US-AUP RFD Dressed Cavities

Leonardo Ristori – Fermilab

With contributions from ANL, BNL, Jlab, ODU, SLAC

International Review of the Crab Cavity System – 19-21 June 2019 - CERN

v2

Outline

- Scope
- AUP Team
- RF Design
- Bare Cavity Fabrication Status
- Treatment-Testing Baseline & Validation
- Schedule and Upcoming US Reviews
- Status of Quality Assurance
- Acceptance Plan

Scope and Deliverables

- **Dressed RFD Crab Cavity**
  - **Project Scope includes 2 Prototypes + 2 Pre-Series + 10 Series**
  - Bare Cavities: In Industry with materials provided by FNAL
  - Bare Cavity Tests: Intermediate Qualification at FNAL at 2K
  - Jacketing: Bare Cavity + Magnetic Shields + Helium Tank in Industry
  - HOM Dampers: Fabrication at JLab
  - Dressed Cavity Tests: Final Qualifications at FNAL at 2K + RF Ancillaries
  - Delivery: 10 qualified dressed cavities

Functional Requirements Specification

US-HiLumi-doc-294

RF and Performance Requirements	
F (Resonant Frequency at 2 K)	400.790 ± 0.15 MHz
V_T (Deflecting Voltage)* at 2 K	≥ 4.1 MV
P_{dyn} (Dynamic Heat Load at 2 K and 4.1 MV)	≤ 10 W
Q_0 (Quality Factor at 2 K and 3.4 MV)**	≥ 3.9 10^9
LFD (Lorentz Force Detuning Coefficient)	≤ 865 Hz/MV²
**calculated from P_{dyn} (with R/Q = 429.7 Ω)	

Deflecting Voltage

$V_T \geq 4.1$ MV

20% margin for operation above nominal (3.4 MV)

Dynamic Heat Load

$P_{dyn} \leq 10$W (Limited by cryostat design)

Using: R/Q = 429.7 Ω and G = 106.7 Ω (from cavity shape)

Derived requirements: $R_{res} \leq 27$ nΩ and **$Q_0 \geq 3.9\ 10^9$**

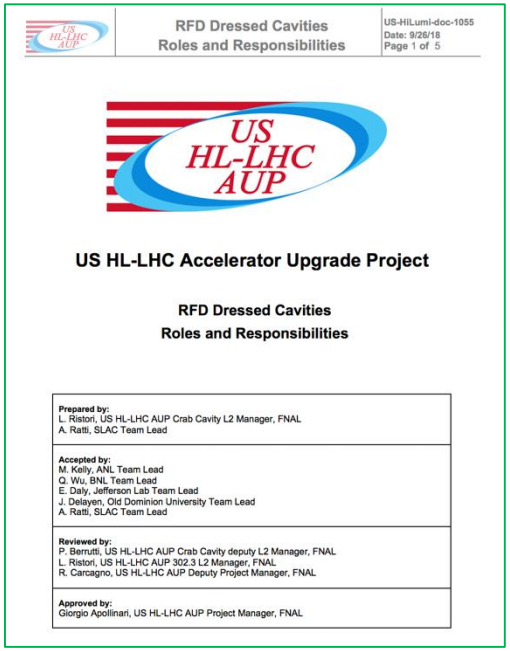
LARP prototype at FNAL exceeded requirements for V_t & Q_0

AUP Crab Cavity Collaboration

Institutions in alphabetical order

- Argonne National Laboratory (Processing):
  - Mike Kelly, Mark Kedzie, Tom Reid
- Brookhaven National Laboratory (Interfaces and MIPs):
  - Silvia Verdu Andres
- Fermilab (Procurements, Heat Treatments, Clean-Room Assembly, Cold Tests):
  - Paolo Berrutti, Manuele Narduzzi, Damon Bice, Alex Melnichuk
- Jefferson Lab (HOM Dampers Fabrication):
  - Naeem Huque
- Old Dominium University (General Oversight and RF measurements):
  - Jean Delayen, Subashini De Silva, HyeKyoung Park
- SLAC National Accelerator Laboratory (EM Design, Coordination):
  - Alessandro Ratti, Zenghai Li

US-HiLumi-doc-1055



Roles & Responsibilities Response to CD-1/3a recommendation

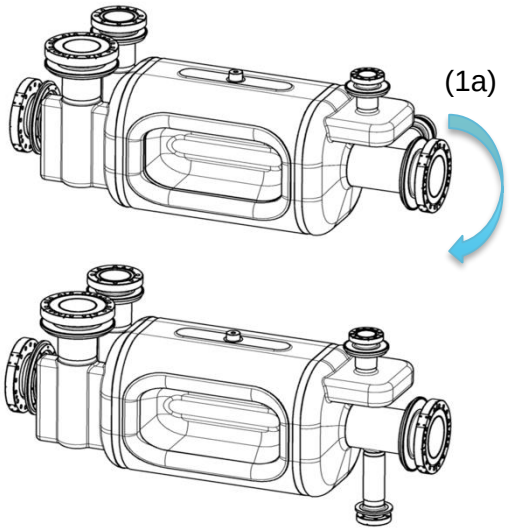
Comment from Preliminary Design Review

> The committee would like to point out that the collaboration between the partner laboratories and Fermilab seems to be very productive and the overall progress should be commended.

Roles & Responsibilities in AUP

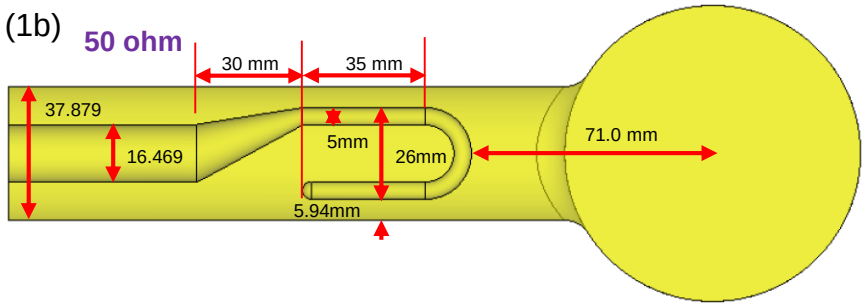
Activity	FNAL	SLAC	ODU	BNL	JLAB	ANL
Requirements and EM Design of the cavity and RF Ancillaries	Converge with CERN on functional requirements, interfaces, acceptance. Converge with CERN on EM Design.	Optimization of cavity system EM design to meet functional requirements. Study effects of manufacturing tolerances with respect to requirements. Provide models and documentation as deliverable to the project.	Cavity conceptual EM Design. Warm cavity Measurements in support of design decisions. Data analysis, troubleshooting, and verification of compliance with general system requirements.	Develop Interface control documents for the dressed cavity. Clarify interfaces between AUP and CERN's SM18, SPS, and LHC areas of operation as needed.	Contribute to cavity system requirements and EM design in order to develop qualification criteria for RF ancillaries.	
Cavity Mechanical Design and Fabrication	Converge with CERN on mechanical design of cavity. Issue POs with Industry for fabrication of cavities, magnetic shields, helium tanks.	Support activities by verifying compliance with modeling and requirements. Provide tolerances for fabrication of cavity.	Support quality control activities and cold measurements as needed.	Prepare Manufacturing Inspection Plans.		
RF Ancillaries Mechanical Design and Fabrication	Converge with CERN on requirements and mechanical design of HOM Dampers.	Provide manufacturing tolerances for HOM dampers.	Contribute to fabrication and qualification of HOM dampers through warm and cold measurements.		Contribute to RF, mechanical and thermal design of RF ancillaries. Prepare Manufacturing Inspection Plans. Fabricate and qualify RF ancillaries.	
Magnetic Shields Design and Fabrication	Design and build all magnetic shields. Test and measure for compliance with requirements.	Facilitate information exchange with CERN-UK.		Facilitate information exchange with CERN-UK.		
Bare and Dressed Cavity Qualifications	Coordinate the chemical processing and cold tests leading to final qualification and shipment.	Perform simulations as needed to verify compliance with requirements.	Support qualification activities, data analysis and troubleshooting of results.		Support qualification activities for RF ancillaries.	Develop rotational chemical processing. Perform chemical processing of all cavities.

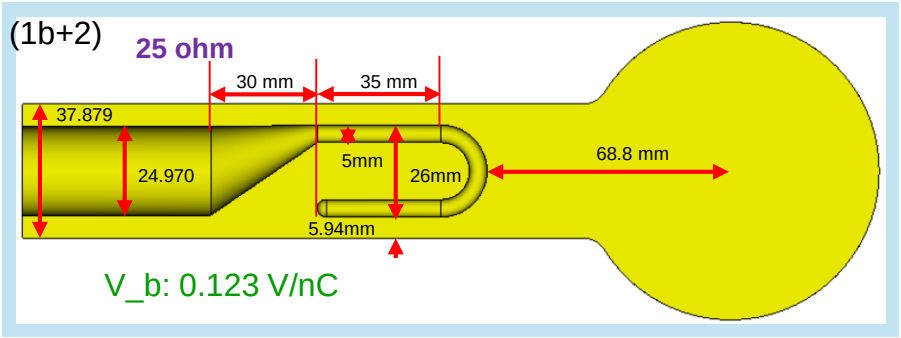
Recent RF design change

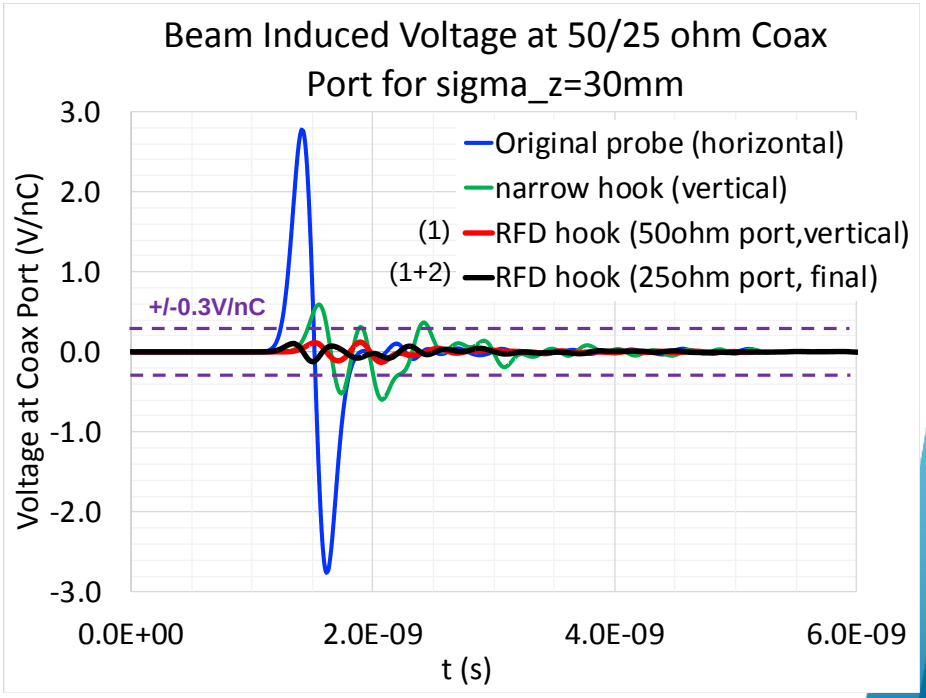


RF design change was necessary to address two issues:

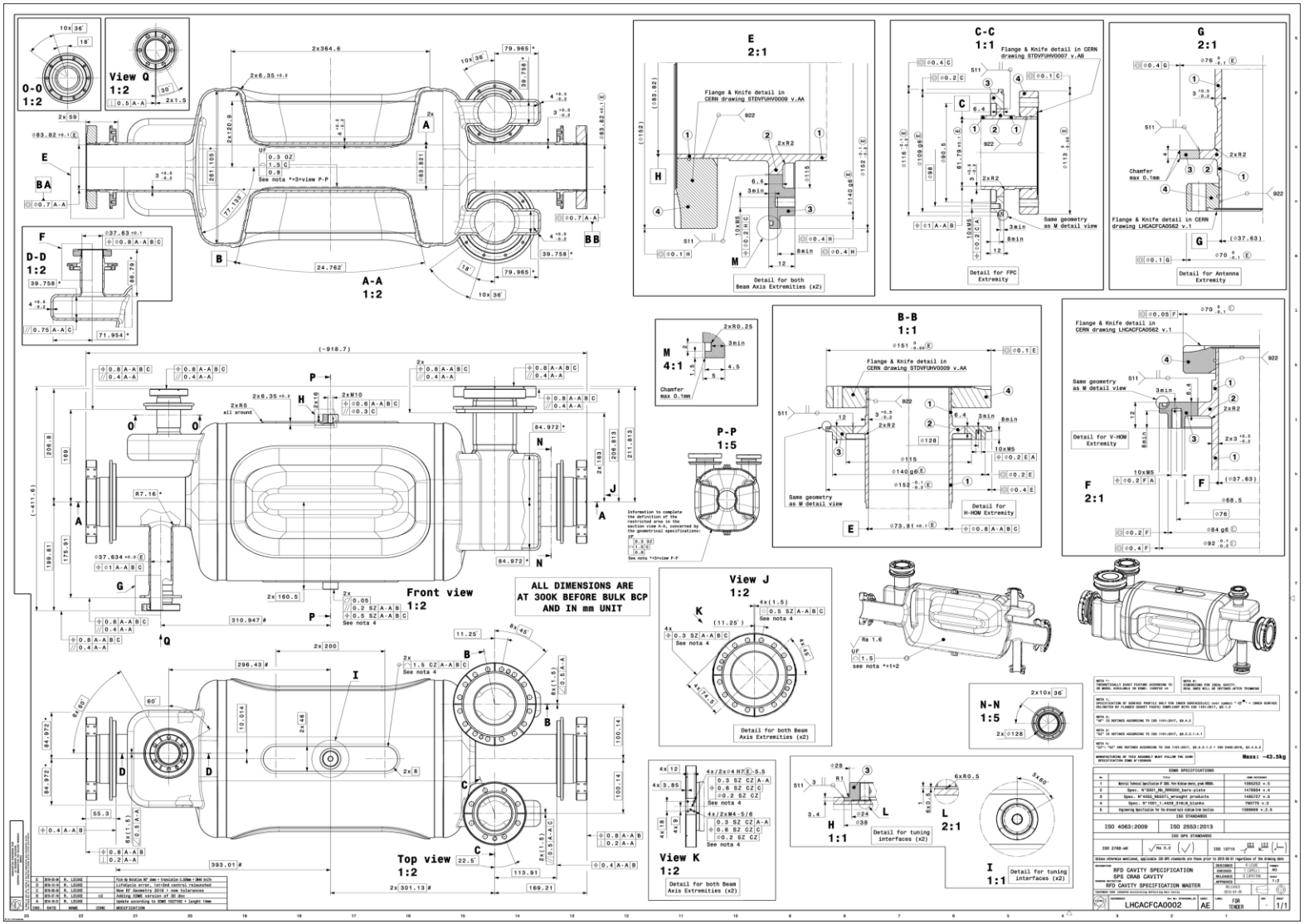
- (1) Excessive beam-induced voltage observed at CERN in SPS tests of similar crab cavity (DQW)
  - New requirement by CERN on beam coupling voltage $V_b < 0.3$ V/nC
  - (1a) Port rotated by 90 deg, (1b) implemented a hook design
- (2) Structural integrity of ceramic window subjected to transportation loads
  - (a) Increased inner diameter of ceramic 50 Ohm → 25 Ohm
  - (b) Adjusted overall length







Bare Cavity Specification Drawing



RFD Bare Cavity Material List

US-HiLumi-doc-668

- All materials contained in the deliverables, must meet CERN requirements
- Formal agreement between CERN and AUP on materials for bare cavities exists
  - RFD Bare Cavity Material List
  - EDMS 2001102 = US-HiLumi-doc-668
- All raw materials for prototype cavities is already on hand
- Raw materials for pre-series cavities are being procured shortly

Type of Raw Material	CERN Document and Edition	EDMS Document and version
RRR300 Nb Sheets	3300 ed.4	1095252 v.5
RRR300 Nb Bars & Plates	3301 ed.4	1476934 v.4
Nb55Ti	4055 ed.4	1485727 v.5
316LN	1001 ed.5	790775 v.3
OFE Cu	2001 ed.8	790779 v.6

EDMS NO. 2001102 | REV. 2.0 | VALIDITY VALID

REFERENCE : N/A

REPORT

RFD BARE CAVITY MATERIAL LIST

Abstract

This document provides the relevant material specifications that are applicable to the manufacturing of the RFD Bare Cavities.

TRACEABILITY

Prepared by: L. Ristori (AUP)	***Date:*** 09/11/2018
Verified by: O. Capatina, L. Dassa, H. Garcia Gavela	***Date:*** 14/11/2018
Approved by: R. Calaga	***Date:*** 16/11/2018
Distribution: HI-LUMI-LHC-WP4-MEMBERS	
Ref. Doc: Dressed Cavities Engineering Specification (EDMS 1389669)	

Rev. No.	***Date***	***Description of Changes*** *(major changes only, minor changes in EDMS)*
1.0	02/06/2017	First issue of the document
1.9	14/11/2018	New version with only the material specifications that are applicable to the RFD Cavities
2.0	16/11/2018	REV. 2.0 VALID

This document is uncontrolled when printed. Check the EDMS to verify that this is the correct version before use

Fabrication at Zanon

- PO placed Sep 2018 for bare cavities only
- Base quantity (2 proto) + options (12 series)
- Milestone payments for Prototypes:
  - 20% Fabrication Drawings ✓
  - 20% Forming tooling (imminent)
  - 30% Sub-components pre-trimming
  - 15% + 15% Delivered cavities
- Estimated deliveries of 2x prototypes
  - October 2019
  - December 2019

- Order for helium tanks not yet placed

Tooling at Zanon

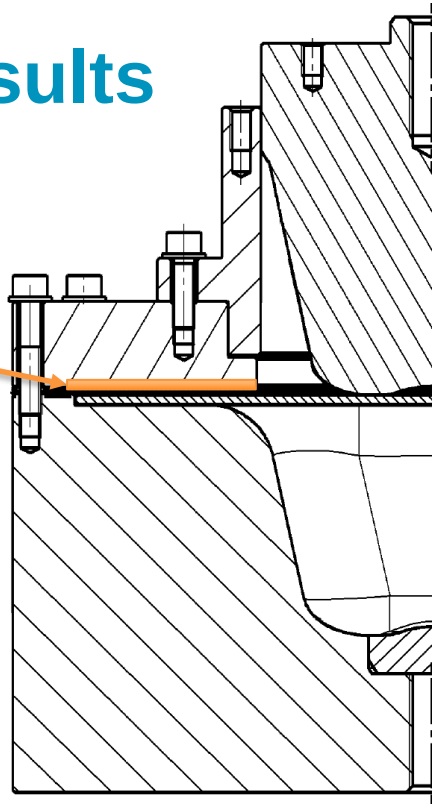
Fabrication Results: *Forming Tool Status*

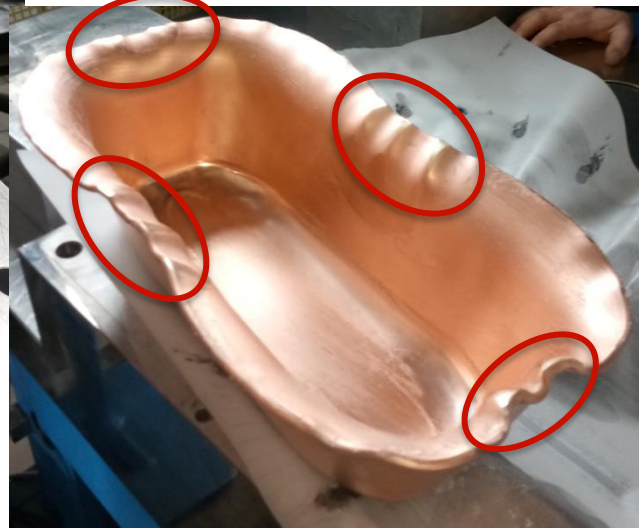
Subcomponents	Details	Status Machining	Tool Validation	Forming Tests
Corner	Pre-Forming	Ready	Ongoing	1 x Cu Test (Ongoing)
	Extrusion	Ready	Not tested	Not Available
	Stamping	Ready	Not tested	Not Available
Pole	Deep Drawing	Ready	Ongoing	3 x Cu Test Done
H-HOM	Box Forming	Ready	Ongoing	1 x Cu Test Done
V-HOM	Box Forming	Ready	Ongoing	1 x Cu Test Done
FPC	Box Forming	Ready	Ongoing	1 x Cu Test Done
End Cap	Forming	Not Ready	Not tested	Not Available
Main Body	Forming	Not Ready	Not tested	Not Available

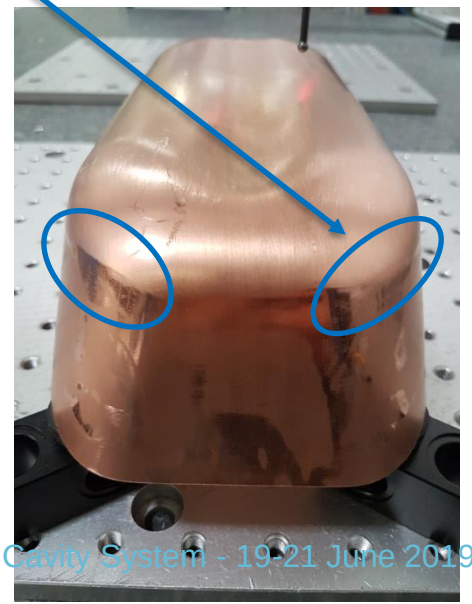
Corner, Pole & H-HOM Forming Tools components

Fabrication Results: Forming Results

- **Copper Pole Shaping**
  - First test: shape accuracy >1.8mm (distant from specification)
  - Wrinkles appears (friction between Cu and Brass)
    - Replace intermediate plate with **Bronze sheet**
  - Improvements in the Forming Procedure
    - **Benefits:** - Better shape accuracy
      - Min thickness >3.45
    - Updates adopted:
      - Increase deep drawing pressure
      - Trimming (+3mm on theoretical shape)
      - 3 x Stamping at 300bar (120 Ton)

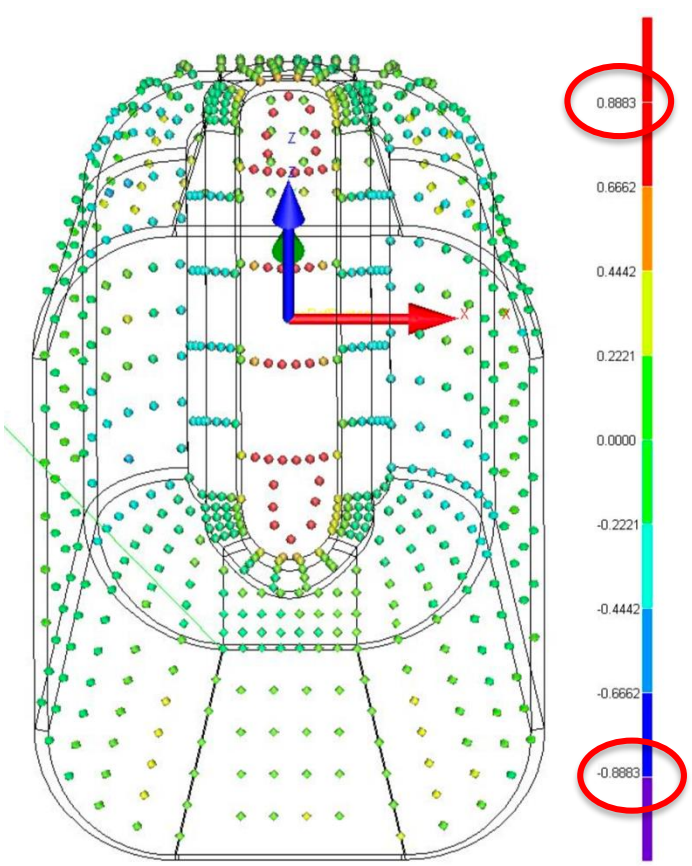




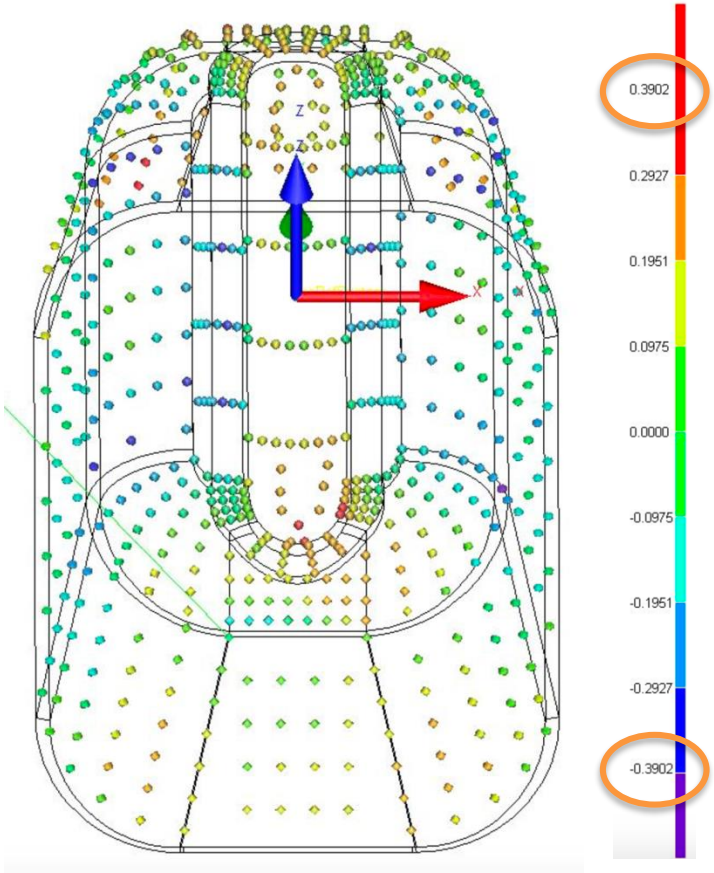


Fabrication Results: Forming Results

- **Copper Pole Metrology Results**
  - Shape accuracy after trimming: ~**1.8mm (±0.9mm)**
  - Shape accuracy after reshaping 300bar: encouraging ~**0.78mm (±0.39mm)**
  - Minimum thickness: 3.45mm (only local area)



Metrology after trimming

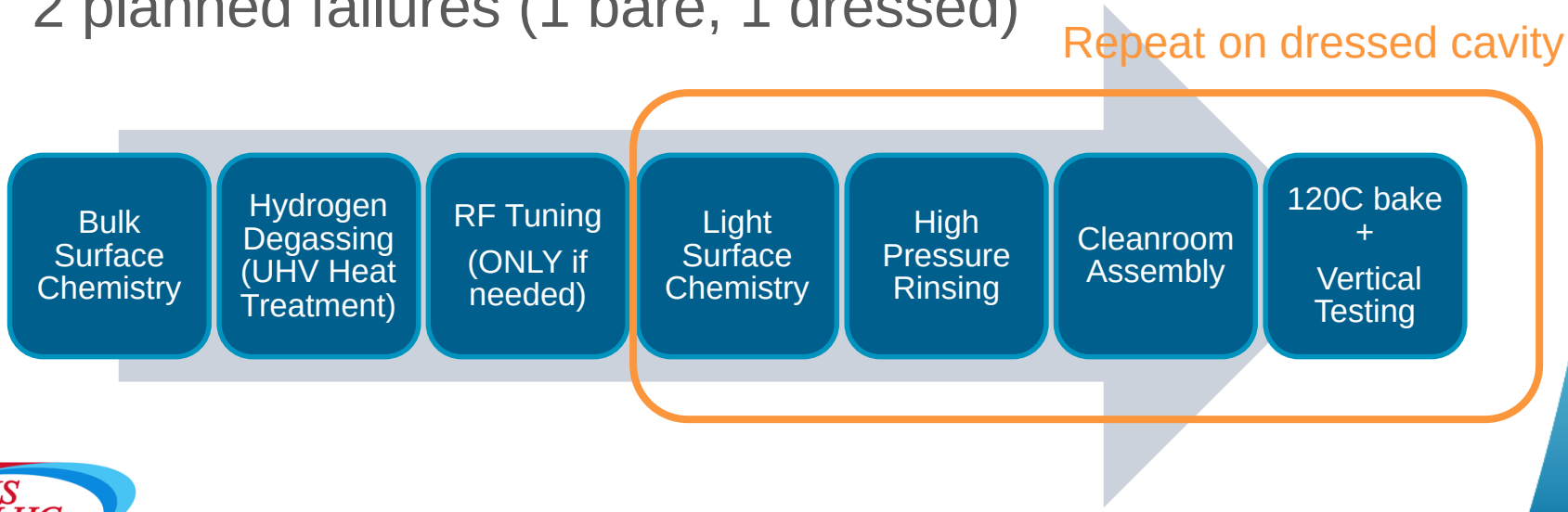


Metrology after final reshaping

US HL-LHC AUP

Processing-Testing Baseline

- All processing, heat treatments and testing will be performed at ANL and FNAL
- All bare cavities tested before & after jacketing
- Final test (jacketed) to include HOM dampers
- 50% reprocessing+re-testing rate for bare cavities and dressed cavities
- 2 planned failures (1 bare, 1 dressed)



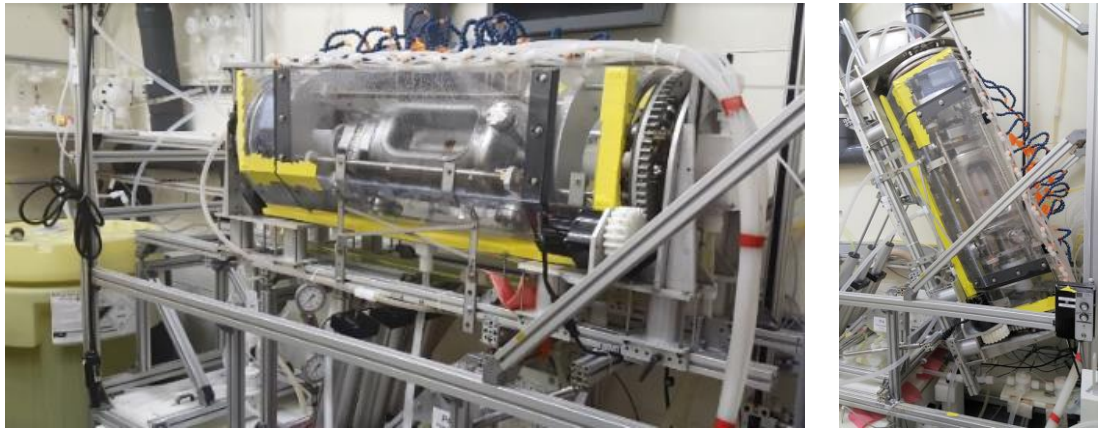
Summary of RFD Cold Tests

Test Date	Cavity #	Location	HHOM	VHOM	Max Voltage	Q at 4.1MV
2/12/2017	LARP RFD#1	JLab	☐	☐	4.04	1.60E+09
3/23/2017	LARP RFD#1	JLab	☐	☐	4.38	8.21E+09
6/2/2017	LARP RFD#2	JLab	☐	☐	5.75	1.13E+10
8/20/2017	LARP RFD#1	FNAL	☐	☐	4.70	1.10E+10
4/30/2018	LARP RFD#1	FNAL	☐	☐	3.54	N/A
5/8/2018	LARP RFD#2	JLab	☑	☑	4.77	1.22E+09
5/31/2018	LARP RFD#2	JLab	☑	☑	5.03	1.32E+09
6/13/2018	LARP RFD#1	FNAL	☐	☐	3.47	N/A
8/16/2018	LARP RFD#2	JLab	☑	☐	5.26	6.60E+08
10/9/2018	LARP RFD#2	JLab	☑	☐	4.18	1.08E+09
11/14/2018	LARP RFD#2	JLab	☑	☑	5.50	5.00E+09
11/28/2018	LARP RFD#2	JLab	☑	☑	5.50	7.35E+09
3/27/2019	LARP RFD#2	JLab	☑	☑	5.33	6.50E+09
5/2/2019	LARP RFD#1	FNAL	☐	☐	5.10	1.00E+10

- All 14 tests (with and w/o dampers) exceeded nominal voltage of 3.4MV
- Highest voltage achieved with dampers = 5.5 MV
- Highest Q_0 achieved at 4.1 MV with dampers = 7.3e9 (~2x requirement)

Rotational BCP + HPR Validation

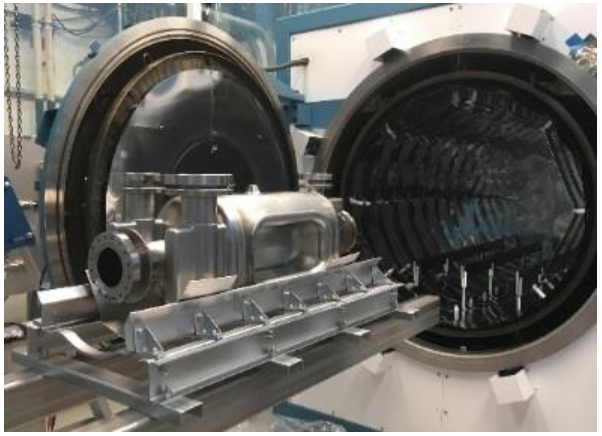
- RFD-LARP-001 has been **successfully tested at FNAL**, after undergoing full processing at APS-TD and ANL facilities: **processing and facilities validation is complete**
- New rotational Bulk & Light BCP
- 600 C degassing
- HPR and clean assembly
- 120 C bake
- VTS test



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

RFD HPR and Cleanroom Assembly (ANL/FNAL facility)

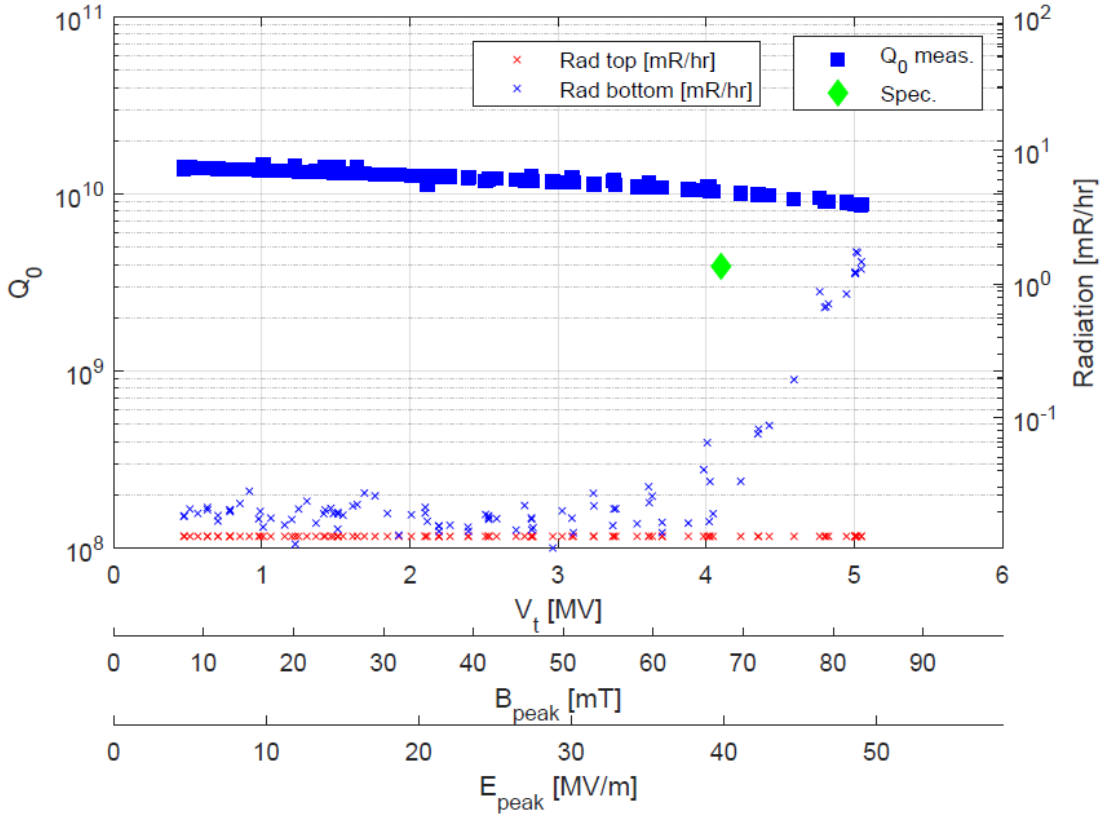
Heat Treatments + Cleanroom Assy Validation



600’C Heat Treatment (FNAL)

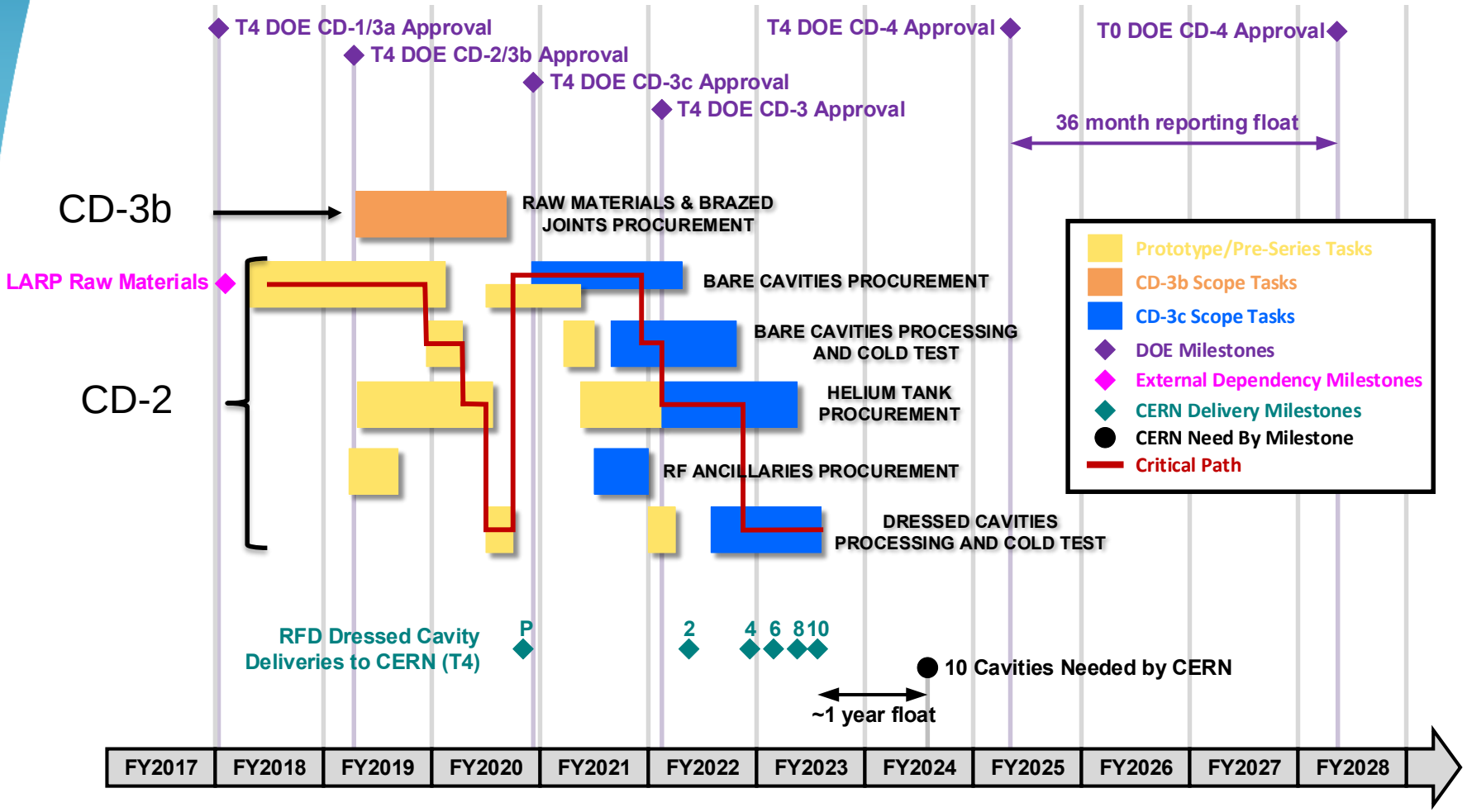
120’C Bake (FNAL)

VTS preparation (FNAL)



RFD-LARP-001 exceeded requirements for HL-LHC

Schedule


T4 DOE CD-1/3a Approval
T4 DOE CD-2/3b Approval
T4 DOE CD-3c Approval
T4 DOE CD-3 Approval
T4 DOE CD-4 Approval
T0 DOE CD-4 Approval
36 month reporting float
CD-3b
RAW MATERIALS & BRAZED JOINTS PROCUREMENT
LARP Raw Materials
BARE CAVITIES PROCUREMENT
BARE CAVITIES PROCESSING AND COLD TEST
CD-2
HELIUM TANK PROCUREMENT
RF ANCILLARIES PROCUREMENT
DRESSED CAVITIES PROCESSING AND COLD TEST
Prototype/Pre-Series Tasks
CD-3b Scope Tasks
CD-3c Scope Tasks
DOE Milestones
External Dependency Milestones
CERN Delivery Milestones
CERN Need By Milestone
Critical Path
RFD Dressed Cavity Deliveries to CERN (T4)
P
2
4 6 8 10
10 Cavities Needed by CERN
~1 year float
FY2017
FY2018
FY2019
FY2020
FY2021
FY2022
FY2023
FY2024
FY2025
FY2026
FY2027
FY2028

Delivery Dates

- AUP will launch 12 production dressed cavities, with the goal of 10 deliveries.
- Project baseline aims at “early delivery dates” below (already agreed between CERN and AUP).
- Delivery dates do not include the 2 prototypes (~ end 2020).
- Best use of prototypes is still under discussion. Once qualification at FNAL is successful, cavities could be used for prototype cryomodule integration.

RFD Dressed Cavities

	Early Delivery Date	Late Delivery Date
	HL project schedule	US project schedule
HCACFDC002-UP000001	July 2022	June 2023
HCACFDC002-UP000002	July 2022	June 2023
HCACFDC002-UP000003	September 2022	September 2023
HCACFDC002-UP000004	September 2022	September 2023
HCACFDC002-UP000005	November 2022	December 2023
HCACFDC002-UP000006	November 2022	December 2023
HCACFDC002-UP000007	January 2023	February 2024
HCACFDC002-UP000008	January 2023	February 2024
HCACFDC002-UP000009	March 2023	May 2024
HCACFDC002-UP000010	March 2023	May 2024

Upcoming Reviews

- Procurement Readiness Review (Raw Materials) – Oct 2019
  - Need feedback from successful prototype cavity fabrication (thickness tolerance of sheets, sizes of blanks, types of blanks,..)
  - Necessary for placing orders for materials for series bare cavities
- Final Design Review (Dressed Cavities) – Feb 2020
  - Need design at > 90% plus qualification of cavity prototypes
  - Necessary for launching 2 bare cavity pre-series in April 2020 and later seek DOE approval for everything else.
- CD-3c – June 2020
  - Need successful Final Design Review, a number of key documents (e.g. interface control and acceptance criteria)
  - Approval for construction of series hardware

Quality Assurance

- For each procedure required by CERN, AUP is uploading in EDMS a draft for approval
- Approval process is managed in EDMS. Despite being still at the prototype phase, certain AUP procedures for bare cavity fabrication are already approved
- Plan is for AUP to use MTF for all qualification and production data for pre-series and series cavities
- Convergence on procedures is needed before April 2020 when bare cavity pre-series are launched

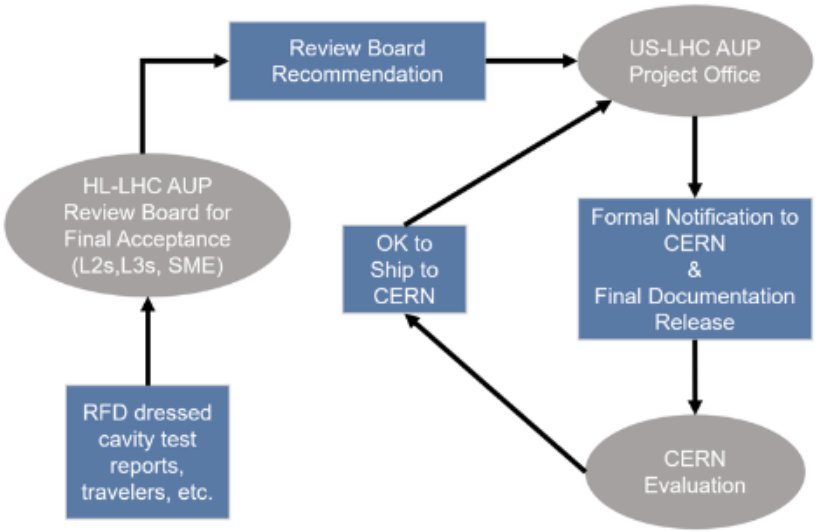
QA documentation tracking

CERN requirements				AUP QA Documents			
No.	EDMS document	EDMS number	EDMS Description	AUP Procedure	AUP Title/ Description	Revision	Rev. Date
1	NA	NA	NA	3326.E.001	Document List	2	14/5/2019
2	NA	NA	NA	3326.P.001	Time Schedule		3/19/19
3	NA	NA	NA	3326.S.007	Packing Procedure	0	NA
4	Specification	2067770	LHC-ACFCA-CI-0001 (v1.0) Technical Specification for RFD Bare Cavities production	RFD Bare Cavity Fabrication	US HL-LHC AUP -Technical Specification Supply of RFD Cavities (US-HiLumi-doc-803)	0	2/23/18
5		2001102	List of Materials RFD Bare Cavity	RFD Bare Cavity Material List V7	RFD Bare Cavity Material List V7	2	11/16/18
6	Drawings & 3D Models	2080712	Manufacturing Drawings RFD Bare Cavities	3326.1.000.000 manfacturing drawings	RFD Crab Cavity Drawings Package	0	12/5/18
7		2080713	Manufacturing Drawings Tooling BCs	Not yet available	NA	NA	NA
8	Documentation Prior to manufacturing	2080715	Welding map	3326.W.001	Welding Book - section 1 Welding Map	0	12/18/18
9		2080716	Welding procedures qualification record (WPQR)	3326.W.001	Welding Book - section 3 Test Coupon		12/18/18
10		2080717	Welding procedure specification (WPS)	3326.W.001	Welding Book - section 2 WPS		12/18/18
11		2080719	Welding operator performance qualification (WOPQ)	3326.W.001	Welding Book - Section 4 Welding Operators		12/18/18
12		2080723	Non-destructive Test personnel qualification	To Be Defined (see notes)	NA		NA
13		2100570	Welding Book	3326.W.001	Welding Book - section 1-4		12/18/18
14	MIP and Procedures	2069490	Manufacturing Inspection Plan - MIP	3326.F.001	Quality Control Plan - RFD Crab Cavities prototypes	2	8/5/19
		NA	Manufacturing Inspection Plan - MIP	3326.F.002	Quality Control Plan - Deep drawing of copper foils	0	8/5/19
15		2069492	Cleaning and Etching Procedure	3326.S.004	Cleaning & Chemical Etching	0	10/23/18
17		2069496	Identification, Marking and Traceability Procedure	3326.S.001	Identification, Marking, Traceability	1	1/30/19
18		2069497	Procedure for Radiographic Examination of Welds	3326.S.005	Radiographic Examination (RT)	1	1/28/19
19		2069497	Procedure for Radiographic Examination of Welds	20190121_Radiographic__Tests_Extent	Radiographic Test Extent	0	1/28/19
20		2080726	Manufacturing procedures	3326.S.008	Manufacturing Sequence	0	11/28/18
21		2080731	HPWR procedure	Not yet available	NA	NA	NA
22		2080734	Heat Treatment Procedure	Not yet available	NA	NA	NA
16		2080830	BCP Procedure	3326.S.004	Cleaning & Chemical Etching	1	8/5/19
23		2080831	Leak Test procedure	3326.S.006	Helium Leak (LT)	0	2/19/19
24		2080832	UT Procedure	Not yet available	NA	NA	NA
25		2080833	RF measurements & Trimming Procedure	Not yet available	NA	NA	NA
26		2080834	Dimensional Control Procedure	3326.S.002	Dimensional Control	0	1/28/19
27		2080835	Pressure Test Procedure	Not yet available	NA	NA	NA
28		2100569	Visual Testing	3326.S.003	Visual Inspection (VT)	1	8/5/19
29	Qualifications	2080739	Documentation of welding samples	Not yet available	NA	NA	NA
30		1999885	Brazing qualifications for the transition joints used in the fabrication of the prototype RFD cavities by Fermilab	Brazing qualifications for the transition joints used in the fabrication of the prototype RFD cavities by Fermilab	BPS_ANL-Nb To SS test coupon-Joint Design for BPS workmanship- BOPQ- BPQR- BP- Report ANL- MSLD procedure- Material Certificates- Leak Check coupon	0	10/25/18
31	Material Traceability	2080735	Traceability Sheets for BCs	Not yet available	NA	NA	NA
32		2135589	Material certificate TO20190126 with UT reports from Ningxia for AUP prototypes	Material Certificate UT Ningxia	Material certificate TO20190126 with UT report	0	4/5/19
33	Manufacturing Records	1876981	Materials for Protos	Nb and NbTi material certifications and test reports - Fermilab prototype RFD cavities	RRR 300 Nb sheet certificate, TO20170267-Fermilab, TO20170268-Fermilab, Niobium Sheet Thickness Measurements, UT reports (from ATS)	0	11/28/17

Acceptance of RFD cavities (Draft)

Acceptance Plan (#1744)

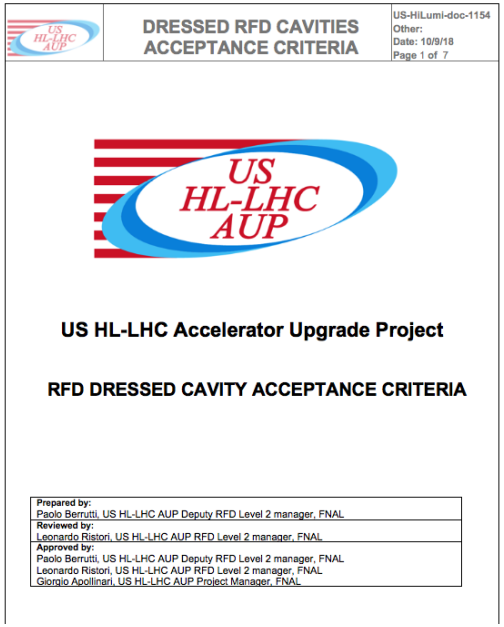
Describes the process for acceptance between AUP and CERN, including OK to ship from CERN, and final checks after receiving



Acceptance Criteria (#1154):

Discussions with CERN continuing towards a final version

Details of how each measurement is performed to verify compliance with functional requirements, and more.


DRESSED RFD CAVITIES ACCEPTANCE CRITERIA

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Date: 10/9/18
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US HL-LHC AUP

US HL-LHC Accelerator Upgrade Project

RFD DRESSED CAVITY ACCEPTANCE CRITERIA

Prepared by:
Paolo Berrutti, US HL-LHC AUP Deputy RFD Level 2 manager, FNAL
Reviewed by:
Leonardo Ristori, US HL-LHC AUP RFD Level 2 manager, FNAL
Approved by:
Paolo Berrutti, US HL-LHC AUP Deputy RFD Level 2 manager, FNAL
Leonardo Ristori, US HL-LHC AUP RFD Level 2 manager, FNAL
Giorgio Apollinari, US HL-LHC AUP Project Manager, FNAL

US HL-LHC AUP

Summary

- Design of bare cavity was recently modified after SPS experience at CERN, and adopted for prototypes at Zanon
- Contract with Zanon is progressing according to plans. Includes 2 prototypes + 2 pre-series + 10 series
- ANL/FNAL Facilities, tooling and procedures for processing, heat treatment, cleanroom assembly and cold tests were recently validated thanks to LARP prototypes
- Delivery of qualified dressed cavities is expected to be complete by March 2023. Prototype dressed cavities will be completed at the end of 2020 and could be used to validate cryomodule integration at TRIUMF
- Compliance with CERN QA is defined, tracked and must continue towards a convergence in early 2020
- Acceptance plan is taking shape but still in draft form with a deadline in mid 2020