QXF magnet design and plans

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HiLumi-LHC/LARP Conductor and Cable Internal Review 16-17 October 2013

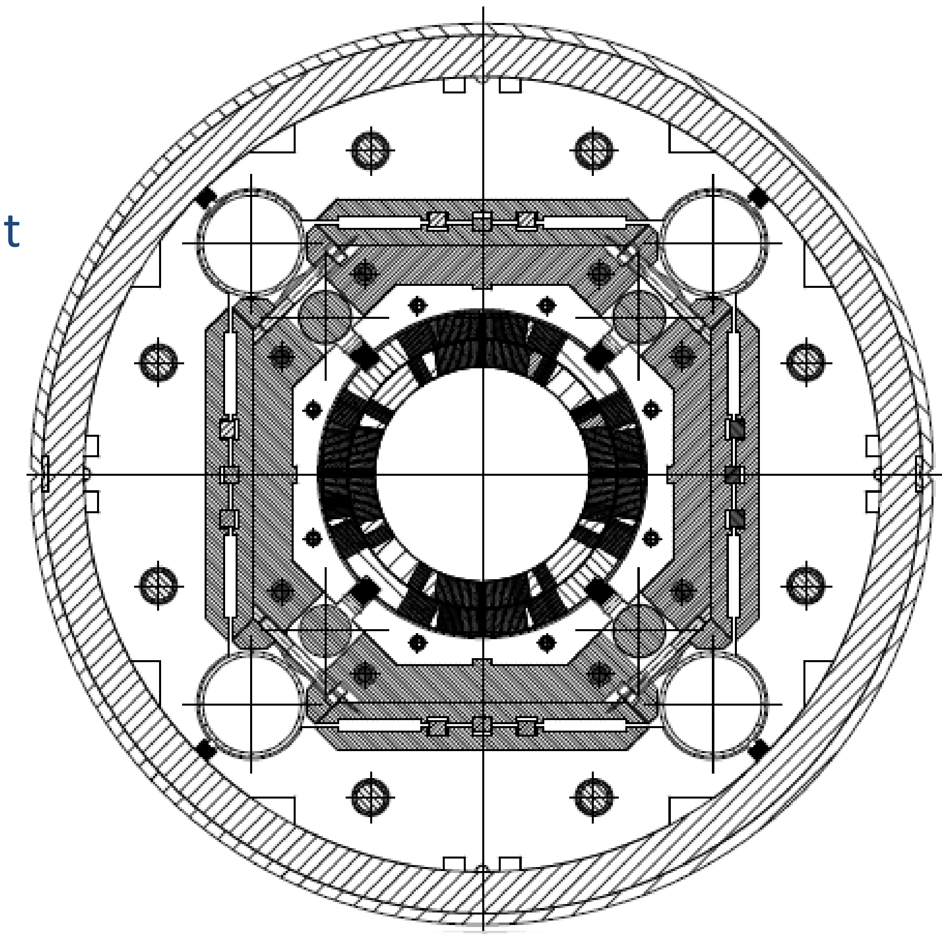
CERN

Outline

- Overview of magnet design
- Strand parameters
- Cable dimensions (first iteration)
- Insulation thickness
- Coil design and cable unit lengths
- Short sample current and magnet parameters
- Planning for short and long models
- Risk analysis

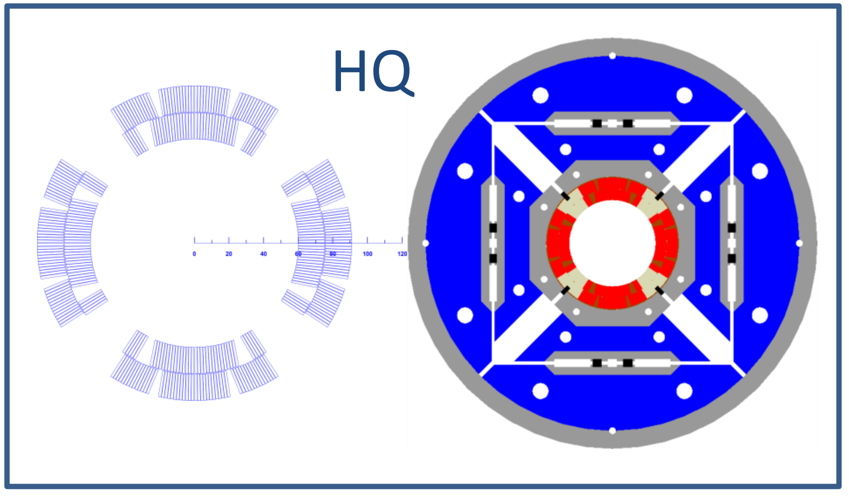
QXF magnet design

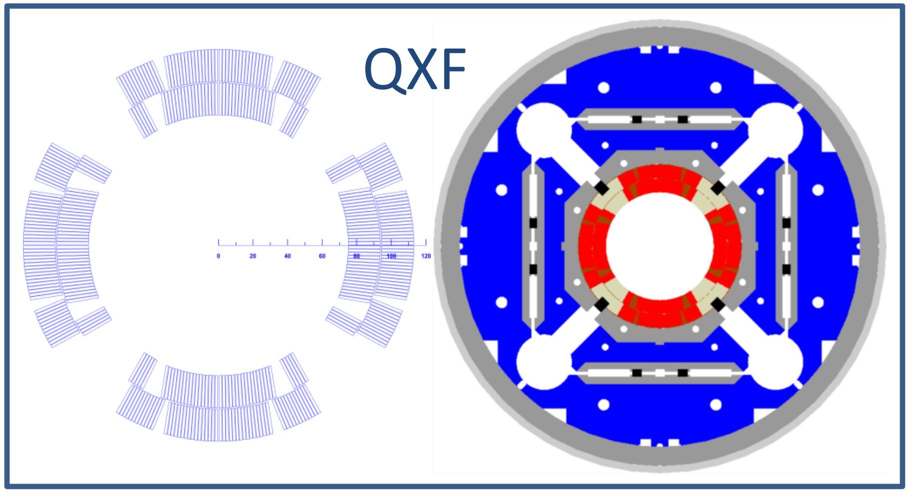
- Target: 140 T/m in 150 mm coil aperture
- OD: 630 m
- SS shell, 8 mm for LHe containment
- Al shell, 29 mm thick
- Iron yoke
  - Cooling holes
  - Slots of assembly/alignment
- Master plates
  - 58 mm wide bladder
- Iron pad
- Aluminum bolted collars
  - Coil alignment with G10 pole key
- Ti alloy poles



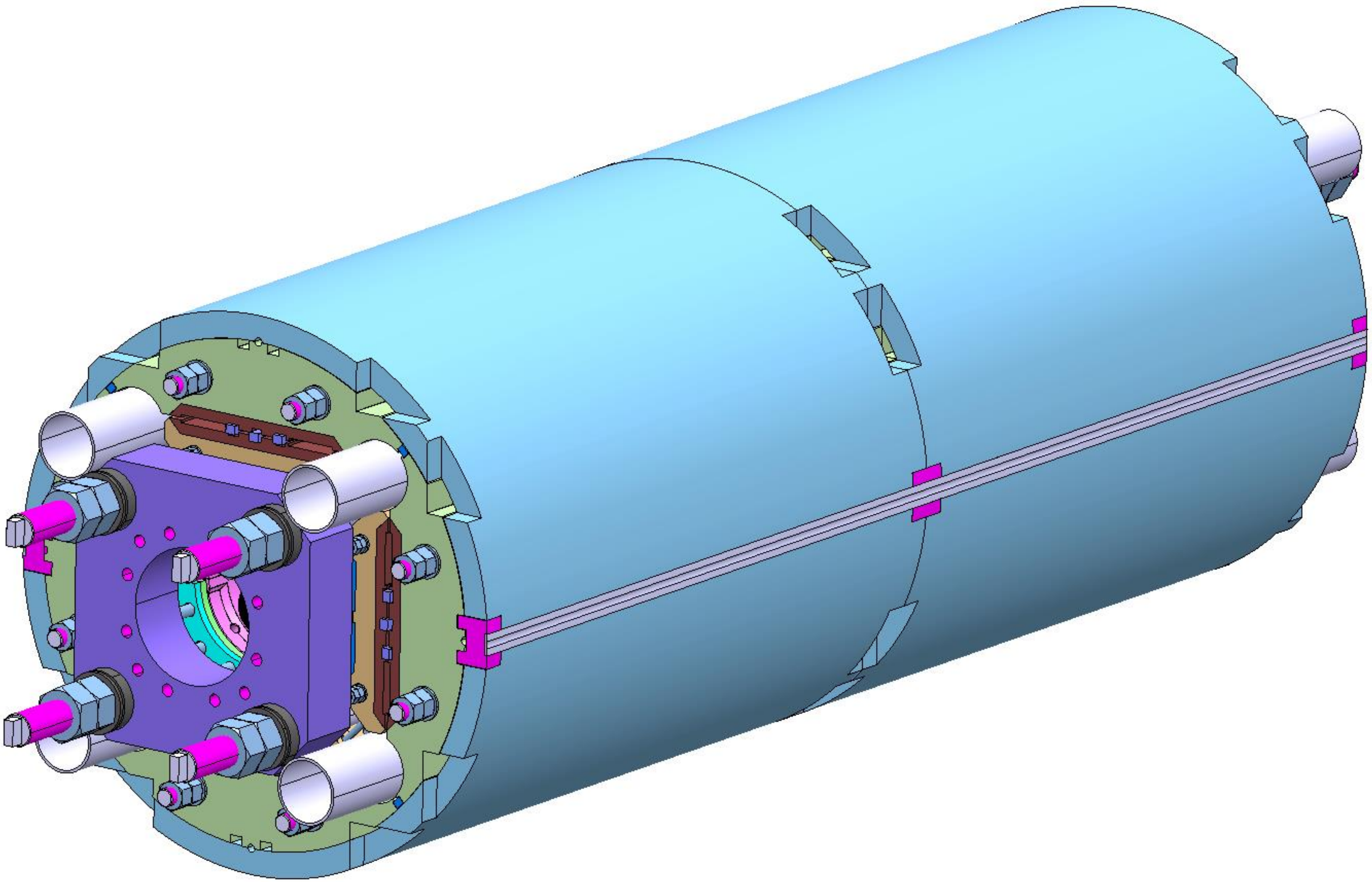
From HQ to QXF

- Similar coil lay-out
  - 4-blocks, 2-layer with same angle
  - Wider cable (from 15 to 18 mm), same stress with +30% forces
- Same structure concept with additional accelerator features
  - Pre-load capabilities of HQ design qualified and successfully tested
  - Larger pole key for cooling holes, cooling channels, alignment – assembly - handling slots, LHe vessel





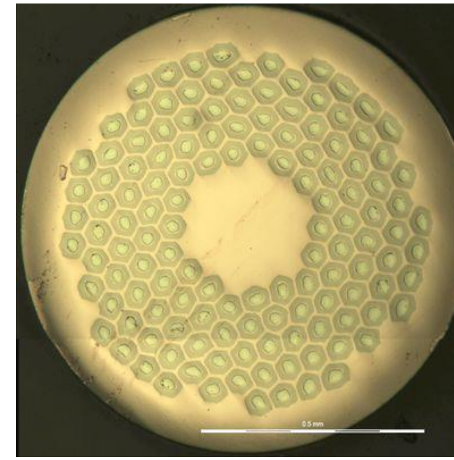
Engineering design
(work in progress)



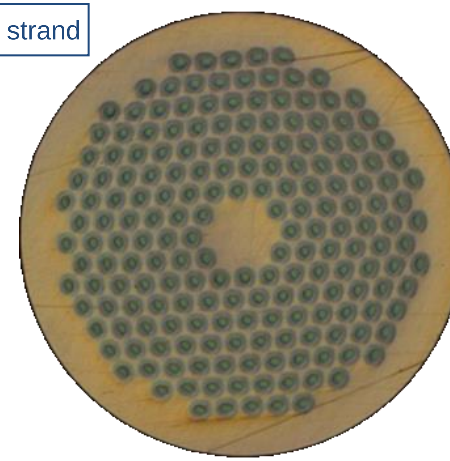
Strand
(from CERN technical specification document)

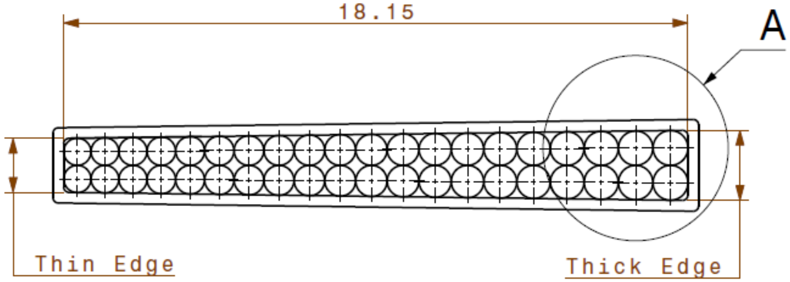
- 0.85 mm strand
  - OST RRP
    - 108/127, 132/169 and 144/169
  - Bruker PIT
    - 192 filaments
- Cu/Sc: **1.2** → 55% Cu
  - For 108/127 and 144/169: **1.13**
- Maximum critical current at 4.2 K
  - 361 A at 15 T
  - 632 A at 12 T

RRP strand

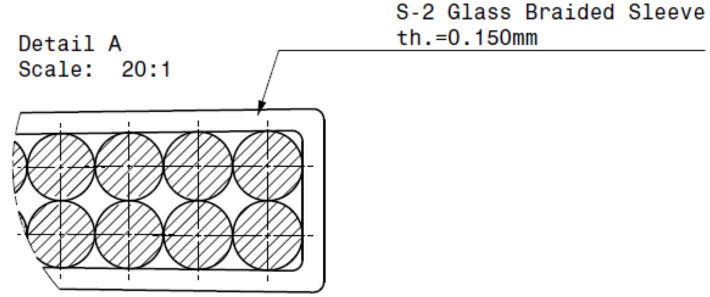


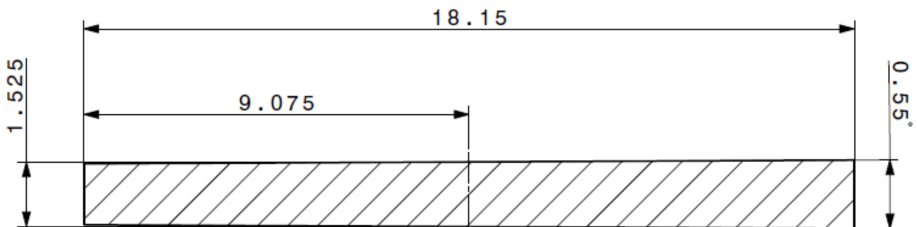
PIT strand





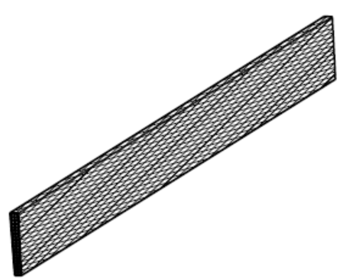
Enlarged and not to scale,
for illustration purposes only





DIMENSION FOR
CONDUCTOR WITHOUT INSULATION
Scale:10:1

UNREACTED CABLE DIMENSIONS	
Strand Type	Nb3Sn
Strand Diameter	0.85 mm
Number of strands	40 (2 x 20)
Width	18.15 mm
Mid-thickness	1.525 mm
Keystone Angle	0.55º
(Thin Edge Height)	(1.438 mm)
(Thick Edge Height)	(1.612 mm)
Inner Core	12 mm x 25 μ
INSULATION THICKNESS	
S-2 Glass Braided Sleeve	0.150 mm



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150mm Single Aperture Nb3Sn Model Magnet both 1.5m and 4m Long

QXF MAGNET
INSULATED CABLE (UNREACTED)

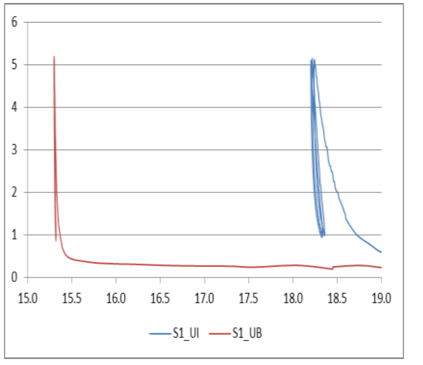
SCALE 1:1

DRAWN	T. SAHNER	2013-09-04
CONTROLLED		
RELEASED		
APPROVED		
CAD Document Number	ST0541952_02	
REPLACES		

NON VALABLE POUR EXECUTION
NOT VALID FOR EXECUTION

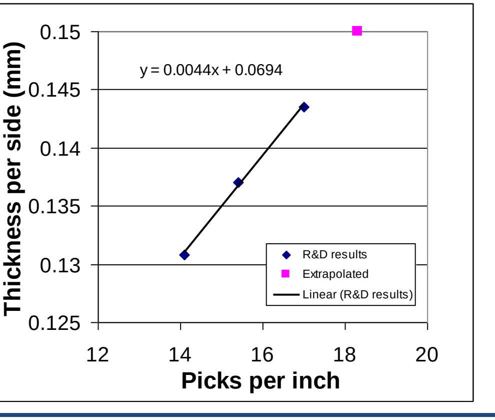
QAC - LHCMQXFM0019 SIZE 3 IND.

Cable insulation



- AGY S2-glass fibers 66 tex with 933 silane sizing
- 32 (CGP) or 48 (NEW) coils (bobbins)
- Variables: # of yarn per coil and of picks/inch
- Target: ≤ 150 μm per side

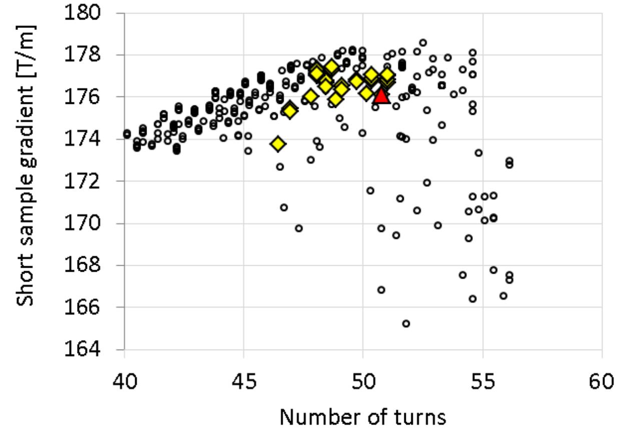
Samples	Insulated cable thickness (mm)	Bare cable thickness (mm)	Insulation thickness (μm)
S1	1.822	1.530	146
S2	1.823	1.531	146
S3	1.821	1.530	146

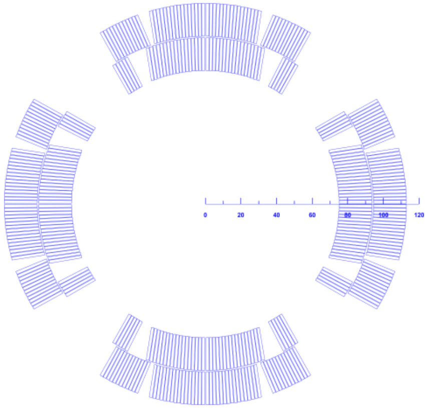


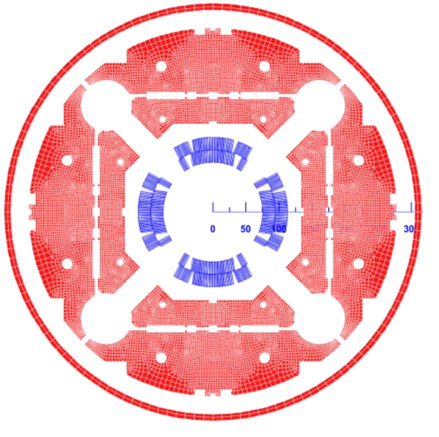
2D magnetic design

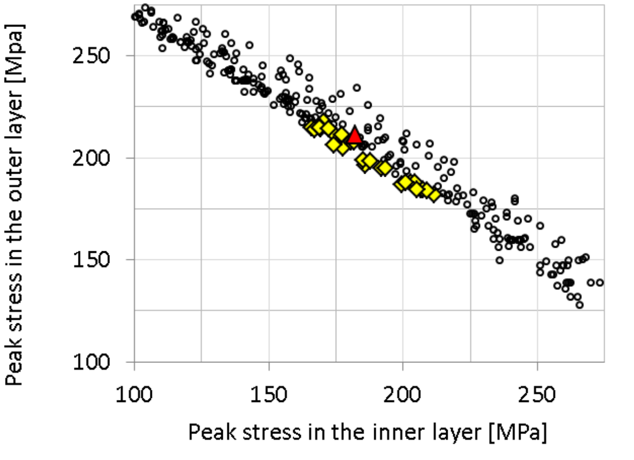
(By F. Borgnolutti)

- Two-layer – four-block design
- Analytical model with sector coil
  - 6 angles to optimize for field quality
- Criteria for the selection
  - Maximize gradient and # of turns (protection)
  - Distribute e.m. forces and minimize stress
- Result: 22+28 = 50 turns
- All harmonics below 1 units at R_{ref} = 50 mm

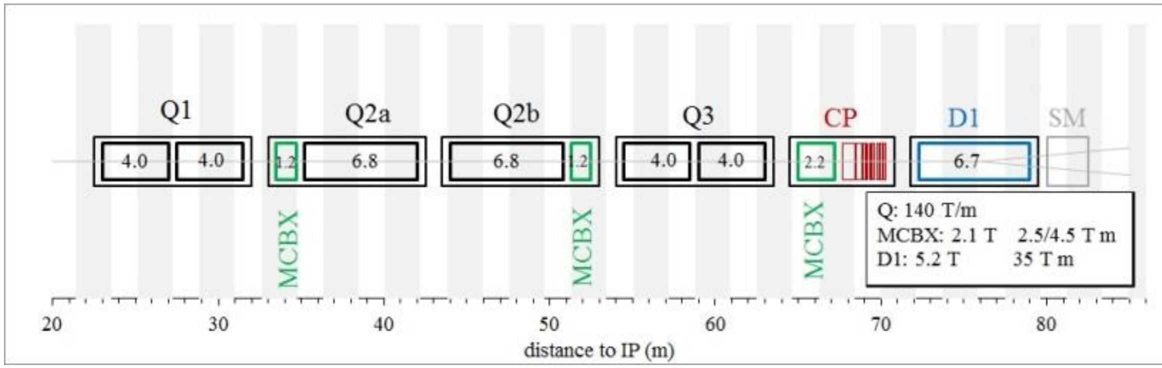


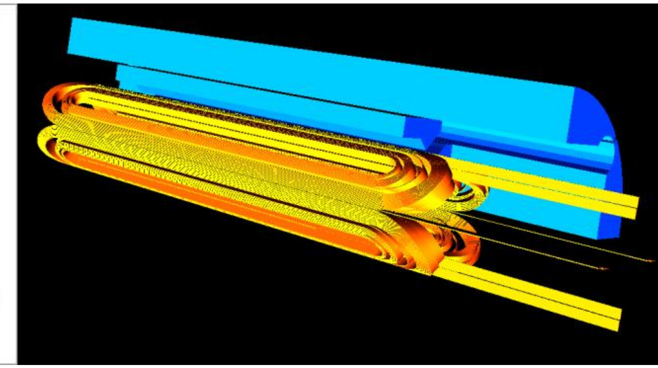






Lengths

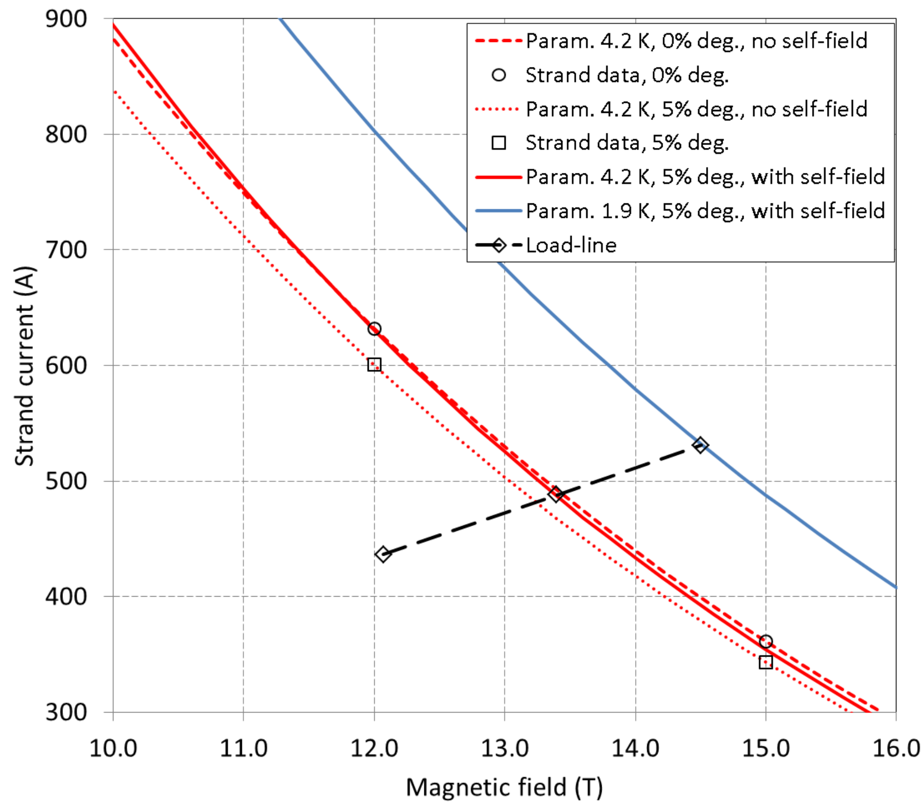




	Short model	Q1/Q3 (half unit)	Q2
Magnetic length [m]	1.2	4.0	6.8
"Good" field quality [m]	0.5	3.3	6.1
Coil physical length [m]	1.5	4.3	7.1
Cable unit length per coil [m]	150	430	710
Strand per coil [km]	6.5	18	30

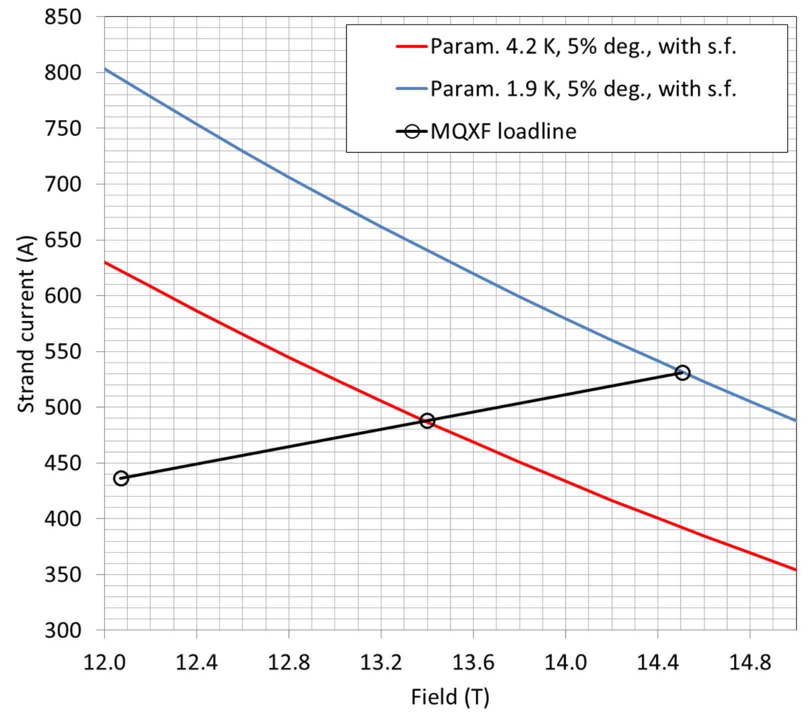
Superconductor properties and I_{ss} computation

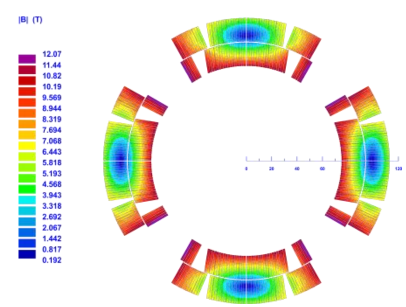
- Non-Cu J_c of virgin strand without self field (s.f.) correction
  - 2450 A/mm^2 (12 T, 4.2 K)
    - 632 A
  - 1400 A/mm^2 (15 T, 4.2 K)
    - 361 A
- Self field corr. (ITER barrel)
  - 0.429 T/kA
- 5% cabling degradation
- Godeke's parameterization

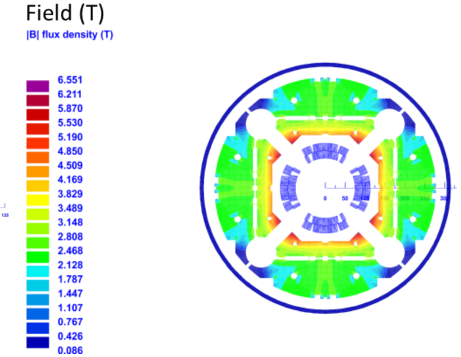


Magnet parameters

- Operational conditions: 140 T/m
  - I_{op}: 17.5 kA
  - B_{peak_op}: 12.1 T
    - 82% of I_{ss} at 1.9 K
    - G_{ss}: 168 T/m
    - I_{ss}: 21.2 kA
    - B_{peak_ss}: 14.5 T
- Stored energy: 1.3 MJ/m
- Inductance: 8.2 mH/m







SQXF status and plan

- First generation cable in 06/2013
- Coil design with 1st generation cable in 07/2013
- Coil parts fabrication/optimization in progress
  - Decision on end parts for first generation coils: 01/2014
- Coil tooling
  - Winding and curing tooling by 11/2013
  - Reaction and impregnation tooling by 02/2014

- Fabrication of full practice coil starts, both at CERN and in the US, in 02/2014 (with 1st gen. cable)

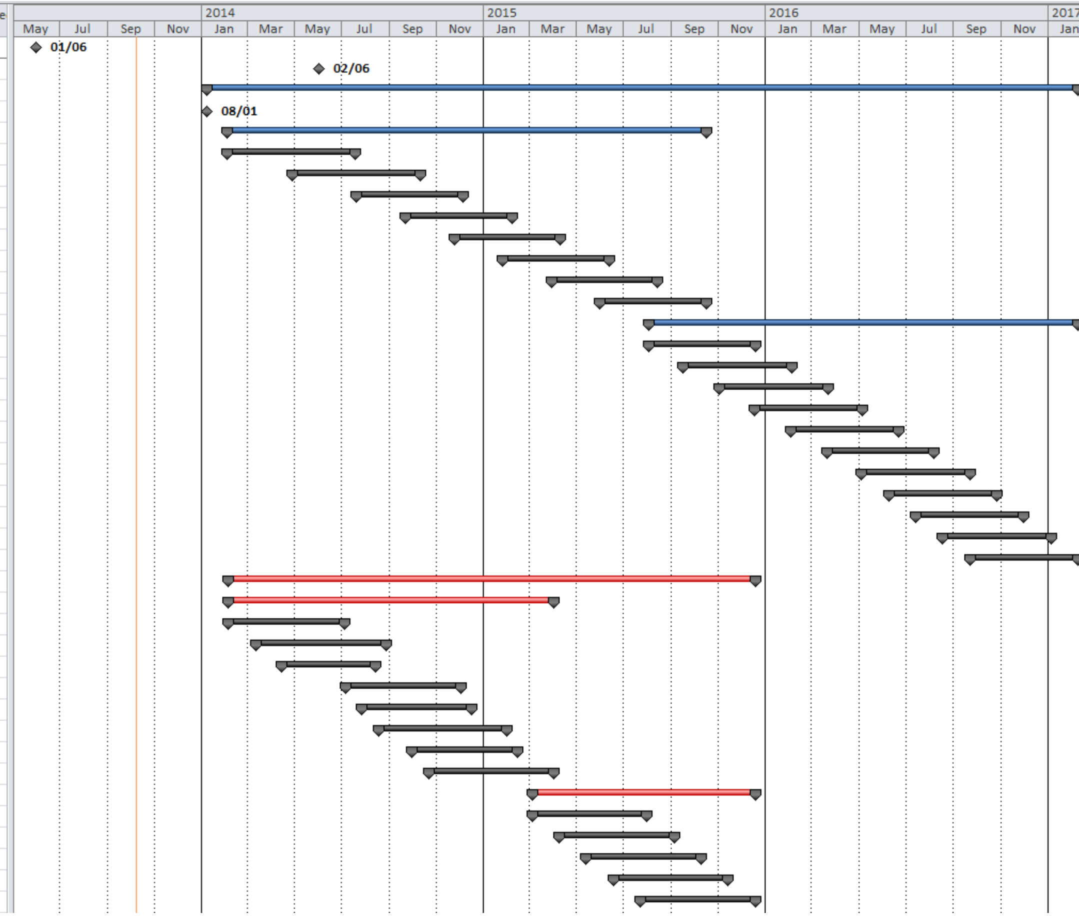
- 2nd gen. cable by 06/2014
- 2nd gen. coil fabr. starts in 03/15 (LARP) and 05/15 (CERN)

SQXF plan and schedule
Coil fabrication

- CERN
  - 1st gen. cable
    - 2 practice coils
    - 1 mirror coil
    - 5 RRP coils
  - 2nd gen. cable
    - 6 PIT coils
    - 5 RRP coils
- LARP
  - 1st gen. cable
    - 2 practice coils
    - 1 mirror coil
    - 5 RRP coils
  - 2nd gen. cable
    - 5 RRP coils

SQXF plan and schedule
Coil fabrication

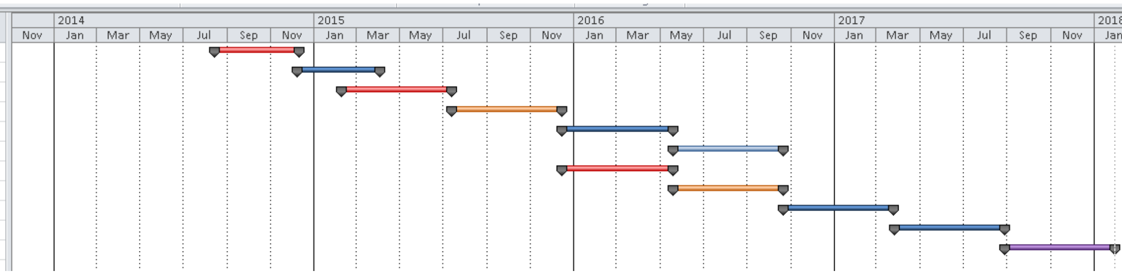
	Task Mode	Task Name	Duration	Start	Finish	Pre
24		First generation cable geometry	0 days	Sat 01/06/13	Sat 01/06/13	
25		Second generation cable geometry	0 days	Mon 02/06/14	Mon 02/06/14	
26		⊟ Coil fabrication CERN	806 days	Wed 08/01/14	Wed 08/02/17	
27		End parts decision	0 days	Wed 08/01/14	Wed 08/01/14	
28		⊟ First generation coils	445 days	Mon 03/02/14	Fri 16/10/15	
29		⊞ Coil C1 (practice)	120 days	Mon 03/02/14	Fri 18/07/14	
34		⊞ Coil C2 (practice)	120 days	Mon 28/04/14	Fri 10/10/14	
39		⊞ Coil C3 (RRP) for mirror	100 days	Mon 21/07/14	Fri 05/12/14	
44		⊞ Coil C4 (RRP)	100 days	Mon 22/09/14	Fri 06/02/15	
49		⊞ Coil C5 (RRP)	100 days	Mon 24/11/14	Fri 10/04/15	
54		⊞ Coil C6 (RRP)	100 days	Mon 26/01/15	Fri 12/06/15	
59		⊞ Coil C7 (RRP)	100 days	Mon 30/03/15	Fri 14/08/15	
64		⊞ Coil C8 (RRP)	100 days	Mon 01/06/15	Fri 16/10/15	
69		⊟ Second generation coils	398 days	Mon 03/08/15	Wed 08/02/17	
70		⊞ Coil C9 (PIT)	100 days	Mon 03/08/15	Fri 18/12/15	
75		⊞ Coil C10 (PIT)	100 days	Thu 17/09/15	Wed 03/02/16	
80		⊞ Coil C11 (PIT)	100 days	Tue 03/11/15	Mon 21/03/16	
85		⊞ Coil C12 (PIT)	100 days	Fri 18/12/15	Thu 05/05/16	
90		⊞ Coil C13 (PIT)	100 days	Wed 03/02/16	Tue 21/06/16	
95		⊞ Coil C14 (PIT)	100 days	Mon 21/03/16	Fri 05/08/16	
100		⊞ Coil C15 (RRP)	100 days	Thu 05/05/16	Wed 21/09/16	
105		⊞ Coil C16 (RRP)	100 days	Thu 09/06/16	Wed 26/10/16	
110		⊞ Coil C17 (RRP)	100 days	Thu 14/07/16	Wed 30/11/16	
115		⊞ Coil C18 (RRP)	100 days	Thu 18/08/16	Wed 04/01/17	
120		⊞ Coil C19 (RRP)	100 days	Thu 22/09/16	Wed 08/02/17	
125		⊟ Coil fabrication LARP	488 days	Wed 05/02/14	Fri 18/12/15	
126		⊟ First generation coils	301 days	Wed 05/02/14	Wed 01/04/15	
127		⊞ Practice Coil #L1	108 days	Wed 05/02/14	Fri 04/07/14	
132		⊞ Practice Coil #L2	120 days	Thu 13/03/14	Wed 27/08/14	
138		⊞ Coil #L3 (for mirror test)	88 days	Mon 14/04/14	Wed 13/08/14	
143		⊞ Coil #L4	107 days	Mon 07/07/14	Tue 02/12/14	
150		⊞ Coil #L5	102 days	Mon 28/07/14	Tue 16/12/14	
156		⊞ Coil #L6	120 days	Mon 18/08/14	Fri 30/01/15	
163		⊞ Coil #L7	98 days	Wed 01/10/14	Fri 13/02/15	
169		⊞ Coil #L8	116 days	Wed 22/10/14	Wed 01/04/15	
176		⊟ Second generation coils	207 days	Thu 05/03/15	Fri 18/12/15	
177		⊞ Coil L9	107 days	Thu 05/03/15	Fri 31/07/15	
184		⊞ Coil L10	107 days	Thu 09/04/15	Fri 04/09/15	
191		⊞ Coil L11	107 days	Thu 14/05/15	Fri 09/10/15	
198		⊞ Coil L12	107 days	Thu 18/06/15	Fri 13/11/15	
205		⊞ Coil L13 (spare)	107 days	Thu 23/07/15	Fri 18/12/15	



SQXF plan and schedule
Tests

- 1st generation coils
  - First **LARP coil mirror test** in 12/2014
  - First **CERN coil mirror test** (mirror) in 04/2015
  - First magnet test (**SQXF1**) in 05/2015
      - Assembled and tested by LARP with 3 LARP coils and 1 CERN coil
  - Then **SQXF1b** (LARP), **SQXF2** (CERN), **SQXF2b** in series (2015-2016)
    - All the coil fabricated to date will be available for 1 magnet (not shared)
  - Test of LHe containment in **SQXF2b**
- 2nd generation coils
  - LARP RRP: **SQXF3** and **SQXF3b** (2016)
  - CERN PIT: **SQXF4** (2016-2017)
  - CERN RRP: **SQXF5** (2017)
- Test of 2-magnets in 1-cold-mass: **SQXF6** (2017)

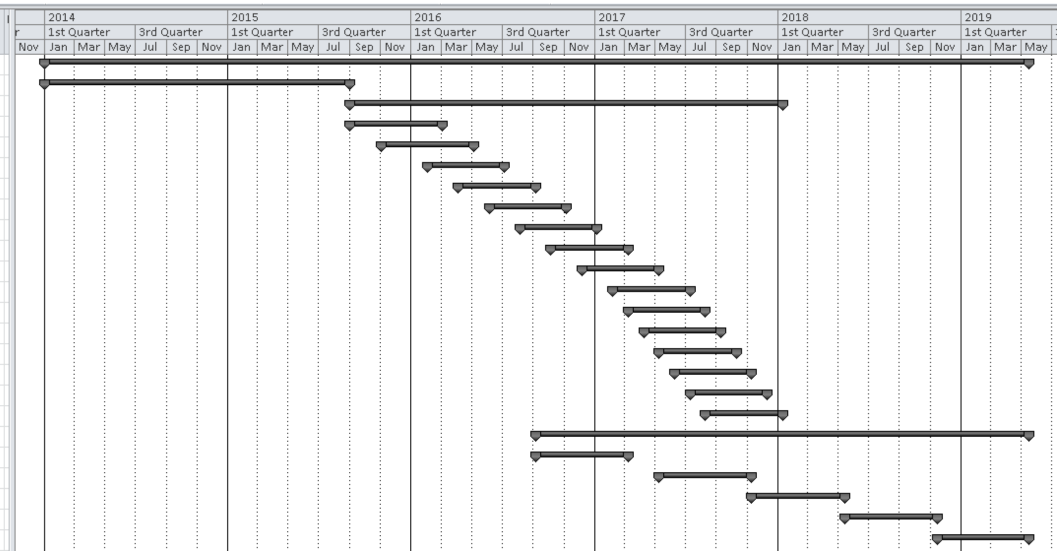
	Task Name	Duration	Start	Finish	Predecessors
212	SQXF mirror (LARP)	85 days	Thu 14/08/14	Wed 10/12/14	
218	SQXF mirror (CERN)	85 days	Mon 08/12/14	Fri 03/04/15	
224	SQXF1 (LARP); coil L4,L5,L6,C4	111 days	Mon 09/02/15	Mon 13/07/15	
228	SQXF1b (LARP)	111 days	Tue 14/07/15	Tue 15/12/15	
232	SQXF2 (CERN)	111 days	Wed 16/12/15	Wed 18/05/16	
236	SQXF2b (CERN) with Lhe containment	111 days	Thu 19/05/16	Thu 20/10/16	
240	SQXF3 (LARP): RRP II generation	111 days	Wed 16/12/15	Wed 18/05/16	
244	SQXF3b (LARP)	111 days	Thu 19/05/16	Thu 20/10/16	
248	SQXF4 (CERN): PIT II generation	111 days	Fri 21/10/16	Fri 24/03/17	
252	SQXF5 (CERN): RRP II generation	111 days	Mon 27/03/17	Mon 28/08/17	
256	SQXF6: 2-magnets, 1-cold-mass	111 days	Tue 29/08/17	Tue 30/01/18	



CERN long models Schedule

- Coil winding starts in 09/2015
  - 3 practice, 6 RRP, 6 PIT
- Mirror test in end 2016 / early 2017
- First long model by mid-2017
- 2 long models, 4 tests in 2017-2018

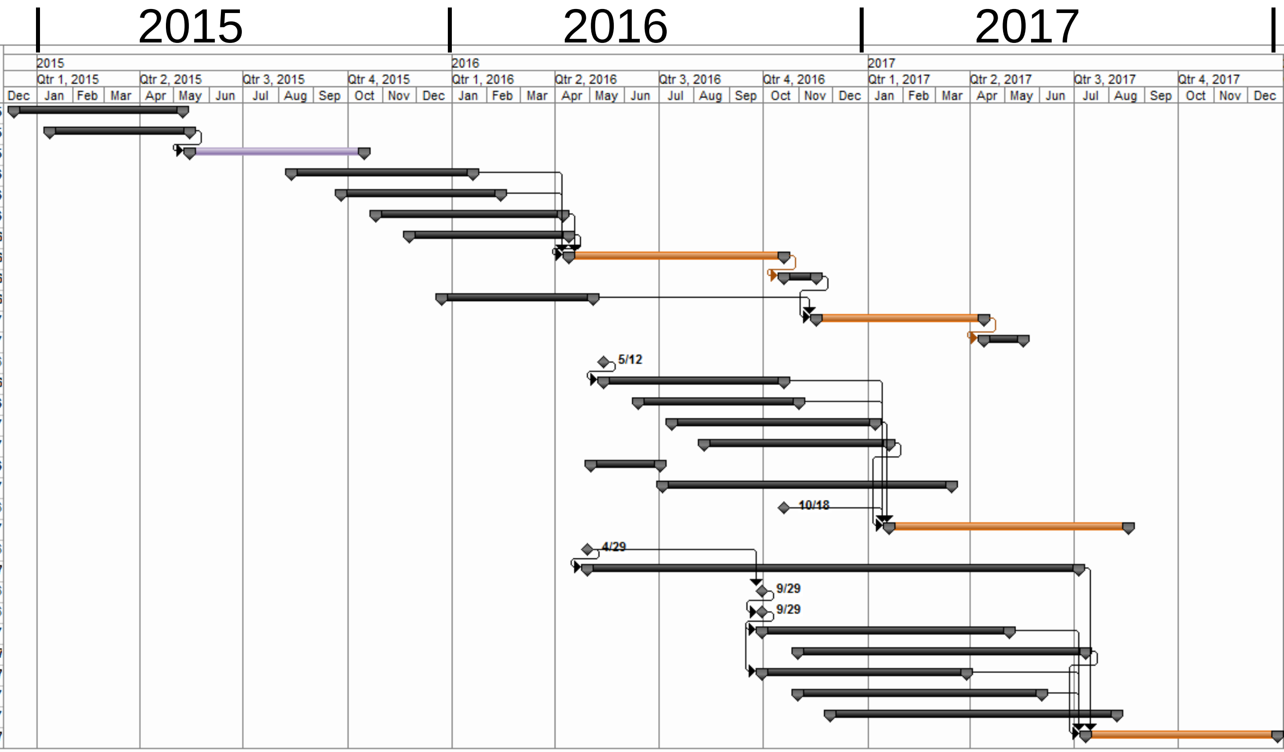
	Task Mode	Task Name	Duration	Start	Finish	Predecessors
5		⊟ Long prototype program	1403 days?	Wed 01/01/14	Fri 17/05/19	
6		⊞ Long prototype tooling design and fabrication	435 days?	Wed 01/01/14	Tue 01/09/15	
10		⊟ Long prototype coils fabrication	616 days	Wed 02/09/15	Wed 10/01/18	
11		⊞ Practice coil 1	132 days	Wed 02/09/15	Thu 03/03/16	
15		⊞ Practice coil 2	132 days	Tue 03/11/15	Wed 04/05/16	
19		⊞ Practice coil 3	110 days	Wed 03/02/16	Tue 05/07/16	
23		⊞ Coil 4 (RRP mirror coil)	110 days	Tue 05/04/16	Mon 05/09/16	
27		⊞ Coil 5 (RRP)	110 days	Mon 06/06/16	Fri 04/11/16	
31		⊞ Coil 6 (RRP)	110 days	Fri 05/08/16	Thu 05/01/17	
35		⊞ Coil 7 (RRP)	110 days	Thu 06/10/16	Wed 08/03/17	
39		⊞ Coil 8 (RRP)	110 days	Wed 07/12/16	Tue 09/05/17	
43		⊞ Coil 9 (RRP)	110 days	Tue 07/02/17	Mon 10/07/17	
47		⊞ Coil 10 (PIT)	110 days	Thu 09/03/17	Wed 09/08/17	
51		⊞ Coil 11 (PIT)	110 days	Mon 10/04/17	Fri 08/09/17	
55		⊞ Coil 12 (PIT)	110 days	Wed 10/05/17	Tue 10/10/17	
59		⊞ Coil 13 (PIT)	110 days	Fri 09/06/17	Thu 09/11/17	
63		⊞ Coil 14 (PIT)	110 days	Tue 11/07/17	Mon 11/12/17	
67		⊞ Coil 15 (PIT)	110 days	Thu 10/08/17	Wed 10/01/18	
71		⊟ Long prototype magnets	704 days	Tue 06/09/16	Fri 17/05/19	
72		⊞ MQXFLP mirror; coil 4	132 days	Tue 06/09/16	Wed 08/03/17	
76		⊞ MQXFLP1; coil 5,6,7,8	132 days	Wed 10/05/17	Thu 09/11/17	
80		⊞ MQXFLP1b; coil 6,7,8,9	132 days	Fri 10/11/17	Mon 14/05/18	
84		⊞ MQXFLP2; coil 10,11,12,13	132 days	Tue 15/05/18	Wed 14/11/18	
88		⊞ MQXFLP2b; coil 12,13,14,15	132 days	Thu 15/11/18	Fri 17/05/19	



LARP long models Schedule

- Coil winding starts in December 2014
- Mirror test in September 2015
- First LQXF test in August 2016
- 3 LQXF tested by end of 2017

ID		Task Name	Duration	Start	Finish
260		Long QXF Practice Coil	106 days	Fri 12/12/14	Fri 5/8/15
266		Lcoil #1 (for mirror)	89 days	Mon 1/12/15	Thu 5/14/15
271		LQXF mirror	110 days	Fri 5/15/15	Thu 10/15/15
277		Lcoil #2	113 days	Thu 8/13/15	Mon 1/18/16
284		Lcoil #3	101 days	Fri 9/25/15	Fri 2/12/16
290		Lcoil #4	119 days	Mon 10/26/15	Thu 4/7/16
297		Lcoil #5	101 days	Tue 11/24/15	Tue 4/12/16
303		LQXF1	135 days	Wed 4/13/16	Tue 10/18/16
309		LQXF1 disassembly	21 days	Wed 10/19/16	Wed 11/16/16
312		Lcoil #6	95 days	Wed 12/23/15	Tue 5/3/16
318		LQXF1b	105 days	Thu 11/17/16	Wed 4/12/17
323		LQXF1b disassembly	25 days	Thu 4/13/17	Wed 5/17/17
326		LQS02 readiness review	0 days	Thu 5/12/16	Thu 5/12/16
327		Lcoil #7	113 days	Fri 5/13/16	Tue 10/18/16
334		Lcoil #8	101 days	Mon 6/13/16	Mon 10/31/16
340		Lcoil #9	129 days	Tue 7/12/16	Fri 1/6/17
347		Lcoil #10	117 days	Wed 8/10/16	Thu 1/19/17
353		Lcoil #11 (W&C PC at BNL)	45 days	Mon 5/2/16	Fri 7/1/16
357		Lcoil #12 (full coil at BNL)	183 days	Mon 7/4/16	Wed 3/15/17
363		2nd LQXF structure procured and qualified	0 days	Tue 10/18/16	Tue 10/18/16
364		LQXF2 horizontal test	150 days	Fri 1/20/17	Thu 8/17/17
369		MQXF TDR completed	0 days	Fri 4/29/16	Fri 4/29/16
370		LQXF3 Magnet structure (design for MQXF)	308 days	Fri 4/29/16	Tue 7/4/17
377		Completed coil modifications based on MQXF TDR	0 days	Thu 9/29/16	Thu 9/29/16
378		LQXF03 Readiness Review	0 days	Thu 9/29/16	Thu 9/29/16
379		Lcoil #13	155 days	Fri 9/30/16	Thu 5/4/17
384		Lcoil #14	182 days	Mon 10/31/16	Tue 7/11/17
389		Lcoil #15	128 days	Fri 9/30/16	Tue 3/28/17
395		Lcoil #16	155 days	Mon 10/31/16	Fri 6/2/17
401		Lcoil #17	180 days	Tue 11/29/16	Mon 8/7/17
406		LQXF3 w MQXF structure	120 days	Wed 7/12/17	Tue 12/26/17



Cable Compaction - Risk Analysis: Winding stability vs. Sheared sub-elements

Risk	Mitigation plan(s)	Effects of mitigation failure	Probability of mitigation failure	Risk rating
Popped strands	Wind with tool (HQ02/03)			
→ Electrical failures	Use binder (11 T)			
→ Degradation	Online turn-turn short detection			
	Impulse test			
	→ Reject coil after QA tests			

Cable Compaction - Risk Analysis: Winding stability vs. Sheared sub-elements

Risk	Mitigation plan(s)	Effects of mitigation failure	Probability of mitigation failure	Risk rating
Sheared subelements	Extracted strand tests			
→ Limited stability	Cable tests			
→ limited magnet performance	→ Reject unit length			

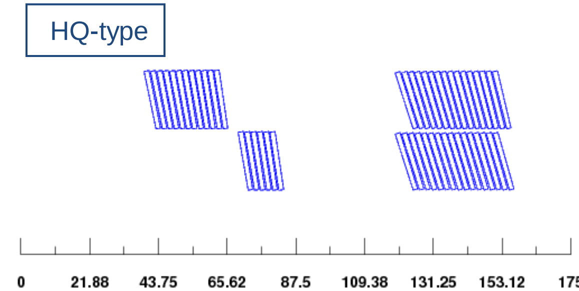
†Bas

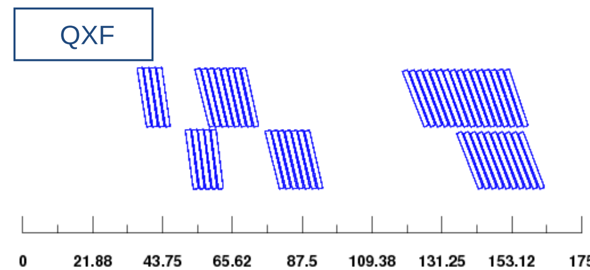
Additional slides

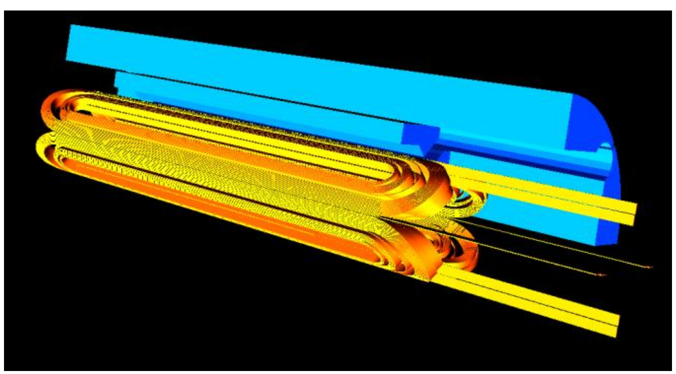
3D magnetic design

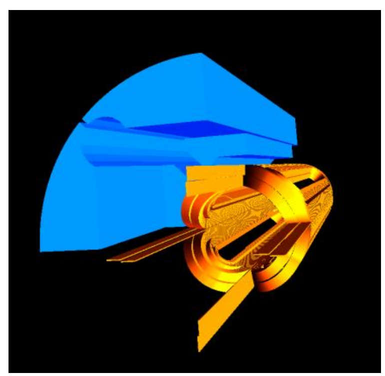
(*By S. Izquierdo Bermudez, 1PoAN-04*)

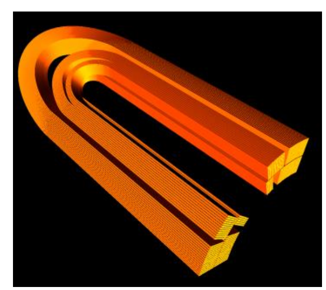
- From 4 (HQ) to 6 blocks in the ends
  - Impact on field quality: $b_6 < 1.1$ unit and $b_{10} < 0.2$ unit
- Iron pad removed with reduced length
- 1% peak field margin in the end
- Short model
  - Magnetic length 1.2 m
  - Coil length: 1.5 m
  - Good field quality region: 0.5 m

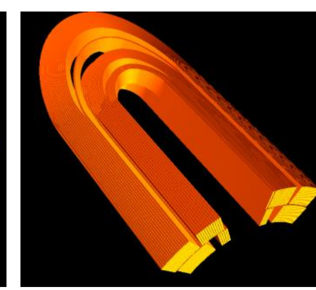










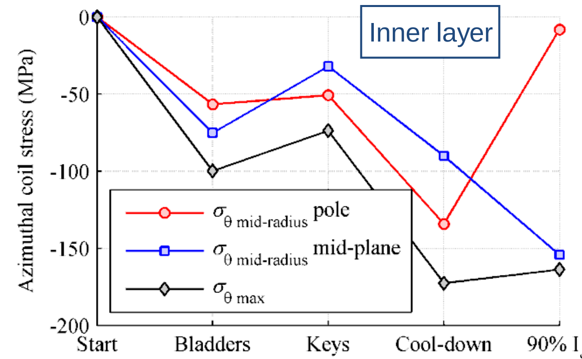


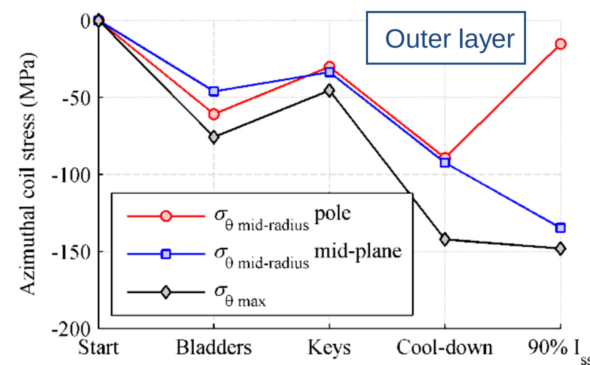
Mechanical analysis

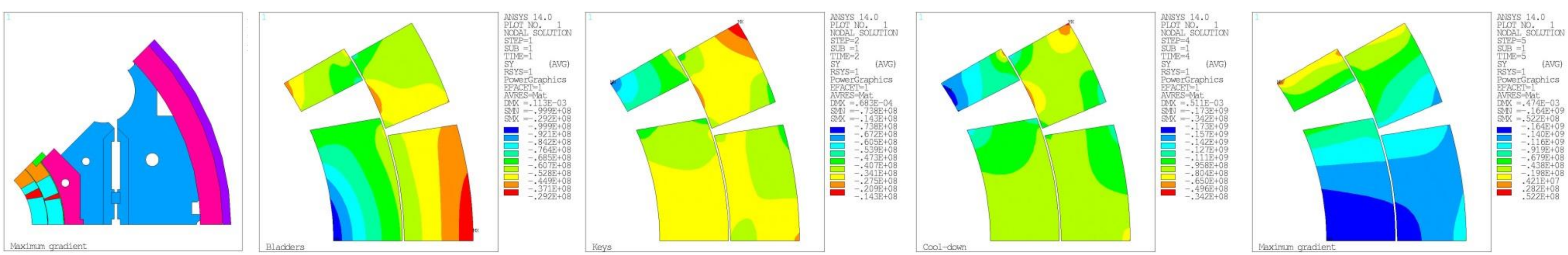
(by M. Juchno)

- Optimization of dimensions and locations of new features
- ≥2 MPa of contact pressure at up to 155 T/m (~90% of I_{ss})

- Peak coil stress: -160/-175 MPa
- Coil displ. from start to nominal grad.
  - Radial/azimuth.: -0.3/-0.04 mm
  - Effect on field quality: 0.75 units of b_6



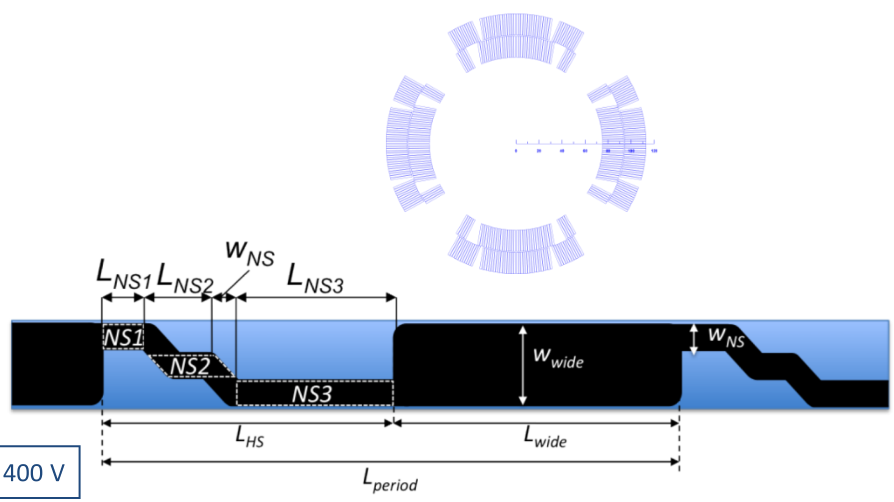




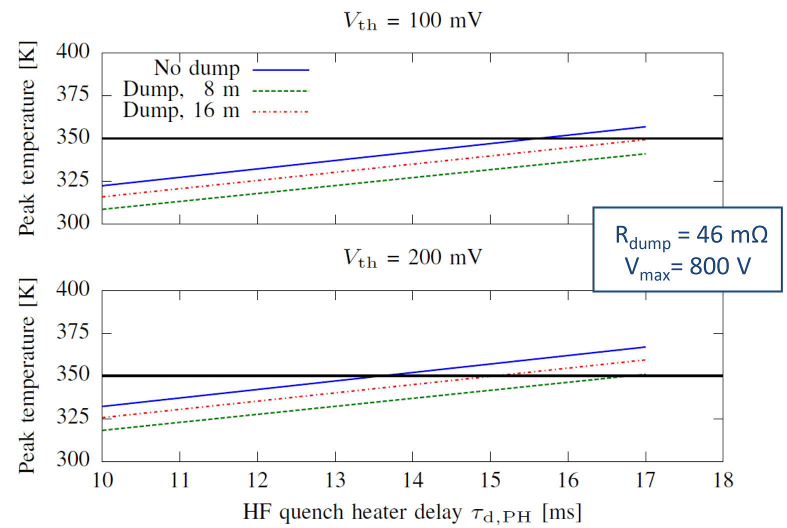
Quench protection

(*see T. Salmi, 2PoCC-03, and G. Manfreda, et al., 2PoCC-05*)

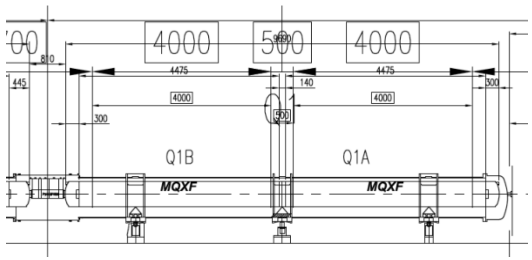
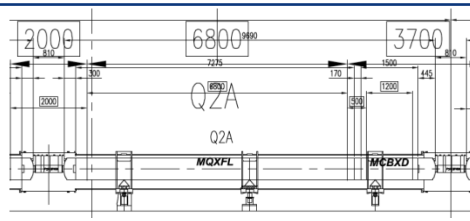
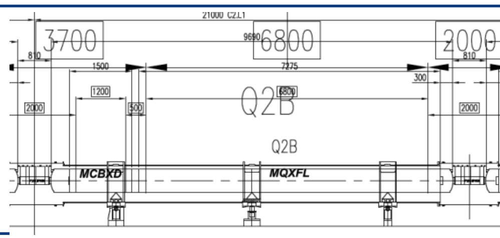
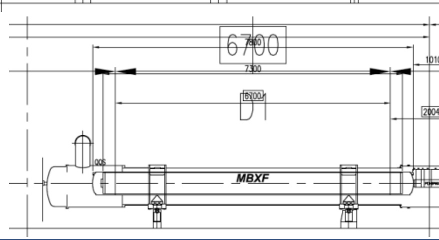
- Trace with 4 heaters strips per coil, with 50 μm polyimide insulation
  - Heating stations in outer layer only
  - Heater delay of about 17 ms
- Before, 10 ms of validation and, after, 20 ms of outer-to-inner delay
- Hot spot T of 350 K (34 MIITS) hardly achieved with no margin
- Under study
  - Modelling of material properties (bronze) and quench-back + *dI/dt* effects
  - Reduced delay of heater (25 μm polyimide?) and inner layer quenching



V_{max}= 400 V



Naming (proposal) 1/3

	Drawing	Cryo-magnet	Cold mass	Magnets
Q1		LQXFA	LMQXFA	MQXF
Q3		(LQXFB)	(LMQXFB)	
Q2a		LQXFC	LMQXFC	MQXFL + MCBXFA/B
Q2b		(LQXFD)	(LMQXFD)	
D1		LBXF	LMBXF	MBXF

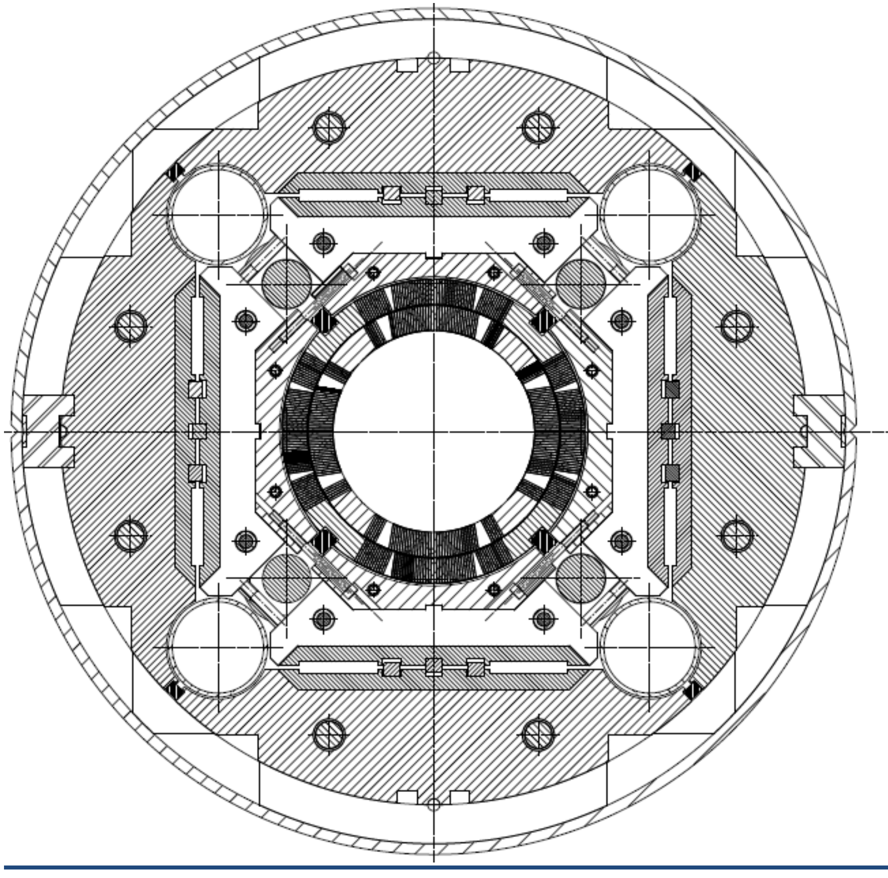
SQXF plan and schedule
Coil fabrication

- CERN
  - Fabrication steps
    - Winding + curing + reaction + impregnation
  - Fabrication time
    - ~100 days (5 months) per coil
    - 1 coil produced
      - every 2 months in the 1st year
      - every 1.5 months in the 2st year
      - every 1 months in the 3st year

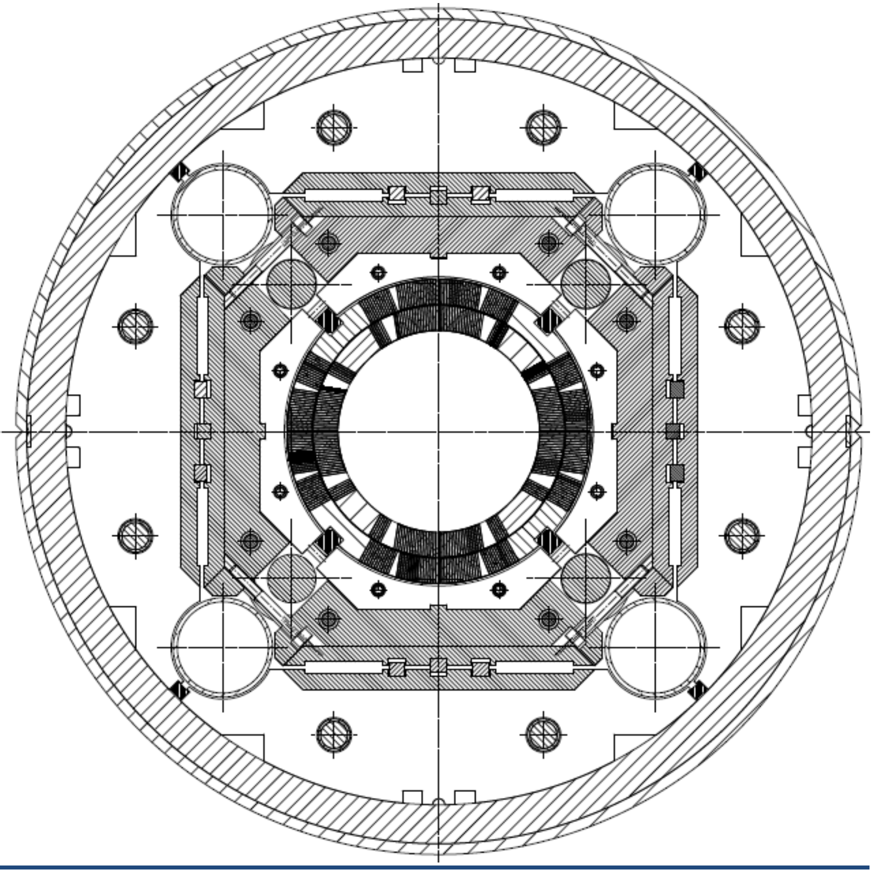
- LARP
  - Fabrication steps
    - First generation
      - FNAL & LBNL: winding + curing
      - BNL & FNAL : reaction + impregnation
    - Second generation
      - LBNL on SQXF
      - FNAL and BNL on LQXF
  - Fabrication time
    - ~100 days (5 months) per coil
    - 1 coil produced every month

Engineering design
(work in progress)

Centre of the magnet



Centre of the aluminium shell



Additional 1% to 2% from higher Tcm*

Ca1*	41.24	T
Ca2* = 1034 x Ca1*	42642	T
eps_0,a	0.250%	
Bc2m*(0)	30.88	T
Tcm*	16.7	K
C*	1519	TA
p	0.5	
q	2	
Strain=	-0.20%	

Ca1*	41.24	T
Ca2* = 1034 x Ca1*	42642	T
eps_0,a	0.250%	
Bc2m*(0)	31.40	T
Tcm*	15.57	K
C*	1535	TA
p	0.5	
q	2	
Strain=	-0.20%