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NOvA Target Downstream Be Window

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TSD Topical Meeting

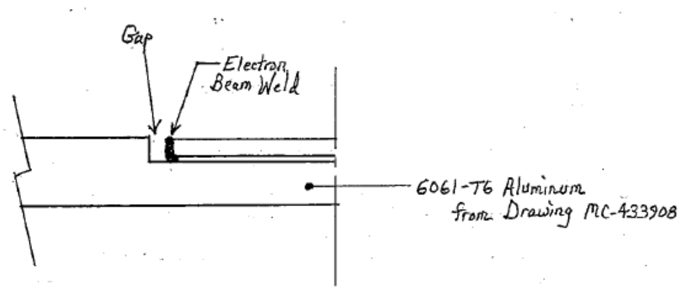
January 11, 2018

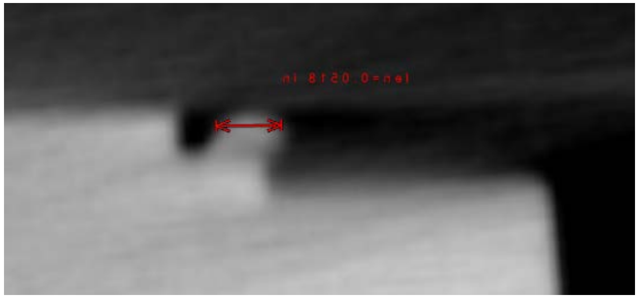
Outline

- Motivation for new design / analysis / testing
- Be window design
- FEA model, material properties, thermal loads, cooling conditions
- Temperature results
  - @steady state
  - @beam spill
- Stresses under different scenarios
  - Vacuum, no beam
  - 3 psig internal pressure, steady state (before beam)
  - 3 psig internal pressure, immediately after beam spill
  - 10 psig internal pressure, immediately after beam spill
- E-beam welding sample testing
  - Leak checking
  - Pressure testing
  - Thermal testing
  - CT scan
- Future plans

Motivation for New Design of Downstream Be Window

- MET-01 DS Be window helium leak developed during operation, MET-03 has a DS Be window leak;
- Leak located at the edge of window near electron beam welded joint;
- CT scan images of spare Be window of same design indicated that there is a gap between the Be foil and aluminum flange (6061-T6) in some segments.





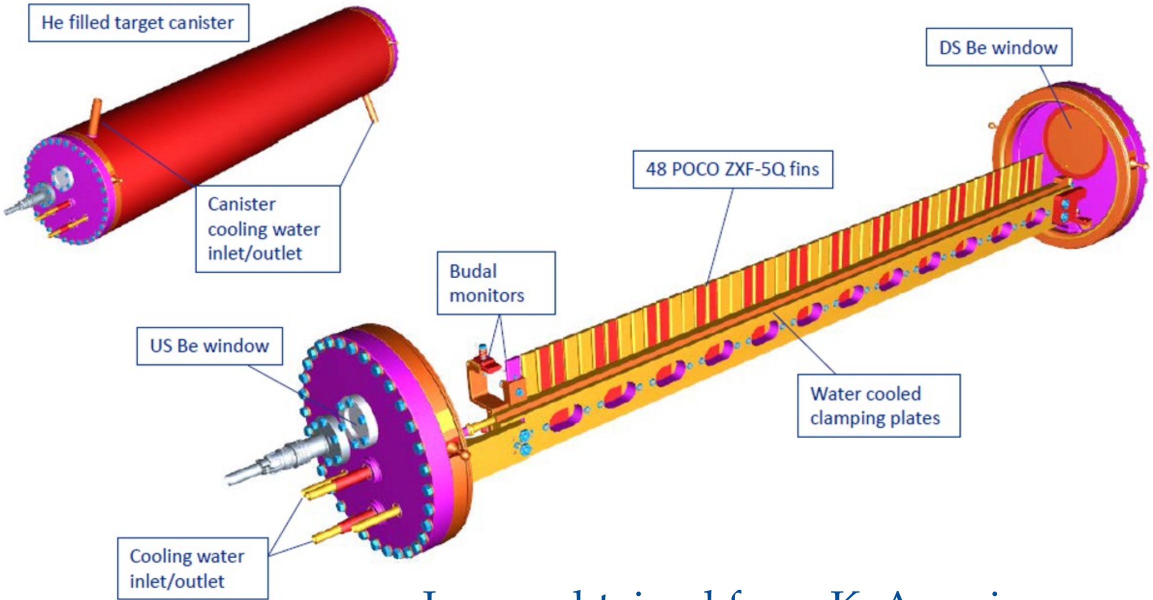
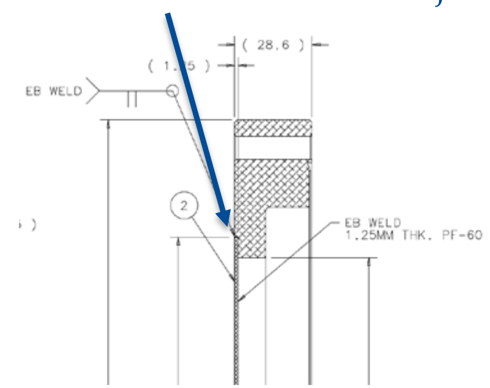


Image obtained from K. Ammigan

Dissimilar thickness at the EBW joint



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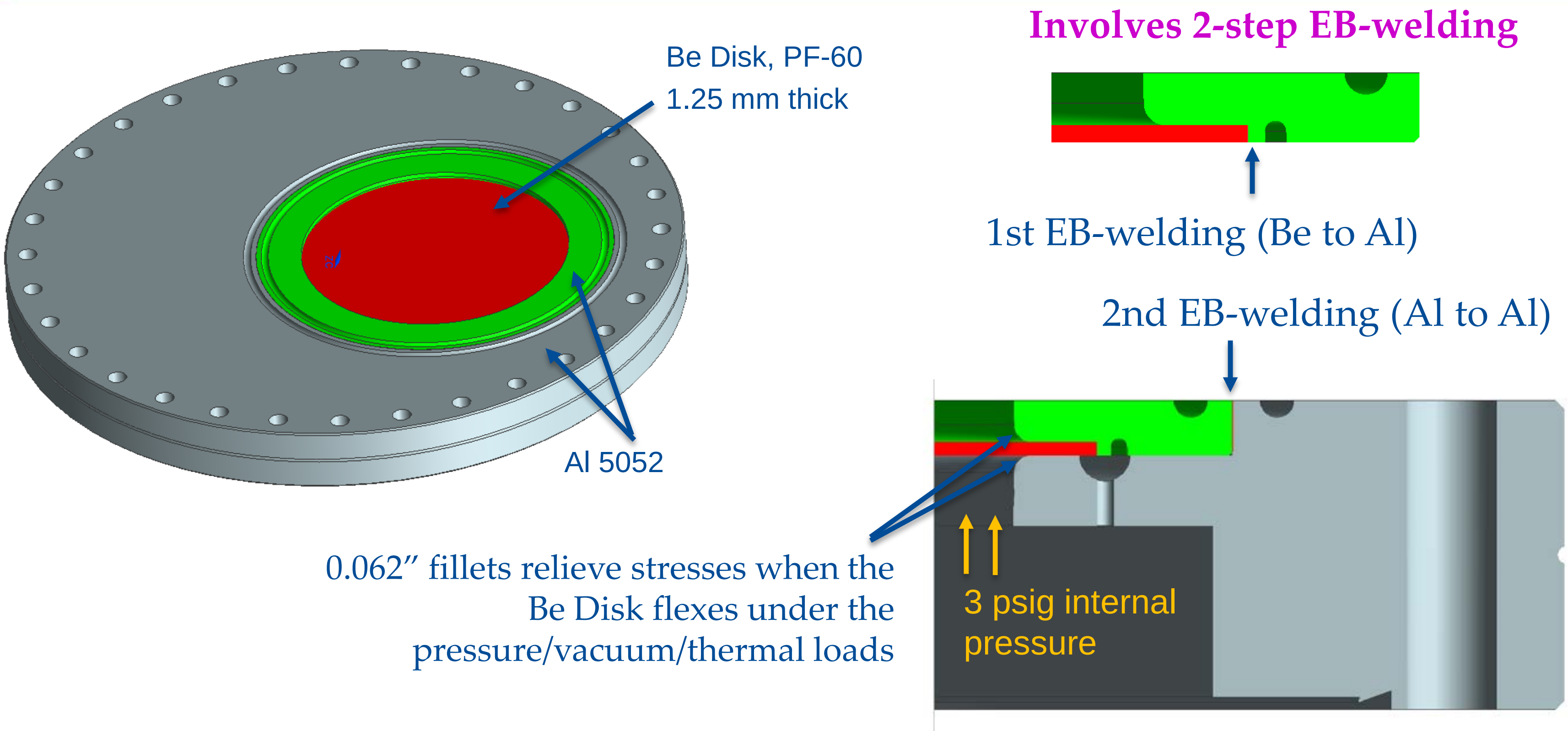
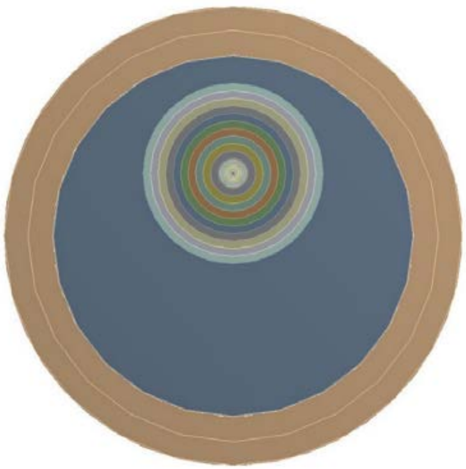
DS Be Window New Design

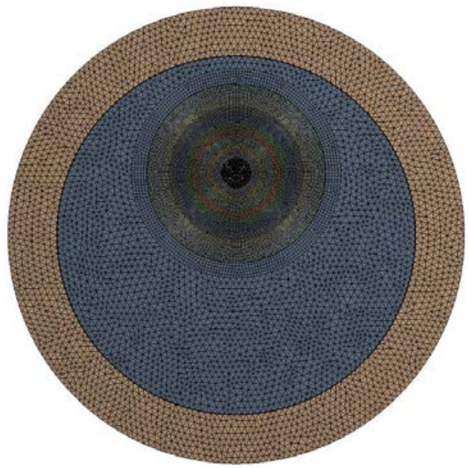


- Uses 5000 series aluminum (more compatible than Al 6061-T6 for Be-Al EBW);
- Welding grooves eliminates dissimilar thickness at the EBW joint, to allow materials to be fully melt before the heat is transferred away in the flange;
- Sandwich structure provides protection/support of the Be-Al EBW joint for both vacuum and internal pressure conditions, and also improves thermal contact

FEA Model, Analysis Scenarios

- Parts are sliced radially, corresponding to bins in the beam energy deposition simulations;
- This allows for fine meshing to the central portion of the Be Disk.





Scenario	Description
1	Vacuum, no beam
2	3 psig internal pressure, steady state (before beam)
3	3 psig internal pressure, immediately after beam spill
4	10 psig internal pressure, immediately after beam spill

- In the beam operation condition, the target canister is filled with helium gas to prevent the target graphite material from oxidation as well as reduce differential pressure on the Be Windows;
- It is expected that the maximum internal pressure will be 3 psig, given the fluctuations in external barometric pressure conditions, internal pressure control and gas heating from beam;
- Target canister is equipped with a safety relief vale set at 10 psig, therefore for the worst condition the window is designed to withstand 10 psig internal pressure with beam operation;
- Beam energy deposition in the material will produce heat loads onto the Be windows;
- During low intensity beam scans, the target canister is evacuated in order to improve the signal-to-noise ratio of the Budal monitor.

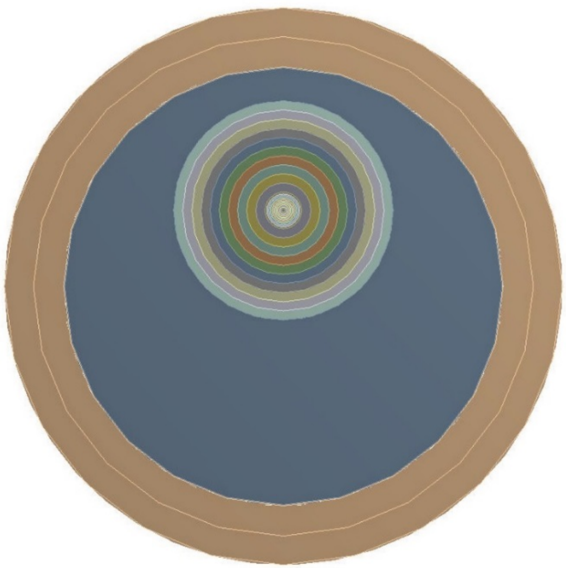
Material Properties

- According to Materion Corporation, PF-60 has only been characterized chemically, but not mechanical properties;
- Therefore, the thermal and mechanical properties of structural beryllium grade S-200F are used in place of PF-60;
- Data obtained from www.webmat.com

	Beryllium (S-200F)	Aluminum 5052-H36
Density (kg/m^3)	1,850	2,680
Modulus of Elasticity (GPa)	303.4	70.3
Poisson's Ratio	0.18	0.33
Thermal Conductivity (W/m-K)	216.3	138
Coef. of Thermal Expansion (µm/m-K)	11.4	22.1
Specific Heat (J/g-K)	1.925	0.88
Ultimate Strength (MPa)	324	276
Yield Strength (MPa)	241 @strain 0.2%	241
Fatigue Strength (MPa).	261 @10^7 cycles	131 @$5x10^8$ cycles

Thermal Loads

Proton beam design parameters	
Proton beam energy	120 GeV
Beam power	700 kW
Protons per pulse	$4.9\text{x}10^{13}$
Beam spill width	10 μsec
Beam repetition time	1.33 sec



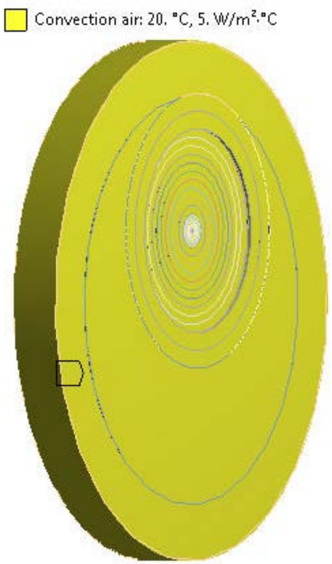
Energy deposition from MARS15

Inner radius (mm)	Outer radius (mm)	Power density over 10 μsec beam spill(W/m^3)	Average power density over 1.33 sec beam repetition pulse (W/m^3)	Total power (W)
0	1	4.84 e12	3.64 e7	**0.14**
1	2	4.51 e12	3.39 e7	**0.40**
2	3	3.18 e12	2.39 e7	**0.47**
3	4	2.52 e12	1.90 e7	**0.52**
4	5	1.93 e12	1.45 e7	**0.51**
5	6	1.74 e12	1.31 e7	**0.57**
6	7	1.54 e12	1.16 e7	**0.59**
7	8	1.35 e12	1.01 e7	**0.59**
8	9	1.17 e12	8.81 e6	**0.59**
9	10	9.34 e11	7.02 e6	**0.52**
10	15	8.43 e11	6.34 e6	**3.11**
15	20	5.63 e11	4.23 e6	**2.91**
20	25	3.77 e11	2.83 e6	**2.50**
25	30	2.78 e11	2.09 e6	**2.26**
30	35	2.25 e11	1.69 e6	**2.16**
35	40	1.65 e11	1.24 e6	**1.83**
40	45	1.59 e11	1.20 e6	**2.00**
45	50	1.16 e11	8.72 e5	**1.63**
50	55	1.06 e11	7.98 e5	**1.64**
55	67.65	6.51 e10	4.08 e5	**2.49**
			Total heat loads in Be Disk	**27.42**
		Aluminum flange		
0*	239*	6.51 e10	4.08 e5	**156.96**
239*	300*	3.48 e10	2.10 e5	**163.94**
			Total heat loads in Al flange	**320.90**

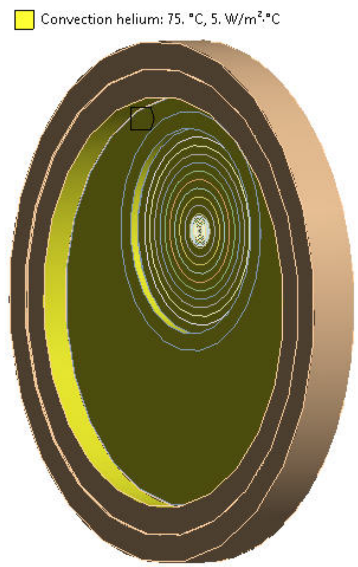
*With respect to aluminum flange center

Cooling Conditions

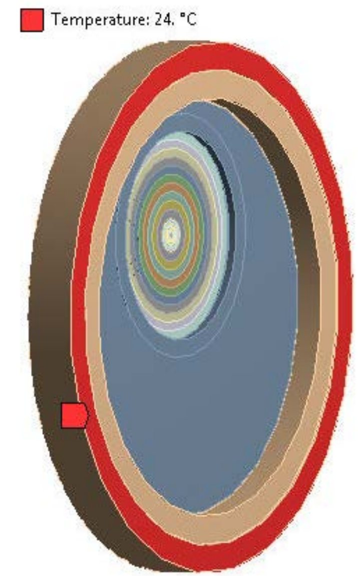
Air cooling



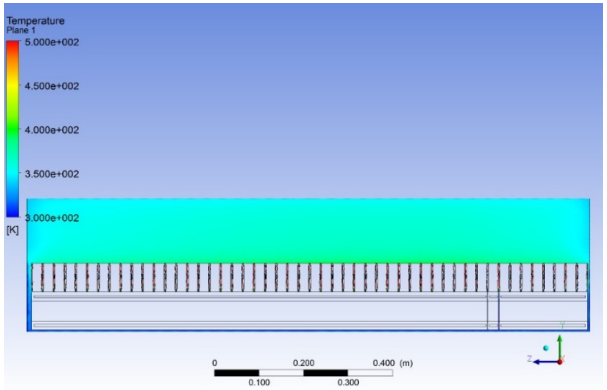
Helium convection

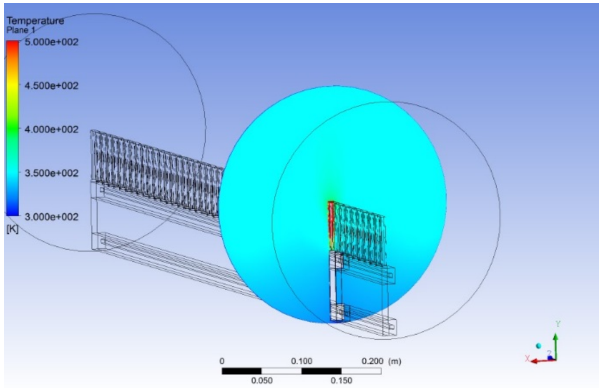


Cold surface



Helium temperature ~ 75 °C from Target CFD analysis, Tristan Davenne, STFC/RAL





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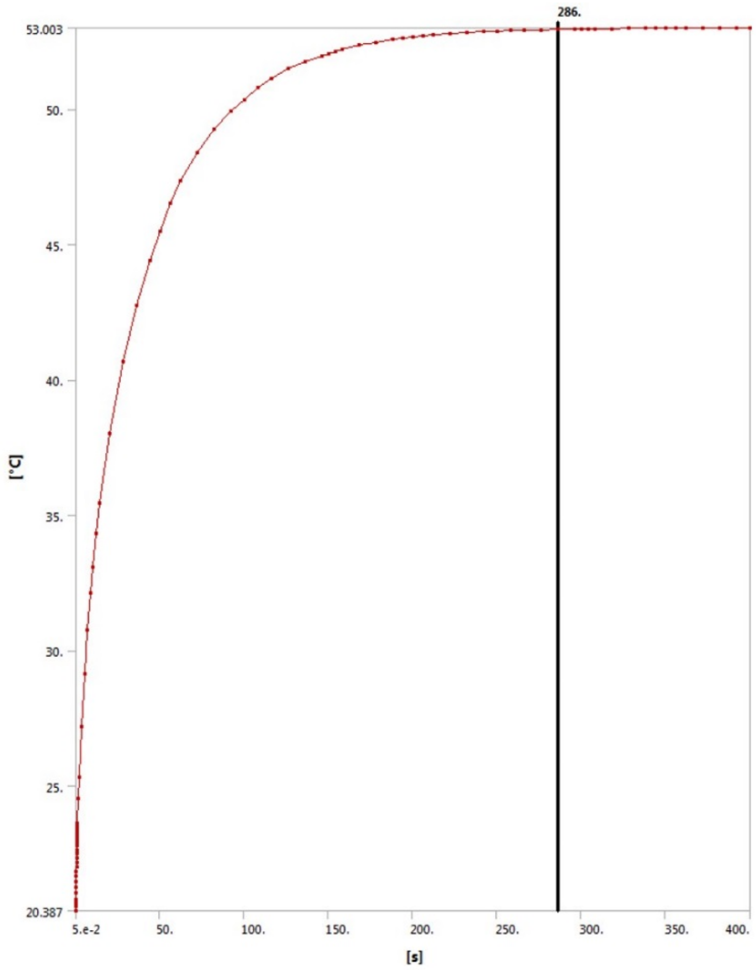
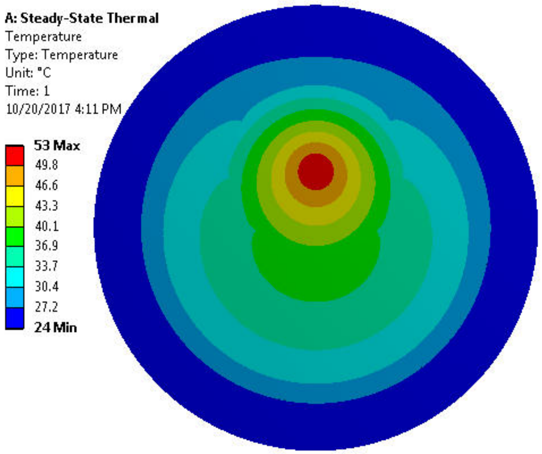
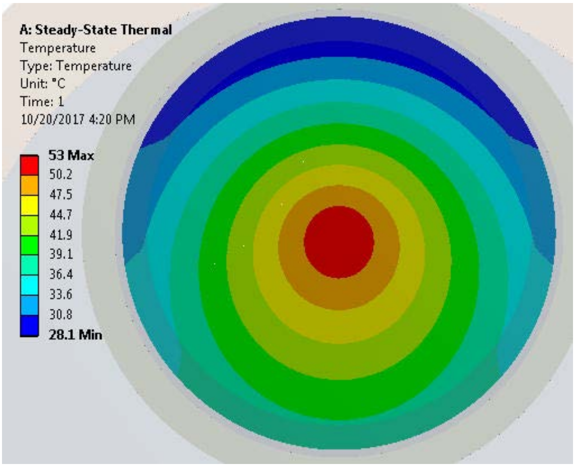
Temperature Trend after Beam Start-up

After beams start up, it will take about 286 sec (or 215 pulses) for the window to reach thermal equilibrium temperature of 53 °C





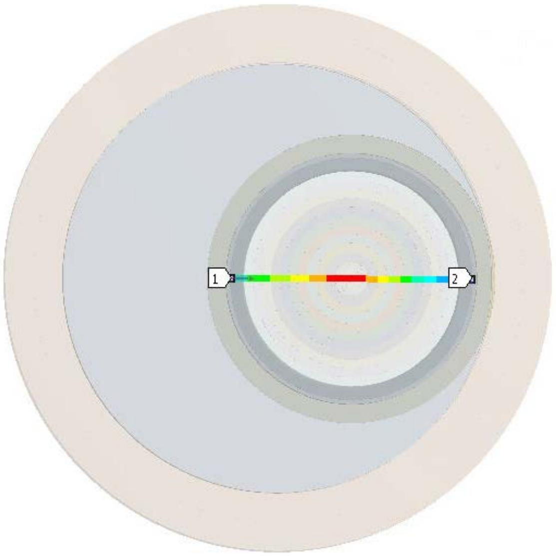
Window assembly

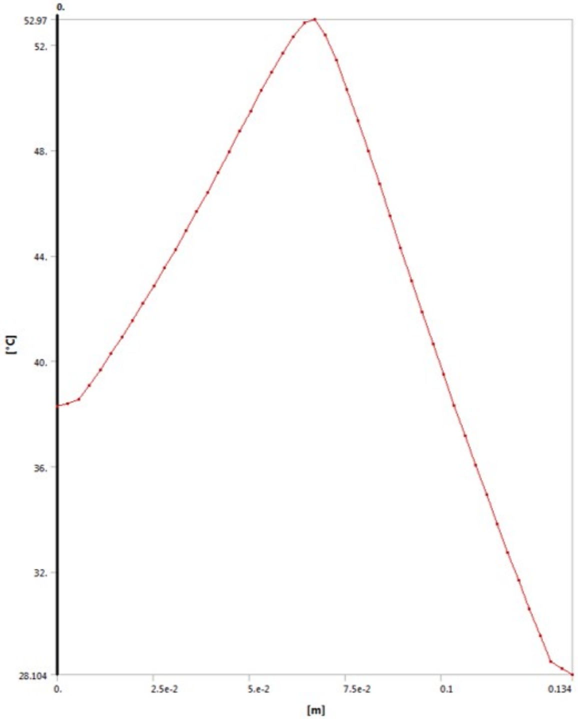


Be Disk

Temperature at Steady State Path Plot

Temperature plot along the path crossing the Be Disk center from "1" to "2"



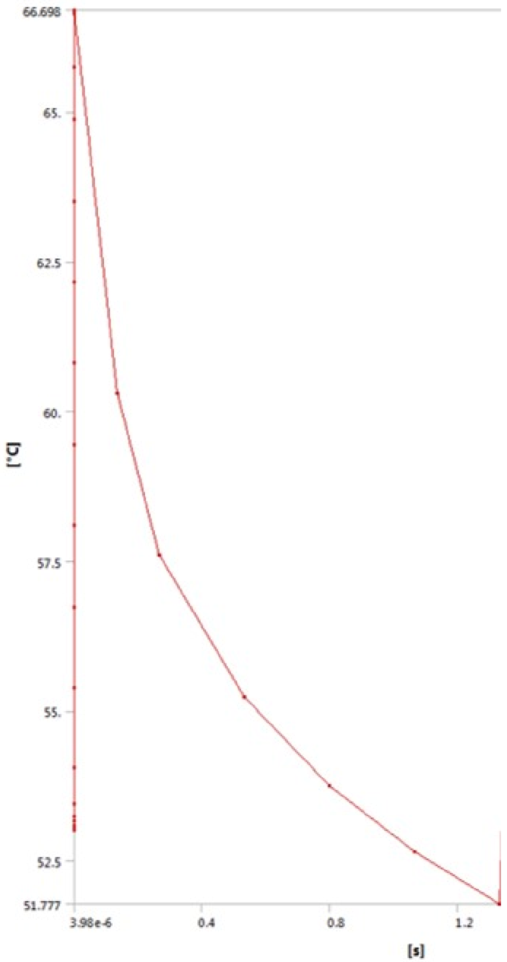


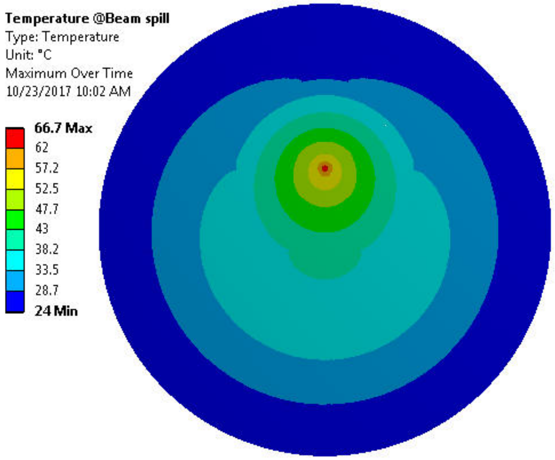
- Being offset from the aluminum flange, the temperature of the Be Disk edge near the flange center is 10 °C higher than the other side, due to being farther from the flange cold interface;

- This indicates that a good thermal conduction or short path to the cold surface can effectively reduce the temperature on the Be Disk.

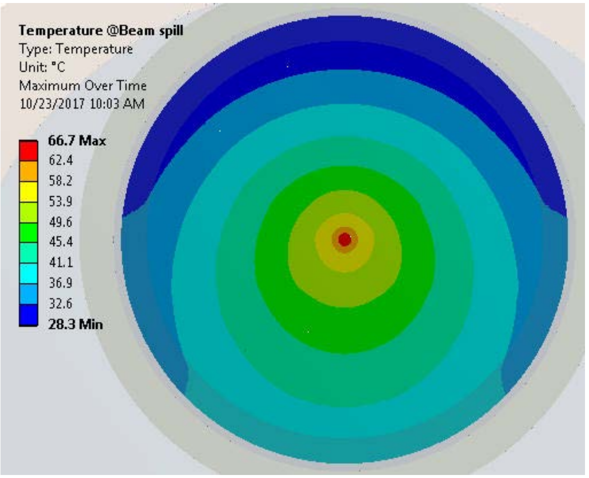
Temperature after Beam Spill

Temperature rises to 66.7 °C from 53 °C during each beam pulse after the window has reached thermal equilibrium





Window assembly

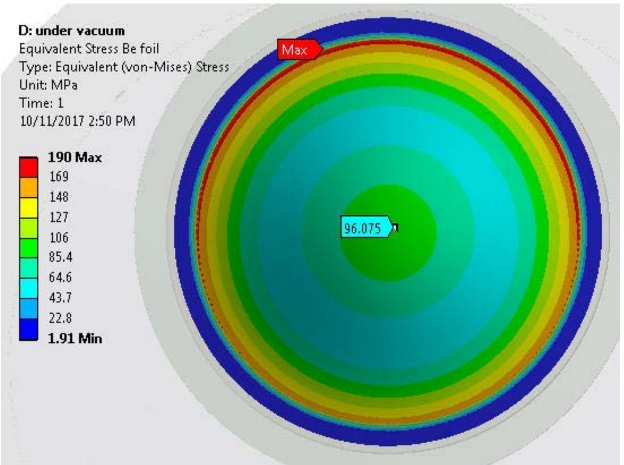


Be Disk

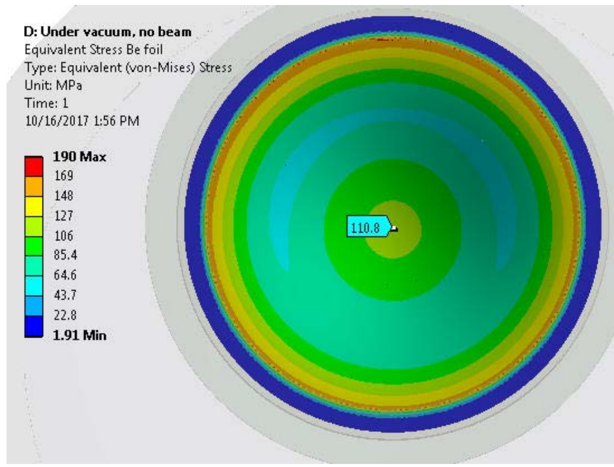
Stresses under Vacuum

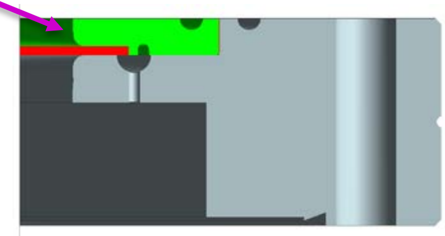
- Maximum stress 190 MPa will occur at the bore interfacing edge of Be-to-Al;
- Stress at the center will be 111 MPa

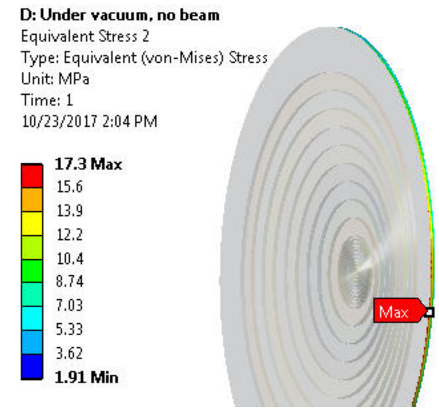
Internal surface



External surface

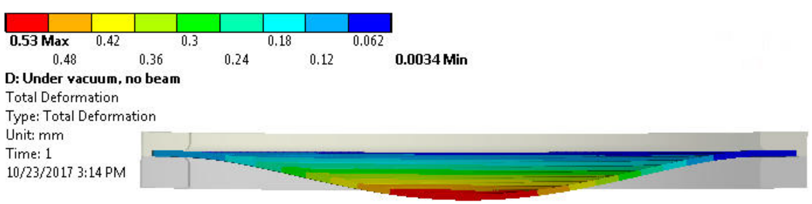




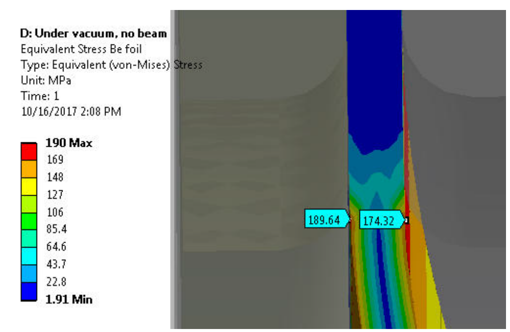


- Fillets on Al plates provide stress relief;
- This location is away from the e-beam welding heat affected zone;
- At EBW joint, maximum stress will be 17 MPa.

Maximum displacement will be 0.53 mm



Crossing Be thickness



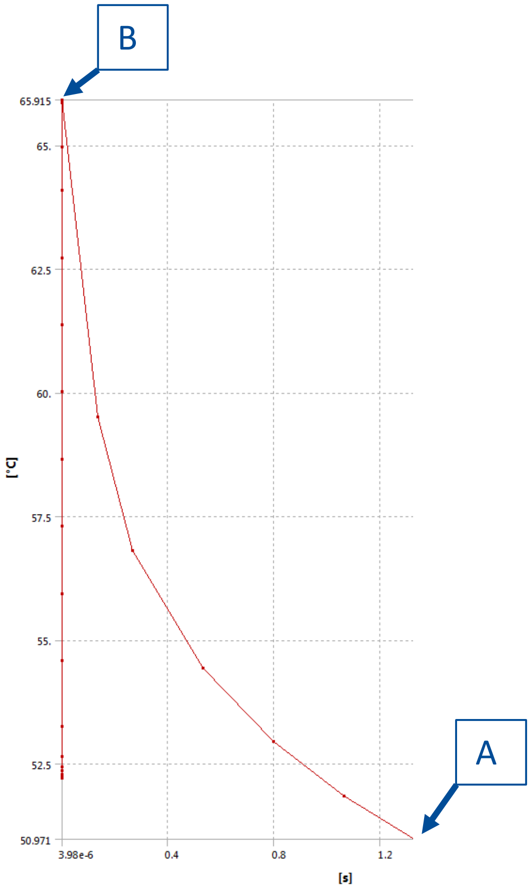
Stresses under Normal Beam Operation Conditions

Temperature profile was loaded for structural analysis for two conditions:

A: at the steady state before the next beam spill

B: immediately after the beam spill

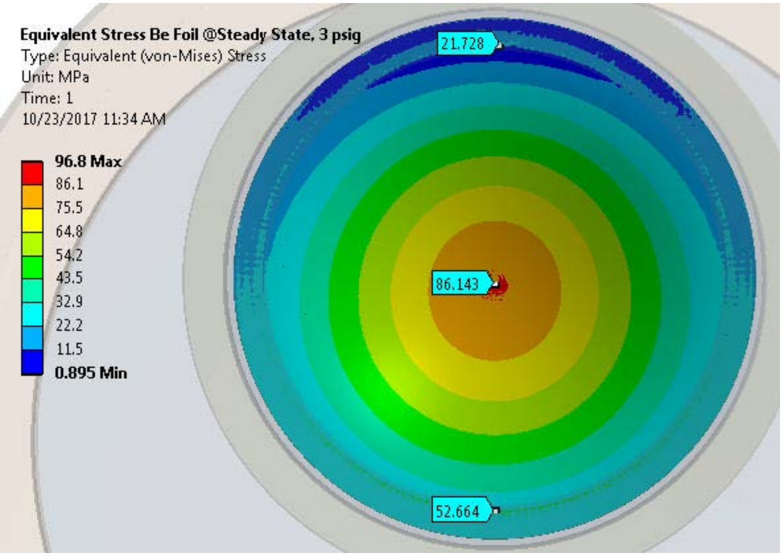
a 3 psig pressure (2.0684 x 10^4 Pa) was applied to the Be window internal surfaces.



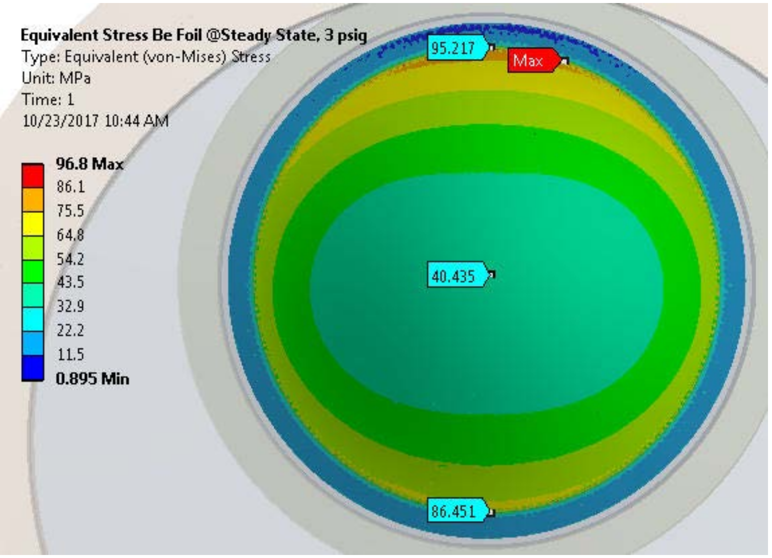
Stresses at Steady State

- Maximum stress 95 MPa will occur at the bore interfacing edge of Be-to-Al;
- Stress at the center will be 86 MPa

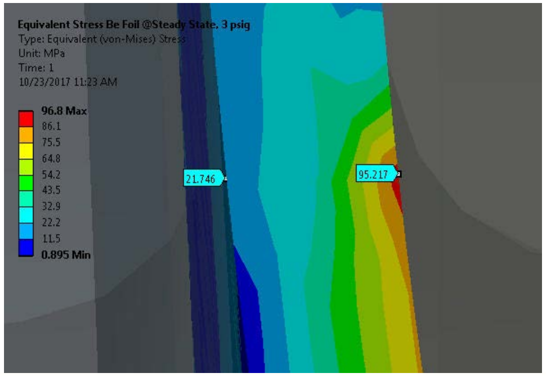
Internal surface



External surface



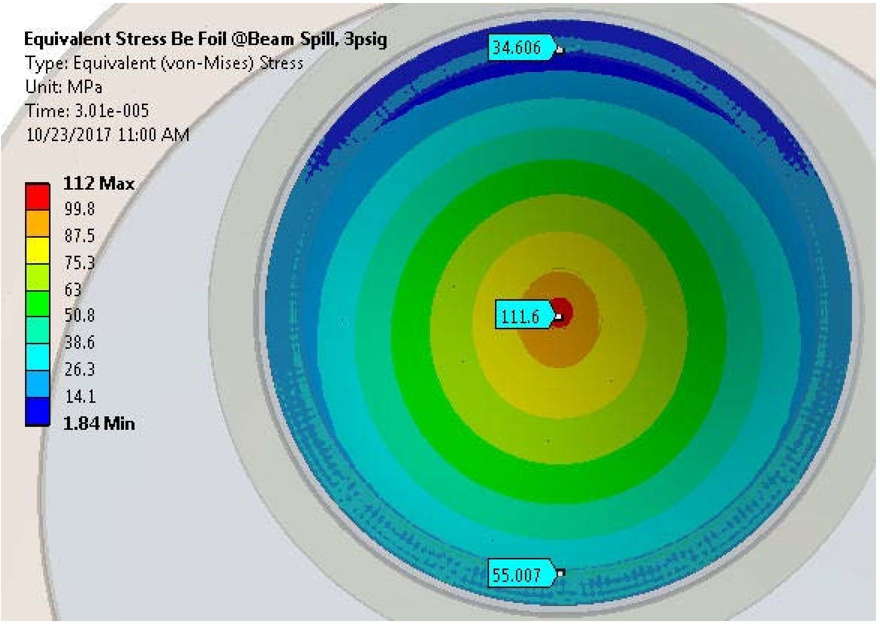
Crossing Be thickness



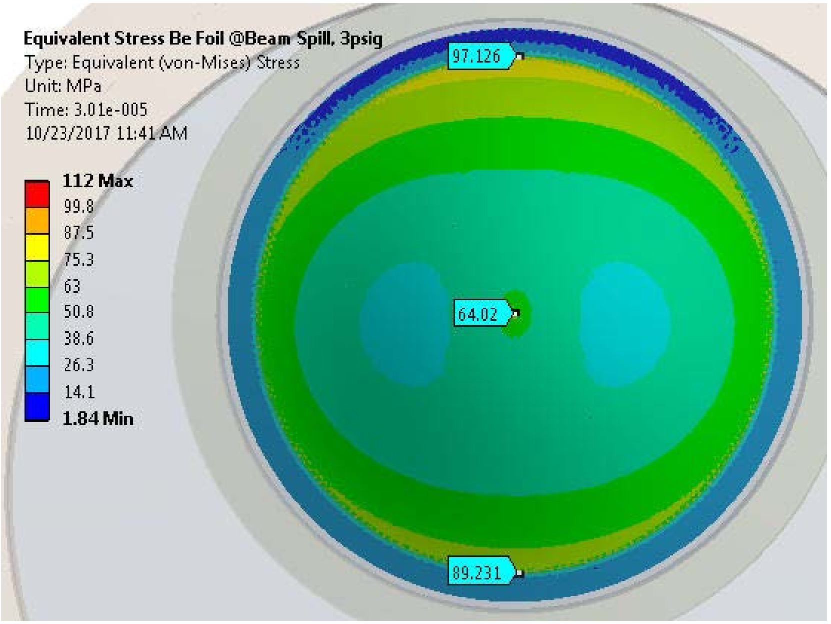
Stresses Immediately after beam Spill

- Maximum stress 112 MPa will occur at the Be Disk center;
- Stress at the interfacing edge of Be Disk with Al Bore will be 97 MPa

Internal surface

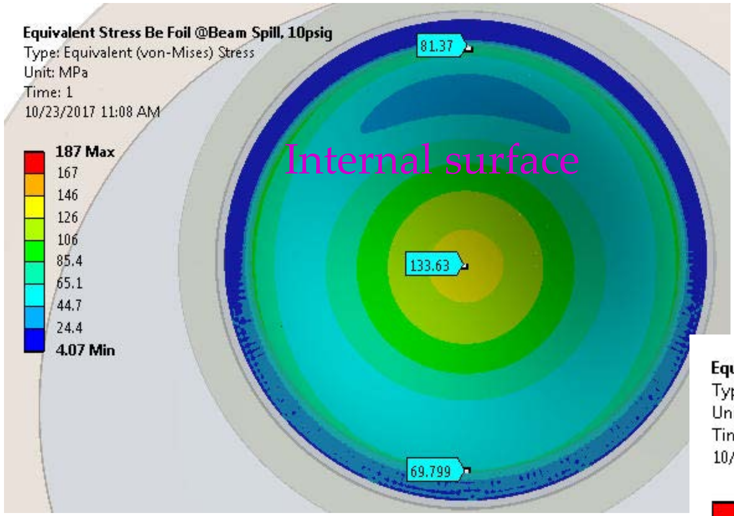


External surface

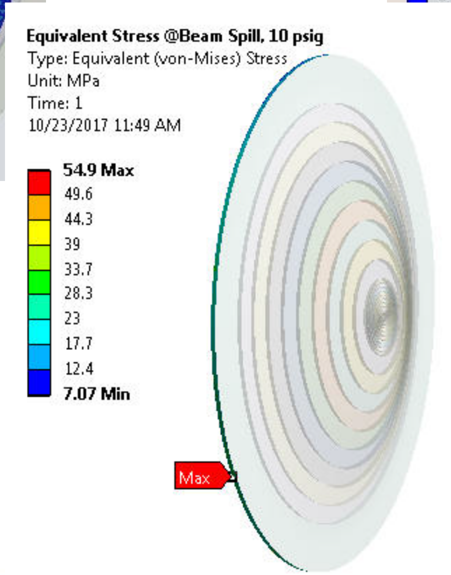


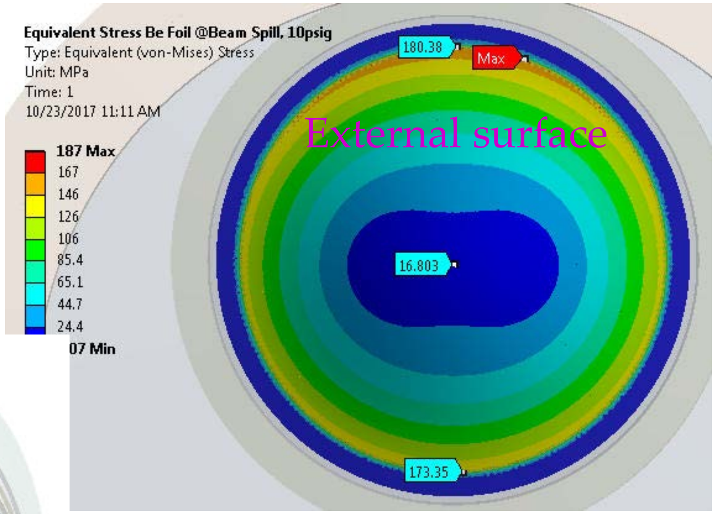
Stresses Immediately after beam Spill, with 10 psi Pressure

- Maximum stress 180 MPa will occur at the bore interfacing edge of Be-to-Al;
- Stress at the center will be 134 MPa, at the EBW joint will be 55 MPa;
- This is the worst case would happen. The target canister is equipped with a safety relief valve set at 10 psig.



EBW joint





Summary FEA Results under Different Scenarios

σ_e – max. stress at bore interfacing edge

σ_c – max. stress at center; σ_c - maximum stress at EBW joint

Scenario	Condition	Peak temperature (°C)	d (mm)	σ_e (MPa)	σ_c (MPa)	σ_J (MPa)
1	Vacuum, no beam	20	-0.53	190	111	**18**
2	3 psig, steady state	53	0.19	97	86	
3	3 psig, after beam spill	66.7	0.19	97	112	
4	**10 psig, after beam spill**	**66.7**	**0.44**	**187**	**134**	**55**

- Maximum stresses meet requirements per FESHM 5033.1, in which it states that allowable stress for vacuum windows is half of the material ultimate strength for Manned Areas and the material ultimate strength for Unmanned Areas, respectively;
- For scenarios 1 & 4, the maximum stress occurs at the interfacing edge of Be Disk with Al bore. This location is away from e-beam welding heat affected zone. The Al plates have 0.062" fillets to relieve stresses when the Be Disk flexes under pressure/vacuum/thermal loads.
- DS Be window reaches thermal equilibrium 53 °C after 286 sec (or 215 pulses) of beam start-up; Temperature rises from 53 °C to 66.7 °C during each beam pulse;
- Dynamic (inertial) stress was not included because the rate of loading is too small to have a significant effect.

Effects of Helium Temperature

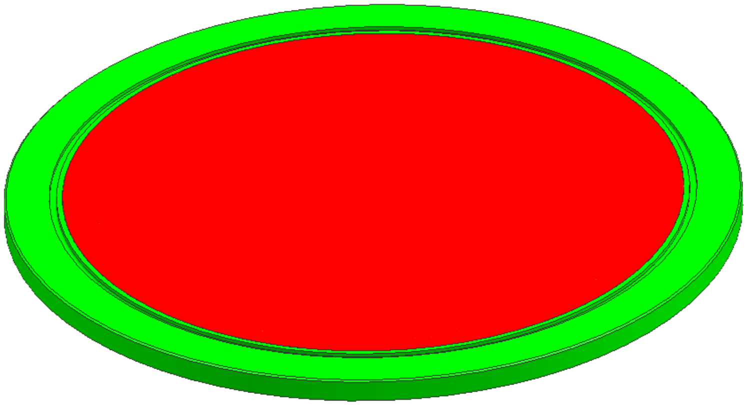
In order to understand the effects of the helium temperature to the DS window, a sensitively check was performed.

Helium temperature	DS window temperature	Reaction probe		
		air conv.	cold flange	helium conv.
150 C	55.4	-5.4 W	-379 W	36 W
100 C	53.8	-5.2 W	-364 W	20.7 W
75 C	53	-5.1 W	-356 W	13.1 W
50 C	52.5	-5 W	-349 W	5.4 W
24 C	51.4	-5 W	-341 W	-2.5 W

- When the helium temperature is over 50 °C , some heat flux will start to go into the DS window, shown by a positive value of the reaction probe;
- However, it will contribute only 4 °C temperature rise to the DS Window even when the helium temperature reaches 150 °C.

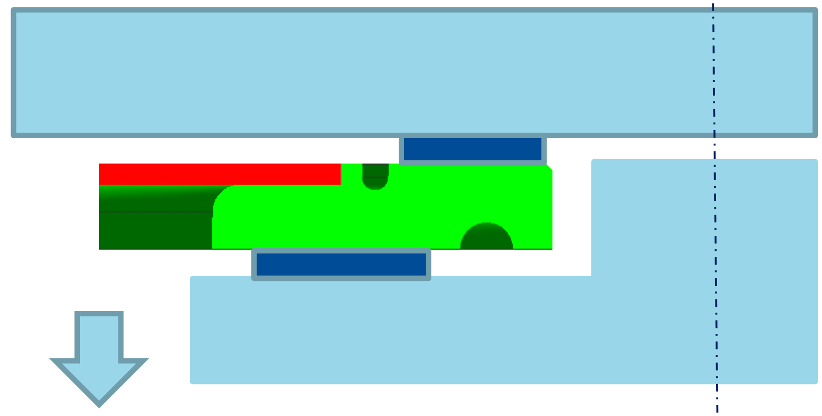
E-beam Welding Sample Leak Checking & Pressure Testing

E-beam welding sample, Qty. 2



Pressure test setup

vacuum – letting up to air - 3 psi cycling test



Leak checking setup

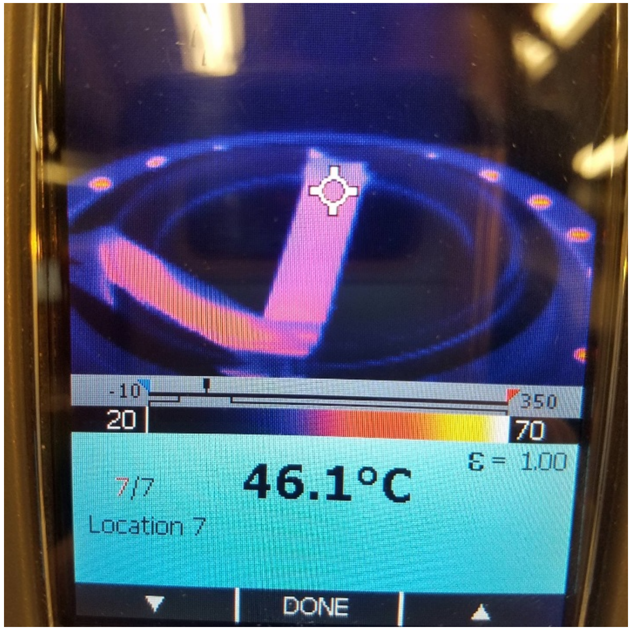
Pressure test setup

- Both samples past leak checking test and pressure test to 3 psi;
- Sample #2 was subjected to a pressure test up to 10 psi, and past 20 cycles of pump-down - letting up to air - 3 psi test

Tests were carried out by M. Stiemann

E-beam Welding Sample Thermal Testing

- A good thermal conduction effectively reduces the temperature on the Be Disk;
- Test was performed by setting the Al ring on a temperature controlled heating stove, and measuring the temperature with an infrared temperature sensor.;
- Temperature on the Be Disk center responded well with the temperature rise on the Al ring.



Tests were carried out by M. Stiemann

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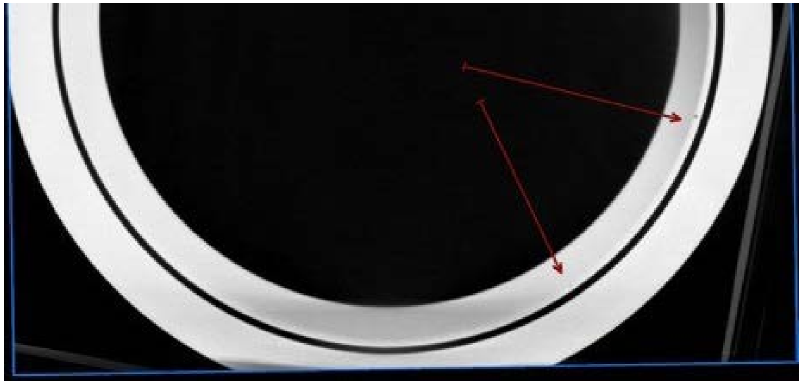
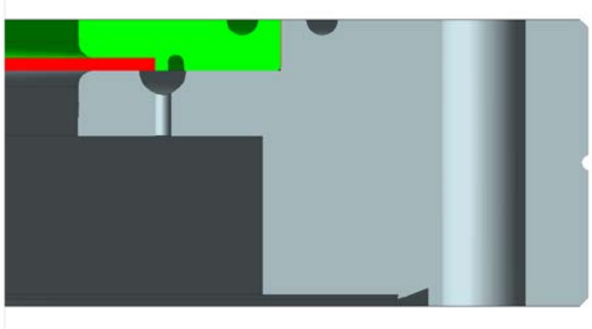
CT Scans

- Sample #1 was subjected to a single test of pressure to 3 psi. CT scan images indicated two large voids were found;
- No voids was found in Sample #2. But this sample has been subjected to a pressure test up to 10 psi and 20 cycles of vacuum -letting up to air -3 psi;

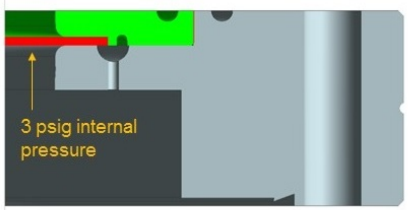


- We plan to send Sample #2 back to Materion for final assembly into an aluminum flange with a second step Al-to-Al e-beam welding;
- Since this sample has gone through multiple pressure tests, we need to evaluate if the stresses during testing were well below the aluminum ultimate strength.

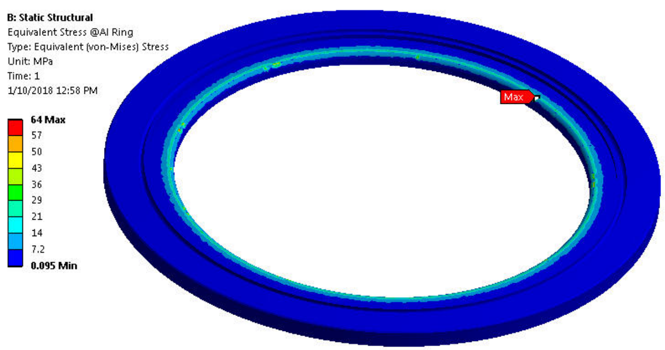


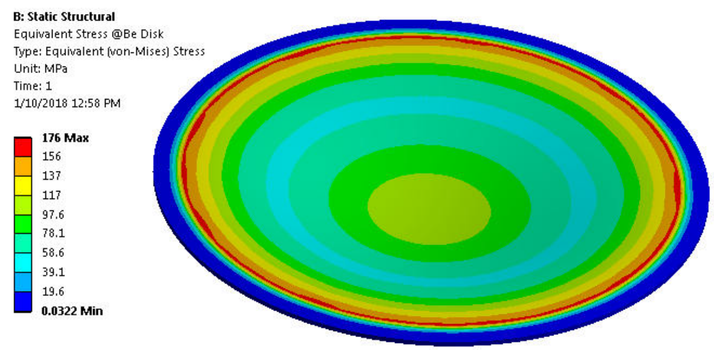
Stresses during Pressure/vacuum Testing

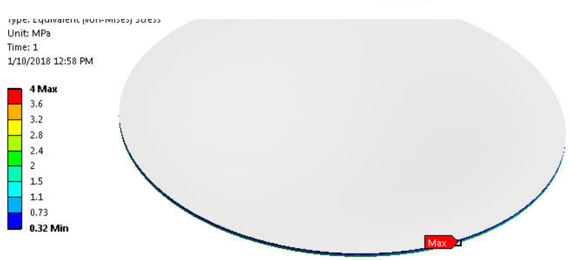
In operation



- Max. stress 64 MPa on Al will occur under vacuum at the bore interfacing edge;
- Max. stress 176 MPa on Be will occur under vacuum at the same location;
- Stresses at the EBW joint were below 4 MPa in Be and Al in any cases;
- Ultimate strength: 276 MPa for Al, 324 MPa for Be.







Scenario	Condition	σ_{Al} (MPa)	σ_{Be} (MPa)	σ_{J_Al}(MPa)	σ_{J_Be}(MPa)
1	Vacuum, 14.7 psig	64	176	1.8	4
2	3 psig	13.1	36	0.36	0.81
3	10 psig	43.6	120	1.2	2.7

Future Plans

- Send Sample #2 back to Materion for final assembly into an aluminum flange with a second step Al-to-Al e-beam welding;
- Send Sample #1 back to Materion for re-welding, and then CT scan;
- Ask Materion to scrape the Al parts prior to EBW within a 2-4 hours window to remove the oxidation, if that was not done for these two samples;
- Develop a Acceptance Criteria for the fabrication specification of future Be Windows.