International Accelerator School: Superconducting Science and Technology for Particle Accelerators

Canadian Light Source | Centre canadien de rayonnement synchrotron

Superconducting Magnets 1

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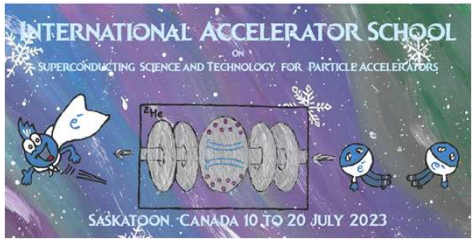
Lawrence Berkeley National Laboratory

IAS 2023

July 16-17, 2023



Introduction

- Superconducting Accelerator Magnet development is a very broad subject combining different disciplines from *material science to magnetics, mechanical engineering, cryogenics, power electronics and related instrumentation and diagnostics*
- This short overview will focus on those aspects that are of more direct relevance to accelerator design, and less on magnet engineering details
- Reference to more extensive courses and literature are provided (next slide)
- We will also try to *minimize overlap with other classes at the IAS*:
  - *Basics of Superconductivity*
    - Type II Superconductors: critical fields and flux pinning
  - *Accelerator Physics Primer*
    - Field errors and their effect on the beam
  - *Linear Optics – Magnets*
    - Magnetic Design: Coil and iron yoke contributions, End fields
    - Quench process
  - *Cryostat Technology for Accelerators*

References

US Courses:

- USPAS 2015: Superconducting Magnets for Particle Accelerators (P. Ferracin, S. Prestemon, E. Todesco) https://indico.cern.ch/event/440690/?view=nicecompact
- USPAS 2022: Superconducting Accelerator Magnets (P. Ferracin, S. M. Marchevsky, Prestemon, E. Todesco) https://conferences.lbl.gov/event/979/

CERN Courses:

- John Adams Institute Accelerator Courses: Magnet Design (A. Milanese): https://indico.cern.ch/event/1101643
- Masterclass - Design of superconducting magnets for particle accelerators (E. Todesco) https://indico.cern.ch/category/12408/
- CERN Summer Student Lectures 2023: Accelerator Technology Challenges – Magnet Design (S. Izquierdo Bermudez) https://indico.cern.ch/event/1254879/
- Upcoming! (November 2023): CAS School on Normal and Superconducting Magnets, St. Polten, Austria, https://indico.cern.ch/event/1227234/

Books: from classics to more recent publications

- Martin N. Wilson, "Superconducting Magnets“ (1983)
- Fred M. Asner, "High Field Superconducting Magnets“ (1999)
- K.-H. Mess, P. Schmuser, S. Wolff, “Superconducting accelerator magnets” (1996)
- S. Russenschuck, “Field computation for accelerator magnets” (2010)
- D. Schoerling and A. V. Zlobin, “ Nb_3Sn Accelerator Magnets” (2019)

Presentation Outline

Part 1: fundamentals of superconducting accelerator magnet design

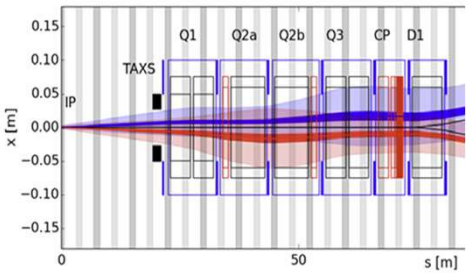
- Superconducting Accelerator Magnet Overview
- Practical Superconductors for Accelerator Magnets
- Wire and Cable Design
- Magnetic Design, margin and training
- Coil forces and stress
- Quench Protection

Part 2: advanced technologies and applications

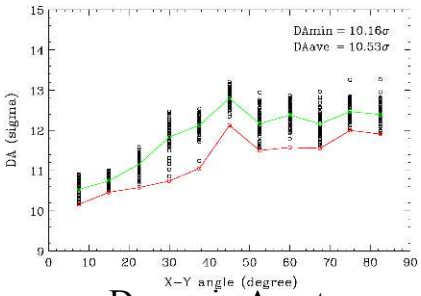
- Recent progress in superconducting accelerator magnet development
  — Selected topics and highlights in magnet design and fabrication
- Special Accelerator magnets
- Benefits of accelerator magnet development to broader applications in science, medicine and industry

Accelerator Magnet Development Overview

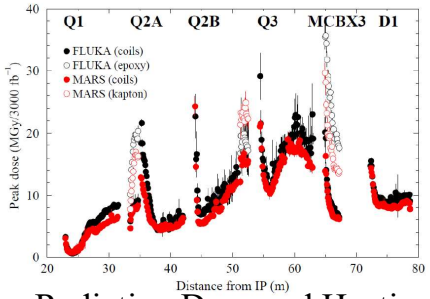
Accelerator Requirements and Constraints



Aperture and Field (integral)



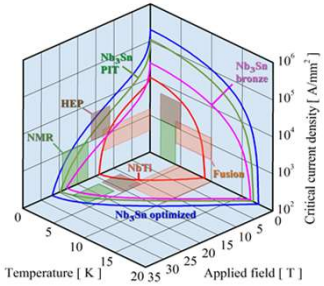
Dynamic Aperture



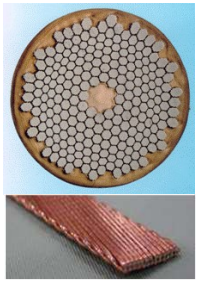
Radiation Dose and Heating

Space, Infrastructure, Transport

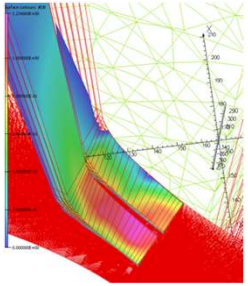
Conceptual Design and Analysis



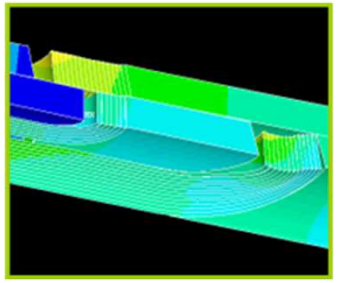
Material properties



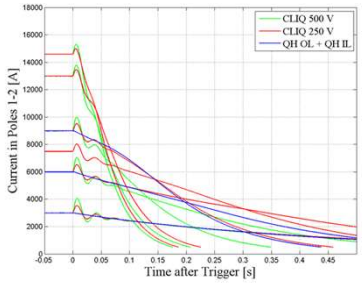
Wire and cable



Magnetic Analysis

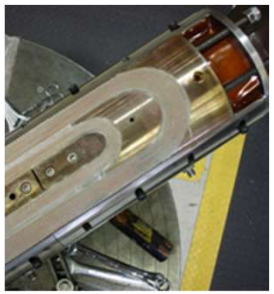


Mechanical Analysis

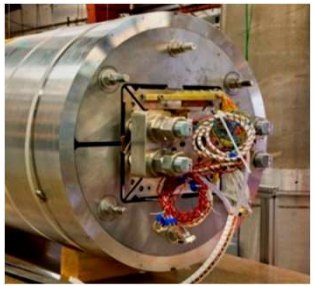


Quench Protection

Engineering Design, Fabrication, Testing and Integration

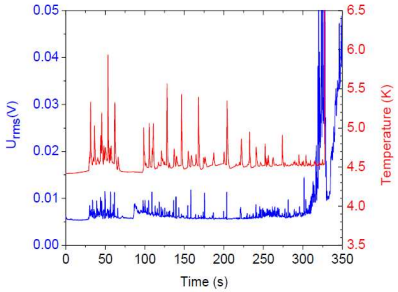


Coil Fabrication

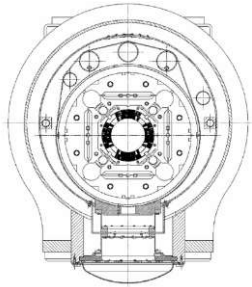


Structure and Assembly

Cryogenic Testing



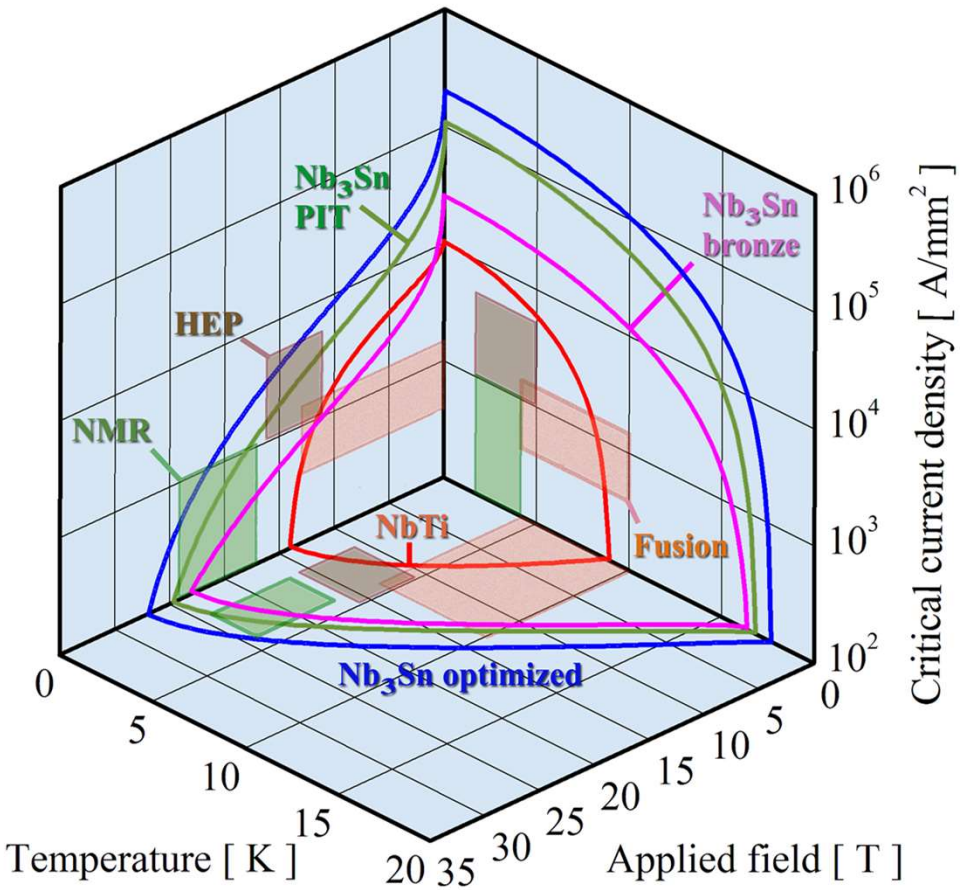
Instrumentation



Cryostat Design

Practical Superconductors: Critical Surface

Operating space of practical
Low-Temperature Superconductors (LTS)
for magnet applications



Niobium-Titanium (NbTi)

- Ductile alloy
- Upper critical field (B_{C2}): ~15T
- Critical Temperature (T_c): ~10K
- Used in most projects to date

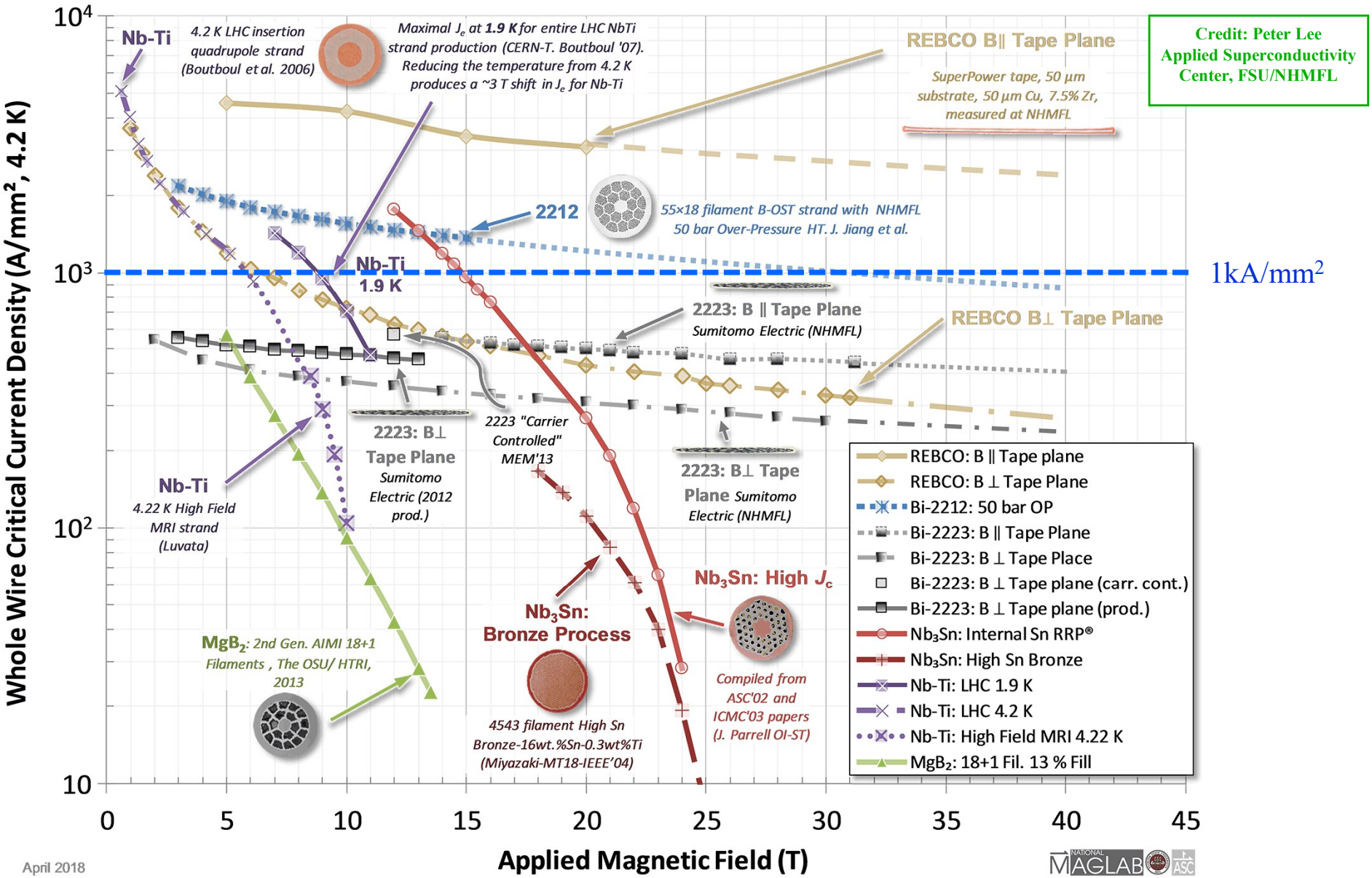
Niobium-Tin (Nb_3Sn)

- Brittle and strain sensitive
- Upper critical field (B_{C2}): ~28T
- Critical Temperature (T_c): ~18K
- In production for HL-LHC

High Temperature Superconductors

- MgB2, Bi-2212, YBCO
- Great potential with significant technology challenges

Conductor Properties and Design Space

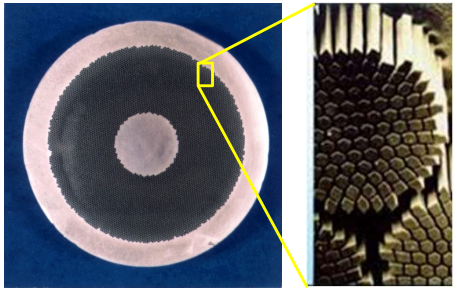


Conductor Technologies

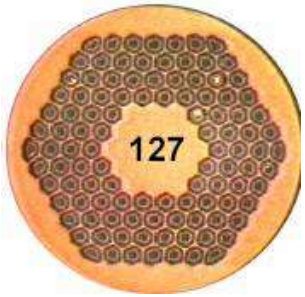
Material	NbTi	Nb_3Sn (Nb_3Al)	Bi-2212	YBCO
Max Field	10-11 T	16-17 T	Stress limited	Stress limited
Reaction	Ductile	~675^{0}C in Air/Vacuum	~890^{0}C in O_2 ($\pm$2^{0}C)	None
Wire axial compression	N/A	Reversible	Irreversible?	Reversible
Transverse stress	N/A	< 200 MPa	60 MPa?	> 150 MPa
Insulation	All	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)	~0.01 m/s? (4.2 K, self-field)

Superconducting Wire Architecture

- The basic building block of an accelerator magnet is the superconducting wire
- Typical diameters in the range of 0.5-1.5 mm and continuous uniform lengths of 1-20 km
- Designed as a matrix of thin superconducting filaments embedded in pure copper



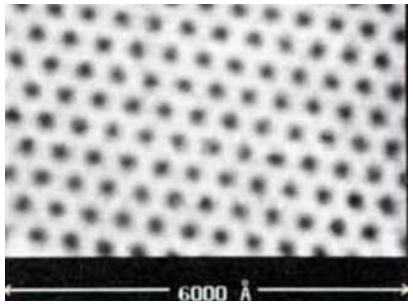
NbTi (LHC MB)



Nb_3Sn (LARP HQ)

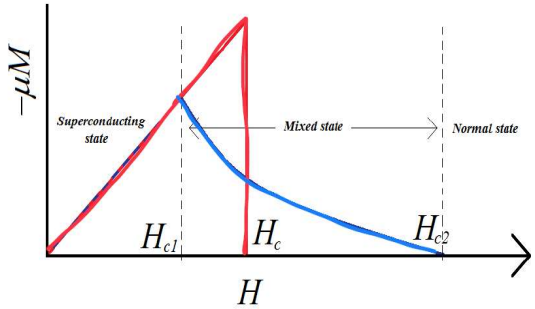
Main drivers of the multi-filamentary wire architecture

Flux pinning



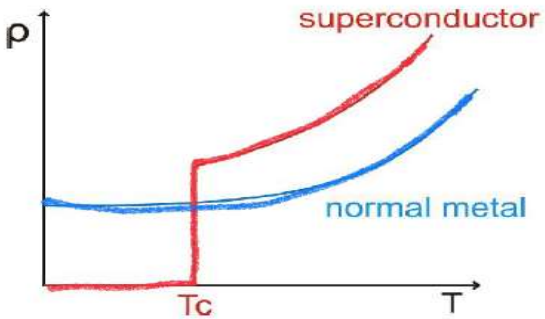
Instabilities due to redistribution of flux vortices ("flux-jumps") limit the current that can be carried as a unit

Magnetization effects



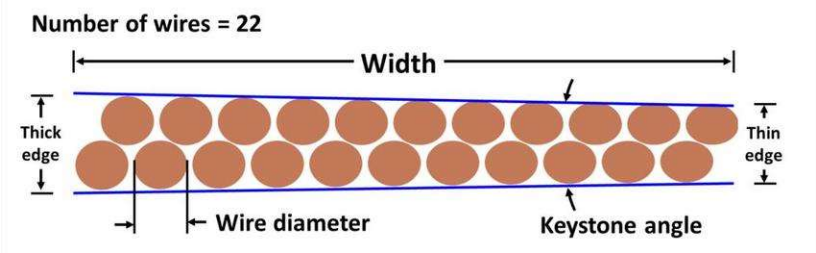
Field errors due to internal shielding "persistent" currents proportional to the SC filament diameter

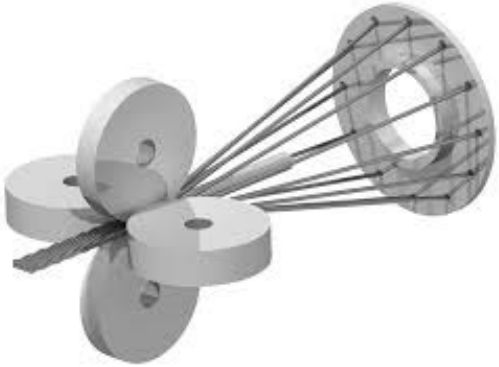
Quench Protection



During a quench, the copper matrix (briefly) provides a low resistance path for the magnet current

Rutherford Cables





Rutherford cables address several fundamental (and conflicting) magnet requirements:

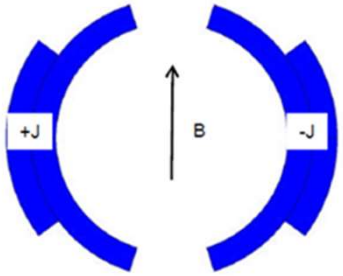
- Provide high current-carrying capability (up to 10-20 kA) to limit magnet inductance and related voltages, in particular during a fast discharge in case of a quench (<1kV)
- …while retaining sufficient flexibility and mechanical stability for coil winding
- …and high compaction (~90%) with low J_c degradation for high coil-pack current densities
- …and precise geometry (~10 μm) for accurate coil field quality and stress control
- …and control of dynamic effects during a current ramp (strands are twisted and transposed)

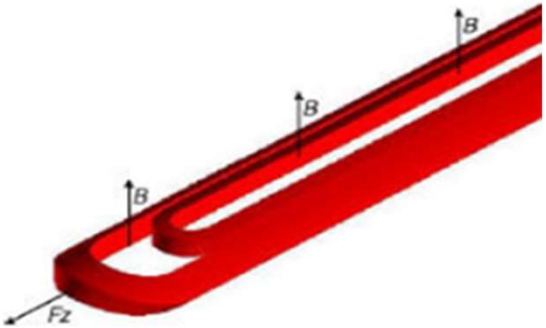
They also offer some important practical advantages:

- Rectangular (or trapezoidal) shape provides effective management of coil internal forces/stress
- Large number of wires (strands) lower the continuous length required in wire production
- Capability to achieve a range of conductor characteristics from a given strand design

Superconducting Coils

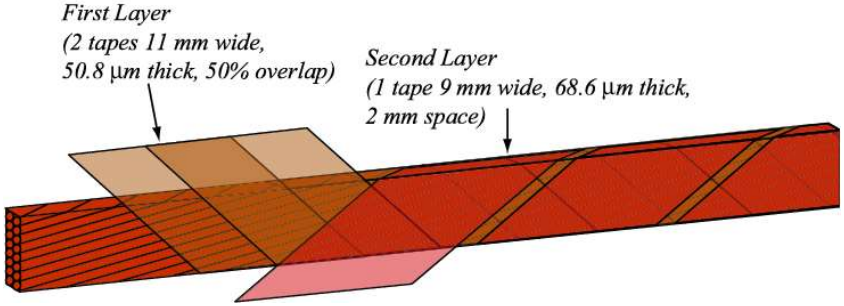
- Typical accelerator coils windings have a long (1-15 m) straight section generating a transverse field, and two short end sections to complete each turn and transition to the next one



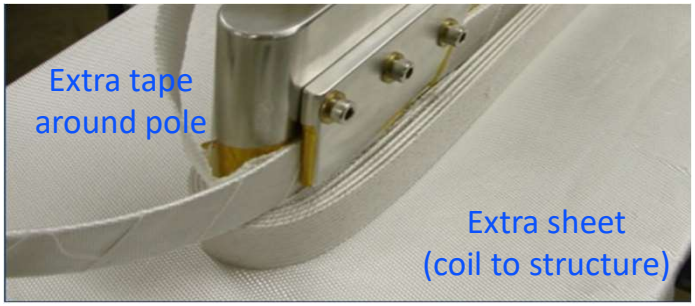


- Electrical insulation is paramount. Each turn is electrically insulated. Additional insulation is placed between coil layers, and around the entire coil to prevent shorts to the structure

Polyimide tape insulation scheme used in LHC magnets (NbTi)



Fiberglass braid/sleeve used in Nb3Sn magnets



- The effective current density is averaged across superconductor, copper stabilizer, internal components (wedges and spacers) and electrical insulation
- About 2 orders of magnitude higher than can be achieved in normal conducting coils

Shell-type coil design

- Basic concept: approximate a cos(nθ) current distribution around the aperture
- For n=1: $j(\theta)=j_0\cos\theta$ generates a perfect dipole; n=2 generates a quadrupole etc.
- In practice, this current distribution is approximated using spacers (wedges) between turns, optimized to reduce deviations from the prescribed field

- In the magnet straight section, the 2D field can be expressed as a series of harmonics (already described in the "linear optics – magnets" presentation):

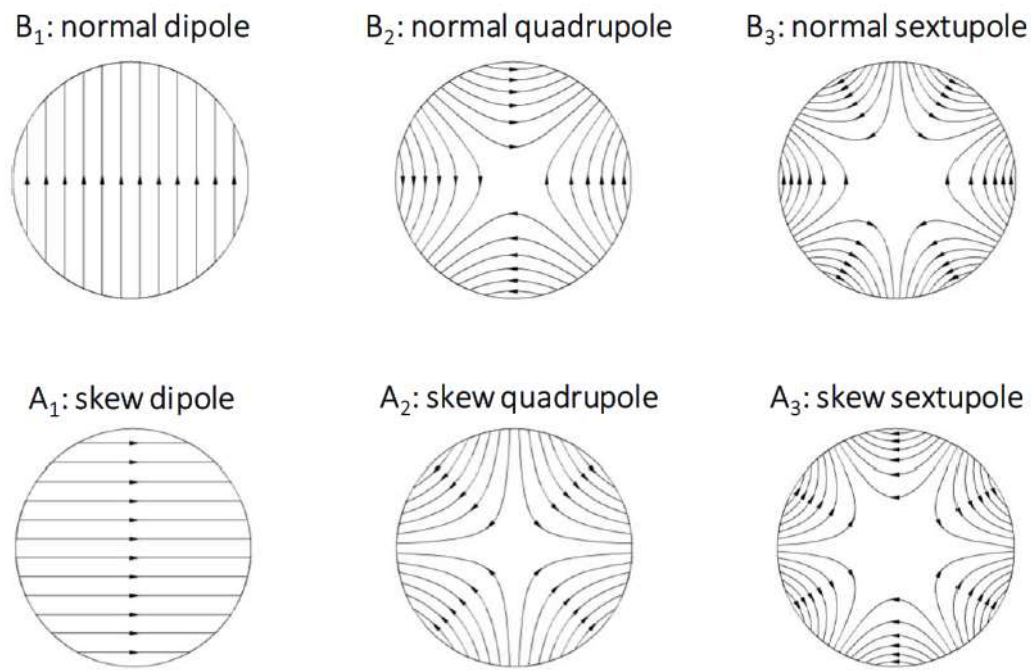
$$B_y(x,y) + iB_x(x,y) = \sum_{n=1}^{\infty}(B_n + iA_n)\left(\frac{x+iy}{r_0}\right)^{n-1}$$

Field Patterns from Harmonic Terms

1. Flux Lines

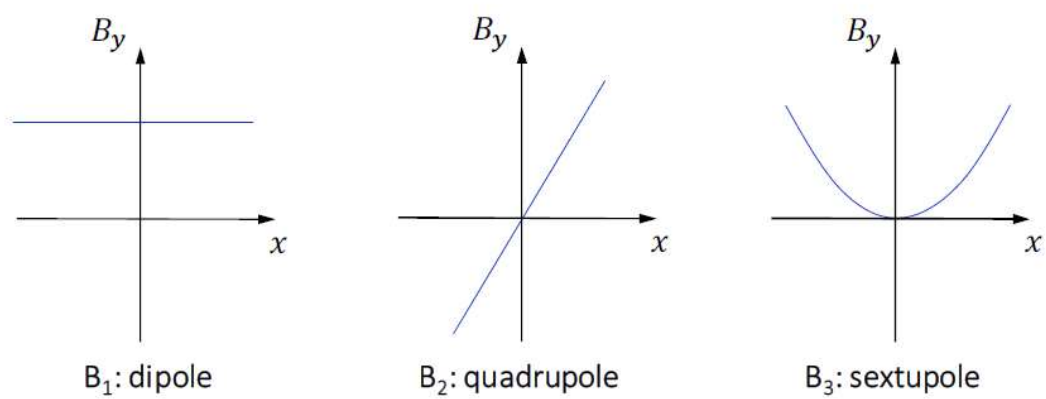
$$B_r = \sum_{n=1}^{\infty} \left(\frac{r}{R}\right)^{n-1} [B_n \sin(n\theta) + A_n \cos(n\theta)]$$

$$B_\theta = \sum_{n=1}^{\infty} \left(\frac{r}{R}\right)^{n-1} [B_n \cos(n\theta) - A_n \sin(n\theta)]$$



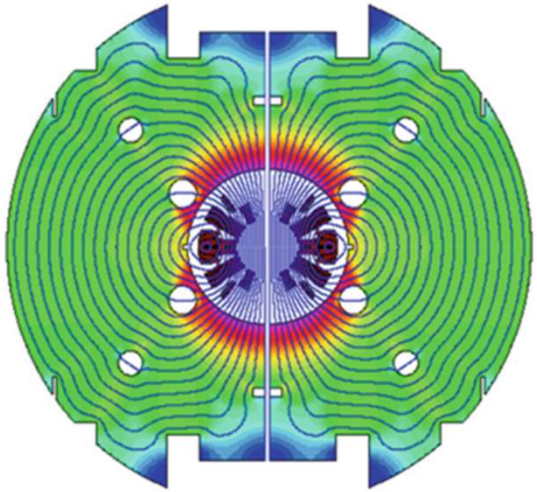
2. Field profile in the horizontal plane

$$B_y(x) = \sum_{n=1}^{\infty} B_n \left(\frac{x}{R}\right)^{n-1} = B_1 + B_2 \frac{x}{R} + B_3 \frac{x^2}{R^2} + \cdots$$



Iron Yoke

The superconducting coil is usually surrounded by an iron yoke made of ferromagnetic steel

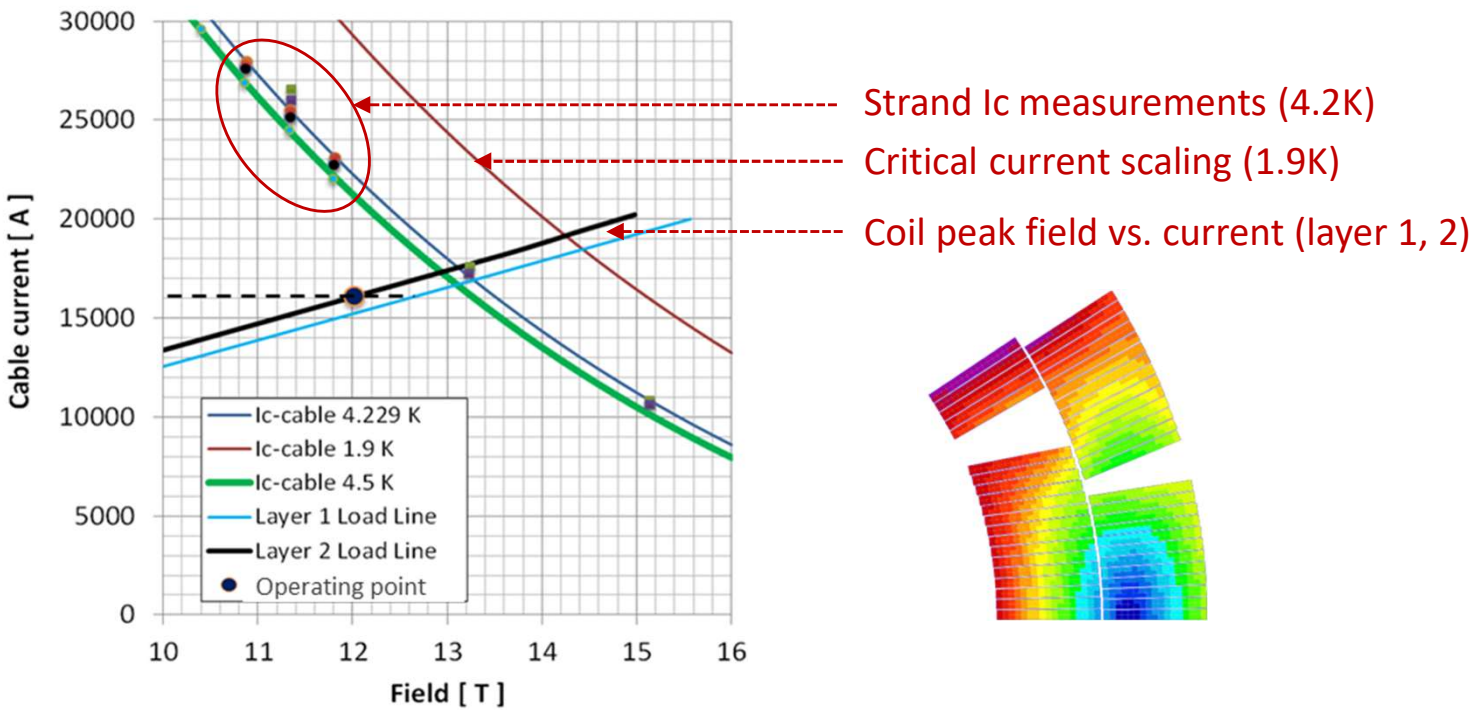


The iron yoke performs several essential functions:

1. Contribute to the field in the aperture. For a circular yoke that is not saturated (<2T) this contribution is linear and can be calculated with the "image currents" method
   - If the yoke is saturated (>2T) non-linear field errors are generated as a function of current: need to optimize geometry to minimize or balance these effects
2. Return the magnetic flux, limiting fringe field and coupling with surrounding elements
   - For a dipole, the required iron thickness is ~B/2 times the aperture radius
3. The yoke is often used as an integral component of the mechanical structure

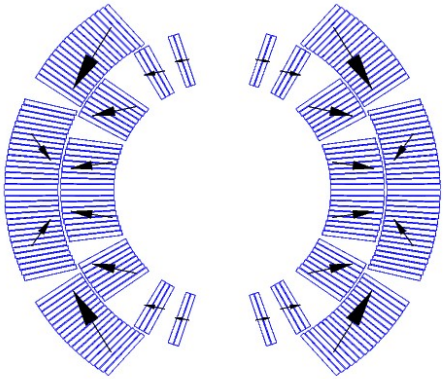
Coil Field and Margin to Quench

- In order to maintain its superconducting state, the conductor must operate within the envelope defined by its critical surface
- Assuming that the temperature is set by the cryogenic system, as the magnet is energized, current density and field increase along the so-called "load line"
- The operating point along the load line is defined as the fraction of the operating current to the critical current, usually below 80-85% to provide sufficient margin



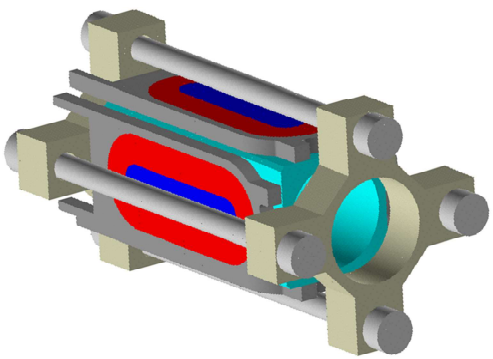
Coil Forces and Stress

- The combination of high field and current results in large electromagnetic forces acting on the superconducting coil as the magnet is energized
- Accumulated force is of the order of 100s of tons/m pointing outward
  - Radial force is linear with aperture and quadratic with field
  - Axial force scales with the square of both aperture and field
- Corresponding coil stress can reach 100-150 MPa (MN/m^2) which can cause insulation damage and conductor degradation
- Any slippage under friction will release thermal energy causing a quench
- Mechanical design approach: pre-compress the coil before energization

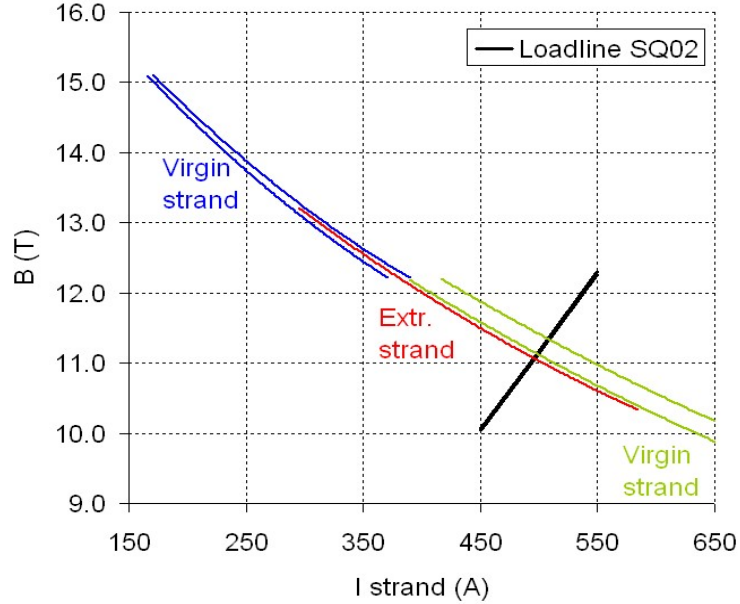


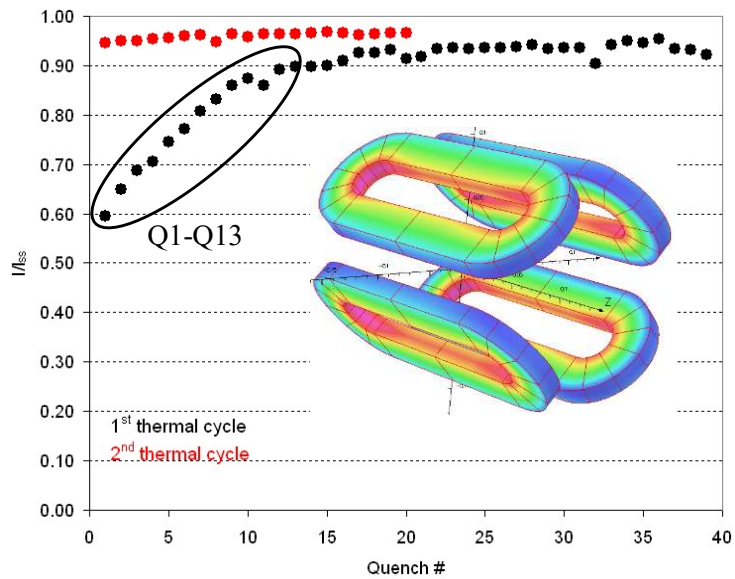
Electromagnetic force pattern in a dipole magnet

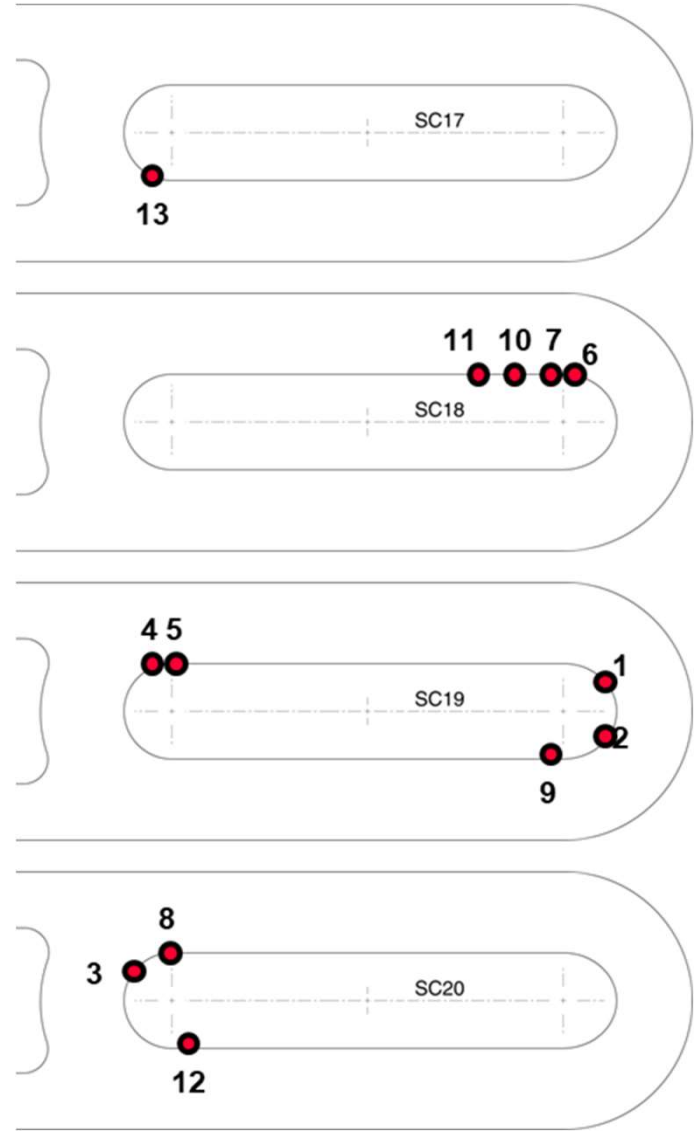
Quench Training: LARP SQ Test



P. Ferracin et al., LBNL







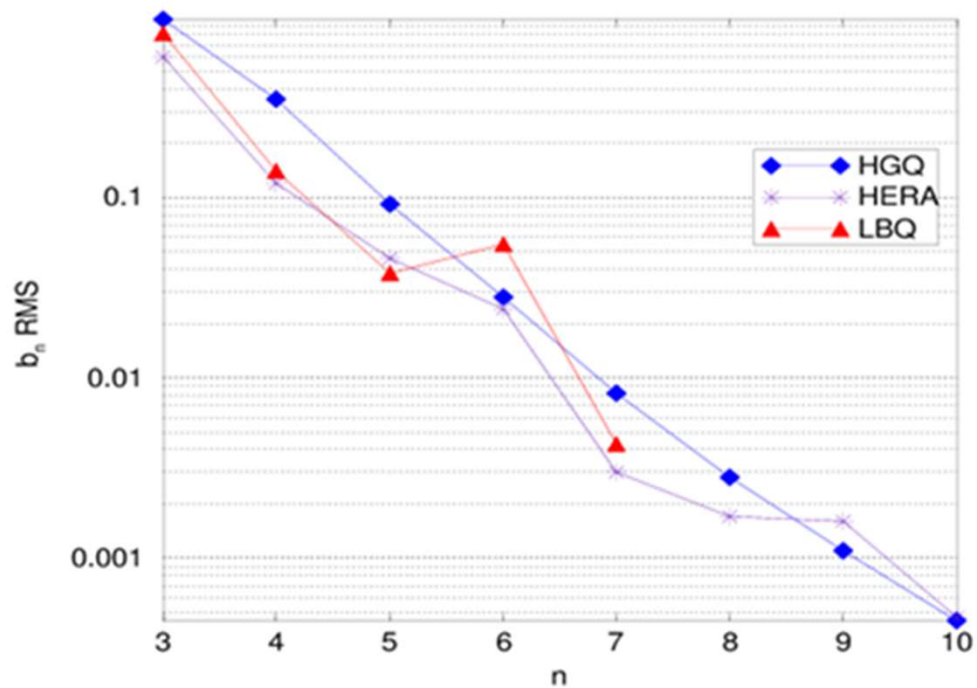
Geometric Field Quality

Design errors:

- Caused by deviations from the ideal current distribution
- Only a subset of harmonic components are “allowed” by symmetry
- Need to balance field quality against complexity (e.g. number of wedges)

Fabrication errors:

- Effect of fabrication tolerances can be estimated by Monte Carlo simulations
- Conductor positioning within ±50 μm is usually achieved in cosθ magnet production
- Larger errors may be expected for first (only) units or other design/fabrication methods



Coil End Optimization: Winding Pattern

End windings often require the bending patterns at the limit of the cable mechanical stability:

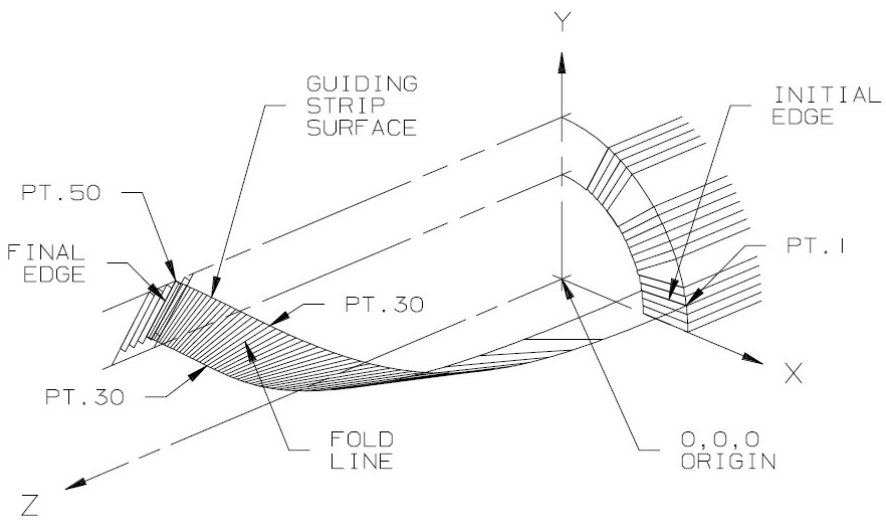
- Individual strands raising above the cable surface cause potential damage and electrical shorts
- If the cable completely loses its shape ("roping") it may result in loss of the entire unit length

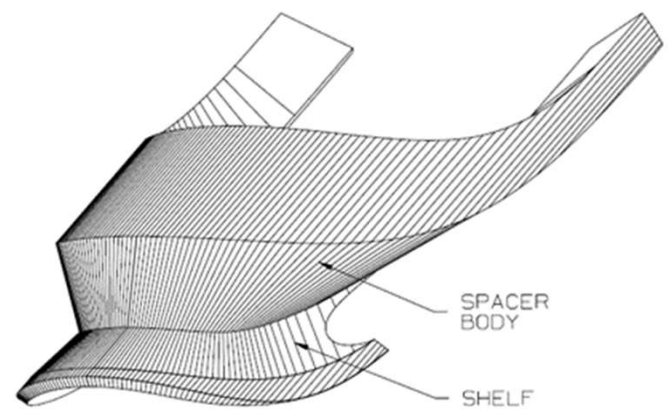
Main objective of the mechanical optimization is minimizing the cable strain energy function:

$$E = \frac{1}{2}\int_0^{s_c} \left(f_\tau\, \tau(s)^2 + f_{\kappa_n}\, \kappa_n(s)^2 + f_{\kappa_g}\, \kappa_g(s)^2\right) \mathrm{d}s$$

τ, κ_n, κ_g are the curvatures (torsion, normal and geodesic) to be optimized along the cable length s

$f_\tau, f_{\kappa_n}, f_{\kappa_g}$ are the mechanical properties (flexural rigidities) for the specific cable parameters

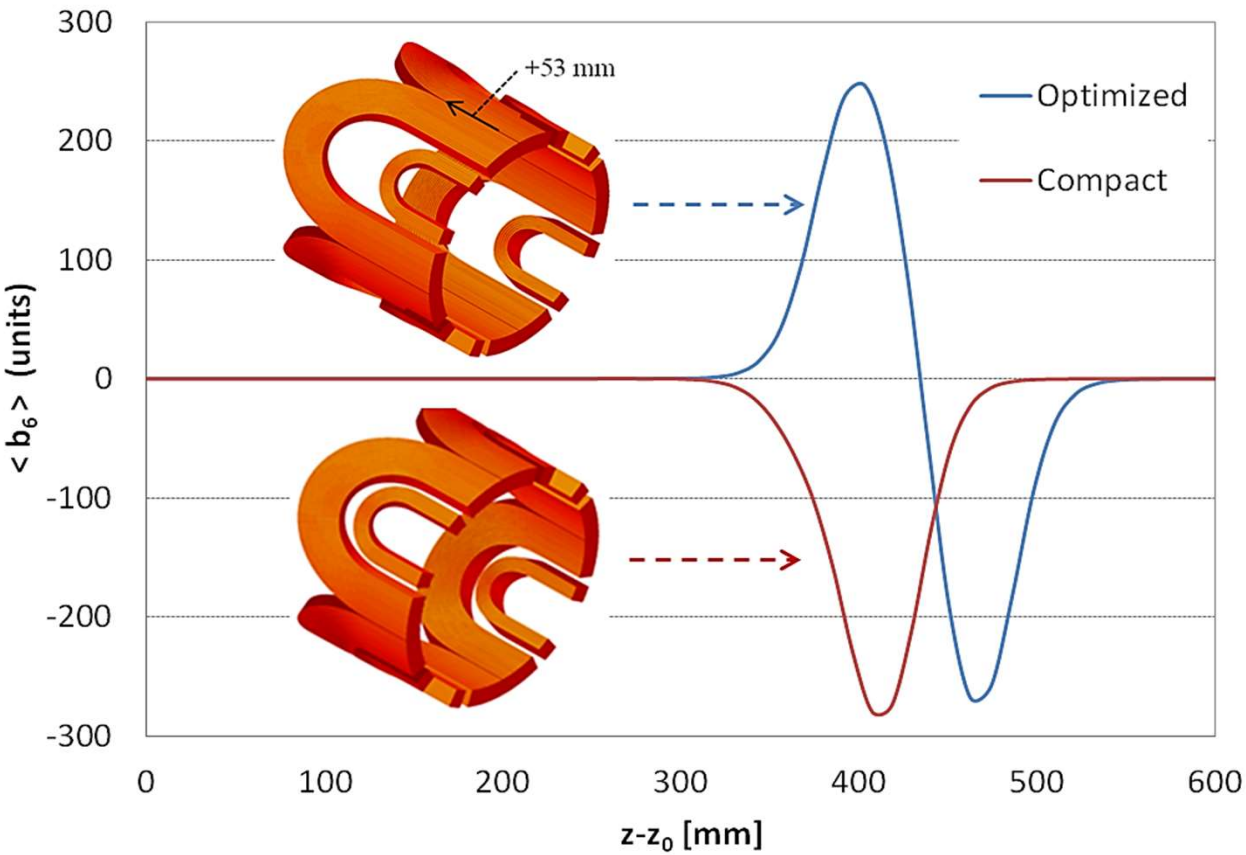


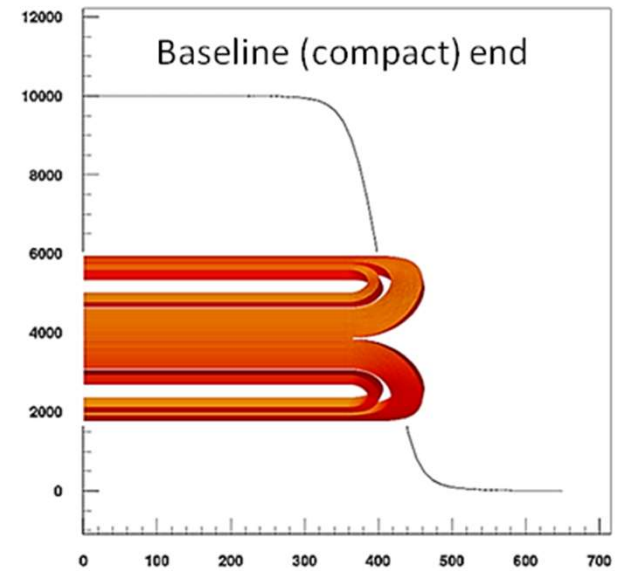


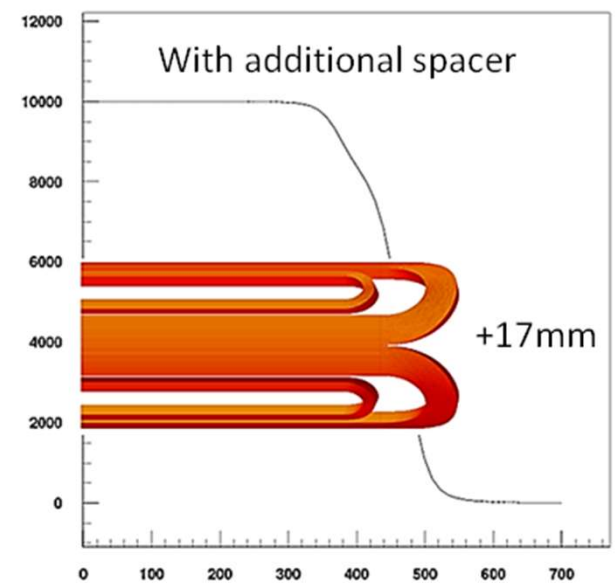
J. Cook, ANL; R. Bossert, J. Brandt (FNAL)

Coil End Optimization: Field Quality

- Integrated harmonics can be corrected with spacers but total magnet length will increase
- For higher order harmonics, need to split blocks
- Feedback from AP will provide guidance

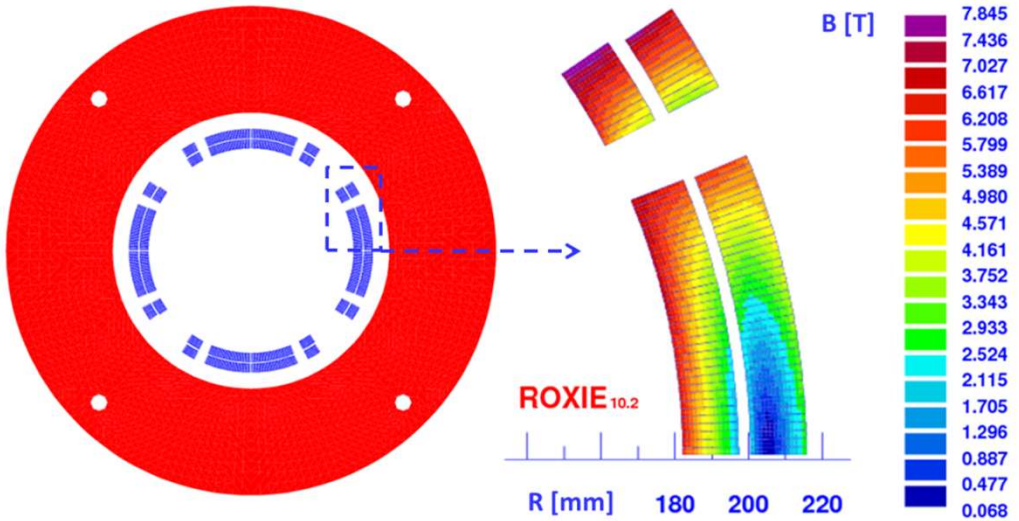


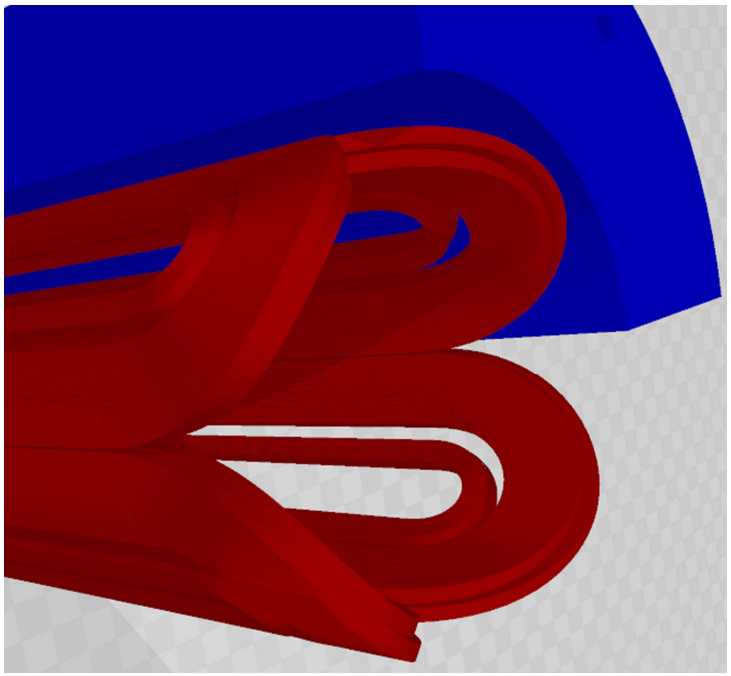


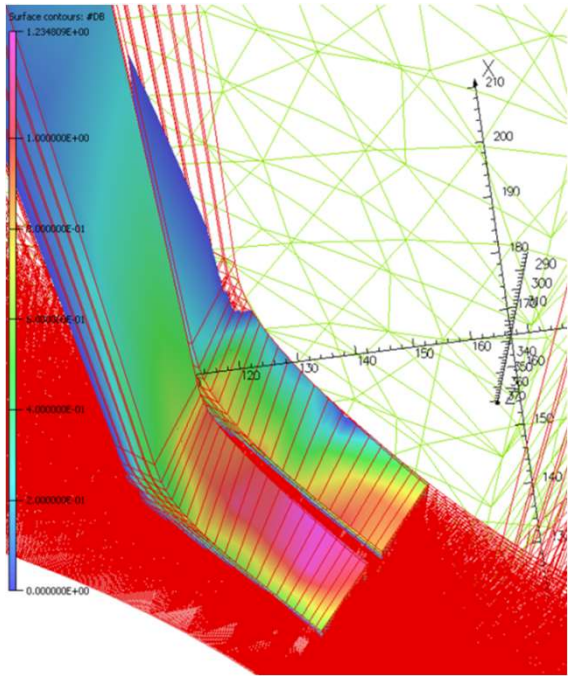


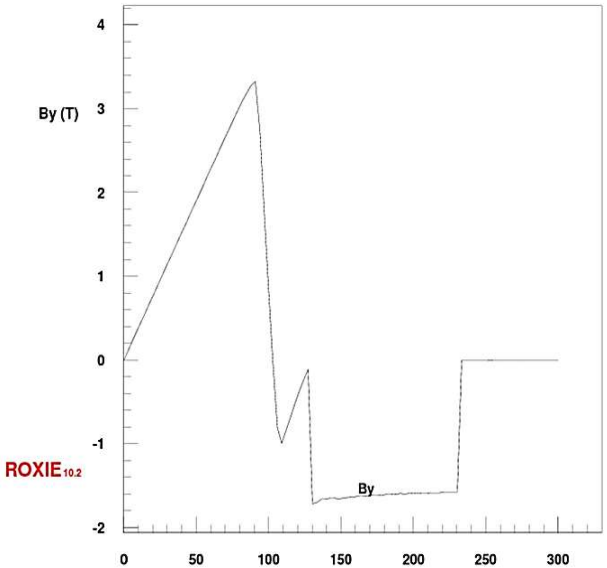
Coil End Optimization: Peak Field

- Coil field may increase by 10-20% in the ends
- Can be offset by reducing or eliminate iron yoke over the ends, but this can affect the mechanical performance and increase the fringe field
- Additional margin from increased block spacing or splitting blocks



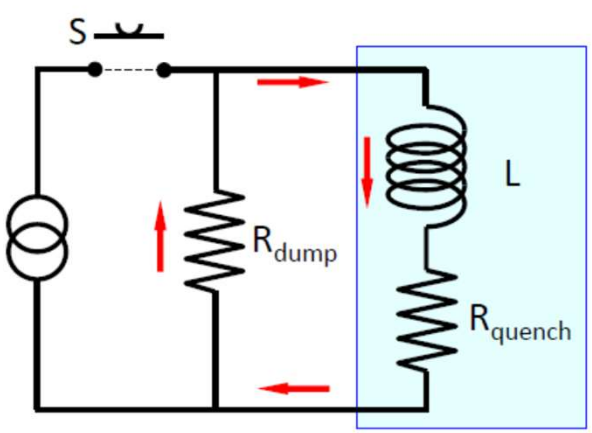


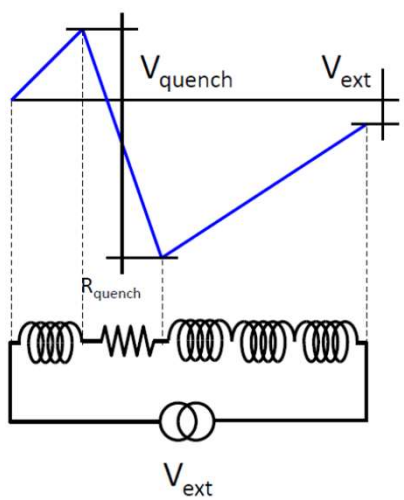




Quench Protection

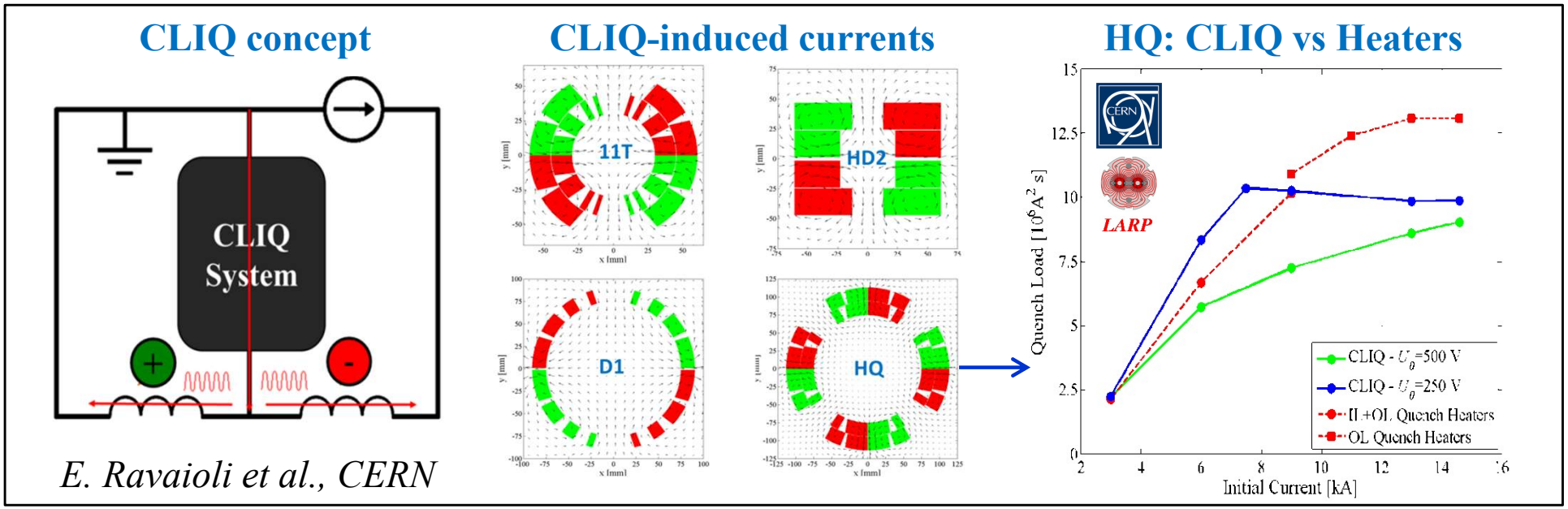
- A quench occurs when a portion of the coil transitions to the normal conducting state due to local degradation or heat release (conductor motion under forces, radiation etc.)
- The magnet stored energy is quickly dissipated in the resistive area, leading to temperature and pressure increase, current variations, resistive/inductive voltage, thermal/EM forces
- Natural propagation of the resistive area is generally too slow to distribute the energy over a sufficiently large volume to avoid damage
- Therefore, quench propagation needs to be accelerated by heating the coil and/or the magnet has to be quickly discharged into an external dump





Advanced Protection Techniques

- More effective protection can broaden the design space in critical areas:
  - *Reducing the copper fraction from 60% to 40% equals a 50% increase of J_c*
  - *Increasing limits on stored energy density leads to more efficient designs*
  - *Limits on the inductance may constrain the cable design to sub-optimal choices, or even eliminate design approaches requiring smaller cables*
- Balancing quench heater efficiency vs. electrical integrity has proven problematic
- The "Coupling Loss Induced Quench" (CLIQ) system developed by CERN is having a transformative impact on design options: take full advantage of this opportunity



Summary: Accelerator Magnet Design

Main drivers: address stringent beam physics requirements and minimize cost

Technical requirements:

- Aperture
- Field quality (*geometric, saturation, persistent currents, eddy currents)*
- Mechanical support
- Quench protection

Efficiency/cost requirements:

- Limit power consumption – use SC magnets
- Minimize conductor & structure cost/size
- Powering of many magnets in series
- Achieve high operational field
- Lifetime under radiation load
- Fabrication in (very) Long Lengths

LHC

- Selection of magnet layout and accelerator parameters is closely coupled *(e.g. optimal coil layout depends on required aperture and field quality)*
- Magnet R&D goal is to inform the overall accelerator optimization process
  - *Initial design simplifications for fast feedback on fundamental issues*
  - But eventually, all accelerator quality issues need to be addressed