MECHANICAL DESIGN OF COSθ-TYPE ACCELERATOR MAGNETS

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- **Support Against Lorentz Force**
- Azimuthal Pre-Compression
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- Manufacturing of NbTi Magnets
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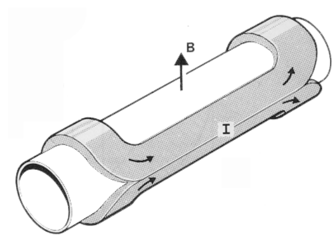
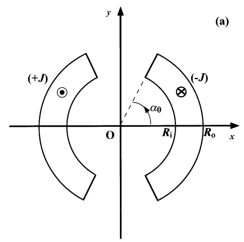
  - **Lorentz Force Components**
  - Minimum Quench Energy
  - Conceptual Design

Cosθ and Cos2θ Coil Designs

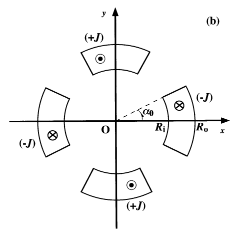
- As explained elsewhere, most superconducting particle accelerator magnets rely on saddle-shaped coils, which, in their long straight section, approximate cosθ or cos2θ conductor distributions.



Saddle-shaped coil assembly for dipole magnets



Cosθ conductor distribution for dipole magnets



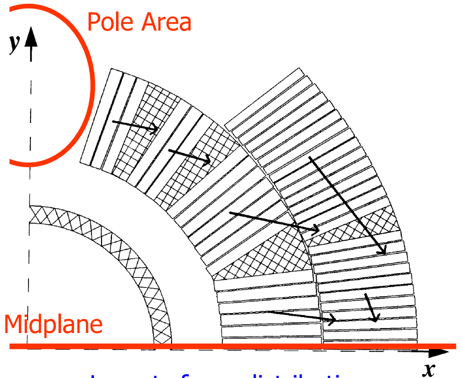
Cos2θ conductor distribution for quadrupole magnets

Lorentz Force Components (1/3)

• In a cosθ-type coil, the Lorentz force has three main components

– an azimuthal component,
– a radial component,
– an axial component.

Lorentz Force Components (2/3)



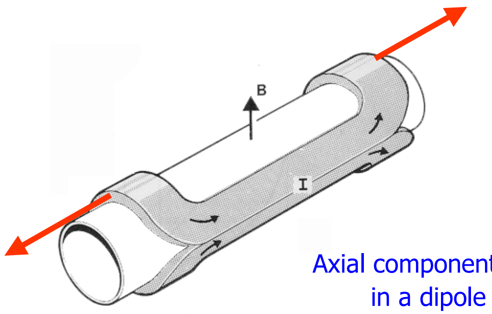
Lorentz force distribution in 2-D X-section of SSC dipole magnet coil (Courtesy R. Gupta)

• The azimuthal component tends to squeeze the coil towards the midplane.

• The radial component tends to bend the coil outwardly, with a maximum displacement at the coil assembly midplane.

Lorentz Force Components (3/3)

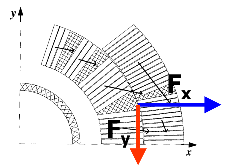
• The axial component, which arises from the solenoidal field generated by the conductors' turnaround in the coil ends, tends to stretch the coil outwardly.

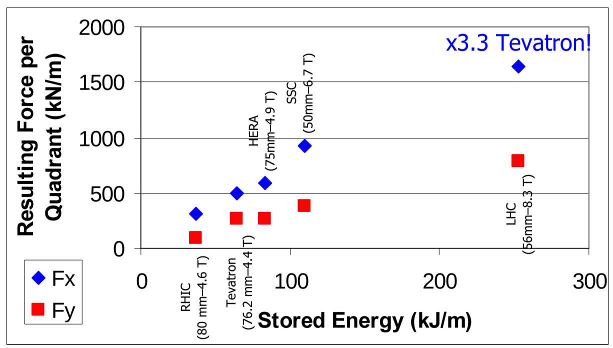


Axial component of Lorentz force in a dipole magnet coil (After M.N. Wilson)

Lorentz Force Summary

• The field increase from the Tevatron to LHC has led to a Lorentz force increase in excess of 3.



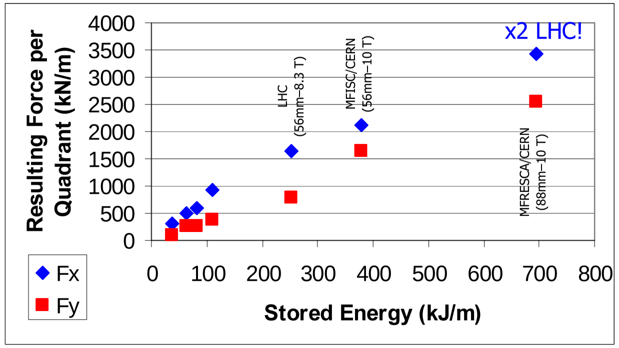


Cosθ Design Limit (1/3)

- How far can the cosθ design be pushed and still lead to suitable quench performance?
- A few examples show that there is still room beyond LHC.

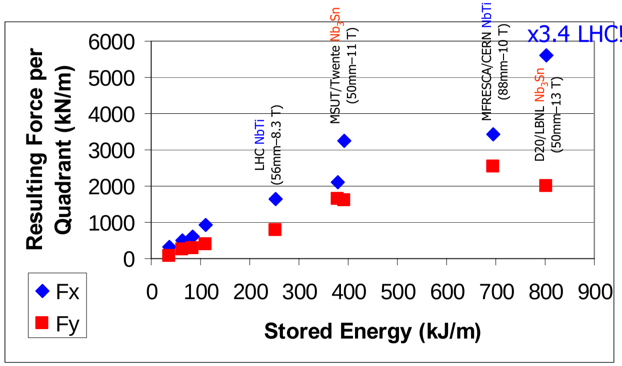
Cosθ Design Limit (2/3)

- A couple of NbTi dipole magnets built at or under contract with CERN operate reliably at force levels which far exceed those of LHC.



Cosθ Design Limit (3/3)

- A couple of Nb_3Sn dipole magnet models have also reached force levels that are well beyond those of LHC.

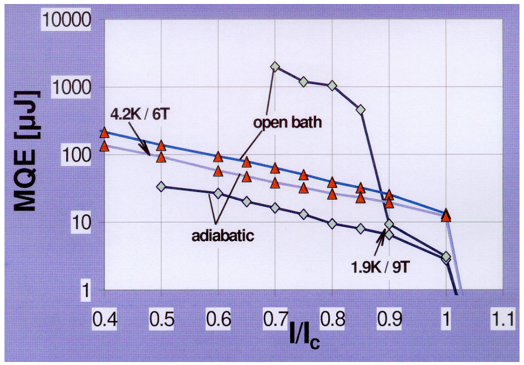


Contents

- **Support Against Lorentz Force**
  - Lorentz Force Components
  - **Minimum Quench Energy**
  - Conceptual Design

Minimum Quench Energy

- Accelerator magnets are operated very close to the critical current limit of their cables.



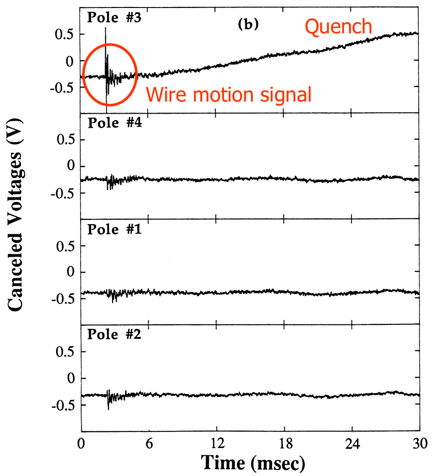
- As a result, the minimum energy deposition that triggers a quench, referred to as Minimum Quench Energy (MQE), is very small.

MQE measurements on LHC-type wire (Courtesy P. Bauer)

Wire Motions (1/2)

- In particular, the MQE is of same order of magnitude as the electromagnetic work produced by minute wire motions in the magnet coil.
- If the motions are purely elastic and/or if helium cooling is very efficient, the coil does not heat up and remains superconducting.

Wire Motions (2/2)



- However, if the motions are frictional and cooling is limited, the associated heat dissipation can be sufficient to initiate a quench.

Example of wire motion signal observed in the voltage across a pole of a superconducting quadrupole magnet at KEK (Courtesy K. Tsuchiya)

Limiting Mechanical Disturbances

- This leaves only two possibilities
  - to prevent wire or coil motion by providing a rigid support against the various components of Lorentz force,
  - to reduce to a minimum the friction coefficients between potentially moving parts of magnet assembly.

Contents

- **Support Against Lorentz Force**
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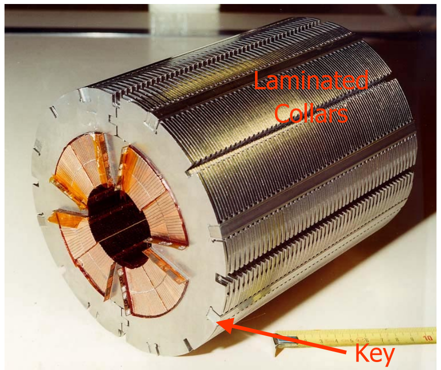
Conceptual Design

- The mechanical design concepts used in present cosθ-type accelerator magnets are more or less the same and were developed at the time of the Tevatron at Fermilab.

Azimuthal and Radial Support



Collared-coil assembly section of LHC arc quadrupole magnet at CEA/Saclay

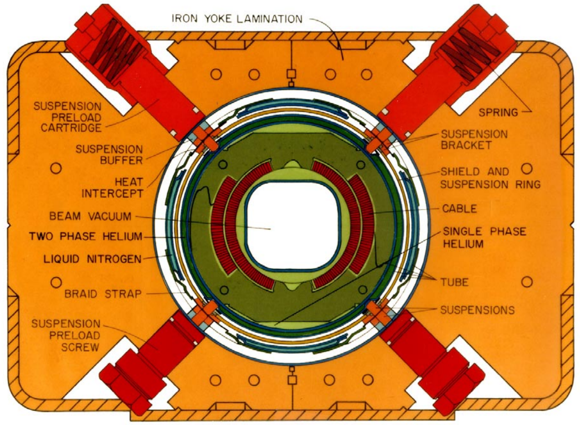
- In the radial direction: the coils are confined in a rigid cavity, defined by laminated collars locked around the coil by means of keys or tie rods.
- In the azimuthal direction: the collars are assembled so as to pre-compress the coils.

On the Use of Laminated Collars

- The use of laminated collars, pioneered at the Tevatron, was a real breakthrough in achieving a rigid mechanical support while keeping tight tolerances over magnet assemblies which are a few meters in length and must be mass-produced.
- The laminations are usually stamped by a fine blanking process, allowing a dimensional accuracy of the order of 0.01 mm to be achieved.
- Such accuracy is needed to ensure proper conductor positioning for field quality.

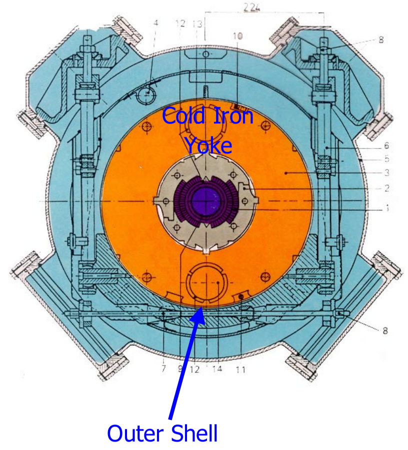
Tevatron Design

- In the case of the Tevatron, the cold mass is limited to the collared-coil assembly and the iron yoke is at room temperature.



- All Lorentz forces are taken up by the free-standing collared-coil assembly.

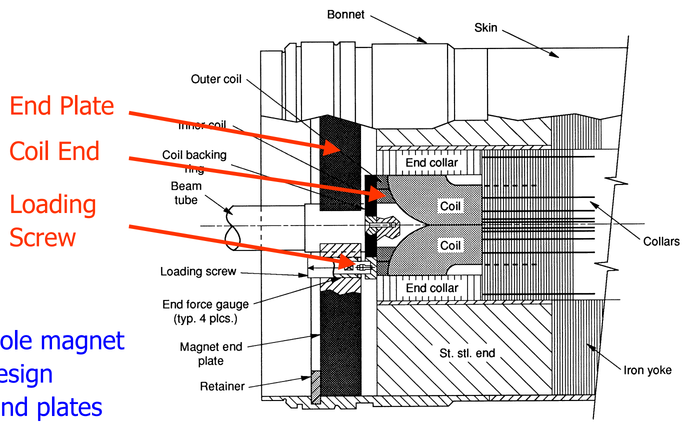
HERA and Post-HERA Designs



- Starting with HERA at DESY, the iron yoke is included into the cold mass and is surrounded by a tube or a welded shell.
- The outer tube or shell provides mechanical integrity and delimits the region of helium circulation.
- In such design, part of the radial component of the Lorentz force can be transferred to the yoke and the outer shell.

Axial Support

- In the axial direction: the coils are either free to expand or restrained by means of stiff end plates.



SSC/BNL dipole magnet end design with stiff end plates

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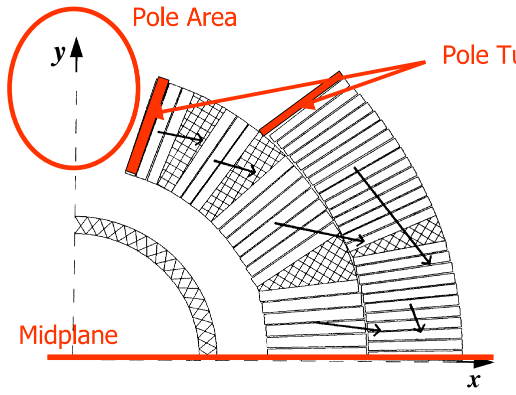
  - **Collar Pole Unloading**
  - Pre-Compression Requirements
  - Coil Mechanical Properties
  - Choice of Collar Material
  - How Critical is Azimuthal Pre-Compression?

Collar Pole Unloading (1/2)

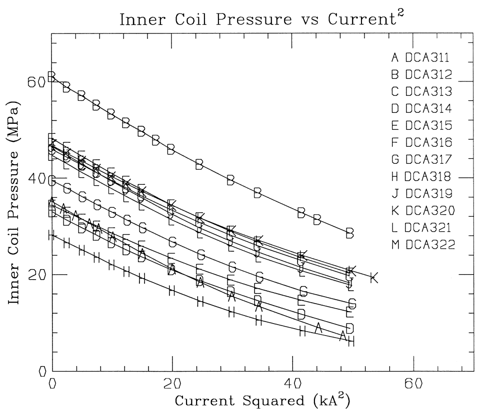
- As we have seen, the azimuthal component of the Lorentz force tends to squeeze the coil towards the midplane.

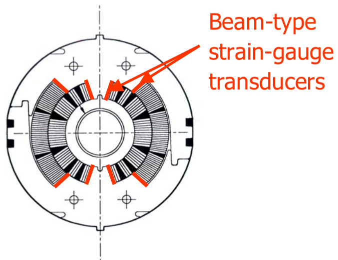


Lorentz force distribution in 2-D X-section of SSC dipole magnet coil (Courtesy R. Gupta)

Collar Pole Unloading (2/2)

- This results in a progressive unloading of collar pole during excitation.

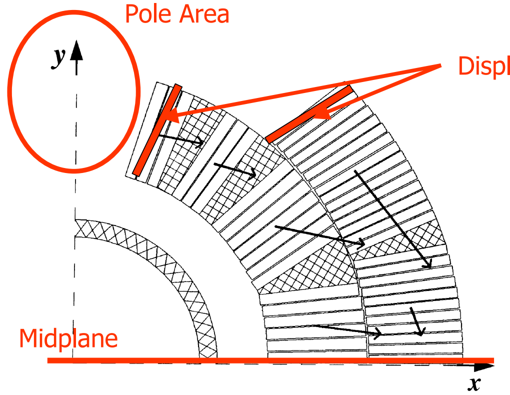




Collar pole unloading measured by beam-type strain-gauge transducers on 5-cm-aperture, 15-m-long SSC/FNAL dipole magnet prototypes (Courtesy T. Ogitsu)

Effects of Collar Pole Unloading (1/2)

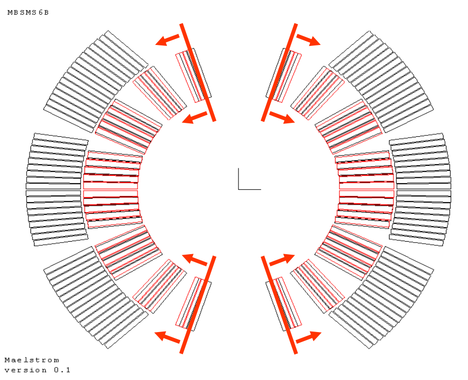
- At high excitation currents (and thus, high fields), it can happen that the coil pole turn moves away from collar pole.



Lorentz force distribution in 2-D X-section of SSC dipole magnet coil (Courtesy R. Gupta)

Effects of Collar Pole Unloading (2/2)

- Pole turn displacements create a risk of mechanical disturbance and distort field quality.



- For LHC arc dipole magnets (@17 mm)

$\Delta b_3 \approx + 1.75$ units/100 μm

$\Delta b_5 \approx - 0.37$ units/100 μm

$\Delta b_7 \approx + 0.13$ units/100 μm

$\Delta b_9 \approx - 0.05$ units/100 μm

Preventing Collar Pole Unloading

- To prevent full unloading, the collars are assembled and locked around the coils so as to apply an azimuthal pre-compression.
- The pre-compression is applied at room temperature and must be sufficient to ensure that, after cooldown and energization, there is still contact between coil pole turns and collar poles.

Contents

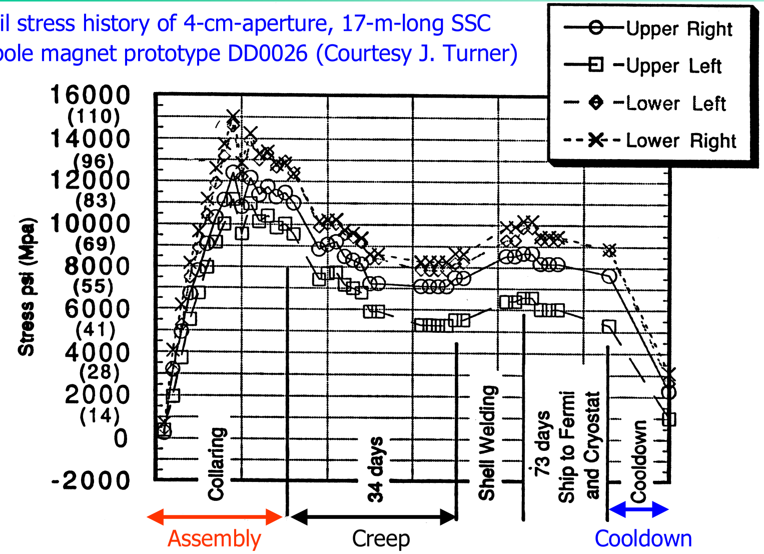
- **Azimuthal Pre-Compression**
  - Collar Pole Unloading
  - **Pre-Compression Requirements**
  - Coil Mechanical Properties
  - Choice of Collar Material
  - How Critical is Azimuthal Pre-Compression?

Pre-Compression Requirements

- To determine the proper level of room temperature pre-compression, at least three effects must be taken into account
  - stress relaxation and insulation creep following collaring operation,
  - thermal shrinkage differential between coil and collars during cooldown (if any),
  - stress redistribution due to azimuthal component of Lorentz force during energization.
- In addition, the collaring operation must be optimized to ensure that the peak pressure seen by the coil does not overstress insulation.

Coil Stress History

Coil stress history of 4-cm-aperture, 17-m-long SSC dipole magnet prototype DD0026 (Courtesy J. Turner)



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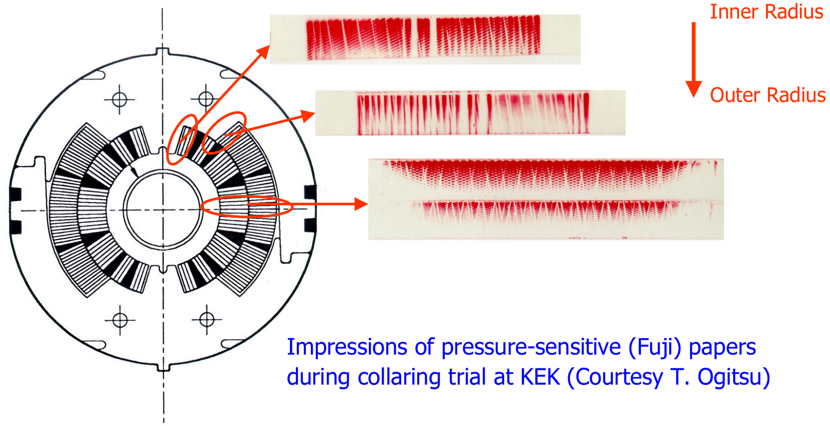
Peak Stress Gradient

- When evaluating the peak pressure seen by the coil during magnet assembly, one must bear in mind that there can be large stress gradients across conductor width.



Impressions of pressure-sensitive (Fuji) papers during collaring trial at KEK (Courtesy T. Ogitsu)

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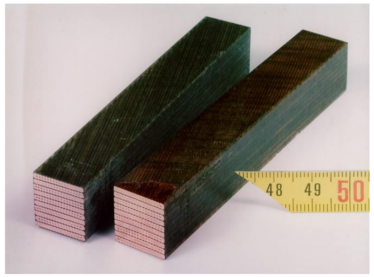
Mechanical Behavior of Accelerator Magnet Coil

- The coils of accelerator magnets constitute a highly composite medium whose mechanical behavior is difficult to predict.



Cable stacks wrapped with quartz fiber tape and vacuum-impregnated with epoxy resin (Courtesy M. Durante)

- In the absence of theoretical models, one must rely on direct measurements of stress-displacement curves on insulated conductor stacks representative of magnet coils.

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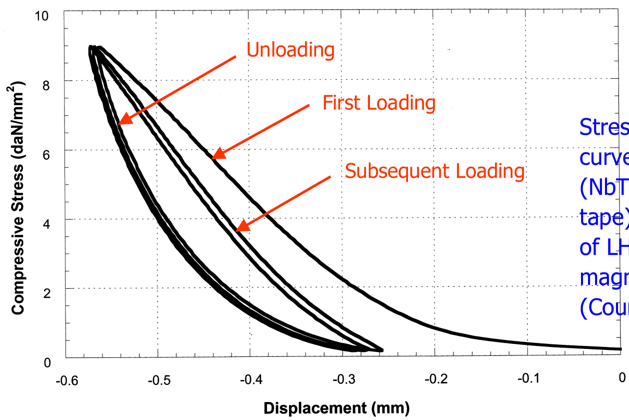
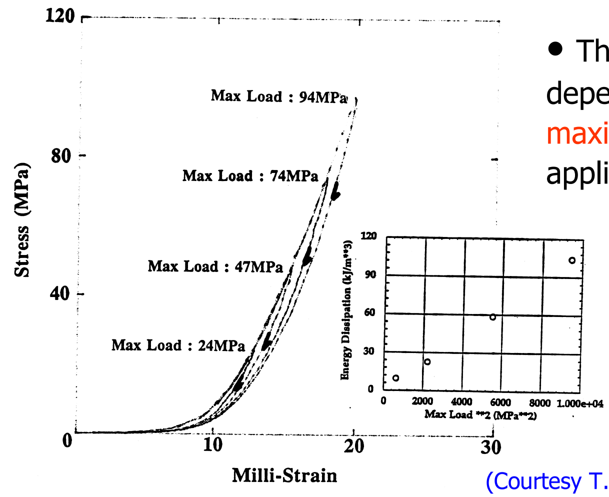
Coil Stress-Strain Curves (1/3)

- The measured stress-strain curves present at least three main features
  - first loading cycle is different from subsequent ones,
  - large hysteresis between loading and unloading branches,
  - unloading branch is non-linear.



Stress-Displacement curves measured on a (NbTi cable + polyimide tape) stack representative of LHC arc quadrupole magnet coil (Courtesy C. Gourdin)

Coil Stress-Strain Curves (2/3)

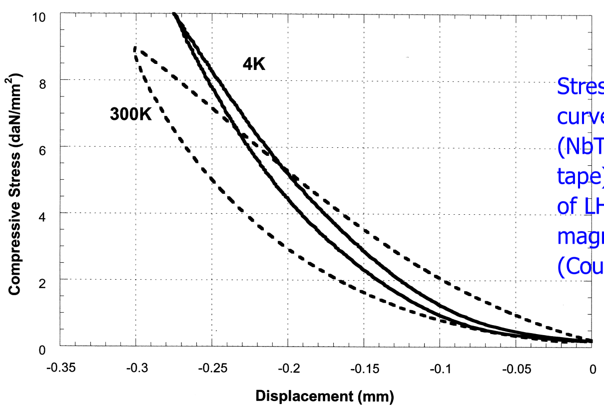


- The hysteresis size depends on the maximum pressure applied upon loading.

(Courtesy T. Ogitsu)

Coil Stress-Strain Curves (3/3)

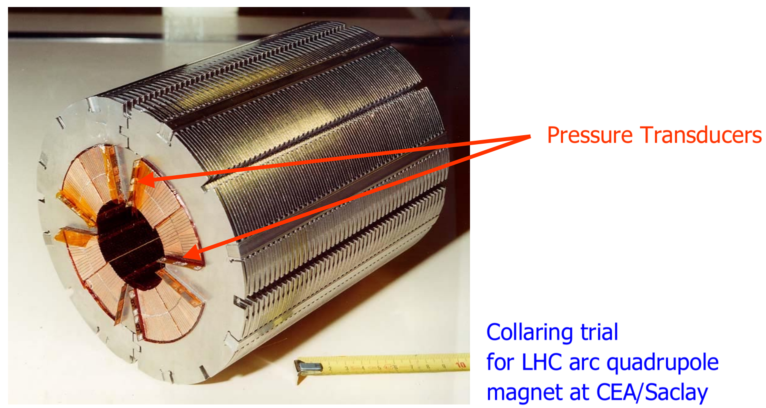
- Two main effects are observed upon cooldown to 4.2K
  - reduction of hysteresis width,
  - significant stiffening.



Stress-Displacement curves measured on a (NbTi cable + polyimide tape) stack representative of LHC arc quadrupole magnet coil (Courtesy C. Gourdin)

Collaring Trials

- Given the problem complexity, collaring trials are usually performed on short coil sections to check the achievement of nominal parameters.



Collaring trial for LHC arc quadrupole magnet at CEA/Saclay

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Factors Influencing Azimuthal Pre-Compresion

- The creep rate is an inherent property of the materials that form the coils (mainly, of strand copper and conductor insulation).
- The stress redistribution due to the azimuthal component of the Lorentz force is determined by the electromagnetic design.
- Hence, the only effect that strongly depends on mechanical design is the pre-compression variation during cooldown.

Pre-stress Loss During Cooldown

- A first-order estimate of the variation of coil azimuthal pre-compression during cooldown, $\Delta\sigma_{c.d.}$, is given by

$$\Delta\sigma_{c.d.} \approx E_{coil}\,(\alpha_{coil} - \alpha_{collar})$$

where E_{coil} is the coil Young's modulus (in the azimuthal direction), and α_{coil} and α_{collar} are the thermal shrinkage coefficients of the coils and of the collars, integrated between room and liquid helium temperatures.

(Note that the previous equation is derived with the assumptions that E_{coil} is constant and the collars are infinitely rigid.)

Mechanical Data

- Young's modulus, integrated thermal shrinkage coefficient and density data for various materials used in superconducting magnets

	Young's Modulus @293 K (GPa)	Young's Modulus @4.2 K (GPa)	Int. Thermal Shrinkage ($\times 10^{-3}$ m/m)	Density (kg/m^3)
Titanium	115	130	1.5	4400
Low Carbon Steel	200		2.0	
Stainless Steel (304/316)	200	210	2.9	7800
Copper (OFHC)	130	140	3.1	8900
Aluminum Alloy	70	80	4.2	2800
NbTi Cables w. Polyimide Insulation[a]	6	9-11	~5	
Resin-Impregnated Nb_3Sn Cables[a]	30	45	3.5–4	

[a] Upon loading @80 MPa; depends on cable and insulation parameters.

- In practice, the main choice for collar material is between aluminum alloy and austenitic stainless steel.

Pros of Aluminum Alloy

- To limit pre-compression loss during cooldown, it is preferable to choose a material whose integrated thermal shrinkage coefficient matches more or less that of the coil.
- This favors aluminum alloy.
- In addition, aluminum alloy has a lower density, and is potentially cheaper.

Pros of Austenitic Stainless Steel

- However, as described in the next section, it is desirable also that the collars be as rigid as possible and/or have an integrated thermal shrinkage coefficient approaching that of the low-carbon steel used for the yoke.
- This favors austenitic stainless steel, which has a a higher Young's modulus and a lower integrated thermal shrinkage coefficient.
- In addition, austenetic stainless steel has a better resistance to stress cycling at low temperature.

Magnetic Permeability

- Let us note that, to prevent undesirable field quality distortions, it is crucial to ensure that the relative magnetic permeability of the collars is very close to 1.
- In the case of stainless steel, this requires a tight control of chemical composition.

Aluminum vs. Stainless Steel

- Over the years, magnets with both collar types have been built: HERA dipole magnets and early LHC dipole magnet prototypes use aluminum alloy collars, whereas Tevatron, most SSC dipole magnet prototypes, and present LHC dipole magnets use stainless steel collars.
- In any case, and whichever collar material material is chosen, the most important is probably to develop a consistent mechanical design and to perform a thorough analysis of the structure under the various loading conditions encountered during assembly and operation.
- As already mentioned, this analysis can be validated by performing collaring trials on short coil sections.

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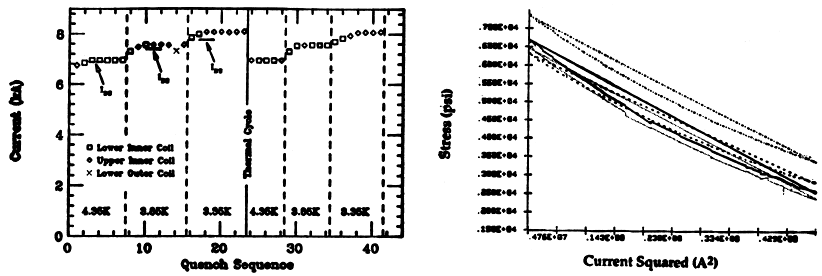
  - **How Critical is Azimuthal Pre-Compression?**

How Critical is Azimuthal Pre-Compression?

- There are experimental evidences that, when a rigid radial support is provided (see next section), the issue of azimuthal pre-compression may not be so critical for quench performance.
- As an illustration, let us consider the data from 4-cm-aperture, 1.8-m-long SSC/BNL dipole magnet model DSV016.

DSV016 High Pre-Stress Data

- DSVO16's design was worked out to ensure a rigid support against the radial component of the Lorentz force and the model magnet was first assembled with a high level of azimuthal pre-compression.

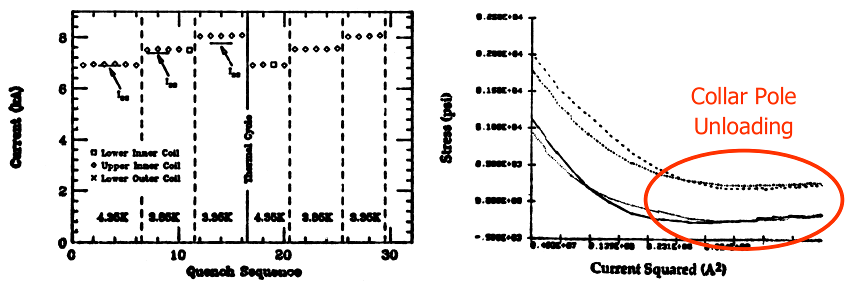


(Courtesy P. Wanderer)

- DSVO16 exhibited good quench performance with no sign of collar pole unloading.

DSV016 Low Pre-Stress Data

- After the first cold test, DSVO16 was taken apart and re-assembled (using the same coils) with a deliberately low level of azimuthal pre-compression.



(Courtesy P. Wanderer)

- During the second cold test, DSVO16 exhibited even better quench performance, while the strain-gauge-transducer data showed clear signs of collar pole unloading.

Notes on DSV016 Data

- The previous data should be taken with caution, for they concern only one short model magnet, of a specific design, that was carefully handcrafted by experienced technicians at BNL.
- Furthermore, the undesirable field distortions resulting from collar pole unloading are still an issue.

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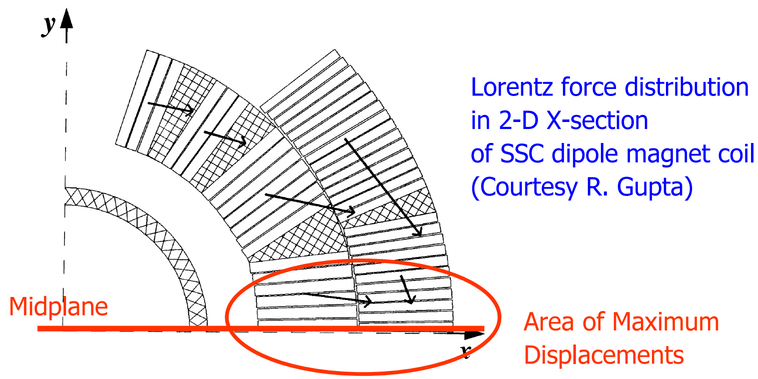
  - Designs with Aluminum Control Gap Spacer
  - RHIC Magnets

Radial Deflections (1/2)

- As we have seen, the radial component of the Lorentz force tends to bend the coil outwardly, with a maximum displacement at the coil assembly midplane.



Radial Deflections (2/2)

- At high excitation currents (and thus, high fields), this bending can result in shear stresses between coil turns and in an ovalization of the coil assembly (along the horizontal *x*-axis for a dipole magnet coil), which generate field distortions.
- To prevent unwanted displacements and deformations, the radial deflections of the coil assembly are usually limited to, typically, less than 0.05 mm.

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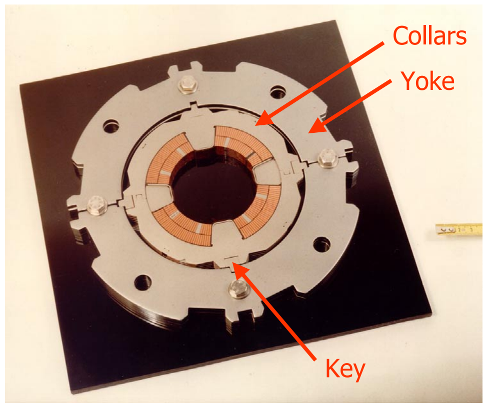
  - RHIC Magnets

Self-Supported Collared Coils

- The main support against the radial component of the Lorentz force is provided by the collars.
- If the collars can be made rigid enough to limit collared-coil assembly deflections within the desired range, there is no need to seek yoke support and the mechanical structure remains fairly simple.

Examples: HERA and LHC arc quadrupole magnet designs with austenitic stainless steel collars developed at CEA/Saclay.

Example: HERA Quadrupole Magnets

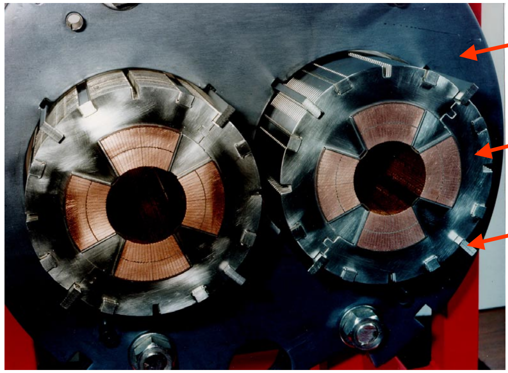


- The collared-coil assembly of the HERA arc quadrupole magnet is self-supported and is centered within the iron yoke by means of collar-locking keys.

HERA quadrupole magnet design developed at CEA/Saclay

Example: LHC Arc Quadrupole Magnets

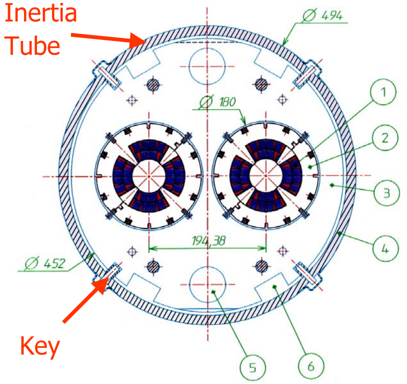
- The same concepts are applied to the design of the twin-aperture LHC arc quadrupole magnets.



LHC arc quadrupole magnet design developed at CEA/Saclay

Inertia Tube

- The coldmass is completed by an inertia tube that is slid around the yoked assembly.



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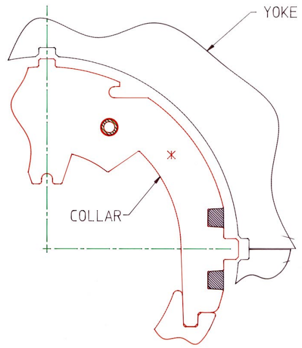
  - Designs with Yoke Midplane Gap
  - Designs with Aluminum Control Gap Spacer
  - RHIC Magnets

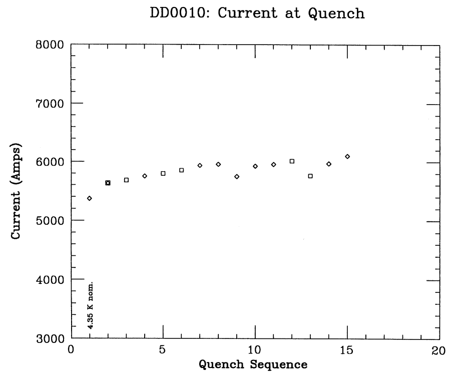
Why Seeking Yoke Support? (1/3)

- In the magnetic design of high-field magnets, the field enhancement provided by the iron yoke is usually maximized by bringing it as close as possible to the coil (at the expense of saturation effects at high currents).
- This reduces the space left for the collars, whose rigidity then becomes insufficient to restrain the radial component of the Lorentz force.
- In such design, yoke and helium containment shell must be used also as part of the coil support structure.

Why Seeking Yoke Support? (2/3)

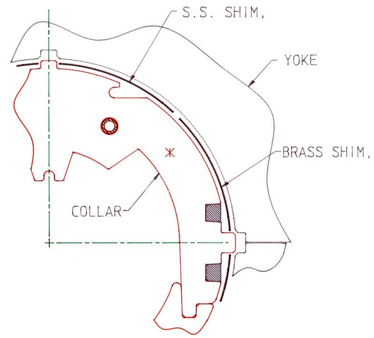
- Early 4-cm aperture, 17-m-long SSC dipole magnet prototypes, such as DD0010, were designed with a gap between collars and yoke and had poor quench performance.

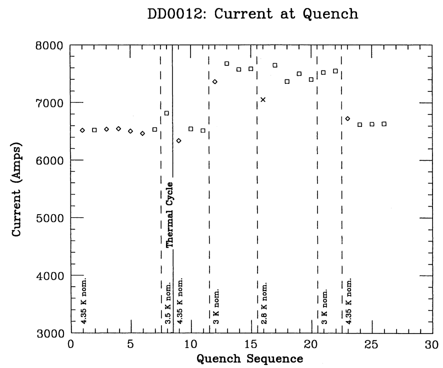




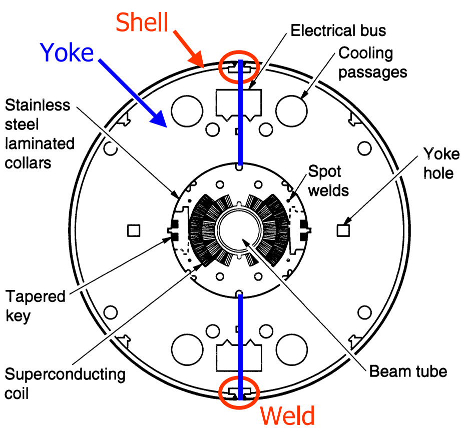
Why Seeking Yoke Support? (3/3)

- The quench performance was improved greatly by implementing shims that locked the collared-coil assembly within the iron yoke, as in DD0012.





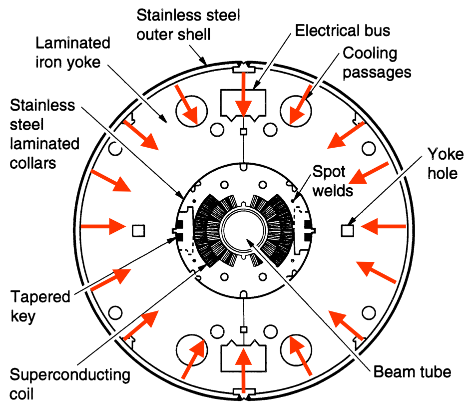
Design with Yoke Support (1/3)



SSC/FNAL dipole magnet design

- To facilitate assembly, the yoke is split in two halves, which are mounted around the collared-coil assembly.
- The cold mass is completed by an outer shell, also split in two halves, which are welded around the yoked assembly.

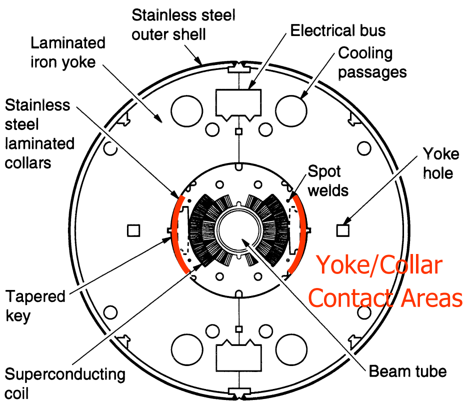
Design with Yoke Support (2/3)



SSC/FNAL dipole magnet design

- The structure is held together by the shell, which applies a radial pressure onto the yoke.
- This pressure results from weld shrinkage and thermal shrinkage differential (between yoke and shell) during cooldown.

Design with Yoke Support (3/3)



SSC/FNAL dipole magnet design

- The mechanical design must be worked out to ensure that the yoke is in contact with critical areas of collared-coil assembly during energization.
- However, one must also prevent overloading of collared-coil assembly at room temperature.

Contact Loss During Cooldown

- The mechanical design of magnets with yoke support is complicated by the fact that the material used for the collars (stainless steel or aluminum) has a larger integrated thermal shrinkage coefficient than the low-carbon steel used for the yoke.
- Hence, during cooldown, the collared-coil assembly has a tendency to shrink away from the yoke, which can result in a contact loss.

Mechanical Data

- Young's modulus, integrated thermal shrinkage coefficient and density data for various materials used in superconducting magnets

	Young's Modulus @293 K (GPa)	Young's Modulus @4.2 K (GPa)	Int. Thermal Shrinkage ($x10^{-3}$ m/m)	Density (kg/m^3)
Titanium	115	130	1.5	4400
Low Carbon Steel	200		2.0	
Stainless Steel (304/316)	200	210	2.9	7800
Copper (OFHC)	130	140	3.1	8900
Aluminum Alloy	70	80	4.2	2800
NbTi Cables w. Polyimide Insulation[a)]	6	9-11	~5	
Resin-Impregnated Nb_3Sn Cables[a)]	30	45	3.5–4	

[a)] Upon loading @80 MPa; depends on cable and insulation parameters.

- In practice, the main choice for collar material is between aluminum alloy and austenitic stainless steel.

Thermal Shrinkage Allowance

- This contact loss can be limited (and even eliminated) by introducing a thermal shrinkage allowance into the coldmass design.
- An estimate of the needed allowance, $\Delta R_{c.d.}$, is given by

$$\Delta R_{c.d.} \approx R_{collar} \left(\alpha_{collar} - \alpha_{yoke}\right)$$

where R_{collar} is the collar outer radius, and α_{collar} and α_{yoke} are the collar and yoke thermal shrinkage coefficients, integrated between room and liquid helium temperatures.

Collar Material (Bis)

- The previous equation shows that to limit the amplitude of the shrinkage allowance, it is preferable to use for the collars a material whose integrated thermal shrinkage coefficient approaches that of low carbon steel.
- This suggests the use of austenitic stainless steel.
- However, and as already discussed in the previous section, it is also desirable to limit pre-stress loss during cooldown, which favors the use of aluminum alloy.
- Once again, let us point out that, whichever collar material is chosen, it is necessary to develop a consistent mechanical design and to perform a thorough analysis of the structure under various loading conditions.

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Designs with Fully Mated Yoke (1/2)

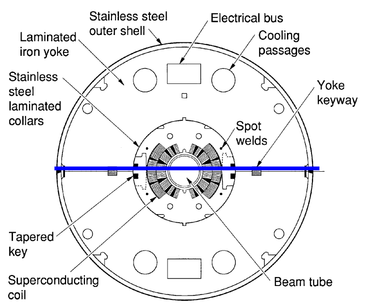
- When the thermal shrinkage differential between collars and yoke is not too large (as in the case of stainless steel collars), it can be compensated for by building the desired thermal shrinkage allowance into the geometry of either the collars or the yoke, and by welding the outer shell so as to exert a compressive load onto the two yoke halves which forces them to mate at room temperature.

Designs with Fully Mated Yoke (2/2)

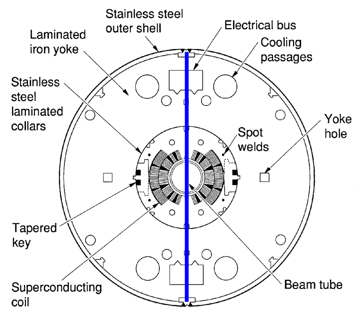
- During cooldown, the collared-coil assembly shrinks away from the yoke, which remains fully mated, resulting in a decrease of the compressive load applied by the yoke.
- However, as long as contacts are maintained over selected areas, the yoke can still ensure a suitable locking of the collared-coil assembly.

Yoke Split Orientation

- In practice, the compressive load provided by the yoke is directed along a given axis.
- The choice of this axis drives the choice of yoke split orientation, which can be either vertical or horizontal.

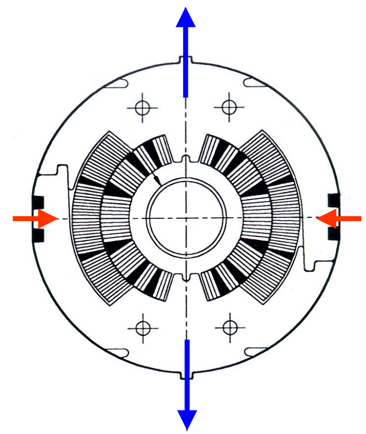


SSC/BNL horizontally split



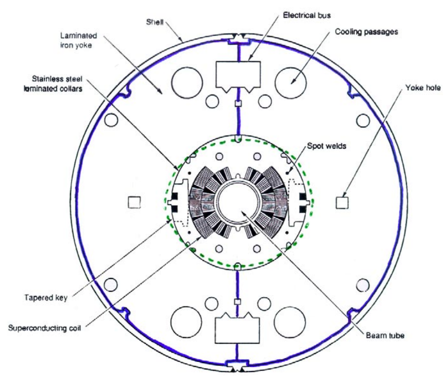
SSC/FNAL vertically split

Collared Coil Deflections



- Note, however, that the azimuthally pre-compressed coils exert a large pressure against the collar poles.
- This pressure can cause a large outward deflection of the collared-coil assembly along the vertical diameter and a slight inward deflection along the horizontal diameter.
- These deflections must be taken into consideration when working out yoke design.

SSC/FNAL Vertically-Split Yoke Design (1/3)



- The 5-cm-aperture dipole magnet design developed by FNAL for SSC relied on stainless steel collars, a two-piece, vertically-split yoke and a welded, stainless steel outer shell.
- The collar and yoke geometries were worked out so that the vertical diameter of the keyed collars (with no coils in them) was ~900 μm smaller than the yoke inner diameter, while the horizontal diameter was ~300 μm larger.

SSC/FNAL Vertically-Split Yoke Design (2/3)

- The clearance along the vertical diameter was introduced to allow yoke assembly and compensate for the vertical deflections of the collared-coil assembly resulting from the forces exerted by the pre-compressed coils against the collar pole.
- The thermal shrinkage allowance along the horizontal diameter was introduced to compensate for the thermal shrinkage differential between collars and yoke and ensure that there was still contact between the two at the end of cooldown in the areas where the effects of the radial component of the Lorentz force are the largest.

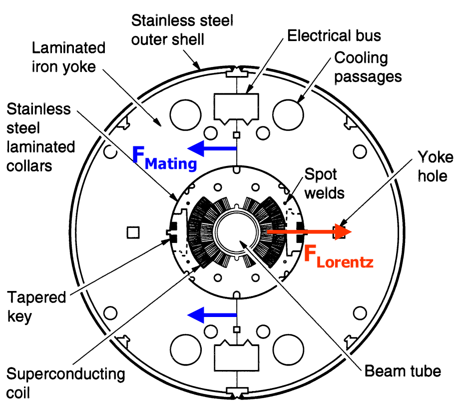
SSC/FNAL Vertically-Split Yoke Design (3/3)

- The existence of a built-in thermal shrinkage allowance between collars and yoke required the use of a press during shell welding to force a full closure of the yoke midplane gap at room temperature.

Yoke Mating Force (1/2)

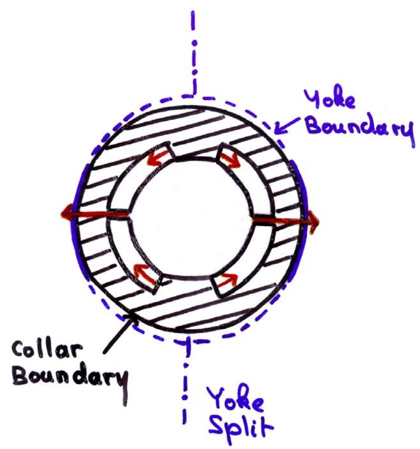
- In a magnet design with a vertically-split yoke, the yoke midplane gap must of course be closed at the end of cooldown, but it must also remain closed during energization.
- This ensures that the structure is very rigid and avoids any risk of oscillation.

Yoke Mating Force (2/2)



- To fulfill this requirement, we not only need a good contact between the two yoke halves at the end of cooldown, but we also need the two yoke halves to be mated with a compressive force at least equal to the fraction of the horizontal component of the Lorentz force transmitted by the collared-coil assembly to the yoke.
- This force is called the yoke mating force.

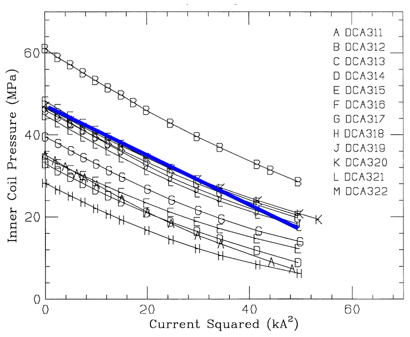
SSC/FNAL Vertically-Split Yoke Design During Energization



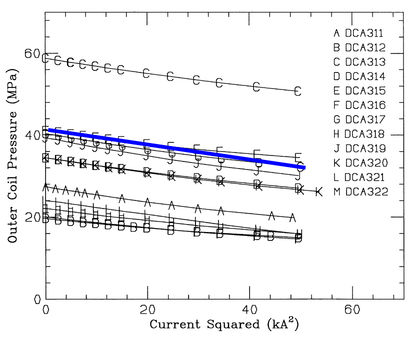
- During energization, the yoke provides a quasi-infinitely stiff support against the radial component of the Lorentz force and the collars do not bend.
- Hence, the unloading of the collar poles only result from the coil compression under the azimuthal component of the Lorentz force.

Collar Pole Unloading of SSC/FNAL Dipole Magnets

Measured Collar Pole Unloading



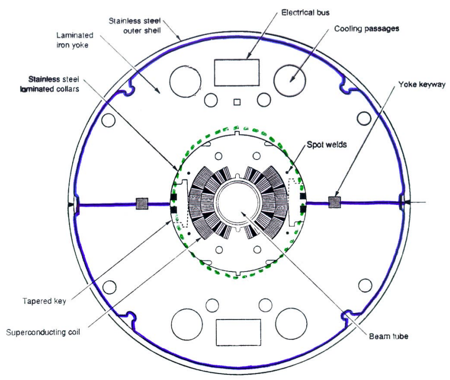
Inner Layer



Outer Layer

(Courtesy T. Ogitsu)

SSC/BNL Horizontally-Split Yoke Design (1/3)



- The 5-cm-aperture dipole magnet design developed by BNL for SSC relied on stainless steel collars, a two-piece, horizontally-split yoke and a welded, stainless steel outer shell.
- The collar and yoke geometries were worked out so that the vertical diameter of the keyed collars (with no coils in them) was ~100 μm smaller than the yoke inner diameter, while the horizontal diameters were the same.

SSC/BNL Horizontally-Split Yoke Design (2/3)

- As already explained, after collaring, the forces exerted by the compressed coils against the collar poles result in a large outward deflection of the collared-coil assembly along the vertical diameter and a small inward deflection along the horizontal diameter.
- The slight inward deflection allows to assemble the horizontally-split yoke around the collared coil assembly, while the large outward deflections ensures a contact between the two along the vertical diameter.

SSC/BNL Horizontally-Split Yoke Design (3/3)

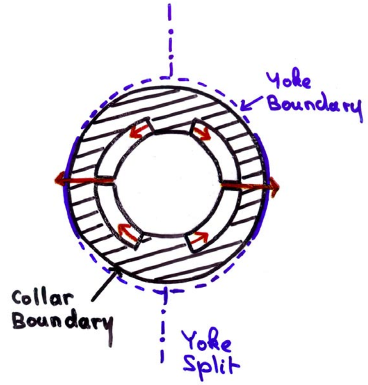
- During welding, the shell is put into tension and compresses the two yoke halves, which, in turn compress the collared-coil assembly along the vertical diameter, thereby enabling a full closure of the yoke midplane gap.
- At the end of shell welding, the yoke midplane gap is closed, and there is a line-to-line fit between the outer circumference of the collared-coil assembly and the inner circumference of the yoke.

SSC/BNL Horizontally-Split Yoke Design During Cooldown

- During cooldown, the coils shrink more than the stainless steel collars, which in turn shrink more than the low carbon steel yoke.
- The pressure exerted by the coils against the collar poles decreases, but remains large enough to keep deflecting the collars, thereby maintaining a contact with the yoke along the vertical diameter.
- Along the horizontal diameter, however, the thermal shrinkage differential can result in a small gap between the collared-coil assembly and the yoke.

SSC/BNL Horizontally-Split Yoke Design During Energization (1/2)

- During energization, the azimuthal component of the Lorentz force causes a redistribution of coil stress and a decrease of the pressure exerted by the coil against the collar poles.



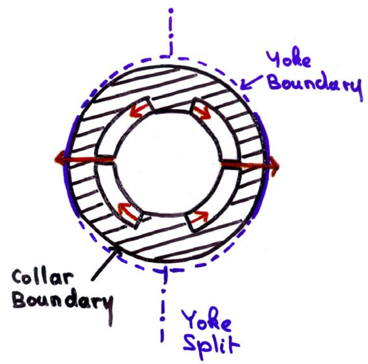
- At the same time, the radial component of the Lorentz force causes a bending of the collars, with a maximum displacement along the horizontal diameter, at the location of the gap between the collared-coil assembly and the yoke.

SSC/BNL Horizontally-Split Yoke Design During Energization (2/2)

- As the current increases, the bending moment increases, and the collars keep deflecting along the horizontal diameter, until they come into contact with the yoke.
- At high currents, the collared-coil assembly touches the yoke on a large perimeter on both sides of the horizontal plane and the yoke provides a quasi-infinitely stiff support against the radial component of the Lorentz force.

Collar Pole Unloading of SSC/BNL Dipole Magnets (1/2)

- As long as the collars are not in contact with the yoke along the horizontal diameter, the coil unloading from the collar poles result from two causes



– the coil compression under the azimuthal component of the Lorentz force,

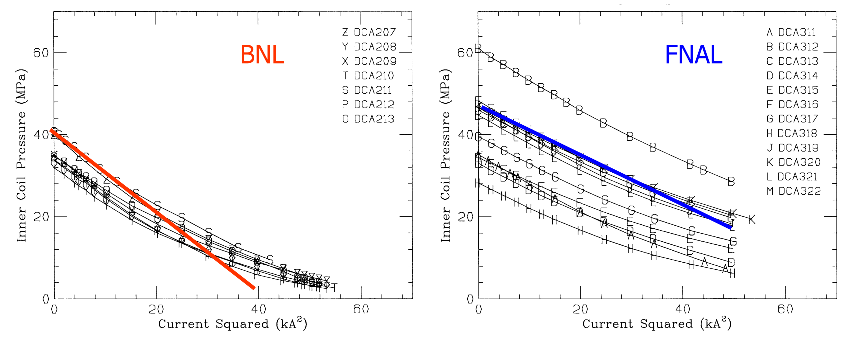
– the bending of the coil under the radial component of the Lorentz force.

Collar Pole Unloading of SSC/BNL Dipole Magnets (2/2)

- However, once the collars are in contact with the yoke, the collar pole unloading only results from the azimuthal component of the Lorentz force and the SSC/BNL magnet behaves the same as the SSC/FNAL magnets.
- Hence, after a faster initial unloading, we can expect the pressure plots of the SSC/BNL magnets to exhibit a change of slope and to become parallel to the SSC/FNAL magnets.

Comparison Between SSC/FNAL and SSC/BNL (1/3)

Measured Collar Pole Unloading

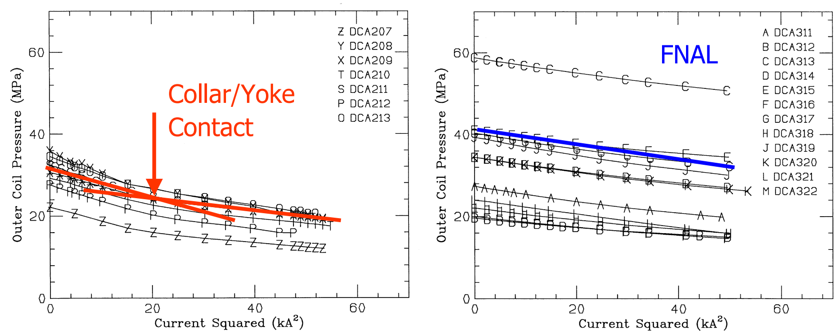


Inner Layer

(Courtesy T. Ogitsu)

Comparison Between SSC/FNAL and SSC/BNL (2/3)

Measured Collar Pole Unloading

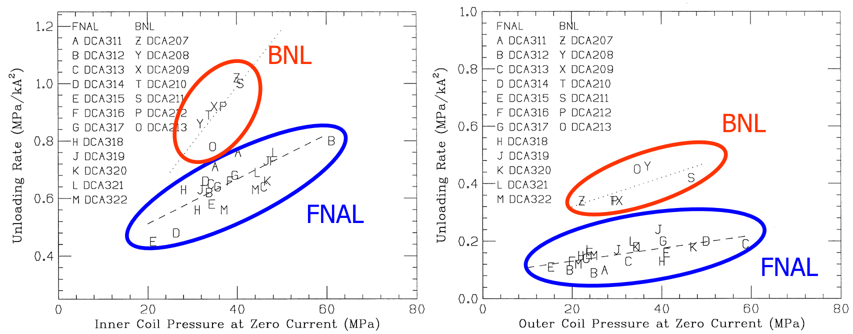


Outer Layer

(Courtesy T. Ogitsu)

Comparison Between SSC/FNAL and SSC/BNL (3/3)

Initial Rate of Collar Pole Unloading



Inner Layer

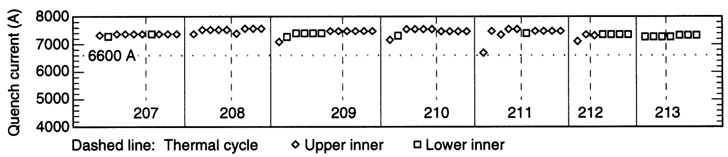
Outer Layer

(Courtesy T. Ogitsu)

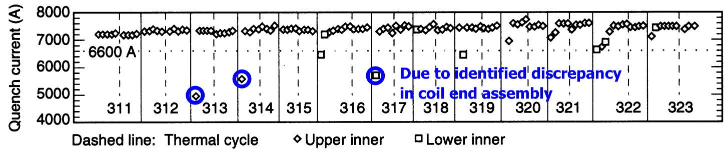
Horizontally Split vs. Vertically Split Yoke (1/2)

• Both designs can be engineered to work, and BNL and FNAL each produced a series of 5-cm-aperture, 15-m-long SSC dipole magnet prototypes that were equally successful in terms of quench performance.

BNL



FNAL

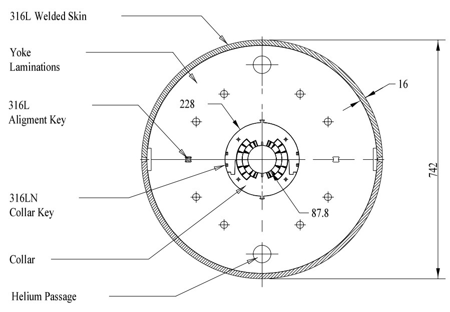


Horizontally Split vs. Vertically Split Yoke (2/2)

• Note that the horizontally-split yoke design can be refined to limit (even eliminate) the contact loss during cooldown along the horizontal diameter.

MFRESCA Design

• MFRESCA relies on stainless steel collars, a two-piece, horizontally-split yoke, and a welded, stainless steel outer shell.

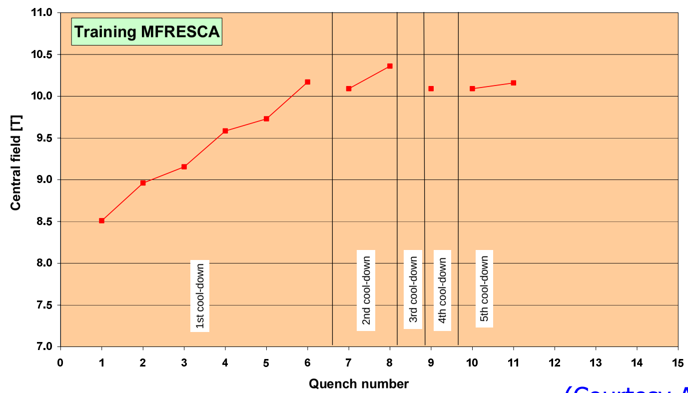


(Courtesy A. Verweij)

• The yoke midplane gap is closed at room temperature, and there is an extended line-to-line fit between the outer circumference of the collared-coil assembly and the inner circumference of the yoke.

MFRESCA performance

• After an initial training which started at 8.5 T, the magnet can now be operated reliably up to 10 T, which corresponds to a F_x-value of 4.4 MN/m, 3.5 times higher than SSC and 2 times higher than LHC!



(Courtesy A. Verweij)

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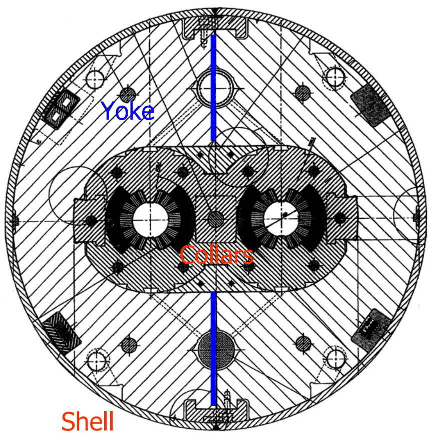
Designs with Yoke Midplane Gap

- For large thermal shrinkage differential (as in the case of aluminum collars), the shrinkage allowance and the yoke/collar compressive load needed at room temperature for a full mating mating of the two yoke halves can overstress the collared-coil assembly.
- Then, the mechanical design must be worked out so as to leave an open gap at the yoke midplane at room temperature and to ensure a progressive closure of this gap during cooldown and the achievement of the desired collared-coil assembly support upon energization.

Early LHC Dipole Magnet Design (1/3)



- Early 5-cm-twin-aperture, 10-m-long LHC dipole magnet prototypes relied on aluminum collars common to the two apertures, a two-piece, vertically-split yoke and a welded, stainless steel outer shell.

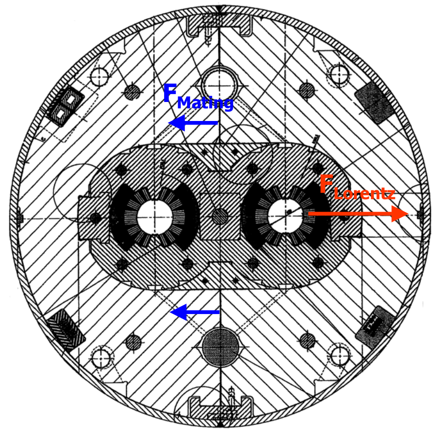
Early LHC Dipole Magnet Design (2/3)

- The two-piece, vertically-split yoke was designed so that, when placed around the collared-coil assembly at room temperature with no pressure applied to it, there remains an opening between the two yoke halves of the order of the expected thermal shrinkage differential.
- The yoke midplane gap was then closed in two stages
  - during shell welding, as a result of the compressive load arising from weld shrinkage,
  - during cooldown, as a result of the compressive load arising from thermal shrinkage differential between yoke and shell.

Early LHC Dipole Magnet Design (3/3)

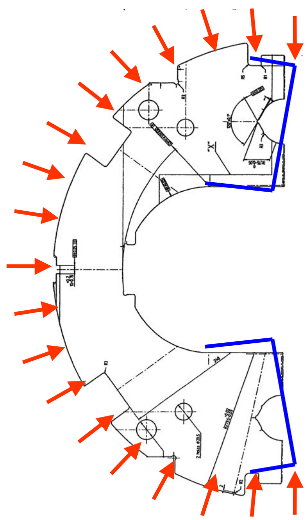
- The compressive load arising from thermal shrinkage differential during cooldown forced the two yoke halves to follow the shrinkage of the collared-coil assembly and to maintain a contact with it along the horizontal diameter.
- Upon energization, up to 50% of the horizontal component of the Lorentz force was transferred from the collared-coil assembly to the yoke and the shell.

Yoke Mating Force (Bis)



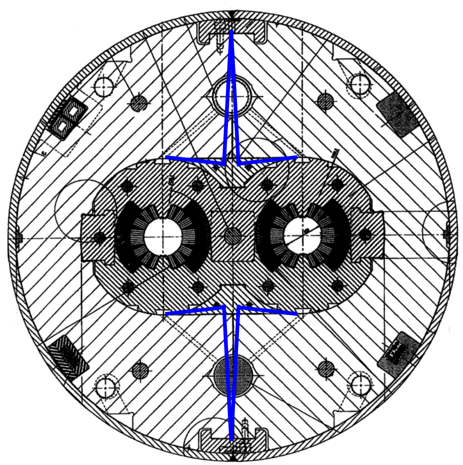
- As for SSC/FNAL dipole magnet design, at the end of cooldown, the two yoke halves needed to be mated with a compressive force at least equal to the fraction of the horizontal component of the Lorentz force transmitted by the collared-coil assembly to the yoke.

LHC Yoke Taper (1/3)



- A particularity of the two-piece, vertically-split yoke used in LHC dipole magnets is that it has a pronounced C-shape.
- Under the compressive load applied by the shell, bending moments arise which tend to deflect inwardly the top and bottom arms of the C.

LHC Yoke Taper (2/3)

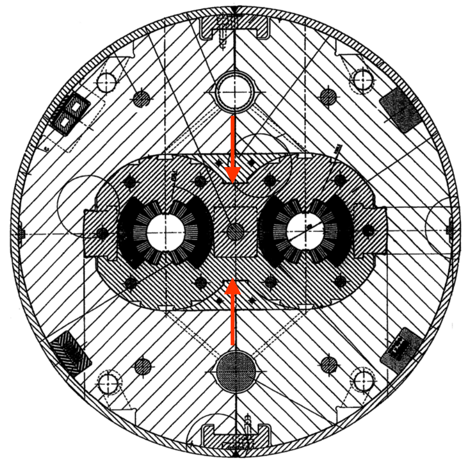


- Hence, if nothing were done, one could end up, at the end of cooldown, in a situation where the yoke midplane gap is closed at the outer radius of the yoke, but is open at the inner radius.

LHC Yoke Taper (3/3)

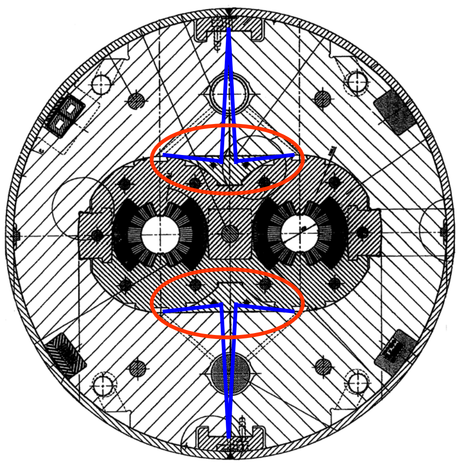
- The occurrence of such situation is prevented by introducing a slight taper in the yoke midplane gap: the yoke is designed so that, when placed around the collared-coil assembly at room temperature with no pressure applied to it, there remains a larger opening at the yoke outer radius than at the yoke inner radius.
- During shell welding and cooldown, the bending moments applied to the C arms bring the mating faces of the two yoke halves parallel and the yoke midplane gap closes progressively.

Vertical Support of LHC Collared-Coil Assembly (1/3)



- When using common collars, as in LHC dipole magnets, one must provide also a support along the vertical axis of the central part of the collared-coil assembly.
- This support is needed to prevent unwanted displacements and enhance the mechanical rigidity of the structure.

Vertical Support of LHC Collared-Coil Assembly (2/3)



- In the design discussed previously, the vertical support is provided by two magnetic inserts, which rest against the central part of the collared-coil assembly, and which are pre-compressed by the inward bending of the C-shaped yoke.

Vertical Support of LHC Collared-Coil Assembly (3/3)

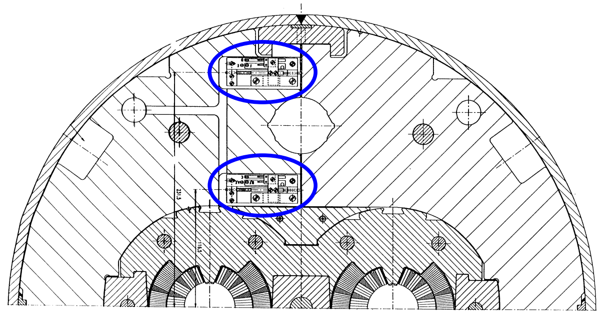
- One problem with the application of such vertical forces is that part of them are transmitted to the coils and result in an increase of azimuthal pre-compression.
- Hence, there is an upper limit on what is admissible, and the magnet assembly must be watched carefully to avoid overloading of collared-coil assembly.

Assembly of Magnets with Yoke Midplane Gap

- In summary, a gap too closed at room temperature can result in coil overloading, while a gap too open can result in contact loss during cooldown or insufficient mating upon energization.
- Then, a crucial issue in the assembly of such a magnet is the ability of performing the shell welding operation in a controlled and reproducible way to achieve the desired yoke midplane gap at room temperature and to keep a tight tolerance on this value.

Measurements of Yoke Midplane Gap (1/5)

- Early LHC dipole magnet prototypes were equipped with displacement transducers to monitor the evolution of the yoke midplane gap during cooldown.

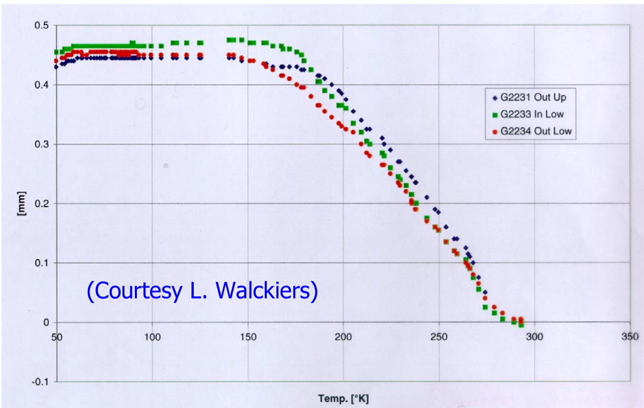


- By design, the gap was expected to close at a temperature between 200 and 150 K.

(Courtesy L. Walckiers)

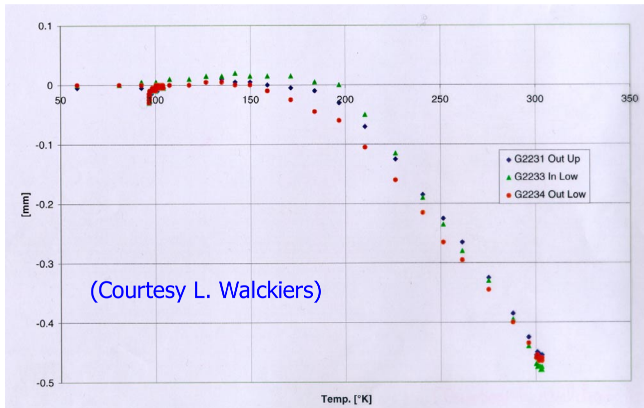
Measurements of Yoke Midplane Gap (2/5)

- Some prototypes did achieve the design goal during cooldown...



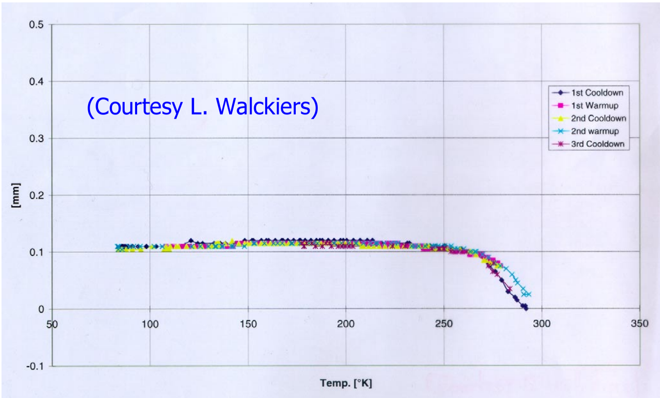
Measurements of Yoke Midplane Gap (3/5)

...and upon warm-up.



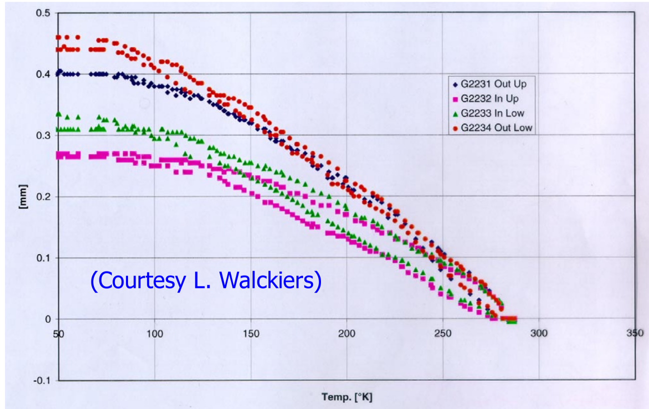
Measurements of Yoke Midplane Gap (4/5)

- However, in one case, the gap was too closed at room temperature and closed too early during cooldown.



Measurements of Yoke Midplane Gap (5/5)

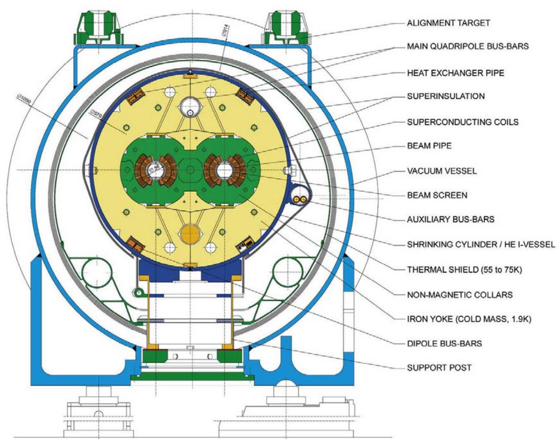
- In another case, the gap was too open at room temperature and closed too late during cooldown.



Controlling Yoke Midplane Gap

- The previous data show the difficulty of assembling magnets with an open yoke midplane gap at room temperature and seems to indicate that such a design is not suitable for industrial production.

Present LHC Dipole Magnet Design (1/2)



- The present LHC dipole magnet design rely on common stainless steel collars, a two-piece, vertically-split yoke and a welded, stainless-steel outer shell.
- The yoke midplane gap is closed at room temperature and remains closed throughout cooldown and excitation.

Present LHC Dipole Magnet Design (2/2)

- In this robust design, about 80% of the horizontal component of the Lorentz force is taken by the collars and only 20% is transmitted to the yoke and the shell.
- The three LHC dipole magnet contractors have now demonstrated their ability to produce magnets with suitable quench performance.

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Contents

- **Radial Support**
  - Radial Deflections
  - Designs with Self-Supported Collared-Coil Assemblies
  - Designs with Yoke Support
  - Designs with Fully Mated Yoke
  - Designs with Yoke Midplane Gap
  - **Designs with Aluminum Control Gap Spacer**
  - RHIC Magnets

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Controling Yoke Midplane Gap (Bis)

- As we have seen, a key issue in the assembly of dipole magnets with an open yoke midplane gap is to prevent the gap from closing too much at room temperature and avoid overloading of collared-coil assembly.
- This can be done by implementing aluminum spacers controlling the mating of the two yoke halves.

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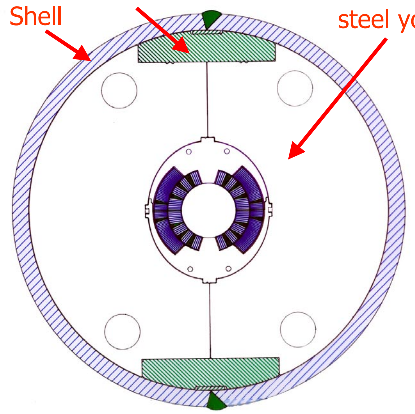
Aluminum Control Gap Spacers (1/3)



LBNL dipole magnet model D19

- The aluminum control gap spacers are designed to have a spring rate similar to the spring rate of the collared-coil assembly (along the horizontal diameter).

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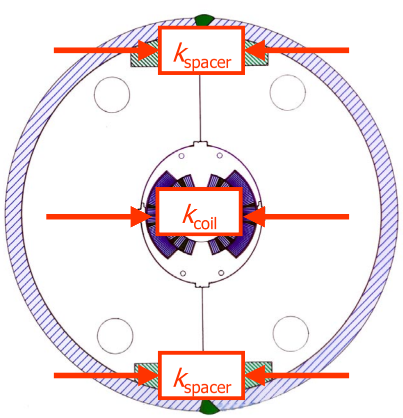
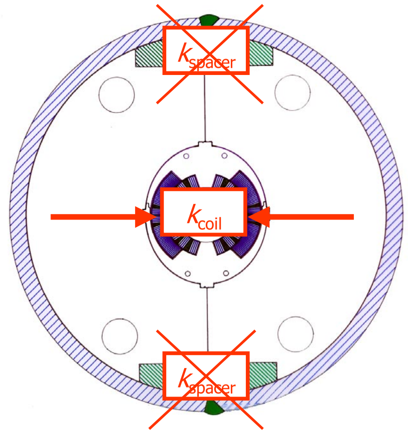
Aluminum Control Gap Spacers (2/3)



LBNL dipole magnet model D19

- Then, at room temperature, the welding of the shell results in a compressive loading of three parallel springs.
- Given the respective spring rates, the spacers take up most of this loading, thereby protecting the collared-coil assembly, and preventing a full mating of the two yoke halves.

Aluminum Control Gap Spacers (3/3)



LBNL dipole magnet model D19

- During cooldown, the aluminum spacers shrink more than the low-carbon steel yoke and become loose.
- This enables a proper mating of the yoke halves and a suitable support of the collared-coil assembly.
- From then on, the spacers do not play any more role.

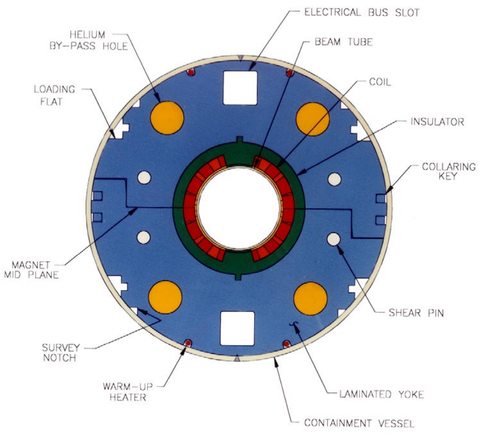
One the Use of Aluminum Control Gap Spacers

- So far, only four NbTi dipole magnets incorporating control-gap spacers have been built and tested (one 5-cm-single-aperture, 1-m-long model at LBNL and three 5-cm-twin-aperture, 10-m-long prototypes at CERN).
- The LBNL model (D19) reached 10 T at 1.8 K (after some training), while the CERN prototypes were less successful (for reasons that could have nothing to do with the use of control gap spacers).
- More work is therefore needed to assess the usefulness and reliability of this promising feature.

Contents

- **Radial Support**
  - **Radial Deflections**
  - **Designs with Self-Supported Collared-Coil Assemblies**
  - **Designs with Yoke Support**
  - **Designs with Fully Mated Yoke**
  - **Designs with Yoke Midplane Gap**
  - **Designs with Aluminum Control Gap Spacer**
  - **RHIC Magnets**

RHIC Magnets (1/2)



RHIC dipole magnet X-section

- In RHIC dipole and quadrupole magnets, the collars are replaced by reinforced plastic spacers and the coil azimuthal pre-compression and radial support are provided directly by the iron yoke.

RHIC Magnets (2/2)

- This simple and cost effective design has proven to be adequate for the low field and low field gradient of the RHIC magnets.
- It remains to be seen if such structure can be scaled up to higher force levels.

Contents

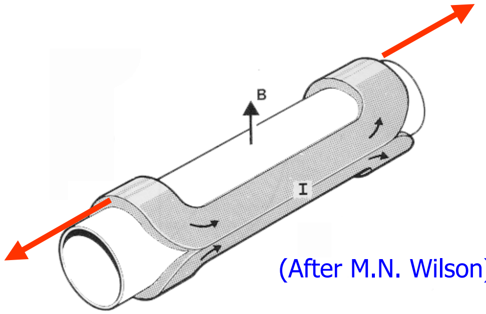
- Support Against Lorentz Force
- Azimuthal Pre-Compression
- Radial Support
- **End Support**
- Manufacturing of NbTi Magnets
- Tentative Summary

Contents

- **End Support**
  - **Axial Component of Lorentz Force**
  - Designs with Self-Supported Collared-Coil Assemblies
  - Designs with Yoke Support

Axial Component of Lorentz Forces

- As we have seen, the axial component of the Lorentz force tends to stretch the coil outwardly.



(After M.N. Wilson)

Contents

- **End Support**
  - Axial Component of Lorentz Force
  - **Designs with Self-Supported Collared-Coil Assemblies**
  - Designs with Yoke Support

Designs with Self-Supported Collared-Coil Assembly

- In magnet designs where the yoke is not needed to support the collared-coil assembly, a clearance can be left between the two.
- Then, if the axial stresses resulting from the Lorentz force do not exceed the yield stress of the coil, it is possible to let the collared-coil assembly expand freely within the iron yoke.

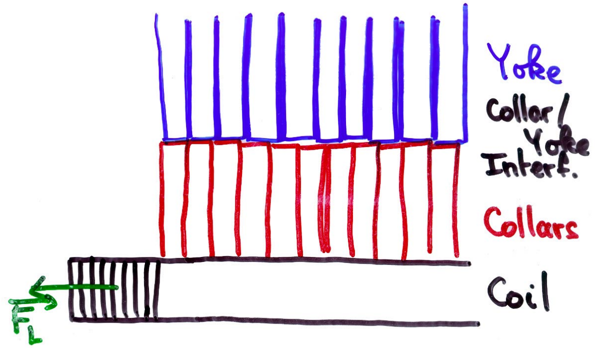
Examples: HERA and LHC arc quadrupole magnet designs developed at CEA/Saclay.

Contents

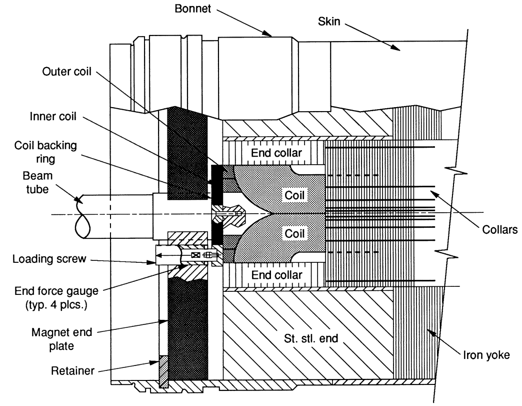
- **End Support**
  - Axial Component of Lorentz Force
  - Designs with Self-Supported Collared-Coil Assemblies
  - **Designs with Yoke Support**

Designs with Yoke Support (1/2)

- In magnets where there is contact between collar and yoke, it is imperative to prevent stick/slip motions of the collar laminations against the yoke laminations, for this can cause a ratcheting of the collared-coil assembly within the iron yoke.



Designs with Yoke Support (2/2)



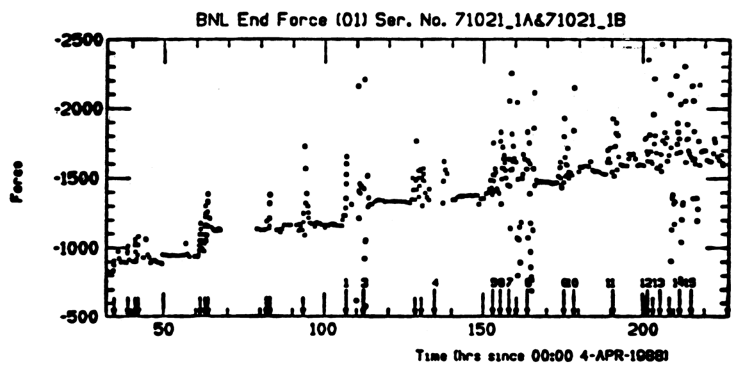
SSC/BNL dipole magnet end design with stiff end plates

- Then, a stiff support must be provided against the axial component of the Lorentz force.

Examples: the ends of SSC and LHC magnets are contained by thick end plates welded to the outer shell.

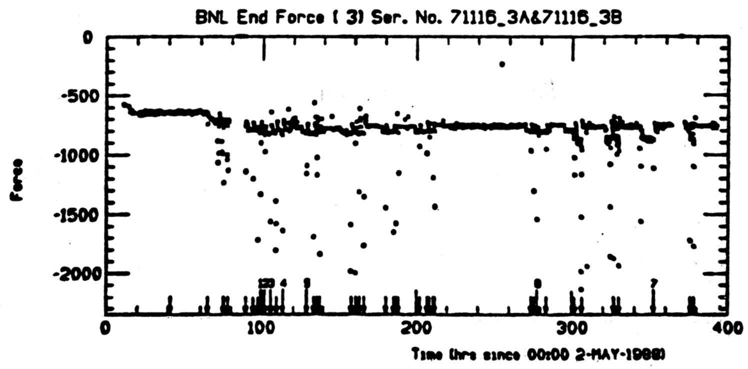
Evidences of Ratcheting (1/3)

- 4-cm-aperture, 17-m-long SSC dipole magnet prototype DD0010 had an ill defined collar/yoke interface and thin (3/4"-thick), split end plates.
- Transducers measuring the axial forces exerted by the coils against the end plates revealed a progressive built up during energization.



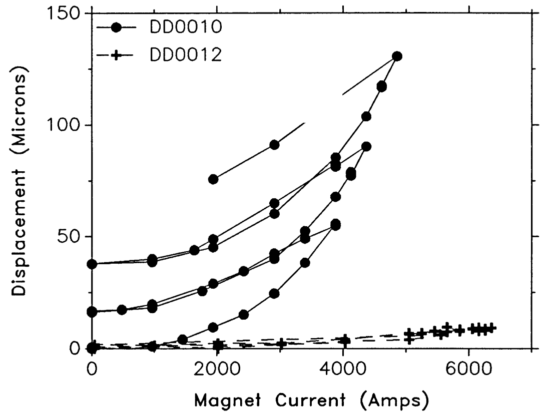
Evidences of Ratcheting (2/3)

- In comparison, 4-cm-aperture, 17-m-long SSC dipole magnet prototype DD0012 had a good clamping of the collared-coil assembly by the iron yoke and thick (1.5"), single-piece end plates.
- The axial forces exerted by the coils against the end plates appeared to remain roughly constant throughout energization test.



Evidences of Ratcheting (3/3)

- The previous measurements were confirmed by displacement transducers mounted on the end plates.

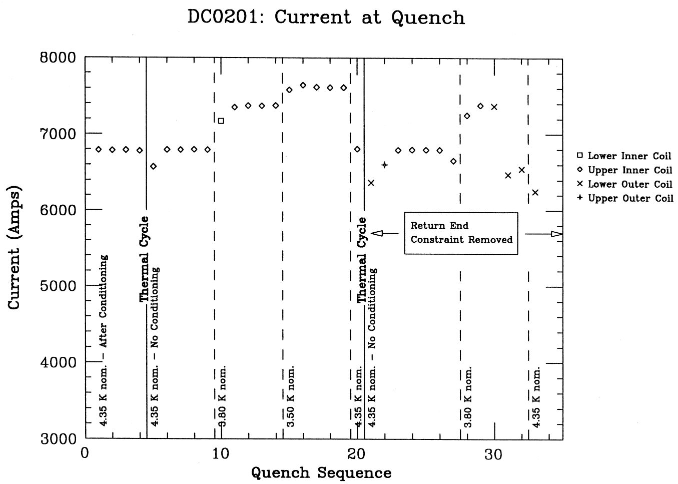


(Courtesy J.B. Strait)

Other Evidences of the Need of Axial Support (1/2)

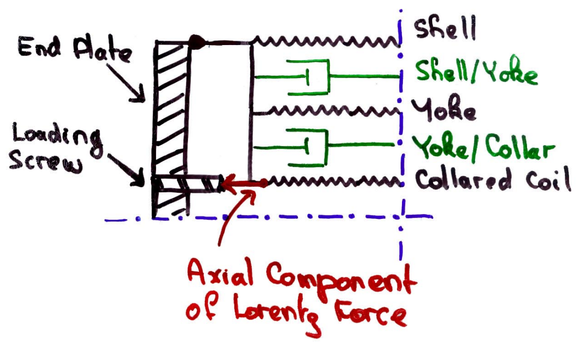
- Further evidences of the need of axial support are provided by 4-cm-aperture, 17-m-long SSC dipole magnet prototype DC0201, which was first assembled with end constraints and exhibited good quench performance.
- Then, the constraint was removed at one end, and, upon retesting, the quench performance appeared seriously degraded (with most of the training quenches originating in the outer coils).

Other Evidences of the Need of Axial Support (2/2)



Model of Axial Mechanics (1/2)

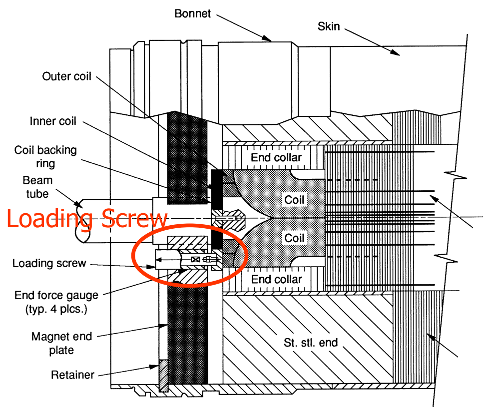
- The axial component of the Lorentz force pulls on coil ends and pushes against coil end spacers and end plates.
- Furthermore, part of this force is shared by friction between the collared-coil assembly, the yoke and the outer shell.



Model of Axial Mechanics (2/2)

- As a result, only a fraction of the electromagnetic force is transferred to the end plates.
- This fraction depends on
  - the rigidity of coil ends,
  - the clamping of the collared-coil assembly by the yoke.

Axial Preloading (1/2)



SSC/BNL dipole magnet
end design
with stiff end plates

- The rigidity of coil ends depends on their compaction.
- To increase compaction and eliminate slacks between conductors and/or conductors and end spacers, the coil ends are usually pre-loaded at room temperature by means of screws mounted in the end plates.

Axial Preloading (2/2)

- The room-temperature axial pre-loading can also compensate for thermal shrinkage differentials between collared-coil assembly, yoke and shell, and prevent the occurrence of gaps between coil ends and end plates during cooldown.
- Let us note however that, unlike the azimuthal pre-compression, which is applied in the same direction as the azimuthal component of the Lorentz force, the axial pre-load is applied in opposite direction to the axial component of the Lorentz force, which is less favorable.

Axial Pre-Tensioning

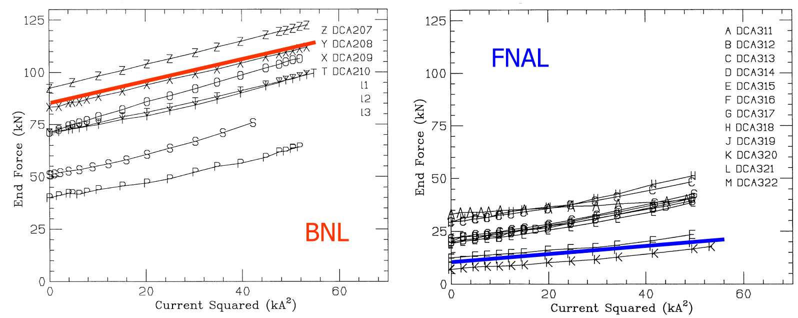
- Some authors have tried to devise ways of pre-tensioning coil ends at room temperature, but this brings quite a bit of complication and requires additional features.

SSC End Force Data (1/3)

- As we have seen, the SSC/FNAL mechanical design ensures a tighter clamping of the collared-coil assembly by the yoke than the SSC/BNL design, resulting in a better sharing of the axial component of the Lorentz force, and a lowering of the fraction that is directly transmitted to the end plate.
- Furthermore, the coil ends of SSC/FNAL magnets were preloaded axially at a lower level than the coil ends of SSC/BNL magnets, resulting in less compaction and rigidity.
- These two facts concur in reducing the apparent loading rate of magnet end plates under the effect if the axial component of the Lorentz force.

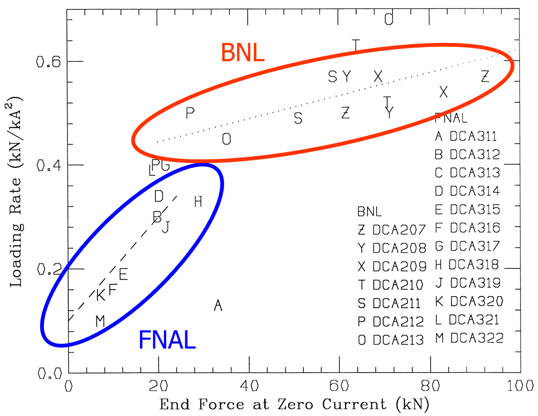
SSC End Force Data (2/3)

- These expectations were confirmed by data from force transducers mounted in coil-end loading screws.



Measured Force Exerted by Coil Against End Plates (Courtesy T. Ogitsu)

SSC End Force Data (3/3)



Initial Rate of End Plate Loading (Courtesy T. Ogitsu)

Contents

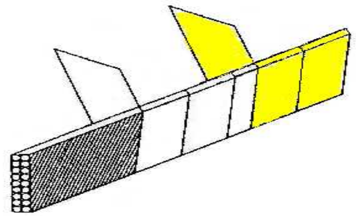
- Support Against Lorentz Force
- Azimuthal Pre-Compression
- Radial Support
- End Support
- **Manufacturing of NbTi Magnets**
- Tentative Summary

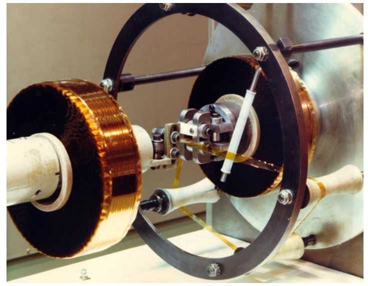
Manufacturing Procedure

- The main steps of NbTi magnet manufacturing are
  - cable wrapping,
  - coil winding,
  - coil curing,
  - azimuthal coil size measurements,
  - coil assembly,
  - collaring,
  - yoking,
  - shell welding or inertia tube insertion,
  - coldmass completion.
- "Warm" magnetic measurements can be performed after collaring and cold mass completion to check field quality.

Cable Wrapping

- NbTi cables are usually wrapped with several layers of polyimide tapes, such as Kapton, Apical or Upilex.



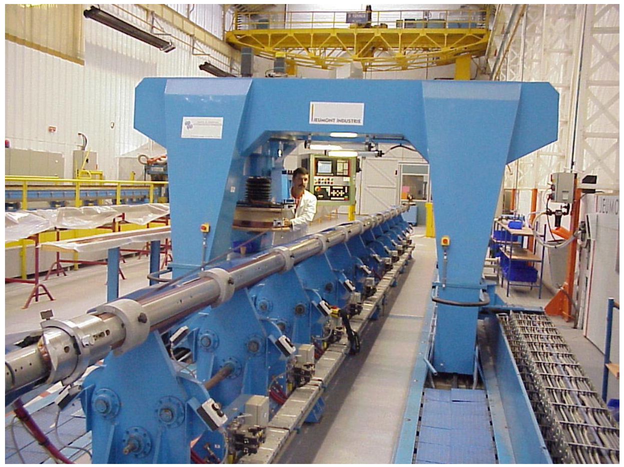


- The outer tape is coated with a polyimide-adhesive on its outer surface, which softens when heated to temperatures in the 150-to-200 °C range.

Winding (1/3)

Rotating winding machine for 3-m-long
LHC arc quadrupole magnet coils at CEA/Saclay

Winding (2/3)

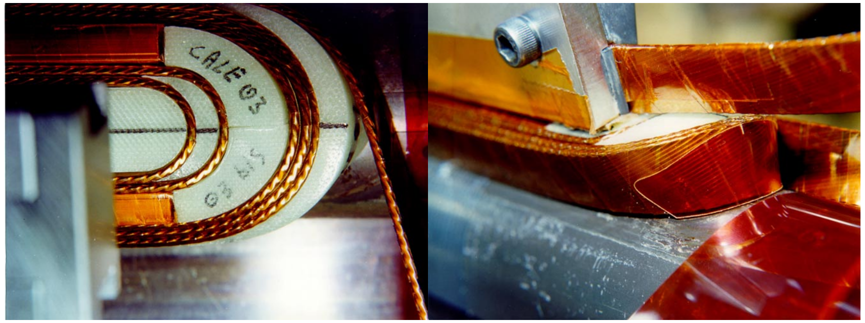


Crane-type winding machine for 14-m-long
LHC arc dipole magnet coils at Jeumont Industries

Winding (3/3)

Shuttle-type winding machine
for 15-m-long SSC dipole magnet coils at BNL
(now dismantled)

Coil End Winding

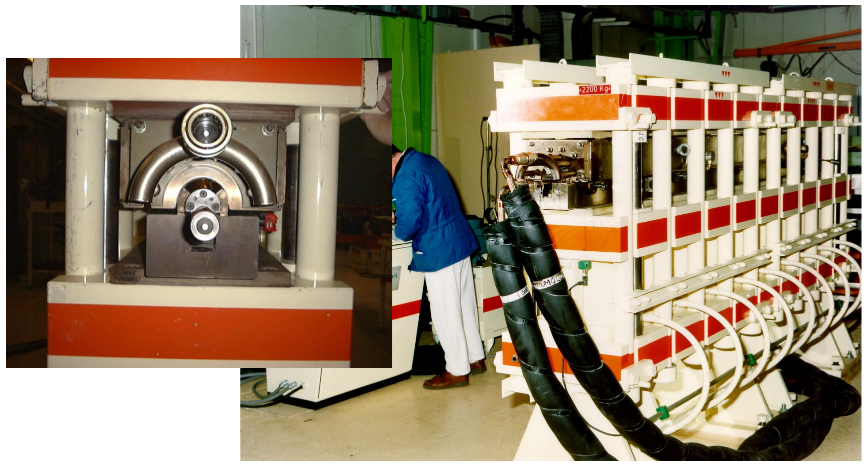


Winding of LHC arc quadrupole magnet coil ends
at CEA/Saclay

Curing (1/2)

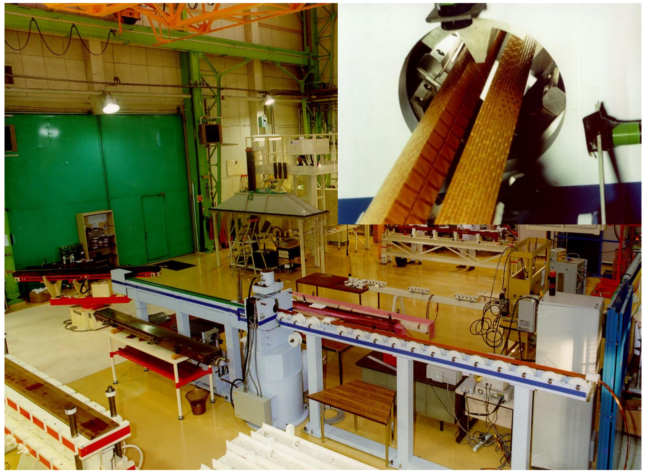
- Upon winding completion, the coils are transferred into a mold of very accurate dimensions and cured into a rigid shape.
- The curing operation is instrumental in determining coil geometry.

Curing (2/2)



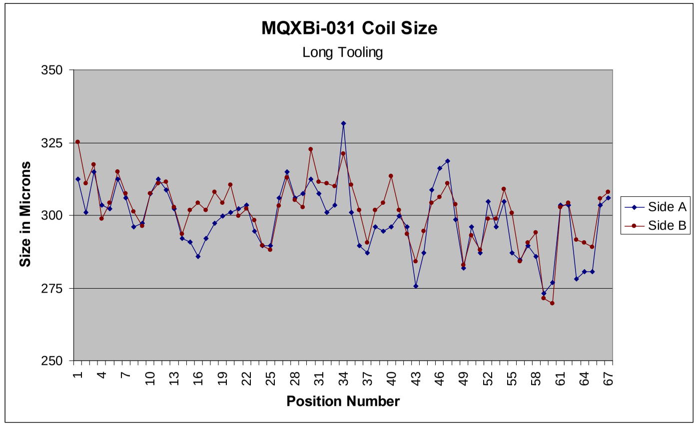
Curing press for 3-m-long LHC arc
quadrupole magnet coils at CEA/Saclay

Coil Size Measurements (1/3)



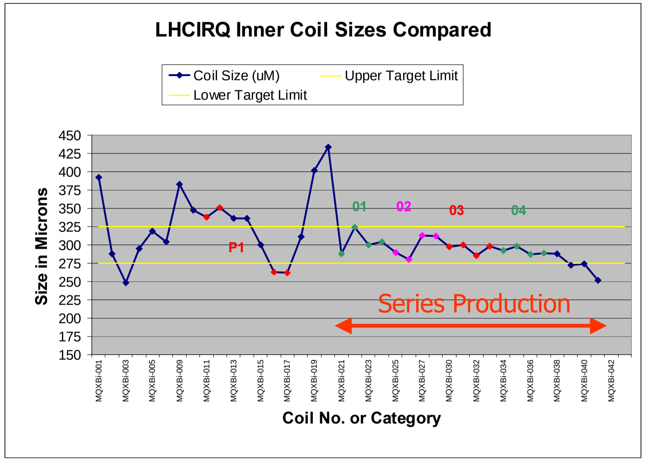
Azimuthal coil size measuring machine for 3-m-long LHC arc quadrupole magnet coils at CEA/Saclay

Coil Size Measurements (2/3)



Azimuthal size variations measured along the axis of a 5.5-m-long LHC/IR quadrupole magnet coil at FNAL (Courtesy R. Bossert)

Coil Size Measurements (3/3)



Average azimuthal sizes as a function of production sequence for LHC/IR quadrupole magnet coils at FNAL (Courtesy R. Bossert)

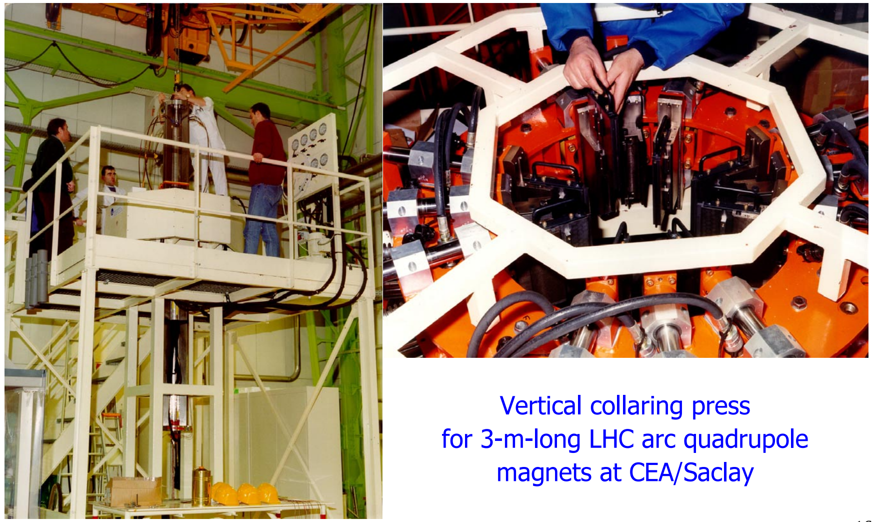
Coil Assembly

Assembly of 14-m-long LHC arc dipole magnet coils at Alstom/MSA

Horizontal Collaring

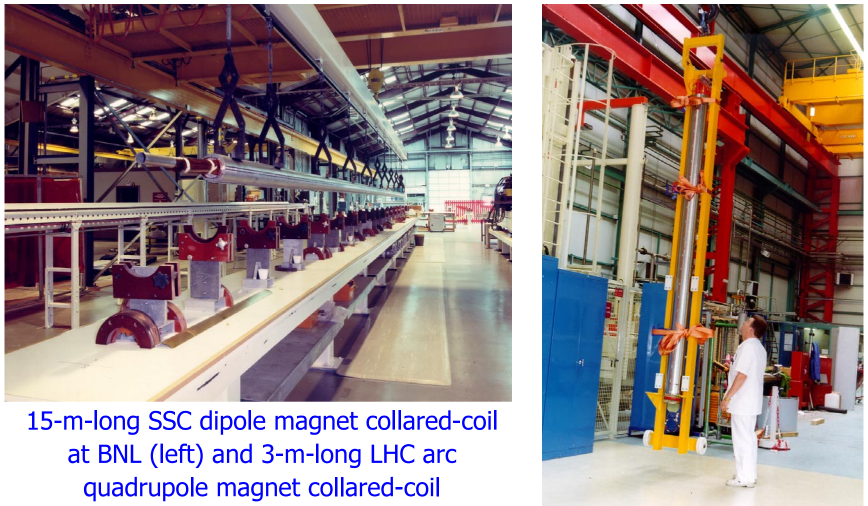
20 MN/m collaring press for 14-m-long, twin-aperture LHC arc dipole magnets at Alstom/MSA

Vertical Collaring



Vertical collaring press for 3-m-long LHC arc quadrupole magnets at CEA/Saclay

Collared-Coil Assembly Handling

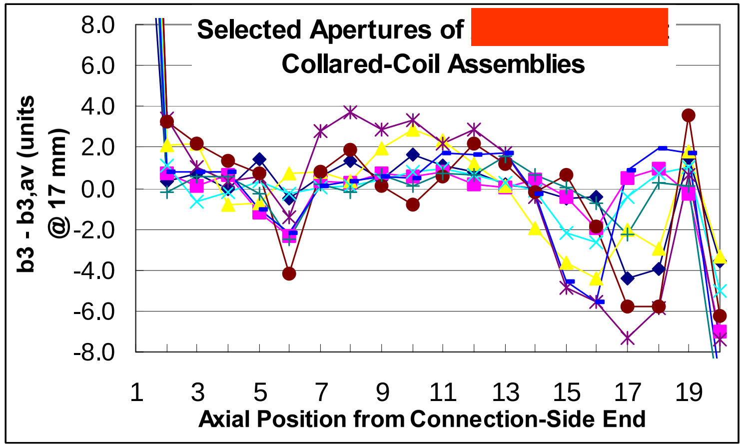


15-m-long SSC dipole magnet collared-coil at BNL (left) and 3-m-long LHC arc quadrupole magnet collared-coil at CEA/Saclay (right)

Magnetic Measurement (1/3)

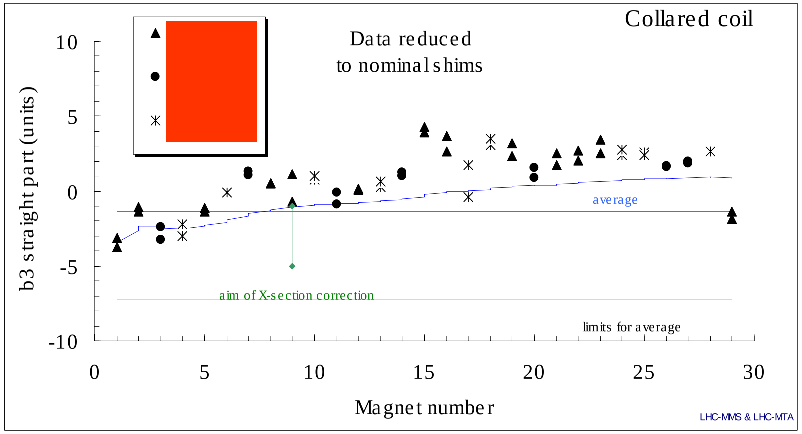
Warm magnetic measurement on collared-coil assembly of LHC arc dipole magnet at Alstom/MSA

Magnetic Measurement (2/3)



Axial variations of normal sextupole field coefficient measured along the axis of selected apertures of LHC dipole magnet collared-coil assemblies

Magnetic Measurement (3/3)

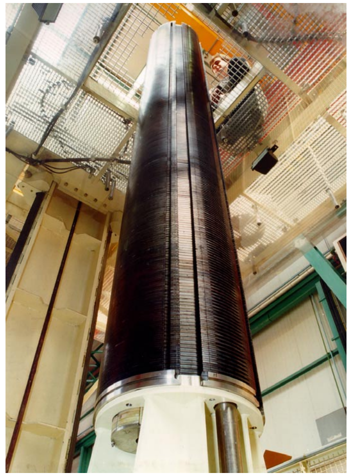


Average normal sextupole field coefficient (over straight part) as a function of production sequence measured on LHC dipole magnet collared-coil assemblies (Courtesy E. Todesco)

Yoking (1/2)

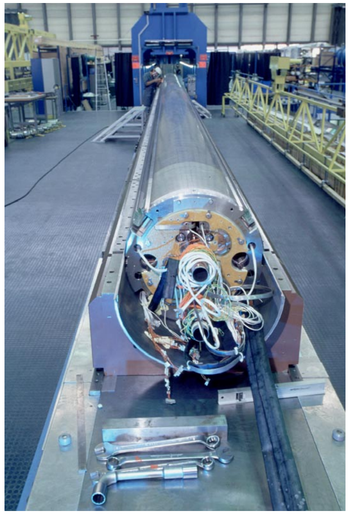
Yoking of 15-m-long, single-aperture SSC dipole magnet at BNL

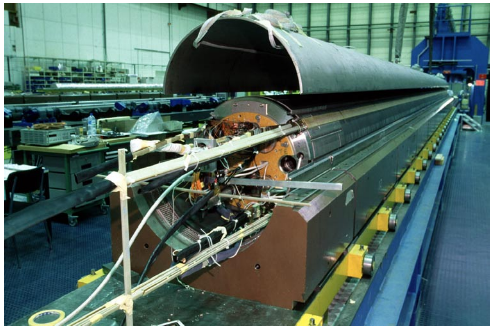
Yoking (2/2)



Vertical yoking of 3-m-long, twin-aperture LHC arc quadrupole magnet at CEA/Saclay

Shell Welding (1/3)



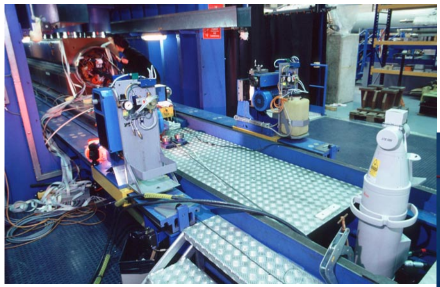


Shell-welding preparation
for 14-m-long, twin-aperture
LHC arc dipole magnet at CERN

Shell Welding (2/3)

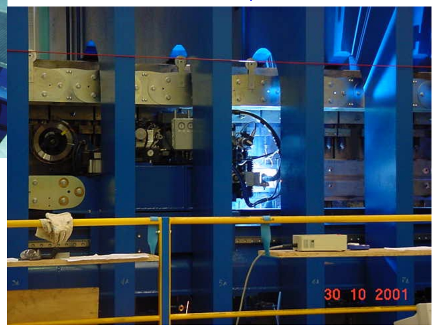
12 MN/m shell-welding press for 14-m-long, twin-aperture, LHC arc dipole magnets at Alstom/MSA

Shell Welding (3/3)



Welding heads for 14-m-long, twin-aperture LHC arc dipole magnets at CERN

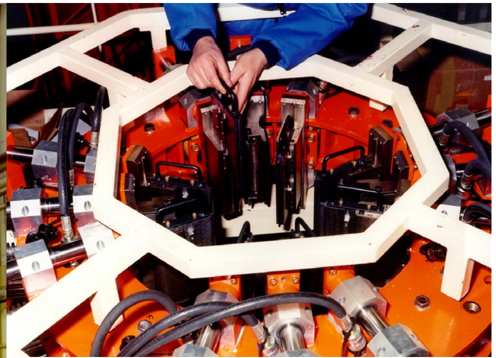
Ongoing shell welding at Alstom/MSA



Collaring (1/2)

Collaring press for twin-aperture, 15-m-long
LHC arc dipole magnets at Alstom/MSA

Collaring (2/2)



Vertical collaring press
for 3-m-long LHC arc quadrupole
magnets at CEA/Saclay

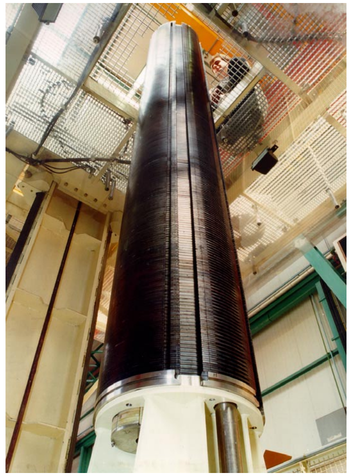
Yoking (1/3)

Handling of collared-coil assembly in
preparation for yoking: SSC at BNL (left)
and LHC at CEA/Saclay (right)

Yoking (2/3)

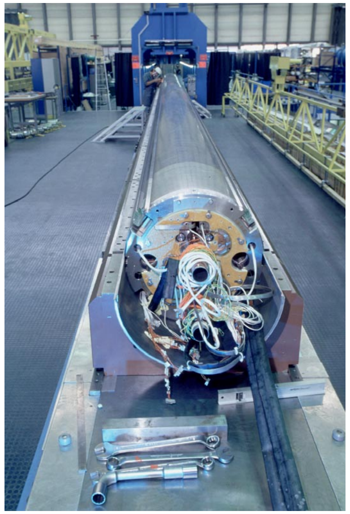
Yoking of single-aperture, 15-m-long
SSC dipole magnet at BNL

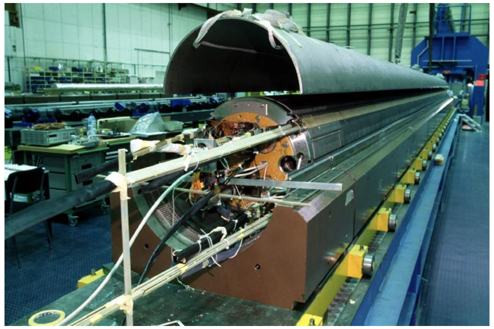
Yoking (3/3)



Vertical yoking of twin-aperture, 3-m-long
LHC arc quadrupole magnet at CEA/Saclay

Shell Welding (1/3)



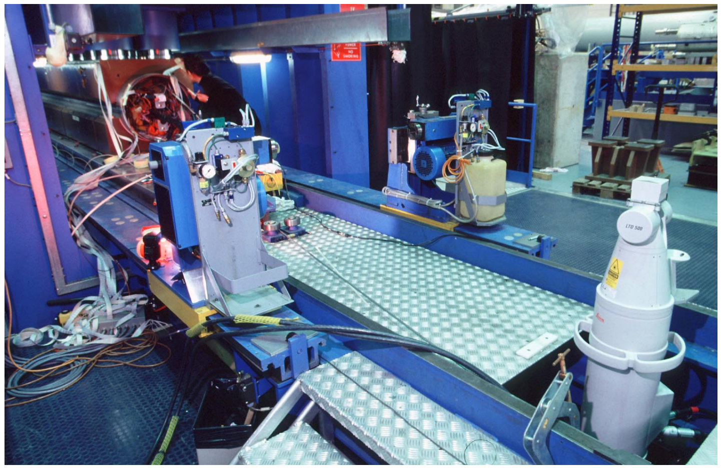


Shell-welding preparation
for twin-aperture, 15-m-long
LHC arc dipole magnet at CERN

Shell Welding (2/3)

Shell-welding press for twin-aperture, 15-m-long
LHC arc dipole magnets at Alstom/MSA

Shell Welding (3/3)

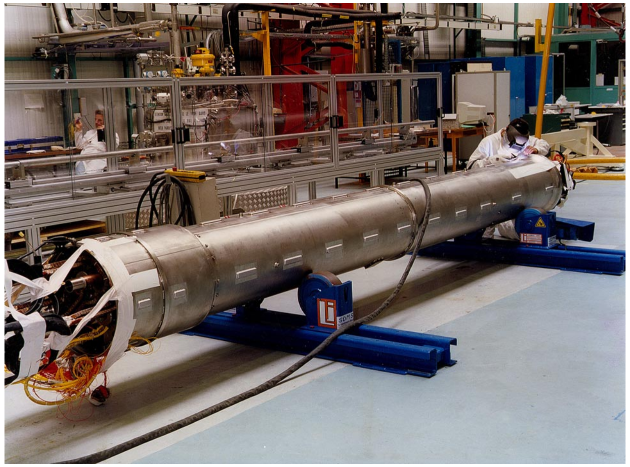


Shell-welding equipment for twin-aperture, 15-m-long
LHC arc dipole magnets at CERN

Inertia Tube Insertion

Insertion of inertia tube
on twin-aperture, 3-m-long
LHC arc quadrupole magnet
at CEA/Saclay

Cold Mass Completion



Welding of end domes on twin-aperture, 3-m-long LHC arc quadrupole magnet at CEA/Saclay

Contents

- Support Against Lorentz Force
- Azimuthal Pre-Compression
- Radial Support
- End Support
- Manufacturing of NbTi Magnets
- **Tentative Summary**

Tentative Summary (1/4)

- The author firmly believes that the Art of making a magnet can be turned into a Science.
- This requires to forsake old beliefs and religious dogmas and to privilege scientific rigor and Cartesian thinking.
- As is usually the case in Engineering, there can be more than one solution, with different pros and cons.
- The most important is to ensure that, whichever options are chosen, they lead to a consistent design that addresses suitably all aspects of the problem.

Tentative Summary (2/4)

- The design parameters must be optimized by thorough numerical analyses that simulate all loading conditions encountered during assembly, cooldown and energization.
- The simulation results must be validated on mock-ups and magnet models or prototypes.
- The mock-ups, models and prototypes must be fully instrumented to develop a good understanding of mechanical behavior and assess design sensitivity to relevant parameters.