RFD Industrial Production Challenges

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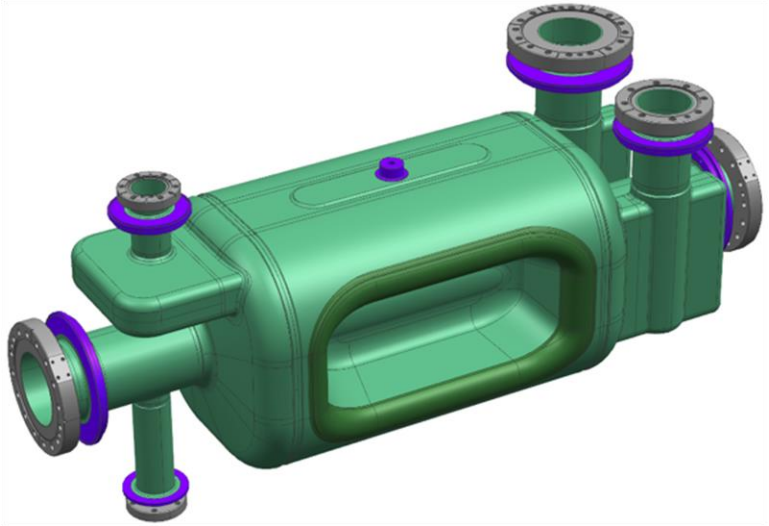
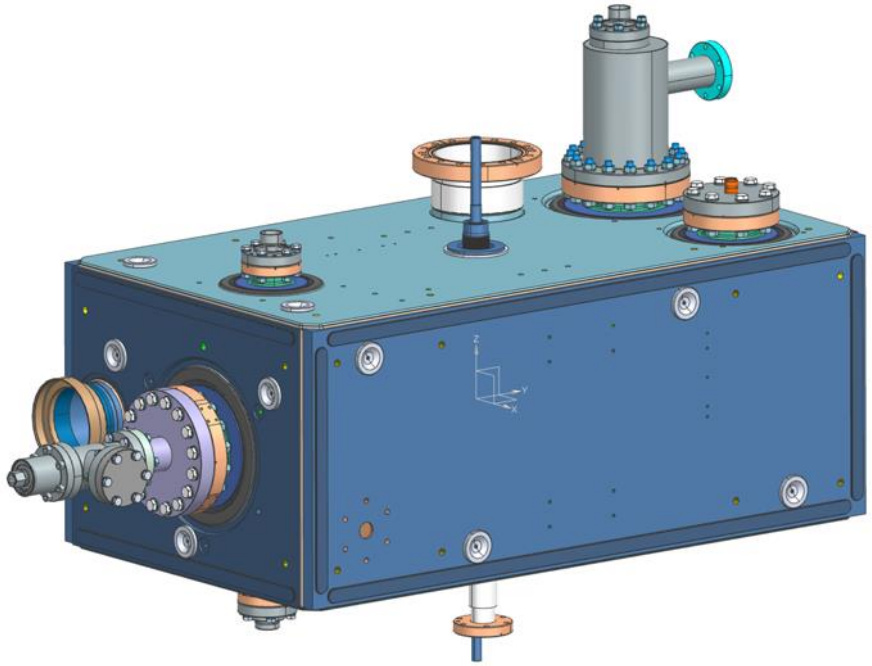
14th HL-LHC Collaboration Meeting – Oct 7th – 10th, 2024

Outline

- Fabrication & Processing Challenges at ZRI
- Production and QA/QC status
- Summary





Fabrication & Processing Challenges at ZRI*

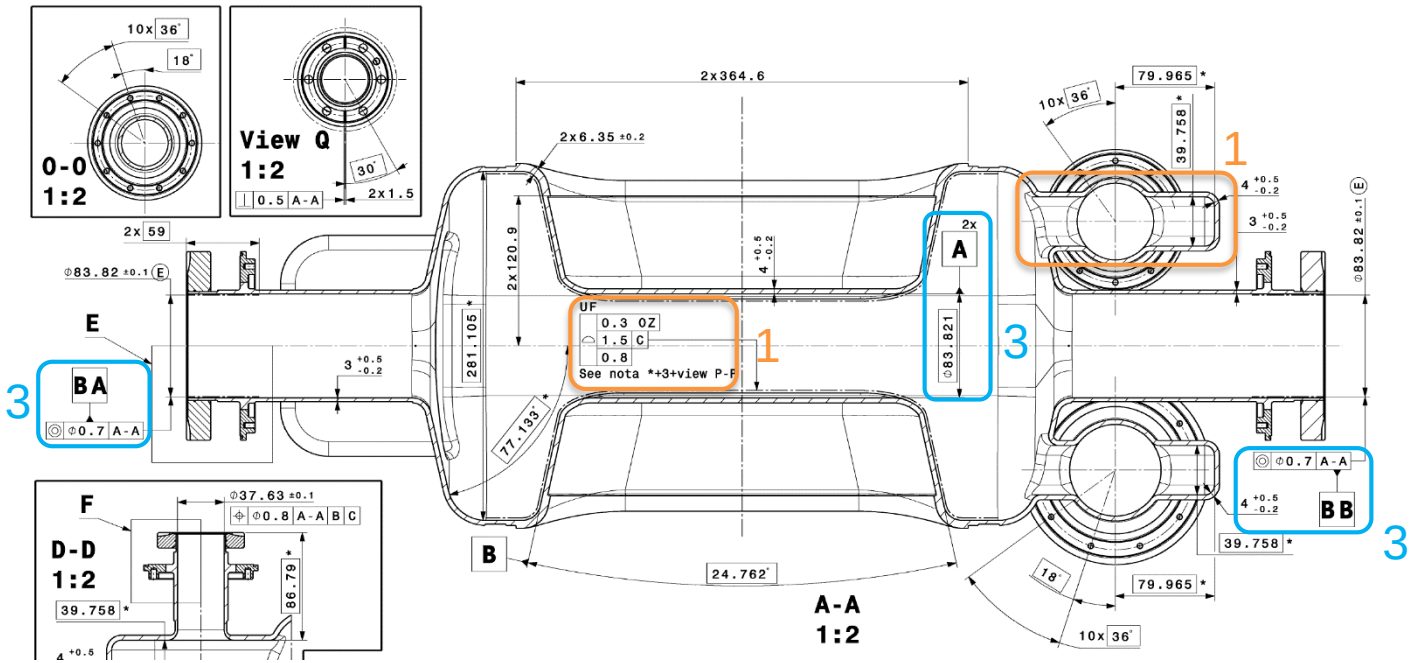
Recap

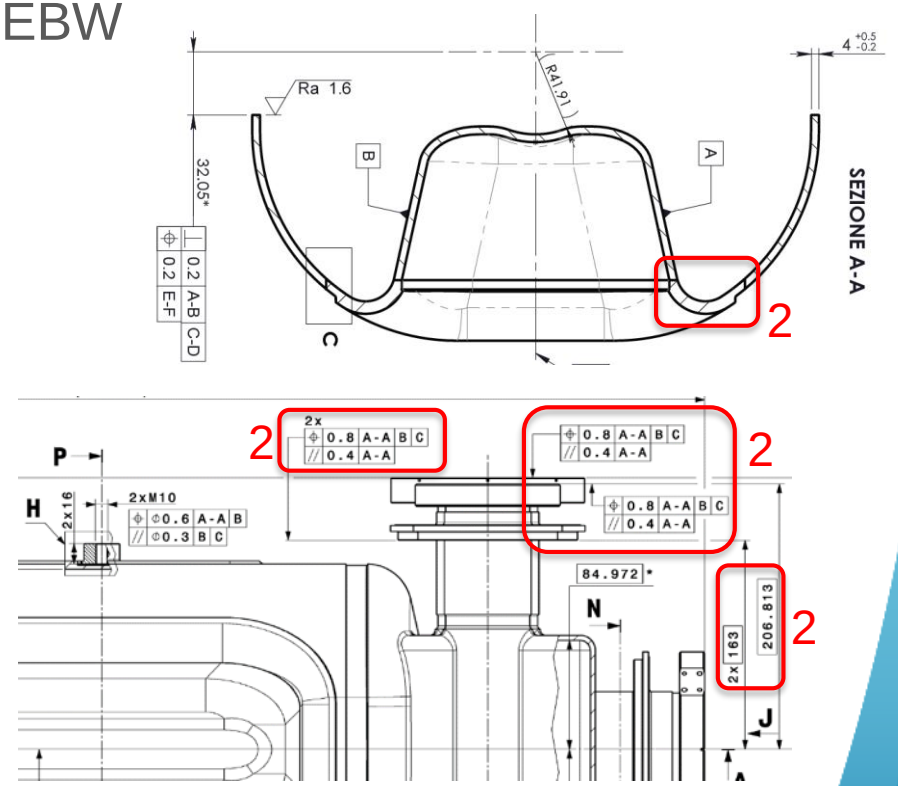
- Achieving the tight tolerances remains an issue and it's driving the schedule
- HPR & BCP are challenging due to the Crab geometry
- QA documents are still not fully approved and contingent on qualifications
- Logistics and international shipping requires considerable coordination

Fabrication & Processing Challenges at ZRI*

RFD Bare Crab Cavities: Manufacturing Challenges

- RFDs required sub-mm tolerances for manufacturing and EBW of complex parts:
  1. Mechanical tolerances on stamped/coined subcomponents (poles & waveguides)
  2. Complex EBW between *Half Main Body* sub-components & *Waveguides Boxes - End Caps*
  3. Alignment between *End Groups-Main Body* during final EBW





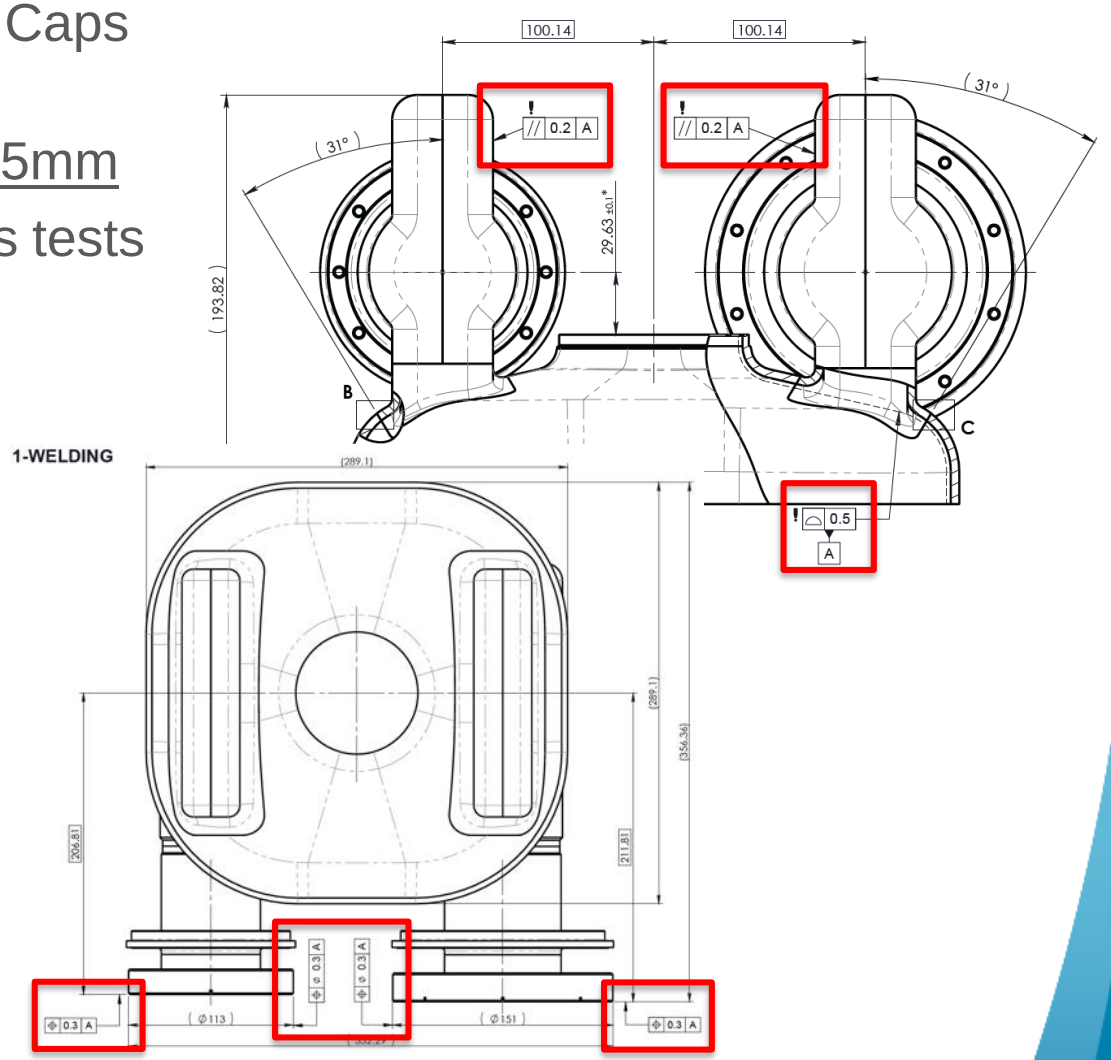
Manufacturing is still facing difficulties for the technological limits/ available resources

*Zanon Research and Innovation srl

Fabrication & Processing Challenges at ZRI

2b- EBW between Waveguides Boxes - End Caps

- Complex EBW between Waveguides boxes and End Caps
  - parallelism better 0.2mm + positioning within 0.3mm
- Variable radii welds to keep shape accuracy below 0.5mm
- ZRI refined the EBW and CNC tooling after numerous tests



ZRI is still improving EBW results on series RFD, even after a lot of experience

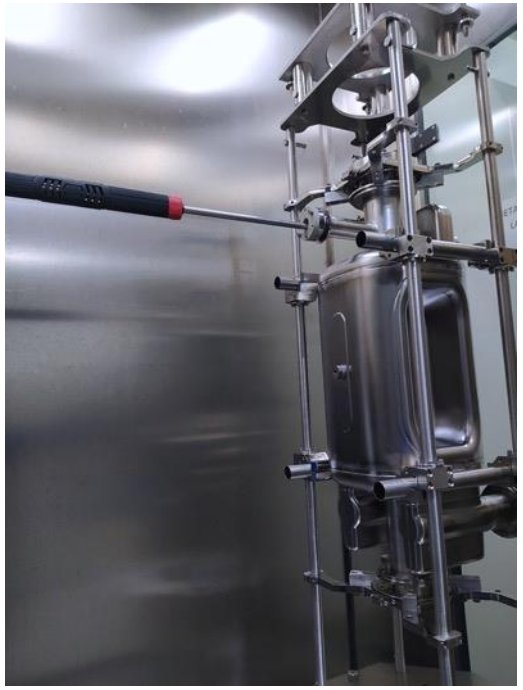
Fabrication & Processing Challenges at ZRI

RFD Bare Crab Cavities: Processing Challenges

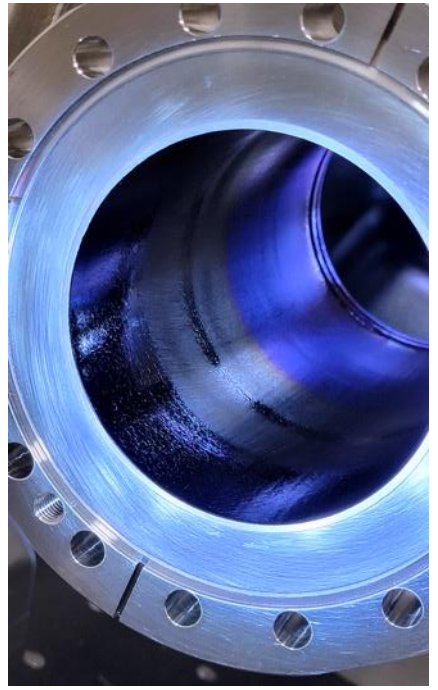
The RFDs processing, due to the RFD Crab geometry, involved great effort at ZRI:

1. Updated rotational BCP machine → after over-etching issues discovered on NRFDP001
2. Implementation of manual HPR on cavity ports → to improve the cavity performances
3. Optimization of automatic HPR parameters → to avoid oxidation on beam ports

Over-etching on NRFDP001



Manual HPR on RFD ports



Oxidation after automatic HPR

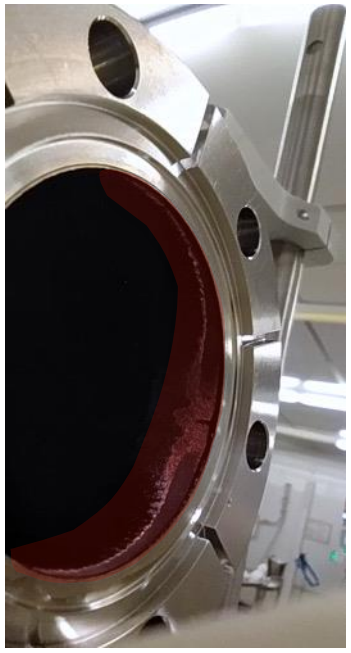
HPR improvements and over-etching issues due to BCP are causing delays

Fabrication & Processing Challenges at ZRI

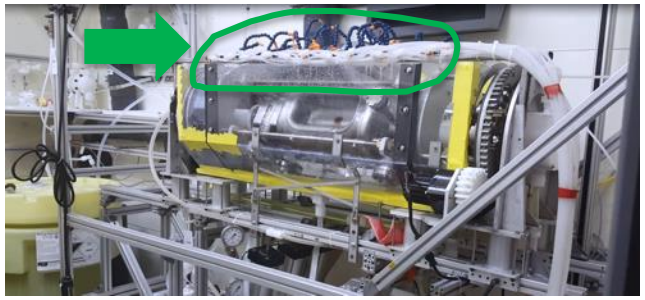
1- Update Rotational BCP machine

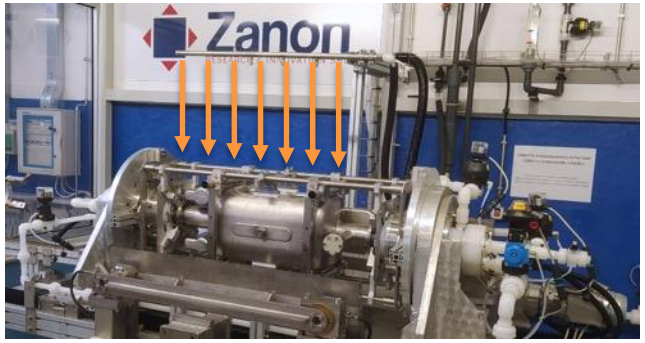
Excessive etching on all ports, during the 3rd rotational BCP of NRFDP001 at ZRI, damaged the V-HOM & Pick-Up ports (exposing the brazing alloy).

- BCP procedure at ANL vs ZRI: powerful waterjet cooling at ANL while water misting at ZRI
- CMM and Visual Inspection performed at JLAB to collect data on available cavities:
  - BCP at ANL → uniform removal; BCP at ZRI → up to 435µm removed vs 220µm targeted
  - VT of inner ports' surfaces: smoother for RFDP002 vs rougher on pre-series

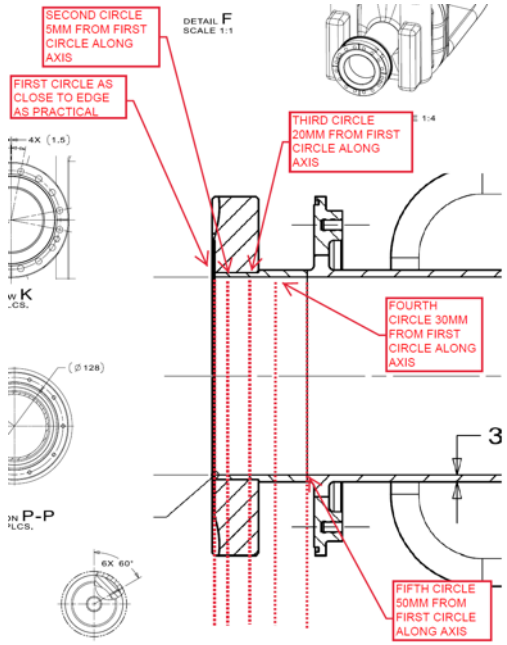


Exposed Cu after BCP

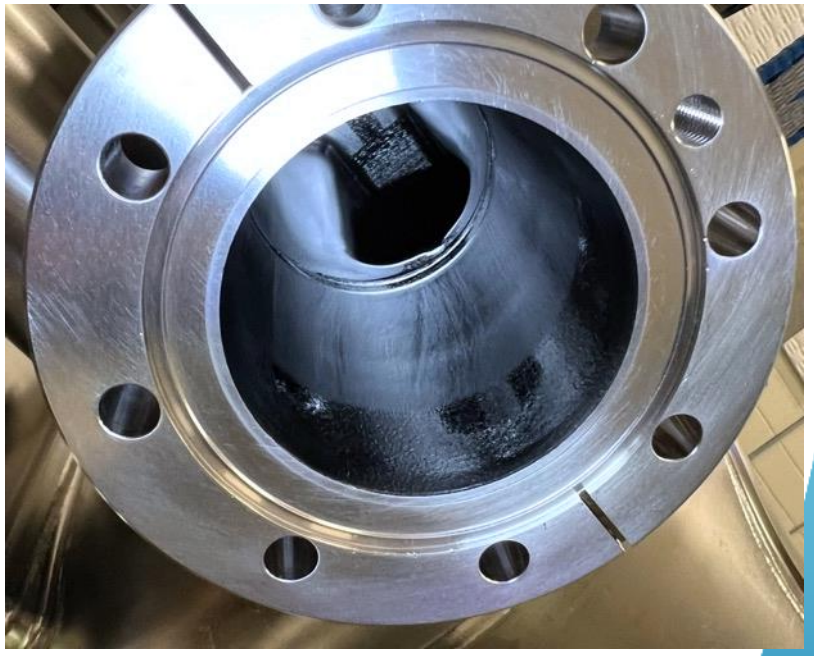




ANL vs ZRI cooling during BCP



CMM data captured at JLAB



BCP streaks on inner surface

Rotation BCP at ZRI updated with improved cooling, successfully tested.

Fabrication & Processing Challenges at ZRI

2- Implementation of manual HPR on cavity ports

- HPR performed at ZRI on NRFD01 → poor performances during VTA at JLAB
- ✓ HPR at JLAB on NRFD02 → success, using manual rinsing of the ports (before automatic HPR)
- ➢ ZRI reprocessed NRFD01 using manual HPR of ports → Particle count decrease considerably
- ❖ Imminent cold test at FNAL will provide final feedback on updated ZRI processing

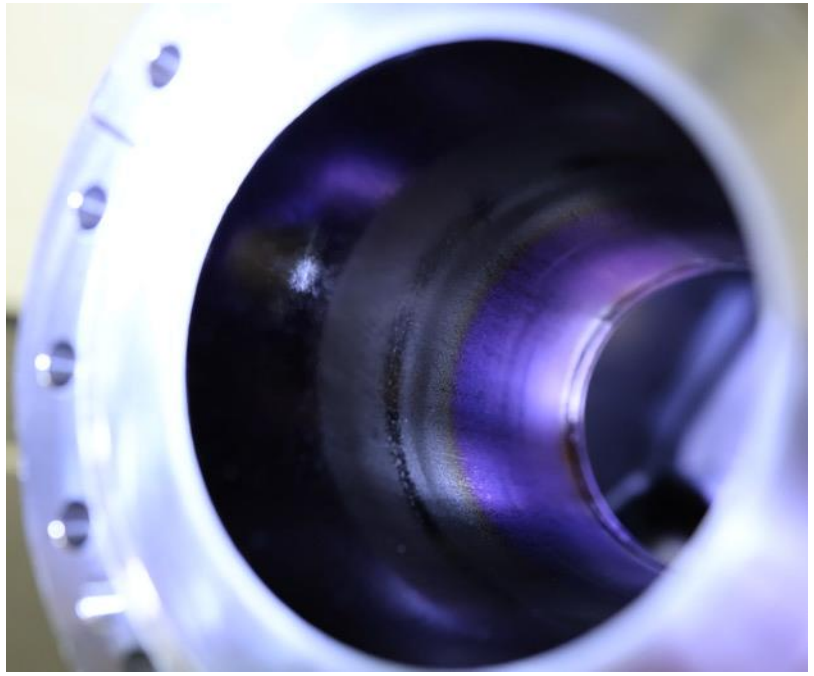
Position	Particle count (previous HPR)	Particle count (updated HPR)
V-HOM Beam tube	190	9
Pick-Up Flange	57	6
V-HOM Flange	51	7
H-HOM Flange	106	8
FPC Flange	73	10
FPC Beam Tube	222	3

Zanon updated the HPR procedure using manual HPR on all the ports following JLAB experience

Fabrication & Processing Challenges at ZRI

3- Optimization of automatic HPR parameters

- A blue-ish oxide layer on Beam Ports of NRFD01 noticed at JLAB (HPRed only at ZRI)
- ZRI HPR procedure was targeted for an upgrade after tests on JLAB (only) HPRed cavities:
  - Upward/downward constant speed: benefits? Avoid stationary waterjet & increase rinsing time
- Updated HPR paramenter + port manual HPR → expecting to increase NRFD01 VTS results



Oxidation after first HPR at ZRI

No oxidation after improved HPR procedure

ZRI updated the automatic HPR parameter, driven by JLAB positive results. Imminent VTS

Fabrication & Processing Challenges at ZRI

RFD Crab Cavities: QA/QC Approval Challenges

The RFDs manufacturing at ZRI required continuous QA/QC follow-up and approval (AUP & CERN):

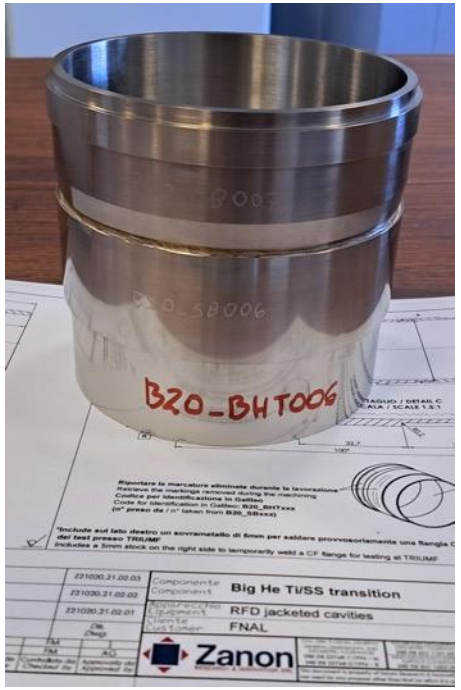
1. QA requirements feedback from industry → uncommon requests for Pressure Equipment Cat 1
2. Feedback and approval on ZRI QCRs and NCRs → AUP & CERN joint effort to minimize delays
3. Brazed Joints approval → Shear testing and UT of Ti/SS joints for He tanks is ongoing

Zanon RESEARCH & INNOVATION SRL	Non Conformity Report		NCR-076
			Rev.0
JOB N°:	Z22013	**ITEM N°:**	FBW110
Drawing:	3326.12.200.000	**Page:**	1 of 2

QUALITY CONTROL SERVICE — Zanon RESEARCH & INNOVATION SRL

VISUAL EXAMINATION REPORT Certificato esame visivo			**Pag 1 di 1** Sheet 1 of 1
			Doc. ID --
Customer Cliente	FNAL	**P.O. No.** Ordine N°	647590
Project Progetto	RFD CRAB CAVITY	**Job No.** Commessa	Z20008
Drawing Disegno	3326.12.131.130	**Serial No°** N° itentificativo	FTR003
QCP No. PCQ N°	Z20008.QCP.001	**Step No.** Fase N°	4.9

NCR and QCR examples from ZRI



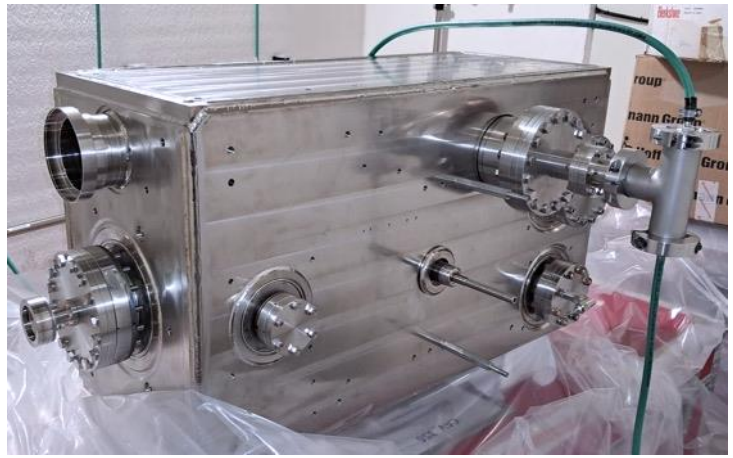
Small and Big TI/SS transitions in qualification

QA/QC approval requires a significant effort from AUP and CERN to minimize delays

Production status

Summary of contracts between AUP and industry (ZRI)

- 12x AUP Pre-series + Series Bare RFDs manufacturing and processing:
  - NRFD01 has been re-processed to remove oxide layer at ZRI, qualification in VTS (FNAL) in Nov 2024
  - NRFD02 qualified via cold tests at both JLAB and FNAL, finalizing QA/QC
  - NRFD03/04 undergoing EBW/ trim-tuning at ZRI, NRFD05-12 subcomponents ready for welding, some QA pending
- 10x AUP Series Jacketed RFDs production:
  - manufacturing of subcomponents ongoing, imminent installation of He Tank onto NRFD02, pending some QA approval
- 2x AUP Prototypes Bare RFDs manufacturing and processing
  - NRFDP002 exceeded functional requirements, processed at ANL. NRFDP001 damaged after reprocessing at ZRI.
- 1x AUP Prototype Jacketed RFD production:
  - RFDP002 has been successfully jacketed at ZRI, waiting for VTA qualification w/wo ancillaries at JLAB by beg. 2025



Production is challenging but under control, schedule is tight. QA/QC need to be finalized

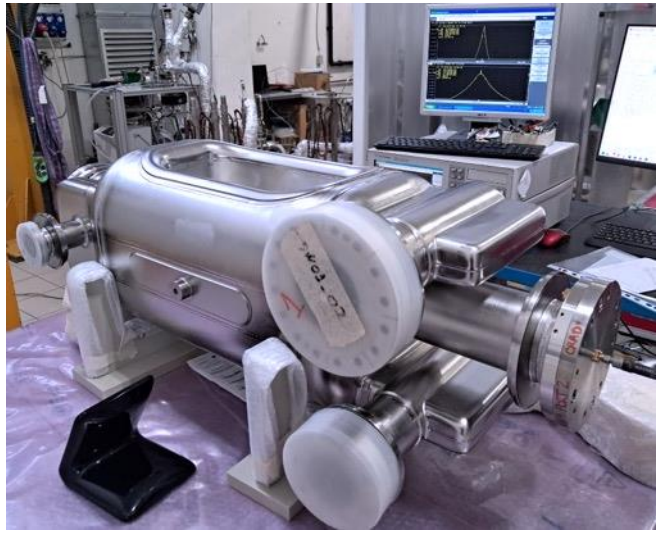
Fabrication and QA/QC Status

AUP RFD bare pre-series production (ZRI)

2 x Pre-series RFDs (PO 647590) manufactured and processed at ZRI:

- NRFD01 recently reprocessed at ZRI to remove blue-ish oxide layer. VTS at FNAL in Nov 2024
- NRFD02 qualified in JLAB/FNAL cold tests (see A. Castilla talk), imminent jacketing at ZRI
- Finalizing QA/QC in MTF for final endorsement of bare cavities
- NCR about excessive removal from BCP at ZRI has been approved by WP4
- Both cavities need frequency ”correction” before Jacketing (to reach the update target)



NRFD01: VTS in Nov 2024 at FNAL. NRFD02 imminent jacketing at ZRI

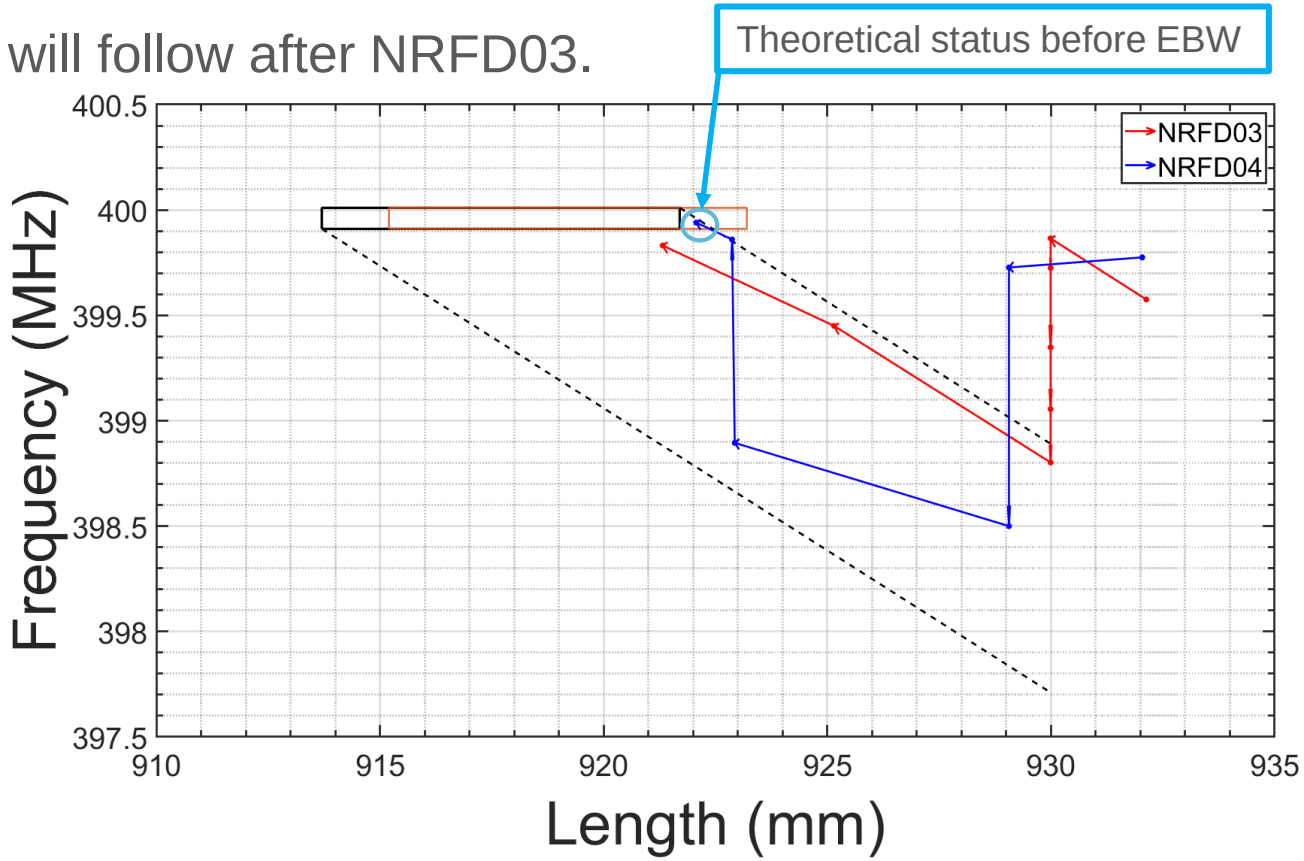
Fabrication and QA/QC Status

AUP RFD series production (ZRI)

10 x Series bare cavity are undergoing manufacturing at ZRI

- NRFD03 final EBW imminent.
- NRFD04 in last stage of trimming, EBW will follow after NRFD03.
- NRFD05 & 06:
  - Ongoing CNC of main bodies to be ready for trim tuning
  - Imminent EBW of Waveguides Boxes onto End Caps
- NRFD07– 12:
  - Subcomponents mostly ready to start welding

❖ <u>Automatic UT (C-scan) of brazed joints required to finalize QA docs</u>

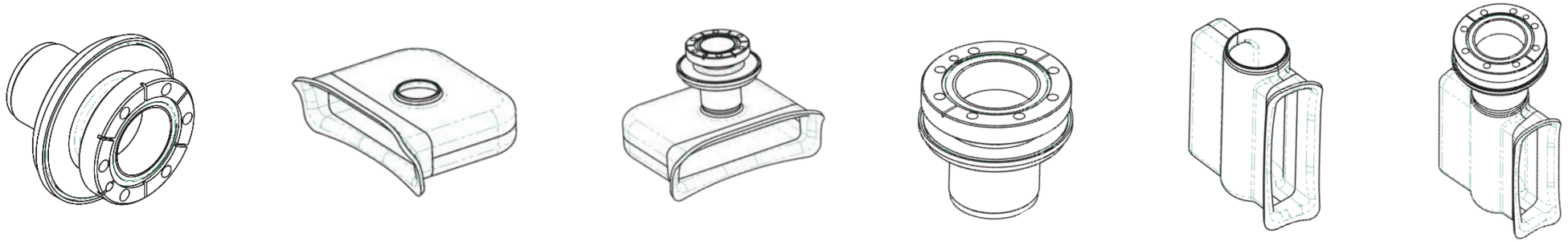


Series bare cavities is advancing. Priority on NRFD03-5. Tight schedule for QA/QC approval

Fabrication and QA/QC Status

AUP RFD series production (ZRI)

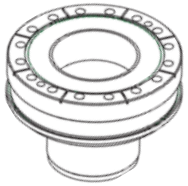
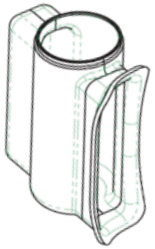
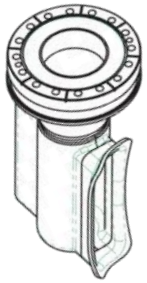
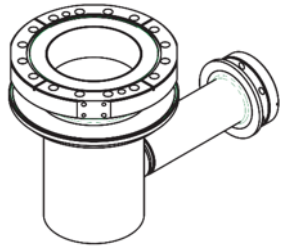
	C: V-HOM Wave Guide Weldment			D: FPC Wave Guide Weldment		
QCP STEP No.	**1**	**2**	**3**	**4**	**5**	**6**
Items	**V-HOM Port Weldment**	**V-HOM WG with Insert**	**V-HOM WG Weldment**	**FPC Port Weldment**	**FPC WG with Insert**	**FPC WG Weldment**
Drawing	**3326.14.121.000**	**3326.14.122.000**	**3326.14.120.000**	**3326.12.131.200**	**3326.12.132.000**	**3326.12.130.000**
NRFD03	100%	100%	100%	100%	100%	100%
NRFD04	100%	100%	100%	100%	100%	100%
NRFD05	100%	100%	100%	100%	100%	100%
NRFD06	100%	100%	100%	100%	100%	100%
NRFD07	48%	82%	0%	61%	84%	0%
NRFD08	48%	82%	0%	61%	84%	0%
NRFD09	48%	82%	0%	61%	84%	0%
NRFD10	48%	82%	0%	61%	84%	0%
NRFD11	48%	82%	0%	61%	84%	0%
NRFD12	48%	82%	0%	61%	84%	0%



V-HOM, FPC and H-HOM waveguides, respectively

Fabrication and QA/QC Status

AUP RFD series production (ZRI)

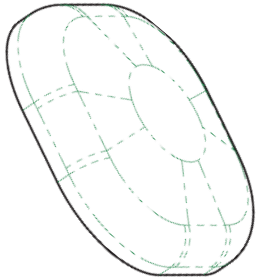
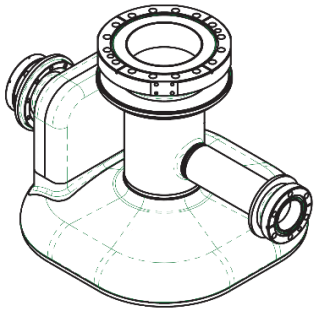
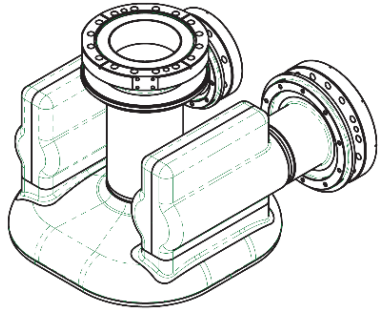
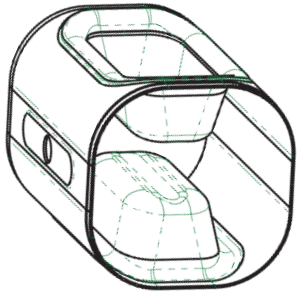






E: H-HOM Wave Guide Weldment			F: Beam Tubes	
7	8	9	10	11
H-HOM Port Weldment	H-HOM WG with Insert	H-HOM WG Weldment	V-HOM Beam Line Weldment	FPC End Group Beam Line Weldment
3326.12.121.100	3326.12.122.000	3326.12.120.000	3326.14.200.000	3326.12.200.000
100%	100%	100%	100%	100%
100%	100%	100%	100%	100%
100%	100%	100%	100%	83%
100%	100%	100%	100%	83%
48%	63%	0%	40%	83%
48%	63%	0%	40%	83%
48%	63%	0%	40%	22%
48%	63%	0%	40%	22%
48%	63%	0%	40%	22%
48%	63%	0%	40%	22%


Example of CNC machined extremities.
Beam Axis tube ready for welding with pick-up extremity

Fabrication and QA/QC Status

AUP RFD series production (ZRI)

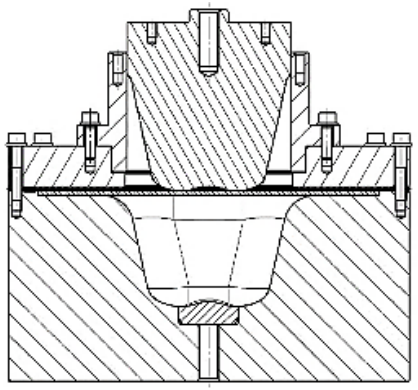
End Groups and Main Body weldment			
12	13	14	15
End Cap	V-HOM End Group	FPC End Group	Main Body Weldment
3326.12.111.001	3326.14.000.000	3326.12.000.000	3326.13.000.000
100%	100%	100%	100%
100%	100%	100%	100%
100%	25%	26%	62%
100%	25%	26%	62%
100%	21%	22%	53%
100%	21%	22%	53%
100%	21%	22%	34%
100%	21%	22%	34%
100%	21%	22%	34%
100%	21%	22%	34%

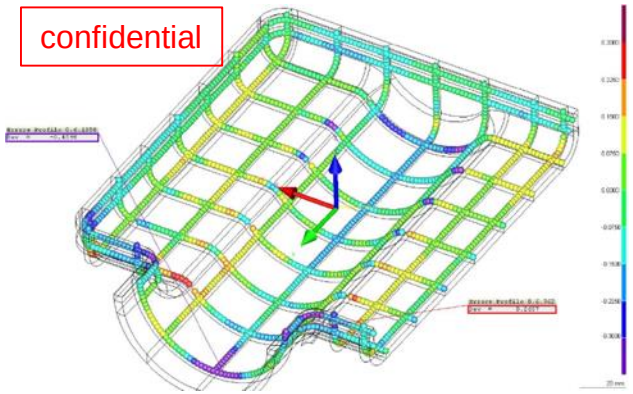
Fabrication and QA/QC Status

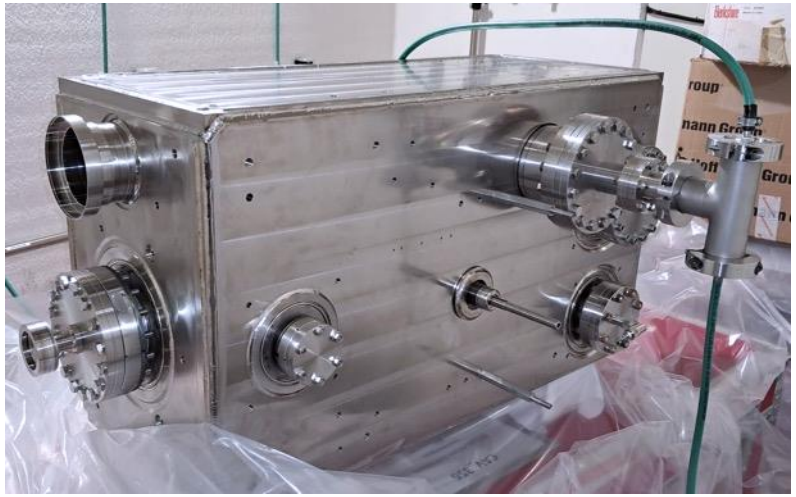
AUP RFD Prototypes qualification (ZRI)

2 x RFD bare cavity prototypes (NRFDP001/002):

- ✓ Manufactured at ZRI (PO 647590) according to HL-LHC WP4 specs
- ✓ ZRI developed: fabrication dwgs, manufacturing & EBW tooling, procedures
- ✓ QA /QC exercised as series production on CERN EDMS* (MTF)
- ✓ QCs, Inspections & VTS tests procedures established at FNAL and JLAB
- ✓ VTS qualification: exceeded functional requirements w/wo ancillaries
  → see A. Castilla's talk
- ✓ NRFDP002 has been successfully jacketed as RFDP02
- ➢ NRFDP001 won't be jacketed but used for testing the revised BCP
- ✓ Rotational BCP and processing performed at ANL and ZRI



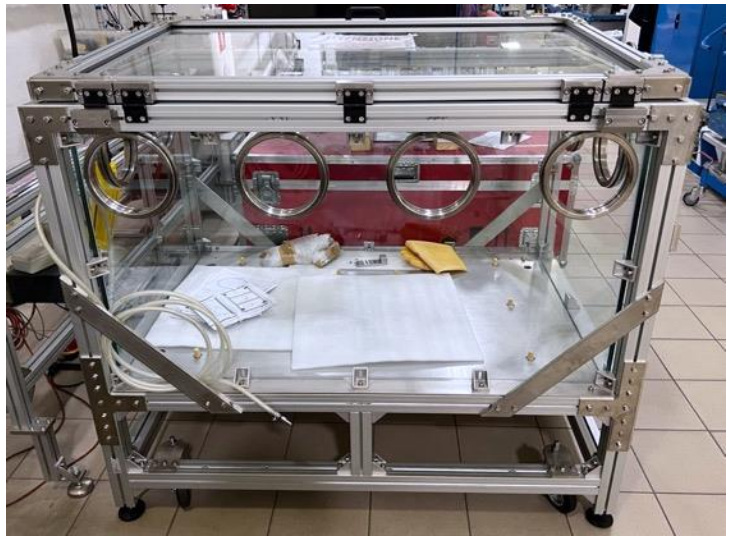


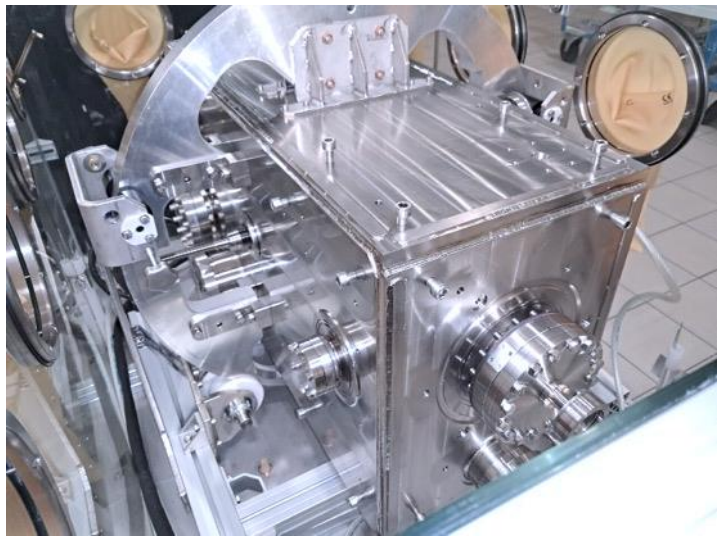


Prototypes paved the way for Series manufacturing & processing

Fabrication and QA/QC Status:
AUP RFD Jacketed Series Cavities (ZRI)

- ✓ PO 681514/ 705071 placed for jacketing and processing Series cavities
- ✓ All materials available at ZRI (Br Schnorr washers required loong procurement)
  - ❖ ZRI is finalizing the raw materials and bellows certificates
- ✓ Fabrication drawings have been approved, QA documentation is undergoing revision at ZRI
- ✓ Bi-metallic transition, brazed Ti/SS joints, in qualification at CERN
- ✓ Complex assembly procedure with minimal forgiveness: no issues
- ✓ Glove box and internal rotating qualified after RFDP02: no frequency shift after welding!





Manufacturing of jacketed RFDs is advancing constrained by QA and qualification approval

Fabrication and QA/QC Status:
Open QA/QC Issues

- Series bare cavities manufacturing is bound by UT C-scans of brazed joints Nb/SS
  - Final review of QCRs, NCRs, cold tests reports by CERN
- Jacketing of series cavities is constrained to:
  - Approval of raw material certificates (such as magnetic shield screws material in 316F)
  - Approval of QA docs (welding and brazing book in particular)
  - Qualification of Ti/SS Brazed joints

Summary & Conclusion

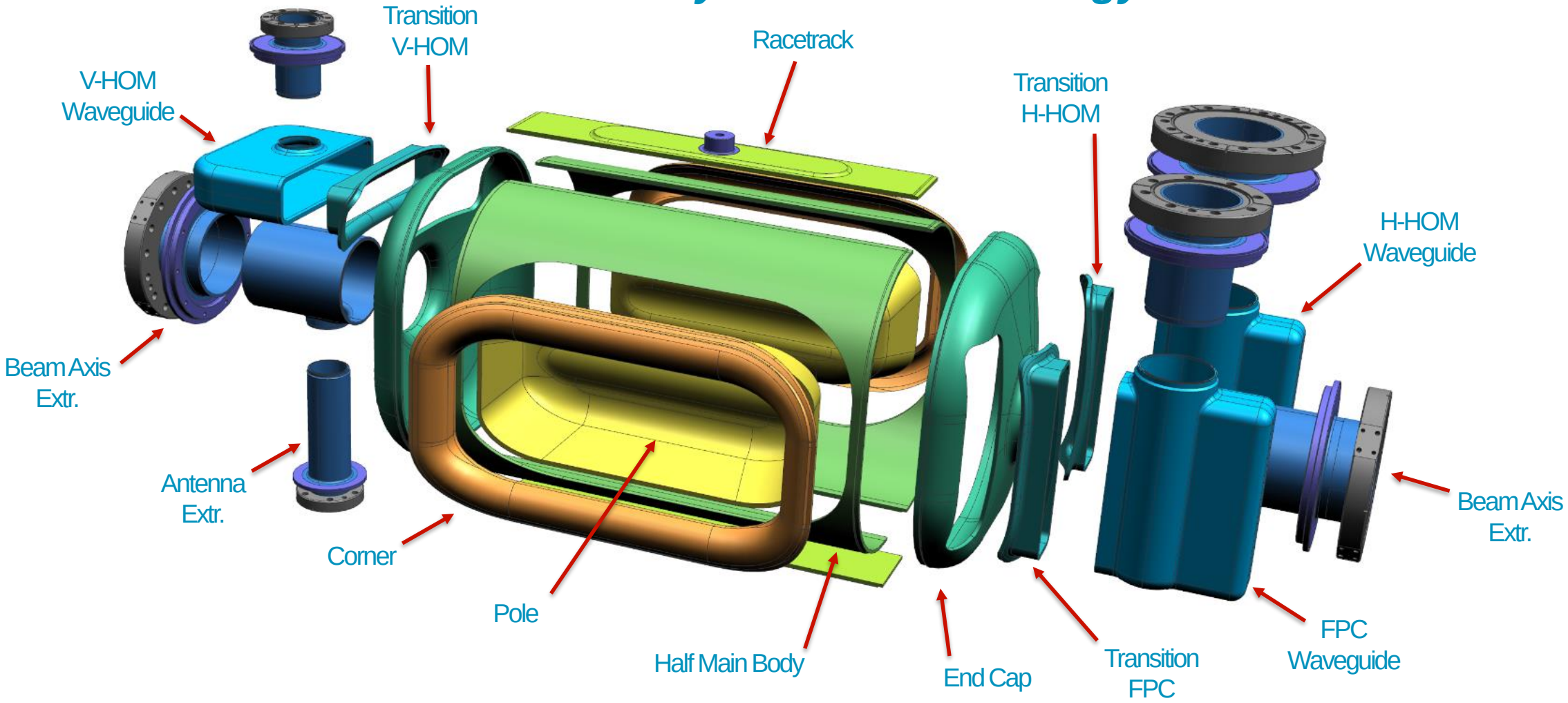
- The manufacturing and welding technologies are being pushed to their limits.
- Significant effort is needed for Processing at ZRI, with improvements in BCP and HPR expected to qualify in the next cold tests.
- Continuous monitoring is essential to address technological challenges in manufacturing, processing, and QA/QC.
- Logistics require careful coordination.

- All materials have been procured per approved specifications, though some certs need revision.
- Series bare cavity manufacturing is progressing well, with forming issues solved, while UT C-scans for Nb/SS brazed joints are still pending.
- RFDP02 has successfully validated glove box welding, showing no frequency shift during the welding of He Tank walls to the cavity.
- Final qualification of Ti/SS brazed joints and QA document approval are needed to complete the jacketed cavities.

Thanks for the attention!

Fabrication & Processing Challenges at ZRI

Bare RFD Crab Cavity fabrication strategy at ZRI



- Deep drawing of thick Nb sheets (4mm to 6.35mm); CNC machining and EBW interfaces as ZRI know-how
- CNC of transitions from Nb blocks & beam pipes from Nb tubes

QA/QCRs handling during fabrication (2):
process between AUP & CERN

- CERN is the “manufacturer” for AUP RFDs cavities (subject to PED)
- More than 3,000 reports for 10x full dressed cavities.

1. CERN: reviews and approves documentation prior to manufacturing:
   - Fabrication drawings and Manufacturing Procedures (MIPs, WPQRs, WPSs, BPQRs and BPSs)
   - NDTs, welders and brazing operators' certificates
   - Raw material certificates and UT reports

2. AUP: uploads and releases all QCRs in EDMS / MTF except the ones in point 3.

3. CERN reviews and releases the following QCs:
   - Bare Cavities: Freq. + CMM after EBW (before BCP). UT thickness (after last BCP). Cold RF tests + RGA.
   - Jacketed Cavities: PT + LT of both He Tanks and 2nd Beam Pipe + Cold RF tests + Frequency at 2K + RGA.
   - Dressed Cavities (JC + ancillaries): Cold RF tests + Frequency at 2K+ RGA after VTS
   - reviews and closes all the critical NCRs

“Approval Process MTF-EDMS for AUP RFD Crab Cavities and ancillaries” (EDMS 2896383)

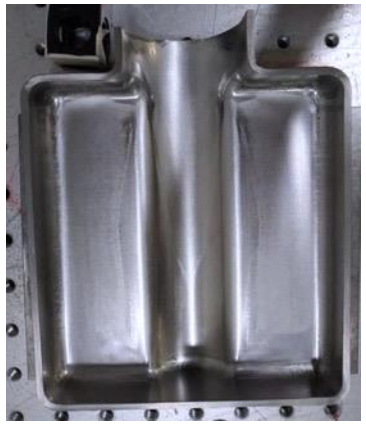
Fabrication & Processing Challenges at ZRI

1- Mechanical tolerances on stamped/coined subcomponents

- Poles and Waveguides, formed from the series Nb batch, showed non-repeatable results:
  - Same Nb supplier, same Nb sheet, same tooling, operators and pressing machine…→ Different results
  - ➢ Ex: ZRI adopted a 2-step Pole forming: better results due to friction reduction (confirmed by CERN sims)
  - Similarly, the waveguides required multiple coining steps to get to the shape and thickness requirements

Unacceptable Poles

Acceptable Poles from same Nb.



Arduous WGs coining

All the sub-components are available at ZRI for series production

Poles forming validated via Forming Limit Diagram failure criteria *Courtesy of CERN*

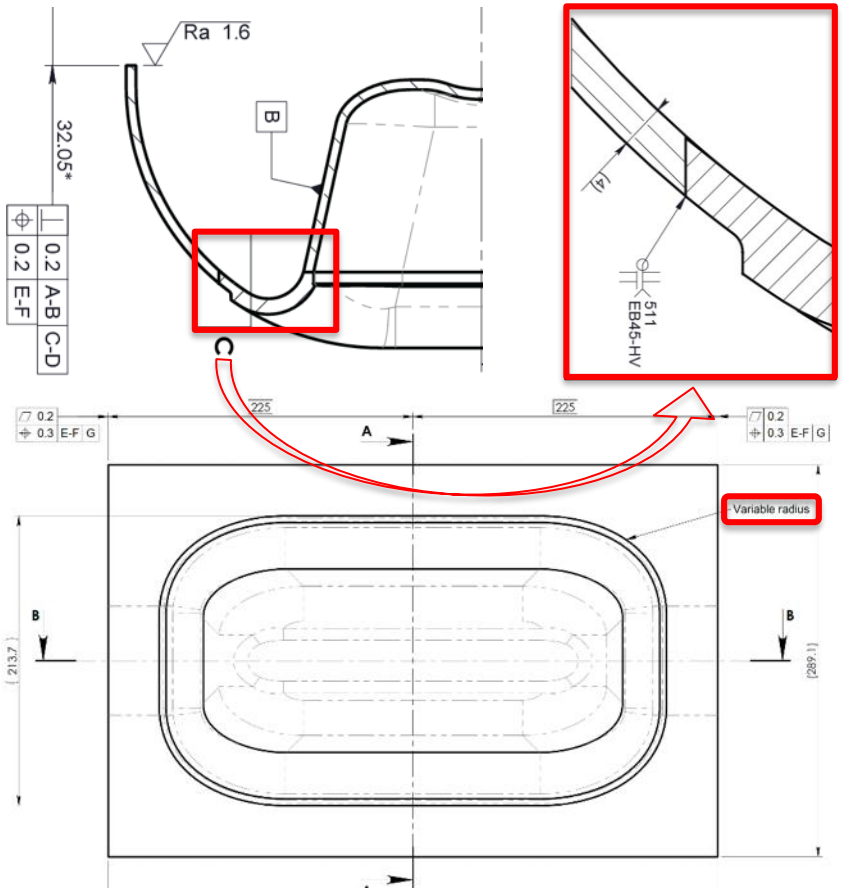
Initial forming — Trimming “crown” wrinkles — Greasing + Final Coining

Forming of RFD subcomponents is approaching the technological limits

Fabrication & Processing Challenges at ZRI

2a- Complex EBW between Half Main Body sub-components

- Shape accuracy of whole inner surface is required to be < 0.4mm after EBW
- Variable radii and thicknesses EBW required careful fixtures design, machining and assembly

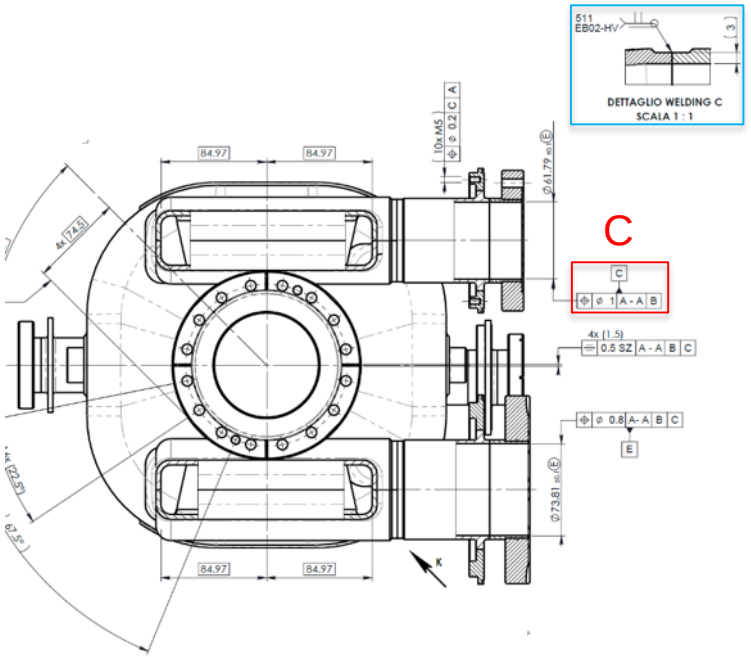


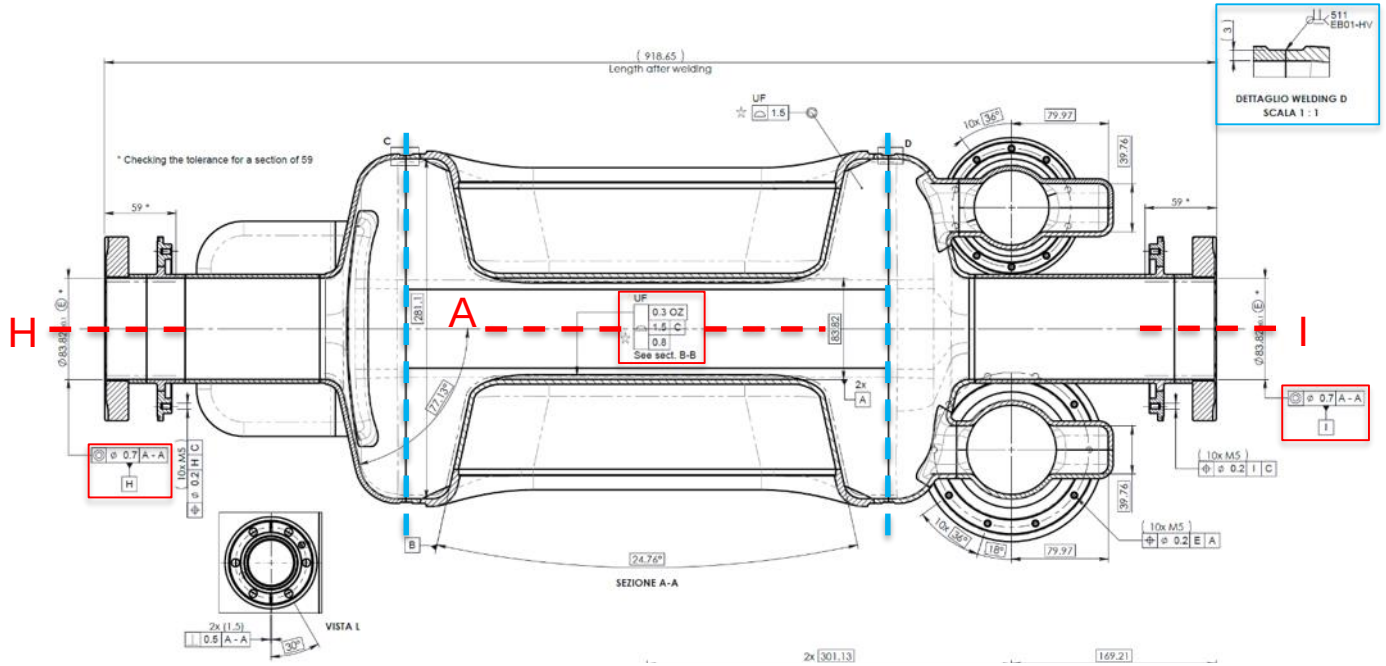
ZRI know-how, extensive R&D and months of tests yield to improved results

Fabrication & Processing Challenges at ZRI

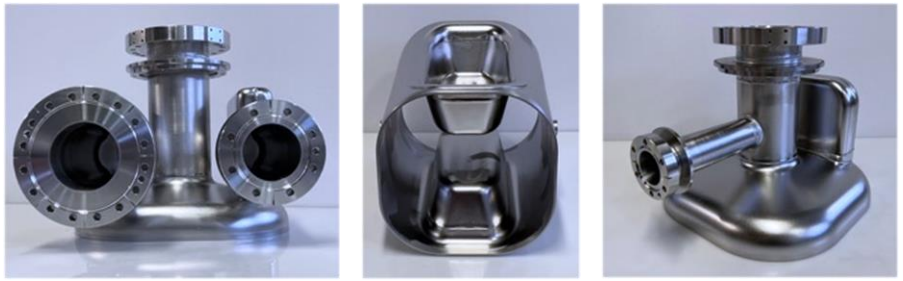
3- Alignment between End Groups-Main Body during final EBW

- RFD required sub-mm alignment between End Caps and Main Body after final EBW





- Matching EBW interfaces machined from CMM data:
  - Concentricity between datums H-A-I (achieved 0.5-0.8mm)
  - Rotational constraints provided by datum C



CNC machining and EBW required special fixtures, years of R&D and trials