US Contribution to SPS Crab Cavity Prototypes and Lessons Learned

Alessandro Ratti - SLAC

for the LARP and AUP collaboration

Outline

- A historic perspective of crab cavities in LARP
- Cavity development path and processes
- Production history and results
- Test results of all LARP cavities
- Summary of major program accomplishments

Historic Perspective

- CC proposal started before the commissioning of the LHC
  - First CC workshop (CC-08 BNL/LARP/CARE-HHH) held at BNL 24-5 Feb. 2008
  - Motivated by the great benefit in luminosity leveling and coping with the necessary crossing angles in the LHC
  - HL-LHC makes it even more compelling

- Initial challenge → demonstrate sufficient deflecting voltage in the limited space available = Local vs. Global
  - Beampipe separation 40 cm
  - Limited longitudinal space in the IR → significant gradients

- Three candidate designs were built and successfully tested by 2013
  - LARP led the DQW and RFD;
  - STFC led the 4-rod cavity
  - All PoP cavities built by Niowave

Initial Cavity System Requirements

Resonance frequency [MHz]	400.79
Bunch length [ns]	1.0 (4 σ)
Maximum cavity radius [mm]	≤145
Nominal kick voltage [MV]	3.4
R/Q (assumed, linac convention) [Ω]	400
Dynamic Load	~3W (for SPS)
Q_{ext} (fixed coupling range)	3×10^5–5×10^5
RF power [kW]	80
Power coupler OD (50Ω) [mm]	62
LLRF loop delay [μs]	≈1
Cavity detuning [kHz]	≈1.0

First LARP Results – the PoP Program

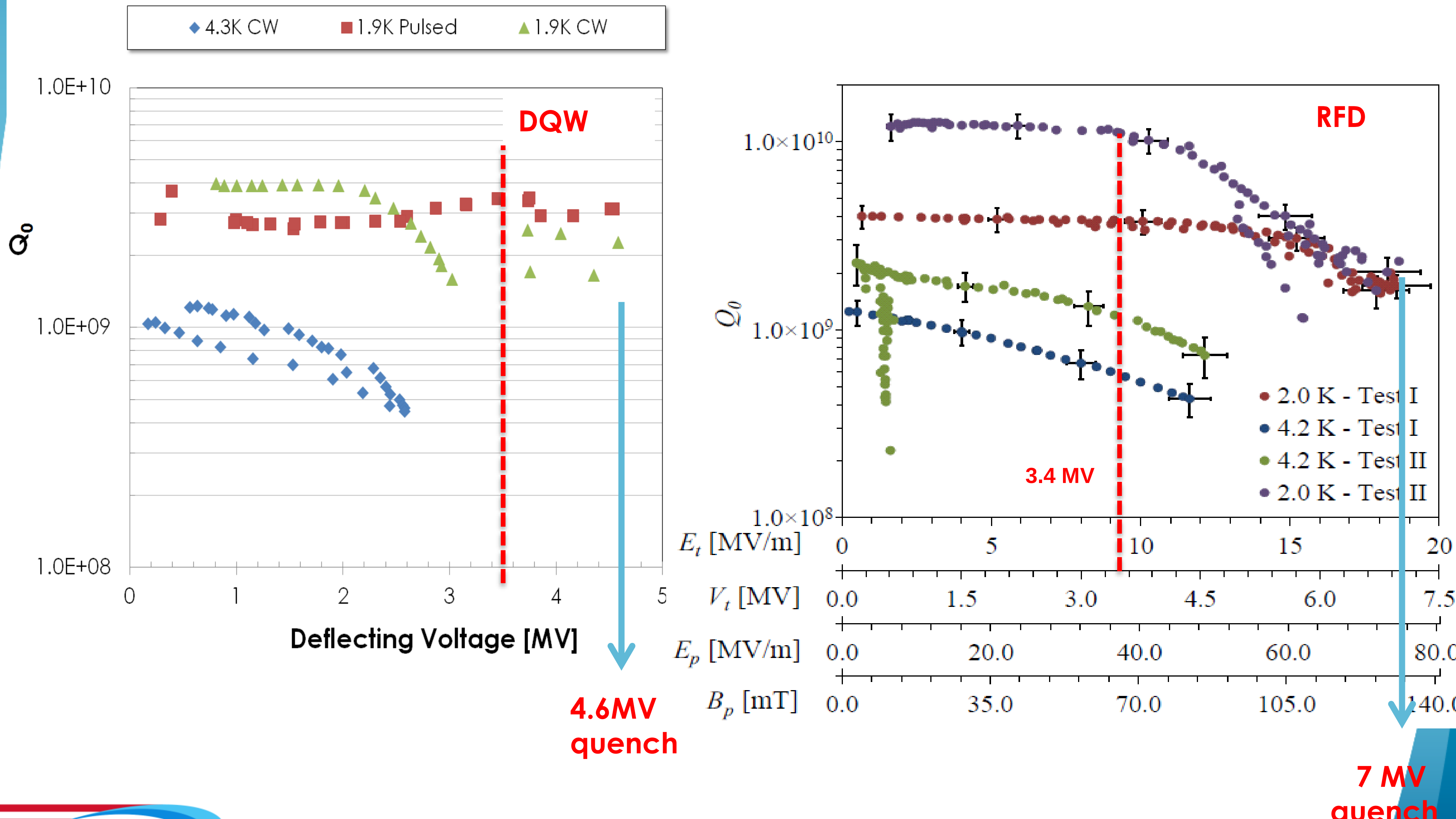
2008-2013

- Demonstrated EM conceptual design and feasibility

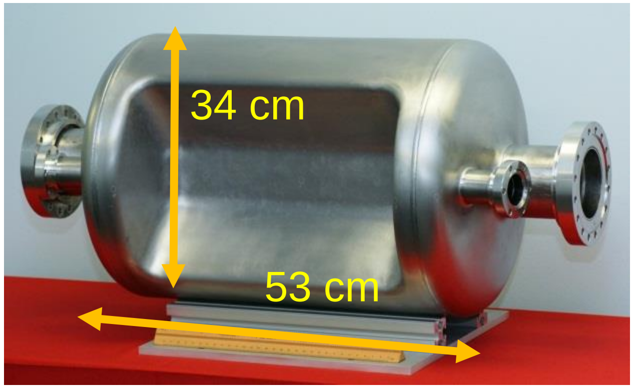
- Not ready for beam
- No peripherals

LARP PoP Test Results

2013

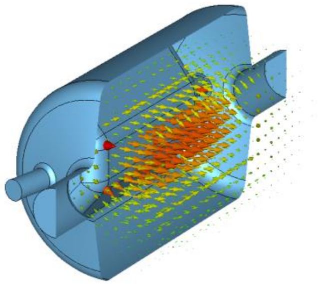


RFD - Proof-of-Principle Design

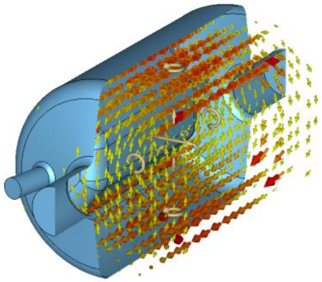


Proof-of-Principle cavity fabricated at Niowave Inc.

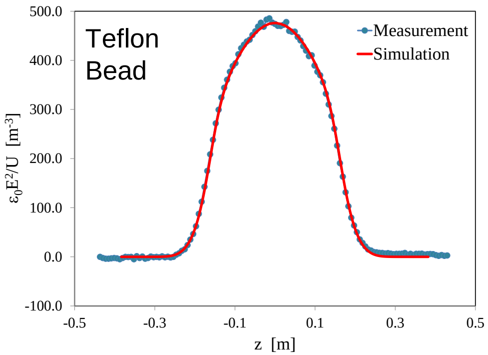
Parameters	Value	Units
Frequency of fundamental	400	MHz
Frequency 1st HOM	590	MHz
Deflecting Voltage (V_t^*)	0.375	MV
Peak Electric Field (E_p^*)	4.02	MV/m
Peak Magnetic Field (B_p^*)	7.06	mT
B_p^*/E_p^*	1.76	mT/ (MV/m)
Stored Energy (U^*)	0.195	J
$[R/Q]_t$	287.0	Ω
Geometrical Factor (G)	140.9	Ω
R_tR_s	4.0×10^4	Ω^2
At E_t^* = 1 MV/m		

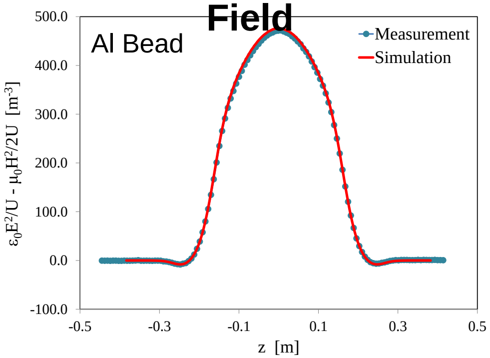


E Field



B Field





Bead pull measurements of on axis electric and magnetic field components

J. Delayen
S. De Silva

Two Crab Cavity Designs Selected

May 2014

- LARP supported the R&D that led to both designs that are part of the baseline HL-LHC design
- Proof of Principle cavities were built and tested in a VT
  - Successful measurements demonstrated feasibility
- Both LARP designs were chosen to address kicks in the H (CMS) and V (ATLAS) planes.
- Two main reasons to keep both designs:
  - HOMs are a dominant factor
    - different cavities have different spectra
  - Cryomodule integration
    - 90 deg rotations are “easy” only in principle

First LARP Prototype Cavities

- We started a program to build two DQW and two RFDs
  - Complete with tuners, couplers (HOM and pickups) and He tanks
- Funding was not available through LARP
- Cavities were developed through small business grants from DOE to Niowave

Functional Specification for SPS tests

- System Specifications
- Functional parameters
  - Including HOMs, Z…
- Enclosures (incl. materials…)
- Cryogenics
- RF Power incl. couplers
- LLRF
- SPS Integration

Released by CERN in Feb. 2013

Updated for HL-LHC


CERN-ACC-NOTE-2013-003

HiLumi LHC

FP7 High Luminosity Large Hadron Collider Design Study

Scientific / Technical Note

Functional Specifications of the LHC Prototype Crab Cavity System

Baudrenghien, P

et al

28 February 2013

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

This work is part of HiLumi LHC Work Package **4: Crab cavities**.

The electronic version of this HiLumi LHC Publication is available via the HiLumi LHC web site <http://hilumilhc.web.cern.ch> or on the CERN Document Server at the following URL: <http://cds.cern.ch/search?p=CERN-ACC-NOTE-2013-003>

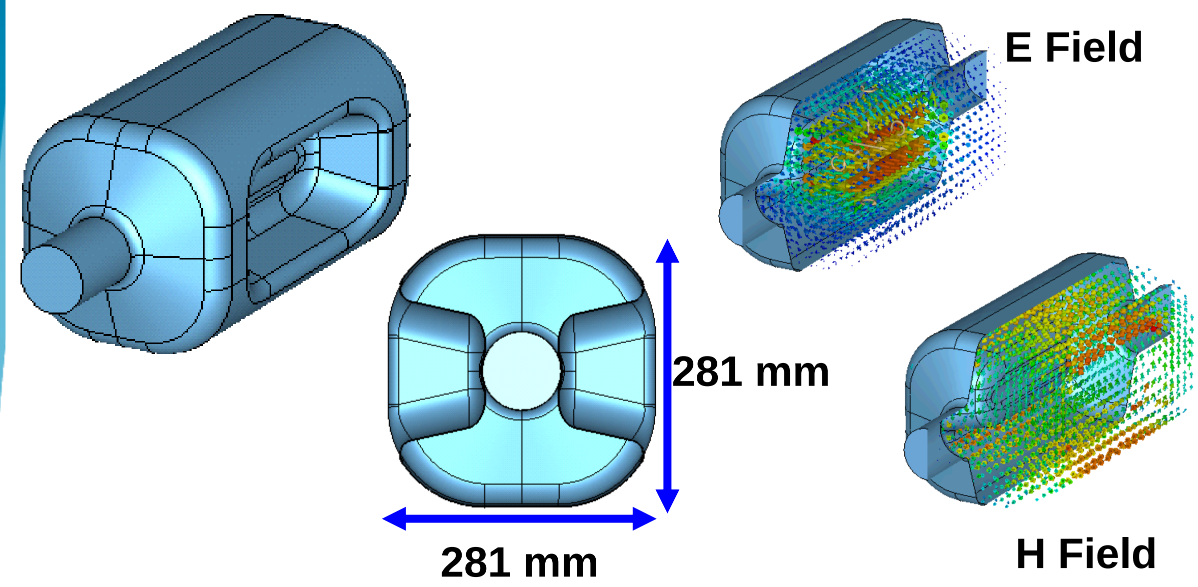
CERN-ACC-NOTE-2013-003

QA Requirements for Manufacturing Readiness

Due 1 month before start of manufacturing for CERN approval

#	Requirements
1	Niobium material samples according to Section 3.2
2	Material certificates and quality control of raw materials (including RRR measurements)
3	Material certificates of welding consumables (whenever applicable)
4	Functional and manufacturing drawings (with tolerances)
5	Design reports demonstrating that welds are designed to withstand the specified load cases (refer to Section 3.6.1)
6	Welding plan including: • Welding maps • Welding and brazing procedure qualification record including CERN acceptance criteria in Section 4.2 (WPQR and BPQR) • Welding and brazing procedure specification (WPS and BPS) • Welders performance qualification (GTAW), Welding and Brazing Operators Performance Qualifications (electron-beam welding and vacuum brazing) – WPQ, WOPQ and BOPQ
7	Manufacturing procedures (whenever required in Annex 6.3)
8	Test procedures (whenever required in Annex 6.3)
9	EB welded and vacuum brazed samples according to the requirements specified in Section 3.8.4
10	NDT personnel qualifications
11	Manufacturing and inspection plan (MIP) – list of all manufacturing and quality control operations.

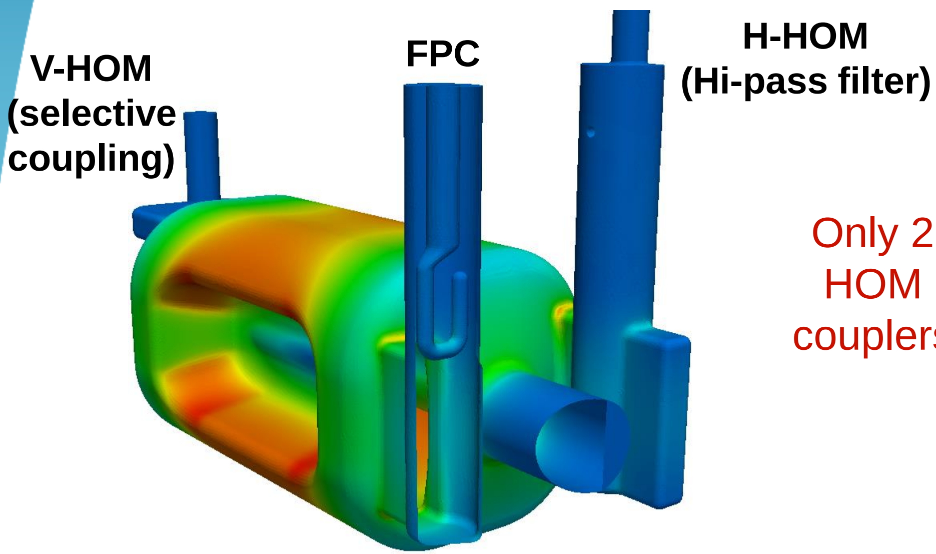
Initial RFD Cavity Design for SPS



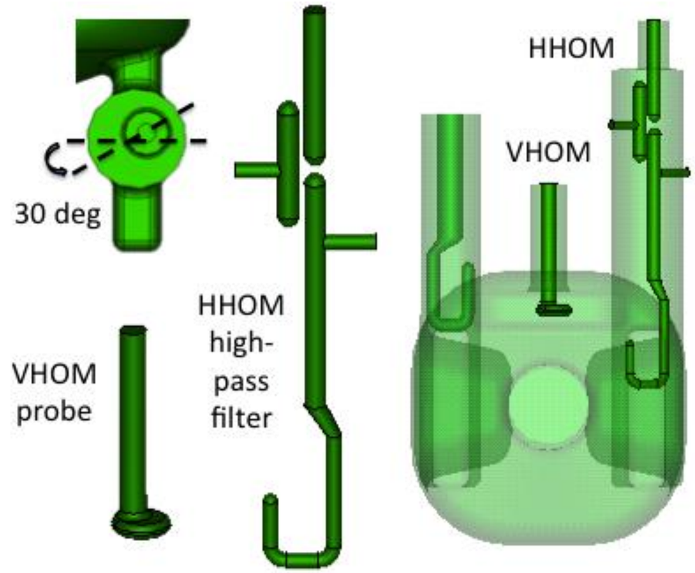
Frequency	400	MHz
Aperture	84	Mm
Nearest HOM	633.5	MHz
E_p^*	3.6	MV/m
B_p^*	6.2	mT
$[R/Q]_t$	429.7	Ω
Geometrical Factor (G)	106.7	Ω
R_tR_s	4.6×10^5	Ω^2
At E_t^* = 1.0 MV/m		
V_t	3.4	MV
E_p^*	33	MV/m
B_p^*	56	mT

- Operates in TE_{11} like mode
- Next HOM is 1.5 times fundamental mode
- Multipacting is improved compared to P-o-P cavity
- Surface fields are lower compared to P-o-P cavity
- Shunt impedance higher compared to P-o-P cavity
- Reduced multipoles components with curved poles

FPC & HOM Coupler Designs



Only 2 HOM couplers

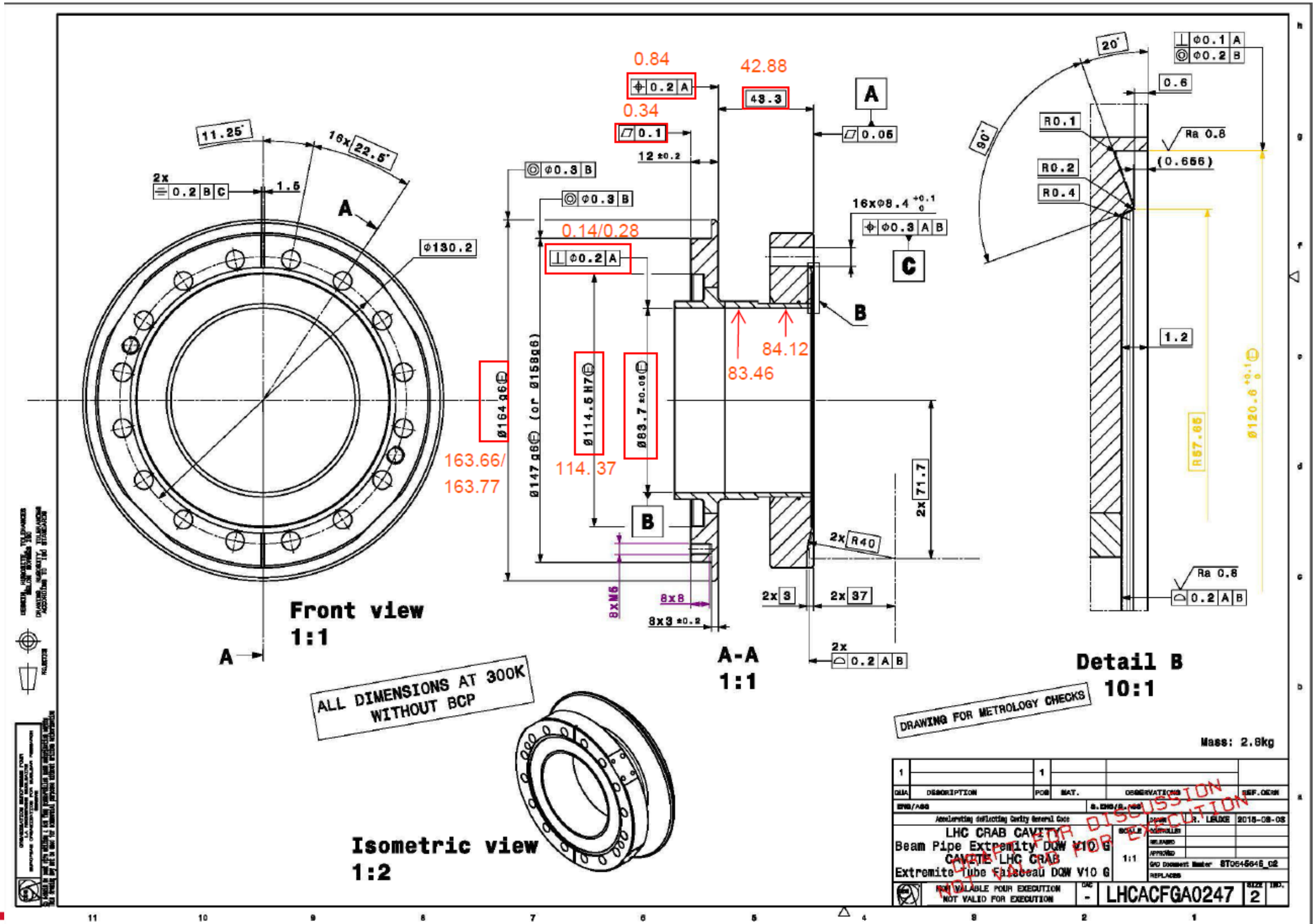


- FPC/HOM ports oriented to keep clearance for the second beam pipe
- Couplers at locations of low field region on cavity body
  - Minimizes RF heating on the coupler components
- Location preserves field symmetry
  - Electrical center moved by only 50 microns
- H-HOM coupler with 30 degree hook orientation with no change to filter elements

- Selective coupling (V-HOM) to reduce the number of filters
  - 7 mm offset incorporated into the pickup tip to enhance coupling to the dipole modes at around 2GHz
  - Small RF power leakage through the coupler, ~1.5W, due to asymmetry
- FPC coupler: $Q_L = 5.0\times10^5$
  - Hook shaped coupler reduces RF heating → 69 W

Zenghai Li, S de Silva, J Delayen

Beampipe Assembly Dimensional Control at CERN - some non compliance



Beam Pipe Testing Summary

Assembly and Dimensions:

- Some dimensions are not compliant with spec. tolerances
  - The parallelism between the flange and the ring, and the diameter of the ring are the most relevant tolerances <u>not achieved</u>

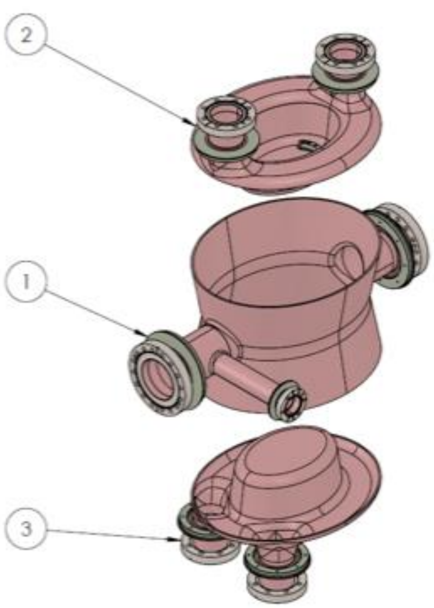
- The knife edge is <u>acceptable</u>

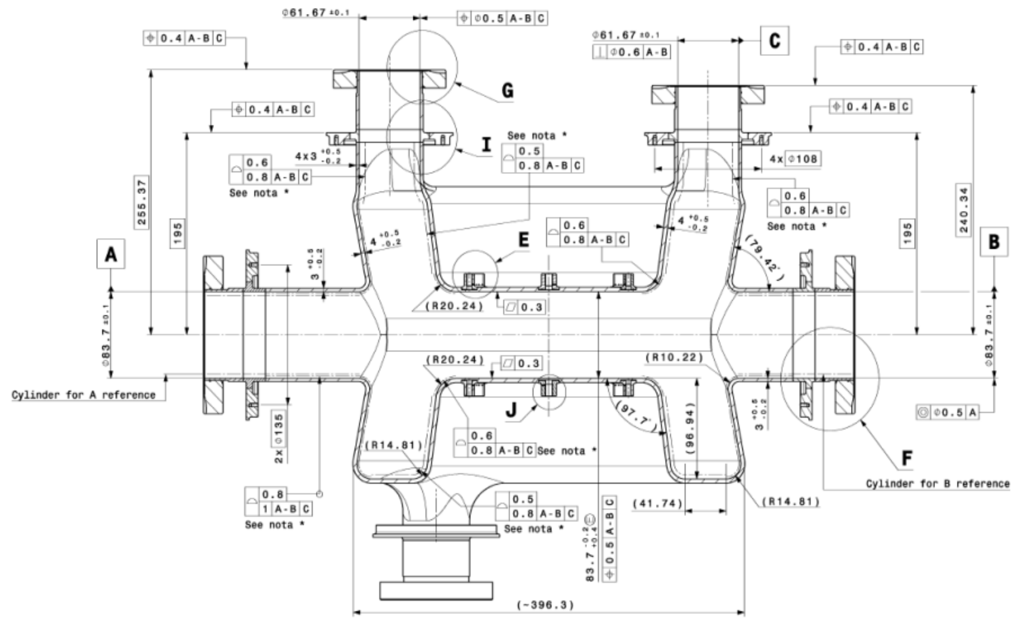
Welding and brazing:

- Radiographic tests were <u>acceptable</u>

- Metallurgic tests were <u>acceptable</u>

DQW – Assembly and Specifications

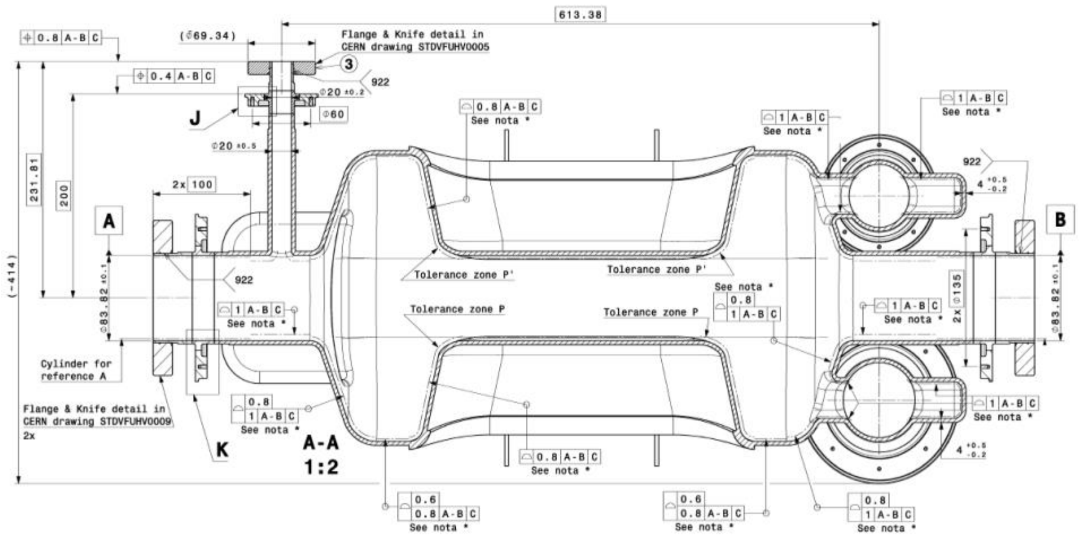


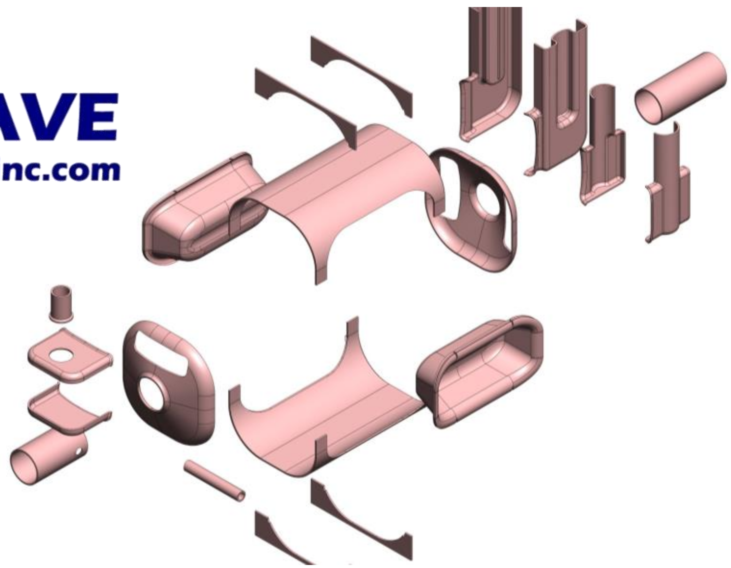


DQW Main Components

NIOWAVE
www.niowaveinc.com

RFD – Assembly and Specification





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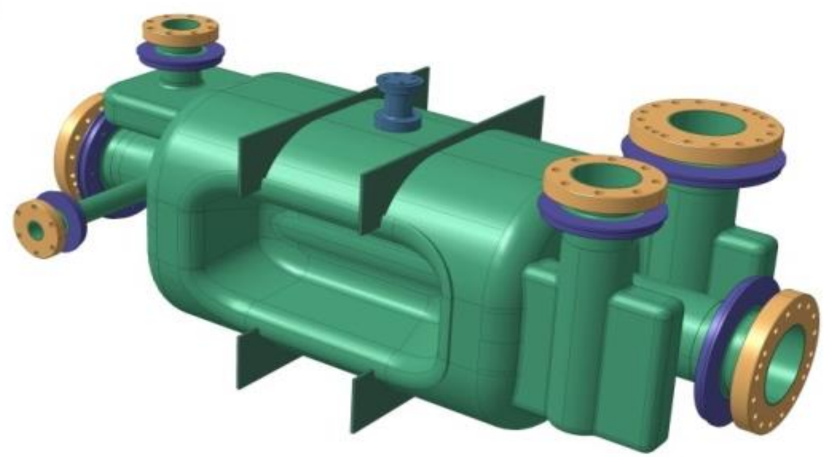

RFD – Main Components

NIOWAVE
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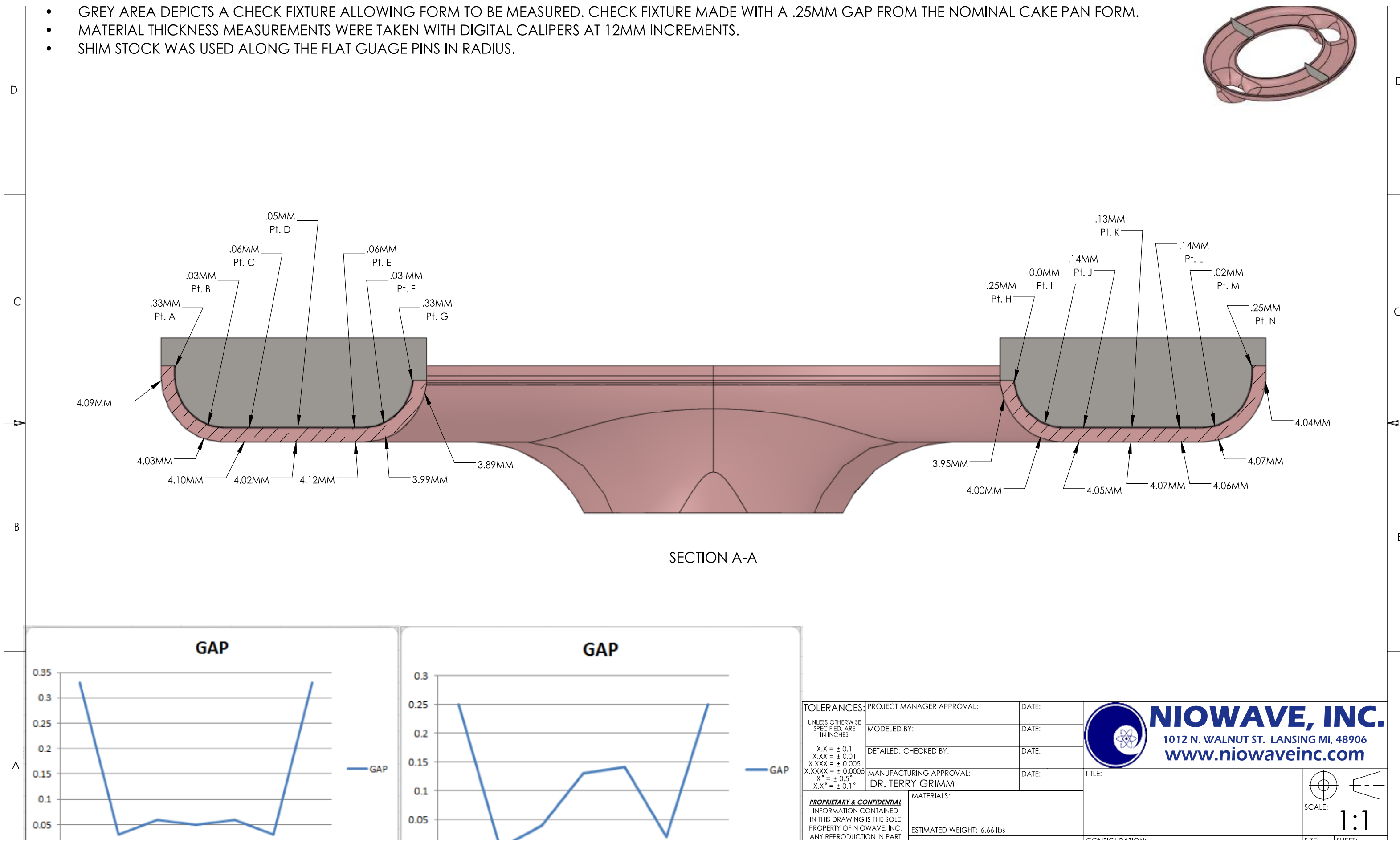
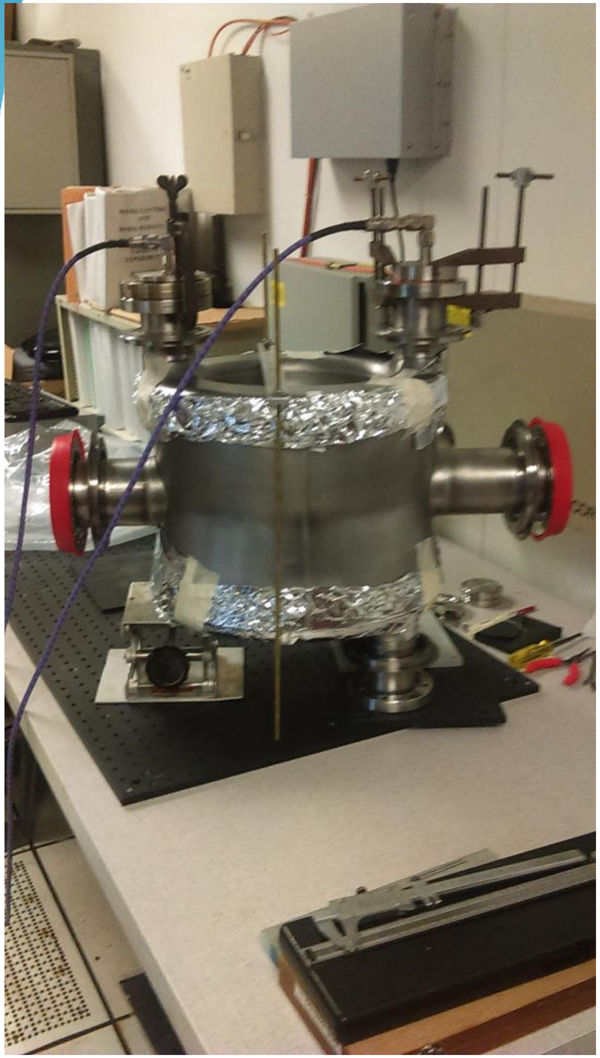
Nb Parts Measurements



RFD Subassemblies at Jefferson Lab

NIOWAVE
www.niowaveinc.com

DQW Sub-Assemblies at BNL



NIOWAVE
www.niowaveinc.com

Issues with Cavity Production at the company

- Some tests and qualifications not shared or not verified
  - Ie. parts unavailable for a few months until after welding
- Company treated several steps as proprietary information
- After the fact QA showed some non compliances that were not reported
  - Ie. double weld on RFD external assembly

Role of LARP cavities

- Due to lack of documentation and inspections, CERN was forced to run a rush program to complete cavities (and CMs) for the SPS beam test of 2018
  - See the next talk

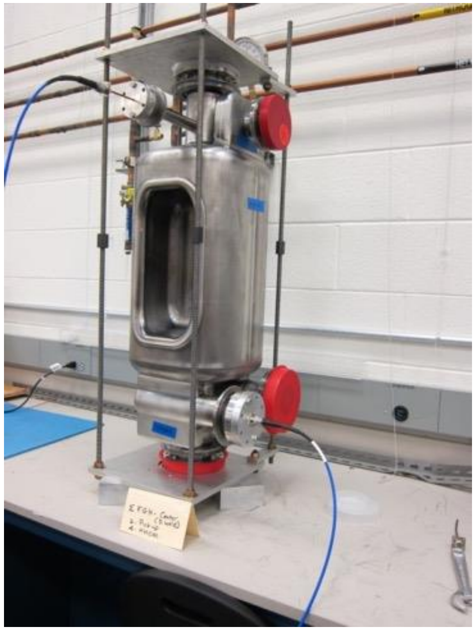
- Nevertheless the LARP cavities played a crucial role developing processes and understanding limits and performance

Summary of LARP/CERN Cavities Test Results

	CERN DQW1	CERN DQW2	LARP DQW1	LARP DQW2	LARP RFD1	LARP RFD2	LARP RFD1 @FNAL
VMax [MV]	5.0	4.8	5.9	5.3	4.4	5.7	5.02
Epeak [MV/m]	56	54	65	58	42	54	56
Bpeak [mT]	109	103	125	113	73	95	109
Rs min [nOhm]	10	10	9	10	11	7	
Rs @ 3.4MV [nOhm]	15	18	15	12	13	9	
FE onset [MV]	4.0	3.5	4.1	2.8	> 4.4	4.5	
Q0 max			9.2E+9	8.8E+9	1.1E+10	1.5E+10	1.5E+10
Q0 @3.4MV			6.2E+9	7.3E+9	8.5E+9	1.2E+10	1.1E+10

Niowave RFD Cavities at JLAB

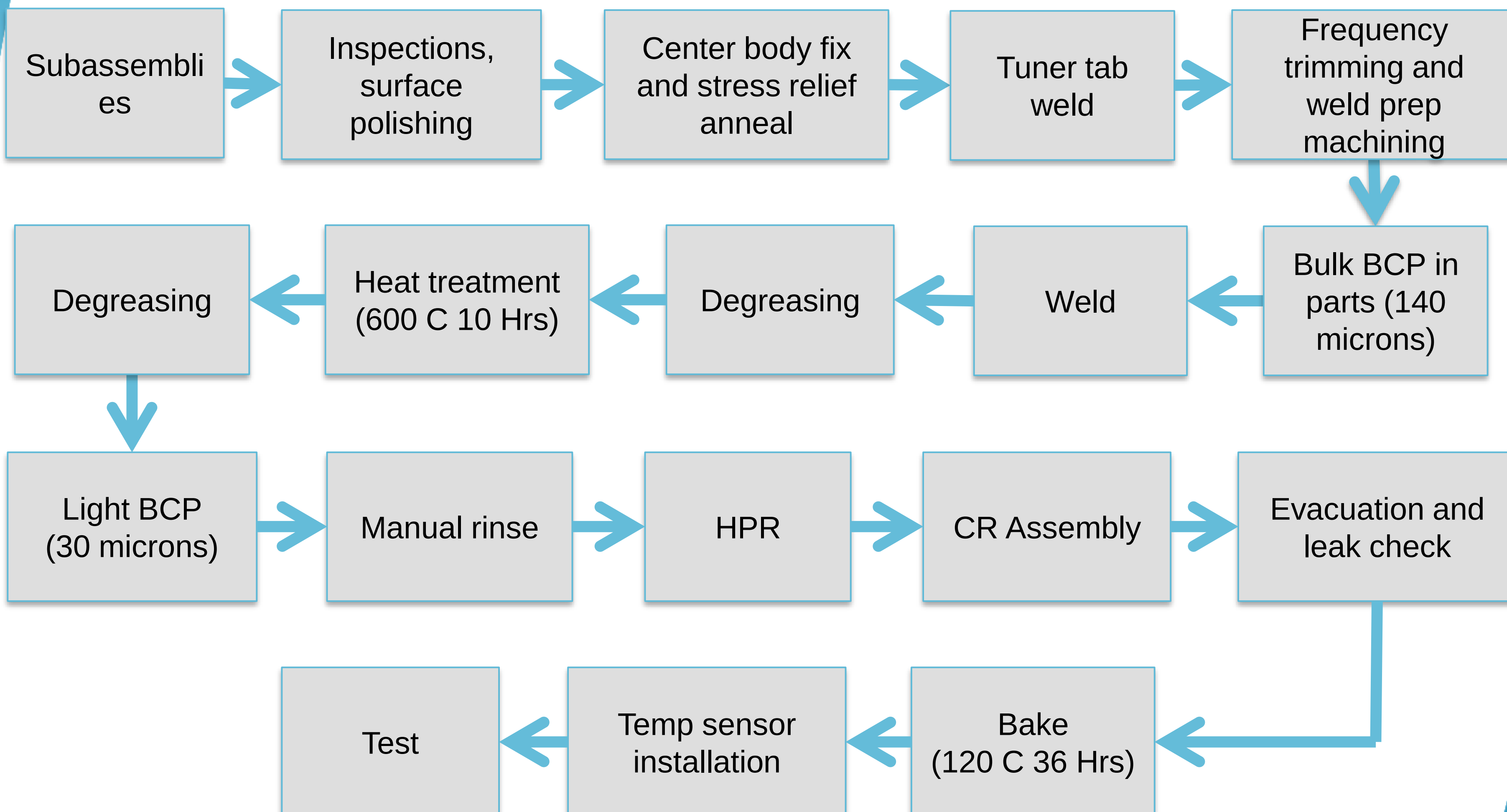
- Two cavity sub assemblies arrive at JLAB



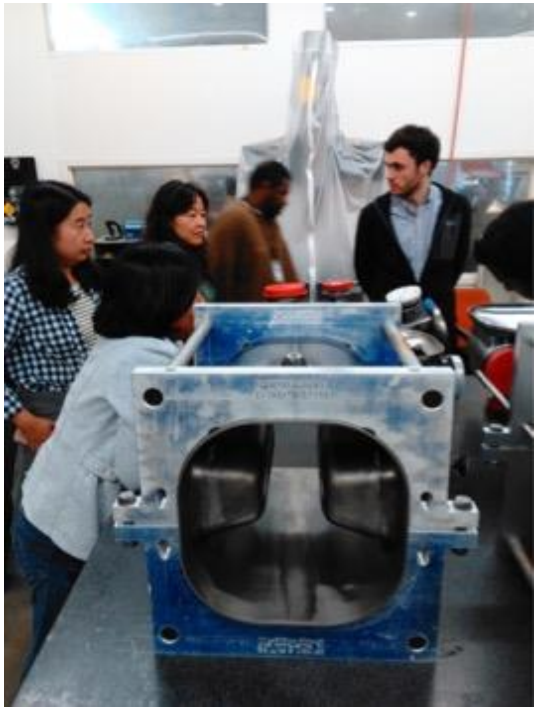
28 April 2016

RFD Process Flow at JLAB

Inspection and frequency measurement between each step



RFD final Machining at JLAB



BNL
CERN
LU/STFC
JLAB
ODU
SLAC

contributed

27 Oct 2016

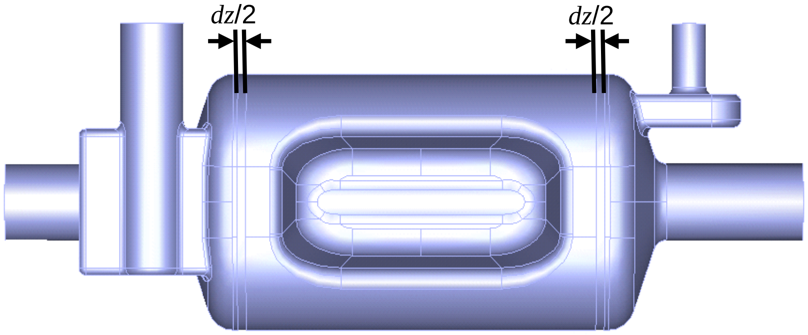
SPS-RFD Cavity: Trimming Sensitivity

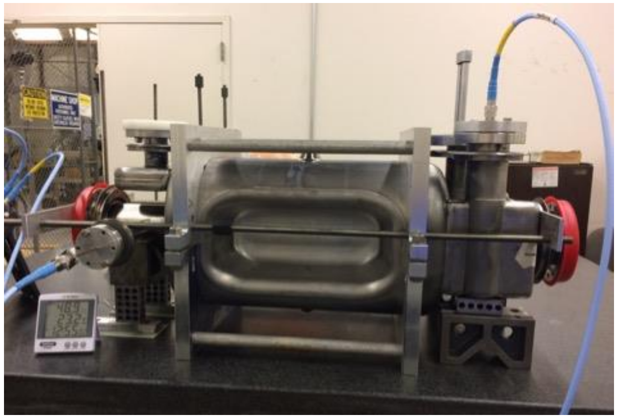
Trimming sensitivity for RFD cavities

df/dz = -119.85 kHz/mm

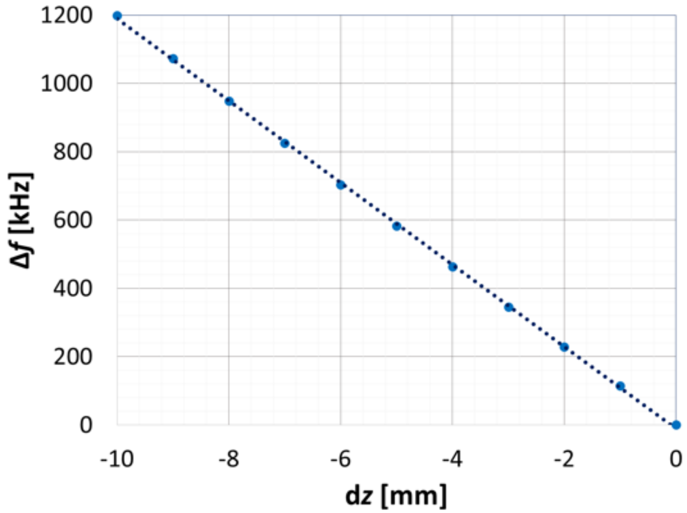
Measured sensitivity:

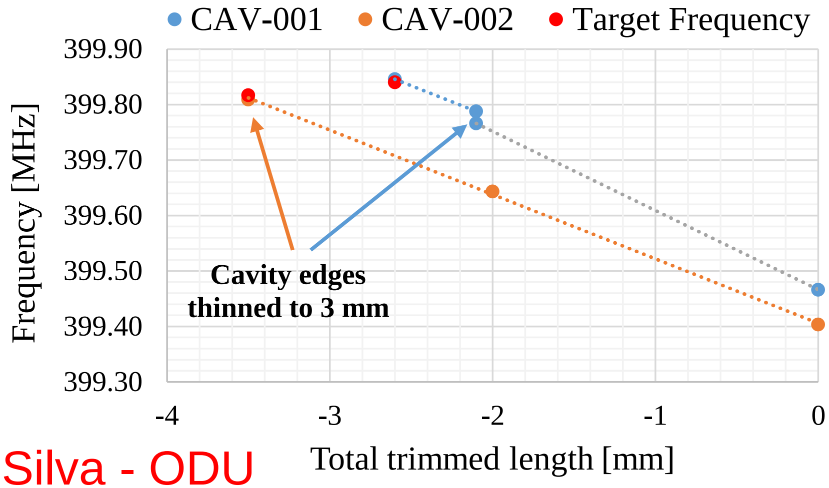
- CAV001: -129.3 kHz/mm
- CAV002: -116.1 kHz/mm





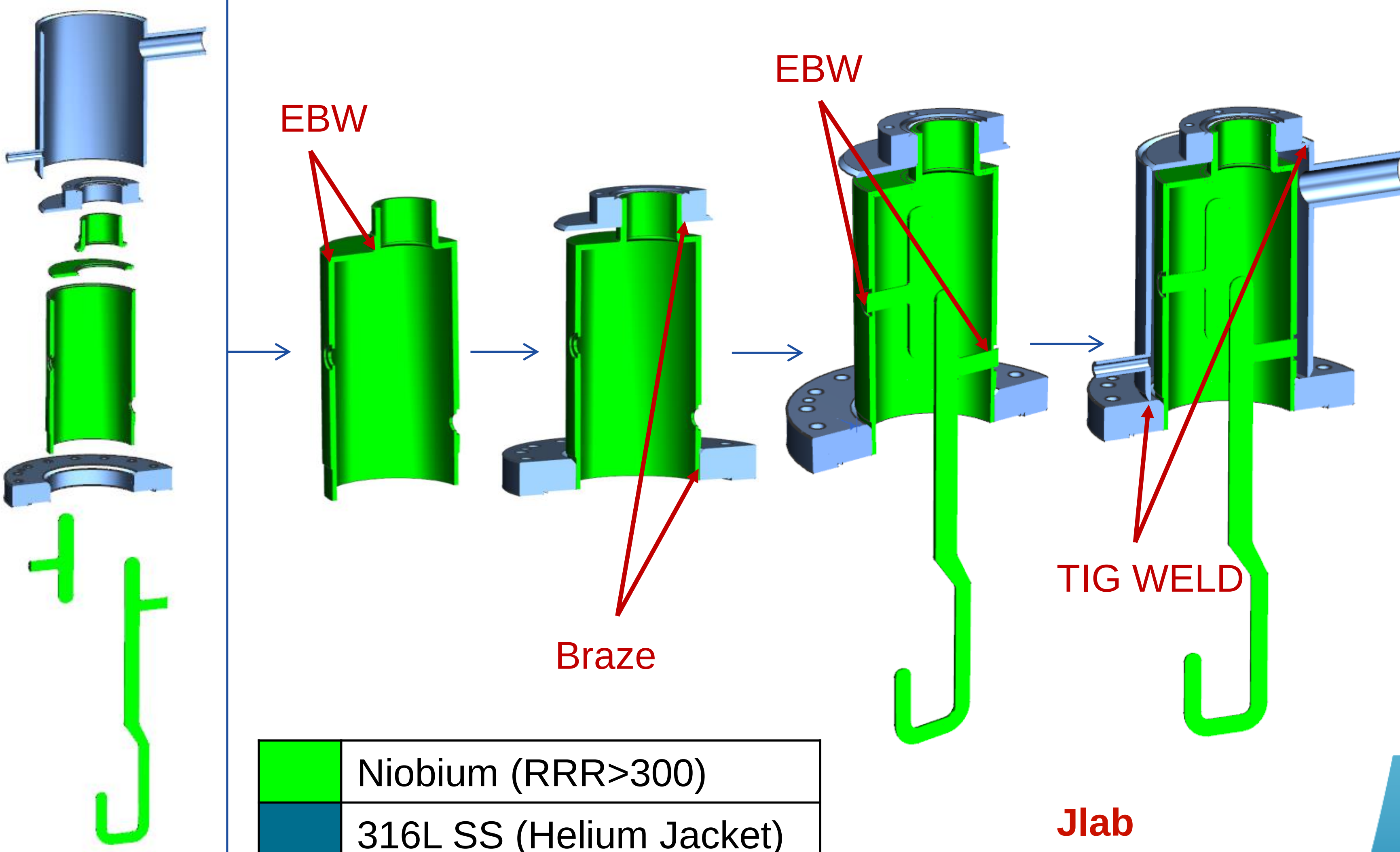
Good agreement with simulations





S. DeSilva - ODU

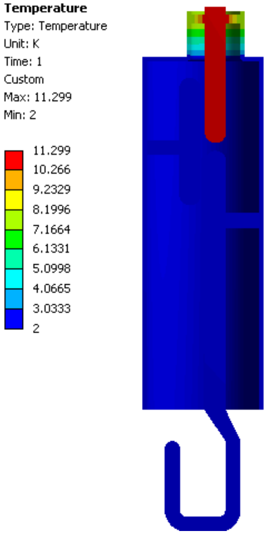
HOM Dampers Fabrication Process

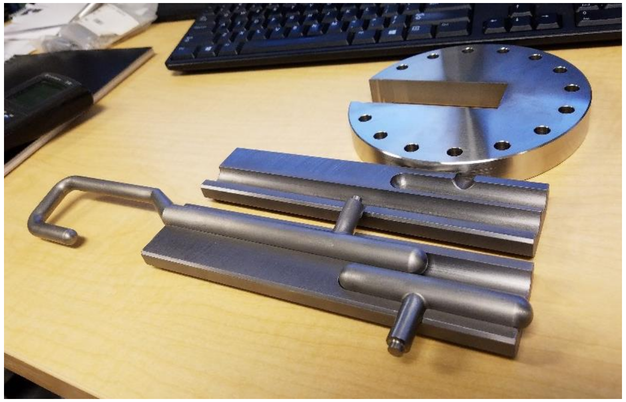


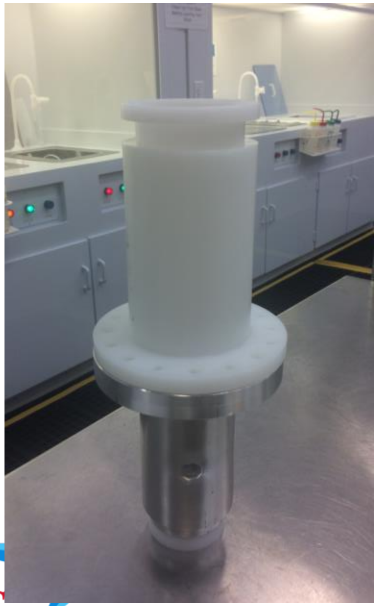
	Niobium (RRR>300)
	316L SS (Helium Jacket)
	316LN SS (Flanges)

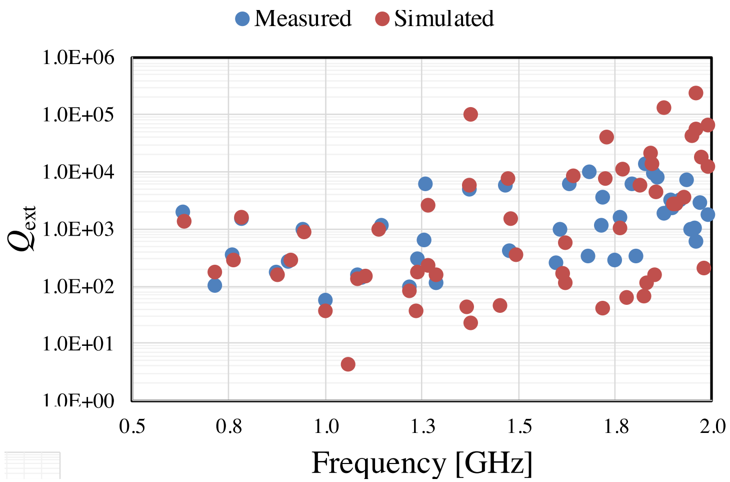
Jlab

HOM Dampers Fabrication









Jlab

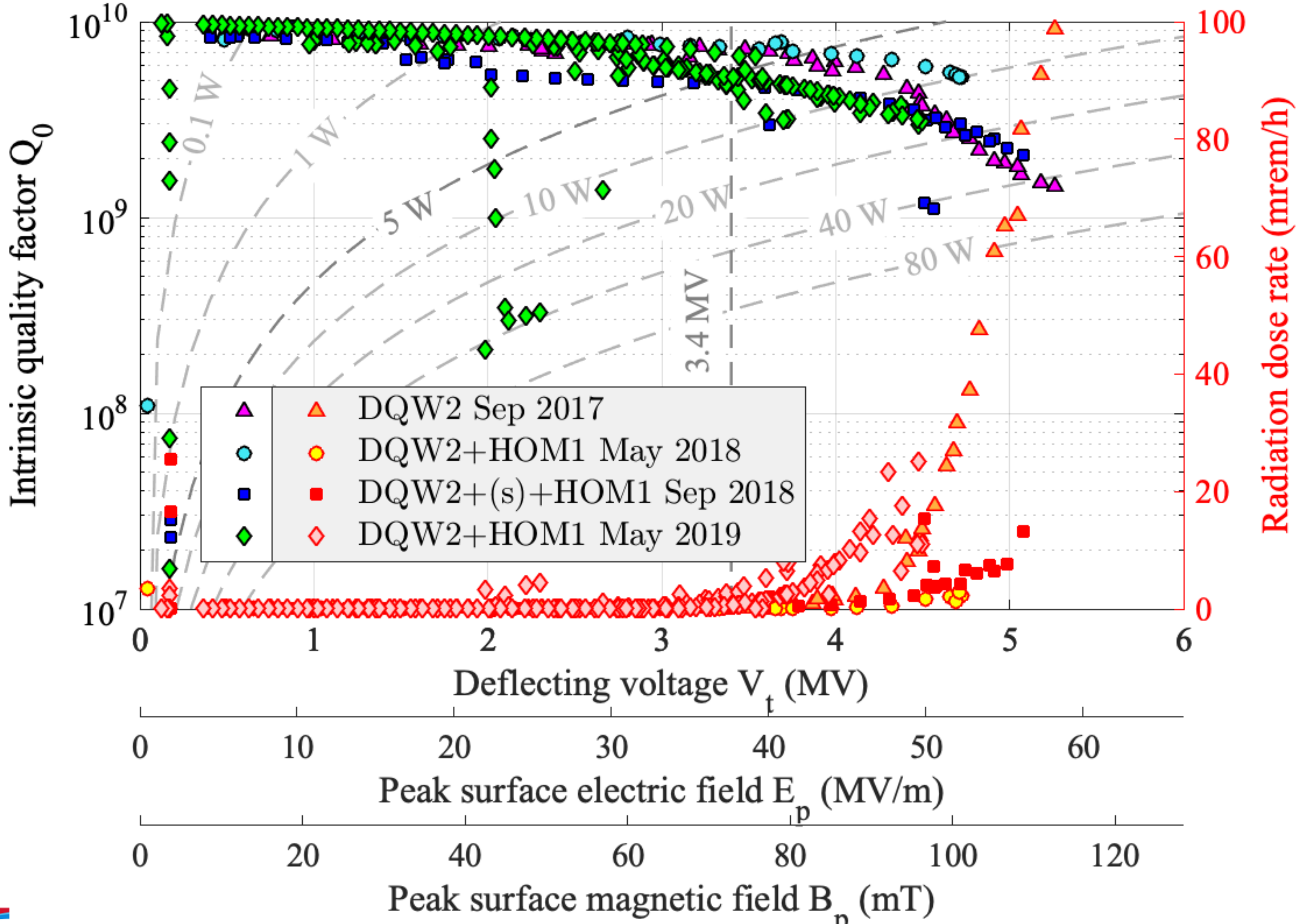
Summary of LARP RFD test data

Test Date	Cavity #	Location	HHOM	VHOM	MAX V	Q AT 4.1 MV	Low field Q
2/12/2017	LARP RFD#1	JLab			4.04	1.60E+09	1.23E+10
3/23/2017	LARP RFD#1	JLab			4.38	8.21E+09	1.03E+10
6/2/2017	LARP RFD#2	JLab			5.75	1.13E+10	1.46E+10
8/20/2017	LARP RFD#1	FNAL			4.70	1.10E+10	1.95E+10
4/30/2018	LARP RFD#1	FNAL			3.54	N/A	1.49E+10
5/8/2018	LARP RFD#2	JLab	YES	YES	4.77	1.22E+09	measure error
5/31/2018	LARP RFD#2	JLab	YES	YES	5.03	1.32E+09	1.45E+09
6/13/2018	LARP RFD#1	FNAL			3.47	N/A	1.67E+10
8/16/2018	LARP RFD#2	JLab	YES		5.26	6.60E+08	7.18E+08
10/9/2018	LARP RFD#2	JLab	YES		4.18	1.08E+09	1.56E+09
11/14/2018	LARP RFD#2	JLab	YES	YES	5.50	5.00E+09	6.50E+09
11/28/2018	LARP RFD#2	JLab	YES	YES	5.50	7.35E+09	1.05E+10
3/27/2018	LARP RFD#2	JLab	YES	YES	5.33	6.50E+09	9.00E+09
5/2/2019	LARP RFD#1	FNAL			5.10	1.00E+10	1.50E+10

Summary of LARP DQW test data

Test	Assembly	Surface preparation		Max Vt (MV)	FE (MV)	Q0, low	Q0,nom	CX	LFD
		Cavity	HOM filter				[P (W)]		(Hz/(MV)2
Feb'17	DQW01	Bulk BCP, 600C, light BCP, HPR, 120C	N/A	5.9	4.1	1.00E+10	6.00E+09 [4.5]	#B-2 #F-4	
May'17	DQW01+HOM01 Flange set #b	None	Flash BCP (on hook); rinse	2.8	n/a	1.00E+10	n/a	#B-5 #D-7 #E-8	-450
Jun'17	DQW02	Bulk BCP, 600C, light BCP, HPR, 120C	N/A	5.3	3.3	9.00E+09	5.00E+09 [5.4]	#A-567 #F-4	
Sep'17	DQW02	Light BCP, HPR	N/A	5.3	4.1	1.00E+10	6.00E+09 [4.5]	#C-1 #A-7	-554
Oct'17	DQW02+HOM01 Flange set #a	Light BCP, HPR	Flash BCP (on hook); rinse	3.6	n/a	1.00E+10	6.00E+09 [4.5]	#F-4 #D-7 #E-8	-499
Jan'18	DQW02+HOM01 Flange set #a	None	100 um BCP, 600C, light BCP, rinse	3.1	2.6	1.00E+10	n/a	N/A	-599
May'18	DQW02+HOM01 Flange set #a	HPR, 120C	Rinse, 120C	4.7	3.2	1.00E+10	7.00E+09 [3.8]	None	-772
Jul'18 (testing anomaly)	DQW02+HOM01 20mm NbTi spacer Flange set #a	HPR, 120C	Rinse, 120C	5.9	None	8.00E+09	5.00E+09 [5.4]	N/A	
Sep'18	DQW02+HOM01 20mm NbTi spacer Flange set #a	HPR, 120C	None	5.1	2.7	9.00E+09	5.00E+09 [5.4]	#E-8	
May'19	DQW02+HOM01 Flange set #a	None	None	4.4	2.1	1.00E+10	5.00E+09 [5.4]	#C-1 #F-5 #D-7	-700

All the US DQW cavity tests with one HOM filter



Transition to AUP and First HL-LHC Prototypes

- Many more details available for tuners, HOM dampers…
  - Focused on RFD cavity production here
- Lessons learned from LARP cavity production and testing applied to first AUP and HL-LHC prototypes
- AUP developed a lessons learned document for RFD
  - See US-HiLumi-doc-2152
    - Frequency recipe, dimensional adjustments, tolerances, chemistry
- See talk by L. Ristori

Funding

- LARP
  - Engineering and Design
- DOE SBIR
  - Cavity production, PoP RFD Design
- CERN
  - Welding and processing at JLAB (through LARP)
  - Final DQW testing at JLAB
- AUP
  - All RFD testing and development since AUP start in 2017

Summary

- The LARP program led the way to:
  - Demonstrate the design of SRF cavities capable of meeting the field and dimensional requirements
  - Including the HOM spectra and impedance requirements
  - Demonstrate the fabrication and assembly procedures
  - Including the chemistry and all cavity processing leading to test results that exceeded the required performance

Conclusions

- LARP was a key contributor to enable the CC program by demonstrating the feasibility of SRF cavities meeting the constraints of the HL-LHC upgrade

- LARP program gave very important results for HL-LHC and AUP
  - Both cavity designs exceed performance requirements
  - Developed processes that lead to successful results
    - For the DQW good results came from both sides of the ocean -> good sign of the maturity of the design

- The LARP processes and cavities are giving very valuable support to the AUP tasks and to the HL-LHC

Questions

RFD Bulk BCP Chemistry at JLAB

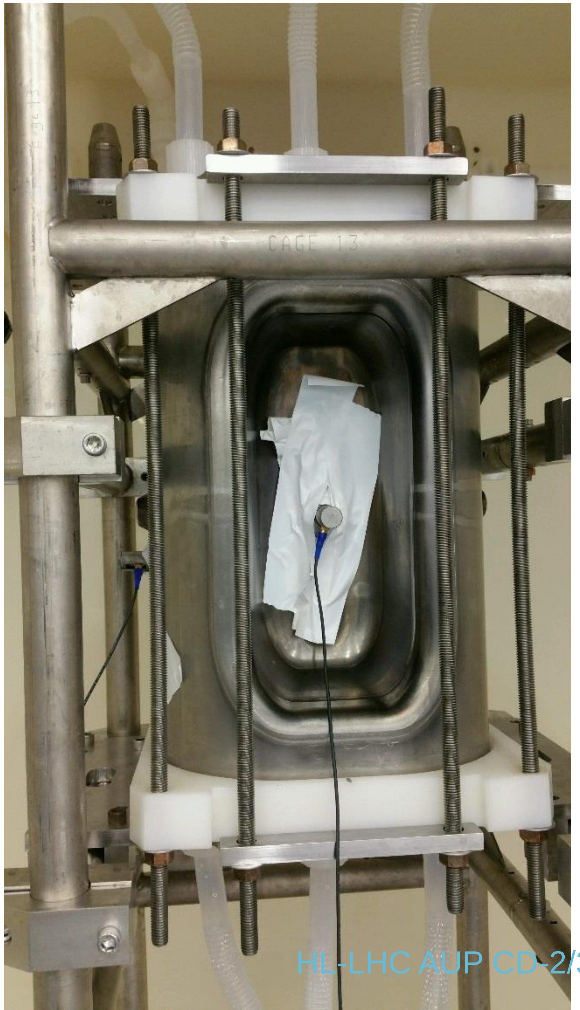
Assembly

VHOM-002 After BCP

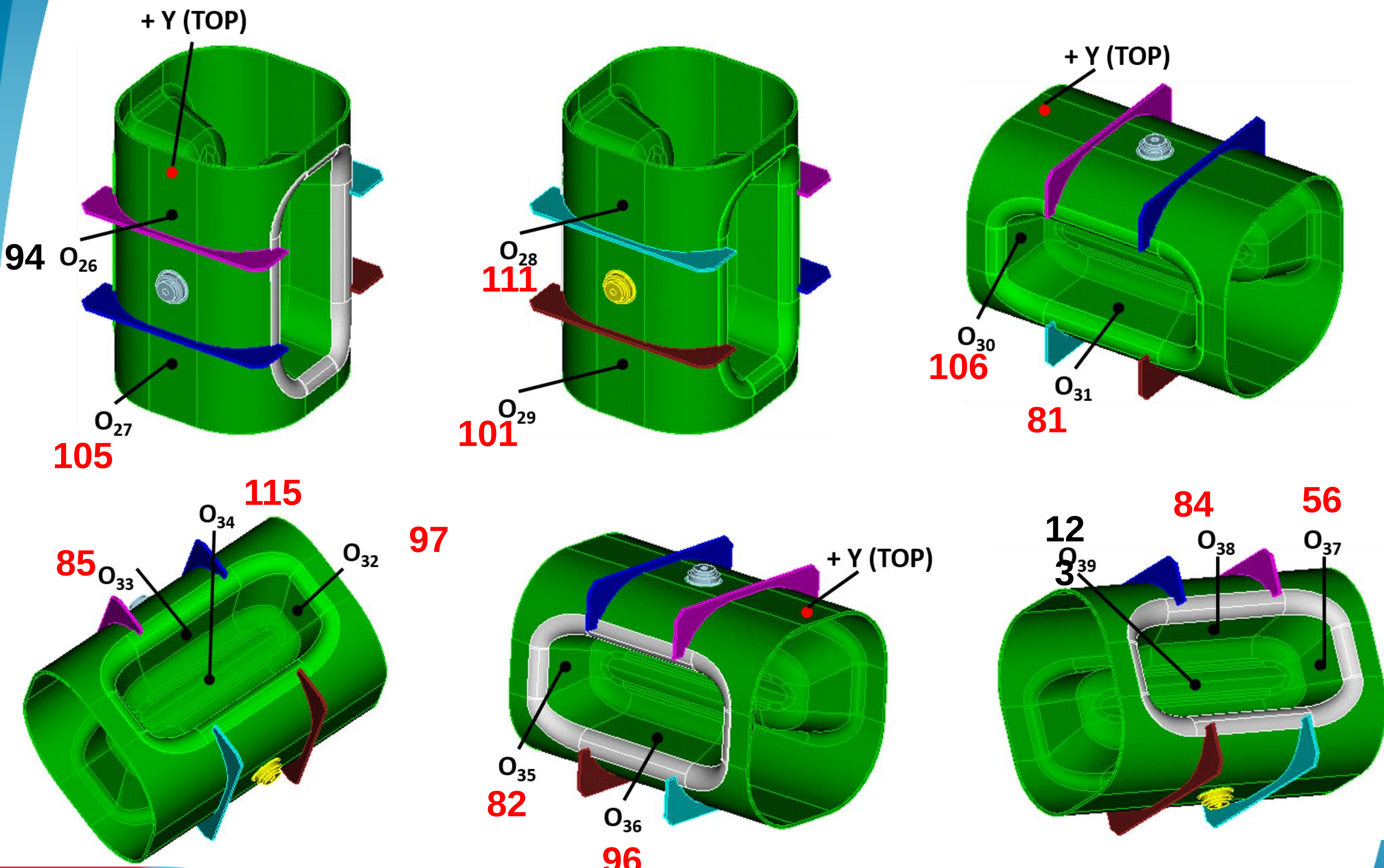
- Bulk BCP completed for HHOM-002 and VHOM-002

RFD BCP Setup – CTR-002

Two thickness gauges were used.



RFD Thickness Measurements Results – CTR-002



Average removal – 95 micron

RFD Frequency Recipes

CAV-001

Step (Recipe for 20 C, 50 % and 1013.25 mbar)	Δf	f_n
	[kHz]	[MHz]
Cavity after trimming and thinning		**399.840296**
Shift due to bulk BCP (140 microns)	-39.441	
Cavity after bulk BCP		399.800855
Weld shrinkage	115.645	
Weld bead	5.000	
Cavity after final weld		399.921500
Shift due to light BCP (20 microns)	-5.762	
Cavity after light BCP		399.915738
Shift due to mounted couplers	4.906	
Fully assembled cavity with HOM couplers		399.920644
Pressure effect (760 Torr differential)	-60.800	
Dielectric effect air to vacuum	130.341	
Evacuated cavity at 20 C		399.990185
Thermal shrinkage	572.877	
Colled down cavity at 4.2 K		400.563062
Shift due to change in skin depth	28.000	
Cavity frequency adjusted for skin depth		400.591062
Pressure from 760 Torr to 23 Torr in He tank	58.960	
Cooled down cavity at 2.0 K		400.650022
Shift due to tuner activation to its mid range	150.000	
Cavity with tuner activated		400.800022
Lorentz detuning	-10.022	
Operational cavity with RF on		400.790000

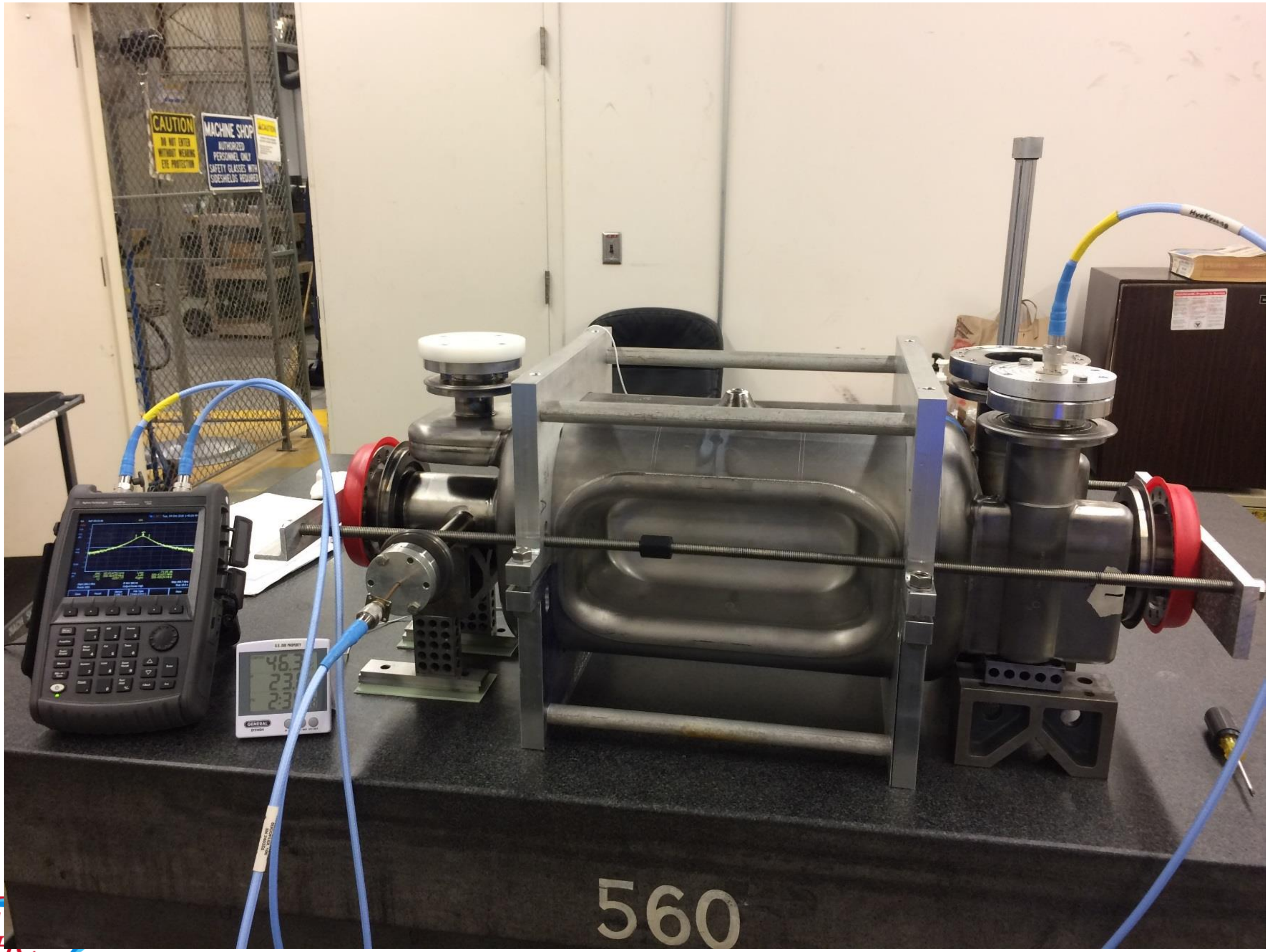
Achieved after trimming - 399.845874 MHz

CAV-002

Step (Recipe for 20 C, 50 % and 1013.25 mbar)	Δf	f_n
	[kHz]	[MHz]
Cavity after sub-assembly fabrication		399.843949
Shift due to bulk BCP of End Plates (140 microns)	-26.988	
Cavity after trimming and thinning		**399.816961**
Shift due to bulk BCP of Center Body (140 microns)	-16.106	
Cavity after bulk BCP		399.800855
Weld shrinkage	115.645	
Weld bead	5.000	
Cavity after final weld		399.921500
Shift due to light BCP (20 microns)	-5.762	
Cavity after light BCP		399.915738
Shift due to mounted couplers	4.906	
Fully assembled cavity with HOM couplers		399.920644
Pressure effect (760 Torr differential)	-60.800	
Dielectric effect air to vacuum	130.341	
Evacuated cavity at 20 C		399.990185
Thermal shrinkage	572.877	
Colled down cavity at 4.2 K		400.563062
Shift due to change in skin depth	28.000	
Cavity frequency adjusted for skin depth		400.591062
Pressure from 760 Torr to 23 Torr in He tank	58.960	
Cooled down cavity at 2.0 K		400.650022
Shift due to tuner activation to its mid range	150.000	
Cavity with tuner activated		400.800022
Lorentz detuning	-10.022	
Operational cavity with RF on		400.790000

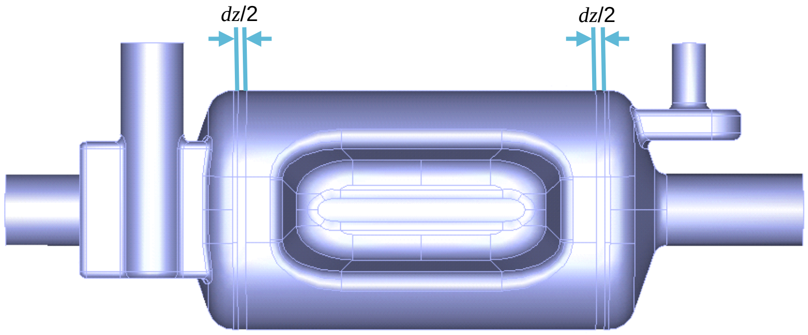
Achieved after trimming - 399.809239 MHz

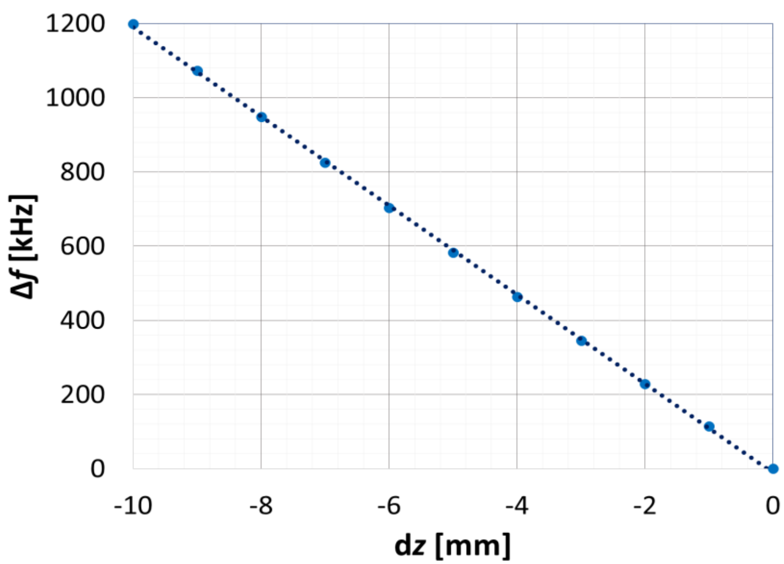
RFD Frequency Measurement Setup



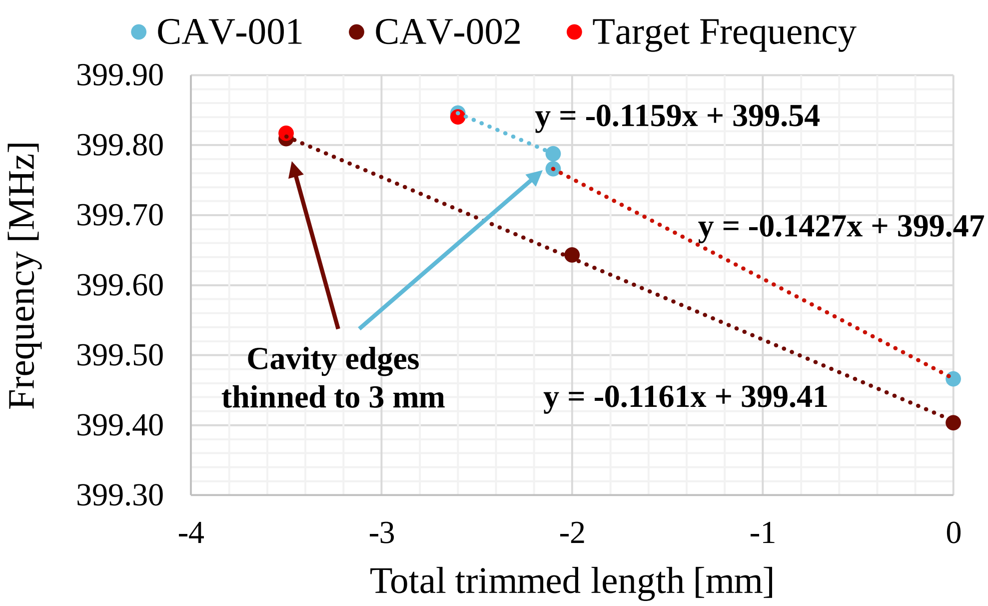
RFD Frequency Measurements

- Trim center body to achieve target frequency at pre welding
- **d*f*/dz = -119.85 kHz/mm**

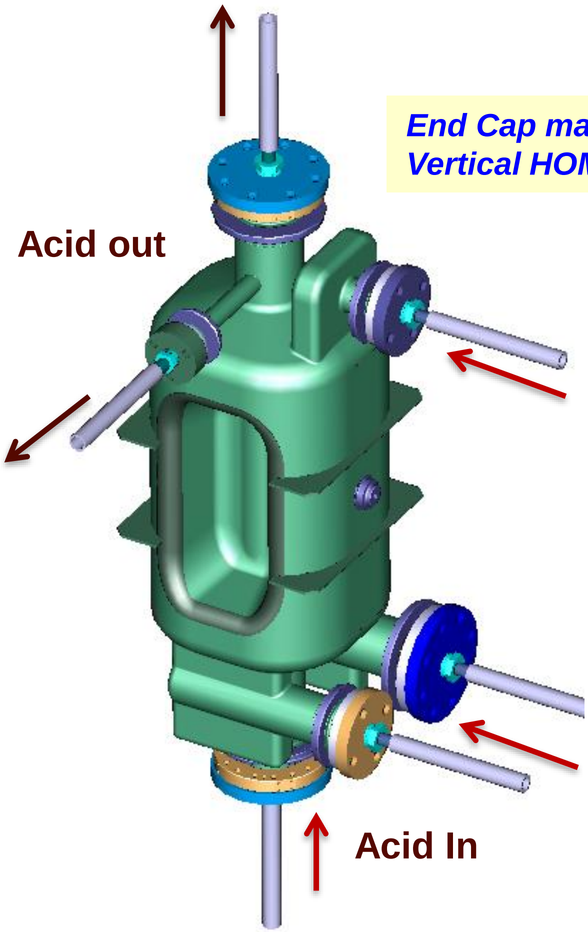




- Trimming sensitivity for
  - CAV-001 → **d*f*/dz = -129.3 kHz/mm**
  - CAV-002 → **d*f*/dz = -116.1 kHz/mm**

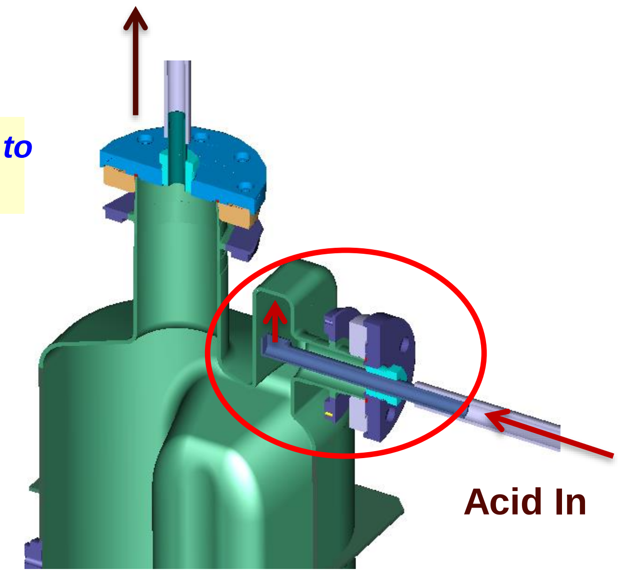


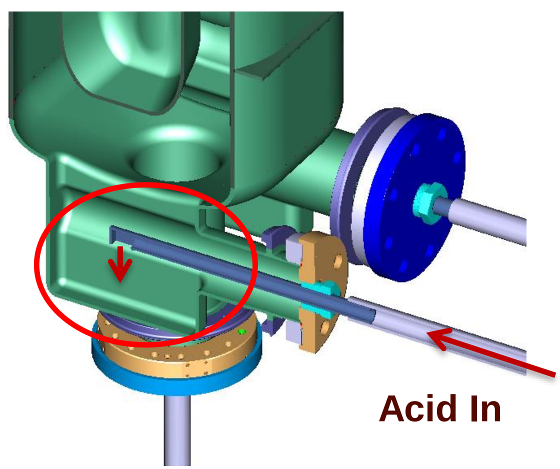
Final BCP Closed Chemistry Cabinet

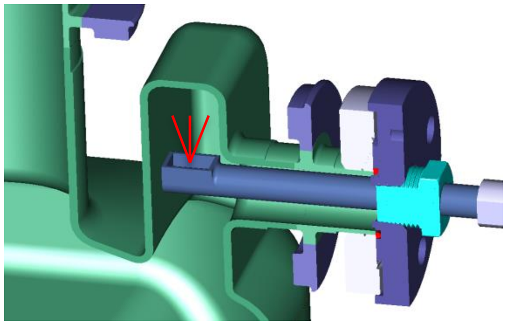


End Cap mating to Vertical HOM

End cap mating to Horizontal HOM





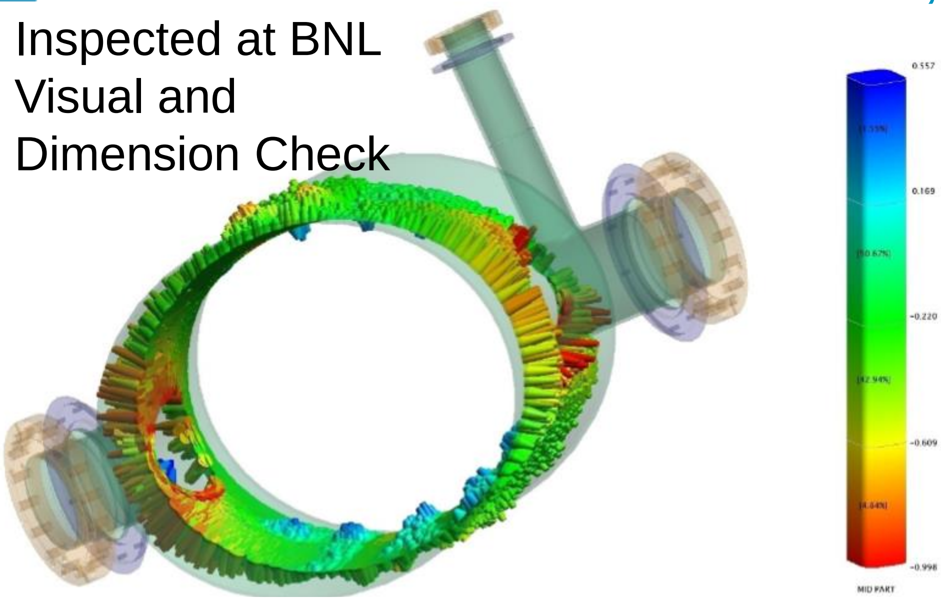


Chemical Injection Quill "*Snorkel*" directs the flow of Acid & Water

DQW cavities at BNL

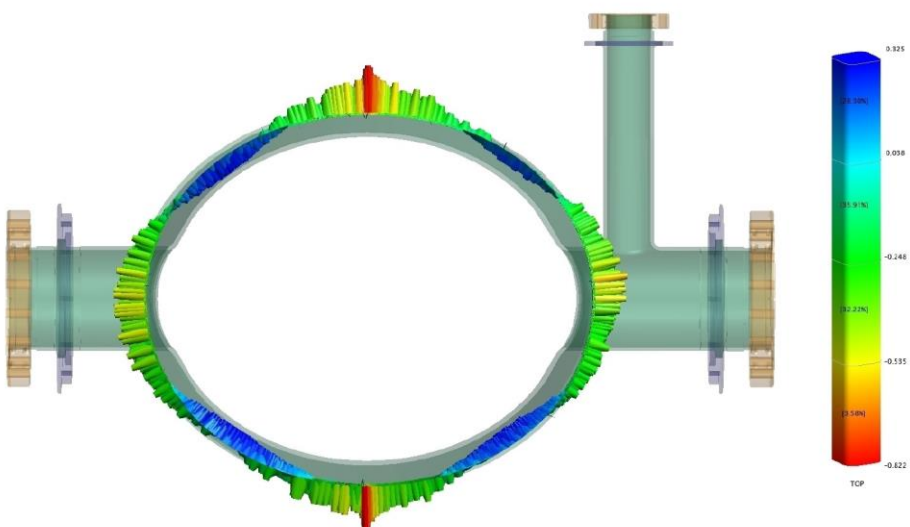
Jun 26, 2016

Inspected at BNL
Visual and
Dimension Check



All Vectors Summary: Vector Group ANALYSIS::MID PART				
Statistic	dX (mm)	dY (mm)	dZ (mm)	Mag (mm)
Min	-0.781	-0.849	-0.674	-0.998
Max	0.754	0.907	0.491	0.557
Average	0.006	0.002	0.001	-0.227
StdDev from Avg	0.216	0.211	0.056	0.207
StdDev from Zero	0.216	0.211	0.056	0.307
RMS	0.216	0.211	0.056	0.307
Tol Range				-0.400
				0.400
In Tol				8010 (80.6%)
Out Tol				1930 (19.4%)
Count	9940			

Profile spec ≤ 0.8 mm

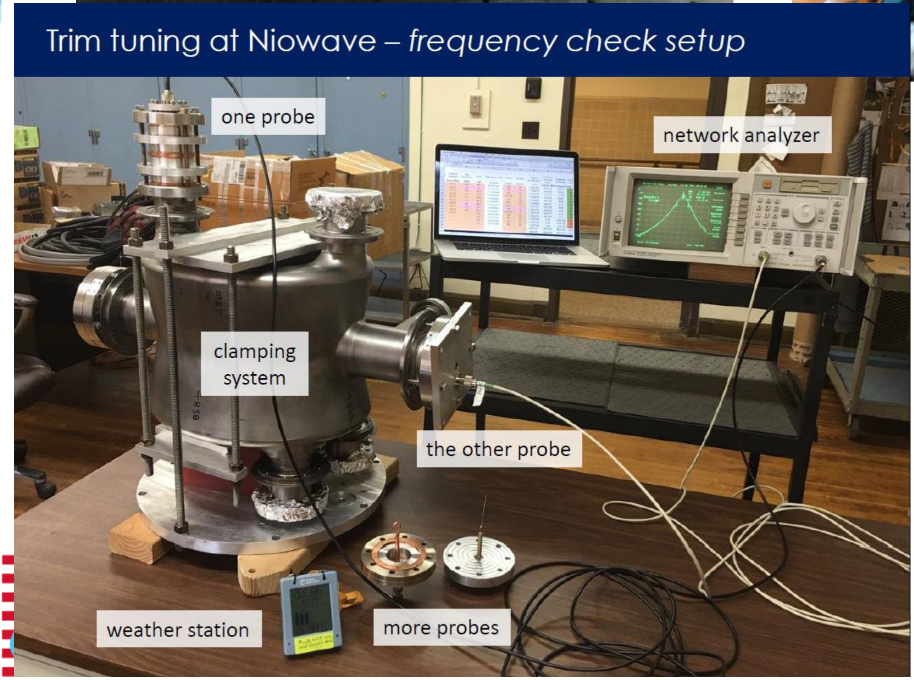


All Vectors Summary: Vector Group ANALYSIS::TOP			
Statistic	dX (mm)	dY (mm)	MagXY (mm)
Min	-0.822	-0.566	-0.822
Max	0.810	0.517	0.325
Average	0.006	-0.002	-0.131
StdDev from Avg	0.218	0.153	0.232
StdDev from Zero	0.218	0.153	0.267
RMS	0.218	0.153	0.267
Tol Range			-0.400
			0.400
In Tol			5569 (87.0%)
Out Tol			834 (13.0%)
Count	6403		

Edge deviation 9.293 mm down from the edge

DQW n 1 Final Trimming at Niowave

15 Sep 2016



Evolution of LARP proposals

LARP initial proposal was to contribute all cryomodules, for both the SPS test and the HL-LHC then….

- **Nov 2013**
  - LARP and CERN realize this was too ambitious
  - New LARP scope → deliver all cold masses only
- **May 2014**
  - CC System External Project Review
    - A. Yamamoto (Chair), M. Champion (SNS), A. Facco (INFN), M. Kelly (ANL), C. Pagani (U. Milano), H. Padamsee (Cornell/FNAL)
  - Down-selected cavities and established a prioritization criteria for SPS CC production
- LARP is not able to secure funding for M&S and cavity fabrication
  - Only option to team up with an ongoing SBIR effort at Niowave
    - No contractual agreement between Niowave and LARP

Evolution of LARP proposals (2)

- **Aug. 2014**
  - Niowave starts the extensive manufacturing qualification process requested by CERN
- **Winter of 2014/5**
  - LARP and CERN agree to modify the scope of the collaboration a second time
    - CERN loans magnet wire to LARP freeing up M&S funds
    - LARP engages JLAB to weld all cavity parts, process and test the completed cavities
    - Niowave agrees to provide formed cavity parts for welding at JLAB
- **March 2015**
  - CERN takes on responsibility for tuners and HOM dampers for the SPS
    - LARP held the HOM Design Review - Feb. 2015, JLAB
  - LARP now delivering for the SPS only DQW and RFD cavities with He tanks

Evolution of LARP proposals (3)

- **May 2015**
  - Niowave informs the collaboration that it will weld cavity subassemblies
  - JLAB is now only welding the final sub-assemblies
- **August 2015**
  - Niowave provides the first welded cavity parts for inspection
- **October 2015**
  - After a ~6 months process, JLAB receives the funding to start the work

Evolution of LARP proposals (4)

- **Jan 2016**
  - CERN starts its effort to produce DQW cavities for the SPS
  - LARP decides to build bare cavities only, without He tanks
    - CERN and LARP agree the DQW cavities produced at CERN are the lead candidate for integration in the SPS test.

- **Mar 2016**
  - In light of schedule constraints for the SPS test, CERN decides to test the DQW first, before LS2
  - The RFD prototypes for the HL-LHC will be tested after LS2

- **May 2016**
  - LARP-AUP and CERN agree on the US contribution to the HL-LHC: limited to all RFD dressed cavities only.

The Team – Principal Contributors

- LARP
  - BNL – Q.Wu, S. Verdu-Andres, B. Xiao, J. Skaritka, Ilan Ben-Zvi
  - FNAL – C. Ginsburg, T. Nicol, T. Peterson, L. Ristori
  - JLAB – A. McEwen, E. Daly, H. Park (also ODU)
  - LBNL – J. Qiang
  - ODU – J. Delayen, S. De Silva, H. Park
  - SLAC – Z. Li, A. Ratti (formerly LBNL)

- World Wide Collaboration
  - CERN – R. Calaga, O. Capatina, M. Garlasche', C. Zanoni
  - STFC – G. Burt, N. Templeton, T. Jones

- Many others are actively involved, in particular in the work centers of CERN and JLAB
  - and many contributed in the past

LARP Team Organization

- Cavity EM Design - BNL, ODU/SLAC
  - RF measurements, Frequency Analysis (w. Proc.), HOM studies
- Cavity processing and testing – Jefferson Lab
  - Parts inspection and acceptance
  - Welding (w. procedures)
  - Chemistry (w. procedures)
  - Vertical Testing (w. procedures)
- Project Coordination – SLAC
- Project Engineering – FNAL
  - Development of Pre-Series cavities
  - Planning for AUP

Working as a team, everyone encouraged to contribute

CERN actively involved