THERMO-MECHANICAL STRESSES ON THE BEAM WINDOW

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Abstract

The Centre for Advanced Studies, Research and Development in Sardinia (CRS4) is participating to an Italian R&D program, together with Ansaldo, ENEA and INFN, devoted to the design of a 80 MW prototype of the Energy Amplifier proposed by C. Rubbia. The use of advanced numerical tools has been of practical support in the design of critical elements of the machine such as the fuel element and the beam target. The aim of this work is to study the sensitivity of beam window stresses to the beam distribution, size and interruption. In order to compute thermal stresses, the heat deposition in the window and in the coolant generated by the interaction with the proton beam is calculated and used as input data for the fluid dynamic simulation of the natural convection flow of the target coolant.

Introduction

The Energy Amplifier (EA) [1,2] is a nuclear system in which a beam target, driven by a proton accelerator, supplies an external source of neutrons to the subcritical core. The beam target represents one of the main technological problems related not only to the design of the EA, but to all High Power Spallation Sources currently under study or in construction world-wide [3,4].

Neutrons come from the interaction of a high power proton beam with the material contained in the target. Such interaction, called spallation, has the undesirable effects of producing a large quantity of heat (typically some MW concentrated in a small volume) and inducing an intense radiation damage in the structural materials. Liquid metals are currently considered the best choice in terms of target materials since they satisfy the important criteria of being the spallation medium and the cooling fluid at the same time and since their structural and thermal properties are not degraded by the radiation damage induced by proton interactions. Nevertheless, the corrosion of structural materials in a liquid metal environment is an important problem. Given the fact that the primary cooling loop of the EA is made of lead-bismuth eutectic (LBE), we consider the same coolant for the beam target. The LBE flow is driven by natural convection whose efficiency depends on the target height (which is related to the dimensions of the EA) and on the fluid dynamic design of the coolant circuit.

In the EA prototype target a window separates the internal part of the beam pipe from the coolant. Configurations using a beam window have additional problems of beam window cooling (in the window the highest temperatures and stresses are reached) and radiation damage induced in the window material. This damage is of a slight different nature from that induced in the other structures, since the window is exposed not only to back-scattered high-energy neutrons, but also to the high-energy proton flux. While steels for low power applications keep a sufficient structural resistance and are suitable candidates for the EA prototype [3-5], refractory alloys or more advanced materials are mandatory for high power applications [6,7].

The EA prototype target

The EA prototype target [5] is an axial symmetric device consisting of a ≥beam pipe≤ enclosed in a coaxial ≥container≤ (see Fig. 1). The beam pipe is made of martensitic HT-9 steel and is a vertical cylinder of 10 cm radius, 635 cm height and 3 mm thickness closed at the bottom by an HT-9 ≥window≤. The window has a hemispherical external surface and an ellipsoidal internal surface so that the thickness varies from a minimum of 1.5 mm in the beam pipe axis to a maximum of 3 mm in the junction with the cylindrical part of the beam pipe. The window is so tapered in order to reduce the beam heating in the beam pipe axis. The container is a vertical cylinder of 27 cm radius and 724 cm height with a hemispherical bottom. The region between the beam pipe and the container is filled with LBE and ≥vacuum≤ is made inside the beam pipe.

Having neglected the heat flux through the beam pipe and the container, the heat produced in the window and in the coolant is removed by a natural convection flow. This flow is guided by the ≥flow guide≤, that is a 17 cm internal radius cylinder laying between the beam pipe and the container. The flow guide separates the internal hot flow rising from the spallation region from the external cooled flow downcoming from the heat exchanger positioned on the top of the downcoming duct. In the spallation region the flow guide assumes a funnel shape which accelerates the flow and enhances the cooling of the window. The flow guide is made of two HT-9 layers 1 mm thick separated by a 1 mm layer of insulating material (Zirconium oxide). The heat exchanger is located at 25 cm from the container top, is 45 cm height and its outlet temperature is set to 180 C.

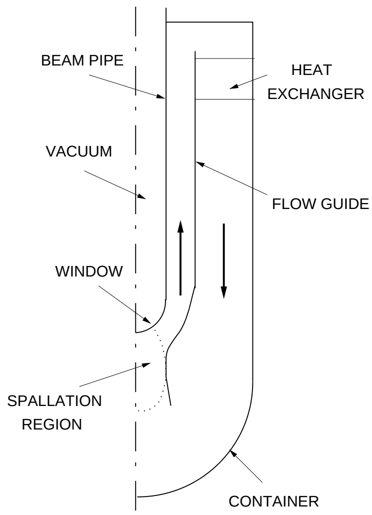


Figure 1 *≠ Description of the EA prototype target.*

Neutronic analysis

The proton beam is injected through the top of the beam pipe and interacts with the window, the coolant and the flow guide. The proton energy is 600 MeV and the beam size is assumed to be as a circular spot of radius r_0 = 7.5 cm (the window radius allows a correct defocusing of the beam spot in order to prevent localised high power densities in the target materials). The beam current density is given by the three-dimensional parabolic profile

$$J = \frac{2I_0}{\pi r_0^2}\left(1 - \frac{r^2}{r_0^2}\right) \quad (1)$$

where the beam current I_0 ranges from about 2 to 6 mA. In the following we assume the maximum beam current of 6 mA corresponding to a beam power of 3.6 MW.

The FLUKA Monte-Carlo code [8,9] is employed to calculate the heat source distribution, taking into account not only the electromagnetic interactions, but all kind of nuclear reactions induced by both protons and secondary generated particles. A 40∞70 orthogonal grid is used for the FLUKA simulation. The heat generated inside the funnel is calculated by applying the distribution for the coolant multiplied by the ratio between the flow guide density and the coolant density. According to the FLUKA computation, inside the window the proton beam deposits in form of heat about 22 kW (i.e. 0.6% of the beam power). The heat production in the coolant and in the flow guide is 72% and 1% of the beam power respectively, the rest of the beam energy being contained in the particles escaping the system or in the binding energy of the target nucleus. Fig. 2 illustrates the contours of the beam power released in the LBE.

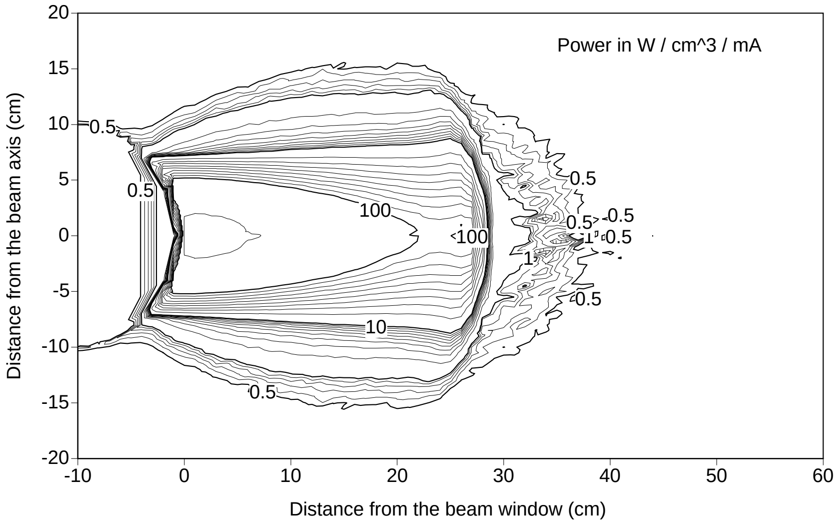


Figure 2 *≠ Neutronic calculation of the power generated in a thick LBE target by the proton beam.*

Fluid dynamic analysis

The turbulent natural convection flow of the coolant and the thermal field in solids are simulated using the STAR-CD fluid dynamic code [10] where the heat source distribution calculated by the FLUKA code is used as input data. The vacuum inside the beam pipe is simulated by means of air at very low pressure. The heat exchanger is modelled as a thermal sink uniformly distributed. The numerical model employs a third order scheme for the spatial discretisation of the convective terms. The Chen k-ε model with a two-layer algorithm in the near wall region accounts for turbulence effects. The radiative heat flux through the beam pipe and the pressure losses in the heat exchanger are neglected. The container walls are assumed as adiabatic.

The IDEAS CAD and mesh generator [11] is employed to create a mixed structured/unstructured mesh. The fluid regions near the walls are meshed with structured grids, easier to handle and more suitable for the application of the turbulent near-wall algorithms. Structured meshing is also used for the discretisation of the solids. The total number of cells is about 14000 and the discretisation is very accurate in the funnel zone, especially next to the window stagnation point.

Fig. 3 shows the computed velocity and temperature fields in the funnel region. The recirculation zone in the downcoming duct increases the temperature and reduces the natural convection pumping. However, the target height and the flow acceleration due to the convergent funnel shape generate the coolant velocity necessary for cooling the beam window to a maximum temperature of 427 C.

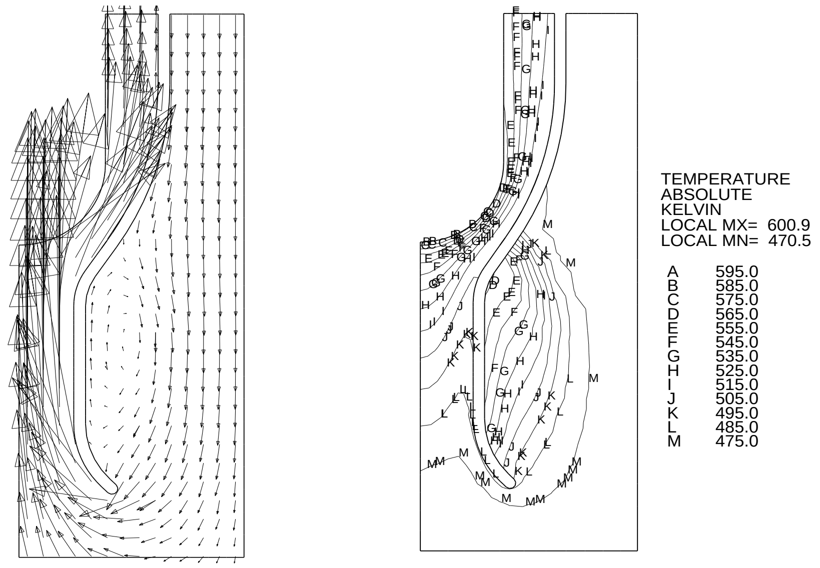


Figure 3 *≠ Velocity and temperature fields in the funnel region.*

Structural analysis

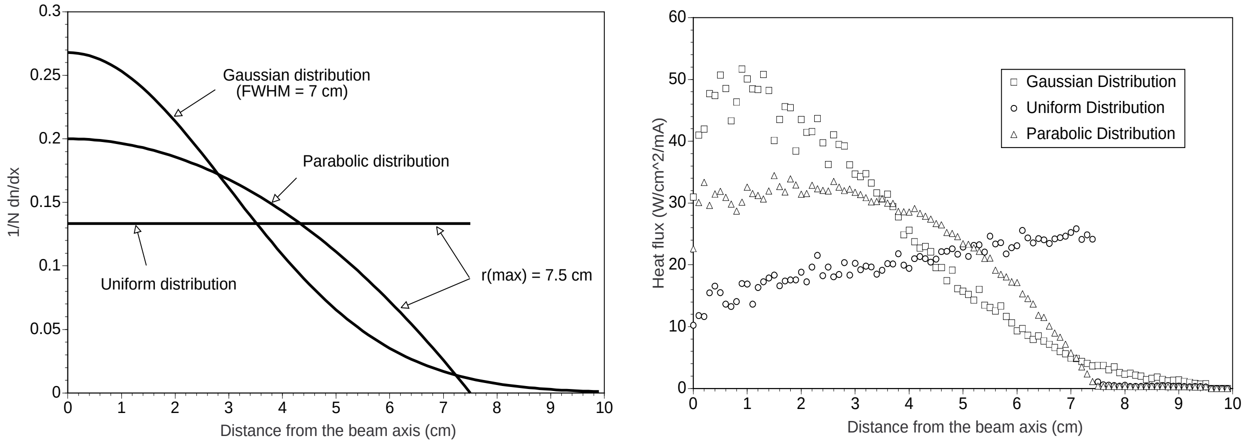
The MSC/NASTRAN structural code [12] is employed to calculate the stresses induced in the window/pipe system by using a linear (elastic) model applied to the same window/pipe grid used for the fluid dynamic simulation. The temperature field is assigned to the elements of the model and the coolant hydrostatic pressure distribution is applied onto the external surface.

The maximum Von Mises stress is 109 MPa, the maximum ≥meridional≤ (i.e. tangent to the window profile) stress is 102 MPa and the maximum ≥hoop≤ (i.e. perpendicular to the plane of study) stress is 101 MPa. The maximum window temperature is 427 C which corresponds to an Ultimate Tensile Strength (UTS) of 610 MPa (this value is conservative due to the UTS decrease when the temperature increases). The values of temperature and stress are within the HT-9 application range described in [13].

Beam distribution effects

The window stresses sensitivity to the beam distribution is studied by considering gaussian and uniform distributions having the same proton energy and beam current of the parabolic distribution given by Eq. (1) (see Figs. 4 and 5). The corresponding heat flux to be removed from the window decreases in the beam axis according to the smaller window thickness.

Fig. 6 shows the temperature distributions on the internal (window/vacuum) and external (window/coolant) surfaces as a function of the angle α between the target axis and the window (or pipe) circumference orthogonal to the axis (the proton beam crosses the window up to an angle of 48.6).



***Figures 4 and 5** ≠ Assigned proton beam particle distributions and corresponding heat flux calculated by FLUKA in the window for different beam distributions.*

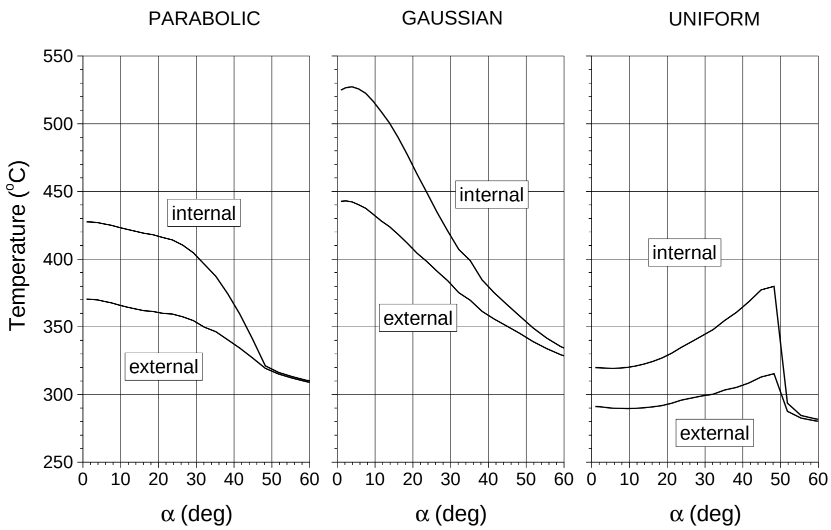


***Figure 6** ≠ Temperature distributions on the internal and external window surfaces.*

The gaussian distribution leads to window temperatures out of the HT-9 application range. With respect to the parabolic distribution, the gaussian and uniform distributions have greater temperature gradients and therefore greater stresses close to the beam axis and edge respectively, as illustrated in Figs. 7 and 8 where the meridional and hoop stress components in the internal and external window fibres are reported. The maximum Von Mises stresses are 189 and 149 MPa for the gaussian and uniform distribution respectively. The gaussian distribution produces stresses out of the HT-9 application range. The thinner part of the window, which is also the most loaded in the non-uniform distribution case, undergoes strong bending moments (depending basically on the temperature gradient along the thickness).

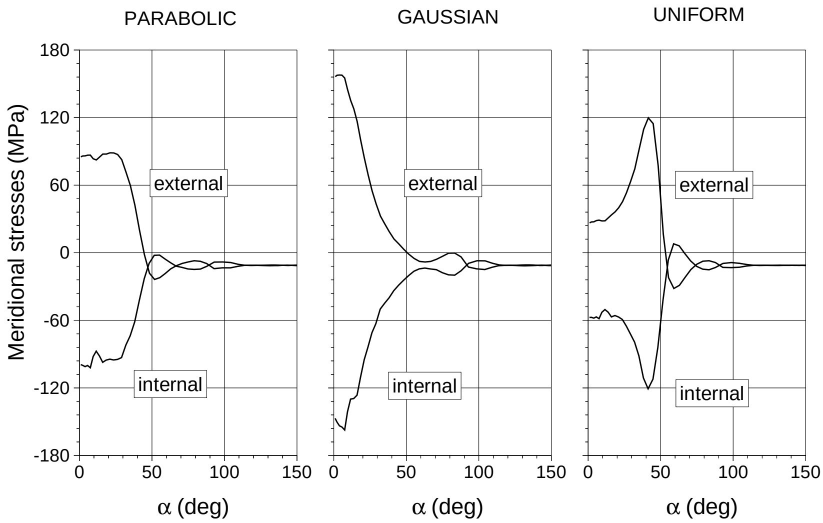


Figure 7 *≠ Meridional stress components in the internal and external window fibres.*

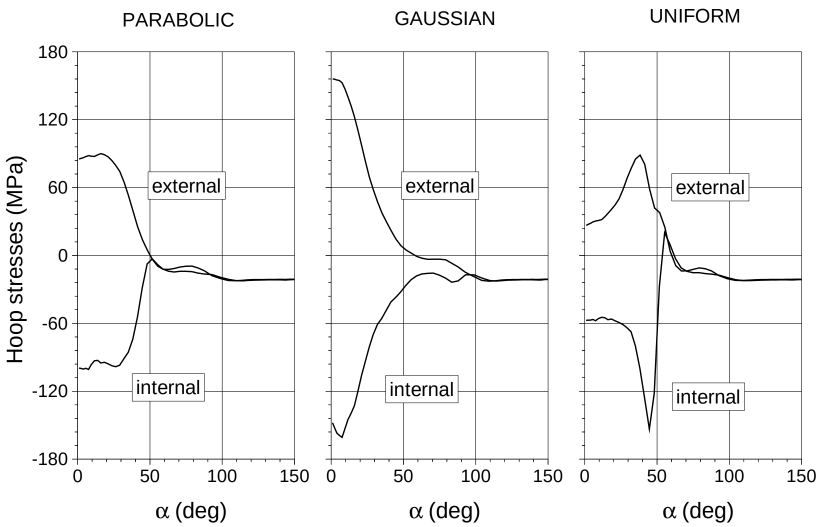


Figure 8 *≠ Hoop stress components in the internal and external window fibres.*

Beam size effects

One of the most dangerous accidents expected in the beam window is a reduction of the beam size. In order to analyse such effect we reduced the beam spot radius down to a dimension of 3 cm. Fig. 9 shows that the maximum temperatures reached on the external and internal window surfaces in the beam axis are immediately out of the utilisation range of a HT-9 steel.

The corresponding maximum meridional, hoop and Von Mises stresses normalised with respect to the UTS are shown in Fig. 10 and illustrate that also stresses are immediately out of the application range when reducing the spot size.

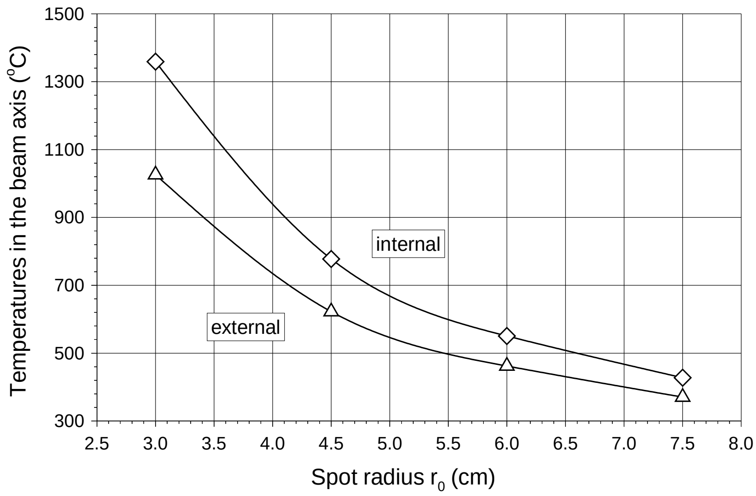


Figure 9 *≠ Temperature on the window surfaces in the beam axis vs beam radius.*

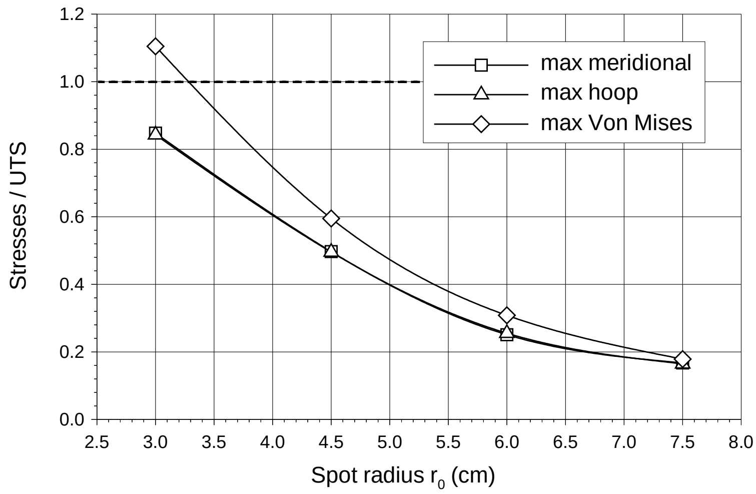
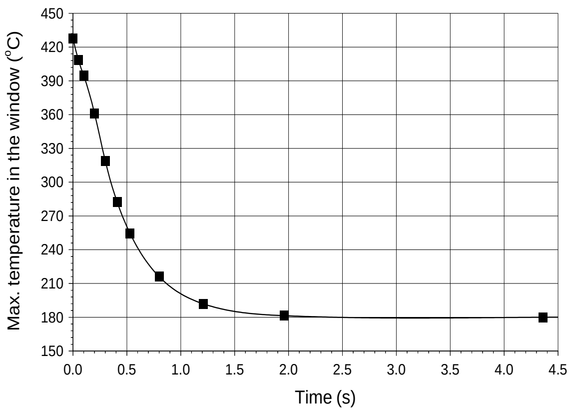
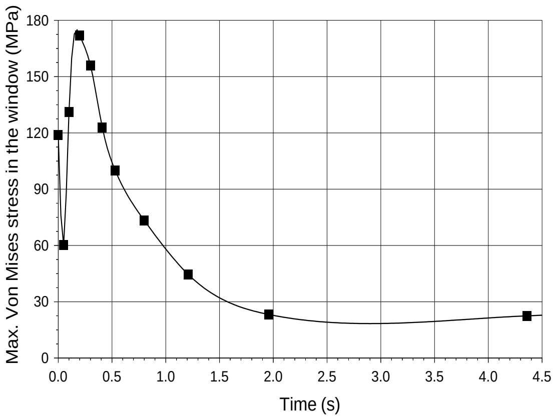


Figure 10 *≠ Normalised maximum meridional, hoop and Von Mises stresses vs beam radius.*

Beam interruption effects

When the beam is interrupted, window temperatures decrease to the heat exchanger exit temperature. The beam interruption transient is calculated by a structural analysis decoupled by the fluid dynamic transient. The MSC/NASTRAN code is used where the coolant temperature is supposed to decrease from 360 C (see Fig. 6) to 180 C in 0.15 s, according to the coolant velocity field near the window. The window/coolant heat flux is computed by using a heat transfer coefficient of 20000 $Wm^{-2}K^{-1}$ obtained by a forced convection fluid dynamic analysis of the window flow without the LBE heat source. Figs. 10 and 11 show the maximum temperature and Von Mises stress in the window during the transient.





***Figures 10 and 11** ≠ Maximum window temperature and Von Mises stress during the beam interruption transient.*

Under the approximation done on the coolant temperature transient, each beam interruption longer than about 4.5 s produces a stress cycle whose maximum Von Mises stress is 175 MPa. By neglecting the creep damage, the fatigue life may be determined from a design curve based upon strain cycling fatigue data generated at the maximum temperature [14]. In [15] a design curve for medium-strength pressure vessel steels is given, leading to a number of cycles to failure equal to 10^5. However to predict thermal fatigue life with a higher degree of accuracy it is necessary to simulate the coupled thermal and fluid-dynamic transient and to acquire data about the thermal stress behaviour of the specific steel, the irradiation damage and the corrosion effects.

Conclusions

Extensive numerical calculations have been performed to study the thermo-fluid dynamics and the structural loads on the EA 80 MW prototype target. In the limits of the geometrical constraints of the system, a thermal hydraulic optimisation of the target allows the use of natural convection. The relatively low power beam of the machine (600 MeV of beam energy and 2|6 mA of beam current) allows the use of a martensitic steel in the beam window. This deeply alleviates the problems related to the construction, the assembly and the operation of the window under intense proton irradiation.

When changing the uniform beam distribution from parabolic to gaussian or uniform, window temperatures and thermal stresses increase and eventually go out of the steel application range. When reducing the beam size temperatures and stresses still increase but in this case are immediately out of the steel utilisation range.

A simplified study of the fatigue damage induced by cyclic beam interruptions (longer than about 4.5 s) leads to predict the allowable number of interruptions to failure. In this analysis the more critical points remain the need of data on steel thermal cycle fatigue, irradiation damage and corrosion.

References

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