ACADEMIC TRAINING

Technology and applications of high field accelerator magnets

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Lesson 2:

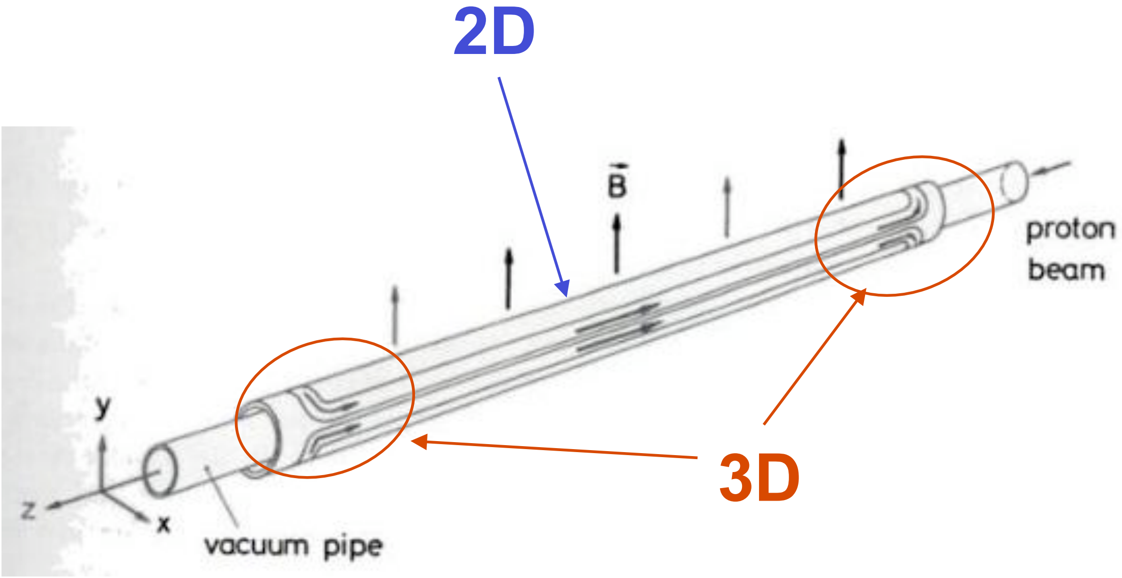
- Magnetic design
- Mechanical design

CERN June 2-6, 2008

Outline

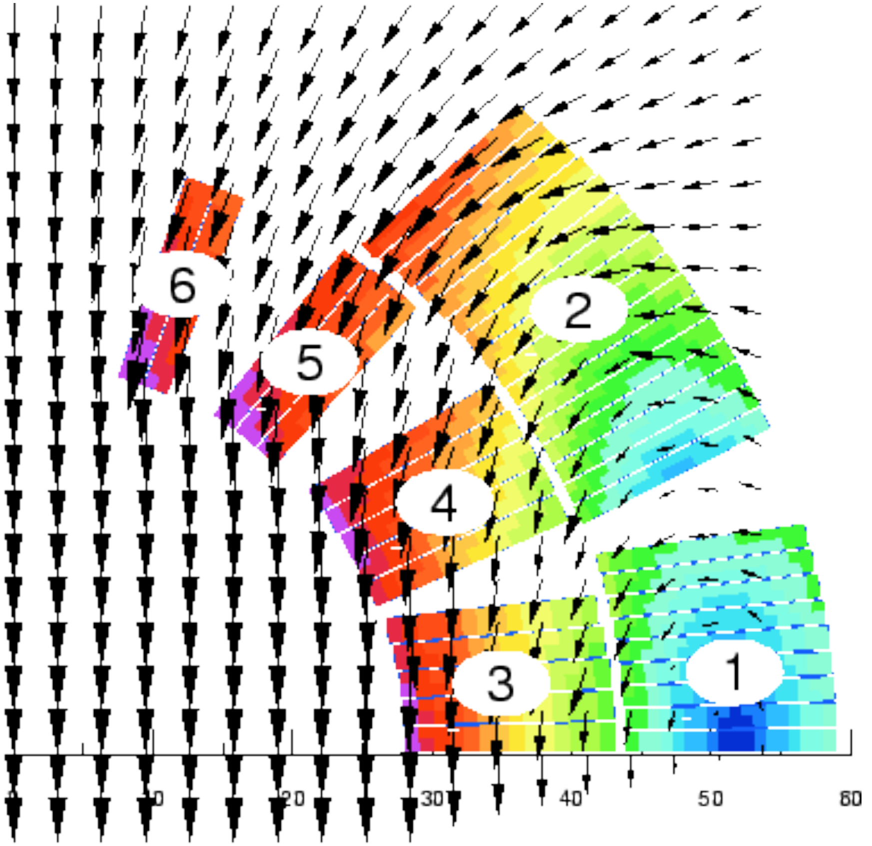
- Magnetic design
  - Analytical tools
  - Iron saturation
  - Conductor magnetization
  - Scaling laws
- Mechanical design
  - Magnetic forces and pre-stress
  - Case study: High gradient, large aperture quadrupole
  - FEM analysis steps
- Exploring the “limits” of a new technology
  - Case study: LARP Magnets R&D

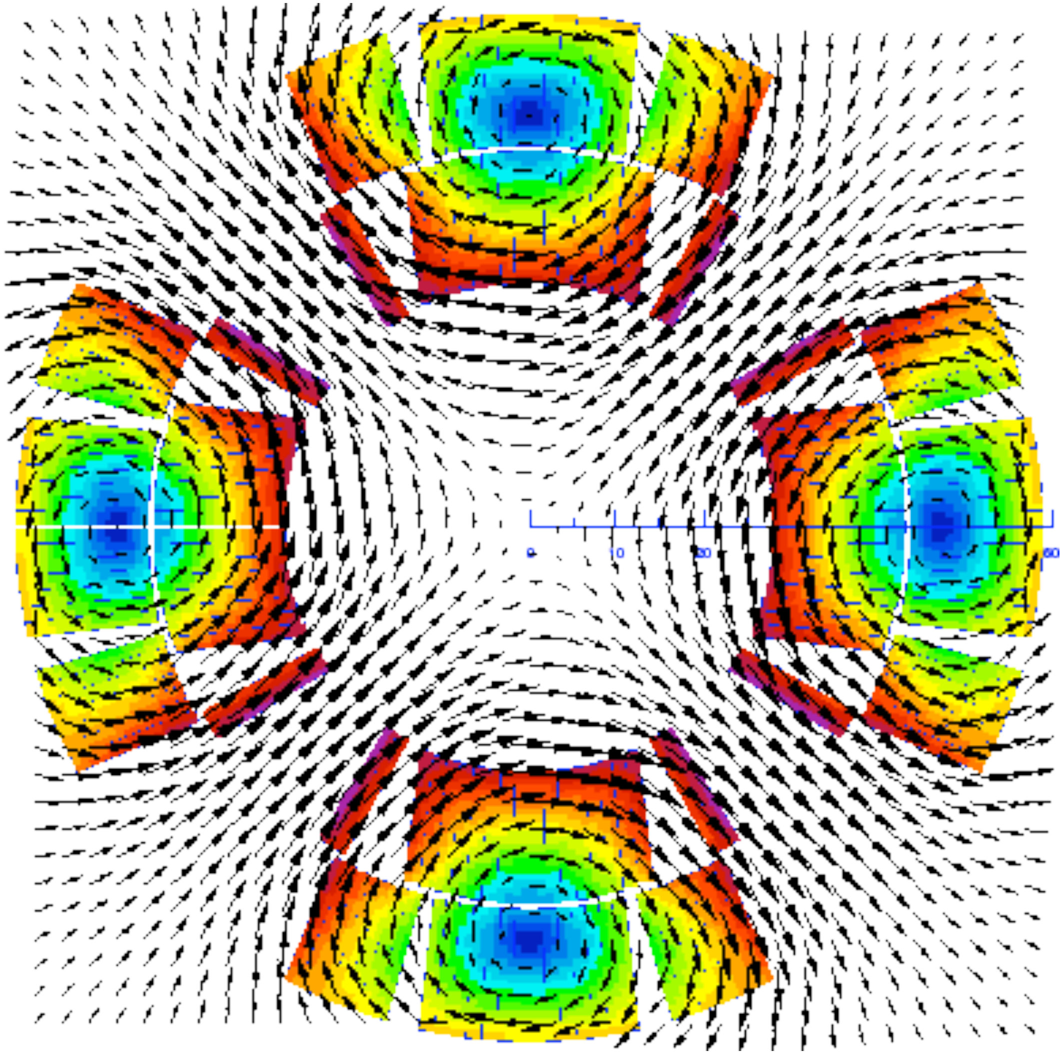
Magnetic design



Examples

- Dipole field:
  - Bend the beam
- Quadrupole field:
  - Focus the beam





LHC main dipole and main quadrupole fields

Goals

A random distribution of longitudinal conductors around a beam pipe generates all multipoles (dipole, quadrupole, sextupole, …) in all orientations (normal and skew).

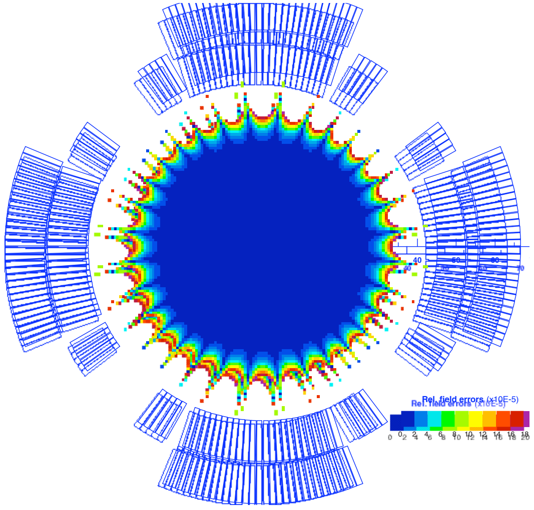
- Multipole expansion: $B_y(x,y) + iB_x(x,y) = 10^{-4} \times B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1}$
- See references in lesson 1

The goals of the magnetic design are:

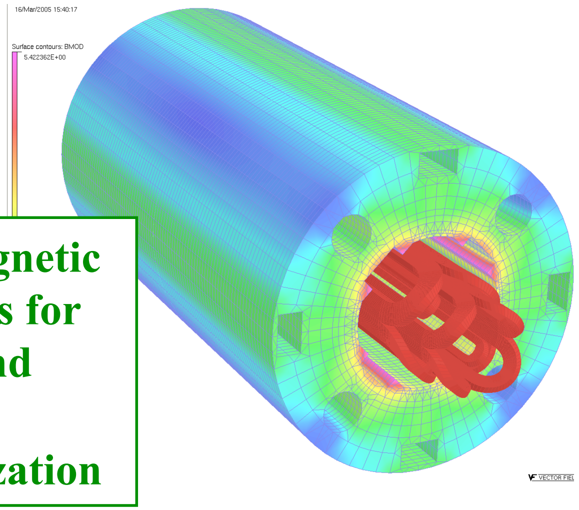
- To generate “mostly” the required field component
  - Unless you are designing a combined-function magnet
- To have powerful magnets
  - Energy and luminosity depends on main dipoles and IR quadrupoles
- To allow sufficient margin for operation

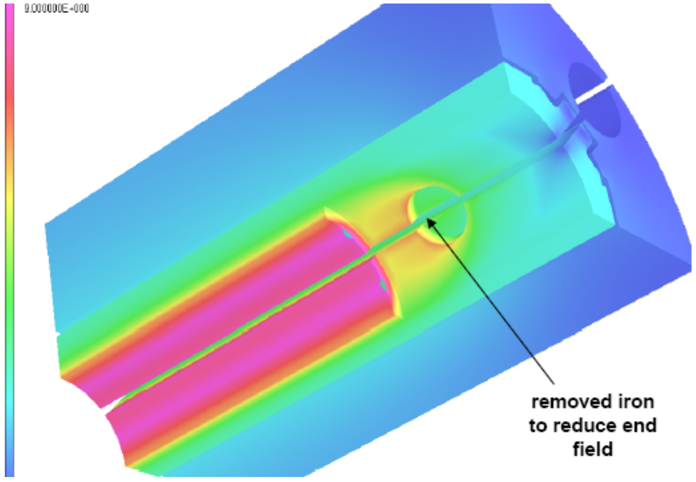
Tools

- Great tools for magnetic design are available
  - ROXIE, Vector Fields codes (OPERA, TOSCA), ANSYS …
  - 2D and 3D analysis with iron saturation, conductor magnetization, eddy currents, ..



3D magnetic analysis for ends and yoke optimization

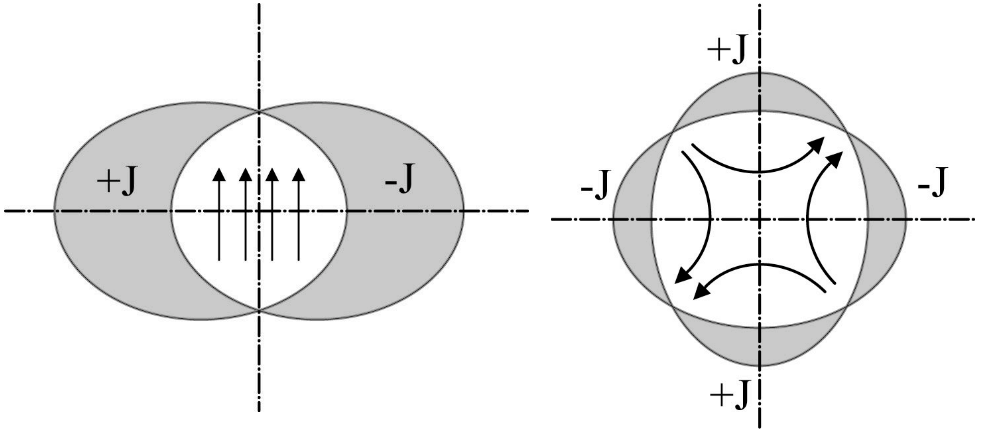




- But you should better know **where to go** before starting!

Analytical tools

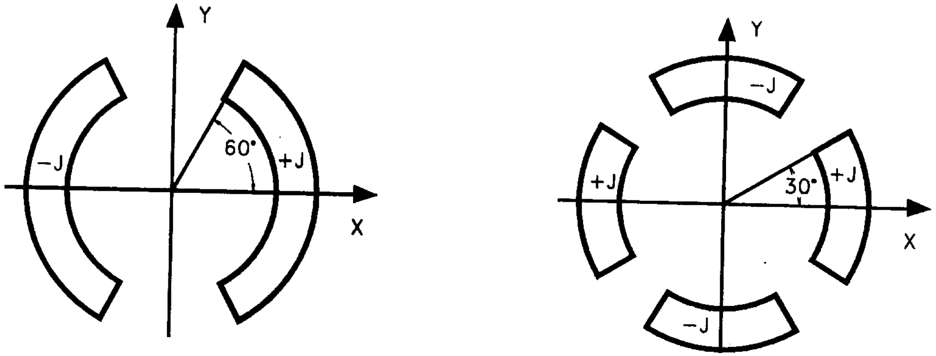
- A cos(nθ) current distribution over a cylindrical surface gives an ideal 2n-pole field
  - cos(θ) ➔ dipole; cos(2θ) ➔ quadrupole
- A constant current in a coil configuration generated by two intersecting ellipses produces the perfect dipole or quadrupole fields
  - at 180° ➔ dipole
  - at 90° ➔ quadrupole



Cables

- In a real superconducting magnet cross section there are cables
- Analytical tools for 2D:
  - Each strand is simulated as a current line
    ➔ Biot-Savart law
  - Uniform current density distribution in simple geometries (sectors) ➔ Analytical expressions

Sector coils with uniform current density
Angles chose to set to zero the first
higher order harmonic

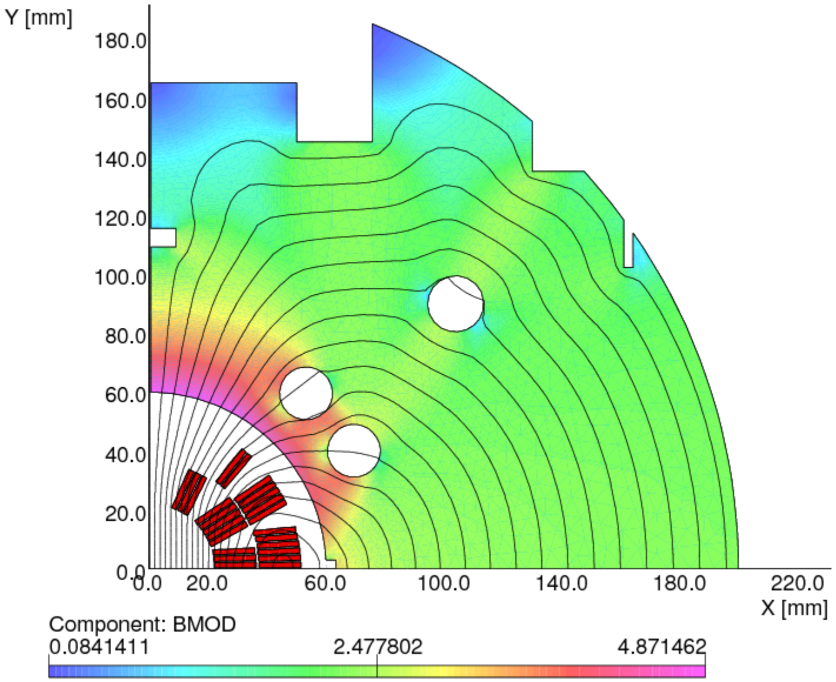


Iron Yoke - I

- An iron yoke is needed to:
  - Increase the field & contain the flux return
- But the iron magnetization decreases with applied field (saturation at ~ 2T)
  - ➔ non-linear effects (and analysis)
- Analytical tools:
  - Perfect iron ring with infinite permeability (mirror)
  - Perfect iron ring with finite permeability and infinite thickness

Iron Yoke - II

- With Finite Element Analysis (FEM) tools the real geometry and iron properties can be simulated
  - Optimization of dimensions and shape
  - Addition of holes to optimize field quality



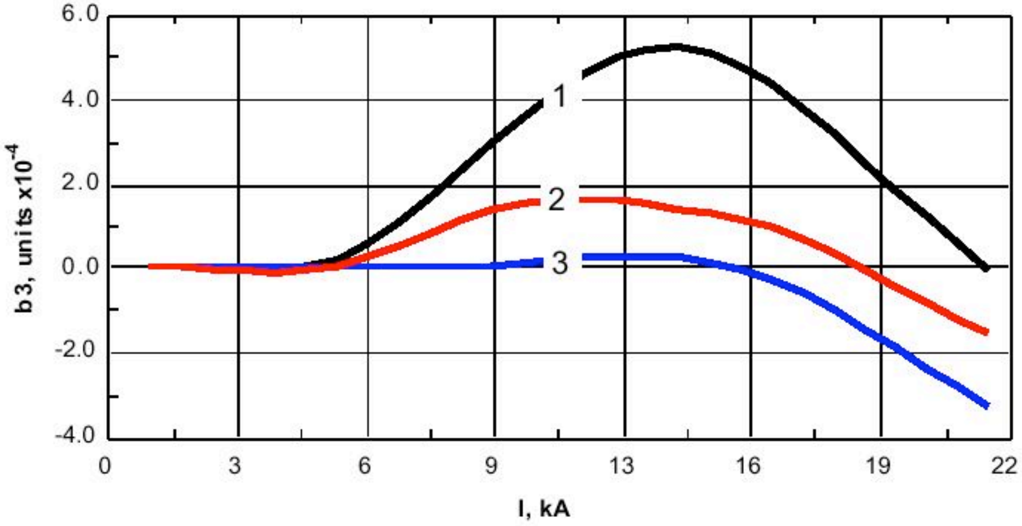


Figure 8: Sextupole change with magnet current: 1 – no holes; 2 – two holes; 3 – one hole.

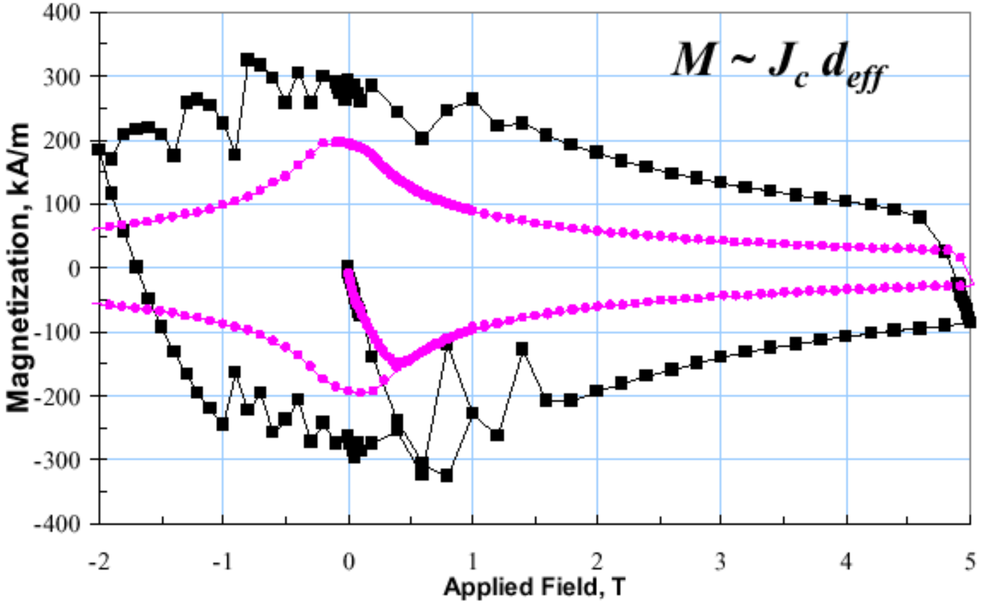
G. Ambrosio, et al., "*Magnetic Design of the Fermilab 11 T Nb3Sn Short Dipole Model*" IEEE Trans. on Appl. Superc., v. 10, No. 1, March 2000, pp.322-325.

Conductor Magnetization - I

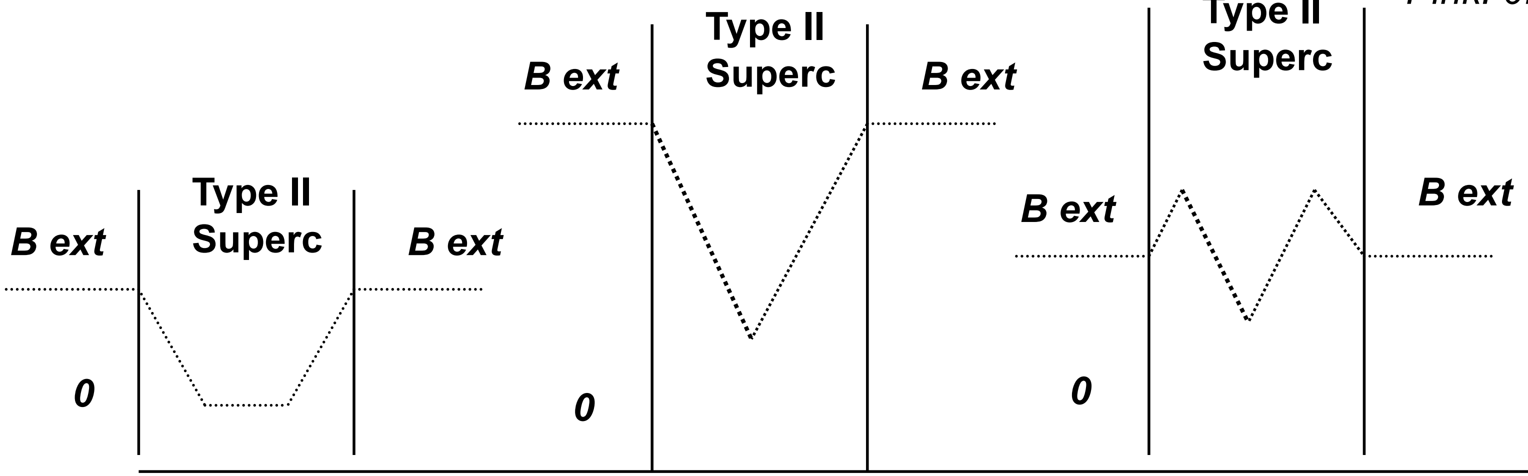
- Conductors for high field magnets have large magnetization

  Because of high critical current & large effective filament size

  ➔ non-linear effects

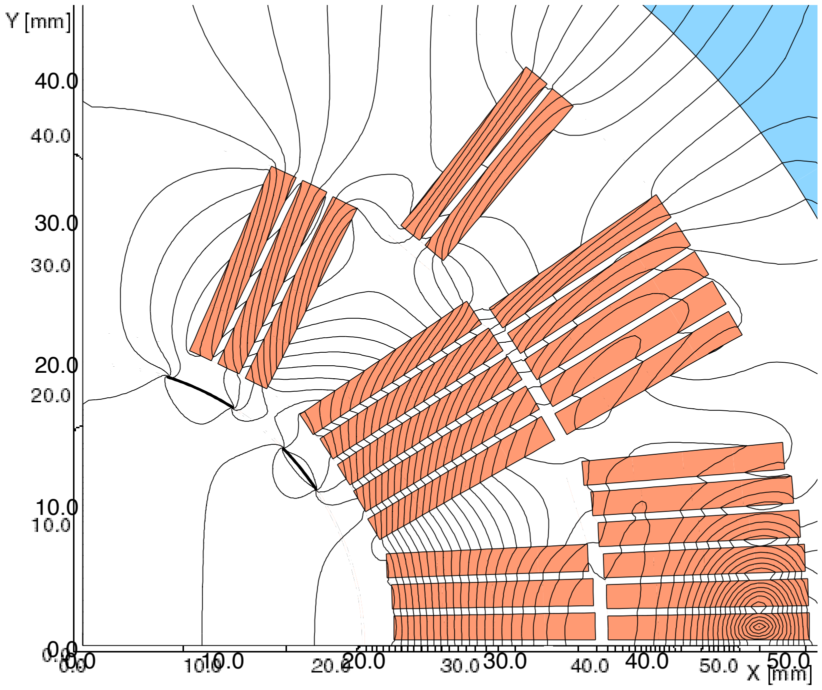


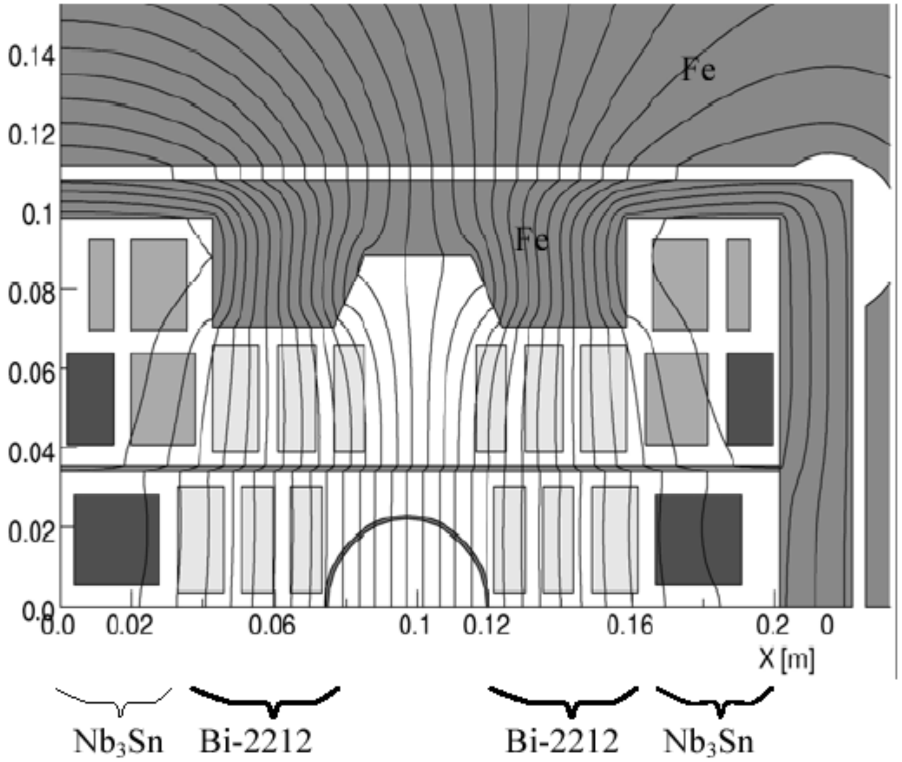
Black: 0.7 mm RRP 54 sb 70μm
Pink: 0.8 mm PIT 288 sb 32 μm
Courtesy A. Ghosh



Conductor Magnetization - II

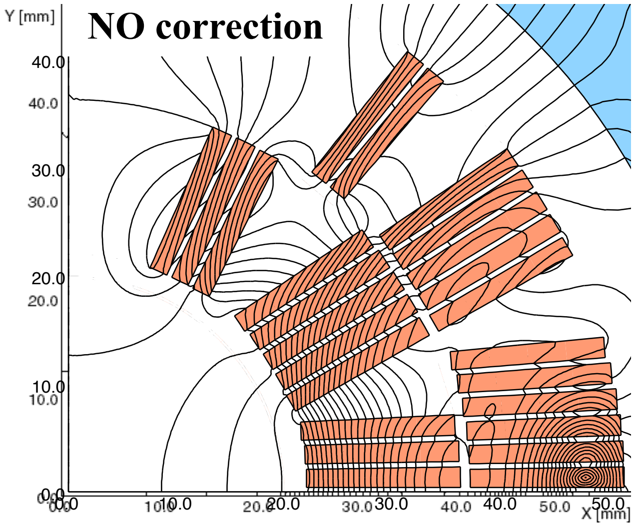
- Techniques to compensate/correct this problem
  - Iron strips (cos θ coils)
  - Iron plate (block type coils)

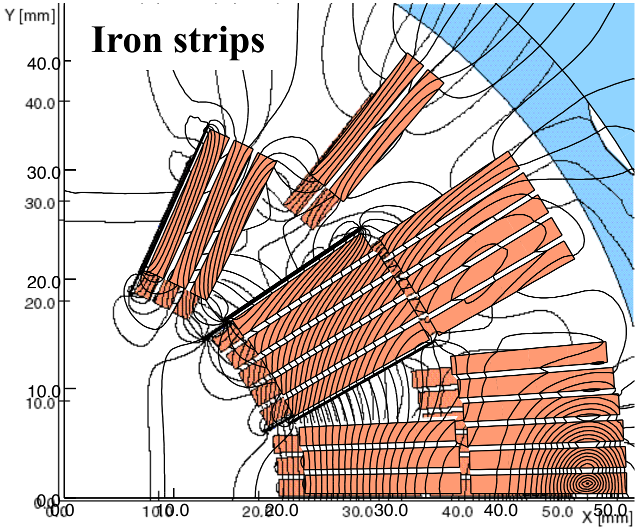




- E. Barzi, et al., *"Passive Correction of the Persistent Current Effect in Nb3Sn Accelerator Magnets"*, IEEE Trans. on Appl. Superc., Vol. 13, No. 2, June 2003, pp.1270-1273.
- P McIntyre, A. Sattarov, *"HYBRID DIPOLES FOR FUTURE HADRON COLLIDERS"* available at care-hhh.web.cern.ch

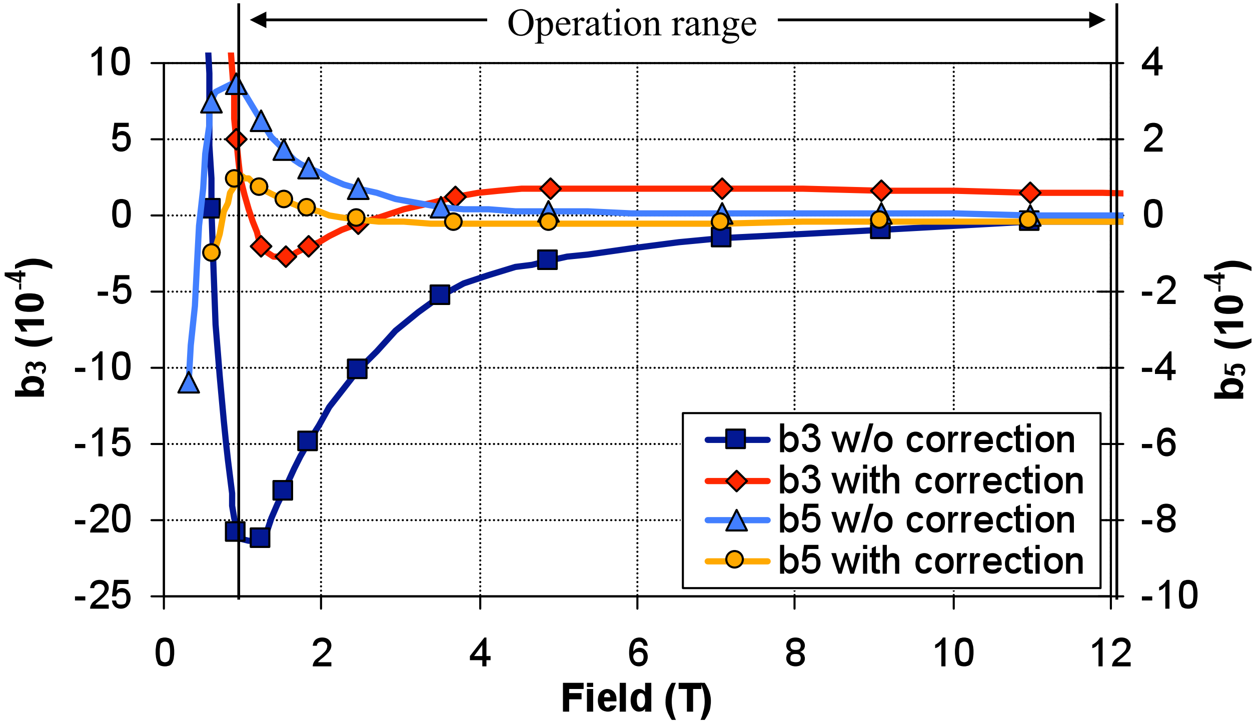
Conductor Magnetization - III





Example: correction with iron strips

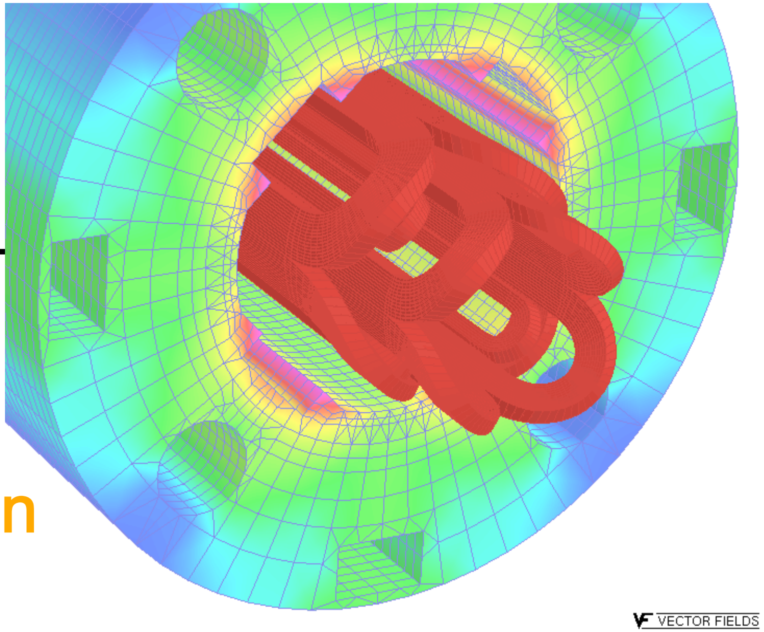
Magnetization flux in dipole magnet (no transport current nor iron yoke magnetization). Flux increment between adjacent lines is kept constant and equal to 5x10^{-5} Wb/m in both plots.

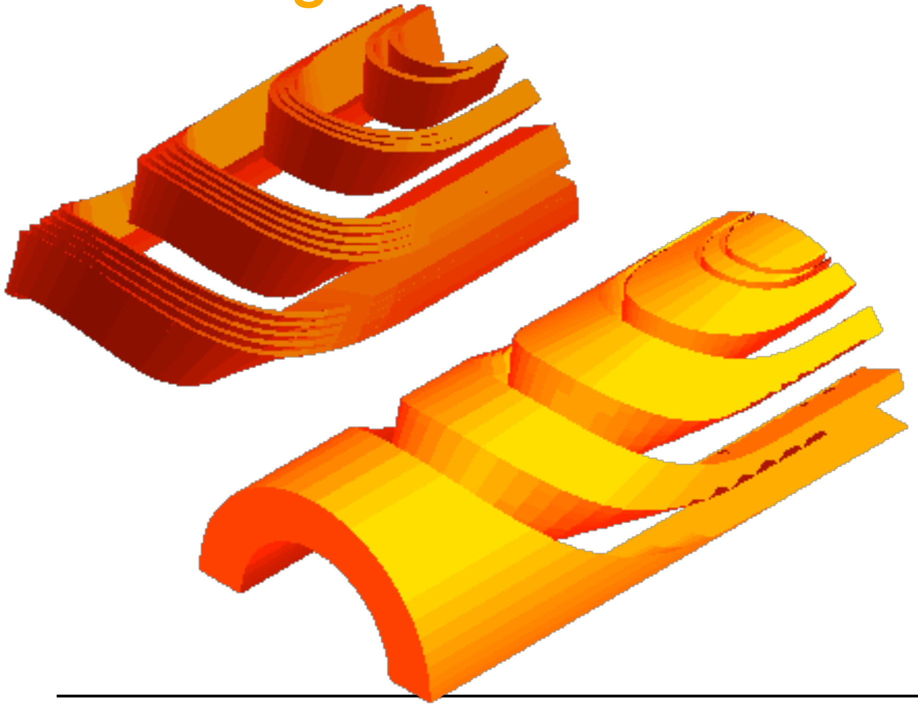


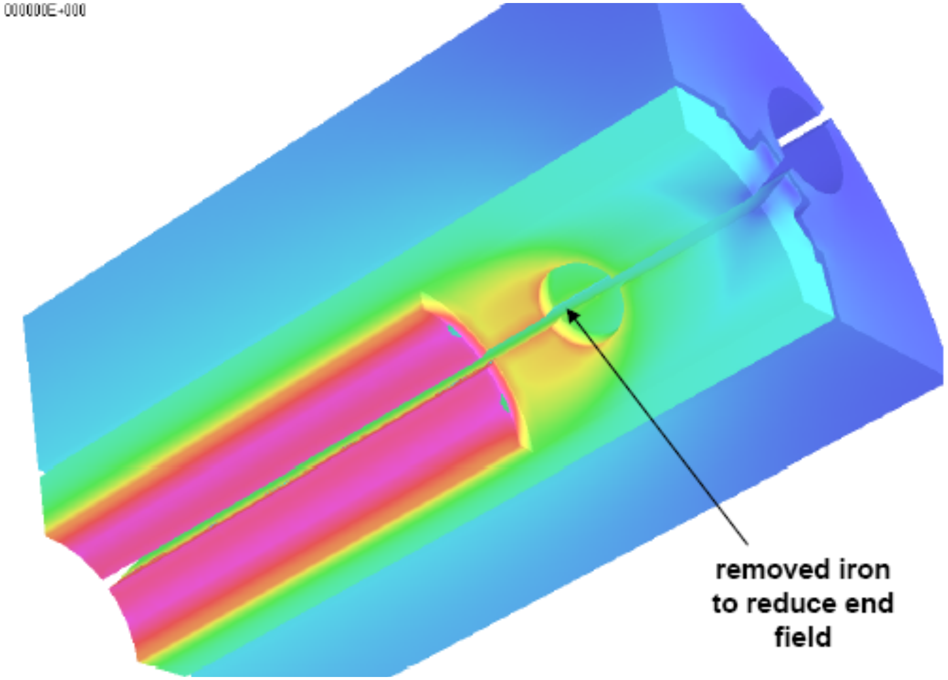
Multipoles in dipole magnet before and after correction

Ends

- Need FEM optimization for:
  - Field quality
  - Keep max field in the straight section (iron)
  - Winding



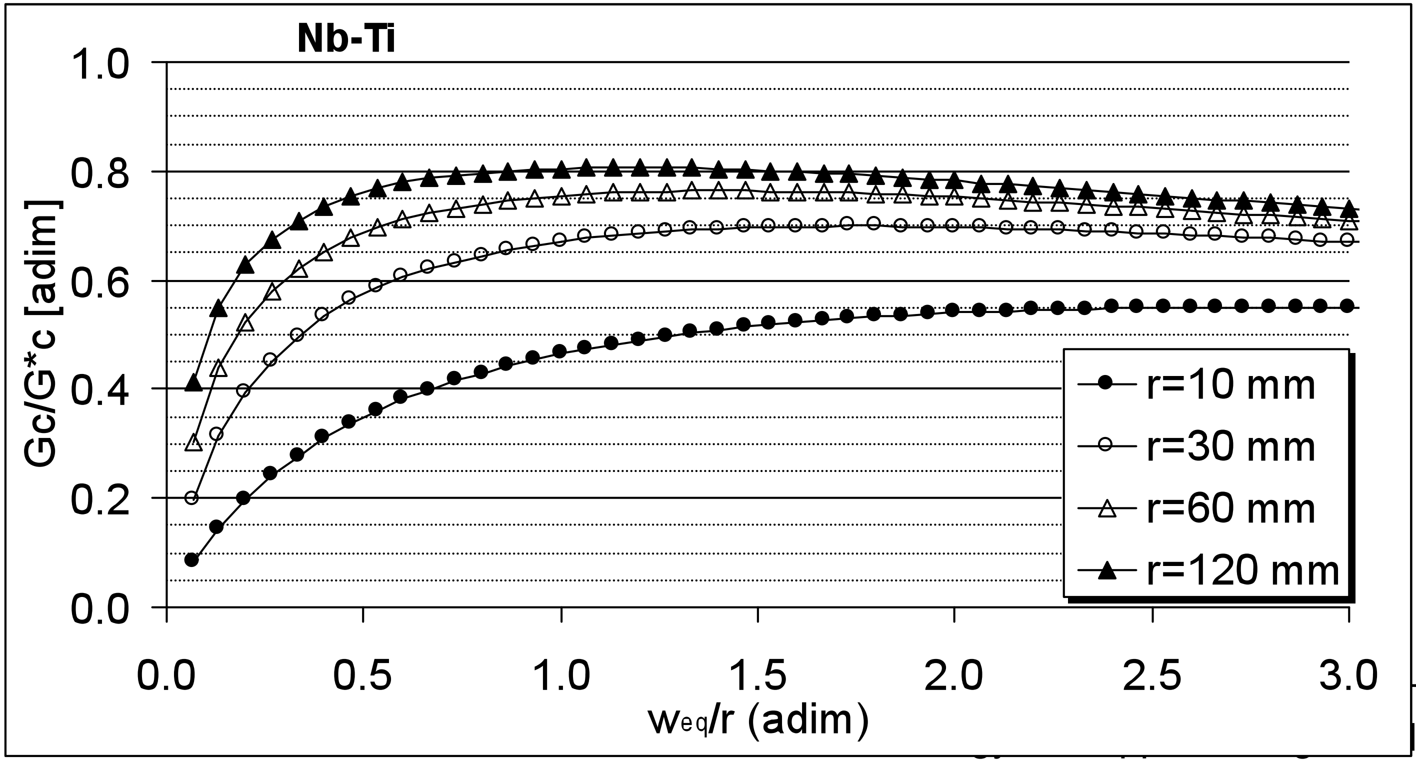




Scaling Laws

- What is the max field/gradient for a given conductor?
- Scaling laws to predict field/gradient when the peak field is at short sample limit (SSL)

L Rossi, E Todesco *“Electromagnetic design of superconducting quadrupoles”*
Physical Review Special Topics-Accelerators and Beams, 2006 - APS



Ratio between gradient at SSL and theoretical limit (B_{c2}/R)
vs. ratio of coil width over coil radius

Mechanical design

Case study:

Large gradient (220 T/m)
Large aperture (110 mm)
Quadrupole

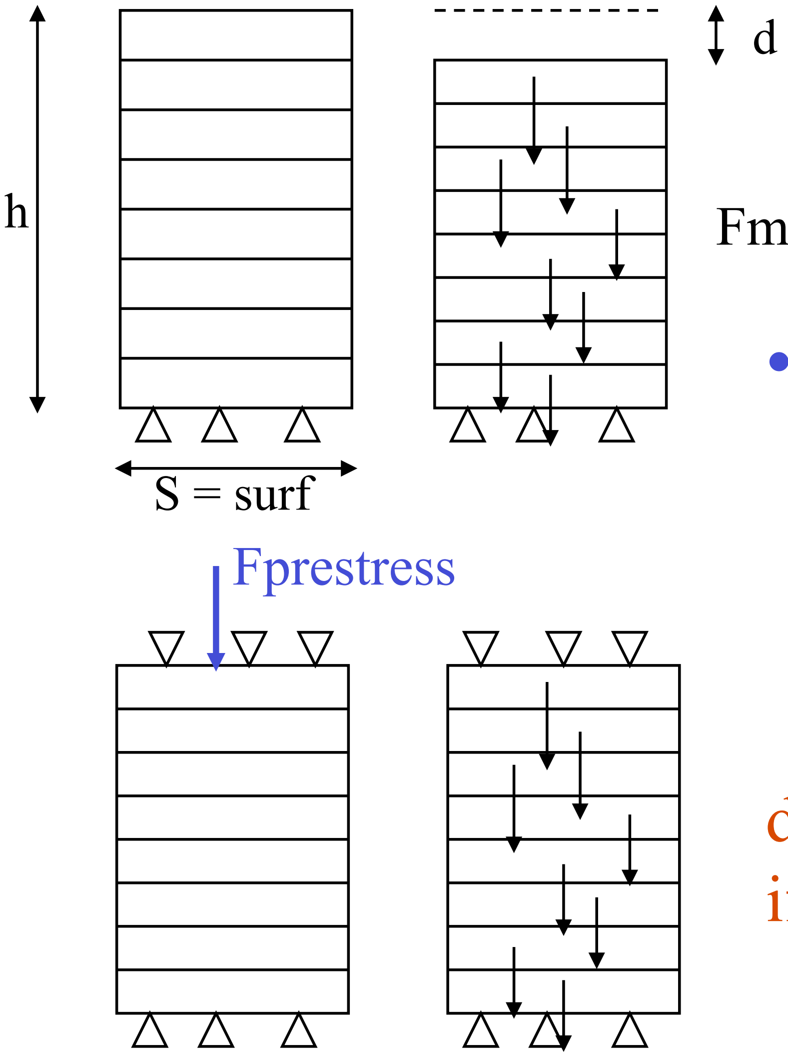
Goals

The goals of the mechanical design are:

- Provide support against magnetic forces
- Maintain the conductor within acceptable limits (strain and stress) during all stages of magnet assembly and operation:
  - Nb_3Sn Max longitudinal strain ~ 0.2%
    - depends on conductor
  - Nb_3Sn Max transverse pressure ~ 150 MPa
    - depends on conductor
- Minimize coil displacements under magnetic forces (pre-stress + rigid structure)

  ➔ to preserve field quality

Pre-stress



$d = h\,F / S\,E = h\,\sigma / E$

E is the elastic module

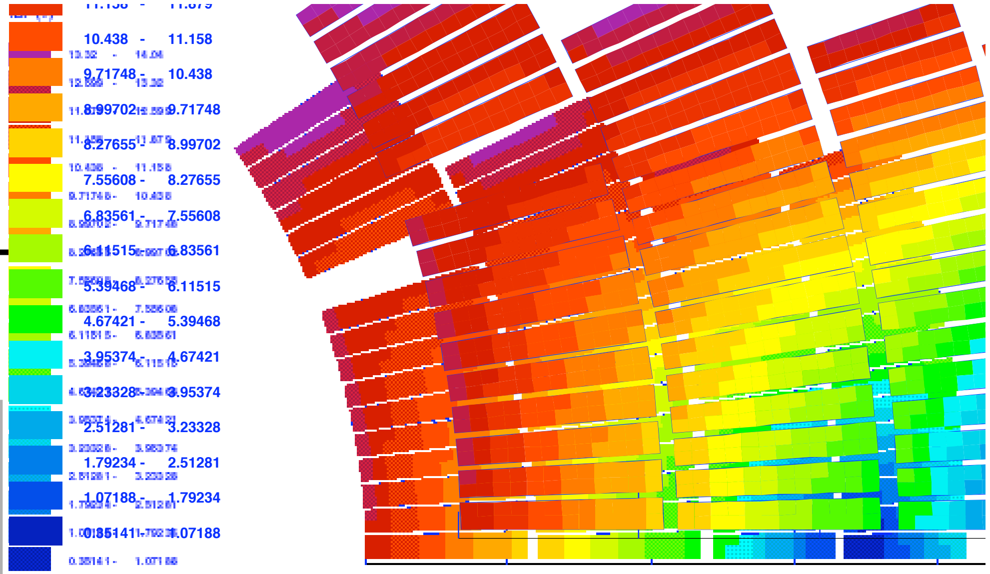
$F_{mag} = \Sigma\, F_{cable}$

- Pre-stress is needed to avoid or reduce excessive coil deformation under magnetic forces
  - ➔ preserve field quality

$d = 0$

if $F_{prestress} > F_{mag}$

Magnetic Design



CONDUCTOR PARAMETERS

Parameter	Unit	110 mm design	
		Inner	Outer
Number of strands	-	24	18
Strand diameter	mm	1.000	1.000
Cable bare width	mm	12.329	9.230
Bare inner edge thickness	mm	1.587	1.662
Bare outer edge thickness	mm	1.943	1.867
Cabling angle	deg.	14.5	14.5
Keystone angle	deg.	1.655	1.273
Average packing factor	%	89.0	89.0
Inner edge compression	%	20.6	16.9
Outer edge compression	%	2.8	6.6
Width compression	%	0.0	0.0
Radial insulation thickness	mm	0.18	0.18
Azimuthal insulat. thickness	mm	0.18	0.18
Copper to non-copper ratio	-	1.2	1.2

MAGNET PARAMETERS

Parameter	Unit	
N of layers		4
N of turns		248
Coil area (Cu + nonCu)	cm^2	84.88
NonCu Jc at 12 T, 4.5 K	A/mm^2	2400
Quench gradient	T/m	228
Quench current	kA	12.94
Peak field in coil at quench	T	14.04
Inductance	mH/m	17.46
Stored energy	kJ/m	1461

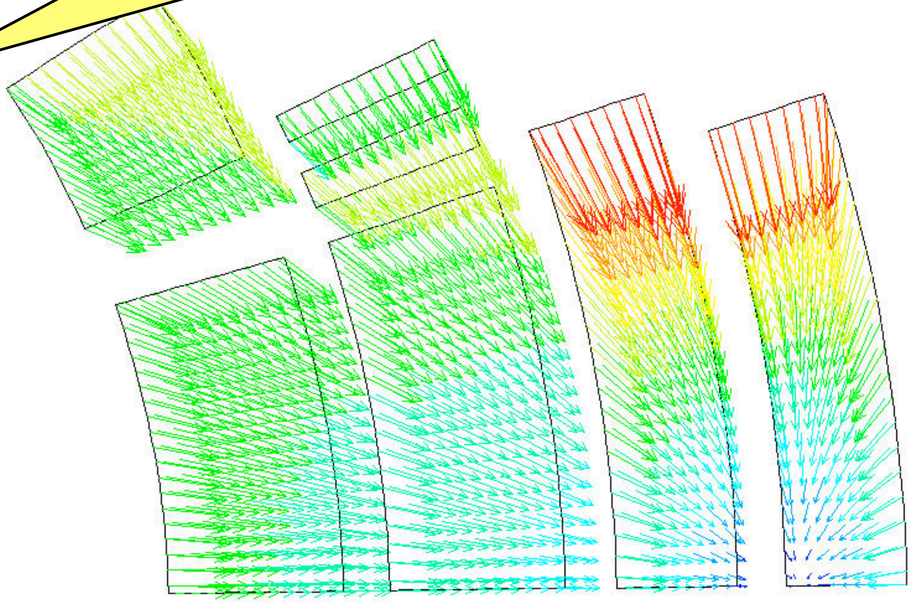
Electro-magnetic forces

- Computation of electro-magnetic forces at maximum field, and comparison with present magnets

1 MN/m ~ 100 ton/m

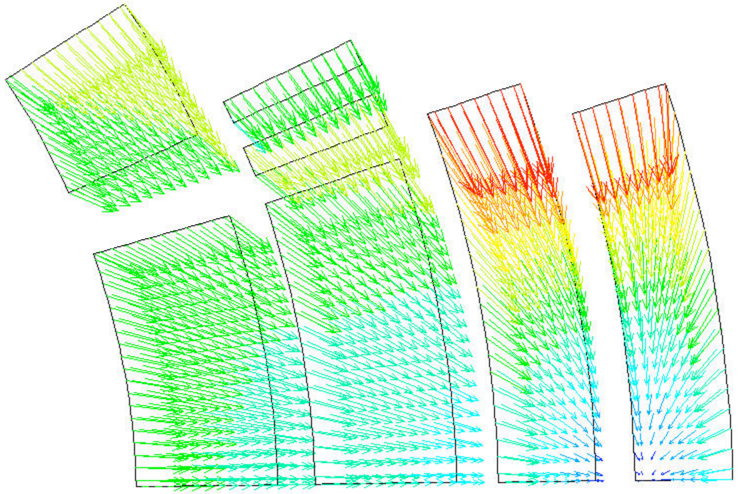
	HGQ† (MN/m)	TQ* (MN/m)	110 mm (MN/m) ROXIE	110 mm (MN/m) ANSYS
Fx	1.6	1.4	4.24	4.16
Fy	-1.9	-2.0	-4.23	-4.1
Fr				2.8
F_θ				-5

† LHC-IR Quad KEK design scaled to 228 T/m
* LARP TQC scaled to 228 T/m



G. Ambrosio, "Study of Mechanical Designs for 110-mm aperture quadrupole with 230-T/m Gradient" FNAL TD-07-012, available at http://tdserver1.fnal.gov/tdlibry/TD-Notes/

Analytical study



- 1st shell: F_θ = 1.5 MN/m,
  - Width = 12.3 mm,

    $\underline{\sigma_\theta = 122\ \text{MPa}}$

- Bottom half of coil: F_r = 1.7 MN/m,
  - E_{r_coil} = 50 GPa, E_{r_ins} = 14 GPa

    ➔ $\underline{\Delta r = 87\ \mu\text{m}}$ (average)

    And this deflection is going to increase the stress in the 1st shell!

Material properties

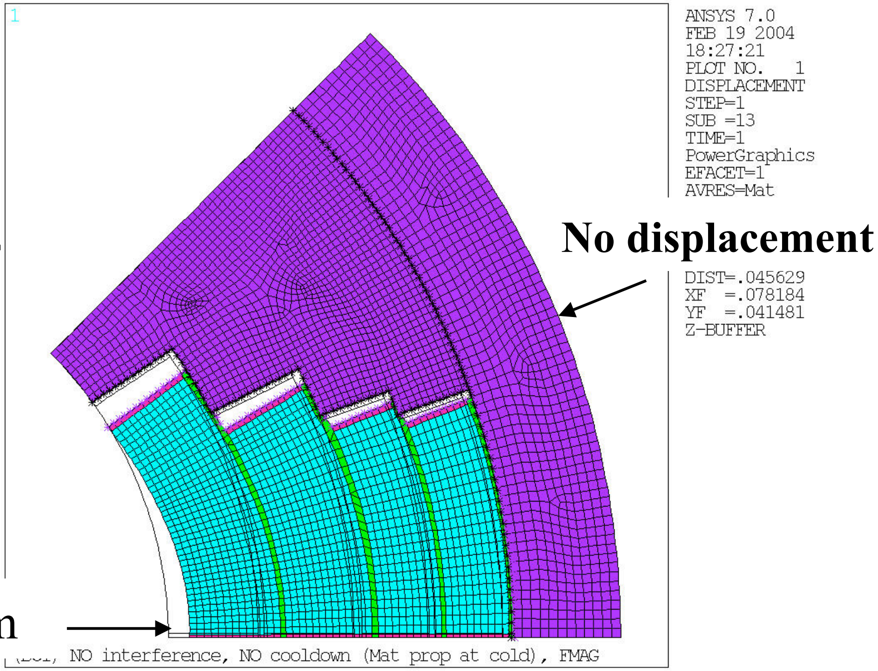
- Reliable FEM results depend on several factors
  - Good modeling (boundaries, pre-stress, contacts, …)
    - ➔ check simple model with analytical solutions
  - Correct material properties

Magnet Component		Elasticity Modulus				Thermal Contraction Coefficient			
Note: material Properties are in radial coordinates		293 K [GPa]		4.2 K [GPa]		293–4.2K [mm/m]		per 1 K [µm/m/K]*	
		X	Y	X	Y	X	Y	X	Y
Cable stack	Impregn. Cu/ Nb_3Sn, +ceramic ins.	40	38	50	38	3.3	4.3	11.4	15
Layer-layer & ground insul. on coil side	G10	14	18	14	18	7.62	2.75	26.4	9.5
Mid-plane & ground insul. on coil top	G10	18	14	18	14	2.75	7.62	9.5	26.4
Collar wedge & ring, SS outer shell	Stainless Steel 316	210	210	225	225	2.97	2.97	10.3	10.3
Yoke	Iron	210	210	225	225	2.04	2.04	6.9	6.9
Al outer shell	Aluminum	70	70	81.6	81.6	4.23	4.23	14.3	14.3

Infinitely rigid boundary con.

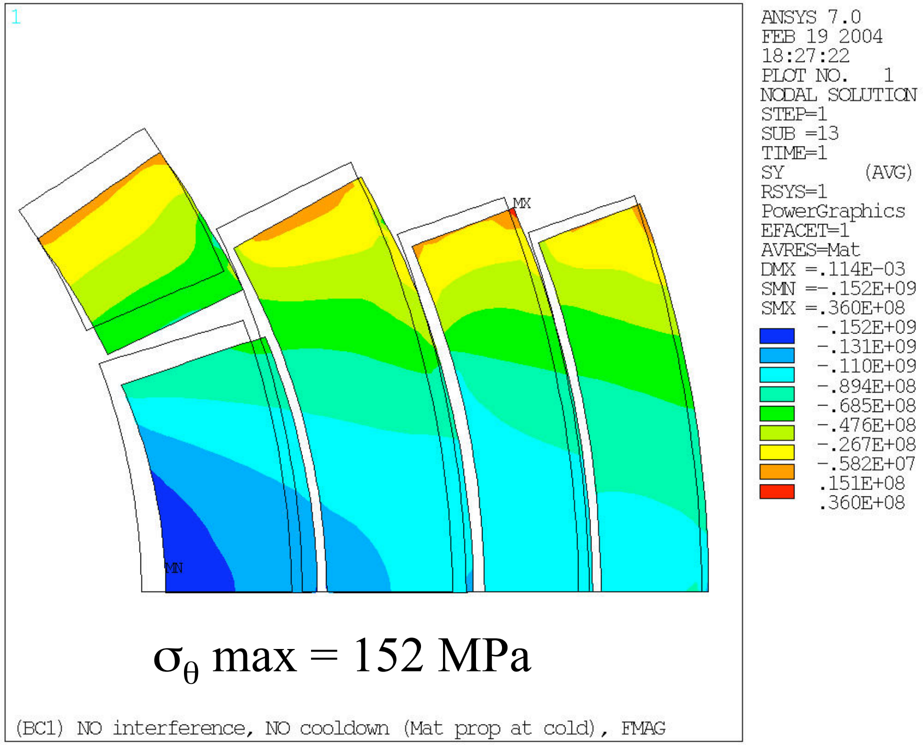
Stress in the coil with inf. rigid BC on the outer surface of the collars

- NO pre-stress
- Material properties @ 4.2 K
- Fmag @ 13 kA = 228 T/m

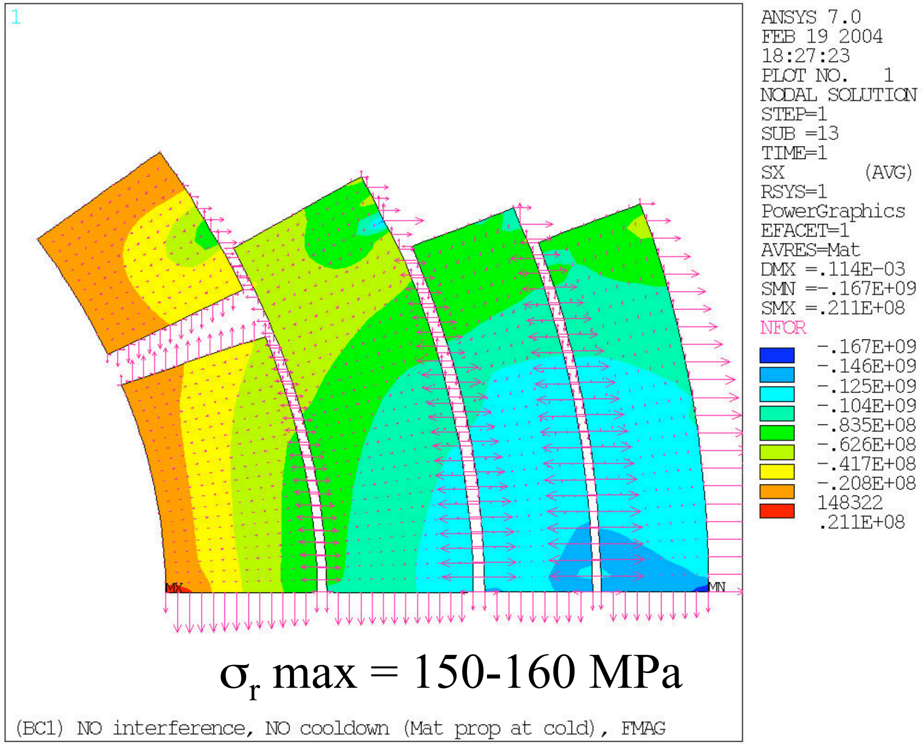


No displacement

$\Delta r = 87\ \mu m$



σ_θ max = 152 MPa

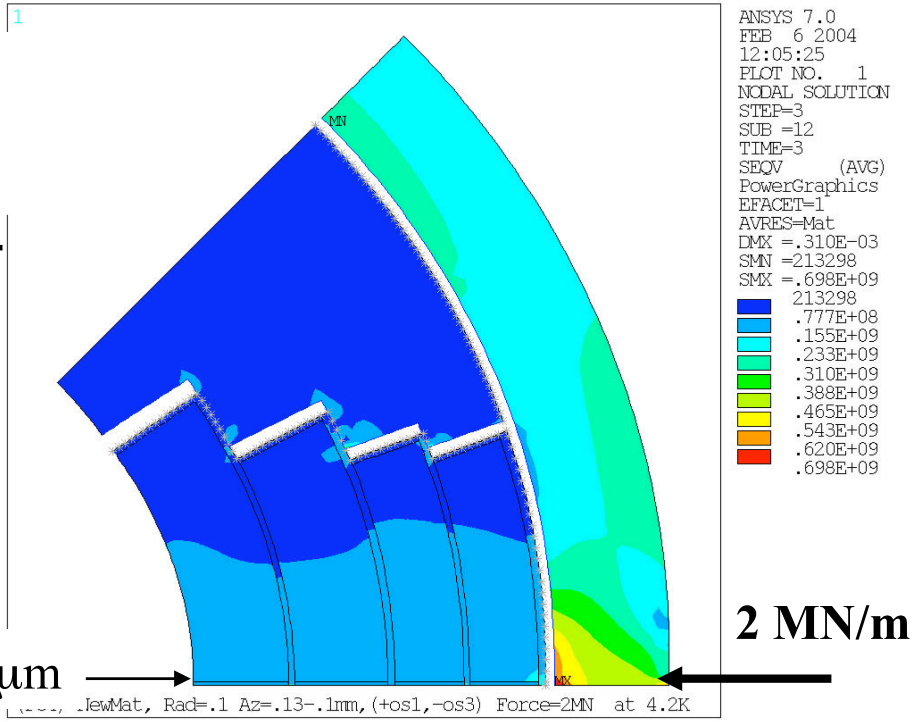


σ_r max = 150-160 MPa

External force

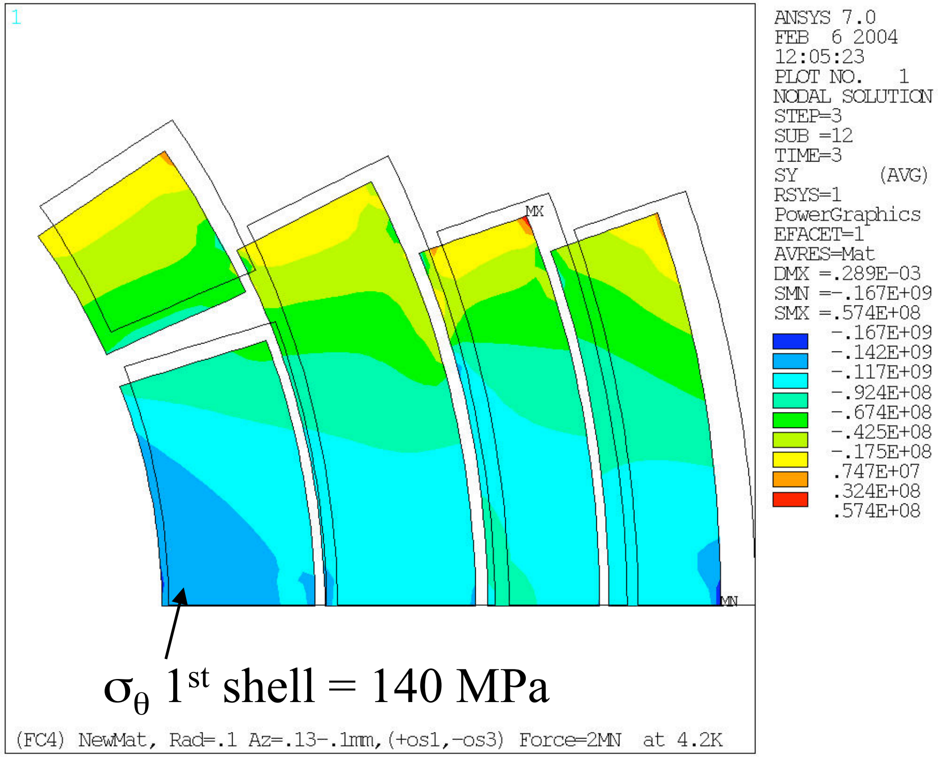
Stress in the coil with horizontal force on the midplane

- With some pre-stress <120 MPa
- Fmag @ 13 kA = 228 T/m

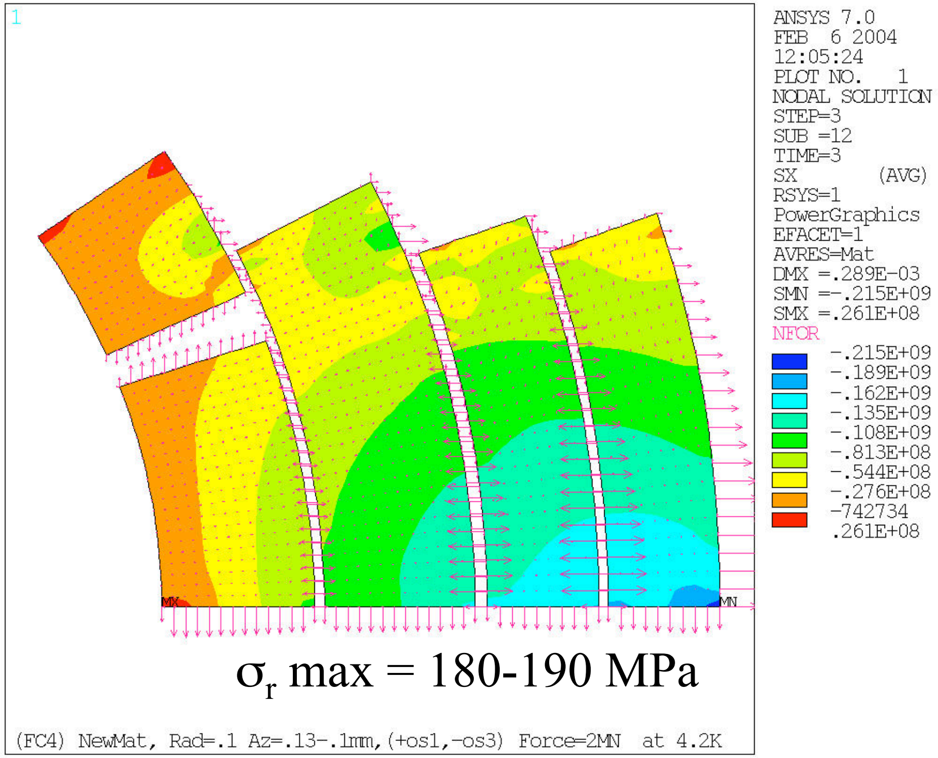


Δr = 203 μm

2 MN/m



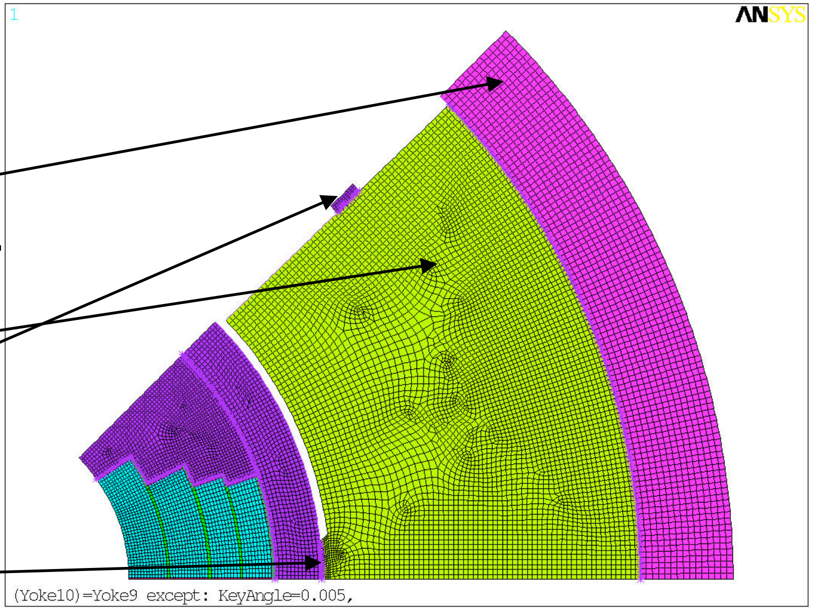
σ_θ 1st shell = 140 MPa



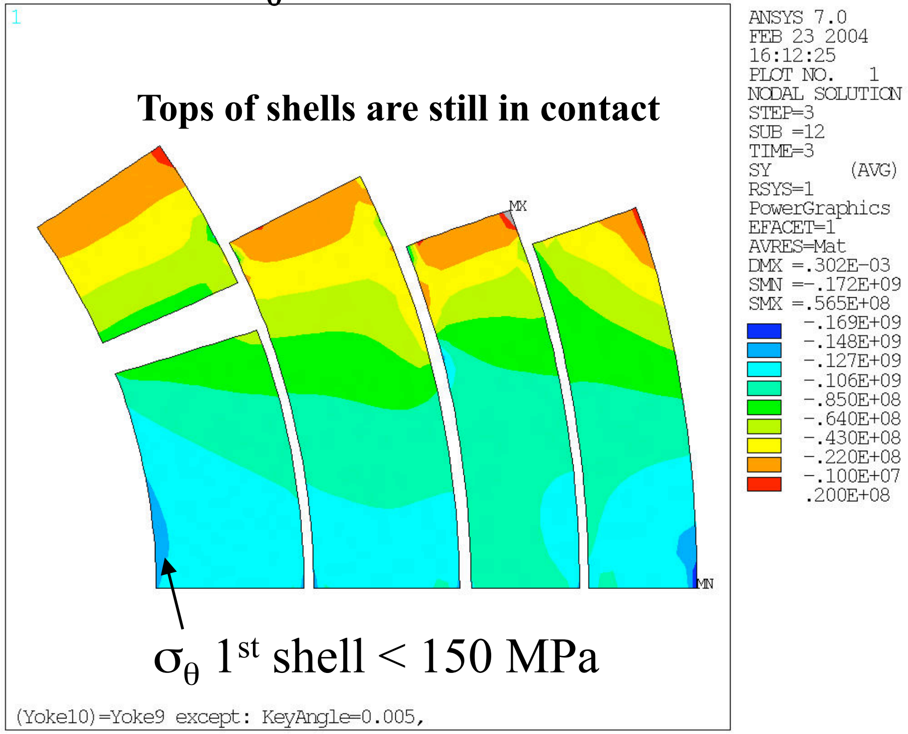
σ_r max = 180-190 MPa

With Al outer shell

- Al shell
- Yoke with gap at 45 deg.
- SS keys in contact after cooldown and at max Grad.
- Collar-Yoke contact 0-6 deg.
- Bladder technology

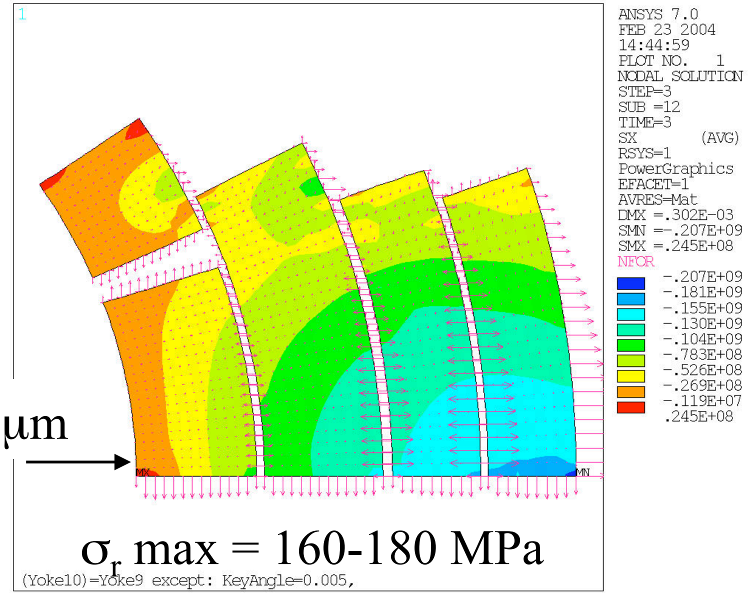


σ_θ at 228 T/m


Tops of shells are still in contact

σ_θ 1st shell < 150 MPa

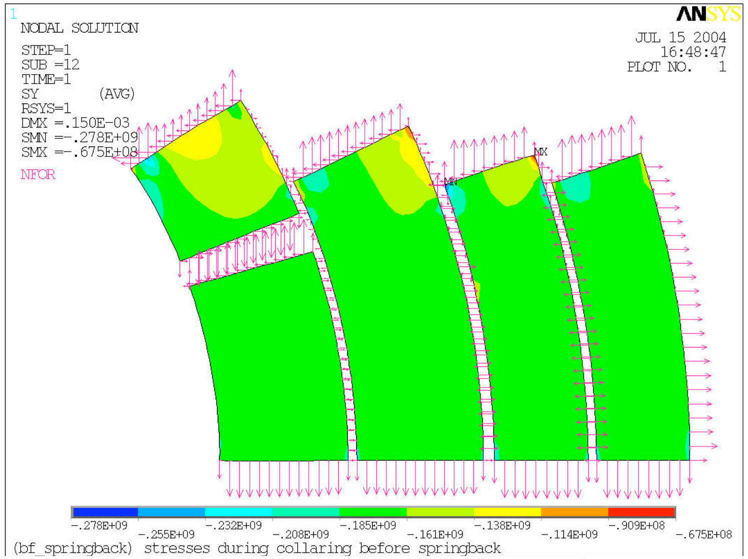
σ_r at 228 T/m


$\Delta r = 131\ \mu m$

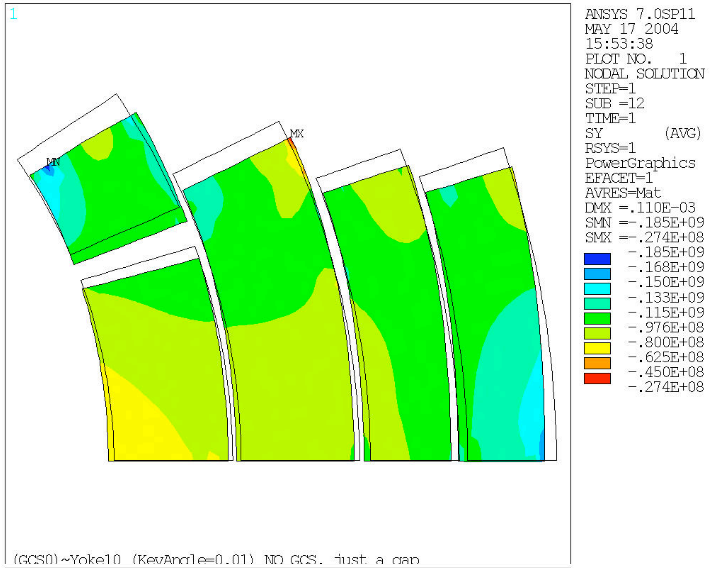
σ_r max = 160-180 MPa

All steps

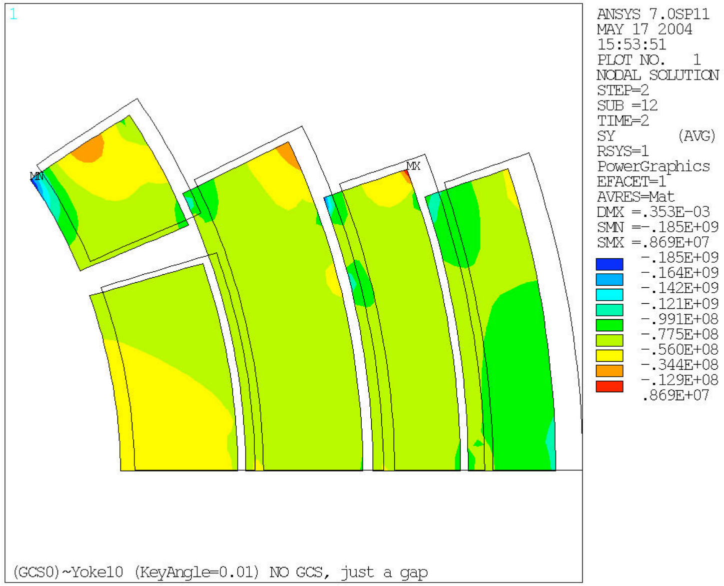
- Stresses at all steps, displacements at Fmax



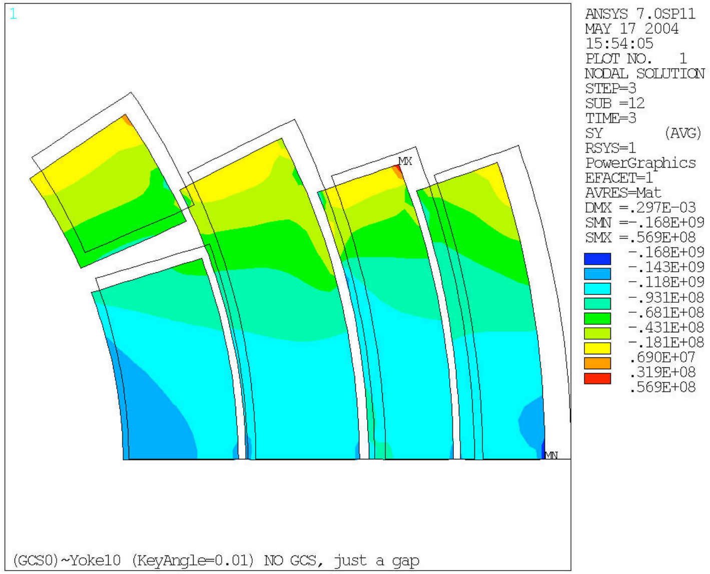
Azimuthal stress
During collaring



After assembly



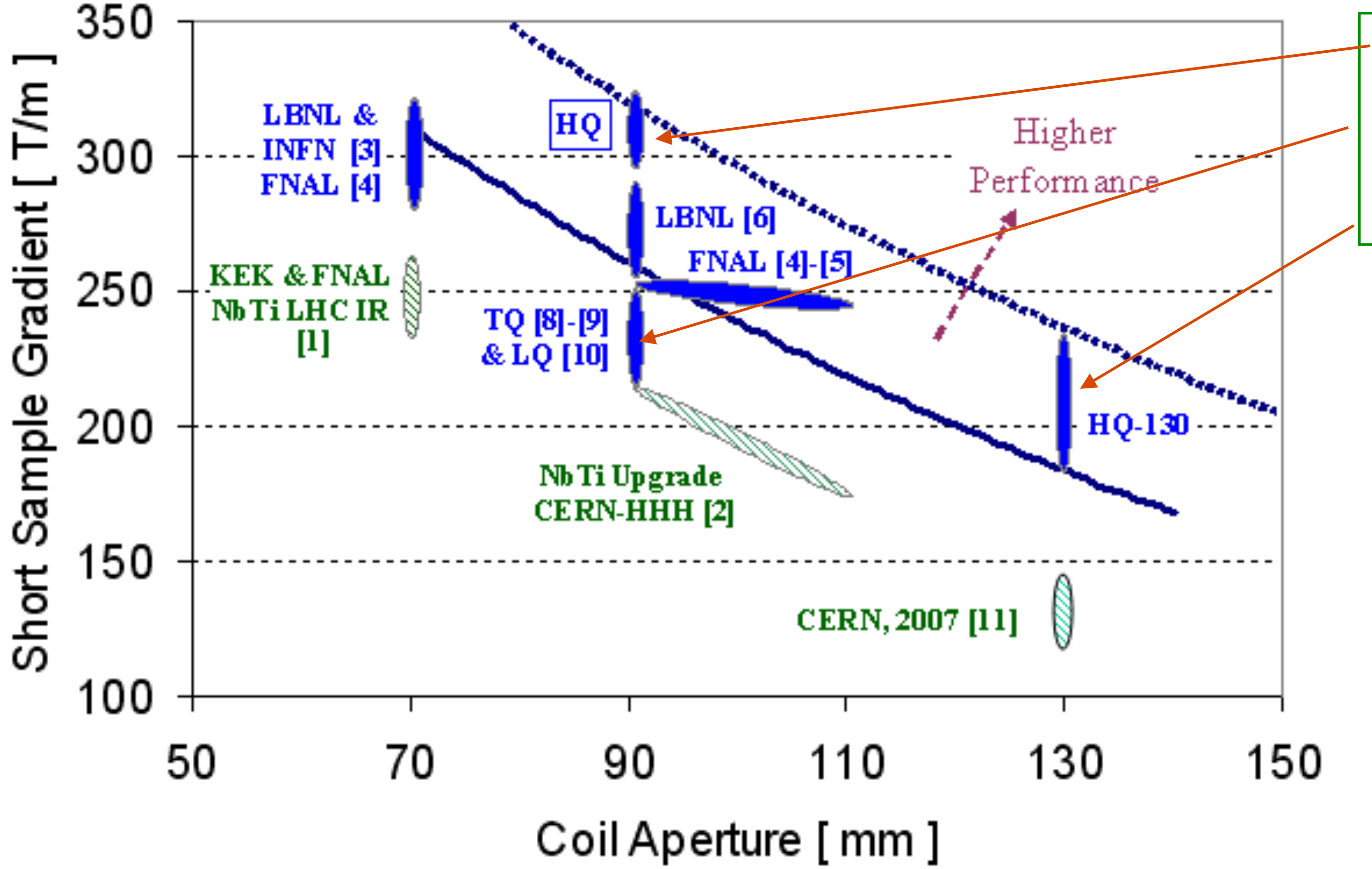
After cooldown



At max forces

Technology Limits

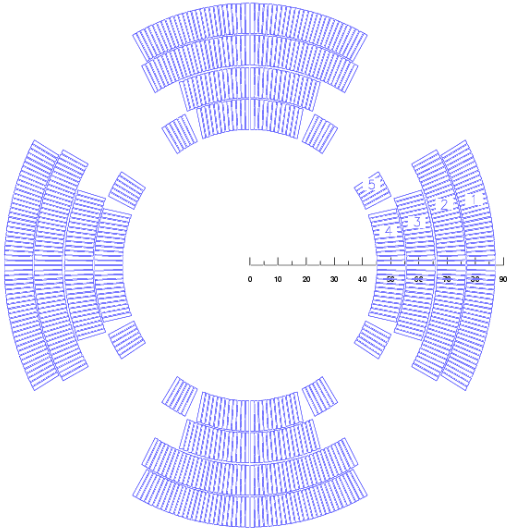
- What are the limits for a given technology?
- LARP is exploring the limits for Nb_3Sn technology



HQ: 4 layers, 90 mm

TQ & LQ: 2 layers, 90 mm

HQ: 2 layers, 130 mm



[1] LHC Design Report
[2] R. Ostojic et al., PAC-05
[3] S. Caspi et al, MT-15
[4] T. Sen et al, PAC-01
[5] A. Zlobin et al, EPAC 02
[6] G. Sabbi et al., ASC-02
[8] R. Bossert et al., ASC-06
[9] S. Caspi et al., ASC-06
[10] G. Ambrosio et al., ASC-06
[11] J-P. Koutchouk et al., 2007

Case study: LARP Magnet R&D

“Demonstrate that Nb_3Sn magnets are a viable choice for an LHC IR upgrade”

R&D phase:

- **Technological Quadrupoles (TQ)** for performance reproducibility
  - 1 m long, 90 mm aperture, $G_{nom} > 200$ T/m, $B_{coil} > 12$ T

Deadline: 2009

- **Long Racetracks** and **quadrupoles (LQ)** addressing long magnet issues
  - LQs have same features of TQs 4 m long
- **High gradient quadrupoles (HQ)** similar to the NbTi quads for Phase-I
  - 1 m long, 110-130 mm aperture,

Options under discussion

- **Long Mirror (LM)** addressing long coil & magnet issues
  - 2 and 4 m long, single cos θ coil, $B_{coil} \sim 11$ T

FNAL core program task
In support of LARP

Outline of the lessons

D1
- Introduction
- Conductors

D2
- Magnetic design
- Mechanical design

D3
- Coil fabrication technology

D4
- Magnet assembly
  - Long magnets

D5
- Quench protection design
- Cryogenic design
- Magnet test and analysis
- Lifetime issues
- Next steps

Acknowledgement

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LBNL

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