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BNL - FNAL - LBNL - SLAC

High Field Nb_3Sn Magnets

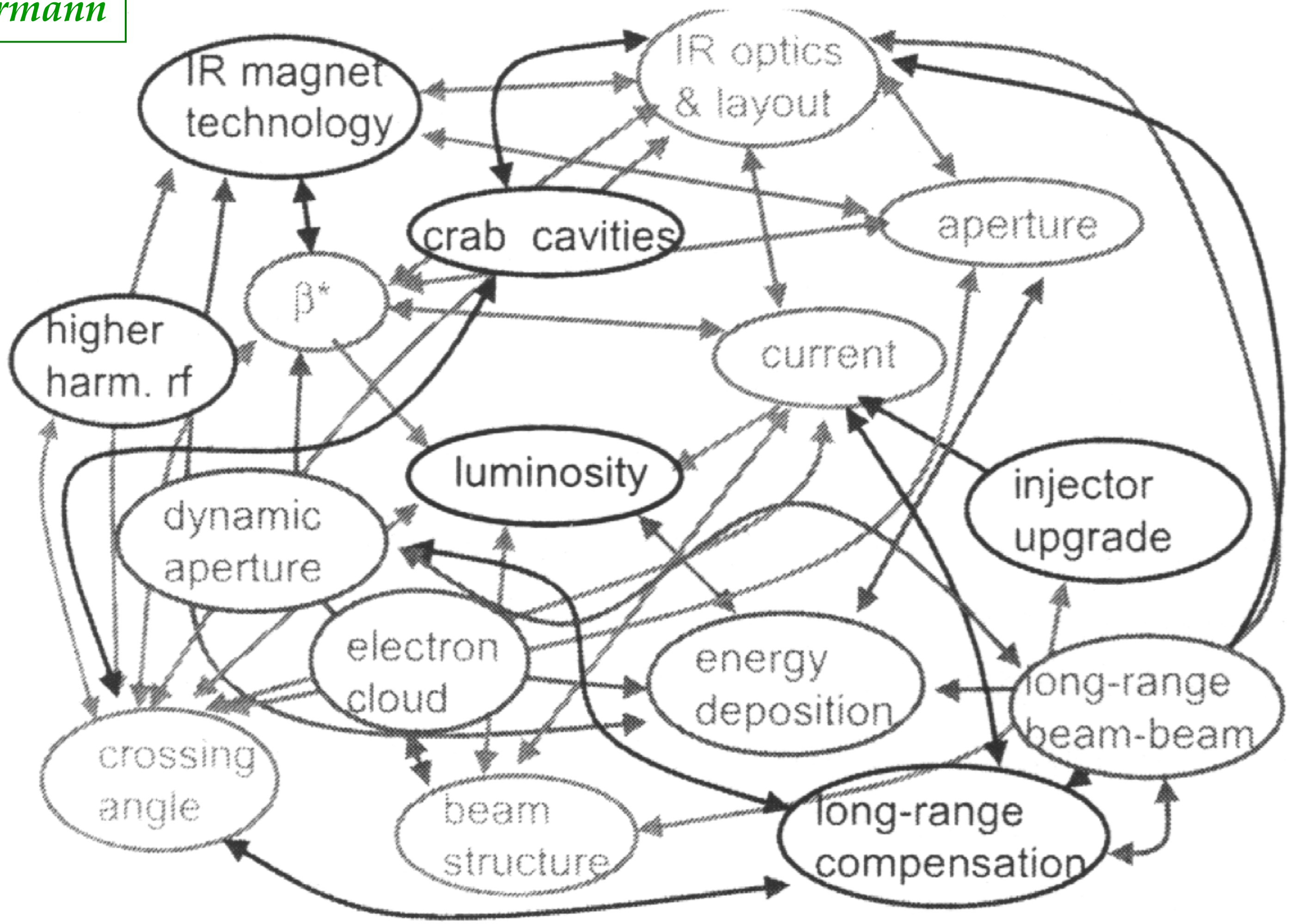
IR'07 Workshop

Frascati, November 7-9, 2007

Gian Luca Sabbi

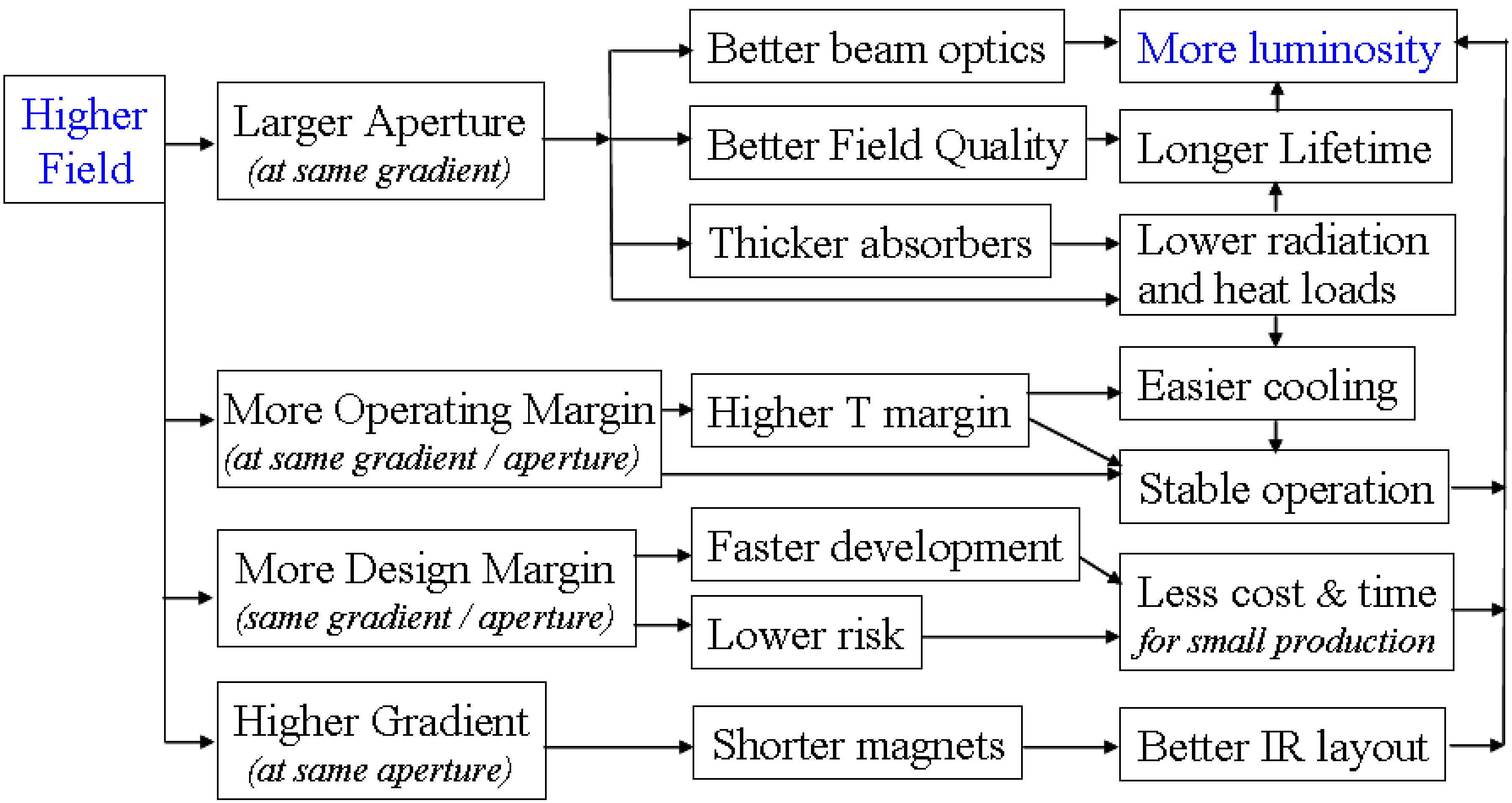
IR Upgrade Roadmap

F. Zimmermann



Quad Upgrade Roadmap

Access to higher fields ⇒ better performance and more design options



HQ Goal: Demonstrate Coil Field >15 T

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HQ Design Study (FY06-07):

1. Investigate design options in preparation for model fabrication:
   - Magnetic, mechanical and quench analysis
   - R&D issues, magnet parameters and features
2. Provide input to LHC IR quad conceptual design and analysis:
   - Optics, IR layout, radiation deposition, cryogenics studies

R&D Issues:

- Materials: conductor, cable, insulation
- Coil design efficiency (magnetic & mechanical)
- Structures to handle large forces and stresses
- Quench Protection parameters and limits
- Analysis and diagnostics

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

From TQ to HQ

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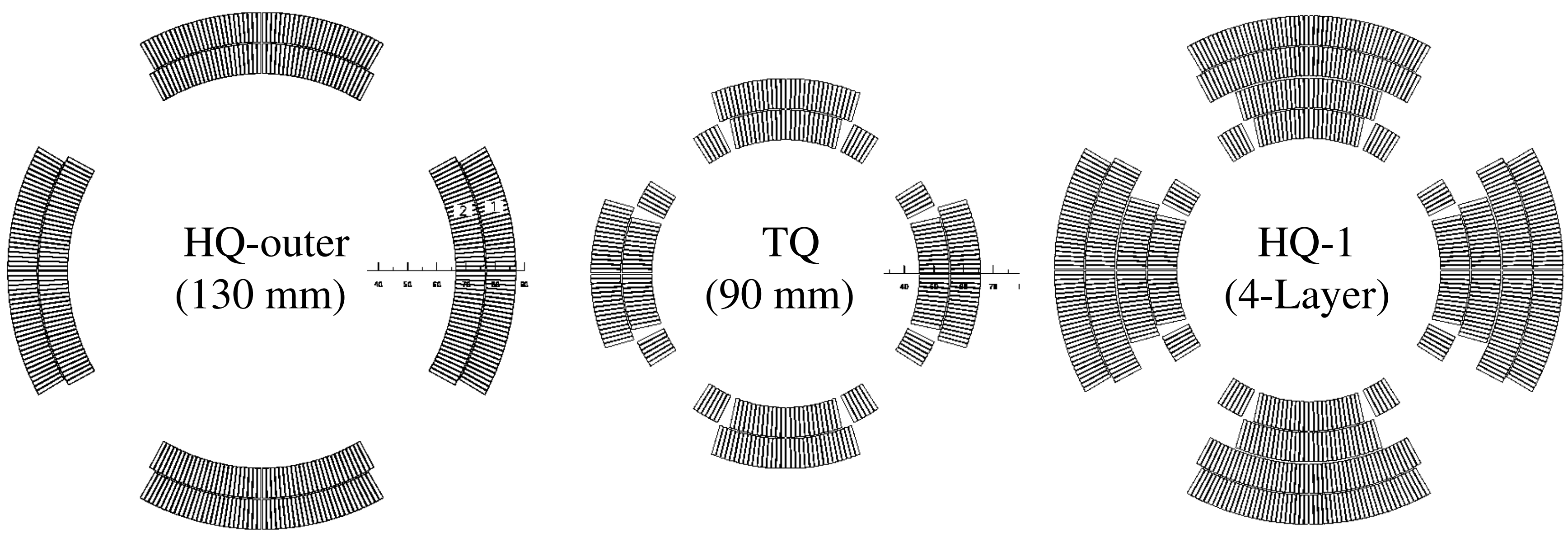
<u>Initial strategy</u>: Use a 4-Layer design with the TQ coil as inner double-layer

<u>Implementation</u>: 1) Build and test outer double layer (~130 mm aperture)
2) Assemble 4-layer magnet using existing TQ coils

<u>Motivation</u>: Addresses main R&D goals: 15 T coil field, high stresses
Two aperture data points with only one set of new coils
Can use TQ strand and cable with small modifications



Field, Energy and Force Comparisons

	TQS	HQ1out	HQ1	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	14.5	15.7	16.1	14.8
Stored Energy (MJ/m)	0.56	1.1	1.46	0.66	1.2
Inductance (mH/m)	5	12	26	11	22
Fx (MN/m)	4.2	2.7	4.1	4.7	3.7

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

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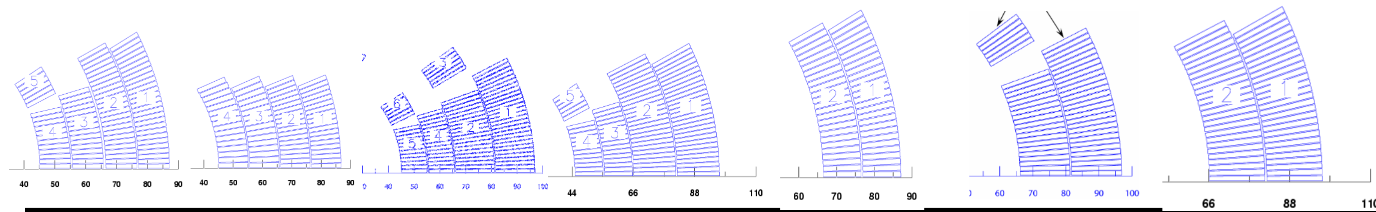
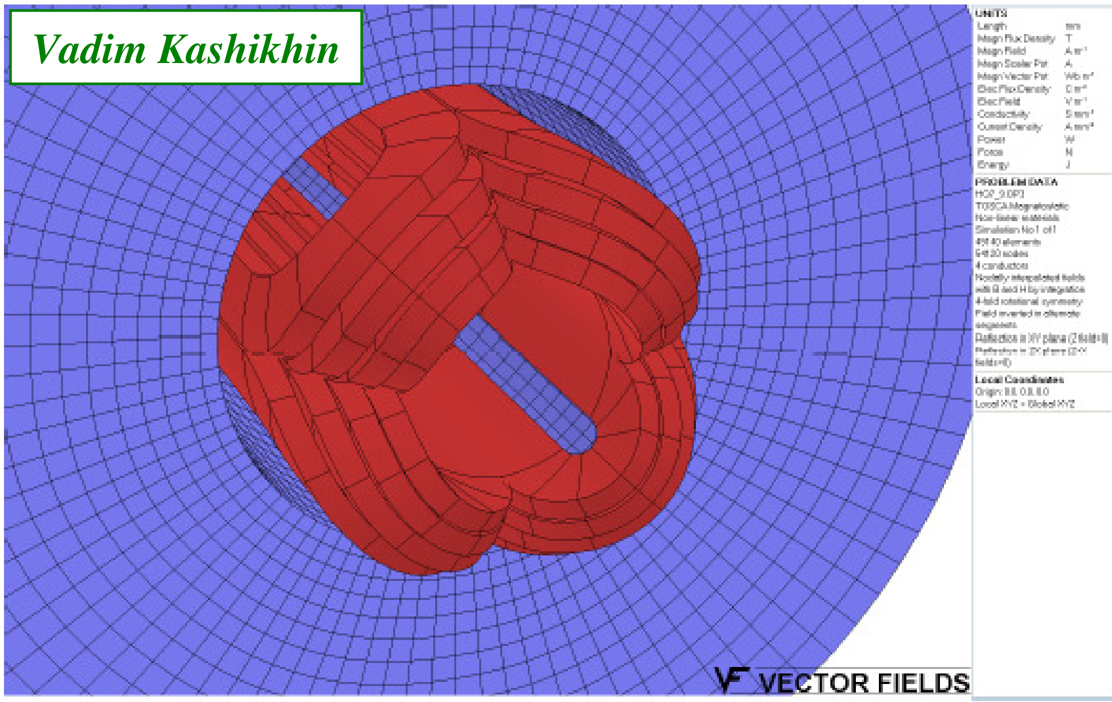
Magnetic Design Studies

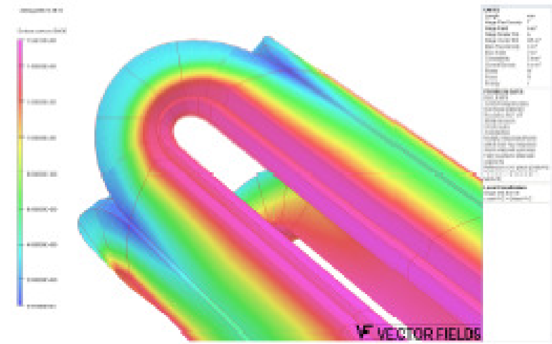
Vadim Kashikhin,
Helene Felice &
Paolo Ferracin

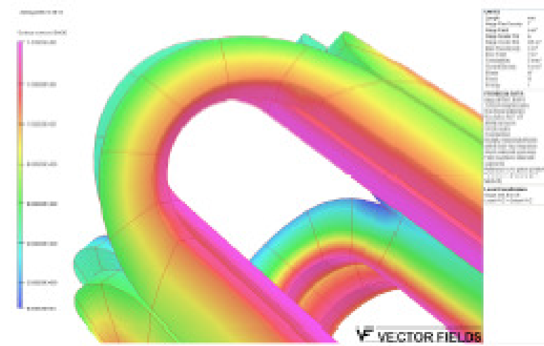


	HQ1	HQ2	HQ3	HQ4	HQ1out	HQ3out	HQ1out*
Aperture (mm)	90	90	**90**	90	130	**130**	130
Cable width (mm)	10	10	**10/15**	10/15	10	**15**	15
SS Gradient	312	319	**308**	307	185	**205**	204
I short sample (kA)	10.6	12.45	**11.01**	10.87	13.5	**17.03**	16.5
SS Peak field (T)	15.74	16.03	**15.49**	15.49	14.53	**15.37**	15.59
Stored Energy (MJ/m)	1.46	1.46	**1.49**	1.5	1.1	**1.65**	1.63
Inductance (mH/m)	26	18.8	**24.58**	25.39	12.1	**11.38**	11.97
Fx (MN/m)	4.13	3.85	**4.25**	4.14	2.73	**3.9**	3.67
Fy (MN/m)	-5.28	-5.18	**-5.33**	-5.22	-3.48	**-5.14**	-4.85

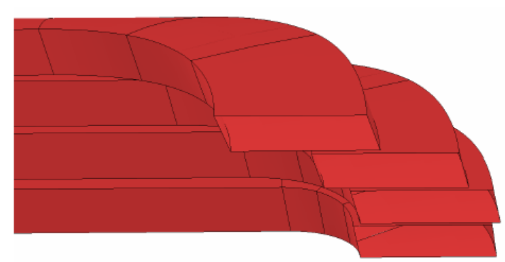
Coil End Optimization





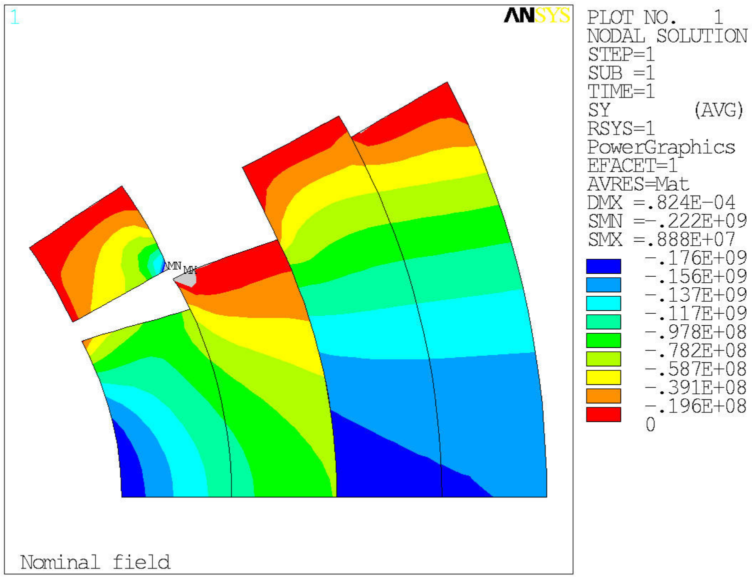


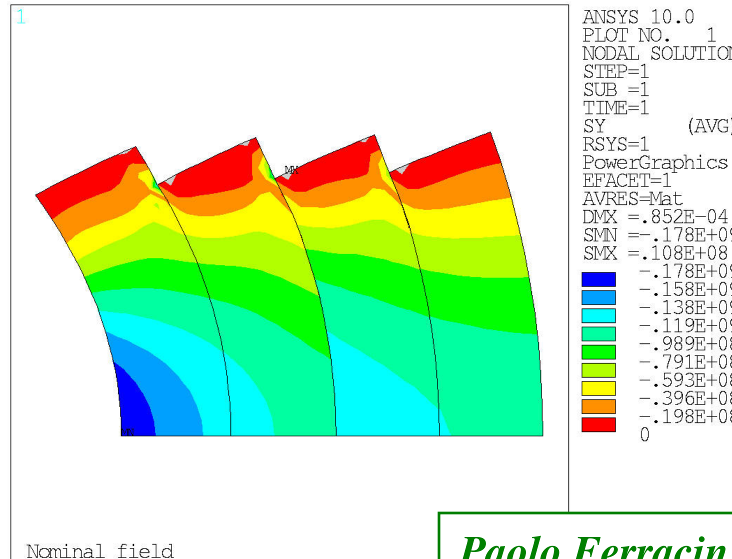
№	Offsets, mm					End length, mm	B_p^{end}, T			
	BL 1	BL 2	BL 3	BL 4	Yoke		BL 1	BL 2	BL 3	BL 4
9	380	371	355	328	328	97.4	13.96 (-1.50) [-9.7%]	13.43 (-2.03) [-13.1%]	13.47 (-0.67) [-4.7%]	13.10 (-1.04) [-7.3%]



Coil Stress (Lorentz force, rigid structure)

Stress considerations were taken into account in the cross-section optimization





Paolo Ferracin

LORENTZ STRESS AT 300 TESLA/METER (MPA)

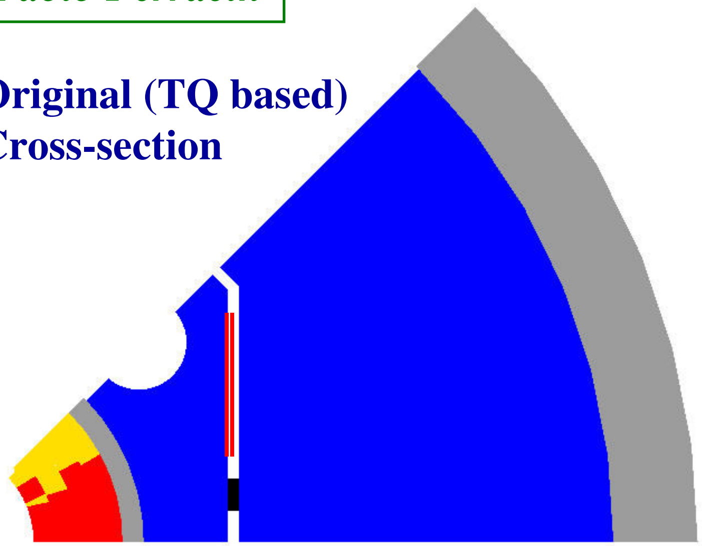
Coil	ANSYS (Fig 3)		Mid-plane stress: ΣF_θ/(layer width)			
Design	L1&2	L3&4	L1	L2	L3	L4
HQ1	176	167	139	98	179	150
HQ2	178	131	148	143	159	114

Coil Stress during Pre-load

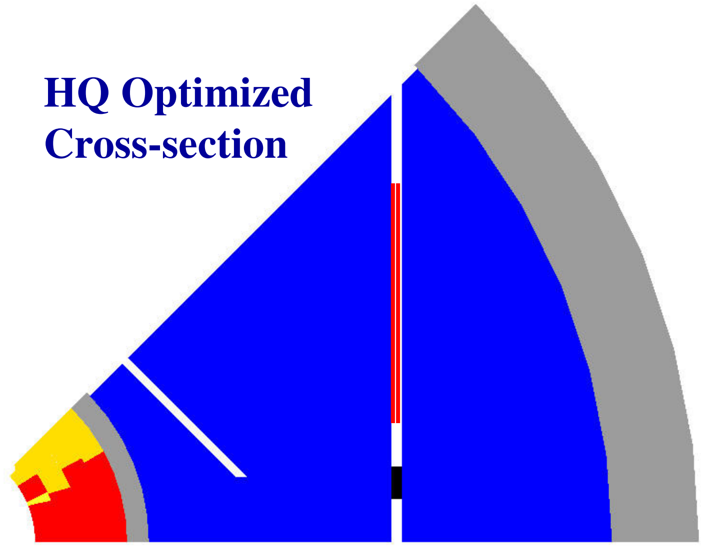
Helene Felice,
Paolo Ferracin

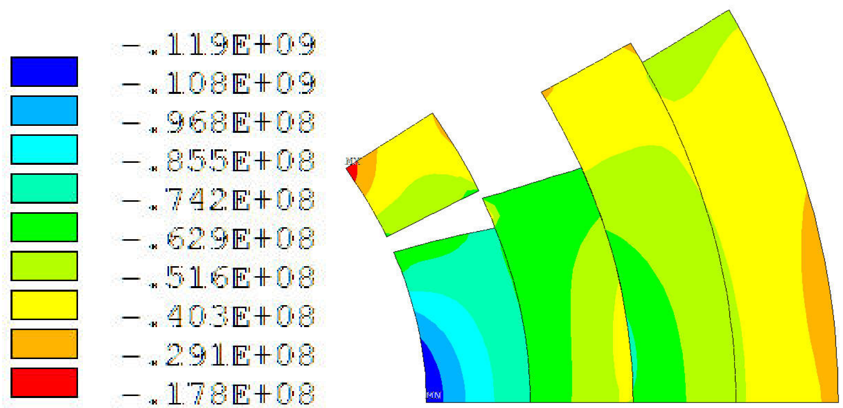
450 mm +50 mm clearance ⬄ 40 MPa in two 60 mm bladders

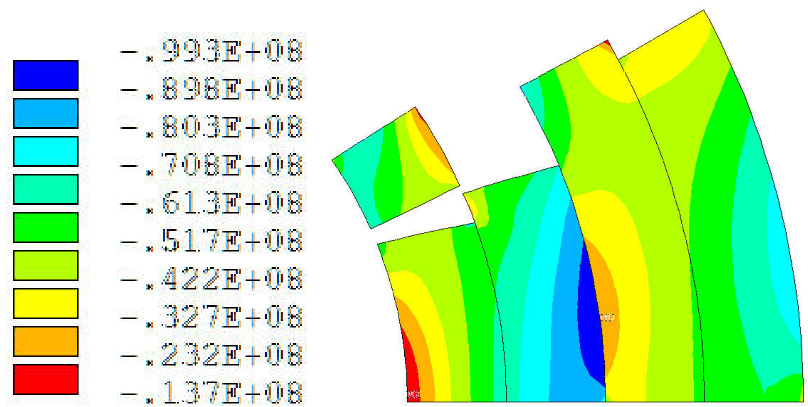
Original (TQ based) Cross-section



HQ Optimized Cross-section







Optimization of Load Key Position

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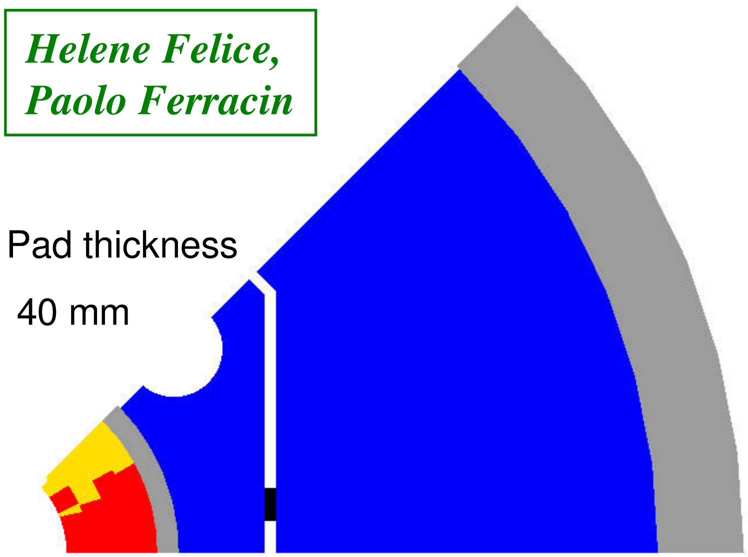
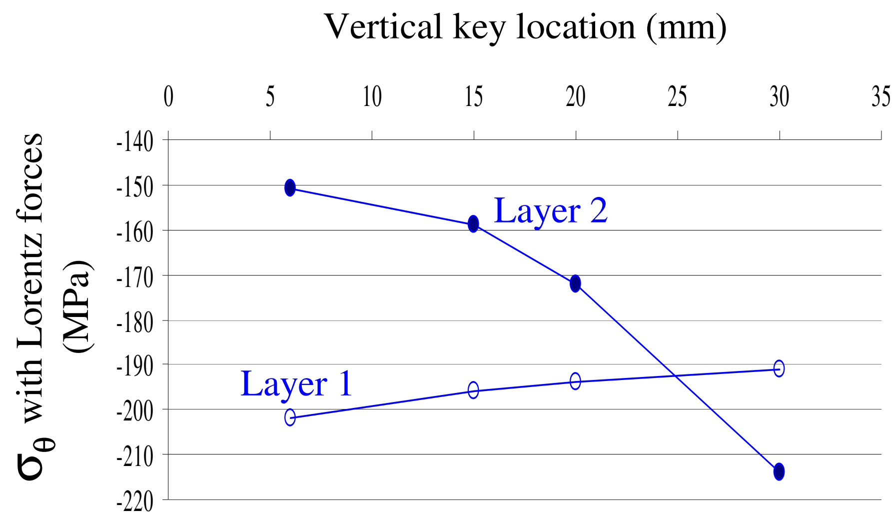
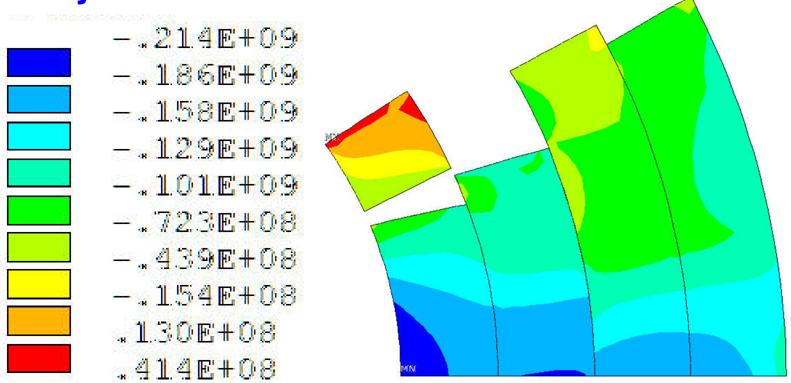
Helene Felice,
Paolo Ferracin

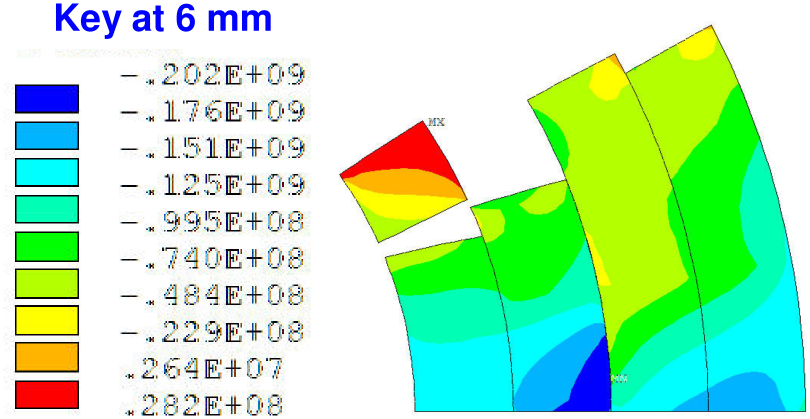




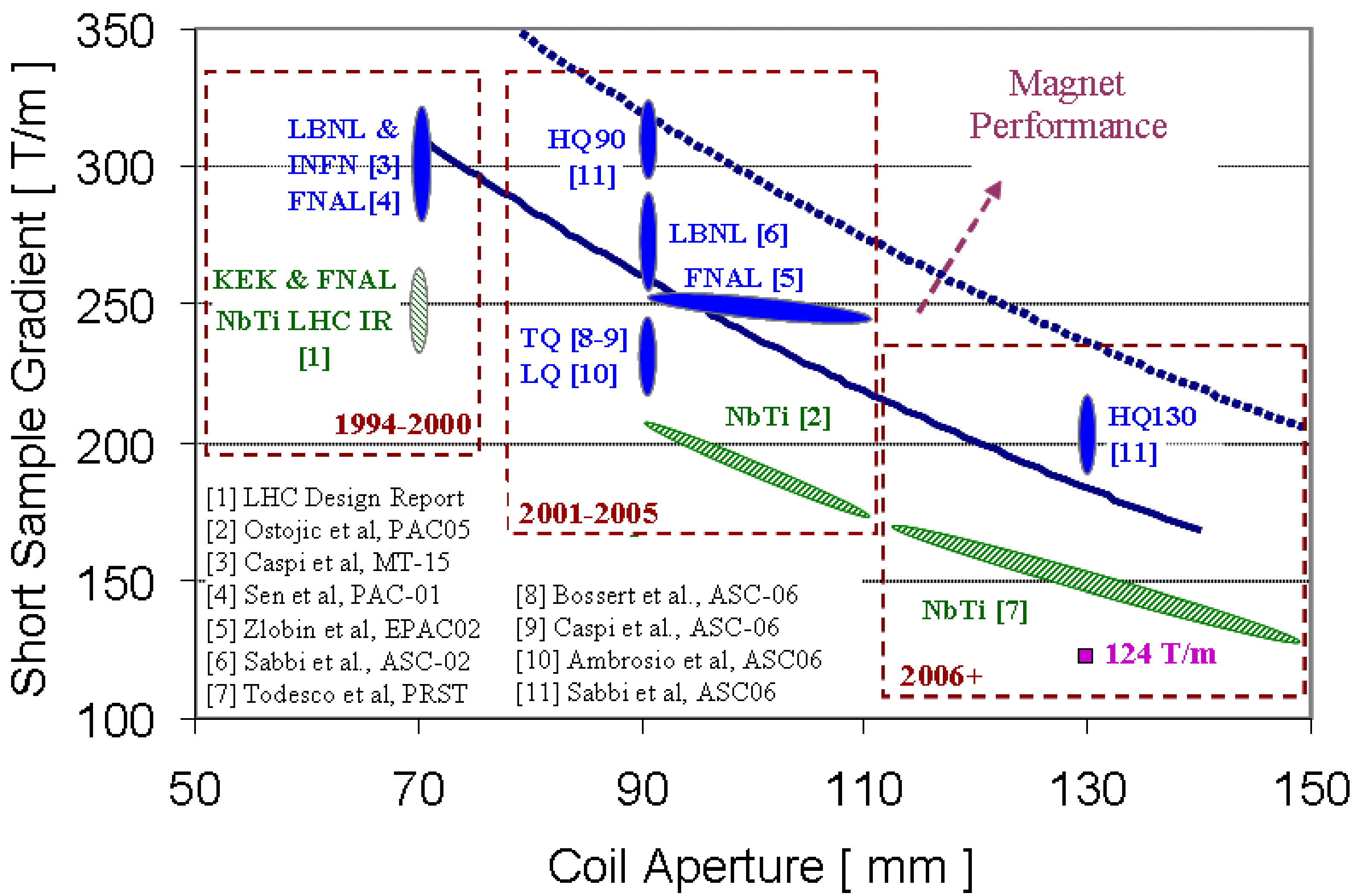
Key at 30 mm



Key at 6 mm



IR Quadrupole Design Space



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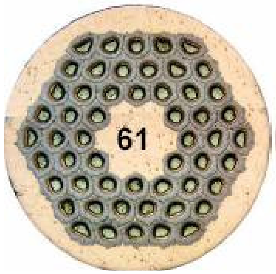
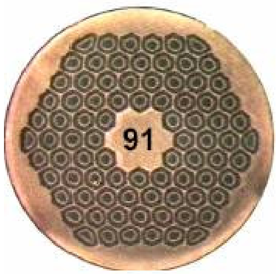
Conductor Options



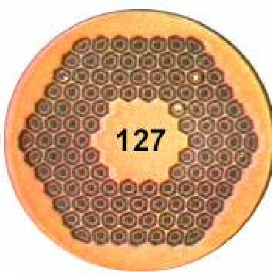
61 sub-element designs (54/61 and 60/61):

☺ Production wire, highest Jc, long piece length, best characterized
☹ Large sub-elements, flux jumps esp. in larger diameter wires



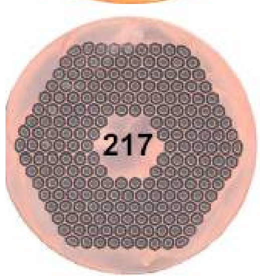
91 sub-element design (90/91):

☺ Experience at OST from previous production-size orders
☹ Small improvement from 60/61, no experience in LARP



127 sub-element designs (108/127 and 114/127):

☺ D_{eff} reduced by 30%, some experience, showing promise
☹ Still being optimized, 10-20% lower Jc, cabling degradation



127 sub-element designs (108/127 and 114/127):

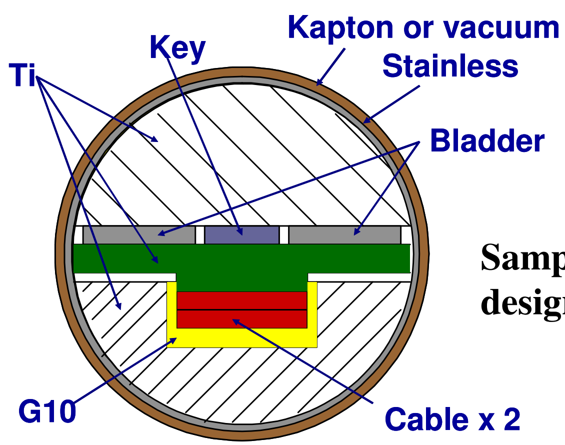
☺ D_{eff} reduced by 50%, optimization effort through CDP
☹ Early R&D wire, many issues (yeld, Jc, cabling etc)

Conductor Characterization

- Critical current degradation under stress is a critical magnet design parameter
- No facilities are available to measure cable under transverse fields >12 T

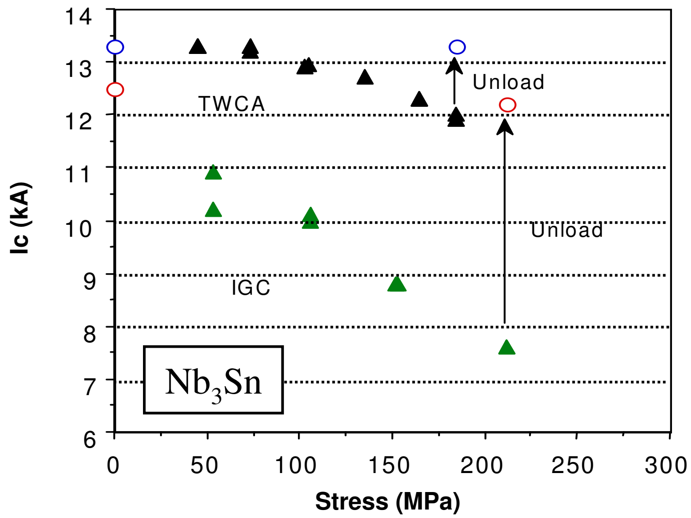
Features of a high field test facility:

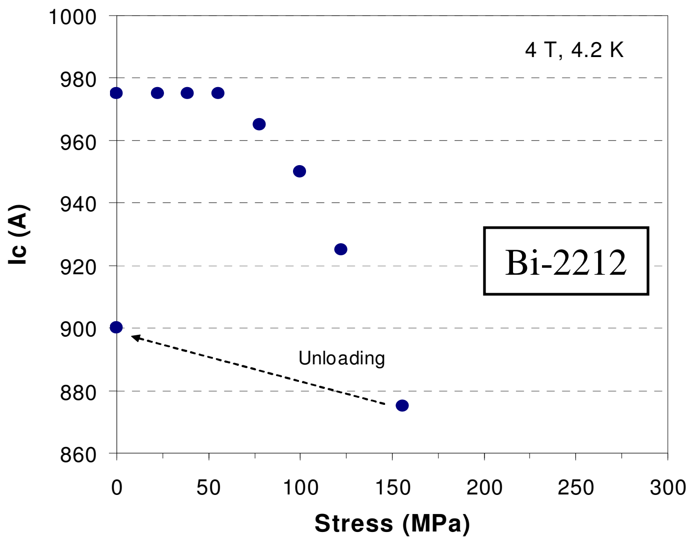
- Background field up to 15 T
- Uniform high field >30 cm
- 70*2 MPa load (warm)
- Stress increase at cool-down



Sample holder design concept

Cable Ic degradation (D. Dietderich)





High Field Dipole Development

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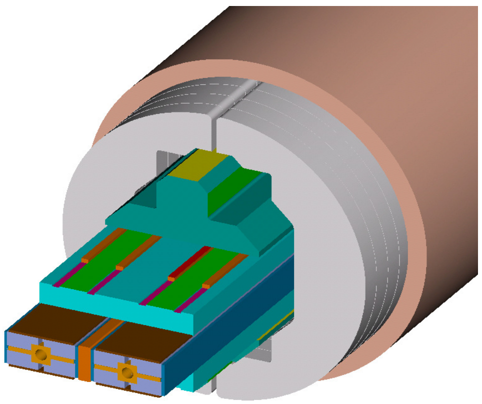
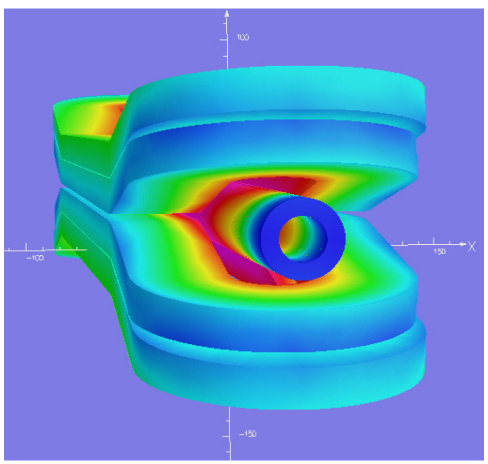
LHC Energy Upgrade





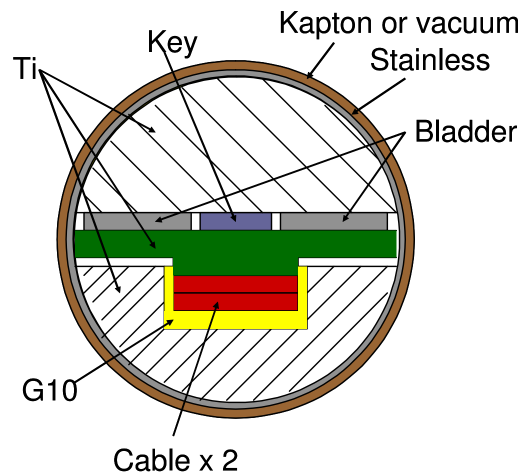
Design Features & Applications

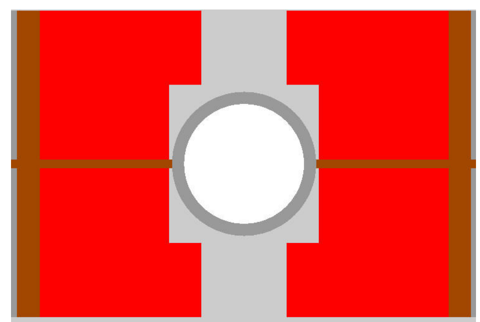
- Target field 15 Tesla
- Clear bore 36 mm
- Simple coil configuration
- Designed for high field quality
- Suitable for HF cable testing
- Compatible with HTS inserts

4.5 K Short Sample Parameters

Parameter	Unit	HD1	**HD2**
Clear bore	mm	8	**36**
Coil field	Tesla	16.1	**15.8**
Bore field	Tesla	16.7	**15.0**
Max current	kA	11.4	**17.3**
Stored Energy	MJ/m	0.66	**0.84**
F_x (quadrant, 1ap)	MN/m	4.7	**5.6**
F_y (quadrant, 1ap)	MN/m	-1.5	**-2.6**
Ave. stress (h)	MPa	150	**150**

High-field cable testing





2-layer winding without spacers in body or ends

HQ Conductor and Cable Plan

- Target cable width is 15.1 mm (match LHC Dipole)
- Wire diameter will be in 0.8 to 1 mm range (w/same cable width)
- Designs based on two wire diameters may be considered/compared
  - *1 mm diameter is desirable but introduces additional issues/risk*
- Proposing to choose 127 sub-element strand as the baseline
  - *Push wire development for a possible Phase I upgrade*
  - *180 kg in order for March delivery*
- Cable optimization: 2 prototype runs of 50 m each in the near term
  - *Width: 9 pairs of rolls available in 14.8-15.2 mm range*
  - *Keystone angle: 0.7-1.3 degrees*
  - *Thickness: 1.45 mm (0.8 mm wire) or 1.80 mm (1 mm wire)*
  - *No. strands: 35/36 (0.8 mm wire) or 27/28 (1 mm wire)*
- Plan: demonstrate cable design by January 2008

Structure Alignment

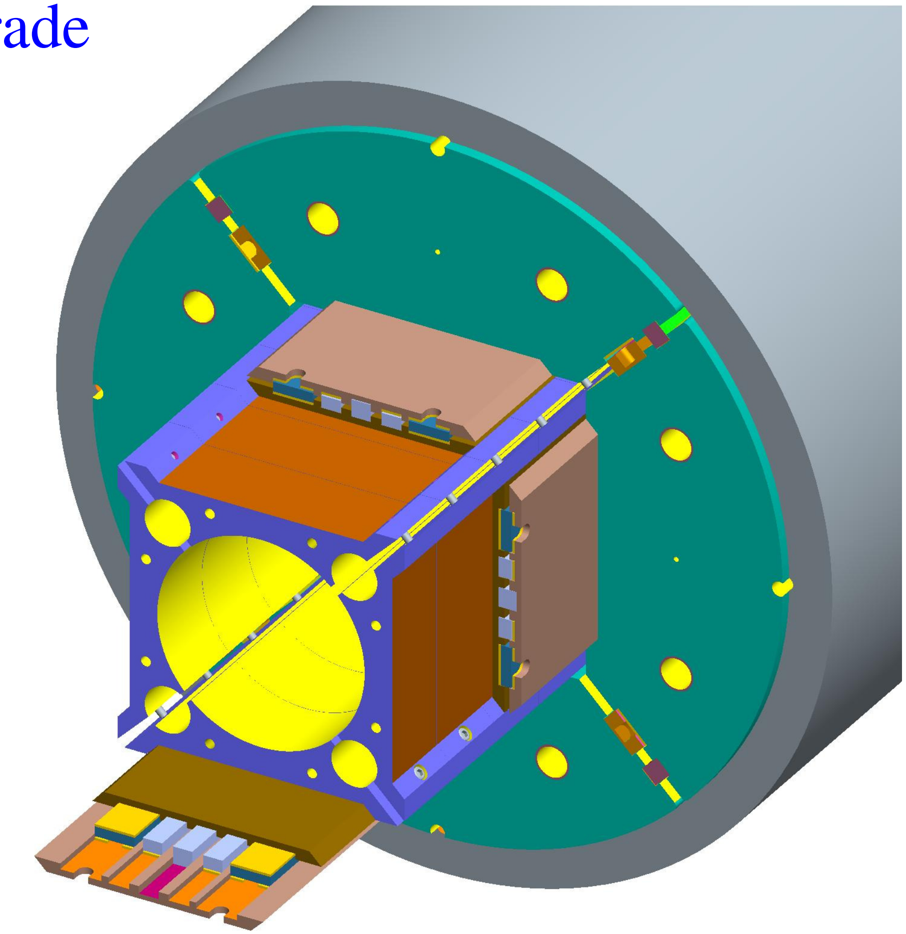
Include in HQ for Phase I upgrade

Near term:

- Shell to yoke alignment pins
- Yoke-to-yoke radial keys
- Yoke to pad master blocks
  - *align during loading*
  - *preserve during cool-down*

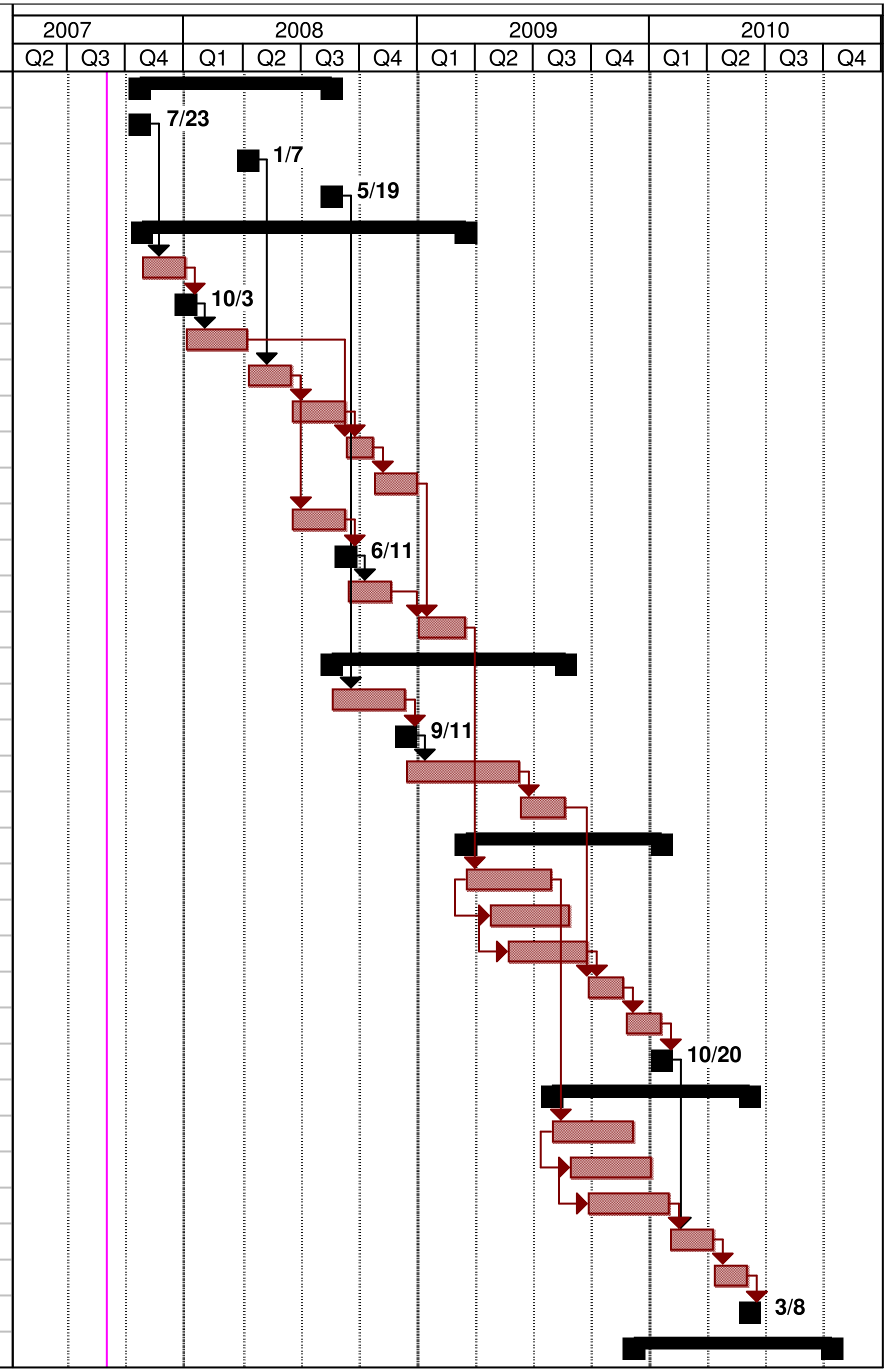
Longer term:

- Close yoke at cool-down
- Pad-coil alignment
  - *options studied in HQ DS*
  - *mid-plane or pole keys*



Alignment concept for shell-based structures

ID	HQ Plan (DOE Review 6/07)	Start	Finish
105	**HQ Design**	**Mon 7/23/07**	**Mon 5/19/08**
106	Coil layout & basic parameters	Mon 7/23/07	Mon 7/23/07
107	Optimized cable & coil design	Mon 1/7/08	Mon 1/7/08
108	Mechanical structure design	Mon 5/19/08	Mon 5/19/08
109	**HQ Tooling & Practice Coils**	**Tue 7/24/07**	**Mon 12/15/08**
110	Winding/Curing Tooling Design	Tue 7/24/07	Tue 10/2/07
111	Design Review	Wed 10/3/07	Wed 10/3/07
112	Winding/Curing Tooling Procurement	Thu 10/4/07	Tue 1/8/08
113	Coil parts design	Tue 1/8/08	Mon 3/17/08
114	Coil parts procurement	Tue 3/18/08	Tue 6/10/08
115	Practice coil #1	Wed 6/11/08	Wed 7/23/08
116	Tooling/coil parts optimization	Thu 7/24/08	Thu 10/2/08
117	Reaction/potting tooling design	Tue 3/18/08	Tue 6/10/08
118	Design Review	Wed 6/11/08	Wed 6/11/08
119	Reaction/potting tooling procurement	Thu 6/12/08	Thu 8/21/08
120	Practice coil #2	Fri 10/3/08	Mon 12/15/08
121	**HQ Structure Fabrication**	**Tue 5/20/08**	**Wed 5/20/09**
122	Engineering Design	Tue 5/20/08	Thu 9/11/08
123	Review	Thu 9/11/08	Thu 9/11/08
124	Procurement	Fri 9/12/08	Wed 3/11/09
125	Testing	Thu 3/12/09	Wed 5/20/09
126	**HQ01 Model**	**Tue 12/16/08**	**Tue 10/20/09**
127	Coil Wind / Cure (6 coils)	Tue 12/16/08	Wed 4/29/09
128	Coil React	Thu 1/22/09	Thu 5/28/09
129	Coil Impreg	Thu 2/19/09	Thu 6/25/09
130	Magnet Assembly	Fri 6/26/09	Fri 8/21/09
131	Test & Analysis	Mon 8/24/09	Mon 10/19/09
132	Review	Tue 10/20/09	Tue 10/20/09
133	**HQ02 Model**	**Thu 4/30/09**	**Mon 3/8/10**
134	Coil Wind / Cure (12 coils)	Thu 4/30/09	Fri 9/4/09
135	Coil React	Fri 5/29/09	Mon 10/5/09
136	Coil Impreg	Fri 6/26/09	Mon 11/2/09
137	Magnet Assembly	Tue 11/3/09	Fri 1/8/10
138	Test & Analysis	Mon 1/11/10	Fri 3/5/10
139	Review	Mon 3/8/10	Mon 3/8/10
140	**HQ03 Model**	**Tue 9/8/09**	**Wed 7/14/10**



HQ Coil and Tooling Spec Sheet

LARP

Shlomo Caspi,
Dan Cheng,
Rodger Bossert,
Nikolai Andreev

Cable Parameters			
Cable Width	15.10	0.59449	LHC Standard; subject to actual cabling test measurements
Cable Insulation	0.10	0.00394	Depends on sleeving/tape, insulation type
Coil Parameters			
Magnetic ID	134	5.27559	ID Location of conductor (minus insulation stack)
Mechanical ID	133.419	5.25272	Calculated from Coil ID below
Magnetic Length			*TBD*
Mechanical Length			*TBD*
Magnetic OD	164.65	6.48244	Calculated from Coil OD below
Mechanical OD	195.89	7.7122	Calculated from Coil OD below
Basic Coil ID Envelope			
Magnetic ID	134	5.27559	OD of non-insulated cable
Cable Insulation	0.10	0.00394	One layer of cable insulation, above
Trace	0.0635	0.0025	1.5 mil kapton + 1 mil stainless (no cover sheet, otherwise .005)
Glass Sheet	0.127	0.005	
Clear Bore	**133.419**	**5.25272**	diameter through which the bore is completely clear
Basic Coil OD Envelope			
Magnetic ID	134	5.27559	From coil parameters above
1 layer cable width	15.10	0.59449	
1 layer cable insul.	0.10	0.00394	
Glass sheet	0.254	0.010	Glass sheet for ground plane insulation
1 layer cable insul.	0.10	0.00394	
1 layer cable width	15.10	0.59449	
1 layer cable insul.	0.10	0.00394	
Trace	0.06	0.00250	Instrumentation trace, see notes above
Glass sheet	0.127	0.00500	
Mechanical OD	**195.89**	**7.71217**	Coil envelope, as potted
OD of Winding Mandrel			
Clear bore dia.	133.419	5.25272	from Coil ID calcs above
subtract	*0.1905*	*0.0075*	Subtract Trace and glass Sheet from above calculations
Mylar sheet	0.127	0.005	For winding process only.
Mandrel OD	**133.546**	**5.25772**	
ID of Mandrel Sizing Blocks			
Mechanical OD	195.89	7.71217	From Coil OD calcs above
subtract	*0.19*	*0.00750*	Subtract Trace and glass Sheet from above calculations
Kapton	0.127	0.005	Single Layer wrap over coils
Sizing Block ID	**195.254**	**7.68717**	

Summary

- HQ will determine the quad design envelope for the Phase II Upgrade
- Coil peak field and stresses are the key limiting factors
- Baseline parameters, design approach and features were selected

- The HQ design is also directly relevant to a Phase I upgrade
- Large design and operating margins for 130 mm, 122 T/m requirement
- Application toward Phase I increases accelerator-quality priorities:
  - Strand design with 127 sub-elements may be selected as baseline
  - Alignment features will be incorporated in the structure design
  - Welded SS shell above Al shell was studied for LHe containment:
    - *contact between shells is preserved at all stages*
    - *negligible effects on mechanical performance*

- Schedule will depend on the overall strategy and priorities