Development of Q4 large aperture 2-in-1 quadrupole

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2nd joint HiLumi LHC-LARP Annual meeting

14-16 November 2012

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

Outline

- Q4 Magnet Specifications
- Scope of the study
- Magnetic configuration
- Mechanics
- Estimation of conductor needs
- Conclusion and Next steps

Q4 Magnet specifications

- The 2-in-1 Q4 is actually of MQY type (aperture = 70 mm; Gradient = 160 T/m; L =3.4m; T= 4.5K
- The needs or constrains for the new Q4 2-in-1 magnet are:
  - Inner aperture larger than 80 mm
  - Working temperature = 1.9 K
  - Nominal Integrated gradient = 544 T
  - Margin on the load line = 20 % at nominal current (Inom)
  - Harmonics lower than 1 unit at 2/3 of aperture
  - Use of MQ or MQM conductor

Scope of the study

- Magnetic optimization of 2D cross section with cross talk due to 2-in-1 configuration using:
  - MQM cable with 1 or 2 layers
  - MQ cable with 1 layer
  - Study for aperture varying from 85 to 120 mm for each case
- Check effect of 20 % and 50 % current unbalance (one aperture being at Inom current)
- First mechanical calculations to check stress distribution and displacements
- Estimation of conductor needs

Remark

- Results presented here have been extensively discussed
  - →The most probable configuration will use MQ cable and 90 mm aperture.
  - → only the results for this configuration will be presented here

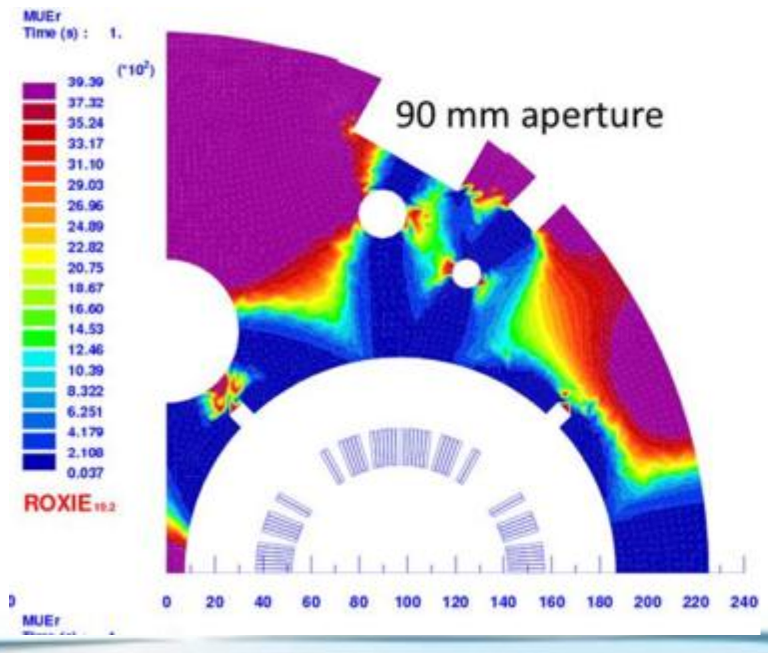
Magnetic configuration

- MQ cable and strand charasteristics

Width (mm)	Min thick (mm)	Max thick (mm)	Nb strands	Transp (mm)	Degrad (%)	Fil
15.1	1.362	1.598	36	100	5	NbTi

Diam (mm)	Cu/sc	RRR	Tr (K)	Br (T)	Jc @ BrTr	dJc/dB
0.825	1.9	80	1.9	9	1953	550

- 2D magnetic configuration
  - 3 blocs
  - MQ yoke, heat exchanger hole verticale position adjusted to optimize b3



Magnetic configuration

- Field quality (units at r = 30 mm) at Inom in both apertures

Current (A)	Gradient(T/m)	Magn. Length (m)	Field harmonics (normal relative multipoles × 10^{-4})							
			b1	b3	b4	b5	b6	b10	b14	b18
16188	120	4.53	-9.21	-1.01	0.22	-0.17	0.00	0.00	2.23	0.06

b1 corresponds to an off-centering of less than 0.03 mm

b3 is of the order of 1 unit

All other harmonics are small except b14, which cannot be changed

Unbalanced regime

- Harmonics with 20% unbalaced current

Current	multipoles (× 10^{-4}) in the left aperture								
(A)	b1	b3	b4	b5	b6	b7	b10	b14	b18
16188	23.54	**4.10**	-0.01	1.05	-0.27	0.10	0.00	2.27	0.06
Current	Normal relative multipoles (× 10^{-4}) in the right aperture								
(A)	b1	b3	b4	b5	b6	b7	b10	b14	b18
12950	-105.83	**-16.07**	2.84	-1.95	0.00	-0.16	0.00	2.22	0.06

- Harmonics with 50% unbalaced current

Current	multipoles (× 10^{-4}) in the left aperture								
(A)	b1	b3	b4	b5	b6	b7	b10	b14	b18
16188	24.30	**25.46**	4.50	3.69	-0.37	0.09	0.00	2.36	0.06
Current	Normal relative multipoles (× 10^{-4}) in the right aperture								
(A)	b1	b3	b4	b5	b6	b7	b10	b14	b18
8094	-354.54	**-92.26**	19.90	-9.59	0.59	-0.30	0.00	2.22	0.06

- The effect is more sensitive on the aperture where the current is lower
- b1, b3 are strongly affected
- b4 and b5 are also affected

- Same order of effect with other cable and aperture

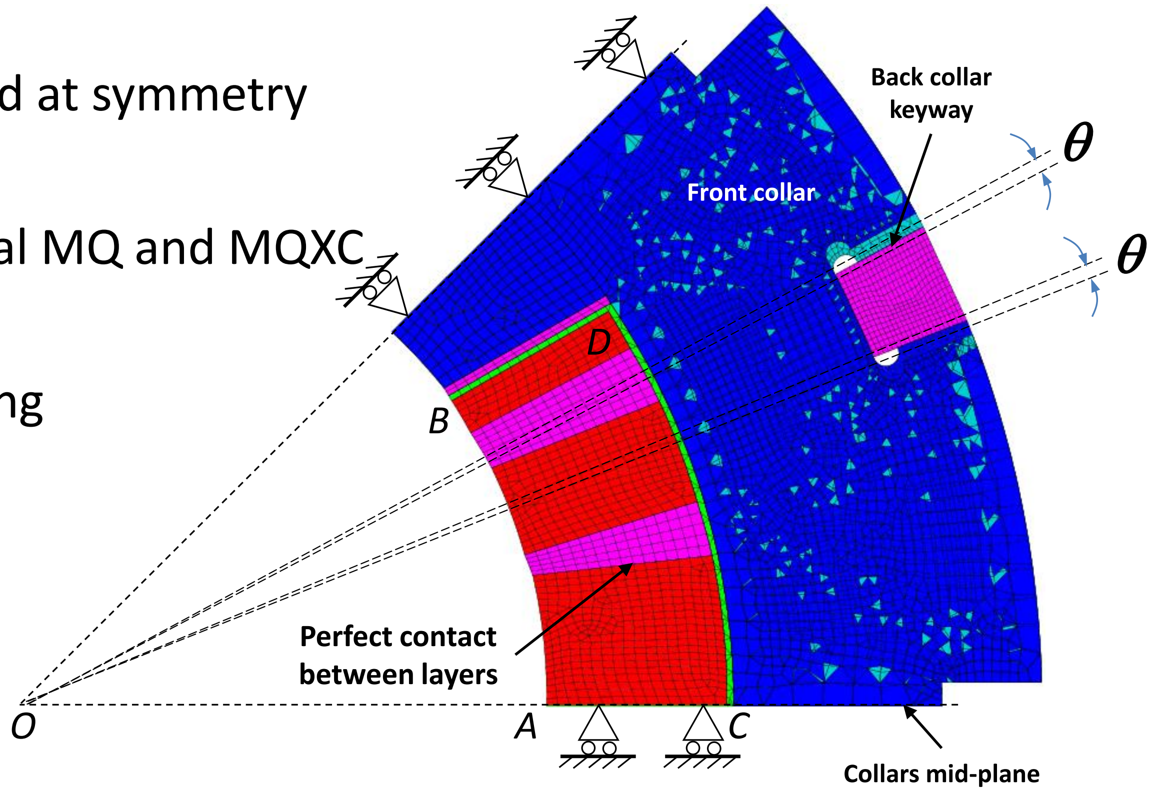
Mechanics

- Calculations at 110 % of Inom
- Conductor insulation : MQ type (not porous)
- Thermo-mechanical properties

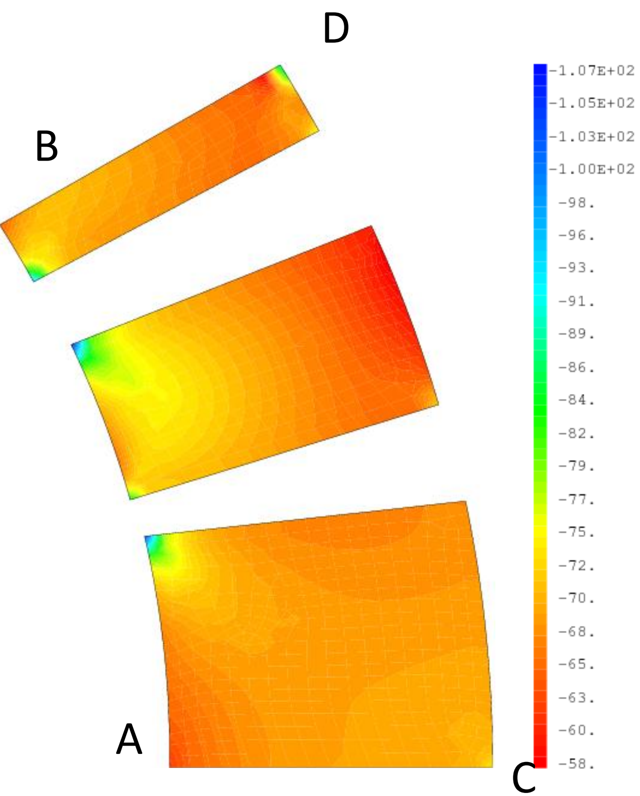
Materials Componants	Temp. (K)	Elastic Modulus E (GPa)	Yield Strength (MPa)	Ultimate Strength (MPa)	Integrated Thermal Shrinkage α (mm/m)
yus 130 S Nippon Steel Collars	300	190	445	795	
	2	210	1023	1595	2.4
316L Stainless Steel Keys	300	205	275	596	
	2	210	666	1570	2.9
Copper Angular wedges	300	136			
	2	136			3.3
Kapton Foils inter-layer & inter-pole insulations	300	2.5			
	2	4			6.0
insulated NbTi conductor blocks Coils with MQ cable	300	10.00			
	2	15.00			4.9

Mechanics : FE model

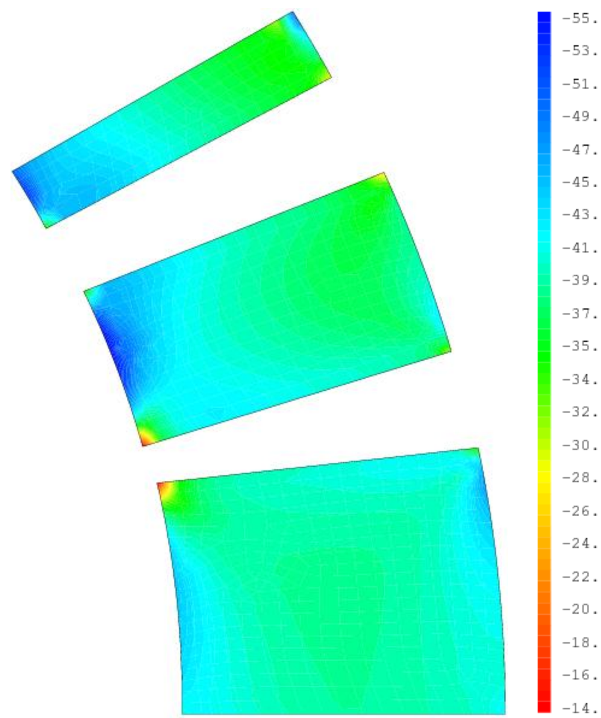
- Calculations with 2D CASTEM
- Symmetries → model restricted to one octant
- 2 levels of collars to simulate effect of stacking in alternated layers
- Boundary conditions imposed at symmetry planes
- Keyway angle : same as actual MQ and MQXC (25° from coil midplane)
- Creeping of 20% after collaring



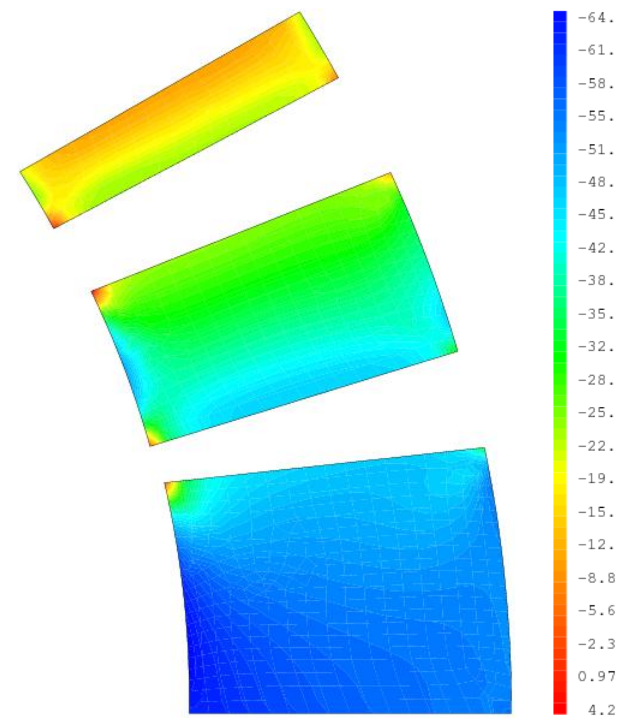
Mechanics :Stress distribution in coil



After collaring
Max : 108 MPa
Average : 68 MPa



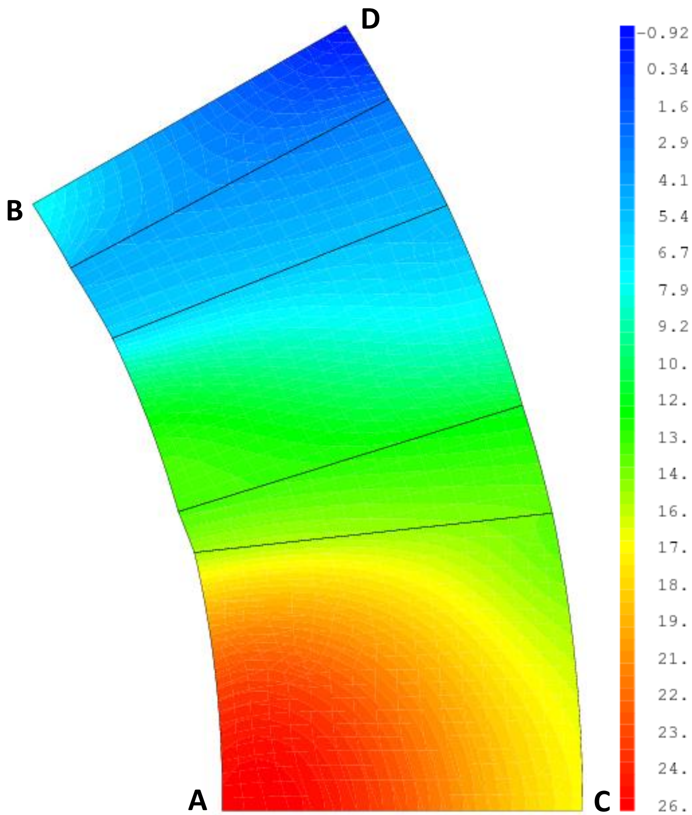
After cool down
Max : 56 MPa
Average : 40 MPa



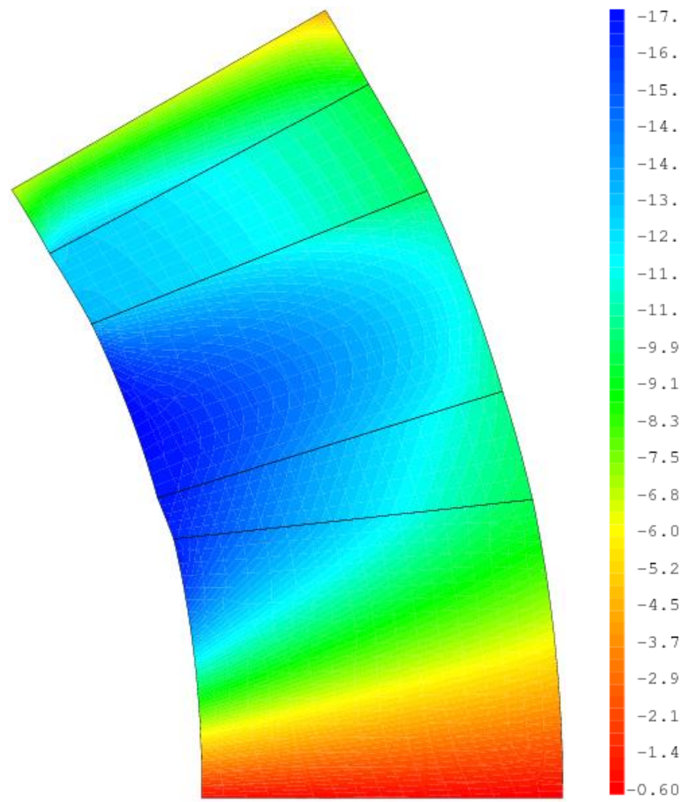
At Inom x 1.1
Max : 65 MPa
Average : 42 MPa

Mechanics : Displacements due to lorentz forces

at Inom x 1.1



Radial : max = 25 µm



Azimutal : max = XXX µm

Mechanics

90 mm aperture	Collaring	Creep (20%)	Cool down	Energization **110% Inom**
Azimuthal stress in coil (MPa)				
Max	-108	-86	-56	-65
Average	-68	-55	-40	-42
Min on polar plane				-10
Average on polar plane				-12
Coil radial displacement due to Lorentz forces (µm)				
Point A				25
Point B				8
Point C				17
Point D				-1
Max von Mises stress (MPa)				
In collars	840	672	617	721
In keys	231	184	191	219

Maximum stress never exceed 150 MPa during the life of the magnet → safe

Estimation of conductor needs

We plane to fabricate :

- one 2-m long trial coil 0
- one 2-m long single-aperture model
- one 2-m long double-aperture model
- one full length cold mass prototype
- Five full length cold masses for the series

Mag. configuration	Ø aper (mm)	Mag. Length (m)	Nr of turns per coil	Cable length per coil for 2m model (m)	number of 2m coils (model)	Cable length per coil for series (m)	number of real-length coils	Total needed cable (m)
1 layer MQM cable	90	5.33	24	96	13	256	48	13528
2 layers MQM cable	90	4.25	51	204	13	434	48	23460
1 layer MQ cable	90	4.53	14	56	13	127	48	6816

- MQ is the less demanding option.
- No stock available for MQM cable
- → MQ is the most probable option and is kept for further studies

Conclusions

We have studied Q4 magnet and shown that it can be made with MQ cable:

Main parameters of the magnet:

- Aperture : 90 mm, 3 blocks (7-5-2), one layer
- Nominal gradient : 120 T/m with 20 % margin and 2K temperature margin
- Nominal current : 16188 A !!!! Power supply ?
- Magnetic length : 4.53 m for integrated gradient of 544 T
- Peak Field : 5.9 T
- Inductance : 6.9 mH per aperture.
- Stored energy : 0.93 MJ per aperture
- Conductor lenght per coil : ~130 m

Conclusions

Next steps:

- Further optimization of iron yoke
- Study of geometrical errors on field quality
- Magnet protection (preliminary calculations show that it should not be an issue)
- Study of conductor path for coil connexions (1 single layer)

- Thermal studies (heat deposition) as soon as data are available