# Magnet Technology Developments

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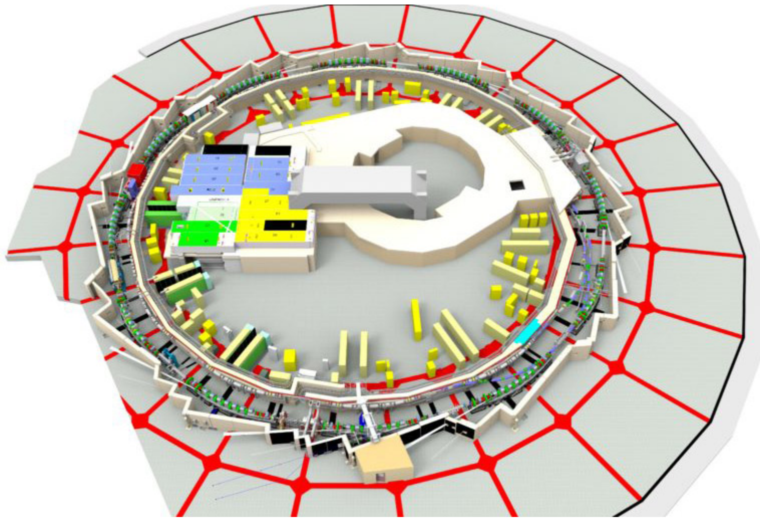
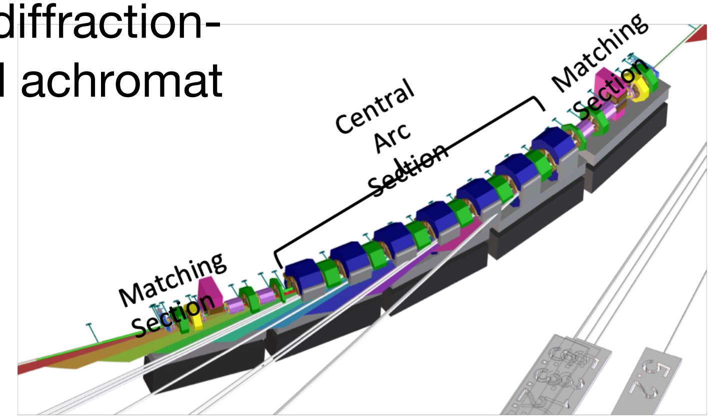
# Outline

- Magnet technologies for accelerators colliders
- Some highlights of modern magnet concepts and their implementations for accelerators
- Advanced superconducting accelerator magnets
  - Current status and ongoing research
  - What the future promises
- Summary

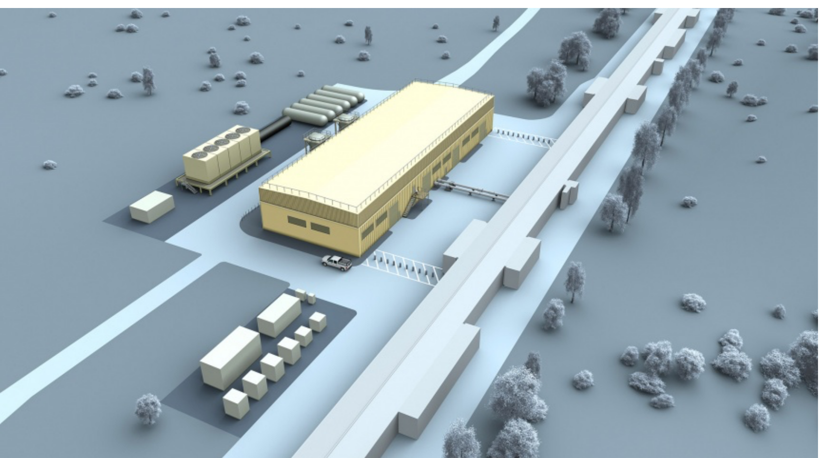
# Light sources are ubiquitous, with greatly enhanced performance – a couple of local examples…



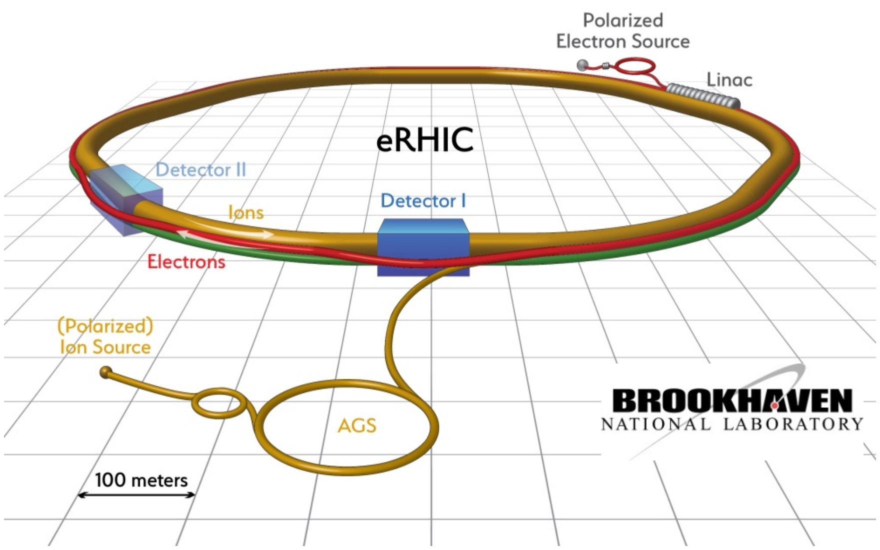
ALS-U: a planned upgrade of LBNL's ALS to a diffraction-limited multi-bend achromat storage ring

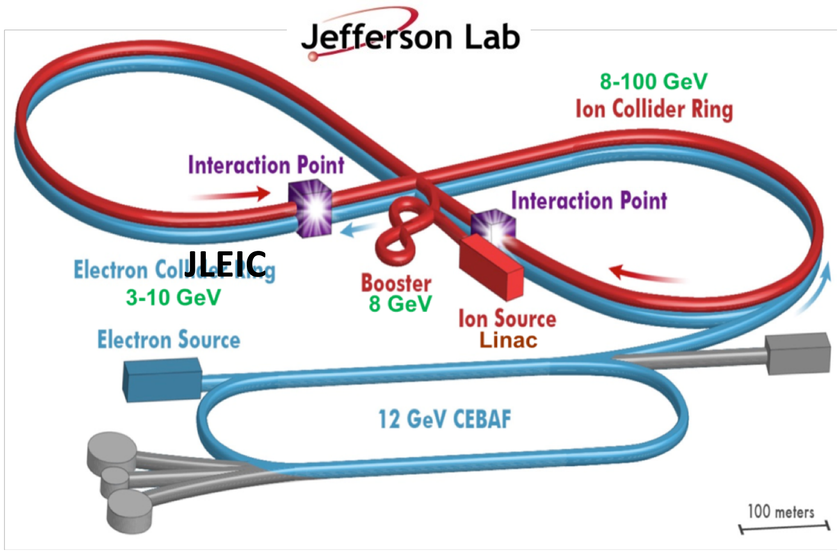



LCLS-II: a high-repetition-rate soft and hard x-ray FEL under construction at SLAC



# In the US, an electron-ion collider is under consideration



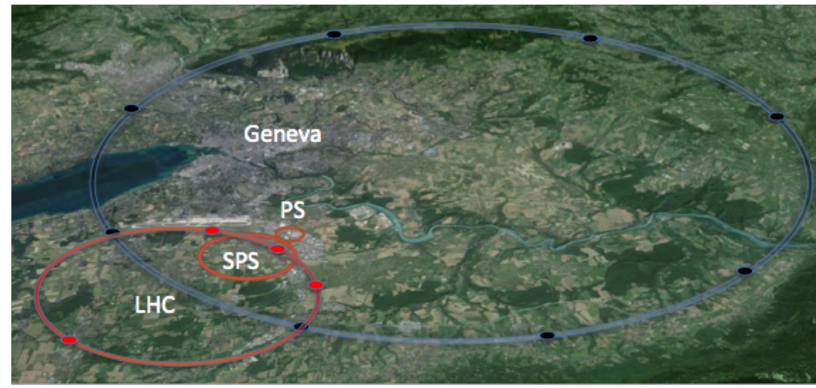

| Collider design parameters (*) | Unit | eRHIC | JLEIC |
|---|---|---|---|
| Proton beam energy | GeV | 275 | 100 |
| Electron beam energy | GeV | 10 | 10 |
| COM energy | GeV | 100 | 65 |
| Maximum Luminosity | $10^{34}cm^{-2}s^{-1}$ | 1.21 | 1 |

(*) Initial targets. Performance upgrades are foreseen for both machines.

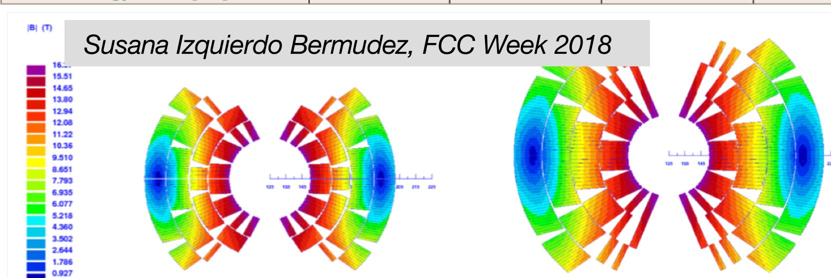
# CERN is advancing serious designs for an FCC, HE-LHC

*Frank Zimmermann, FCC Week 2018*

| parameter | FCC-hh | | HE-LHC | HL-LHC | LHC |
|---|---|---|---|---|---|
| collision energy cms [TeV] | 100 | | 27 | 14 | 14 |
| dipole field [T] | 16 | | 16 | 8.33 | 8.33 |
| circumference [km] | 97.75 | | 26.7 | 26.7 | 26.7 |
| beam current [A] | 0.5 | | 1.1 | 1.1 | 0.58 |
| bunch intensity [$10^{11}$] | 1 | 1 | 2.2 | 2.2 | 1.15 |
| bunch spacing [ns] | 25 | 25 | 25 | 25 | 25 |
| synchr. rad. power / ring [kW] | 2400 | | 101 | 7.3 | 3.6 |
| SR power / length [W/m/ap.] | 28.4 | | 4.6 | 0.33 | 0.17 |
| long. emit. damping time [h] | 0.54 | | 1.8 | 12.9 | 12.9 |
| beta* [m] | 1.1 | 0.3 | 0.25 | 0.15 (min.) | 0.55 (0.25) |
| normalized emittance [μm] | 2.2 | | 2.5 | 2.5 | 3.75 |
| peak luminosity [$10^{34}$ $cm^{-2}s^{-1}$] | 5 | 30 | 28 | 5 (lev.) | 1 |
| events/bunch crossing | 170 | 1000 | 800 | 132 | 27 |
| stored energy/beam [GJ] | 8.4 | | 1.3 | 0.7 | 0.36 |

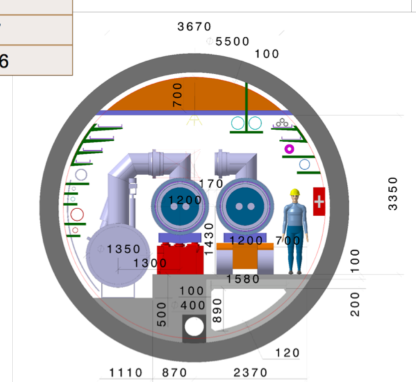


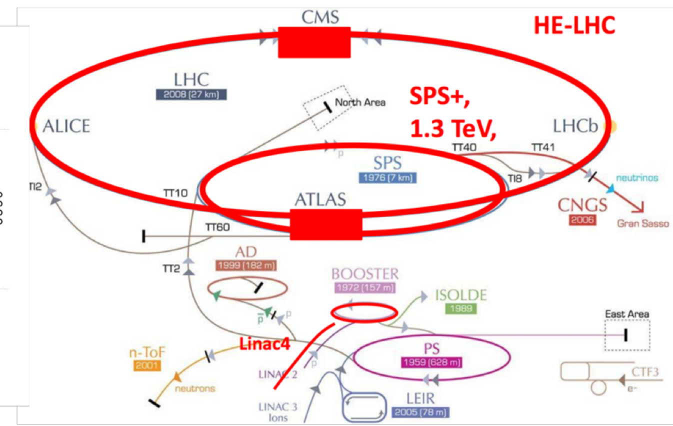

*Susana Izquierdo Bermudez, FCC Week 2018*




**FCC target strand**
($J_c$ = 1500 A/mm² at 4.2 K, 16 T)

**HL-LHC strand**
($J_c$ = 1000 A/mm² at 4.2 K, 16 T)



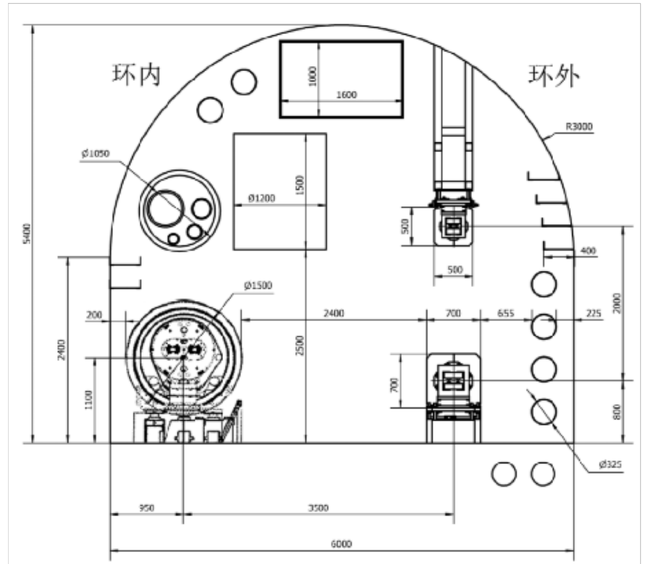
# China is proposing the SPPC using a unique conductor

**SPPC**

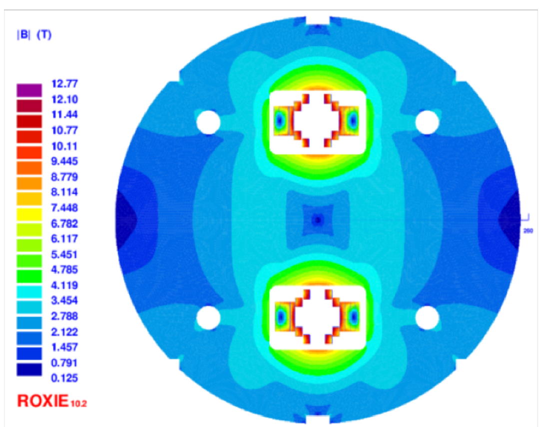
- **100 km** in circumference
- C.M. energy 70-150 (Upgrading) TeV
- Timeline

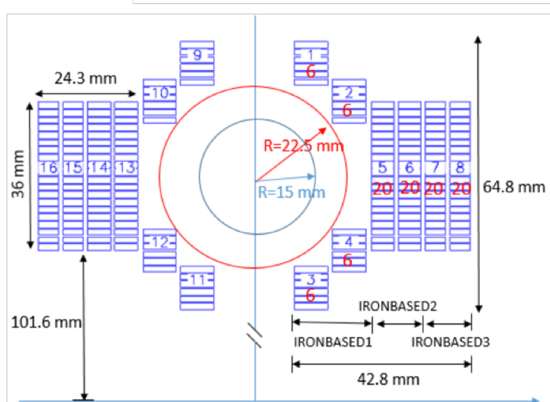
| | |
|---|---|
| Pre-study: | 2013-2020 |
| R&D: | 2020-2030 |
| Eng. Design: | 2030-2035 |
| **Construction:** | **2035-2042** |

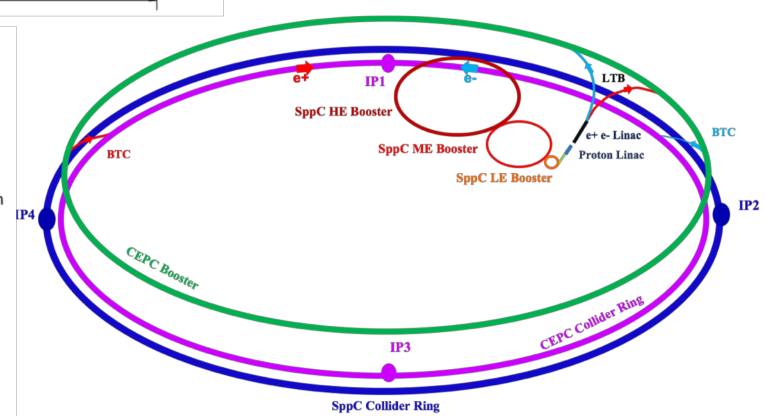
*Qingjin XU, FCC Week, April 11-14, Amsterdam*




***Make IBS the high-field "NbTi" Conductor in 10 years!***



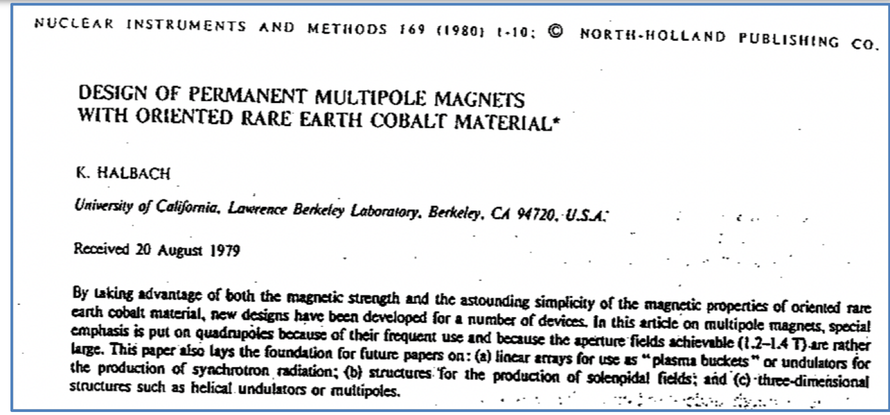



# Magnet designers have three primary magnet technologies to leverage for the control of beams

- Permanent magnets
  - Common for “insertion devices”
  - Growing interest and implementation in storage rings
- Electromagnets
  - Workhorse for light sources
  - Well-established, but continued development, especially in combined-function conditions
- Superconducting magnets
  - Workhorse of modern proton/ion colliders
  - Continued advances towards higher field
  - Growing interest in HTS materials

# Permanent magnets have a number of features that motivate a renaissance in light-source applications

- Impressive energy density makes PMs competitive for "small" scales; that is the direction modern diffraction-limited storage rings are headed
- Light weight, relatively low initial cost, no operational cost
- Elegant theory enables accurate modeling of fields, including error fields and their correction
- Issues
  - Not well suited for applications requiring significant varying fields
  - Somewhat intolerant of radiation – need to take into consideration in design


NUCLEAR INSTRUMENTS AND METHODS 169 (1980) 1-10; © NORTH-HOLLAND PUBLISHING CO.

DESIGN OF PERMANENT MULTIPOLE MAGNETS WITH ORIENTED RARE EARTH COBALT MATERIAL*

K. HALBACH

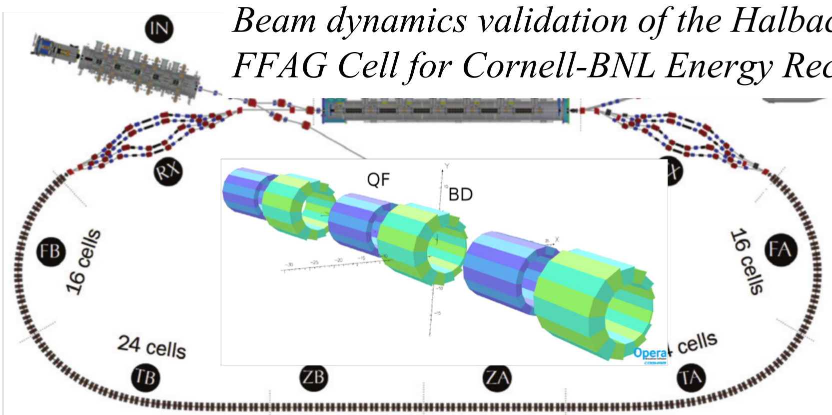
*University of California, Lawrence Berkeley Laboratory, Berkeley, CA 94720, U.S.A.*

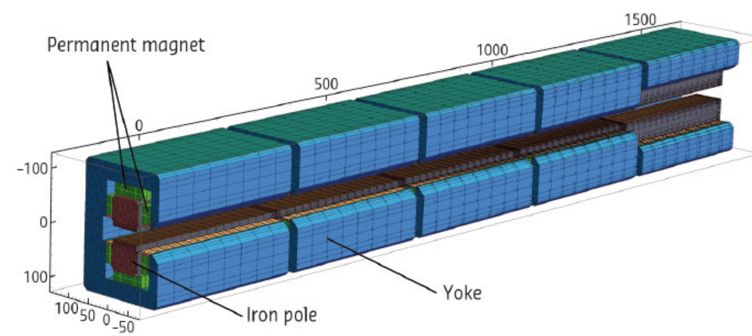
Received 20 August 1979

By taking advantage of both the magnetic strength and the astounding simplicity of the magnetic properties of oriented rare earth cobalt material, new designs have been developed for a number of devices. In this article on multipole magnets, special emphasis is put on quadrupoles because of their frequent use and because the aperture fields achievable (1.2–1.4 T) are rather large. This paper also lays the foundation for future papers on: (a) linear arrays for use as "plasma buckets" or undulators for the production of synchrotron radiation; (b) structures for the production of solenoidal fields; and (c) three-dimensional structures such as helical undulators or multipoles.

*See Ross Schlueter*
*USPAS course "Magnetic Systems: Insertion Device Design"*

*F. Meott et al., BNL-203292-2018-TECH*
*Beam dynamics validation of the Halbach Technology FFAG Cell for Cornell-BNL Energy Recovery Linac*



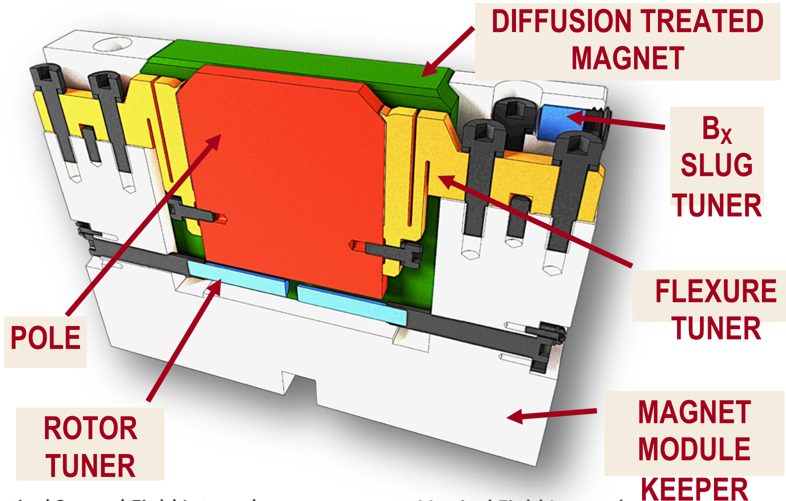



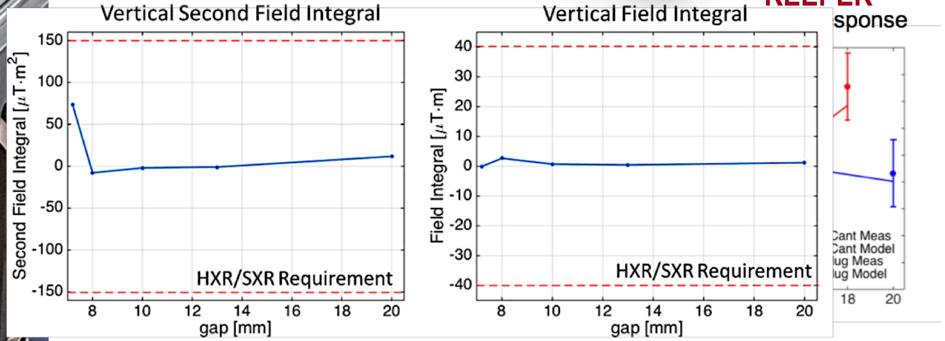

*J. Chavanne and G.Le Bec, IPAC **14**, Dresden Germany (2014)*

# LCLS-II Undulator magnet modules are designed for fine tuning

## Complementary Tuning Options Improve Corrections For Different Gap-Dependent Errors: Flexure Tuners, Rotor Tuners, $B_x$ Slug Tuners


*Courtesy Matthaius Leitner, Diego Arbelaez*



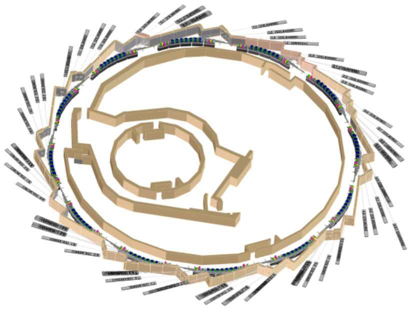



# Resistive magnets continue to evolve to enable the next generation storage rings

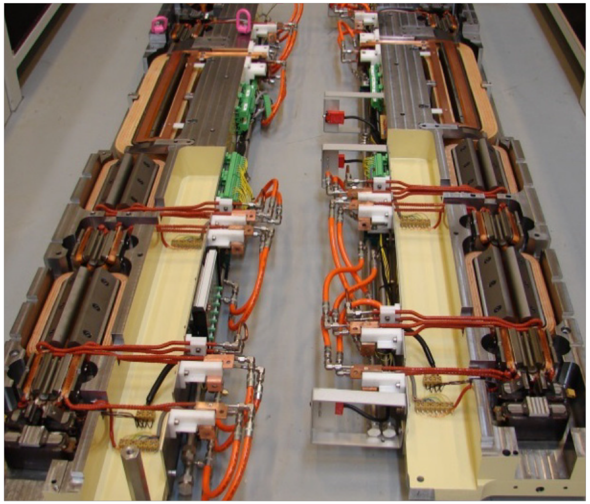
- Primary evolution directions:
  - Cost effective solutions – fewer parts, accurate machining with little or no in-situ measurements
  - Combined function magnets enabling sophisticated, compact lattices
    - main focus in storage rings is diffraction limited beams utilizing multi-bend achromats

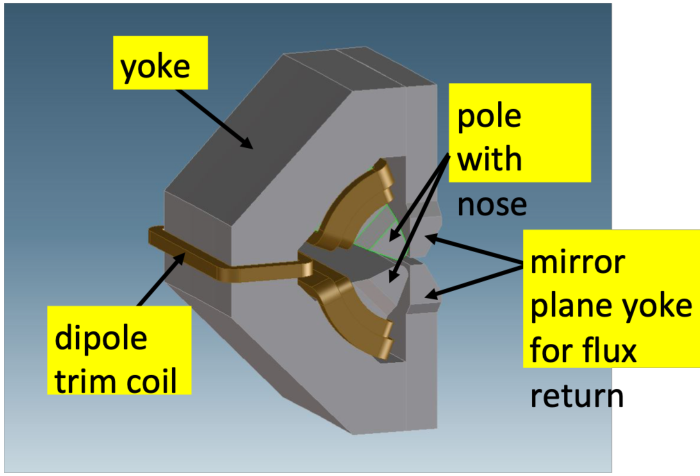
*Swenson et al, IPAC 2016*
*Conceptual design of storage ring magnets for a diffraction limited light source upgrade of ALS, ALSU*

ALS-U Ring



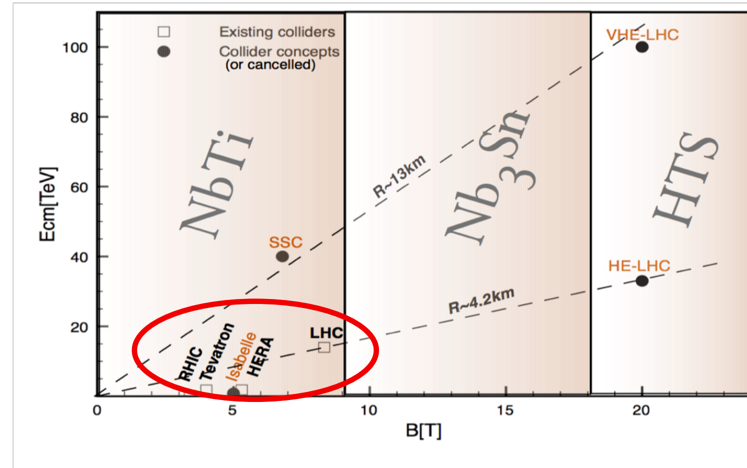
*Bodker et. al, IPAC 2013*
*Multiple function magnet systems for MaxIV*

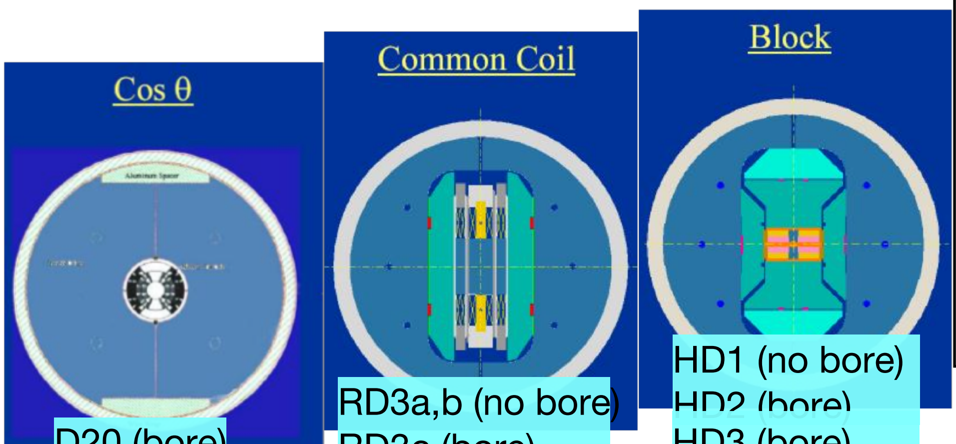


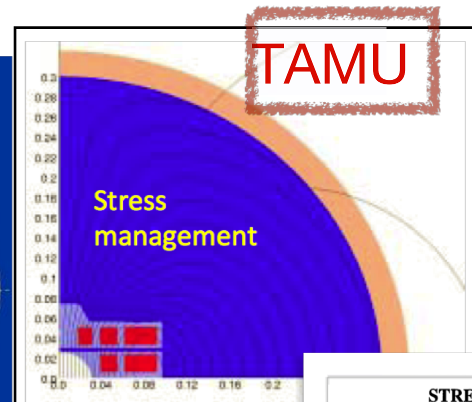


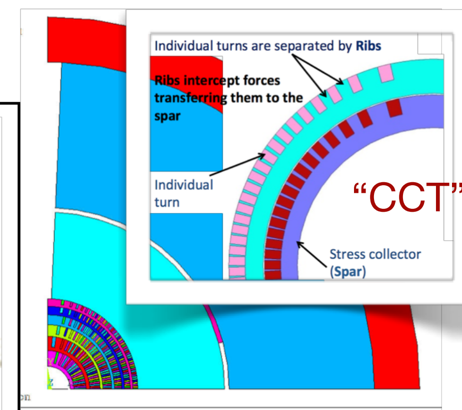
# Superconducting magnets are essential to modern colliders, and their performance limits the energy reach

- All colliders to-date utilize the “standard” Cos(φ) geometry
- Much broader spectrum of designs are under research
  - “Block”
  - “Common coil”
  - ”Canted Cos(φ)”



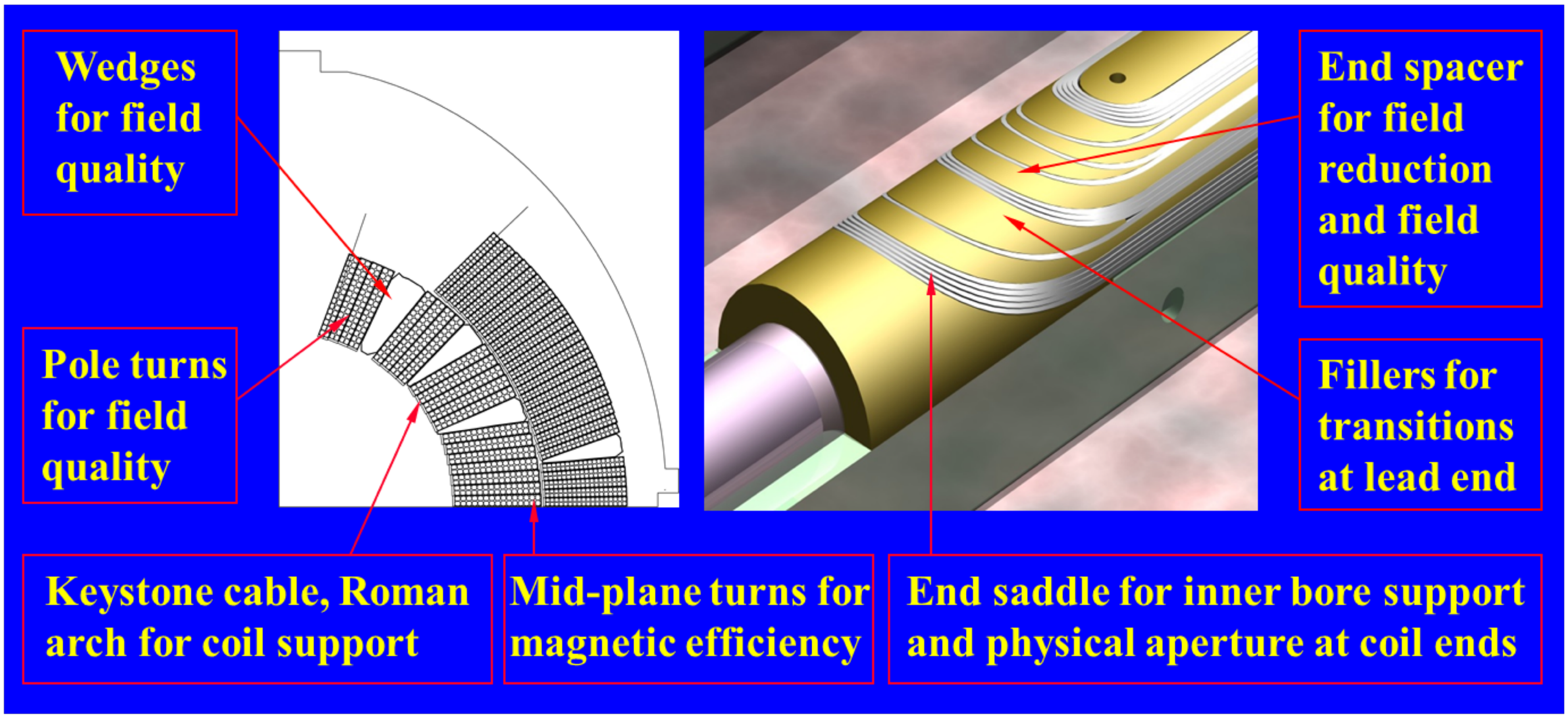




**STRESS MANAGEMENT IN HIGH-FIELD DIPOLES**

N. Diaczenko, T. Elliott, A. Jaisle, D. Latypov, P. McIntyre, P. McJunkins, L. Richards, W. Shen, R. Soika, D. Wendt, Dept. of Physics, Texas A&M University, College Station, TX 77843
R. Gaedke, Dept. of Physics, Trinity University, San Antonio, TX 78212

# The Cos(φ) winding is a well-understood geometry, with optimized components for field quality and efficiency

*Courtesy GianLuca Sabbi*

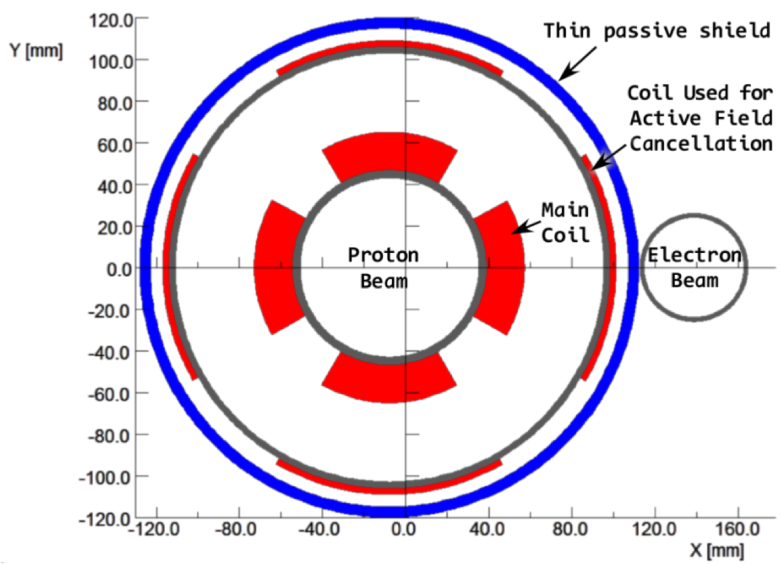


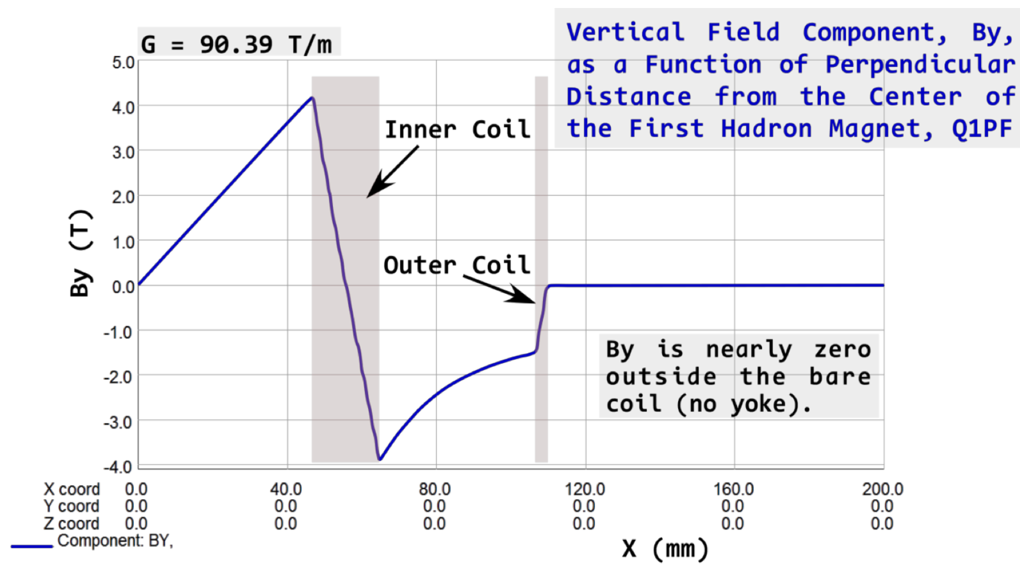
# Applications such as the EIC interaction region quadrupoles require novel magnetic field configurations

Design approach and main features:

- Cancellation of fringe field by outer active coil
- No iron yoke
- Passive shield for cancellation of residual field, in particular at the coil ends
- Both coils fabricated with direct wind technology

| Design Parameters | Unit | Value |
|---|---|---|
| Clear aperture | mm | 86 |
| Gradient | T/m | 90 |
| Peak Field | T | 4.5 |
| Length | m | 2 |

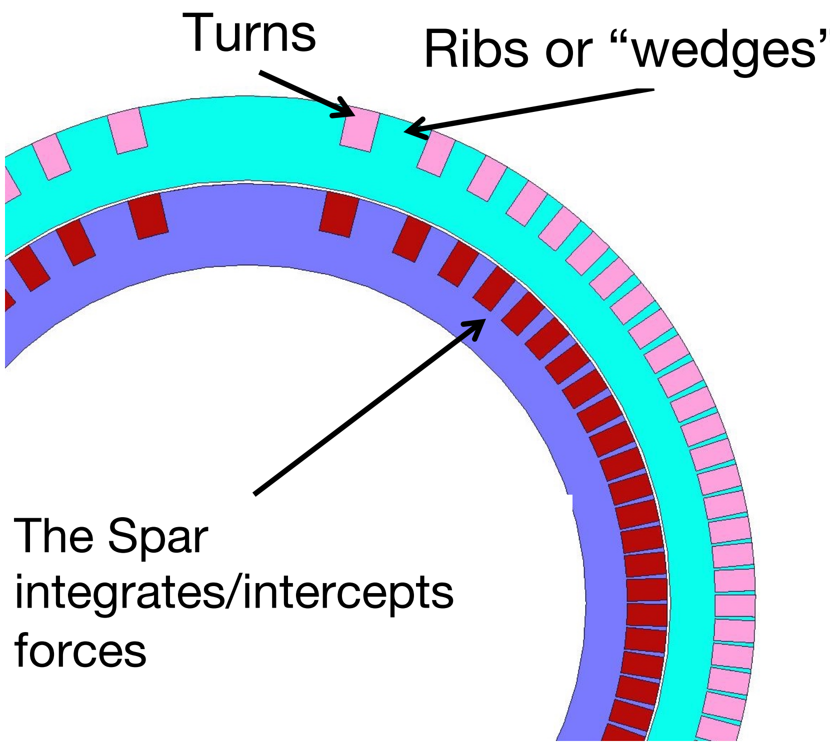


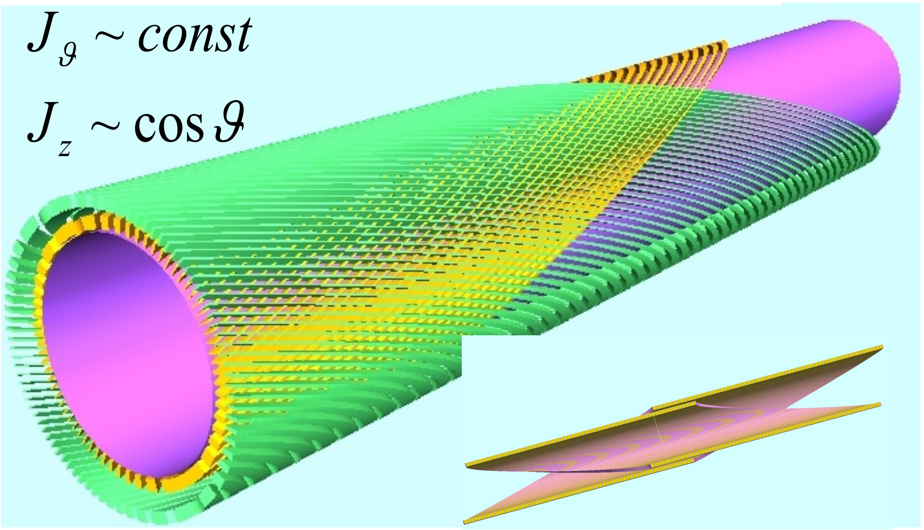



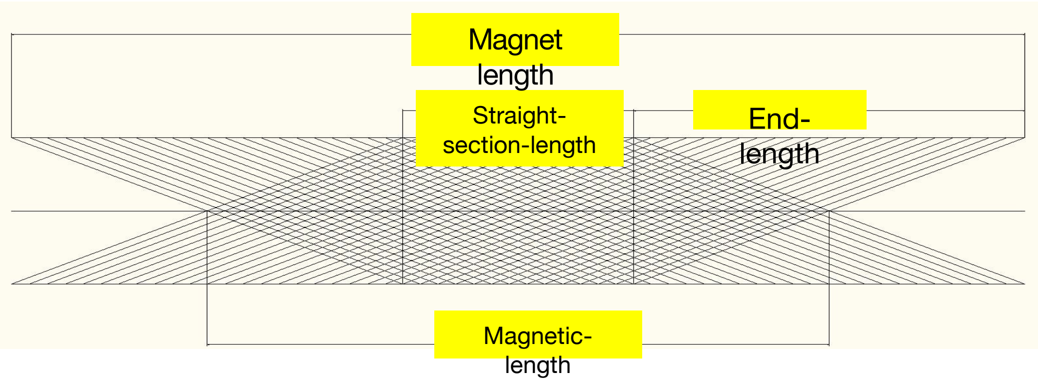

*B. Parker et al., BNL*

# An alternative concept, the "canted-cosine-theta" is under development, where "ribs" and "spars" create excellent field quality and intercept the Lorentz forces

***Two superimposed coils, oppositely skewed, achieve a pure cosine-theta field and eliminate axial field.***



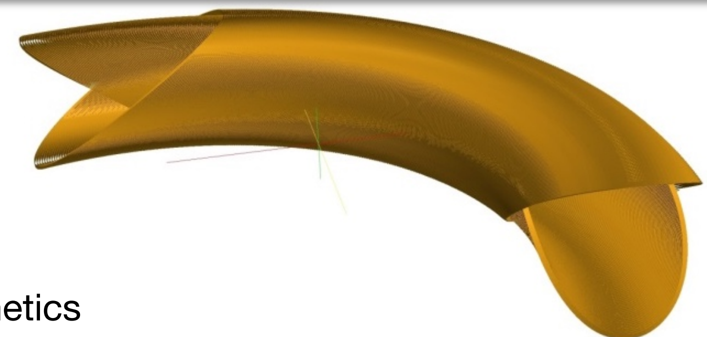




Harmonics over each "end" integrate to zero

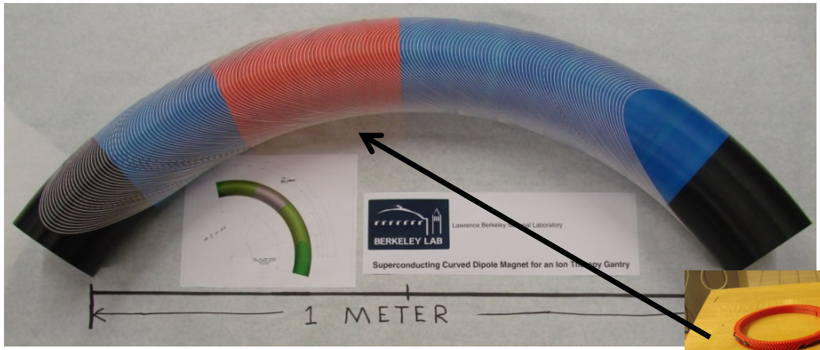
Magnetic-length = pitch*Nturns

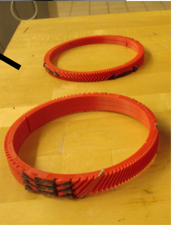
❖ L. J. Laslett, S. Caspi, and M. Helm, Configuration of coil ends for multipole magnets, Particle Accelerators, 1987, Vol. 22, pp. 1-14.

# As an aside, note that the "CCT" can be applied in curved accelerator magnets and multipole components can be superimposed



Curved configuration

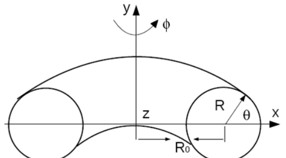


Magnetics

- Curved CCT winding path can be optimized to produce the desired combined function field

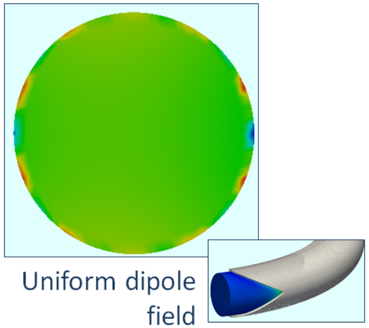
- A winding concept on a toroid that produces a combined function field and higher multipole fields (e.g. gantry magnets for proton/carbon beam therapy)



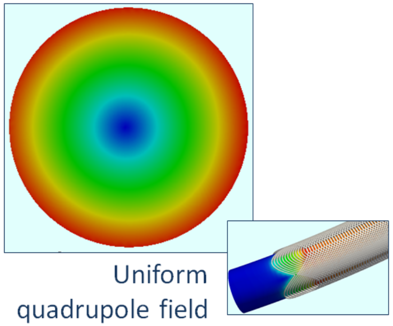

Toroidal coordinate system.

**Multipole Winding Path**

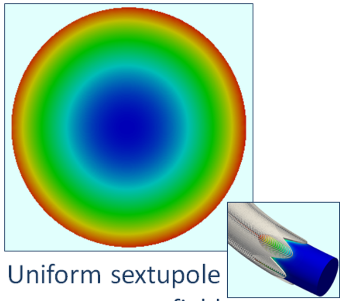
$$\varphi = \frac{R}{R_0}\left(\frac{2\cdot B_d}{B_{0-sol}}\sin\theta + \frac{2\cdot G\cdot R}{2\cdot B_{0-sol}}\sin 2\theta + \frac{2\cdot S\cdot R^2}{3\cdot B_{0-sol}}\sin 3\theta + \cdots\right)$$



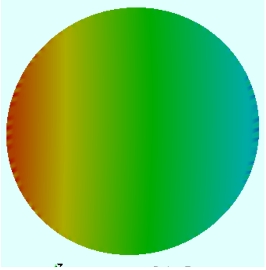
Uniform dipole field



Uniform quadrupole field



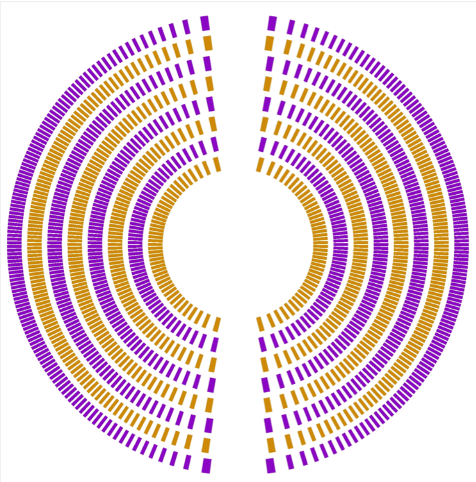
Uniform sextupole field

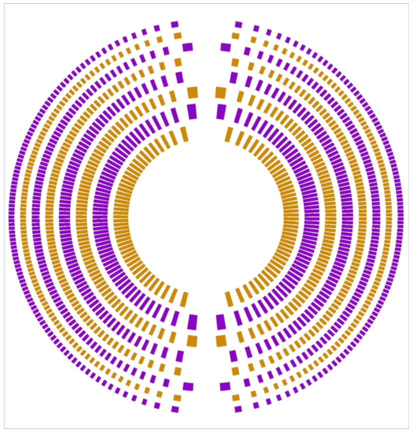


Combined function

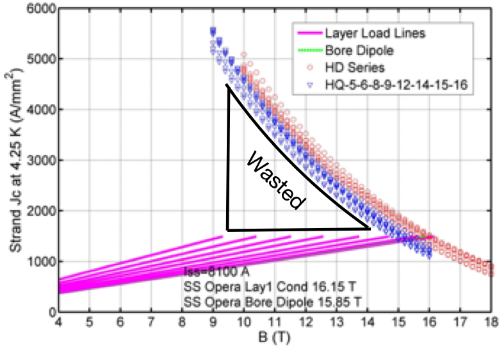
# Layouts can be optimized for conductor efficiency and field profiles

## Grading is critical for efficiency at high field

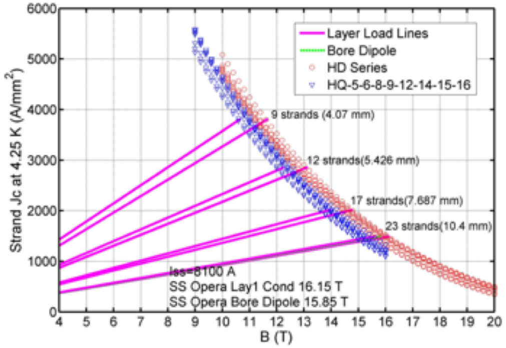




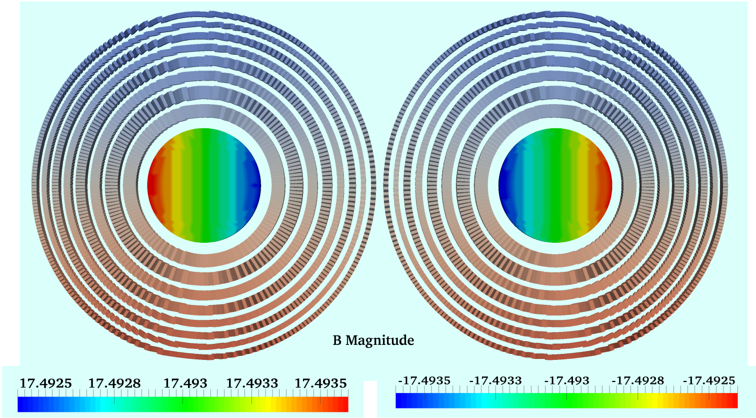
Un-graded



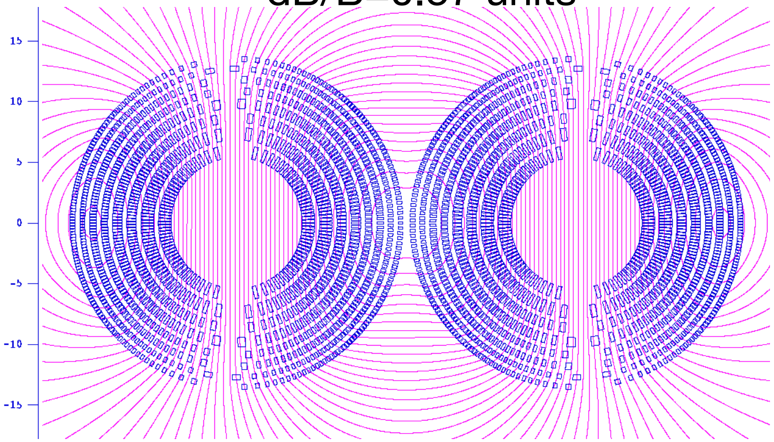

Graded



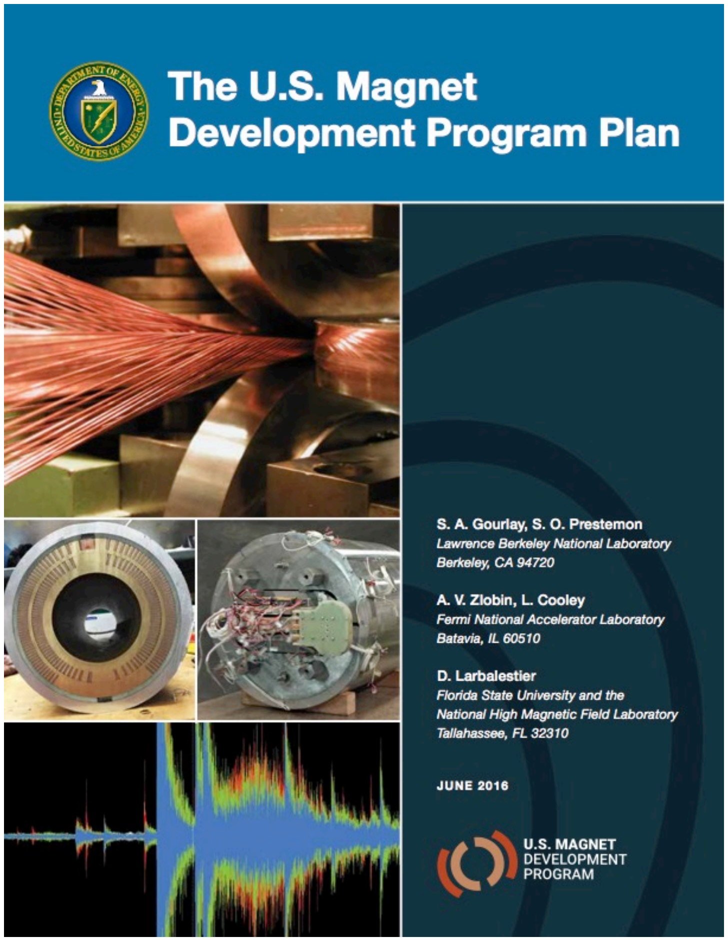

## CCT winding profile can account for cross-talk in 2-in-1 layouts




dB/B=0.57 units



# The US Magnet Development Program was founded by DOE-OHEP to advance superconducting magnet technology for future colliders




Strong support from the Physics Prioritization Panel (P5) and its sub-panel on Accelerator R&D

A clear set of goals have been developed and serve to guide the program

Technology roadmaps have been developed for each area: LTS and HTS magnets, Technology, and Conductor R&D

**US Magnet Development Program (MDP) Goals:**

**GOAL 1:**

Explore the performance limits of $Nb_3Sn$ accelerator magnets with a focus on minimizing the required operating margin and significantly reducing or eliminating training.

**GOAL 2:**

Develop and demonstrate an HTS accelerator magnet with a self-field of 5 T or greater compatible with operation in a hybrid LTS/HTS magnet for fields beyond 16 T.

**GOAL 3:**

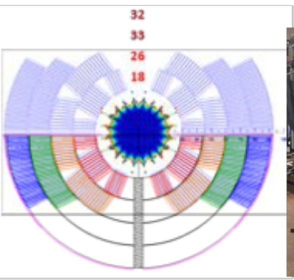
Investigate fundamental aspects of magnet design and technology that can lead to substantial performance improvements and magnet cost reduction.

**GOAL 4:**

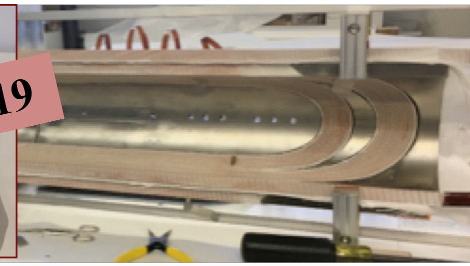
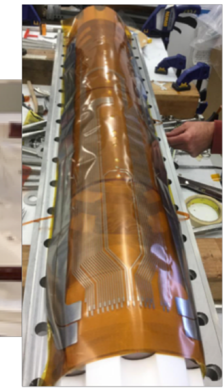
Pursue $Nb_3Sn$ and HTS conductor R&D with clear targets to increase performance and reduce the cost of accelerator magnets.

# Progress on high-field magnet concepts

- Block Cosine-theta magnet fabrication is progressing well, with coil fabrication complete and mechanical structure tested

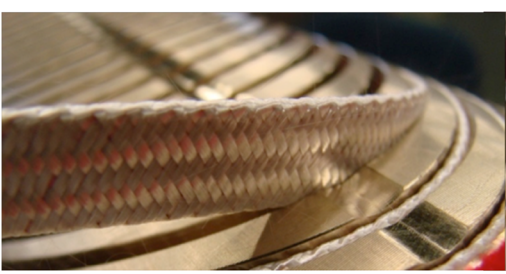


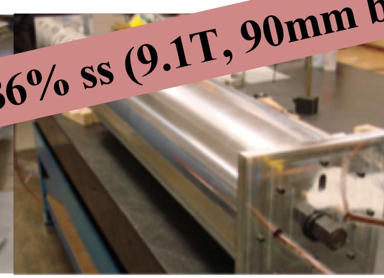
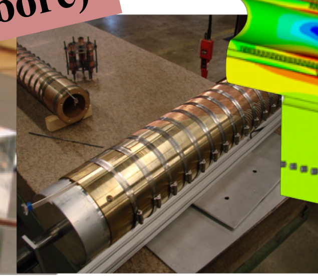
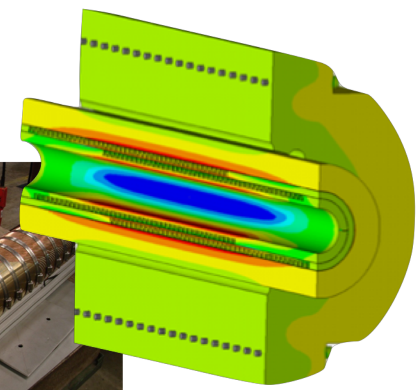


Expect test in ~January 2019

- Canted Cosine-theta:
  - Subscale CCT currently being pursued for fast turn-around technology development
  - CCT4 (the second $Nb_3Sn$ CCT 2-layer magnet) was tested, and thermally cycled
  - CCT5 is in design, incorporating feedback from CCT4



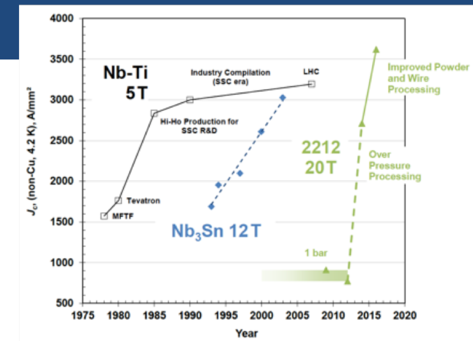
CCT4 achieved 86% ss (9.1T, 90mm bore)

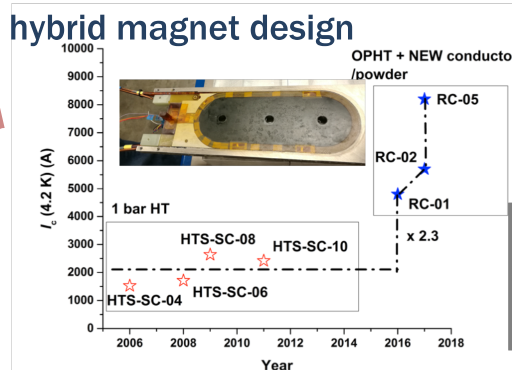
**CCT5, designed to address training, will be tested in October 2018**

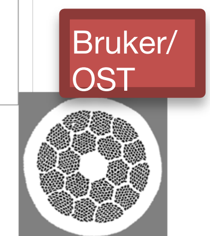
# Significant progress on the HTS magnet front

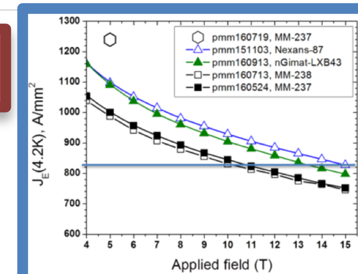
- Bi2212 has made dramatic strides in $J_c$ over last 3 years –ready for magnets
  - Wire has been cabled and tested in racetrack configuration (RC5)
  - First Bi2212 CCT dipole has been wound; reaction and testing soon
  - Roadmap integrates Bi2212 CCT in a high-field hybrid magnet design

**Bi2212 is now a magnet-ready conductor**

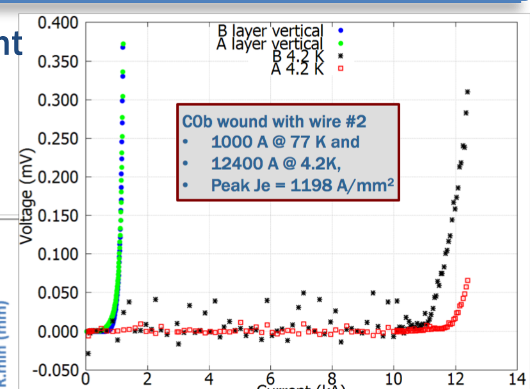


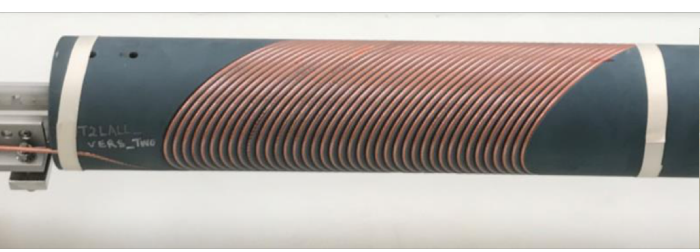



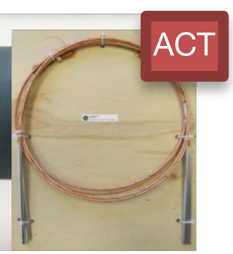



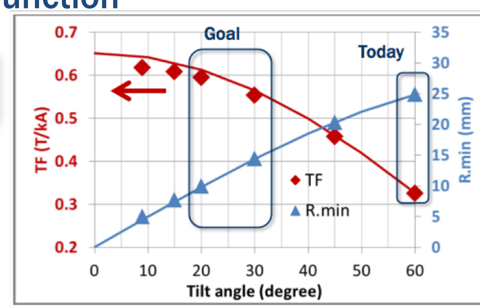




- REBCO development focused on CORC® cables and magnet technology development
  - 3-turn C0 "dipole" was used to develop winding tooling, fabrication processes
  - 40-turn C1 dipole was then fabricated and tested
  - Anticipate >x3 improvement in tape $J_E$ and transfer function



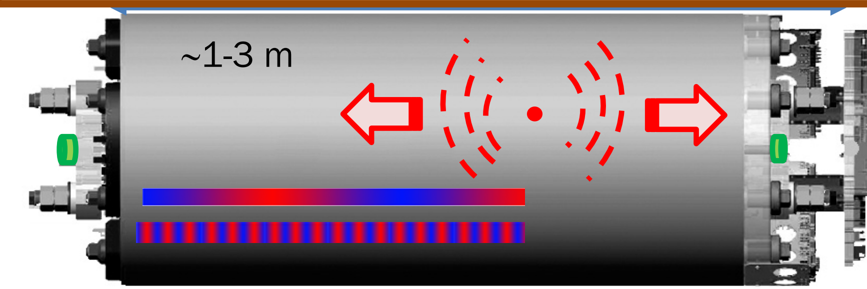


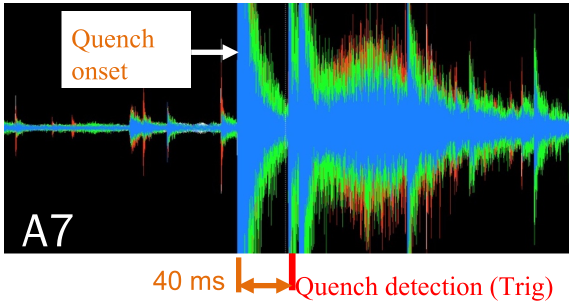



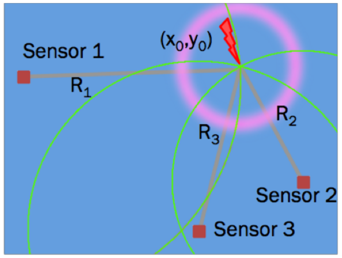
# Novel diagnostics are critical to identify and characterize the disturbance spectrum sources responsible for magnet training

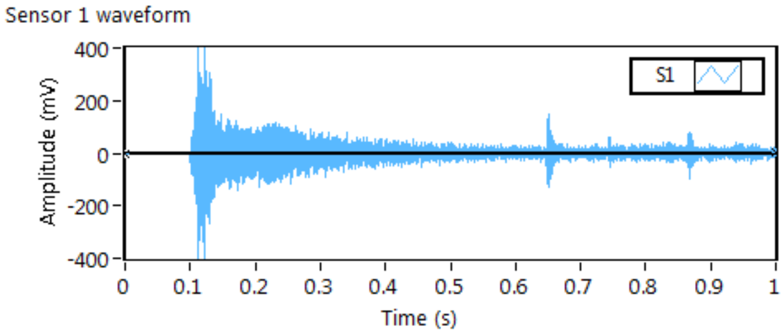
| | |
|---|---|
| Voltage taps | Most common technique. Intrusive. Not optimal for longer magnets and may be not viable in newer complex magnet geometries (multi-layers, etc.) |
| Inductive quench antenna | Less intrusive, but occupies space in the bore. Data requires significant post-processing. Shielding by metallic structures can implead the performance |

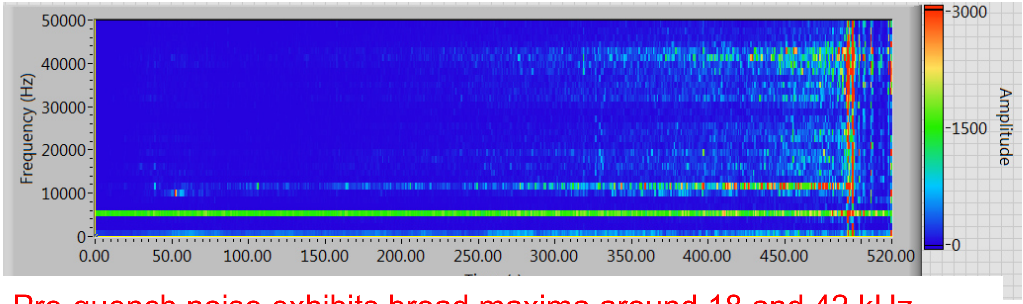
**Now developing *Acoustic Techniques* that are fast and non-intrusive – are there other diagnostics that complement these?**



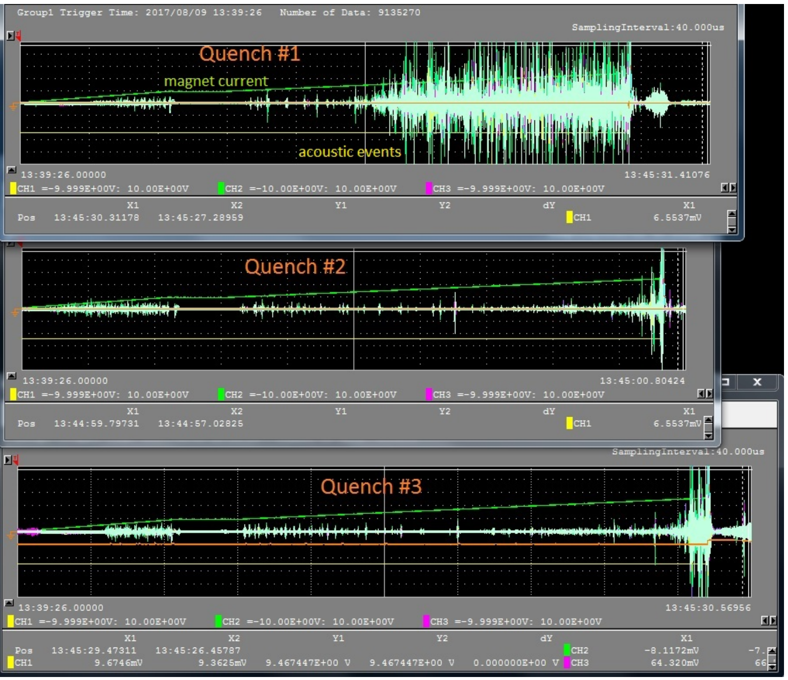



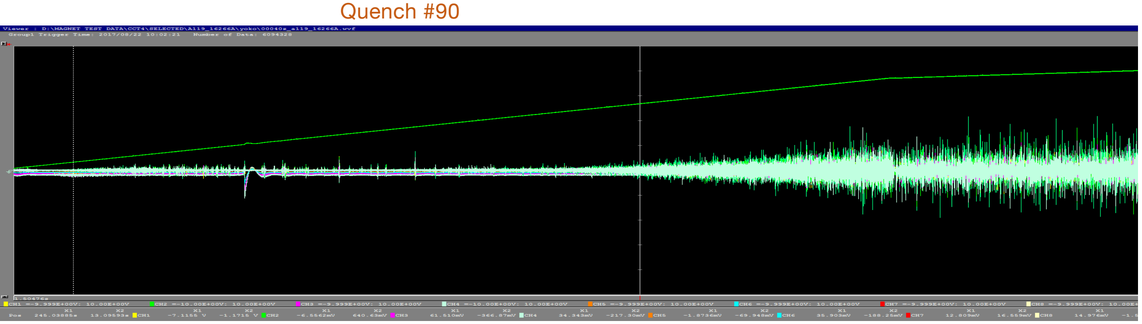



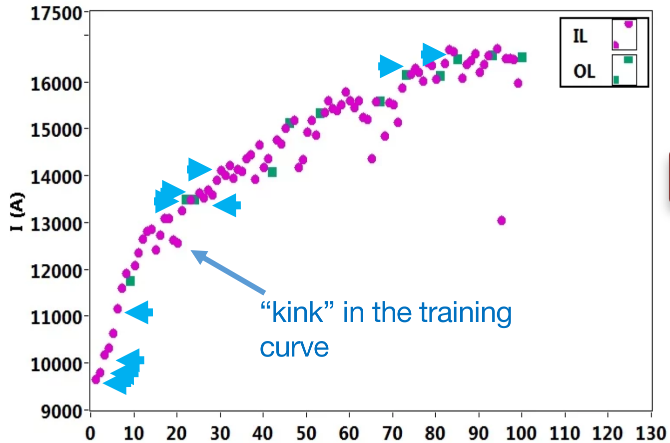

Pre-quench noise exhibits broad maxima around 18 and 42 kHz

# Quench memory and two distinct training regimes are seen on the CCT4 test - note that these diagnostics can be applied on any superconducting magnet

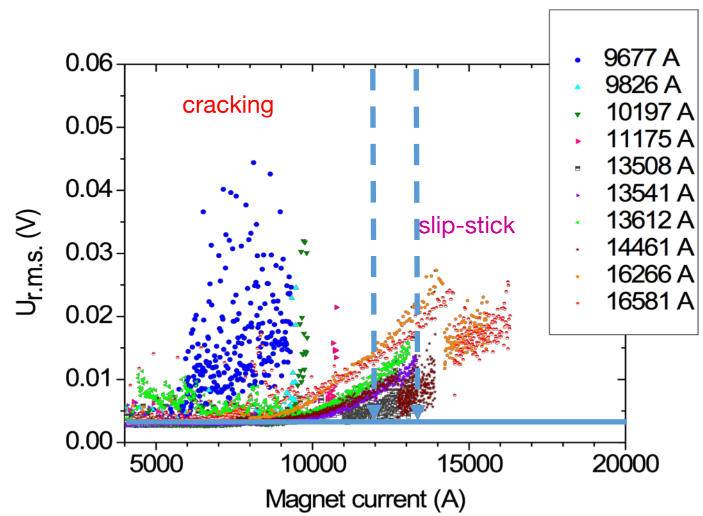



Quench #90






Marchevsky, LBNL



# Advanced multi-physics coupling using custom elements, and leveraging of computing clusters with FEA

Geometry Generation
Meshing
Boundary conditions
Loads

Solution

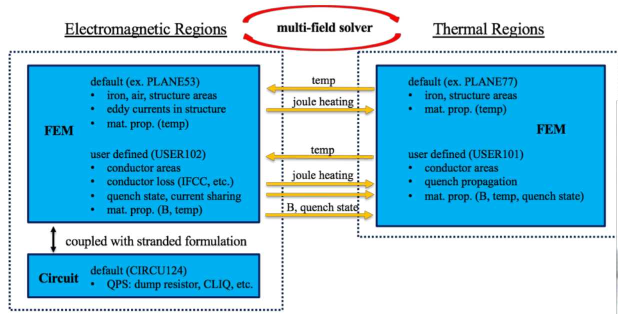
Post processing
Load transfer between models

Replace code which builds element matrices: uel.f, uec.f -> compile custom ANSYS.exe

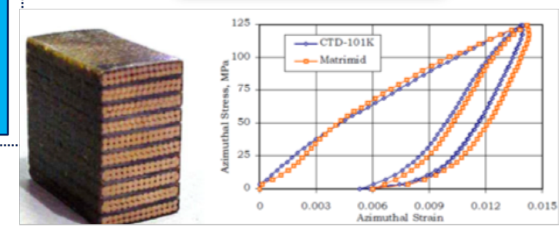
Available
- node location
- loads
- node temperature
- material prop.
- ANSYS functions

Element customized by defining
- element shape functions
- material properties: if complex function desired (T,B,Jc,etc.)
- formulation

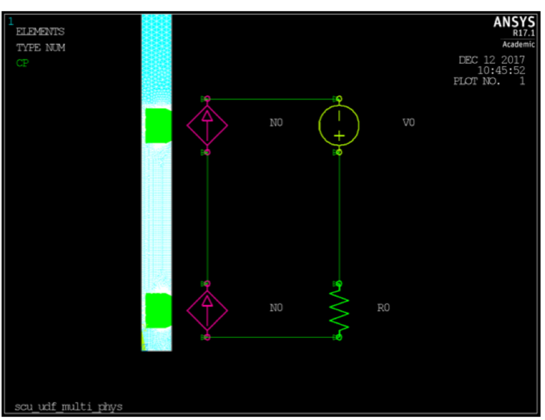
Element matrix generation is now determined by user program
- stiffness, damping, etc.

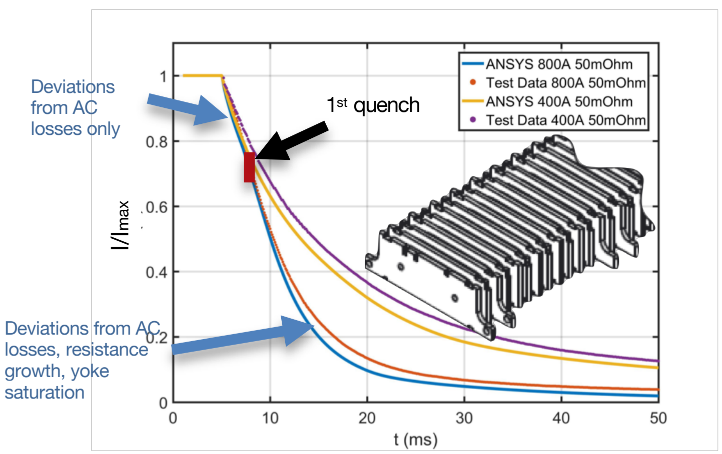


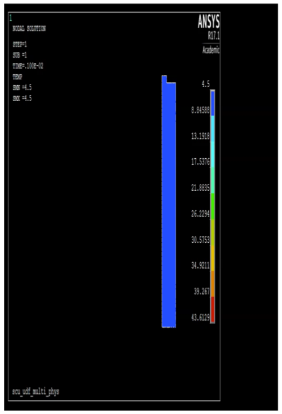

S. Krave, FNAL

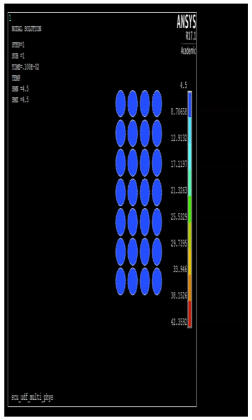



Brouwer, LBNL; Auchmann, PSI/CERN



# Summary

- Magnet technology is evolving actively on all fronts
  - Permanent magnets may see a renaissance
  - Superconducting magnets have tremendous potential
    - But need better understanding and control of technology

- Impact of magnet technology on accelerators depends on improvements on multiple fronts:
  - Material properties – performance and measured data
  - Advances in modeling – faster processors, improved physics, improved feedback on design
  - Advances in diagnostics: key for understanding and feedback to design