



## **RFD Crab Cavity Contribution from the U.S. *Recent Progress and Plans***

Leonardo Ristori – Crab Cavity L2 Manager, Fermilab  
*With input from: ANL, BNL, JLAB, ODU, SLAC*

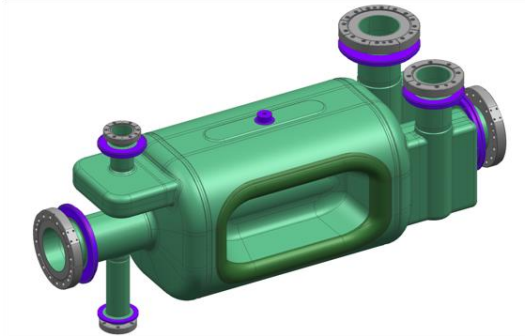
9<sup>th</sup> HL-LHC Collaboration Meeting – Fermilab 14<sup>th</sup>-16<sup>th</sup> October 2019



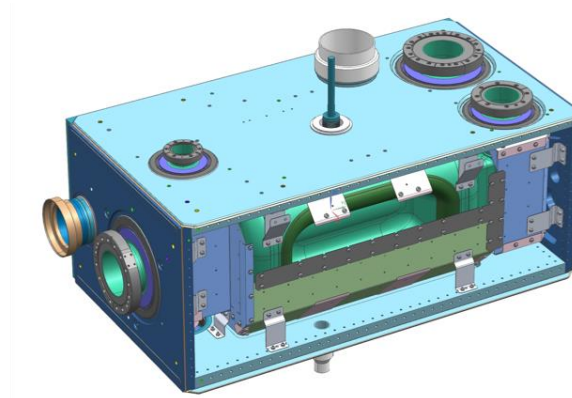
# Outline

- Scope and Deliverables
- RF Design Iterations by AUP
- Technical Achievements and Validations of 2019
- Cavity Prototype Fabrication at Zanon
- Immediate Needs
- Schedule
- Quality Assurance
- Acceptance Plan
- Goals for 2020
- Topics for discussion

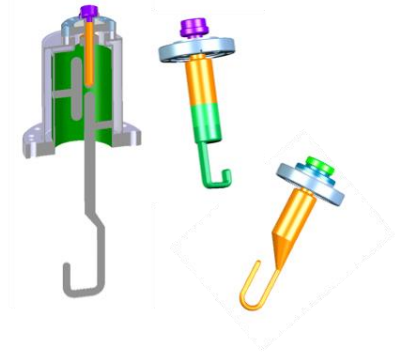
# Scope and Deliverables



Bare RFD Cavity



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



RF Ancillaries

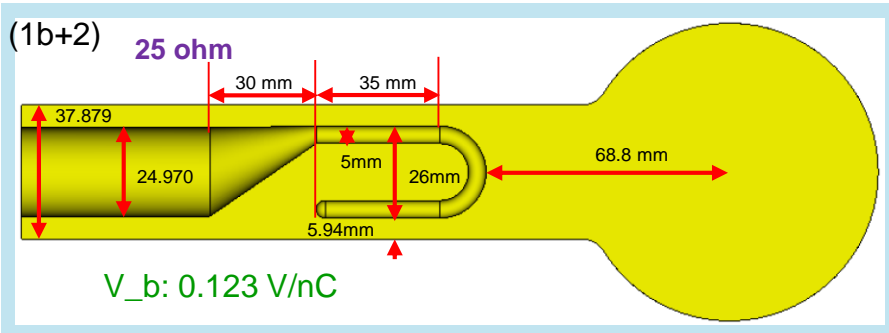
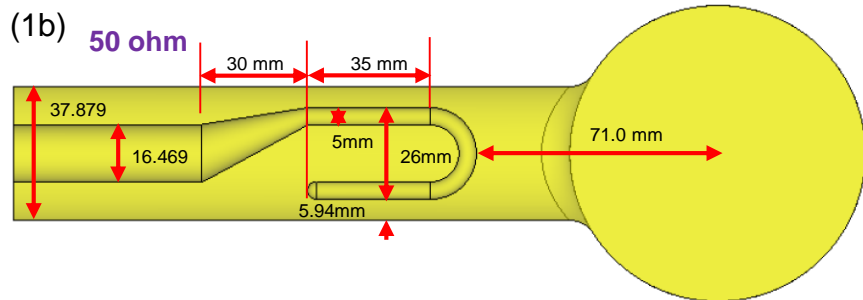
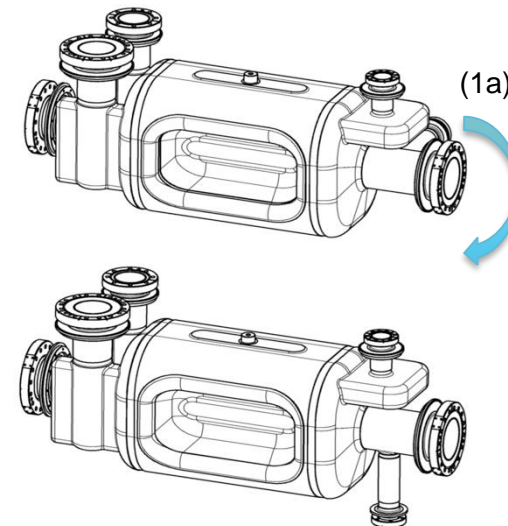
- **Dressed RFD Crab Cavity**

- **Project Scope includes 2 Prototypes + 2 Pre-Series + 10 Series**
- Bare Cavities: Intermediate Qualification at FNAL at 2K
- Integration: Bare Cavity + Magnetic Shields + Helium Tank + RF Ancillaries
- Dressed Cavities: Final Qualification at FNAL at 2K + RF Ancillaries
- Delivery: 10 qualified dressed cavities (mix of pre-series + series)

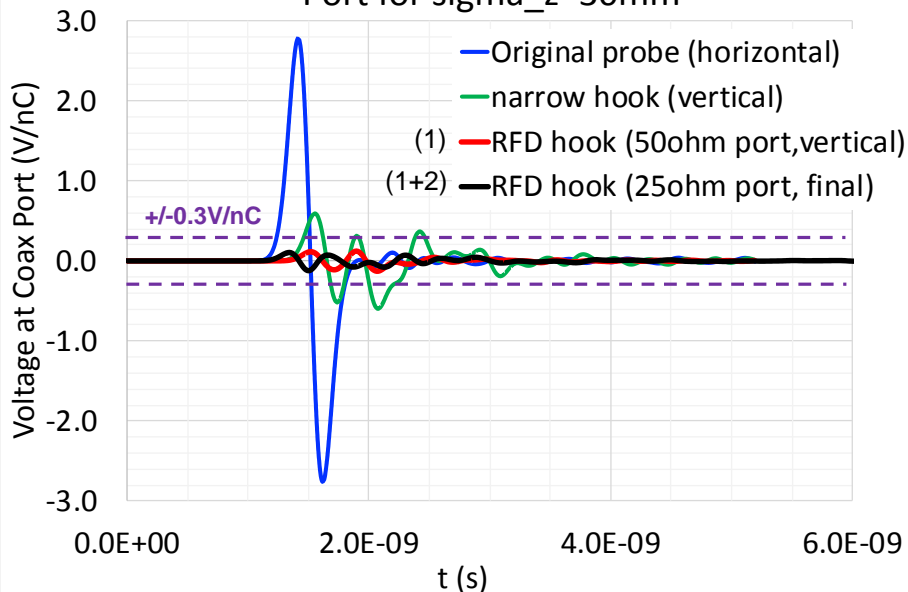
# Recent RF design change

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  $V_b < 0.3 \text{ V/nC}$
  - (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  $\rightarrow$  25 Ohm
  - (b) Adjusted overall length



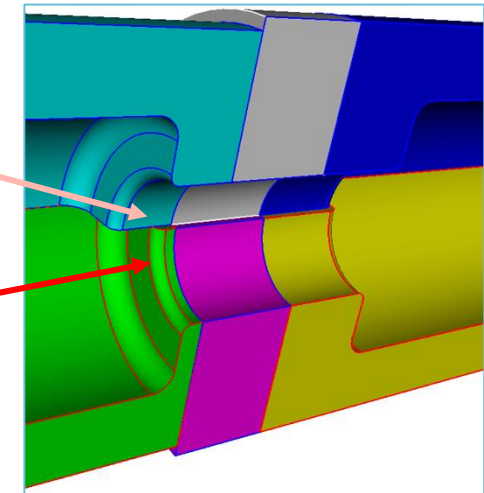
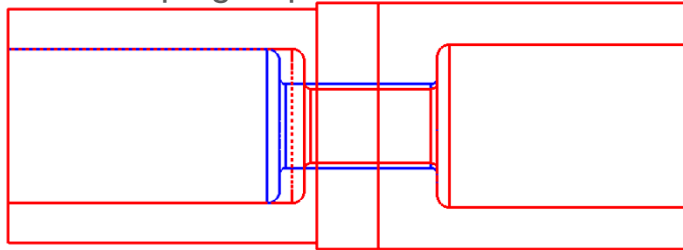
Beam Induced Voltage at 50/25 ohm Coax Port for  $\sigma_z=30\text{mm}$



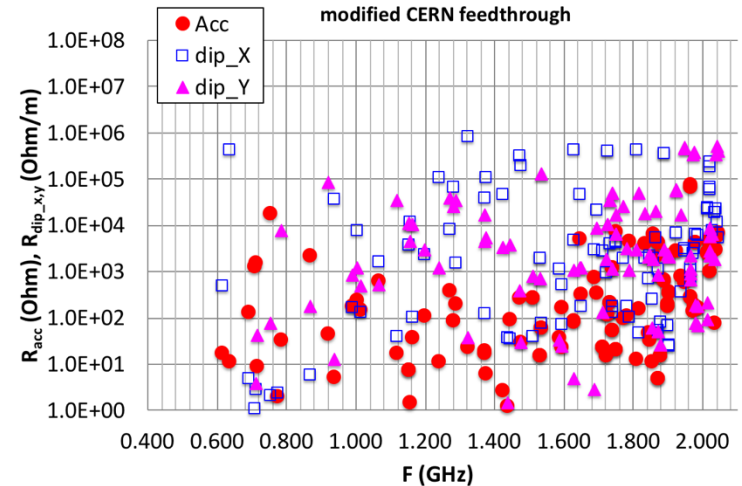
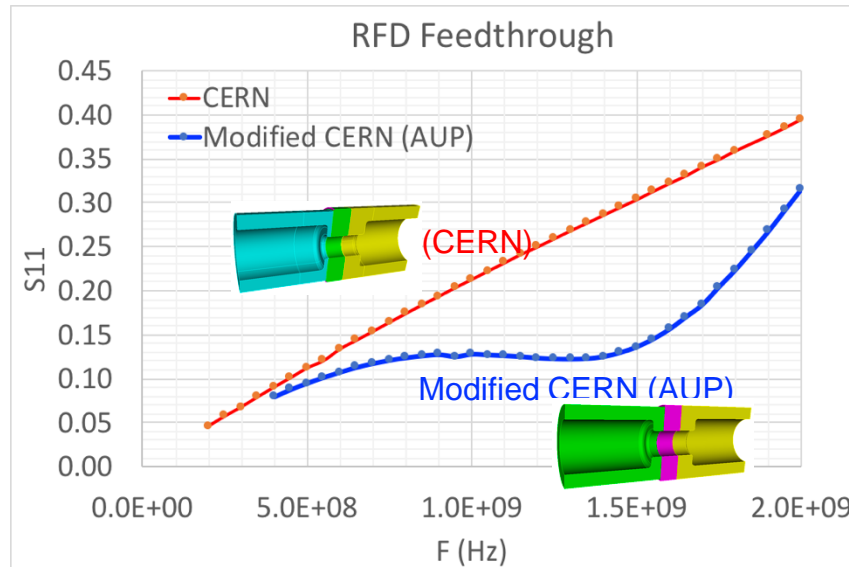
# Design of Feedthrough for Dampers

HOMs feed-thrus RF design change 50 Ohm  $\rightarrow$  25 Ohm :

- The change has been implemented to reduce transportation risks, increasing structural stiffness of the ceramic at the RF vacuum-RF lines interface.
- CERN and AUP have converged on a design.
- HOMs damping requirements are still satisfied.



dyjoint: 5 mm, dyhook: 0mm  
modified CERN feedthrough



# Summary of RFD Cold Tests

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

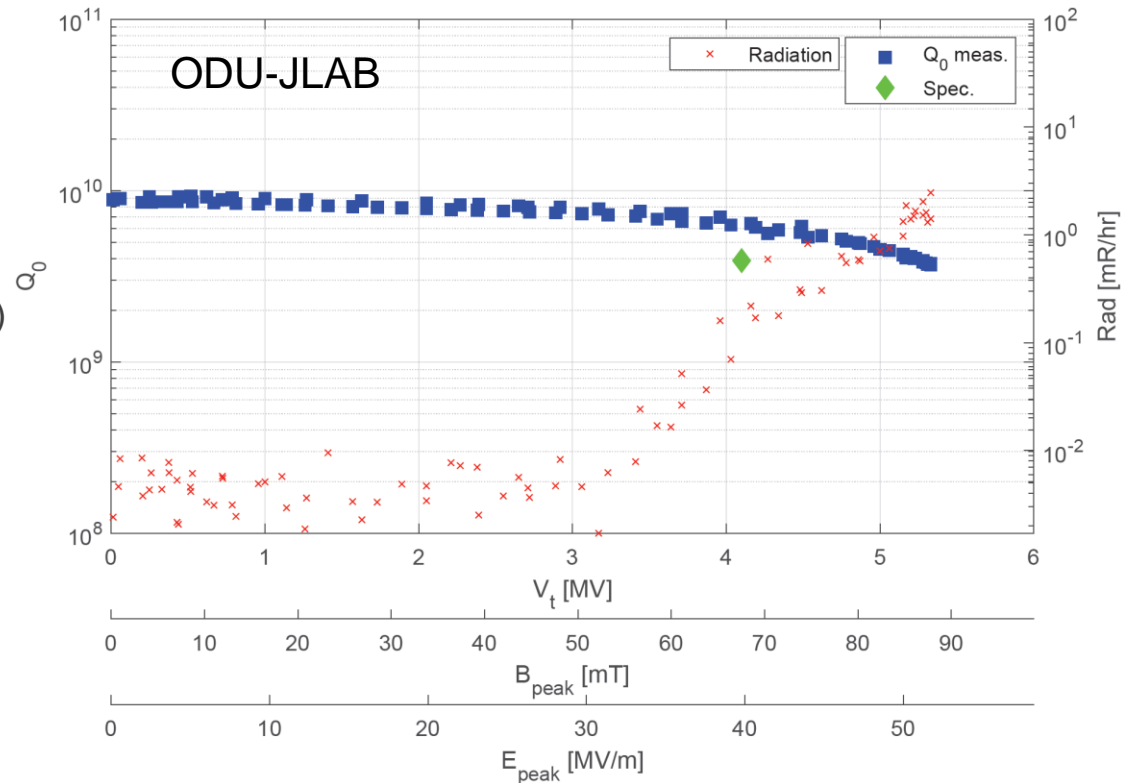
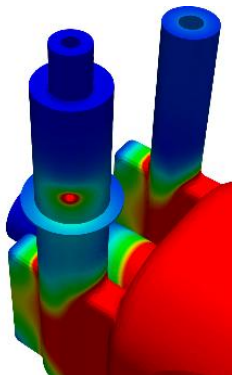
- All 14 tests (with and w/o dampers) exceeded nominal voltage of 3.4MV
- Highest voltage achieved with dampers = 5.5 MV
- Highest  $Q_0$  achieved at 4.1 MV with dampers =  $7.3e9$  (~2x requirement)

# RFD cavity + HHOM and VHOM validation

- RFD2 cavity has been successfully tested with all RF ancillaries.
- HHOM RF leakage has been resolved  $Q_0$  exceeds requirement, quench  $V_t$  is 5.3 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)





# 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



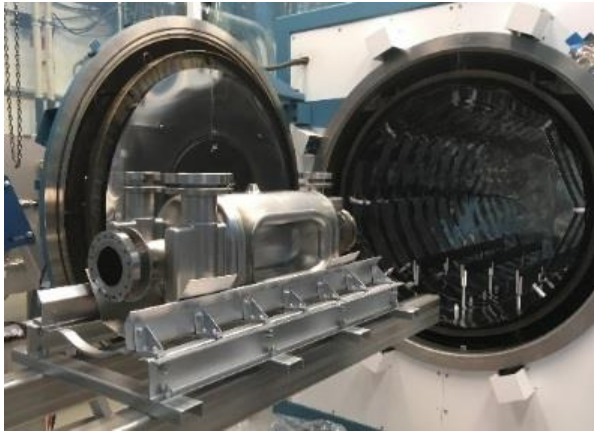
Rotational BCP tool for RFD cavity (ANL/FNAL facility)



RFD HPR and Cleanroom Assembly (ANL/FNAL facility)



# Heat Treatments + Cleanroom Assy Validation



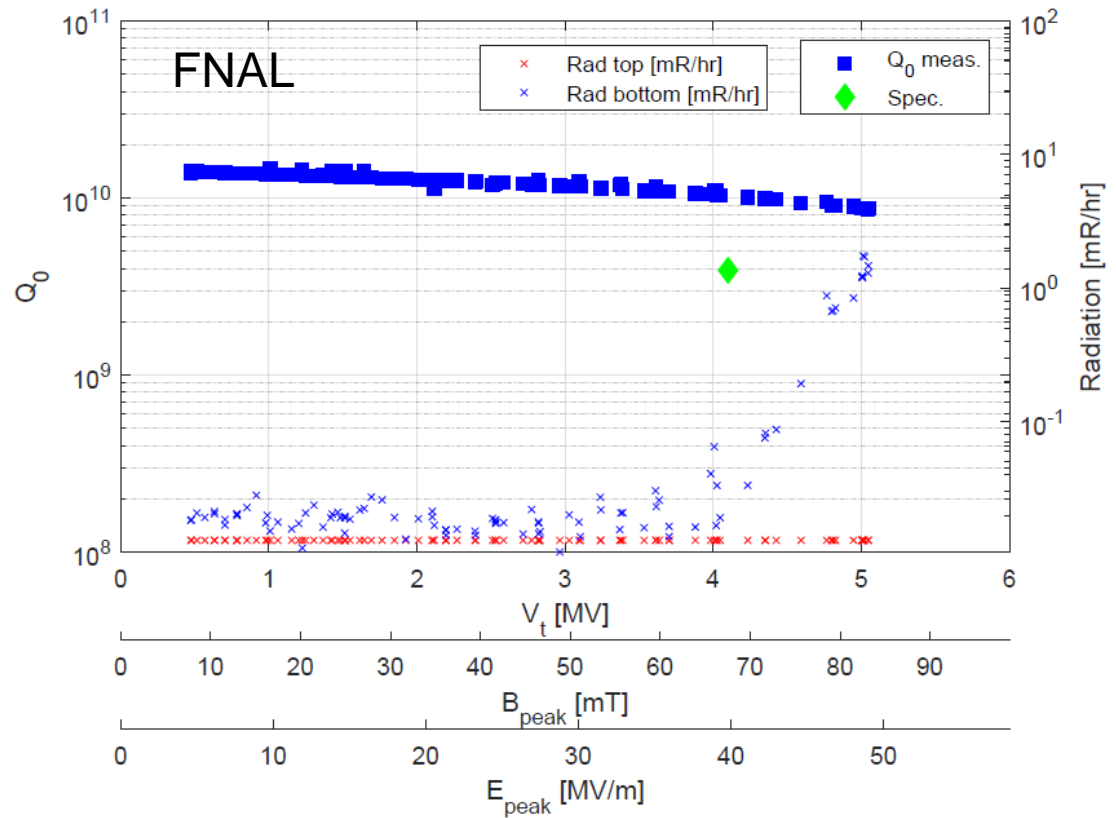
600°C Heat Treatment (FNAL)



120°C Bake (FNAL)



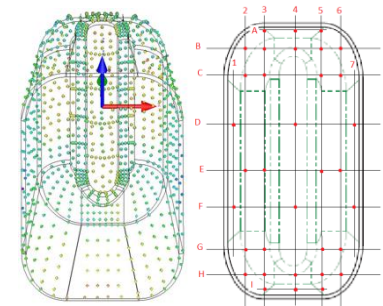
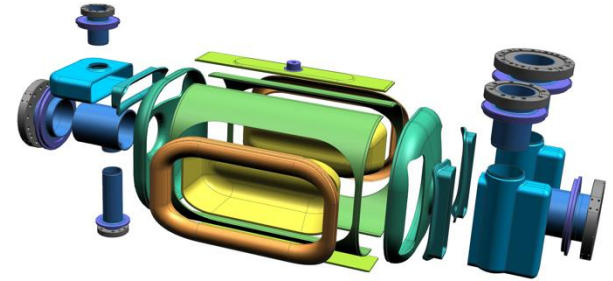
VTS preparation (FNAL)



RFD-LARP-001 exceeded requirements for HL-LHC

# Fabrication at Zanon

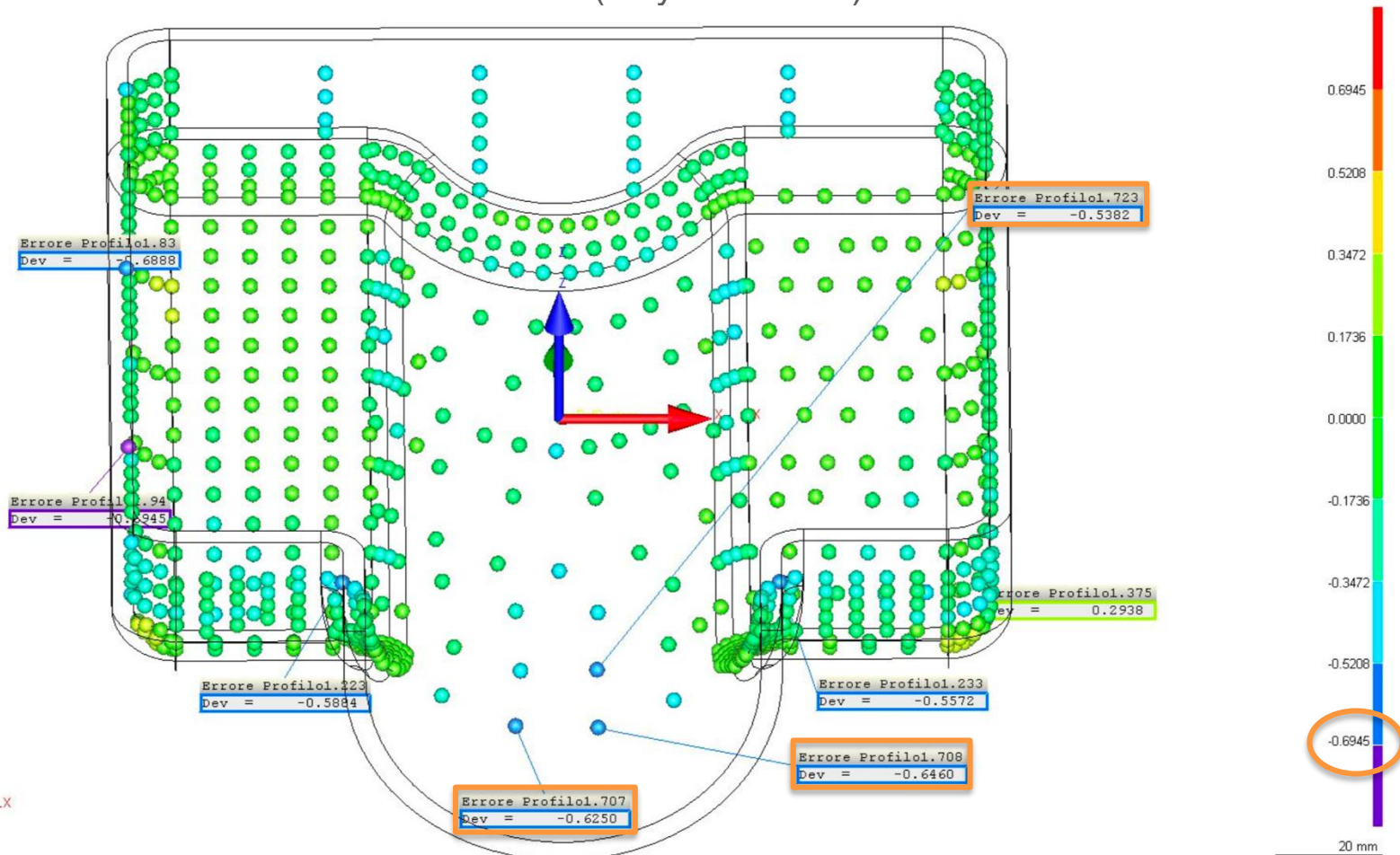
- PO placed Sep 2018 for 2 Proto bare cavities
- Milestone payments for Prototypes:
  - 20% Fabrication Drawings ✓□
  - 20% Forming tooling ✓□
  - 30% Sub-components pre-trimming (in-progress)
  - 15% each delivered cavity
- Estimated deliveries of 2x prototypes
  - March 2020
  - April 2020



# Fabrication Results: *Waveguide Boxes Forming Results*

## ■ Copper H-HOM Box Metrology Results

- Shape accuracy after reshaping 300bar:
  - Flat surfaces encouraging  $\sim 0.7\text{mm}$  ( $\pm 0.35\text{mm}$ ) shape accuracy
  - Tube interface area to be improve by calibration  $\sim 1.3\text{mm}$  ( $\pm 0.65\text{mm}$ ) shape accuracy
- Minimum thickness:  $3.85\text{mm}$  (only local area)

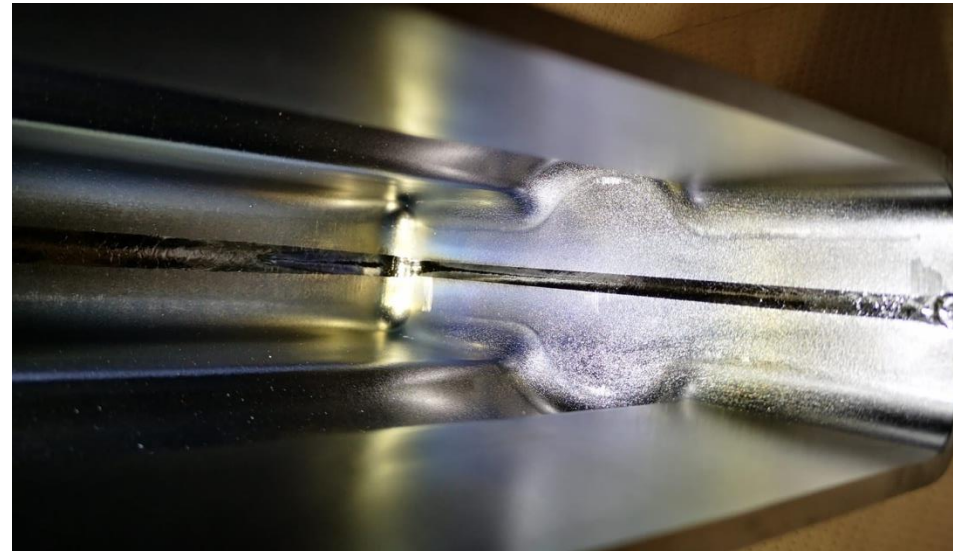
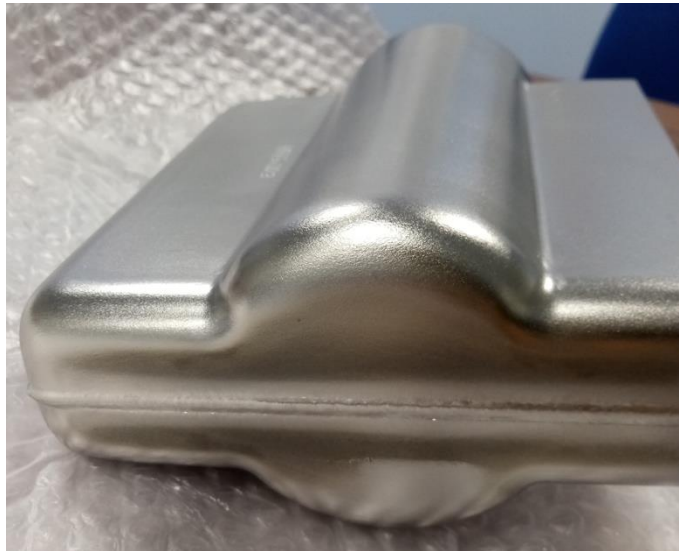




# Fabrication Results: *Waveguide Boxes Forming Results*

## ■ H-HOM Boxes: EBW

- ❖ No official fixture used
  - tight schedule need creativity!
- ❖ Metrology ongoing
- ✓ External weld bead is homogeneous and clean
- ✓ RF side: smooth and constant welding width
- ✓ No undercut
- ✓ No excessive penetration
- ✓ No misalignments
- ✓ No sagging



# Immediate Needs

- Drawings for Magnetic Shields and Helium Tank
  - Mechanical Design is CERN responsibility and recently complete
  - Drawings needed by AUP and will be used for launching prototypes only
- Converge on frequency shift estimates for prototypes
  - Necessary to define frequency goal at supplier
  - Frequency as-built is different from frequency in operation
- Converge and approval of revision of Functional Requirement Specification before end of 2019
  - Clarification and addition of certain requirements
- Address (together) open recommendations collected by AUP at past reviews

# Delivery Dates

- 2 Bare Cavity prototypes are delayed at supplier
- Zanon recently split in two independent companies. Before the maneuver, it experienced several months of “financial-freeze” which caused a delay for all outsourced work. Currently all business as usual, but ~4 month delays were accumulated.
- As of now, no effect foreseen for launching bare cavity pre-series (April 2020) and series (end of 2020)
- Final delivery dates of 10 dressed cavities remain unchanged (July 2022 – March 2023)

	Early Delivery Date	Late Delivery Date
RFD Dressed Cavities		
	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



# 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

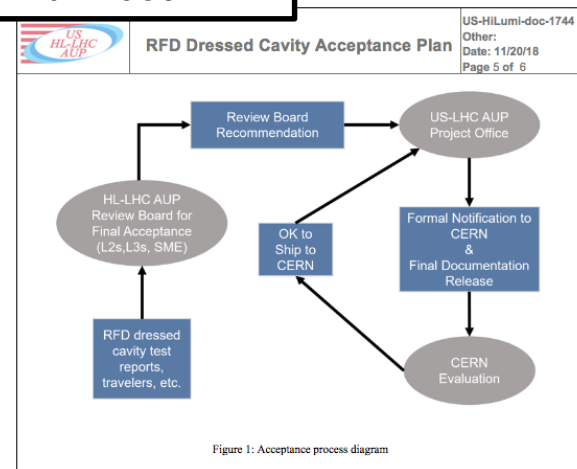
# QA documentation tracking

CERN requirements				AUP QA Documents				CERN Comments		FNAL reply	
No.	EDMS document	EDMS number	EDMS Description	AUP Procedure	AUP Title/ Description	Revision	Rev. Date	EDMS	Date	EDMS	Date
1	NA	NA	NA	3326.E.001	Document List	2	14/5/2019	NA	NA	NA	NA
2	NA	NA	NA	3326.P.001	Time Schedule		3/19/19	NA	NA	NA	NA
3	NA	NA	NA	3326.S.007	Packing Procedure	0	NA	NA	NA	NA	NA
4	Specification	2067770	Specification for RFD Bare Cavities	RFD Bare Cavity Fabrication	US HL-LHC AUP - Technical Specification Supply of RFD Cavities (US-HILumi-doc-803)	0	2/23/18	2080289	1/22/19	2143873	4/26/19
5		2001102	List of Materials RFD Bare Cavity	RFD Bare Cavity Material List V7	RFD Bare Cavity Material List V7	2	11/16/18	NA	NA	NA	NA
6	Drawings & 3D Models	2080712	Manufacturing Drawings RFD Bare Cavities	3326.1.000.000 manufacturing drawings	RFD Crab Cavity Drawings Package	0	12/5/18	2113614	3/18/19	2143872	4/26/19
7		2080713	Manufacturing Drawings Tooling BCs	Not yet available	NA	NA	NA	NA	NA	NA	NA
8		2080715	Welding map	3326.W.001	Welding Book - section 1 Welding Map		12/18/18	2113654	3/20/19	2143870	4/26/19
9		2080716	Welding procedures qualification record (WPC)	3326.W.001	Welding Book - section 3 Test Coupon		12/18/18	2113654	3/20/19	2143870	4/26/19
10	Documentation Prior to	2080717	Welding procedure specification (WPS)	3326.W.001	Welding Book - section 2 WPS	0	12/18/18	2113654	3/20/19	2143870	4/26/19
11		2080719	Welding operator performance qualification (WOP)	3326.W.001	Welding Book - Section 4 Welding Operators		12/18/18	2113654	3/20/19	2143870	4/26/19
12		2080723	Non-destructive Test personnel qualification	To Be Defined (see notes)	NA		NA	NA	NA	NA	NA
13		2100570	Welding Book	3326.W.001	Welding Book - section 1-4		12/18/18	2113654	3/20/19	2143870	4/26/19
14		2069490	Manufacturing Inspection Plan - MIP	3326.F.001	Quality Control Plan - RFD Crab Cavities prototypes	2	8/5/19	2079935	1/22/19	2143869	4/26/19
		NA	Manufacturing Inspection Plan - MIP	3326.F.002	Quality Control Plan - Deep drawing of copper foils	0	8/5/19	NA	NA	NA	NA
15		2069492	Cleaning and Etching Procedure	3326.S.004	Cleaning & Chemical Etching	0	10/23/18	2114426	3/20/19	2143871	4/26/19
17		2069496	Identification, Marking and Traceability Procedure	3326.S.001	Identification, Marking, Traceability	1	1/30/19	2069496	3/20/19	NA	NA
18		2069497	Procedure for Radiographic Examination of W	3326.S.005	Radiographic Examination (RT)	1	1/28/19	2079949	1/22/19	2143867	4/26/19
19		2069497	Procedure for Radiographic Examination of W	20190121_Radiographic_Tests_Extent	Radiographic Test Extent	0	1/28/19	2132054	1/22/19	2143868	4/26/19
20		2080726	Manufacturing procedures	3326.S.008	Manufacturing Sequence	0	11/28/18	NA	NA	NA	NA
21		2080731	HPWR procedure	Not yet available	NA	NA	NA	NA	NA	NA	NA
22		2080734	Heat Treatment Procedure	Not yet available	NA	NA	NA	NA	NA	NA	NA
26	MIP and Procedures	2080830	BCP Procedure	3326.S.004	Cleaning & Chemical Etching	1	8/5/19	2114426	3/19/19	2143871	4/25/19
23		2080831	Leak Test procedure	3326.S.006	Helium Leak (LT)	0	2/19/19	NA	NA	NA	NA
24		2080832	UT Procedure	Not yet available	NA	NA	NA	NA	NA	NA	NA
25		2080833	RF measurements & Trimming Procedure	Not yet available	NA	NA	NA	NA	NA	NA	NA
26		2080834	Dimensional Control Procedure	3326.S.002	Dimensional Control	0	1/28/19	NA	NA	NA	NA
27		2080835	Pressure Test Procedure	Not yet available	NA	NA	NA	NA	NA	NA	NA
28			2100569	Visual Testing	3326.S.003	Visual Inspection (VT)	1	8/5/19	2100569	3/29/19	Not needed
29		2080739	Documentation of welding samples	Not yet available	NA	NA	NA	NA	NA	NA	NA
30	Qualifications	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	1999885	10/25/18	NA	NA
31		2080735	Traceability Sheets for BCs	Not yet available	NA	NA	NA	NA	NA	NA	NA
32	Material Traceability	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	2142589	4/29/19	NA	NA
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	1876981	8/1/18	NA	NA

# Acceptance of RFD cavities

- Acceptance Plan (#1744)
  - Describes the process for acceptance between AUP and CERN, including OK to ship from CERN, and final checks at CERN after receiving
- Acceptance Criteria (#1154):
  - Discussions with CERN continuing towards a final version
  - All requirements from FRS will be verified with a test or a set of measurements during cavity production or during final tests at FNAL.
- Electronic travelers (VECTOR):
  - Already in place for several activities (see below)

## US-HiLumi-doc-1744



**Vector - Select Travelers - Read Only**

15 Records Found

Serial Number - ID	Document Number - Revision - % Done	Issue Date
RFD-LARP-001-0	464233-NONE-Cavity Location Auditing Traveler-4/5 (80%) Done	8/2/2017 10:33:58 AM
RFD-LARP-001-0	464379-NONE-HL-LHC AUP RFD Crab Cavity 2K VTS Testing-36/62 (58%) Done	9/20/2017 9:10:35 AM
RFD-LARP-001-1	464233-NONE-Cavity Location Auditing Traveler-4/5 (80%) Done	10/2/2017 3:57:52 PM
RFD-LARP-001-2	464233-NONE-Cavity Location Auditing Traveler-4/5 (80%) Done	10/5/2017 3:20:50 PM
RFD-LARP-001-3	464233-NONE-Cavity Location Auditing Traveler-4/5 (80%) Done	10/16/2017 11:32:05 AM
RFD-LARP-001-0	464412-NONE-RFD Cavity Buffered Chemical Polishing (BCP) Etch Traveler-55/151 (36%) Done	4/4/2018 9:43:18 AM
RFD-LARP-001-4	464233-NONE-Cavity Location Auditing Traveler-4/5 (80%) Done	4/17/2018 11:28:50 AM
RFD-LARP-001-5	464233-NONE-Cavity Location Auditing Traveler-4/5 (80%) Done	4/23/2018 11:47:26 AM
RFD-LARP-001-0	464121-B -SCRF Low Temperature Bake at MP9-1/27 (62%) Done	4/23/2018 11:18:34 PM
RFD-LARP-001-1	464379-NONE-HL-LHC AUP RFD Crab Cavity 2K VTS Testing-39/62 (62%) Done	4/30/2018 7:25:14 AM
RFD-LARP-001-6	464233-NONE-Cavity Location Auditing Traveler-4/5 (80%) Done	5/14/2018 12:33:30 PM
RFD-LARP-001-7	464233-NONE-Cavity Location Auditing Traveler-4/5 (80%) Done	6/5/2018 3:13:09 PM
RFD-LARP-001-1	464121-B -SCRF Low Temperature Bake at MP9-3/27 (11%) Done	6/8/2018 11:02:50 AM
RFD-LARP-001-8	464233-NONE-Cavity Location Auditing Traveler-4/5 (80%) Done	6/11/2018 10:39:02 AM
RFD-LARP-001-2	464379-NONE-HL-LHC AUP RFD Crab Cavity 2K VTS Testing-37/62 (59%) Done	6/12/2018 2:42:43 PM

## US-HiLumi-doc-1154

**US HL-LHC Accelerator Upgrade Project**

**RFD DRESSED CAVITY ACCEPTANCE CRITERIA**

**DRESSED RFD CAVITIES ACCEPTANCE CRITERIA**

Other: Date: 10/9/18 Page 1 of 7

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Leonardo Ristori, US HL-LHC AUP RFD Level 2 manager, FNAL  
Giorgio Apollinari, US HL-LHC AUP Project Manager, FNAL



# Goals for FY2020

- Launch procurement of magnetic shields and Helium tanks for prototypes
- Complete fabrication of 2x prototype bare cavities at supplier
- Assess quality and 2K performance of prototypes
- Converge with CERN on MIP for bare cavity by February 2020 (PRR)
- Launch fabrication of pre-series bare cavities
- Complete fabrication of 3x sets of Proto-HOM dampers at Jlab and assess quality & performance

# Upcoming Project Reviews

- Procurement Readiness Reviews (Raw Materials) ~ Dec-Jan
  - AUP soon launching procurement of raw materials for pre-series
  - Material List agreed upon and approved a while back, good (next slide)
  - Small “pilot” order placed earlier this year for small batch of Nb sheets, QA documentation recently approved by CERN, good start.
  - AUP will inform CERN of upcoming PRRs as needed
- PRR Bare Cavities Pre-Series – Feb 2020 (TBC)
  - Necessary to launch construction April 2020
- Final Design Review (Dressed Cavities) ~ Summer 2020
  - Participation of WP4 necessary (at min.) to defend mechanical design
  - Necessary to seek DOE approval for launching series in ~ Fall 2020.

# 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



EDMS NO. 2001102	REV. 2.0	VALIDITY VALID
REFERENCE : N/A		

REPORT		
<b>RFD BARE CAVITY MATERIAL LIST</b>		
<b>Abstract</b> This document provides the relevant material specifications that are applicable to the manufacturing of the RFD Bare Cavities.		
<b>TRACEABILITY</b>		
<i>Prepared by:</i> L. Ristori (AUP)		<i>Date:</i> 09/11/2018
<i>Verified by:</i> O. Capatina, L. Dassa, H. Garcia Gavela		<i>Date:</i> 14/11/2018
<i>Approved by:</i> R. Calaga		<i>Date:</i> 16/11/2018
<i>Distribution:</i> HI-LUMI-LHC-WP4-MEMBERS		
<i>Ref. Doc:</i> Dressed Cavities Engineering Specification ( <a href="#">EDMS 1389669</a> )		
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

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





# Topics for Discussion

- Fully integrated test of dressed cavity + dampers + FPC
  - It's a necessary validation for entire collaboration
  - Who/how/when/funding?
- Best use of AUP Prototypes in early 2021?
- Details of Final 2K tests at FNAL
  - 50 Ohm  $\leftrightarrow$  25 Ohm
  - Converge on Traveler for cold test
- Verification at receiving end (Triumpf)
  - Cold tests for prototypes?
  - Warm measurements for series?
- Transportation specification
  - CERN recently defined transportation requirement for the design of all crab cavity components (10g,...)
  - Transportation will need to be carried out avoiding exceeding design requirements

# Summary

- Design of bare cavity was recently modified after SPS experience at CERN, and adopted for prototypes at Zanon. Design of HOM dampers was modified to accommodate CERN feedthrough design
- ANL/FNAL Facilities, tooling and procedures for processing, heat treatment, cleanroom assembly were recently validated thanks to LARP prototype
- Fabrication of 2 cavity prototypes is progressing well in terms of quality. Heavy oversight of AUP. Delays outside AUP control are not impacting delivery dates originally agreed between AUP-CERN
- 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
- US RFD Team and CERN WP4 have many topics to discuss this week!

# Thank you to the US RFD Team!

## Institutions in alphabetical order

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

## *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.