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A NUMERICAL ANALYSIS TO CHOOSE THE MOST PERFORMING OPTICAL TRANSITION RADIATION SCREEN

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Abstract

Optical Transition Radiation (OTR) screen represents the most appropriate instrument to measure and verify the characteristics of a beam spot size produced by a particle accelerator. In order to measure beam properties, OTR screens must sustain thermal and mechanical stresses due to the energy that several bunches deposit. Owing to these requirements, it is essential to identify the more suitable material to optimize the OTR performance and to get reliable measures from the diagnostic system. In this paper, we describe a multi-purpose numerical procedure, based on finite element analysis, to choose the most performing material, considering the physical characteristics of an electron beam. The procedure is based on a dedicated ANSYS® APDL script able to evaluate the thermal distribution on the OTR generated by the beam. The main characteristic of this script is the capability to simulate the real thermal effect on the target that the hitting particle beam produces. The numerical procedure has been applied to compare the performance of two relevant materials – Aluminum and Graphite – simulating a beam hitting with well-known parameters. The validity of the APDL scripts were demonstrated by comparing the results with those obtained by a different study.

INTRODUCTION

The electron beams are implemented in nuclear research as well as in a wide spectrum of industrial applications [1] (e.g. welding, biological sterilization). In each application, the electron beam properties assume specific values as well as different target materials are employed; in this context, the control of the beam parameters and their related interaction with targets are crucial for the effective and efficient functioning of equipment.

This paper deals with a multi-purpose numerical procedure, based on finite element analysis (FEA), to control the temperature distribution in the mechanical components that the beam hits.

This numerical procedure, which is based on a dedicated ANSYS® APDL script, was developed to predict the thermo-mechanical behaviour of the Optical Transition Radiation (OTR) screens that are used to measure and verify the properties of electron beams in particle accelerators.

The procedure has been used to identify the most performing material for the OTR screens to get the most reliable measures, since they have to sustain thermal and mechanical stresses due to the energy that the beam deposits during the operations. In a previous research [2,3], we compared the performance of two relevant materials, i.e. Aluminum (Al) and monocrystalline Silicon. To validate the results obtained, the same APDL script has been used to benchmark the results obtained in a different study [4] that investigates Aluminum and Graphite targets. In the first part of this paper, we introduce the APDL script and the case study used to develop the numerical approach, while in the second part we illustrate the benchmark results to confirm the goodness of the developed script.

NUMERICAL APPROACH: APDL SCRIPT

Particle beams lose energy in the form of heat by interacting with targets, determining the generation of a thermal power density inside these. Particles are distributed according to a Gaussian distribution along the beam transverse section and, consequently, the generated power density is not uniform on the target surfaces. Moreover, if the beam is pulsed, the generated power density is not constant over the time, but it has a cyclic trend oscillating between zero and a maximum peak.

The ANSYS® Parametric Design Language (APDL) is a scripting language inside the ANSYS® Mechanical software environment. It allows the user to implement in FEA thermal power density with peculiar spatial and time distribution as the one generated in the interaction of particle beams with the target matter.

The APDL script, which we developed for the interaction of beam electrons with OTR targets, carries out thermal transient analyses and it is structured in three main parts.

The first refers to the definition of the electron beam's properties and the OTR target's material and geometry: this parametrisation allows the user to easily tailor the simulations to specific applications and to perform sensitivity analysis. The second spatially models through an ANSYS® 2-dimensional table parameter the power density resulting from the interaction between the electrons and the target: we assumed the power density inside the target unchanged along the beam longitudinal axis (this is reasonable when the range of the beam's particles in the target material is larger than the thickness of the target, as in our case study). The third models the power density over time assuming a pulsed operation mode for the beam: it simulates a high number of thermal cycles on the target material through specific do-loops with two different load steps (one for the heating phase during the interaction and one for the cooling phase in the period intervening between two pulses).

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CASE STUDY: OTR SCREEN FOR HIGH BRIGHTNESS ACCELERATOR

The APDL script was developed during the design of a facility for an advanced source of gamma rays (≈ 20 MeV) based on Compton back scattering, i.e. collision of a high brightness electron beam (that a LINAC accelerates up to 740 MeV) and an intense high-power laser beam. The high brightness electron beam is pulsed consisting in trains of 32 electron bunches, 250 pC each, separated by 16 ns and distributed along a 0.5 µs RF pulse with a repetition rate of 100 Hz [2]. In this condition the high charge density of the electron beam produce on the OTR screen a continuous oscillating change of the temperature distribution.

The geometry of the OTR target (30 mm of length for each edge, 1 mm of thickness) was modelled in ANSYS® APDL applying a mesh refinement close to the electron beam spot where is concentrated the heat generation in order to obtain a correct distribution of the power density due to the beam-target interaction (Fig. 1).

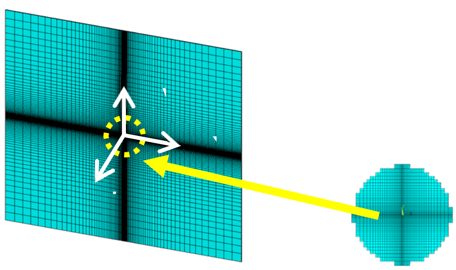

Figure 1: OTR screen finite element model.

THERMAL TRANSIENT ANALYSIS AND COMPARISON OF THE RESULTS

In order to verify its goodness, the same APDL script was used to reproduce the results obtained in similar studies [4] conducted for the Clic Test Facility stage 3 (CTF3) and following a different calculation methodology. Table 1 and Table 2 reports the properties, respectively, for the electron beam and the OTR screen materials (i.e. Al and Graphite) considered for CTF3 studies.

Table 1: Electron Beam Properties

Parameter	Value
Beam Current	3.5 A
Pulse Length	1.54 µs
Beam Energy	360 MeV
Analysis Length	50 cycles

Table 2: OTR Material Properties

	Aluminium	Graphite
Density [kg/m^3]	2,700	2,200
Thermal Conductivity [W/(m*K)]	235	157
Electron mass stopping power [MeV*m^2/kg]	0.19	0.21

That study assumes the beam sigma equal for both transversal axes defining a perfectly cylinder symmetry for the physical problem. Exploiting such symmetry, the methodology originally followed for CTF3 subdivided the OTR surface in a series of concentric rings and for each single ring calculated an energy balance considering the heat exchanged between the rings and that deposited by the electron beam.

The different configurations of the CTF3 study [4] used as reference tests to benchmark the APDL script are reported in Table 3.

Table 3: Different Test Configurations

Test	Material	Beam Size σ	Repetition Rate
A1	Aluminium	0.50 x 10^{-3} mm	10 Hz
A2	Aluminium	0.60 x 10^{-3} mm	10 Hz
A3	Aluminium	0.60 x 10^{-3} mm	50 Hz
G1	Graphite	0.25 x 10^{-3} mm	10 Hz
G2	Graphite	0.25 x 10^{-3} mm	50 Hz

The geometry of the OTR target (30 mm of length for each edge, 100 µm of thickness) was modelled in ANSYS® APDL applying the same methodology described in the previous section. Figure 2 illustrates the spatial distribution on the target surface of the thermal power distribution that, for the considered configurations of the CTF3 study, assume an equal shape for both axes (x-y). Moreover, the same figure shows how the small spot size deposited a high concentrated energy on the OTR hotspot with a potential danger, considering also the high repetition rate, for the OTR performance. As thermal boundary condition was set a constant temperature on the OTR edge of 295.1 K.

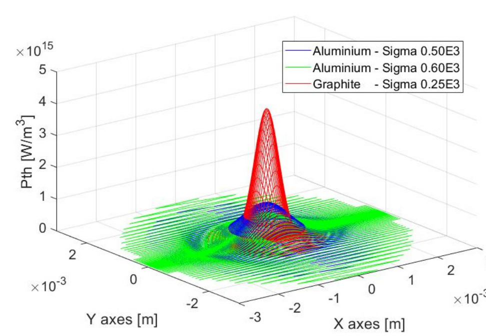

Figure 2: Thermal power distribution on the OTR hotspot.

In the APDL script, the specific heat capacity (c_p) of both materials has been implemented as a function of the temperature (Fig. 3). This solution has been necessary considering the temperature range over the heating and the cooling of the OTR target (thermal cycles). For the Al, there is no difference between the APDL scripts and the methodology of the CTF3 study because of the c_p for the interest range of temperature is almost linear. On the other hand, for the Graphite it was necessary use six points to

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properly model the behaviour over the temperature respect the only two points used by CTF3 analysis.

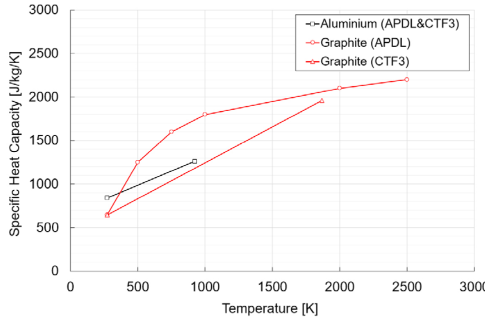

Figure 3: Specific heat capacity [J/(kg*K)] model for the APDL script and the CTF3 study methodology.

The maximum temperature reached for both materials after 50 thermal cycles, under the different test configurations, is reported in Table 4.

The results show how the maximum temperatures obtained by the APDL script are perfectly comparable with those of CTF3 study. The average deviation between the values is about -2%.

Table 4: Comparison of the Results (APDL Script and the CTF3 Study Methodology) after 50 Thermal Cycles

Test	APDL script	CTF3 study	Difference
	Max. Temp.	Max. Temp.	
A1	931 K	953 K	-2.3 %
A2	767 K	783 K	-2.0 %
A3	900 K	923 K	-2.5 %
G1	1,986 K	2,003 K	-0.8 %
G2	2,127 K	2,523 K	-15.7 %

For the Test A1, A2 and G1 with a repetition rate of 10 Hz, the constant temperature is reached after about 20 thermal cycles, whereas for the Test A3 and G2 the constant value is not totally reached after 50 cycles (Fig. 4 and Fig. 5). The only considerable difference in the result is for the Test G2. This behaviour is produced by the different c_p model used for the Graphite.

In the CTF3 study has been used a linear model with only two points up to about 2000 K, without considering the higher temperatures.

This produces an overestimation of the maximum temperature, compared to the results of the APDL script, because a lower specific heat is used.

For the Test G1, this behaviour is less accentuated thanks to the low repetition rate which allows a better cooling of the OTR between the thermal cycles. Figure 6 show the spatial thermal distribution on the OTR surface at the peak temperature in the beam hotspot after 50 cycles for the Test G2. How it is possible to see, the thermal gradient is high concentrated in the middle of the hotspot, differently to case with a higher beam sigma (Table 3).

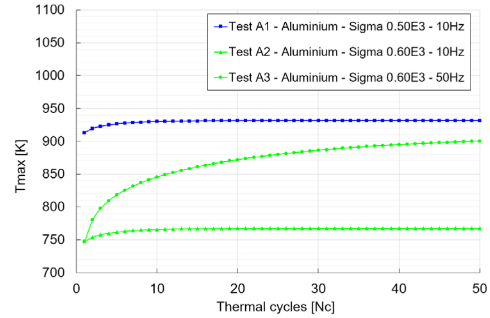

Figure 4: Maximum temperature [K] reached by the Aluminium during the different thermal cycles [Nc].

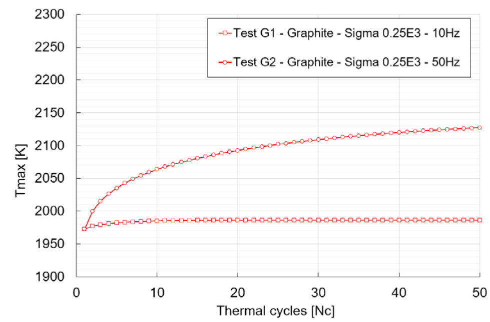

Figure 5: Maximum temperature [K] reached by the Graphite during the different thermal cycles [Nc].

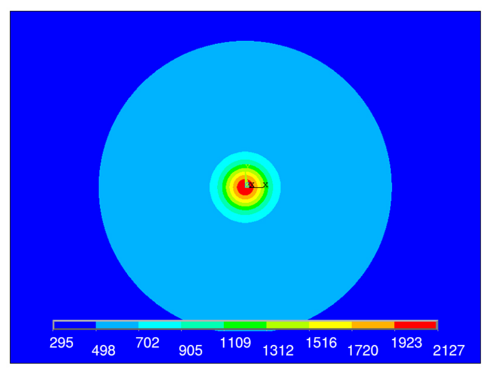

Figure 6: Temperature distribution [K] after 50 thermal cycles on the OTR: Test G2, sigma 0.25 x 10^{-3} mm.

CONCLUSION

We developed an ANSYS® APDL script simulating the thermal distribution in OTR screens interacting with electron beams having peculiar spatial and time distributions. We tested the developed script against the results obtained in a similar study for the CTF3 facility that follows a different methodology. Investigating the peak temperatures reached in the OTR screens at the CLIC3 facility the values obtained with the approach of the original study and with our approach are totally comparable. In this sense, the performed benchmark brings a high confidence in the ANSYS® APDL script that we have developed up to now. Next steps will concern the utilisation of the developed APDL script for more complex geometries in order to reach a full application for all the typical cases of the electron beams for industry, research and medicine.

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