# HL-LHC AUP:
# Status of the US Contribution to LHC

Giorgio Apollinari – FNAL
*HL-LHC AUP Project Manager*

21th -22th November 2019, HEPAP

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# Goals of HL-LHC

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 $L_{peak}$ = **$5\times10^{34}$ $cm^{-2}s^{-1}$ 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.

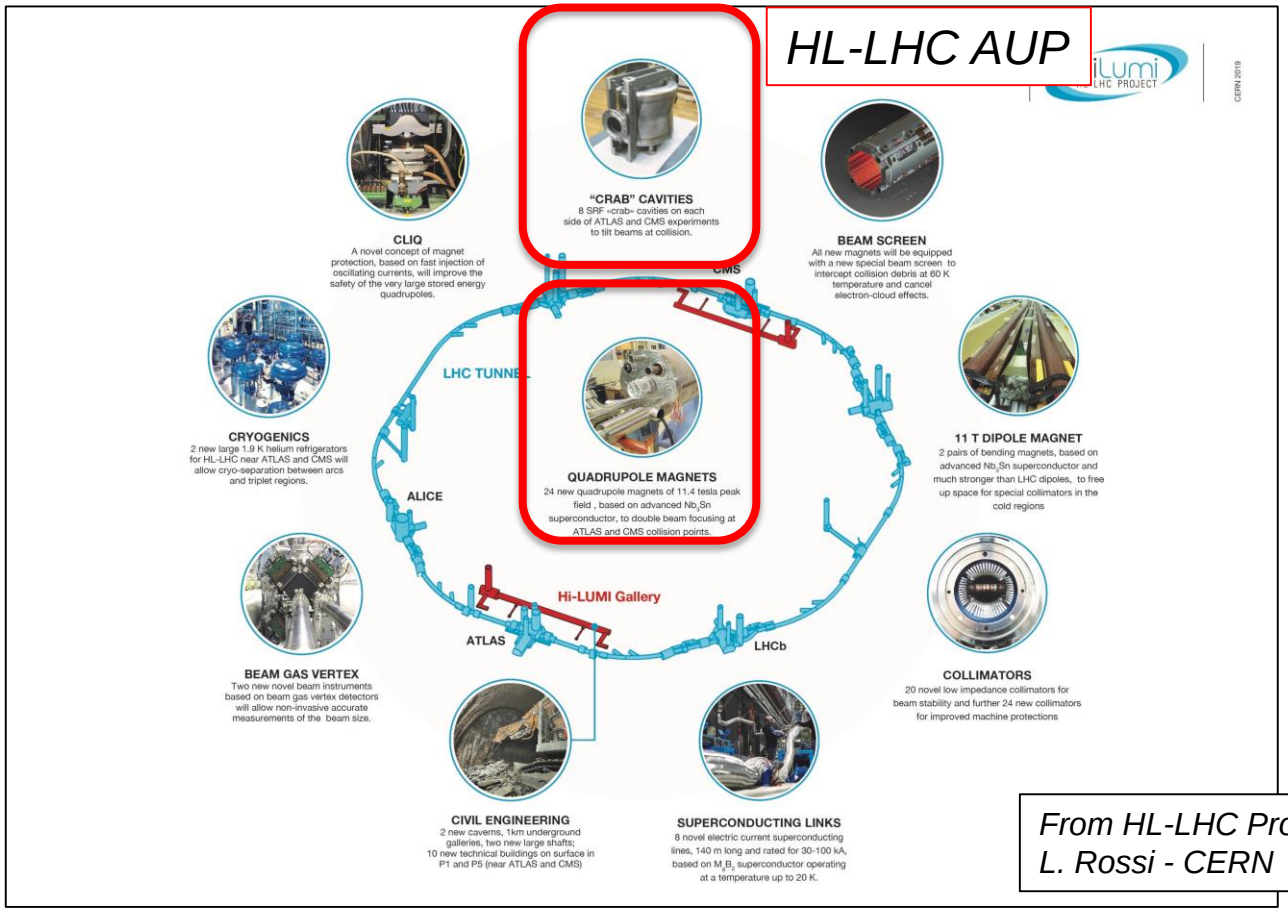
This luminosity is more than ten times the luminosity reach of the first 10 years of the LHC lifetime.

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

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

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

# US Contribution to HL-LHC



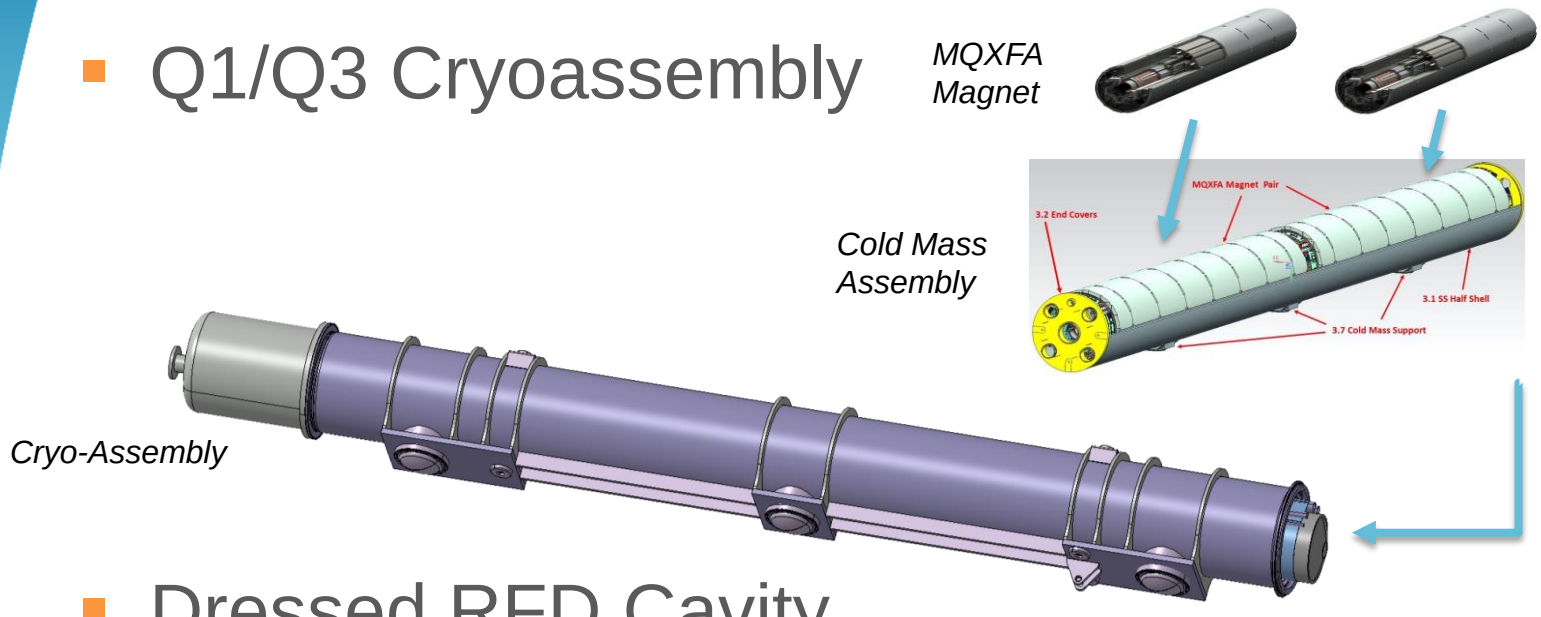

*From HL-LHC Project Leader L. Rossi - CERN*

- LARP established the necessary technology for the HL-LHC Focusing Magnets and Crab Cavities (WP3 & WP4)
- DOE created **HL-LHC AUP** Project, coordinating efforts from US Labs (FNAL, BNL, LBNL with contributions from SLAC, JLAB & ODU)

US HL-LHC AUP

# HL-LHC AUP Scope – Technical Details

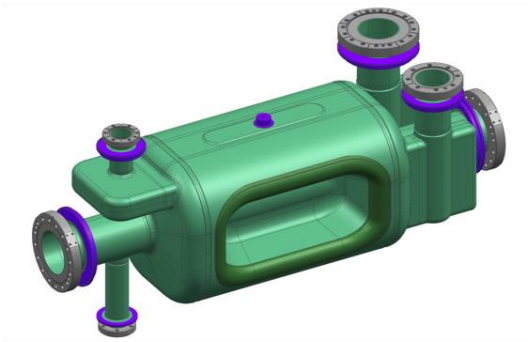
- Q1/Q3 Cryoassembly



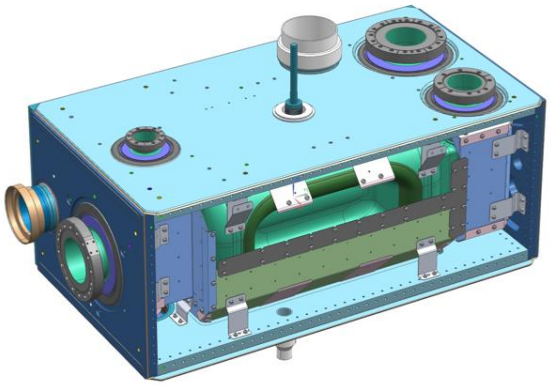

302.2

302.4

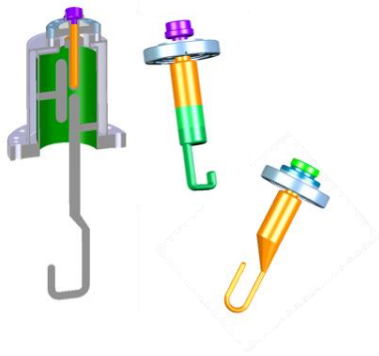
- Dressed RFD Cavity



Bare RFD Cavity



Dressed RFD Cavity
(front wall removed to show internal components)



RF Ancillaries

302.3

# HL-LHC AUP Scope as Key Performance Parameters

| Parameters | Threshold Performance | Objective Performance |
|---|---|---|
| Inner Triplet Focusing Quadrupoles (Q1 and Q3) | a) 5 Q1-Cryoassemblies and 4 Q3-Cryoassemblies are accepted by CERN after testing at HL-LHC nominal temperature and ultimate gradient for the magnets, and functionality for the Cryoassembly. The Cryoassemblies will be assembled from Cold Masses built by HL-LHC AUP and Cryostat kits prov 9 CryoAssemblies + Parts<br>b) Procurement of components for 1 additional Q3 Cold Mass | 1 additional Q3-Cryoassembly is accepted by CERN after testing at HL-LHC nominal temperature and ultimate gradient for the magnets, and functionality for the Cryoassembly. The Cryoassembly will be assembled from Cold Masses built by HL-LHC AUP and Cryostat kits provided by CERN |
| SRF Crab Cavities | a) 8 Radio Frequency Dipoles (RFDs) Dressed cavities for the HL-LHC Crab Cavity System are accepted by CERN after being tested at HL-LHC nominal temperature, nominal frequency, and ultimate cavity voltage. Dressed cavities include HOM couplers, pick-ups, He Vessel and magnetic shi 8 Cavities + Parts<br>b) Procurement of components for 2 additional RFD Dressed Cavities | 2 additional Radio Frequency Dipoles (RFDs) Dressed cavities for the HL-LHC Crab Cavity System are accepted by CERN after being tested at HL-LHC nominal temperature, nominal frequency, and ultimate cavity voltage. Dressed cavities include HOM couplers, pick-ups, He Vessel and magnetic shields. |

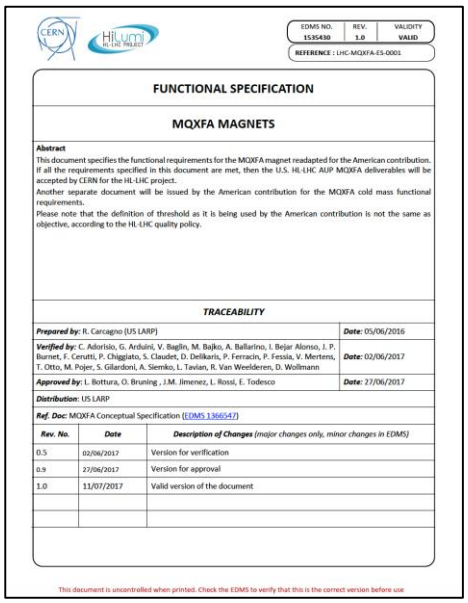
10 Q1/Q3 Cryoassemblies

10 RFD Dressed Cavities

- HL-LHC AUP Project include Objective KPPs
- The difference between Threshold and Objective KPPs represents scope contingency that provides technical, schedule, and cost margin for a successful completion of the Project.
- *AUP does not contain any activity of Installation or Commissioning at the HL-LHC.*

# HL-LHC Scope by Performance Requirements

- Performance Requirements and Acceptance Criteria documented in appropriate documentation:
  - Approved by CERN and accepted by AUP
  - Changes (to Performance Requisitions or Acceptance Criteria) have inevitable effects on AUP.



FUNCTIONAL SPECIFICATION

MQXFA MAGNETS

Abstract

This document specifies the functional requirements for the MQXFA magnet readapted for the American contribution. If all the requirements specified in this document are met, then the U.S. HL-LHC AUP MQXFA deliverables will be accepted by CERN for the HL-LHC project.
Another separate document will be issued by the American contribution for the MQXFA cold mass functional requirements.
Please note that the definition of threshold as it is being used by the American contribution is not the same as objective, according to the HL-LHC quality policy.

TRACEABILITY

| | |
|---|---|
| **Prepared by:** R. Carcagno (US LARP) | **Date:** 05/06/2016 |
| **Verified by:** C. Adorisio, G. Arduini, V. Baglin, M. Bajko, A. Ballarino, I. Bejar Alonso, J. P. Burnet, F. Cerutti, P. Chiggiato, S. Claudet, D. Delikaris, P. Ferracin, P. Fessia, V. Mertens, T. Otto, M. Pojer, S. Gilardoni, A. Siemko, L. Tavian, R. Van Weelderen, D. Wollmann | **Date:** 02/06/2017 |
| **Approved by:** I. Bottura, O. Bruning , J.M. Jimenez, L. Rossi, E. Todesco | **Date:** 27/06/2017 |
| **Distribution:** US LARP | |
| **Ref. Doc:** MQXFA Conceptual Specification (EDMS 1366547) | |

| Rev. No. | Date | Description of Changes (major changes only, minor changes in EDMS) |
|---|---|---|
| 0.5 | 02/06/2017 | Version for verification |
| 0.9 | 27/06/2017 | Version for approval |
| 1.0 | 11/07/2017 | Valid version of the document |

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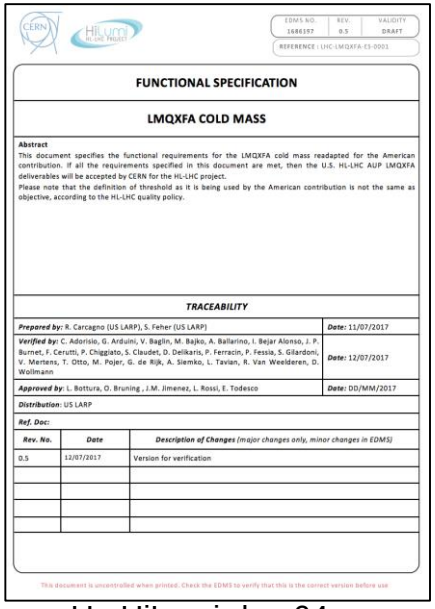

FUNCTIONAL SPECIFICATION

LMQXFA COLD MASS

Abstract

This document specifies the functional requirements for the LMQXFA cold mass readapted for the American contribution. If all the requirements specified in this document are met, then the U.S. HL-LHC AUP LMQXFA deliverables will be accepted by CERN for the HL-LHC project.
Please note that the definition of threshold as it is being used by the American contribution is not the same as objective, according to the HL-LHC quality policy.

TRACEABILITY

| | |
|---|---|
| **Prepared by:** R. Carcagno (US LARP), S. Feher (US LARP) | **Date:** 11/07/2017 |
| **Verified by:** C. Adorisio, G. Arduini, V. Baglin, M. Bajko, A. Ballarino, I. Bejar Alonso, J. P. Burnet, F. Cerutti, P. Chiggiato, S. Claudet, D. Delikaris, P. Ferracin, P. Fessia, S. Gilardoni, V. Mertens, T. Otto, M. Pojer, G. de Rijk, A. Siemko, L. Tavian, R. Van Weelderen, D. Wollmann | **Date:** 12/07/2017 |
| **Approved by:** L. Bottura, O. Bruning , J.M. Jimenez, L. Rossi, E. Todesco | **Date:** DD/MM/2017 |
| **Distribution:** US LARP | |
| **Ref. Doc:** | |

| Rev. No. | Date | Description of Changes (major changes only, minor changes in EDMS) |
|---|---|---|
| 0.5 | 12/07/2017 | Version for verification |

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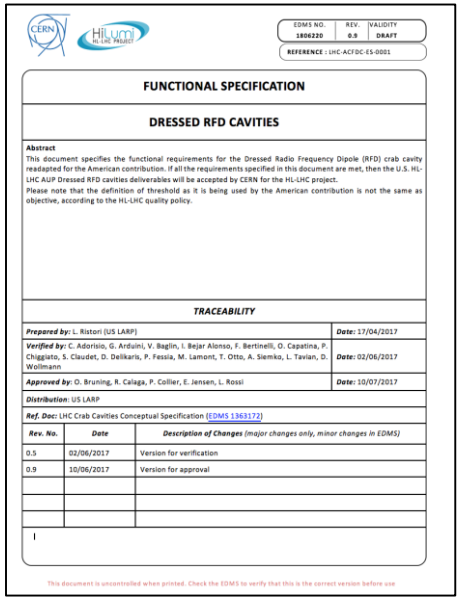

FUNCTIONAL SPECIFICATION

DRESSED RFD CAVITIES

Abstract

This document specifies the functional requirements for the Dressed Radio Frequency Dipole (RFD) crab cavity readapted for the American contribution. If all the requirements specified in this document are met, then the U.S. HL-LHC AUP Dressed RFD cavities deliverables will be accepted by CERN for the HL-LHC project.
Please note that the definition of threshold as it is being used by the American contribution is not the same as objective, according to the HL-LHC quality policy.

TRACEABILITY

| | |
|---|---|
| **Prepared by:** L. Ristori (US LARP) | **Date:** 17/04/2017 |
| **Verified by:** C. Adorisio, G. Arduini, V. Baglin, I. Bejar Alonso, F. Bertinelli, O. Capatina, P. Chiggiato, S. Claudet, D. Delikaris, P. Fessia, M. Lamont, T. Otto, A. Siemko, L. Tavian, D. Wollmann | **Date:** 02/06/2017 |
| **Approved by:** O. Bruning, R. Calaga, P. Collier, E. Jensen, L. Rossi | **Date:** 10/07/2017 |
| **Distribution:** US LARP | |
| **Ref. Doc:** LHC Crab Cavities Conceptual Specification (EDMS 1363172) | |

| Rev. No. | Date | Description of Changes (major changes only, minor changes in EDMS) |
|---|---|---|
| 0.5 | 02/06/2017 | Version for verification |
| 0.9 | 10/06/2017 | Version for approval |

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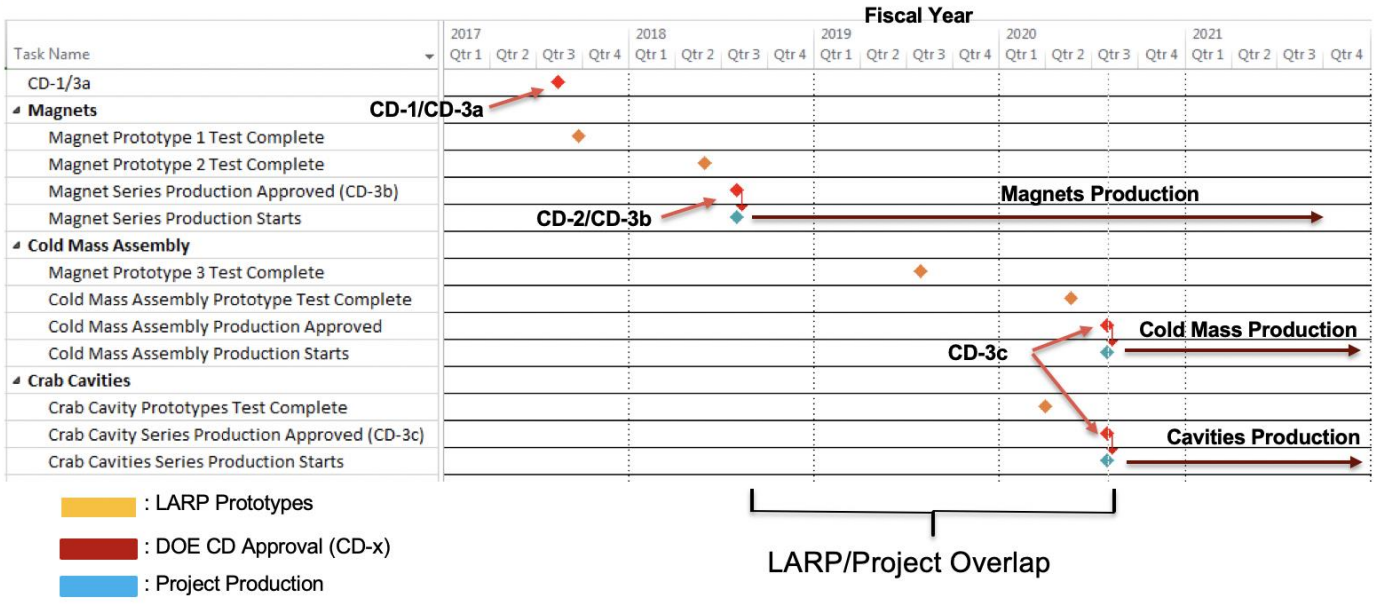
# From the Dec '16 Report to HEPAP

## LARP Prototypes - Milestones




- There is an overlap of ~ 2 years (mid-CY18 to mid-CY20) between LARP prototypes and project series production
  - First two magnet prototypes needed to approve start of magnet series production (CD-3b)
    - Series production starts with coil fabrication
  - Last two magnet prototypes needed for HL-LHC tunnel ready cold mass assembly
- LARP funding slow ramp down (FY18-19-20) while project funding ramps up

HiLumi HL-LHC PROJECT LARP

G. Apollinari – HEPAP Report: From LARP to HL-LHC AUP Dec. '16 68

US HL-LHC AUP

# HL-LHC AUP CD Tailoring Strategy *(Schedule Driven)*

- ✓ CD-0: Achieved (April 2016)
  - Approved Mission Need Statement
- ✓ CD-1/3a (Oct. 2017)
  - CD-1 approval for Cost and Schedule Range
  - CD-3a approval for full procurement of $Nb_3Sn$ strand
- ✓ CD-2/3b (Feb. 2019)
  - CD-2 approval of performance baseline
  - CD-2 approval for pre-series (*CA1*, *CA2* & 2 pRFD Cavities)
  - CD-3b for construction approval of fraction of coils and magnets parts
- CD-3c & CD-3:
  - Construction approval of remaining items (all coils and magnets, cold mass and cryo-assemblies, RFD cavities)
  - DOE reviews FY20/21

# Project Cost Status (Sep '19) and Funding Profile

| WBS Element | Item | BCWP | BCWS | Total |
|---|---|---|---|---|
| 302.1 | Project Management | 7.3 | 20.9 | 28.2 |
| 302.2 | MQXFA Magnets Fabrication | 26.0 | 70.4 | 96.4 |
| 302.3 | Crab Cavities Fabrication | 2.4 | 13.6 | 16.0 |
| 302.4 | Q1/Q3 CryoAssemblies Fabrication | 11.3 | 30.6 | 41.9 |
| | Budget At Completion (BAC) | 182.4 | | |
| | **DOE TPC** | | | **242.72** |
| | **Total DOE Contingency** | | | **60.3** |
| | Cost of Work Performed (ACWP) | | | 45.3 |
| | Work Remaining (BAC-ACWP) | | | 137.1 |
| | **Contingency on Work Remaining** | | | **43.98%** |

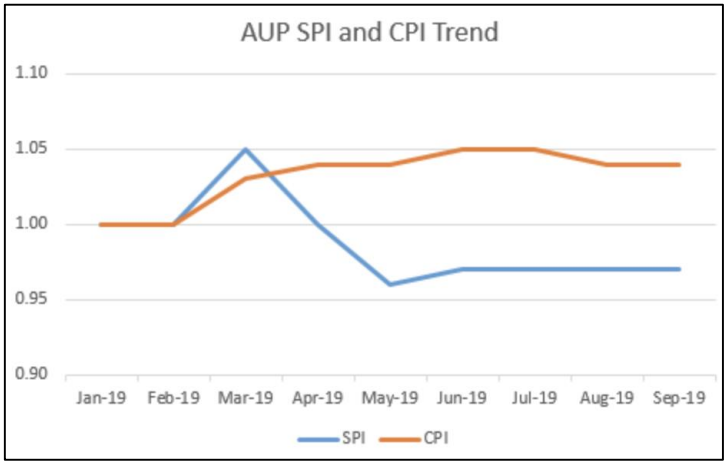
- Funding

| | FY16 | FY17 | FY18 | FY19 | FY20 | FY21 | FY22 | FY23 | FY24 | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| M$ | 0.12 | 0.5 | 27.0 | 50.0 | 50.0 | 48.7 | 33.9 | 21.0 | 11.5 | 242.72 |

*Disbursed*

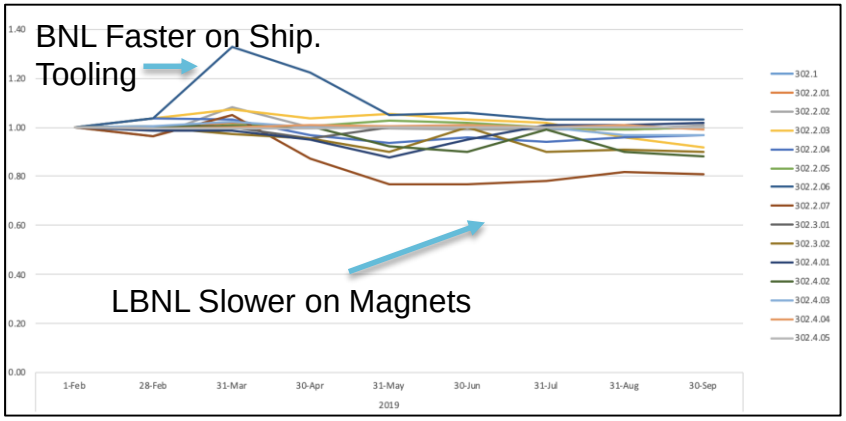
*On the way, CR effects*

# Cost Performance Trends

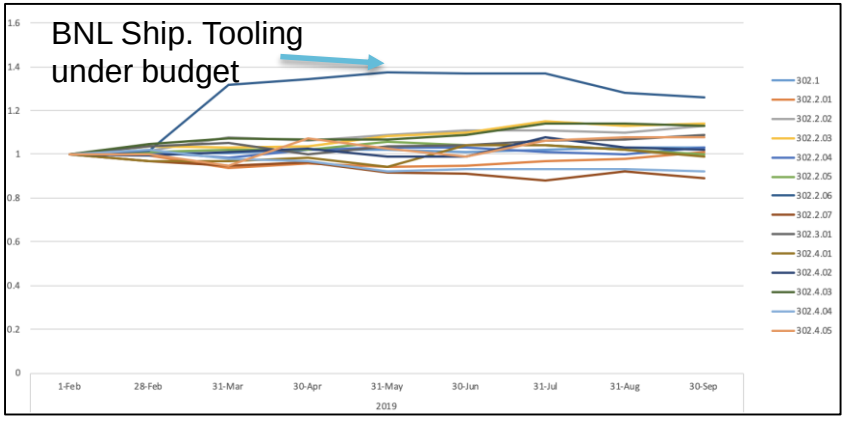



- SPI = 0.97
- CPI = 1.04

*SPI by CA*

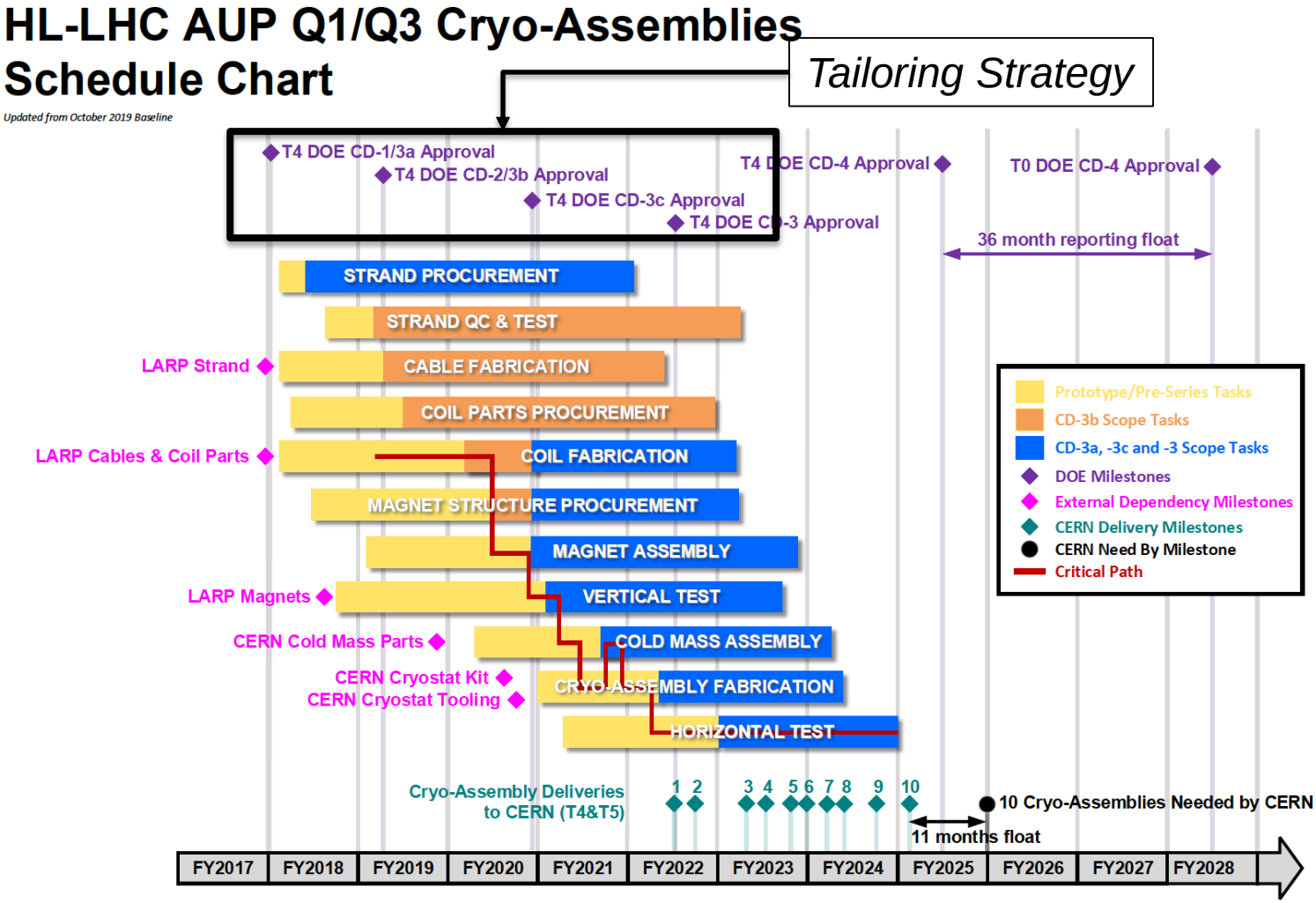



*CPI by CA*




- Monthly Risk Management & Change Control Boards:
  - Ex: 39 BCRs processed, with 13 positive impact and 26 negative impacts
  - Used ~3.1 M$ Contingency since baseline

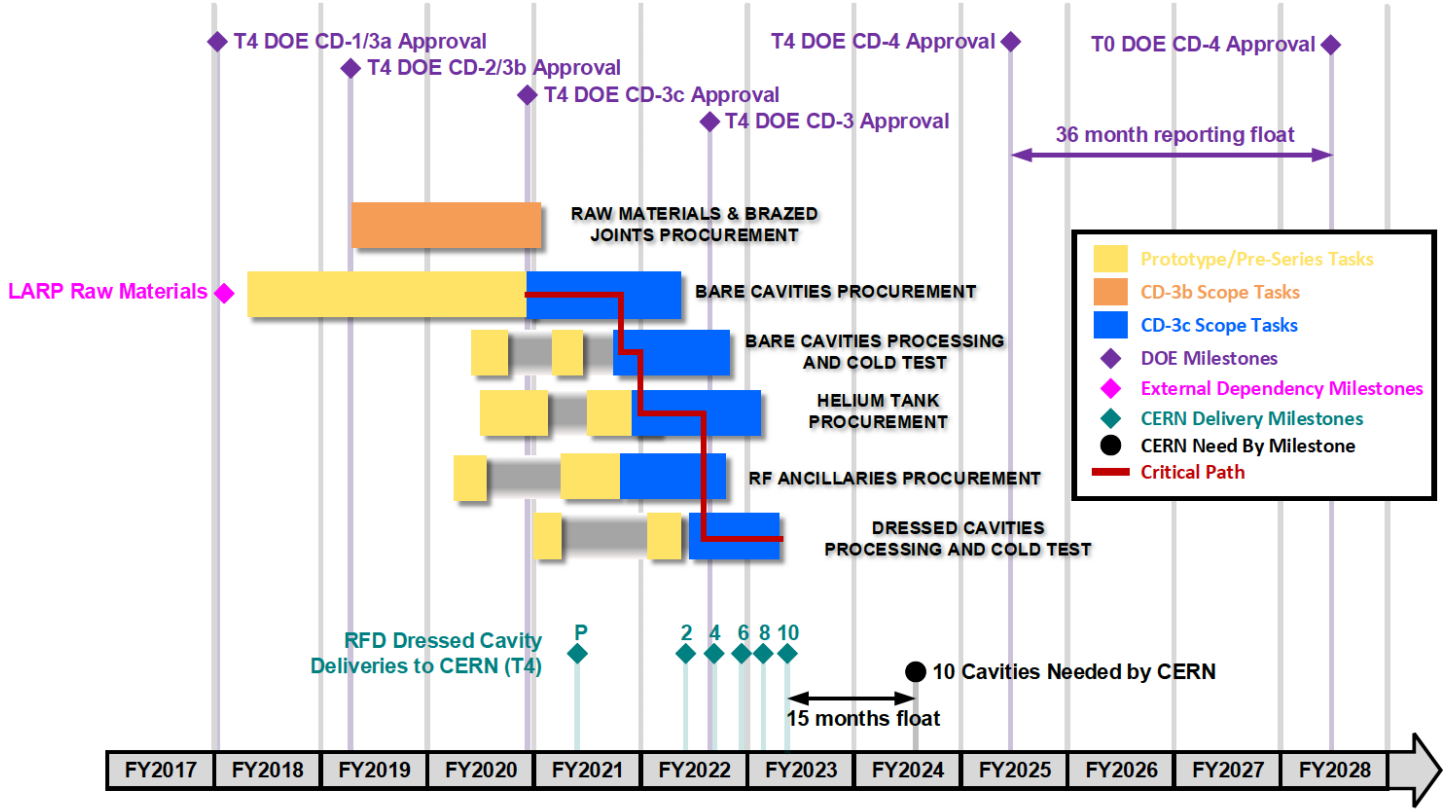
# HL-LHC AUP - Q1/Q3 Cryo-Assemblies Integrated Schedule



# HL-LHC AUP - RFD Dressed Crab Cavities Integrated Schedule

## HL-LHC AUP Crab Cavities Assembly Schedule Chart

*Updated from October 2019 Baseline*



# Delivery Dates – CryoAssemblies & Cavities

- Funding Agency endorsed AUP to agree with CERN on Delivery Dates with ~11 months of schedule float (called “US Project Schedule”)
  - Agreement achieved on Feb. 2018 and Jul. 2019
- AUP developed RLS to complete deliverables ~11 months ahead of agreed dates (called ”HL Project Schedule”)
  - These “HL Project Schedule” AUP dates contain production yield assumptions based on LARP experience
- At this time, CERN has decided to:
  - Build Master HL Schedule using the “HL Project Schedule”
  - Install in LHC tunnel Deliverables #3 to #8

CryoAssemblies

| | US Project schedule (11 month float) |
|---|---|
| LQXFA/B01 | Feb. 2023 |
| LQXFA/B02 | May 2023 |
| LQXFA/B03 | Dec. 2023 |
| LQXFA/B04 | Feb. 2024 |
| LQXFA/B05 | Jun. 2024 |
| LQXFA/B06 | Aug. 2024 |
| LQXFA/B07 | Nov. 2024 |
| LQXFA/B08 | Jan. 2025 |
| LQXFA/B09 | Jun. 2025 |
| LQXFA/B10 | Oct. 2025 |

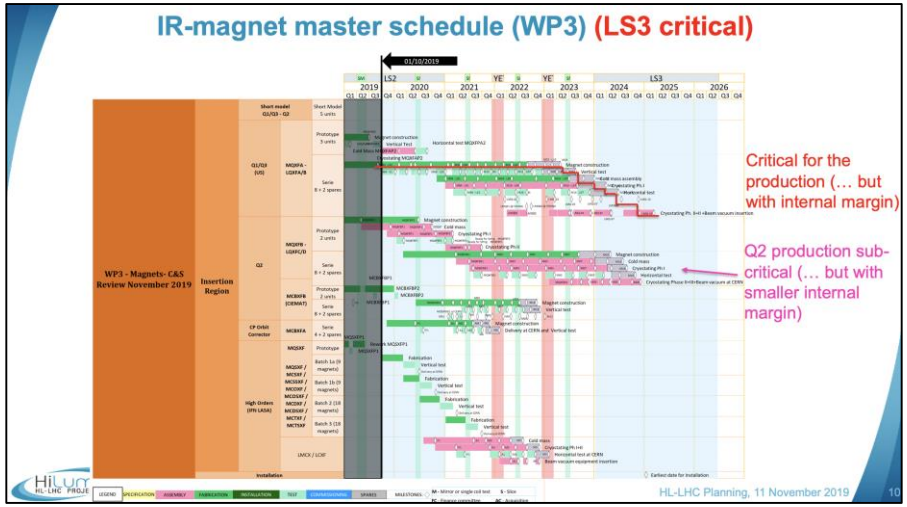
Dressed Cavities

| | US project schedule |
|---|---|
| HCACFDC002-UP000001 | June 2023 |
| HCACFDC002-UP000002 | June 2023 |
| HCACFDC002-UP000003 | September 2023 |
| HCACFDC002-UP000004 | September 2023 |
| HCACFDC002-UP000005 | December 2023 |
| HCACFDC002-UP000006 | December 2023 |
| HCACFDC002-UP000007 | February 2024 |
| HCACFDC002-UP000008 | February 2024 |
| HCACFDC002-UP000009 | May 2024 |
| HCACFDC002-UP000010 | May 2024 |

US HL-LHC AUP

# Nov. ‘19 Cost & Schedule Review at CERN

- Review on status of HL-LHC, report to CERN DG.
  - Chair: N. Holtkamp
- HL-LHC declared no need to postpone start of LS3 (Jan. ‘24)
- HL-LHC declared AUP on the critical path
  - Notification arrived 1 week before review !




- (Recall of) Review Committee Assessment relevant to AUP:
  - Schedule risk for the Q2 (CERN) is significant compared to Q1/Q3 (AUP) that has imbedded float.
  - Requirement to reach ultimate performance is not uniformly applied to all upgrade systems and adds to technical and schedule risk.
  - It is unlikely that LS3 can be executed within 2.5 years without taking a more aggressive approach
  - CERN master schedule needs to make explicit float of in-kind contributions visible.

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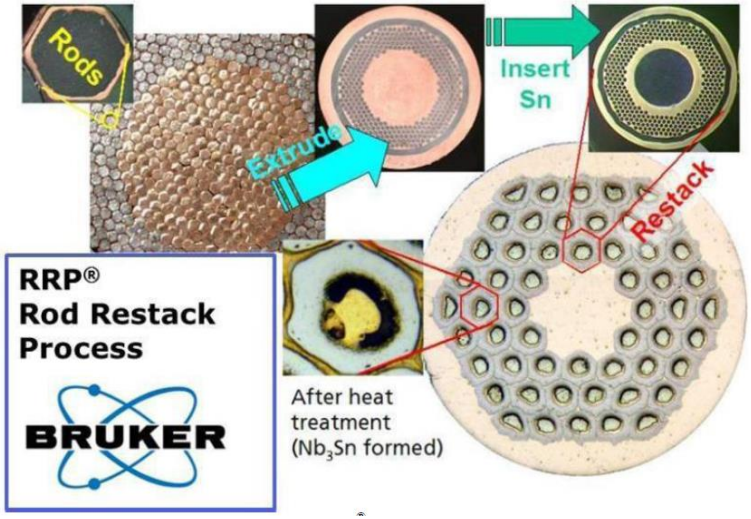
- ✓ Introduction
- ✓ Project Management Progress since last report to HEPAP
  - ✓ CD Approvals
  - ✓ Funding, EVMS Performance, etc.
  - ✓ Schedule
- Technical Progress since last report at HEPAP
  - Magnets
  - Cold Mass and CryoAssemblies
  - RFD Cavities
- Conclusions

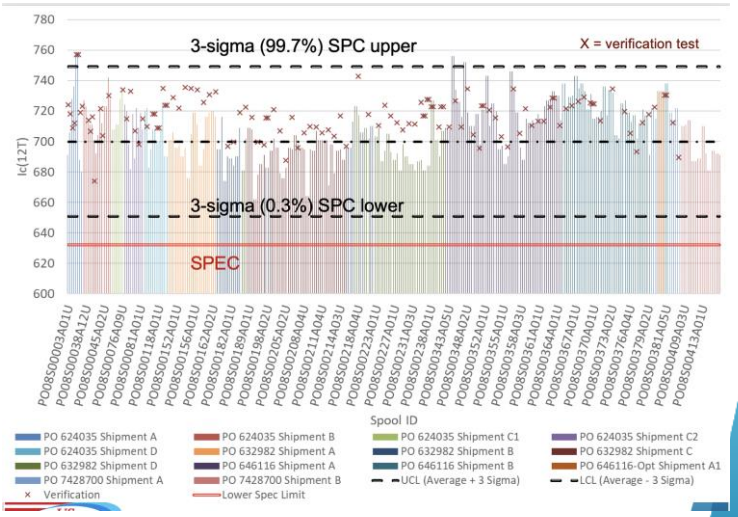
# Technical Status: progress since Dec '16

- Short Models (S) and Prototypes (P)
  - MQXFS1 — LARP/CERN – Built/Tested
  - MQXFAP1 — LARP-Built/Tested
  - MQXFAP2 — LARP-Built/ AUP Tested
  - MQXFAP1b — P06(AUP) + Reuse 3 coils from AP1
  - RFD-LARP#1 & #2 — LARP Built
- In a sentence: *good success on short model Magnets, piecemeal successes with no overall winner on Prototype Magnets, good results on Cavities*
  - Coils of the appropriate dimensions can be built
  - CLIQ and QH protected MQXFA magnets in 87(-1) quenches
  - Present HiPot of Coils/Magnets provide appropriate QC
  - Achieved Nominal on 2 Magnets
  - Several coils got to few ~100A from Ultimate
  - Magnetic Field Quality acceptable
- <u>Due to CERN schedule requirements, magnet pre-series deliverables production has started in ~Dec'18.</u>

# Status: Conductor Procurement & QC

- Strand Procurement and QC:
  - 50% strand received
  - 1 contract remaining to be placed in FY20
  - Conductor is being delivered timely
  - No significant issues on performance
  - Helium cap by BOST's helium supplier; Fermilab is providing He gas and getting credit back



# 302.2 Magnets Update:
## ~100 Cables, ~90 Coils, ~23 Assemblies of Magnets

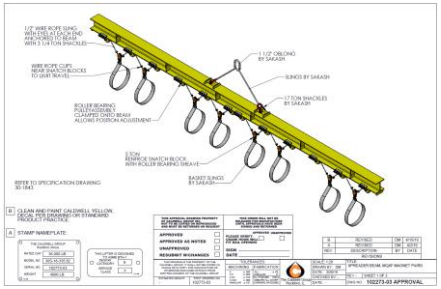
- Strand and Cable Fabrication
  - 28 Manufactured
    - 27 Accepted
- Coils at FNAL and BNL
  - 23 (being) Manufactured
    - 11 Accepted, 5 in progress
    - *3 quarantined, 4 rejected*
- Magnets
  - MQXFA03 at BNL for vertical test.
    - First *deliverable* Magnet
  - MQXFA04 Coil selection now, ready by early 2020

MQXFA03 ”verticalized” at BNL

# 302.4 Cold Mass and Cryostat Update ~20 Cryostats

L2-S. Feher

CM Tooling designed procurement in progress



Cold Mass Welding Table under Alignment

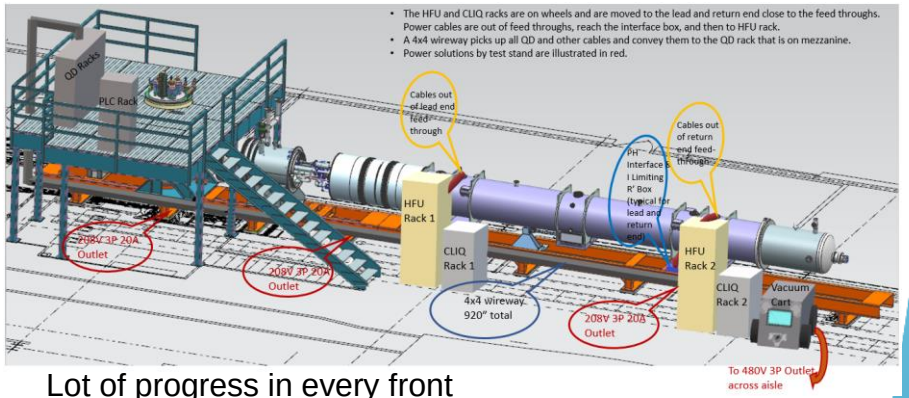
## BNL CRYOGENICS UPGRADES

Linde 1610 Liquefier 80-100 L/hr

Linde 1430 is in house, not yet plumbed in.
Linde 1610 at BNL still under refurbishment.

- Plan B being prepared

## TEST STAND 4 @ FERMILAB



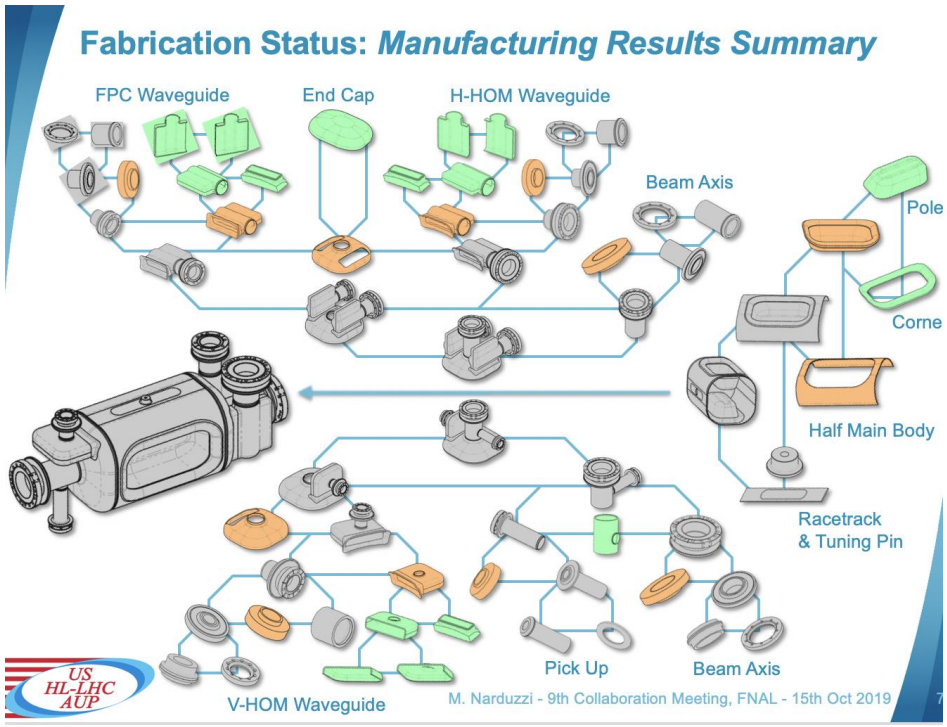

Lot of progress in every front

- Lambda plug has been fabricated and being tested
- Adapter box fabrication
- Cryogenic infrastructure upgrade
- QP modules completed waiting for system tests
- MM probe driving module successfully tested

Zero magnet test milestone is in March 2020

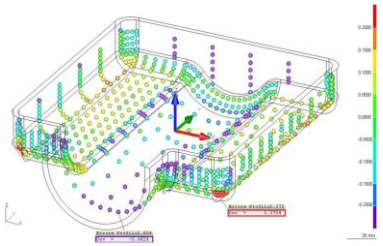
# 302.3 RFD Crab Cavities Status
# AUP: 2 Proto+2 pre-series+10 Cavities

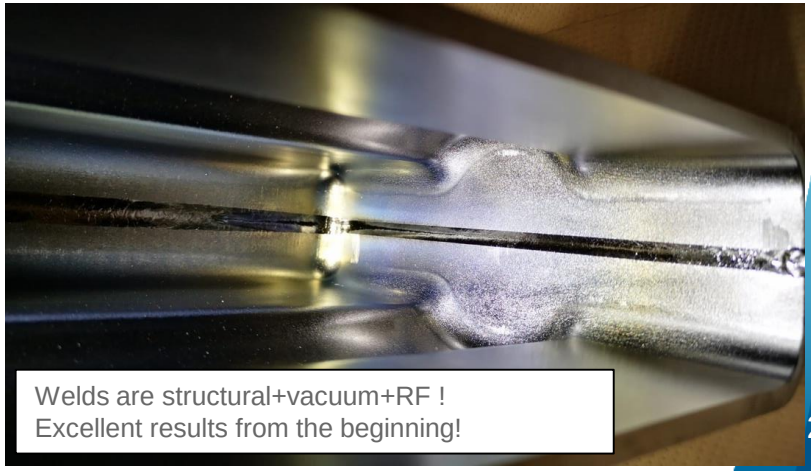
*L2-L. Ristori*




Nb Raw Material @FNAL from Ningxia for pre-series Cavities

Work at Zanon for prototype Cavities





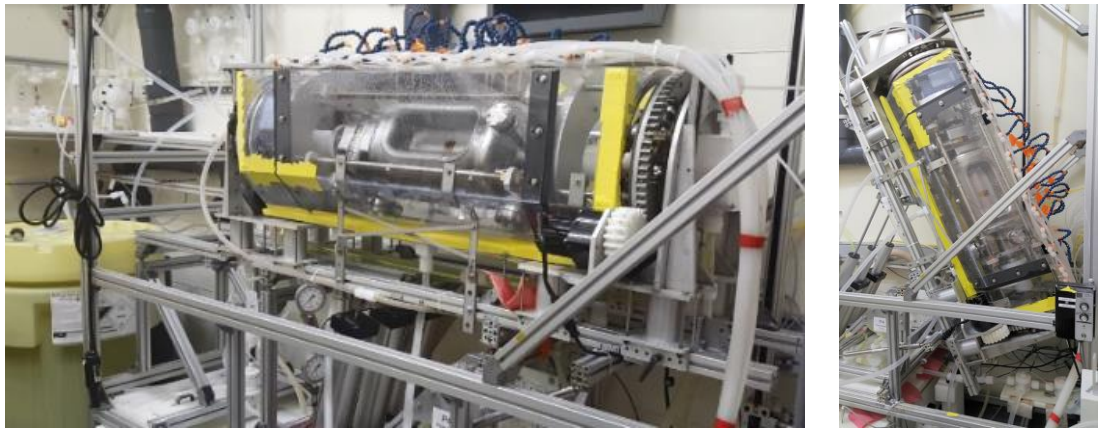
Welds are structural+vacuum+RF !
Excellent results from the beginning!

US HL-LHC AUP

# Rotational BCP + HPR Validation

*M. Kelly (ANL) – D. Bice (FNAL)*

- RFD-LARP-001 has been **successfully tested at FNAL**, after undergoing full processing at APS-TD and ANL facilities: **processing and facilities validation is complete**
- New rotational Bulk & Light BCP
- 600 C degassing
- HPR and clean assembly
- 120 C bake
- VTS test



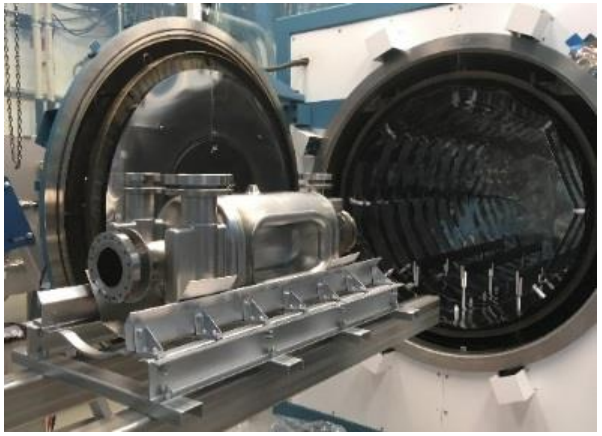
Rotational BCP tool for RFD cavity (ANL/FNAL facility)

RFD HPR and Cleanroom Assembly (ANL/FNAL facility)

US HL-LHC AUP

# Heat Treatments + Cleanroom Assy Validation

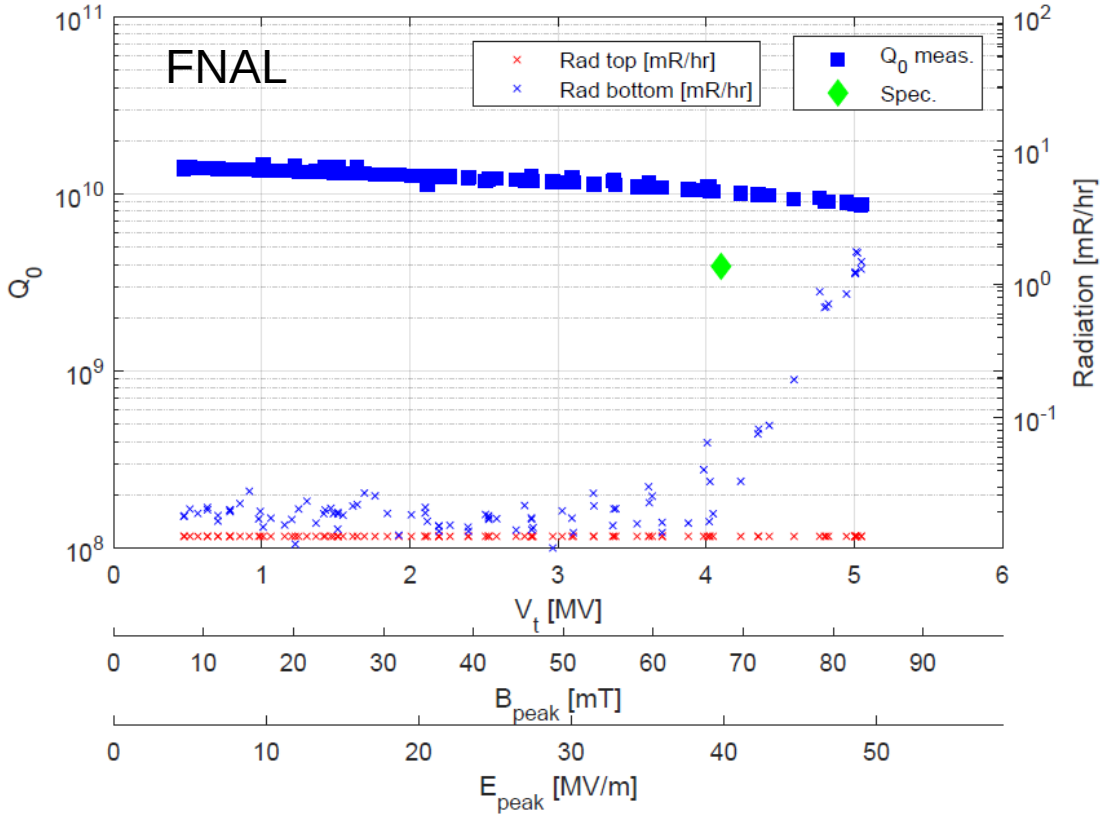
*P. Berrutti (FNAL)*



600'C Heat Treatment (FNAL)

120'C Bake (FNAL)

VTS preparation (FNAL)




RFD-LARP-001 exceeded requirements for HL-LHC

# Conclusions

- HL-LHC AUP Project has received CD-2 (baseline) and CD-3a/CD-3b ($Nb_3Sn$ & Magnets 1-to-7) approval by DOE
- Technical Challenges
  - Demonstrate performance of first deliverables (MQXFA03 & MQXFA04) or Prototypes (RFD Cavities)
- Next hurdle: IPR Review in Jan. ‘20 and CD-3c for full magnet/bare cavities production by ~end 2020.
- Delivery dates to CERN agreed upon and integrated in HL-LHC Master Schedule.