Lawrence Berkeley National Laboratory

Development of High Field Superconducting Accelerator Magnets

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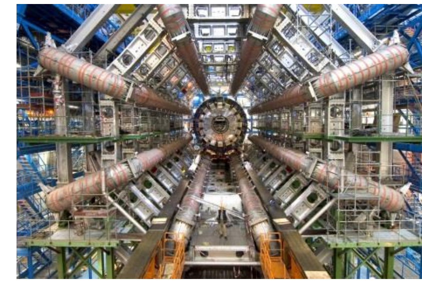
Context and Outline

High Energy Physics requires powerful linear or circular machines to collide e+/e- and proton beams and explore fundamental laws of the universe.

The LHC is the biggest proton collider ever built.



- Why do we need High field Superconducting Magnets in colliders such as LHC?
- A specific challenge: the mechanical preload
- Beyond LHC: what kind of magnets?
- How the high field accelerator dipole for colliders finds its way to everyday application: gantry for ion beam cancer therapy

Magnets for Colliders

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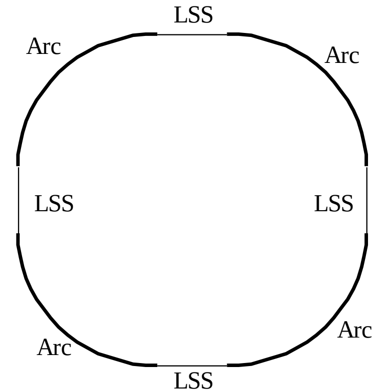
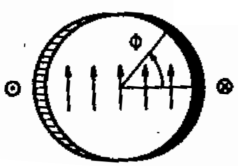
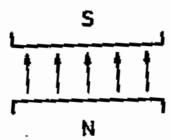
- The **colliders** are a sub-species of circular accelerators

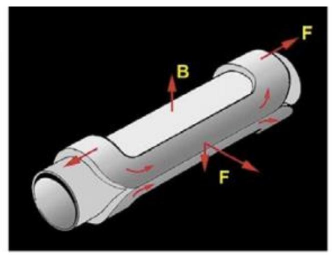


Arc

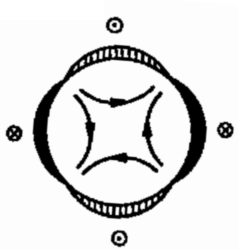
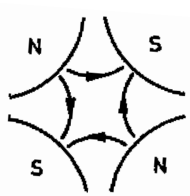
- Dipole: constant field to bend the beam: **F**=e **v** x **B**

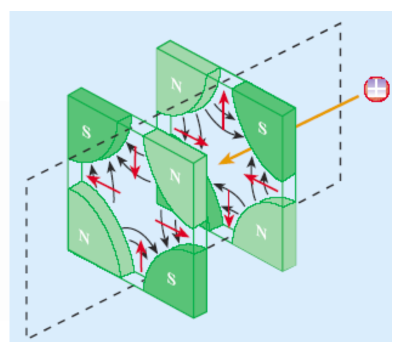
(!! No change of momentum)



- Quadrupole: gradient of field to focus the beam

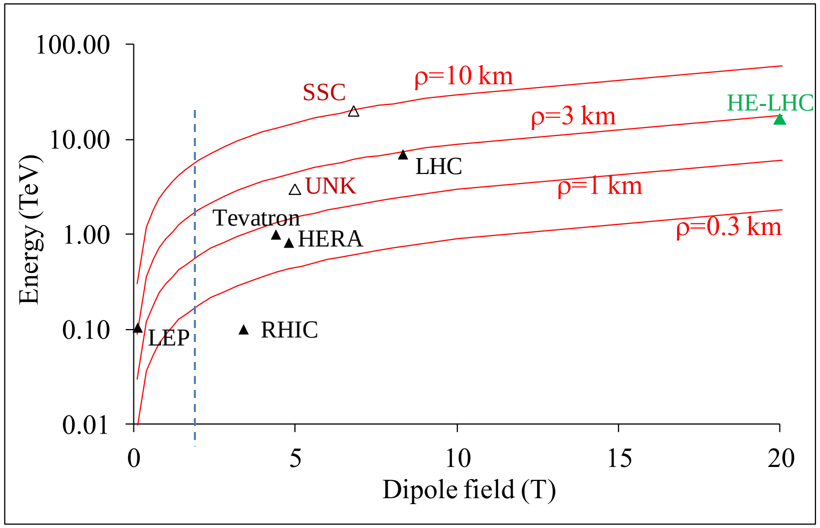


Long Straight section

Interaction Regions where collisions occur:

- Quadrupoles to focus the beam
- Dipole for beam crossing in two-ring machines
- Other functionalities not addressed here

High Field Superconducting Magnets for Colliders

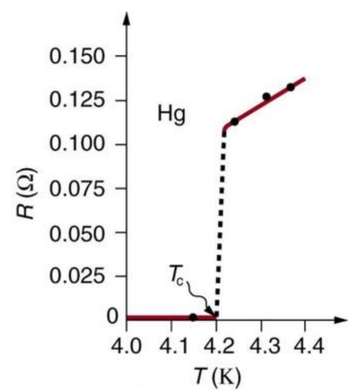


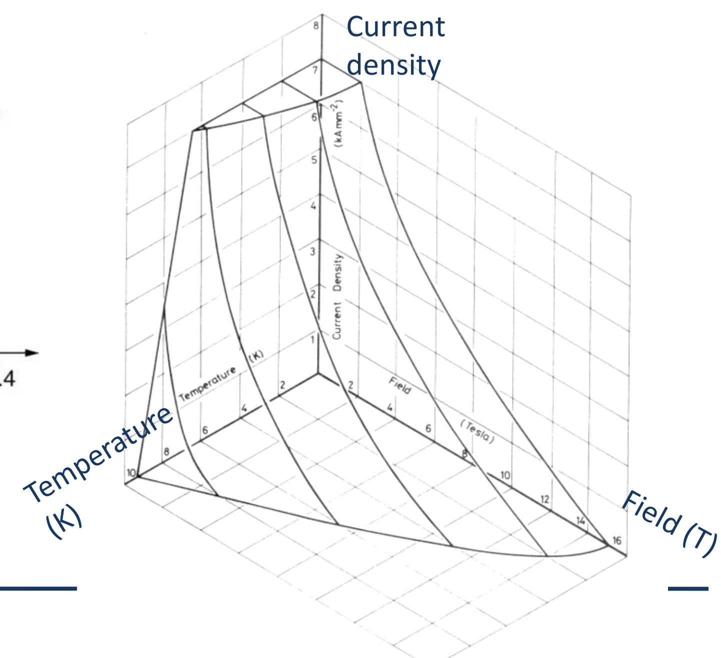
Courtesy of Ezio Todesco (CERN)

- The beam energy:

  E [GeV] = 0.3 x B[T] x ρ[m]

- Beyond 2 T => use of superconducting material
  - zero electrical resistance at cryogenic temperature
  - operate below a critical surface defined with 3 parameters: field, current and temperature.



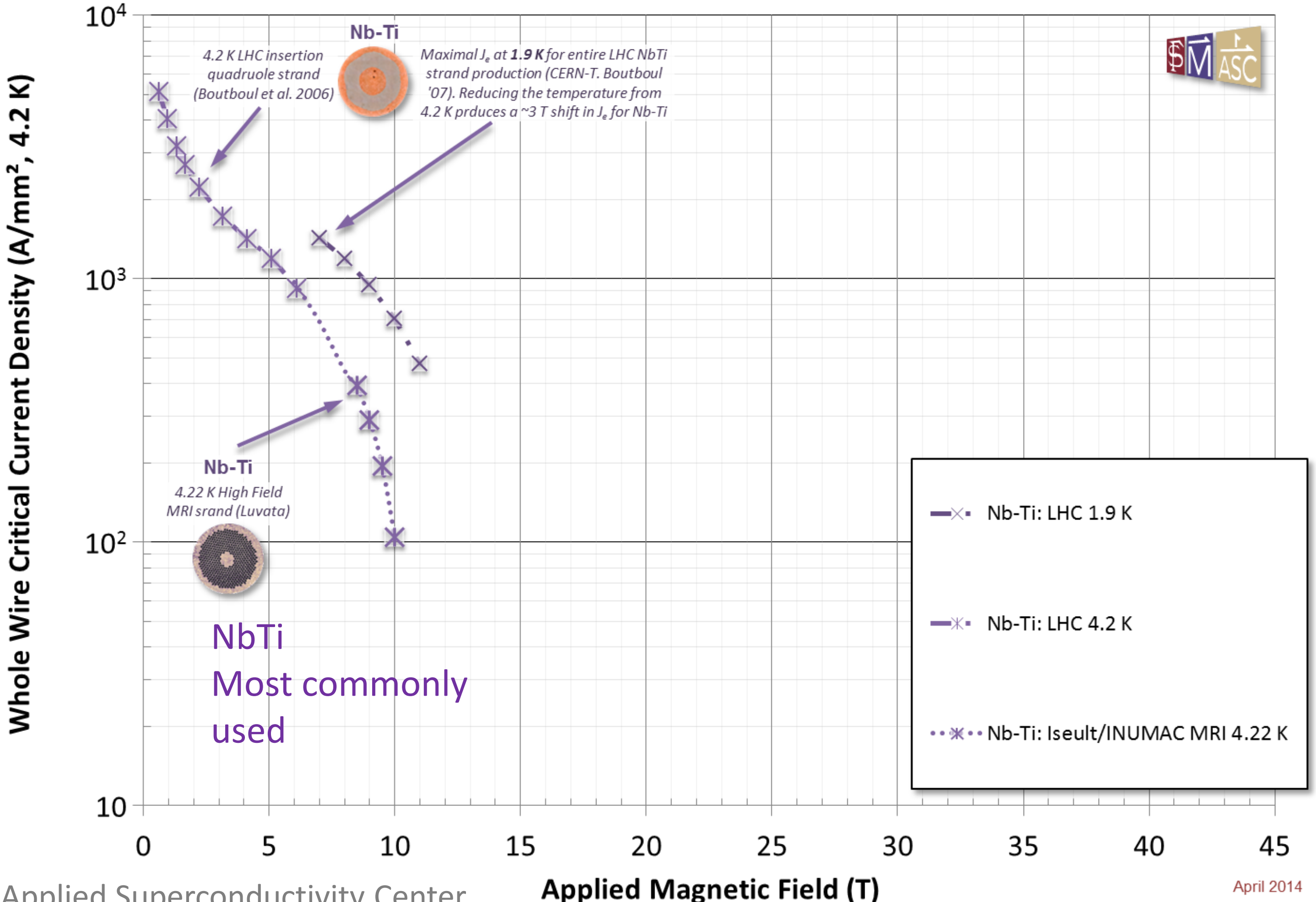


Beyond the critical surface, the superconductor quenches
= transition to a normal conducting state

High Field reachable but high complexity

A (not so) large variety of superconductors

~250$/kg

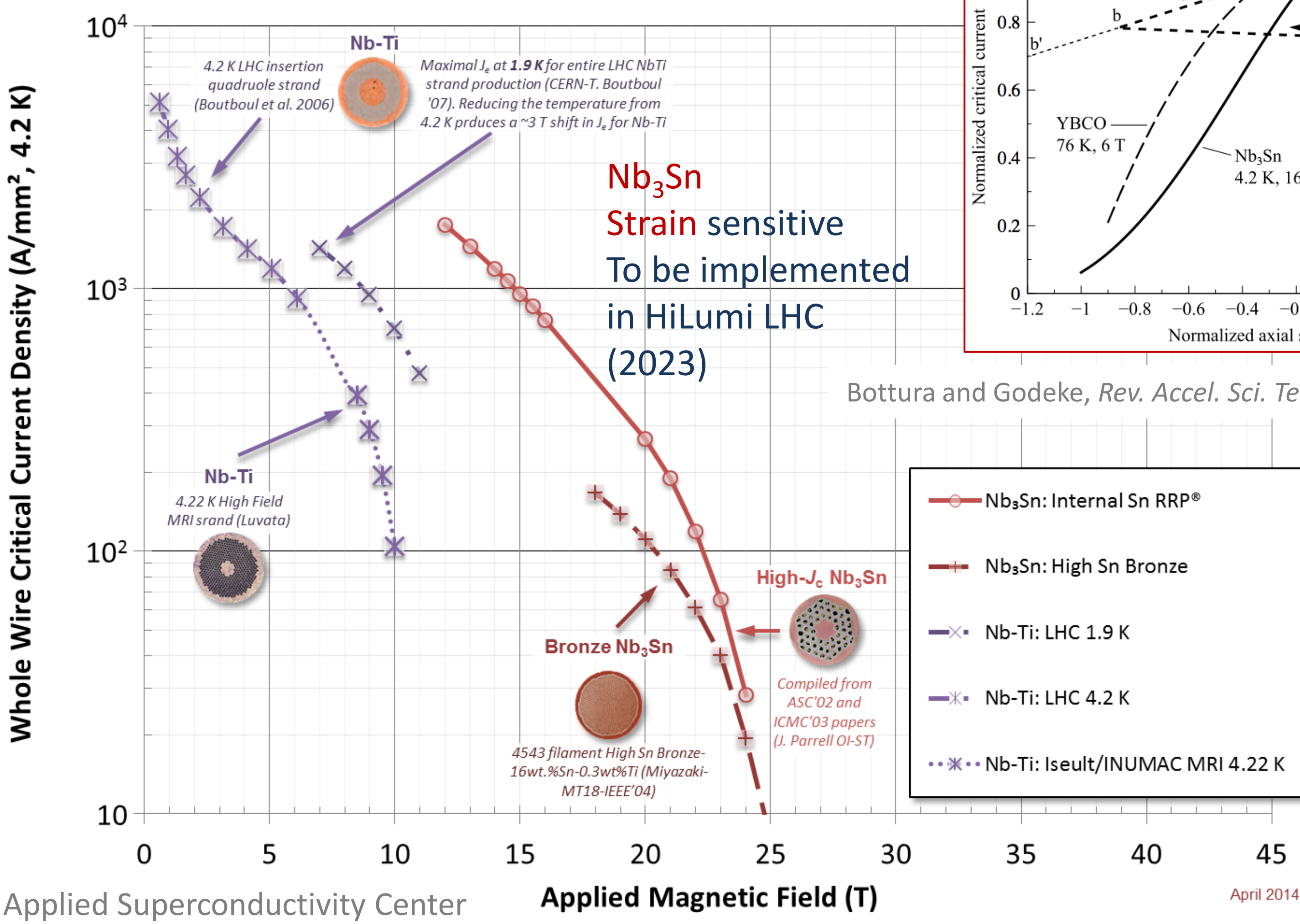


P. Lee et al., Applied Superconductivity Center

A (not so) large variety of superconductors

250$/kg

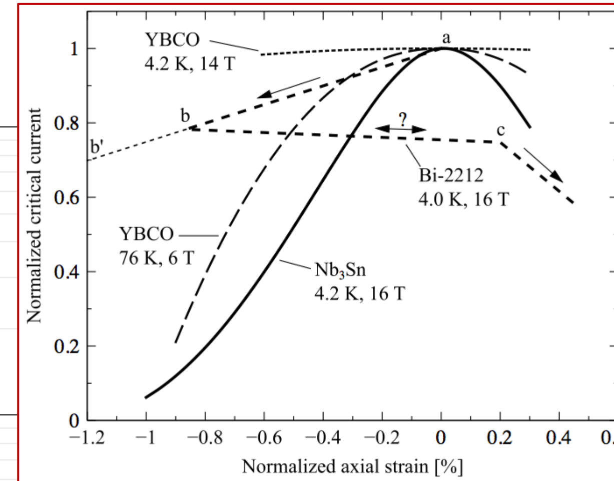
x10



Nb_3Sn

Strain sensitive

To be implemented in HiLumi LHC (2023)



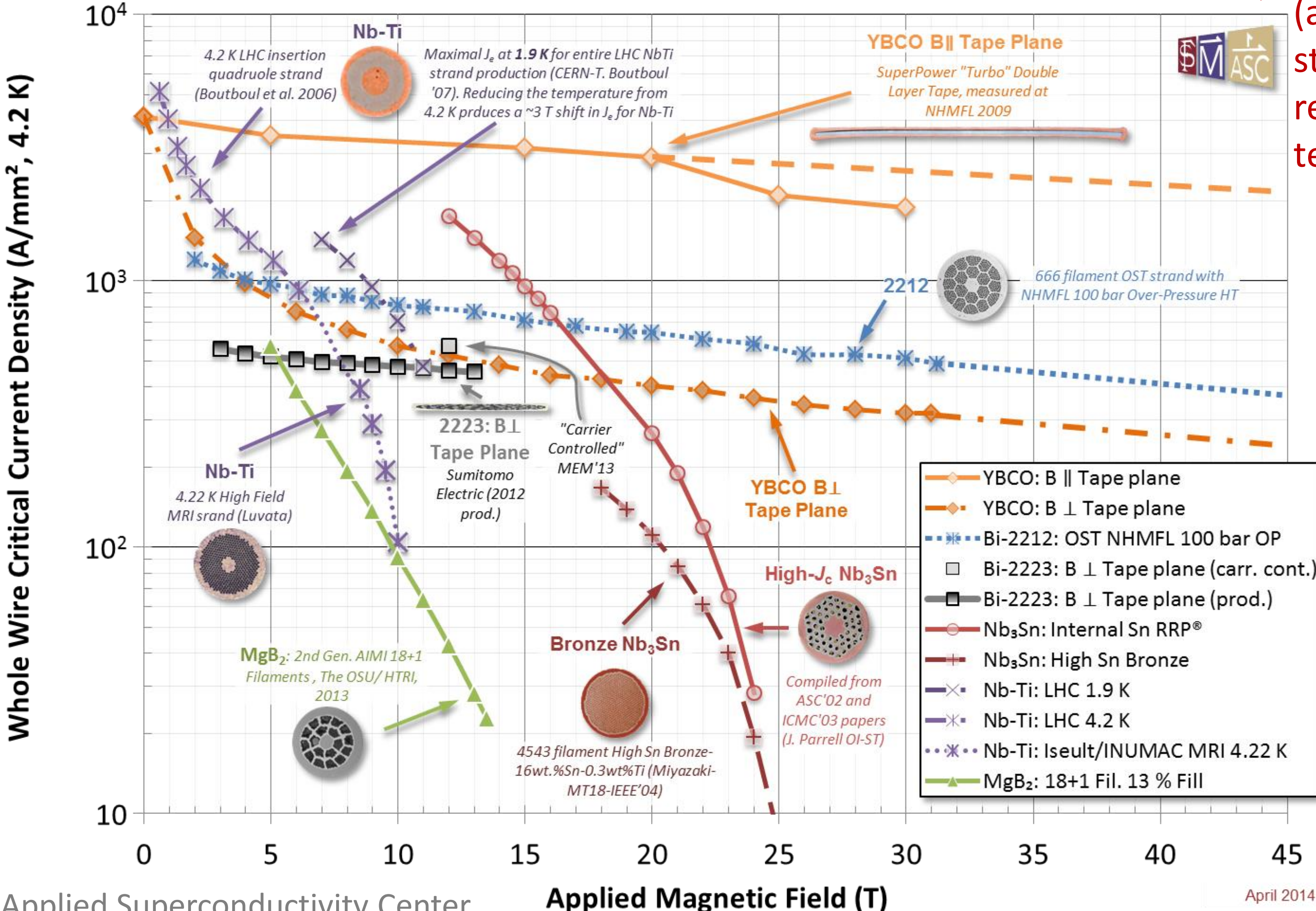
Bottura and Godeke, *Rev. Accel. Sci. Techn.* **5** 25 (2012)

P. Lee et al., Applied Superconductivity Center

A (not so) large variety of superconductors

250$/kg	x10	x10

Cost
Complexity
(anisotropy,
strain sensitivity,
reaction
temperature…)



P. Lee et al., Applied Superconductivity Center

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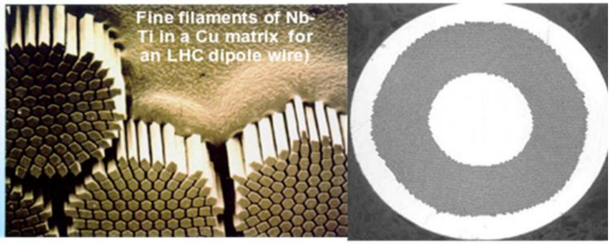
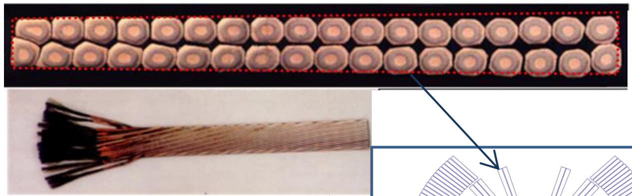
High Field Superconducting Magnets for Colliders
The example of the LHC Main Dipole

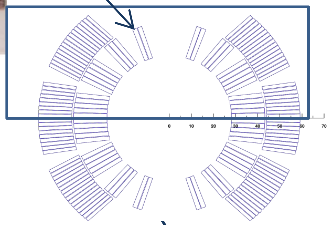
Wire cross-section

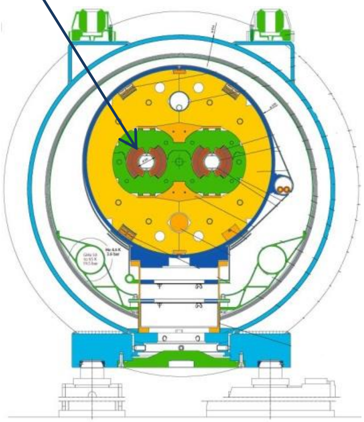


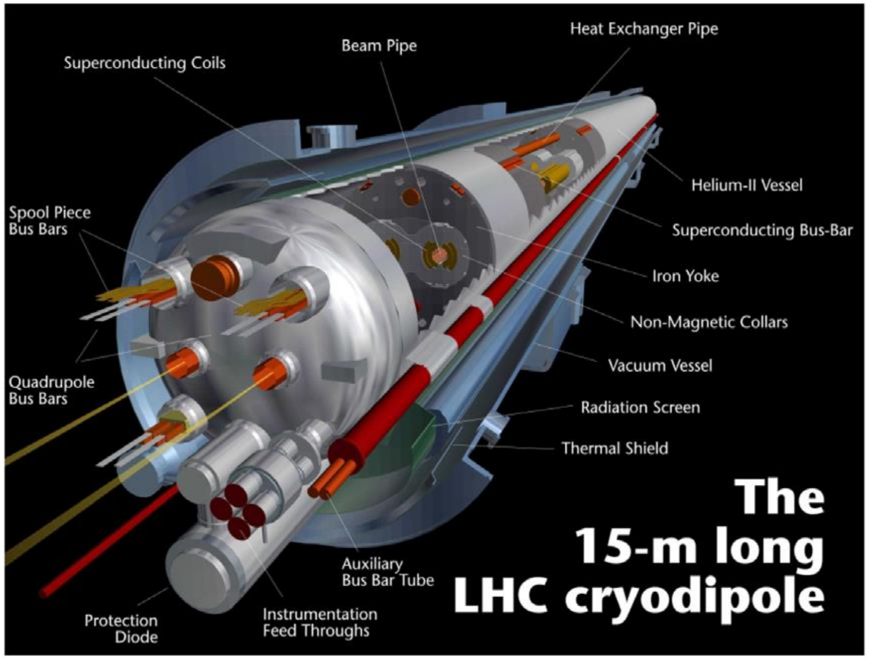
- Cable made out of wire
- Cable is wound in coil
- 2 coils per beam pipe
- Assembly in the support structure
- Assembly in cryostat



Rutherford Cable







Lucio Rossi (CERN)

The example of the LHC Main Dipole
A few numbers

- 15 m long magnet
- 27.5 ton
- 0.5 MCHF

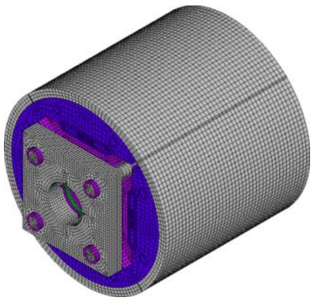
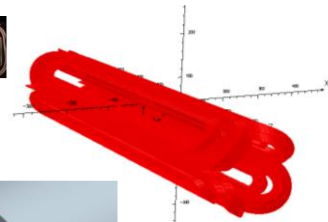
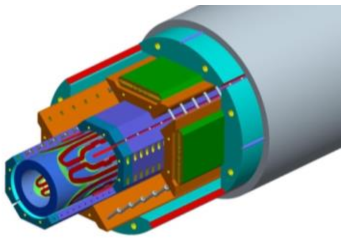
- Nominal: 14 TeV c.o.m.
- B_{nom}= 8.33 T
- I_{nom} = 11.8 kA

- E_{stored} at nominal = 7.1 MJ

- Forces at B_{nom}
    - Fx = 1.7 MN/m
    - Fy = -0.8 MN/m
    - Fz = 370 kN

LHC Project Report 623, Lucio Rossi (CERN)

Magnet Design and Fabrication what kind of engineering?


Material Science: conductor, insulation

Electrical Engineering

- Magnetic FEM analysis
- Field quality requirements = field purity
- Magnet testing
  - Magnetic measurements
  - Diagnostics…

Mechanical Engineering

- Coil fabrication tooling
- Coil and magnet handling tooling
- Support structure
- LHe containment…

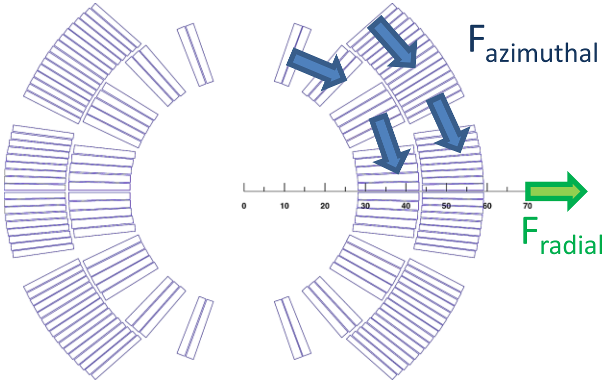
Thermal analysis and Cryogenics

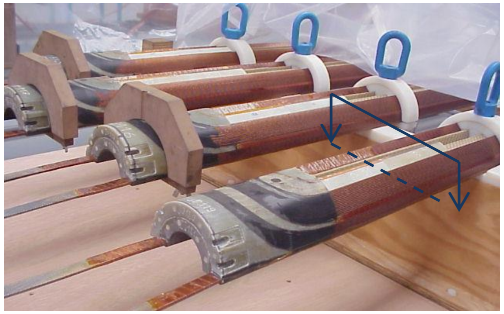
- Protection in case of quench
- Cryostating

Integrated design approach required
Broad Engineering from design to fabrication

The concept of pre-stress

- **Lorentz forces: JxB**





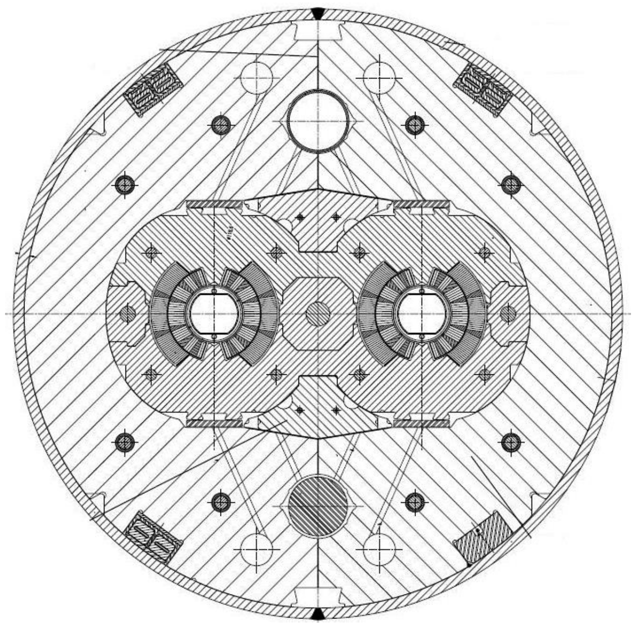
- **Requirements for the support structure**
  - Preserve the superconductor in operating condition by minimizing motion
  - Control the position of each conductor
    - Conductor position = field quality in the aperture => 10-100 ppm

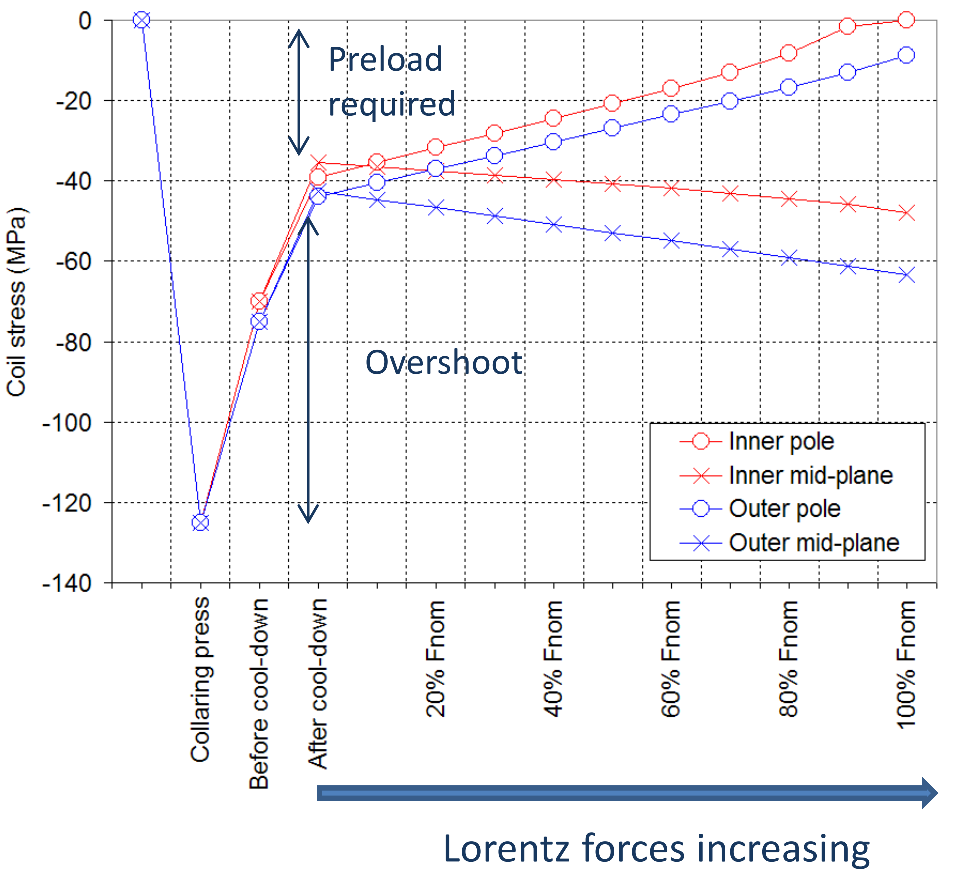
- The pre-stress consists in applying before excitation and via the support structure a force equivalent to the Lorentz force in order to pre-compress the coil and minimize motion during excitation

- **Challenges toward high fields:** large forces and strain sensitive material

Pre-stress in the LHC Dipole

- Support structure using collaring process
  - Same kind of concept used in quadrupoles





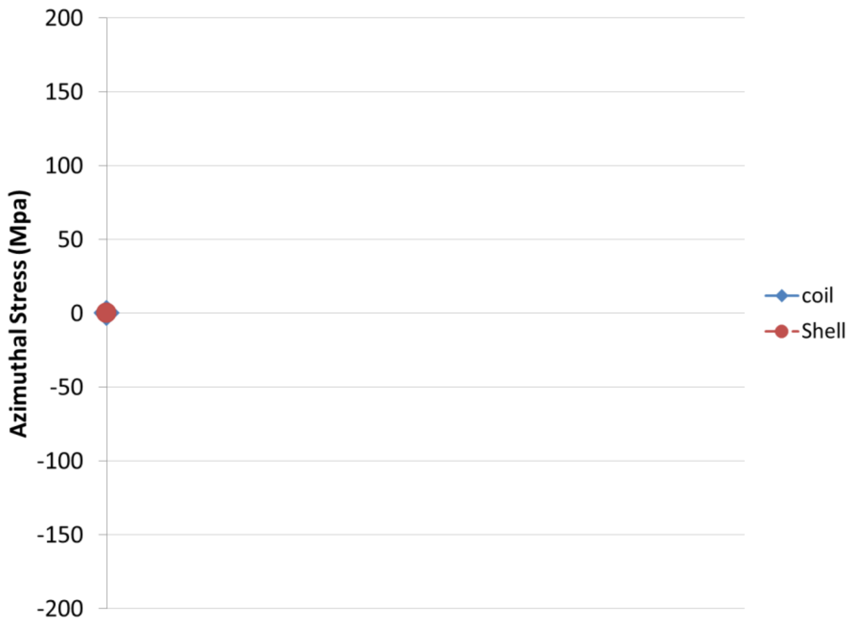
Courtesy of Paolo Ferracin (CERN)

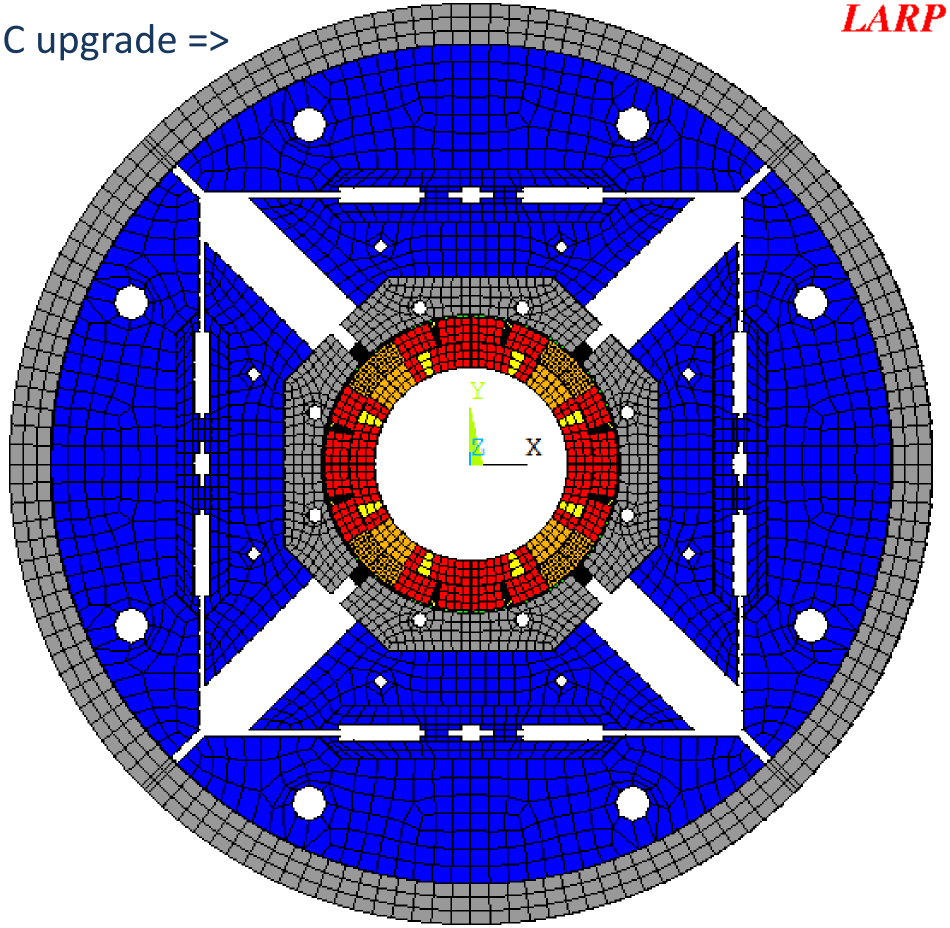
Shell-based support structure
Concept

Case study

Prototype Nb_3Sn **quadrupole** for the Hi-Luminosity LHC upgrade => interaction region quad

- Strain sensitive material
- 12 T peak field in the conductor
- Large Lorentz forces
    - 2.7MN/m horiz, -3.8 MN/m vert





Shell-based support structure Concept

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High Luminosity LHC

LARP

Case study

Prototype Nb_3Sn **quadrupole** for the Hi-Luminosity LHC upgrade => interaction region quad

- Strain sensitive material
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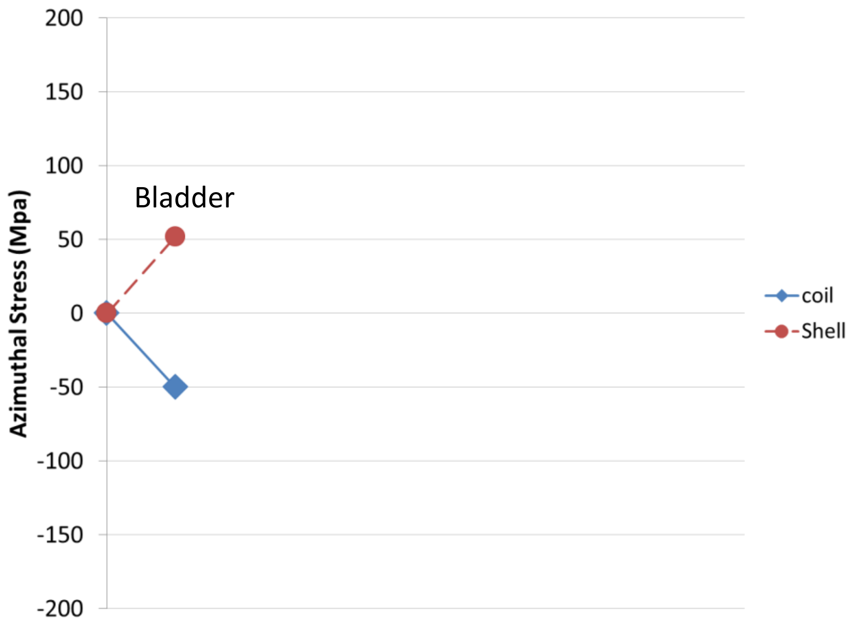
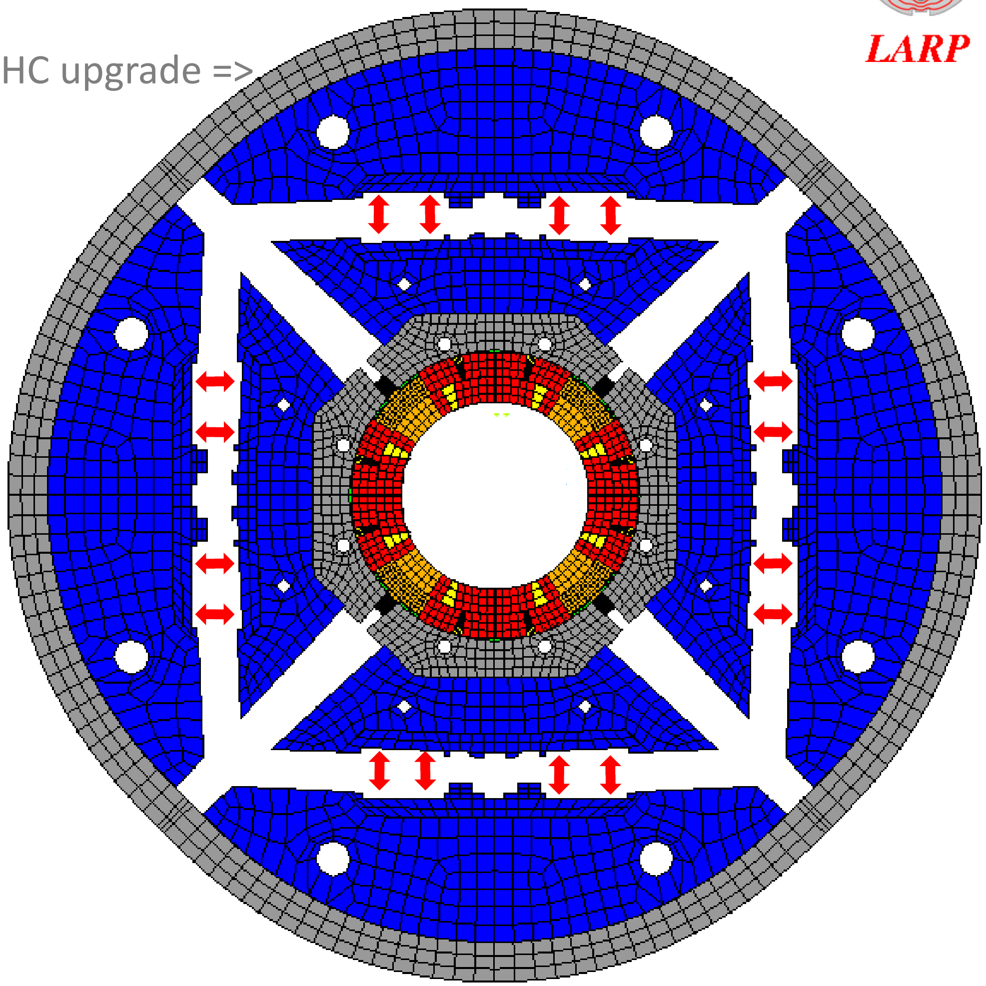


Inflated Bladders



Displacement scaling 30

Shell-based support structure Concept

Shimming of the load leys

Case study

Prototype Nb_3Sn **quadrupole** for the Hi-Luminosity LHC upgrade => interaction region quad

- Strain sensitive material
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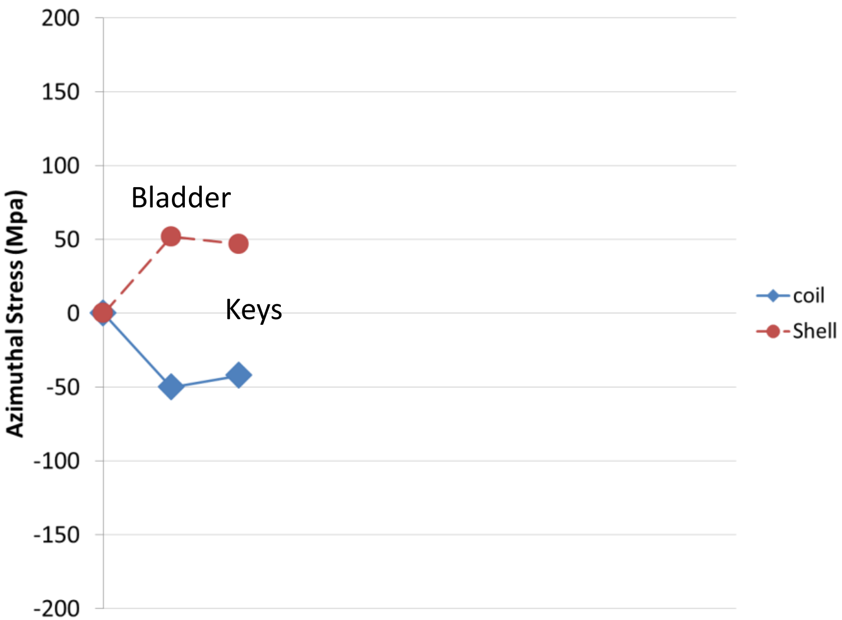
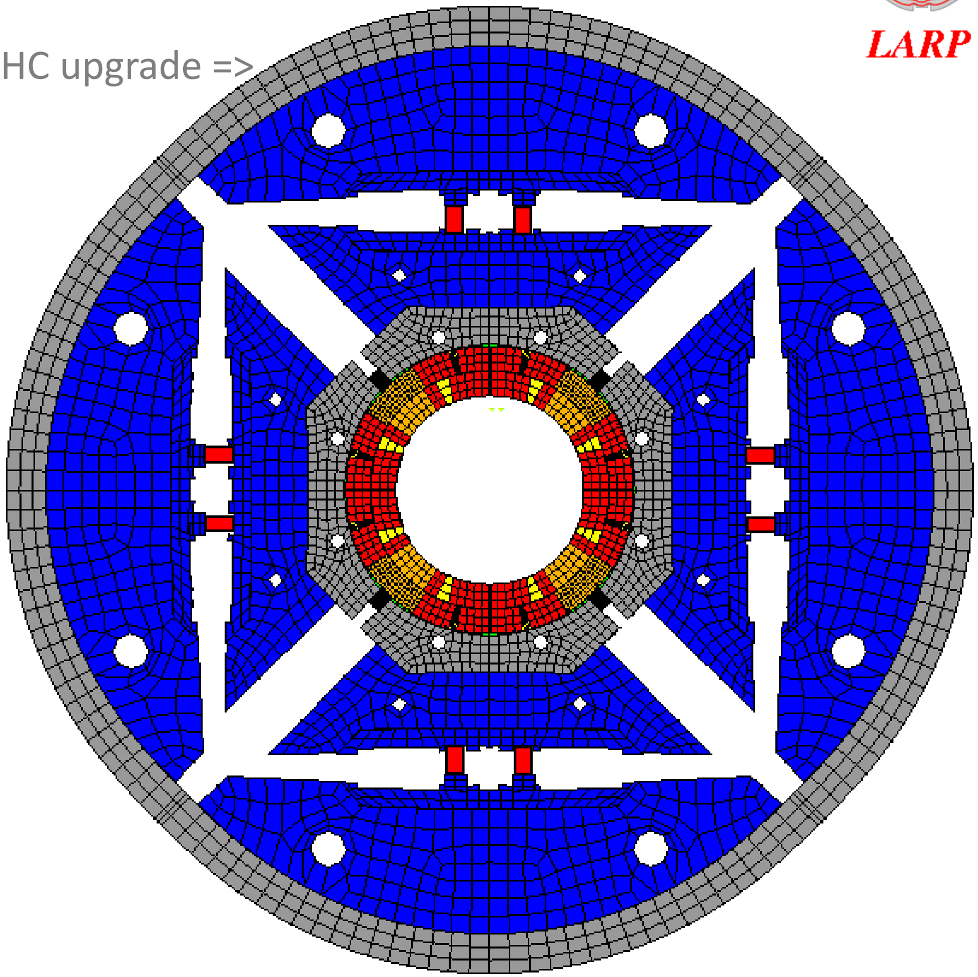




Displacement scaling 30

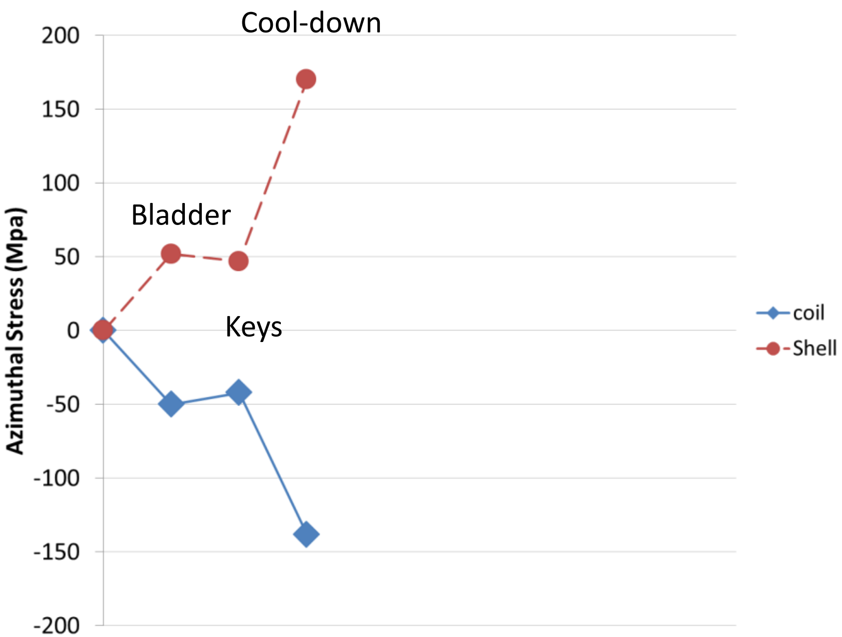
Shell-based support structure Concept

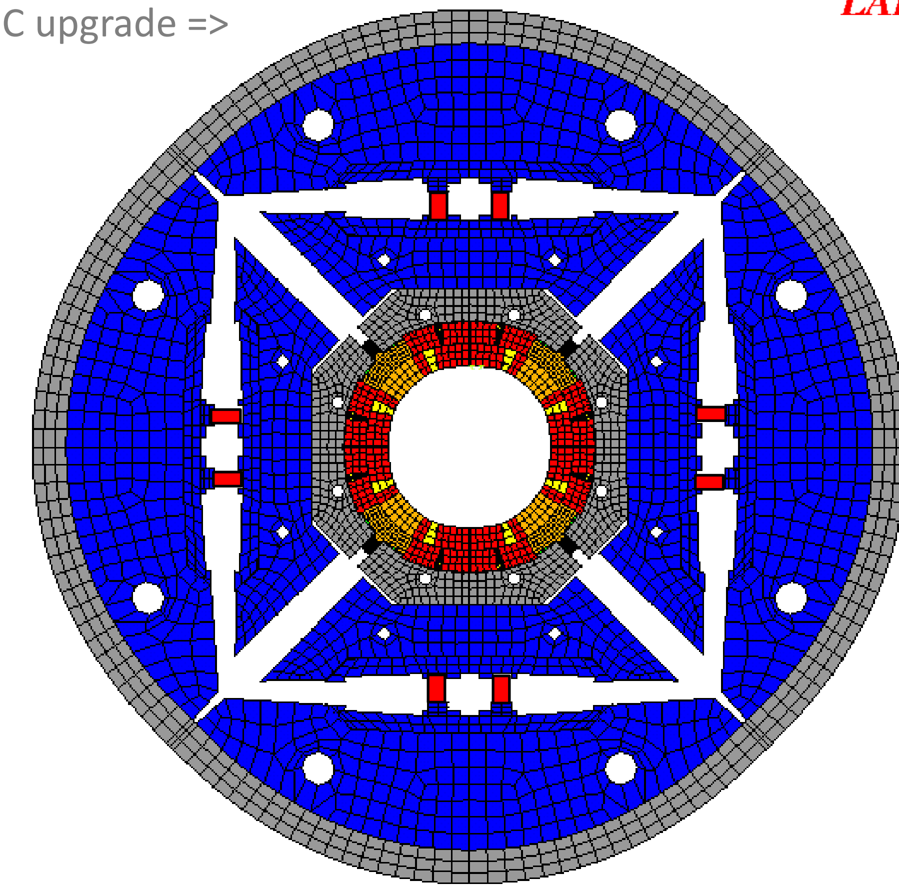
Cool-down

Case study

Prototype Nb_3Sn **quadrupole** for the Hi-Luminosity LHC upgrade => interaction region quad

- Strain sensitive material
- 12 T peak field in the conductor
- Large Lorentz forces



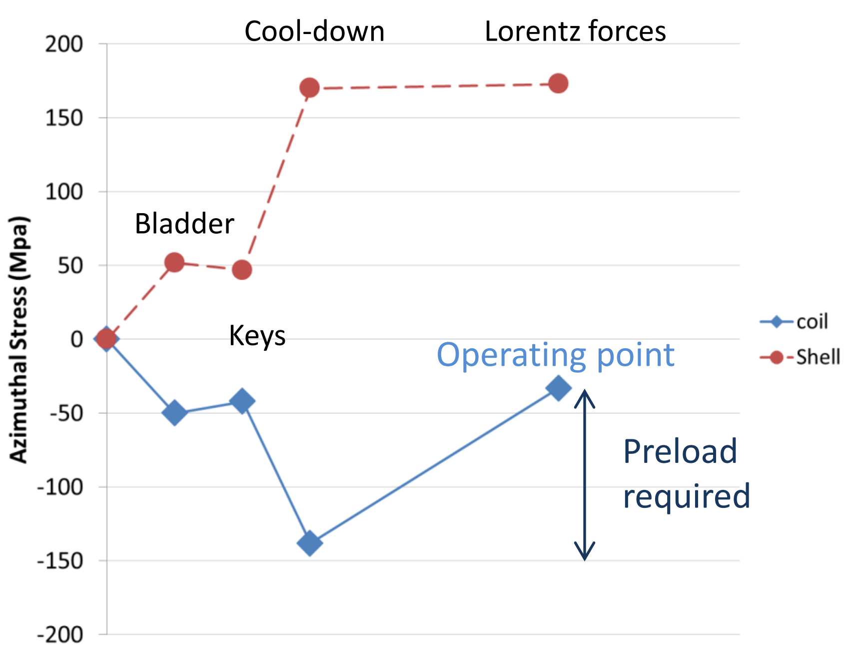


Displacement scaling 30

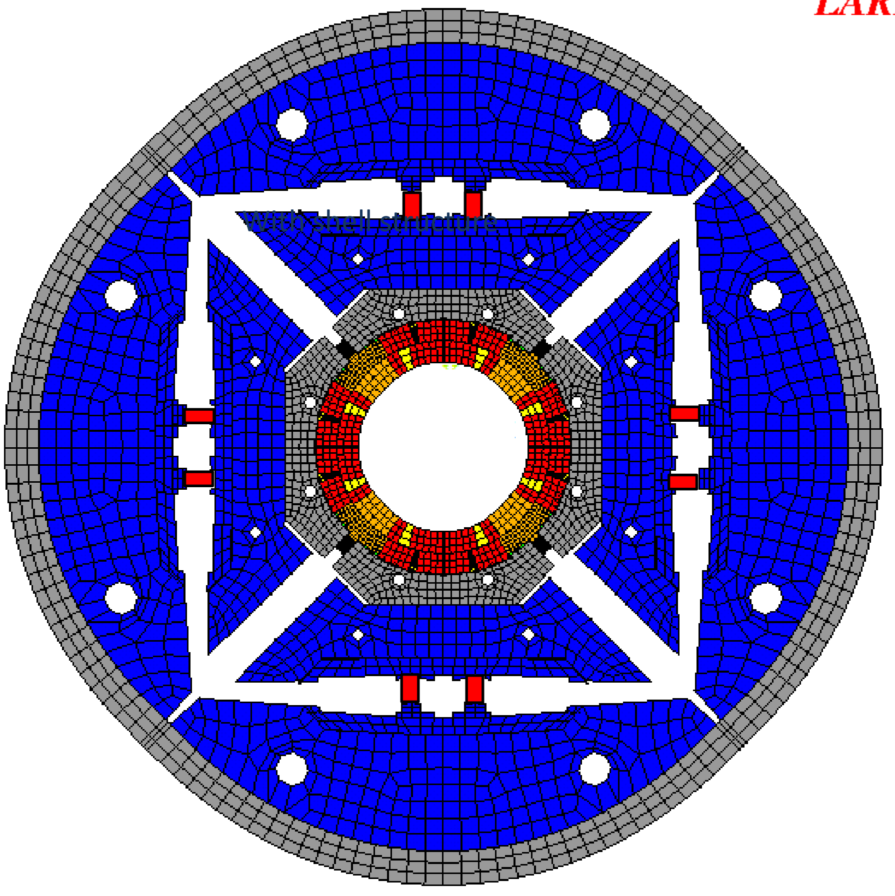
Shell-based support structure Concept

Innovative support structure

- Gradual application of the preload
- Tunable preload
- Reversible assembly process
- Implemented in the HL-LHC upgrade (2023)



Energized



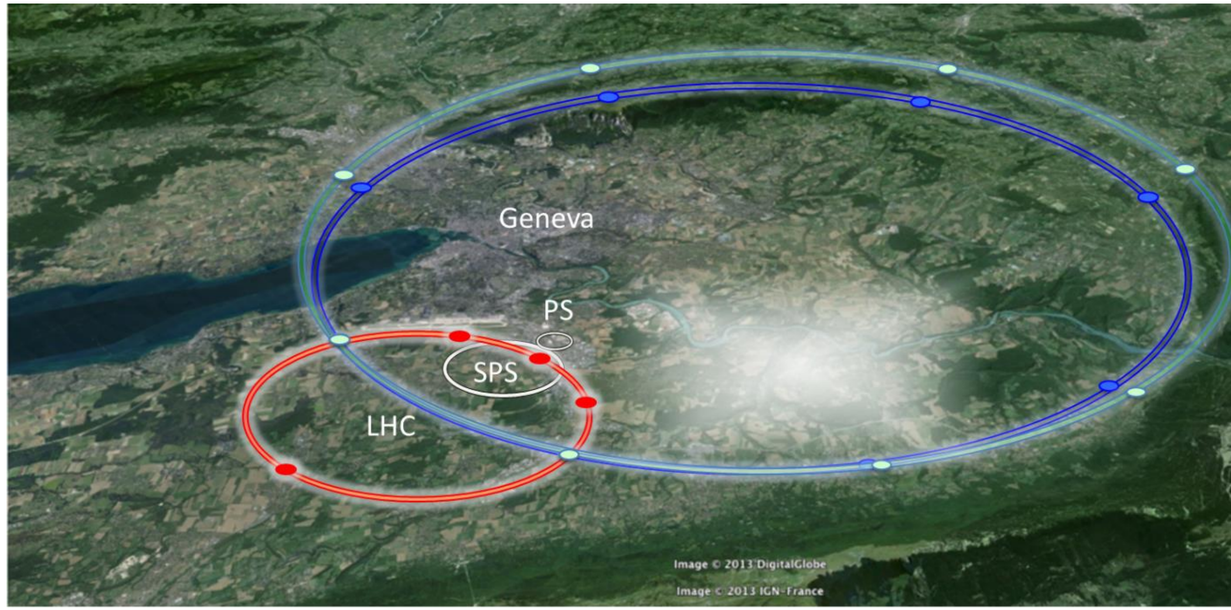
Displacement scaling 30

Challenges for the future: the post-LHC era

L. Bottura (CERN)

Future Circular Collider

More beam energy…
=> More field, more forces
=> More magnets
In LHC , 18km out of 27km are dipoles!



LHC	HE-LHC	FCC-hh	FCC-hh
27 km, 8.33 T	27 km, **20 T**	80 km, **20 T**	100 km, **16 T**
14 TeV (c.o.m.)	33 TeV (c.o.m.)	100 TeV (c.o.m.)	100 TeV (c.o.m.)
1300 tons NbTi	3000 tons LTS	9000 tons LTS	6000 tons Nb_3Sn
	700 tons HTS	2000 tons HTS	3000 tons Nb-Ti

Example of questions among the magnet community :

Is there a "stress wall"? Making high field magnets out of reach?

⇒ Need for a change of approach?
⇒ Innovative design?

How can we reduce the cost?

The Canted Cosine Theta
An example of new paradigm

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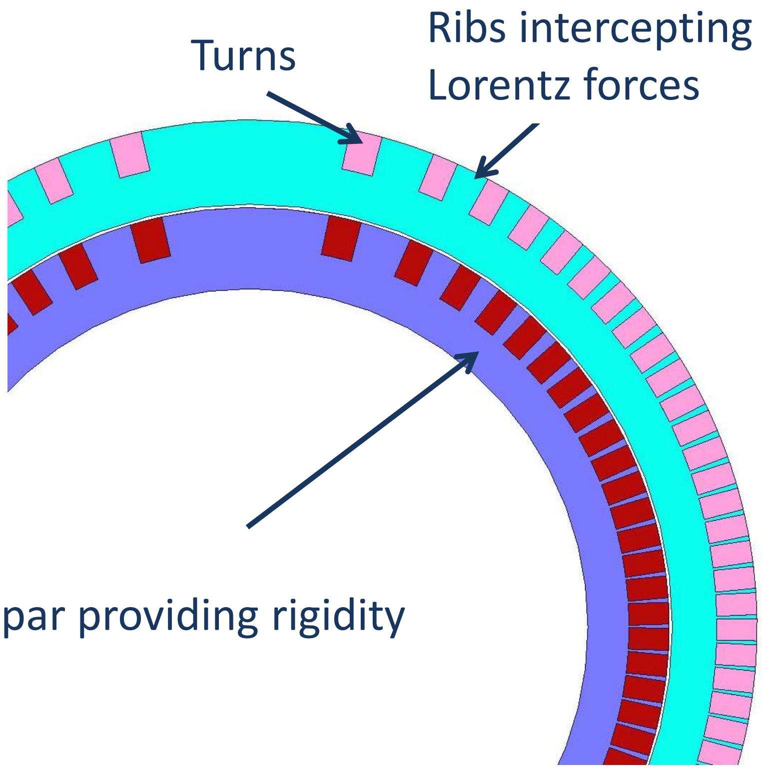
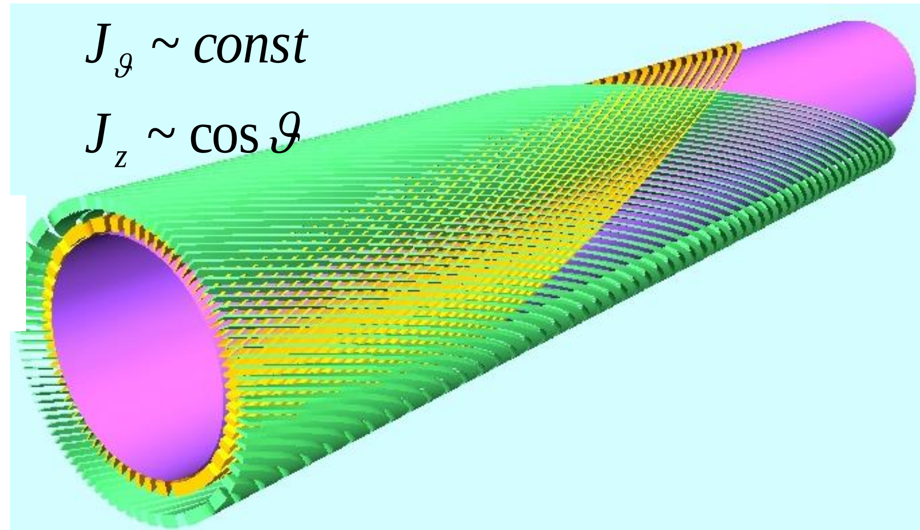
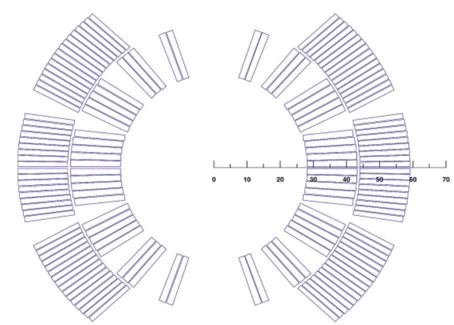
Courtesy of Lucas Brouwer and Shlomo Caspi (LBNL)

Two superimposed coils, oppositely skewed, achieve a pure dipole field and eliminate axial field.





Structure "embedded" in the coil
⇒ Avoid azimuthal force accumulation
⇒ Minimize number of components
Ongoing development program at LBNL



LHC dipole for comparison

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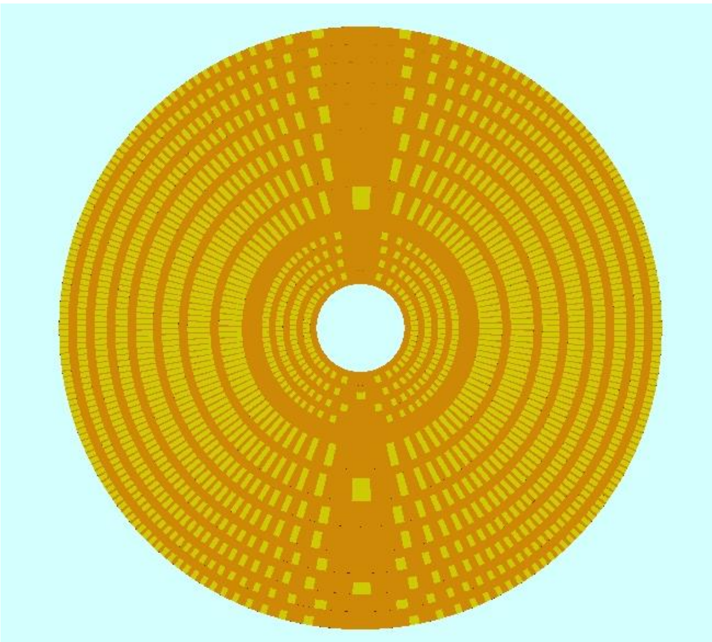
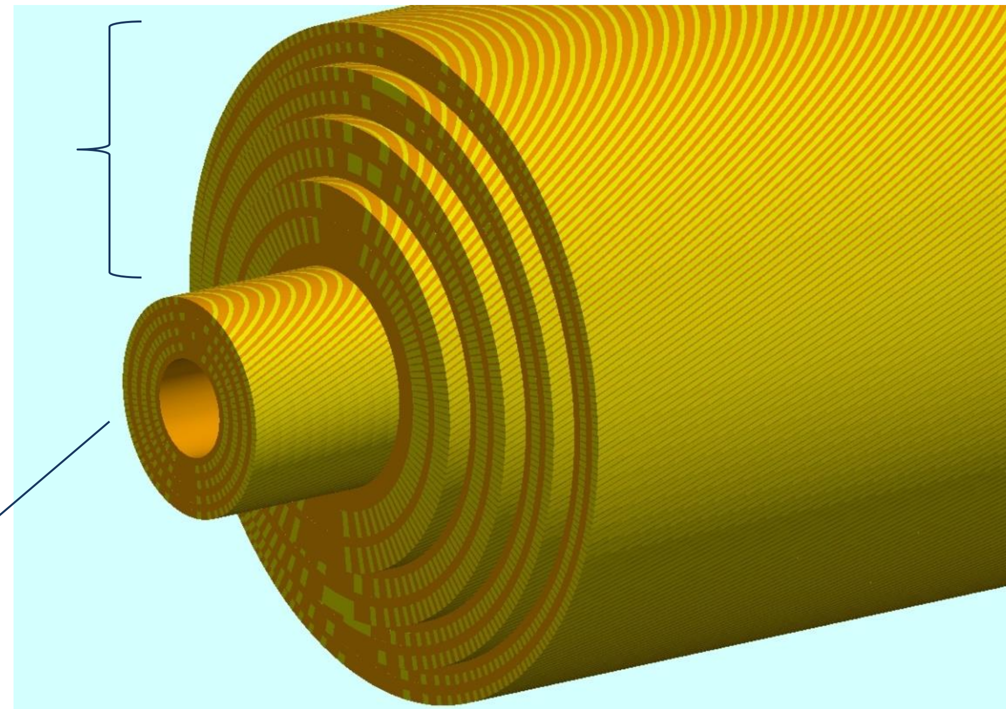
18 T Design using CCT concept

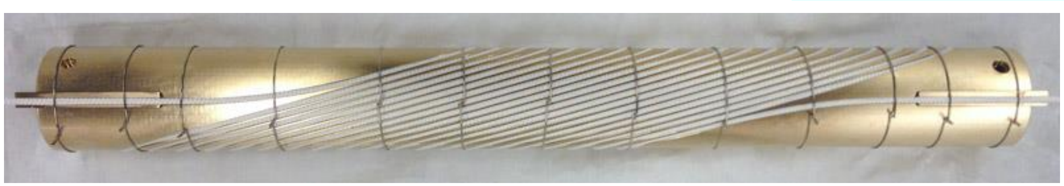
Courtesy of Lucas Brouwer and Shlomo Caspi (LBNL)



8 layers Nb_3Sn



4 layers Bi2212 insert

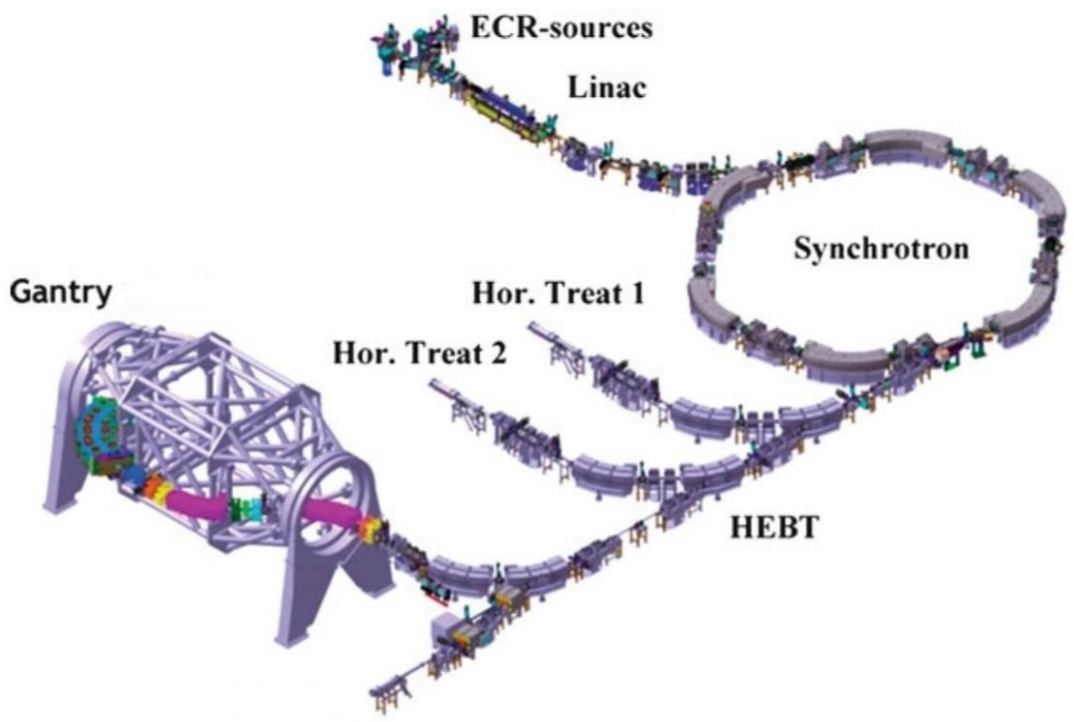


Courtesy of Xiaorong Wang (LBNL)

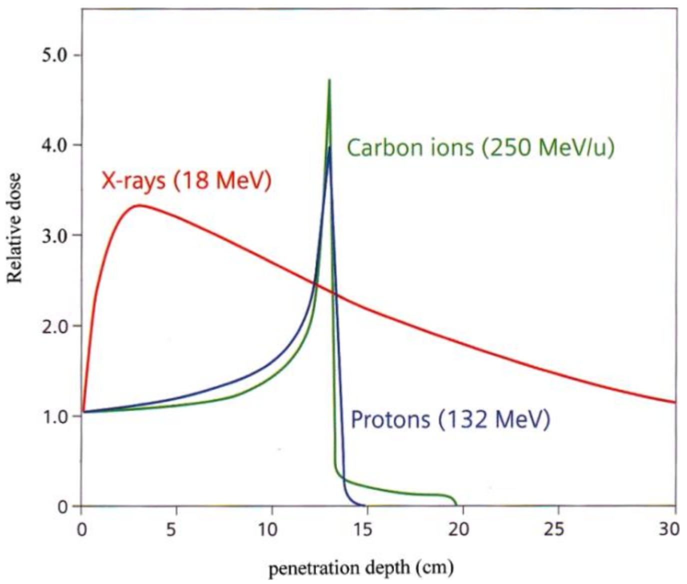
Clear bore ID=40mm, OD=274.3mm

From Fundamental use to medical application: Cancer Ion beam therapy

Heidelberg Carbon Ion Therapy Gantry – Germany – unique Carbon therapy facility
A gantry is a beam line that directs and focuses the beam onto the patient at whatever angle is required for the treatment plan optimization



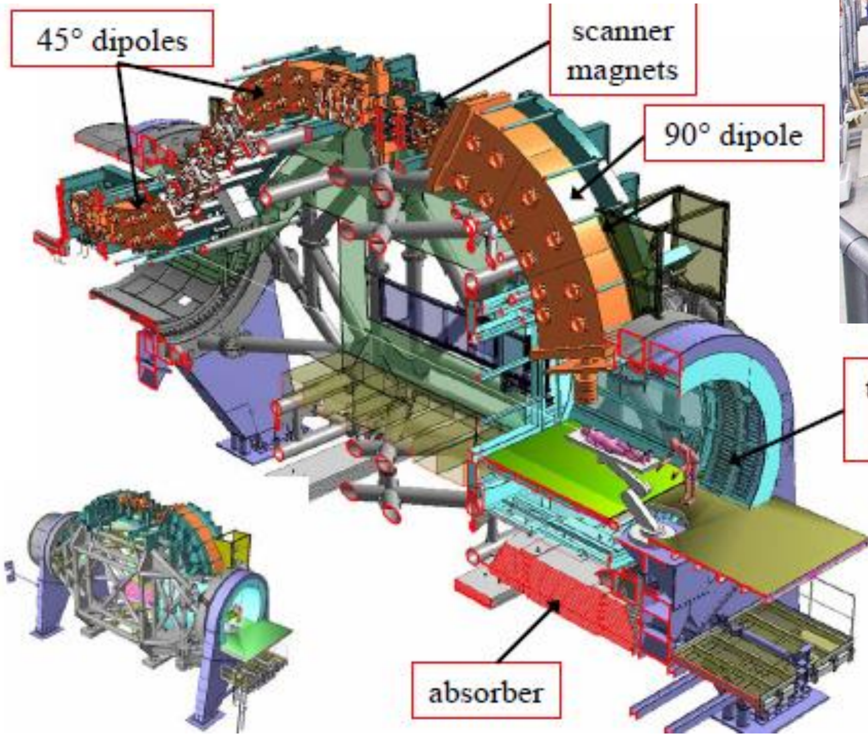
Interest
Sparing healthy tissues
Bragg peak



Courtesy of David Robin (LBNL)

From Fundamental use to medical application: Cancer Ion beam therapy (II)

- Unique Carbon gantry in the world
- Rotating device
- 600 tons => final dipole ~100 tons



Superconducting final dipole would allow compactness and weight reduction

Courtesy of David Robin (LBNL)

Concept of curved CCT for carbon gantry

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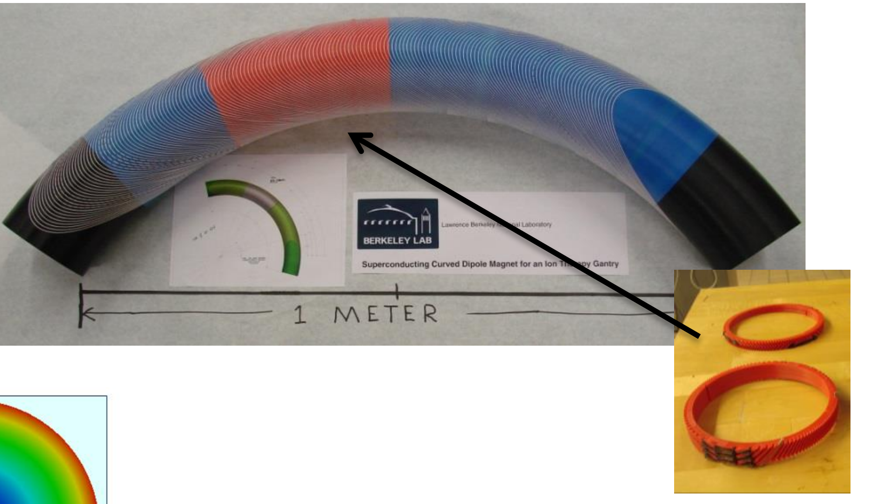
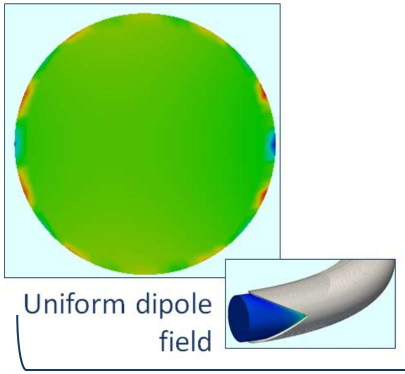
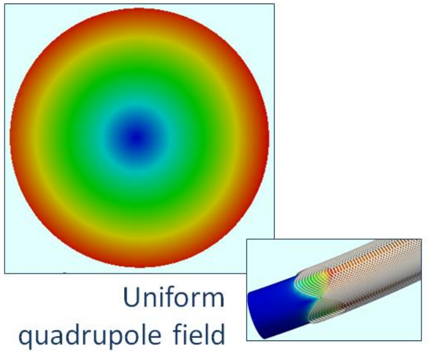


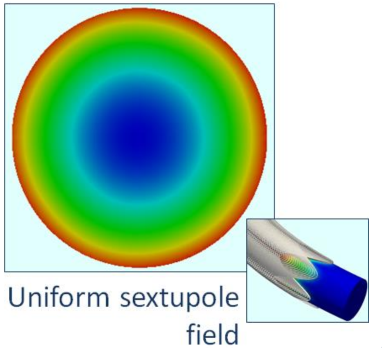
- Concept of curved CCT
- Allows combined function magnet



Uniform dipole field

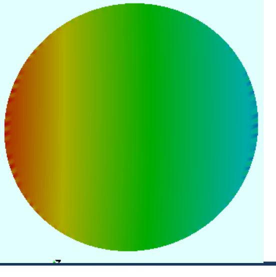


Uniform quadrupole field

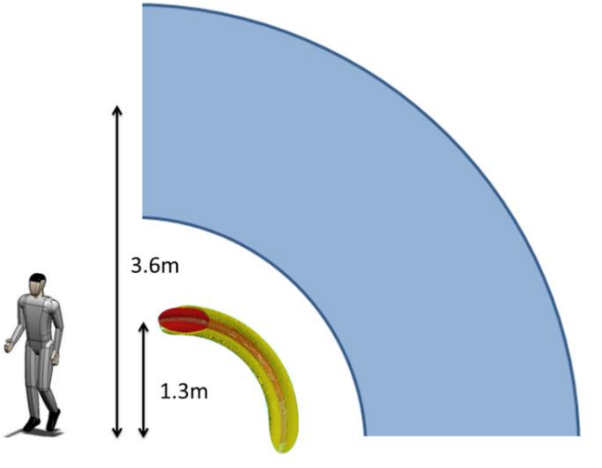


Uniform sextupole field

Combined function



Ongoing stewardship program at LBNL



Courtesy of Shlomo Caspi (LBNL)

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Summary and Next steps

- Superconducting Accelerator Magnets are multi-disciplinary objects requiring an integrated design approach

- Dipoles and Quadrupoles are key components of high energy colliders

- Producing higher field requires the use of more challenging superconducting materials
  - Innovative "shell-based" support structure was demonstrated

- **Beyond LHC**: Superconducting Magnets for accelerator are in an interesting phase, looking for new concepts and designs
  - CCT is one of them and require demonstration: ongoing program at LBNL

- Pushing the limits for fundamental application opens possibility for everyday applications
  - Curved CCT could be a major asset for carbon therapy

We need to keep probing the limits of magnet technology!

Acknowledgment

LBNL:
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CERN:
Paolo Ferracin, Ezio Todesco

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