15 T and Beyond -
Dipoles and Quadrupoles

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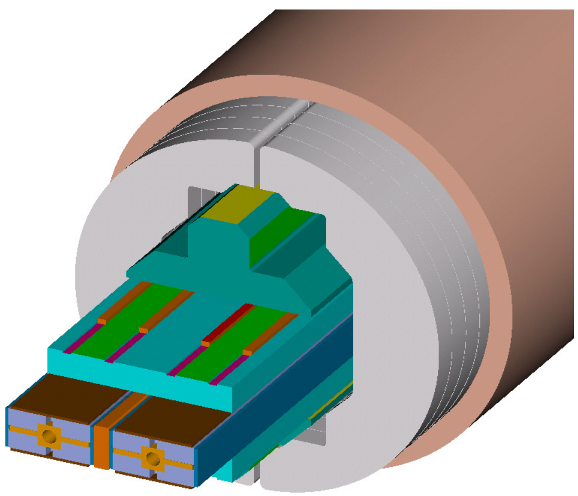
High Field Accelerators & Magnets

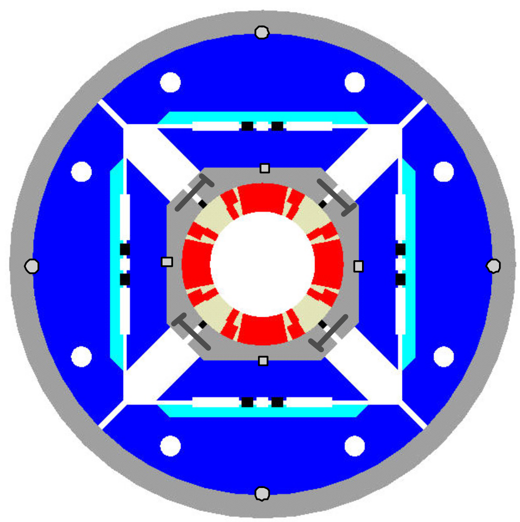
SLHC kick-off meeting: “14 → 28 TeV is great, 14 → 42 is even better”

PAF: “Maximize integrated luminosity, be ready to prepare for DLHC”

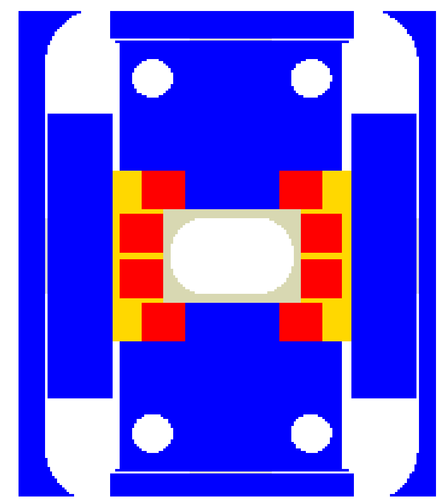
US HEPAP: “The science of extending exploration of the energy frontier with the LHC is absolutely central”



Arc Dipoles



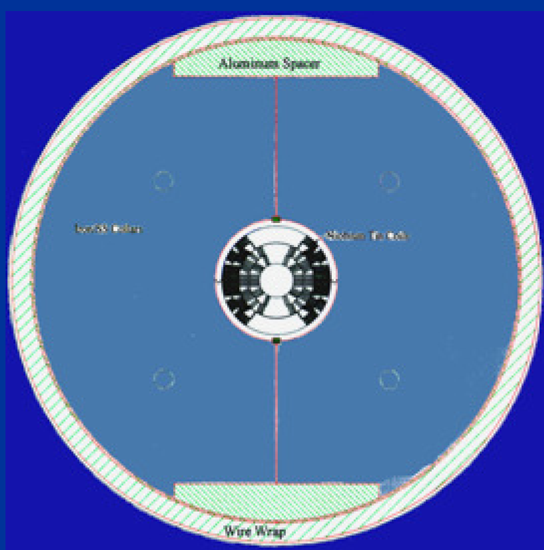
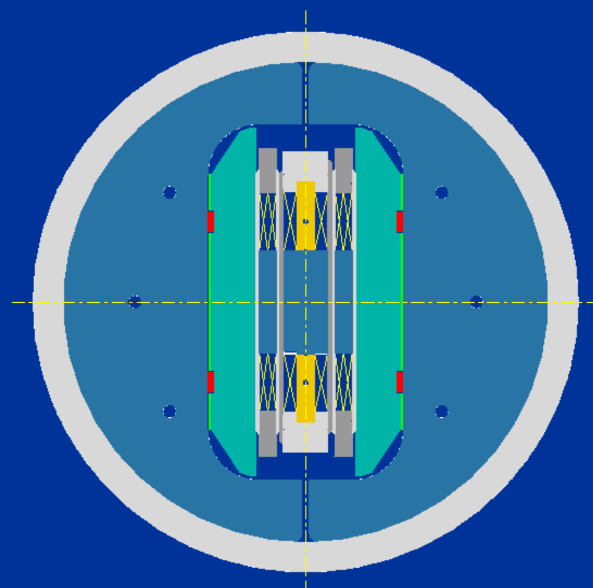
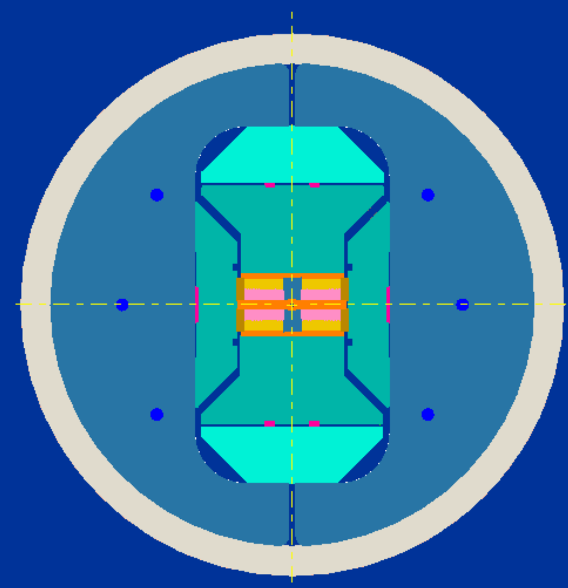
IR Quadrupoles



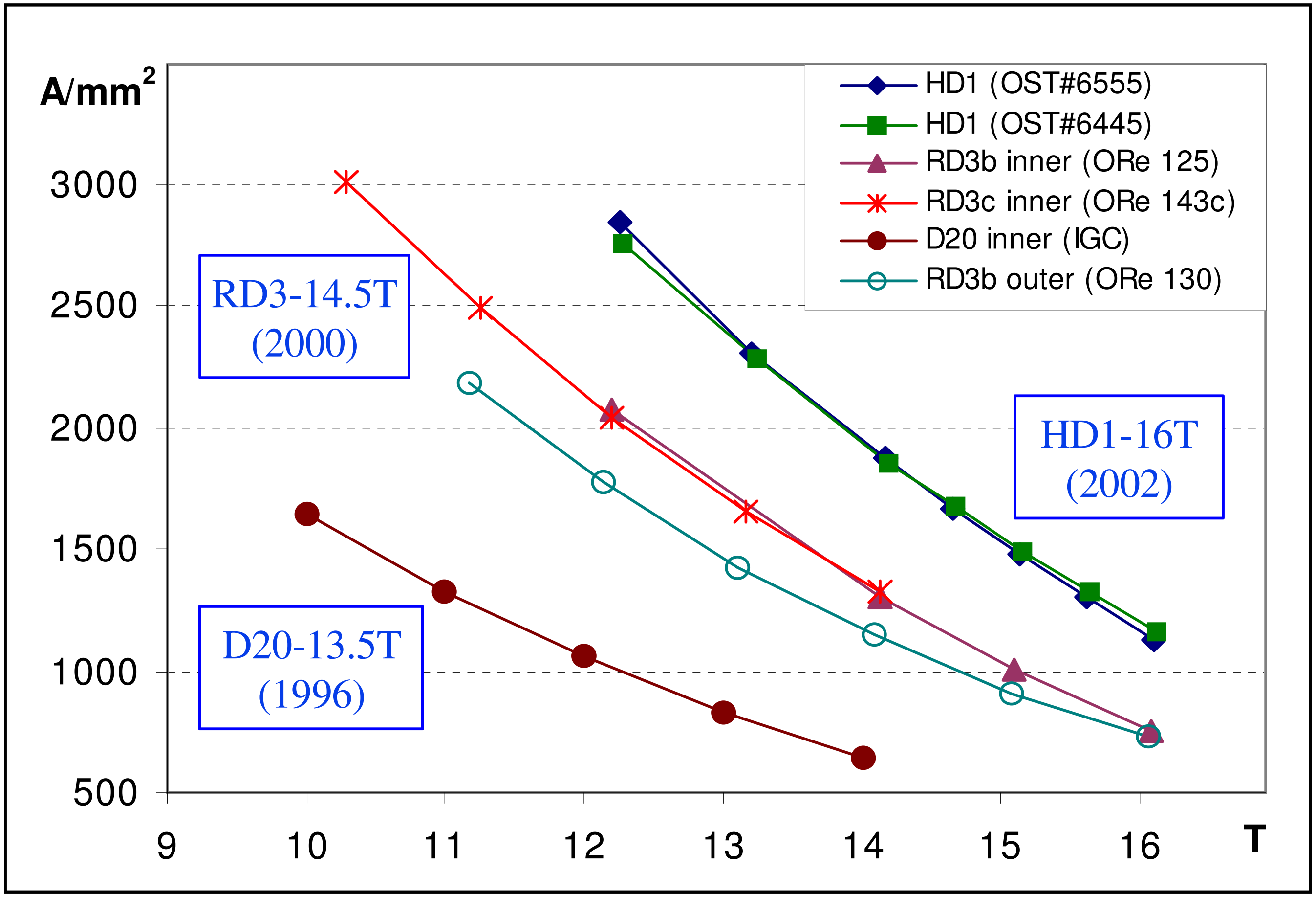
IR Dipoles

Nb_3Sn Arc Dipole R&D

- *Several coil configurations options, each has specific advantages*
- *Compare features by fabricating and testing prototypes of each type*

Cos θ	Common Coil	Block
		
D20	RD3	HD-1

Conductor and Magnet Progress



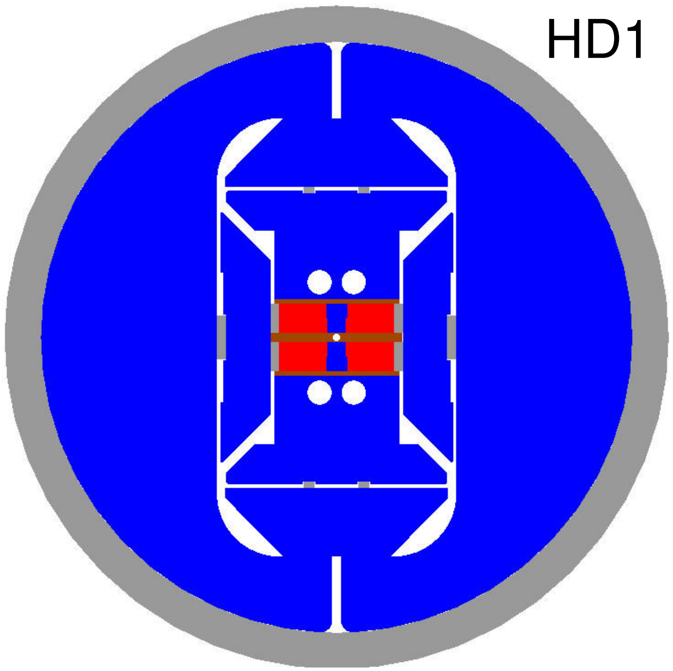
Critical current densities in Nb_3Sn wires for LBNL high-field dipoles

Comparison of Coil Layouts

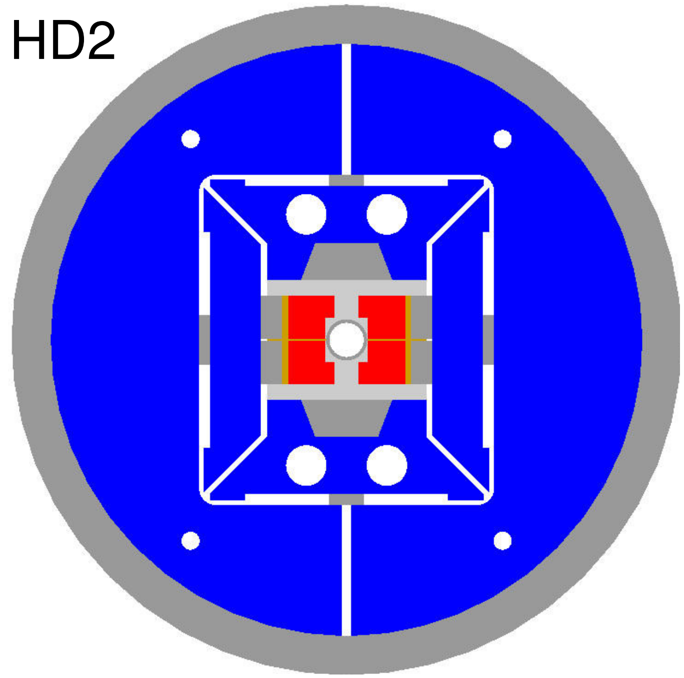
Parameter	Cos(θ)	Common Coil	Block
Cable design	Keystone	Rectangular	Rectangular
Internal bore support	Self supporting	Required	Required
Minimum winding radius	Small	Large	Small
Conductor efficiency	Large aperture	Lower	Small aperture
React-and-wind	No	Yes	No
2-in-1 arrangement	Horizontal	Vertical	Horizontal
2-in-1 pre-load	2x	2x	1x
High field/stress locations	Combined	Separated	Separated
Stress intercepts	No	Layer	Block
Coil width/layer	Cable width	Cable width	No. turns
Grading efficiency	Low	Low	High
End peak field	High	Low	High
End design/winding	Saddle	Flat or Flared	Flat or Flared
Layer transition	High field	Low field	High field

HD Series Objectives & Features

HD1



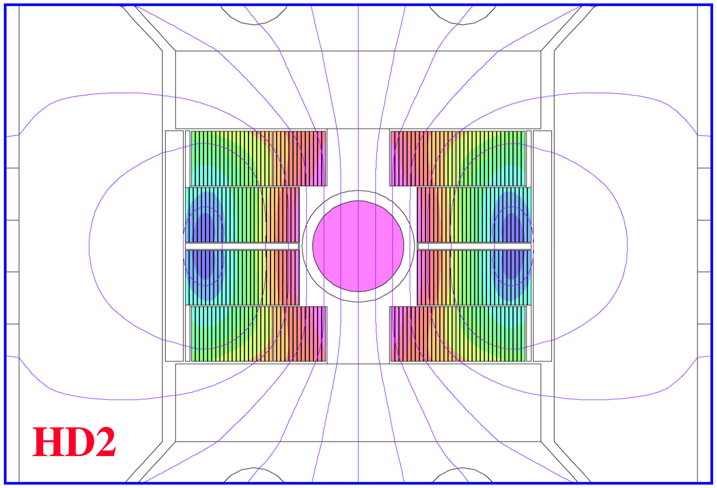
HD2



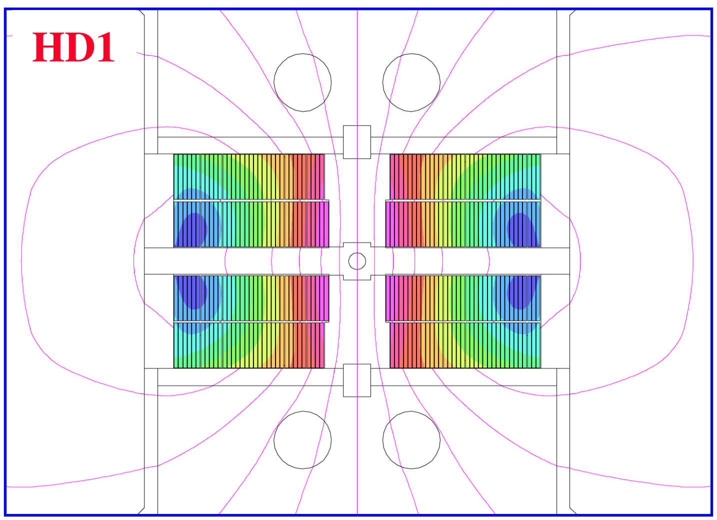
HD1: Force and Stress
- Mechanical structure
- Conductor Limits

HD2: Aperture and Field Quality
- Bore support
- Coil End layout

HD Coil Design



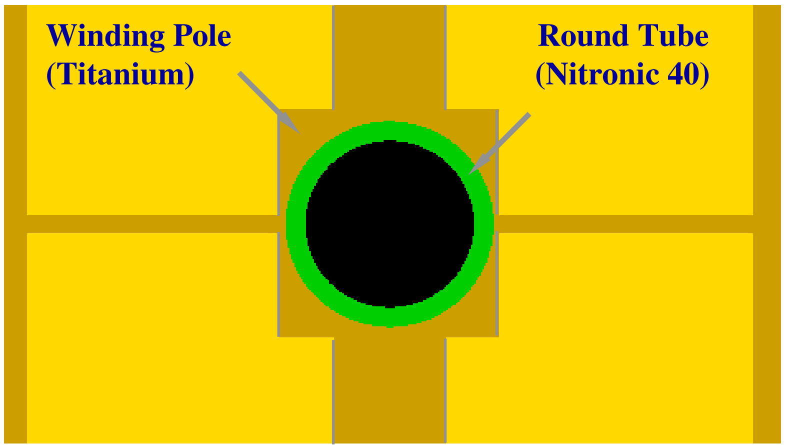
- ☺ Efficient coil design in small aperture
- ☺ High Je (no spacers required)
- ☺ Large cable with 2-layers/pole
- ☺ Possibility of efficient grading
- ☹ Some coil aperture lost to structure



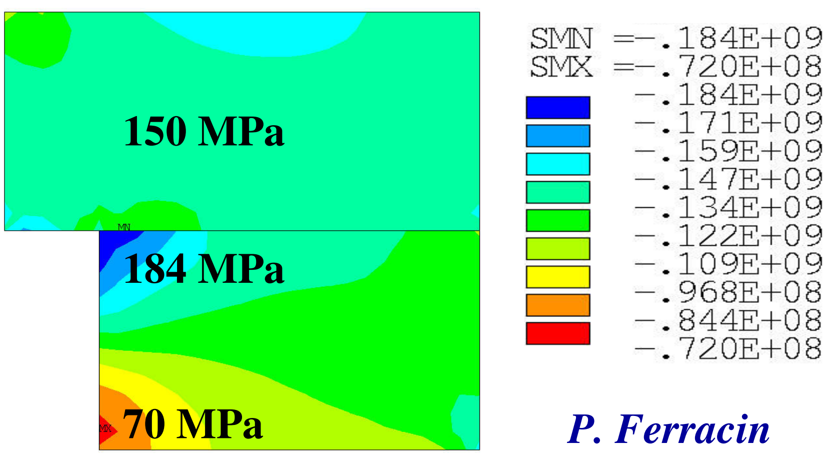
Parameter	Unit	HD2	HD1
Clear bore size	mm	36	8
Strand diameter	mm	0.8	0.8
No. strands		51	36
No. turns/quadr.		54	69
Bore field	Tesla	15.1	16.7
Coil field	Tesla	15.9	16.1
Max current	kA	17.4	11.4
Stored Energy	MJ/m	0.77	0.66
Inductance	MH/m	8	10
F_x (quadrant, 1ap)	MN/m	5.9	4.7
F_y (quadrant, 1ap)	MN/m	-2.7	-1.5
Ave. stress (h)	MPa	150	150

Bore Design and Coil Stress

Mechanical Assembly



Coil stress after cool-down (no field)



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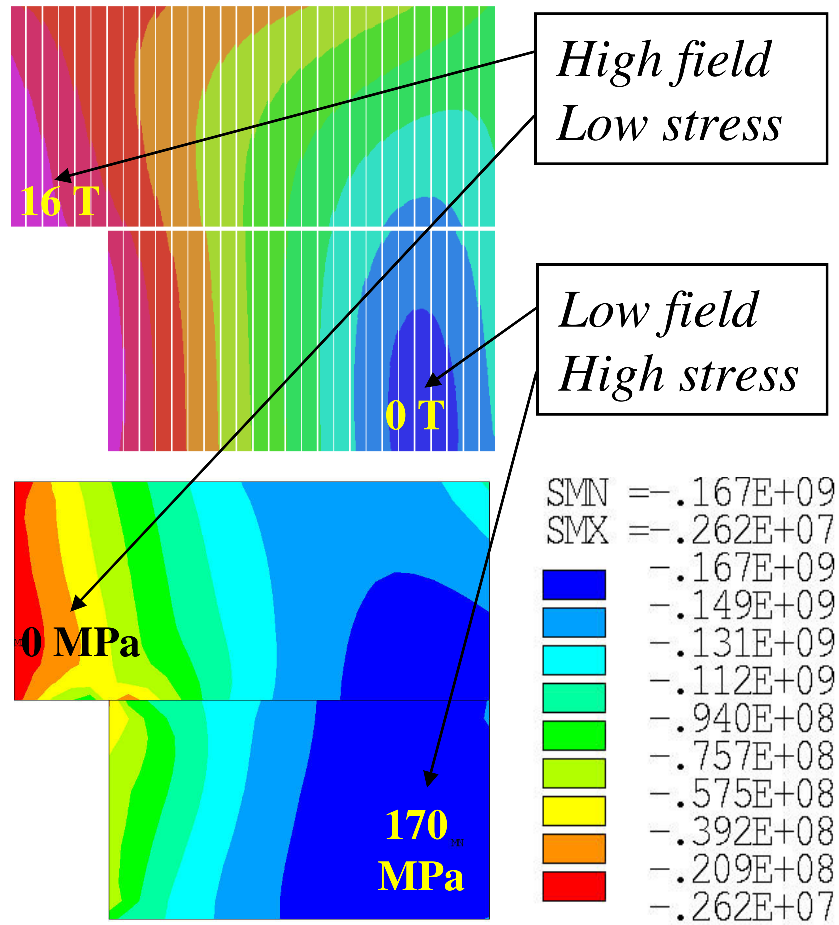
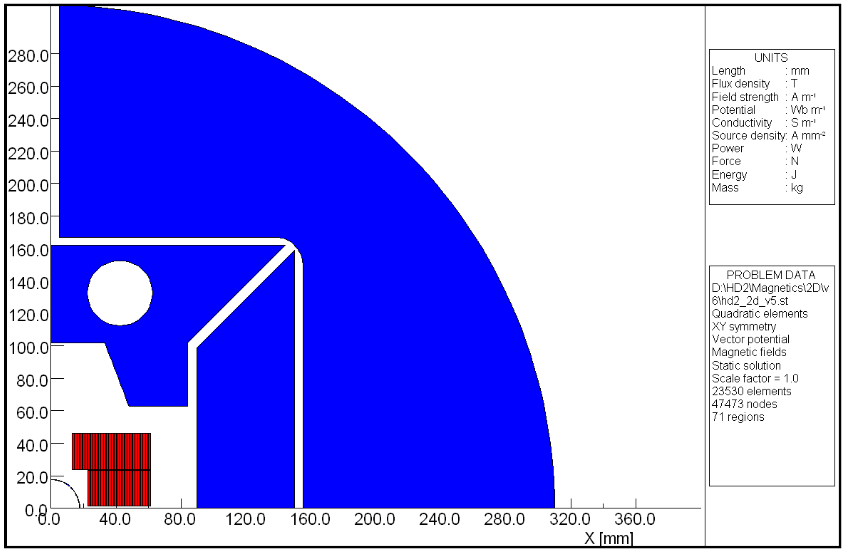
Physical separation of high field & high stress regions at full excitation

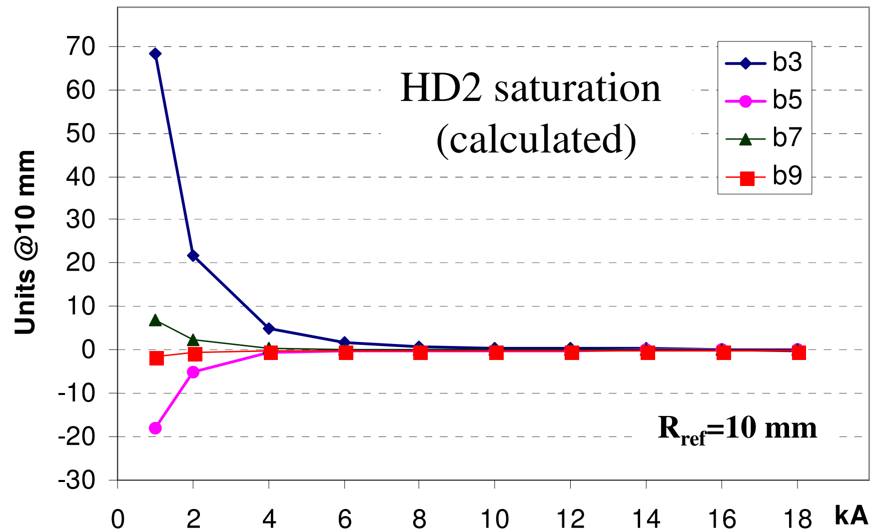


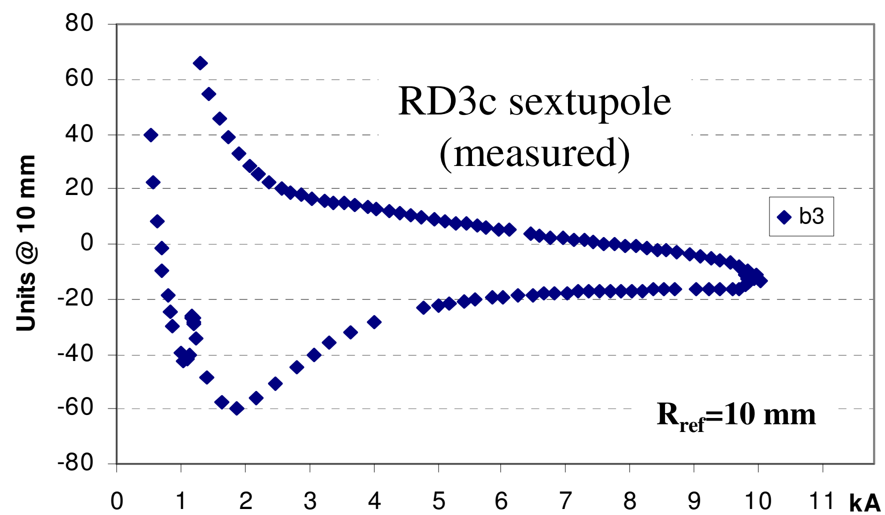
Field Quality Optimization



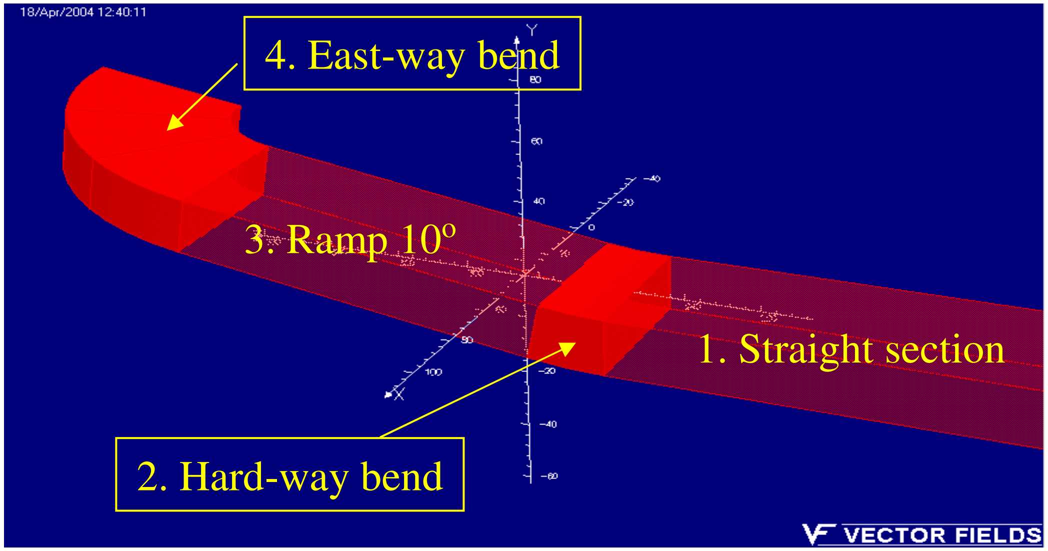
- Coil can be optimized for very small geometric harmonics, without spacers
- Yoke cross-section and iron insert optimized to compensate persistent current harmonics
- Goal: all measured high field harmonics at 10^{-4} or lower (R_{ref} = 10 mm)

Saturation and magnetization effects





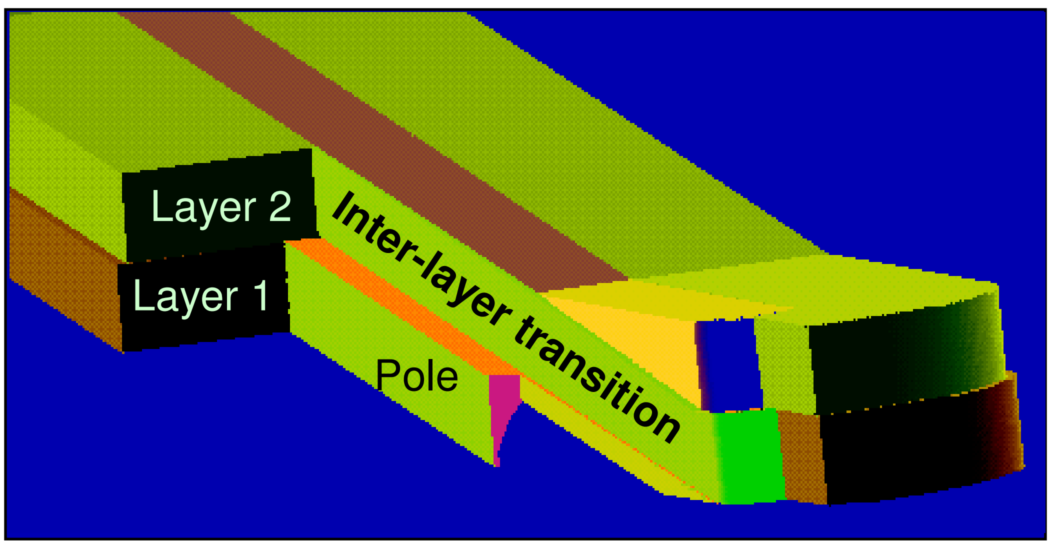
Coil end winding and layer transition

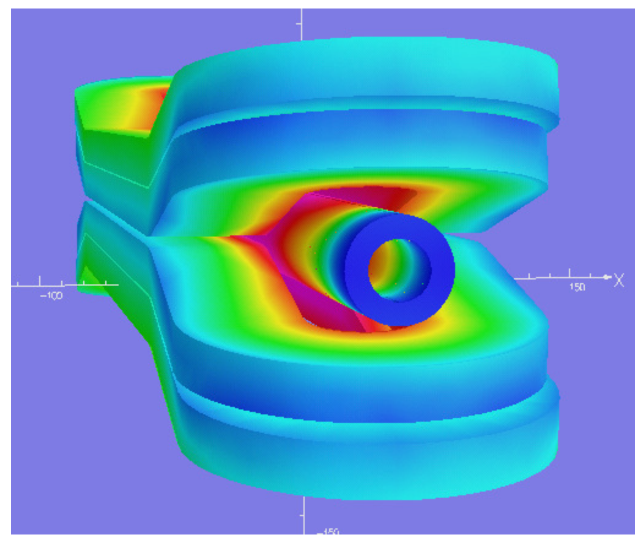


Design based on D10 dipole *(IEEE MAG-21, 1985, p.967)*

Layer 2 pole turn (transition) proceeds parallel to magnet axis as main blocks ramp up

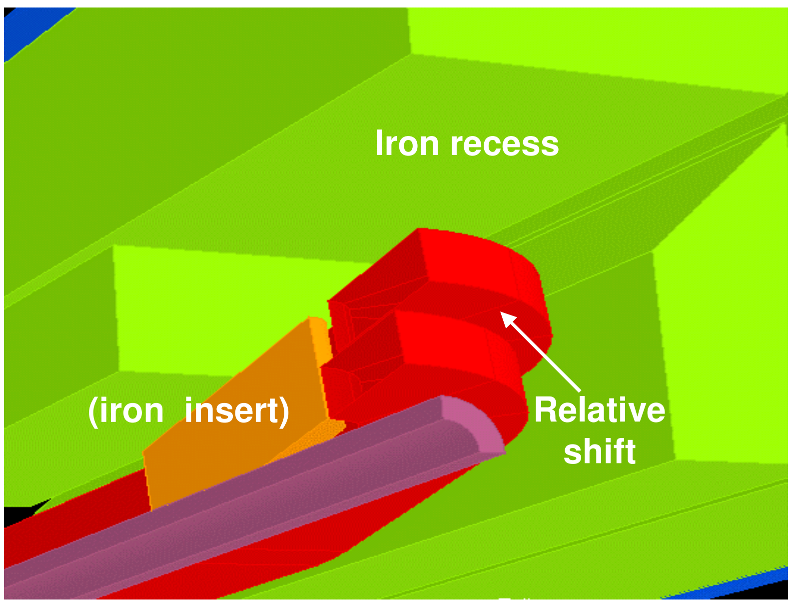
When elevation matches layer 1, easy-way bends into pole

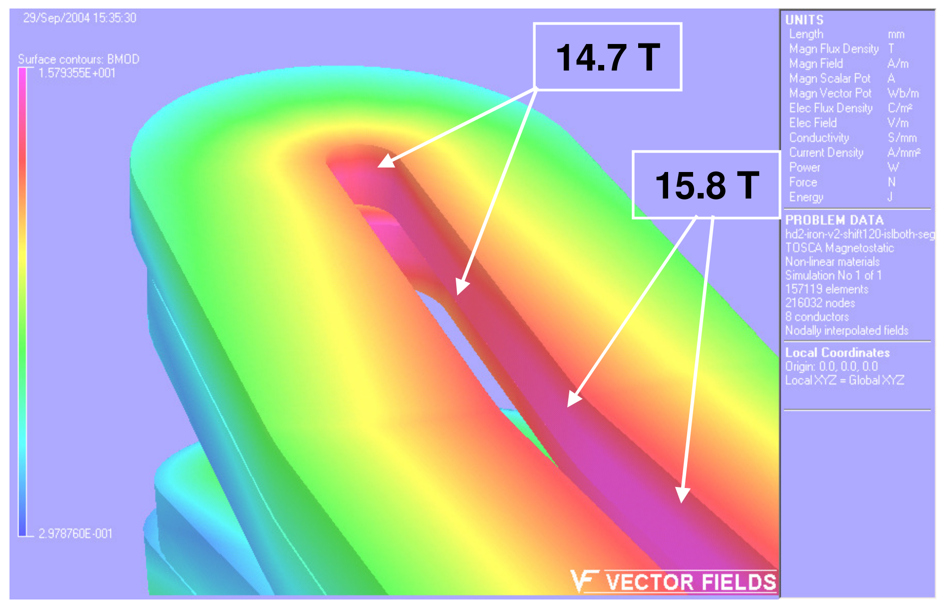




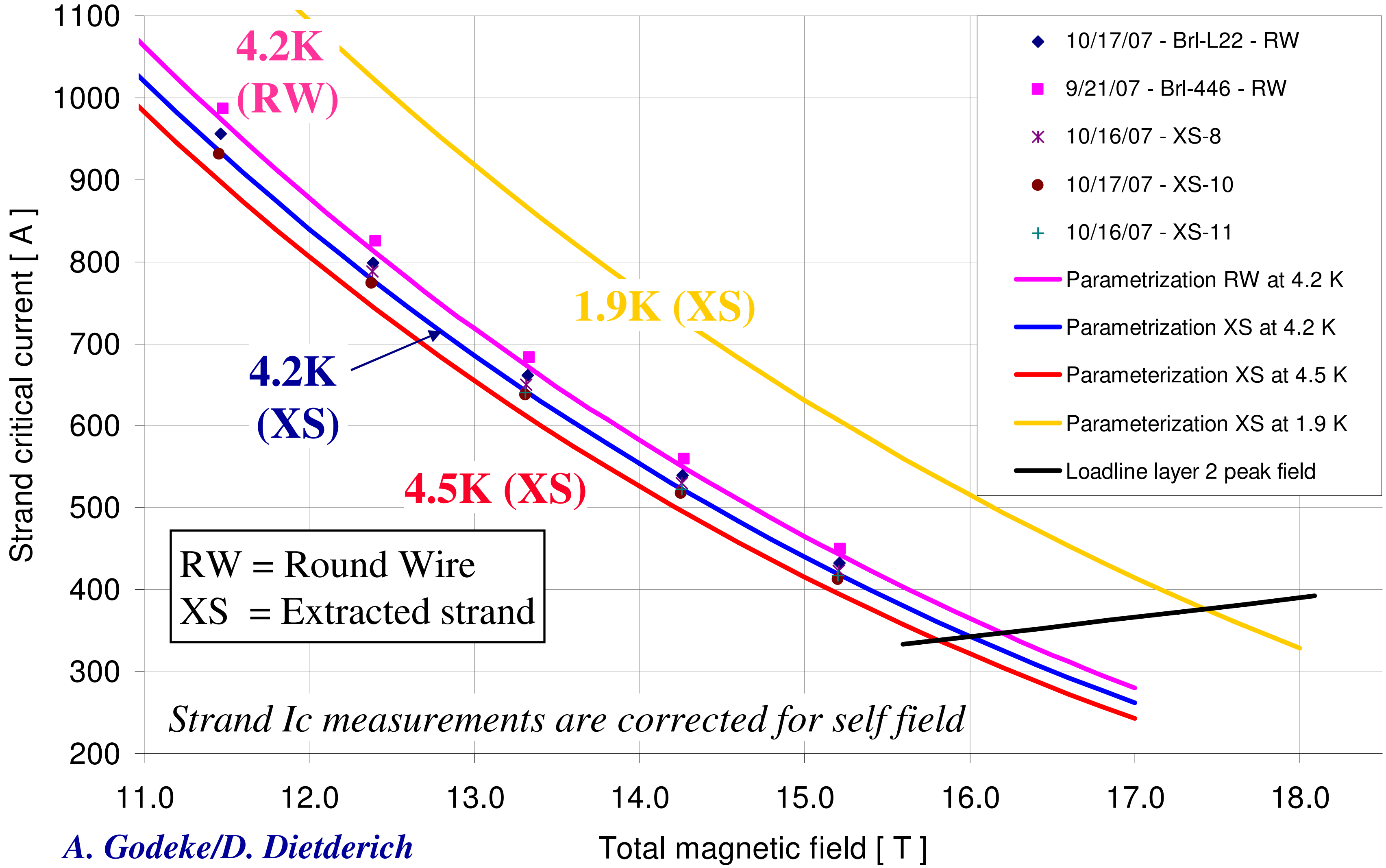
End Field Optimization

- End flare effectively increased distance among poles, reducing the end field
- End field Optimization: relative shift of blocks between layer 1/2
  iron recess or inserts (no insert used in HD2)
- No end spacers are needed, allowing easier fabrication
- Field margin in the end regions after optimization ~ 6% (1.1 T at short sample)



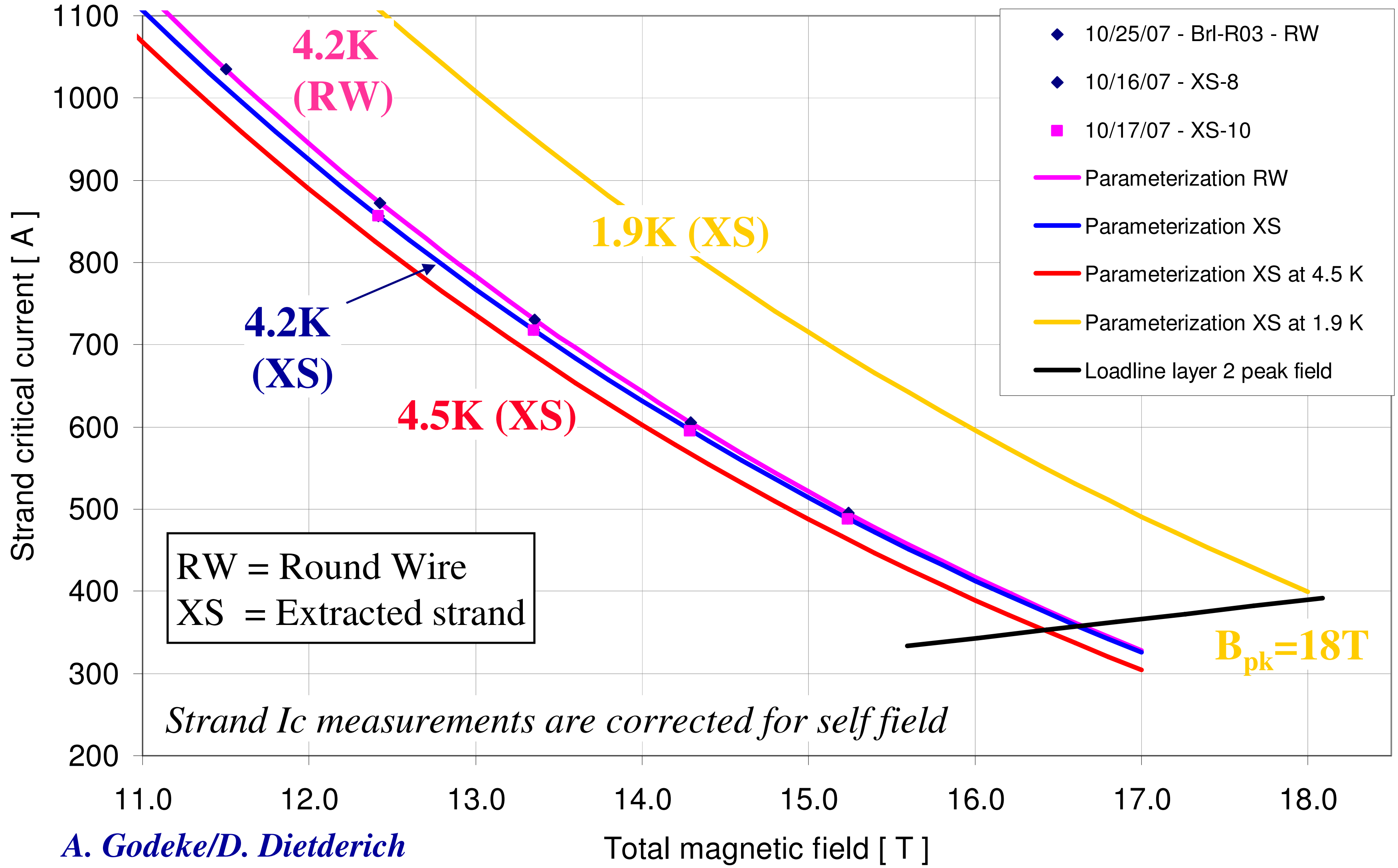


HD2 Short Sample Limit (Coil 1)



A. Godeke/D. Dietderich

HD2 Short Sample Limit (Coil 2&3)



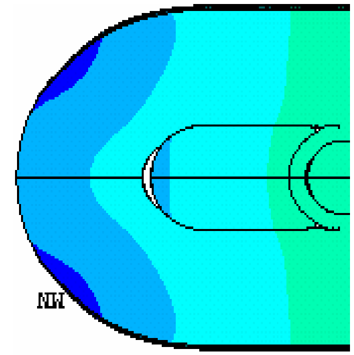
A. Godeke/D. Dietderich

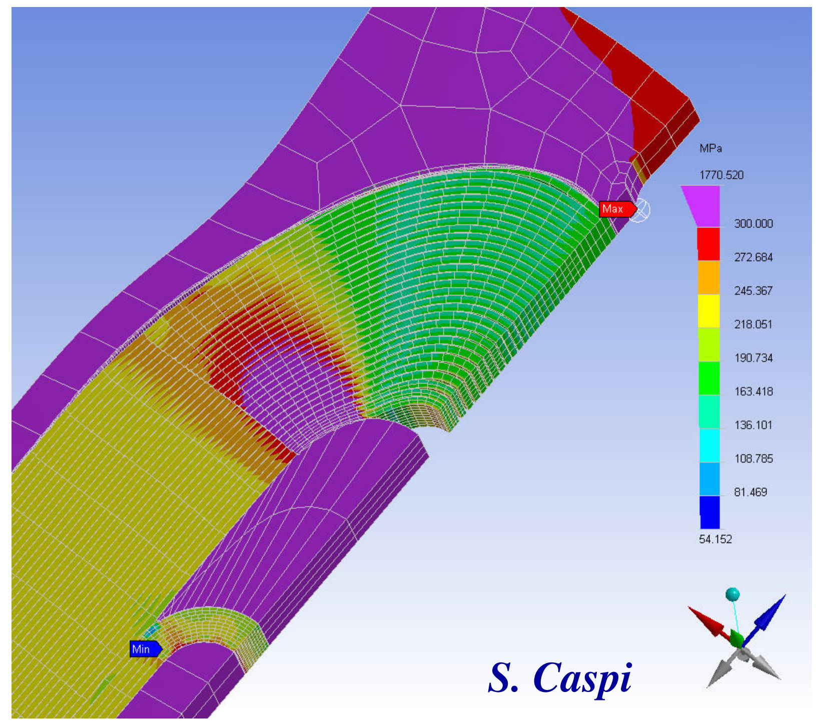
Conductor Performance and SSL

- Accurate and consistent strand I_c measurements (RW & XS)
- Minimal/no cabling degradation for wide (51 strand) cable
- Production wire (54/61) is still improving (both J_c & RRR)
- Further I_c improvement possible using 60/61 conductor
- Different factors affect short sample limit calculation:
  - *Cabling degradation (round or extracted strands)*
  - *Stress degradation (reversible/irreversible)*
  - *Self field correction*
- We intend SSL to represent a magnet performance ***target***
- SSL is achieved under optimal design/execution choices
- *Conductor limited quenches may happen well below SSL*
- *Performance degradation in magnet does not affect SSL*

HD1 Mechanical Support & Analysis

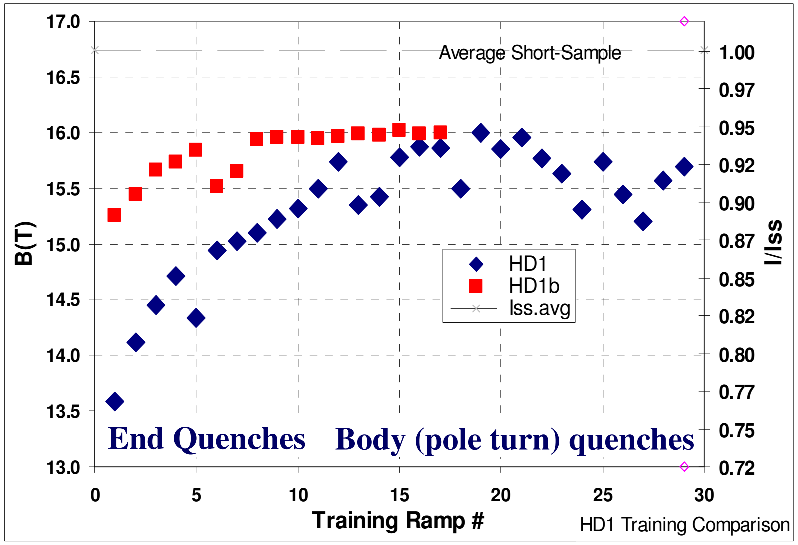
- A full 3D support was implemented in HD1a
- Nevertheless, it was not possible to avoid opening of longitudinal gaps between end spacer and turns
- This situation was improved in HD1b

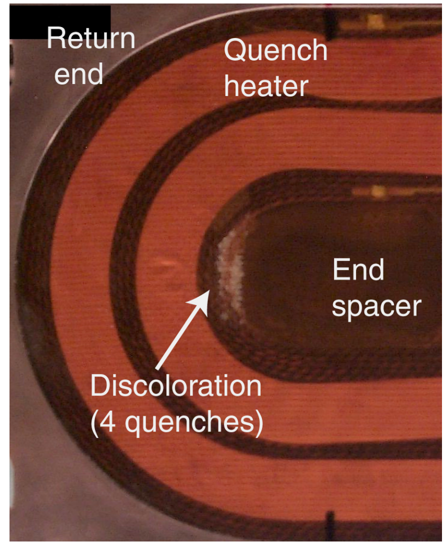


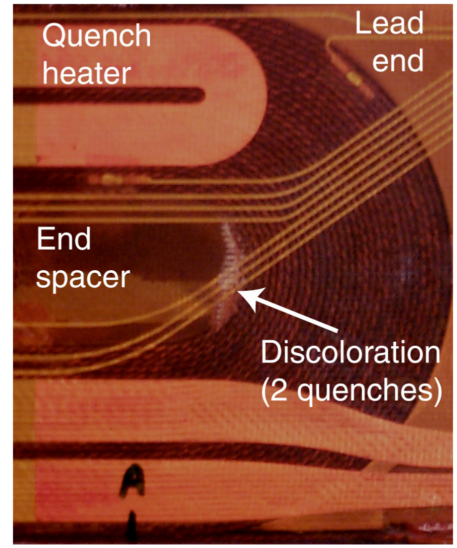


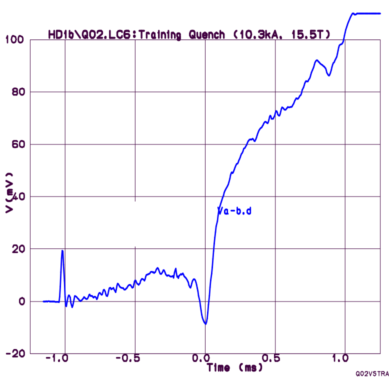
S. Caspi

HD1 End Training

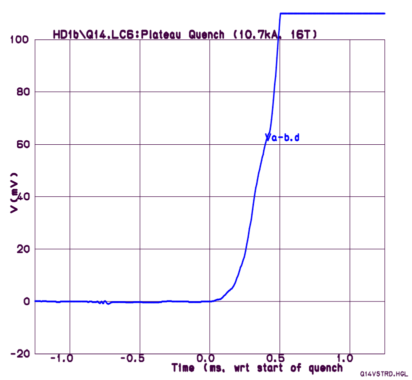




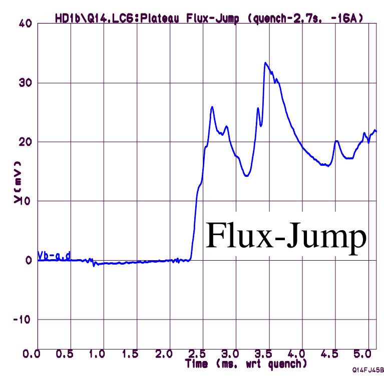




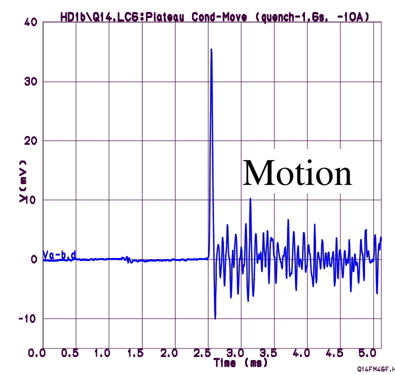
Training Quench #2



Plateau Quench #14



Quench #14 (-16A)



Quench #14 (-10A)

A. Lietzke

HD2 End Support

Despite a more complex configuration, no end quenches or epoxy discoloration were observed in HD2

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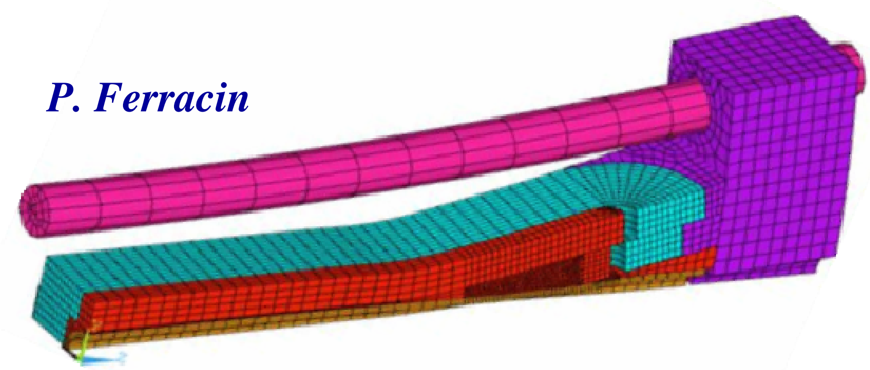
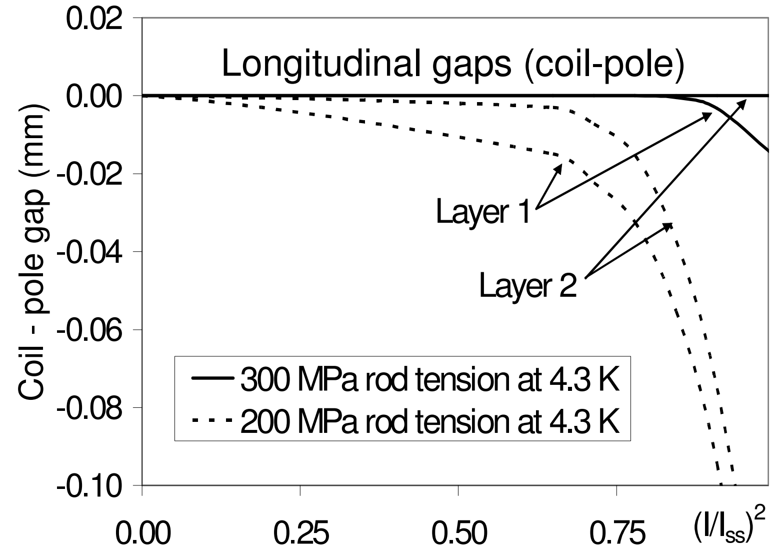
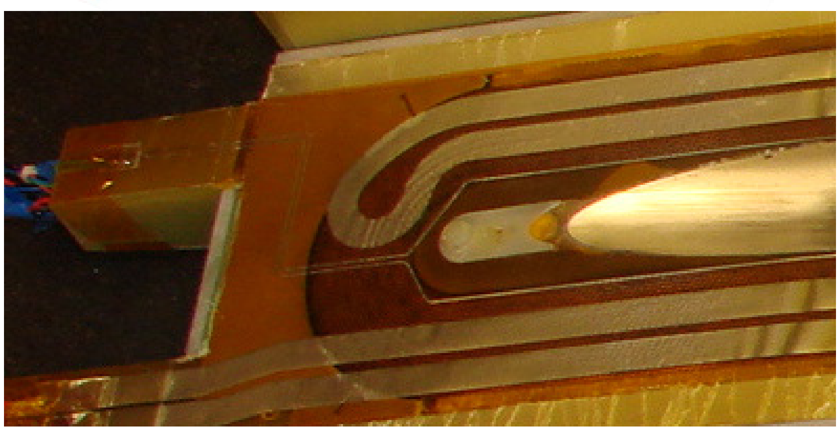
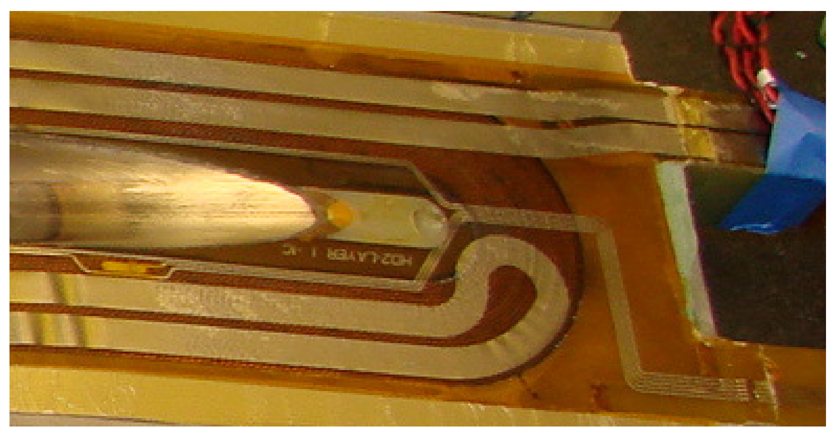




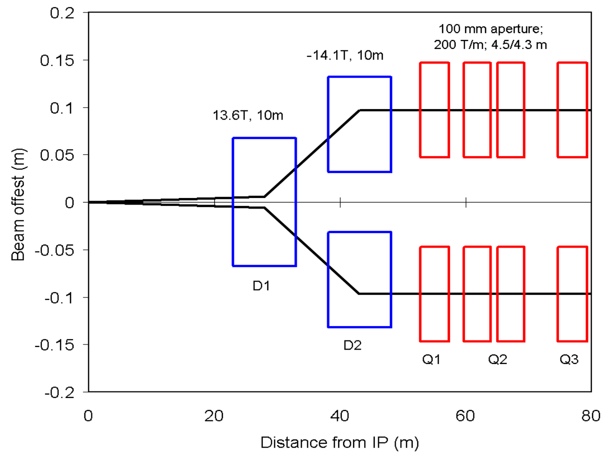


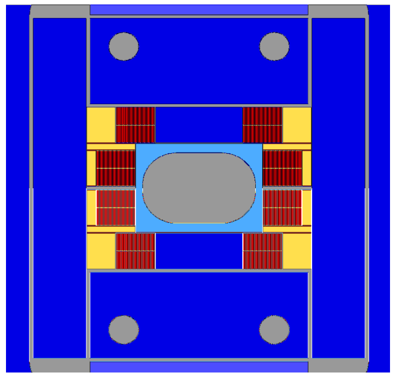


LHC Luminosity Upgrade Magnets

Dipole first optics
⇒ IR Dipoles

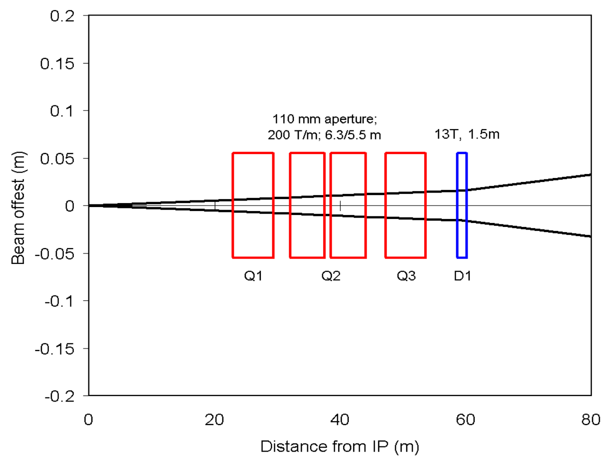
- IR radiation
- Coil stress
- Large aperture
- High field

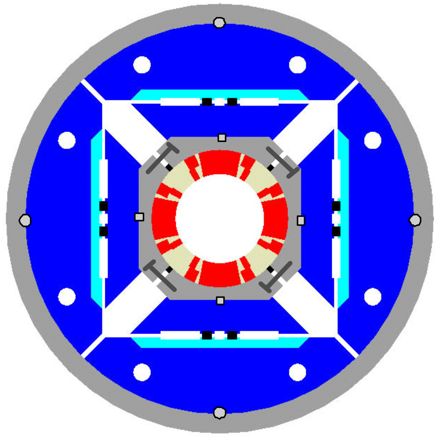




Quad first optics
⇒ IR Quads

- Large aperture
- High gradient
- IR radiation
- Collision FQ





The LHC Accelerator Research Program (LARP) coordinates the IR Quad R&D

Large Aperture IR Dipole

<u>Approach</u>: scale HD2-type coil and structure to full aperture

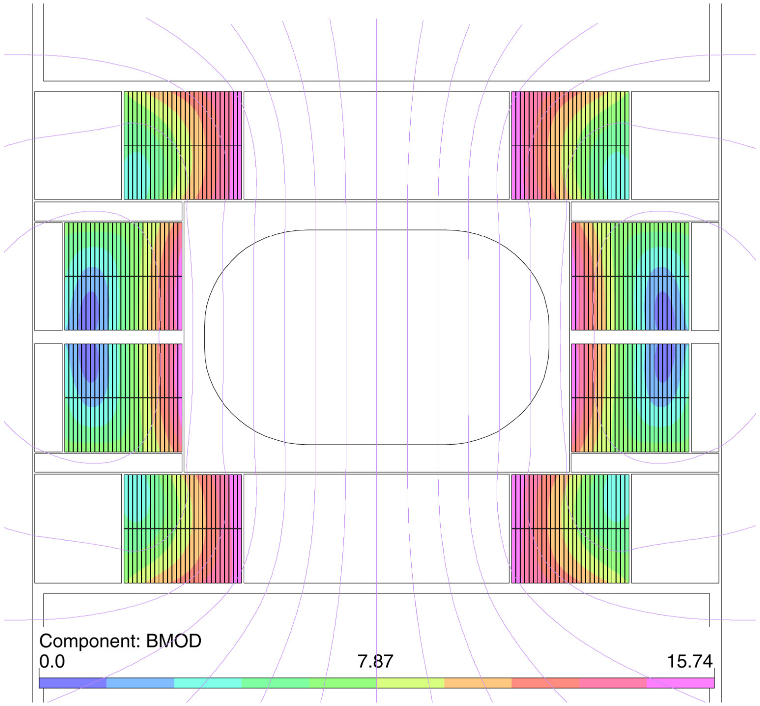
Design features:

- *Target field: 15 T*
- *Clear bore: 150 mm x 100 mm*
- *Strand: 1 mm diam. (with increased sub-elements)*
- *Iron insert in "pole" module*
- *Tilted ends in "mid-plane" module*
- *No conductor at the mid-plane (±3 mm)*

The IR dipole model can also support high field magnet R&D:

- *Cable testing under pressure*
- *HTS insert coils*

Performance Parameters



Harmonics (15 T, 50 mm radius)

All b_n < 20 units (0.2%)

Parameter	Unit	LD1	HD1
Bore field	Tesla	15.9	16.7
Coil field	Tesla	16.7	16.1
Max current	kA	20.2	11.4
Stored Energy	MJ/m	6.0	0.66
Inductance	MH/m	29	10
F_x (quadrant, 1ap)	MN/m	14.4	4.7
F_y (quadrant, 1ap)	MN/m	-7.3	-1.5
Ave. stress (h)	MPa	140	150

Parameter	Unit	LD1	HD1
Strand diameter	mm	1.0	0.8
Ic (16 T, 4.2 K)	A	503	322
No. strands		50	36
No. turns/quadr.		108	69

Support Structure

Aluminum shell:

Thickness:	100 mm
Stress (293K):	50 MPa
Stress (4.3K):	170 MPa

Iron yoke:

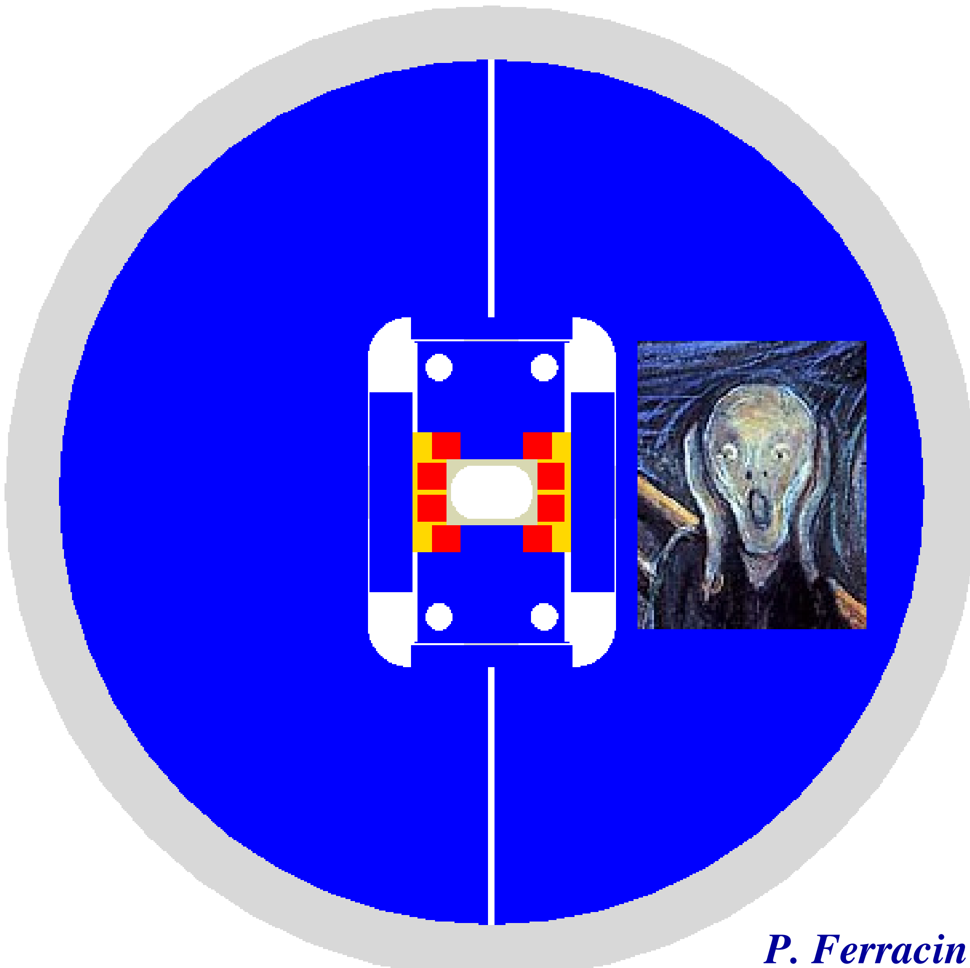
Outer diameter: 1.6 m

Assembly bladders:

Width:	100 mm
Pressure:	50 MPa

Bore:

Width:	150 mm
Height:	100 mm



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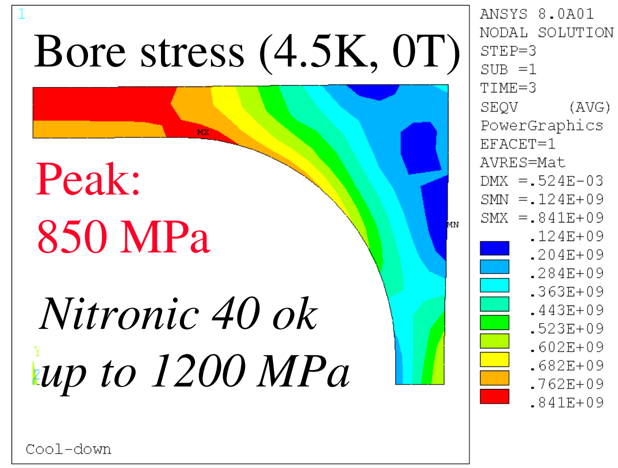
Forces and Stresses

Layer 1 Lorentz forces:

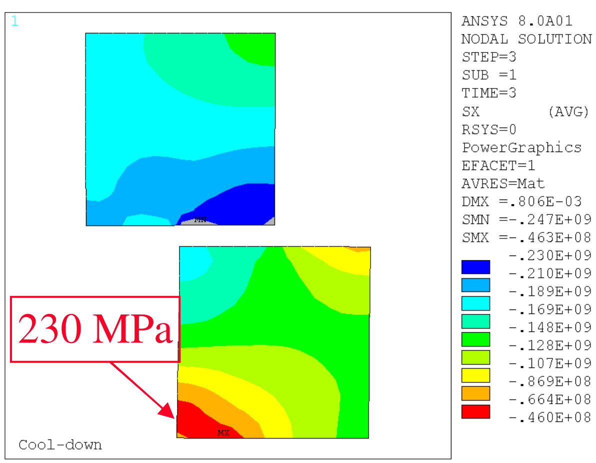
- Fx = + 5.6 kN/mm (115 MPa)
- Fy = - 2.1 kN/mm (45 MPa)

Layer 2 Lorentz forces:

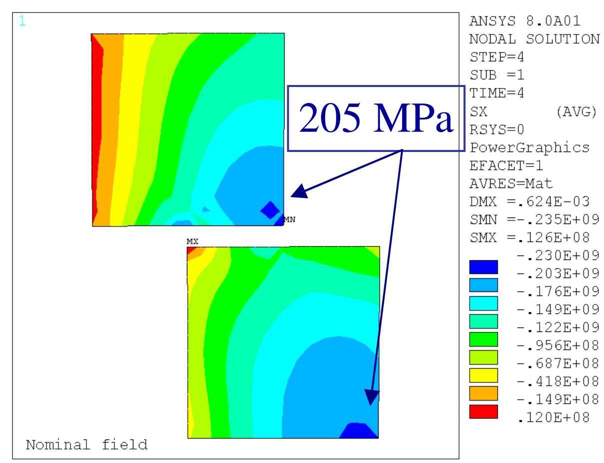
- Fx = + 8.9 kN/mm (165 MPa)
- Fy = - 5.1 kN/mm (100 MPa)



Cool-down



Nominal field (15 T)



Coil stresses are presently too high, but the design is not fully optimized

Quench Protection Parameters

<u>Quench heater design:</u>

- Stainless steel (23 mm thick) with distributed Cu 12 mm thick foil
- Heater is contained between two layers of Kapton
- Active sections are 210 mm long, 42% of total magnet length
- Two Heater Power Supplies (450V, 24mF)
- Each coil modules has one layer powered by each of the supplies

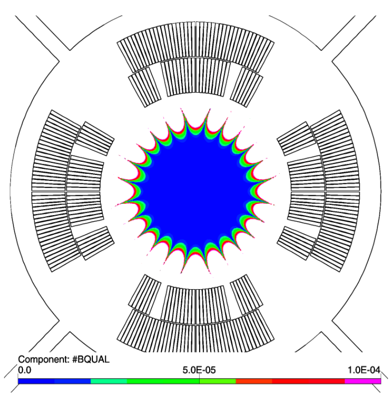
Number of PS powered	Capacitance mF	RC constant ms	Voltage V	Tpeak K
2	24	41	340	150
1	24	41	340	180

IR Quadrupoles (LARP)

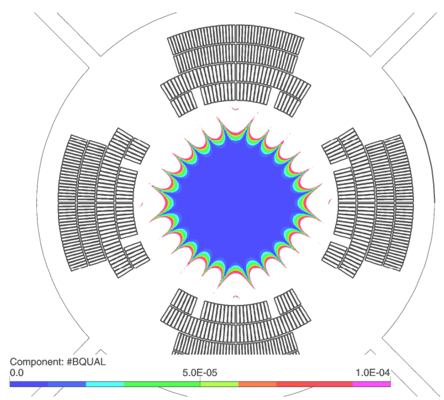
Cos2θ was selected as the best option for Large Aperture IR Quads

Parameter	Cos2θ (2L)	Cos2θ (4L)	Block (2L)	Racetrack (4L)
G_{ss} (T/m) (*)	245	265	230	234
$b_{6, 10, 14, 18}$ @ 22 mm	< 0.05	< 0.05	< 0.05	< 0.07
Inductance (mH/m)	4.9	23.7	4.8	14.2
$J_{cu}^{(ss)}$ (A/mm^2)	1.5	1.4	1.5	1.5
SC area (cm^2)	46.5	48.5	47.8	51.4

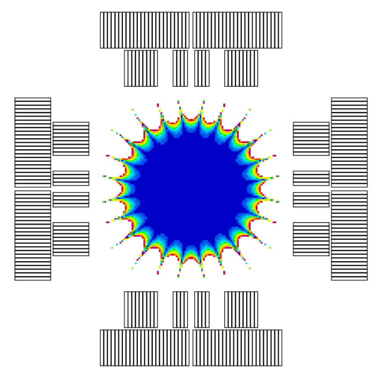
(*) J_c (12T, 4.2K) = 2.4 kA/mm^2 and T_{op} = 1.9 K; actual yoke geometry; 90 mm aperture at the main quadrupole axes

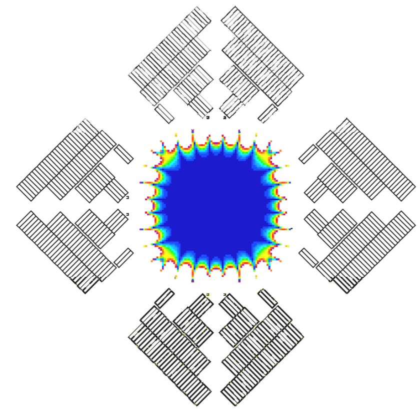


Cos2θ (2L)

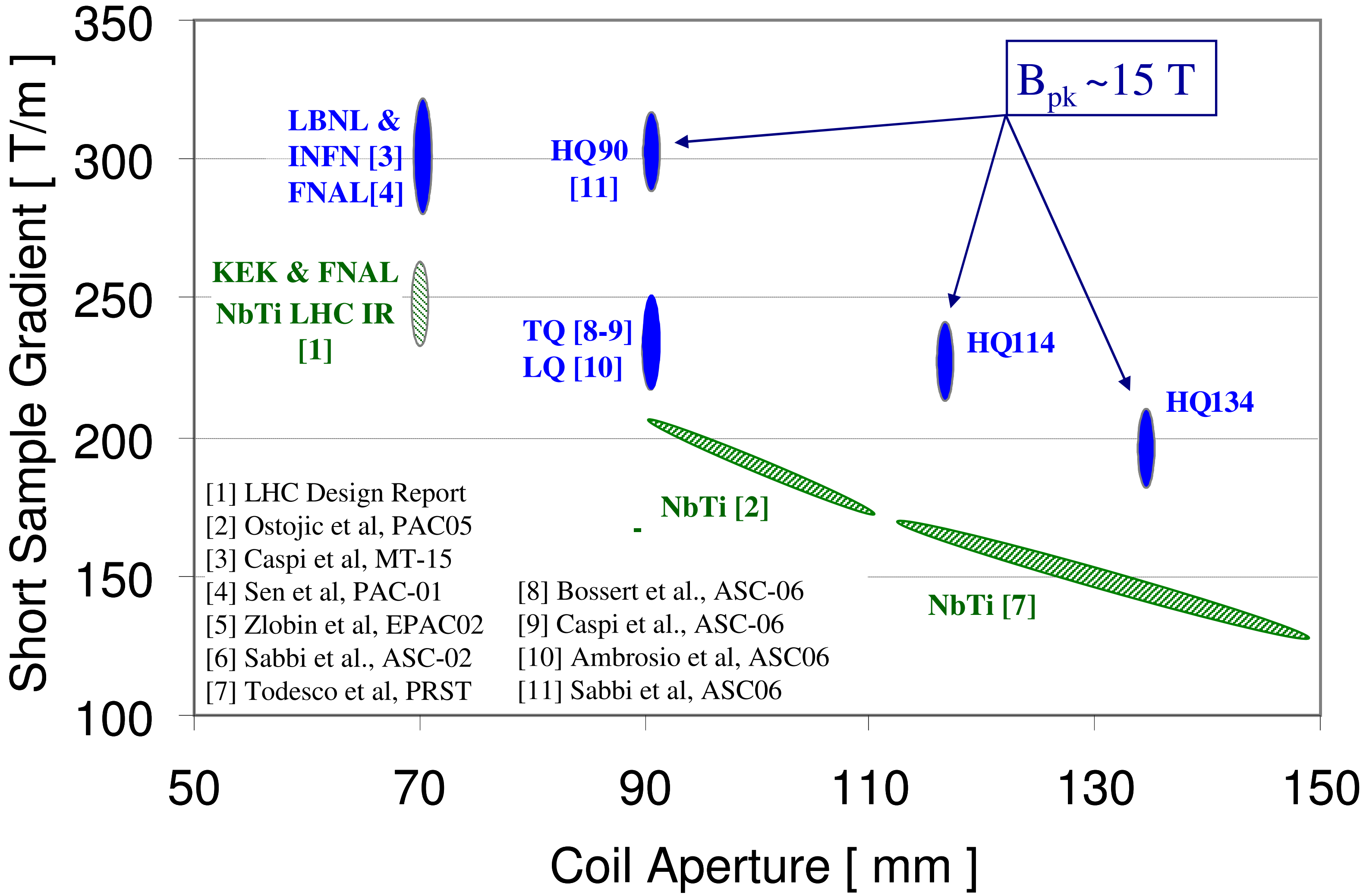


Cos2θ (4L)


Block (2L)


Racetrack (4L)

Quadrupole Design Space



HQ Design Study (LARP)

HQ Goals:

1. Investigate ultimate performance levels for Nb_3Sn Quads
2. Provide input for defining the upgrade optics and layout

R&D Issues:

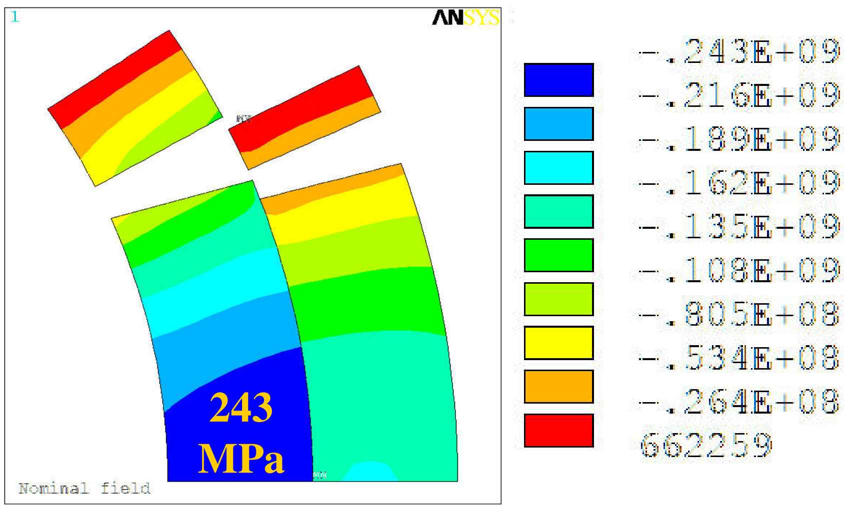
- Materials: conductor, cable, insulation
- Coil design optimization (magnetic & mechanical)
- Structures to handle large forces and stresses
- Achievable Field Quality and Alignment
- Quench Protection parameters and requirements
- Thermal margins and cooling requirements

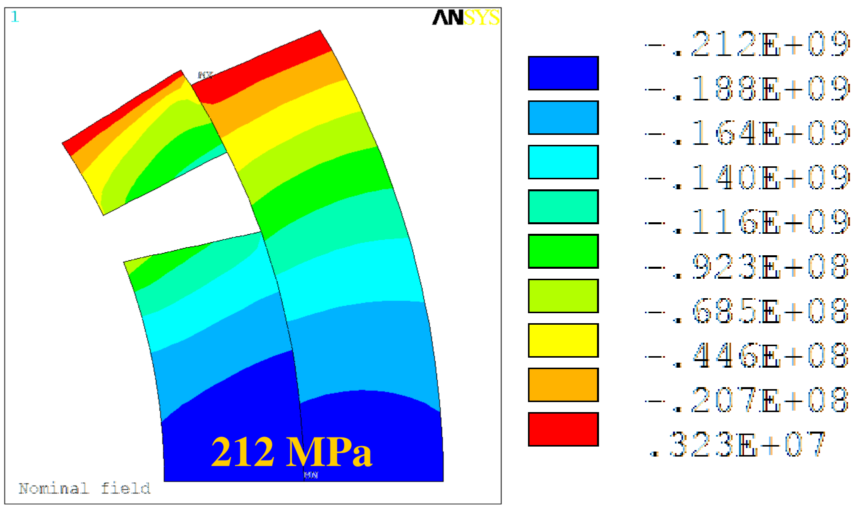
High Coil Stress was identified as the most critical issue for HQ

Coil Design Optimization

Mechanical consideration are driving the HQ coil cross-section design

Lorentz stress in an infinitely rigid structure (L1/L2 sliding, no friction)



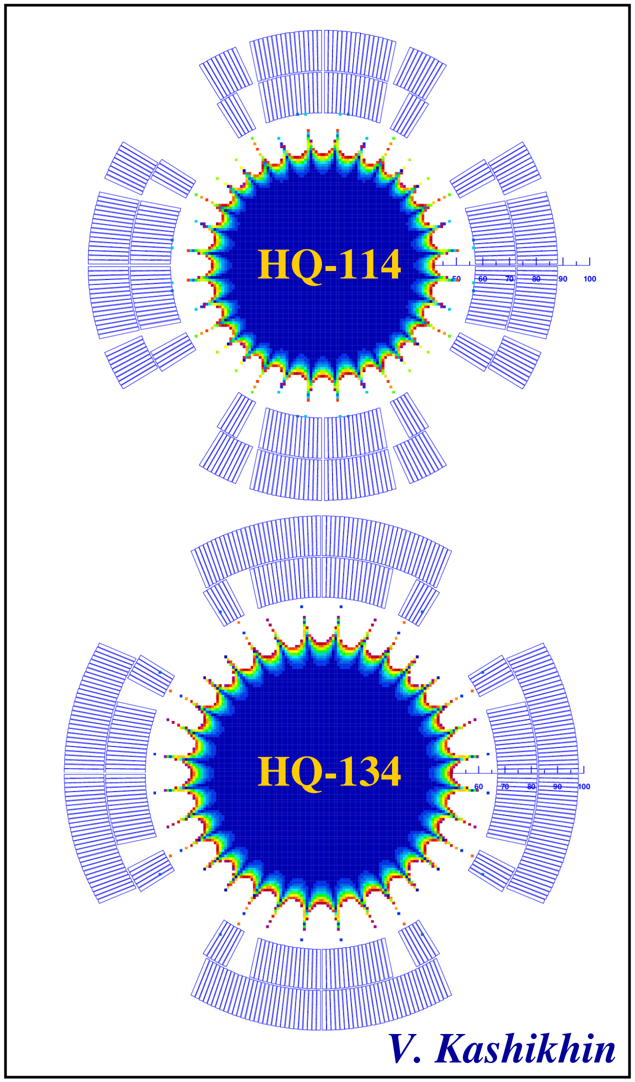


Aperture: 134 mm
Gradient: 200 T/m
F_θ layer 1 = -3.58 MN/m
F_θ layer 2 = -2.46 MN/m

Aperture: 134 mm
Gradient: 200 T/m
F_θ layer 1 = - 2.7 MN/m
F_θ layer 2 = - 3.4 MN/m

H. Felice

Optimized Cross-sections



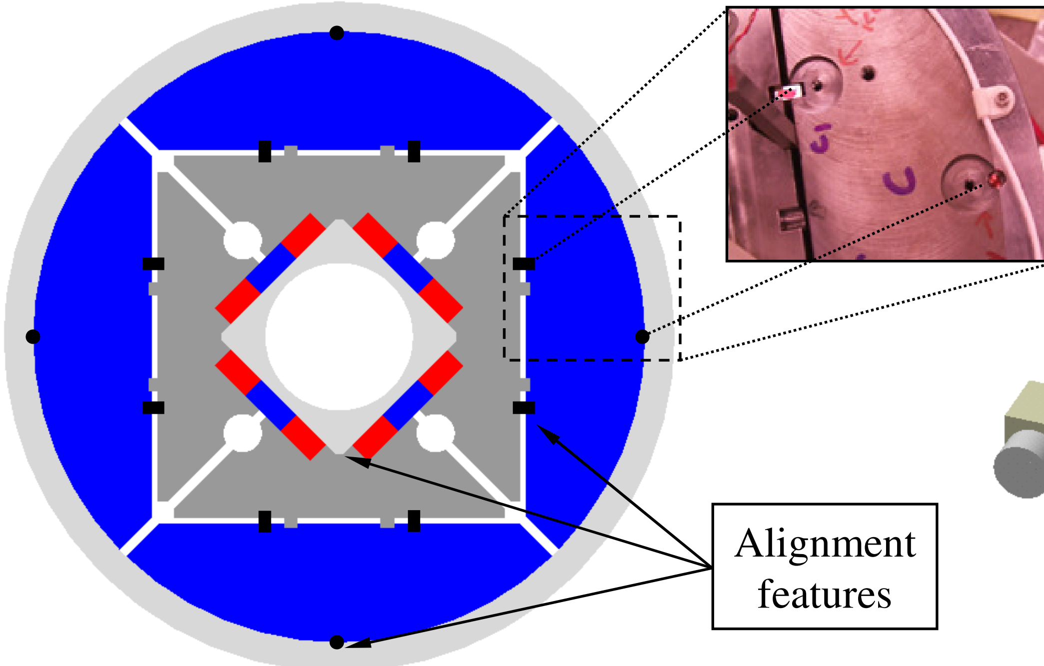
Parameter	Unit	HQ114	HQ134
Gradient (1.9K)	T/m	234	201
Coil field	Tesla	15.4	15.7
Max current (I_{ss})	kA	19.2	18.2
Stored En. @ I_{ss}	MJ/m	1.3	1.7
Inductance @ I_{ss}	MH/m	7.2	10.4
F_x (quadrant)	MN/m	3.62	4.7
F_y (quadrant)	MN/m	-4.7	-1.5
F_θ (inner layer)	MN/m	2.5	4.0
F_θ (outer layer)	MN/m	3.0	-5.2
Pole width	mm	22.4	26.4
$b_{6-10-14}$ @ 45 mm		<0.15	<0.02
Strand diameter	mm	0.8	0.8
Ic (16 T, 4.2 K)	A	322	322
No. strands		35	35
Cable width	mm	15.15	15.15
Keystone angle		0.75	0.75
No. turns/quadr.		19/25	22/30

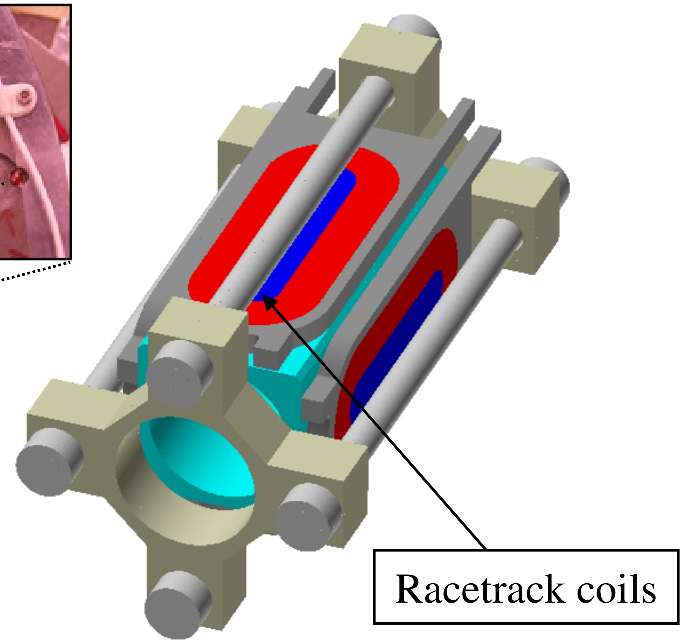
Quadrupole Parameters

	TQS	HQ114	HQ134	HD1	RD3
Temperature (K)	1.9	1.9	1.9	4.5	4.5
Short sample current (kA)	15.1	13.5	10.6	11.4	10.8
Coil peak field @ S.S. (T)	13.5	15.4	15.7	16.1	14.8
Stored Energy (MJ/m)	0.56	1.3	1.7	0.66	1.2
Inductance (mH/m)	5	7	11	11	22
Fx (MN/m)	4.2	3.6	4.7	4.7	3.7

HQ parameters are very challenging but comparable to those that were achieved in the HD and RD series

SQ End Load Studies





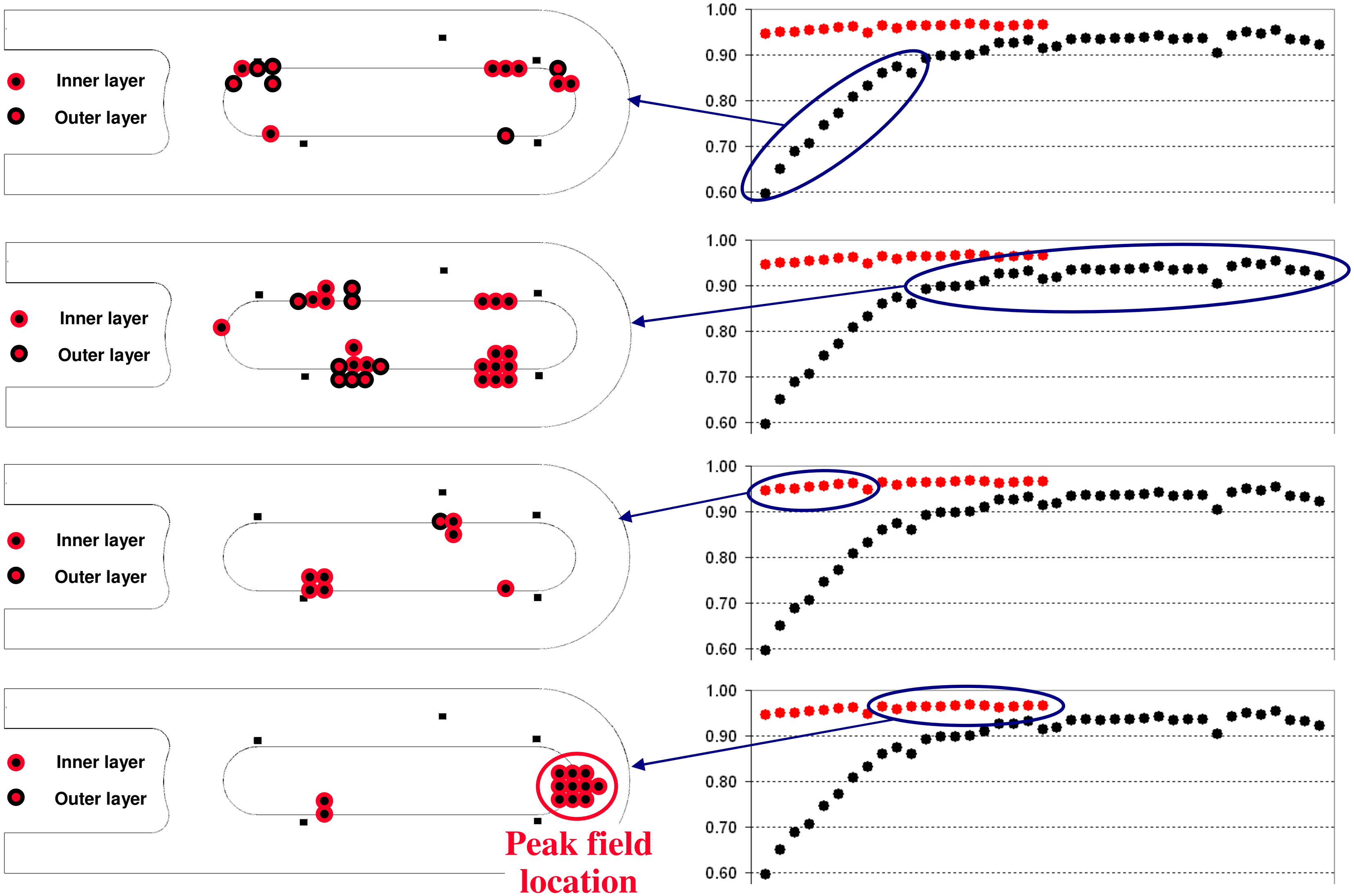
<u>Transverse support</u>:

- Aluminum shell, 22 mm thick
- Stainless steel pads
- Alignment features included
- Aluminum bore, <u>110 mm</u> ID

<u>Axial support</u>:

- Four aluminum rods (D=25 mm)
- Rods are located next to coils
- Stainless steel end plate (50 mm)
- Strain gauges on shell and rods

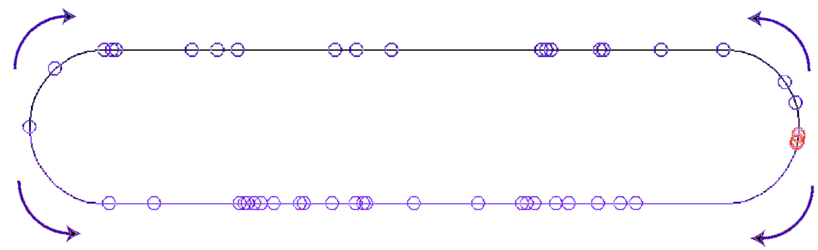
SQ02 Quench Training



SQ02 Quench Analysis

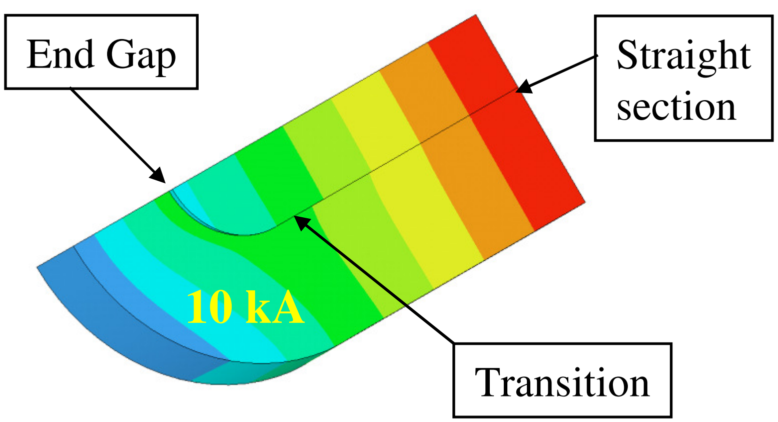
Measurements:

- *All quenches in the innermost turn*
- *Trend from end to central segments*

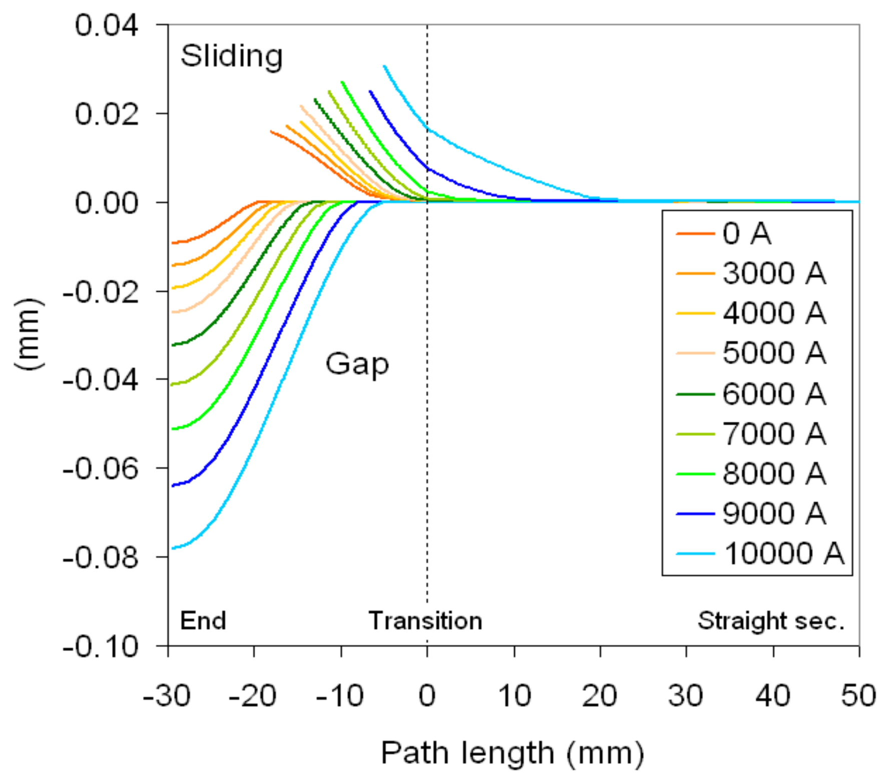


Finite element model:

- *Gaps in the ends*
- *Sliding in the straight section*

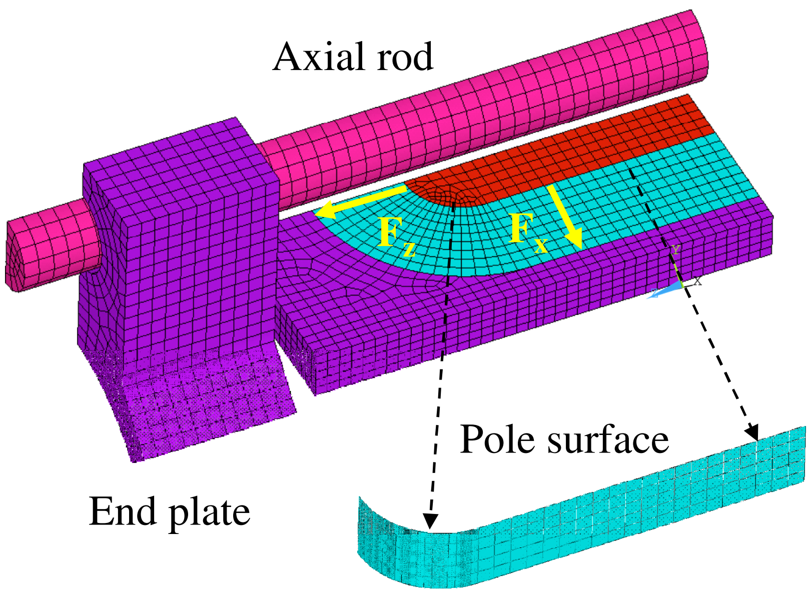


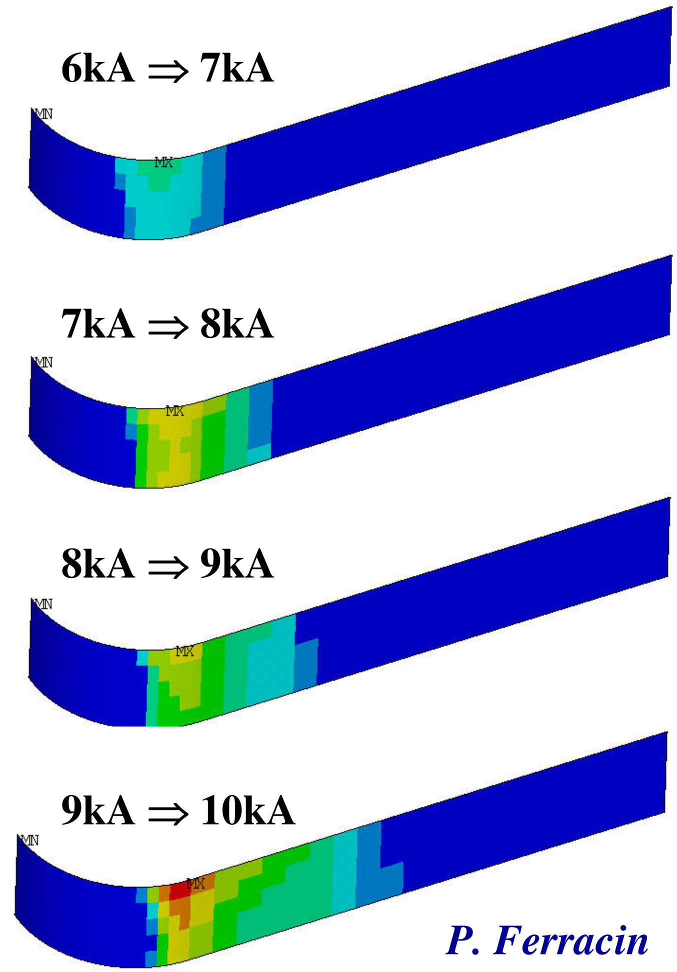
P. Ferracin



Frictional Energy Dissipation

Pole-turn sliding under friction models quench patterns & training





- Friction factor → μ (0.2)
- Sliding distance → δ [m]
- Contact frictional stress → σ [N/m^2]
- Frictional energy density → σ δ [J/m^2]

P. Ferracin

Magnet R&D Goals

- Achieving the required field is the first goal of magnet development
- Design simplifications may help to focus R&D on fundamental issues
- However, all accelerator quality issues need to be ultimately addressed
- Complete qualification program to demonstrate accelerator quality

Technical requirements:

- Aperture
- Field quality
  - *Geometric*
  - *Saturation*
  - *Persistent currents*
  - *Eddy currents*

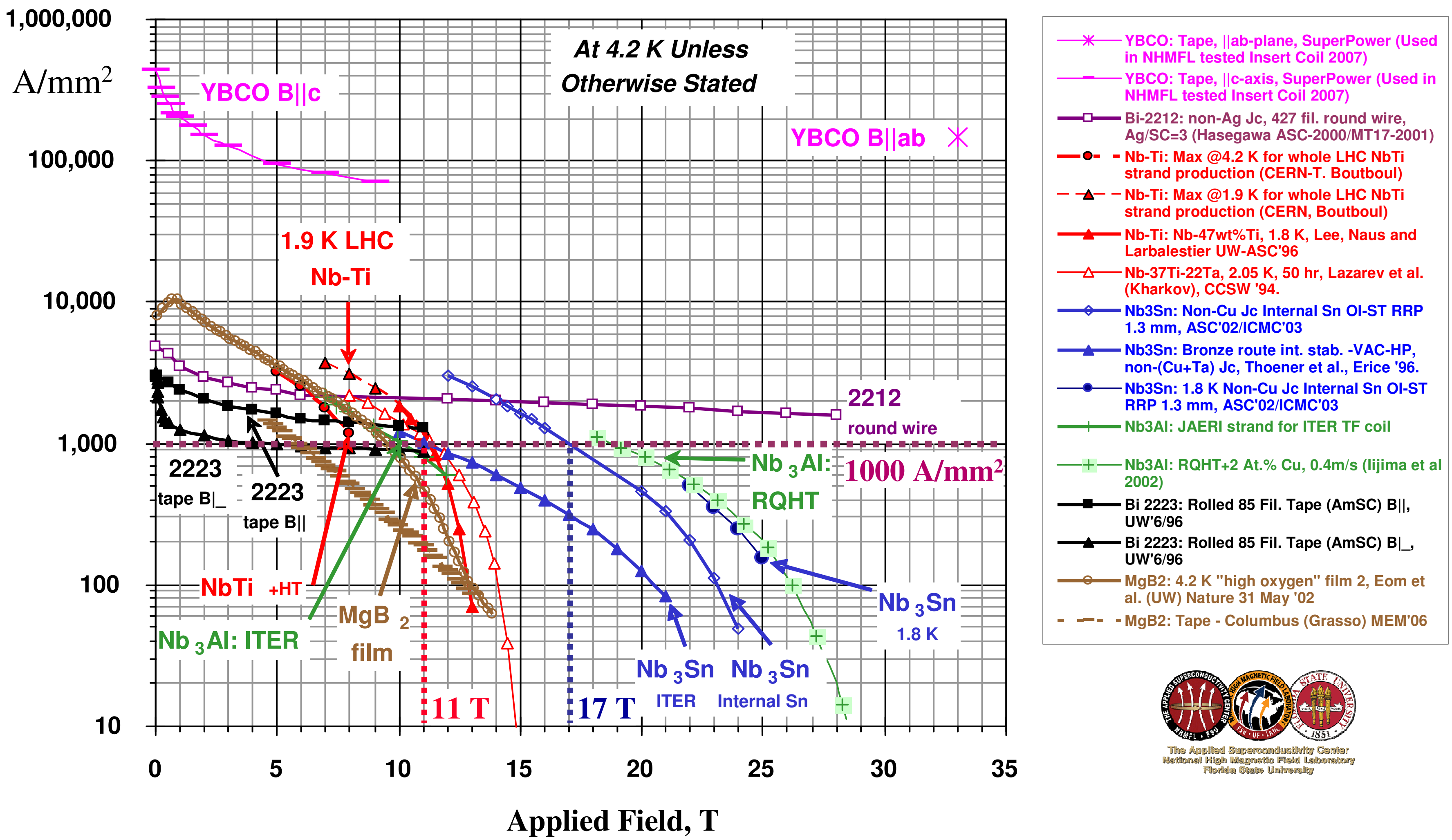
Efficiency/cost requirements:

- Minimize training
- Operate close to critical surface
- Minimize conductor & structure cost
- "Simple", reliable fabrication procedures
- Lifetime under radiation load
- Fabrication in Long Lengths

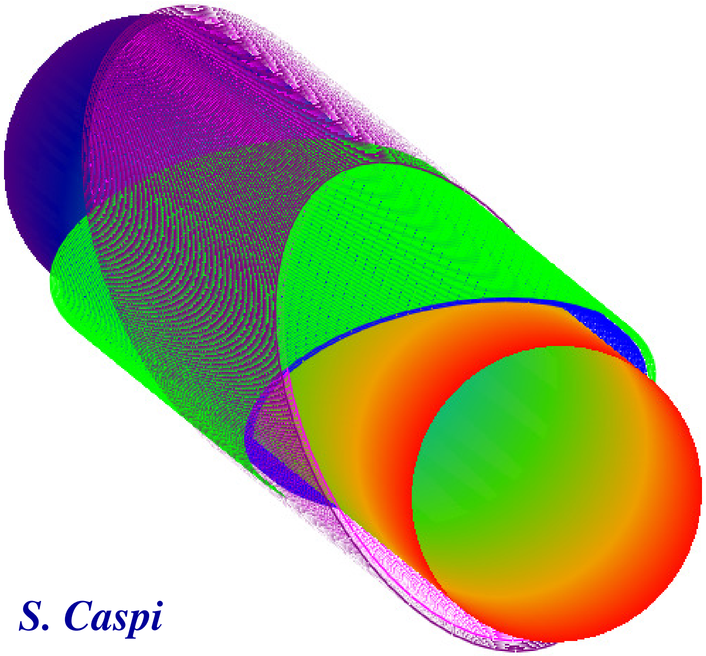
Accelerator Quality magnets must meet both technical and cost targets

Beyond ~18 T: HFS (Bi-2212 & YBCO)

Superconductor critical currents (P. Lee, Applied Superconductivity Center, FSU/NHMFL)

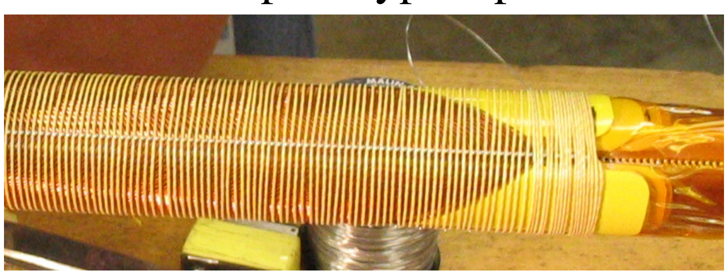


Helical Inserts for Higher Field



S. Caspi

NbTi prototype dipole



Superimposed solenoids with alternating tilt

- Combined field is perfect dipole (Meyer, 1969)
- Use as high-field insert in magnet bore:
  - *Continuous winding with larger radius*
  - *Small quantities of conductor*
  - *Small mass for heat treatment*
  - *May be compatible with YBCO*

R&D Issues:

- Effective J_e (insulation, winding forms, tilt)
- Accuracy of conductor positioning
- Application of pre-load
- Axial forces in winding body
- Force distribution in coil ends
- Inductance & magnet protection

Summary

Progress:

- Established a **technology foundation for fields up to 15 T**
- Expanding the **accelerator magnet design toolbox**
- Improved **analysis of magnet behavior**

Challenges: accelerator quality and fields beyond 15 T

- **Materials**: superconductors, insulation, structural
- **Coil design:** efficiency, simplicity
- **Coil fabrication technologies**
- **Mechanical structures** and **stress limits**
- **Alignment and Accelerator Quality**