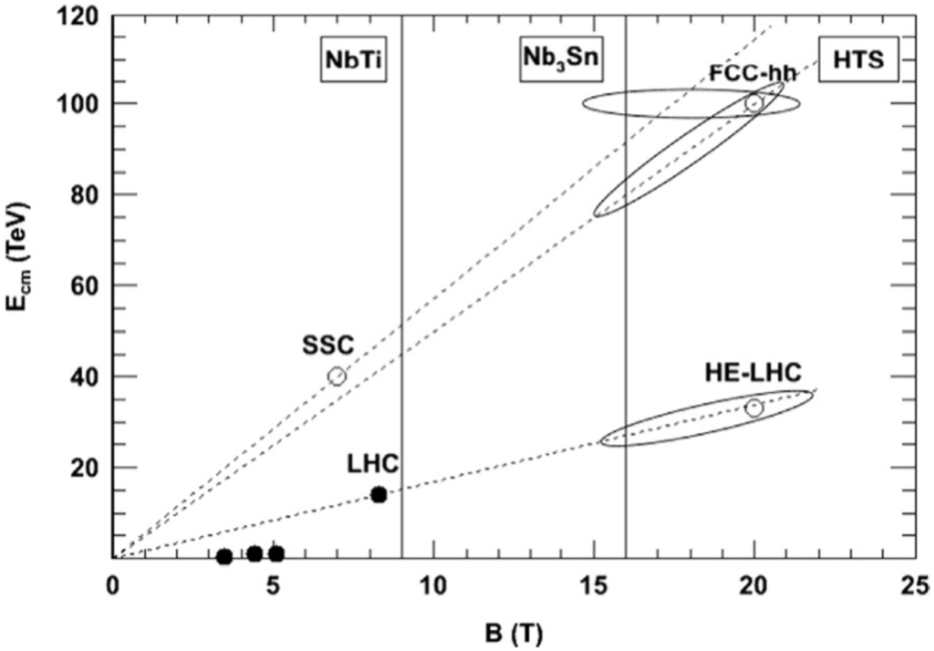
Crosscut:

Accelerator and Beam Physics ⇔ High Field Magnets

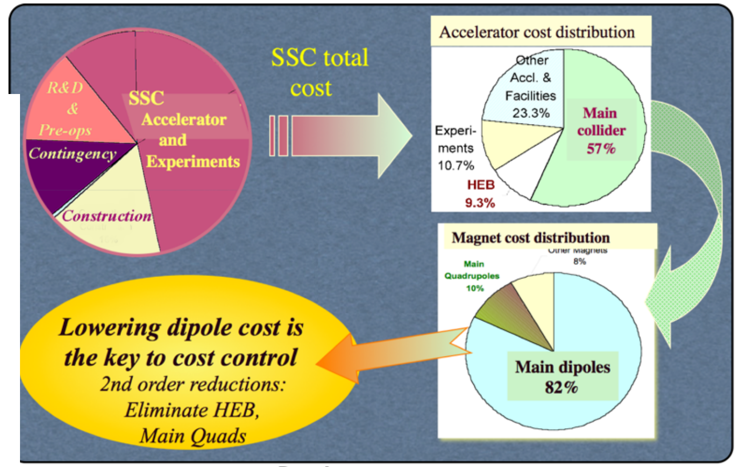
Soren Prestemon

Lawrence Berkeley National Laboratory

Magnet technology is driving the cost and reach of a future collider



Barletta et al., NIMS A, vol. 764, no. C, pp. 352–368, Nov. 2014

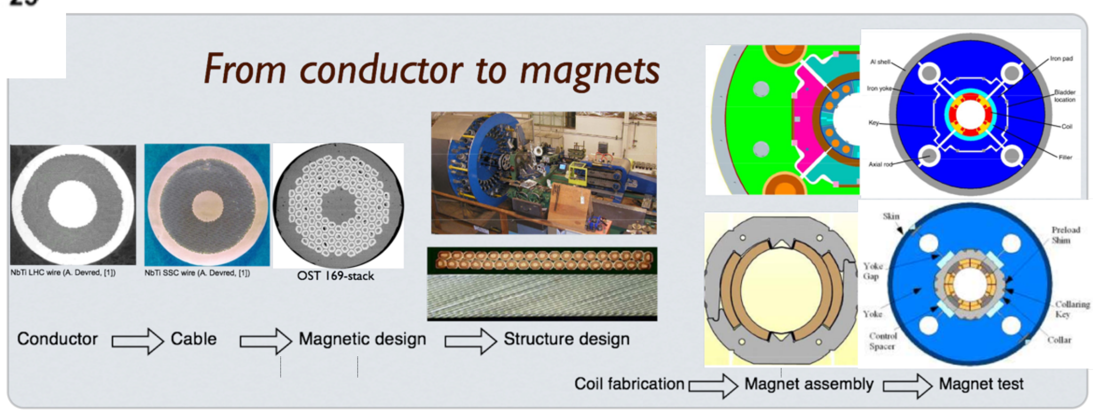


Barletta

CERN cost estimates*:
$\$_{magnets}/\$_{tot}$

LHC: 57%
HE-LHC:
- 70% (26TeV; Nb_3Sn)
- 77% (33TeV; HTS)

**L. Rossi, "TOE" talk*



Message I

- Paradigm shifts that influence / benefit from ABP⇔HFM
  - Significantly reduce static multipole content constraint
    - Idea proposed by Sergei Nagaitsev
    - ”simple” magnets + decoupled “correctors” = “clean” optics?
    - May be particularly relevant for 2-in-1 systems
    - May open opportunities for new structure concepts
      - *Potential* to impact performance and cost
  - Significantly reduce magnetization constraints
    - Magnetization drives conductor and magnet design considerations, and impacts operations
    - How much hysteresis can be tolerated if it is well characterized and reproducible?
    - May be critical issue for application of HTS (REBCO) to accelerators
  - Large momentum acceptance optics
    - dB/dt is ”costly” – cryogenics, dM/dt,…
    - Can we address provide adequate field quality for large energy-spread beams? Can we envision storing beams of varying energies?
    - *Potential* for high-power boosters

Message II

- Modeling of magnet is advancing and we can quite accurately predict 3D fields for "complex" magnet layouts
- Modeling of beam optics can be tackled from multiple fronts
  - Q: do we have, or need, improved modeling tools to fully leverage ABP⇔HFM linkages?

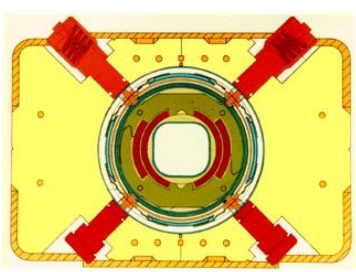
Acknowledgements

- This presentation was cobbled together from a wide range of sources, including…
  - GianLuca Sabbi…
  - …and other Colleagues from the US Magnet Development Program
  - USPAS course notes (courtesy of colleagues P. Ferracin, E. Todesco, S. Gourlay)
  - H. Felice (SACLAY)
  - Colleagues from LARP and now HL-LHC AUP

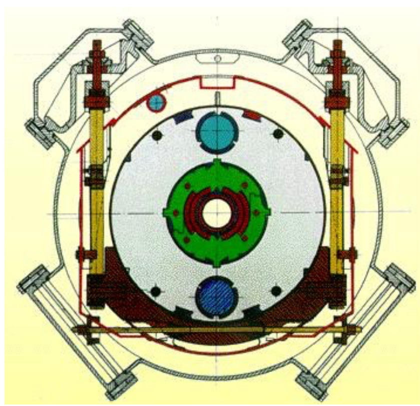
Overview of Accelerator Magnets to-date

- All magnets in accelerators to-date have used…
  - A Cos-theta coil layout (of different flavors)
  - NbTi (HiLumi will be first application of Nb_3Sn in accelerators)
  - "Collar" approach to provide prestress
  - Iron laminations – facilitate fabrication, cost, performance

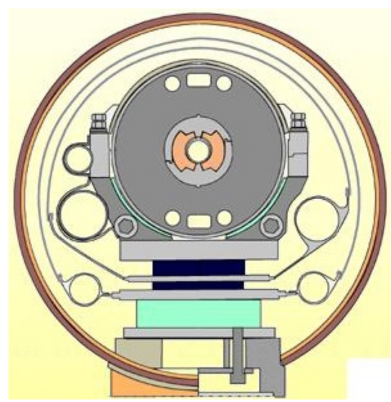
Tevatron



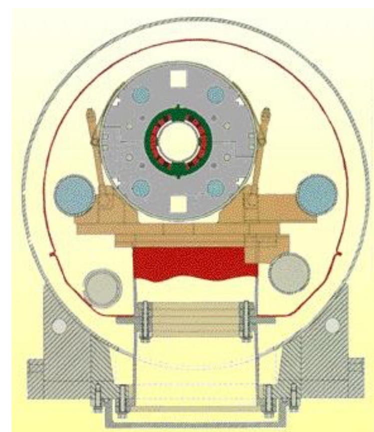
HERA



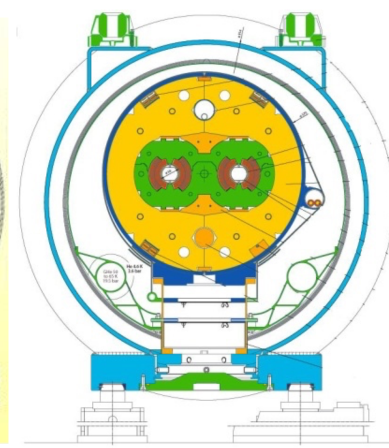
SSC



RHIC



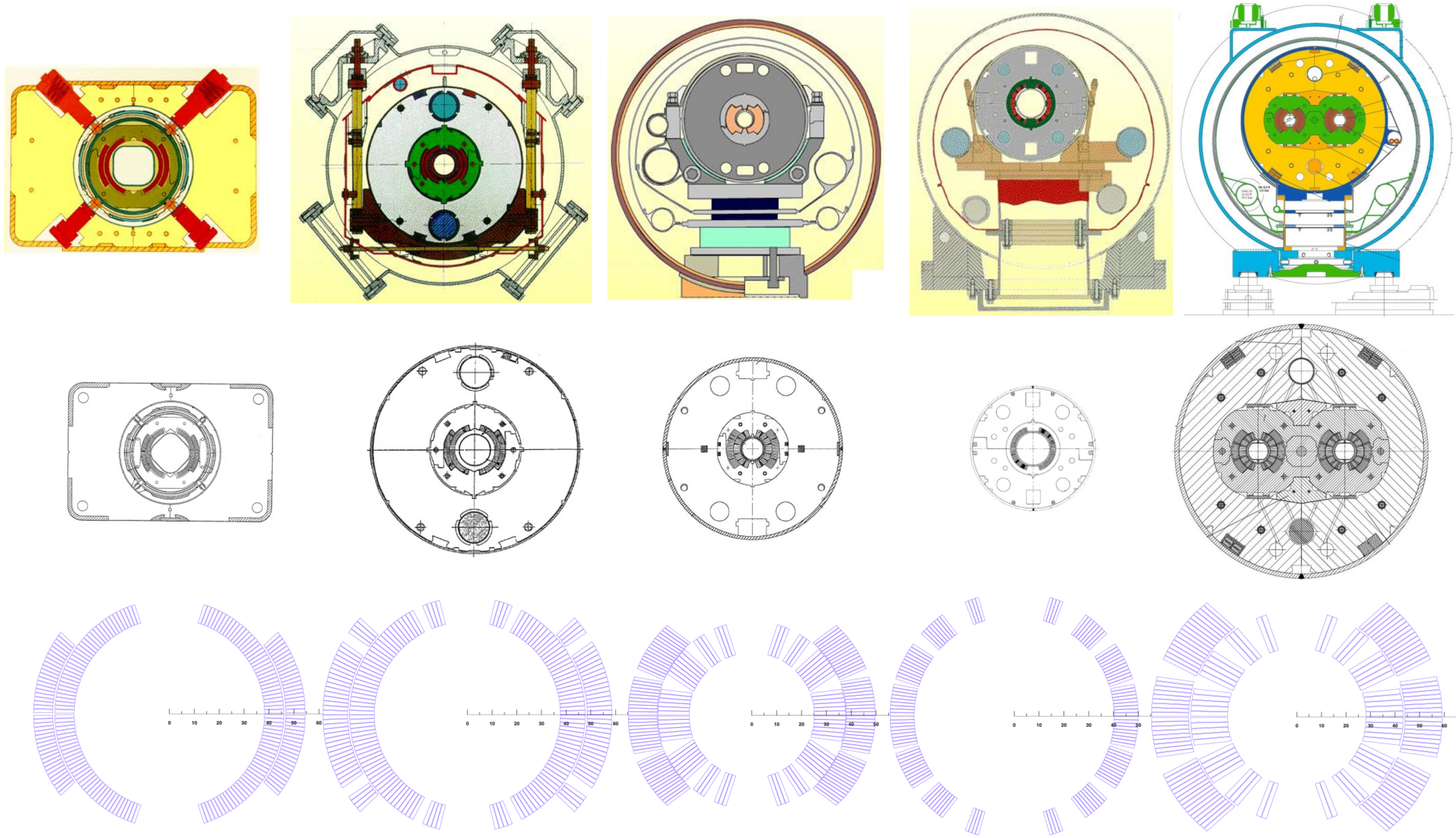
LHC



Not in scale

Overview of accelerator dipole magnets

Tevatron | HERA | SSC | RHIC | LHC



Superconducting Magnet Technology – driving considerations

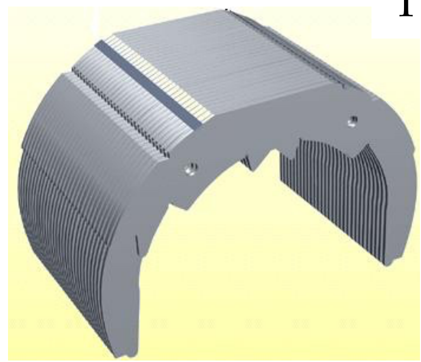
- Three general "regimes" of operation:
  - o Low-field, iron-dominated
    - Field is dictated by scalar potential of the iron surface; field quality is dictated by surface shape/placement
  - o Mid-field regime: saturated iron that contributes significant field
    - Both coil and iron placement important for field quality
  - o High field regime: iron saturated through significant operating range
    - Coil placement dominates field quality; iron adds modest field, plays important structural role, enables some fine tuning of harmonic content
- For quench performance reasons, conductor motion during operation must be eliminated/minimized
  - o For SC magnets, control of conductor location has two purposes: field quality and training performance
    - "Freeing" the design from the field quality constraint may enable new magnet/structure approaches that improve training, reduce cost

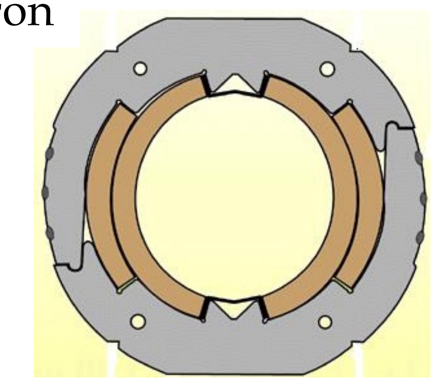
Idea proposed by Sergei Nagaitsev

Support structures typically feature ”Collars”

- Collars were implemented for the first time in the Tevatron dipoles.
    - they have been used in all but one (RHIC) accelerator magnet and in most R&D magnets
- They are composed of stainless-steel or aluminum laminations, typically few mm thick.
- By clamping the coils, the collars provide
    - coil pre-stressing;
    - rigid support against e.m. forces (it can be self-supporting or not);
    - precise cavity (tolerance ~20 μm).

Tevatron





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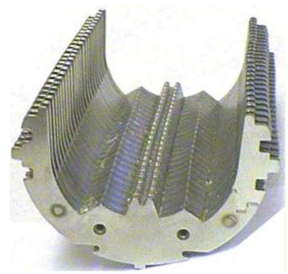
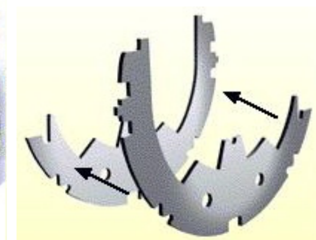
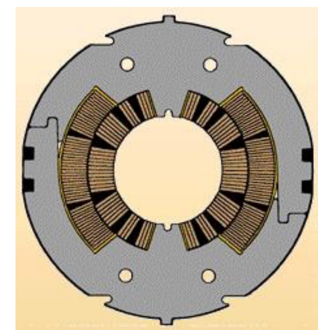
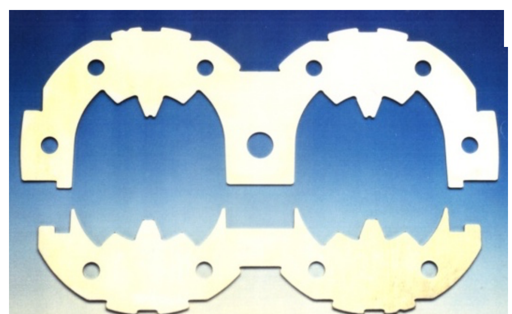


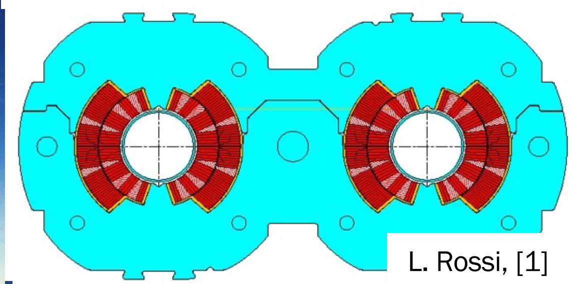




MJB Plus, Inc., [2]

LHC

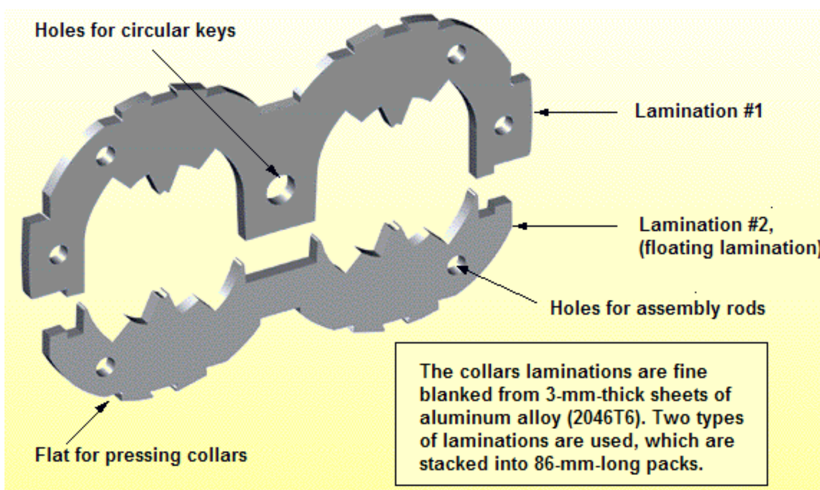


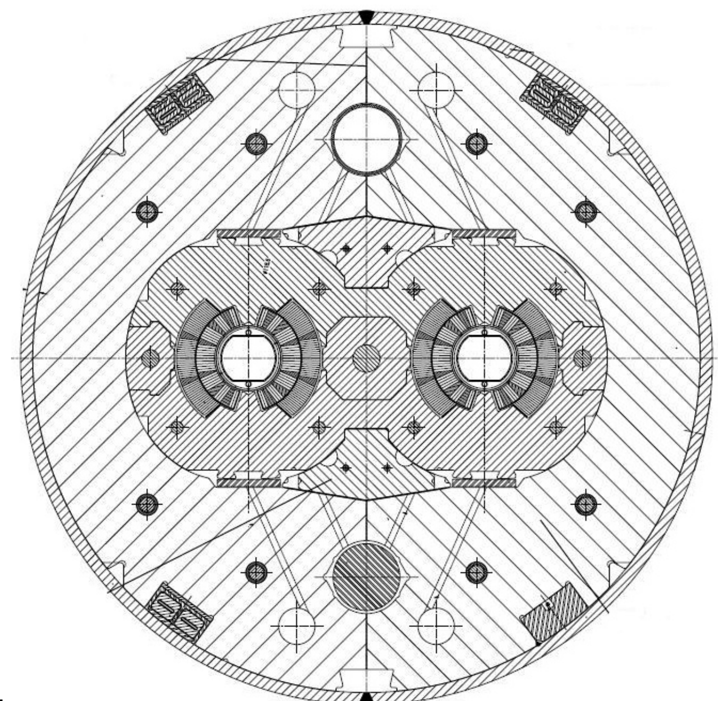


L. Rossi, [1]

The LHC main dipole as an example

- Two-in-one configuration
  - Both beam pipes are contained within one cold mass
- Stainless steel collars are locked by three full-length rods.
- Magnetic insert
  - It transfers vertical force from the yoke to the collared coils
  - It improves field quality
- Iron yoke vertically split
  - At the end of the welding operation the yoke gap is closed
- Stainless steel shell halves are welded around the yoke to provide He containment, a 9 mm sagitta, and to increase rigidity.

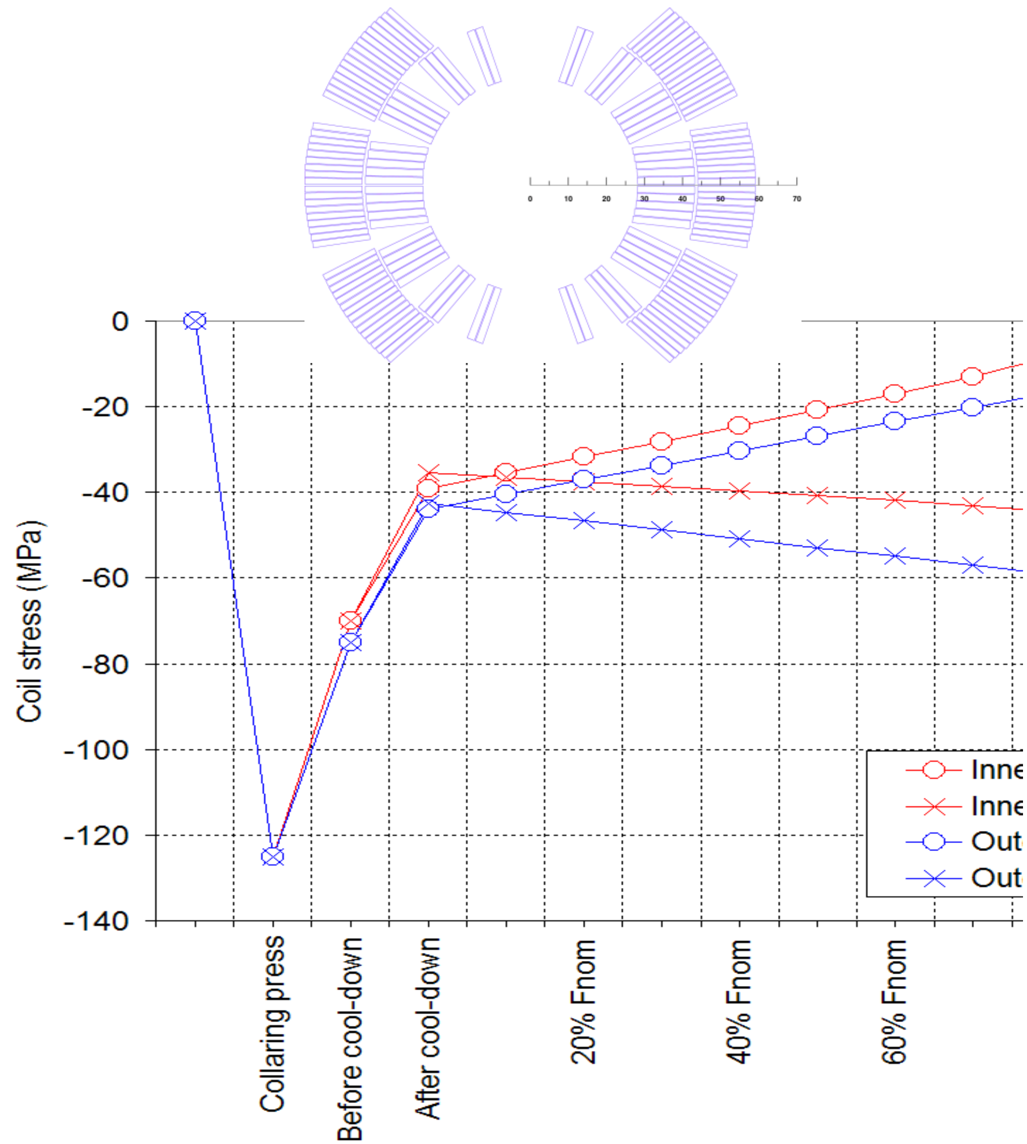




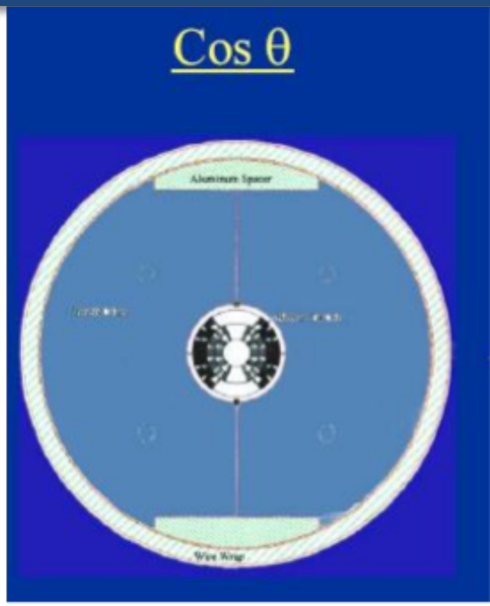
MJB Plus, Inc

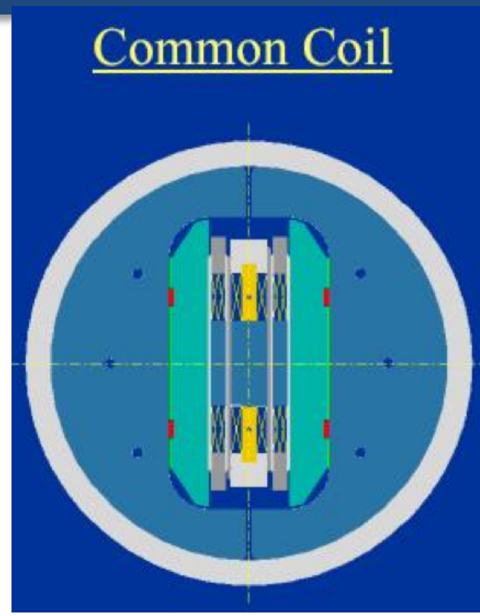
Example: LHC main dipole

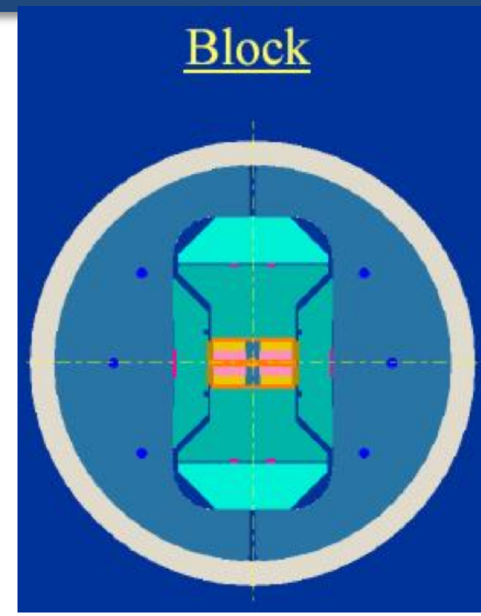
- Coil stress evolution
  - After cool-down the coil is pre-compressed to about 40 MPa.
  - Pre-stress is lost during assembly and cool-down.
  - By computing the coil response in a infinitely rigid structure, it appears that the coil pole remains (almost) always in contact with the collar during excitation.

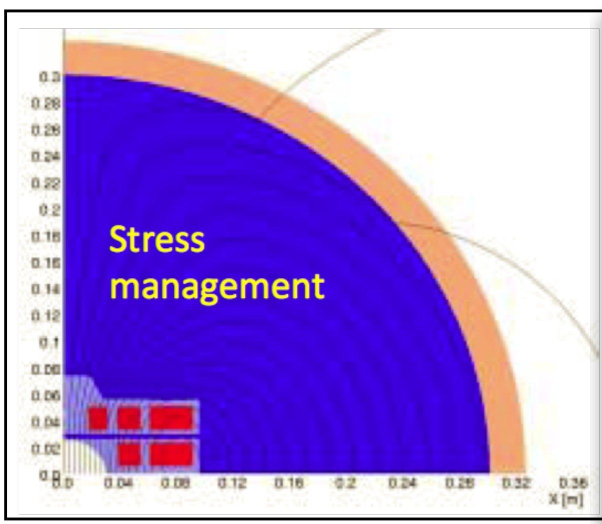


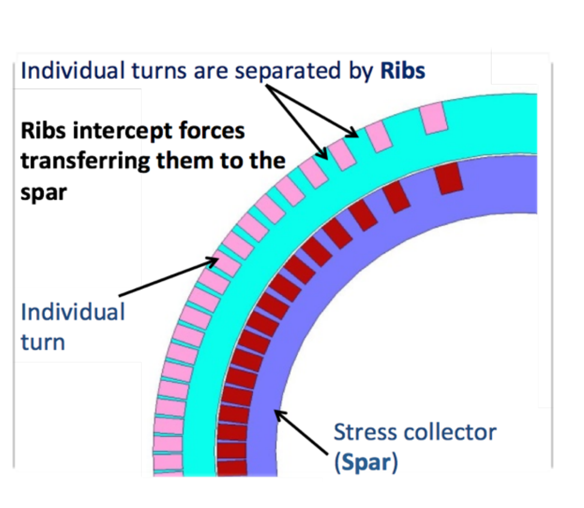
The “zoo” of magnet design concepts that have been researched…



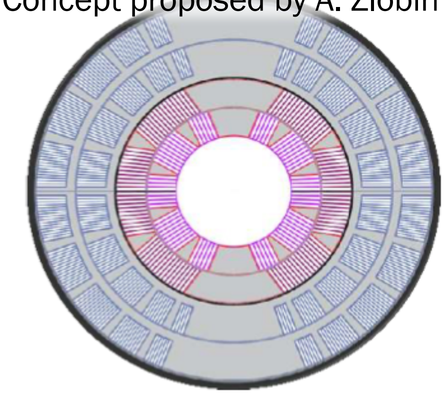






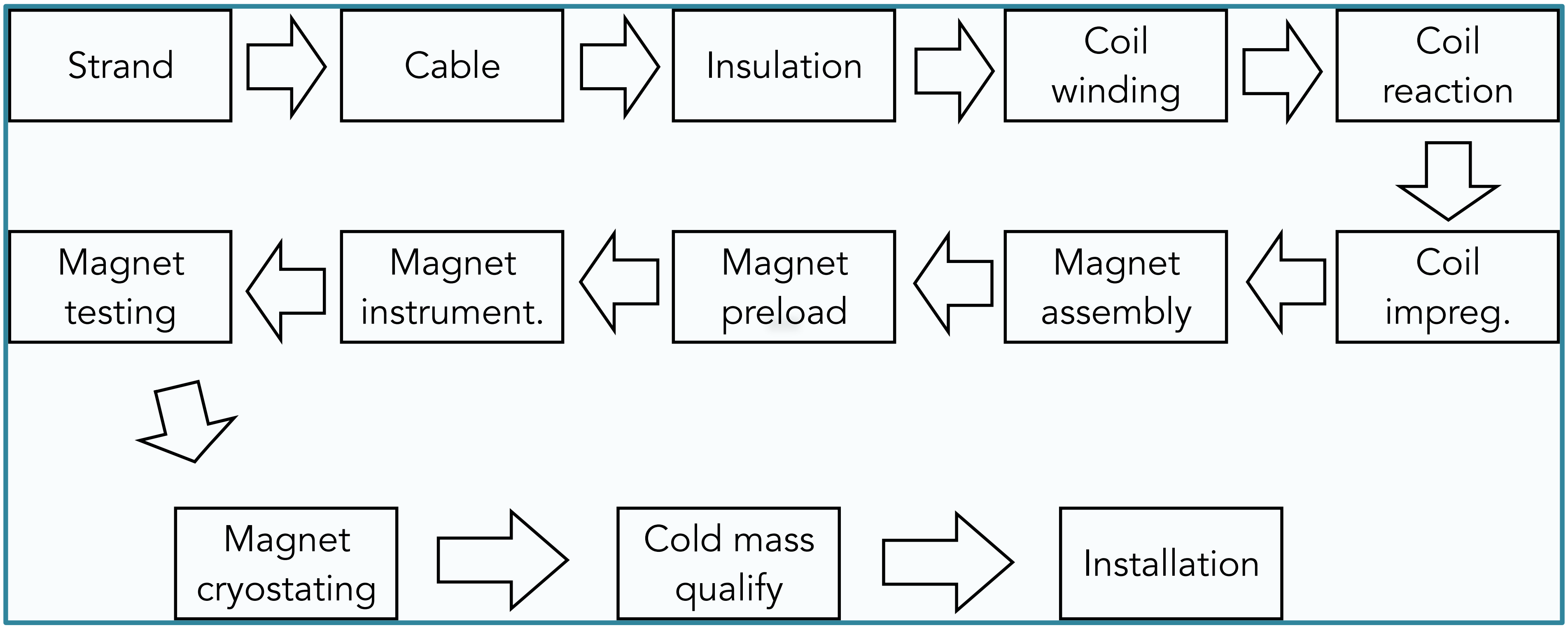


Concept proposed by A. Zlobin



Stress management in outer layers (small aperture)

An example process flow in Nb_3Sn high-field magnets



Every element has requirements and QC; in every case examples of issues exist!
Start to end time not a critical parameter <u>if</u> the process flow is reliable

”blocks” in cos-t designs dicate multipole content

From USPAS lecture…

- Let us see two coil lay-outs of real magnets
  - The Tevatron has two blocks on two layers – with two (thin !!) layers one can set to zero B_3 and B_5
  - The RHIC dipole has four blocks

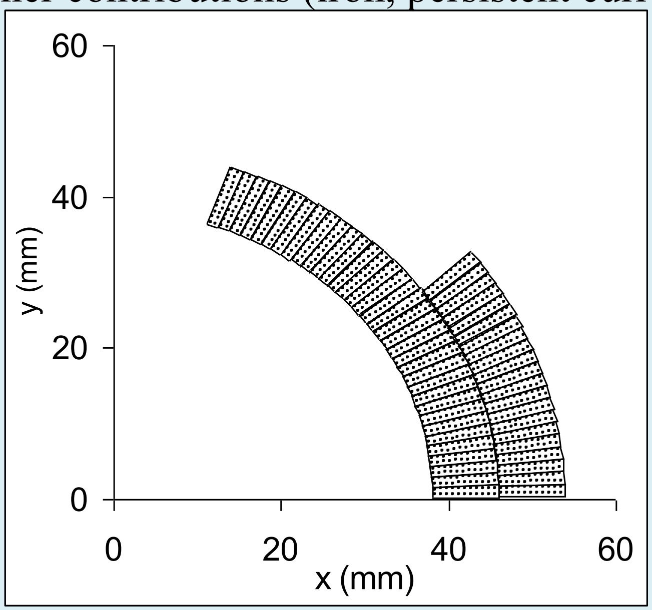
Limits due to the cable geometry

Finite thickness → one cannot produce sectors of any width

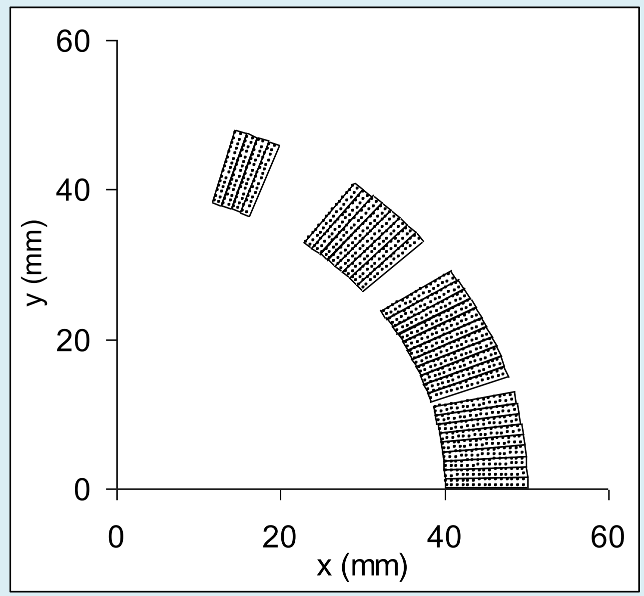
Cables cannot be key-stoned beyond a certain angle, some wedges can be used to better follow the arch

One does not always aim at having zero multipoles

There are other contributions (iron, persistent currents …)



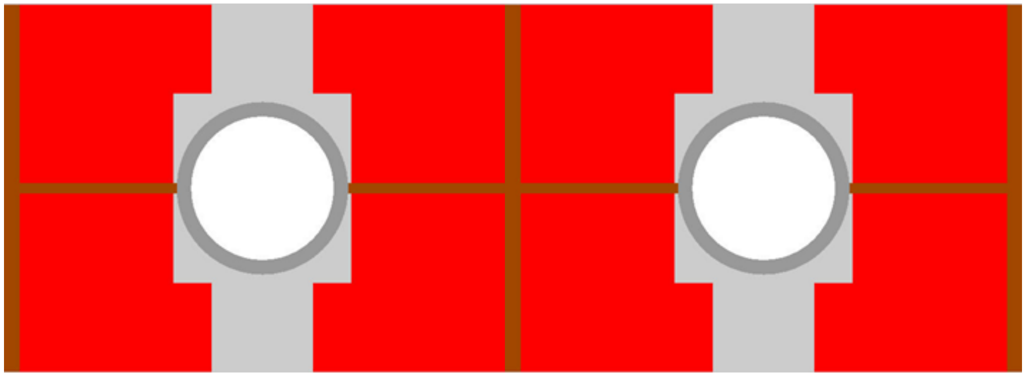
Tevatron main dipole - 1980

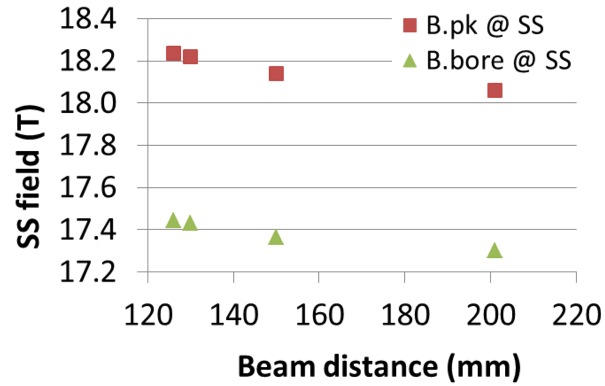


RHIC main dipole - 1995

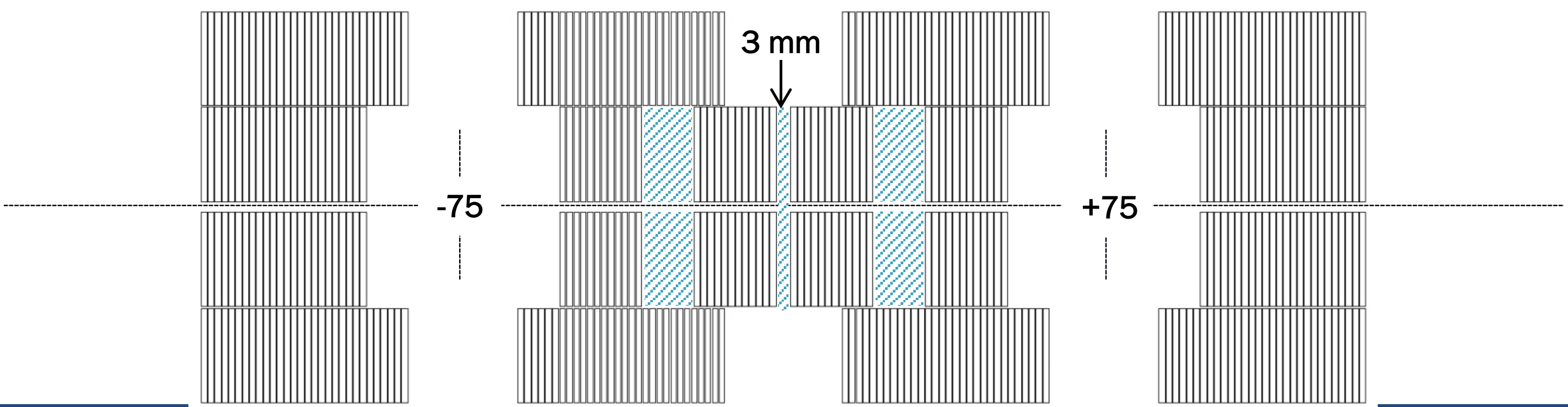
Two-in-one Configuration

- Geometrically the two coils can be brought in contact: 126 mm separation
- Field actually *increases* but field quality degrades due to left-right asymmetry





- This can be corrected with an asymmetric coil (same concept as for HiLumi D2)
- Satisfactory solution found for 150 mm separation:

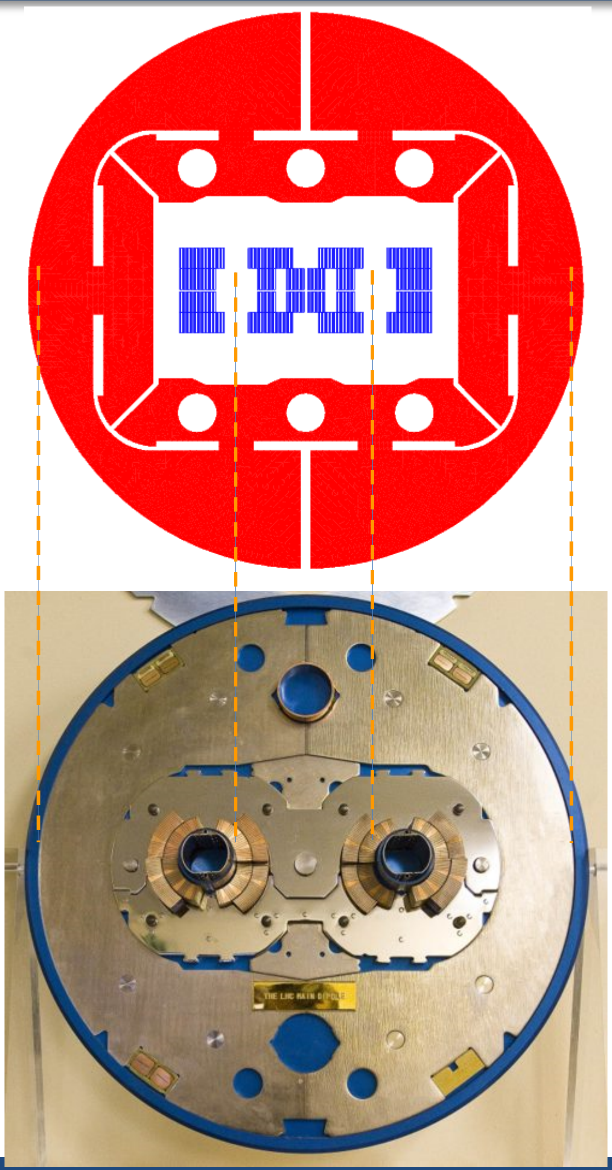


Compactness

- Compact arrangement has significant cost benefits
- 150 mm separation *smaller* than 194 mm in LHC
- Small beam separation allows small yoke OD
- 60 cm yoke OD to be compared with 55 cm LHC
- May be further reduced, need mechanical analysis
- Mechanical envelope will still be larger (shell)
- Short sample field is identical to single aperture:

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

- However, also need to consider other systems
- IR dipoles, RF etc.

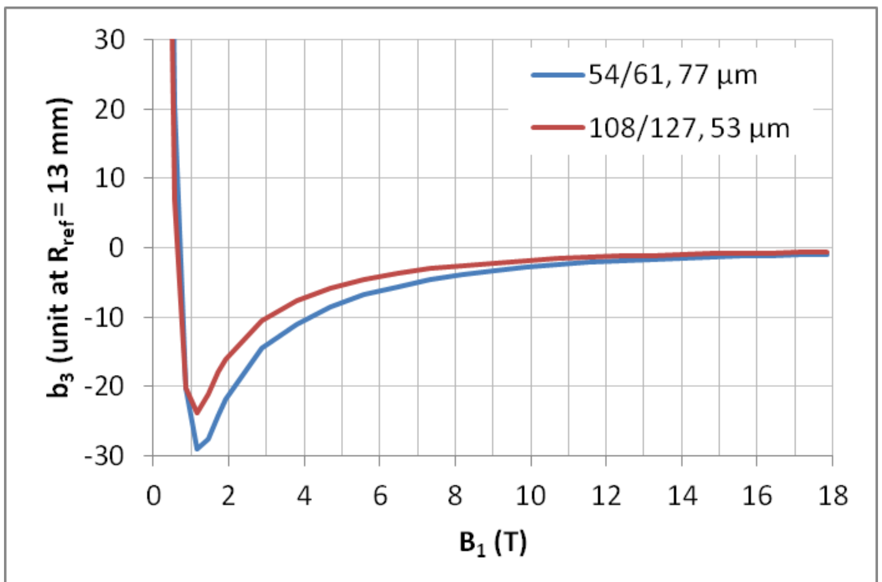


Field Quality Considerations

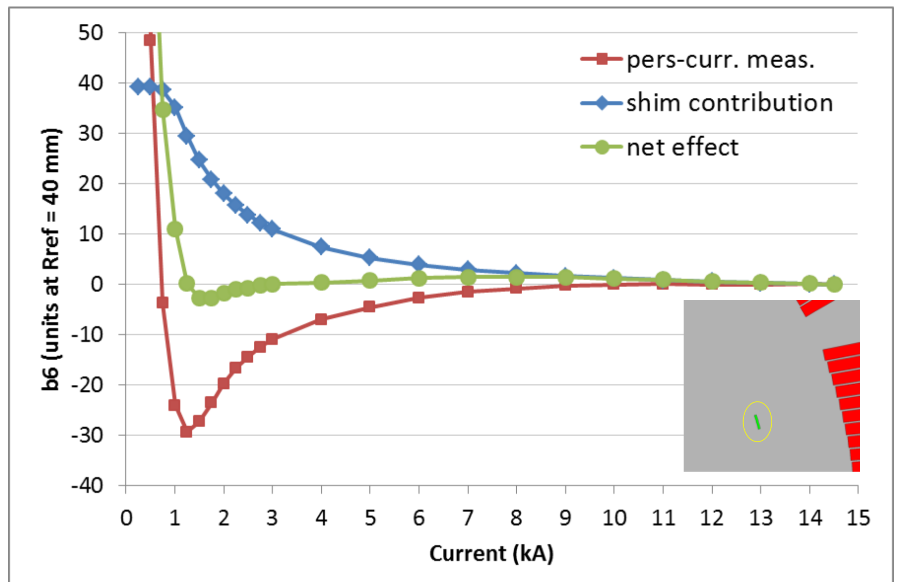
- All cases optimized for low geometric harmonics (<1 unit at R=13 mm)
  - *As required in order to make meaningful comparisons*
- HD2 was also optimized for low saturation (will work also for graded)
- For 2-in-1, we need some further improvement for low orders (n=2,3)
  - *Should be done together with mechanical analysis*

Large persistent current harmonics will require magnetic shim correction:

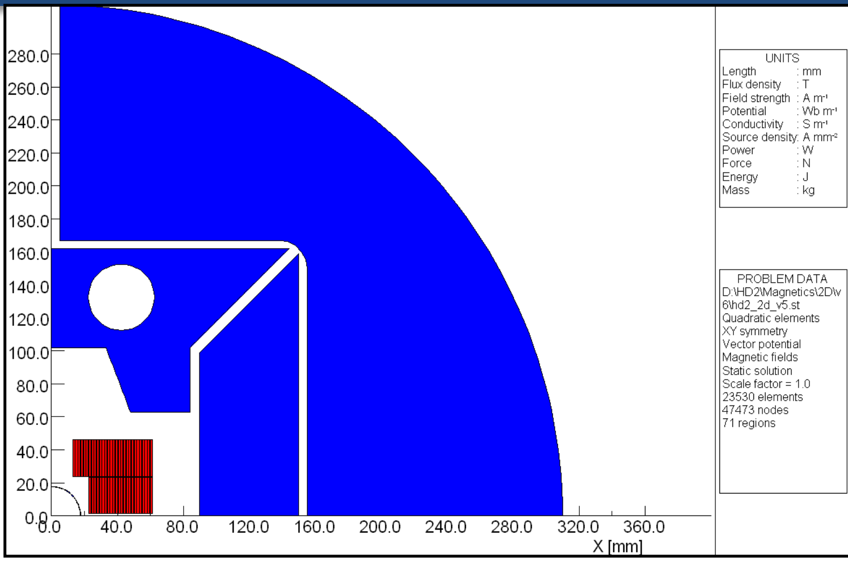
HD2 calculation

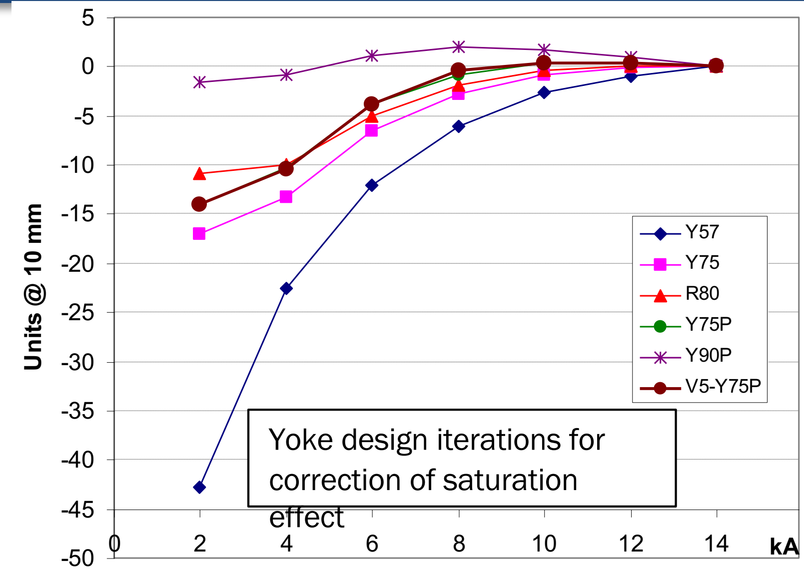


HQ calculation and correction



Field Quality Optimization





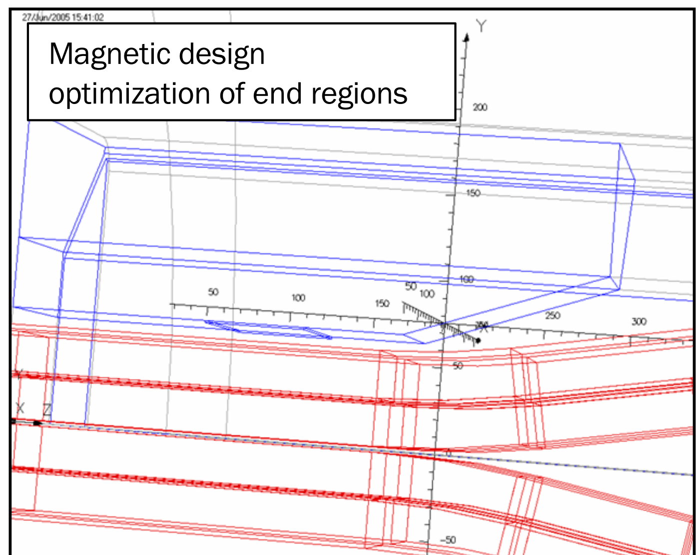
Implemented in HD2:

- Iron yoke optimized for saturation effects
- Cross-section optimized for geometric effects
- All harmonics <1unit @ 60% radius (13 mm)
- Ends optimized for magnetic length, peak field

Not implemented, but compatible with:

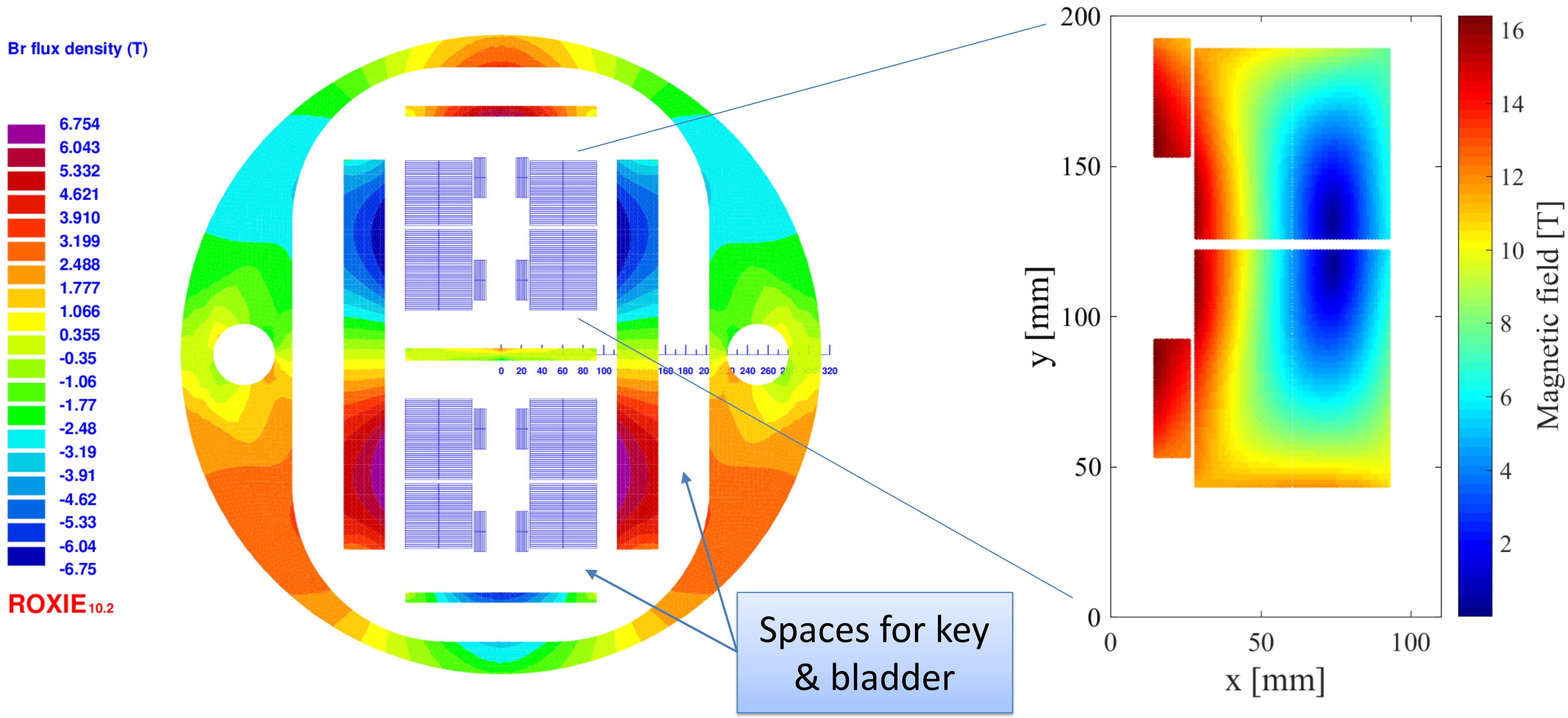
- Magnetic shims for geometric correction
- Magnetization correction w/iron strips
- Eddy current suppression cored cable

} LARP



Another example: Common coil

Magnet cross-section

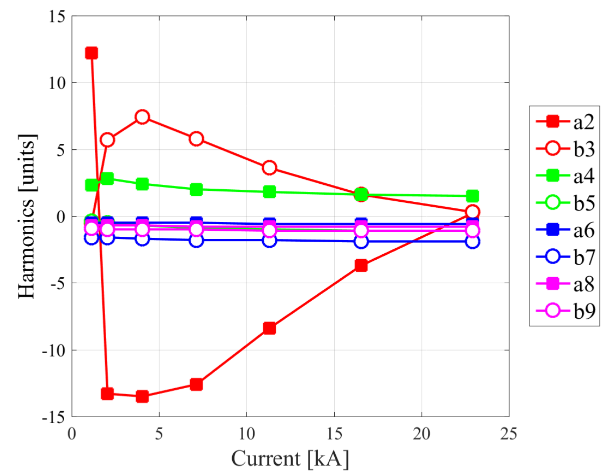


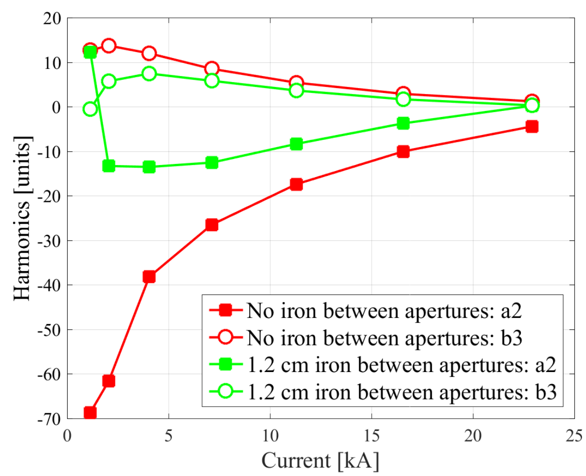
Calculated harmonics for the common-coil configuration

- We try to optimize the current-dependent harmonics through efforts on iron shape & placement, superconductor architecture, etc.

Magnetic field quality

Harmonics at nominal current at 2/3 of the aperture [units]			
Normal		Skew	
b3	0.3	a2	0.2
b5	-1.1	a4	1.5
b7	-1.9	a6	-0.6
b9	-1.1	a8	-0.8





- Magnetic analysis and **optimization** performed with ROXIE
- Control of the **harmonics** in the range 5-100% of nominal current
- Several features included in the **iron cross-section** to improve field quality

Example: Effect of the layer of iron added between apertures

In the early 2000's the "shell-based", "bladder and key" structure was developed to address strain-sensitivity of Nb_3Sn

- Example from HD3 – a block-style dipole that reached 13.4T at 4.4K
  - This development set the stage for CERN's FRESCA 2

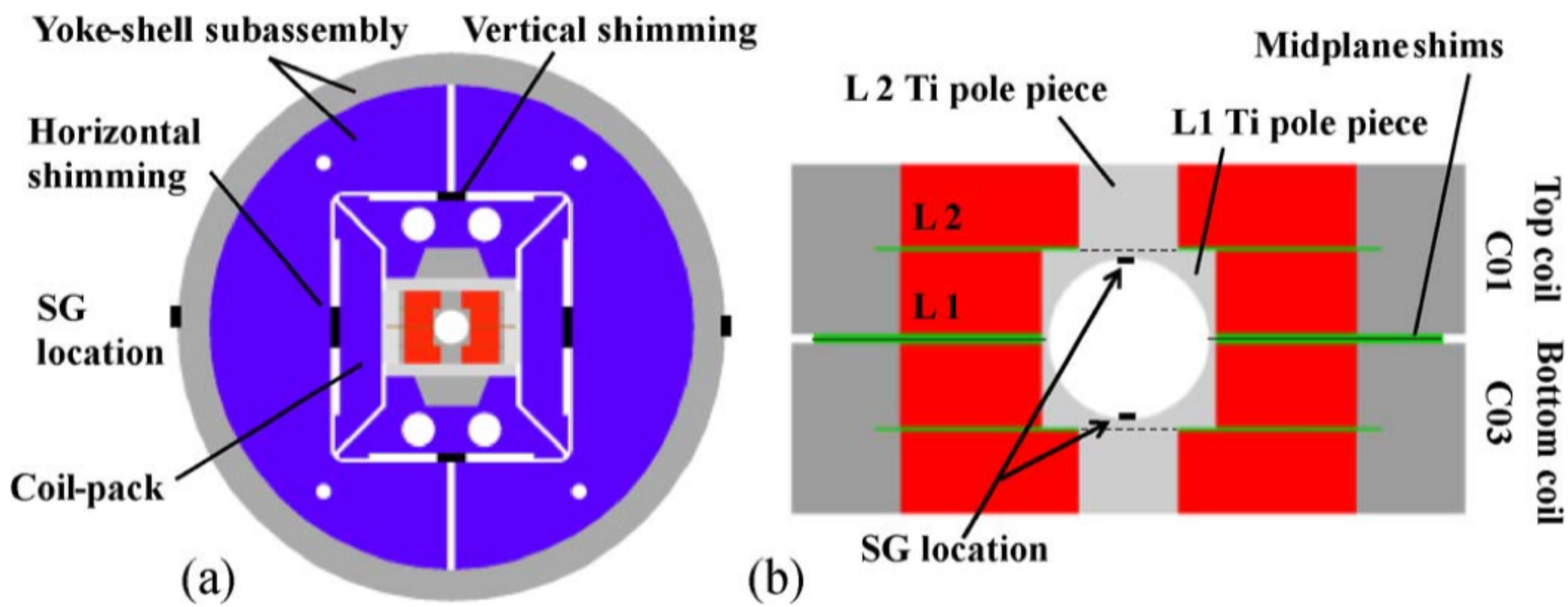
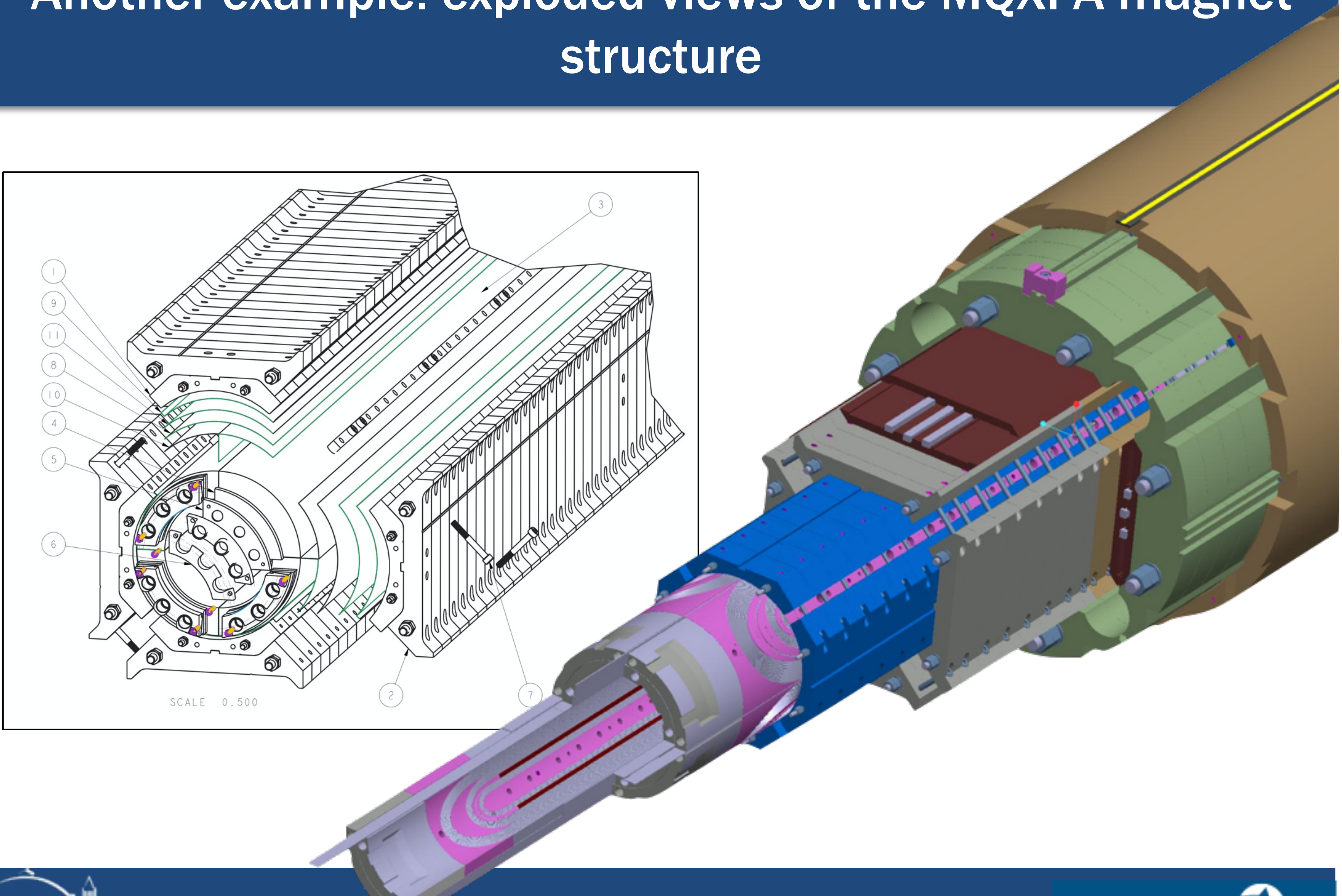


Fig. 1. (a) HD3 magnet cross-section. (b) HD3a coils cross-section showing layer 1 (L1) and 2 (L2), midplane shims and strain gauges location.

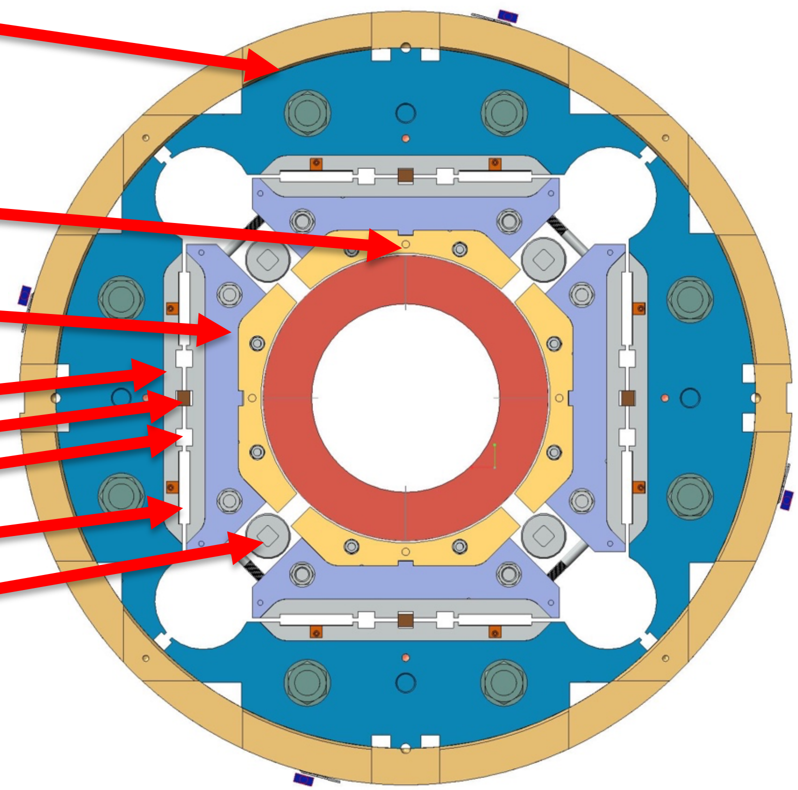
Felice et al., TAS, vol. 23, no. 3, June 2013

Another example: exploded views of the MQXFA magnet structure



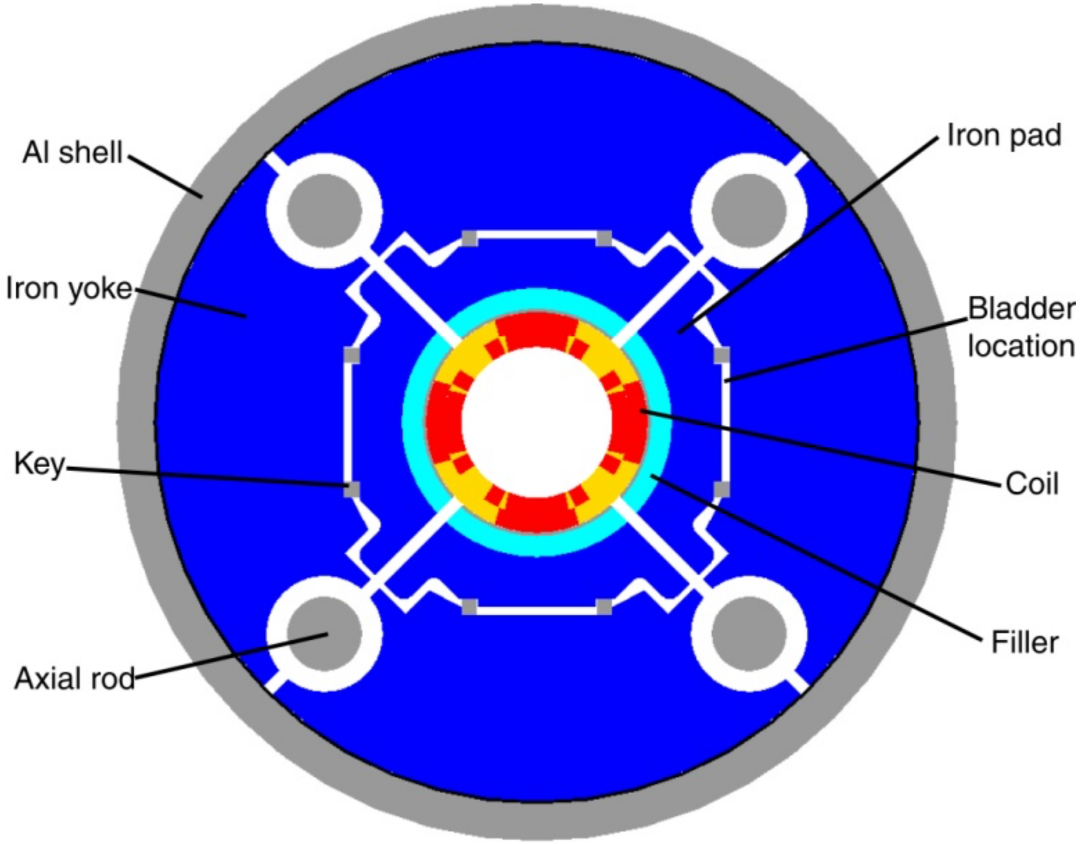
Primary MQXFA Structure Subassemblies

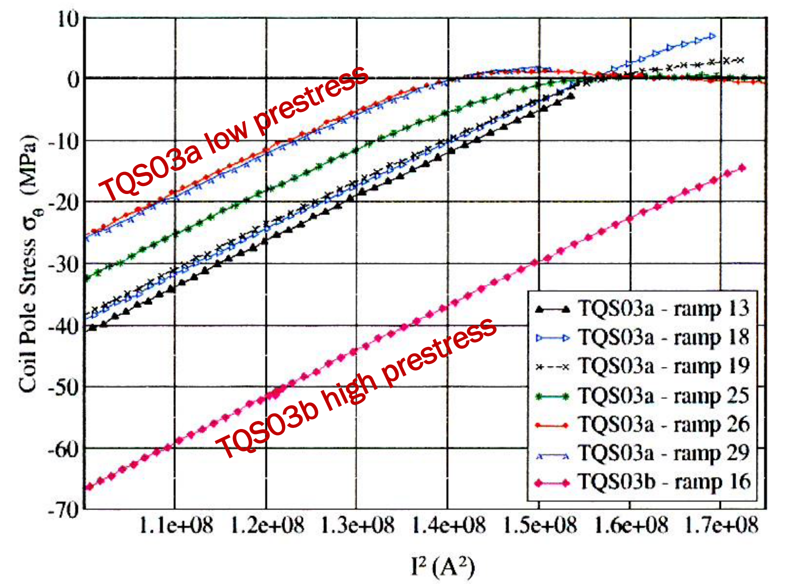
- Shell-Yoke Structure
  - Half-length subassemblies
  - Joined shell-yoke subassembly, full-length
- Coilpack
  - Coil pack subassembly
    - Load pad stacks
  - Collar pack subassembly
    - Collar stacks
    - Instrumented and GPI wrapped coils
- Master Key packages
  - Alignment keys
  - Load keys
  - Bladders
- Axial load
  - Axial rods, [end plates, wire guides]
- Splice Connection box
- Magnet support ring
  - Instrumentation connector skirt

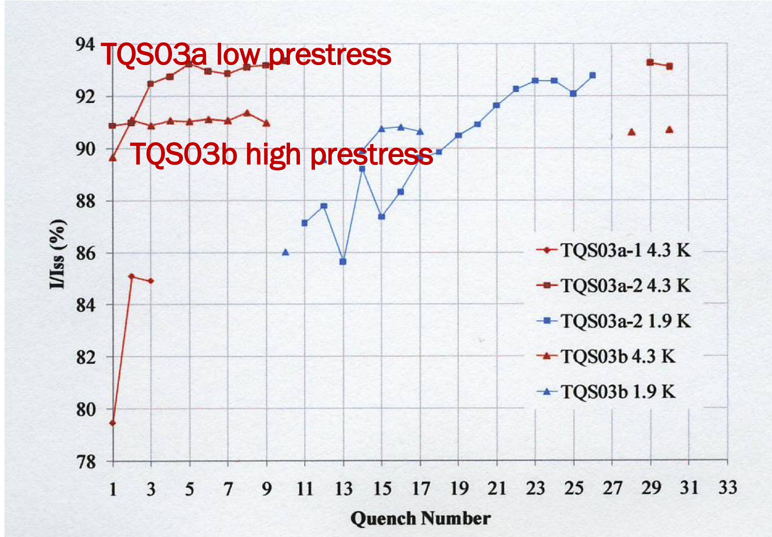


Application of prestress to eliminate separation: LARP TQ quadrupole

- With low pre-stress, unloading but still good quench performance
- With high pre-stress, stable plateau but small degradation

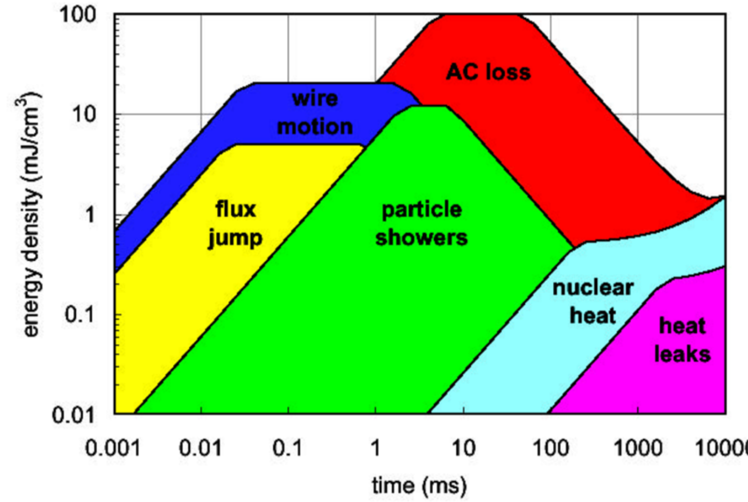






What are paradigm changes that might impact the landscape of magnet technologies for HEP?
1: tolerance to disturbances

Luca Bottura



- The (sensitivity to…) disturbance spectrum is a major limitation to high field magnet development
  - o Magnet training is extremely painful for a large project
  - o Performance variability is not tolerable – results in need for "margin" that captures performance σ
- Operation at superfluid helium comes at huge system cost
  - o Originally motivation: leverage NbTi
    - Less relevant for Nb_3Sn;
    - Irrelevant for HTS
  - o >2 cost (already from Carnot), + other inefficiencies

- Increasing heat capacity of conductor reduces sensitivity to disturbance spectrum
  - o Fusion addresses this via CICC - cryostability
  - o LHC magnets allow superfluid helium to percolate into magnets
- *HTS dramatically increases tolerance to disturbances & eases cryogenic constraints*

What are paradigm changes that might impact the landscape of magnet technologies for HEP? 2: structures that mitigate conductor stress & motion

- High-field magnets are limited by issues related to forces:
  - Strain sensitivity of conductor Jc
    - Particularly true with Nb_3Sn and HTS
  - Motion (in many forms) are components of the disturbance spectrum
- Current approaches in HEP balance these two elements via optimized "prestress"
  - Coils in compression throughout (most of…) operating range
  - Peak prestress at cooldown (leverage differential thermal contraction, e.g. shell-based magnets)
- "Stress management" schemes are under investigation
  - Limiting case is design approaching "pinning curve", e.g. no force accumulation

This is where the "freeing" of magnet designs from field quality constraints may be very useful

What are paradigm changes that might change the landscape of magnet technologies for HEP and FES?
2: designs adapted to industry strengths

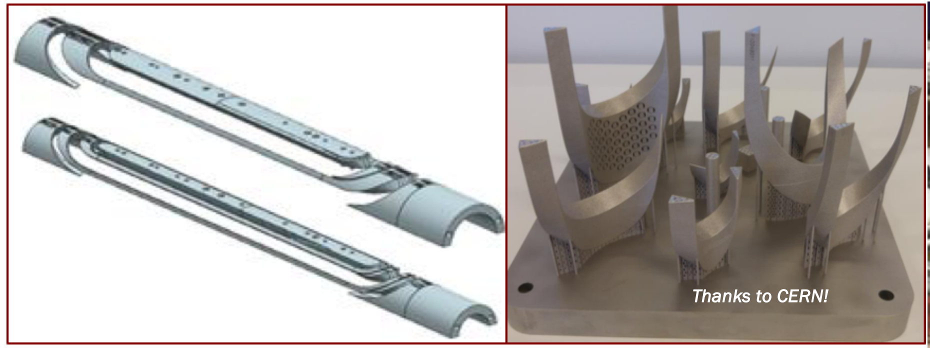
- Built in modularity throughout the design
- Design for less sensitivity to fabrication tolerances
    - Clearly identify all tolerances in specifications and fabrication documents
- Long range strategies:
    - Recruit staff from industry to provide insight into their perspectives and strengths
    - Look at examples from other industries that incorporate advanced technologies of scale
        - Aerospace? Transportation? …
        - What elements make them successful in performance (reliability, reproducibility, cost reduction,…)?

”Boutique” vs “mass” production – a very significant change in design paradigm

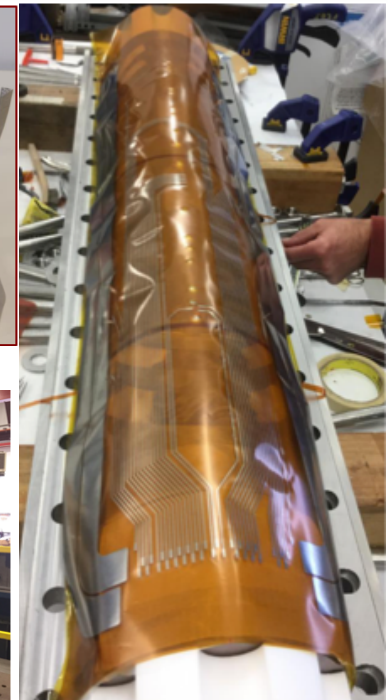
- Example: HiLumi needs ~20 high field dipoles: “Boutique” production
  - Does not justify full technology transfer to industry (from a cost and schedule perspective)
- Example: LHC
  - >1000 dipoles, multiple vendors, robust QC
- Development via a technology readiness program (Directed R&D) is critical
  - Example: LARP (~13 years)
  - Focus on “good enough” performance:
    - experimental verification of performance
    - Diagnostics and testing that provide quantitative feedback
    - Engineering and technical expertise “on the floor”
    - Cost of components and processes second to “getting job done”
    - Modest level of “value engineering”
- For mass production focus on reliability and simplicity in design
  - Fabrication focus on simplicity: significant value engineering
    - Technicians follow procedures – goal is not to “add expertise”
  - Reproducibility is paramount
  - Diagnostics are “the enemy” – costly and can be source of issues

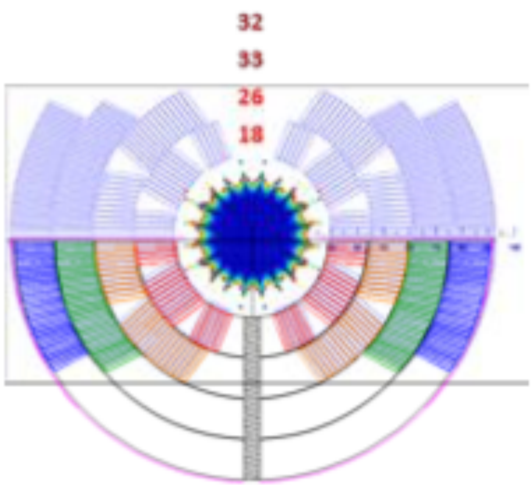
A Cos(t) 4-layer design led by FNAL is being pursued with the ultimate goal of achieving ~15T

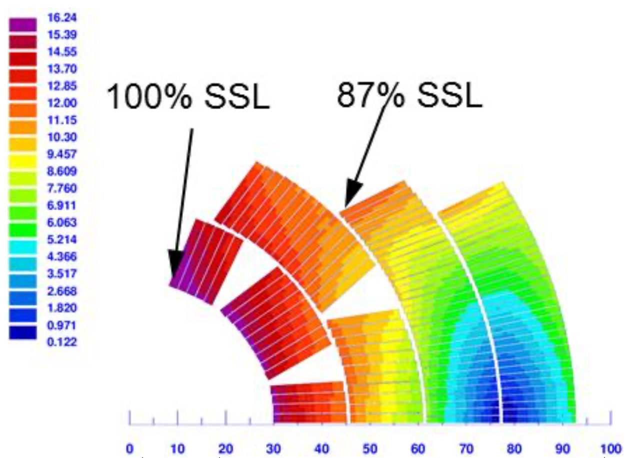
- Design minimizes midplane stress for highest field
- A technical challenge is to provide adequate prestress on inner coils
  - Intrinsic difficulty with 4 layers
  - Collared-structure approach includes new features that provide some prestress increase during cool down



- Thin StSt coil-yoke spacer
- Vertically split iron laminations
- Aluminum I-clamps
- 12-mm thick StSt skin
- Thick end plates and StSt rods





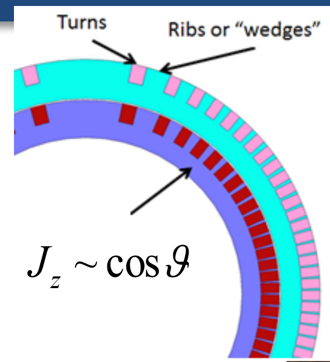


60-m aperture, 4-layer graded coil

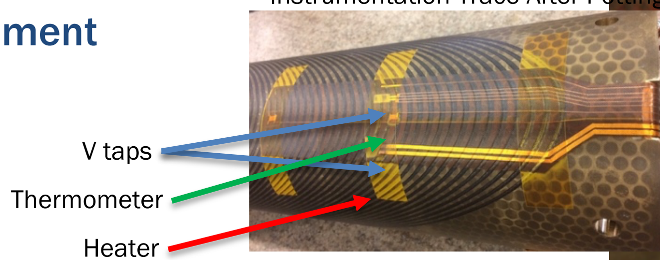
The Canted-Cos(t) concept led by LBNL is being explored as an alternative for high-field magnets

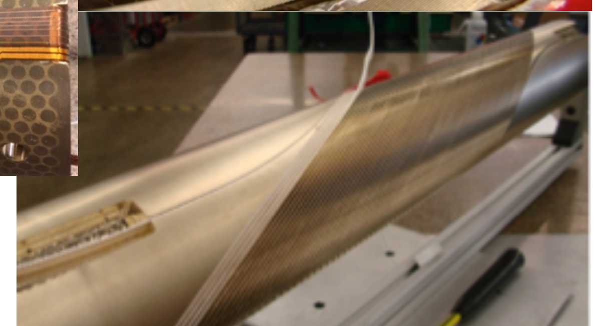
- Fabrication of mandrels is "complex" (advanced CNC)
- Simple, scalable winding, reacting, and potting tooling

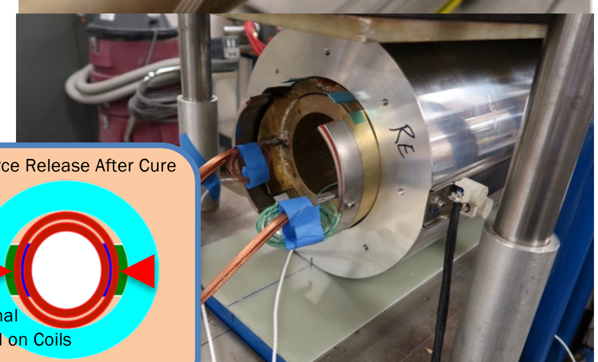
- CCT4 (the second Nb3Sn CCT 2-layer magnet)
- CCT5 incorporated modifications based on CC4 experience
- Magnet was tested and thermally cycled
- Subscale CCT currently being pursued
  - o fast turn-around technology development



Instrumentation Trace After Potting

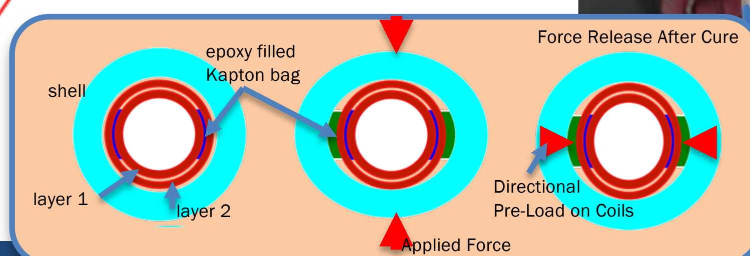






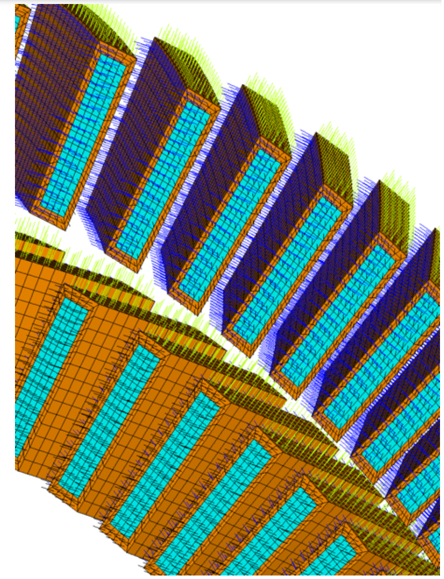
	CCT3	CCT4	CCT5
Bore size [mm]	90	90	90
Groove design	constant width	1.25 mm gap at pole	1.65 mm gap at pole
Conductor	RRP 54/61 Ta doped	RRP 54/61 Ta doped	RRP 108/127 Ti doped
HT Temp [C]	650	660	665
Potting configuration	full magnet	full magnet	individual layers
Epoxy	CTD-101K	CTD-101K	FSU Mix 61
Layer-to-layer interface	bonded	mold released	bend & shim

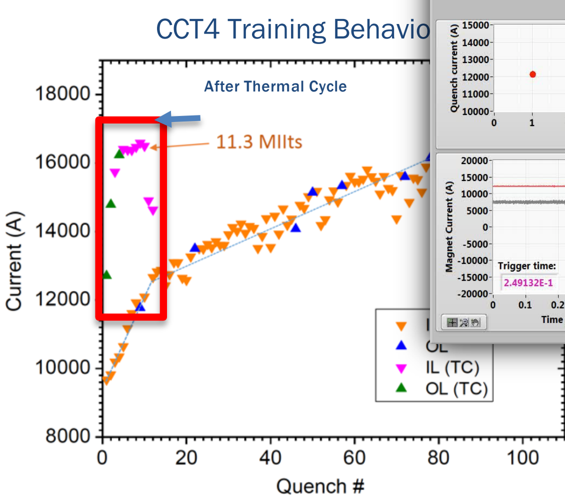
- Conductor damage
- Field quality
- Cost and scalability
- Training

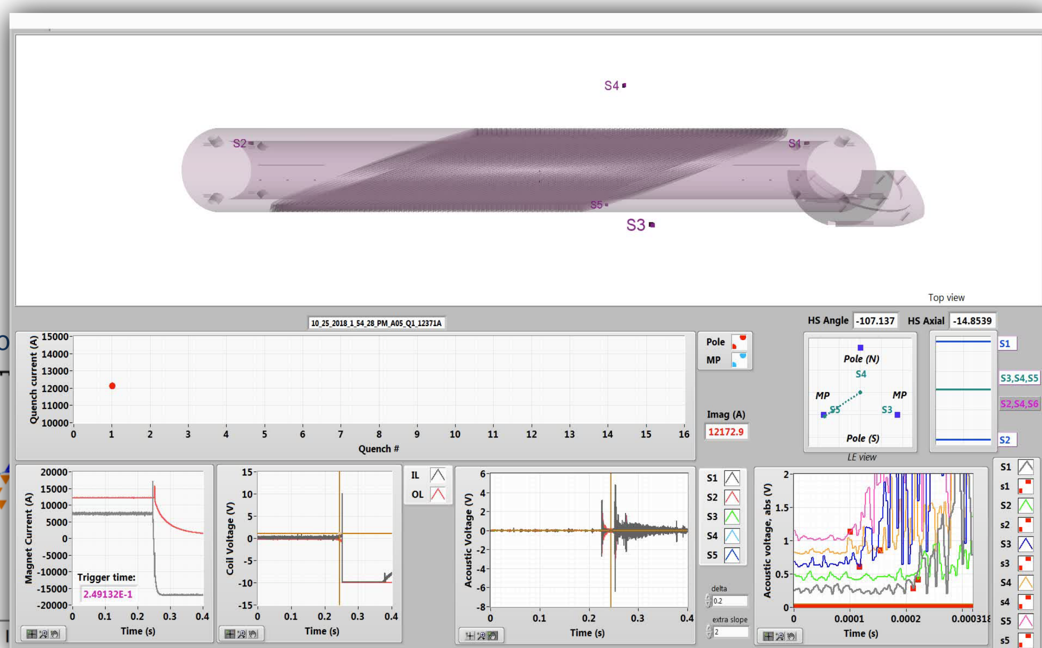


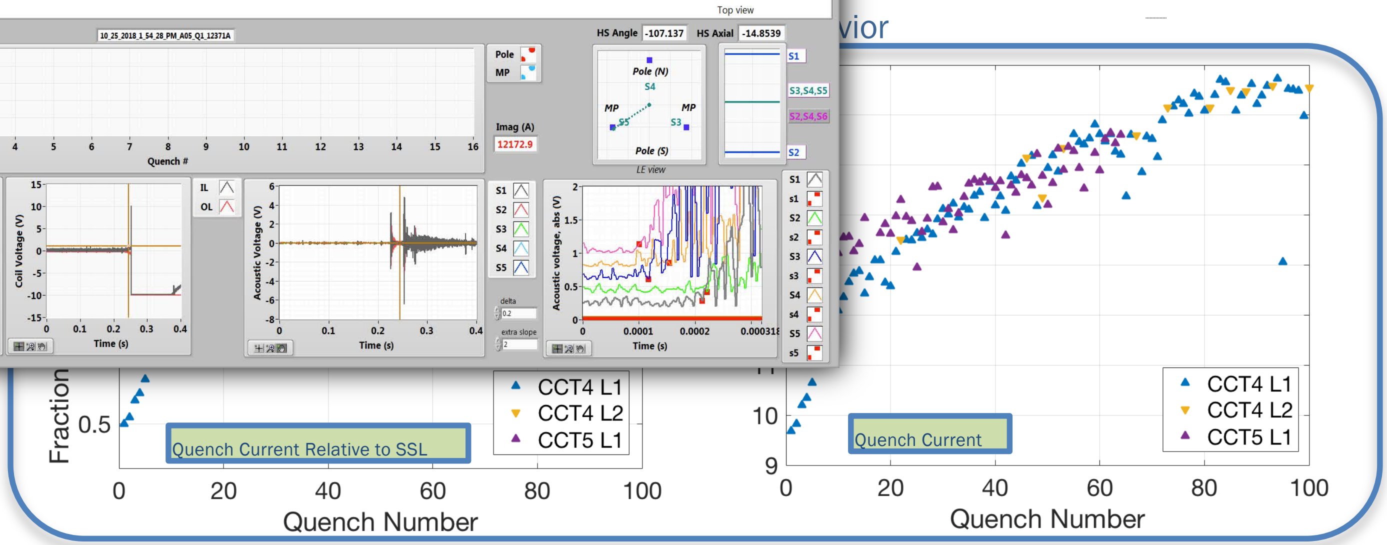
CCT test results show significant training - feedback has led to improvements, but further work needed

- CCT4 conductor has higher Ic (CCT4: 54/61 RRP; CCT5: 108/127 RRP)
- CCT5: First quench at 69% of short sample, magnet reached 88% of short sample after 59 training quenches
  - After initial improvement training rate is similar to CCT4
  - After approx. quench #20 there are many detraining quenches with large drops in quench current (similar to CCT4 after approx. quench #30)



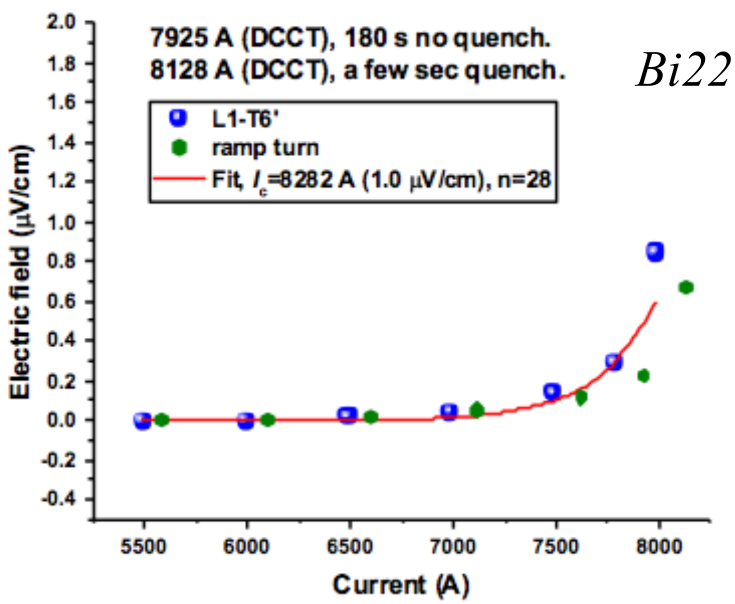






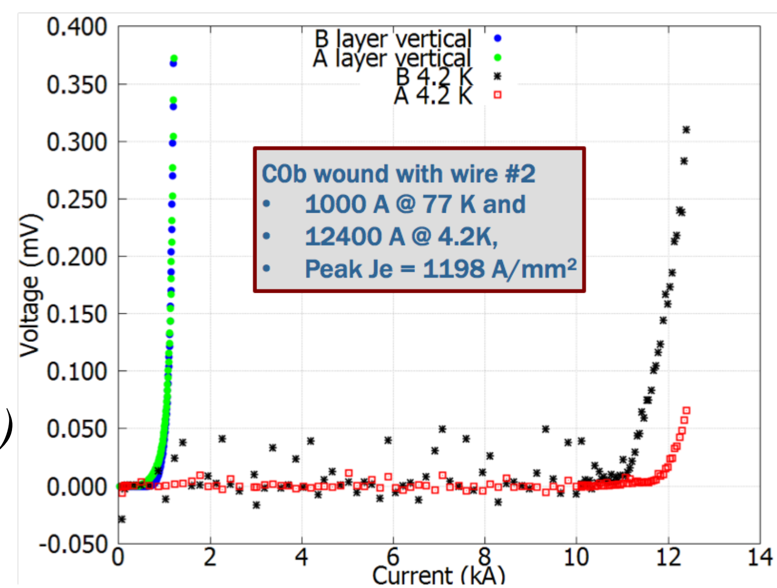
Magnet protection considerations with HTS is an active area of research - detection and energy extraction are concerns

- Traditional protection paradigms are challenged by HTS materials
  - Large temperature margin results in slow quench propagation
    - impacts detection: slow voltage growth implies difficulty in detecting onset of quench
    - increases hot-spot temperature and strong thermal gradients that can cause mechanical damage
  - Higher-field, more compact magnets ⟹ higher J_E ⟹ higher stabilizer current density ⟹ aggravates the hot-spot issue
  - Measuring small normal voltage signals (<<100mΩ) in a background terminal voltage of >10 kV is a challenge
- However… some early indications are that HTS magnets transition, with ample time to identify issues and react
  - Does that characteristic scale? Do high current HTS cables amplify that characteristic (e.g. via current sharing)?



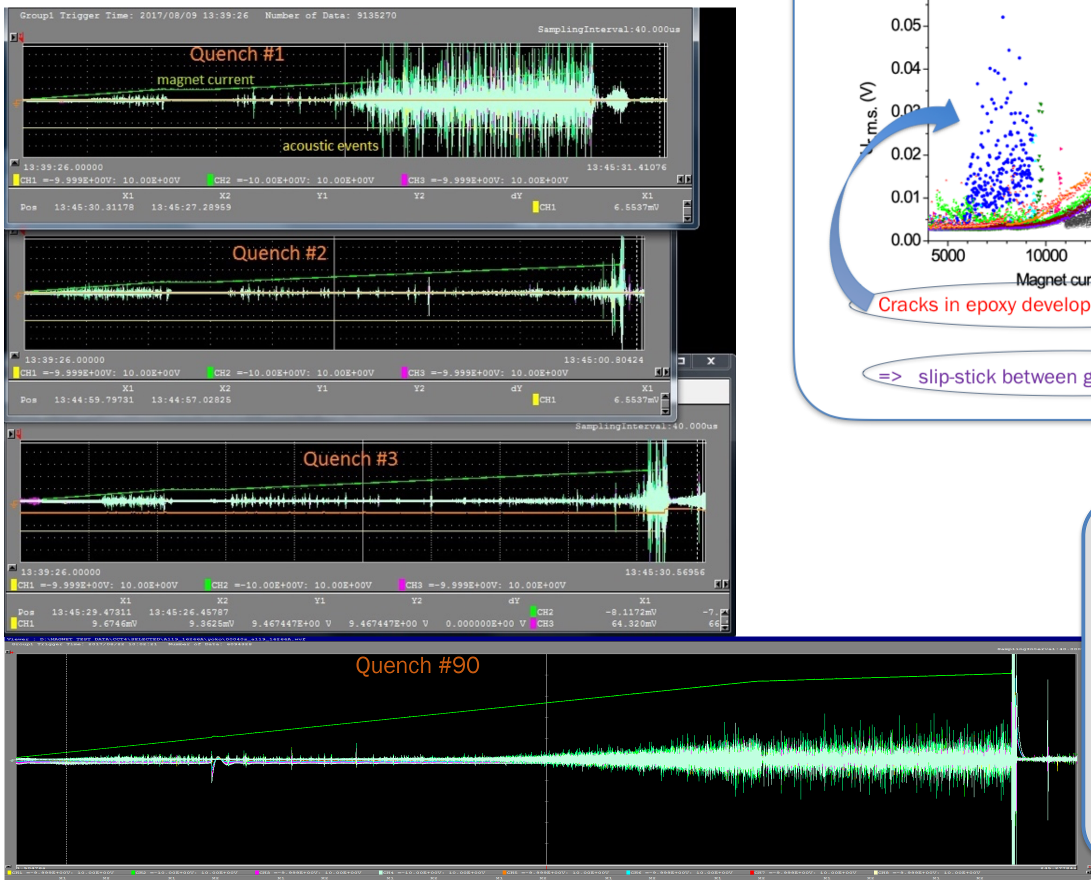
Bi2212 (Shen)

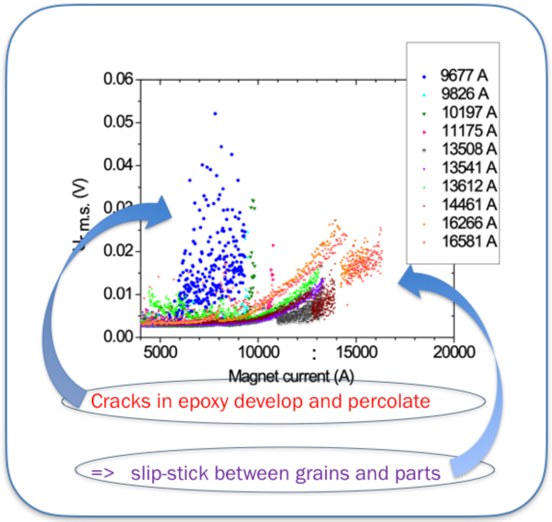
REBCO (Wang)

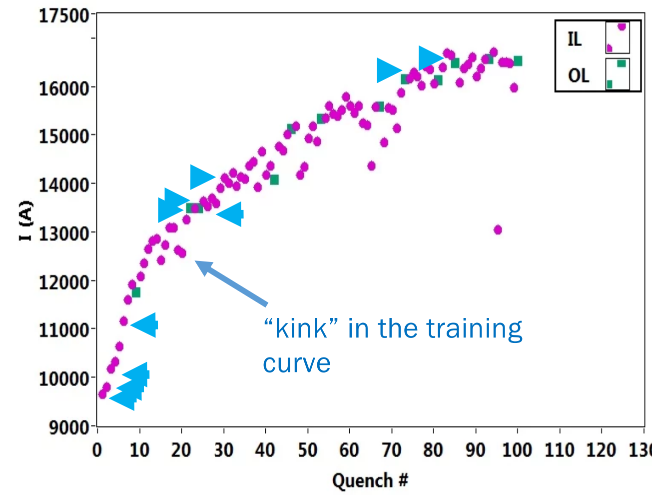


Diagnostics are critical for understanding of magnet performance and to provide feedback to magnet design

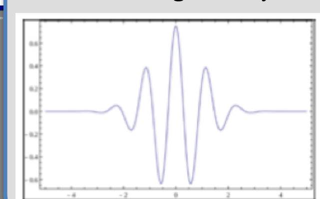
Acoustic signatures provide a wealth of data on energy perturbations in magnets

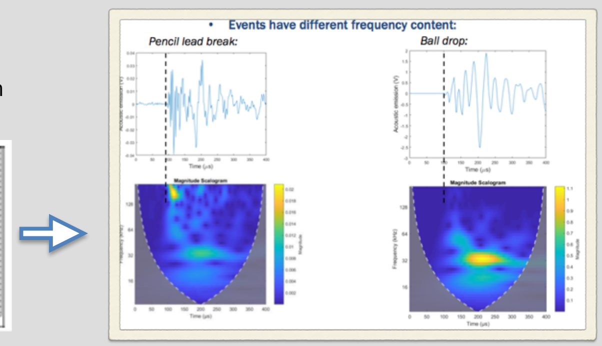






Wavelet analysis provides robust mathematics platform for transient signal analysis

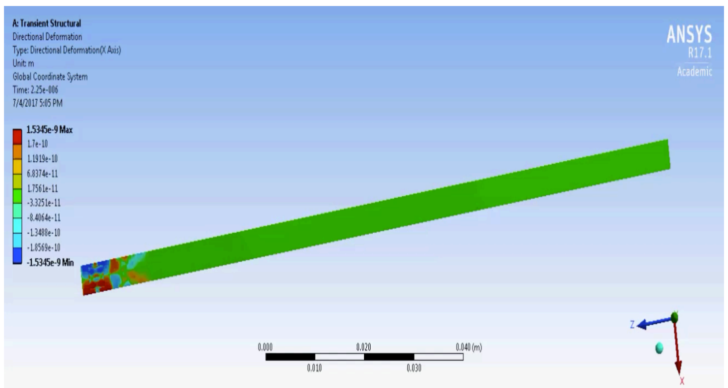


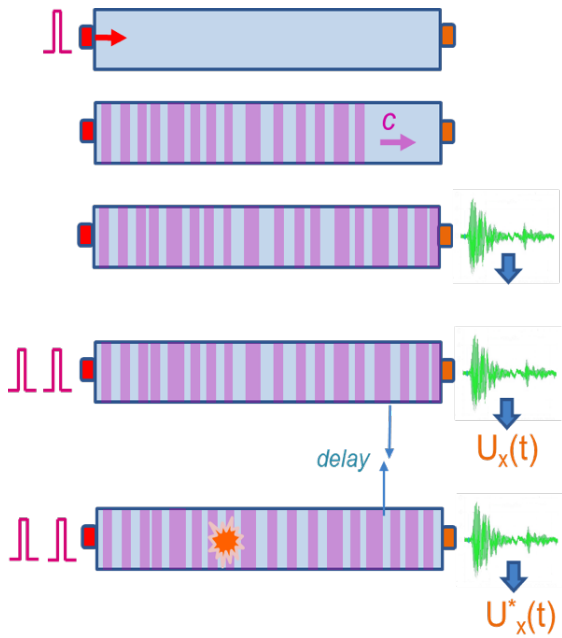


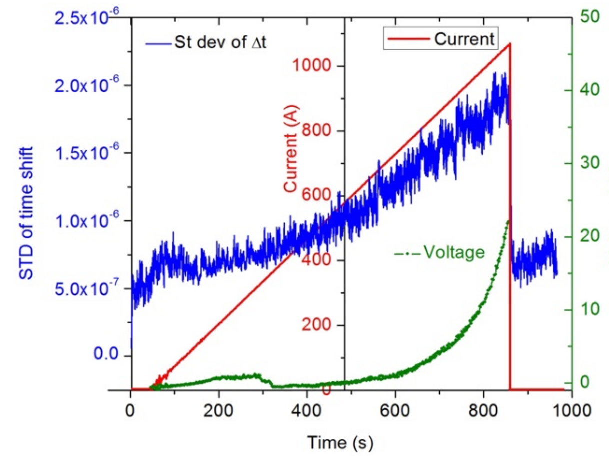
U.S. MAGNET DEVELOPMENT PROGRAM

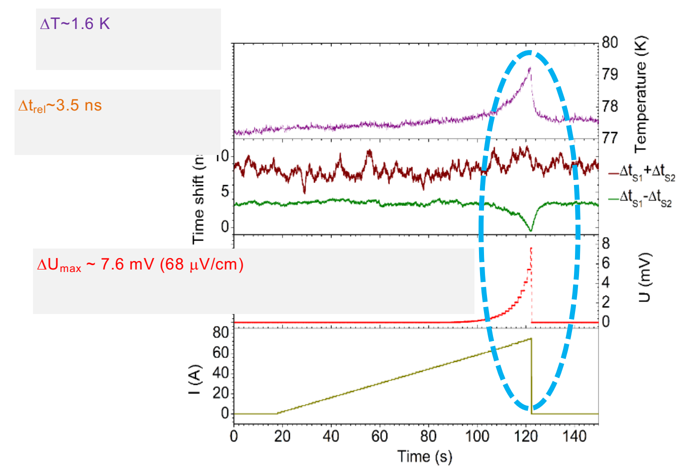
Diagnostics are critical for understanding of magnet performance and to provide feedback to magnet design

Active acoustics can utilize phase-shift of the complex signal response pattern to identify thermal changes in the system => independent mechanism to see transition









- "**Acoustic thermometry for detecting quenches in superconducting coils and conductor stacks**," M. Marchevsky and S. A. Gourlay, *Appl. Phys. Lett.*, vol. 110, p. 012601, (2017), doi:10.1063/1.4973466
- "**Quench Detection for High-Temperature Superconductor Conductors using Acoustic Thermometry** ", M. Marchevsky et al., *IEEE Trans Appl. Supercond.* vol 28, issue 4 (2018), doi:10.1109/TASC.2018.2817218

Advanced magnet diagnostics are critical for the application of HTS - provide design flexibility and enable new operational paradigms

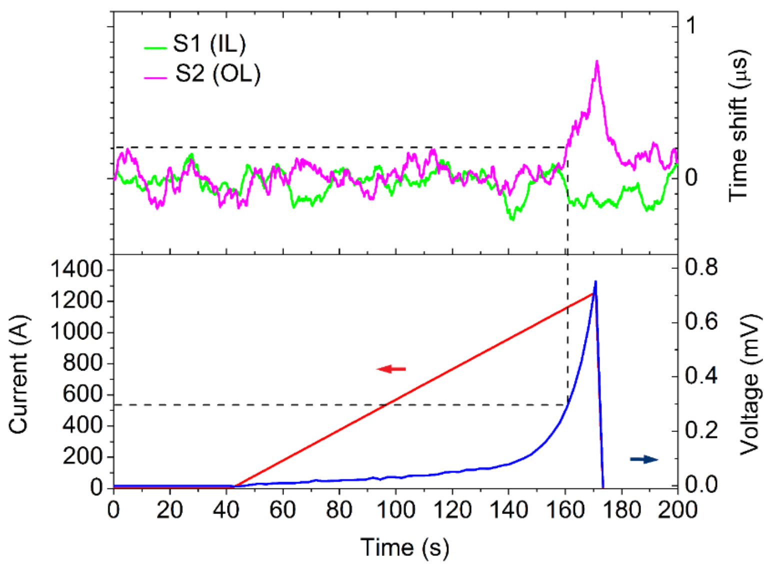
- **Fiber-optics promise minimally invasive measurement of temperature/strain⟹ quench diagnostic that avoids the signal to noise issue associated with voltage taps**

F. Scurti, S. Ishmael, G. Flanagan, and J. Schwartz, SUST, vol. 29, no. 3, p. 03LT01, Mar. 2016.

- **Acoustic signals (both passive and active) are proving to be extremely valuable in identifying and locating quench events in HTS - non-invasive and independent of voltage**
  - **See https://atap.lbl.gov/atap-news-september-2018/#quenchdetection**

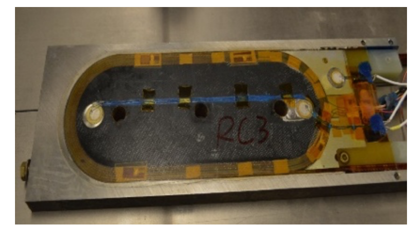
M. Marchevsky and S. A. Gourlay, *Appl. Phys. Lett.,* vol. 110, p. 012601, (2017), doi:10.1063/1.4973466

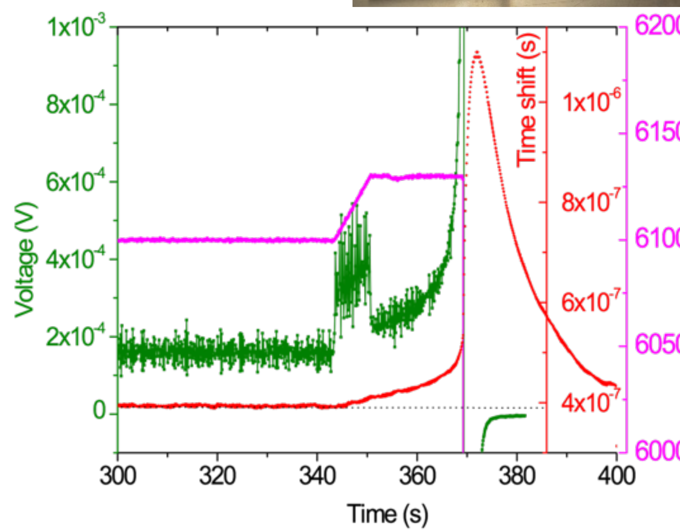
M. Marchevsky et al., *IEEE Trans Appl. Supercond.* vol 28, issue 4 (2018), doi:10.1109/TASC.2018.2817218



ReBCO CORC coil
(X. Wang)

Bi-2212 coil RC3
(K. Zhang, T. Shen)





What are key characteristics we are looking for in magnet designs for real colliders?

- Robust and manufacturable design
  - performance insensitive to variations within specified tolerances, and tolerances comfortably within industries capabilities
  - Specifications that are clear, concise, crisp, and measureable
- Efficient and effective quality control and assurance (QC/QA)
  - Timely – provide feedback with minimal schedule impact
  - Effective – QC demonstrated to correlate with specifications and performance
- Scalability of the component fabrication and the assembly techniques
  - Leverage industries ability to produce efficiently and reliably
  - Leverage competition in the marketplace – design to enable large vendor pool, opportunities for scale-up

Some ideas on where major developments are likely to occur on the ~20 year timescale: certainly…

- Diagnostics, measurements…, and Machine Learning/AI
  - Expect massive amounts of performance data to be available
  - Expect powerful algorithms and computing power to probe the data
  - In the near term these will serve to guide research; in the future they will likely be integral to production and operation

- Machining advances
  - 3D printing will be commonplace (including metals, ceramics)
    - Need different design approach to fully leverage

- Improved optical metrology
  - fast, non-invasive systems integrated into fabrication and assembly processes

- Modeling advances that enable system optimization and thorough sensitivity analysis

- Steady continued development of superconductors
  - (as we have seen over the last 30 years!)

Some ideas on where major developments are likely to occur on the ~20 year timescale: possibly…

- Tailored magnet materials that address critical technology issues, e.g.…
  - “porous” but strong impregnations that provide cryostability along with mechanical support
  - Insulations that are compatible with heat treatment yet provide high dielectric strength
- Ubiquitous automation that minimizes “touch labor”
- Emerging markets for HTS fuel larger production capabilities and steady cost reduction, making them viable for large-scale science
- …

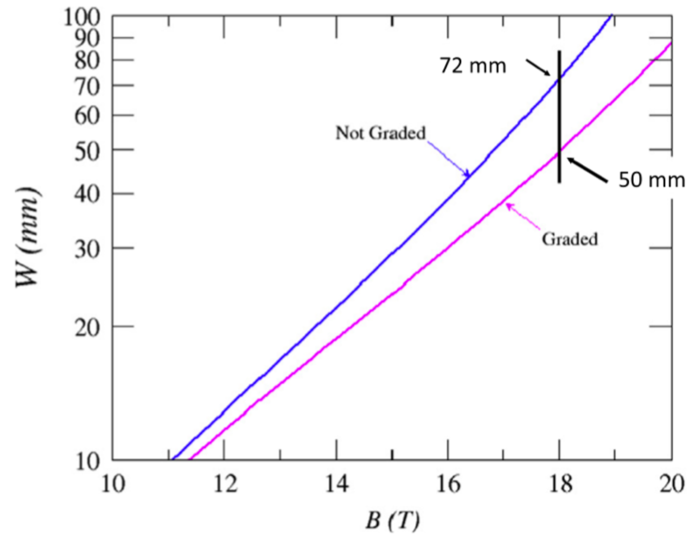
Summary

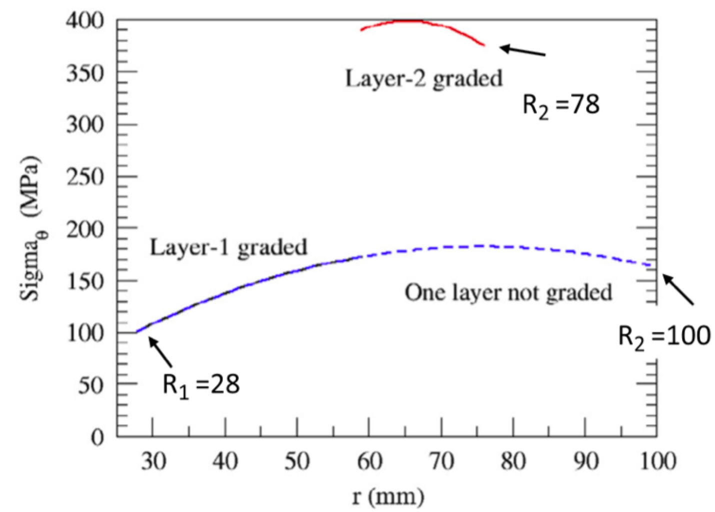
- Technology for the next big colliders and fusion machines will require effective use of / collaboration with industry
  - How do we best tap into the resources / capabilities of industry?
  - Can we do anything to help industry well in advance of the next big project? Just show up with money?
  - Can we better prepare ourselves to work with industry?

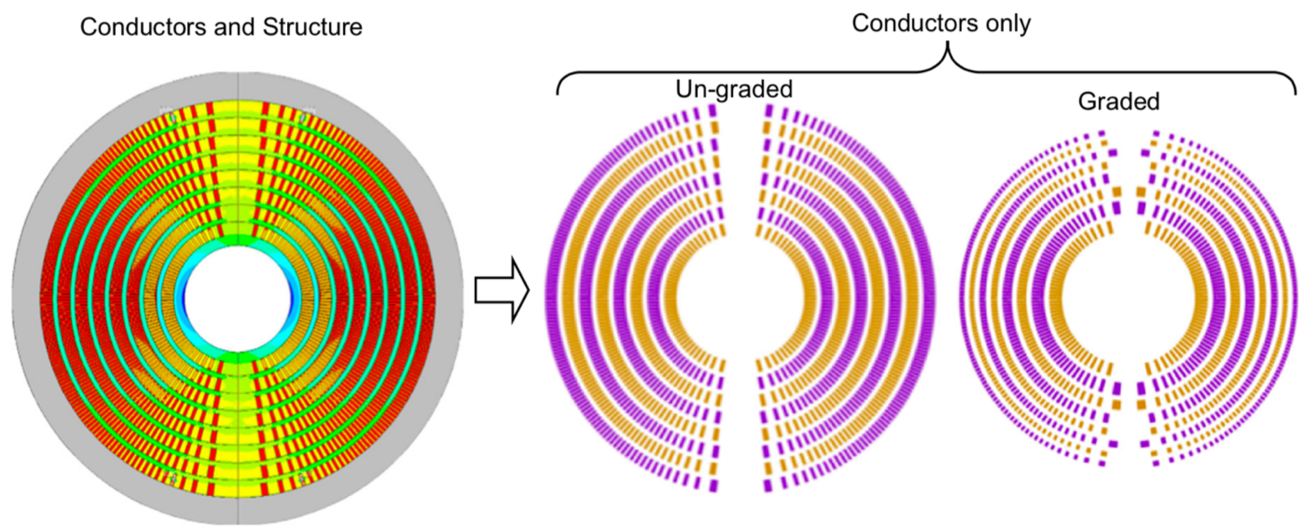
- We are working to develop core magnet technologies
  - To optimize conductors for our science needs requires coordination/collaboration with the wire industry
    - Need to “meet in the middle” – not all issues should be “dumped” on the conductor

Backup slides

Importance of grading for high-field dipoles

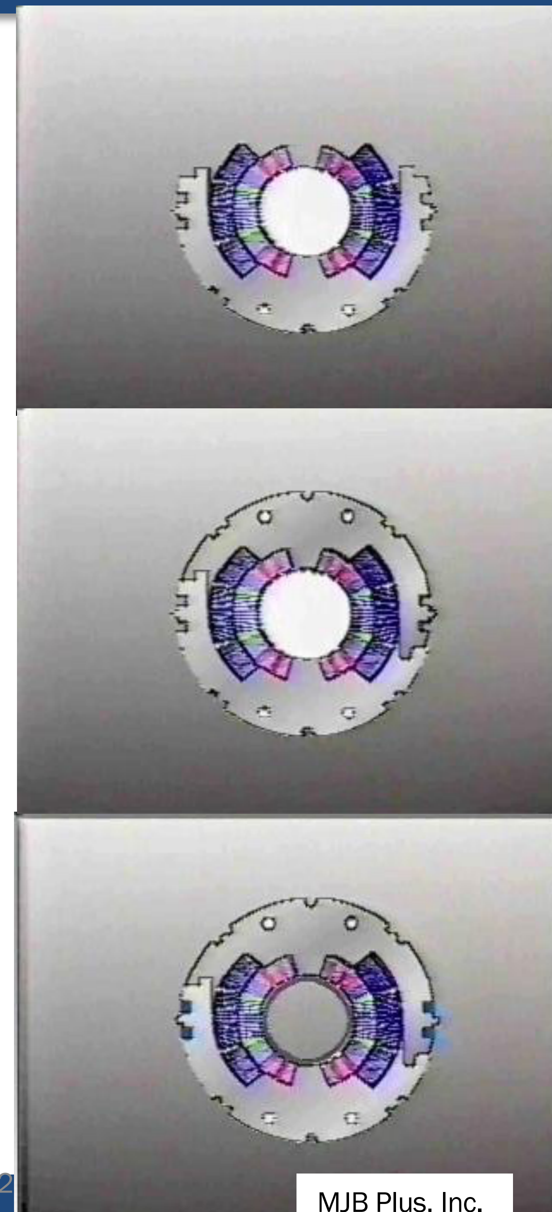






Review of Collaring process

- Collaring procedure
  - Collars are pre-assembled in packs (several cm long) and placed around the coil.
    - The collar laminations are divided in “short” and “long”.
  - Since the uncompressed coil is oversized with respect to the collar cavity dimension, at the beginning of the collaring procedure the collars are not locked (open).
  - The coil/collar pack is then introduced into a collaring press.
  - The pressure of the press is increased until a nominal value.
  - Collars are locked with keys, rods or welded, and the press released.
  - Once the collaring press is released, the collar experience a “spring back” due to the clearance of the locking feature and deformation.

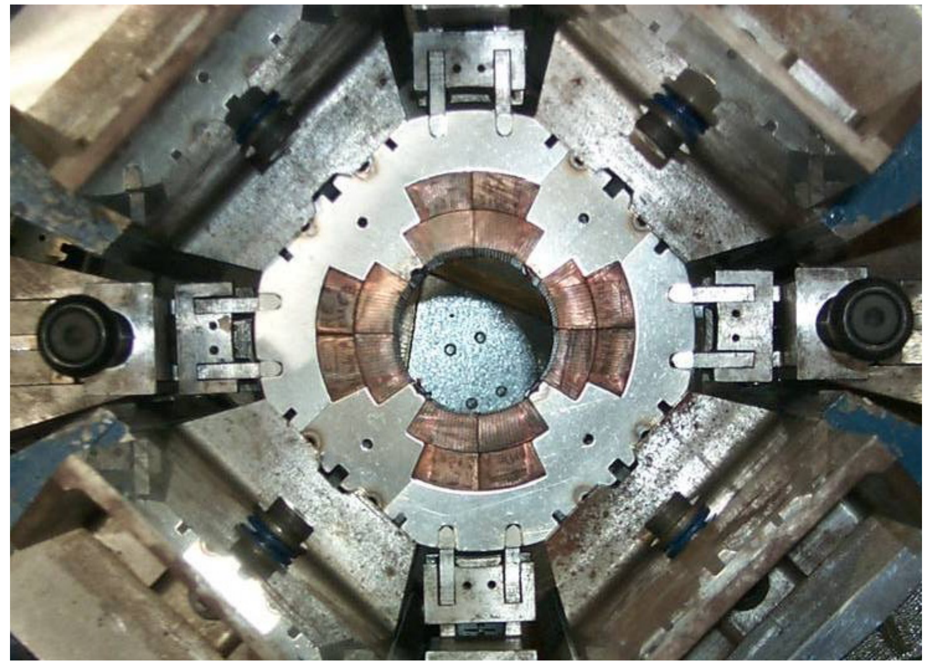


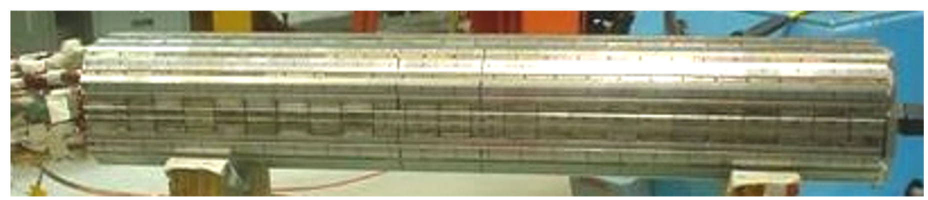
MJB Plus, Inc.

Examples of the Collaring process

Collaring of a dipole magnet

Collaring of a quadrupole magnet





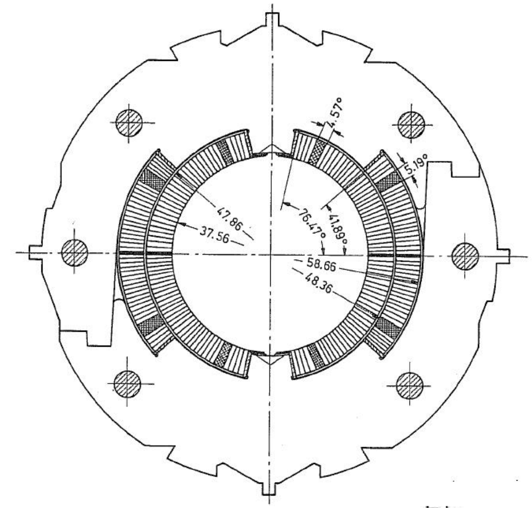
Collars serve a number of purposes – field quality and mechanical support

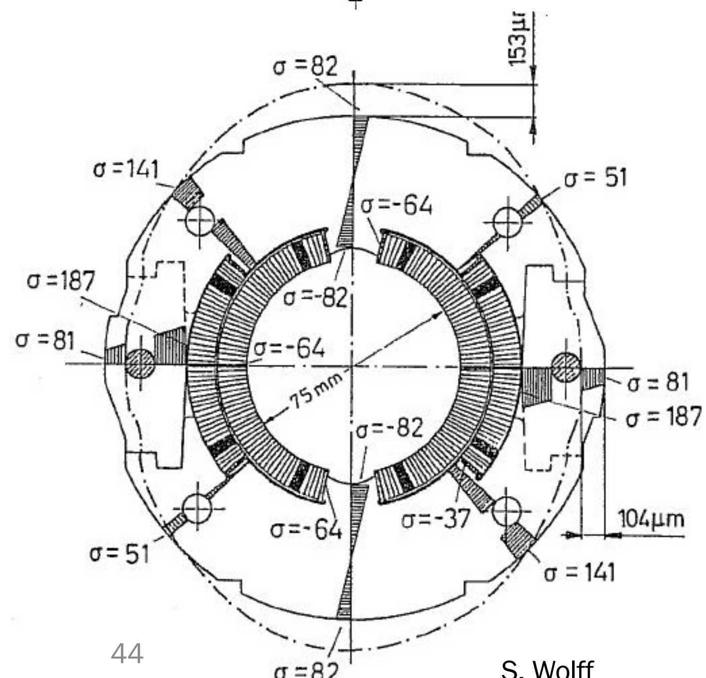
- **The purpose of the collar is to pre-compress the coil inside a "rigid" cavity.**
  - **The collar cavity fixes the dimension of the coil.**
  - **Coil geometry is given by the collars.**
- **Coil stress-strain is given by**

$$\varepsilon_{coil}=(l_{coil\_0}-l_{cavity})/l_{coil\_0}$$

$$\sigma_{coil}=E_{coil}\varepsilon$$

- **A good knowledge of the coil properties (l_{coil_0} and E) is mandatory to predict final coil status.**
- **In addition, collar deformation must be taken into account.**

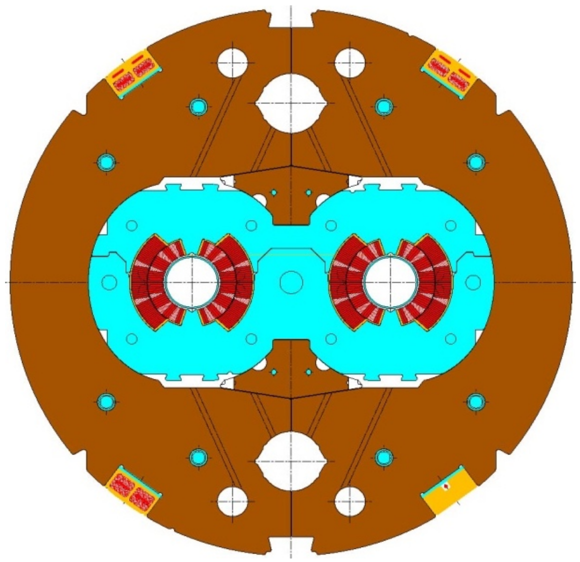




S. Wolff

The Iron yoke also serves multiple functions

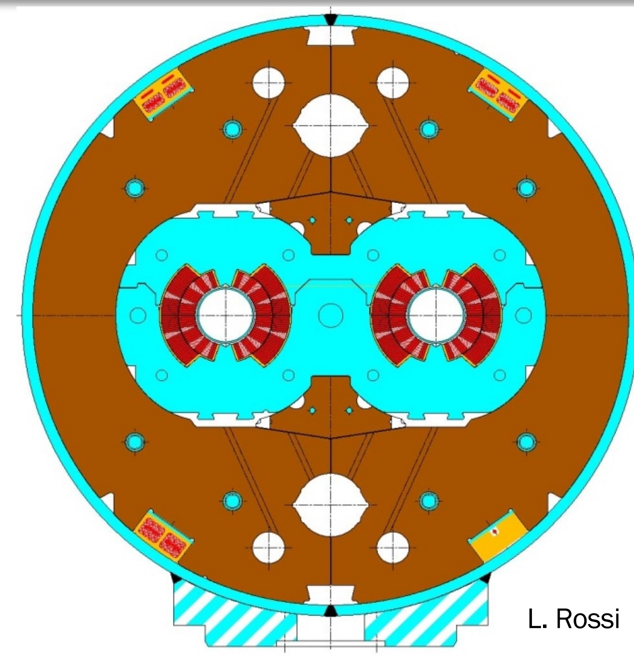
- As the collars, iron yoke are made in laminations (several mm thick), with a packing factor > 95%.
- Magnetic function
  - The yoke contains and enhances the magnetic field.
- Structural function
  - Except for the cases where the collars are self supporting (i.e. like in Tevatron and HERA dipoles), the yoke is in tight contact with the collar. Therefore, it contributes to increase the rigidity of the coil support structure and limit radial displacement.
- Holes are included in the yoke design for
  - Correction of saturation effect
  - Cooling channel
  - Assembly features
  - Electrical bus



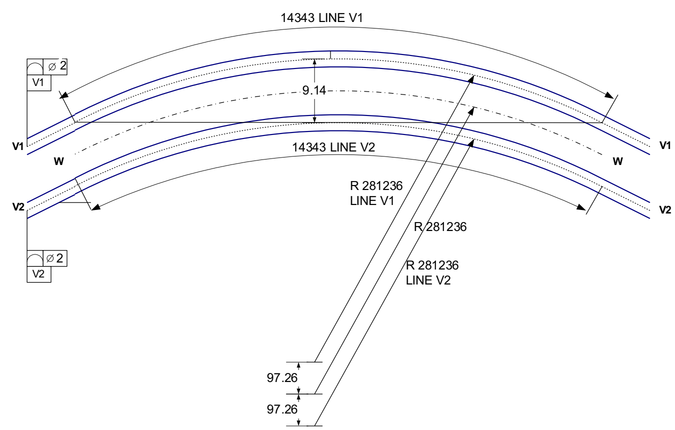
L. Rossi

A stainless steel shell is typically used to contain the liquid helium

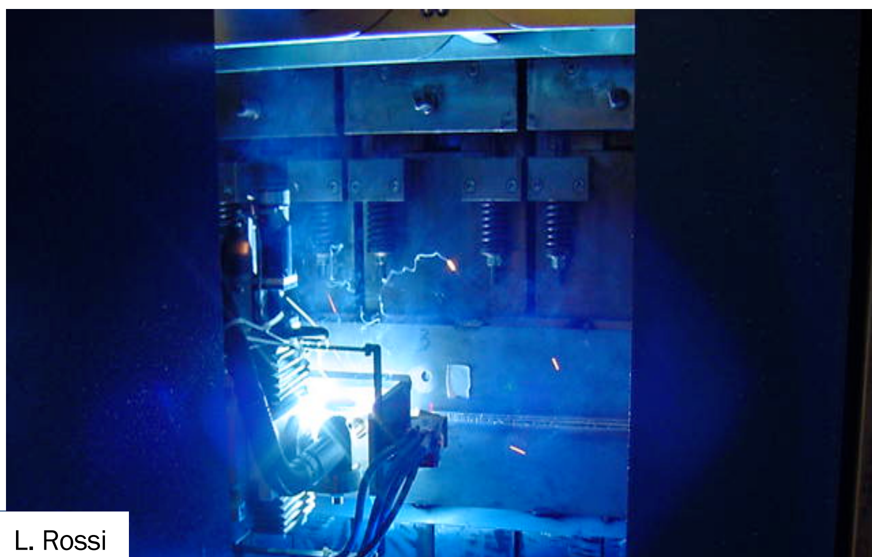
- The cold mass is contained within a shell (or shrinking cylinder).
- The shell constitutes a containment structure for the liquid Helium.
- It is composed by two half shells of stainless steel welded around the yoke with high tension (about 150 MPa for the LHC dipole).
  - With the iron yoke, it contributes to create a rigid boundary to the collared coil.
- If necessary, during the welding process, the welding press can impose the desired curvature on the cold mass.
  - In the LHC dipole the nominal sagitta is of 9.14 mm.

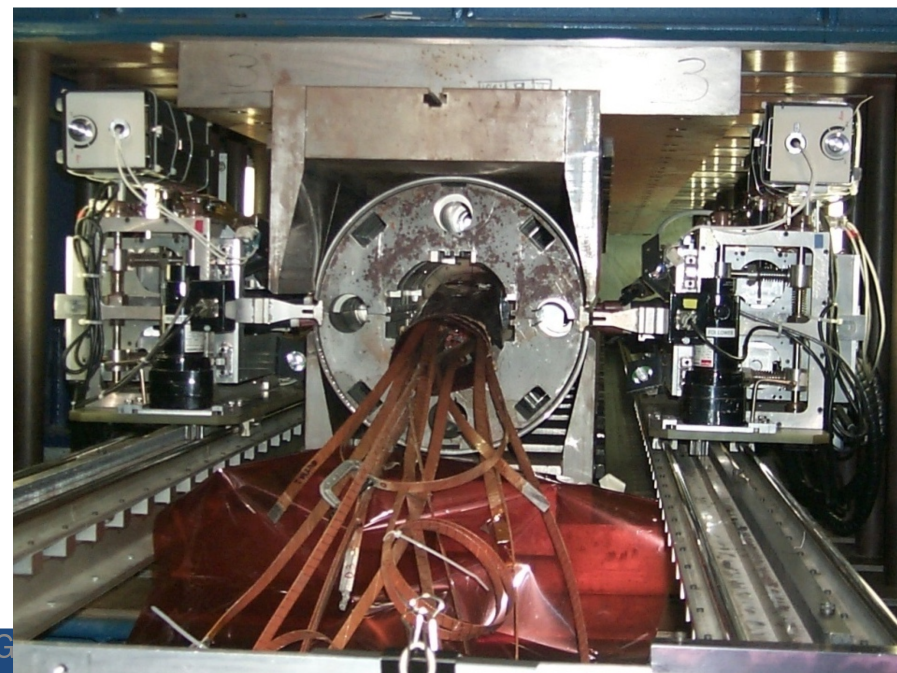


L. Rossi



Examples of helium containment shell fabrication

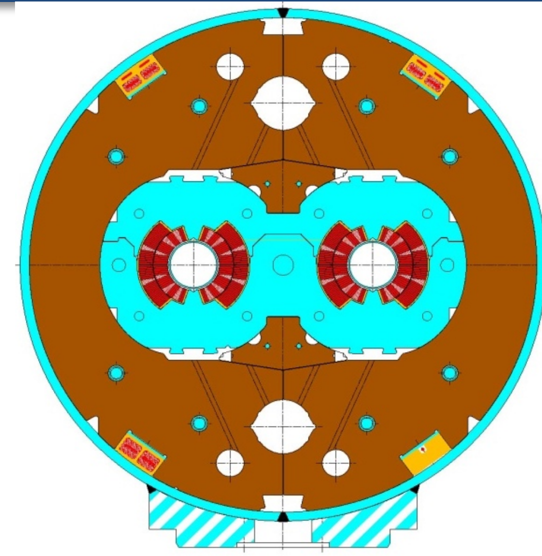


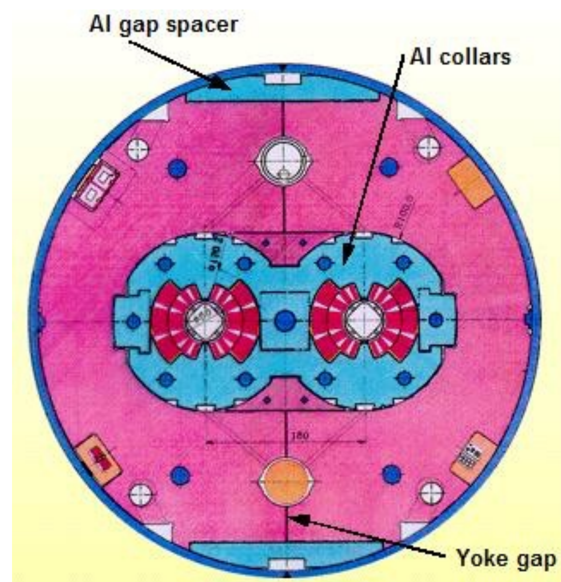


L. Rossi

The shell integration can also serve multiple purposes and requires critical process control

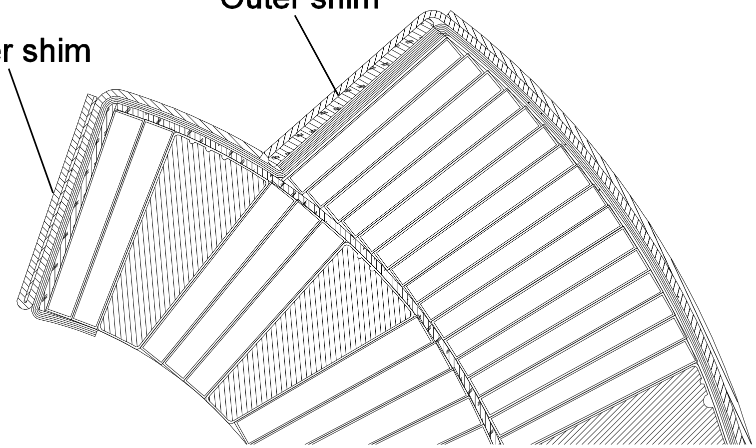
- The shell tension provided by the welding may contribute to the overall support of the collared coil.
- An often (SSC, LHC) implemented approach is the line-to-line fit.
  - When the yoke is put around the collared coil, a gap (vertical or horizontal) remains between the two halves; this gap is due to the collar deformation induced by coil pre-stress.
  - After welding, the shell tension closes the gap, and good contact is provided between yoke and collar.
  - After cool-down, despite the higher thermal contraction of the collared coil with respect to iron, the gap remain closed (high rigidity), and the collared coil in good contact with the yoke.
- Aluminum spacer may be used to control the yoke gap.





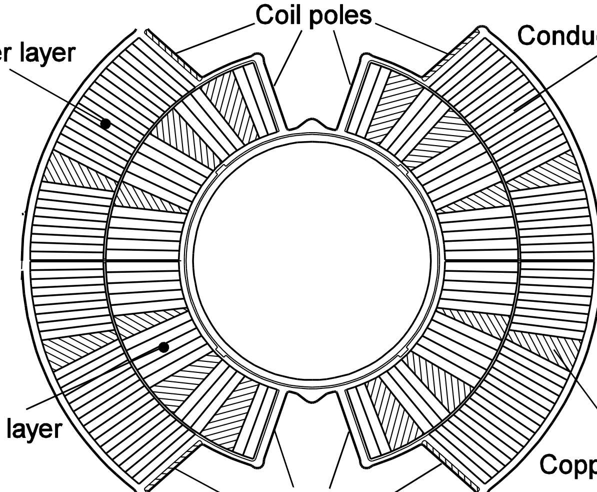
3. SYSTEMATIC COMPONENTS, RELATIVE

- Example 1. The impact of a **variation of pole shims** in the LHC dipoles
  - Shims are used to steer both field quality and stress
  - Data relative to a **dedicated experiment**
  - **Good agreement** found (model including deformations)



		Δb_3	Δb_5	Δb_7
Inner layer	Model	1.88	-0.29	0.12
	Measurement	1.85±0.26	-0.24±0.06	0.13±0.04
Outer layer	Model	1.46	-0.05	-0.02
	Measurement	1.36±0.10	-0.05±0.06	-0.01±0.04

Multipole variation induced by a change of 0.1 mm of the pole shim,
From P. Ferracin, et al, *Phys. Rev. STAB* **5** (2002) 062401.

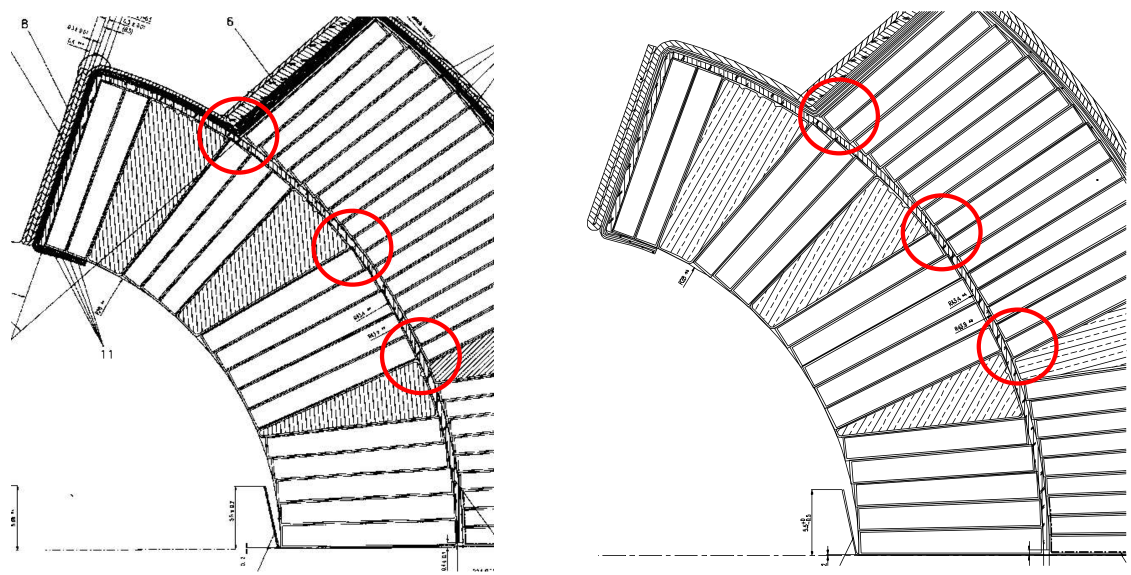


3. SYSTEMATIC COMPONENTS, RELATIVE

- Example 2. **Change of cross-section** in the LHC dipole to reduce b_3, b_5
  - Change decided after 9 series magnets, implemented at n. 33
  - **0.1-0.4 mm change of 3 copper wedges**, keeping the same coil size
  - Data relative to 33 magnets with X-section 1 and 154 with X-section 2
  - Agreement not very good (**relevant trends in production**, see later)

	Δb_3	Δb_5	Δb_7
Model	-4.0±1.2	-1.35±0.35	0.17±0.12
Measurement	-1.85	-0.85	0.53

Multipole variation induced by the cross-section change from 1 to 2 (change in internal copper wedges) in the main LHC dipole



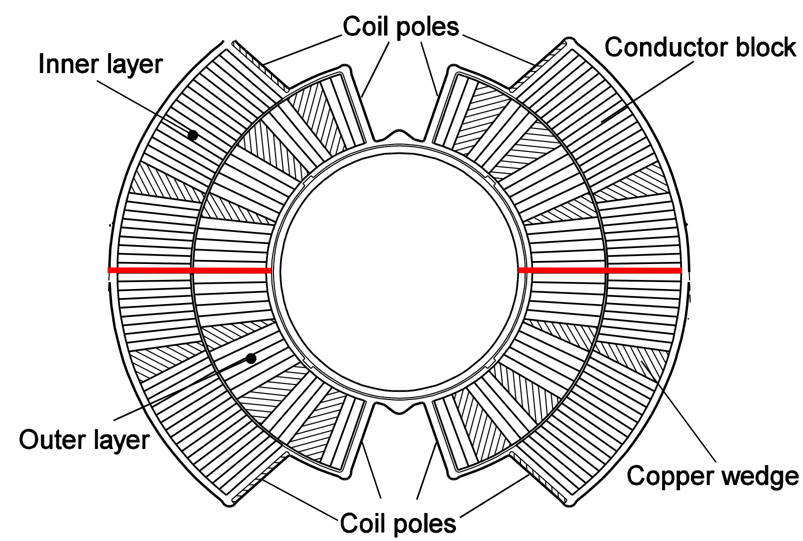
Change of the copper wedges of the inner layer in the main LHC dipole: cross-section 1 (left) and cross-section 2 (right)

3. SYSTEMATIC COMPONENTS, RELATIVE

- Example 3. **Additional mid-plane** shim in LHC dipole to reduce b_3, b_5
  - Change decided after 80 series magnets, implemented at n. 154
  - Additional mid-plane shim of 0.25 mm thickness
  - Data relative to 154 magnets with X-section 2 and ~1000 with X-section 3
  - Agreement **rather good**

	Δb_3	Δb_5	Δb_7
Model	-2.12	-0.53	-0.14
Measurement	-2.20	-0.38	-0.09

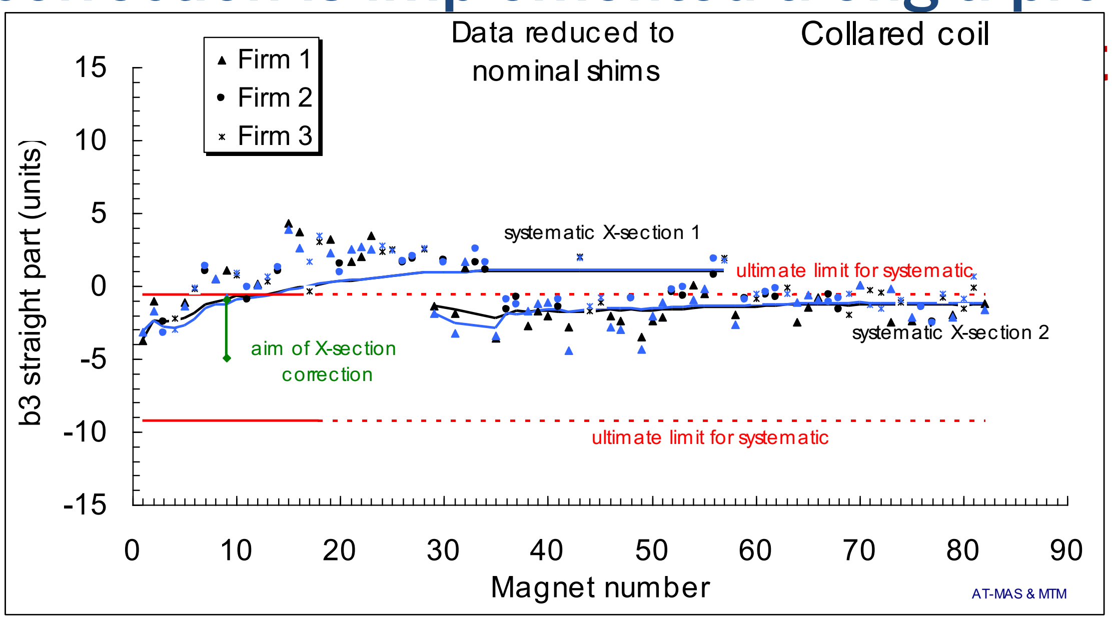
Multipole variation induced by the cross-section change from 2 to 3 (additional mid-plane shim) in the main LHC dipole



Additional mid-plane shim: cross-section 1 (left) and cross-section 2 (right)

3. SYSTEMATIC COMPONENTS, RELATIVE

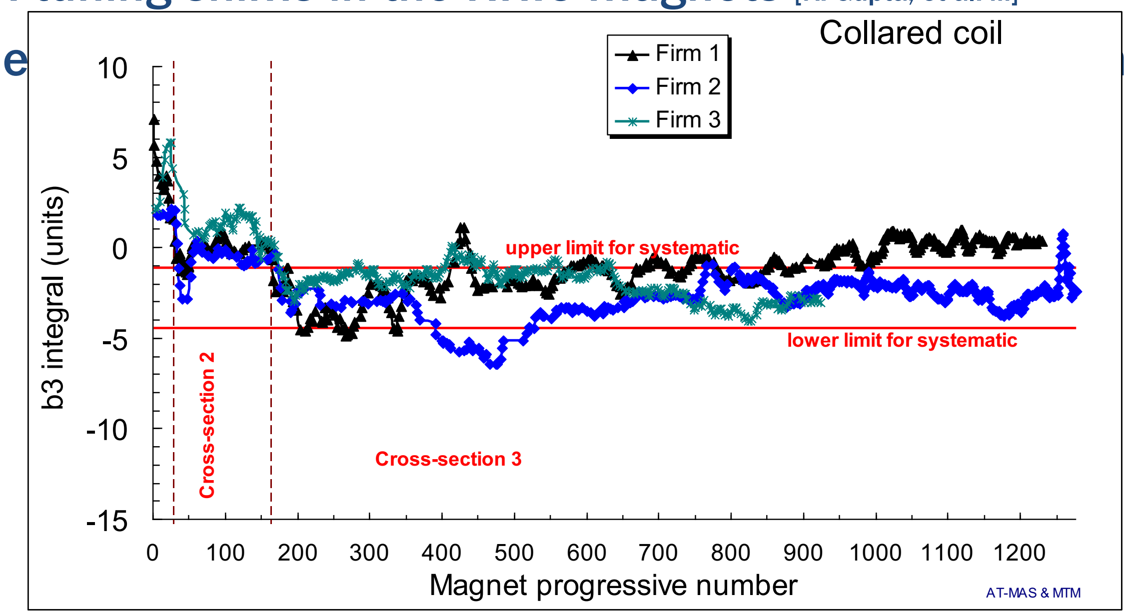
- Conclusions – estimating the impact of a variation in the design on field harmonics
  - For dedicated experiments (the same magnet assembled with different configurations) the agreement is within the errors
  - When a correction is implemented along a production, its effect ca … can be different



The first correction of the cross-section in the main LHC dipoles

3. SYSTEMATIC COMPONENTS, RELATIVE

- Conclusions – estimating the impact of a variation in the design on field harmonics
  - One has to **gently insist** in bringing the field quality within targets
  - It is mandatory to have a **flexible design**
    - Example: tuning shims in the RHIC magnets [R. Gupta, et al. …]
    - Put in the … the Firm



b3 along the production of 1276 LHC dipoles – red limits are for the final average