US CONTRIBUTION TO THE HIGH LUMINOSITY LHC UPGRADE: FOCUSING QUADRUPOLES AND CRAB CAVITIES

Accelerator Upgrade Project (AUP)

Sandor Feher – FNAL

HL-LHC AUP L2 Project Manager

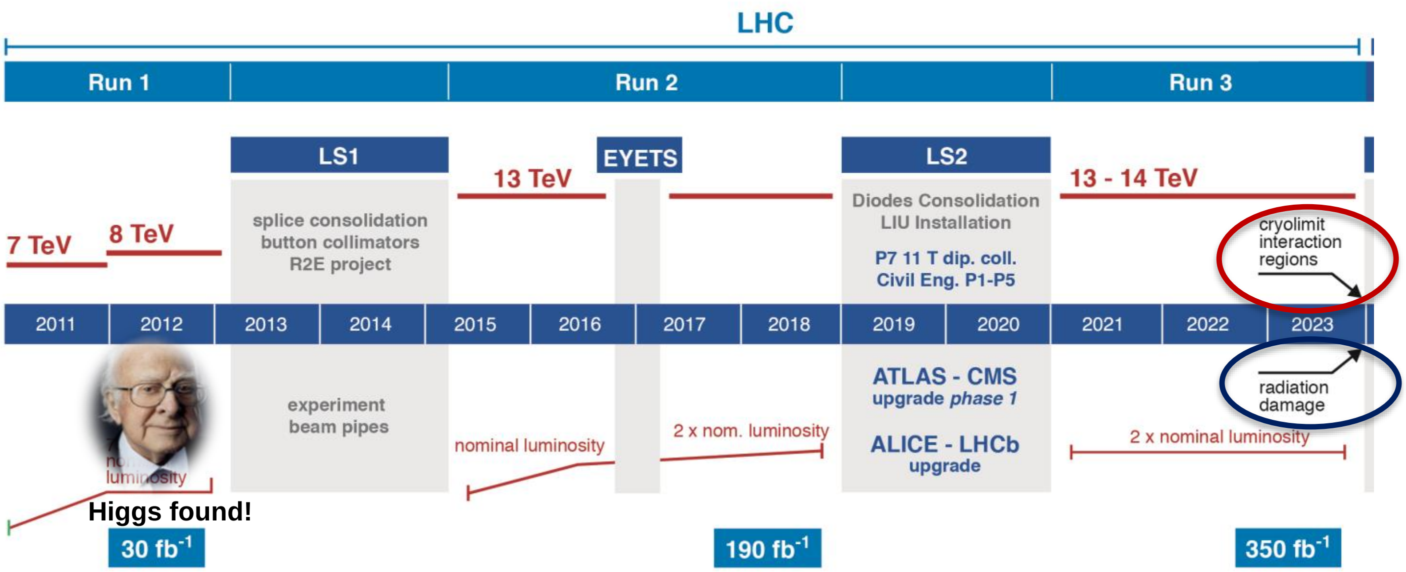
Behalf of the AUP Project Team

APS DPF 2019 – Northeastern University

Outline

- High Luminosity Upgrade goals
- Accelerator Upgrade Project (AUP)
  - Interaction region Quadrupoles
  - Crab Cavities
  - Project Status
- Summary

LHC / HL-LHC Plan



Technical limitation on the istantaneous lumi:
1. **Collider** (cryolimit in the triplet region) at 2×10^{34} cm^{-2}s^{-1} twice the nominal design luminosity)
2. **Experiments** (pile up in the detectors). Designed for PU 40 they are actually dealing with 60 (average)!

Technical limitation on integrated lumi:
1. **Collider** (radiation damage to the IT magnets – correctors and quadrupoles)
2. **Experiments** (radiation damage in the Inner Tracker)

LHC is at 93% of the design energy (now planned for 2021-23)
LHC is 20% above planned luminosity (number of collisions)

From HL-LHC Project Leader
L. Rossi - CERN

Goal of HL-LHC

From EC-FP7 HiLumi LHC Design Study application of 2010

The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

A peak luminosity of L_{peak} = **5×10^{34} $cm^{-2}s^{-1}$ with levelling**, allowing:

An integrated luminosity of **250 fb^{-1} per year**, enabling the goal of **L_{int} = 3000 fb^{-1}** twelve years after the upgrade.

This luminosity is more than ten times the luminosity reach of the first 10 years of the LHC lifetime.

Ultimate performance established 2015-2016: with same hardware and same beam parameters: use of **engineering margins:**

$L_{peak\ ult}$ ≅ 7.5 10^{34} $cm^{-2}s^{-1}$ and **Ultimate Integrated $L_{int\ ult}$ ~ 4000 fb^{-1}**

LHC should not be the limit, would Physics require more…

From HL-LHC Project Leader
L. Rossi - CERN

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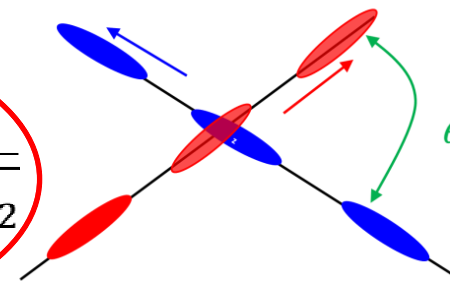
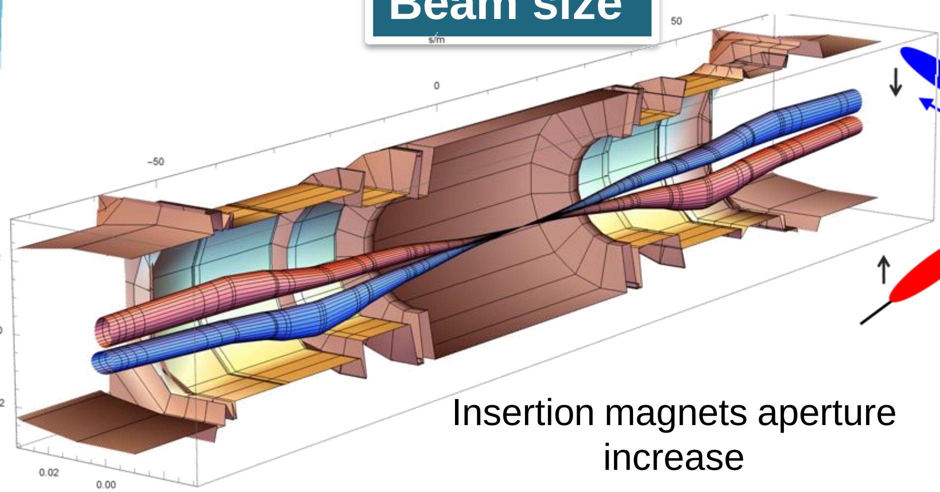
Luminosity Parameters to Increase

$$L = \gamma \frac{f_{rev}\, n_b\, N_b{}^2}{4\pi \varepsilon_n \beta^*} R$$

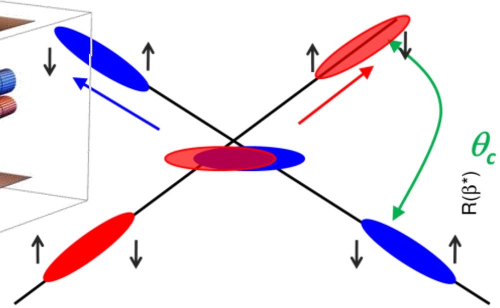
$$R = \frac{1}{\sqrt{1 + \left(\frac{\theta_c \sigma_s}{2\varepsilon_n \beta^*}\gamma\right)^2}}$$



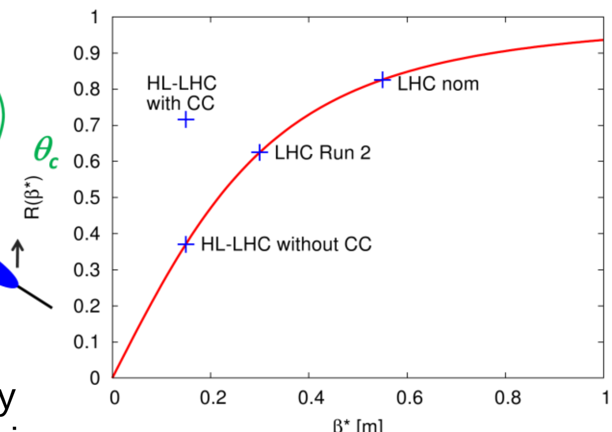
Beam size



Insertion magnets aperture increase

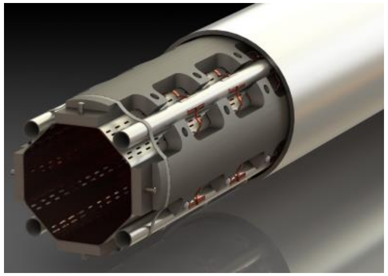


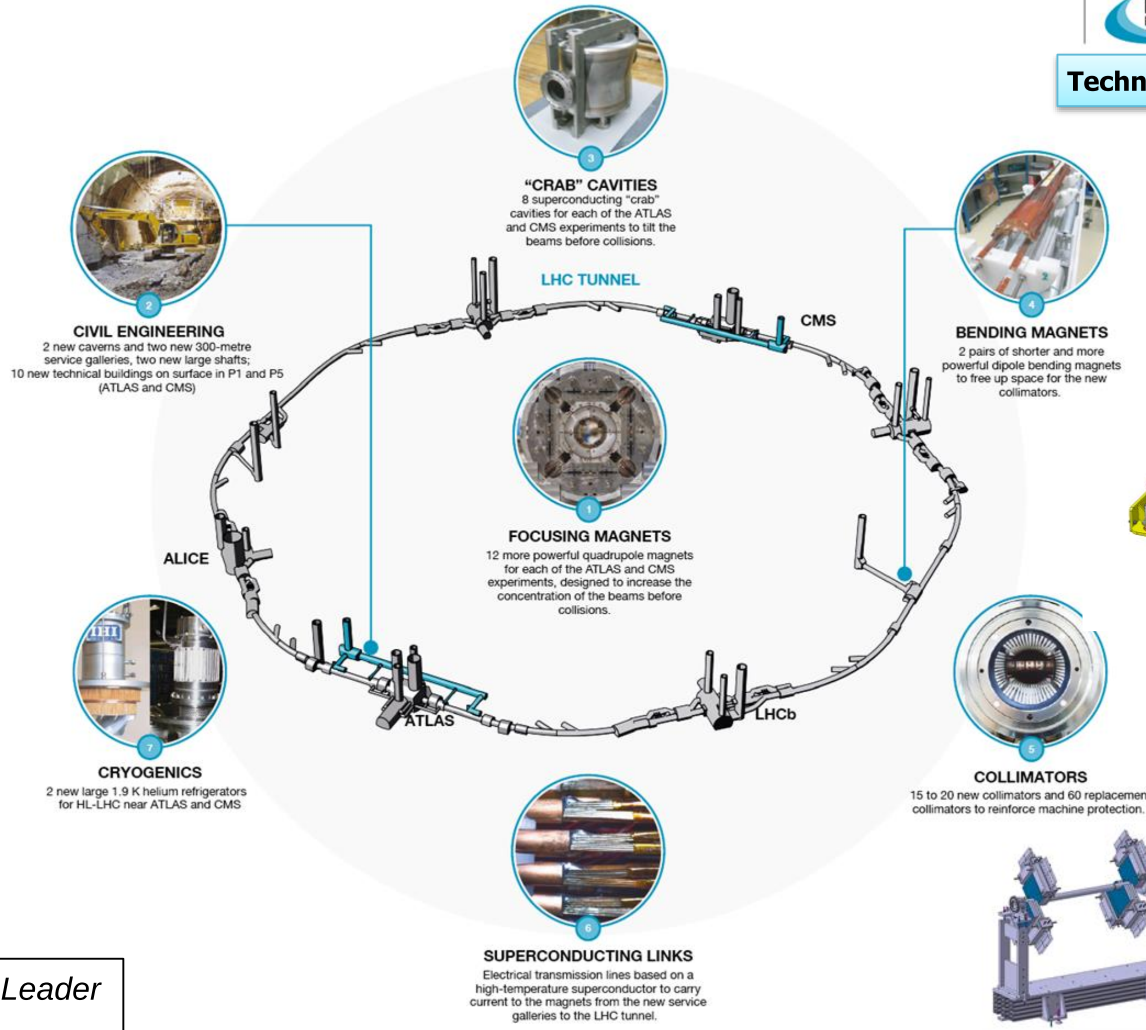
Crab cavity
Head on Collision

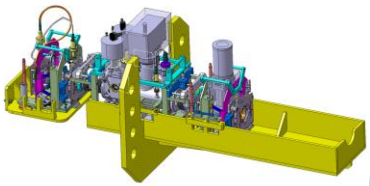


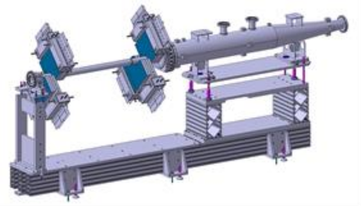
From HL-LHC Project Leader L. Rossi - CERN

Technology landmarks



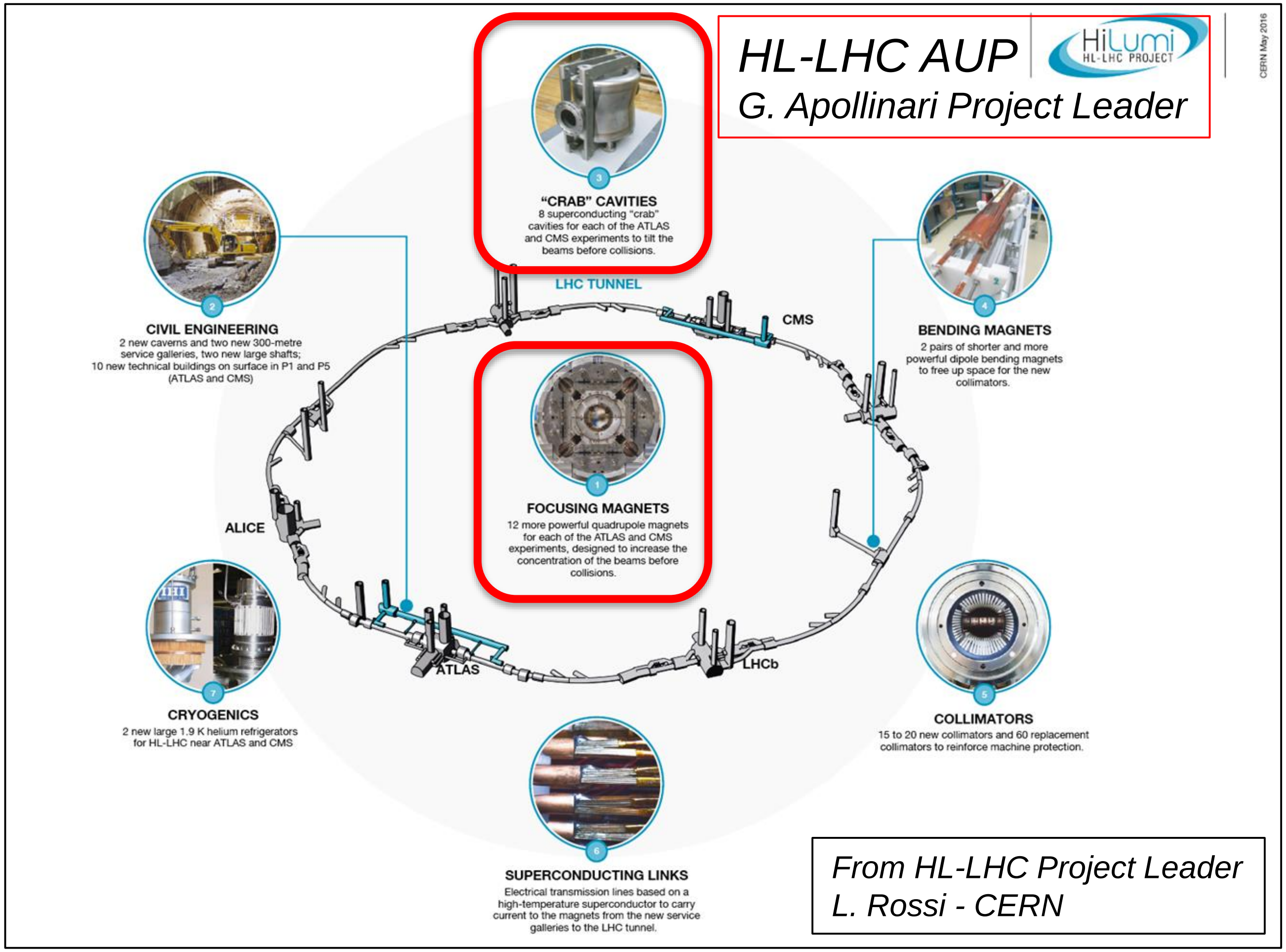






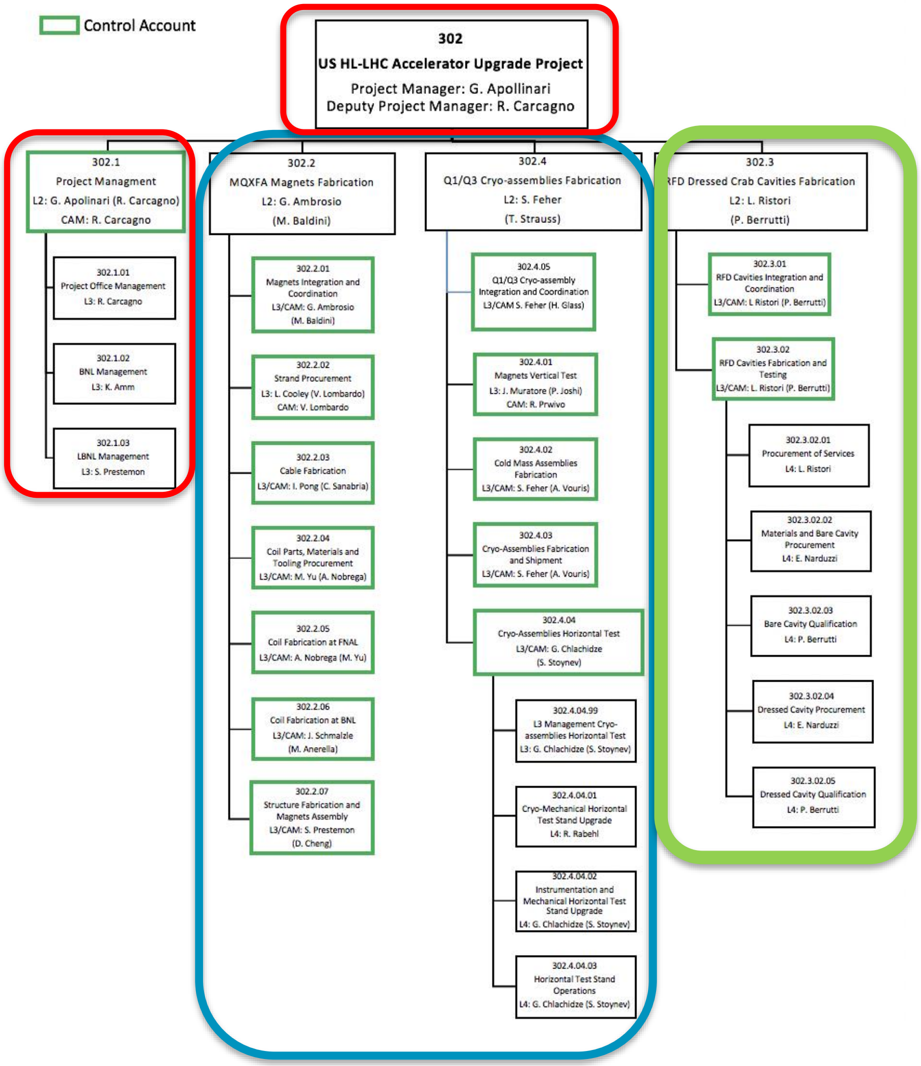
From HL-LHC Project Leader L. Rossi - CERN

HL-LHC Accelerator Upgrade Project Scope in HL-LHC



- LARP (LHC Accelerator Research Program), funded by DOE since ~2003, has established the necessary technology for the HL-LHC Focusing Magnets and Crab Cavities.

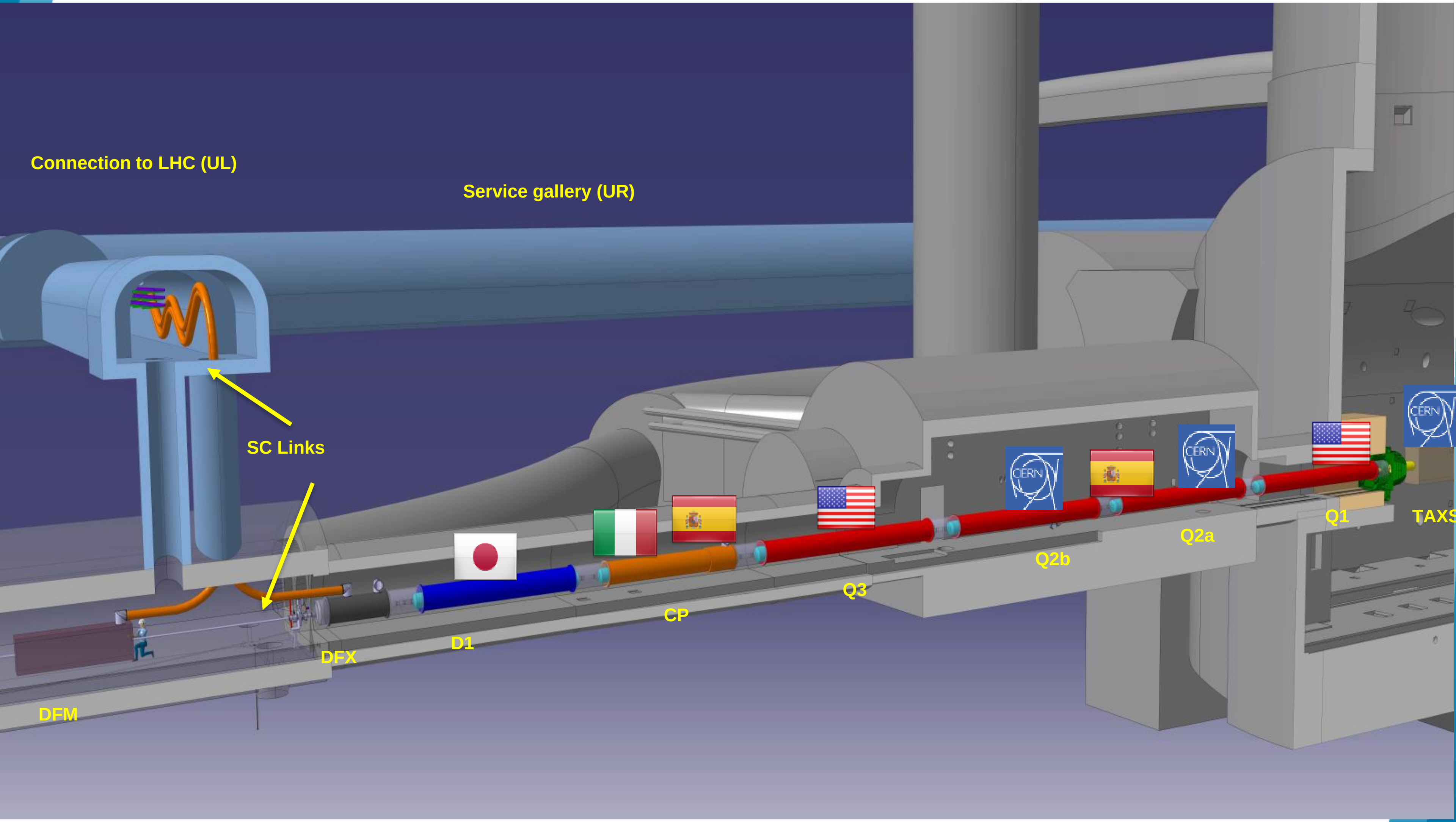
Management and Organization



- L2 Managers & Deputies
  - Project Management:
    - G. Apollinari
    - R. Carcagno
  - MQXFA Magnets:
    - G. Ambrosio
    - M. Baldini
  - Q1/Q3 CryoAssemblies:
    - S. Feher
    - T. Strauss
  - RFD Dressed Cavities:
    - L. Ristori
    - P. Berrutti

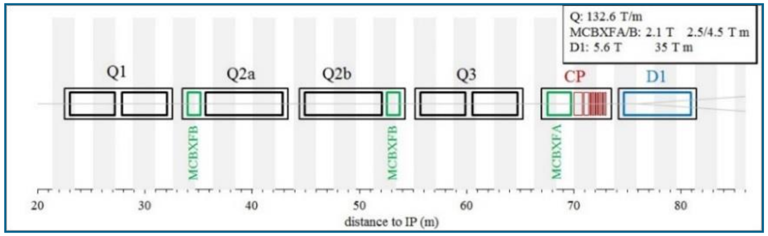
US HL-LHC AUP

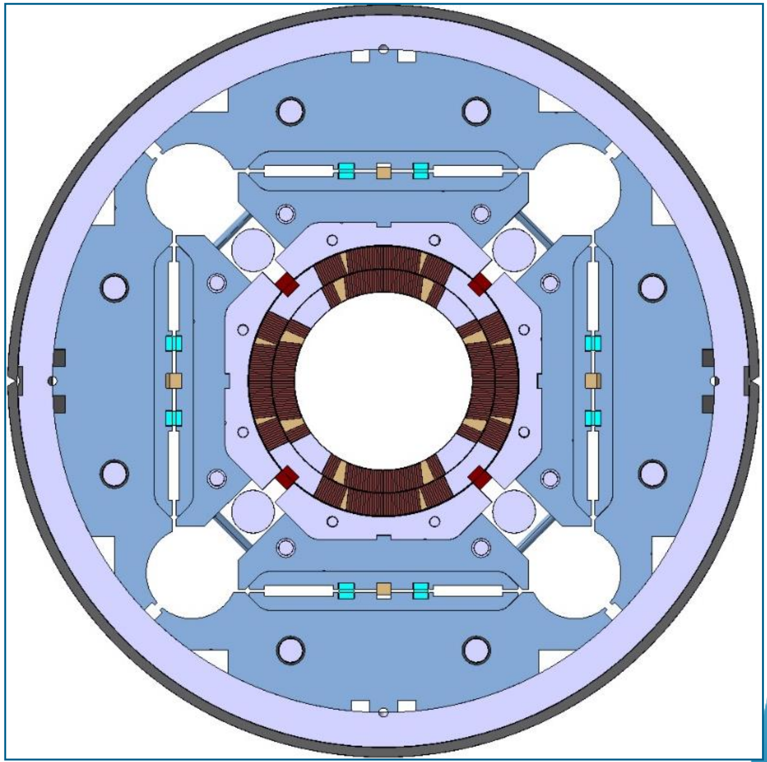
Interaction Region Magnets



HiLumi low-β quadrupole MQXF

- Target
  - G_{nom}=132.6 T/m, 11.4 T B_{peak_nom}
    - Corresponds to 14 Tev in LHC
  - G_{ult}=143.2 T/m, 12.3 T B_{peak_ult}
- Q1/Q3 (by AUP)
  - 2 magnets MQXFA with 4.2 m
    - Series: 20 magnets
- Q2a/Q2b (by CERN)
  - 1 magnet MQXFB with 7.15 m
    - Series: 10 magnets
- Different lengths, same design
  - Identical short models





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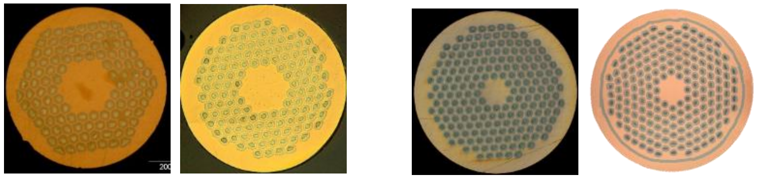
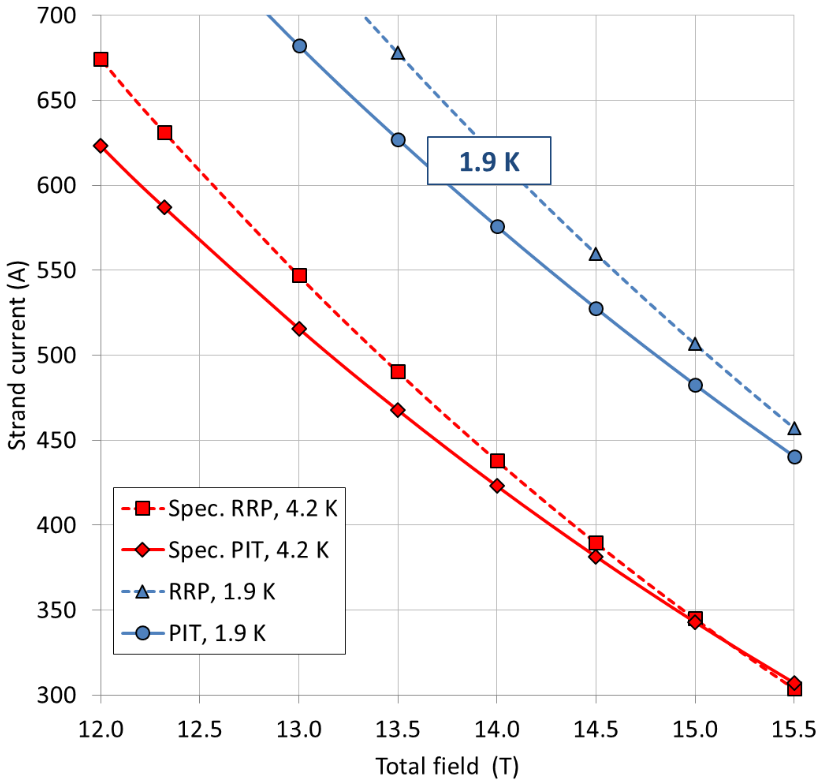
Superconducting Strand

(Nb_3Sn)

- 0.85 mm strand, 1.2 Cu/SC
- Specifications
  - RRP
    - 632 A (2450 A/mm^2) at 12
    - 331 A (1280 A/mm^2) at 15
  - PIT
    - 590 A (2290 A/mm^2) at 12
    - 331 A (1280 A/mm^2) at 15
- Filament ∅ ≤ 55 µm





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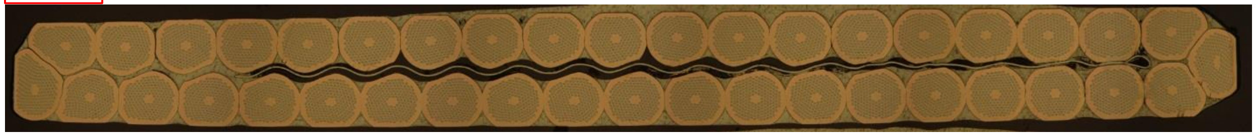
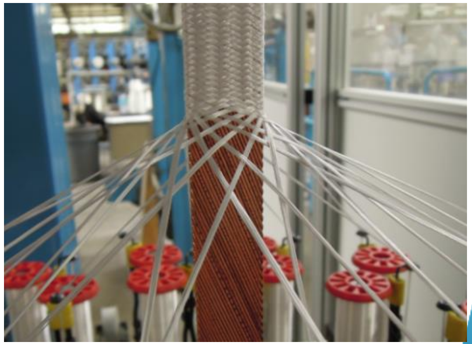
Superconducting cable

- 40-strand cable
  - Bare width X thickness: 18.150 X 1.525 mm
  - SS core 12 mm wide and 25 μm thick
- Keystone angle: 0.4 degree
- Braided insulation: 0.145 mm (S2-Glass)

PIT



RRP



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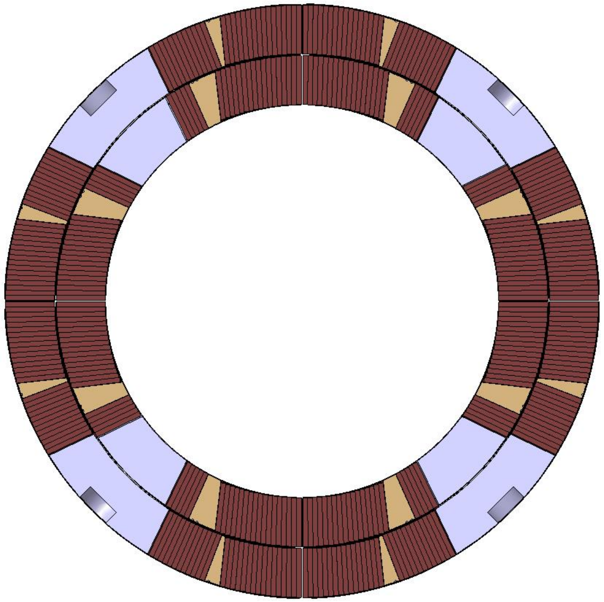
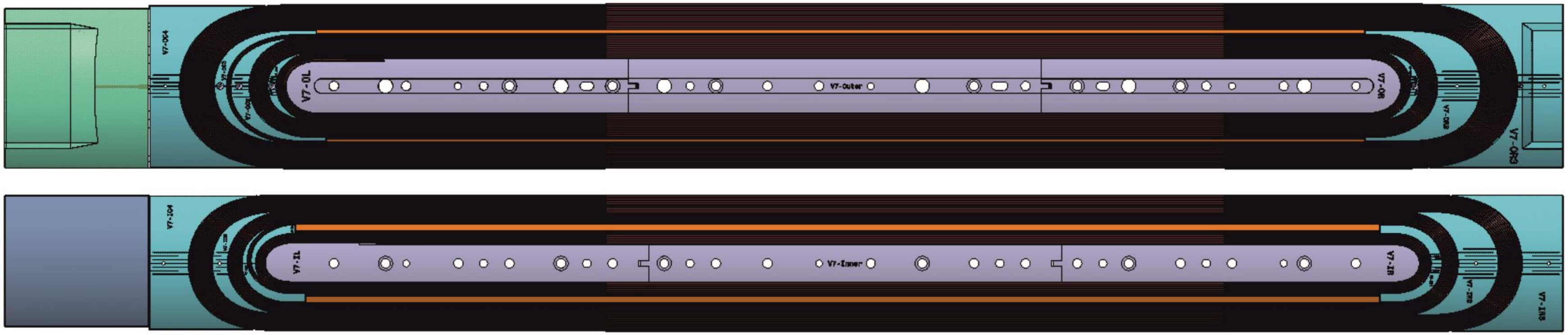
Coil design

- Wind and react technology being used
  - Heat treatment ~ 650 C
  - Coil is epoxy impregnated

- Two-layer, four-blocks design
  - 22+28 = 50 turns
- Pole impregnated with the coil
- Splice extension 140 mm long
- 2 end spacers for peak field reduction (1%) and field quality





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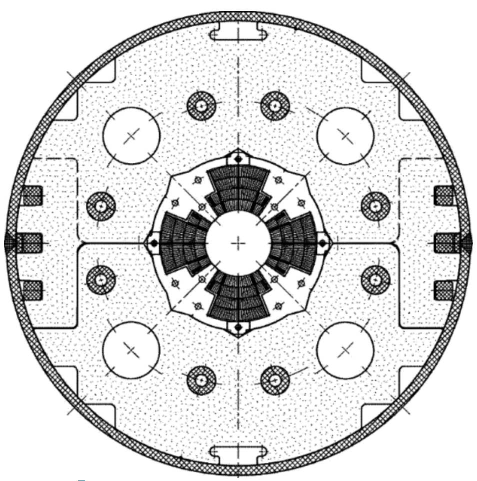
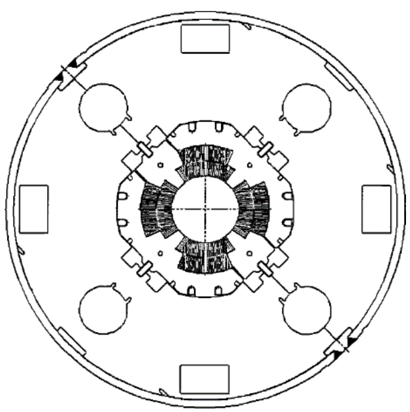
LHC low-β quadrupole support structures

- Cold mass OD from 490/420 to 630 mm
- More than double the aperture: from 70 to 150 mm
- ~4 times the e.m. forces in straight section
- ~6 times the e.m. forces in the ends

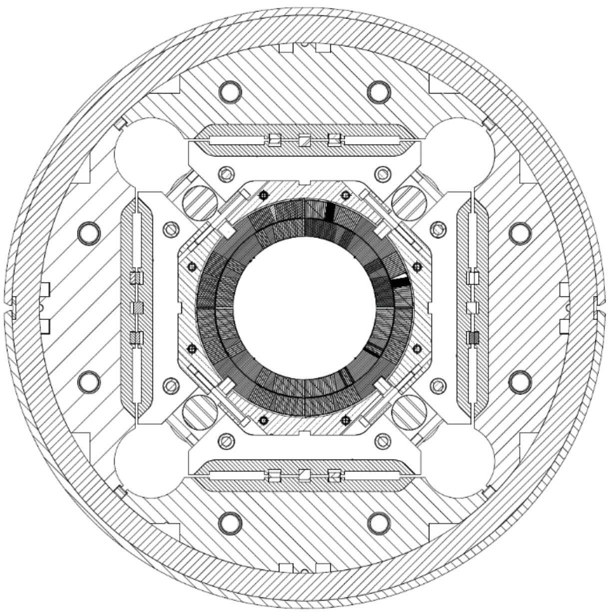
MQXA



MQXB



MQXF



In scale

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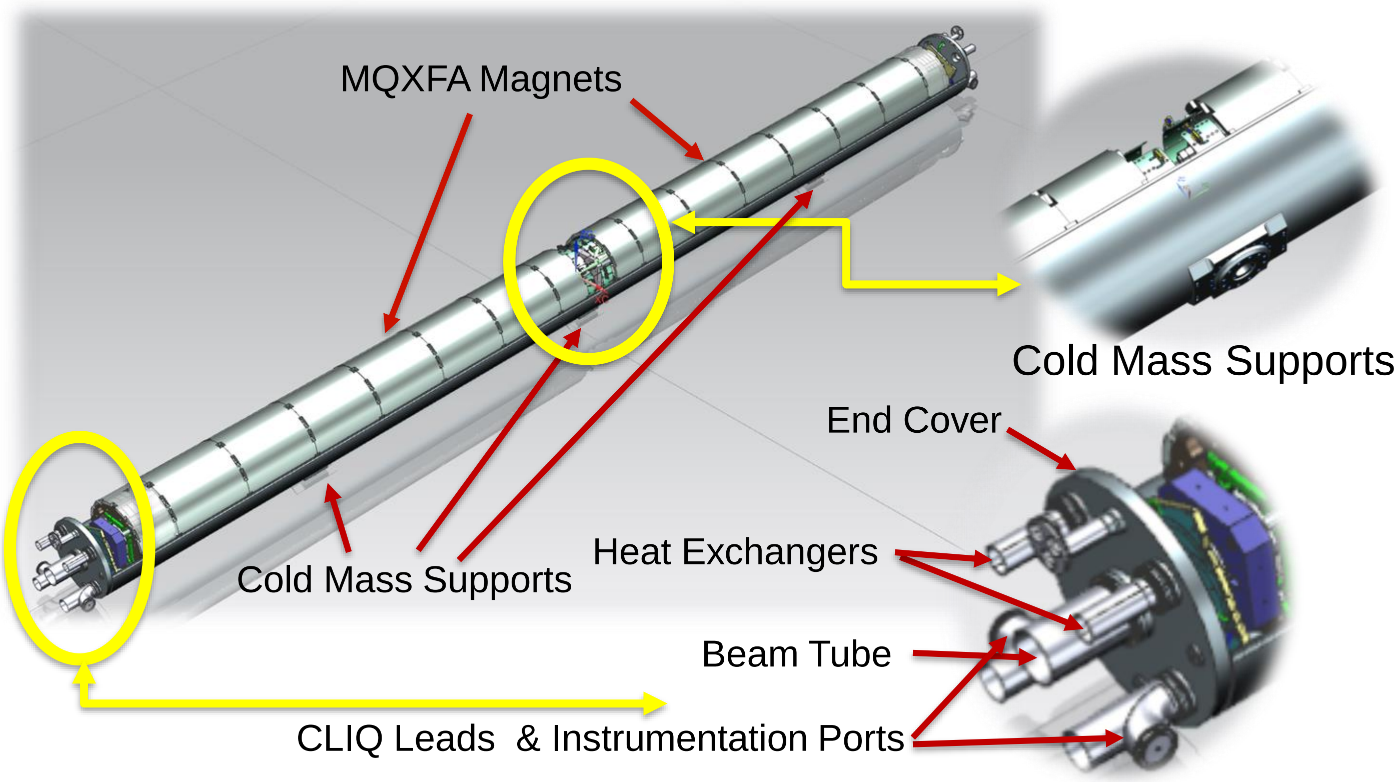
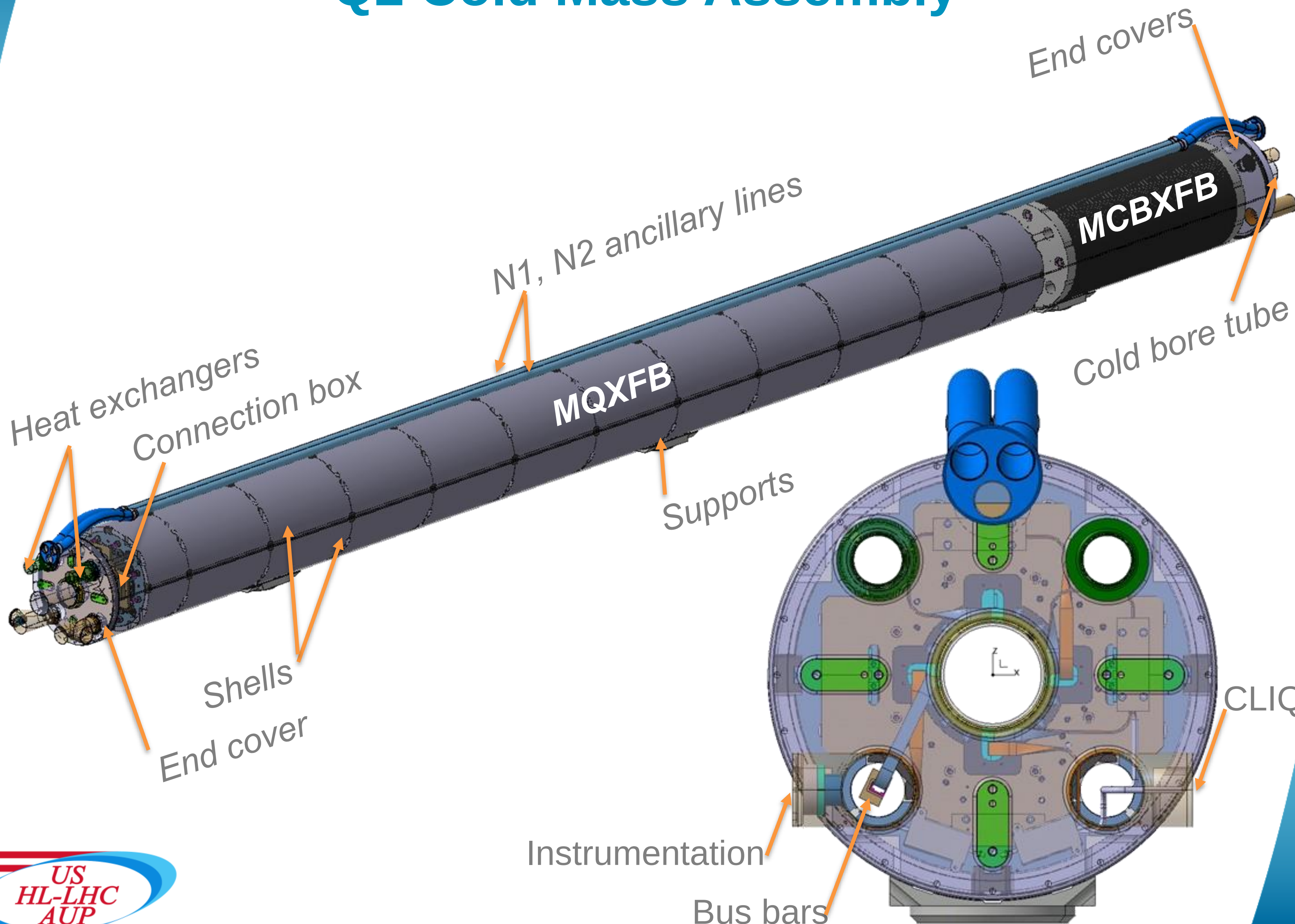
Q1/3 Cold Mass Assembly

- The **LMQXFA Cold Mass (Q1/3)** is the He pressure vessel assembly containing 2 MQXFA magnets
  - MAWP 20 bar differential @1.9K & pneumatically tested @ 25 bar (rm. temp.)
  - Material for shell, beam pipe & end covers is Low Co (<0.1%) 316LN (supplied by CERN)



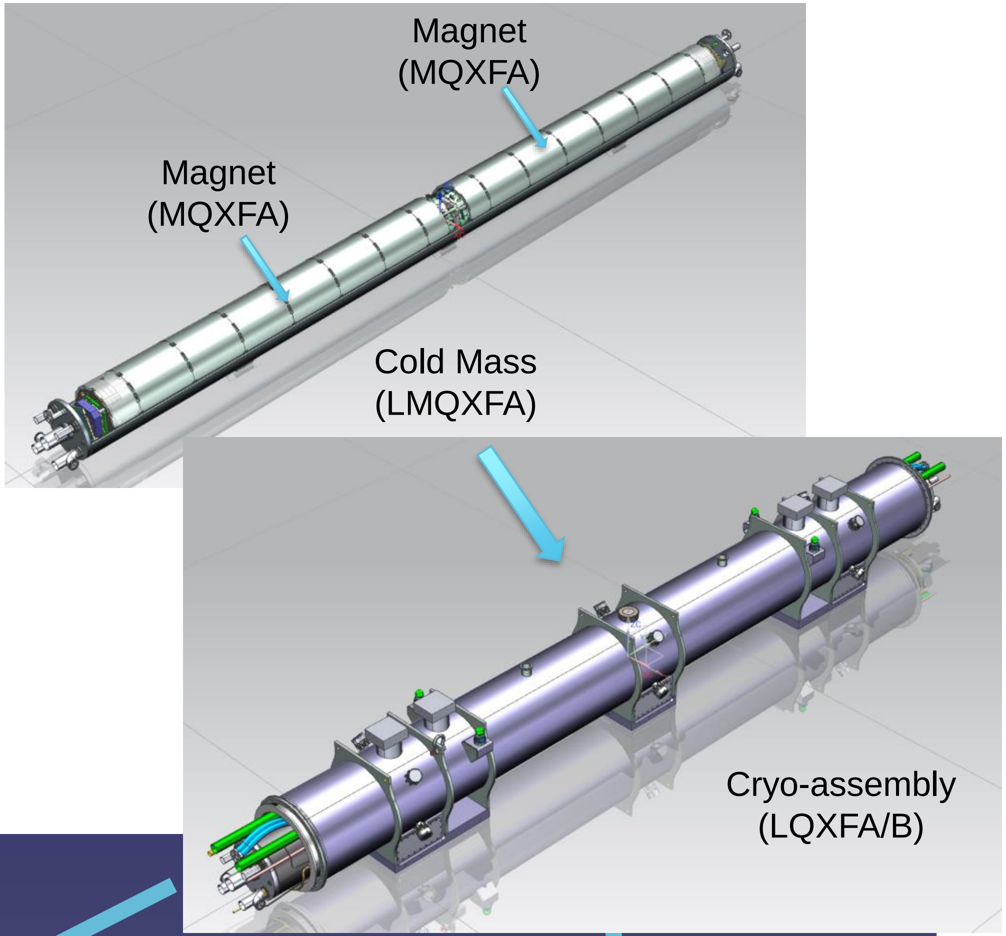
Q2 Cold Mass Assembly

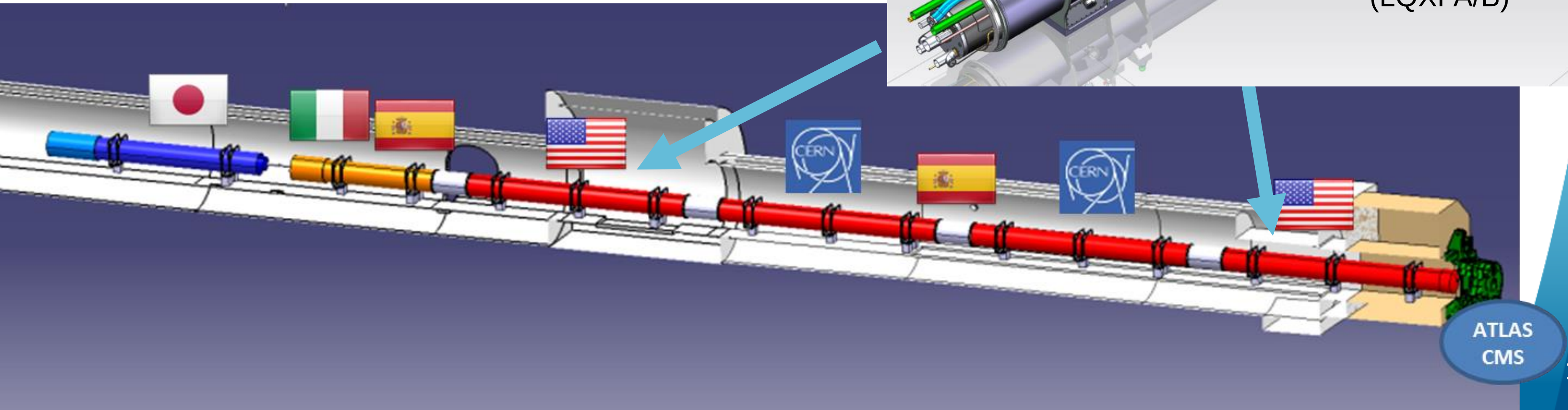


AUP Magnet Scope

12 Q1/Q3 Cryo-Assemblies

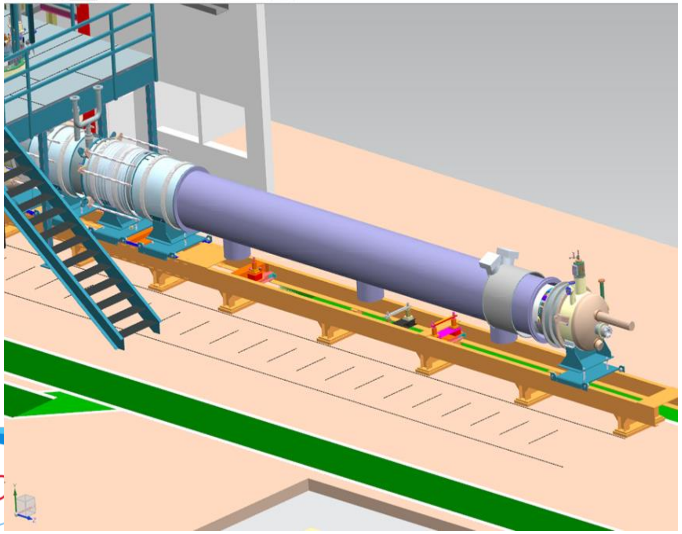
- 1 prototype (not tunnel bound)
- 1 pre-series
- 9 series production
- re-building one Cryo-assembly assumed

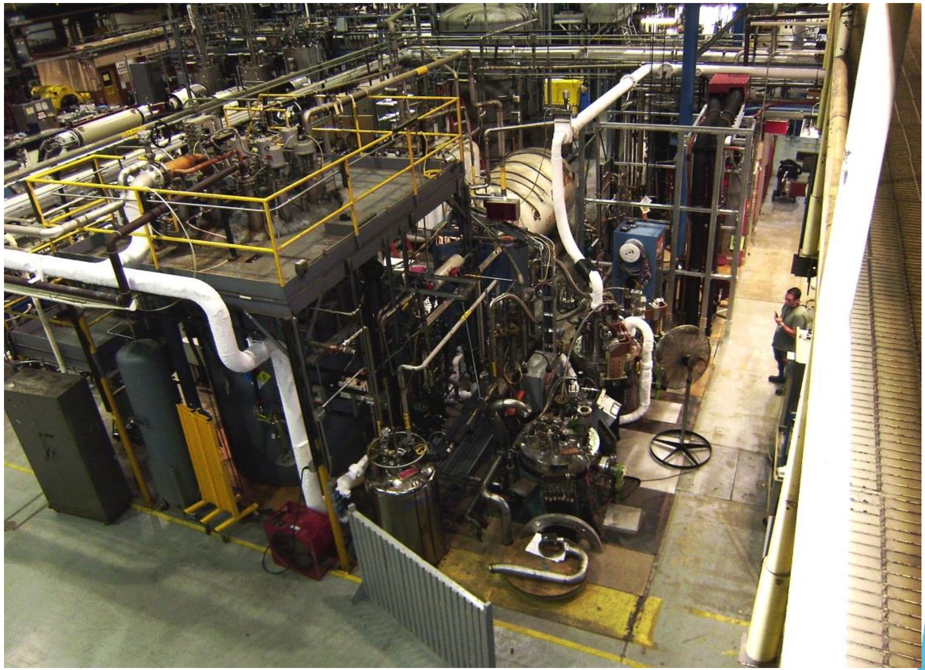




Tests and Test Facilities

- Vertical test of 27 magnets
- Horizontal test of 12 Cryostat Assemblies



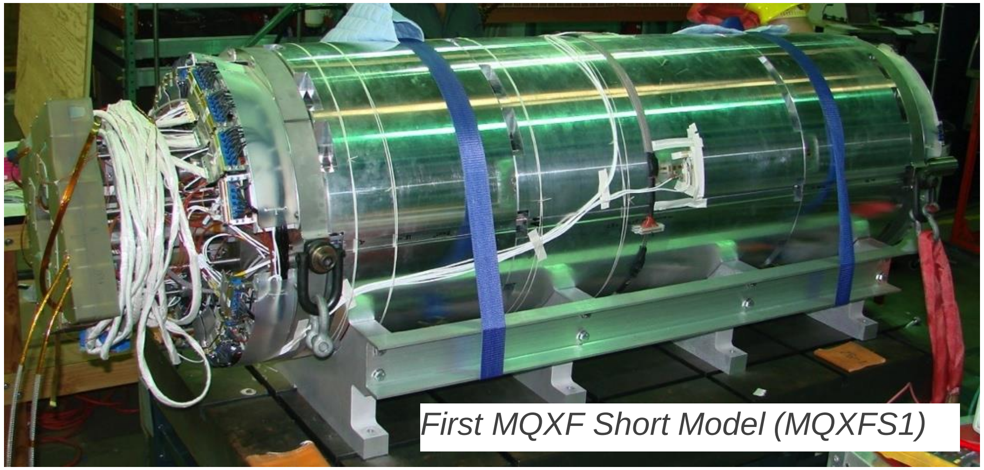


BNL Vertical Magnet Test facility

Fermilab Horizontal Magnet Test facility

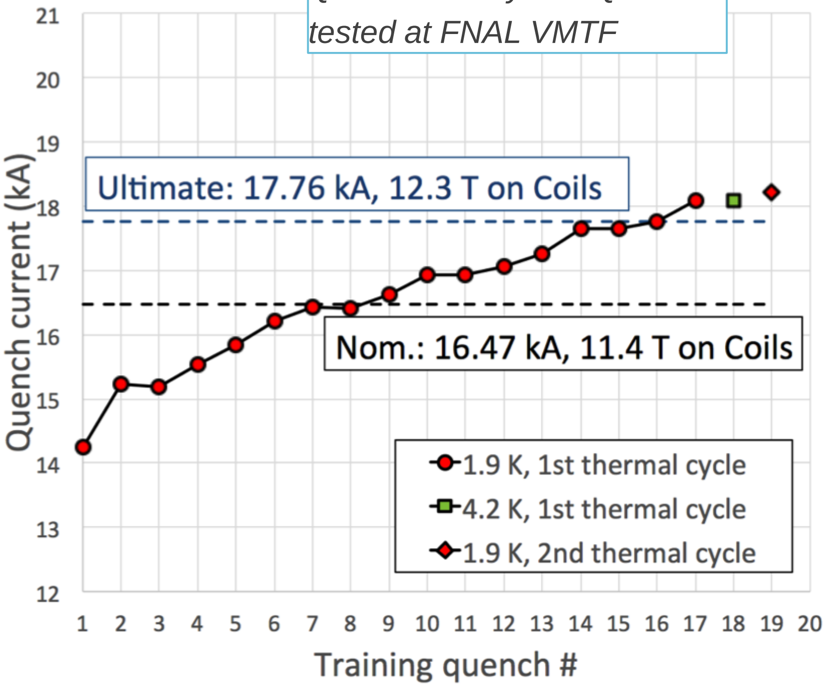
Short Model Magnet Tests

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



First MQXF Short Model (MQXFS1)

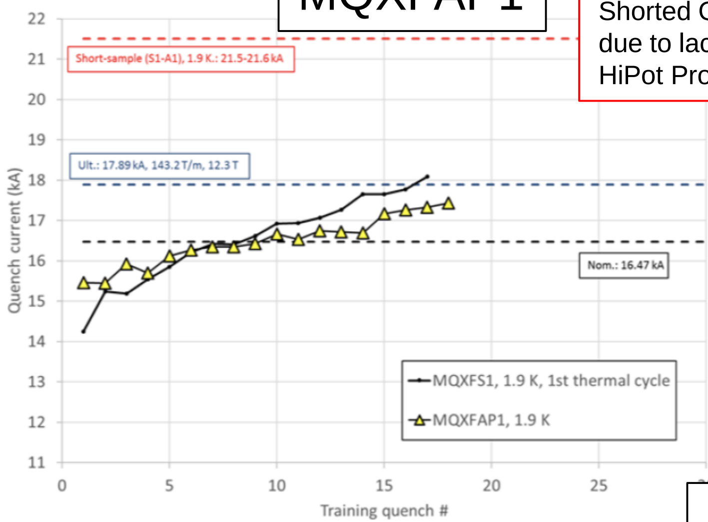
Quench history of MQXFS1 tested at FNAL VMTF



AUP Prototypes Technical Status (cont.)

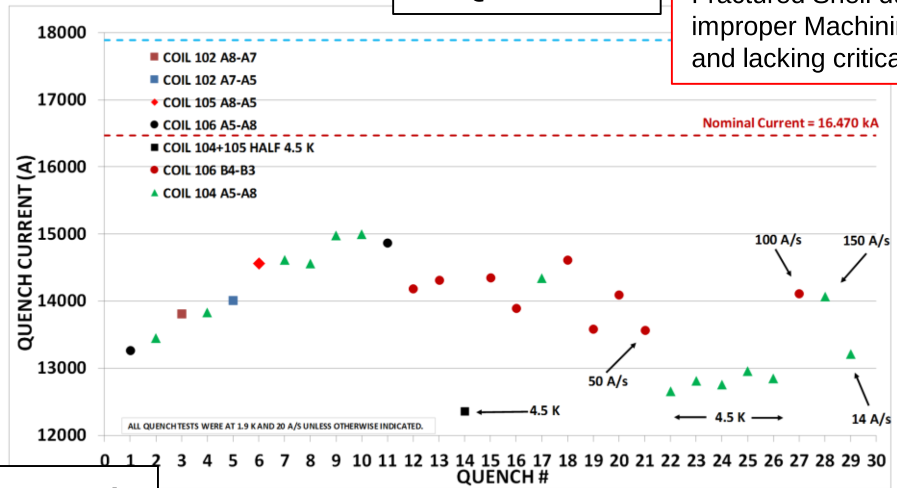
MQXFAP1

Shorted QH due to lacking HiPot Procedure

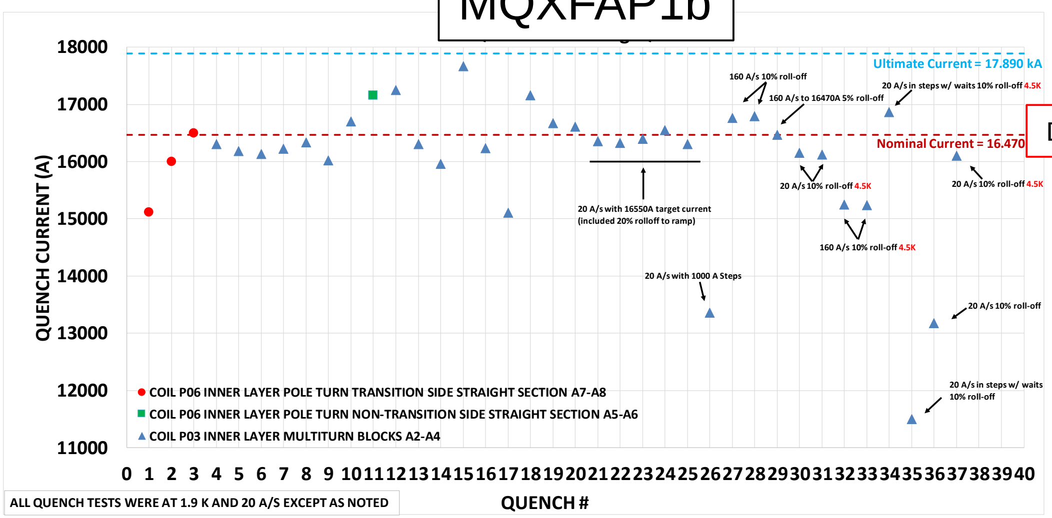


MQXFAP2

Fractured Shell due to improper Machining and lacking critical QC



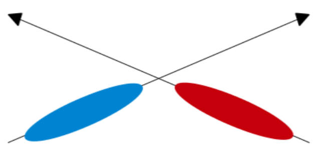
MQXFAP1b



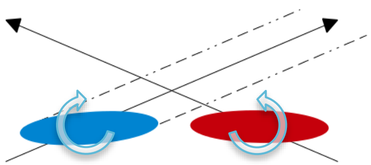
Degraded LARP (P03) Coil

- Next Magnet (MQXFA03) tested in ~October '19
- Following (MQXFA04) in early CY20

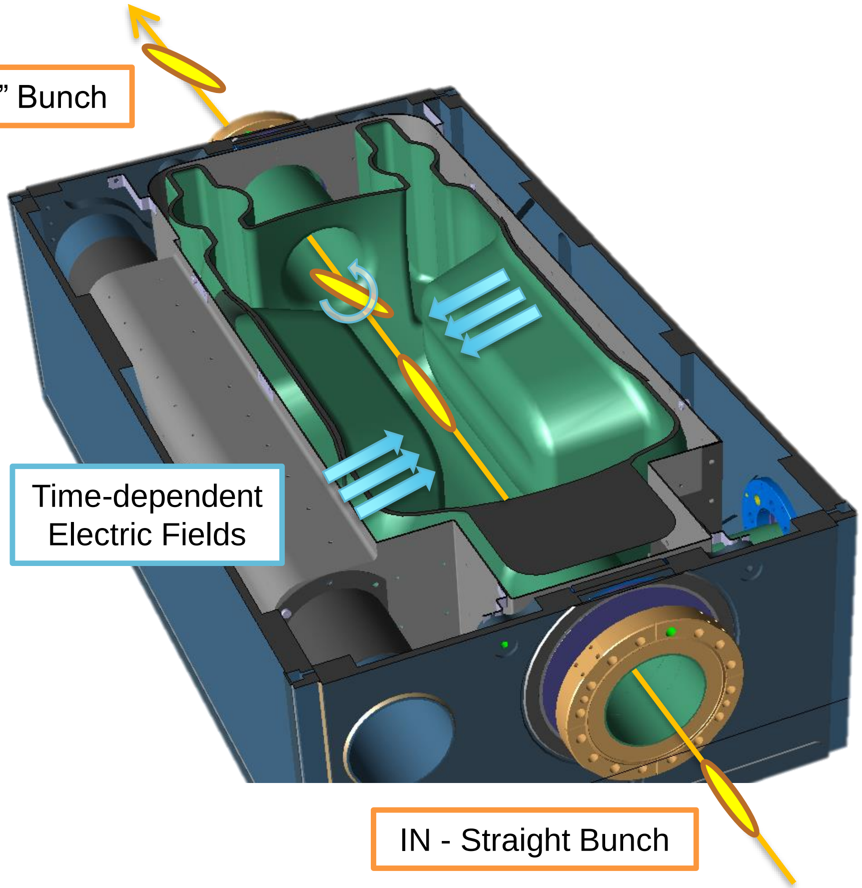
AUP Crab Cavities



Non crabbed bunches
Non head-on collisions



Crabbed bunches
Head-on collisions



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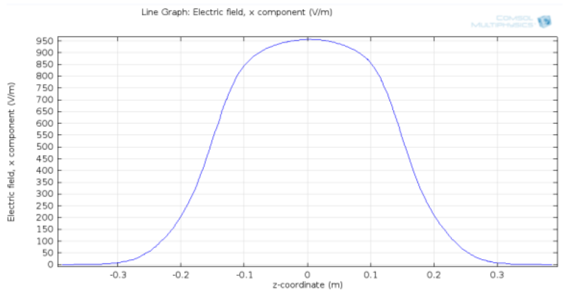
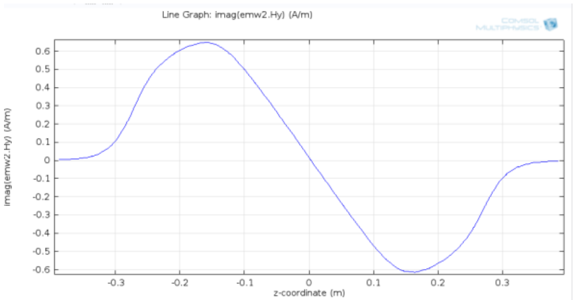
RFD cavity design



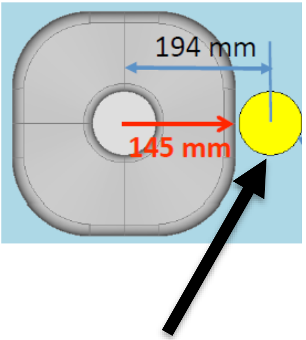
Ex field on axis



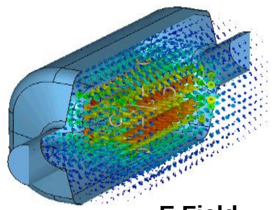
Hy field on axis

$$V_t = \int (E_x - Z_0 H_y) e^{ikz} dz$$

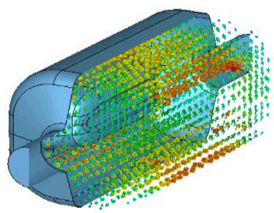
- LARP prototype design is a fully integrated design
- Operates in TE_{11} like mode
- Crabbing in horizontal plane
- Meet the compactness requirement for LHC



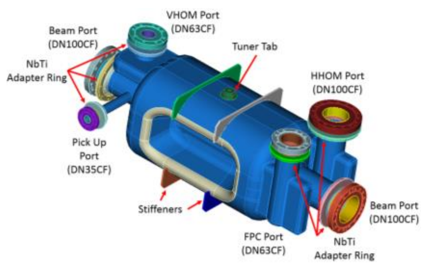
Second LHC beam pipe



E Field



H Field



RFD Electromagnetic Design – Zenghai Li (SLAC)

Frequency	400.79	MHz
Aperture	84	mm
Nearest HOM	633.5	MHz
E_p^*	3.6	MV/m
B_p^*	6.2	mT
$[R/Q]_t$	429.7	Ω
Geometrical Factor (G)	106.7	Ω
$R_t R_s$	4.6×10^4	Ω^2
At $E_t^* = 1.0$ MV/m		
V_t	3.4	MV
E_p	33	MV/m
B_p	56	mT

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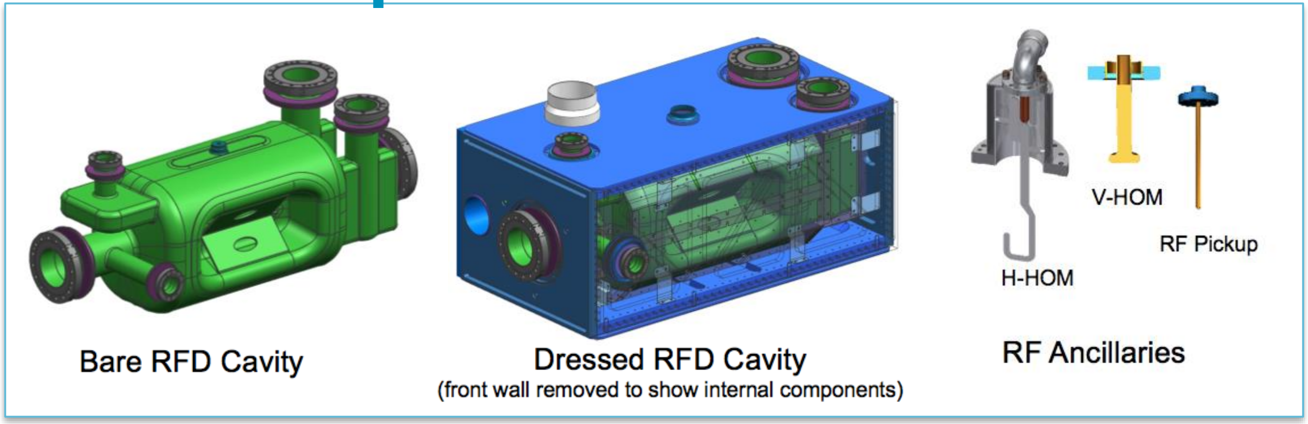
Scope and Deliverables



- **Dressed RFD Crab Cavity**
  - **Project Scope includes 2 Prototypes + 2 Pre-Series + 10 Series**
  - Bare Cavities: Intermediate Qualification at FNAL at 2K
  - Assembly: Bare Cavity + Magnetic Shields + Helium Tank + RF Ancillaries
  - Dressed Cavities: Final Qualifications at FNAL at 2K + RF Ancillaries
  - Shipped to CERN ready for integration in cryomodule (CERN scope)
  - Delivery of (10) qualified dressed cavities (objective KPP)

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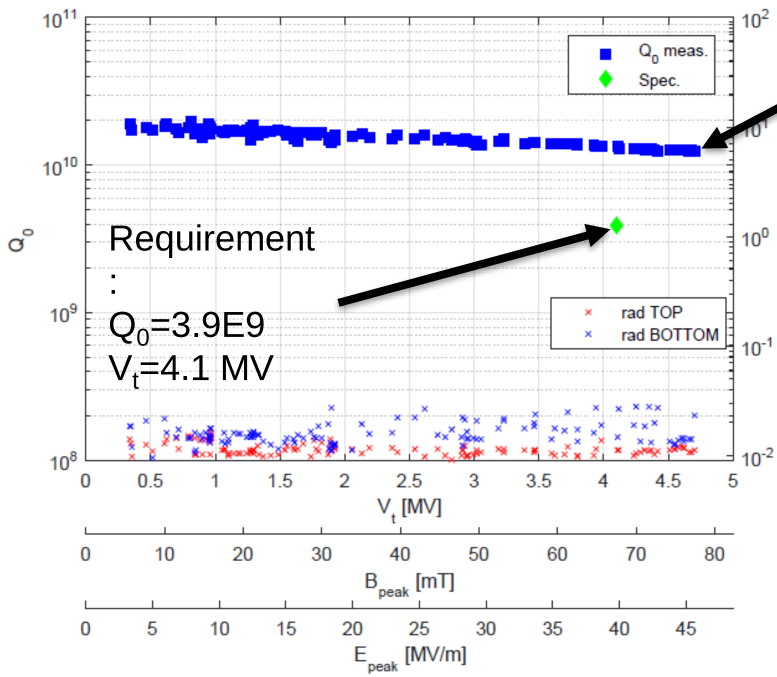
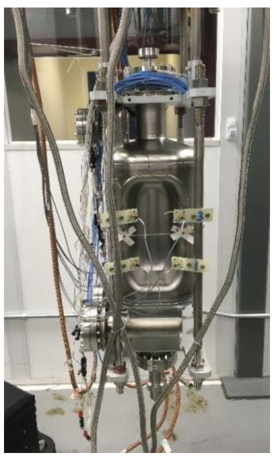
RFD-LARP-001 bare performance

- Validation of 400 MHz RF system and capability of testing RFD cavities at FNAL, outperforming JLAB test results.
- Q_0 and V_t exceeded FRS values, bare cavity performance verified at JLAB and FNAL.

Measured:
Q_0=1.2E10
V_t=4.7 MV



Requirement
:
Q_0=3.9E9
V_t=4.1 MV



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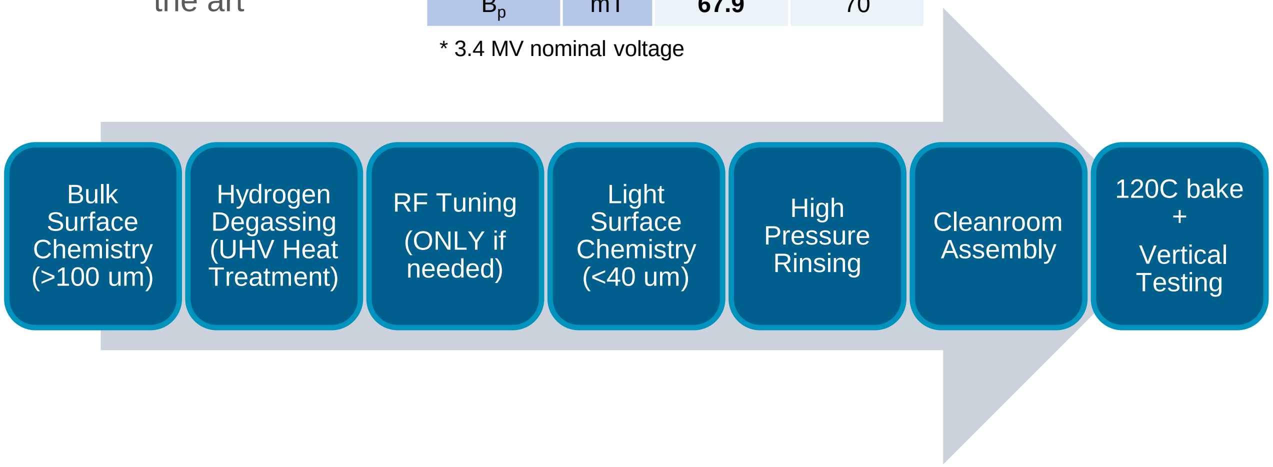
Bare Cavities Processing and Testing Plan

- Buffered Chemical Polishing is suitable for RFD cavities: complex shape and relatively low peak fields make BCP favorable over EP.
- Standard SRF Cavity Cleanroom and Heat Treatment Techniques can be adapted to work on RFD cavity geometry.

Peak Fields of RFD Cavity ~50% of state of the art

V_t	MV	**4.1***	Peak field limitation
E_p	MV/m	**39.3**	40
B_p	mT	**67.9**	70

* 3.4 MV nominal voltage



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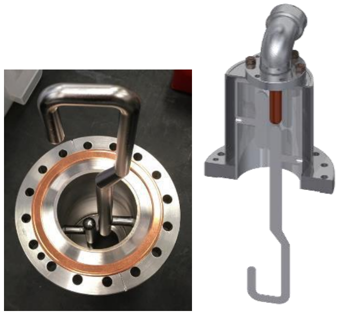
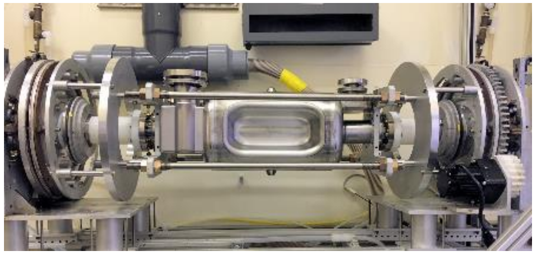
Validation Activities (LARP+AUP)

- Upgraded & Validated FNAL Vertical Test Stand for Bare Cavities
  - Thanks to FNAL + LARP investments
- Upgraded rotational-chemistry tool/facility at ANL
- Successful cold-tests on LARP prototypes
  - Exceeded requirements of field and quality factor
  - Also with H-HOM damper installed
- Newly fabricated HOM dampers at Jlab
- Placed PO for bare cavity prototypes
  - Includes options for pre-series and series



HHOM damper fabricated at JLab

LARP prototype in FNAL VTS facility



Rotational Chemistry tool at ANL (Response to CD-1/3a recommendation)

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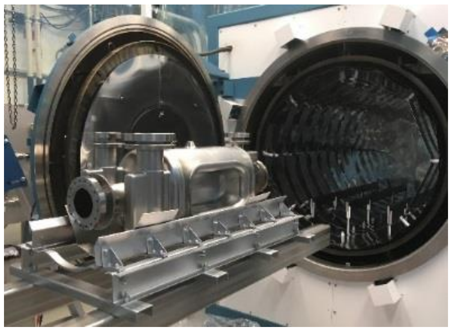
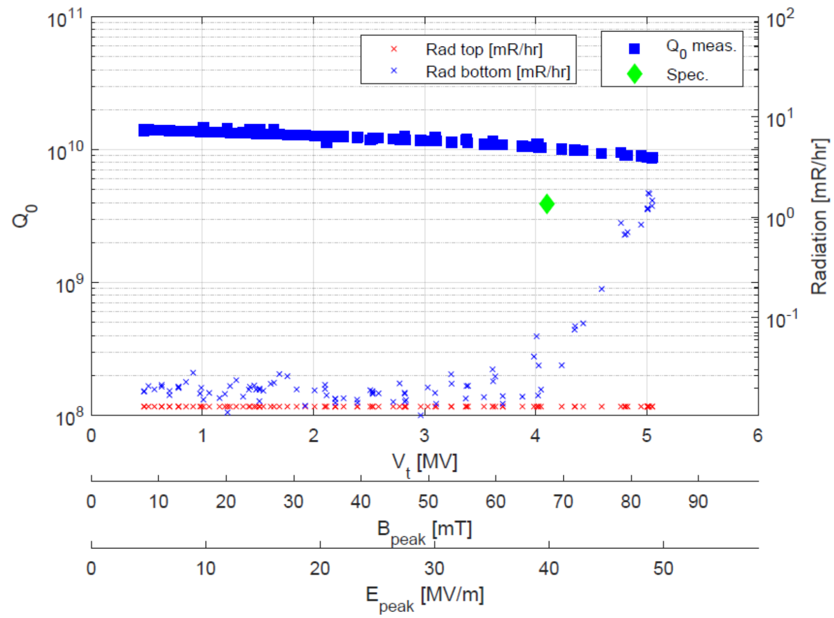
Heat Treatments + Cleanroom Assy Validation



600'C Heat Treatment (FNAL)

120'C Bake (FNAL)

VTS preparation (FNAL)



RFD-LARP-001 exceeded requirements for HL-LHC

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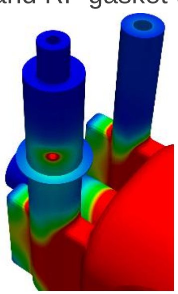
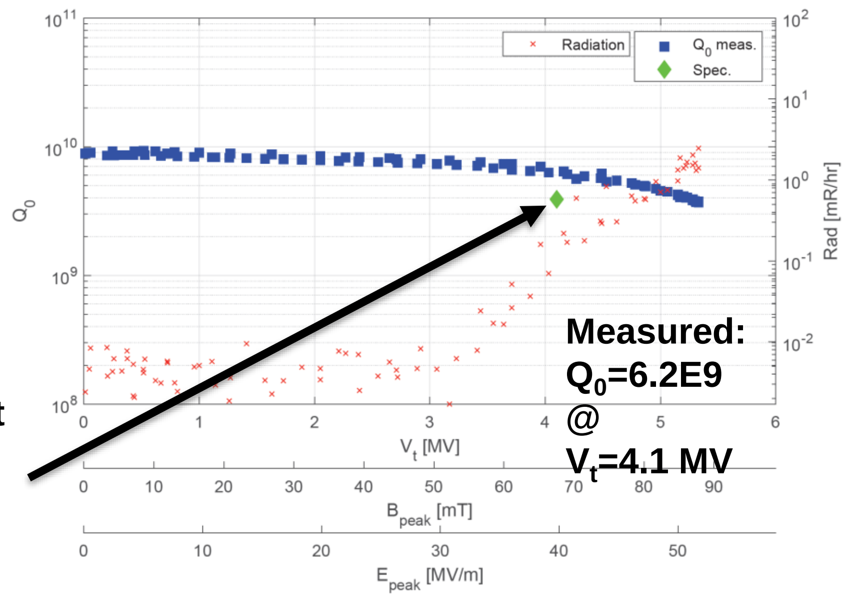
RFD cavity + HHOM and VHOM validation

- RFD2 cavity has been successfully tested with all RF ancillaries at JLab.
- HHOM RF leakage has been resolved **Q_0 exceeds requirement, quench Vt is 5.5 MV>4.1 MV.**
- HHOM and VHOM dampers design has been successfully tested.
- Fundamental mode rejection has been tuned for both HHOM and VHOM.

Regular gasket on HHOM coupler (left) and RF gasket (right)



Requirement:
Q_0=3.9E9
V_t=4.1 MV



Measured:
Q_0=6.2E9
@
V_t=4.1 MV

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Summary

- HL-LHC AUP scope is to deliver to CERN:
  - Fully tested 10 Q1/Q3 Cryo-Assemblies
  - 10 qualified dressed crab cavities
- Magnets are being produced and tested
  - Successful short model magnet program completed
  - Long prototypes still need improvements
- Successful validation tests of RF Crab Cavities
  - Successful cold-tests on LARP prototypes; Exceeded requirements of field and quality factor
  - RFD2 cavity has been successfully tested with all RF ancillaries at Jlab
  - HHOM and VHOM dampers design has been successfully tested

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