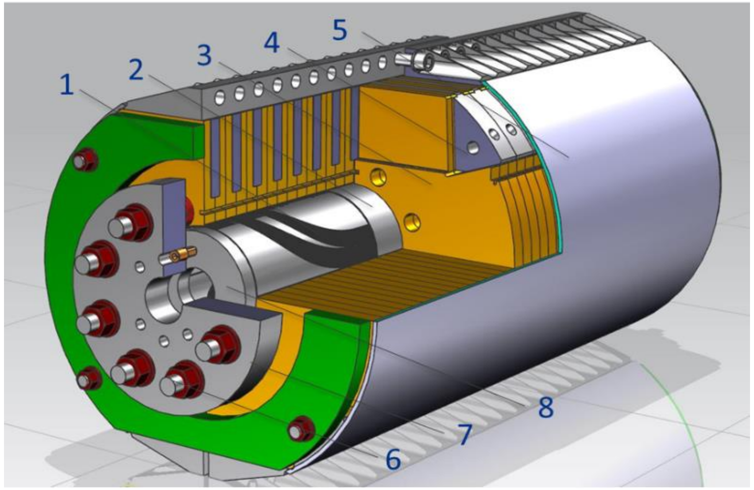
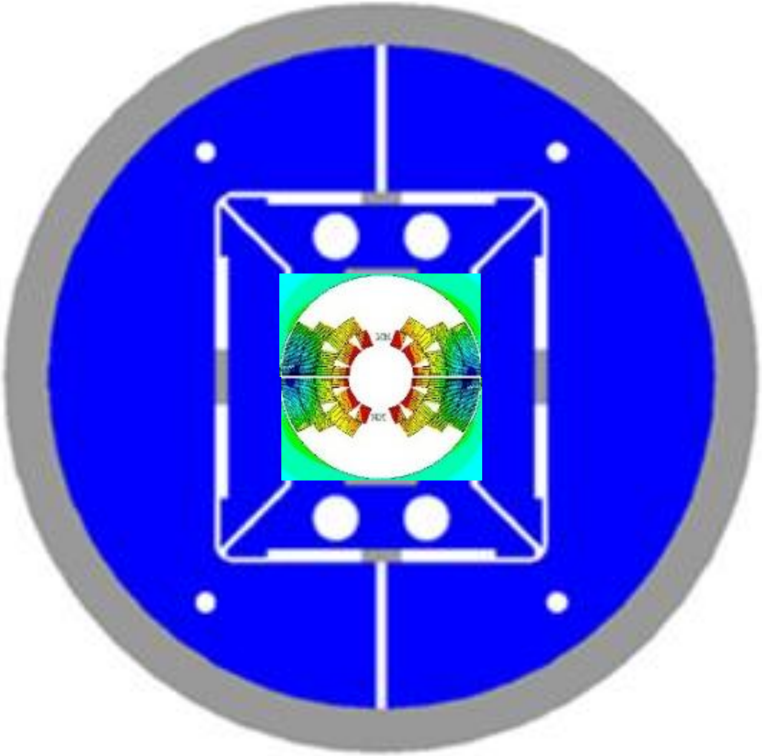
# Mechanical Structure

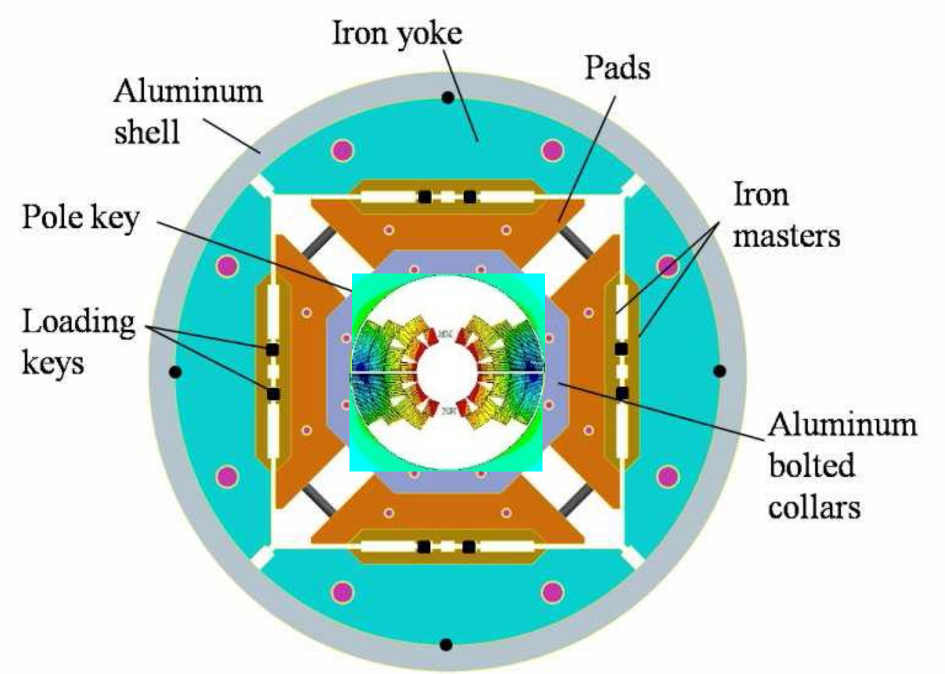
- Thin coil-yoke spacer (no collar)
- 2-piece vertically split yoke
- Yoke clamp
  - Stainless steel C-clamps (v.1)
    - this approach with Al clamps was used in previous FNAL magnets
  - Aluminum I-clamps (v.2)
- Skin
  - Bolted skin from 11 T dipole (v.1)
  - New thick bolted or welded skin (v.2)
- Cold mass OD<610 mm
  - VMTF Dewar limit
- Axial support
  - Thick SS rods and end plates





# Use of HD2 or HQ structure






- 45-mm HD2:
  - cold mass OD=705 mm
  - Al shell thickness 40 mm
- 120-mm HQ:
  - cold mass OD= 570 mm
  - Al shell thickness 25 mm

# Magnet Design Parameters at 4.3 K

| Parameter | Units | v.2 |
|---|---|---|
| Bore field at short sample limit | T | **15.61** |
| Peak field at short sample limit | T | 16.25 |
| Current at short sample limit, $I_c$ | kA | 11.34 |
| Inductance at $I_c$ | mH/m | 25.61 |
| Stored energy at $I_c$ | MJ/m | **1.65** |
| Horizontal Lorentz force per quadrant at $I_c$ | MN/m | 7.36 |
| Vertical Lorentz force per quadrant at $I_c$ | MN/m | -4.50 |

**$J_c$(12T, 4.2K)=2500 A/mm$^2$**

# FCC-hh Magnet target parameters

| | B / G (T) / (T/m) | $B_{peak}$ (T) | Bore (mm) | Length (units x m) |
|---|---|---|---|---|
| MB | **16** | 16.4 | **50** | 4500 x 14.3 |
| MQ | 450 | 13 | 50 | 800 x 6 |
| MQX | 225 | 13 | 100 | |
| D1 | 12 | 13 | 60 | 4x2 x 12 |
| D2 | 10 | 10.5 | 60 | 4x3 x 10 |

Inter-aperture distance ≈ 250 mm
Yoke diameter ≤ 700 mm
Stray field ≤ 100 mT

FNAL dipole parameters are close to MB and also D1, D2

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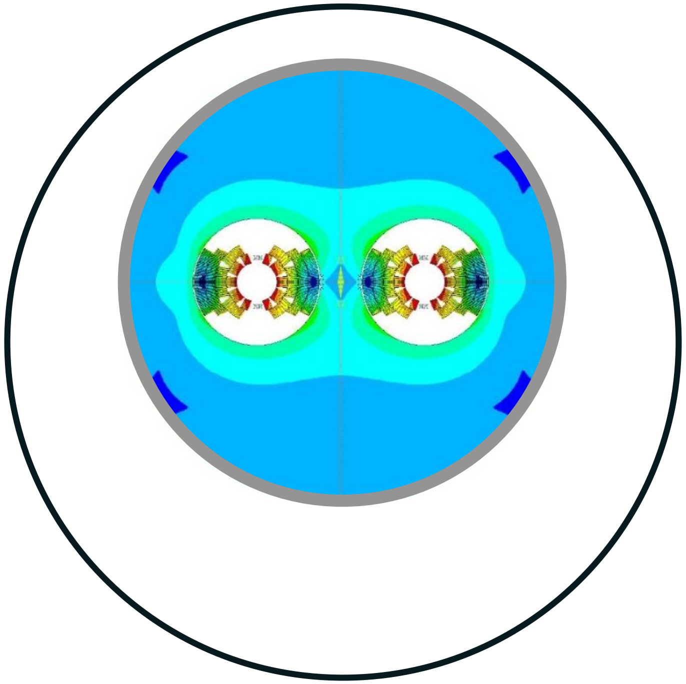
# FNAL Dipole coils in 2-in-1 configuration (MB)



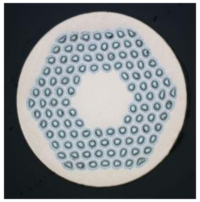
1 m OD “cryostat” envelope

| | |
|---|---|
| Number of apertures | 2 |
| Aperture(mm) | 60 |
| Aperture spacing (mm) | 250 |
| Coil current (kA) | 11.1 |
| Operating temperature (K) | 4.3 |
| Max bore field at 4.3 K (T) | 16.4 |
| Max coil field at 4.3 K (T) | 16.9 |
| Yoke ID (mm) | 190.8 |
| Yoke OD (mm) | 650 |

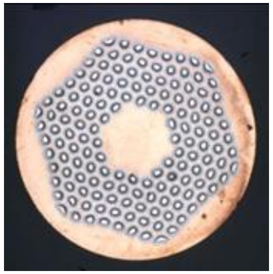
Operation margin can be increased by using wires with higher $J_c$ or operation at 1.9 K

# Strand and Cable

- Outer coil (layer 3 and 4)
  - Cable: Rutherford-type, 40-strands, 11mm wide 0.025 mm thick SS core
  - Strand: 0.7 mm RRP108/127
  - Cable available from 11 T Dipole program
- Inner coil (layer 1 and 2)
  - Cable: Rutherford-type, 28-strands, 11mm wide 0.025 mm thick SS core
  - Strand: 1.0 mm RRP150/169
  - ~450 m long cable piece is available
- Cable insulation
  - E-glass tape
  - 12.7mm wide 0.075 mm thick
  - 2 layers with ~50% overlap

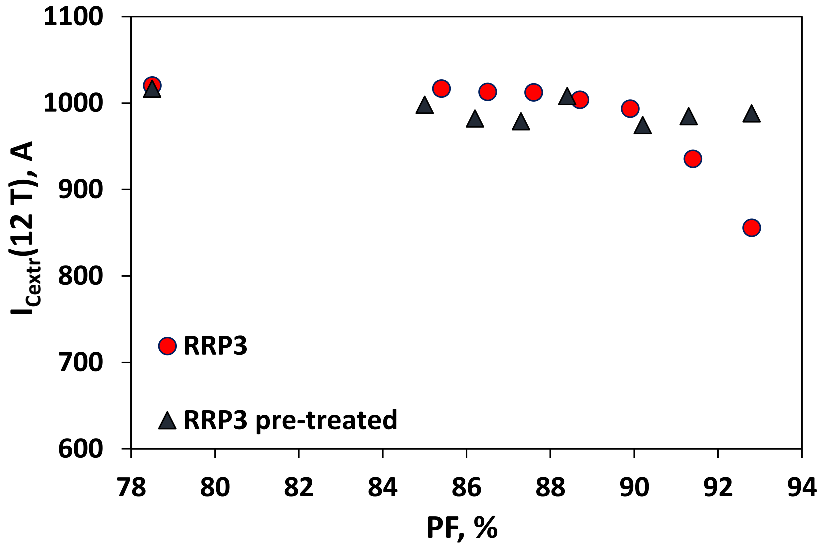


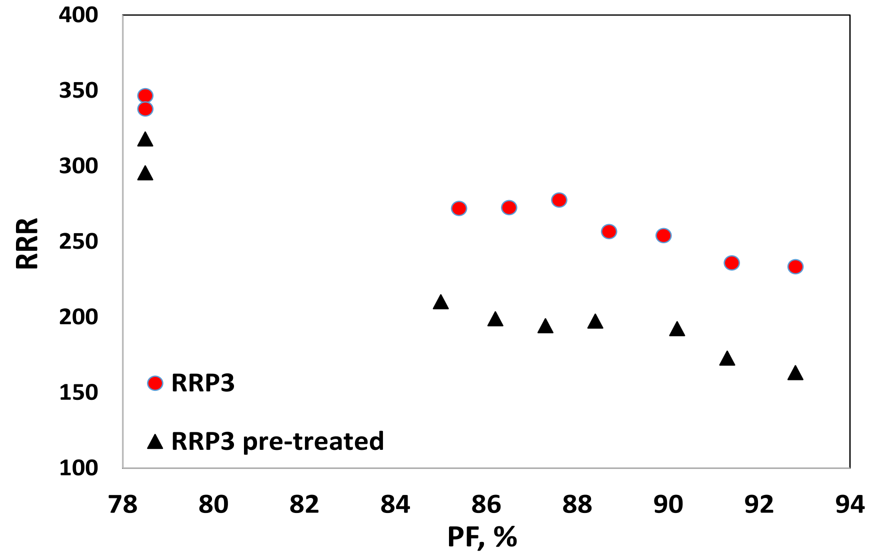
RRP108/127

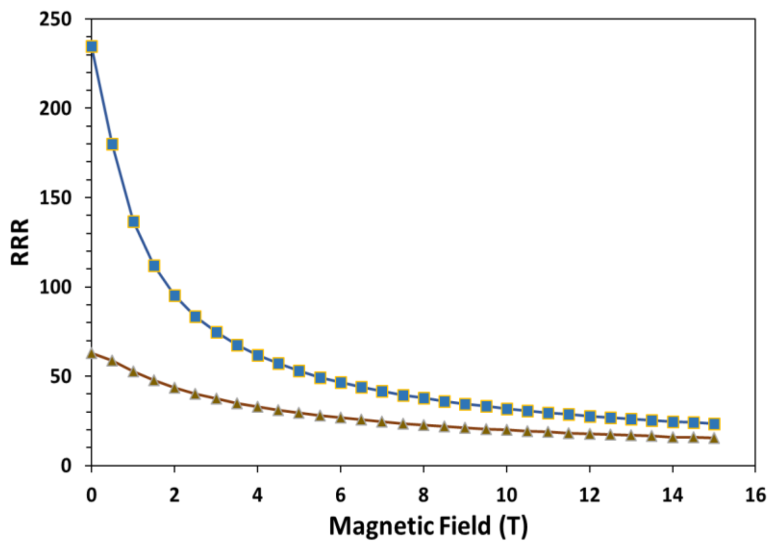


RRP150/169

# Cable performance optimization



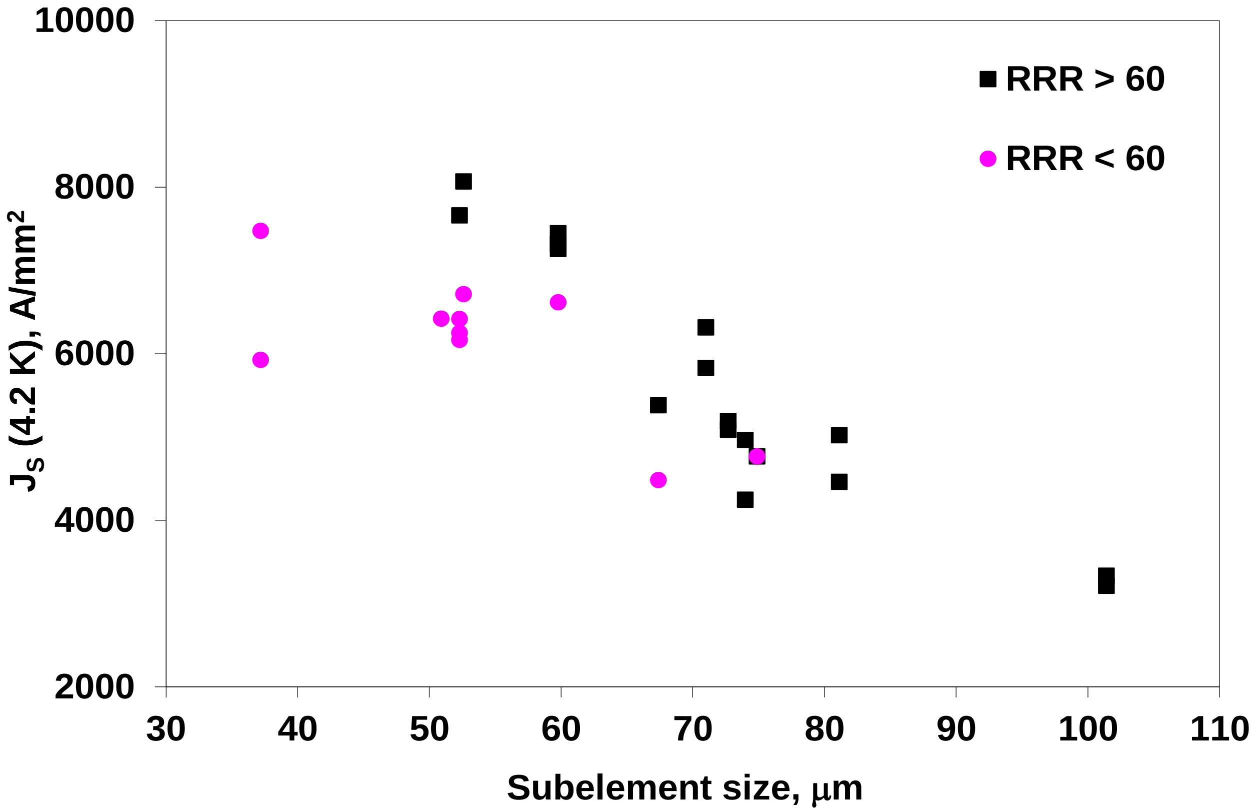




- Cable PF~87%
- $I_c$ degradation <4%
- RRR retention ~60-85%
- RRR at 15 T ~ always 20-30

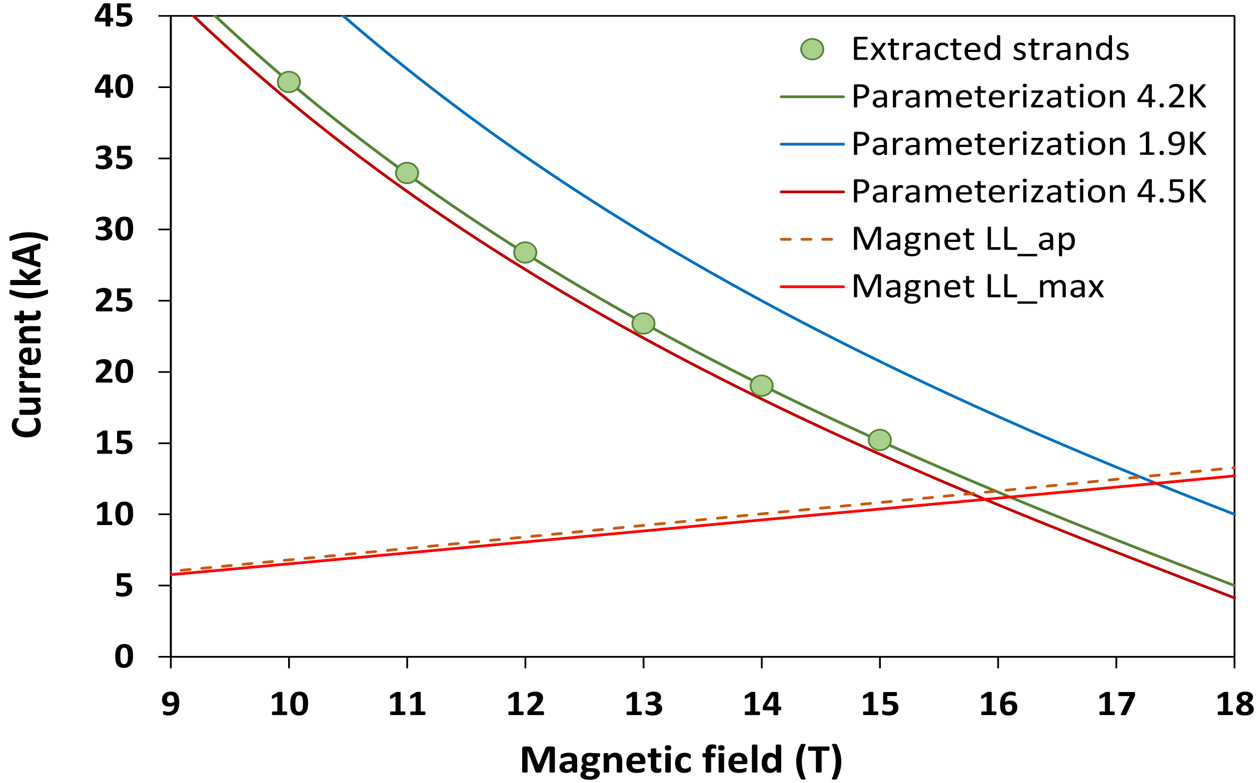
# A Prospectus of Parameters Effect on Stability

***$J_S$* (4.2K) vs. subelement size for RRP® round wires of 0.5 to 1 mm diameter. The samples in the *RRP*<60 set had *RRR* values down to 11 and *$J_c$(12T,4.2K)* between 2.45 and 2.92 kA/mm². The samples in the *RRR*>60 set had *RRR* values up to 300 and *$J_c$(12T,4.2K)* between 2.38 and 3.13 kA/mm².**



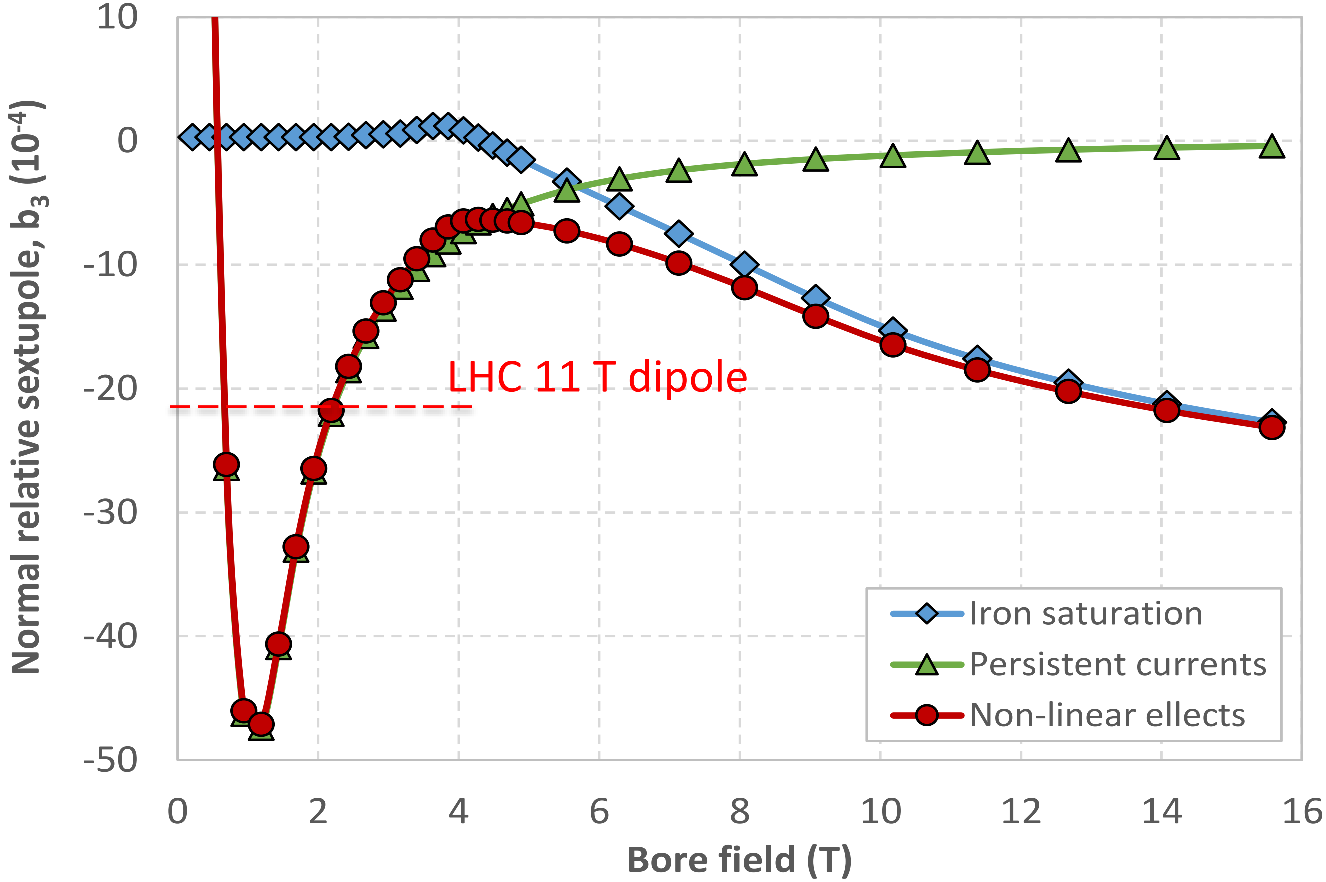

***"Research and Development of $Nb_3Sn$ Wires and Cables for High-Field Accelerator Magnets"*, Emanuela Barzi, Alexander V. Zlobin, REVIEW paper on PAC 50th anniversary issue, IEEE Transactions on Nuclear Science: http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=7410112&newsearch=true&queryText=2500440**

# Magnet Short Sample Limit




- Magnet short sample estimated based on the cable test data:
  - 11.1 kA ($B_{ap}$=15.3 T) at 4.5 K
  - 12.2 kA ($B_{ap}$=16.7 T) at 1.9 K

# Coil magnetization and iron saturation




Coil magnetization effect was calculated using RRP-150/169 1 mm strand and RRP-108/127 0.7 mm strand parameters

# RRP Strand R&D (with OST)

- Goal: increase $J_c$(15T) with an ultimate target of 2000 A/mm$^2$ for a 169 stack strand at 1.0 mm ($D_s$~58 µm)
  - the present subelement design - average $J_c$(15T)~1500 A/mm$^2$
- Approach: modifications to the subelement designs
- Chemical optimization
  - Produce a half height high-$J_c$ subelement billet having Nb and Nb-Ti filaments with a Nb-Ta diffusion barrier
  - Deliver ~45 kg of 1 mm wire
- Local Area Ratio (LAR) optimization
  - Produce two half height high-$J_c$ subelement billets having Nb and Nb-Ti filaments with variable LAR from annulus to barrier
  - Deliver ~90 kg of 1 mm wire
- Wire sample diameter: 0.8, 0.9, 1.0, 1.1 and 1.2 mm
- Next: 1-1.2 mm RRP-217 stack design.

# Conclusions

- R&D of 60-mm aperture 15 T $Nb_3Sn$ dipole demonstrator for future HC has started at Fermilab:
  - **Magnet design study phase is complete**
  - **Cable samples for the inner coils were fabricated and tested**
  - **Practice coils are being presently wound**
  - Magnet engineering design is in progress
  - Magnet fabrication and first tests are planned for 2016-2017
  - Schedule is coordinated with CERN FCC Design Study Report
- The work on optimization of $Nb_3Sn$ RRP wires for 15-16 T accelerator magnets continues in collaboration with industry and universities:
  - To produce further $J_c$ increase at 15 T
  - For larger wire D and smaller $D_{eff}$
  - Wire cost reduction through flux pinning enhancement research