International Accelerator School: Superconducting Science and Technology for Particle Accelerators

Canadian Light Source | Centre canadien de rayonnement synchrotron

Superconducting Magnets 2

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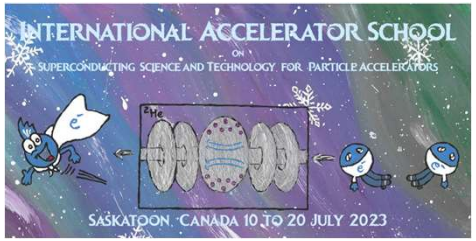
Lawrence Berkeley National Laboratory

IAS 2023

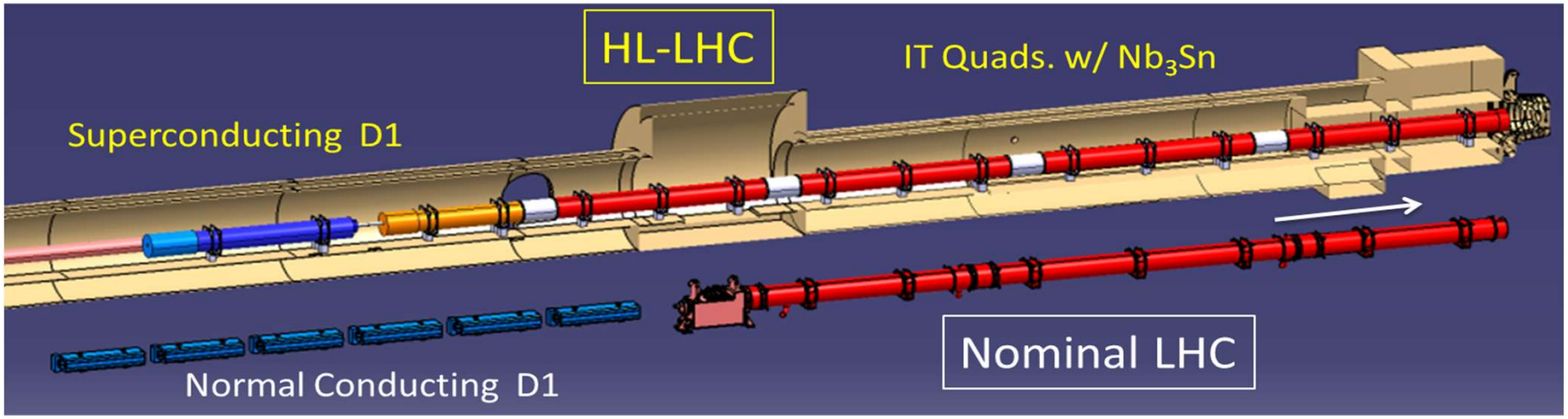
July 16-17, 2023

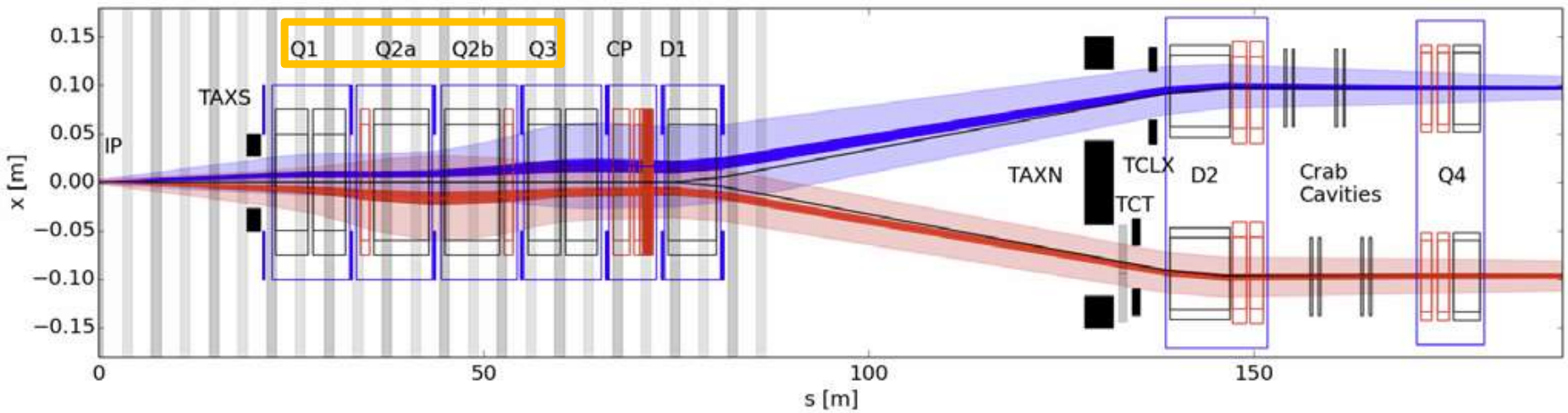


Next HEP collider: HL-LHC

Goal: **10x integrated luminosity enabled by new IR magnets**

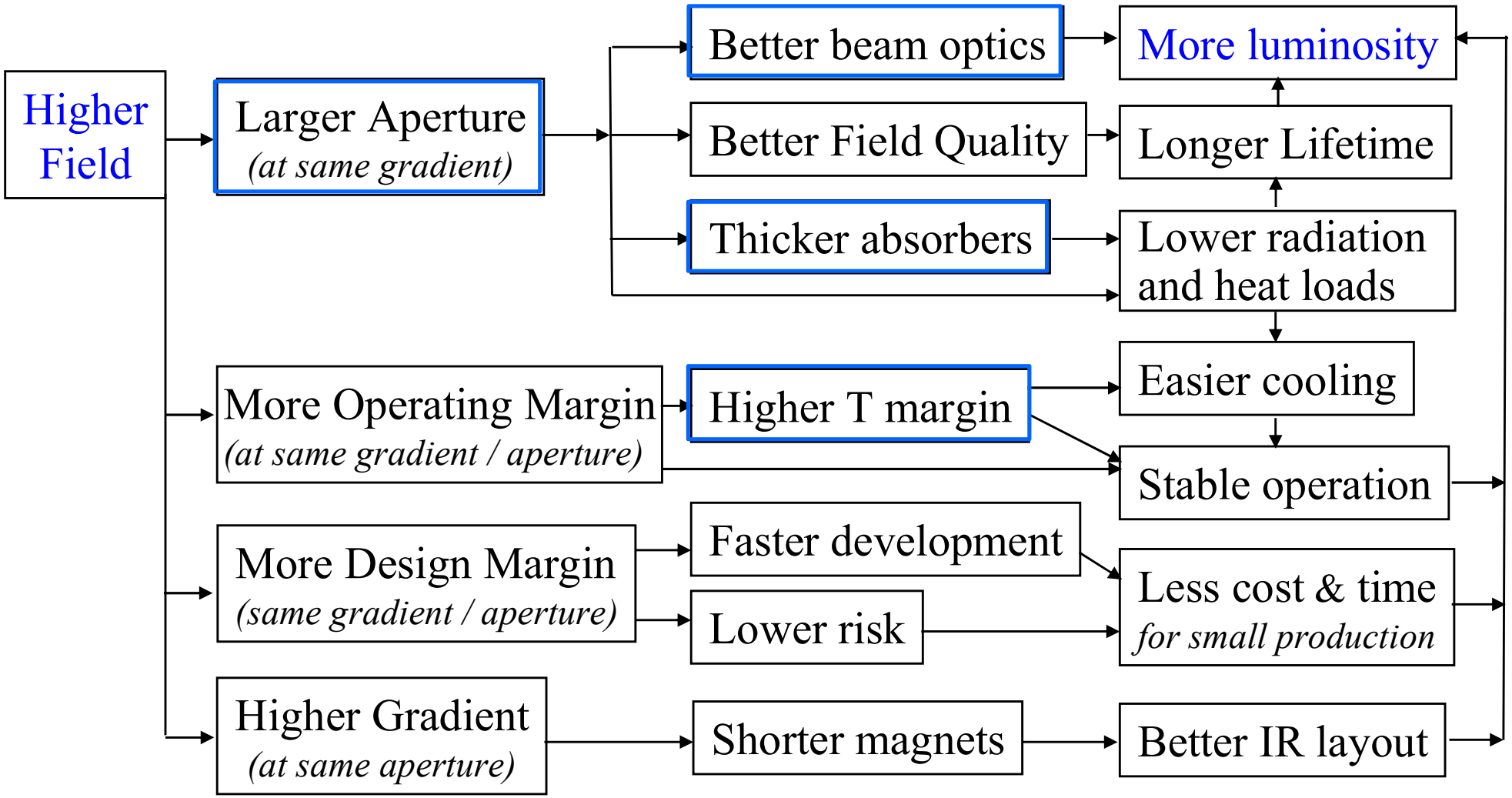
first application of Nb_3Sn technology in a high energy collider





IR Quadrupole Parameter Optimization

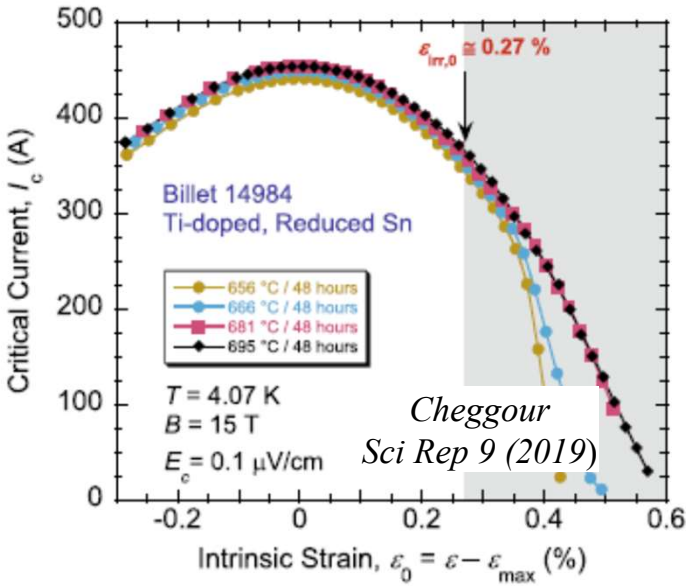
Nb_3Sn technology enables HL-LHC luminosity target



Nb_3Sn Technology

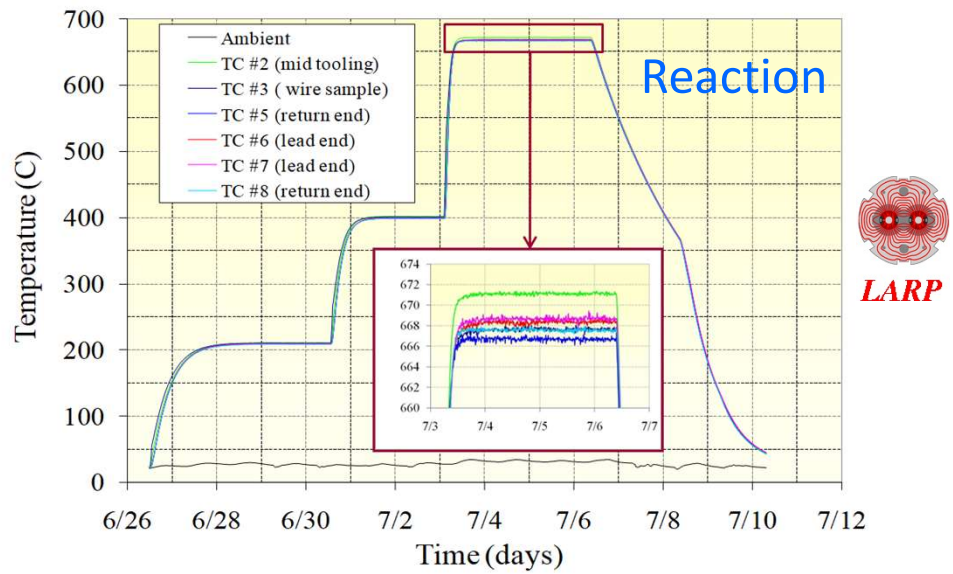
Brittle material:

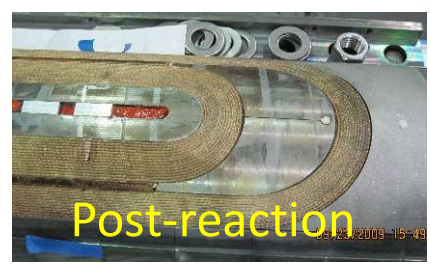
- Severe damage in cabling/winding
- ***React coils after winding***
- New coil materials (insulation, parts)



Sensitivity to stress/strain:

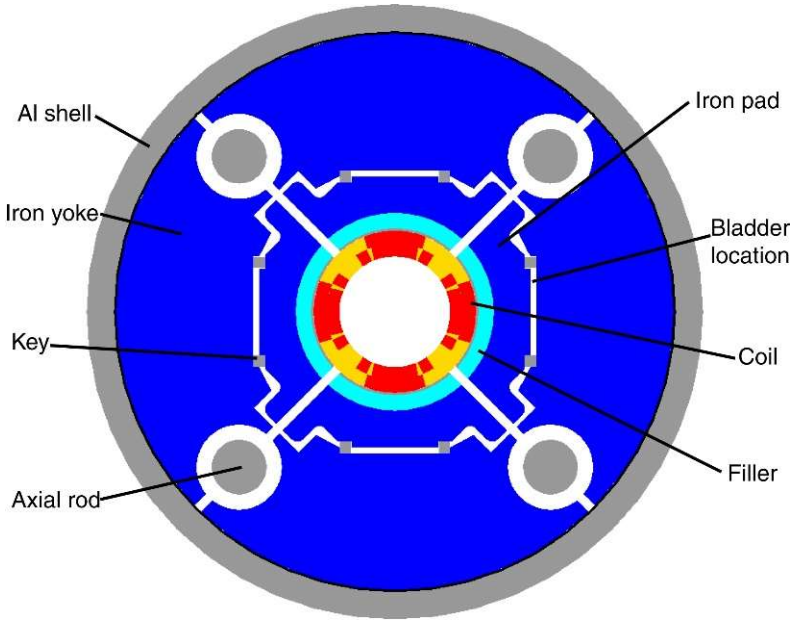
- Epoxy impregnation
- New mechanical designs

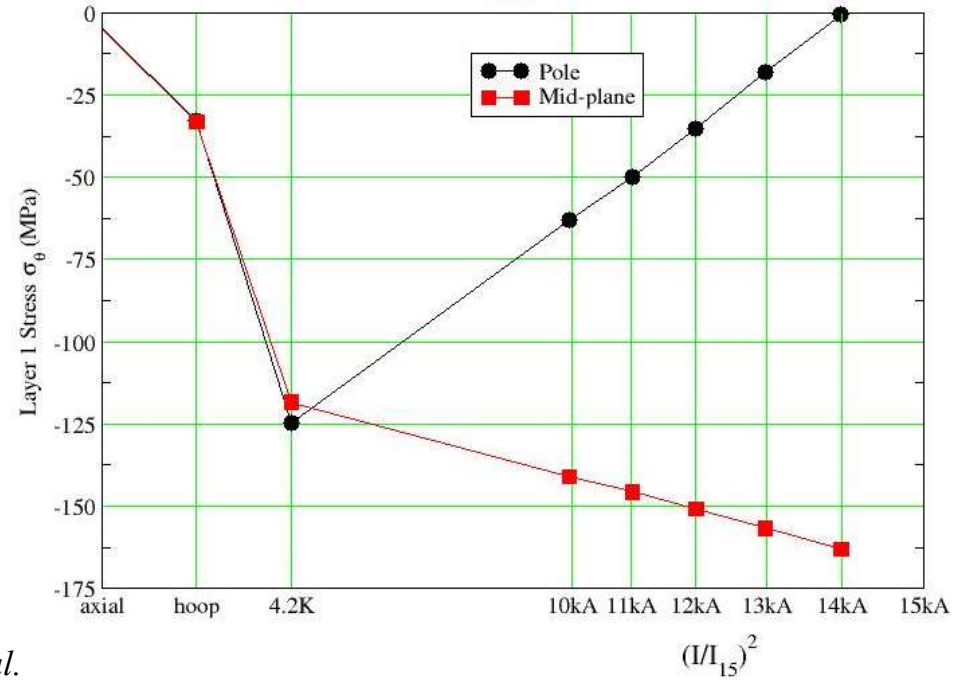




Aluminum-shell based support structure

- Mechanical design of Nb_3Sn magnets needs to satisfy stringent constraints
  - Full support without exceeding stress limits (150-200 MPa cold)
- Selected structure is based on aluminum shell over iron yoke, preloaded with pressurized bladders and interference keys
  - Minimize and precisely control warm pre-load
  - Increase to full pre-load during cool-down, avoiding overshoot

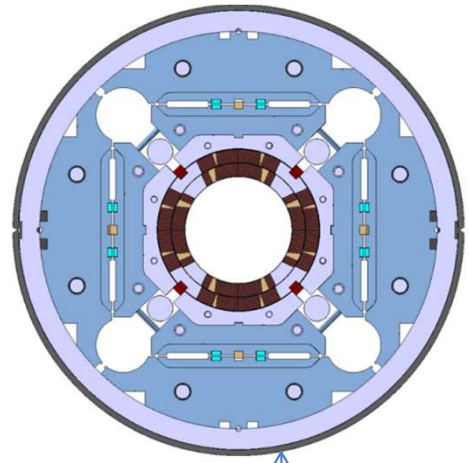




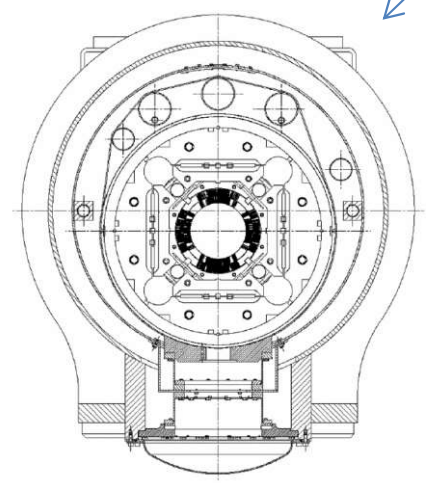
S. Caspi, P. Ferracin et al.

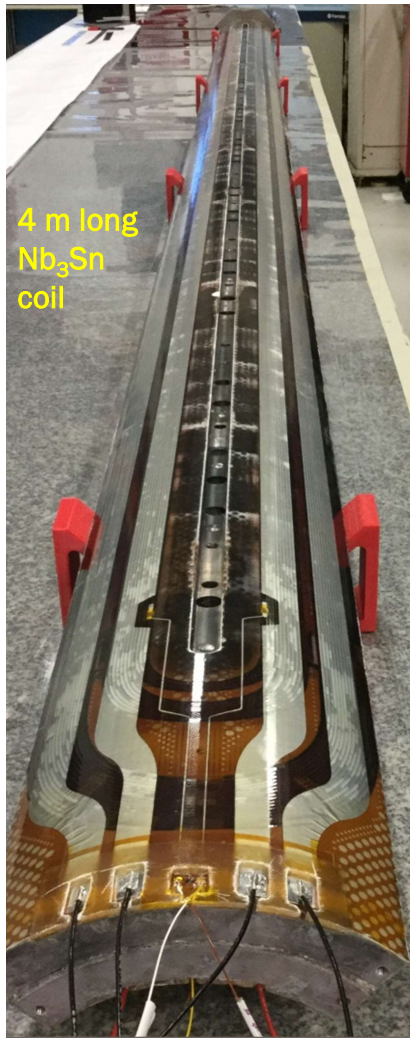
HL-LHC IR Quad production is underway

Parameter	Unit	MQXFA/B
Coil aperture	mm	150
Magnetic length	m	4.2/7.15
N. of layers		2
N. of turns Inner-Outer layer		22-28
Operation temperature	K	1.9
Nominal gradient	T/m	132.6
Nominal current	kA	16.5
Peak field at nominal current	T	11.4
Stored energy at nominal	MJ/m	1.2
Peak field at ultimate current	T	12.4



Cross-section of cold mass and cryostat





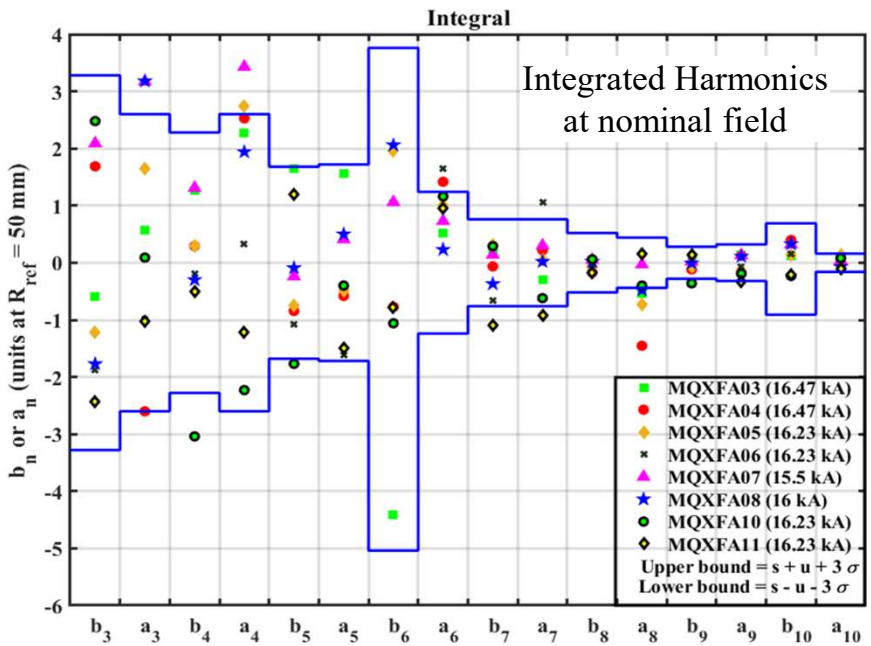
Common design for US (Q1/Q3) and CERN (Q2a/b) Quadrupoles except for different length (4.2+4.2 m vs 7.15 m)

Field Quality Table

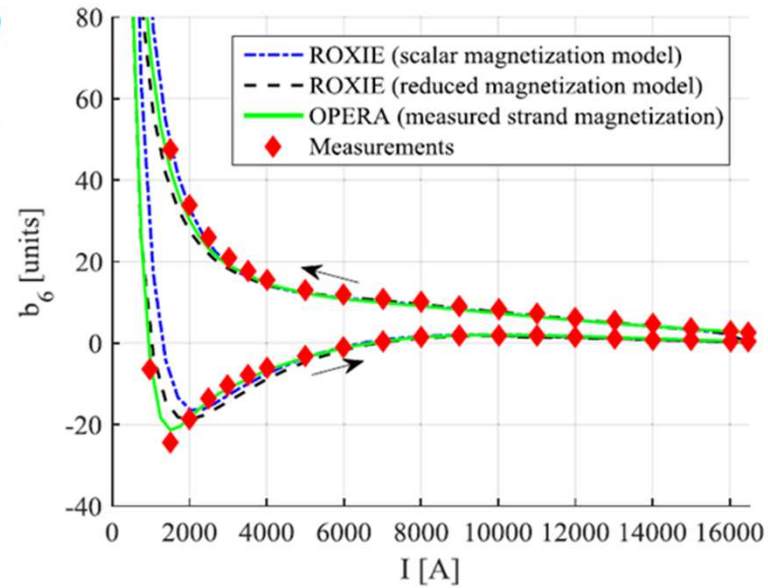
	Triplet field quality version 4 - May 20 2015 - R_{ref}=50 mm															
	Straight part										Ends		Integral			
	Systematic						Uncertainty		Random				Q1/Q3		Q2a/b	
Normal	Geometric	Ass. & cool	Saturation	Persistent	Injection	High Field	Injection	High Field	Injection	High Field	Conn. Side	Non conn. Side	Injection	High Field	Injection	High Field
3	0.000	0.000	0.000	0.000	0.000	0.000	0.820	0.820	0.820	0.820			0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.000	0.570	0.570	0.570	0.570			0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.000	0.420	0.420	0.420	0.420			0.000	0.000	0.000	0.000
6	-2.200	0.900	0.660	-20.000	-21.300	-0.640	1.100	1.100	1.100	1.100	8.943	-0.025	-16.692	0.323	-18.593	-0.075
7	0.000	0.000	0.000	0.000	0.000	0.000	0.190	0.190	0.190	0.190			0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000	0.000	0.000	0.130	0.130	0.130	0.130			0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000	0.000	0.000	0.070	0.070	0.070	0.070			0.000	0.000	0.000	0.000
10	-0.110	0.000	0.000	4.000	3.890	-0.110	0.200	0.200	0.200	0.200	-0.189	-0.821	3.119	-0.175	3.437	-0.148
11	0.000	0.000	0.000	0.000	0.000	0.000	0.026	0.026	0.026	0.026			0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000	0.000	0.000	0.018	0.018	0.018	0.018			0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000	0.000	0.000	0.009	0.009	0.009	0.009			0.000	0.000	0.000	0.000
14	-0.790	0.000	-0.080	1.000	0.210	-0.870	0.023	0.023	0.023	0.023	-0.545	-1.083	0.033	-0.856	0.106	-0.862
Skew																
3	0.000	0.000	0.000	0.000	0.000	0.000	0.650	0.650	0.650	0.650			0.000	0.000	0.000	0.000
4	0.000	0.000	0.000	0.000	0.000	0.000	0.650	0.650	0.650	0.650			0.000	0.000	0.000	0.000
5	0.000	0.000	0.000	0.000	0.000	0.000	0.430	0.430	0.430	0.430			0.000	0.000	0.000	0.000
6	0.000	0.000	0.000	0.000	0.000	0.000	0.310	0.310	0.310	0.310	2.209		0.210	0.210	0.124	0.124
7	0.000	0.000	0.000	0.000	0.000	0.000	0.190	0.190	0.190	0.190			0.000	0.000	0.000	0.000
8	0.000	0.000	0.000	0.000	0.000	0.000	0.110	0.110	0.110	0.110			0.000	0.000	0.000	0.000
9	0.000	0.000	0.000	0.000	0.000	0.000	0.080	0.080	0.080	0.080			0.000	0.000	0.000	0.000
10	0.000	0.000	0.000	0.000	0.000	0.000	0.040	0.040	0.040	0.040	0.065		0.006	0.006	0.004	0.004
11	0.000	0.000	0.000	0.000	0.000	0.000	0.026	0.026	0.026	0.026			0.000	0.000	0.000	0.000
12	0.000	0.000	0.000	0.000	0.000	0.000	0.014	0.014	0.014	0.014			0.000	0.000	0.000	0.000
13	0.000	0.000	0.000	0.000	0.000	0.000	0.010	0.010	0.010	0.010			0.000	0.000	0.000	0.000
14	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.005	0.005	0.005	-0.222		-0.021	-0.021	-0.012	-0.012
	Magnetic length straight part				Q1/Q3	3.459	Q2a/b	6.409	Mag. Len. Ends		0.400	0.341				

Reference: Hi Lumi LHC Work Package 3 - Magnets for Insertion Regions https://espace.cern.ch/HiLumi/WP3/SitePages/Home.aspx

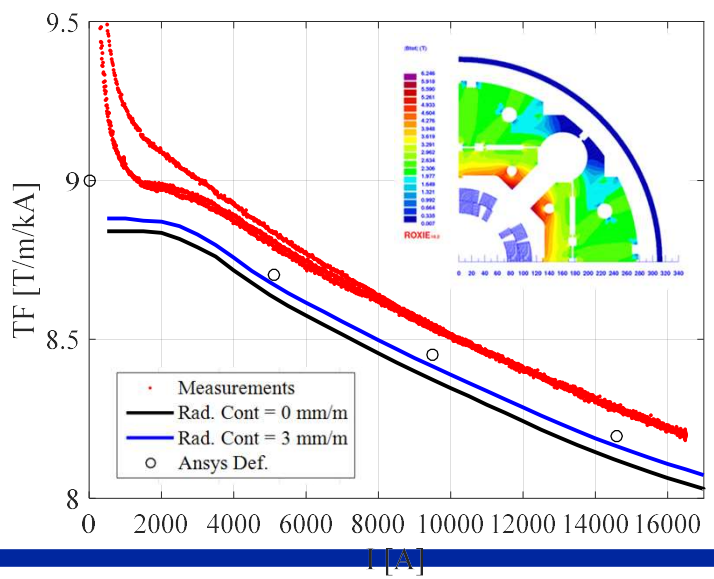
Field Error Measurements and Analysis



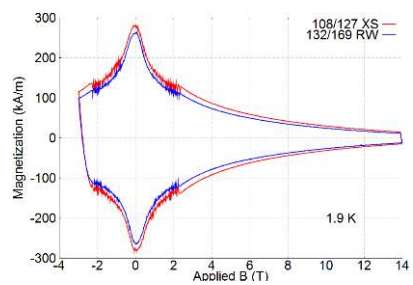
Conductor Magnetization



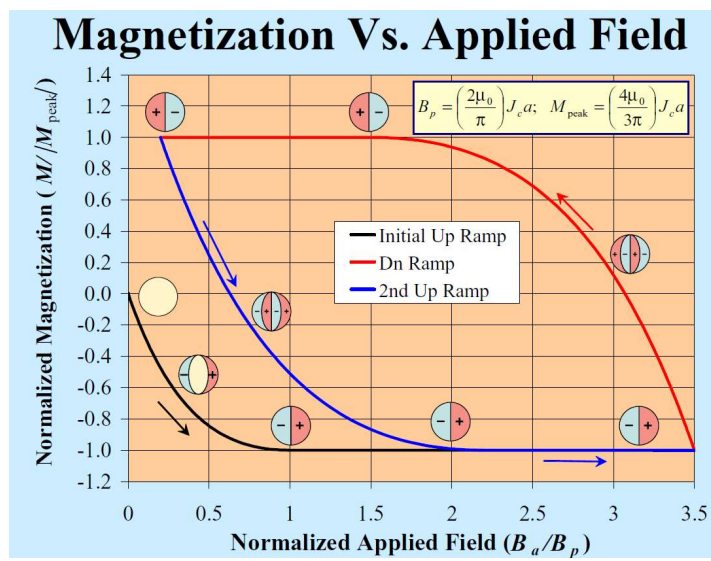
Iron saturation



Magnetization measurement



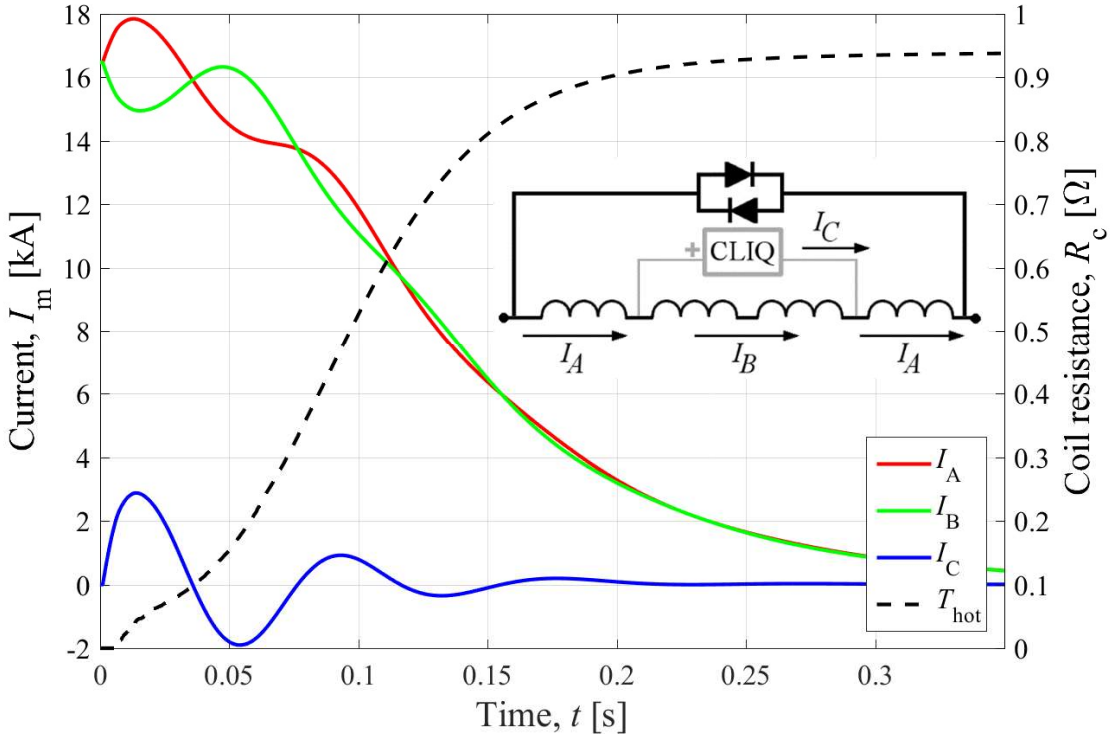
S. Izquierdo Bermudez, X. Wang, A. Ben Yahia, M. Sumption et al.

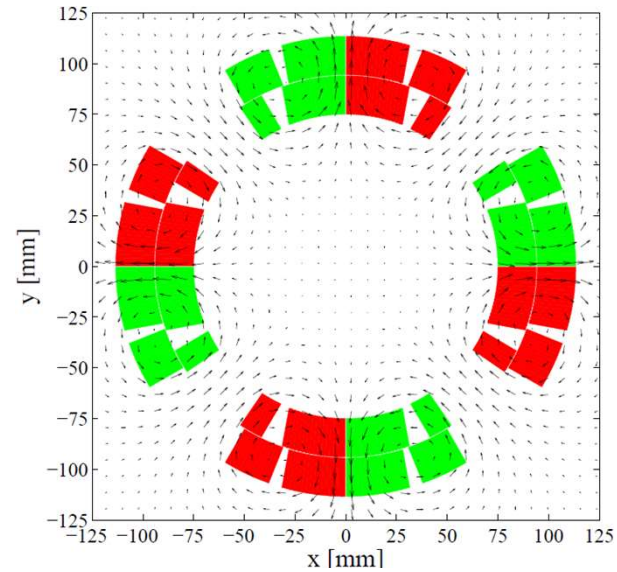


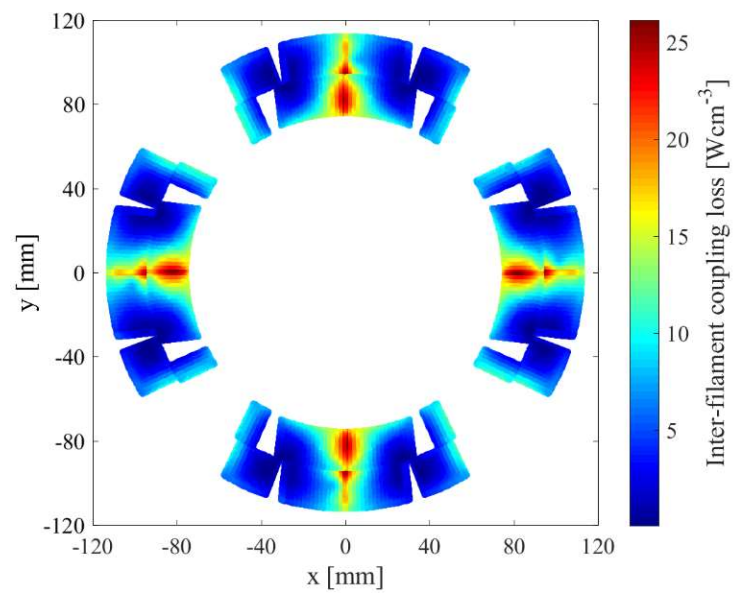
USPAS 2006 - A. Jan, BNL

Quench Protection with CLIQ

E. Ravaioli, CERN

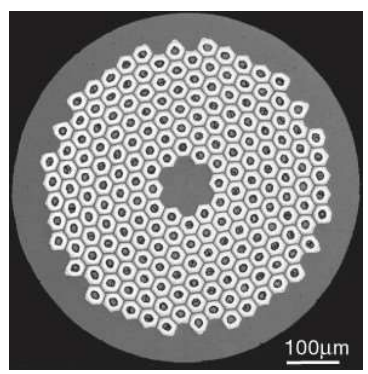






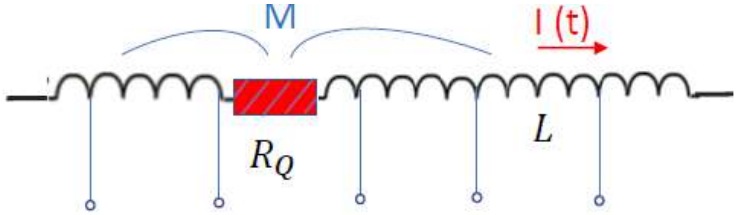
Power is deposited by inter-filament coupling currents induced by the rapid current oscillations

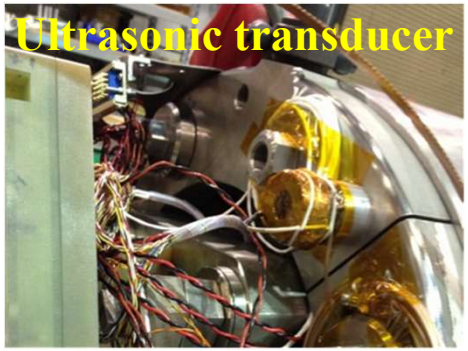
$$\tau_{\mathrm{if}} = \frac{\mu_0}{2}\left(\frac{l_{\mathrm{f}}}{2\pi}\right)^2 \frac{1}{\rho_{\mathrm{eff}}}$$

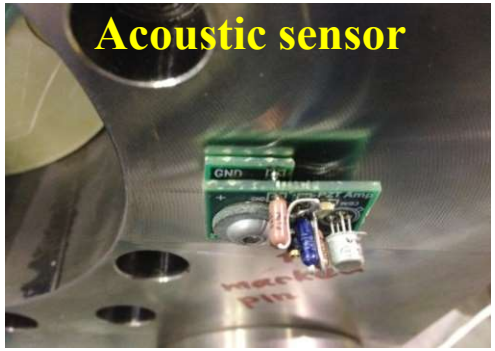


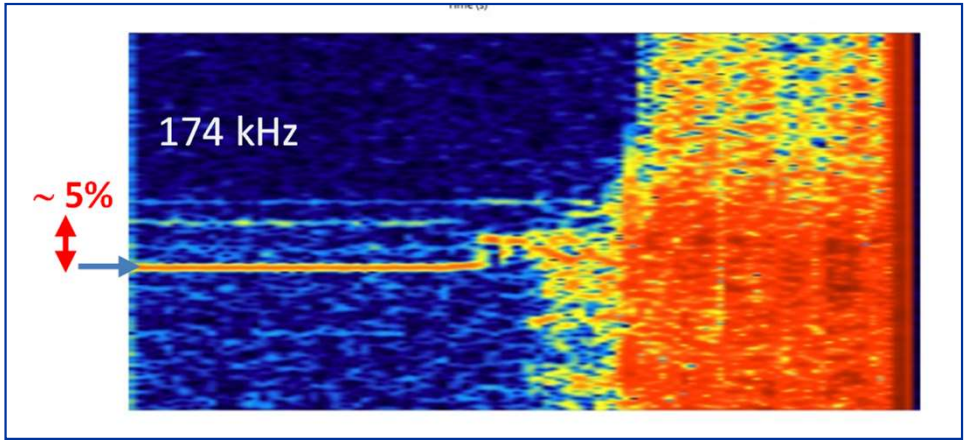
Test Instrumentation

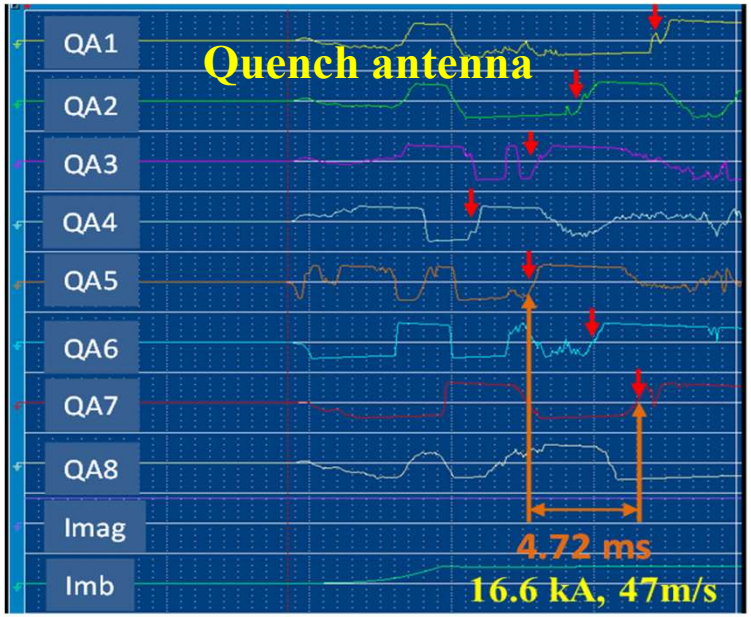
New diagnostics are being developed to complement the traditional approach based on voltage taps











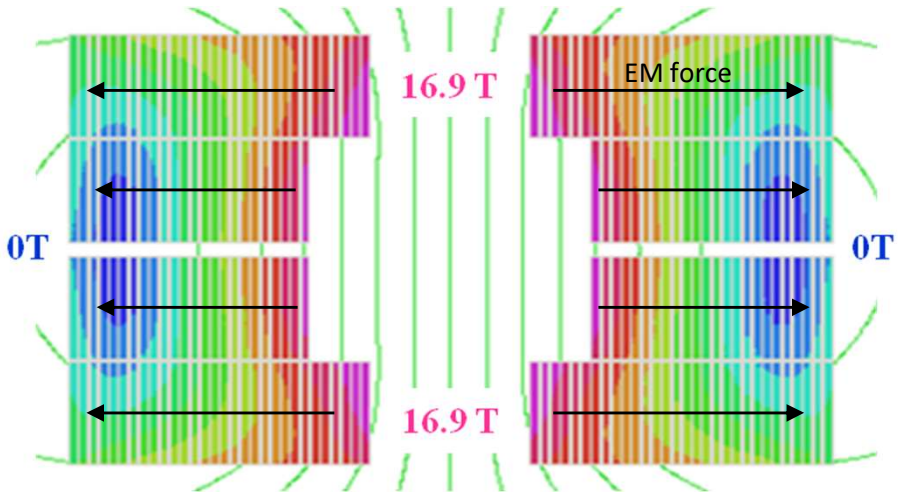
M. Marchevsky, USPAS 2022

Block-coil High Field Dipole Design

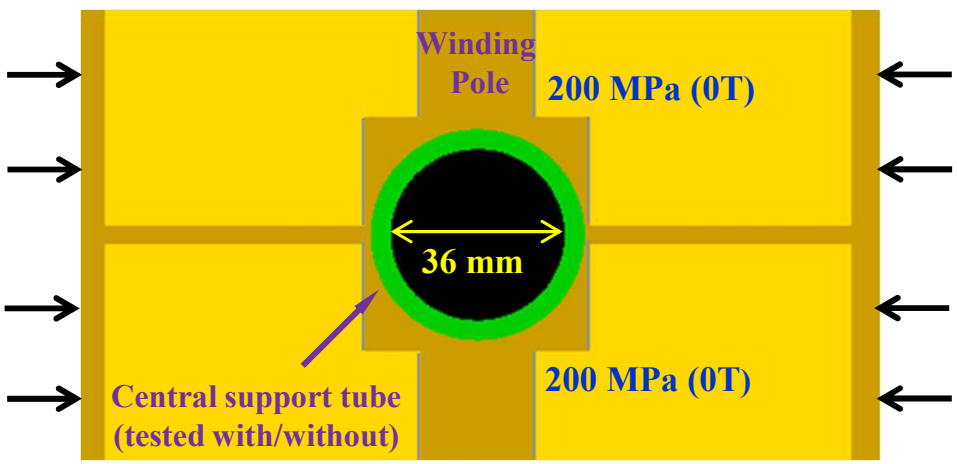
HD2 Design:

- ✓ High Je (no spacers/structure in coil)
  - Efficient design for small aperture
- ✓ Only two co-wound layers/pole
  - Optimize performance and cost
- ✓ Concentrates stress in low-field region
- ? Internal bore support (vs. Roman arch)
- ? Flared ends (vs. saddle ends)

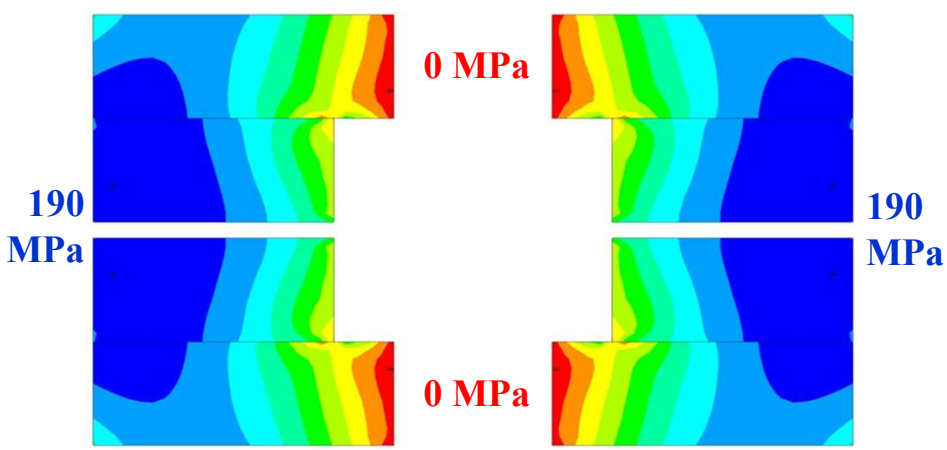
Magnetic Field @ B_0 = 16 T



Bore structural support

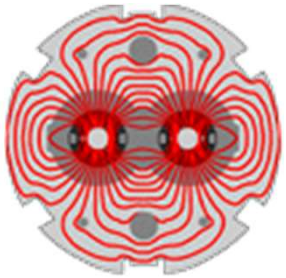


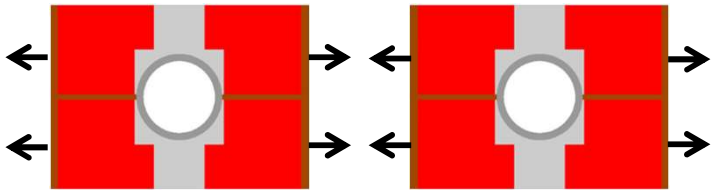
Coil Stress @ B_0 = 16 T



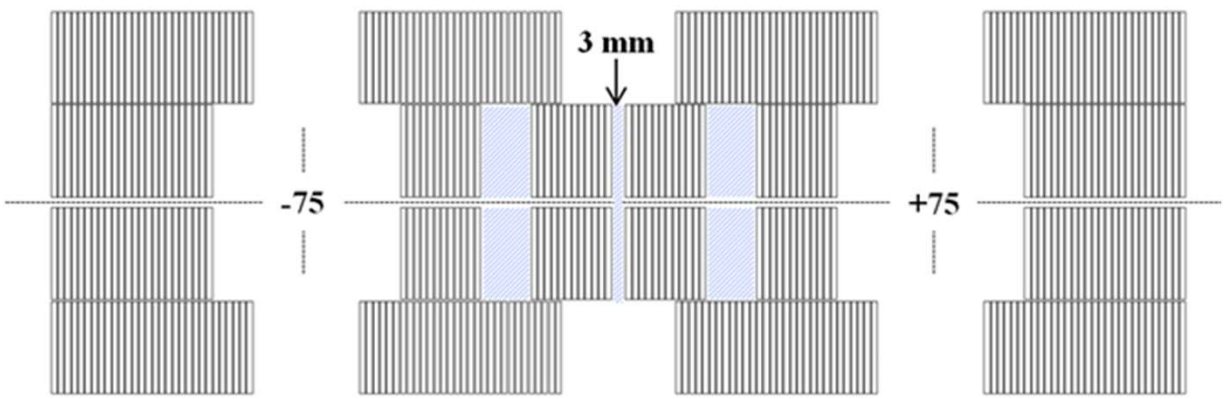
Twin-Aperture Collider Dipoles

Horizontal layout has good magnetic and mechanical efficiency

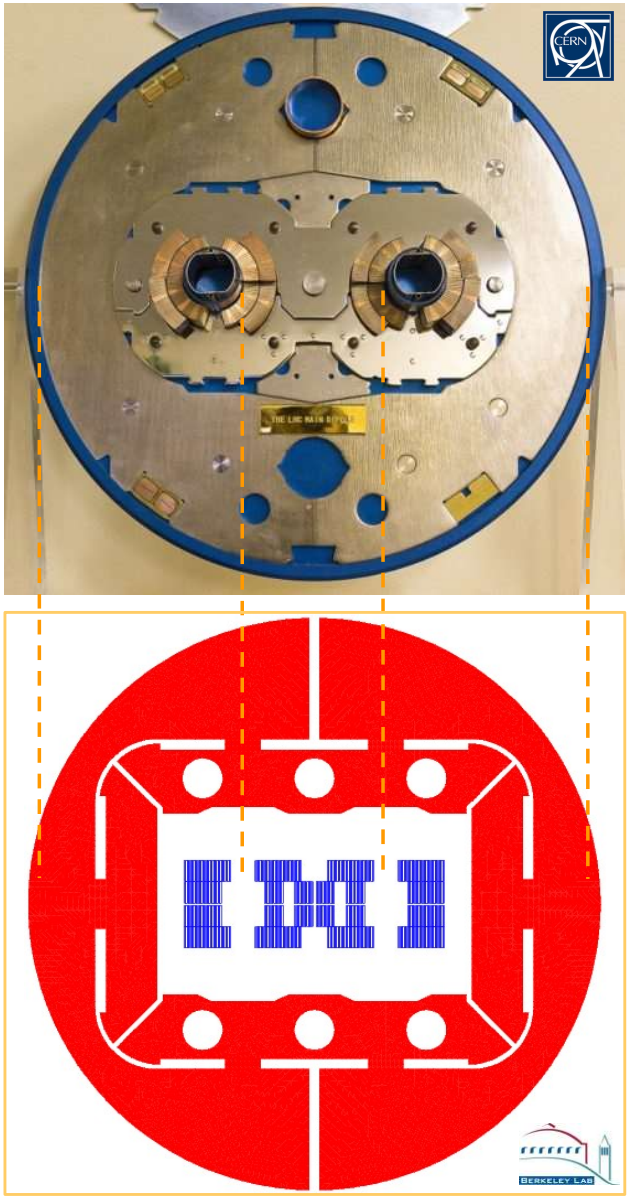




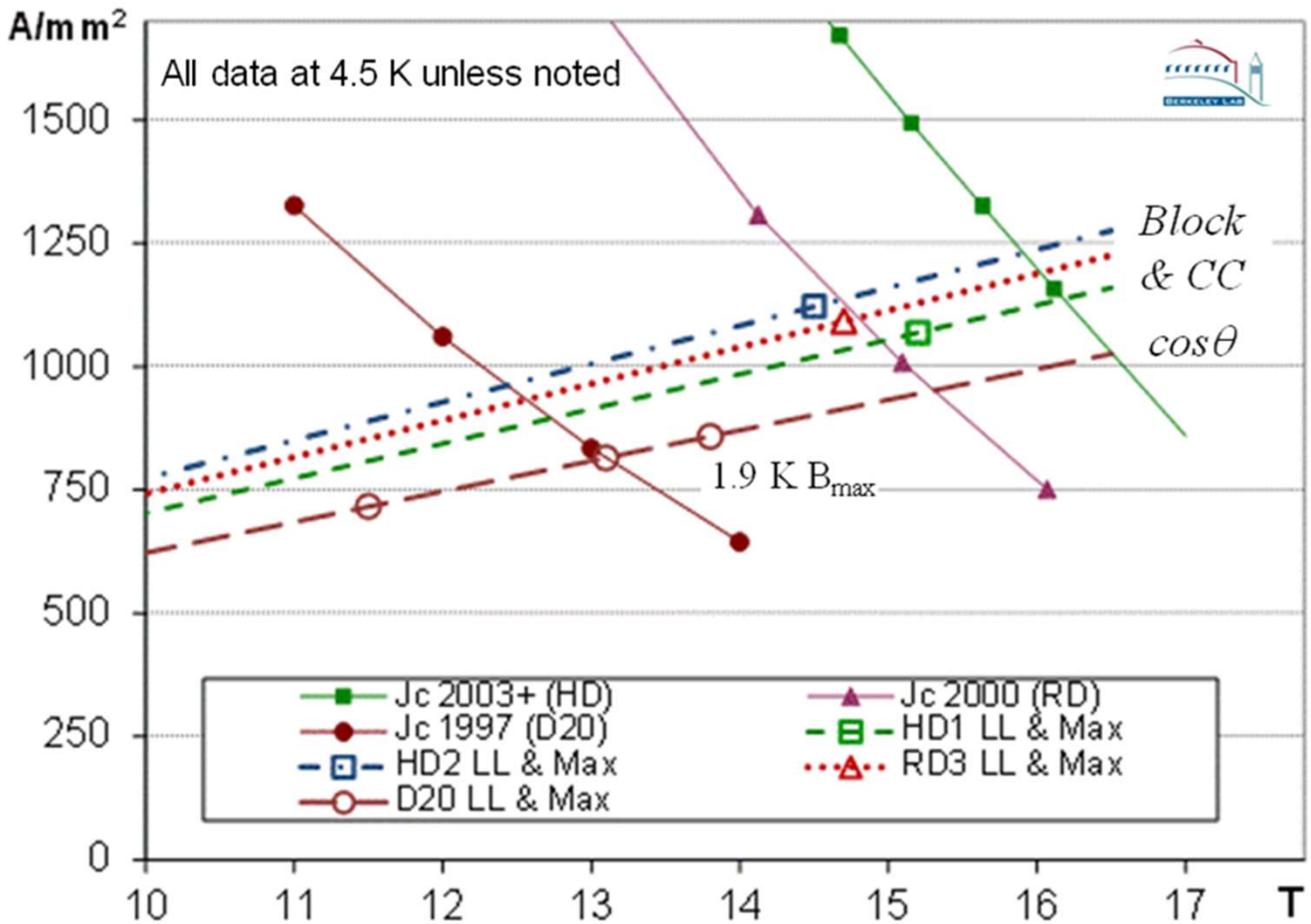
Asymmetric coil design for smaller spacing between apertures

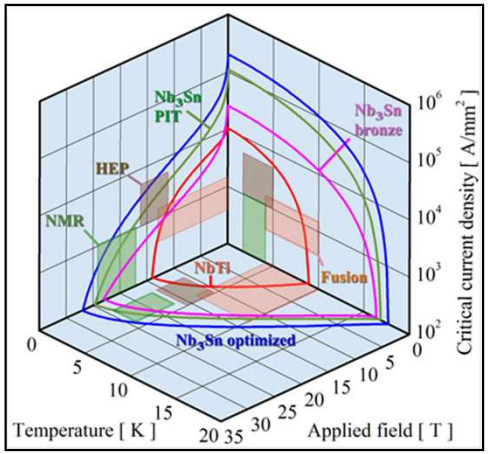


Short sample performance	I_{ss}		B_1^{ss}	
Temperature	4.5K	1.9K	4.5K	1.9K
Single aperture (HD2)	18.0	20.1	15.52	17.15
Double aperture (2HD)	17.8	19.7	15.49	17.12



Past improvements of Nb_3Sn J_c





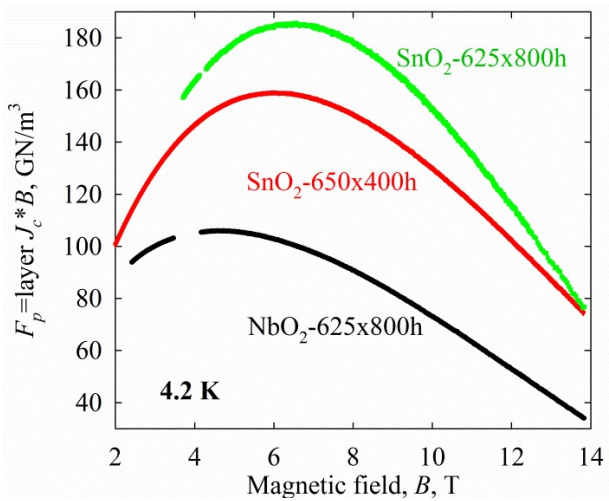
Bore field to peak field ratios:

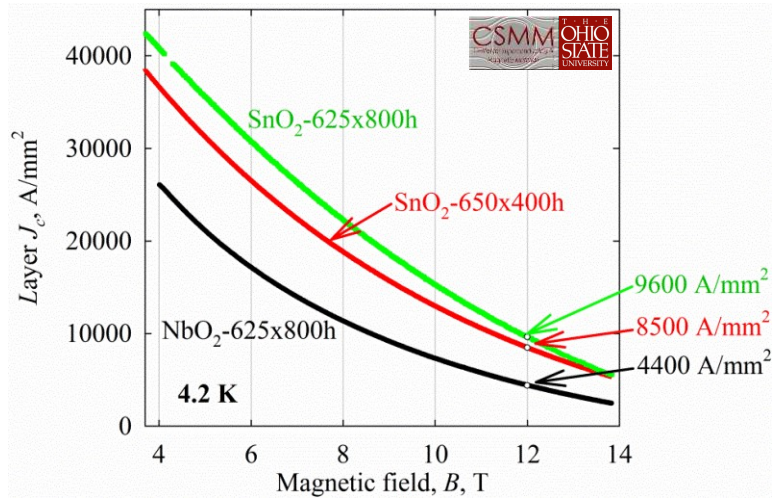
D20 : 0.98
HD2: 0.95
HD1: 1.06
RD3: 0.99

- HEP conductor development program resulted in +3T field potential (4.5K)
- Achieved performance consistent with improvements in conductor properties
- Optimal design choices driven by accelerator requirements and production cost

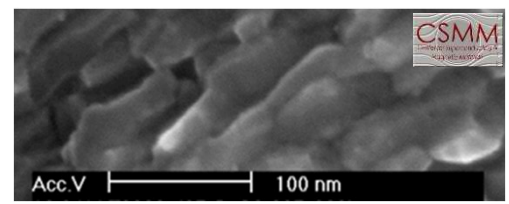
Potential for further improvements

- Principle: increase of Nb_3Sn pinning force at high field through grain refinement
- Promising results in short samples *(X. Xu et al, Appl. Phys. Lett. 104 082602):*

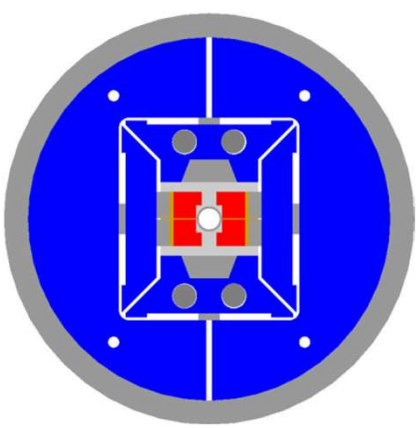




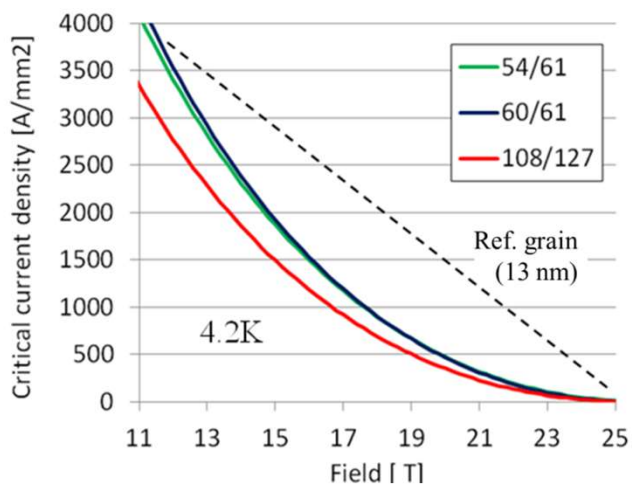
J_c(12 T, 4.2K): from
3.5 kA/mm^2 @ 100+ nm
(e.g. best HD2 wire) to
9.6 kA/mm^2 @ ~35 nm

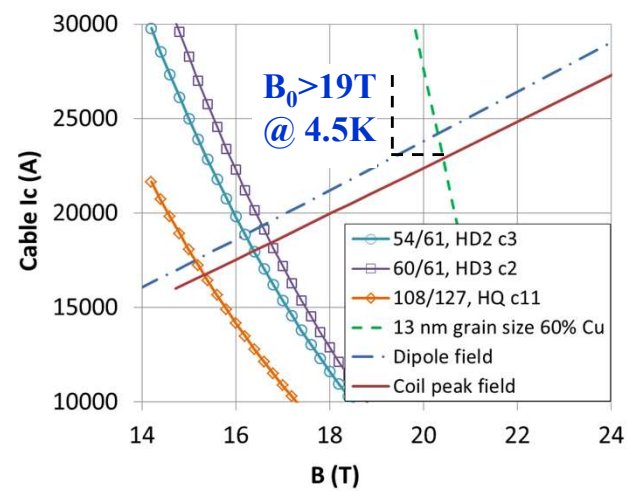


- Extrapolation to HD2 & **13 nm** grain size *(G. Sabbi et al., IEEE-TAS 25 (3) 4001407):*



HD2 cross-section





High Temperature Superconductors (HTS)

Bi-2212
YBCO

Technology foundation:

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

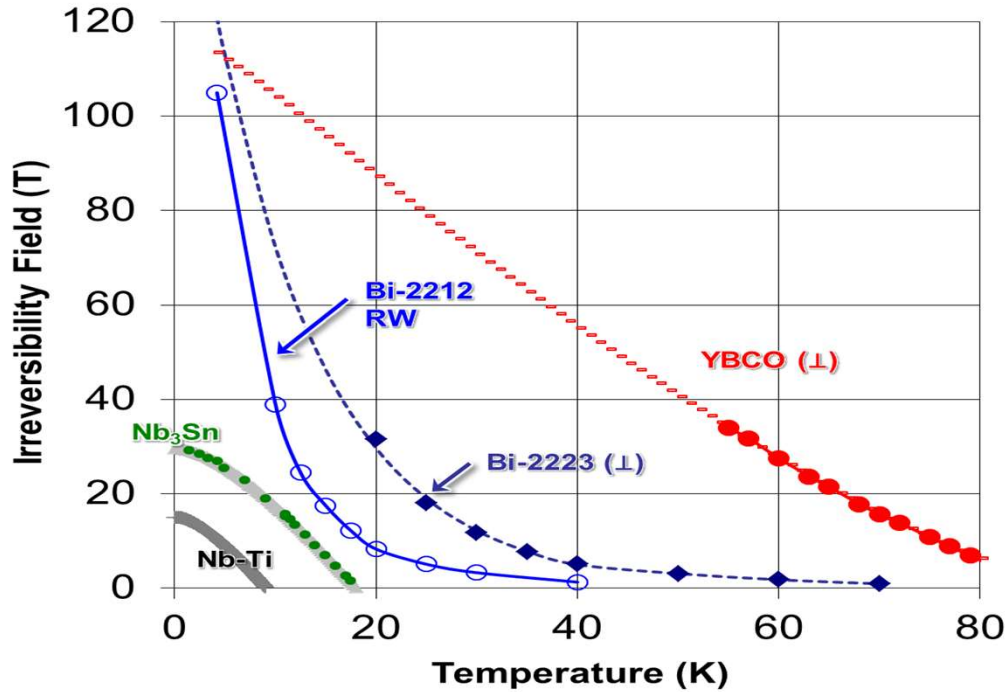
Performance demonstration in simple configurations

Nb_3Sn

Full qualification in accelerator configurations

NbTi

System integration

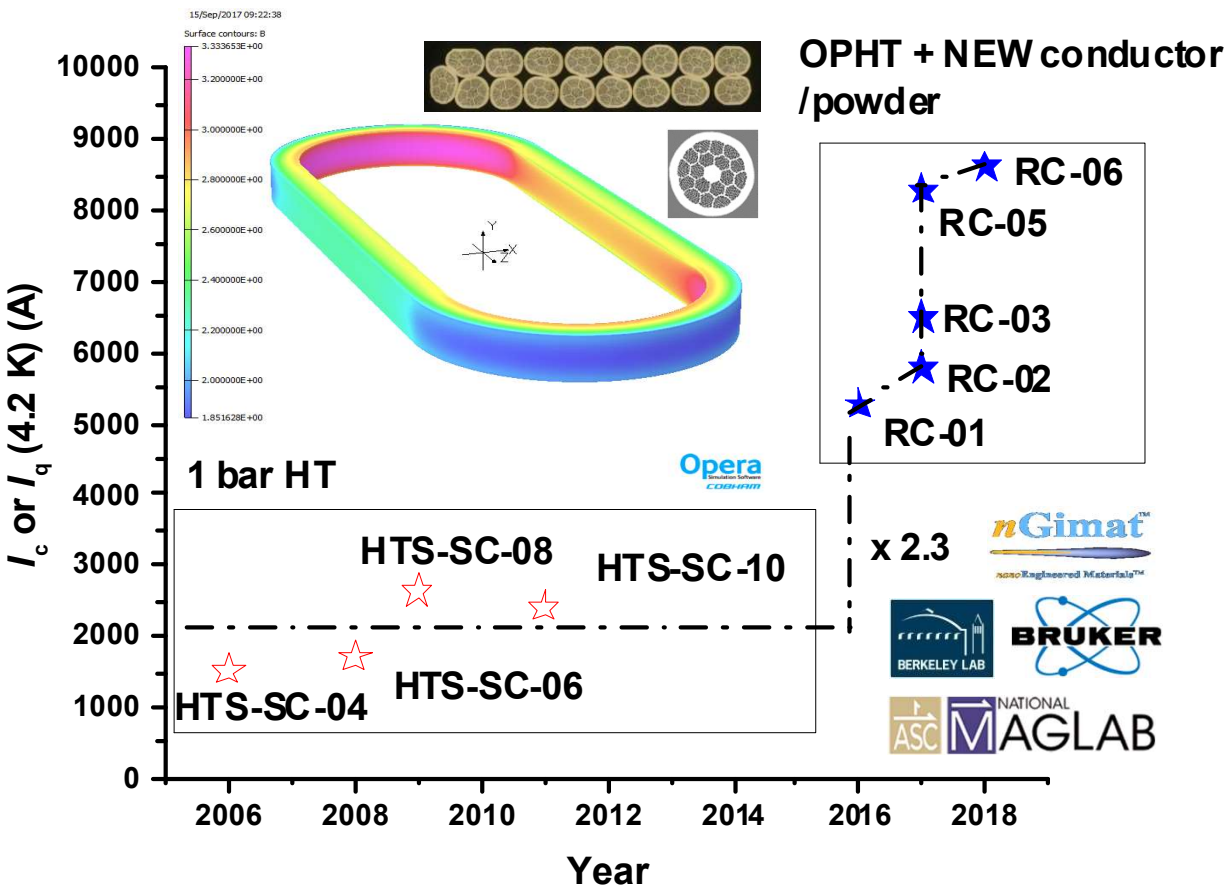


In-depth analysis & optimization

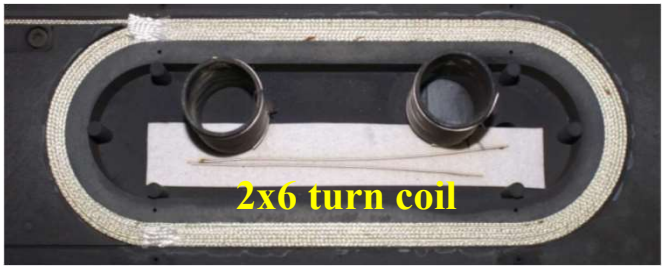
- *Conductor properties*
- *Fabrication technology*
- *Material characterization*
- *Modeling and diagnostics*

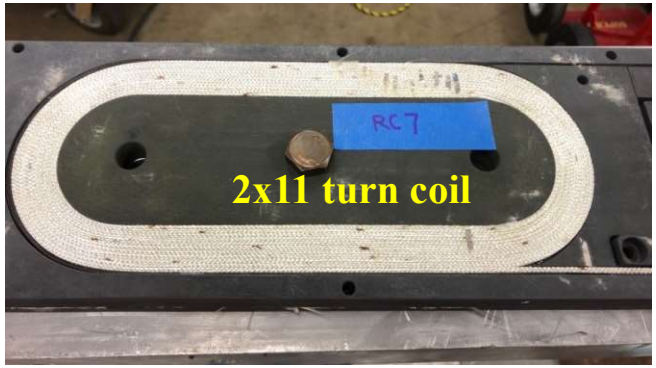
Accelerator-type coils with Bi-2212

- Significant J_c improvements with new high pressure heat treatment and powers
- RC-06 results (0.8 mm strand, 17-strand Rutherford cable, 2-layer, 6-turn/layer):
  - J_e - 1365 A/mm^2 at 15 T (2xFCC spec); 1000 A/mm^2 at 27 T (1.3 GHz NMR)
- Two larger 11-turn coils (RC7-8) generated 4.5 T field in a shell-based structure



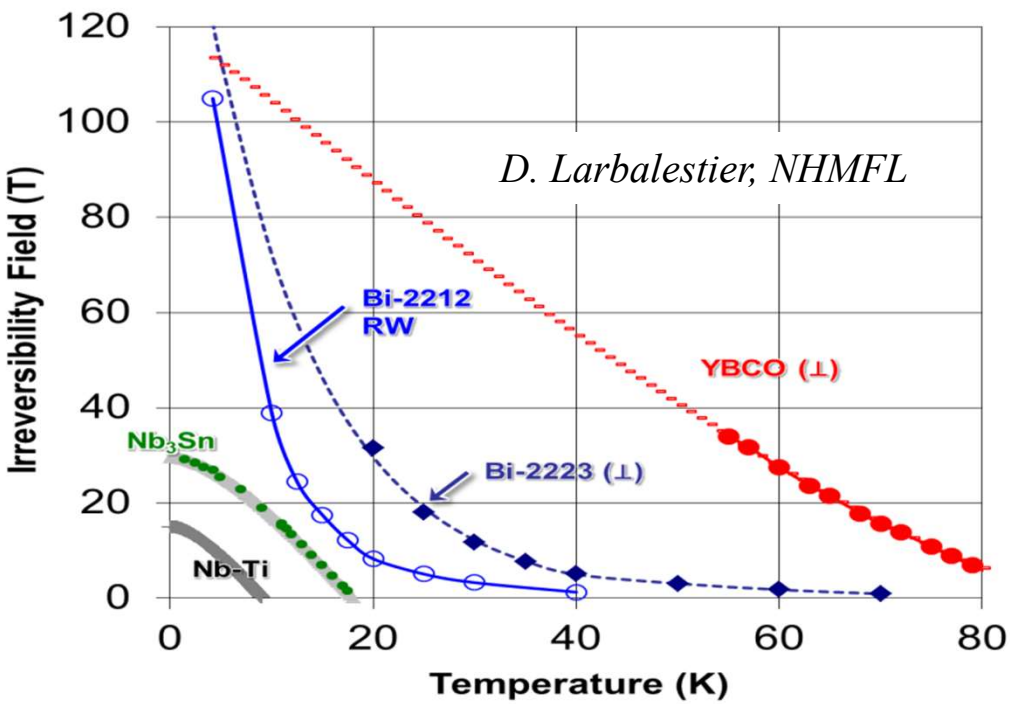
Zhang et al. SuST, 31 (2018) 105009
Jiang et al., IEEE TAS, 29 (2019), 6400405
Shen et al., arXiv preprint arXiv:1808.02864

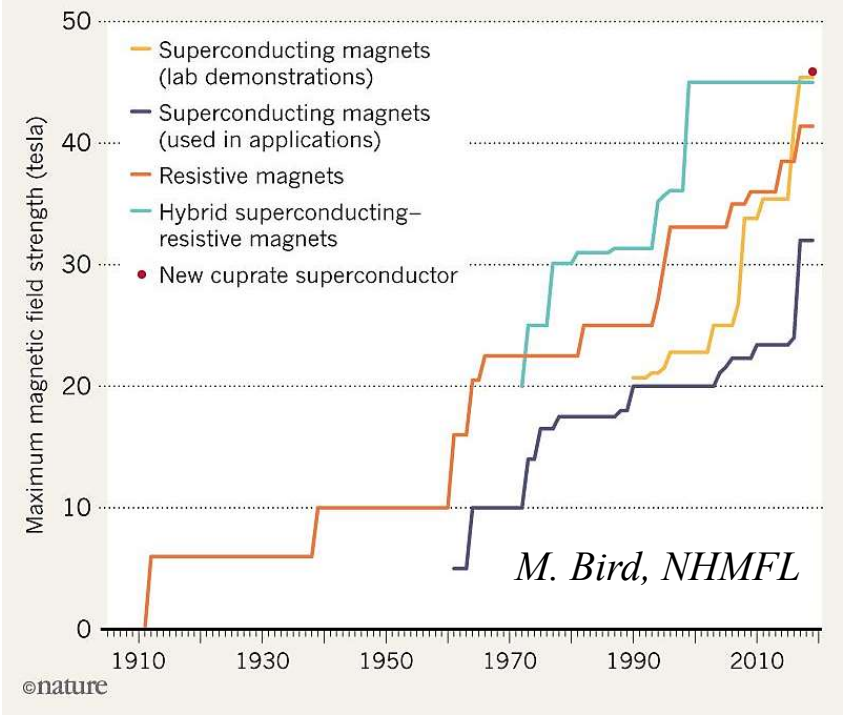




REBCO tapes: the high field frontier

- REBCO tapes provide by far the best current densities at the highest field
- Enabling impressive progress in hybrid LTS/HTS superconducting solenoids
  - Highest field all superconducting user facility (32 T) – 12/2017
  - All-SC test achieves highest magnetic field on record (45.5 T) – 2/2019
  - First commercial 1.2 GHz NMR (28.2T) system by Bruker – 8/2019

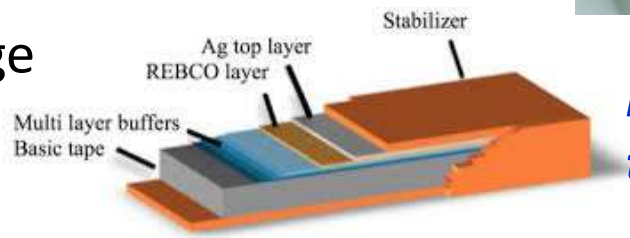




Key technology: high current HS cables

- Goal: develop multi-kA HTS cables with low degradation from cabling, bending and stress, and low AC losses
- REBCO is strongly preferred to Bi-2212 in large systems due to lower projected cost and avoiding the challenging reaction

ITER CICC (Nb_3Sn)



REBCO tape

Twisted stack

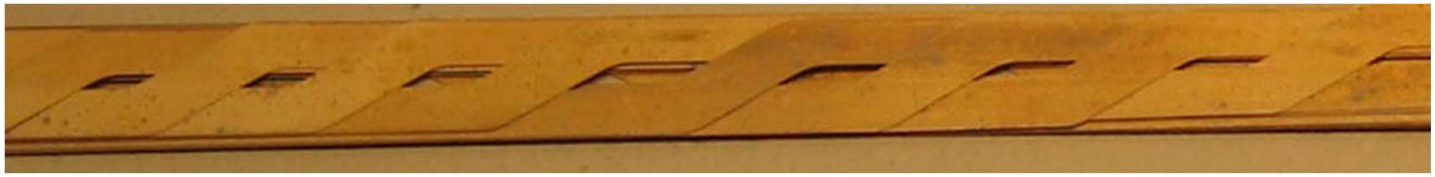
Massachusetts Institute of Technology

D.C. van der Laan, *SUST* 22, 065013 (2009).

Conductor on Round Core (CORC)

Advanced Conductor Technologies LLC
www.advancedconductor.com

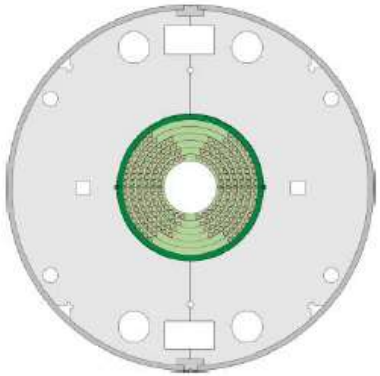
Robel cable



IRL

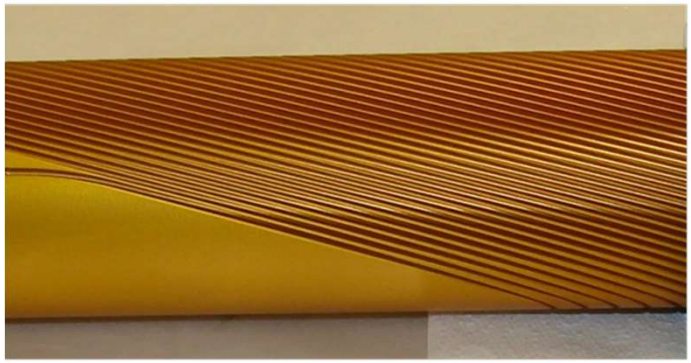
Cable-in-groove

- Concept: place individual turns in grooved formers
- Goals:
  - More flexibility in the winding pattern, cable design, and coil grading
  - Internal structure to protect the conductor from force accumulation
- Issues to be addressed for application to high field magnets
  - Magnetic: engineering current density, quench propagation
  - Mechanical: pre-load transfer, or capability to operate without pre-load
  - Tooling/processes for reaction and impregnation; reliable insulation
  - Field quality: tolerances for cable insertion, module assembly/alignment



Cosθ

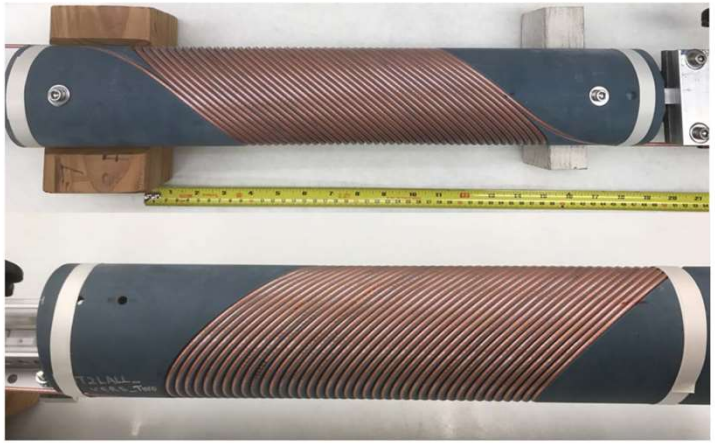
Racetrack



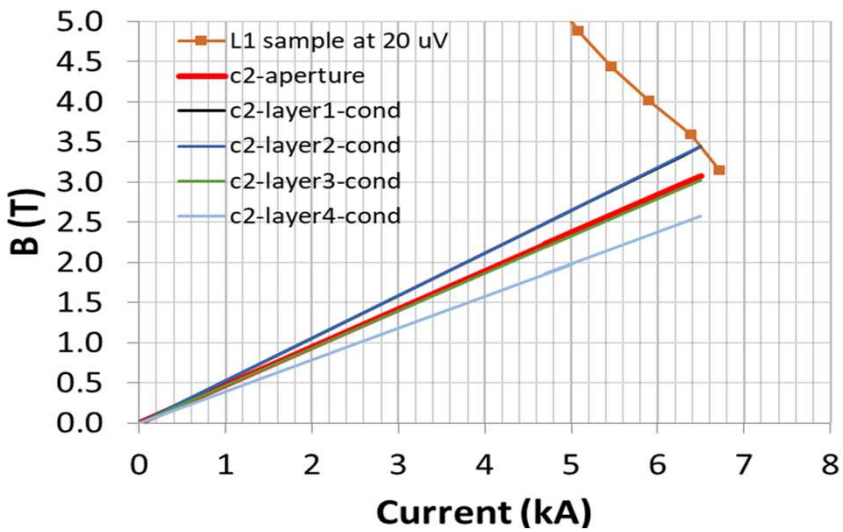
Helical Winding

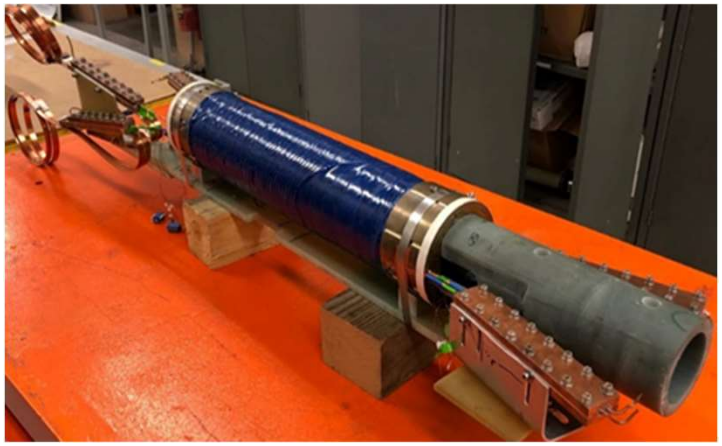
CORC Wires in Helical Windings

- Basic concept: superposition of tilted solenoids to generate a dipole field (Meyer, NIM 1970)
- Windings can be further modulated to generate higher order multipoles and control the field in curved or tapered geometries



Two-layer dipole: 1.2 T at 4.2 K

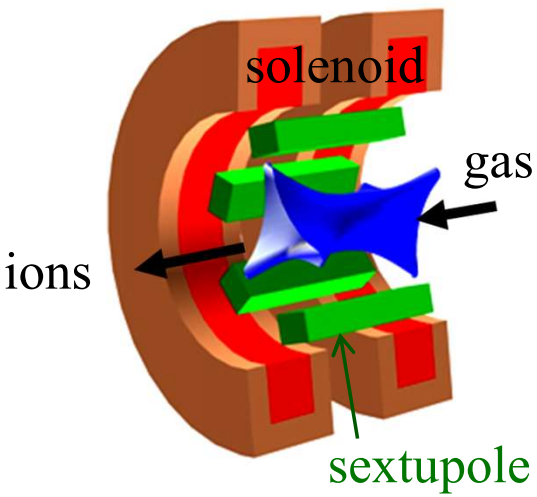




Four-layer dipole: 2.9 T at 4.2 K

X. Wang et al. SuST (2018) 075002

Accelerator-type coils for ECR sources



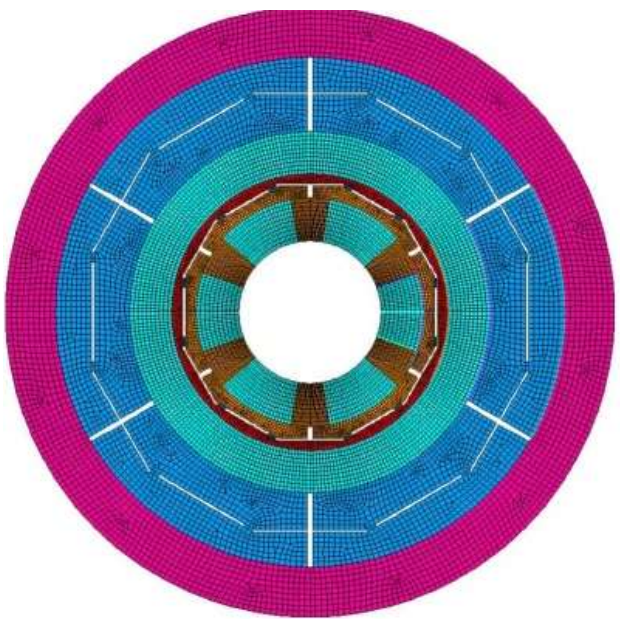
Resonant electron heating

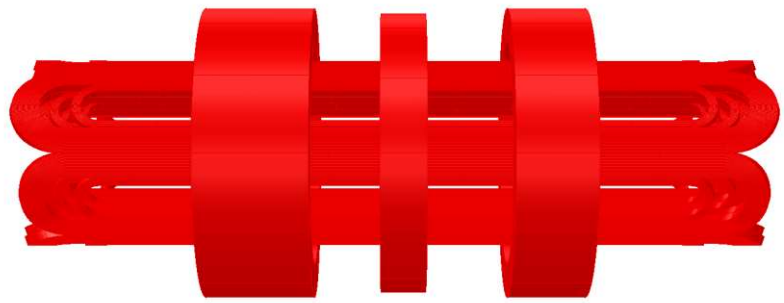
$$\omega_e = \frac{e \cdot B}{m} = \omega_{rf}$$

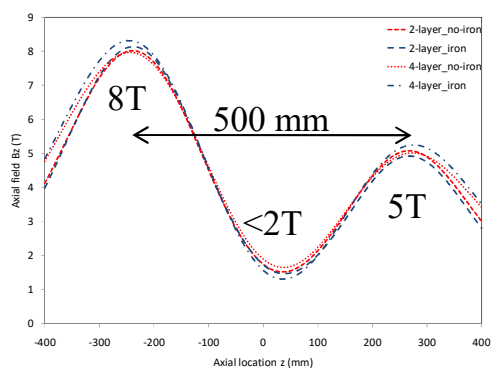
$$n_e \propto \omega_{rf}^2$$

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

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



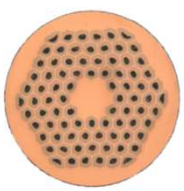




45-56 GHz ECR magnets with Nb_3Sn

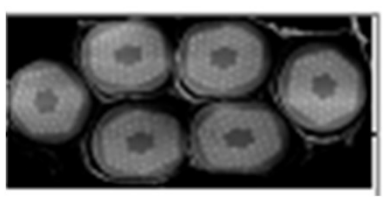
- Very favorable performance (current) scaling with square of frequency/field
- Main challenge is the sextupole coil fabrication and mechanical support
- Requires lower current (<1-2 kA) than typical in large accelerator applications
  - Single wire or small Rutherford cable – but both require many layers
- Shell based structure is directly applicable with additional challenges
  - Asymmetric force distribution and sextupole-solenoid integration

45 GHz Design by IMP and LBNL

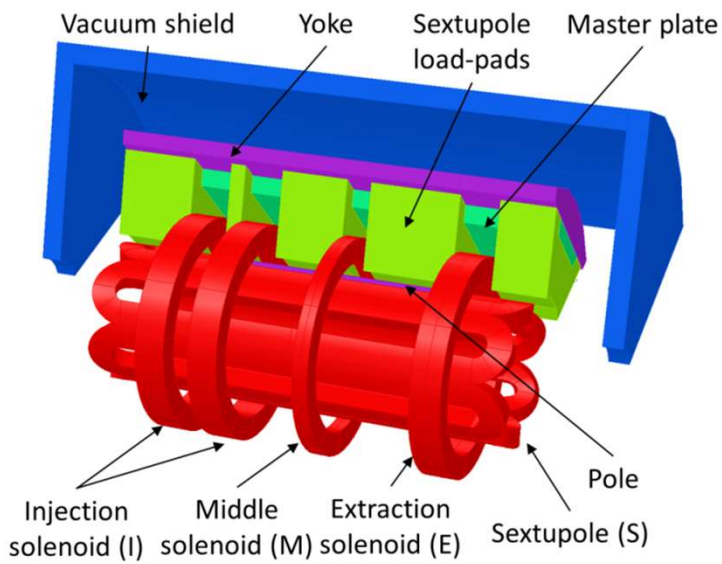


Single wire (baseline)

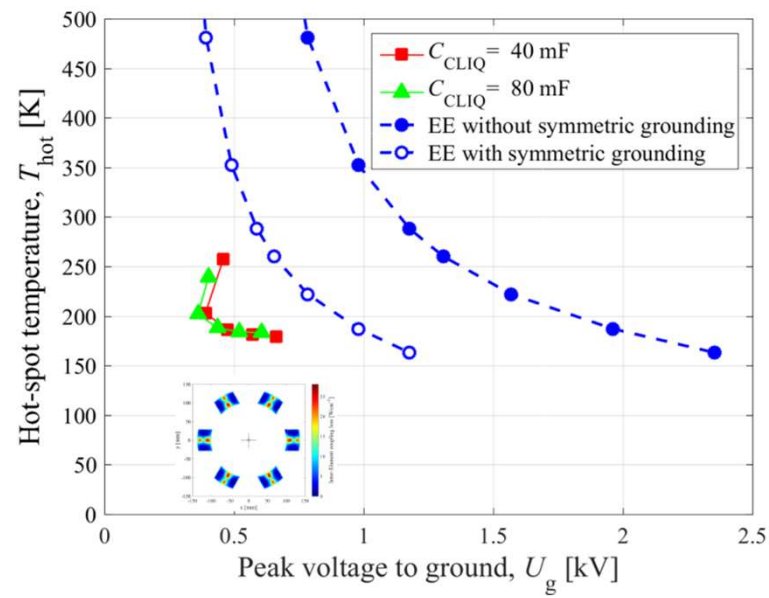
6-strand mini-cable (alternative)



Conductor options



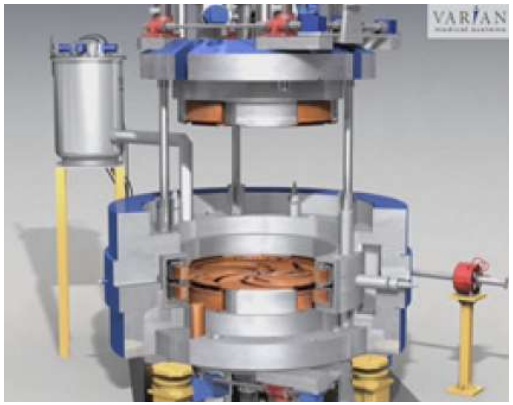
Magnetic and mechanical design

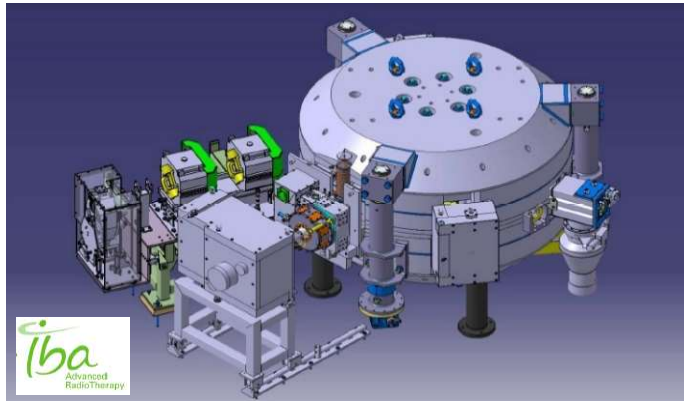


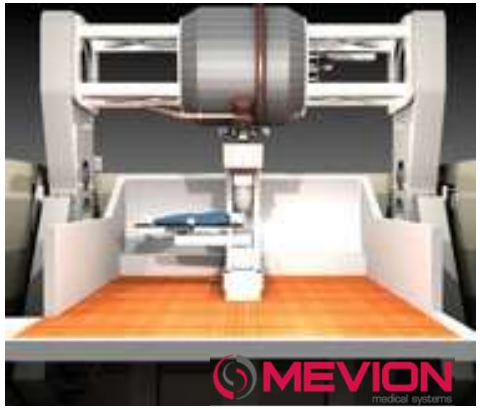
Energy extraction vs. CLIQ

Medical applications: compact cyclotrons

- Strong reduction of cyclotron size and weight at higher field ($1/B^3$)
  - *Of particular benefit for installations in medical facilities*
- Significant progress in compact (synchro)cyclotrons for proton therapy
  - *Up to 7 T with NbTi and 9 T with Nb_3Sn*







- Higher field is possible from a magnet perspective, but there are challenges in beam physics and system integration
  - Potential opportunities in carbon therapy
- Consider potential benefits from "high field" technology in specific sub-systems: gantries, cryogenics, flux return coils etc.

Concluding Remarks

- Superconducting Accelerator Magnets are a very broad subject combining different disciplines from material science to magnetics, mechanical engineering, cryogenics, power electronics and related instrumentation and diagnostics
- Solid technological basis and exciting developments with many technical challenges, both near term and long term
- Progress in high field magnets requires a convergence of technical feasibility, performance benefits for the application and critical mass to support the R&D
- Several new technologies are reaching maturity, offering opportunities for new application