

LARP



U.S. DEPARTMENT OF
ENERGY

Office of
Science



October 9 - 14, 2016

Chicago, IL U.S.A.

First Test Results of the 150 mm Aperture IR Quadrupole Models for the High Luminosity LHC

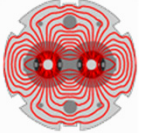
G. Ambrosio, G. Chlachidze, Fermilab, Batavia, IL USA

P. Wanderer, BNL, Upton, NY USA

P. Ferracin, CERN, CH

G. Sabbi, LBNL, Berkeley, CA USA

on behalf of the LARP-CERN collaboration for HL-LHC



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BNL

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CERN

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FNAL

G. Ambrosio, G. Apollinari, R. Bossert, R. Carcagno, G. Chlachidze, L. Cooley, S. Feher, E. Holik, S. Krave, F. Nobrega, I. Novitski, C. Santini, S. Stoynev, T. Strauss, C. Sylvester, A. Vouris, M. Yu, A. Zlobin

LBNL

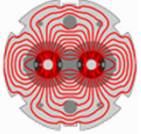
E. Anderssen, D. Cheng, D.R. Dietderich, H. Felice, R. Hafalia, M. Marchevsky, H. Pan, I. Pong, S. Prestemon, E. Ravaioli, G. Sabbi, X. Wang

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LASA V. Marinozzi, M. Sorbi

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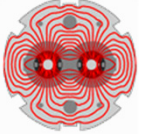


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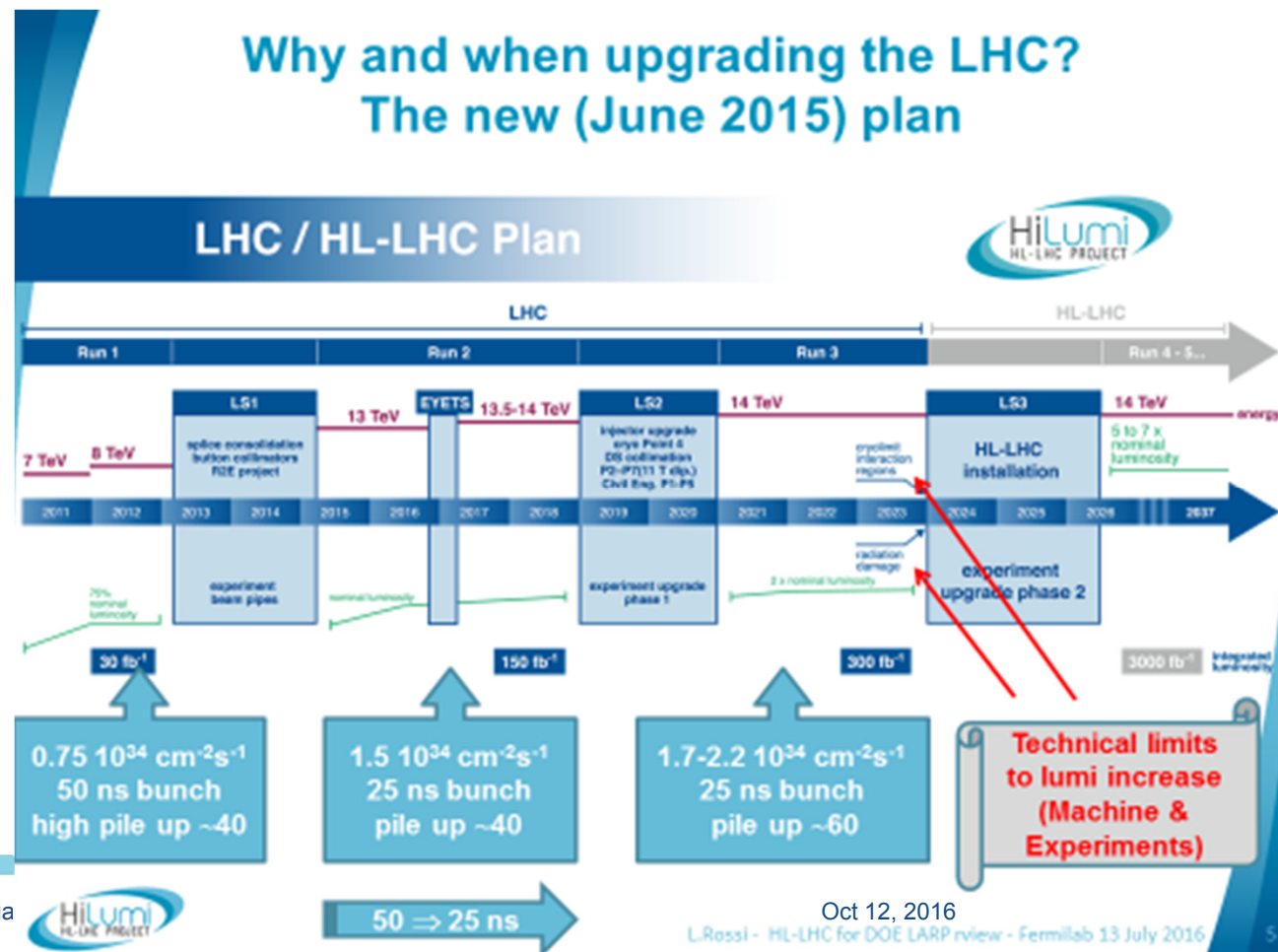
Outline

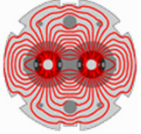


- Scope & Requirements
- The past development: LARP
- The present design: MQXF
- Test Results
- Challenges & Plans
- Conclusions



- New IT quads: a key component for the High Luminosity LHC
 - GOAL: $L_{int} = 3000 \text{ fb}^{-1}$ twelve years after the upgrade
 - Ultimate performance: $L_{int} = 4000 \text{ fb}^{-1}$





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New Inner Triplets for HiLumi LHC



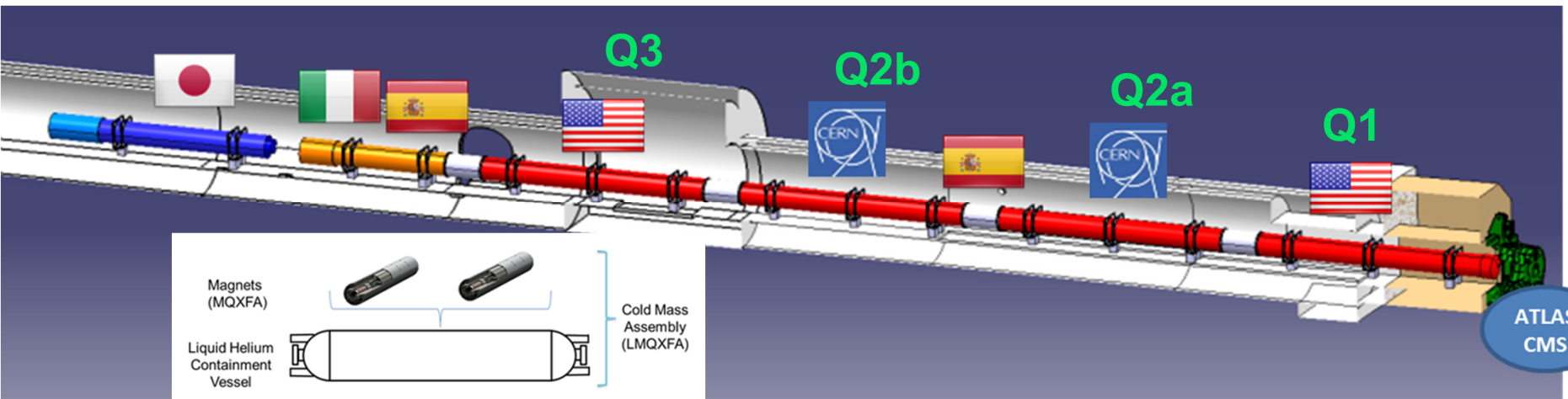
Main Requirements:

- Aperture: 150 mm
 - Allows tungsten liner → dose ~ present IT magnets
- Gradient: 132.6 T/m
- Magnetic length: 8.4 m (Q1 & Q3); 7.15 m (Q2a & Q2b)
 - Q1 & Q3 are made of two 4.2m in one cold mass

The magnet (MQXF) design is done

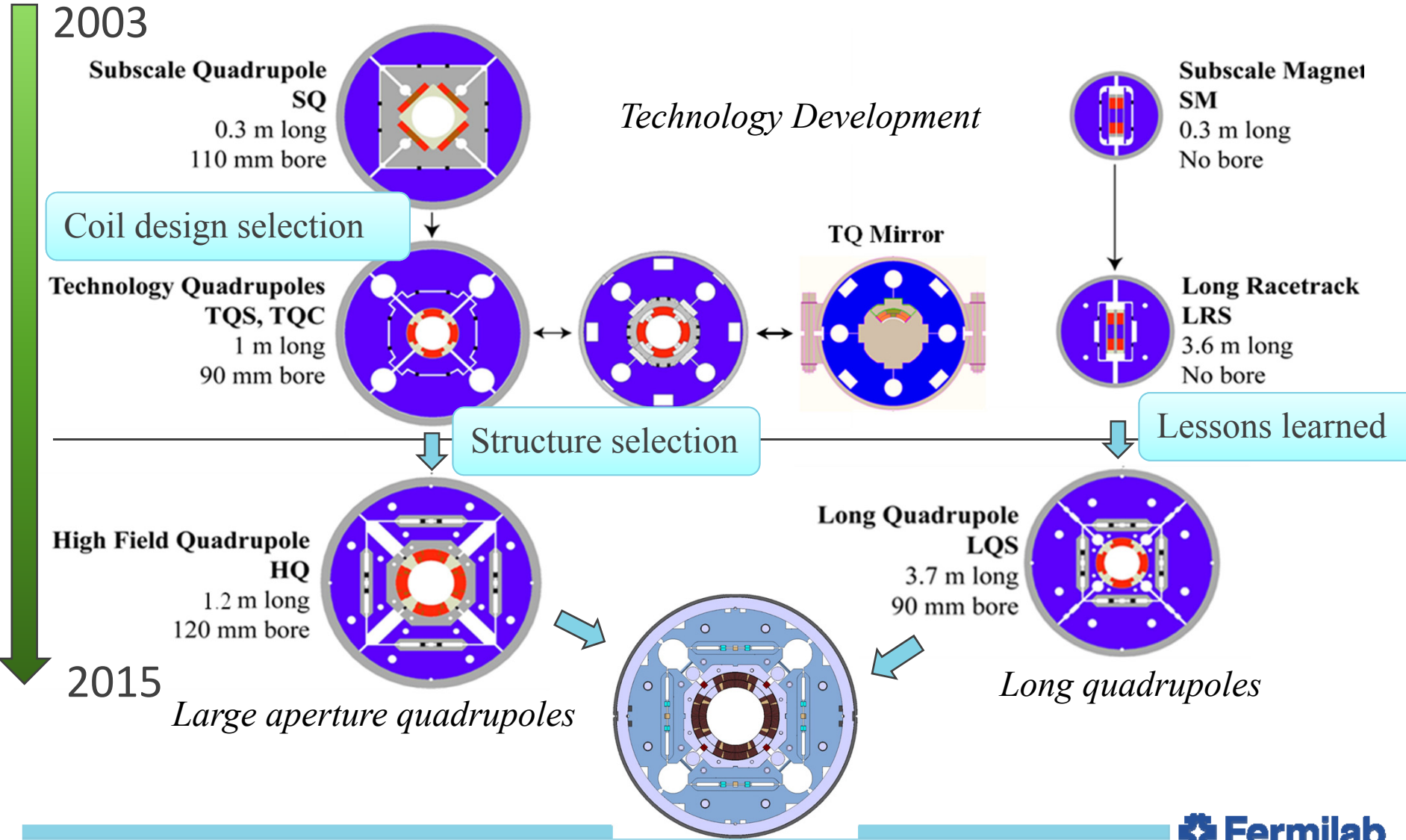
Same design for Q1/Q3 (US) and Q2a/Q2b (CERN)

MQXF development is in the demonstration phase



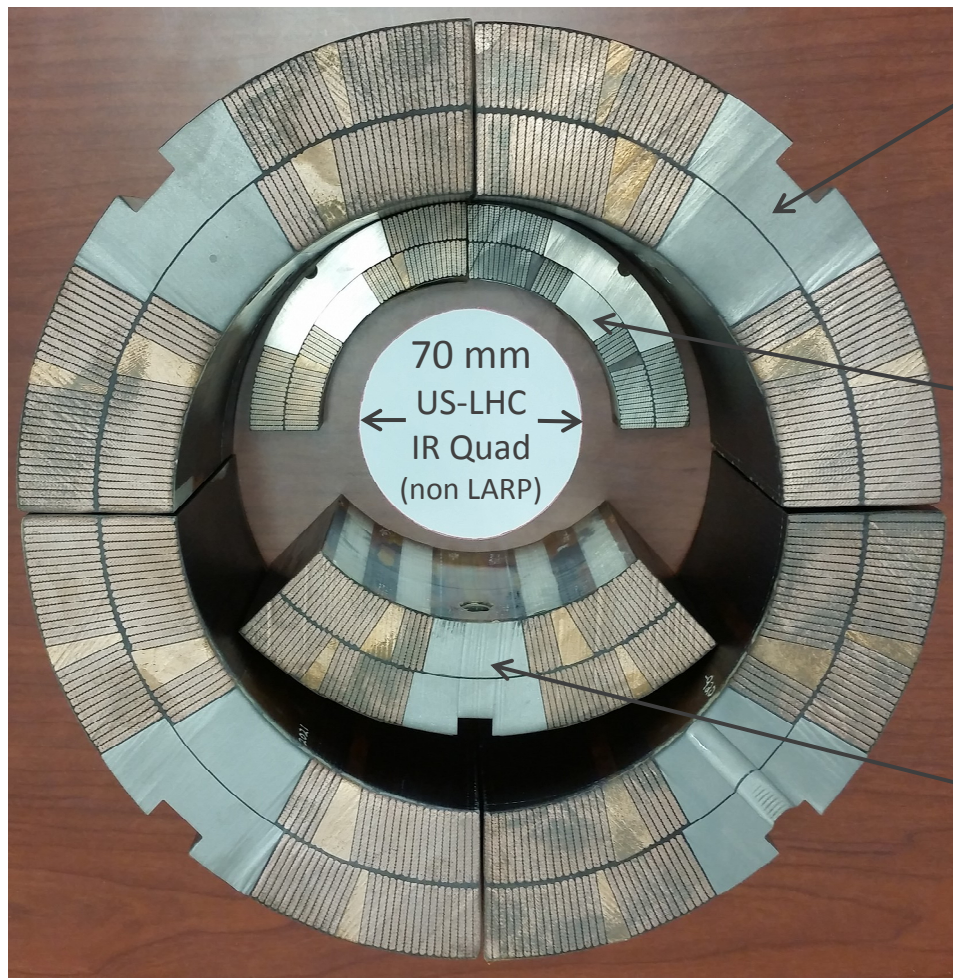


MQXF Design based on LARP Development





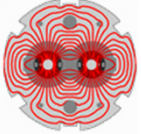
From 70 to 150 ...



LARP MQXF
Aperture: 150 mm
Gradient: 133 T/m

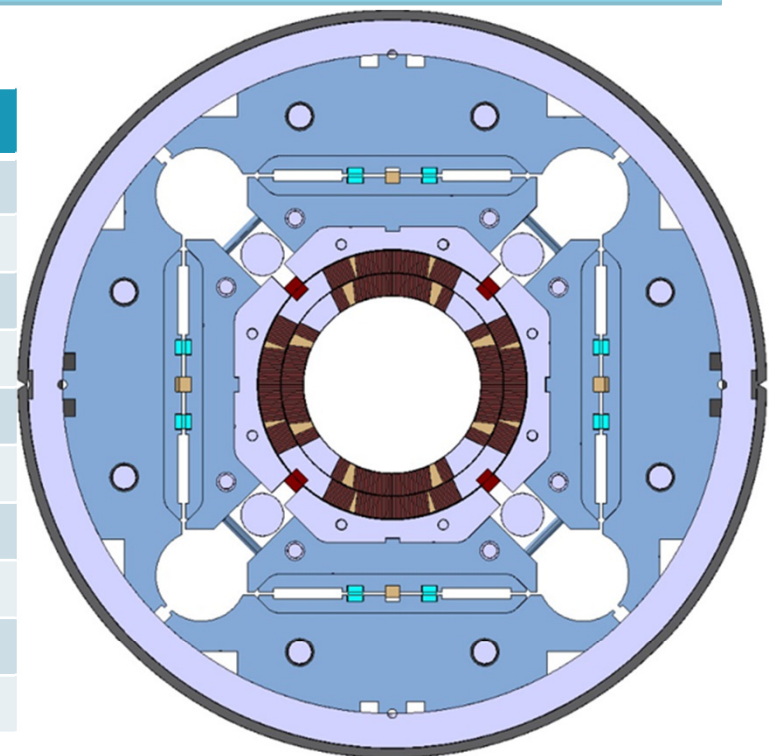
LARP TQ-LQ
Aperture: 90 mm
Gradient: 200 T/m

LARP HQ
Aperture: 120 mm
Gradient: 170 T/m

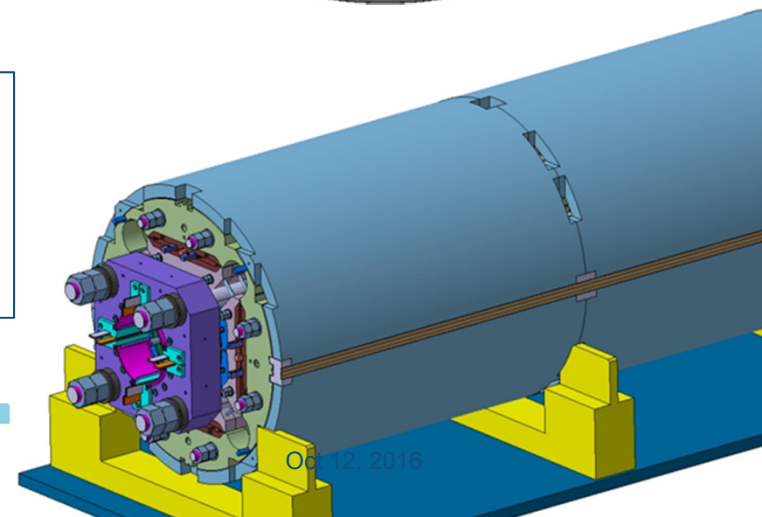


MQXFA/B Main Parameters†

PARAMETER	Unit	MQXFA/B
Coil aperture	mm	150
Magnetic length	m	4.2/7.15
N. of layers		2
N. of turns Inner-Outer layer		22-28
Operation temperature	K	1.9
Nominal gradient	T/m	132.6
Nominal current	kA	16.5
Peak field at nom. current	T	11.4
Stored energy at nom. curr.	MJ/m	1.2
Diff. inductance	mH/m	8.2

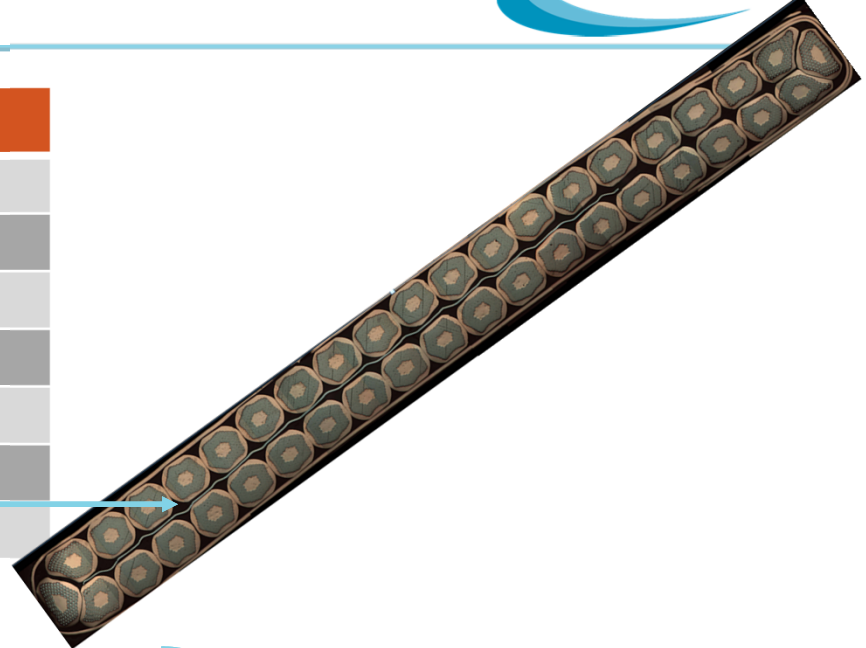


†- P. Ferracin, et al., “Magnet design of the 150 mm aperture low-beta quadrupoles for the high luminosity LHC”, *IEEE Trans. Appl. Supercond.*, vol. 24, no. 3, Jun. 2014, Article # 4002306.
 - G. Ambrosio, et al., “MQXFS1 Quadrupole Design Report” LARP DocDB #1074





Nb₃Sn Conductor



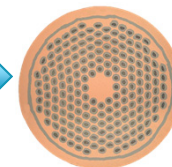
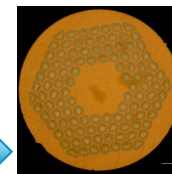
PARAMETER	Unit	MQXFA/B
Strand diameter	mm	0.85
Strand number		40
Cable width	mm	18.15
Cable mid thickness	mm	1.525
Keystone angle	deg.	0.4
SS core thickness	um	25
SS core width	mm	12

- Cu/SC: 1.2
- I_c at 4.2 K, 12 T: 632 A (RRP) – 590 A (PIT)
- I_c at 4.2 K, 15 T: 331 A

$$I_{op}/I_{ss} = 77\%$$

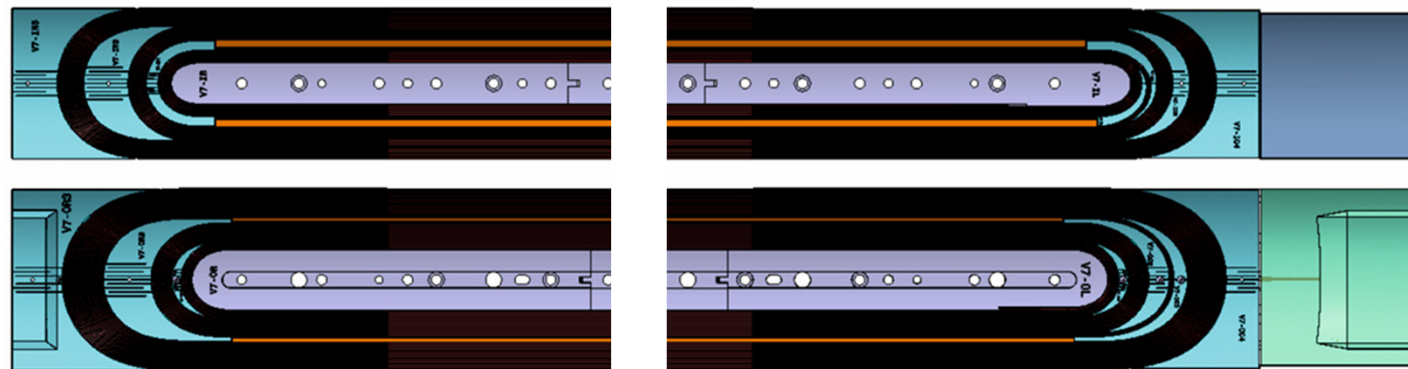
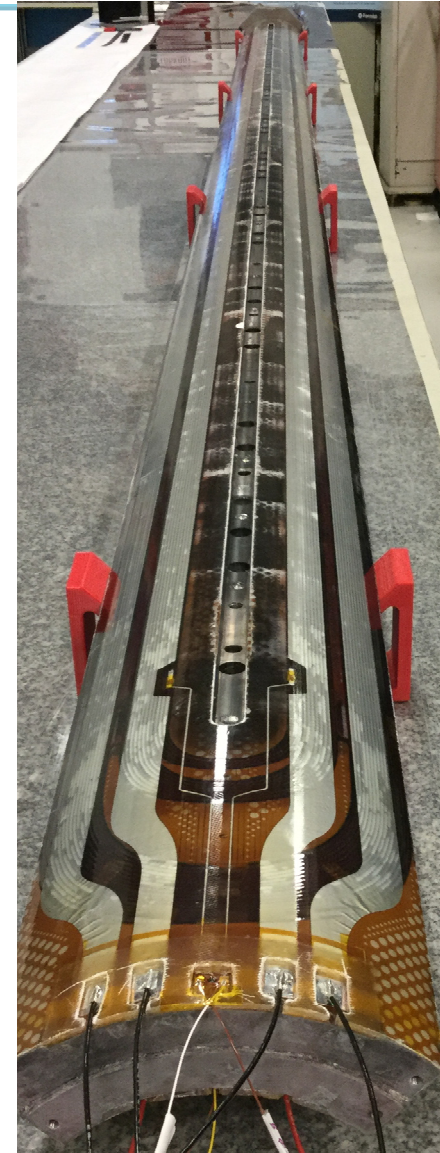
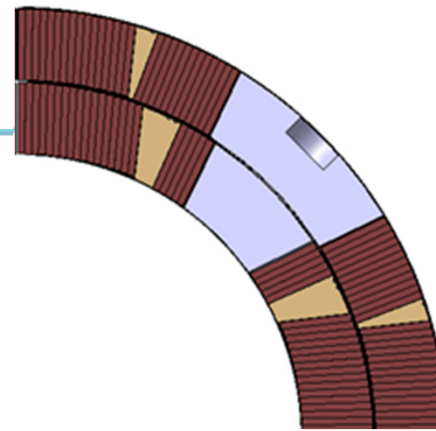
	Strand Type	Vendor	Km
LARP	RRP 108/127	OST	90
CERN	RRP 108/127	OST	74
CERN	PIT 192	EAS	65

Strand procured according to final specs.

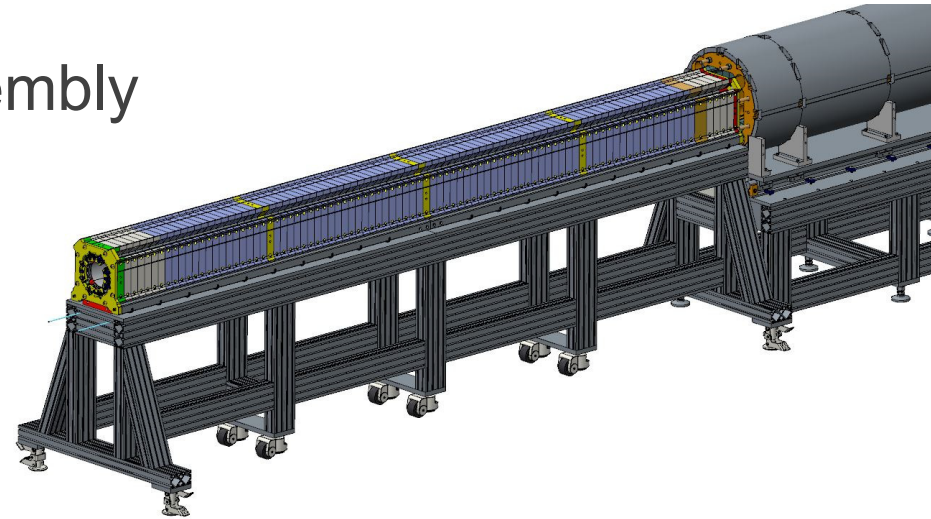
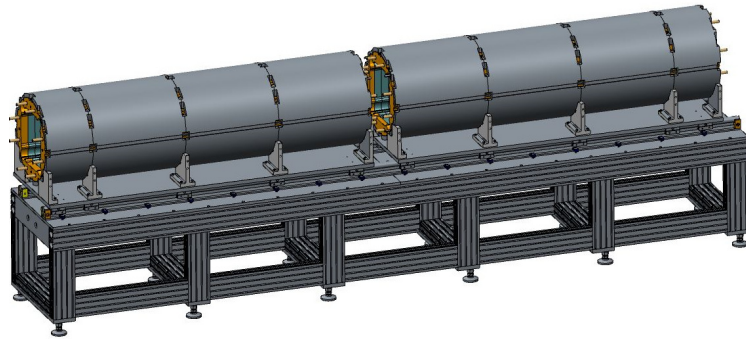


Coils

- 2 Layers (22+28 = 50 turns)
- No splice between layers
- Four-blocks design
- **2 end spacers** for peak field reduction (1%) and field quality
- Pole impregnated with the coil
- Very similar to HQ (120 mm) design

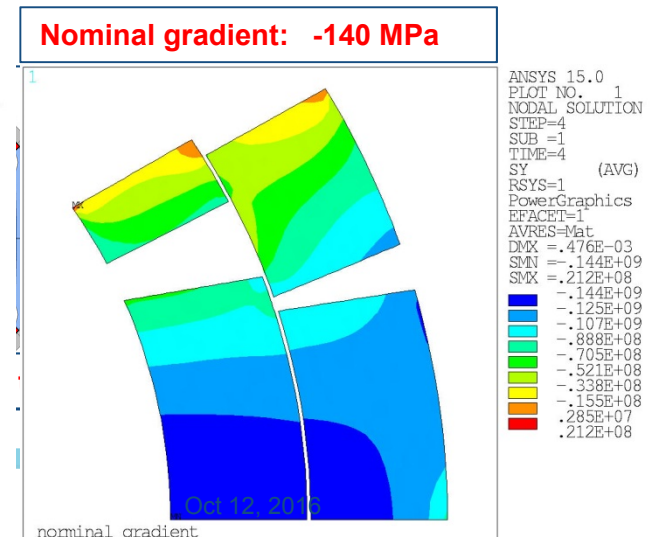
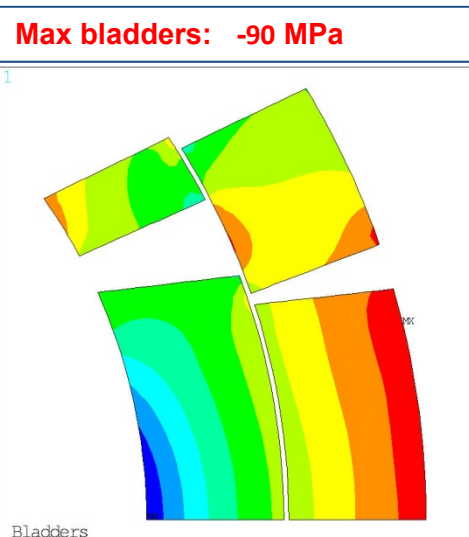


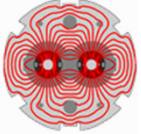
- Shell-yoke modules combined
- Insertion of coil-pack sub-assembly



- Then bladder operation

Coil peak azimuthal stress:



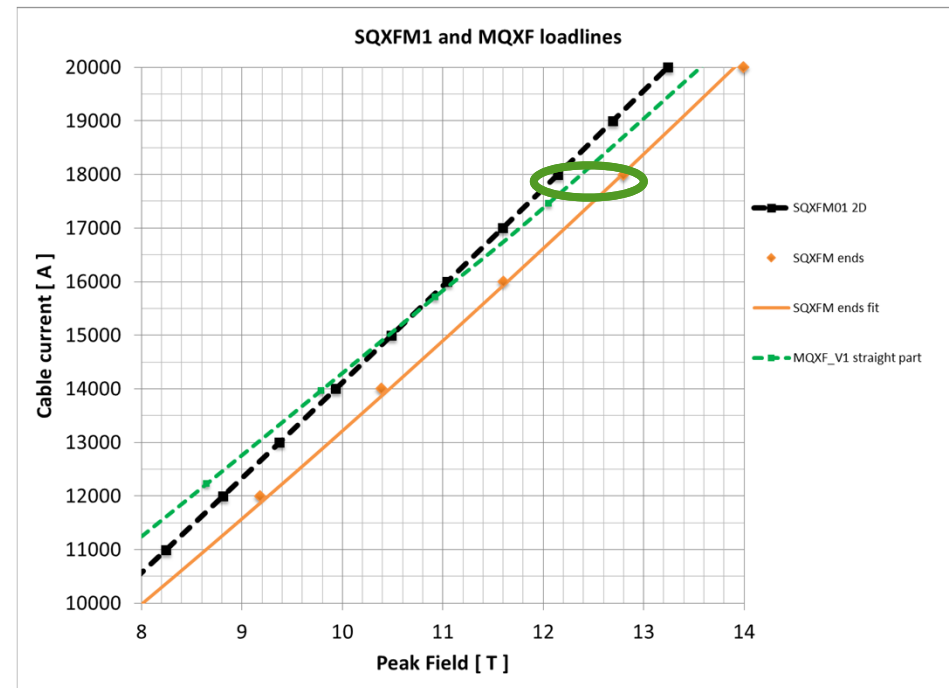
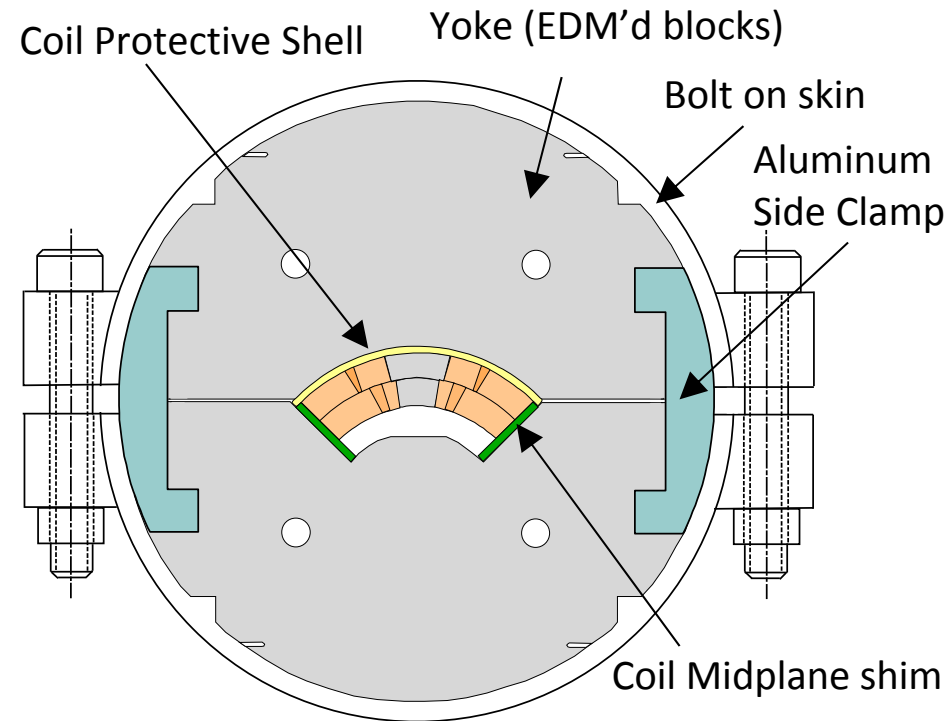


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TEST RESULTS

- Mirror structure as coil test facility for QC:
 - Load line within a few percent from MQXF load line
 - Low prestress to avoid damage

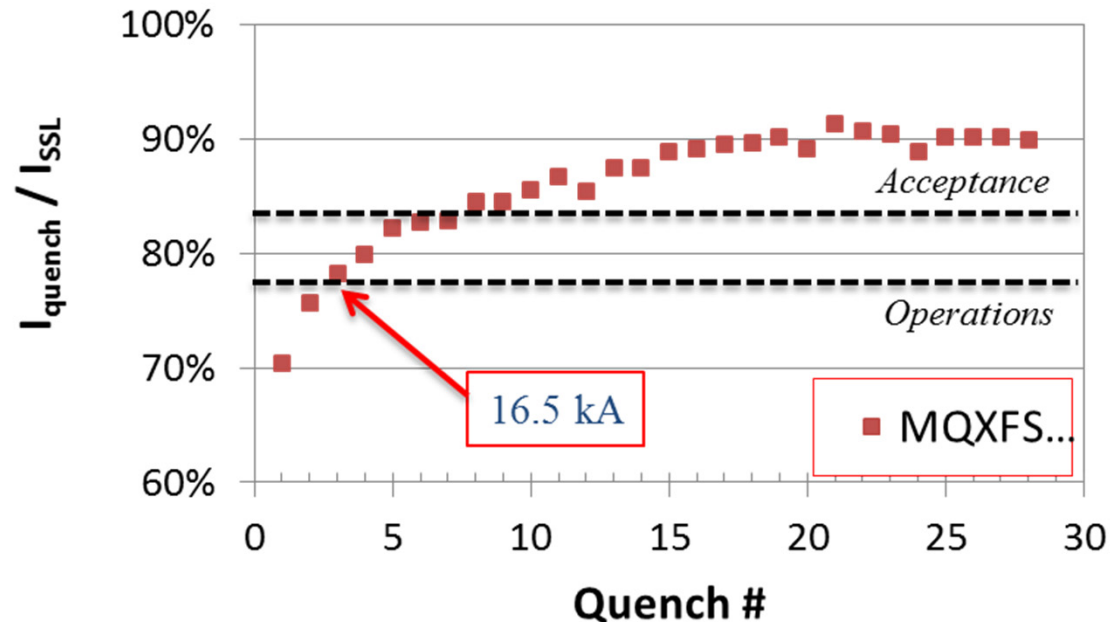


- Conductor:
 - RRP 108/127 with Ta doping
 - smaller strain tolerance than 108/127 with Ti doping (used for all other QXF coils, and for production)
- Acceptance = Ultimate Operation Current = 17.8 kA

T [K]	B _{peak} SS [T]	I _{cable} SS [A]
4.5	13.20	18734
1.9	14.49	21065



First QXF Short Coil (MQXFSM1)





MQXFSM1 Ramp Rate & Temperature Dependence

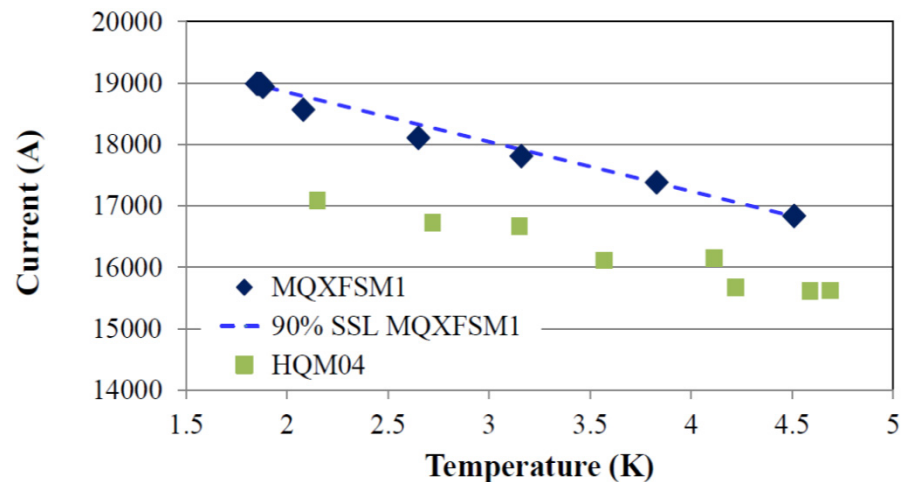
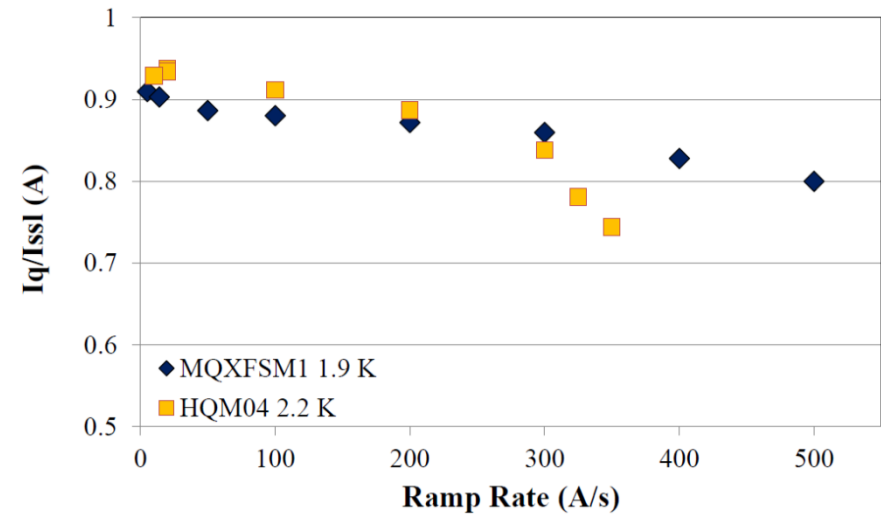
Courtesy of S. Stoynev

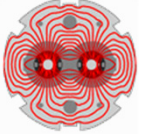
Quench ramp rate dependence at 1.9 K:

- No quench in ramp down from 16.5 kA at 300 A/s
- Core in cable is effective

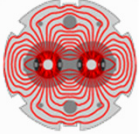
Temperature dependence study at 20 A/s

- 90% of SSL both at 1.9 K and 4.5 K
- Temp. dependence as expected





- Single coil in mirror structure:
 - Successfully demonstrated coil & parts design, and coil fabrication process
 - The 10% missing on the load line, can be explained by the small strain tolerance of the strand used
 - To be demonstrated by the 1st short model (RRP with Ti doping)

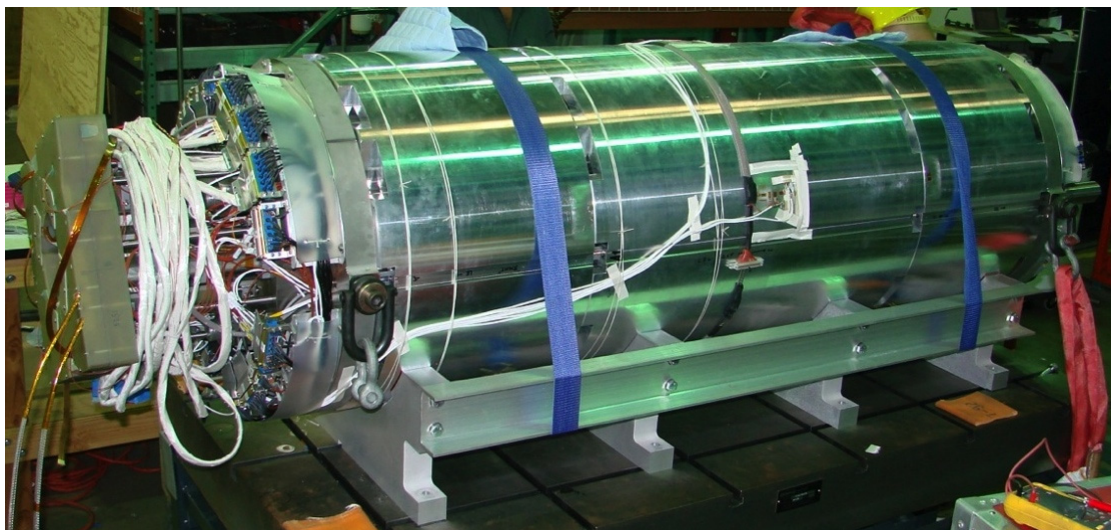


LARP

Test Results – MQXFS1

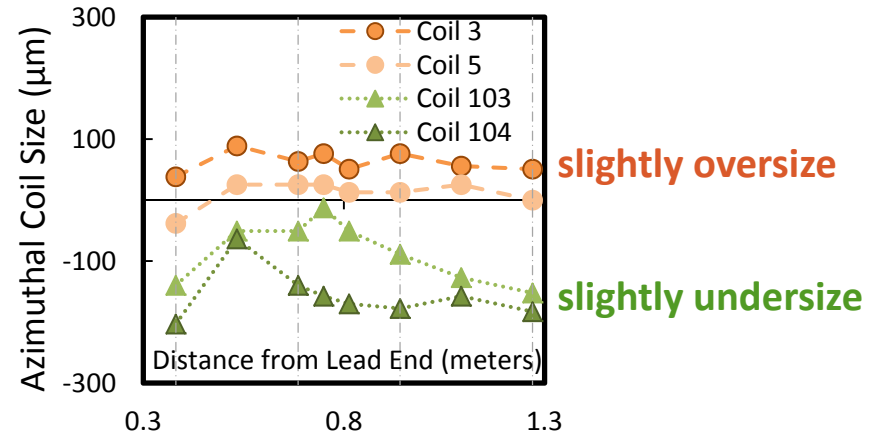


- Short MQXF magnet, with 2 coils by LARP, 2 coils by CERN, and segmented structure
 - LARP coils: RRP 108/127 (by FNAL & BNL)
 - CERN coils: RRP 132/169
 - smaller filaments, less critical current
 - Structure: 1 full-unit + 2 half-units at the ends (assembly at LBNL)

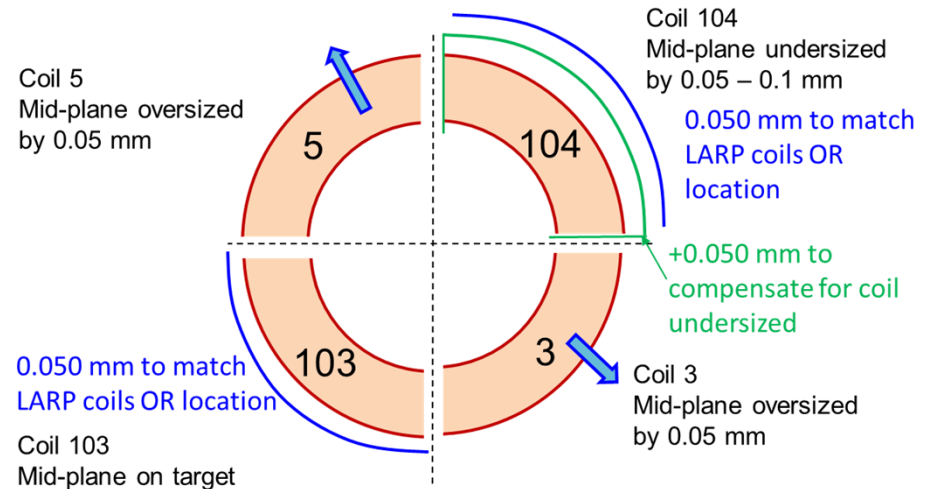


*First MQXF Short Model (MQXFS1)
1.2 m magnetic length*

- Different coil sizes



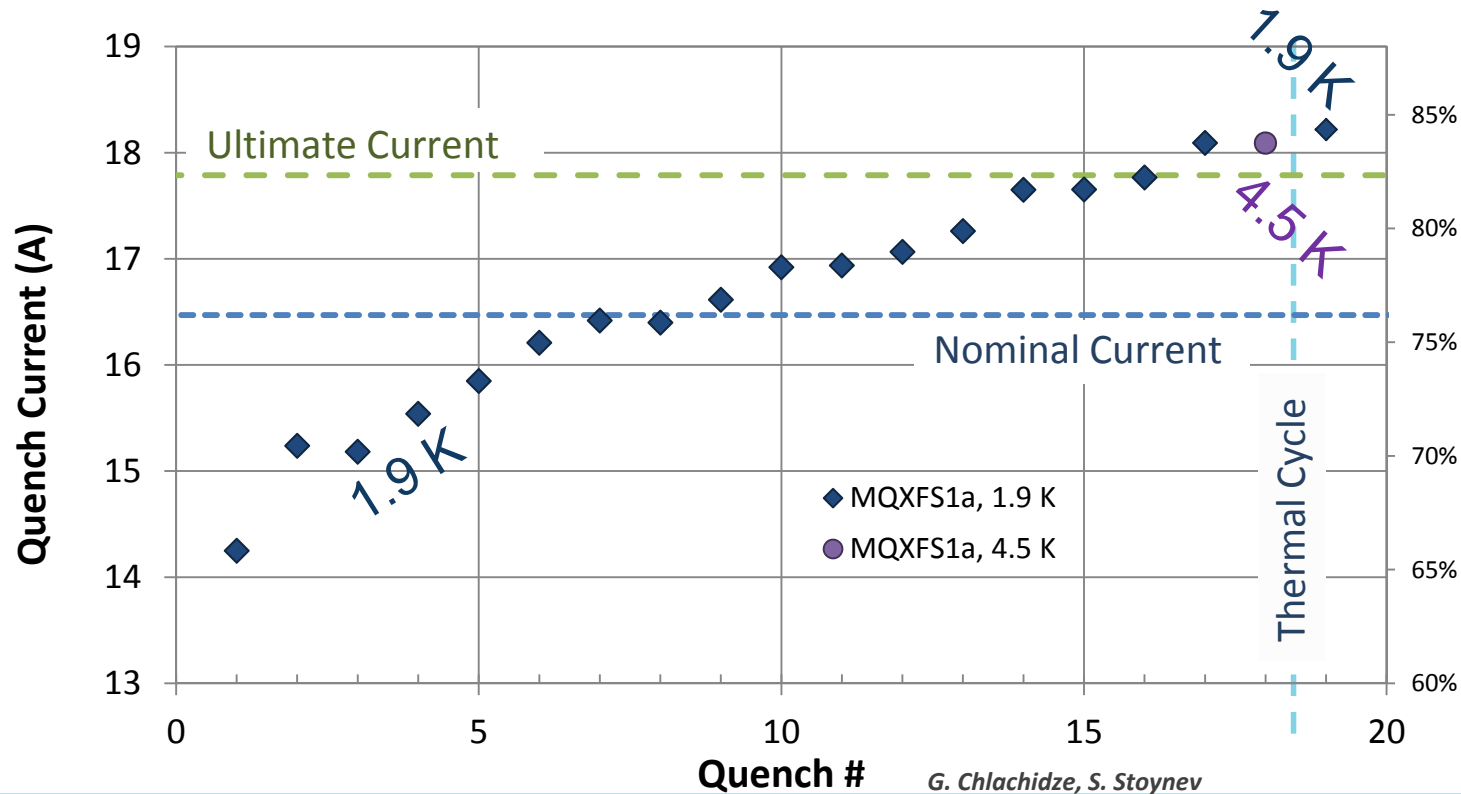
➔ Different coil-structure shims for uniform coil pre-load





Test Results – MQXFS1 (tests at FNAL)

- Exceeded ultimate current
 - Training stopped to increase preload
- Demonstrated temperature margin
- Demonstrated excellent memory



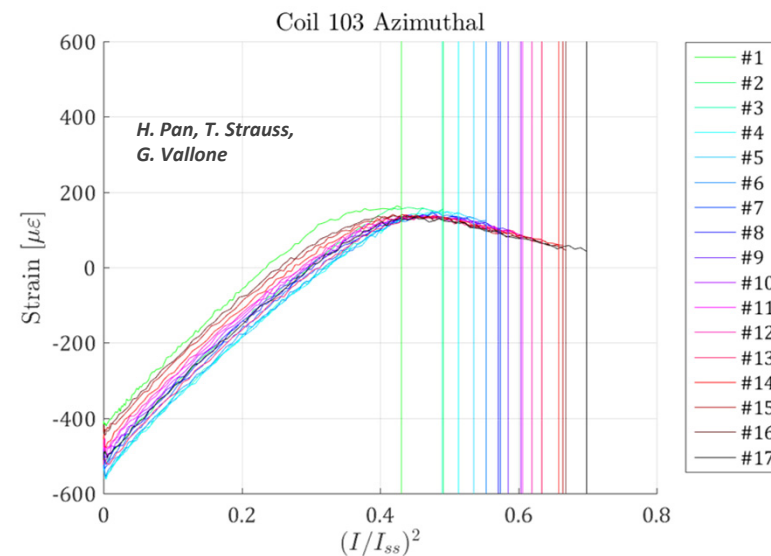
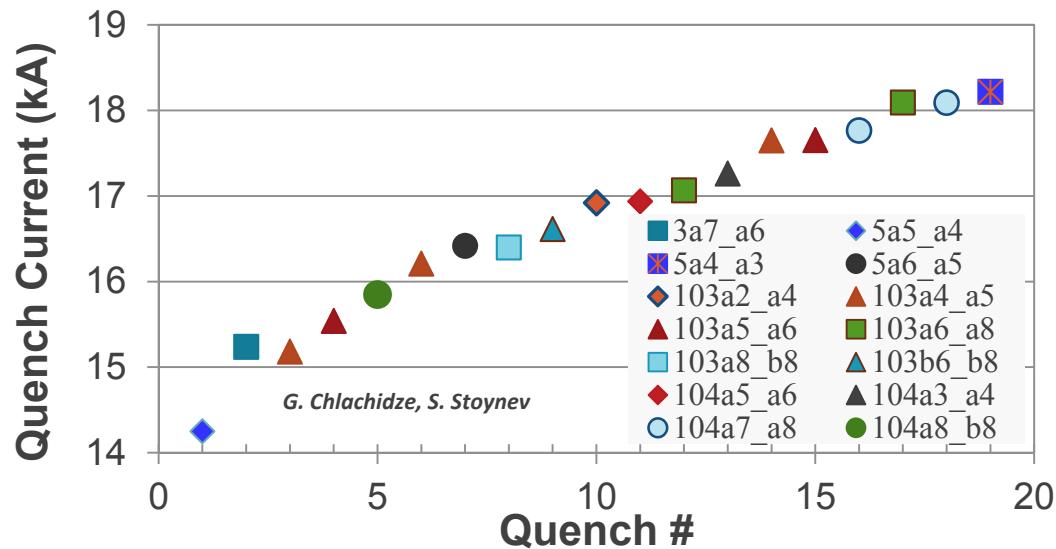
G. Chlachidze, S. Stoynev

Quench locations:

- Quenches observed in all coils and distributed over many locations in the high field areas

Strain gauges:

- Preload increase during cool-down lower than expected



→ Coil pre-load lower than expected

→ Test will continue (MQXFS1b) after pre-load increase



MQXFS1 Ramp rate, High-I plateau

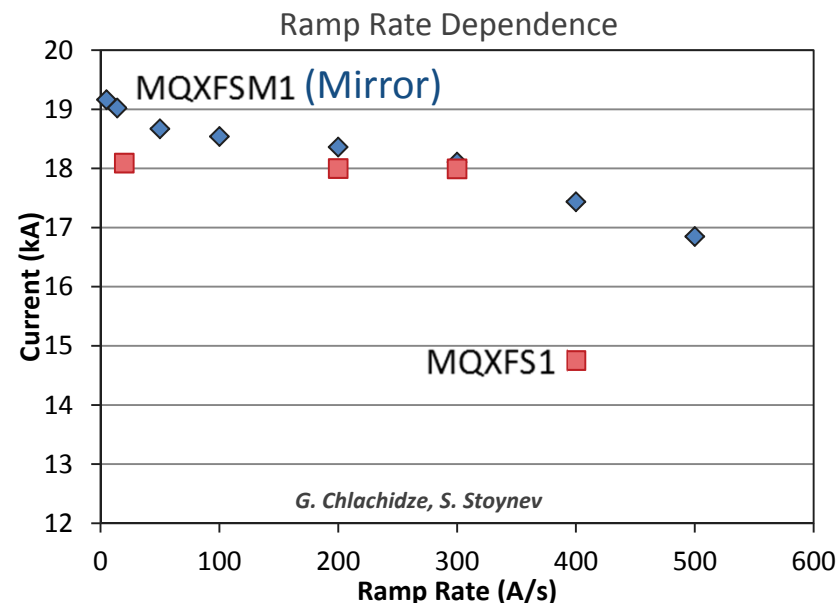


Quench ramp rate dependence at 1.9 K:

→ Core in cable is effective

High current operation:

- Capability of maintaining the operating level over an extended period of time was demonstrated in both thermal cycles
 - **TC1: 8 hours at Nominal Current**
 - **TC2: 8 hours at Ultimate Current**

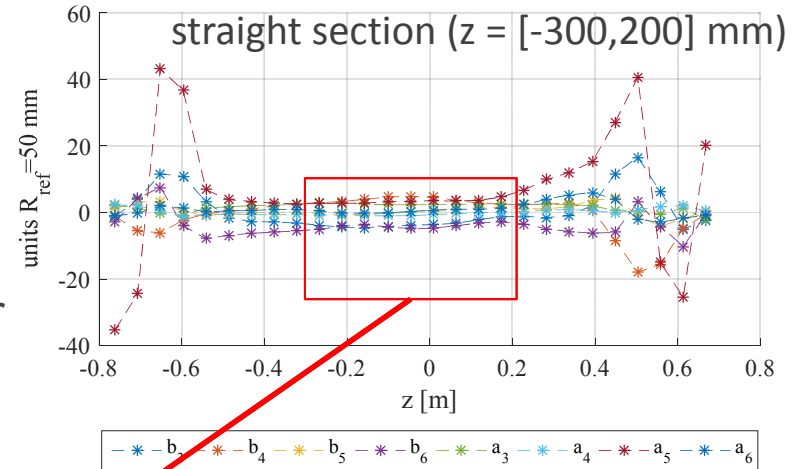




MQXFS1 Field Quality at Nominal Current

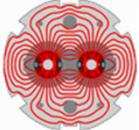


- Field harmonics are evaluated at 2/3 of the aperture radius ($R_{ref} = 50$ mm).
- The standard deviation of the harmonics in the straight section ($z = [-300,200]$ mm) corresponds to a 50 μ m random shifting or waviness of the coil blocks.



n	Normal Components (b_n)			Skew Components (a_n)		
	Nominal	Average	Std. Dev.	Nominal	Average	Std. Dev.
3	0 ± 0.82	-4.44	0.88	0 ± 0.65	3.37	1.42
4	0 ± 0.57	0.18	1.05	0 ± 0.65	-6.62	0.92
5	0 ± 0.42	2.77	0.20	0 ± 0.43	-0.96	0.41
6	0.64 ± 1.10	0.69	0.43	0 ± 0.31	0.40	0.58
7	0 ± 0.19	0.22	0.15	0 ± 0.19	0.28	0.14
8	0 ± 0.13	0.26	0.06	0 ± 0.11	-0.66	0.15
9	0 ± 0.07	0.20	0.11	0 ± 0.08	0.32	0.09
10	-0.39 ± 0.20	-0.45	0.05	0 ± 0.04	0.15	0.07





Sources of Harmonic Errors

- Large a_3 , b_3 , and b_5 are possibly due to significant conductor displacements

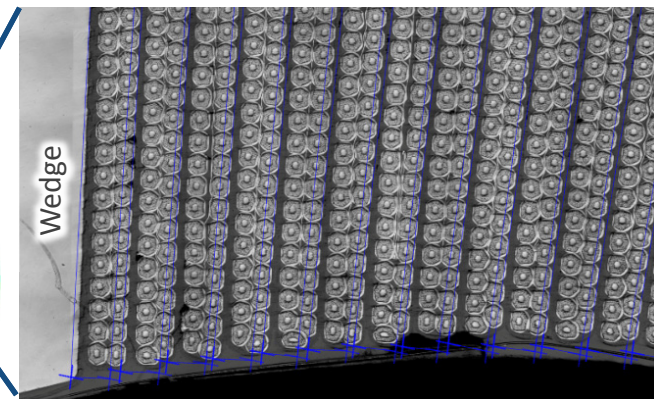
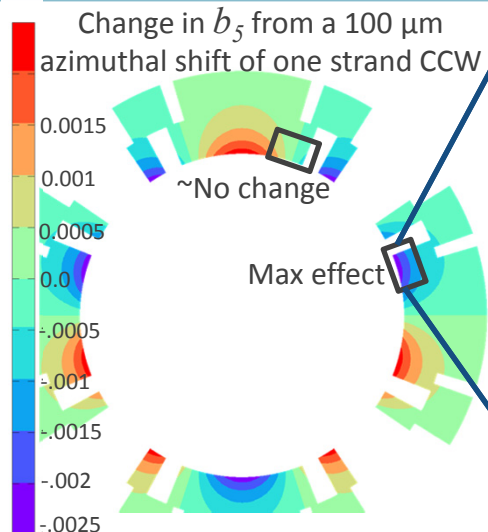
- **Example: b_5**

If all other coils were nominal:

- Peak shift within box is 700 μm
- Max effect region has ~ 0.002 units per strand

-> $40/2$ strands * 10 turns * -0.002 * $-700/100$

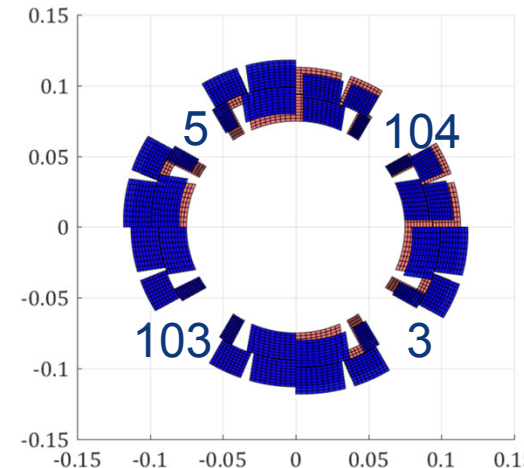
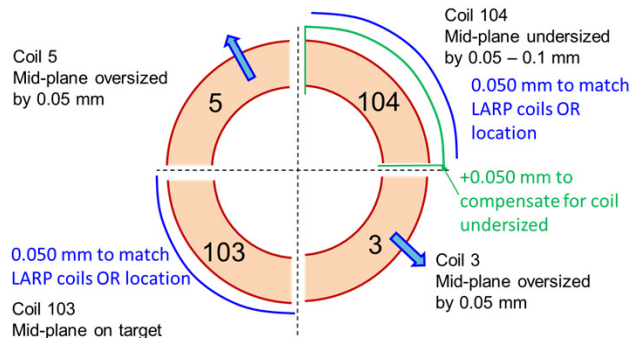
= **2.8 Units** from one coil



QXFS1 Practice coil cross section
Blue lines indicate nominal turn location

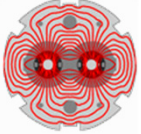
- Large a_4 is **expected** due to the **differences between CERN and LARP coils**

– Should improve when assembling coils produced in the same manufacturing line.



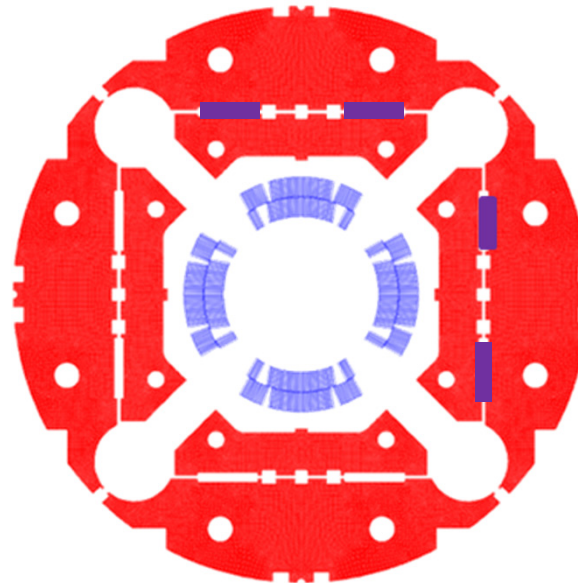
S. Izquierdo Bermudez

	b_4		a_4	
	Warm	Cold	Warm	Cold
Computed	0		-5.75	
Measured	0.30	0.32	-4.18	-6.49



Correcting Harmonics

- Measured normal and skew sextupole can be corrected by inserting **magnetic shims** in the bladders slot
 - Magnetic shims installed in MQXFS1b to prove correction capabilities



Correction capabilities using 9x58 mm shim in the bladder slots

Order	b_n	a_n
3	4.24	-4.24
4	0.00	0.00
5	0.40	0.40
6	0.00	0.00

MQXFS1 Meas.	b_3	a_3
	-4.44	3.37

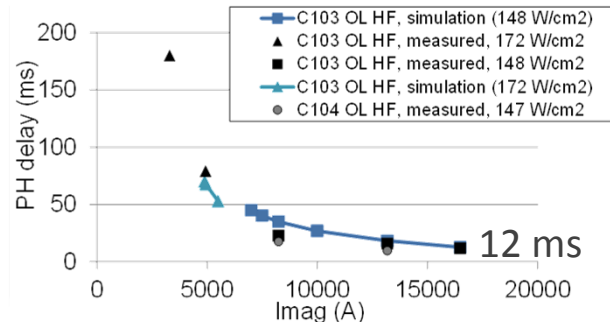
Conductor displacements should reduce in 2nd generation MQXF

- Actions taken:** Reduction of free space by 50%
- From 2% to **1.2%** in width (Measured cable expansion ~0.1 to 0.4%)
- From 5.2% to **4.5%** in thickness (Measured cable expansion ~3.5%)

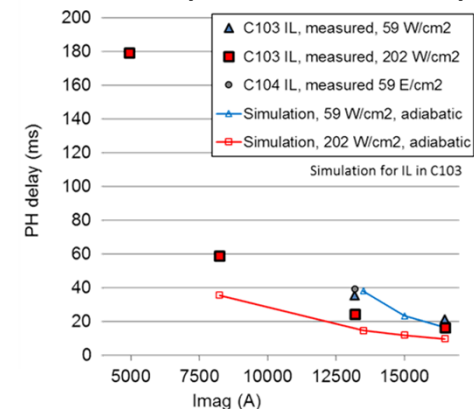
- **Heater Delays**

- Outer layer delays and simulation in **excellent agreement**
- Inner layer delays larger than expected

Outer Layer Heater Delays



Inner Layer Heater Delays



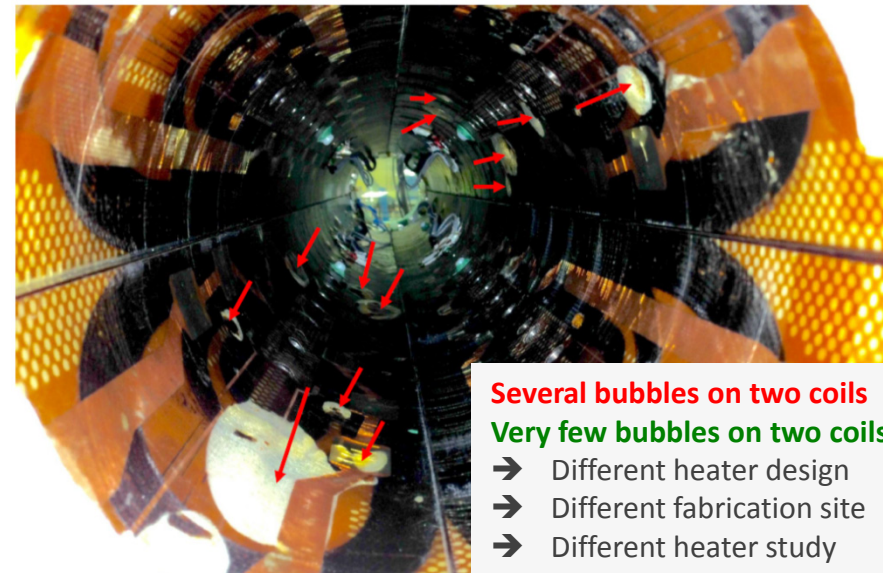
Simulations performed with CoHDA by T. Salmi (TUT)

- **Outer Layer heaters: very reliable**

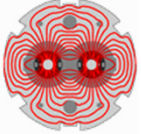
- Survived large number of quenches and heater studies on many LARP magnets

- **Inner Layer heaters** are not pushed toward the coils as Outer Layer heaters → “bubbles”

- Polyimide perforation (40%) should help
- Different designs



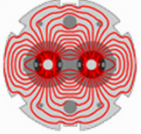
Several bubbles on two coils
Very few bubbles on two coils
 → Different heater design
 → Different fabrication site
 → Different heater study



LARP



CHALLENGES & PLANS



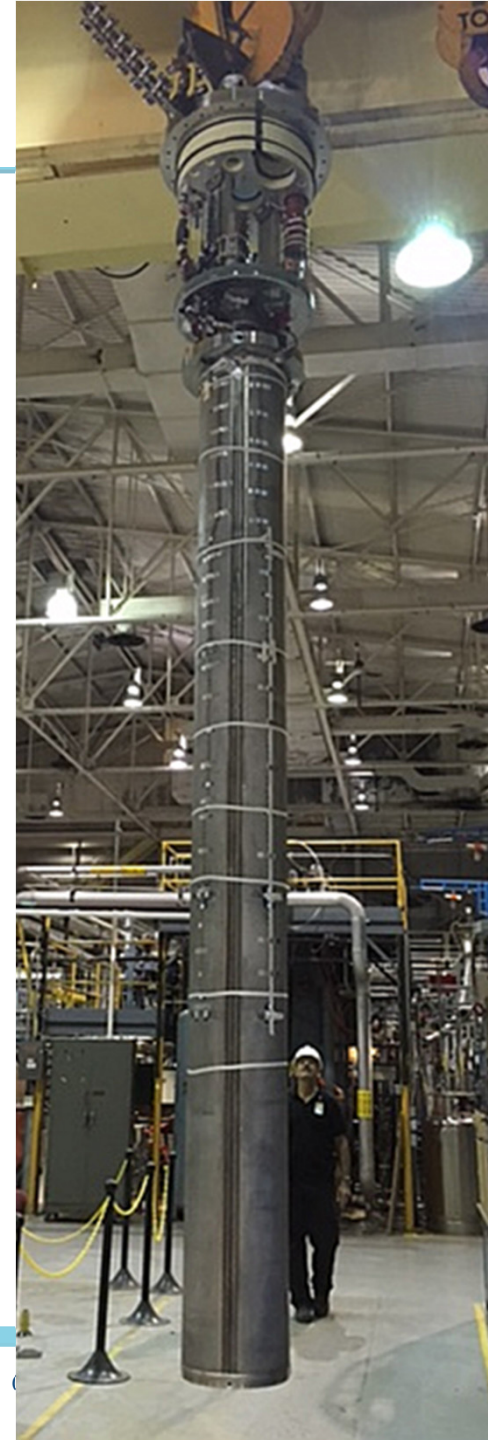
Coil Scale-up

LARP: Risk reduction strategy:

- 2 magnets in one cold mass
- Test of a single 4 m coil in mirror structure
 - Test start by end of this month
 - Recently commissioned Vertical Test Facility at BNL for 4.2 m MQXFA magnets

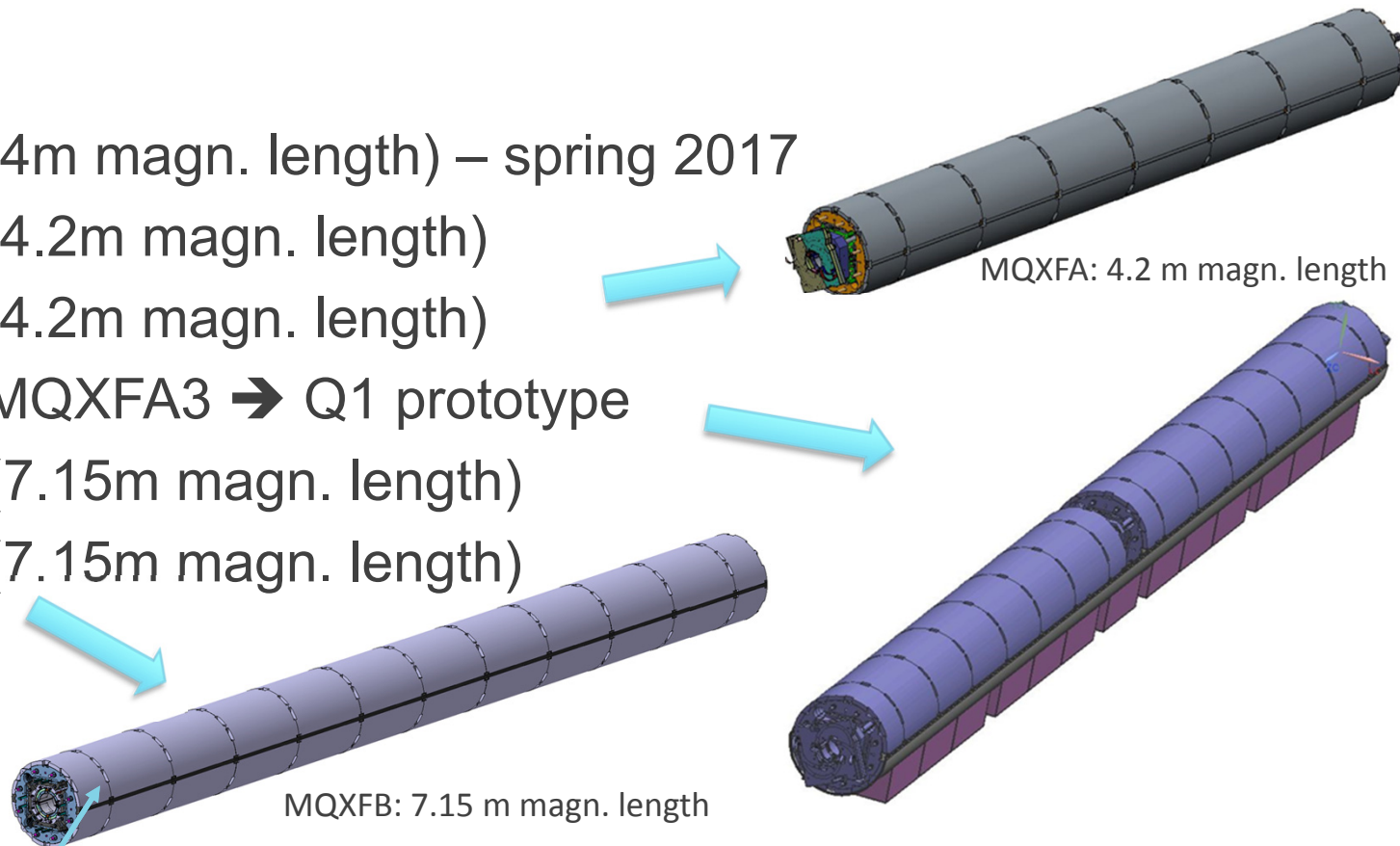
CERN: Risk reduction strategy:

- Development of 5.3 m 11 T dipoles
- Test of a single 7.15 m coil with 3 practice coils in MQXF structure
 - Test in January 2018



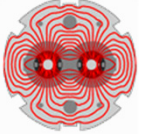
• Prototypes:

- MQXFA1 (4m magn. length) – spring 2017
- MQXFA2 (4.2m magn. length)
- MQXFA3 (4.2m magn. length)
- MQXFA2+MQXFA3 → Q1 prototype
- MQXFB1 (7.15m magn. length)
- MQXFB2 (7.15m magn. length)

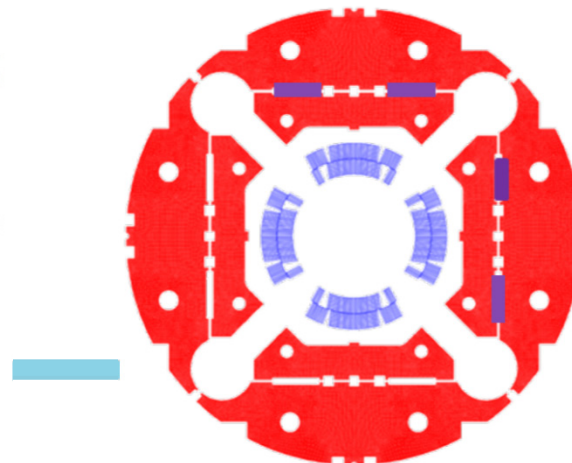
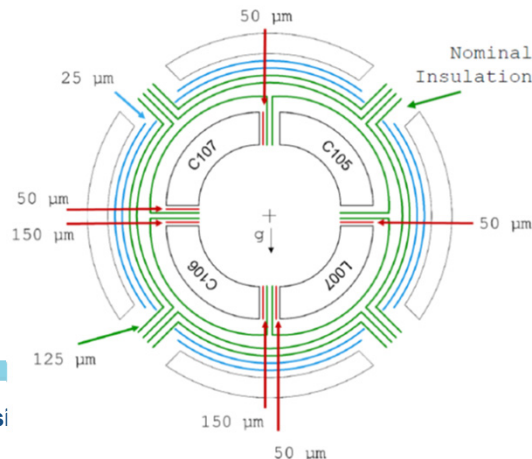
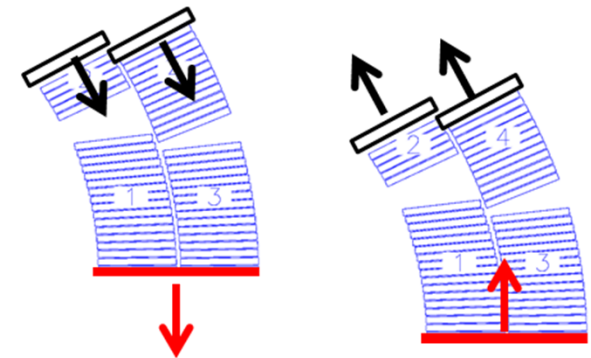


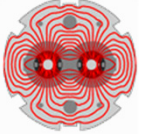
• Alignment

- **Survey & warm magnetic measurements** at all assembly steps
- Openings in the Al-shells allows for magnet alignment & survey



- Present Nb₃Sn coil fabrication technology does not allow for the same precision of turn position as in NbTi coils
- Support structure has more parts than in NbTi magnets
- Solution: **shimming**
 - During coil fabrication (S2-glass)
 - During coil-pads assembly (Polyimide)
 - After magnet assembly (Magnetic shims)



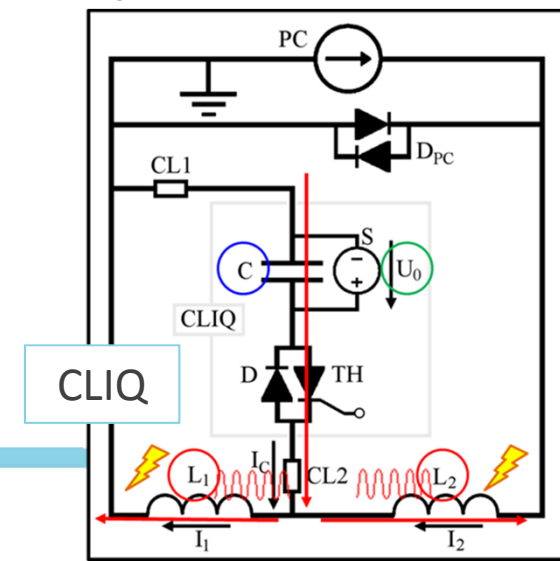
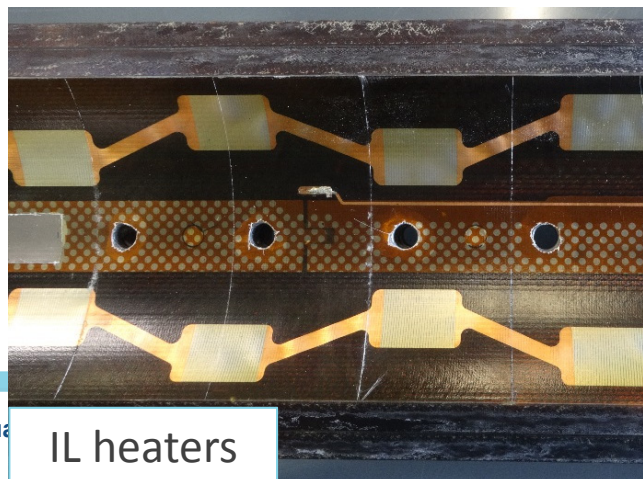
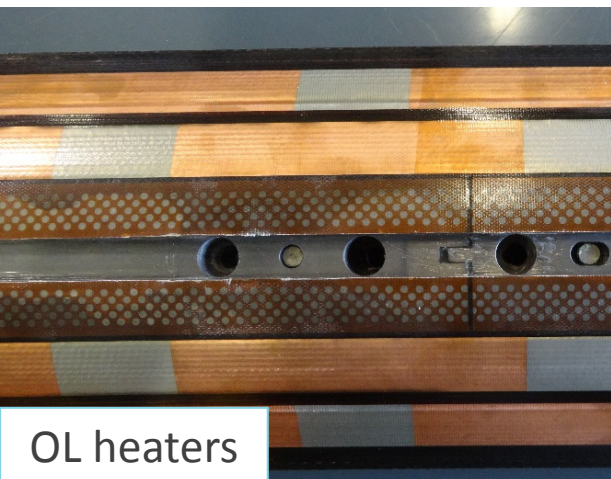


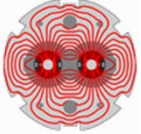
LARP

Quench Protection



- Challenge: 1.5 times energy density of LHC MB
 - No extraction (only 5% of energy, due to high inductance)
- Solution: **Heaters & CLIQ**
 - Outer Layer heaters: very reliable
 - Inner layer heaters: delamination issue being addressed
 - CLIQ (Coupling-Loss-Induced-Quench): new & very promising
 - successfully tested on short Nb₃Sn and long NbTi magnets
 - but system integration has some challenges
- Plan: Test all solutions on short models & prototypes





- The first tests of MQXF coils and short models are giving very promising results
- Some challenges are still ahead (Scale-up, FQ, QP) and there are solid plans to address them
- Prototype testing is starting right now with the first 4m coil

Thank you