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AD/Mechanical Support Department

June 20, 2009
Revised: February 9, 2010

Medium Energy Analysis of Beryllium Thin Windows for NOvA

(MSDN-ME-000095)

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Introduction

A preliminary analysis of the upstream (US) and downstream (DS), medium energy (ME) beryllium "thin" windows by the State Research Center of Russia Institute for High Energy Physics (IHEP) at Protvino, Russia considered a long-term primary beam pulse, given a 1.3 mm (rms) spot size[1]. Each window will be exposed to a higher beam (700 KW) heating load as compared to the NuMI Beam Line with a Low Energy (LE) energy deposition from the proton beam of 400 KW. This report considers the stresses and deflection incurred from the 700 KW ME beam deposition plus the pressure loads on both target windows under different operational conditions.

Target Thin Window Analysis

US pre-target beamline, US target and DS window cases considered:
1. US pre-target beamline window, vacuum load with energy deposition
2. US target window, 15 psig positive helium pressure with energy deposition
3. US target window, 3 psig positive helium pressure with energy deposition
4. US target window, 2 in-H2O positive helium pressure with energy deposition
5. Downstream target window, vacuum load no beam
6. Downstream target window, 15 psig positive helium pressure with energy deposition
7. Downstream target window, 3 psig positive helium pressure with energy deposition
8. Downstream target window, 2 in-H2O positive helium pressure with energy deposition

Beryllium Window and Flange Properties

The beryllium properties given in Table 1 reflect information collected from Brush Wellman Inc.[2] and testing completed by Sandia National Laboratory in conjunction with the Russian Institute for Inorganic Material for ITER[3]. The material properties of the actual Brush Wellman window foil is Beryllium (PF-60), which is 98.0% pure have not been published. According to Brush Wellman Inc. Electrofusion Products, PF-60 has only been characterized chemically. Therefore, S-200F beryllium mechanical properties are used in place of PF-60[4]. The high-strength aluminum alloy AMg6 (Russian grade, GOST 4784-74)[5] material properties for the US and DS flange is given in Table 2. Table 3 provides the material properties for the beryllium window Conflat flange made of 316 L stainless steel.

Table 1. Properties of pure beryllium as a function of temperature.

Temperature (K)	**300**	**400**
Density (kg/m^3)	1,848	1,848
Ultimate Strength (MPa)	448.2*	---
Yield Strength (MPa)	283	---
Modulus of Elasticity (MPa)	296e3	290e3
Poisson's Ratio	0.1	0.1
Fatigue Strength (MPa)	268**	---
Thermal Conductivity (W/m/K)	199	162
Coef. of Thermal Expansion (m/m/K)	1.16e-5	1.25e-5
Specific Heat (J/kg/K))	1,857	2,156

*From Brush Wellman tests performed on 0.25 mm thick PF-60 material (see email in Appendix A).
**Based on > 10^7 cycles.

Table 2. Properties of flange (AMg6 aluminum) as a function of Temperature.

Temperature (K)	**293**	**373**	**423**
Density (kg/m^3)	2,640	2,640	2,640
Ultimate Strength (MPa)	320	300	250
Yield Strength (MPa)	170	150	130
Modulus of Elasticity (MPa)	710e3	680e3	672e3
Poisson's Ratio	0.35	0.35	0.35
Fatigue Strength (MPa)	170	150	130
Thermal Conductivity (W/m/K)	122	131	150
Coef. of Thermal Expansion (m/m/K)	23.9e-6	23.9e-6	24.8e-6
Specific Heat (J/kg/K))	922	980	990

Table 3. Properties of Conflat flange (316 L stainless steel) as a function of Temperature.

Temperature (K)	**300**	**400**
Density (kg/m^3)	8,030	8,030
Ultimate Strength (MPa)	586	496
Yield Strength (MPa)	241	159
Modulus of Elasticity (MPa)	193e3	185e3
Poisson's Ratio	0.35	0.35
Fatigue Strength (MPa)	---	---
Thermal Conductivity (W/m/K)	16.2	17.4
Coef. of Thermal Expansion (m/m/K)	16.9e-6	17.0e-6
Specific Heat (J/kg/K))	500	510

Finite Element Models and Transient Analysis

Two separate finite element (FE) models were considered; US and DS target window. The stresses due to the thermal profile and structural loads on each window were evaluated. The structural model was generated last as it read in the temperature profile (and therefore considered thermal stresses associated with the beam energy deposition) and the applied pressure for each case. In the first 10 μsec beam pulse, a window received the estimated energy deposition described earlier. In the remaining time of the 1.33 second repeated rate, cooling occurs.

The steady-state thermal response considers the following assumptions with an initial temperature condition of 20 ^{o}C. Convection was added as a surface load considering a coefficient value of 5 ($W/m^2/K$) and a conservative estimate of air (bulk) temperature around the target pile during operation of 20 ^{o}C, based on low energy (LE) operational thermocouple measurements from January 2009[6]. A maximum target casing temperature of 24 ^{o}C was reported by IHEP, based on an initial thermal analysis of the ME target[1]. This value was used at the target casing flange periphery as a temperature boundary condition.

Upstream Window

An FE analysis using shell elements (shell131 (thermal) and shell181 (structural)) was considered under the parameters given in Table 4 and Figure 1. The use of shell elements was appropriate, allowing for a finer mesh and more efficient model generation.

Table 4. US pre-target beamline and target window parameters given two window thickness cases.

Beryllium Window Thickness, mm	0.25	0.5
Beryllium Window OD, mm	25.4	
Aluminum Target Flange OD, mm*	300	
SS Conflat Flange OD, mm	69.4	
Offset (flange center to beamline center), mm*	41.5	

*Target window only

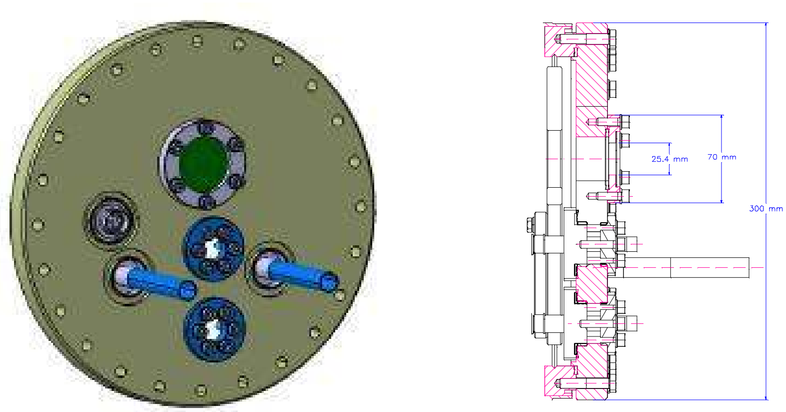


Figure 1. US target window geometry.

The US window energy deposition was considered within a MARS15[7] simulation by Bryon Lundberg. Tables 5 and 6 provides the ME parameters used for this simulation and the energy deposition values in terms of radial bins, respectively. A thickness of 0.25 mm was assumed and used in both cases in the MARS15 estimation, since doubling this thickness caused at most a 9% change in the energy deposition result[8]. The US beryllium window is brazed within a 2-3/4" CF flange as shown in drawing 8030-MB-449112 (see Appendix B).

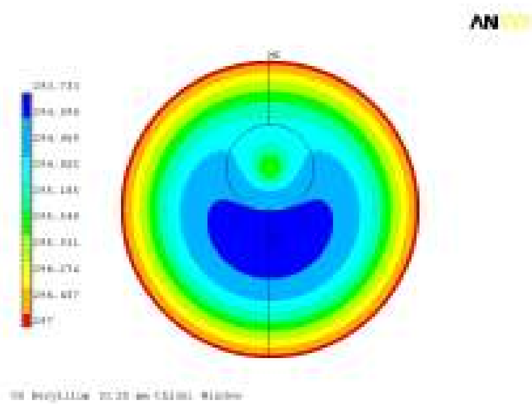
Table 5. NOvA (ME) beam parameters.

Beam Energy	120 GeV/c
Protons per pulse	4.90e13
Cycle Time, sec	1.33
Beam Sigma, mm (rms) in (x,y) plane	1.3
Pulse Length, sec	10e-6
Constant, J/eV	1.6020e-19

Table 6. Energy deposition in US pre-target and target window.

Inner Radius (mm)	Outer Radius (mm)	Power Density (W/m^3)	Averaged Power Density (W/m^3)
0	0.5	2.08 e13	1.57 e8
0.5	1	1.82 e13	1.37 e8
1	1.5	1.36 e13	1.02 e8
1.5	2	8.75 e12	6.58 e7
2	2.5	4.97 e12	3.74 e7
2.5	3	2.47 e12	1.86 e7
3	3.5	1.06 e12	7.97 e6
3.5	4	3.75 e11	2.82 e6
4	4.5	1.28 e11	9.61 e5
4.5	5	4.45 e10	3.34 e5

During the initial transient, the US window temperature at the center varies from 22 ^oC initially to 66 ^oC immediately after beam spill. Steady-state is achieved after 30 seconds of beam operation. Figures 2(a) and 2(b) depict the temperature contour of the 0.25 mm thick US window before and after a beam pulse at steady-state, respectively. Before and after beam maximum temperatures with corresponding heat flow from flange periphery is given in Table 7.



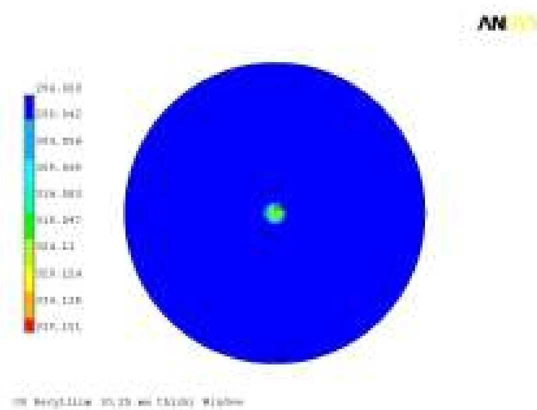


Figure 2(a) US 0.25 mm thick window temperature [K] contour before a beam pulse. **2(b)** After beam [K].

Table 7. Summary of US thermal transient conditions, heat flow and time to reach steady-state.

t (mm)	T_b (^oC)	T_a (^oC)	Q (W)	Time (sec)
0.25	23.9	66	-1.64	
0.50	23.9	65.8	-2.49	30

The corresponding maximum von Mises equivalent stress at the edge σ_e (SEQV) of 223 MPa, given in Table 8 in terms of thermal stress and pressure load, where the worst case is 15 psig helium pressure and/ or vacuum load was found at the US, 0.25 mm thick window edge. The von Mises equivalent stress σ_c (SEQV) at the window center was 132 MPa. These values are within the Fermilab FESHM 5033.1[9] allowable stress σ_a of 224.1 MPa as defined by one half of the ultimate strength value[10] and fatigue limit of 268 MPa (> 10^7 cycles)[11]. Supporting scoping calculations are given in Table 1C, Appendix C[12].

Table 8. US pre-target beamline and target window result summary of thermal and pressure loading.

Case	Pressure	t (mm)	d (mm)	σ_e (MPa)	σ_c (MPa)	σ_a (MPa)
1	Vacuum*	0.25	0.15	219	122	224.1 (per FESHM 5033.1)
		0.50	0.02	79.8	61.5	
2	15 psig	0.25	0.15	223	132	
		0.50	0.045	85.4	107	
3	3 psig	0.25	0.037	57	87.8	
		0.50	0.019	34.2	74.9	
4	2 in-H2O	0.25	0.014	27.2	65.5	
		0.50	0.013	27	65.1	

*Pre-target beamline window.

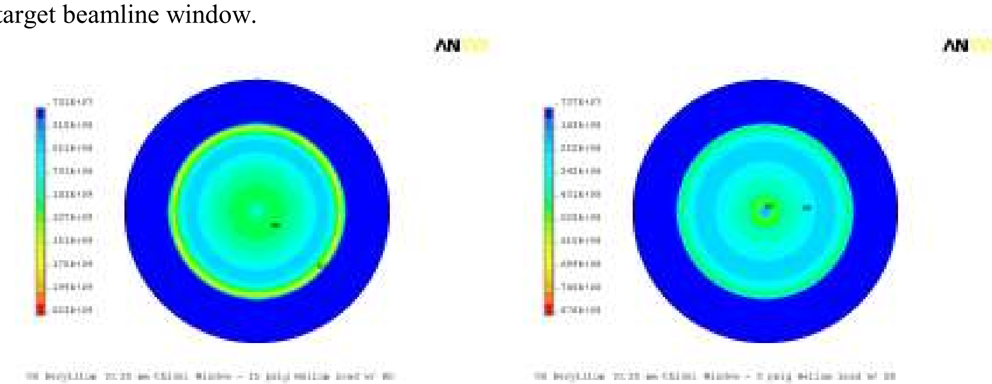


Figure 3(a) US 0.25 mm thick window structural result with 15 psig load in terms of SEQV [MPa].
3(b) With 3 psig helium (maximum operational) load in terms of SEQV [MPa].

Downstream Window

Analysis of the DS window was also completed in ANSYS using shell elements with window parameters listed in Table 9. The range of DS window thickness varies from 1.0 to 1.5 mm in 0.25 mm increments with geometry shown in Figure 4. MARS15 code was used again to estimate the DS energy deposition (body load) given in Table 10 in terms of radial bins, within the window and target casing flange.

Table 9. DS window parameters.

Beryllium Window Thickness, mm	0.5 - 1.5
Beryllium Window OD, mm	120
Flange OD, mm	300
Thickness (up to 239 mm in diameter), mm	8
Thickness (between 239 mm and 300 mm diameter), mm	25
Offset (flange center to beamline center), mm	41.5

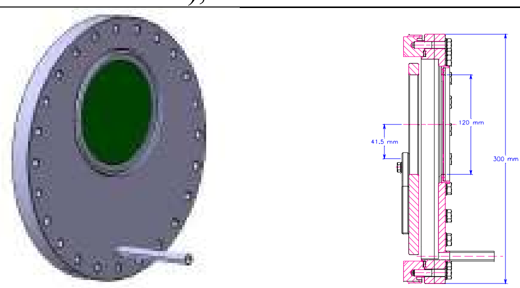


Figure 4. DS window geometry.

Table 10. Energy deposition in DS target window.

Inner Radius (mm)	Outer Radius (mm)	Power Density (W/m^3)	Averaged Power Density (W/m^3)
0	1	4.84 e12	3.64 e7
1	2	4.51 e12	3.39 e7
2	3	3.18 e12	2.39 e7
3	4	2.52 e12	1.90 e7
4	5	1.93 e12	1.45 e7
5	6	1.74 e12	1.31 e7
6	7	1.54 e12	1.16 e7
7	8	1.35 e12	1.01 e7
8	9	1.17 e12	8.81 e6
9	10	9.34 e11	7.02 e6
10	15	8.43 e11	6.34 e6
15	20	5.63 e11	4.23 e6
20	25	3.77 e11	2.83 e6
25	30	2.78 e11	2.09 e6
30	35	2.25 e11	1.69 e6
35	40	1.65 e11	1.24 e6
40	45	1.59 e11	1.20 e6
45	50	1.16 e11	8.72 e5
50	55	1.06 e11	7.98 e5
0*	239*	6.51 e10	4.08 e5
239*	300*	3.48 e10	2.10 e5

*With respect to aluminum flange center.

Boundary conditions such as receiving water cooling at the flange periphery and convective cooling were the same as in the US window case. In the 1.0 mm window thickness case, after receiving the 10 μsec beam pulse, the DS window's center temperature rises from 56.5 ^{o}C to 66.4 ^{o}C at steady-state. For example, Figure 5 provides the transient development of the maximum nodal temperature as a 1.0 mm thick DS window eventually reaches steady-state, after 380 seconds of beam heating. Figures 6(a) and 6(b) depict the temperature contour of the 1.0 mm thick DS window before and after a beam pulse, respectively. The heat flux across the thermal boundary was estimated through the ANSYS model, in order to ensure that adequate cooling can be provided for the given assumptions. The heat (rejected) rate at the flange periphery in terms of Watts, shown in Table 11 varies with DS window thickness.

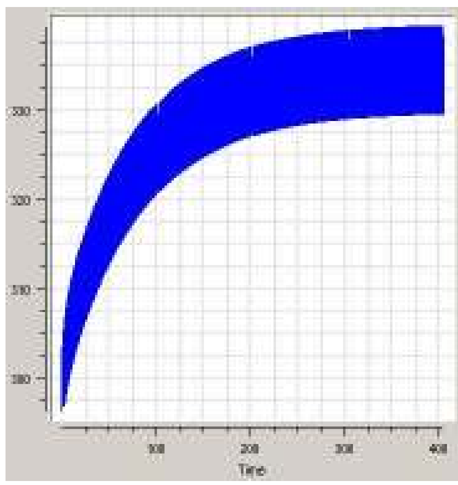


Figure 5. DS 1 mm thick window ANSYS transient nodal temperature [K] over time [sec].

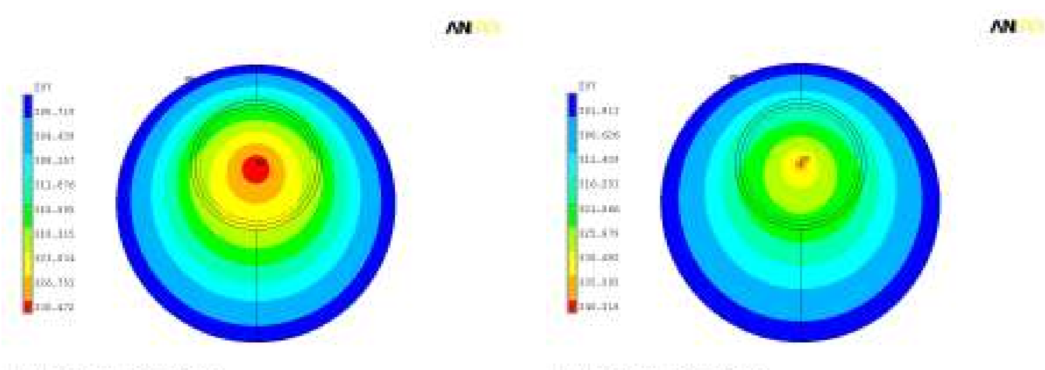


Figure 6(a) DS 1.25 mm thick window temperature [K] contour before a beam pulse. **6(b)** After beam [K].

Table 11. Summary of DS thermal transient conditions, heat flow and time to reach steady-state.

t (mm)	T_b (^oC)	T_a (^oC)	Q (W)	Time (sec)
1.00	56.5	66.4	-33.5	380
1.25	57.4	67.3	-43.3	
1.50	57.9	67.8	-53.1	

Table 12 provides the DS beryllium window result summary of maximum stress and deflection in steady-state, which considers both energy deposition and pressure loading. Supporting DS window scoping calculation results are given in Table 2C, Appendix C[11]. These scoping calculations compare analytical results against equivalent model results calculated in ANSYS Workbench.

Table 12. DS window result summary of maximum stress and deflection.

Case	t (mm)	Pressure	d (mm)	σ_e (MPa)	σ_c (MPa)	σ_a (MPa)
5	1.00	Vacuum*	1.13	270	150	224.1 (per FESHM 5033.1)
6		15 psig	1.24	384.0	226.5	
7		3 psig	0.39	81.7	141	
8		2 in-H2O	0.11	65.6	123	
5	1.25	Vacuum*	0.71	189	130	
6		15 psig	0.86	211	164	
7		3 psig	0.23	42.2	100	
8		2 in-H2O	0.11	21.3	69.4	
5	1.50	Vacuum*	0.52	133	103	
6		15 psig	0.65	159	140	
7		3 psig	0.20	29.4	66.2	
8		2 in-H2O	0.04	16.9	50.6	

*No energy deposition applied.

Figure 7(a) gives the maximum von Mises stresses (σ_c and σ_e) for the 15 psig helium load with maximum energy deposition on center of a 1.25 mm window and at the edge, 164 MPa and 211 MPa, respectively. The allowable stress σ_a for beryllium at the maximum steady-state temperature is 224.1 MPa per FESHM 5033.1[9] with a fatigue limit of 268 MPa (> 10^7 cycles)[11]. Figure 7(b) depicts the von Mises stresses in the operational mode (under a maximum 3 psig helium load with energy deposition applied).

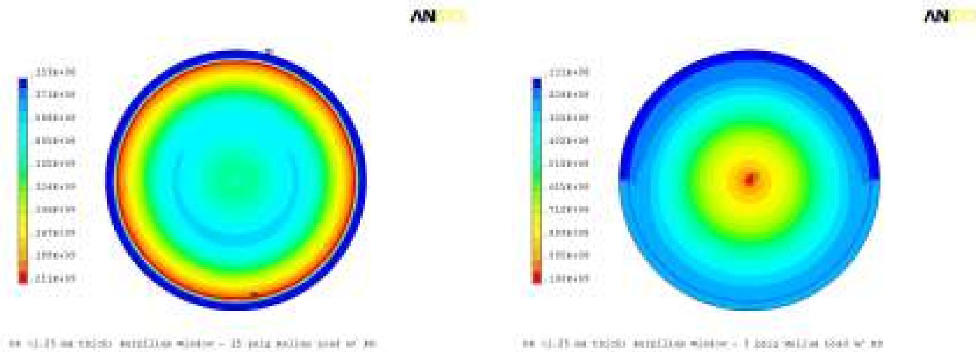


Figure 7(a) DS 1.25 mm thick window structural result with 15 psig load in terms of SEQV [MPa]. **7(b)** With 3 psig helium (maximum operational) load in terms of SEQV [MPa].

Conclusions

Given the proposed ME deposition, the US beryllium target window reaches thermal equilibrium after 30 seconds of beam or 23 pulses with a peak temperature of 66 ^{o}C. The maximum von Mises stress of 219 MPa occurs at the edge of a 0.25 mm thick pre-target window when a vacuum load and ME deposition is applied. This value compares to the design benchmark established by Joel Misek, where the analytical maximum stress at the window edge and center was 222.2 MPa and 143.1 MPa, respectively. Since the US pre-target window analytical maximum stress value was very close to the allowable, this window was hydrostatically tested to failure at a pressure of 160 psig[13].

Similarly, the DS beryllium target window reaches steady-state after 380 seconds of beam operation or 286 pulses with a peak temperature of 67.3 ^{o}C. The maximum von Mises stress of 211 MPa occurs at the edge of a 1.25 mm thick window when a 15 psig helium load and ME deposition is applied. Both the US and DS window equivalent stresses were beneath the allowable stress σ_a of 224.1 MPa as defined by one half of the ultimate strength value[10] (with a safety factor of 2) as specified by FESHM Chapter 5033.1[9] and fatigue limit (considering $>10^7$ cycles) of 268 MPa[11]. A 15 psig helium load was applied to a simplified ANSYS model in each case and then compared to the analytical results. These scoping calculations demonstrate each model's validity.

The load cases for each window regarding vacuum and 15 psig helium positive pressure are very conservative since the highest expected operational pressure with energy deposition is 3 psig, considering the fluctuations in external barometric pressure conditions, internal pressure control and gas heating from the beam. A maximum von

Mises stress of 42.2 MPa and 100 MPa was estimated for the extreme operational case of 3 psig helium load with energy deposition applied for the selected US (0.25 mm thick) and DS (1.25 mm thick) window, respectively. The target casing, protected by a 10 psig safety relief valve will never be considered a pressure vessel.

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Appendices