Progress in High Field Superconducting Magnet Technology for Accelerators

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High Field Accelerator Magnets

Enabling technology *for the highest energy colliders:*

- High-Luminosity LHC, future hadron and muon colliders

Potential for ***transformational impact*** *on a range of applications:*

- ECR sources, heavy ion fusion, medical accelerators

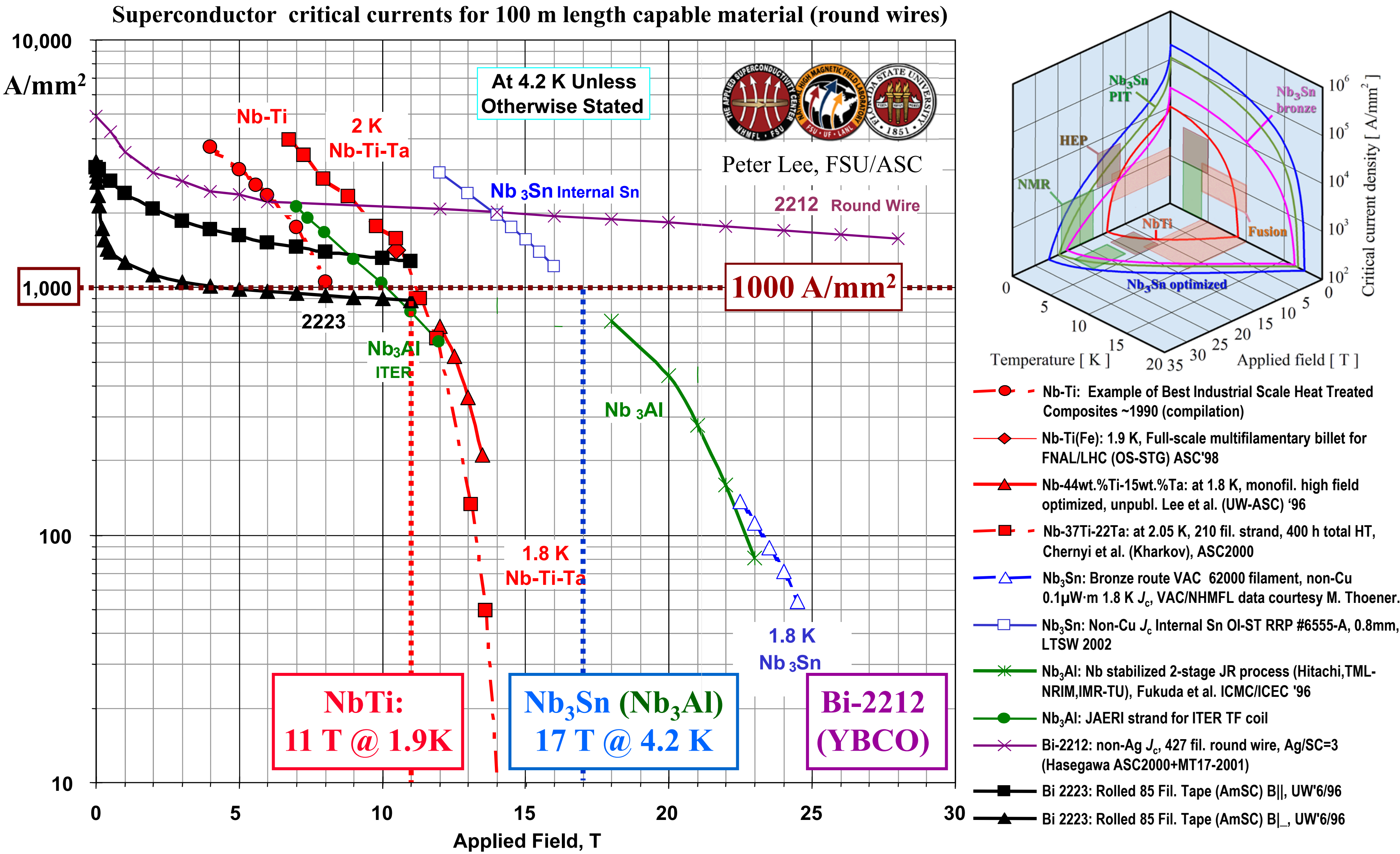
Challenges:

- Control of large forces and stresses
- Advanced superconductors are brittle and strain sensitive

R&D components:

- Development of cable and coil fabrication technology
- New concepts for mechanical support and magnet assembly
- Advances in modeling capabilities and diagnostic techniques

Conductor Options



Technology Challenges

Material	NbTi	Nb_3Sn (Nb_3Al)	Bi-2212	YBCO
Max Field	**10-11 T**	**16-17 T**	**Stress limited**	**Stress limited**
Reaction	**Ductile**	**~675^{0}C in Air/Vacuum**	**~890^{0}C in O_2 (±2^{0}C)**	**None**
Wire axial compression	**N/A**	**Reversible**	**Irreversible?**	**Reversible**
Transverse stress	**N/A**	**< 200 MPa**	**60 MPa?**	**≥ 150 MPa[1]**
Insulation	**All**	**S/E Glass**	**Ceramic**	**All**
Construction	**G-10, stainless...**	**Bronze/Titanium, Stainless**	**Super alloy**	**All**
Quench propagation	**>20m/s**	**~20 m/s**	**~0.05 m/s? (4.2 K, 8 T) [2]**	**~0.01 m/s? (4.2 K, self-field) [3]**

1. Cheggour *et al.*, IEEE TAS (2007) 17(2), pp. 3063 – 3066.
2. Trociewitz *et al.,* SuST 21 (2008) 025015.
3. Song and Schwartz, IEEE TAS (2009) 19(5), pp. 3735 – 3743.

Accelerator Magnet Development

Bi-2212
YBCO

Nb_3Sn

NbTi

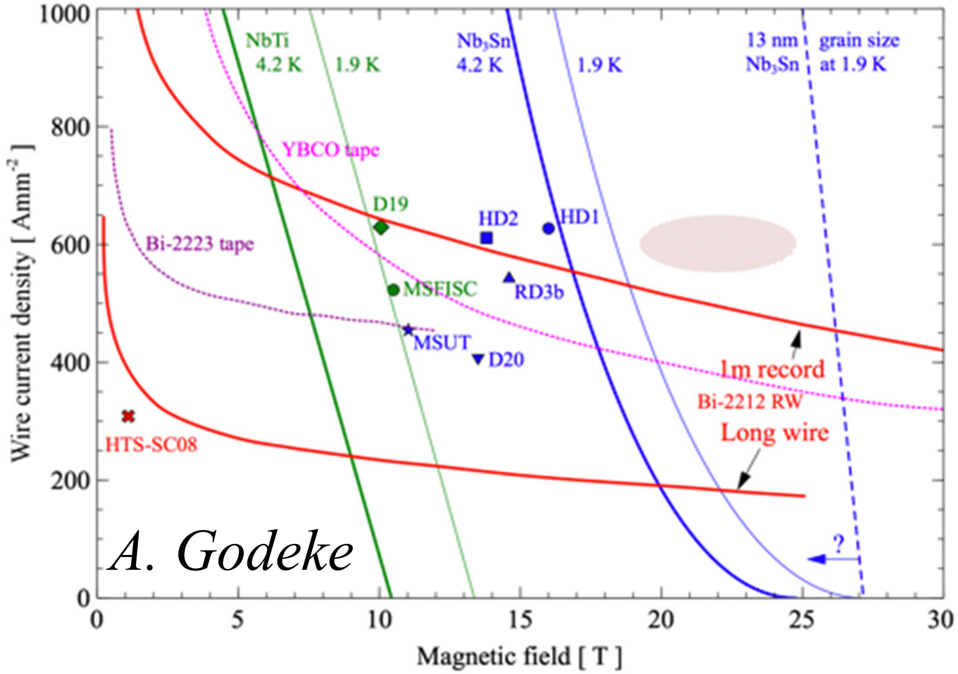
Technology foundation:

- *Conductor properties*
- *Fabrication methods*
- *Design concepts, tools*

Performance demonstration in simple configurations

Full qualification in accelerator configurations

System integration



In-depth analysis & optimization

- *Conductor properties*
- *Fabrication technology*
- *Material characterization*
- *Modeling and diagnostics*

High Luminosity LHC

Goals:

- *Precision measurements of Higgs properties*
- *Search for new physics at the energy frontier*
- *Figure of merit is* ***integrated*** *luminosity, with a target of 3000 fb*$^{-1}$

Required accelerator upgrades include new IR magnets:

- *Directly increase luminosity through stronger focusing*
  $\Rightarrow$ *decrease* β^*
- *Provide design options for overall system optimization/integration*
  $\Rightarrow$ *collimation, optics, vacuum, cryogenics*
- *Be compatible with high luminosity operation*
  $\Rightarrow$ *Radiation lifetime, thermal margins*

Higher field (11T) arc dipoles also required for collimation upgrade

LARP Magnet Program

Goal: **Develop Nb_3Sn quadrupoles for the LHC luminosity upgrade**

Potential for larger apertures and temperature margins

R&D phases:

- 2005-2010: technology development: conductor, coil, structure
- 2007-2012: length scale-up from 1 to 4 meters
- 2009-2014: incorporation of accelerator quality features

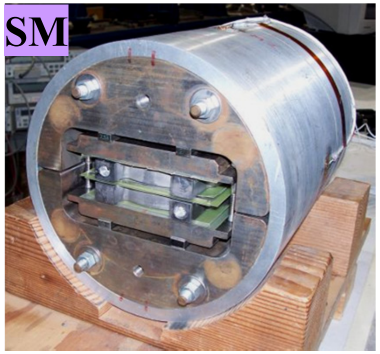
Program achievements to date:

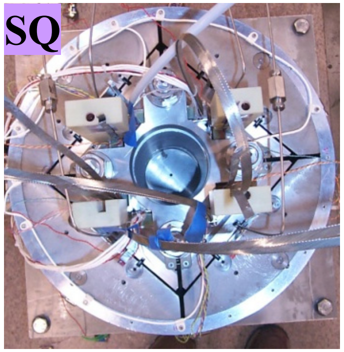
- TQ models (90 mm aperture, 1 m length) reached 240 T/m gradient
- LQ models (90 mm aperture, 4 m length) reached 220 T/m gradient
- HQ models (120 mm aperture, 1 m length) reached 184 T/m gradient

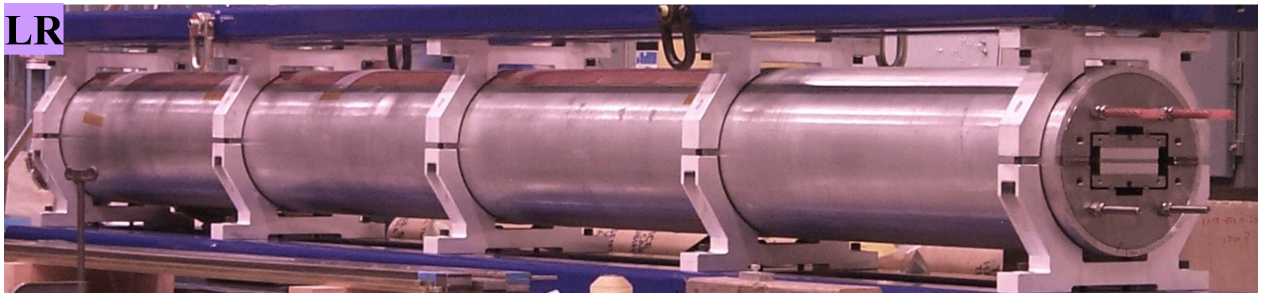
Current activities:

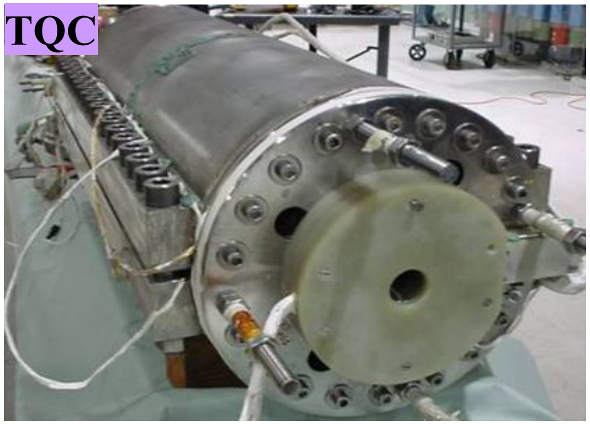
- Optimization of HQ, fabrication of LHQ coils and test in mirror
- Design and planning of the **MQXF** IR Quadrupole development

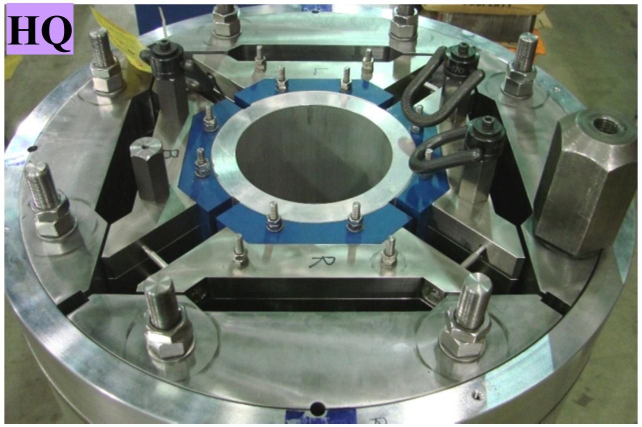
Overview of LARP Magnets











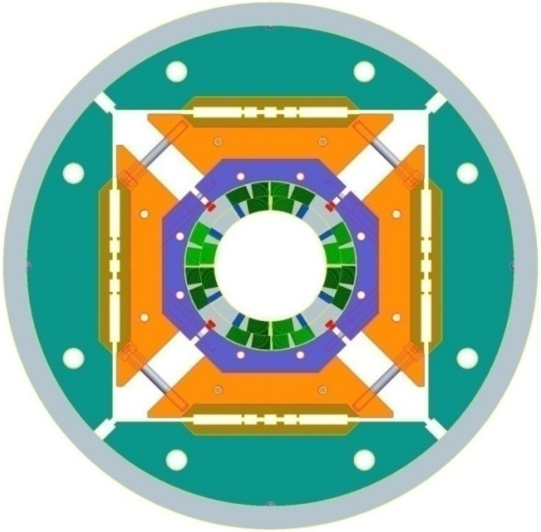
High-Field Quadrupole (HQ) Program

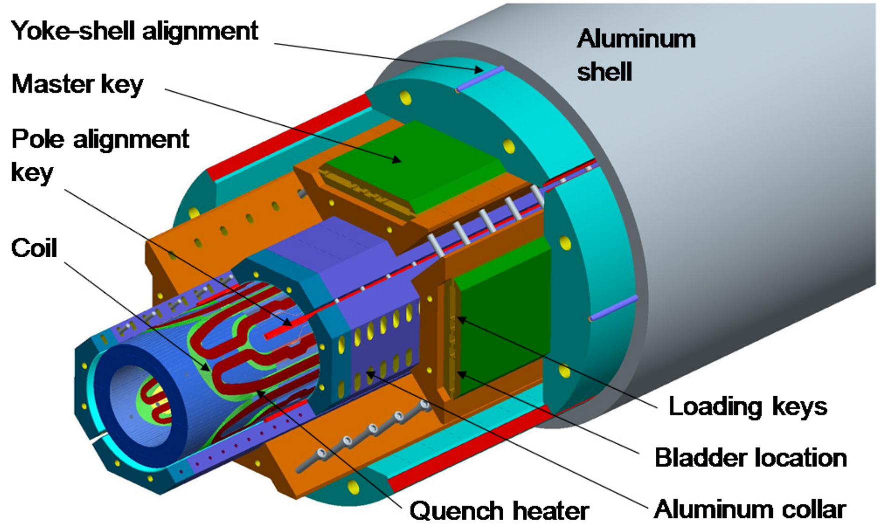
R&D goals:

- Explore larger apertures (optimal choice for HL-LHC IR)
  About three times energy and force levels than 90 mm quads
- Incorporate field quality and full alignment

Main parameters:

- 120 mm aperture, 15 T peak field at 220 T/m (1.9K)
- Coil stresses approaching 200 MPa (if pre-loaded for SSL)



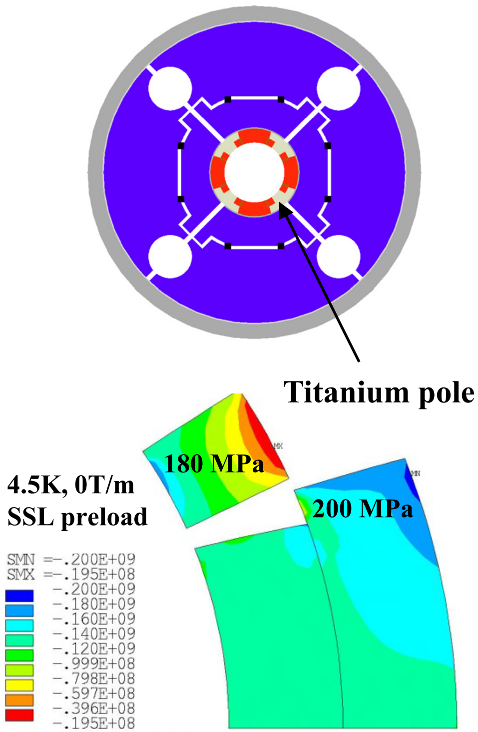


Handling High Stress in Magnet Coils

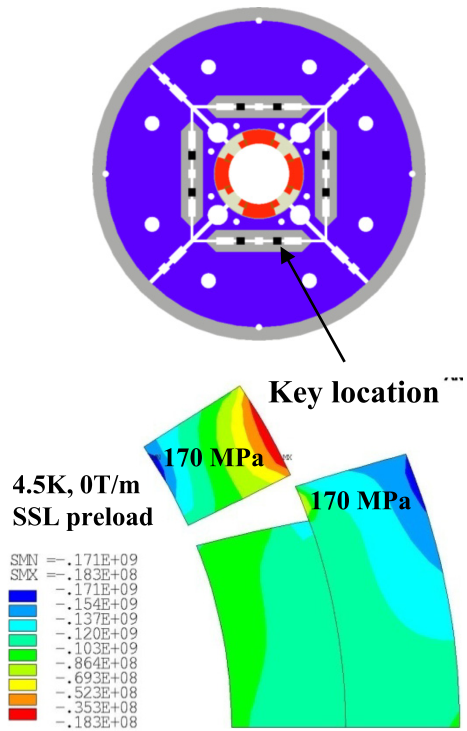
1. Understand limits

2. Optimize structure and coil for minimum stress

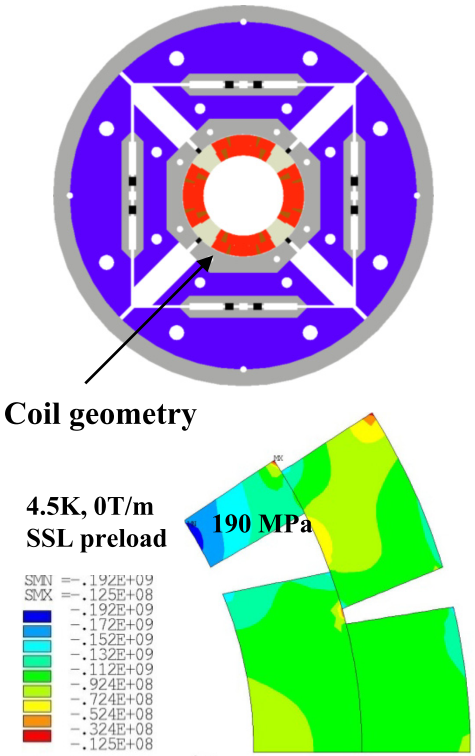
TQ (90 mm, ~12 T)



LQ (90 mm, ~12 T)



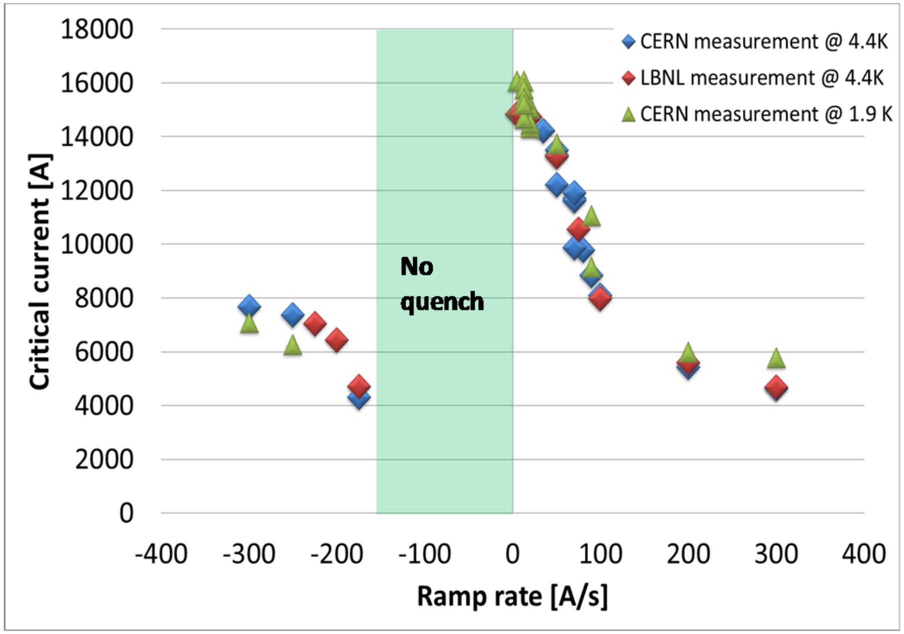
HQ (120 mm, ~15 T)

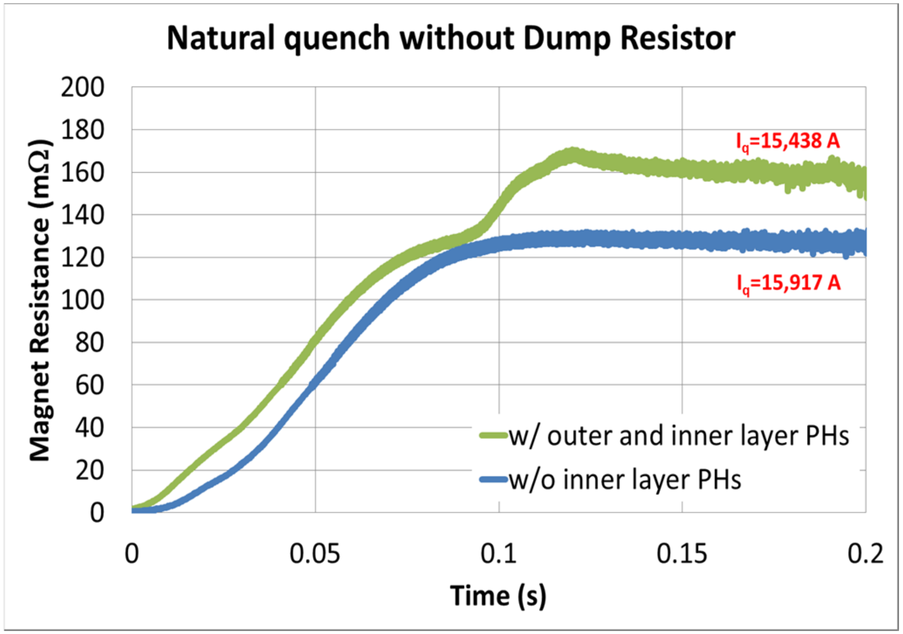


In parallel, a series of TQ tests with progressively increasing pre-load were performed, showing small performance degradation up to 200 MPa average coil stress

Quench Performance in HQ01 series

- Performed 5 magnet assemblies (a-e) and 8 tests (7 at LBNL and 1 at CERN)
- Achieved **184 T/m at 1.9K** (85% of SSL) – well above performance target
- ➢ *However, high rate of coil failures due to high strain and insulation weakness*
- Quench protection studies: energy extraction delay, then removal of IL heaters
- ➢ *No significant performance degradation was observed*



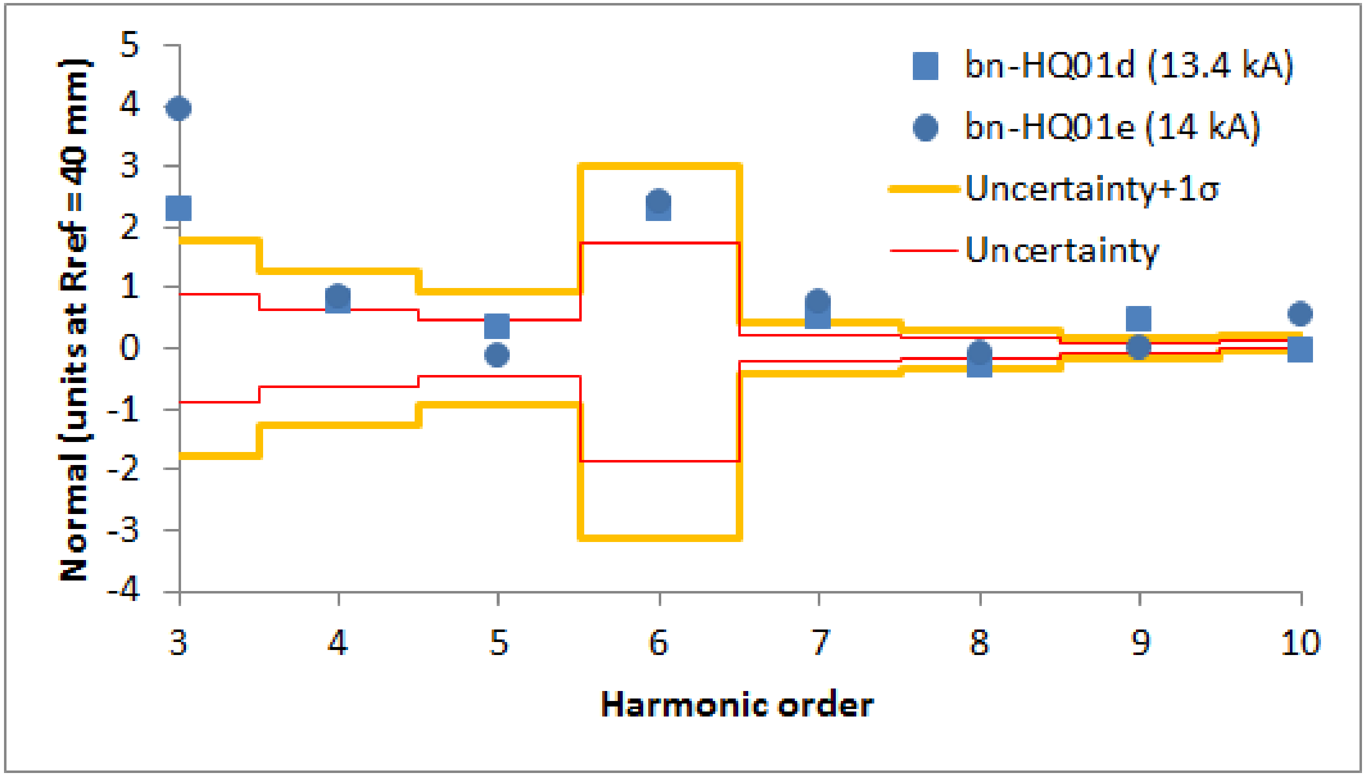


H. Bajas, M. Bajko, H. Felice, J. Feuvrier, M. Martchevsky, T. Salmi

Field Quality: Nb_3Sn vs. NbTi

Comparison between HQ01d/e normal harmonic at operational current (80% I_{ss}) with specs for MQXB “Phase 1” NbTi IR Quadrupoles (same aperture: 120 mm)

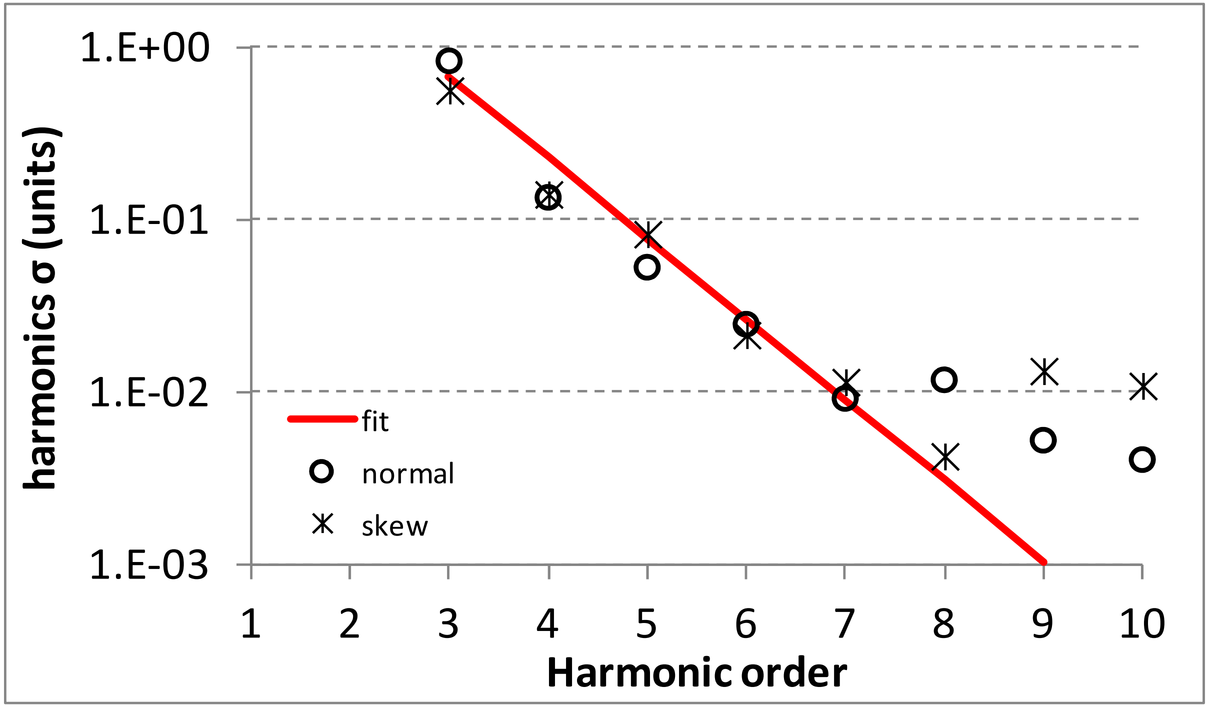
Reference: P. Fessia et. al, IEEE TAS, 2010 (20), p. 140



X. Wang

Fabrication tolerances and random errors

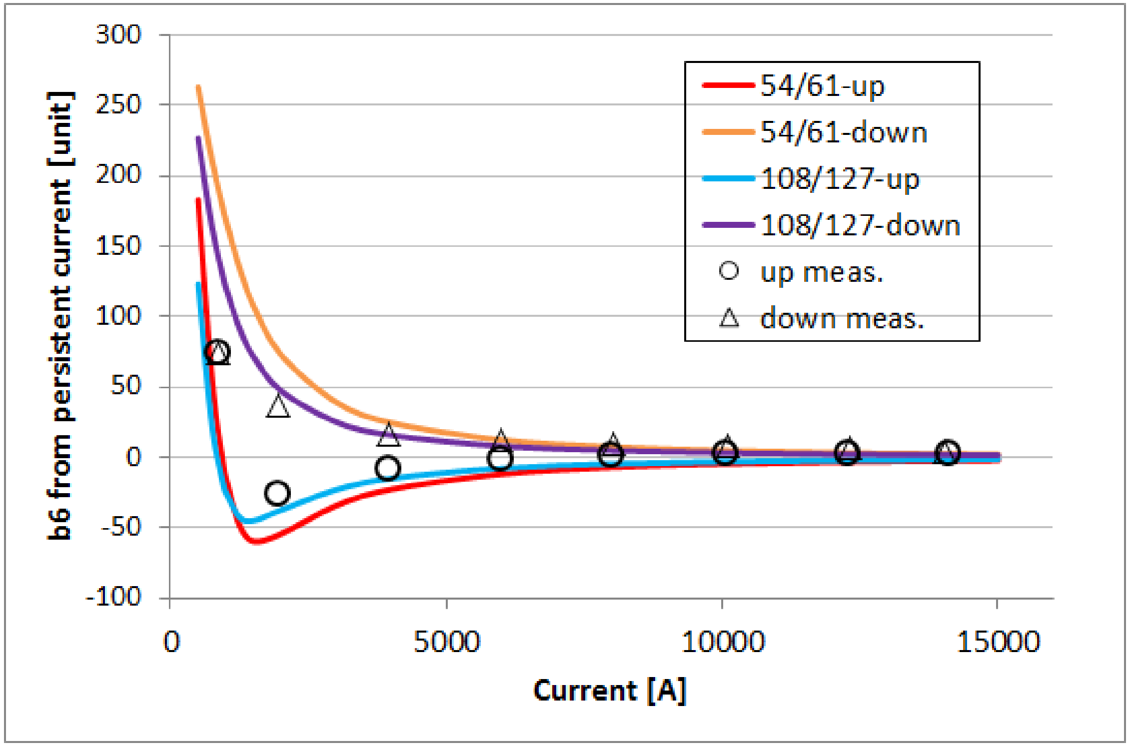
- Simulation of random errors due to coil fabrication tolerances fits HQ01 measured harmonics (n=3 to 7) for a **block positioning error of 30 μm**
- Flat dependance for n>7 attributed to limited probe sensitivity – a more accurate probe is being used for HQ02



X. Wang

Persistent current effects

- Large critical current density and effective filament diameter in Nb_3Sn
- Good general agreement between HQ01e measurements and calculations
- Acceptable for IR Quadrupoles, improvement needed for use in arc dipole



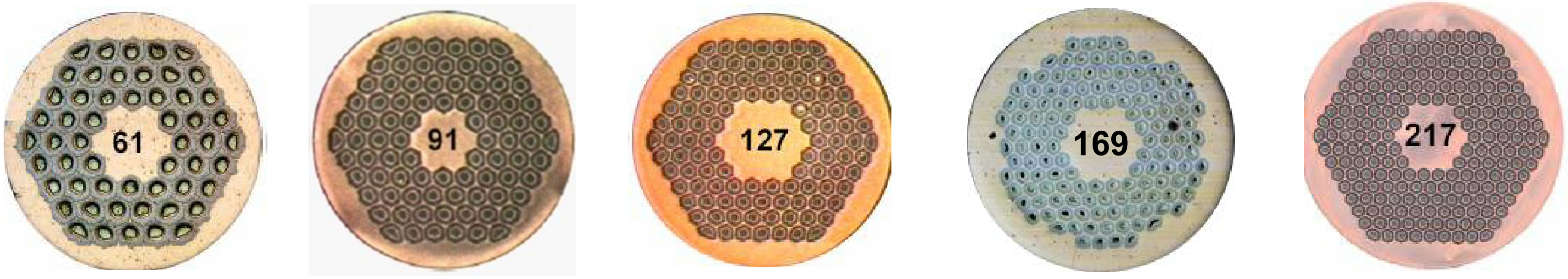
X. Wang

Nb_3Sn Conductor Development

Two leading processes:

- *Internal tin (US-OST-RRP) and powder in tube (EU-Bruker-PIT)*

A quasi-continuous range of "stacks" using fewer or more sub-elements



LARP initial | **[Fusion]** | **LARP current** | **HL-LHC, HE-LHC target**

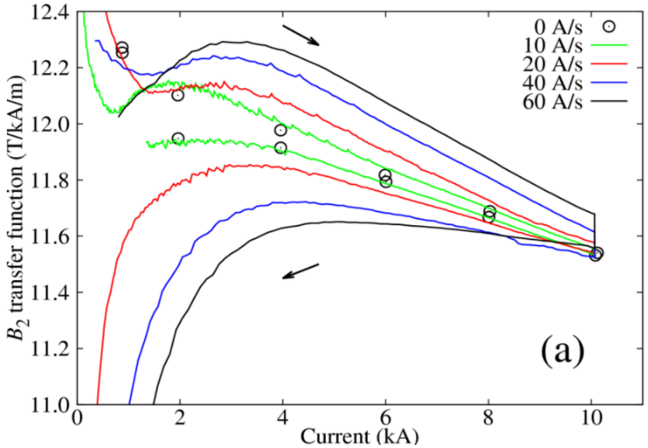
Low range: ☺ Better developed (high/controlled Jc/RRR; long pieces
☹ Larger filament size (magnetization effects, flux-jumps)

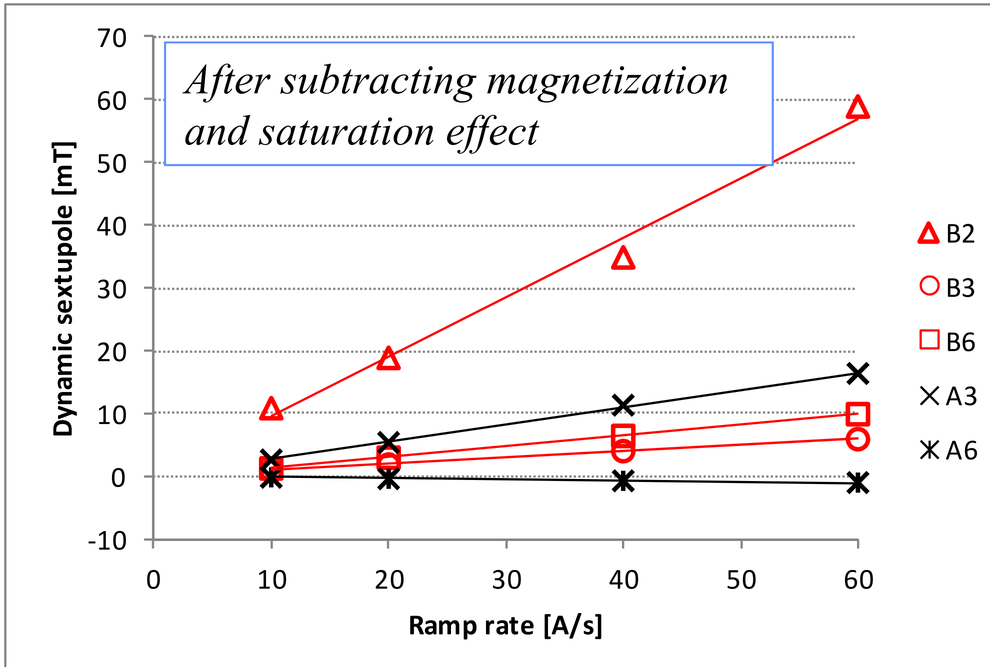
High range: ☺ Smaller magnetization effects and in principle more stable
(only if tolerance to cabling and reaction can be preserved)
☹ Less developed: control of properties, piece length

Dynamic effects

Large dynamic effects indicate need to better control inter-strand resistance

→ ***Cored cables*** *incorporated in second generation HQ coils*





Models fit measurements for $R_c = 0.2–3.6\ \mu\Omega$ (LHC target: ~20 $\mu\Omega$)

Detailed analysis of dynamic effects and correlation with flux-jumps in presentation THPME049 (X. Wang et al.) Thursday 4 – 6 PM

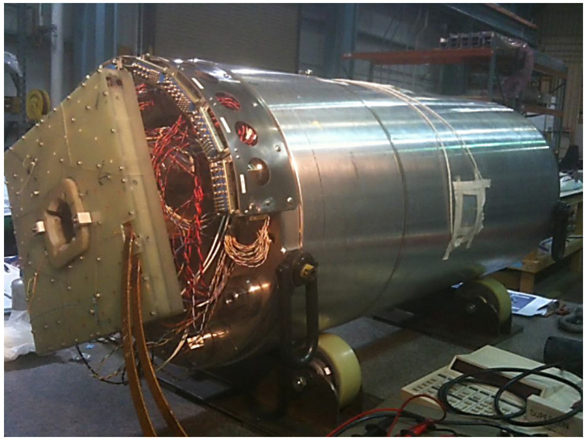
HQ02a Model

Incorporates many critical improvements in cable and coil design and fabrication:

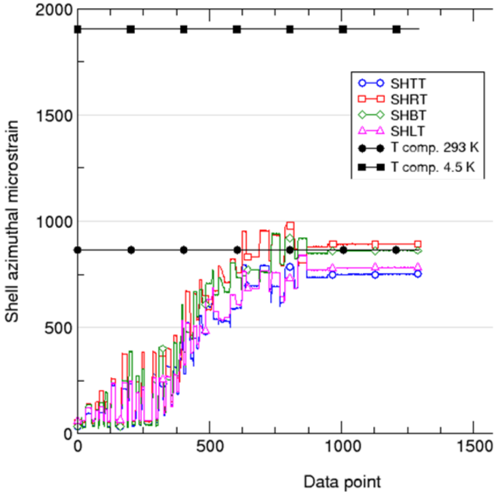
- *Cored cable, decreased compaction, redesigned parts, more robust insulation*

Very positive initial feedback from single coil test in magnetic mirror structure

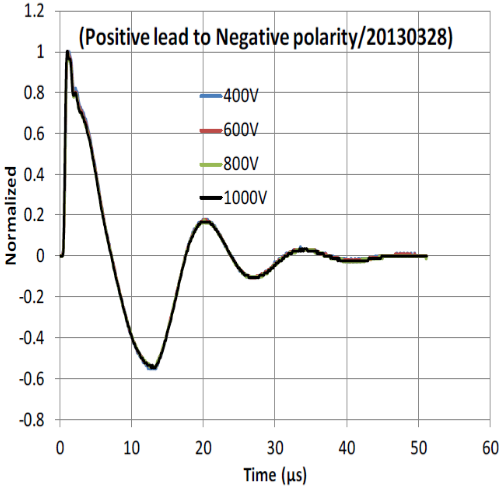
Assembled HQ02a magnet



HQ02a pre-load



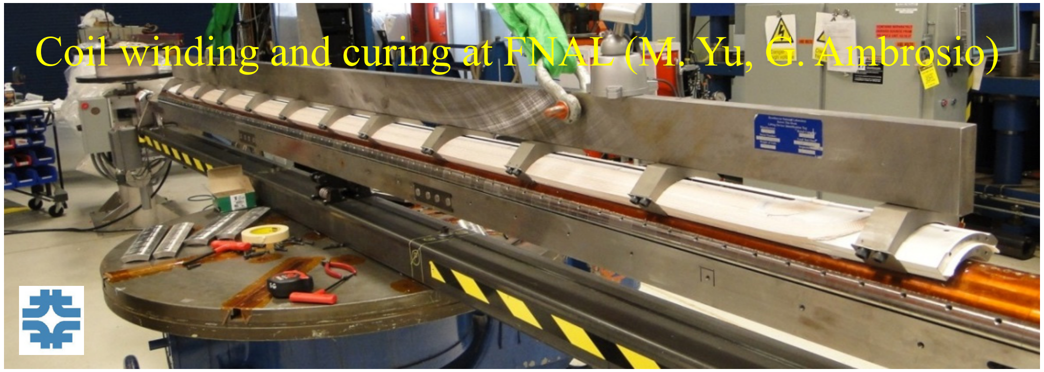
HQ02a impulse test

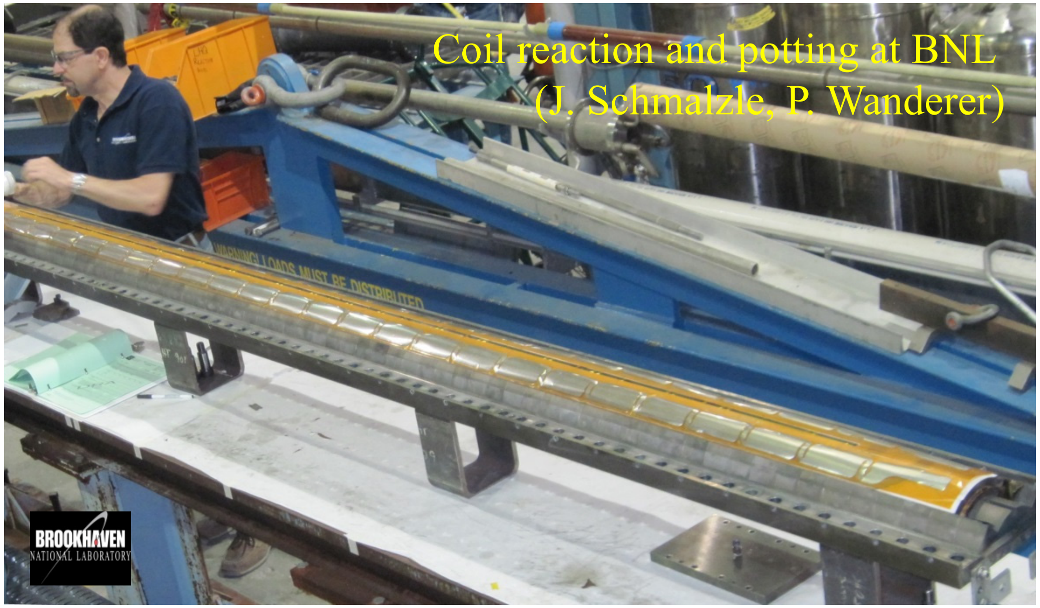


F. Borgnolutti, D. Cheng, H. Felice, M. Martchevsky, P. Roy, J. Schmalzle

- HQ02a is currently being tested at Fermilab
- Completed cool-down and system checks: <u>first high field quenches expected today</u>

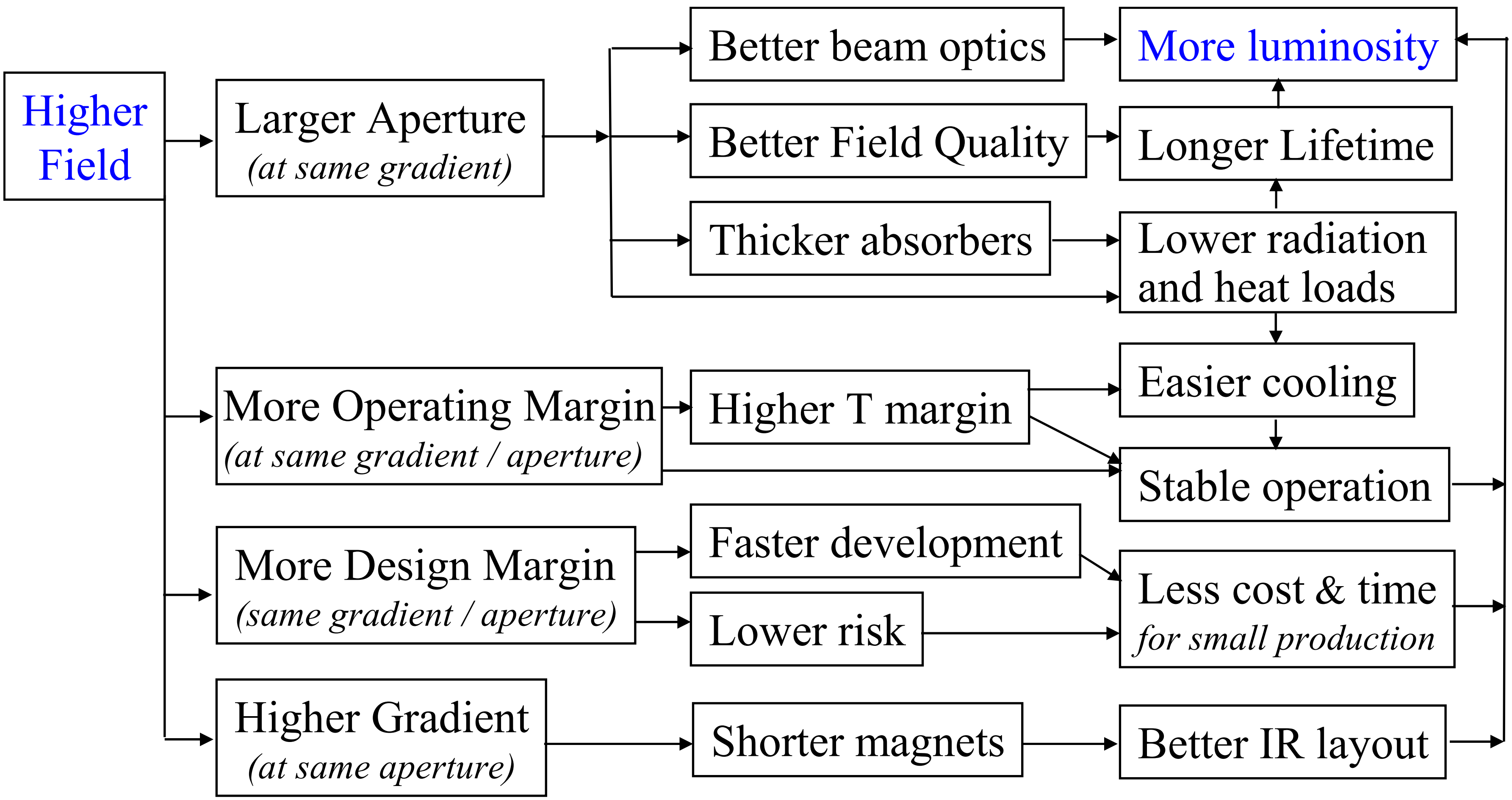
HQ Scale-up: LHQ Coil Fabrication





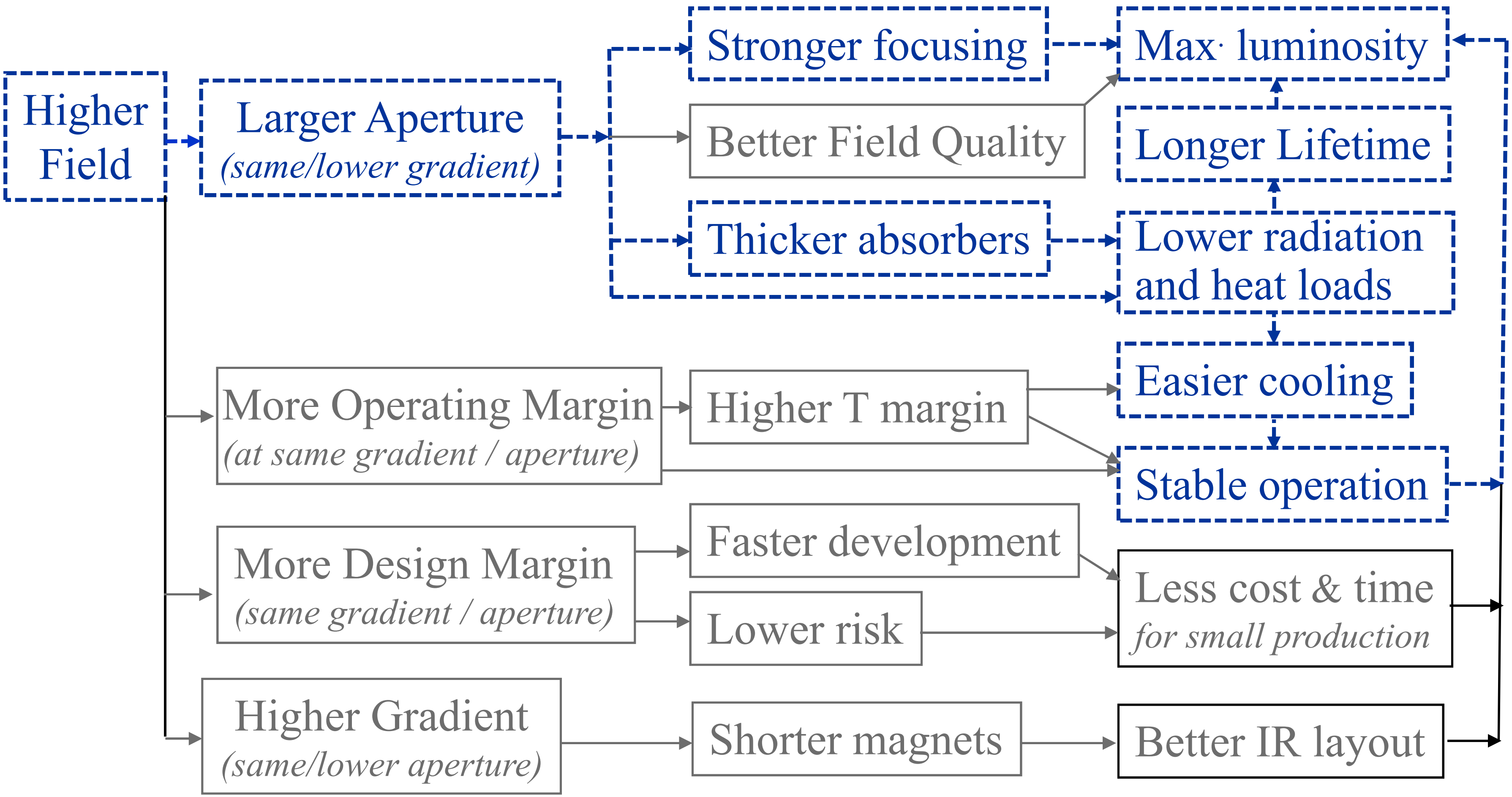
Quadrupoles for the LHC Phase 2 Upgrade

High field technology provides design options to maximize luminosity



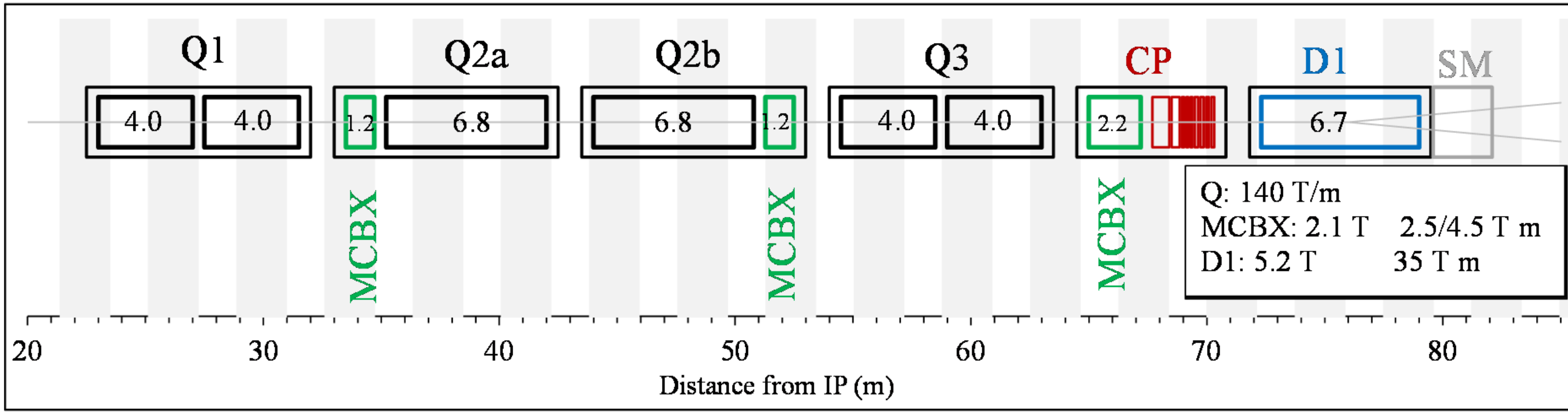
IR Quadrupole Design Specification

An aperture increase to 150 mm is expected to result in best overall performance



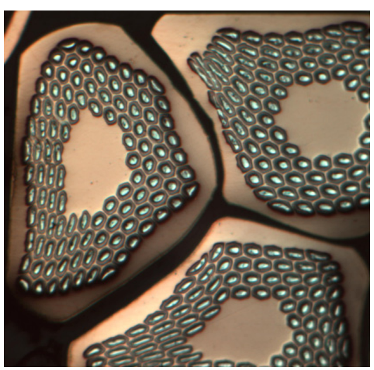
HL-LHC IR Design Status

Developed a complete IR layout based on 150 mm quadrupoles:

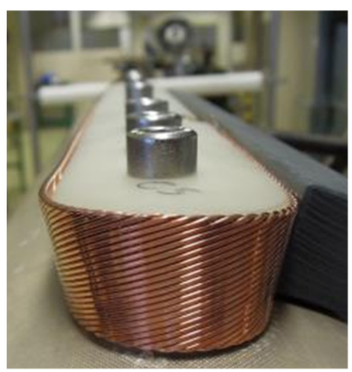


E. Todesco

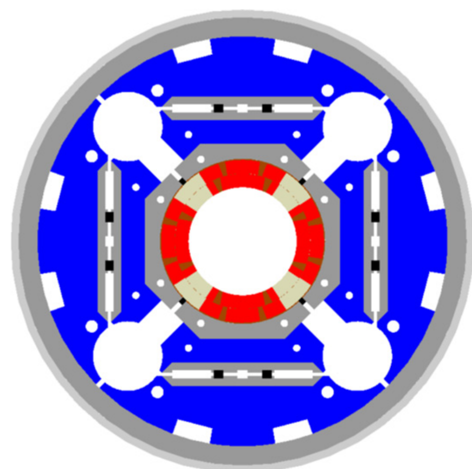
QXF design started:



Cable optimization



Winding tests



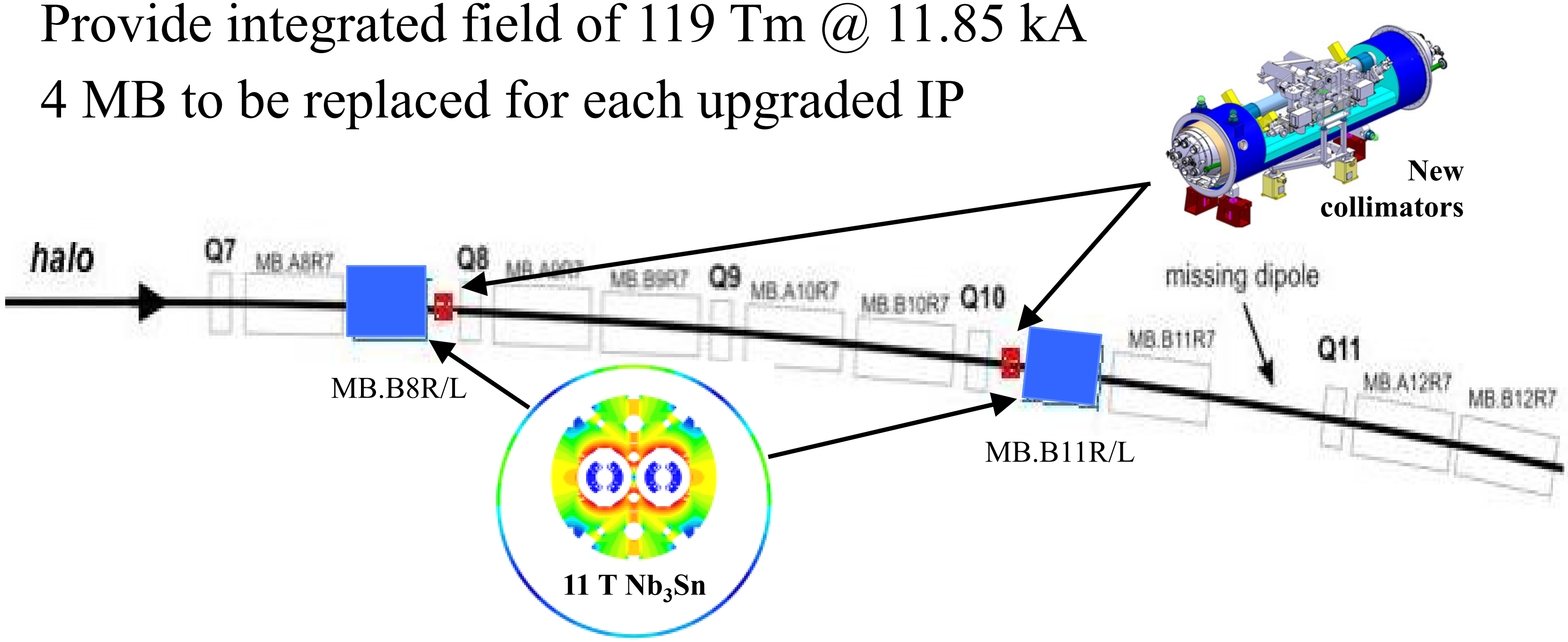
Magnetic and mechanical design

P. Ferracin, G. Ambrosio, D. Dietderich, A. Ghosh, F. Borgnnolutti, S. Bermudez, et al.

Nb_3Sn Dipoles for LHC DS Upgrade

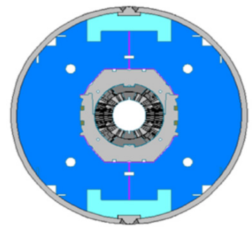
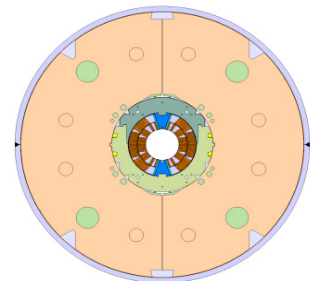
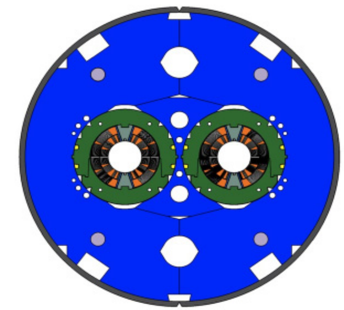
Goal:

- Create space for additional (cryo) collimators by replacing 8.33 T MB with 11 T Nb_3Sn dipoles compatible with LHC lattice & main systems
- Provide integrated field of 119 Tm @ 11.85 kA
- 4 MB to be replaced for each upgraded IP



- Under development as a collaboration between CERN and FNAL

11 T Design Parameters

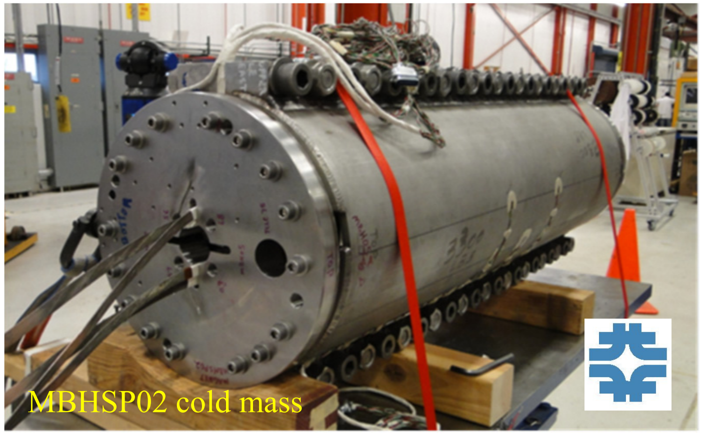
Parameter	Single-aperture FNAL 	Single-aperture CERN 	Twin-aperture 
Aperture	**60 mm**		
Yoke outer diameter	**400 mm**	**510 mm**	**550 mm**
Nominal bore field @11.85 kA	**10.86 T**	**11.25 T**	**11.25 T**
Short-sample bore field at 1.9 K	**13.6 T**	**13.9 T**	**13.9 T**
Margin B_{nom}/B_{max} at 1.9 K	**0.80**	**0.81**	**0.81**
Stored energy at 11.85 kA	**473 kJ/m**	**484 kJ/m**	**969 kJ/m**
F_x per quadrant at 11.85 kA	**2.89 MN/m**	**3.16 MN/m**	**3.16 MN/m**
F_y per quadrant at 11.85 kA	**-1.57 MN/m**	**-1.59 MN/m**	**-1.59 MN/m**

M. Karppinen, A. Zlobin

Model magnet development

Two models (1 and 2 meter long) fabricated and tested at Fermilab:

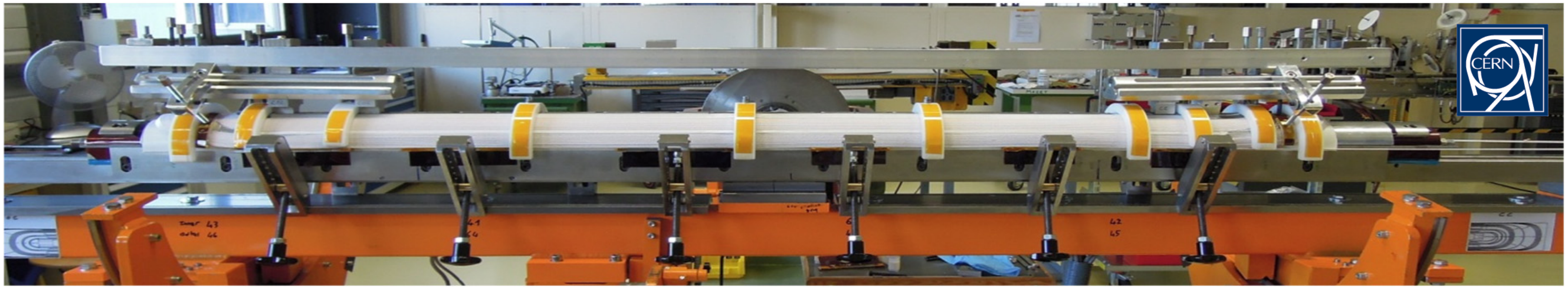
- Tested in June 2012 and April 2013
- Reached 11.7 T at 1.9 K



IPAC 2013 presentation:

- THPME044 *(A. Zlobin et. al)*
- Thursday, 4-6 PM

Model magnet development is also underway at CERN



Very High Energy Hadron Colliders

Several studies in the US over the last two decades:

- 1994 DPF Workshop (T30) 60 TeV; 10^{34} cm^{-2}s^{-1}; 12.5 T; 60 km
- Snowmass ‘96 Low-field 100 TeV; 10^{34} cm^{-2}s^{-1}; 1.8 T; 646 km
- Snowmass ‘96 High-field 100 TeV; 10^{34} cm^{-2}s^{-1}; 12.6 T; 104 km
- Staged VLHC Phase I 40 TeV; 10^{34} cm^{-2}s^{-1}; 2 T; 240 km
- Staged VLHC Phase II 175 TeV; 2×10^{34} cm^{-2}s^{-1}; 10 T; 240 km

Two CERN studies in recent years:

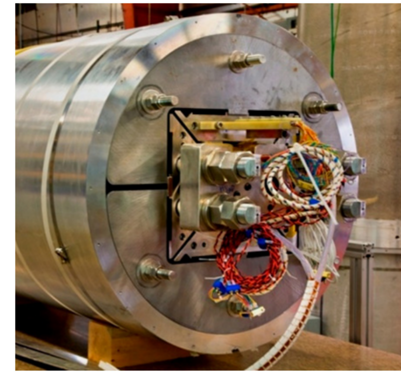
HE-LHC	VHE-LHC
LHC tunnel: 27 km	New tunnel: 80 km
E_{CoM} = 33 TeV	E_{CoM} = 84-104 TeV
L = 5×10^{34} cm^{-2}s^{-1}	L = 5×10^{34} cm^{-2}s^{-1}
B = 20 T	B = 16-20 T

High Field Dipole Development

Two design approaches have reached >13 T using Nb_3Sn

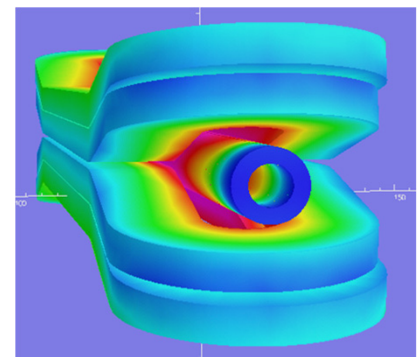
Comparison of key features	Cos(θ)	Block
Maximum dipole field achieved	13.5 T (D20, 1996)	13.8 T (HD2c, 2007)
Cable design	Keystone	Rectangular
Internal bore support	Self supporting	Required
Minimum winding radius	Small	Small
Conductor efficiency	Large aperture	Small aperture
2-in-1 arrangement	Horizontal	Horizontal
2-in-1 pre-load	1x	1x
High field/stress locations	Combined	Separated
Coil width/layer	Cable width	No. turns
Grading efficiency	Low	High
End peak field	High	High
End design/winding	Saddle	Flat or Flared
Layer transition	High field	High field

HD2 and HD3 Dipoles



HD2 dipole:

- Two assembly configurations with 36 or 43 mm bore
- Flared ends (based on LBNL "D10" dipole design)
- Optimized for geometric and saturation harmonics
- Achieved 13.8 T bore field, 14.5 T peak field
- Limited by localized quenches at hard-way bends

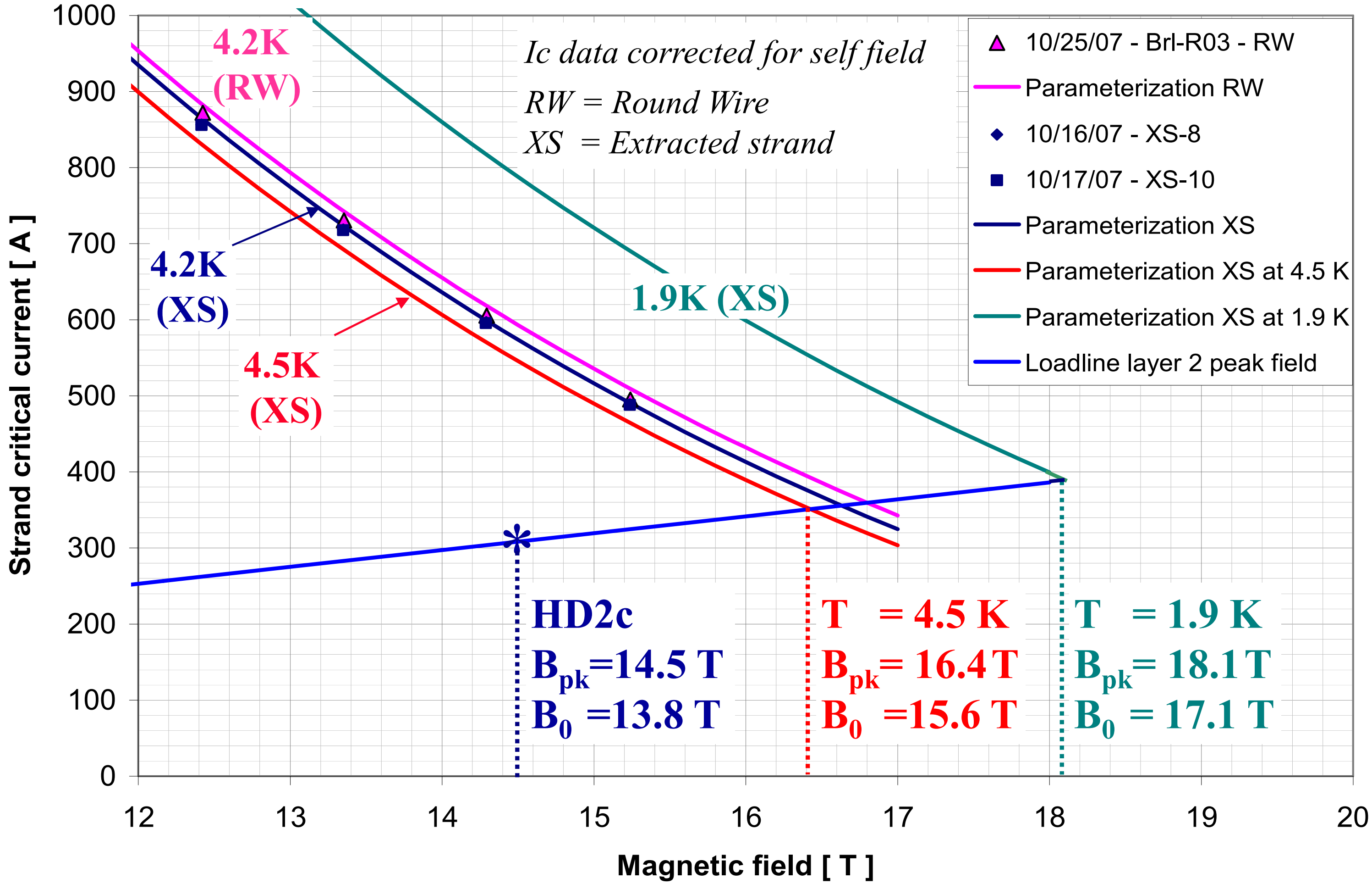


HD3 dipole:

- Design modification based on HD2 analysis
- New cross-section, end design, coil fabrication
- However, no performance improvement in first tests

Field Limits in Nb_3Sn Block Dipoles

- HD2: 17.1 T SSL at 1.9K may provide 14 T operating field (82%)
- A graded coil may provide +1T at the cost of additional complexity

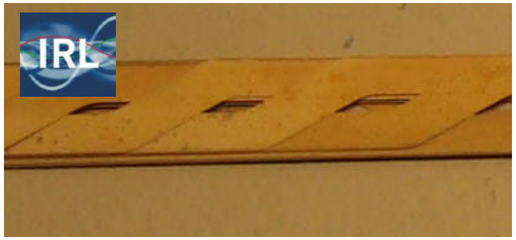


Beyond Nb_3Sn: HTS Technology

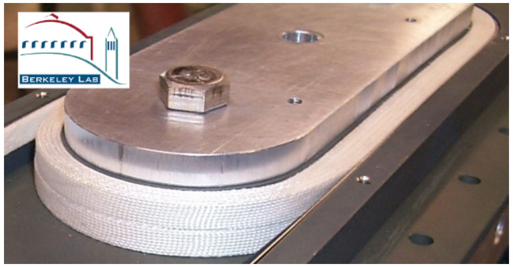
A sustained, long-term effort is required to establish the feasibility of high-field accelerator magnets using HTS materials:

- *Conductor: current density, strain dependence, magnetization, cost*
- *Fabrication of high current cables, especially for YBCO tapes*
- *Simple coils to be tested standalone or in background field*
- *Nested windings, mechanical support, protection of hybrid HTS/LTS*

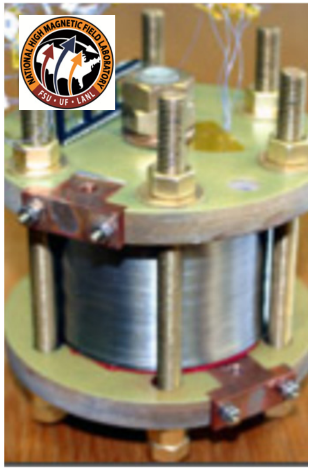
Conductor and cable



Dipole coils/inserts



Solenoid coils/inserts

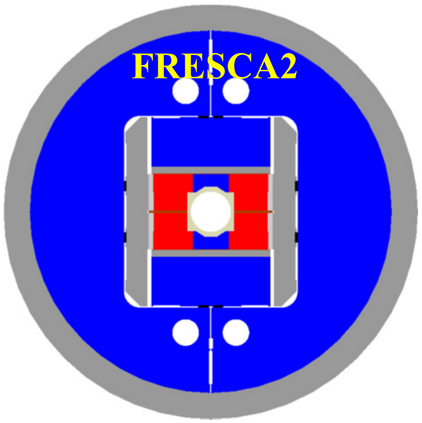


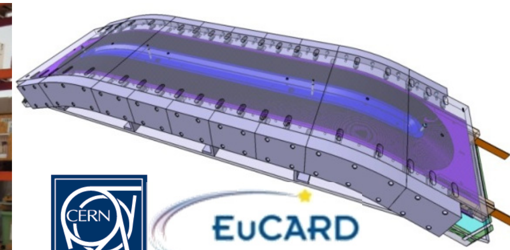
Bi2212: OST; YBCo:Superpower

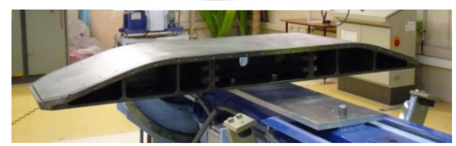
Large Dipoles for High-Field Testing

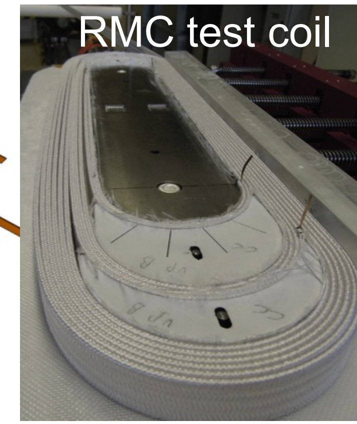
- *FRESCA2 @ CERN, 100 mm round bore*
- *LD1@ LBNL, 140x100 mm square bore*
- *Both designs are based on HD2 layout: block-coil with flared ends*

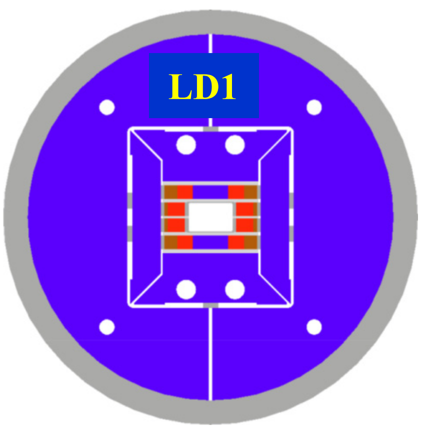
P. Ferracin et al.

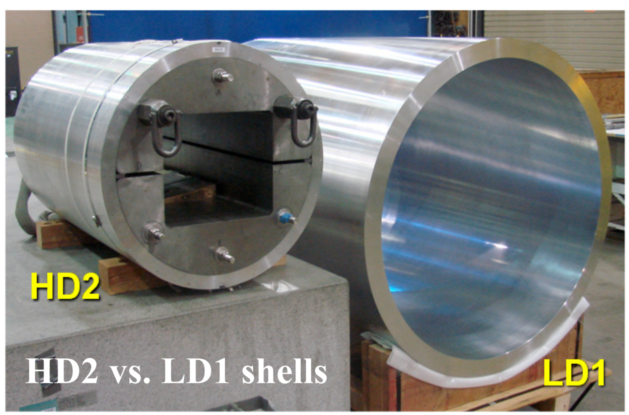










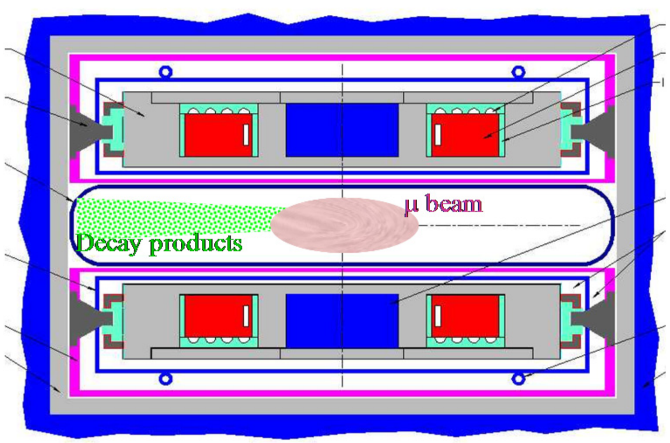


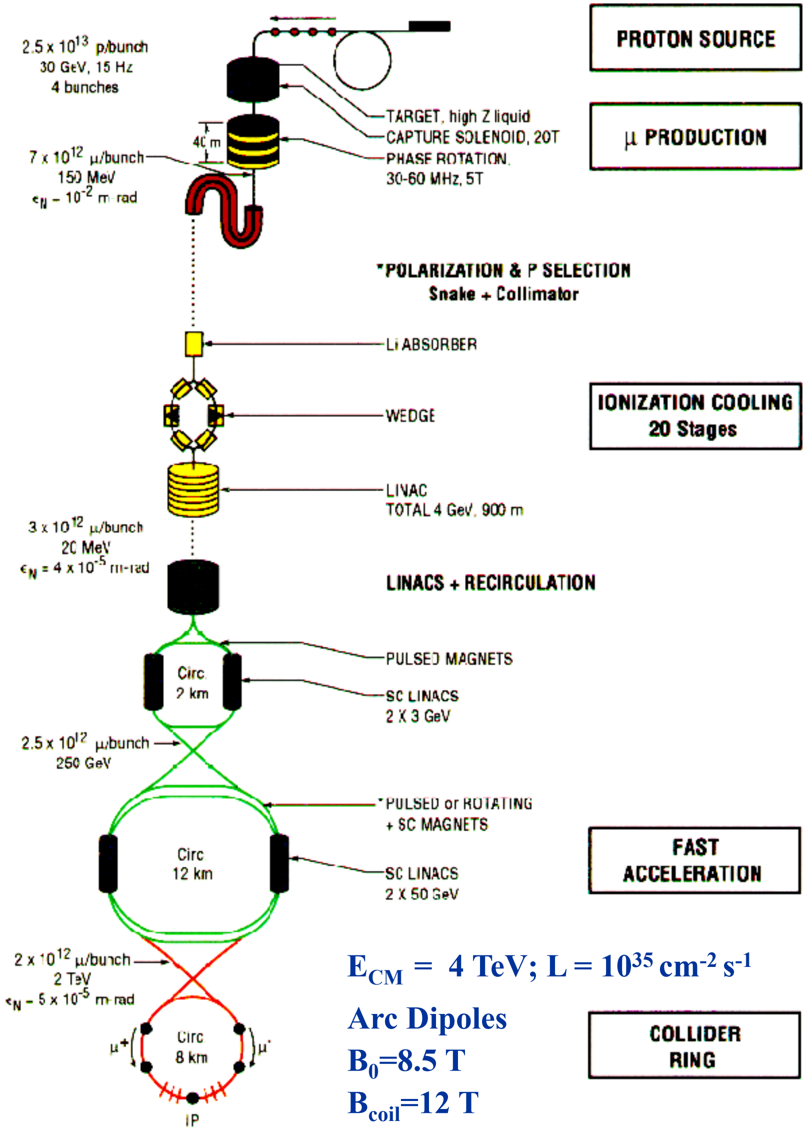
Muon Collider

<u>Key challenges</u>:

- Very high field solenoids for muon cooling
- Large aperture and/or open mid-plane dipoles for the collider

These needs are consistent with current Nb_3Sn & HTS technology development, integrated with MC specific studies and developments





E_{CM} = 4 TeV; L = 10^{35} cm^{-2} s^{-1}

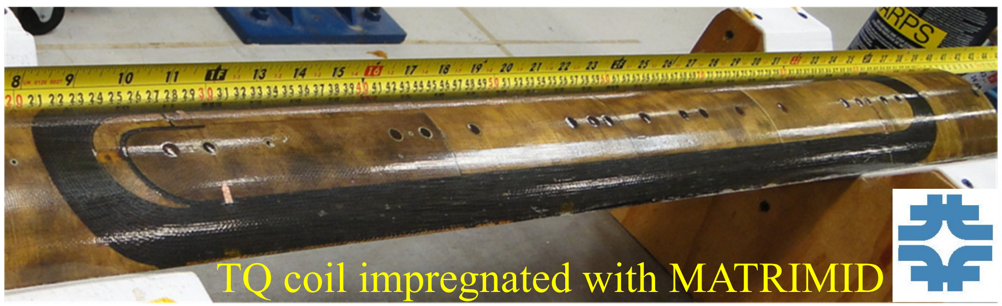
Arc Dipoles

B_0=8.5 T

B_{coil}=12 T

Development of Radiation Resistant Epoxy

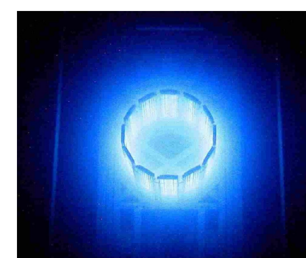
- The Muon Collider, HL-LHC & other future applications of high-field accelerator magnets require operation in a high radiation environment
- Epoxy resin is weakest element in present-generation model magnets
- Two main candidate rad-hard epoxies, Cyanate ester and MATRIMID


TQ coil impregnated with MATRIMID

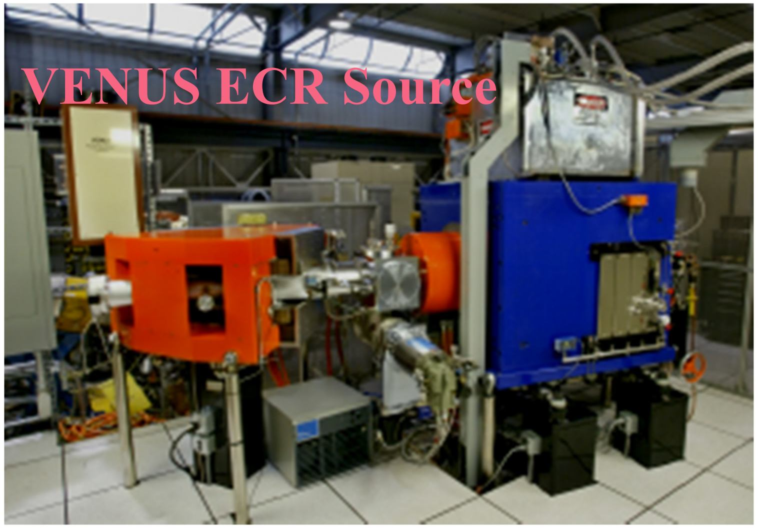
- Successful test of a TQ coil impregnated with MATRIMID at Fermilab
- *IPAC 2013 presentation: THPME045 (A. Zlobin et al, Thursday, 4-6 PM)*
- Impregnation of longer coils underway in the frame of the 11 T program

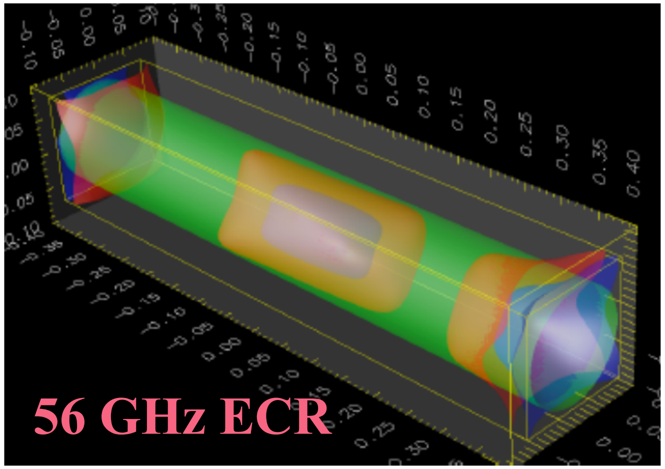
Irradiation + characterization studies in EU & Japan

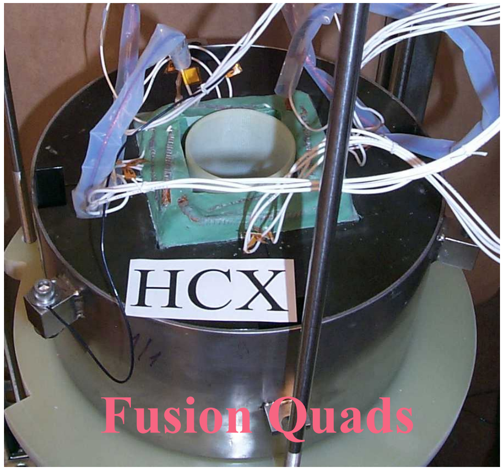

JAEA-Takasaki

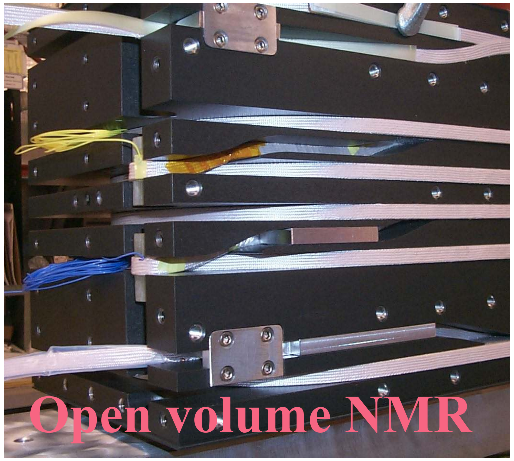


Applications beyond high energy colliders



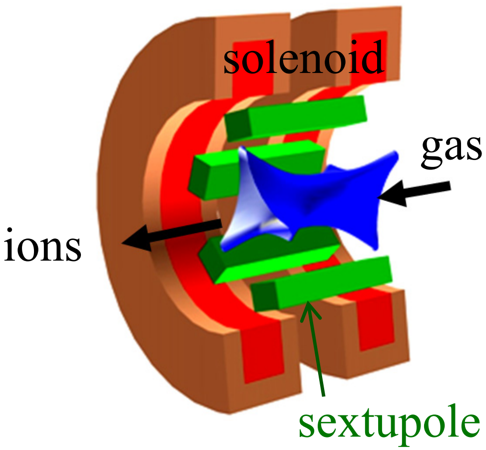






HEP technology applied to nuclear physics, fusion energy, light sources

56 GHz ECR Ion Source Development



Resonant electron heating

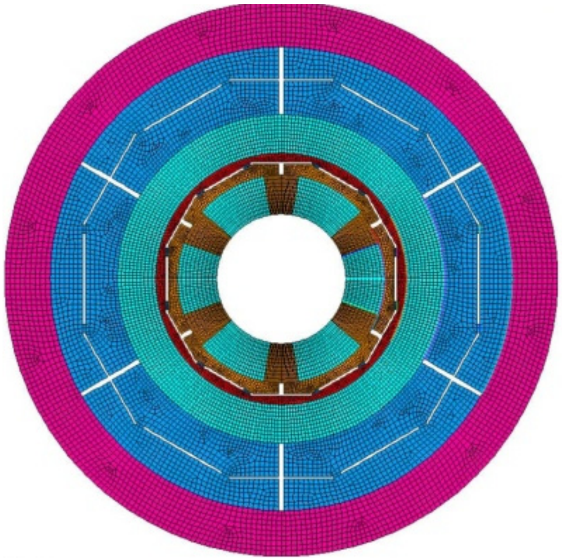
$$\omega_e = \frac{e \cdot B}{m} = \omega_{rf}$$

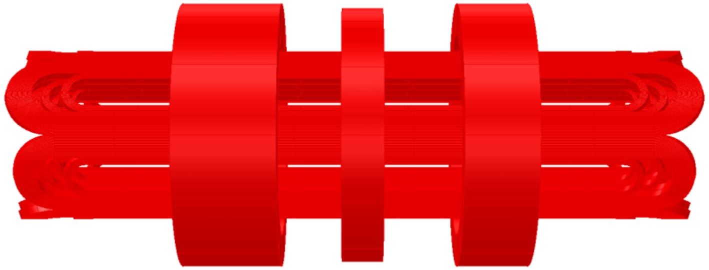
$$n_e \propto \omega_{rf}^2$$

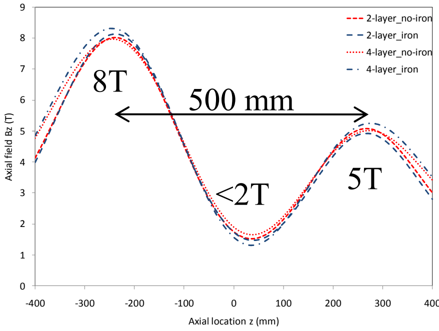
$$q_{opt} \propto \log \omega^3$$

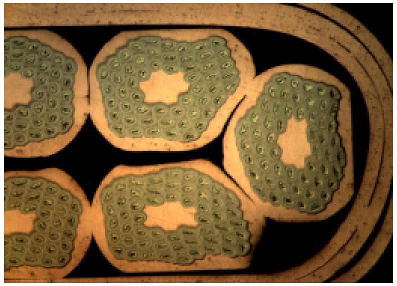
- Ion current scales as square of microwave frequency
- Confinement field scales linearly with frequency

Using LARP-HQ cable!









Summary

- Strong collaboration network among magnet programs
- Demonstrated the fundamental aspects of Nb_3Sn technology:
  - *Conductor & structure performance, length scale-up*
- Complete engineering toolbox and fabrication capabilities
- Nb_3Sn technology selected as baseline for the HL-LHC IR
- Developing high field dipoles with accelerator quality features
- Progress with HTS material & technology development
- Applications in nuclear science, medicine, fusion energy

Acknowledgement

BNL CEA CERN FNAL KEK LBNL NHMFL TAMU UT