THERMAL SIMULATIONS FOR OPTICAL TRANSITION RADIATION SCREEN FOR ELI-NP COMPTON GAMMA SOURCE

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Abstract

The ELI-NP GBS (Extreme Light Infrastructure-Nuclear Physics Gamma Beam Source) is a high brightness electron LINAC that is being built in Romania. The goal for this facility is to provide high luminosity gamma beam through Compton Backscattering. A train of 32 bunches at 100Hz with a nominal charge of 250pC is accelerated up to 740 MeV. Two interaction points with an IR Laser beam produces the gamma beam at different energies. In order to measure the electron beam spot size and the beam properties along the train, the OTR screens must sustain the thermal and mechanical stress due to the energy deposited by the bunches. This paper is an ANSYS study of the issues due to the high quantity of energy transferred to the OTR screen. They will be shown different analysis, steady-state and thermal transient analysis, where the input loads will be the internal heat generation equivalent to the average power, deposited by the ELI-GBS beam in 512 ns, that is the train duration. Each analyses will be followed by the structural analysis to investigate the performance of the OTR material.

INTRODUCTION

The essential part of the Linac in the ELI-GBS is the beam diagnostics and instrumentation because allows to measure and to observe the spot size of the beam along the machine. In order to measure the beam profile the Aluminum or Silicon Optical Transition Radiation screen are used. The radiation is emitted when a charged particle beam crosses the boundary condition between two media with different optical properties and different dielectric constant. This radiation hits the screen for several cycles during the experiments; thus we want to study, with the finite element analysis (Ansys Code), the OTR material behaviour under thermal stress for 512 ns, train duration. After the thermal analysis the scope is to study the performance of the material through structural analysis in order to investigate the deformation and the equivalent stress for each pulse (of 32 bunches).

It will be demonstrate that the analysis is in agreement with the theoretical study where was evaluated the conduction cooling after the heating of a ELI-GBS beam train. In fact the screen cannot completely cool down in the time between two subsequent pulses; therefore, for each bunch there is an increase of temperature of 0.3° C for Al and 0.4° C for Si. As shown in Fig. 1, it can be seen that after 10 ms from the first pulse, the temperature is 295. 3K for the aluminum and 295. 4K for the silicon. However after few cycles, an equilibrium is reached and the cumulative temperature effect is negligible.[1]

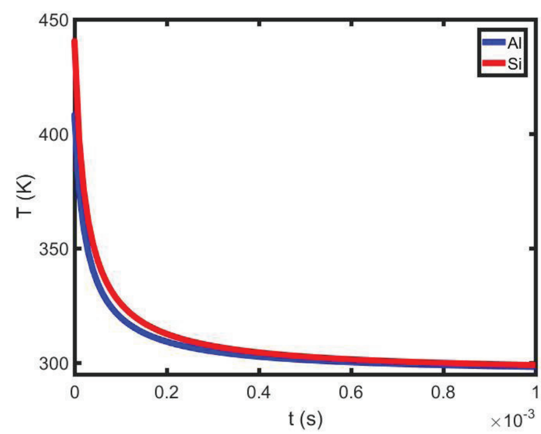

Figure 1: Temporal evolution of the conduction cooling after the heating of a ELI-GBS bunch train (σx =47.5 µm, σy =109 µm). The values refer to the center of the impact area of the beam to the target (x = 0, y = 0).

ANSYS ANALYSIS

The first step in creating geometry is to build a 3D solid model of the item we are analysing and define the material properties. The target has been modelled with 20x20x1 mm Aluminum plate and the worst case of the dimensions of the area hit by the beam are listed in Tab.1.

Table 1: Instantaneous Temperature Increase for an Impulse Train of 32 Bunches with a Charge of 250 pC Each. It Has Also Been Emphasized the Worst Case Scenario for the ELI-GBS

σ_x (σ_y)[µm]	ΔT^+ Al [K]	ΔT^+ Si [K]
298(298)	6	8
251(252)	9	12
211(213)	12	16
184(184)	17	21
47.5(109)	**109**	**141**
241(27.4)	85	110
106(70)	76	99

After the 3D model generation, the OTR has been meshed using hexagonal elements, with size decreasing from the border to the centre. This mapping is crucial to finely impose the energy releasing, concentrating elements only in the target volume that the beam hits. This model is suitable to carry out both steady-state and transient thermal analyses. The cooling mechanism considered is the only

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ISBN 978-3-95450-177-9

conduction from the heated area to the screen flange; the temperature of the flange is independent from the temperature of the heated area and equal to the machine working temperature that corresponds to the room temperature in our case, 22°C: indeed, the site is located in an oversized conditioned environment to remove heat to an extent greater than that emitted by the accelerator. [2].

Assuming an electron beam with a Gaussian spatial distribution we did a steady state analysis because it represents, with a good approximation, the maximum value of temperature increase reaching the equilibrium after a certain amount of thermal stress cycles. Instead, with the thermal transient, it is possible to evaluate the temperature evolution for each pulse along the transient.

STEADY-STATE

Two steady-state thermal analyses, for two different materials Aluminum and Silicon, have been performed in order to determine temperature distributions caused by thermal loads not varying over time. Through the results of steady state is possible to perform a static structural analysis considering the physics properties of the material listed in the table below.

Table 2: Physics and Structural Properties of Aluminum and Silicon OTR [3]

Physics Properties	Symbol	Al	Si
Specific heat (J*kg-1*k^{-1})	c_p	900	700
Density) kg*m^{-3})	ϱ	2700	2330
Melting Temperature (K)	T_{melt}	933	1687
Emissivity	ε	0.18	0.67
Thermal Conductivity(W*m^{-1}*K^{-1})	k	205.5	143.5
Thermal Diffusivity (m^2*s^{-1})	α	$8.5x10^{-5}$	$8.8x10^{-5}$
Tensile Strength (MPa)	σ_{ten}	110	225
Coefficient Thermal liner expansion (K^{-1})	α	$23.9x10^{-6}$	$2.5x10^{-6}$
Young Moduls (GPa)	E_y	70	150

Aluminum Gaussian Distribution

The aluminum OTR profiles have as boundary condition the room temperature 22°C and a Gaussian distribution of the power released on the OTR screen as body load. The power is implemented trough a dedicated command APDL in Ansys, associating the correct Gaussian load to all the target nodes, including those belonging to the elliptic beam section.

The temperature increase calculated is about 14 °C respect to the initial temperature, (see Fig. 2). This result is due to at the thermal inertial of the material and its physics property.

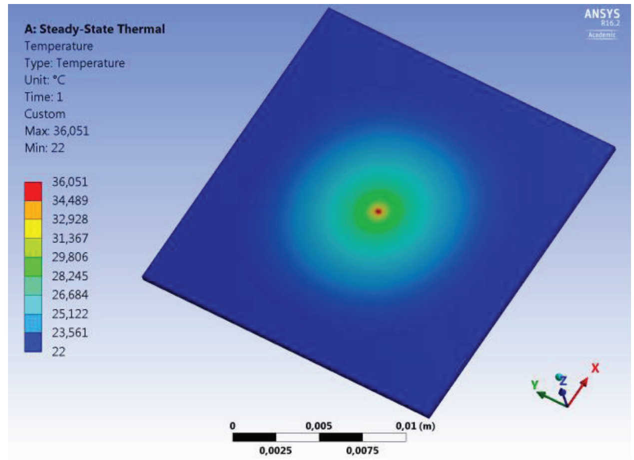

Figure 2: Temperature results at regime considering an Gaussian internal heat generation distribution in a little area 1mm thick and 47.5 µm,109 µm large. This dimension are the one expected during operation at the ELI-GBS in the worst case (Al bulk screen).

Structural Analysis

Using thermal results, output of the previous calculation, a coupled structural analysis has been carried out to evaluate the mechanical behavior of the OTR screen, in terms of deformation, equivalent stress (von Mises) and structural error. As expected the OTR shows a symmetric behavior and the total displacement is about 0.18 µm, with a maximum load of 13.8 MPa (see Fig.3).

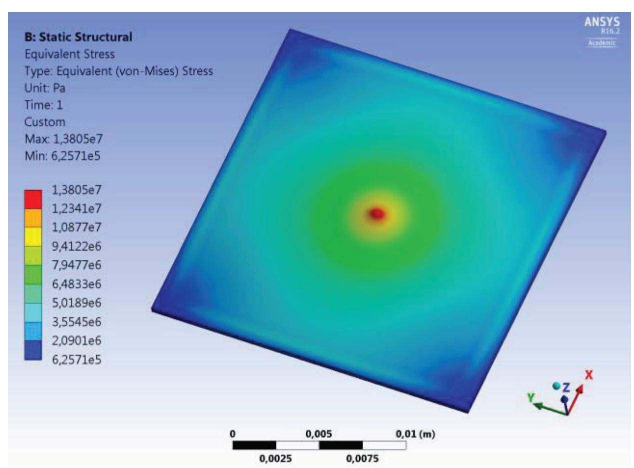

Figure 3: Von Mises equivalent Stress calculated for the Steady-State Aluminum structural analysis

The structural error confirmed the bias strategy used to define target meshing; the regions where the result can be affected by a computational error (due to for example at the size or shape of the mesh), are on the border and in any case by negligible values (see Fig.4).

ISBN 978-3-95450-177-9

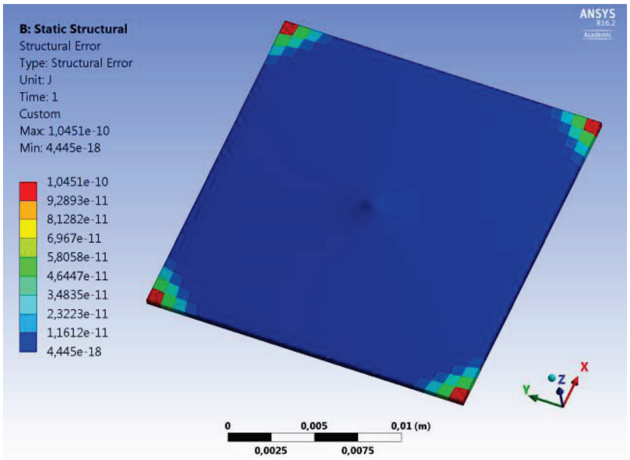

Figure 4: Thermal error for a structural static analysis considering an Gaussian internal heat generation distribution.

Silicon Gaussian Distribution

For the Silicon OTR, the same steady state analysis has been conducted, with the same boundary condition and the Gaussian power distribution. In this case the temperature increase calculated, respect to initial value (22° C) is 14.6°C. Hence, the two materials have a comparable thermal behaviour considering the similar final temperature. As expected, in terms of deformations, the silicon is more rigid than Aluminum (higher Young modulus): the deformation calculated is 0.020 µm with a correspondent equivalent stress by 3.25 MPa.

TRANSIENT ANALYSIS

In the ELI-NP-GBS the variation of temperature distribution over time is necessary to evaluate the temperature increase for each pulse and, then, to estimate the maximum stress reached by the target during each cycle.

Aluminum (Gaussian Distribution): Transient-Thermal

Given the same boundary conditions of the steady state, for this analysis the load is a Gaussian distribution power implemented through a dedicated script imposing an heat generation equivalent to the energy released on the OTR in 512 ns, by the first pulse of the hitting electron beam. The real time-stepping has been simulated, inside an overall analysis period by 10 ms, duration of each macro pulse (beam repetition rate is 100 Hz).

The maximum temperature achieved, after 512 ns, is 129,15 °C and the final temperature after the cooling is 22.5 °C, as depicted in Fig. 5. It's evident that OTR screen cannot completely cool down in the time between two subsequent pulses, and temperature increases by 0.5°C after first. With the previous steady-state analysis, imposing the average power, it has been verified that temperature increase reaches the equilibrium.

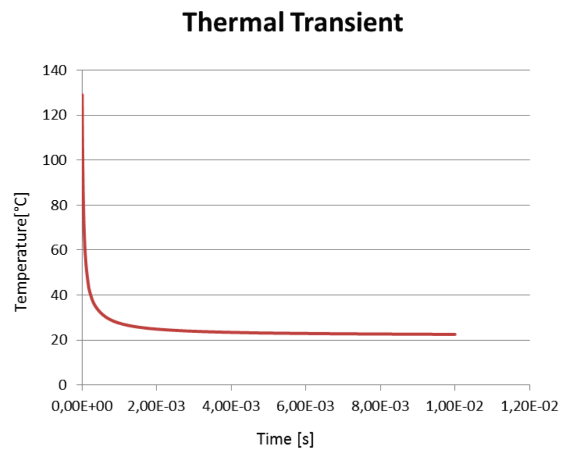

Figure 5: Thermal Transient behavior of Aluminum OTR in ELI-GBS. The temperature curve tends to constant value after 10 ms before the second impulse.

Aluminum (Gaussian Distribution): Transient-Structural

For the first beam pulse simulated, the maximum displacement calculated is about 10 nm, in function of a maximum equivalent stress by 1.4 MPa (see Fig. 6).

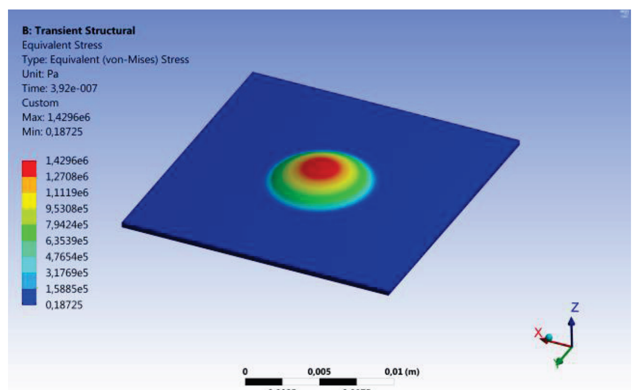

Figure 6: Stress equivalent evolution of Aluminum for one bunch train after 512 ns in the ELI-NP-GBS worst case.

Silicon (Gaussian Distribution): Transient-Thermal

In this case when the beam hits the target, the temperature increases until 159°C and also in this analysis the OTR cool down until 22.4°C. We expected this result because in agreement with the theoretical study.

Silicon (Gaussian Distribution): Transient-Structural

Also in this simulation, for the first beam pulse, the maximum displacement calculated is about 1.07 nm, in function of a maximum equivalent stress by 0.45 MPa (see Fig. 7).

ISBN 978-3-95450-177-9

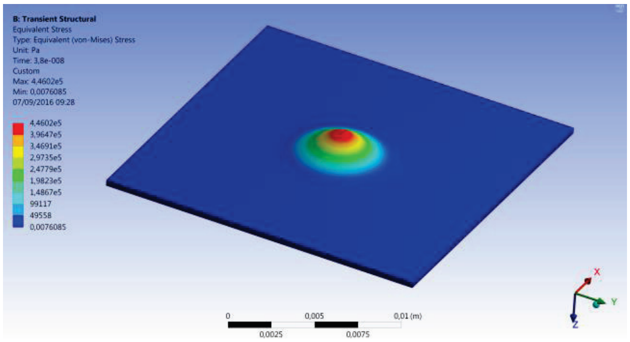

Figure 7: Von Mises equivalent Stress calculated for the transient Structural analysis (made by Silicon, for one bunch train after 512 ns in the ELI-NP-GBS worst case).

CONCLUSION

This paper compares thermal an mechanical results for Silicon and Aluminum OTR screens, performing both steady-state and transient analyses to simulate the energy releasing effects of the ELI-NP-GBS electron beam in the target interaction. The Silicon is the material chosen for the OTR, transient analysis shows a better thermo-mechanical behavior for a single cycle (see Table 3).

Table 3: Maximum Values of Deformation and Equivalent Stress (Von Mises) for the Both Materials Analysed

Material	Maximum Deformation [nm]	Maximum Von Mises [MPa]
Aluminum	10	1.4
Silicon	**1.07**	**0.45**

The next step of the FEM study will be an optimization of the time-stepping imposed in the transient, in order to reduce the necessary computational time and memory to simulate a number of cycles up to the equilibrium. The consequent resulting stress will be used to evaluate the fatigue life of the OTR. Then the final step will be the implementation of all brackets and mechanical support components of the OTR, evaluating the whole system dissipation. The expected result of the last analysis is to confirm that the additional mechanical sup-ports and brackets do not induce further thermal dissipation and hence they do not degrade the thermal-mechanical features of the whole OTR system.

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[3] Material parameters taken by: http://www.matweb.com/

ISBN 978-3-95450-177-9