C-A D Engineering Design Support Documentation Cover Page

57010339 CAL-01

Title: ***W-Line Beam Dump Window***	Author: ***S. Bellavia*** S. Bellavia
Subject: ***W-Line Beam Dump Window Thermal-Stress Analysis***	
C-A Department Group: Mechanical	Checked: [illegible] Approval: [illegible]
Documentation Type: ☐ Written Technical Paper ☑ Design Calculations ☐ Design Review Presentation ☐ Design Certification ☐ Specification ☐ Procurement Documentation ☐ Safety/ALARA Review Presentation ☐ Other:_____	Equipment Type: ☐ Magnets and Power Supplies ☐ Vacuum Systems ☐ RF Systems ☐ Cryogenic Systems ☐ Experimental Equipment ☐ Beam Instrumentation ☐ Water Systems ☐ Buildings, Structures, and Shielding ☑ Other: Beam Dump Window
Equipment Location: ☐ Tandem Van DeGraff ☐ Linac ☐ Booster ☐ AGS ☑ RHIC ☐ 912 Experimental Area ☐ 919 Experimental Area ☐ RHIC Experimental Areas ☐ SNS _____ ☐ Buildings, Structures, and Shielding ☐ Other _____	Associated information for cataloging (if available fill in the number): ☐ C-A D Design Room Job No. _____ ☑ C-A D Design Room Drawing No. 57010339 AND 57070019 ☐ C-A D Specification No. _____ ☐ C-A D Experiment No. _____ ☐ Other _____

Building 911
P.O. Box 5000
Upton, NY 11973-5000
Phone 631 344-4846
Fax 631 344-5954
bellavia@bnl.gov

managed by Brookhaven Science Associates
for the U.S. Department of Energy

Calculations

date: January 2nd, 2008

to: K. Yip; L. Ahrens; J. Tuozzolo

from: Steven Bellavia

subject: W-line Beam Dump Window with Incident Gold Ion Beam

Discussion:

A thermal-stress analysis was performed for the existing AGS W-line Beam Dump Window for the case of being hit directly by a Gold Ion beam. The energy distribution of the beam (for a single Ion) was provided.

Materials, Geometry and Loads:

The window is a type 304 stainless steel, 3.75 inch Diameter x .25 inches thick (9.525 cm x .635 cm thick). See RHIC drawings 57010339 and 57070019 (Appendix A).

The x-y energy deposition profile (Appendix B) was brought into AutoCAD and scaled such that the plot matched the actual coordinates. The coordinates and colors of each contour were then accurately matched using *Pixeur*© color identification software. The data was fitted to a 3rd degree polynomial. See figure 1. Since the profile was essentially X:Y = 2:1, the horizontal profile was used for both x and y, per the equation below. The Z-direction profile was linear, and used as a multiplier for the X-Y profile, ranging from 1.145 at the front to .855 at the back.

This energy profile is then converted to a heat generation per unit volume by using the following beam parameters:

Number of Ions per bunch = 1.25 x 10^9

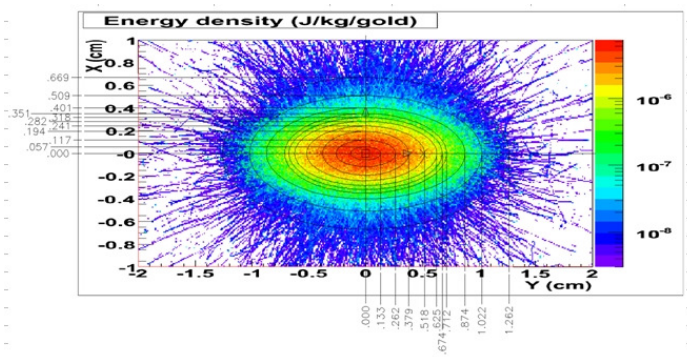
Length of Bunch = 20 x 10^{-9} seconds (Gaussian distr.)
Length of time used (as a step function) = 10.0 x 10^{-9} seconds (FWHM of Gaussian)

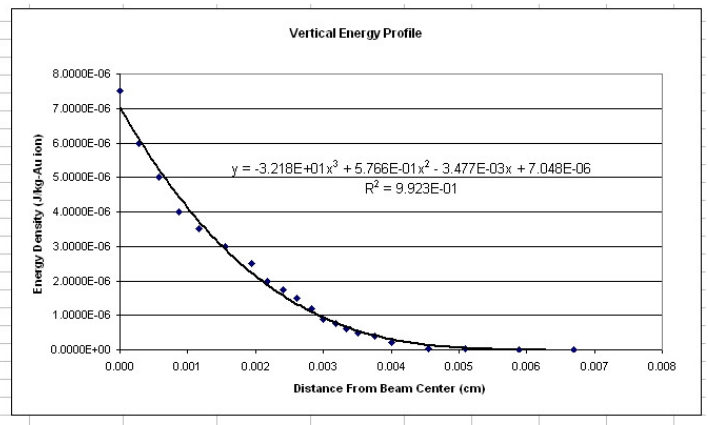
So that the heat generation within the solid is calculated as:

Heat per volume = Energy/mass-ion x density x number of ions / time

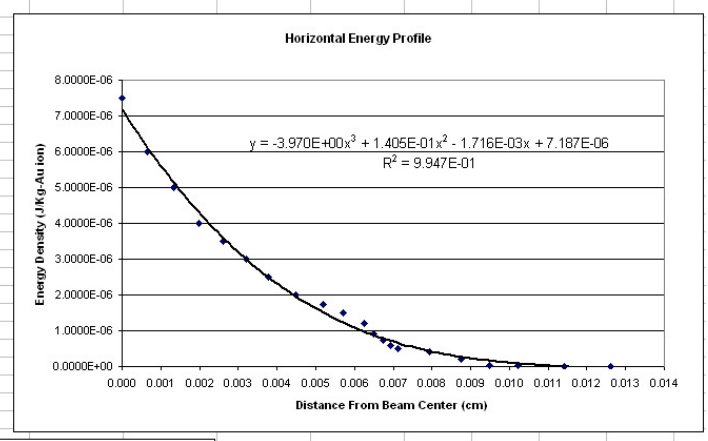
Using the correct units, the heat load (Watts/m^3) as function of (x, y, z):

$$HeatLoad = (-45.669Z + 1.145)(-3.87\times10^{21}\times\left(\sqrt{(x^2+4y^2)}\right)^3 + 1.37\times10^{20}\times\left(\sqrt{(x^2+4y^2)}\right)^2 - 1.67\times10^{18}\times\left(\sqrt{(x^2+4y^2)}\right) + 7.01\times10^{15})$$





Vertical Distance	Energy-X	Horizontal Distance	Energy-Y
0.00000	7.5000E-06	0.00000	7.5000E-06
0.00029	6.0000E-06	0.00067	6.0000E-06
0.00057	5.0000E-06	0.00133	5.0000E-06
0.00087	4.0000E-06	0.00198	4.0000E-06
0.00117	3.5000E-06	0.00262	3.5000E-06
0.00156	3.0000E-06	0.00321	3.0000E-06
0.00194	2.5000E-06	0.00379	2.5000E-06
0.00218	2.0000E-06	0.00449	2.0000E-06
0.00241	1.7500E-06	0.00518	1.7500E-06
0.00262	1.5000E-06	0.00572	1.5000E-06
0.00282	1.2000E-06	0.00625	1.2000E-06
0.00300	9.0000E-07	0.00650	9.0000E-07
0.00318	7.5000E-07	0.00674	7.5000E-07
0.00335	6.0000E-07	0.00693	6.0000E-07
0.00351	5.0000E-07	0.00712	5.0000E-07
0.00376	4.0000E-07	0.00793	4.0000E-07
0.00401	2.2000E-07	0.00874	2.2000E-07
0.00455	4.0000E-08	0.00948	4.0000E-08
0.00509	2.4000E-08	0.01022	2.4000E-08
0.00589	8.0000E-09	0.01142	8.0000E-09
0.00669	4.0000E-09	0.01262	4.0000E-09



z	Z multiplier
0	1.145
0.001	1.099
0.002	1.054
0.003	1.008
0.004	0.962
0.005	0.917
0.006	0.871
0.00635	0.855

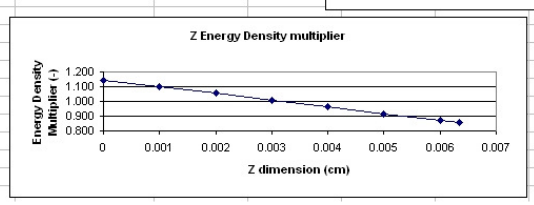


Figure 1. Energy Profiles

Hand Calculations:

A simple calculation was performed using 6 nodes over the region where there is energy deposited (from the center to about 1.4 cm radius). A temperature rise of approximately 36 deg C occurs at the center after a single 4-second cycle (4 bunches) and 72 deg C after two 4-second cycles (8 bunches). See appendix C.

FEA Thermal Model:

A quarter-symmetric model was built using thermal-solid elements. Figure 2 shows the FEA model. The heat load was applied as a heat generation per unit volume per the distribution scheme described earlier.

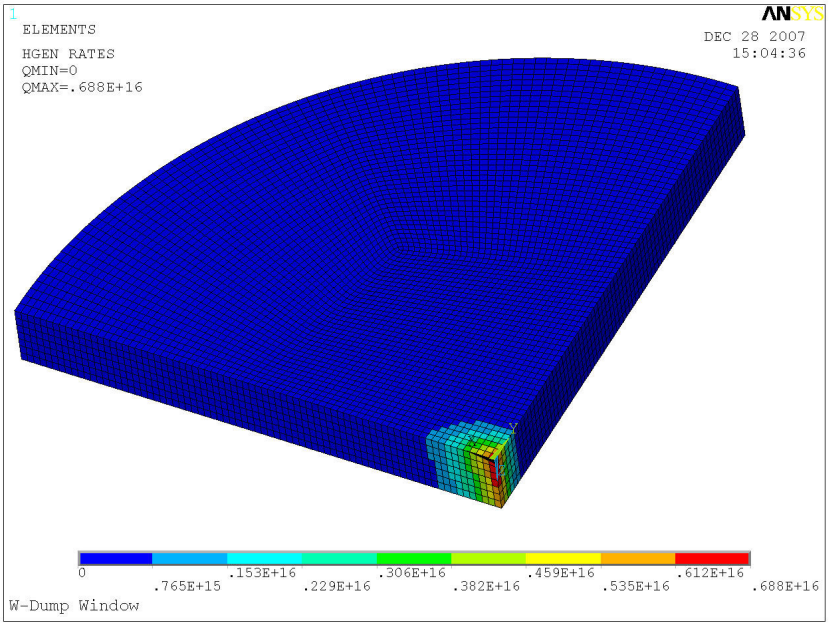


Figure 2. FEA Model with Distributed Heat Load

Thermal Results:

This heat load was applied in a transient analysis as a step function for 10 nanoseconds at 100 milliseconds intervals. This happens 4 times within a 4-second cycle. Figure 3 shows the resulting temperature distribution of selected points on the window for a single cycle and again for 10 cycles (40 bunches).

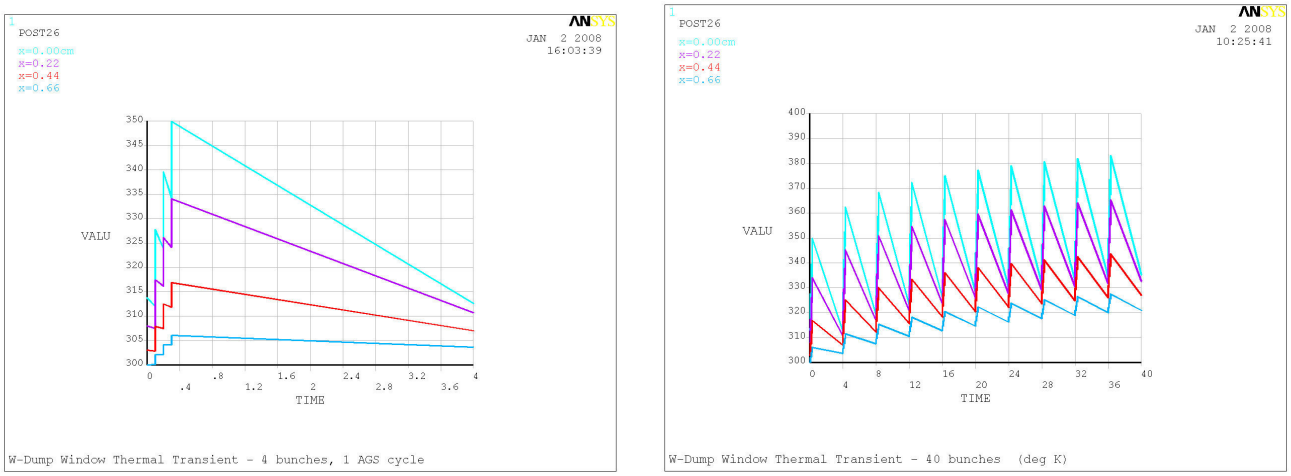


Figure 3: Thermal transient response at select locations on the window face, for 1 and 10 cycles.

Immediately after 4 bunches the peak temperature rise is 52 deg Celsius above its initial temperature. After 40 bunches (ten 4-second cycles), the peak temperature is 85 deg C higher. Figure 4 shows the temperature contour of the window material for 4 and 40 gold-ion bunches.

Note that after the 4th bunch of each cycle there is a lag time allowing the heat to re-distribute within the solid mass, causing local cooling of these hot spots.

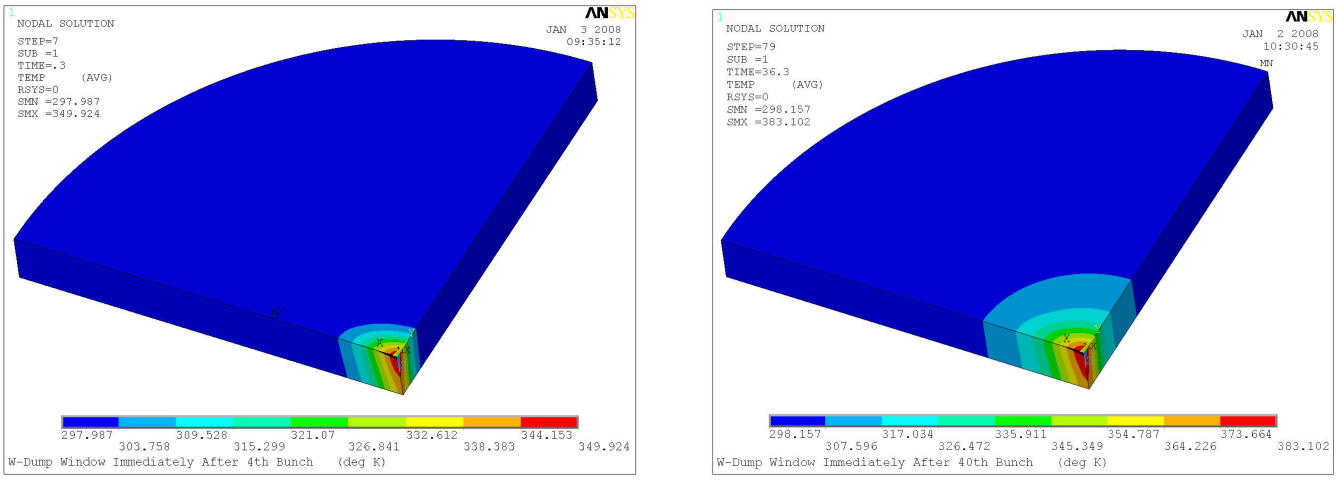


Figure 4: Temperature contour immediately after 4th bunch and 40th bunch

FEA Structural Model:

The same model was used for the thermal-stress analysis. Thermal elements were switched to structural elements and the results of the thermal model used as the thermal boundary conditions of the structural model. Four cases of the thermal model were studied: (1) Immediately after 1 bunch; (2) Immediately after the 8th bunch; (3) Immediately after the 20th bunch, and (4) immediately after the 40th bunch. The resulting material stresses for the 1st and 40th bunch are shown in Figure 5.

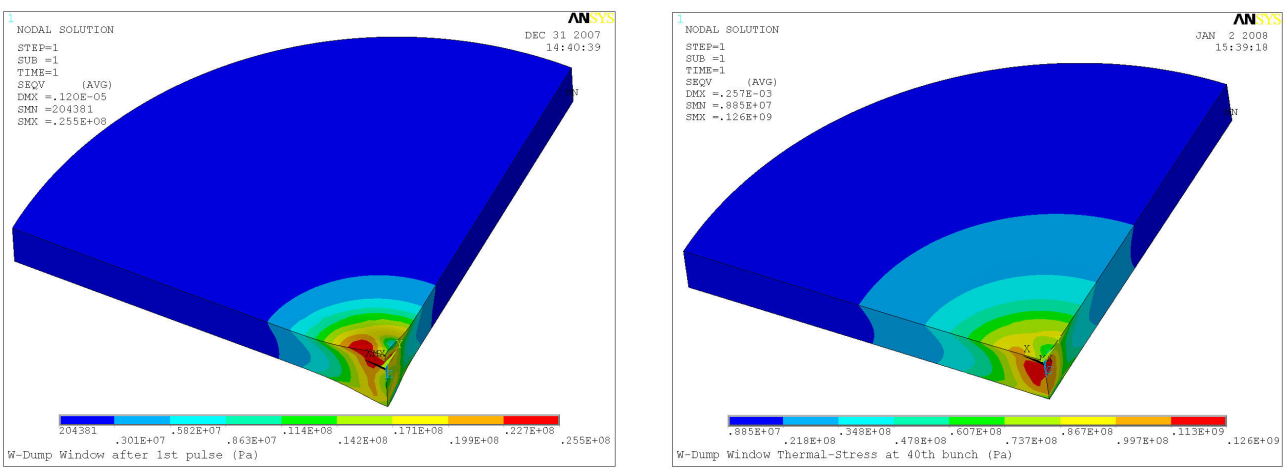


Figure 5: Equivalent (Von Mises) stress Immediately after 1 bunch and 40 bunches.

Structural Results:

It appears that the stress continues to rise from the first bunch to the 40th bunch. The stresses at intermediate points (the 8th and 20th bunch) were looked at to make sure a higher stress had not been missed. After 40 bunches, (10 AGS cycles) the maximum equivalent (Von Mises) stress is 126 MPa (18.3ksi). This is below yield or failure of the material.

Note that at this temperature (110 deg C), the material yield is 29 ksi, lower than its yield strength of 35ksi at room temperature (see Appendix D).

Since Temperature and Stress seem to rise continuously with time, these results were extrapolated for 15 AGS cycles (60 seconds, or 60 bunches), as shown in Figure 6.

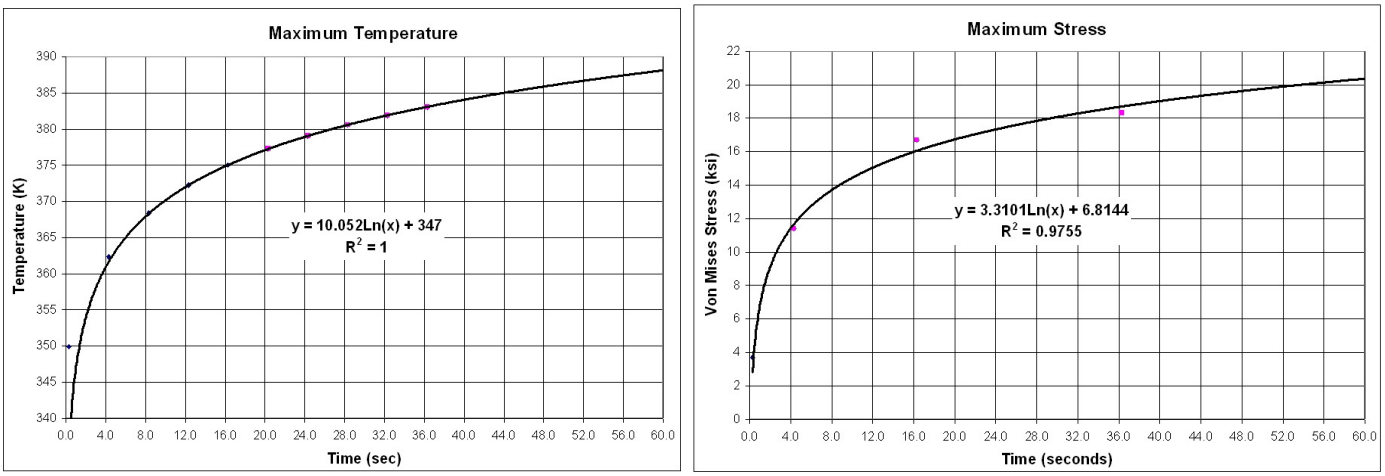


Figure 6: Extrapolated Results for Peak Temperature and Stress.

This would indicate that for 15 AGS cycles, the peak window temperature reaches 388K (115 deg C) and the max stress is 20.4ksi. This is 71% of the yield stress for the material at that temperature.

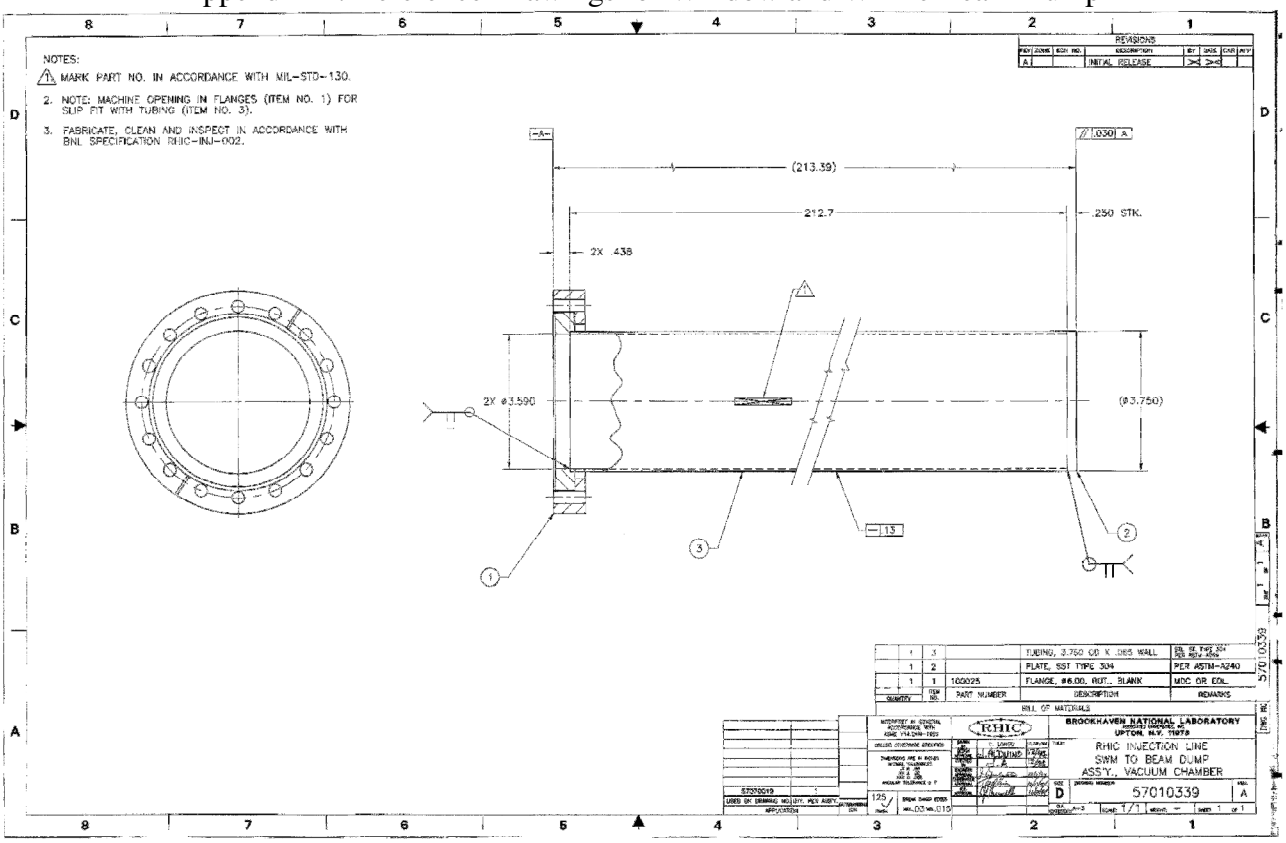
Summary:

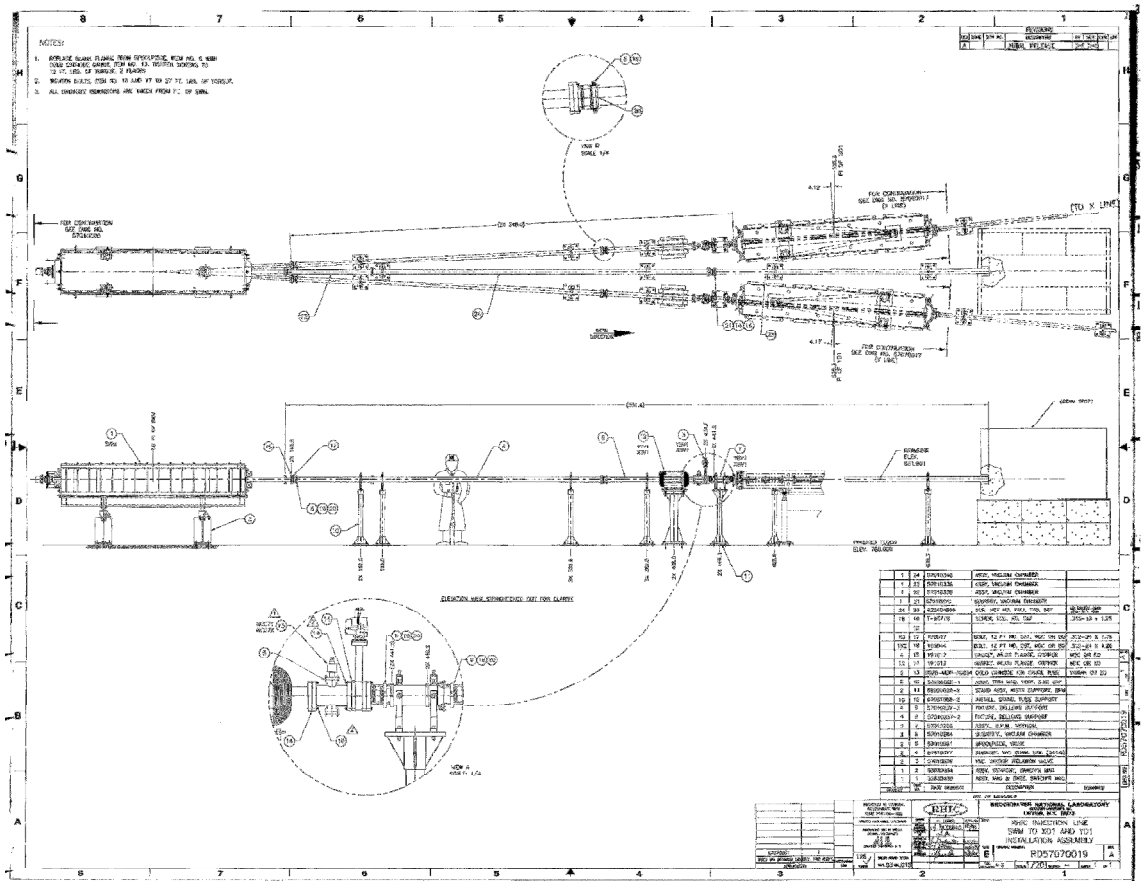
The peak temperature and resulting stresses for 60 bunches of gold beam is 90 deg C above its start temperature. The stress at this point is 71% of the yield for the material at this temperature. This indicates safe operation of the dump window for at least 15 AGS cycles (60 gold-ion bunches), over a 60 second period.

Further extrapolation beyond this is not recommended. Additional FEA runs should be conducted in order to determine the window response for additional gold-ion bunches and beam time beyond this point.

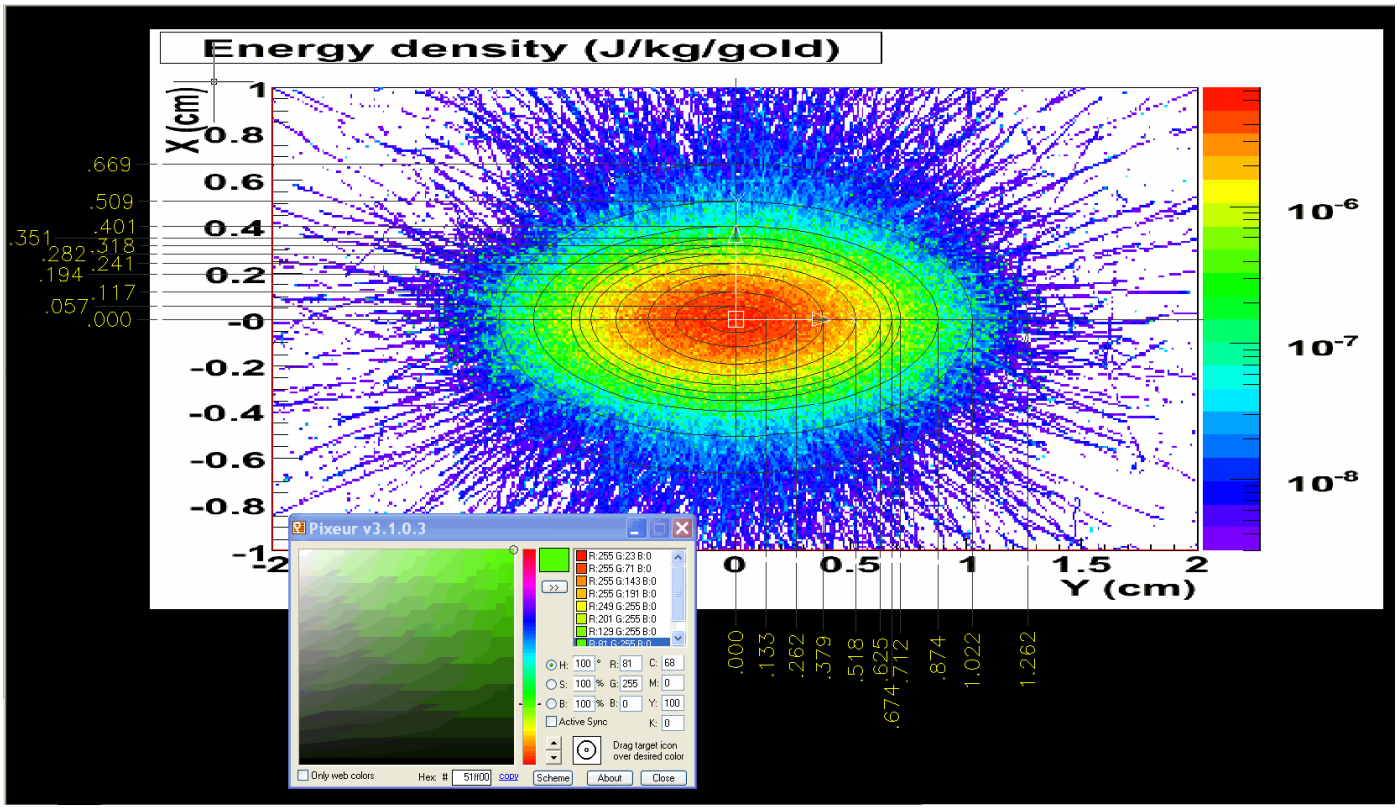
Please direct any questions or concerns to Steven Bellavia (bellavia@bnl.gov)

Appendix A: Reference Drawings for Window and W-line Beam Dump

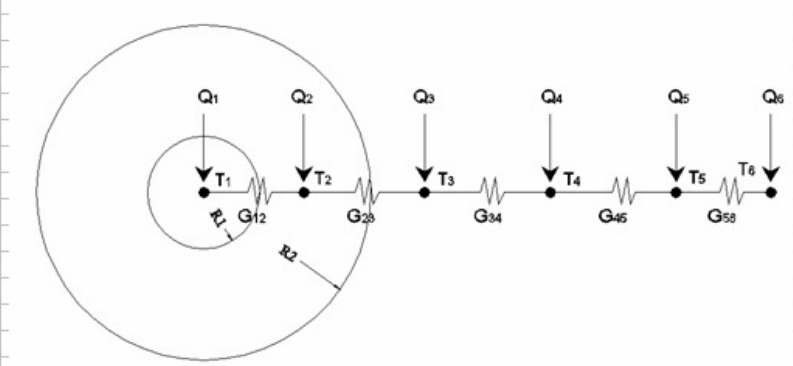




Appendix B: Energy Profiles:



Appendix C: Hand Calculations:



Conductance, Gij = Kij/Ai/X Aij = 2πRi x t X = Rj-Ri

Energy (Heat) Balance:

1	Q1-G12(T1-T2)							=mCPdT1
2		Q2+G12(T1-T2) - G23(T2-T3)						=mCPdT2
3			Q3+G23(T2-T3) - G34(T3-T4)					=mCPdT3
4				Q4+G34(T3-T4) - G45(T4-T5)				=mCPdT4
5					Q5+G45(T4-T5) - G56(T5-T6)			=mCPdT5
6						Q6+G56(T5-T6) - G67(T6-T7)		=mCPdT6

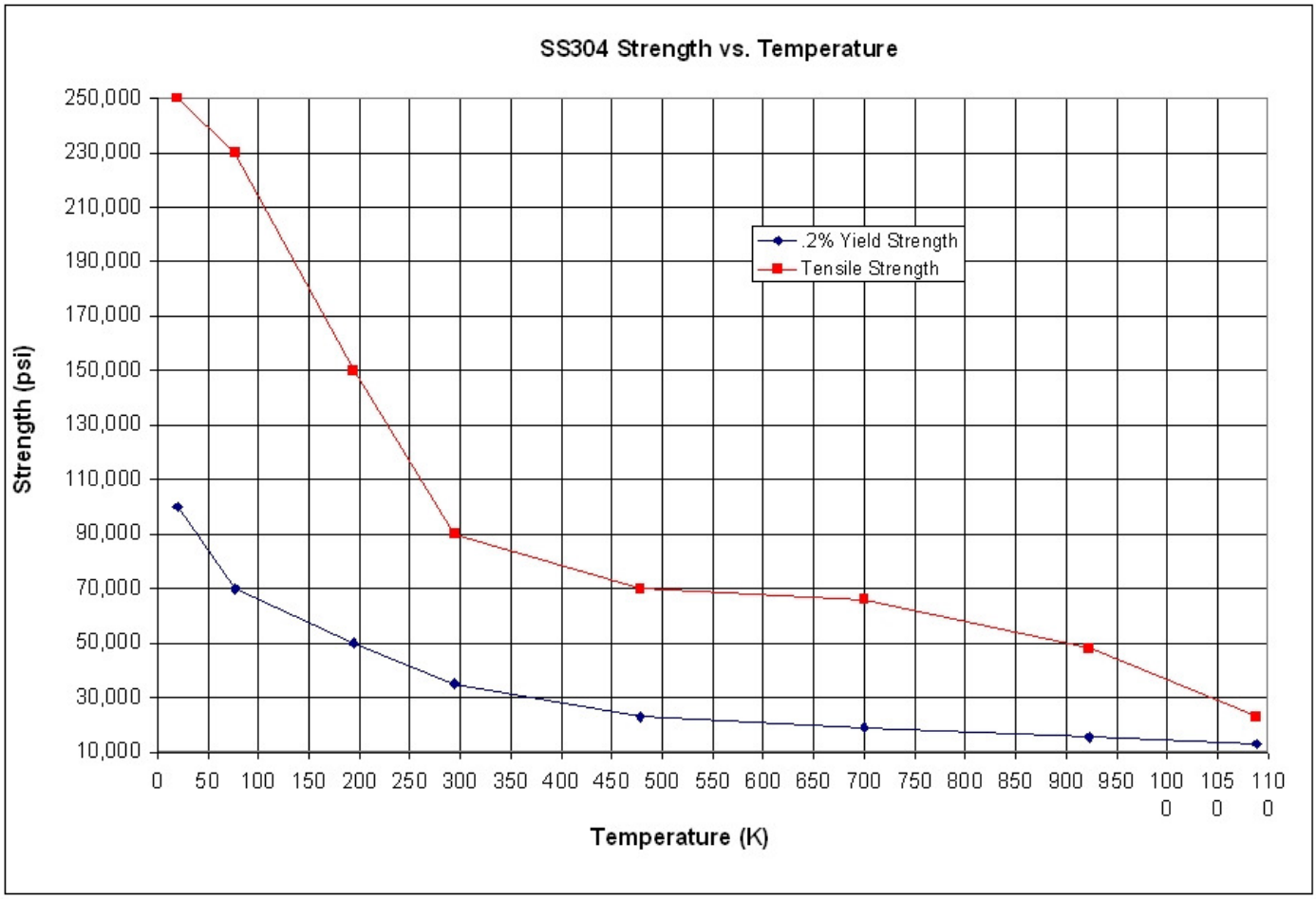
Calculation of constants:

thickness	0.00635	meters
Conductance	16	W/m-K
Capacitance	580	J/Kg-K
density	8030	Kg/m^3
Power Density	"-3.8075E+21*X^3+1.369875E20*X^2-1.6731E18*X+7.007325E15"	W/m^3 For a 10 nsec square pulse
Tambient (T7)	293	K

	Ri	Rj	Ai	Gij	Qi	Qi x m^3	m	mCp
1	2.000E-03	4.000E-03	7.980E-08	6.384E-04	4.179E+15	3.334E+08	6.408E-04	3.716E-01
2	4.000E-03	6.000E-03	3.192E-07	2.553E-03	2.263E+15	7.223E+08	2.563E-03	1.487E+00
3	6.000E-03	8.000E-03	7.182E-07	5.745E-03	1.078E+15	7.741E+08	5.767E-03	3.345E+00
4	8.000E-03	1.000E-02	1.277E-06	1.021E-02	4.403E+14	5.621E+08	1.025E-02	5.946E+00
5	1.000E-02	1.200E-02	1.995E-06	1.596E-02	1.676E+14	3.343E+08	1.602E-02	9.291E+00
6	1.200E-02	1.400E-02	2.873E-06	2.298E-02	7.697E+13	2.211E+08	2.307E-02	1.338E+01
7	1.400E-02							

Perform Calulcation for each time step

let dt = 1.00E-08 (1 bunch)

	T^j	T^{j+1}	T^{j+2}	T^{j+3}	T^{j+4}	T^{j+5}	T^{j+6}	T^{j+7}	T^{j+8}	T^{j+9}	T^{j+10}
1	298	307.0	315.9	324.9	333.9	342.9	351.8	360.8	369.8	378.7	387.7
2	298	302.9	307.7	312.6	317.4	322.3	327.2	332.0	336.9	341.7	346.6
3	298	300.3	302.6	304.9	307.3	309.6	311.9	314.2	316.5	318.8	321.1
4	298	298.9	299.9	300.8	301.8	302.7	303.7	304.6	305.6	306.5	307.5
5	298	298.4	298.7	299.1	299.4	299.8	300.2	300.5	300.9	301.2	301.6
6	298	298.2	298.3	298.5	298.7	298.8	299.0	299.2	299.3	299.5	299.7

Appendix D: SS304 Temperature Dependent Material Properties