

Dressing of Single Spoke Resonators

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Introduction:

- Dressing is building Stainless Steel helium vessel around low power tested Nb cavity by TIG Welding.
- Vessel is built around cavity to submerged it in superfluid liquid He pool at 2K temp. Cooling of these Nb cavity is required for its high power testing.
- This is very involved and complicated process and requires utmost care as distortion and temp rise during welding helium vessel may spoil the cavity.



Helium Vessel

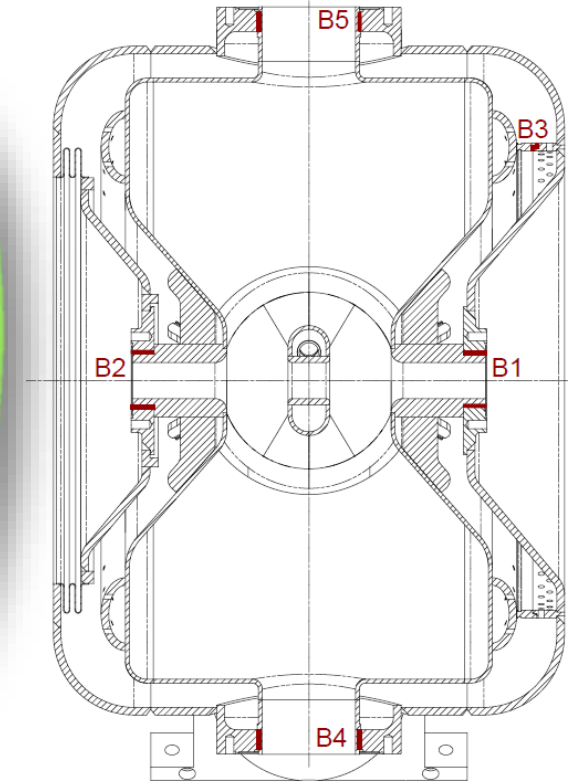
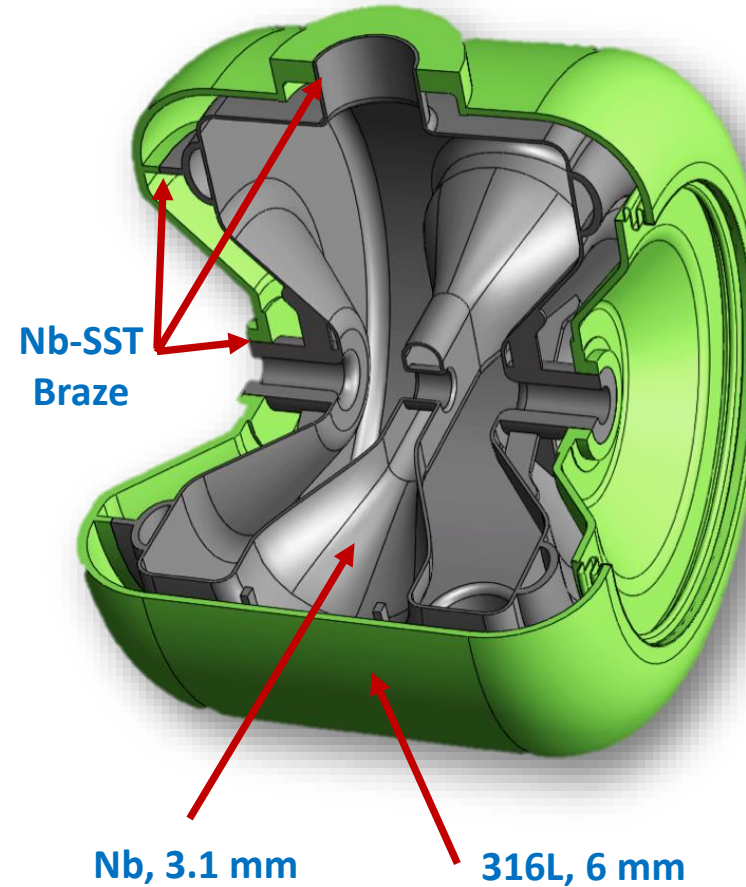
SSR Cavity

Introduction:

- The main parts that comprise the helium vessel are two cylindrical half-shells, two conical plates and two dome heads.
- All parts are TIG-welded with full penetration joints.
- The helium vessel includes also the support base for securing the resonator inside the Cryomodule and for mounting the tuning system.

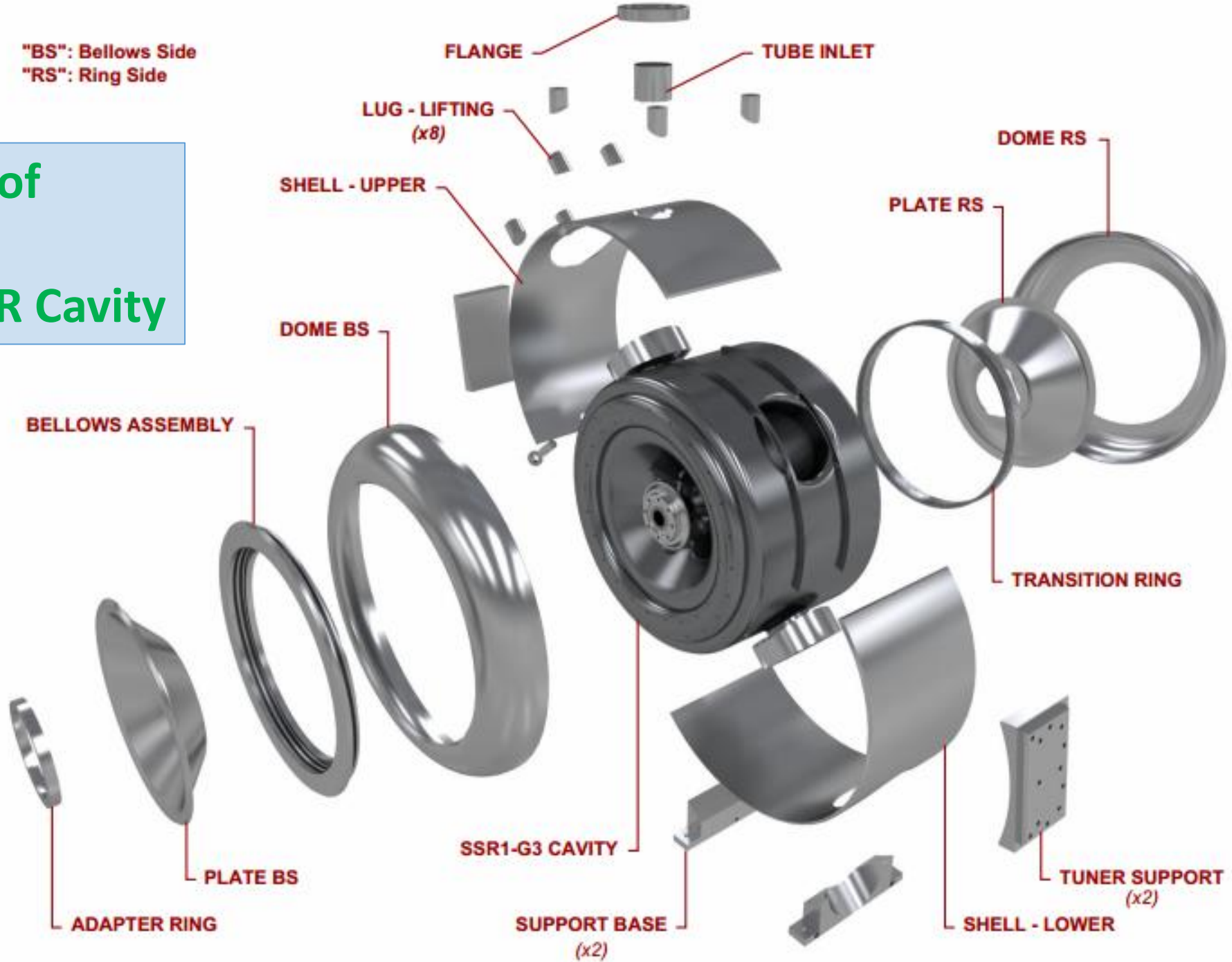
Introduction:

- The helium vessel is connected to the Nb cavity through the coupler flange, vacuum flange, the two beam pipe flanges and the transition ring. The connections between Nb and stainless steel are made by Cu brazed joints.
- Additional shear stresses is caused by the different coefficient of thermal contraction between niobium and stainless steel during the cool down which are below the allowable.



Blown up view of Helium vessel built around SSR Cavity

"BS": Bellows Side
"RS": Ring Side



Technical Requirements:

- SSR system i.e. cavity + helium vessel must meet the maximum allowable working pressure (MAWP) requirement of 2 bar at 293 K and 4 bar at 2 K.
- During initial helium purging, cool-down, and warm-up, pressure excursions of over 1.5 bar are not unusual. Some allowance is added to avoid blowing relief valves during normal operation.
- Vessel contains liquid helium and a loss of insulating vacuum or loss of beam vacuum may result in very rapid boiling of the helium.
- Rapid boiling only occurs in the presence of liquid helium, the larger MAWP is only required for cold conditions.
- Since material strength increases significantly at low temperatures the most stringent requirement is the one at room temperature.

Design Considerations:

- The design of the dressed SSR system i.e. Cavity + Helium Vessel should be as less sensitive as possible to perturbations due to liquid helium pressure variations responsible for the loss of the electromagnetic resonant frequency in the superconducting cavities.
- Targeted sensitivity to liquid helium pressure variations is $df/dp < 25 \text{ Hz/Torr}$.
- A self-compensating design is developed allowing low sensitivity.
- Methods used to balance deformations:
 1. Bellow diameter is optimized to counteract Helium pressure on cavity end-wall.
 2. Opposite end-wall coupled with vessel
- Net frequency shift should be very low. For SSR1 325MHz despite very low deformations (30-90 μm) frequency shift \rightarrow Bare cavity $\sim 650 \text{ Hz/Torr}$, With He vessel 2 Hz/Torr (no tuner), with infinitely rigid tuner 6 Hz/Torr
- A spring constant of $\sim 30 \text{ kN/mm}$ is expected at the interface.
- Ease of tuning. For SSR1 325 MHz $\rightarrow 39 \text{ N/kHz}$ (bare), 40 N/kHz (with He vessel)

Design Consideration:

- SSR1 is designed with large diameter of bellows , Dia. $\sim 350\text{mm}$.
- Just 1 mm error on diameter of bellows causes a pressure change on cavity which accounts for $\sim 4 \text{ Hz/Torr}$.
- Formed bellows do not have high precision on convolutions.
- Bellows are characterized to make the best pairing with cavities.

Design Consideration:

- ASME Boiler and Pressure Vessels Code - Section VIII Division 2, “Design by analysis” is followed.
- Section VIII Division 1, “Design by rule” is followed to pass the welds joints since nondestructive examinations are not done.
- The type of joints used for the helium vessel surrounding the Nb-cavity should be in agreement with the Code.
- For EB welded joints, samples are etched, polished and examined with microscope to certify the quality and the weld parameters.
- Similarly test results on trial pieces are used to qualify the brazed joints.

Materials:

- SSR resonators are constructed from SS316L and Niobium.
- Material properties and the coefficient of thermal expansion at both 293K and 2K are needed.
- The stainless steel 316L is well defined by the Code but the material properties at cryogenic temperature are not defined.
- Adopted as the same of room temperature to avoid expensive tensile tests.
- Conservative approach as material strength at cold temperatures is much higher than at room temperature.
- Niobium is non-code material.
- Niobium mechanical properties are established with extensive tensile test results.

Loads acting on the SSR resonator

P - Pressure in the helium space under the fault conditions: 2 bar and 4 bar

ρ_{He} - Static head from liquid helium (considered as negligible)

D - Dead weight of the vessel and cavity ~ 1250 N

T_1 - Applied tuner maximum displacement of 0.26 mm

T_2 - Cool-down from 293 K to 2 K

Load Cases for Finite Element Analysis			
Case 1	Case 2	Case 3	Case 4
$P + D$	$P + D + T_1$	$P + D + T_2$	$P + D + T_1 + T_2$
MP @293 K	MP @293 K	MP @2 K	MP @2 K

Design of Dressed SSR resonator

- The first step is to use design rules to find out wall thickness of cylindrical shell-Upper and lower, Conical Shell and Dome Heads under pressure loading.
- A helium vessel with a minimum thickness of 2mm satisfy the requirements of the Code. Due to the presence of other loads and to the requirements on stiffness, a value of 6.25mm is assumed for the thickness of the helium vessel parts.
- Openings for the flanges do not require additional reinforcement as the wall thickness of the shell and the tube of the flange are bigger than the minimum thickness required.
- The design requires flexible bellows to allow the tuning operation of the superconducting cavity and also passively mitigate the pressure sensitivity phenomena.
- Bellows are made of Stainless Steel 316L and subject to external pressure ($P_{rt} = 2\text{bar}$, $P_{ct} = 4\text{bar}$). Design of bellow is done as per EJMA standard.
- FE analysis is performed to evaluate the linear elastic behavior of the entire system under earlier mentioned load conditions. The scope of the analysis is to proof the structural integrity of the Nb cavity and SS vessel. This has to be iterated with the CAD design step until reasonable stresses are achieved.
- After optimizing the geometry of the main components and to guarantee the safety of the system more detailed analysis is necessary.

Welded and Brazed Joints

- Niobium parts are joined by electron-beam welding, TIG welding process is used to join the SS316L parts. Copper brazed joints are for Nb-SS interfaces.
- FE analysis is done on model with bonded contacts in place of welded or brazed joints. Analysis for all four load cases are done to extract the forces between parts in contact.
- The normal and tangential component of each force acting on the weld divided by the effective cross section of the joint reduced by the joint efficiency gives the tensile stress and shear stress.
- The resulting equivalent stress must be smaller than the allowable stress of the filler material to consider the joint verified.

Welded and Brazed Joints

- TIG welded joints of the helium vessel are single-welded butt joints with backing strip and single full fillet lap joints.
- No NDE on the final welds of the SS vessel,
- Joint efficiency of 0.65 and 0.45 respectively are taken.
- The helium vessel is connected to the Nb cavity through the coupler flange, vacuum flange, the two beam pipe flanges and the transition ring by Cu brazed joint.
- Load case 4 is the most critical for the brazed joints due to the additional shear stresses caused by the different coefficient of thermal contraction between Nb and SS during the cool down.

Design by Analysis Requirements

- Starting from the preliminary results given by “Design by Rule Requirements” a CAD 3D model of the system is developed.
- This model is used to perform FE Analysis to cover the remaining parts to be designed, in accordance with ASME Section VIII, Div. 2, which provides design-by-analysis requirements to protect the SSR resonator against the followings:

Protection Against Plastic Collapse

- This analysis is done to prevent plastic instability and plastic deformation due to internal pressure that may lead to collapse.

Design by Analysis Requirements

Protection Against Collapse from Buckling

- This analysis is to prevent sudden failure mode due to compressive stresses on the vessel, much below the compressive stresses at Yield Point.

Protection Against Failure from Cyclic Loading

- The purpose of this analysis is to prevent fatigue failure of the vessel based on the number of cycles of pressure loading and unloading the vessel will experience.

Fabrication and Assembly of Helium Vessel around SSR1 325MHz Nb Cavity

- All Welding is done as per qualified WPS, PQR and WPQ.
- Detailed Quality Assurance Plan (QAP) is prepared and followed during entire development process.
- Temperature of the Nb cavity should not exceed 350K at any time, in any location, regardless of the nature of the gas in contact with such surface.
- A thermal camera is used to continuously monitor the temperature of the niobium with a set alarm at 350K.
- These measurements are also beneficial in verifying that enough time is given to the cavity to cool down between welds.

Fabrication and Assembly of Helium Vessel around SSR1 325MHz Nb Cavity

- The resonant frequency of the resonator should be monitored at regular intervals to control that the process is not putting excessive strain on the resonator.
- The entire process must not change the resonant frequency by more than 300 kHz.
- Bigger changes may be difficult to mitigate by inelastic tuning.
- They are also used to monitor the deformations of the niobium cavity during machining and welding, preventing plastic deformations which are above acceptable limits.
- All the joints are sealed off with tape and RF volume and Helium space are purged with Argon.

Fabrication and Assembly of Helium Vessel around SSR1 325MHz Nb Cavity

- Presence of the oxygen is checked in the volumes before performing any weld. Should be less than 20 ppm.
- Heavy TIG welds should be guided in such a way to avoid squeezing the resonator.
- A sequence of welds that allow the mitigation of the effects is to be developed.
- Several passes (~4-5 passes) are needed to complete the $\frac{1}{4}$ inch weld. “Stitches” of ~1 inch long are made alternating the position in order to prevent localized hot spots.

Fabrication and Assembly of Helium Vessel around SSR1 325MHz Nb Cavity

- ***Visual examination*** at each critical step is performed in order to prevent visible defects in the parts.
- All welds for pressure retaining parts are visually examined to assure the acceptance criteria of Table 7.6 of the ASME BPVC, Section VIII, Div. 2, Part 7.
- Integrity of *braze joints is to be* visually checked with a glass magnifier to exclude the presence of defects.
- ***None of the joints are subject to NDE.***
- Backing strips must be used to protect the niobium cavity while making full penetration welds.

Dressing SSR Stage-I

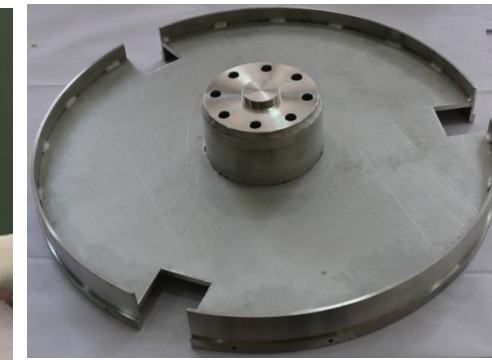
- Transition Ring – SS: Manufactured at CDM
- Transition Ring – Nb: Rolled strip EB Welded at IUAC.
- BPS, BPQ, BPQR for brazing of Nb to SS are prepared
- Brazing of SS Ring with Nb Ring has been done at RRCAT
- Final M/c of Transition Ring will be done at CDM
- Welding fixture to locate Transition Ring w.r.t to beam tube for EBW is designed and manufactured at CDM
- Completed Transition Ring will be EB Welded with the SSR1 Cavity at IUAC



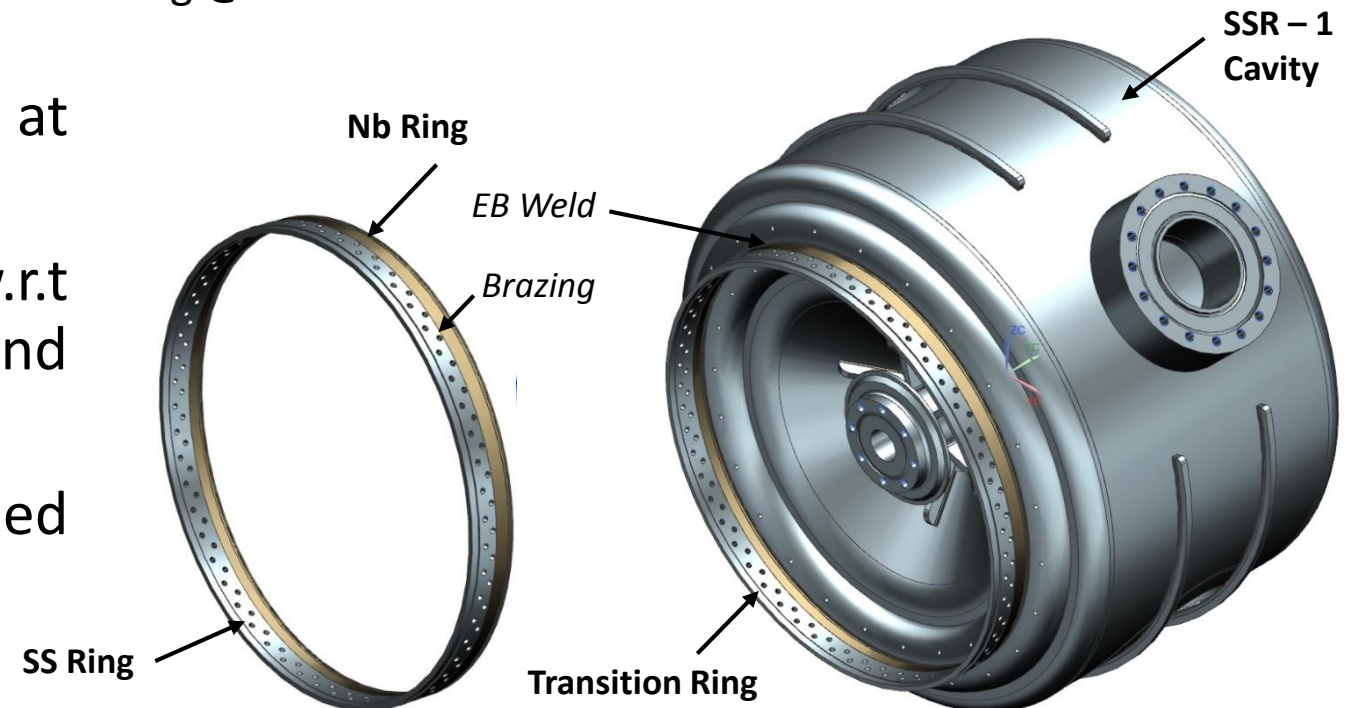
Nb-SS Transition Ring @ RRCAT

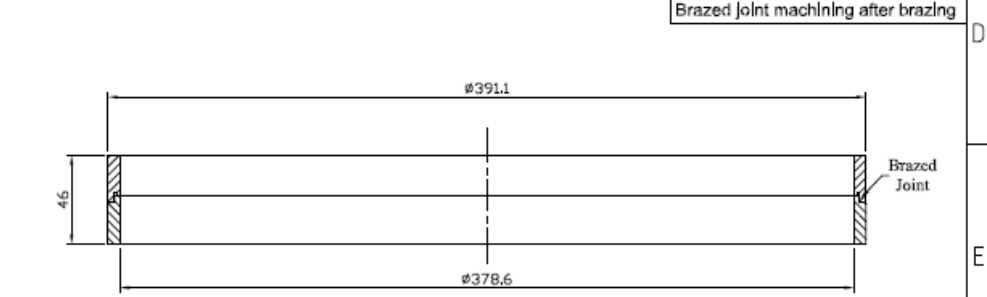
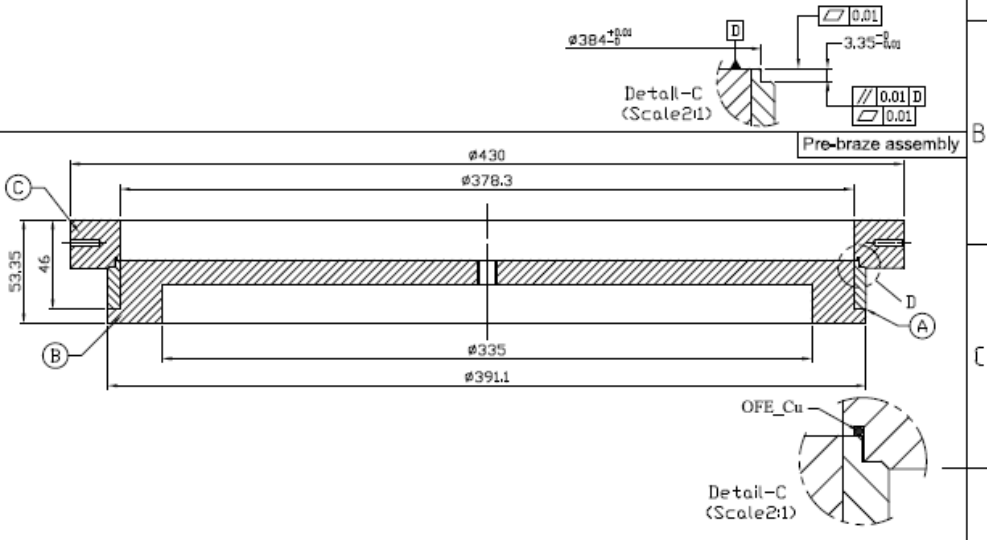
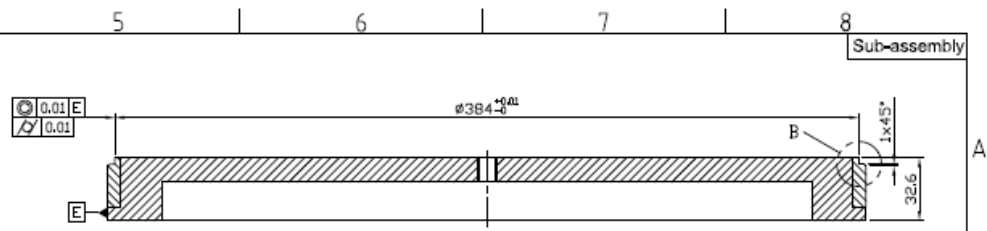
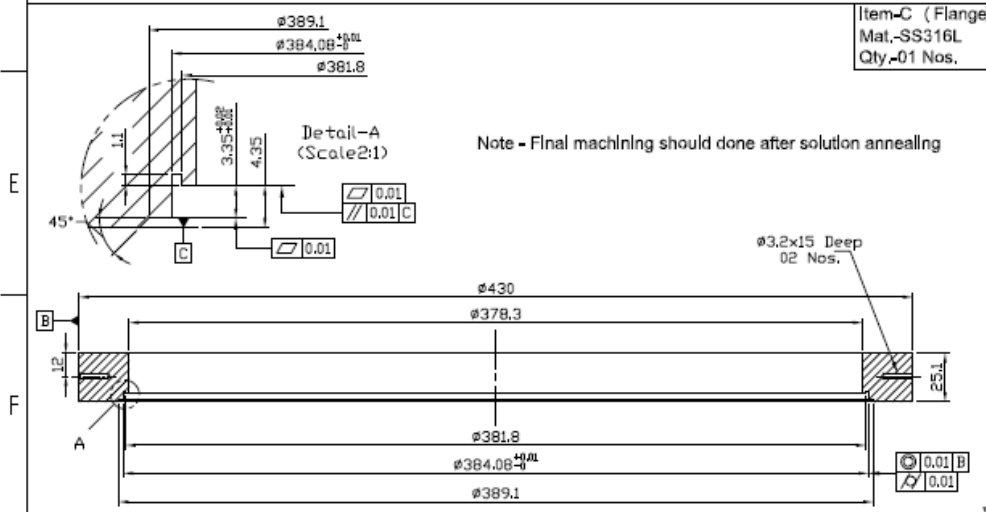
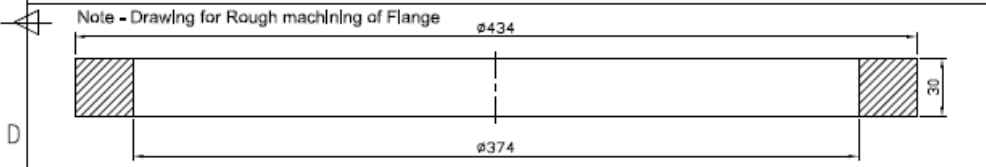
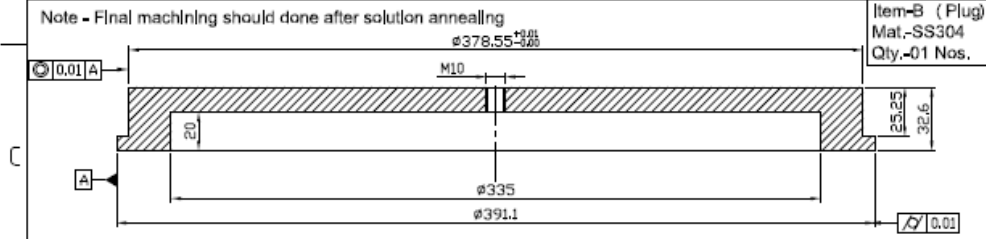
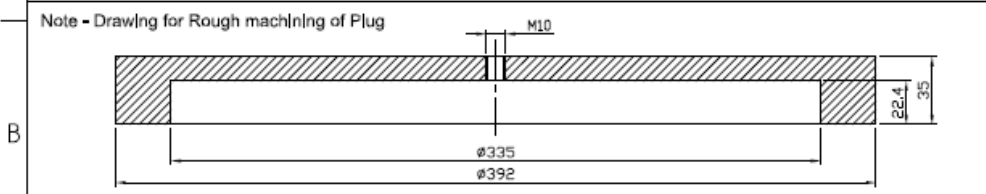
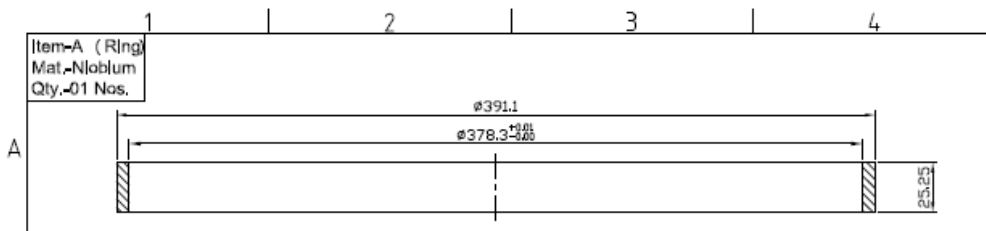


Nb SSR1 Cavity @ IUAC

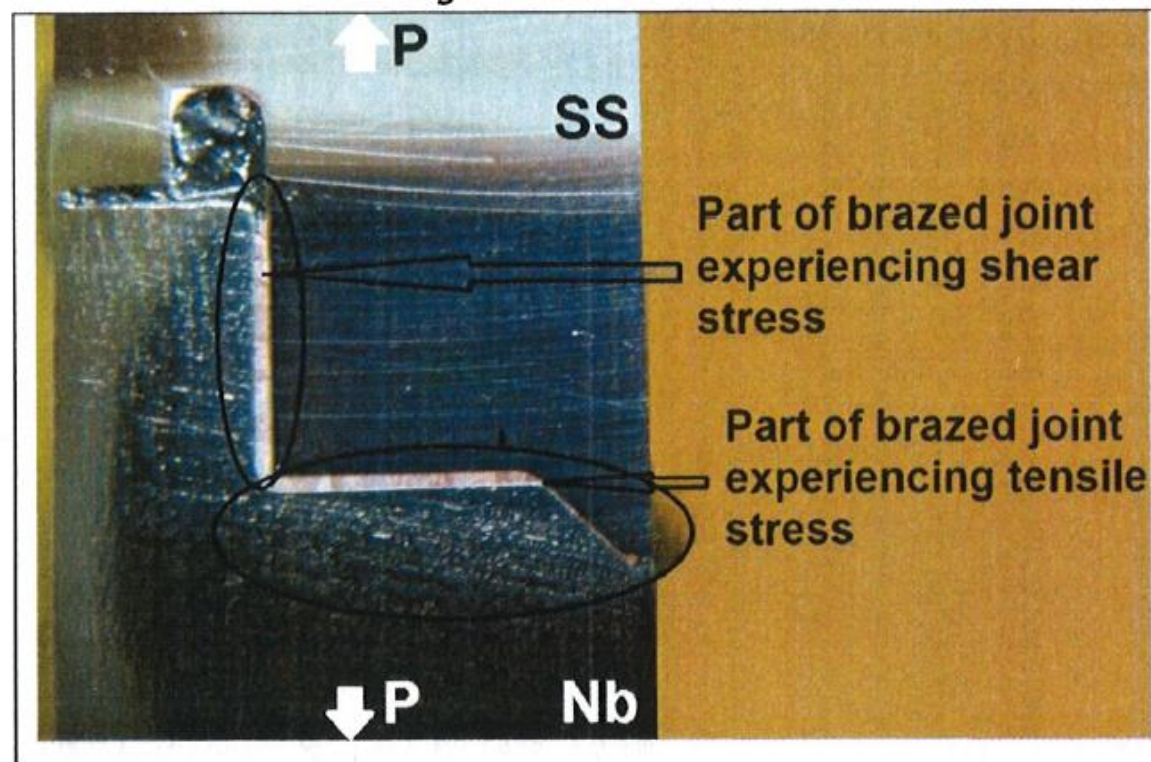


Fixture for EBW





FILE NAME RRCAT-PLSCD-SPLS	FSCM NO	SHEET 01 of 01	SCALE 1:2.5
SIZE A3	Raja Ramanna Centre for Advanced Technology		
DRAWN 12-08-2016 Jasmin Kumar	Braze Joint Part Detail		
CHECK 12-08-2016 Abhay Kumar	Nb to SS (Qty.-02 Nos.)		
APPR. 12-08-2016 Abhay Kumar	DWG NO		
ISSUED 12-08-2016 Abhay Kumar	RRCAT/PLSCD/SPLS/06-16/001-A1		
REV R1			
CONTRACT NO 0731-2482267			

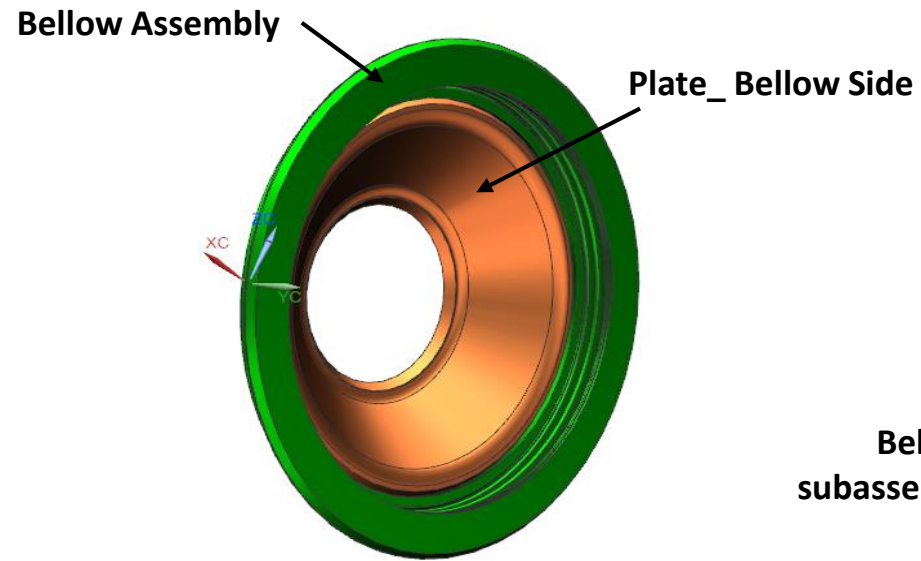


Tensile test results					
S. No.	Specimen ID	Joint area supporting load (mm ²)	Max. Load (N)	Tensile strength (MPa)	Failure site
1	T-1	51.3	5489	107	Nb/braze interface
2	T-2	45	4378	97	Nb/braze interface
3	T-3	45.9	4773	104	Nb/braze interface

Shear test results					
S. No.	Specimen ID	Joint area supporting load (mm ²)	Max. Load (N)	Shear strength (MPa)	Failure site
1	Sh-1	31.0	3200	103	Nb/braze interface
2	Sh-2	32.1	3640	113	Nb/braze interface
3	Sh-3	31.8	3550	112	Nb/braze interface
4	Sh-4	32.3	3326	103	Nb/braze interface

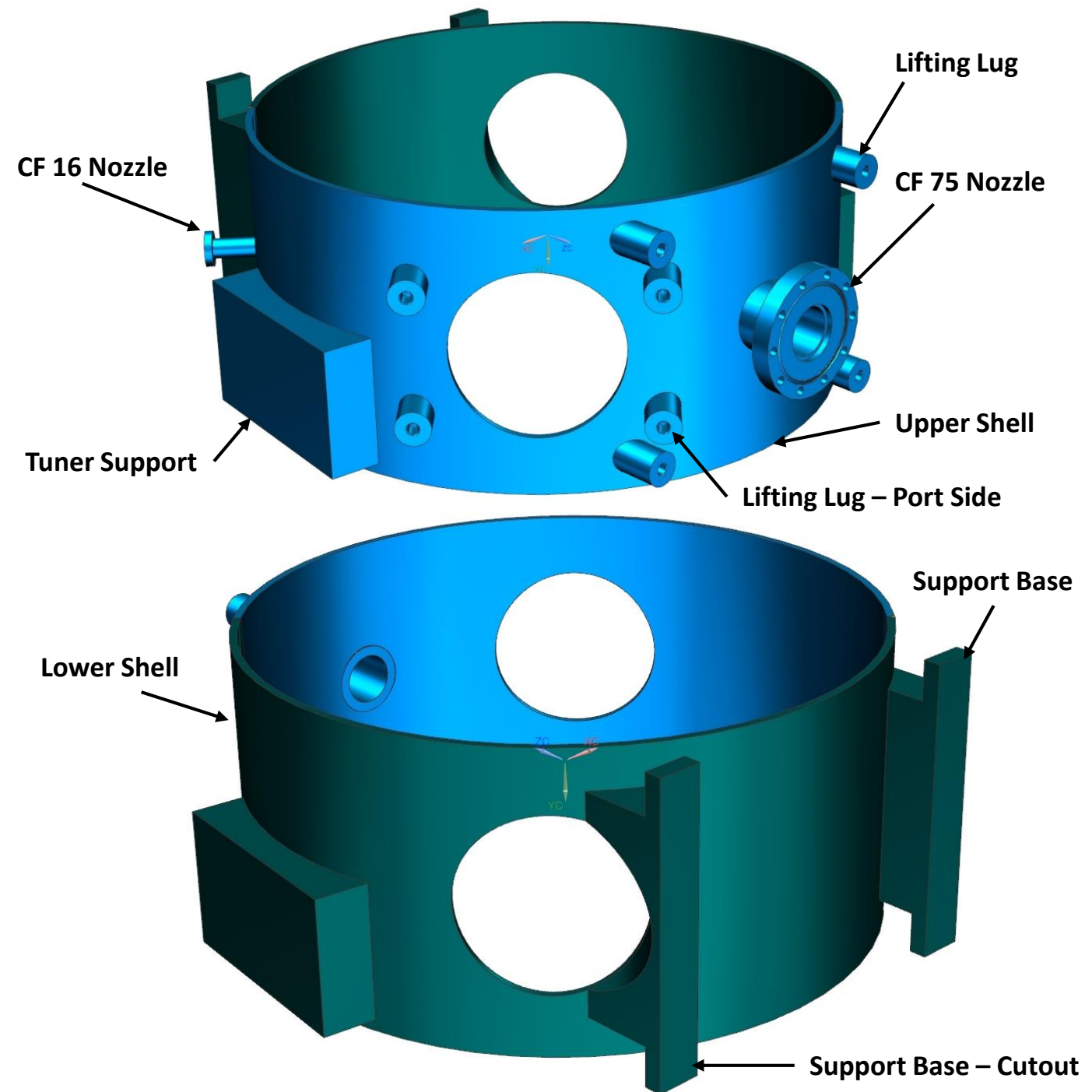
Dressing SSR Stage-I (cont.)

- Plate_Bellow Side & Bellow Assembly is welded together outside the dressed cavity assembly.



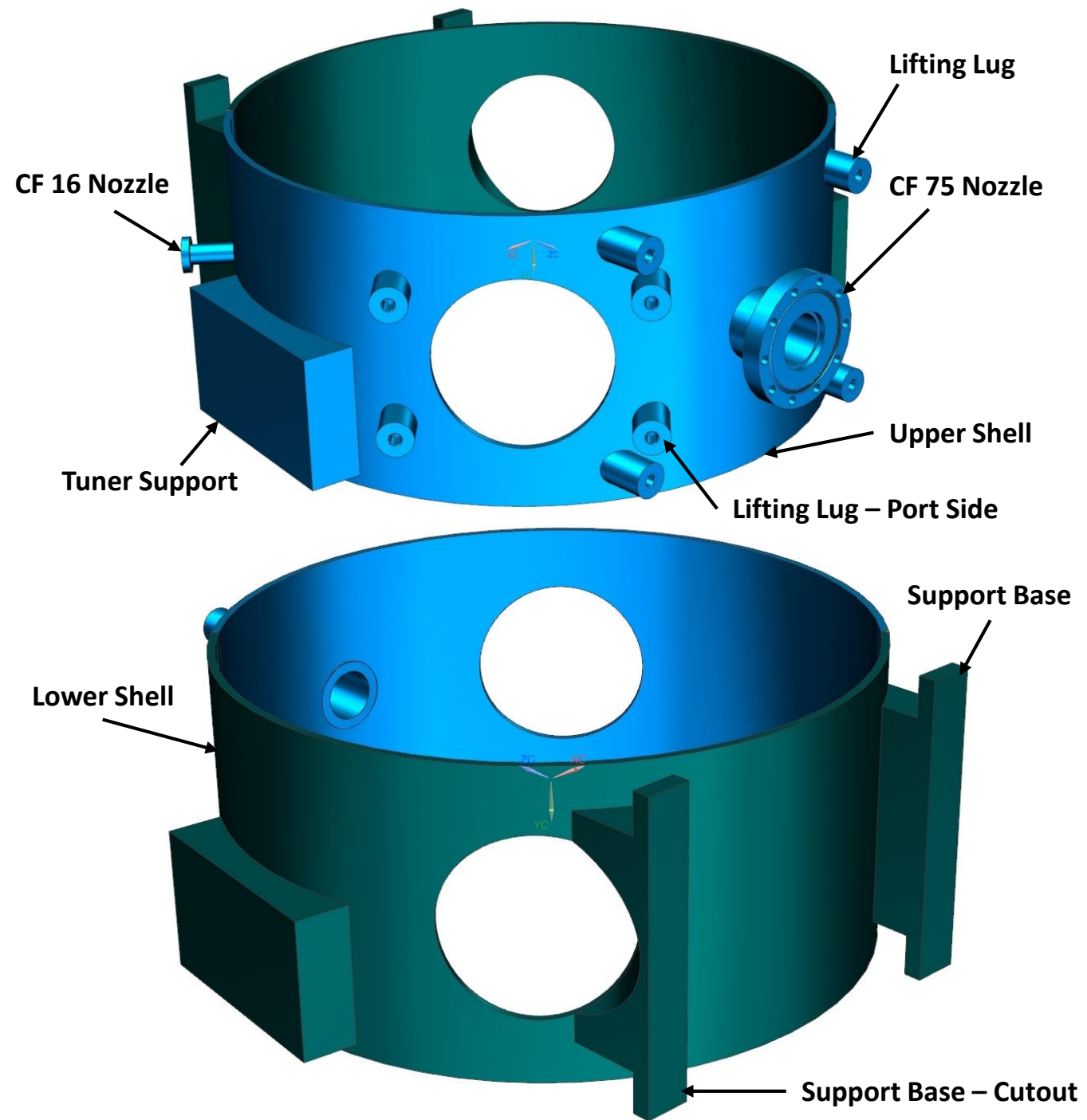
Dressing SSR Stage-II

- Shell is rolled as a single unit and tack welded to make a cylindrical shell keeping additional material to mitigate welding shrinkages.
- A solid cylindrical welding fixture is used to avoid welding distortions.
- DN75 CF Flange, DN16 CF Flange, Lifting Lugs, Lifting Lugs–Port Side, Tuner Support, Support Base and Support Base–Cutout are welded to the Shells as per the drawings.



Dressing SSR Stage-II(cont.)

- Additional material is left on Lifting Lugs, Lifting Lugs– Port Side, Tuner Supports, Supports Base for final machining.
- Cylindrical welding fixture is removed.
- Electro-polishing of weldment is done after this stage along with other components.
- Shell is cut to upper and lower halves as per drawing after electro polishing



Dressing SSR Stage-II(cont.)



**Cylindrical Shell with Fixture
before Weldment**



Machined components



Dome Head

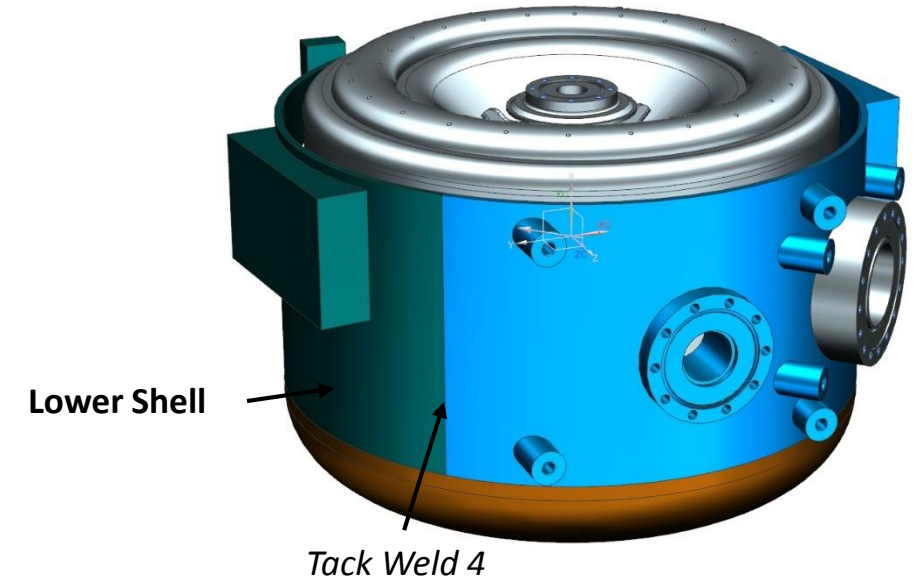
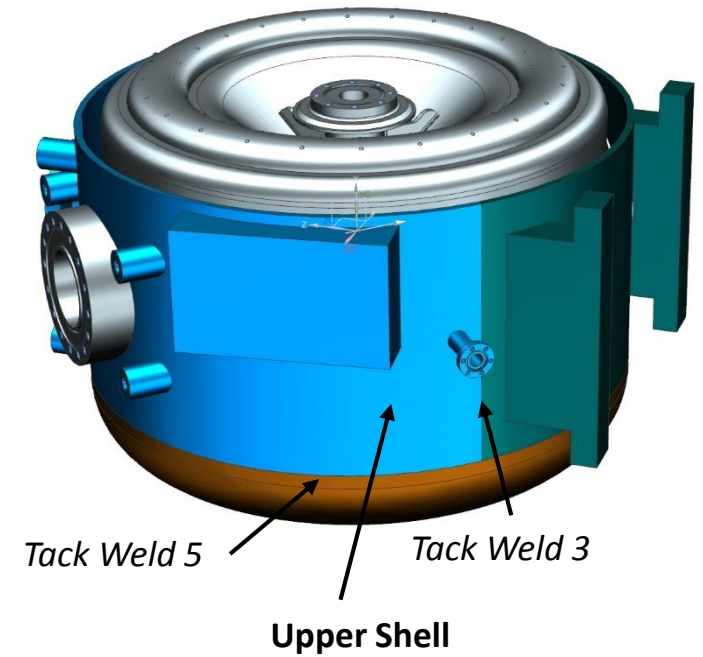
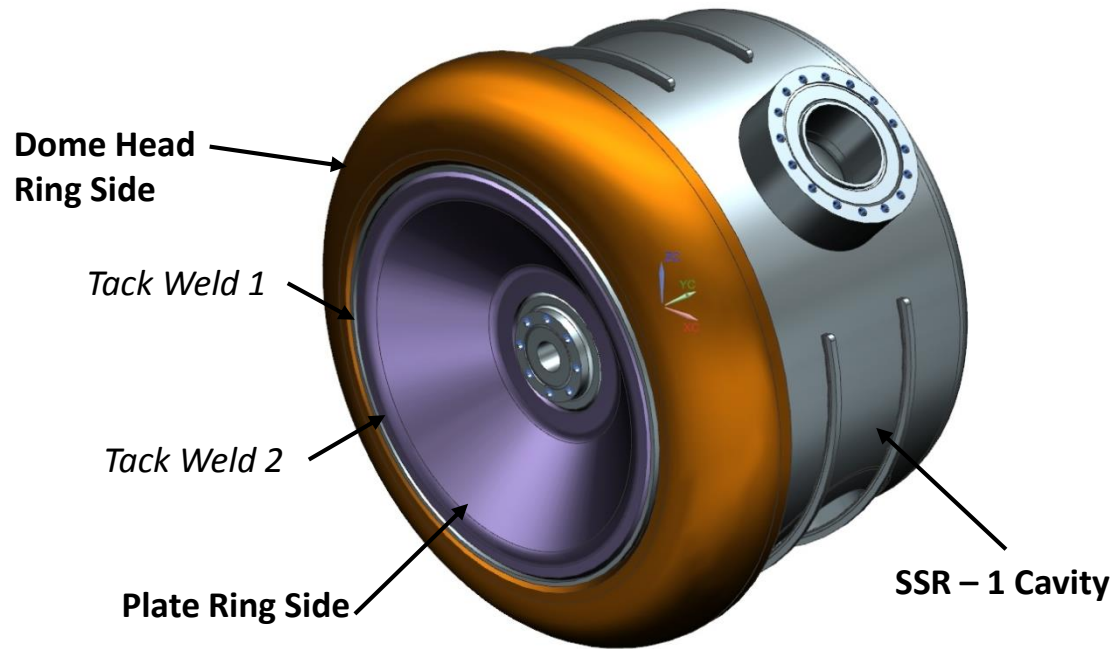
Dressing SSR Stage-II(cont.)



Shell after weldment and electro polishing at CDM, BARC

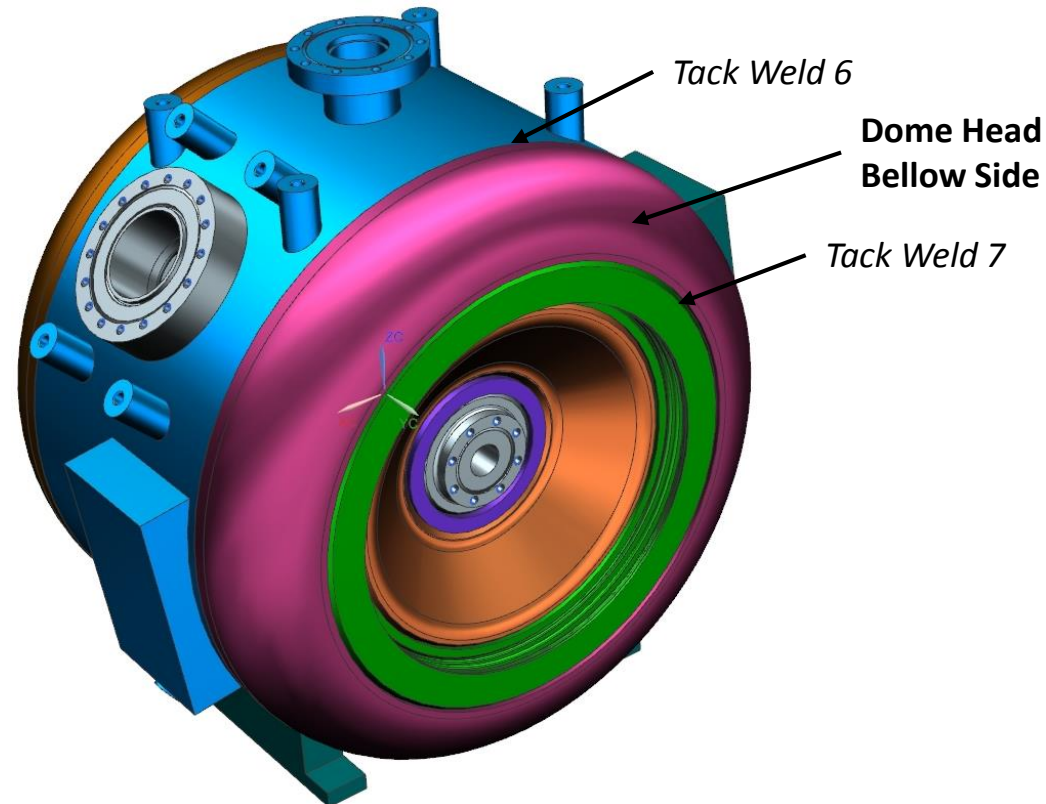
Dressing SSR Stage-II(cont.)

- Ring Side Dome Head and Plate are tack welded (Tack 1 & 2) to the SSR1 Cavity
- Upper and Lower Shell are assembled.
- Shell are assembled with an offset w.r.t. to cavity coupler and vacuum port to account for axial weld shrinkage.
- Sufficient non symmetrical gap is provided so that port on helium vessel become concentric w.r.t. to these ports after all Welds.
- Tack weld 3&4 and then Tack weld 5 is done.



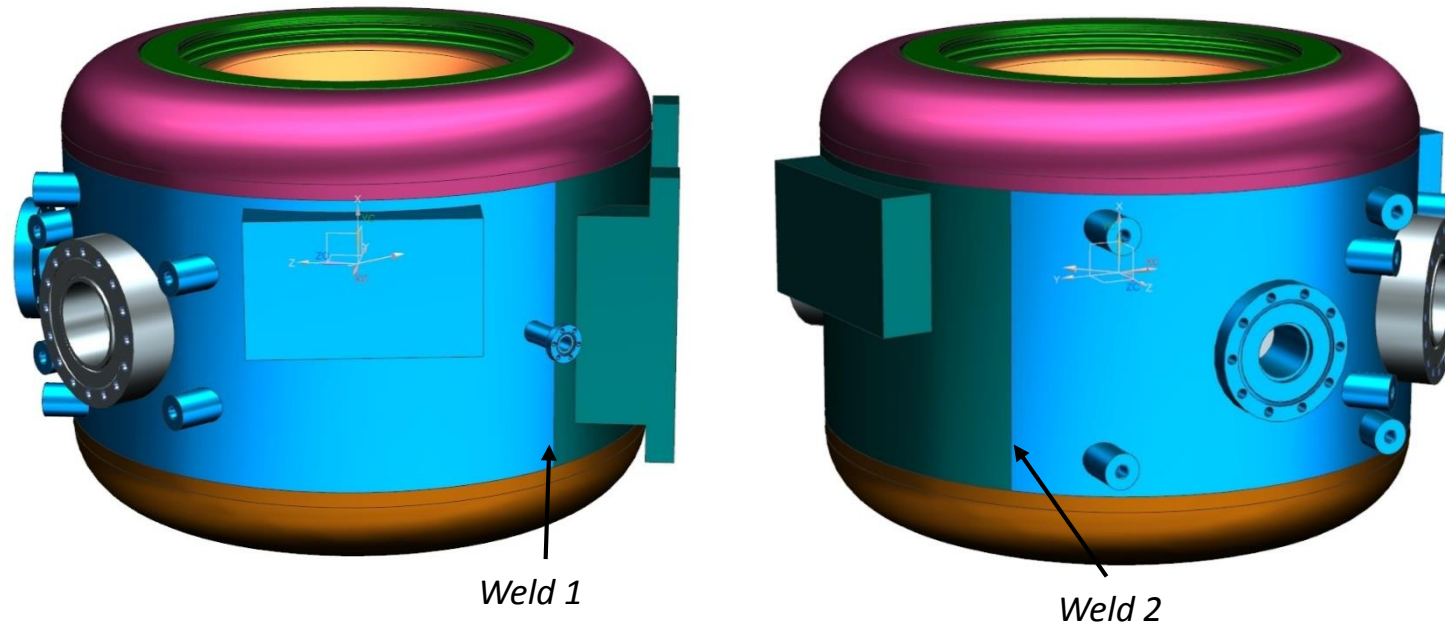
Dressing SSR Stage – II (cont.)

- Dome Head_ Bellow Side is tack welded to the shell with Tack Weld 6
- Centering plate is tack welded to the Dome Head_ Bellow Side in place of Bellow Assembly to prevent uncontrolled deformations.
- M/c of parts as required for initial alignment and assembly is done.
- After complete proof assembly, measurement of the starting RF frequency is done.



Dressing SSR Stage – III

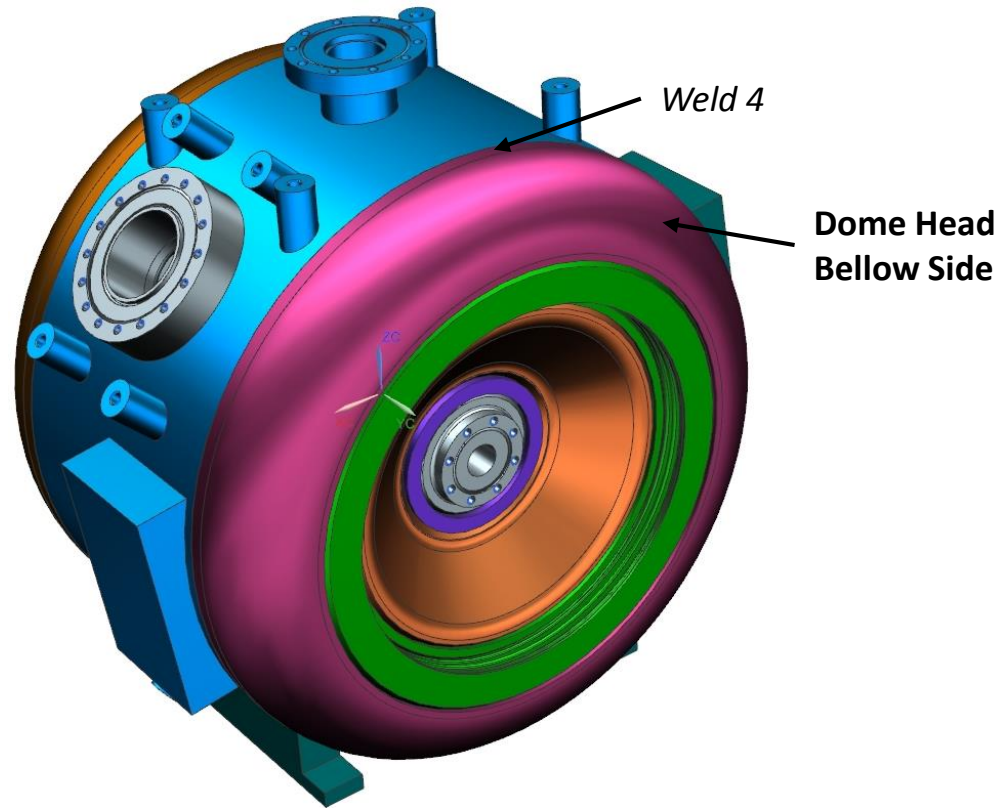
- After this initial alignment and assembly, final weld is taken up.
- All the Tack welds are covered with tape and Argon gas is purged into RF volume and Helium space.
- Welding of Upper Shell and Lower Shell halves at two places (weld 1 & 2) is done first.



Dressing SSR Stage – III (cont.)

- Dome Head and Shell (Transition Ring Side) :- Weld 3
- Dome Head and Shell (Bellow Ring Side):- Weld 4

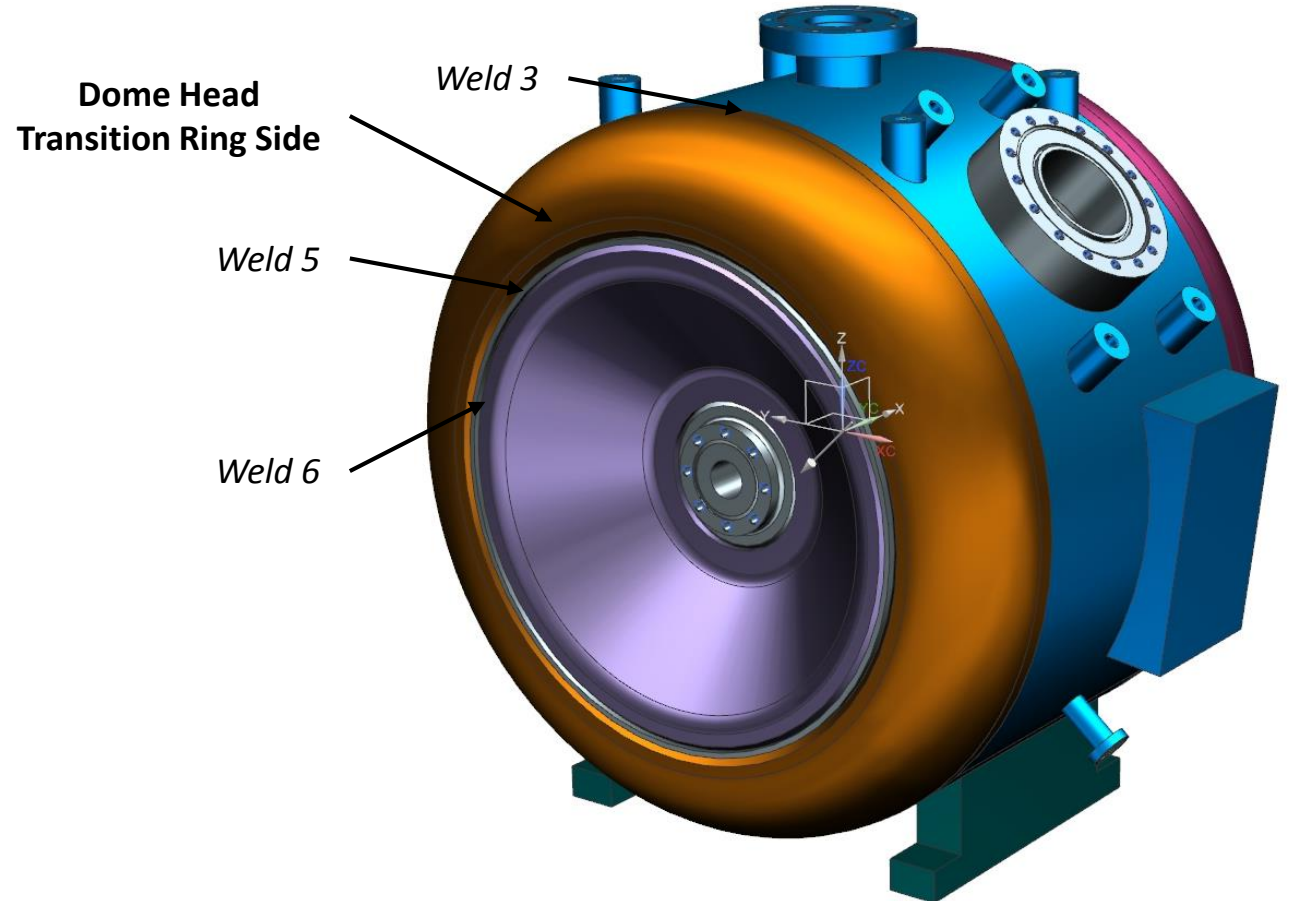
Note:- Weld 1, 2, 3, 4 can be done at the same time (jumping from one to another)



Dressing SSR Stage – IV

- Dome Head and Transition Ring :- Weld 5
- Plate_Ring Side and Transition Ring :- Weld 6

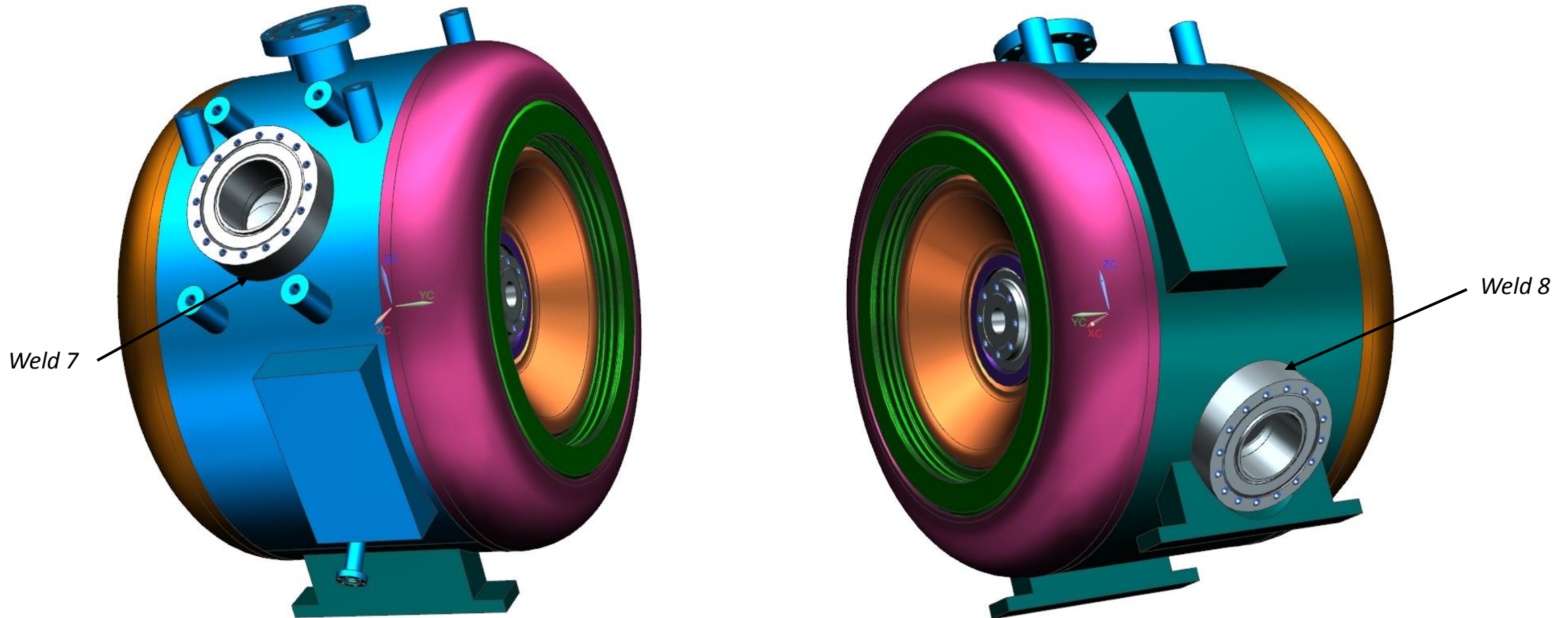
Note:- Weld 5 and weld 6 might be done at the same time



Dressing SSR Stage – V

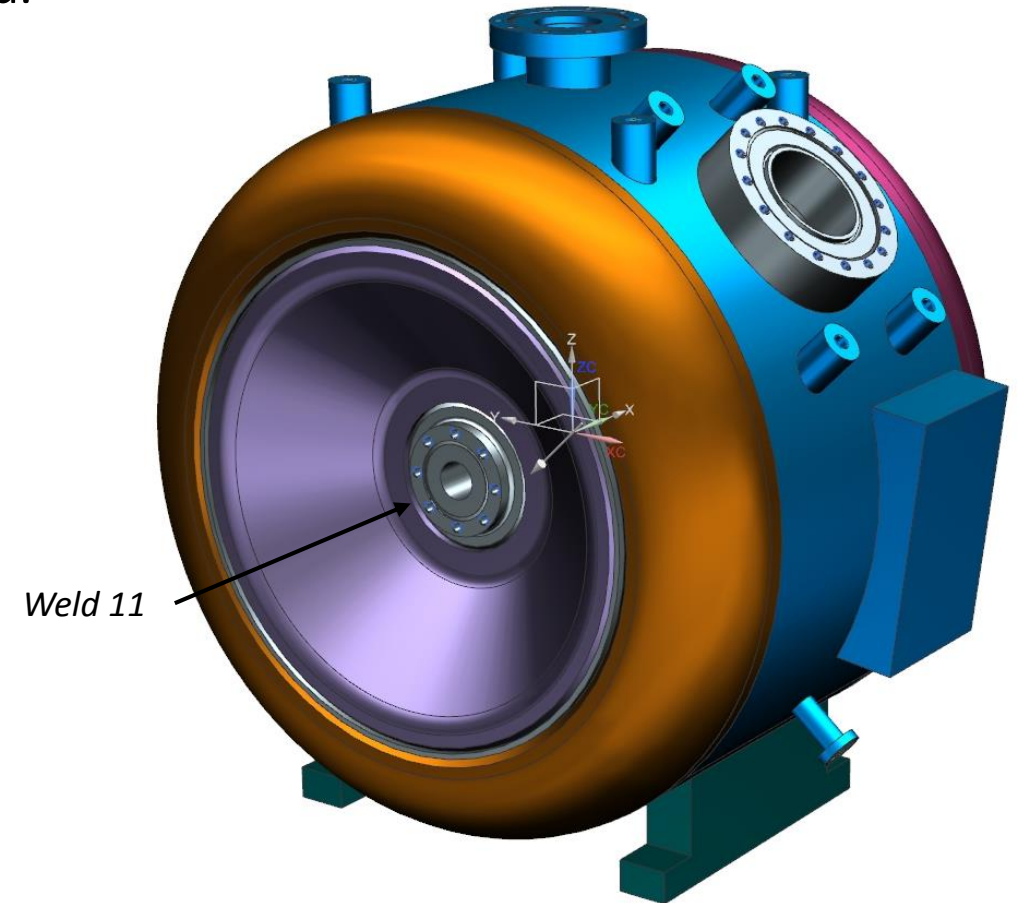
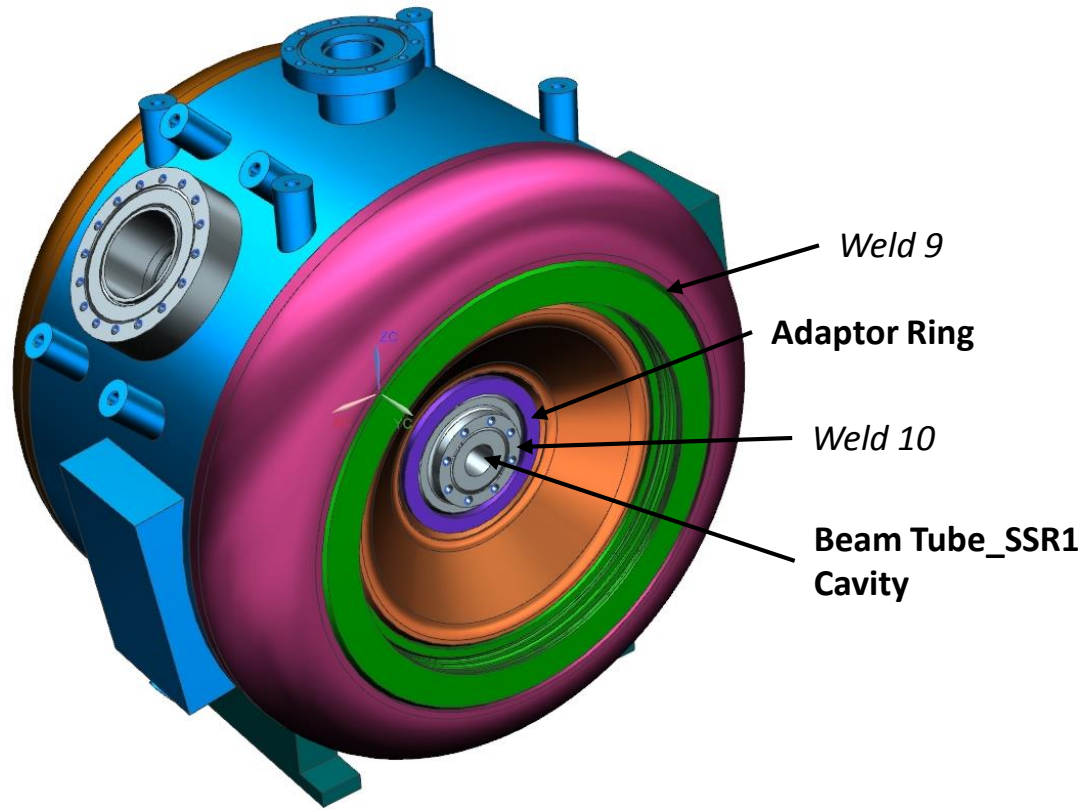
- The ideal case is that before starting this set of welds, there is the same gap between the shell openings and side ports (VP, CP)
- Top Shell is welded to the Vacuum Port of Cavity (Weld 7)
- Bottom Shell is welded to the Coupler Port of Cavity (Weld 8)

Note:- Weld 7 and weld 8 can be done at the same time

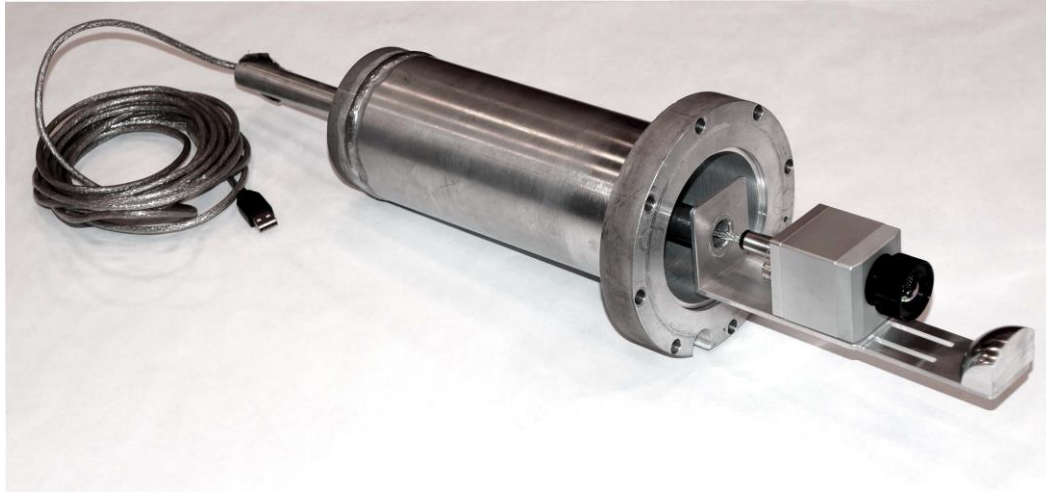


Dressing SSR Stage – VI

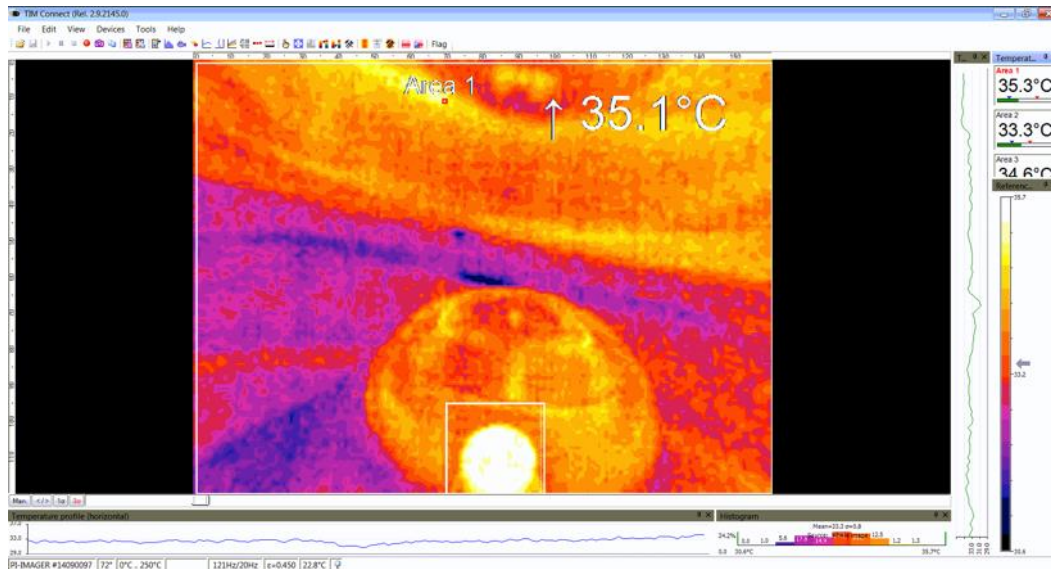
- Centering Plate is removed
- RF frequency is checked. Inelastic tuning is done, if needed.
- Gap between the BP flange and dome head is measured and “adapter ring” is welded to the “bellows assembly” accordingly outside the dressed cavity assembly.
- Center the bellows assembly on the BP flange and tack weld.
- Complete Weld 9 between bellows assembly and dome head.
- Complete weld Beam Port to Adaptor Ring :- Weld 10
- Complete weld Beam Port to Plate-Ring Side :- Weld 11



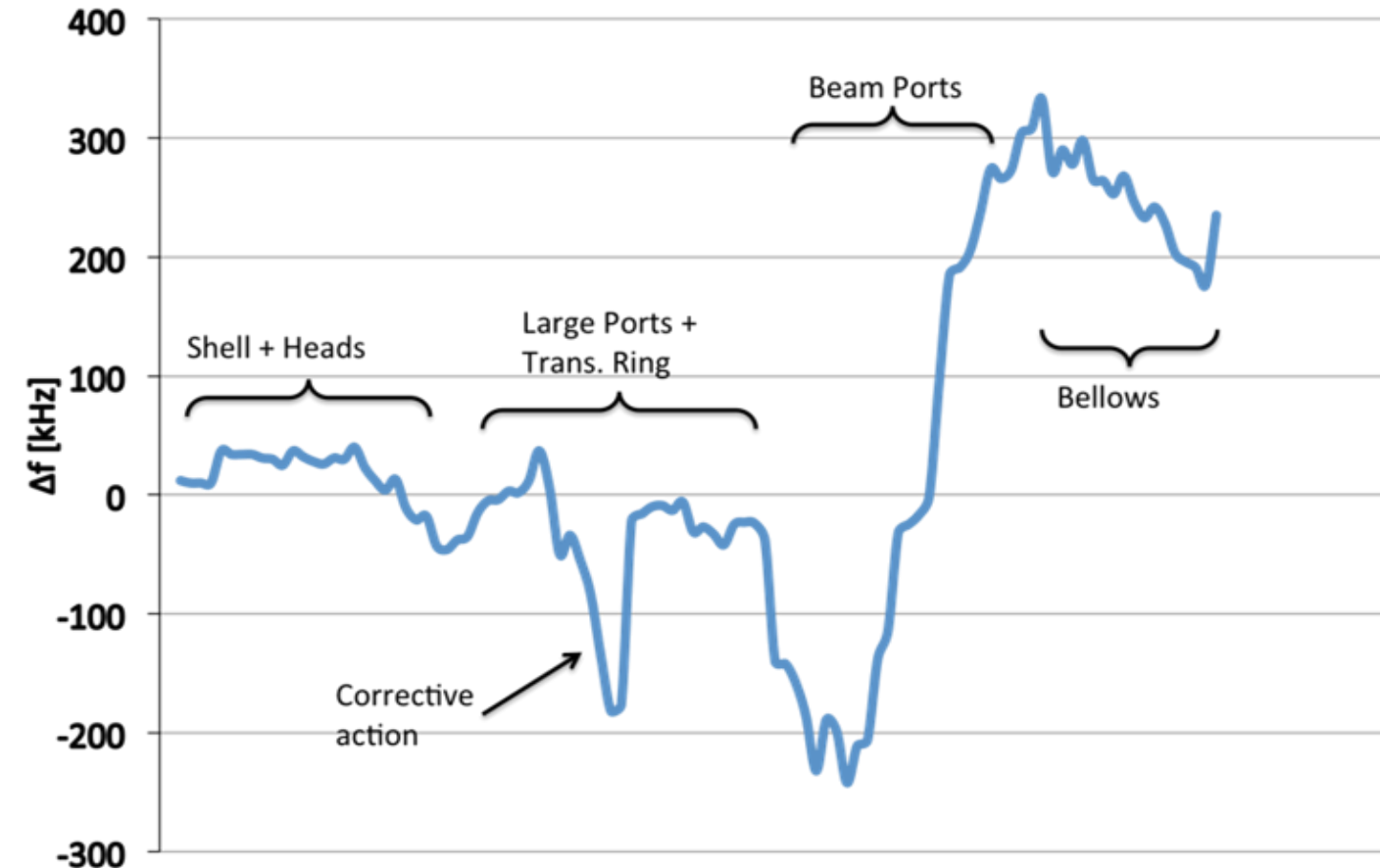
Temperature checks



The **temperature** of the resonator shall not exceed **350K** at any time, in any location, regardless of the nature of the gas in contact with such surface. A thermal camera is used to continuously monitor the temperature of the niobium with a set alarm at 350K. These measurements are also beneficial in verifying that enough time is given to the cavity to cool down between welds.



Frequency checks



The resonant frequency of the resonator shall be monitored at regular intervals to control that the process is not putting excessive strain on the resonator. The entire process must not change the resonant frequency more than **300 kHz**. Bigger changes may be difficult to mitigate by inelastic tuning.

Dressing SSR Stage – VII

- Final machining is performed to keep “critical” parts (i.e. tuner supports, lifting lugs, etc.) into the tolerance ranges as per drawing.
- Visual inspection, CMM, leak check of the helium space (monitoring the RF frequency), pressure test of the helium space (monitoring the RF frequency) are required as steps for preliminary qualification.
- **Leak checks** of the vessels are performed at various stages of the fabrication in order to prove that all welds and brazed joints are leak tight with a minimum sensitivity of $10^9 \text{ atm} \cdot \text{cc/s}$.
- Final RF Measurement is done.
- This completes the dressing of the SSR cavity.



Thank You