Analysis and Design of MEBT Beam Absorber for Project-X

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***Abstract* — A beam absorber is needed for a new high power accelerator to be built in Fermilab. It is called Project-X and should replace the existing linac and the 8 GeV Booster synchrotron. The beam absorber is part of the bunch-by-bunch chopper assigned to create an arbitrary bunch sequence required by experimental program. It will be located in the middle of the medium energy beam transport (MEBT) and has to remove the unnecessary bunches from the initially uniform bunch structure supplied by 2.1 MeV CW RFQ. At nominal RFQ beam current of 5 mA, the maximum power delivered to the beam absorber is about 10 kW. Beam optics requirements result in that the length allocated to the beam absorber is short (~400 mm) and the beam size is small (σ~2mm). That yields high power density of the beam arriving to the absorber. The paper presents the thermal and mechanical analysis of one of proposed designs.**

I. INTRODUCTION

PROJECT-X is a proposed high intensity proton accelerator to be built in Fermilab. It will be targeting the intensity frontier with focus on the study of rare subatomic processes and supporting neutrino experiments. It will deliver high quality beam to several physics experiments including high energy physics and rare nuclear processes [1-2]. Having the beam shared between several experiments with different bunch sequences puts a stringent specification on the overall bunch sequence supplied by the accelerator. In order to achieve the required bunch sequence, it is planned to have a bunch-by-bunch chopper located in the 2.1 MeV medium energy beam transport (MEBT). The beam originates from a 5 mA DC H- source and is then bunched and accelerated by a CW normal-conducting RFQ to 2.1 MeV [3-5]. A chopper with a pre-programmed timeline is used then to format the bunch pattern. Since the linac average beam current is 1 mA and the beam current of the ion source can be as high as 5 mA, up to 80% of beam has to be removed by the chopper in normal operating conditions and close to 100% if only one low power experiment takes the beam [6]. The removed power of the beam is quite high, on order of 10 kW, and thus it would require a dedicated beam absorber. The beam energy of 2.1 MeV was chosen in part because it is below the neutron production threshold for most materials.

Similar systems however with lower power were reported in the literature. For instance, C. Rossi. et. al. presented in 2007 a chopper line design with beam energy of 3 MeV and beam absorber designed for optimum thermal conductance and with a 100 µm nickel inner layer to limit the induced radioactivity, however it could only bare 3.3 kW of beam power [7]. On the other hand, D. Berkovits proposed a 20 kW beam absorber made of 250 micron tungsten sheet and is fused to a water cooled cooper plate, however visual inspection of the tested prototype revealed strong blistering effects [8]. As far as we understand, the beam absorbers of both solutions should have limited lifetime due to removal of nickel or tungsten layer by spattering.

In this paper, a MEBT beam absorber suitable for Project-X is presented. A simplified 2D analysis will be first considered for the proposed structure in Section II followed by full 3D thermal and mechanical analyses in Section III.

II. PROJECT X

Project X is designed to reveal physics phenomena far beyond the energy reach of the Large Hadron Collider, but only in an indirect way [1-2]. Project X will significantly increase the beam power providing a large margin for experiments with neutrino, kaon and muon beams compared to existing facilities. The proposed facility would not only allow for numerous experiments at the intensity frontier, but also it would allow scientists to develop technologies for future machines at the energy frontier. Project X consists of two superconducting linear accelerators, as shown in Figure 1.

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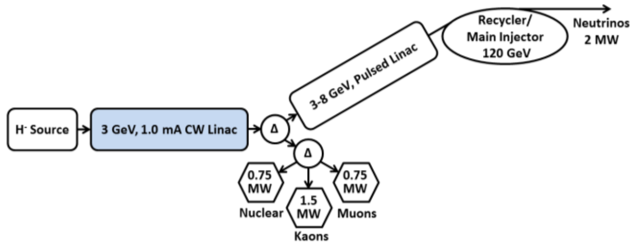

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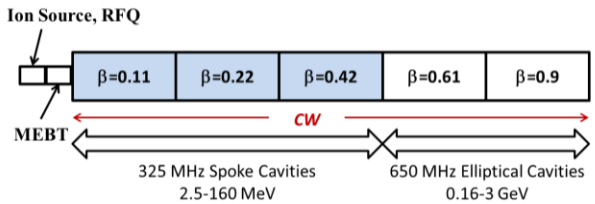


(b)

Figure 1. Project X. (a) Layout. (b) CW linac section showing the MEBT section.

The first one is a continuous wave (CW) linac to get the beam to 3 GeV. It is followed by a pulsed linac boosting the beam from 3 to 8 GeV. The 8 GeV beam is injected in the existing Recycler ring and transferred to the Main Injector to get to 120 GeV, as shown in Figure 1(a). The RF separation of 3 GeV CW beam allows one to supply the beam to a few experiments simultaneously. The CW linac consists of three types of spoke cavities at β=0.11, 0.22, and 0.42 and two types of elliptical cavities at β=0.6 and 0.9 Figure 1(b).

Project X should deliver the beam to several experiments. Three types of experiments are currently discussed. They are: a kaon experiment ($K\rightarrow\pi\nu\nu$), a muon experiment ($\mu\rightarrow e$), and a nuclear physics experiment. Each experiment requires its own beam structure. Figure 2(a) presents a possible bunch sequence consisting of pulses for muon experiment at 1 MHz (red), pulses for Kaon experiment at 20.3 MHz (blue), and pulses for nuclear physics experiments at 10.15 MHz (green) [4]. The desired sequence for each experiment is obtained from uniform stream of RFQ bunches by removing undesired bunches with help of bunch-by-bunch beam chopper followed by a beam dump/absorber as shown in Figure 2(b). Later on, these three bunch streams will be separated at the end of the CW linac using an RF based separation scheme utilizing transverse RF splitter cavity as shown in Figure 2(c).

The beam absorber has to be able to accept about 10 kW in a comparatively short space allocated to it. Figure 3 shows the proposed beam absorber. It is basically a rectangular piece of copper of 400x100x50 mm^3 in size with six longitudinal cooling channels arranged on circular radius from the structure center.

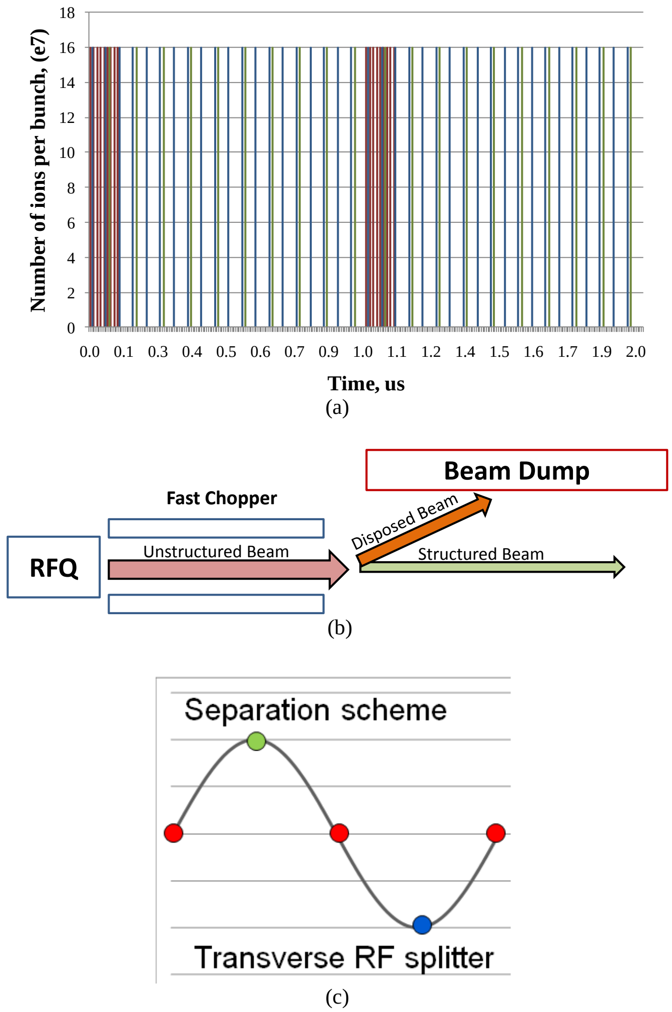


Figure 2. Project X, (a) Beam structure. (b) Beam absorber. (c) Separation scheme.

III. 2D Thermal Analysis

A simplified 2D analysis has been carried out to estimate the differential temperature between the top surface of the beam absorber and the cooling channels where the beam absorber is simplified in 2D to a half circle with constant temperature on the circle arc and certain heat flux distribution on the top edge as shown in Figure 4.

The heat flux P intercepted by the beam absorber is expected to have the following Gaussian distribution in the transverse direction.

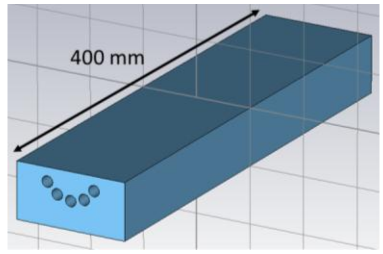
$$P = \frac{dQ}{dL}\frac{1}{\sqrt{2\pi}\sigma_x}e^{-\frac{x^2}{2\sigma_x^2}} \quad , \tag{1}$$

where $\frac{dQ}{dL} = 80$ kW/m, $\sigma_x = 2.2mm$

The temperature distribution along the beam absorber cross-section can be presented in the following form:

$$T(x,y) = \frac{dQ/dL}{(2\pi)^{3/2}\kappa\sigma_x}\int_{-R}^{R} e^{-\frac{x'^2}{2\sigma_x^2}} \ln\frac{\left(xx' - R^2\right)^2 + \left(yx'\right)^2}{R^2\left(\left(x-x'\right)^2 + y^2\right)}dx' \, .$$

For $\sigma_x << R$ the differential temperature between the center of top edge and the constant temperature of arc can be approximated as [9]



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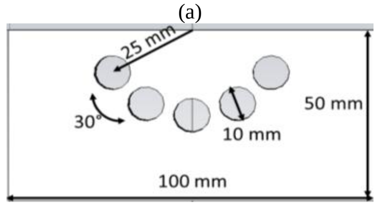

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Figure 3. Proposed beam dump/absorber.

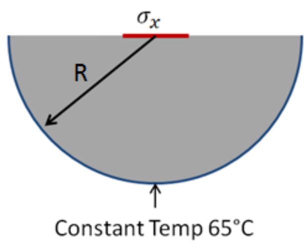


Figure 4. 2D simplified model for the beam absorber.

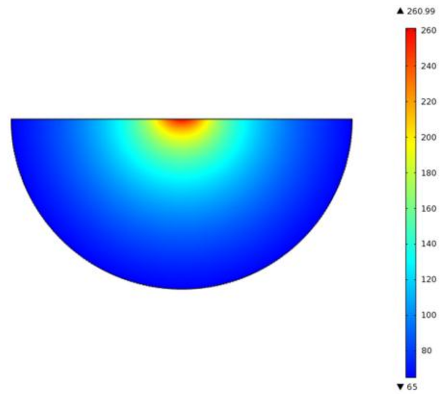
$$\Delta T_{cu} \equiv T(0,0) \approx \frac{dQ}{dL}\frac{1}{\pi \cdot \kappa}\ln\left(1.89\frac{R}{\sigma_x}\right), \qquad (2)$$

which gives for R=25 mm and assuming copper thermal conductivity κ= 400 W.m^{-1}.K^{-1}

$$\Delta T_{cu} = 200° \text{ C}$$

Following the analytical analysis, we have carried out a thermal and mechanical analyses for the simplified 2D model using Comsol [10], a multi-physics finite element based simulation tool.

Figure 5(a) demonstrates the simulated heat distribution under the same heat flux distribution as in Eq. (1) and assuming 65° C temperature on the circle arc. The resultant simulated differential temperature is about 196 °C in good agreement with the analytically computed value. Meanwhile, the von Mises resultant simulated thermal stresses are shown in Figure 5(b) projecting a max stress value of 446 MPa which is well far beyond the 70 MPa yield for cooper which indicates that a simple solid piece of copper cannot tolerate the expected thermal stresses.



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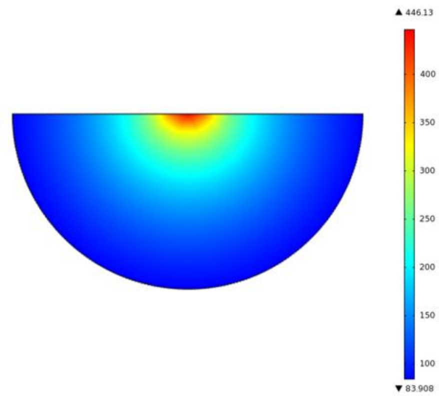

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Figure 5. 2D simplified analysis. (a) Temperature profile. (b) Von Mises mechanical stress.

IV. 3D Thermal and Mechanical Analyses

A full 3D multi-physics analysis has been carried out to investigate further the thermal and mechanical behaviors of the proposed beam absorber. The beam spot along the absorber is determined by the vertical rms beam size σ_y and the beam incident angle θ. The heat flux distribution P_1 at 2D beam dump surface is assumed to be

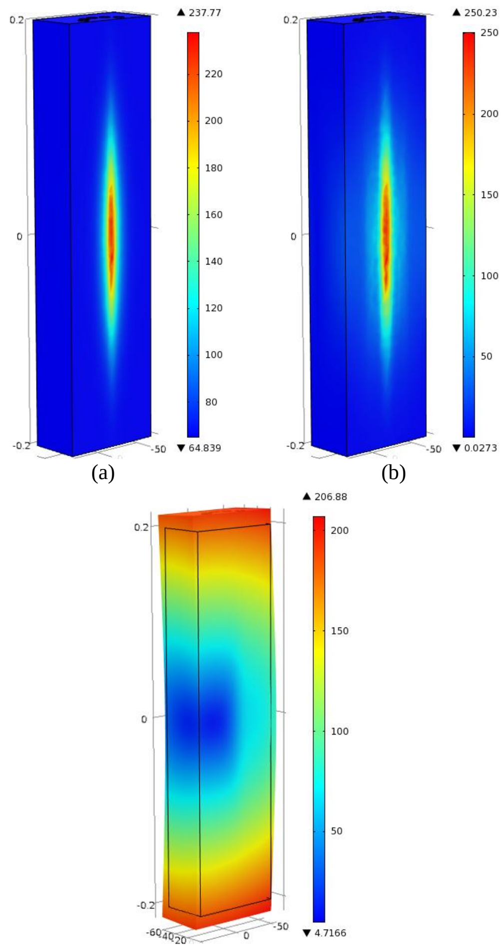
$$P_1 = \frac{dQ}{dL}\frac{1}{\sqrt{2\pi\sigma_x}} e^{-\frac{x^2}{2\sigma_x^2}} e^{-\frac{z^2\theta^2}{2\sigma_y^2}} ,$$

where $\sigma_y = 1.83mm$, and $\theta = 29mrad$.

Figure 6(a) shows the thermal profile under a total heat flux of 12.5 kW. The temperature at the hottest spot in the middle of the beam absorber is about 234° C giving a differential temperature between the top surface and the cooling channels of 169° C. It is smaller than the 200 C expected from the 2D analysis mainly because of the effect of the cooling channels and the heat propagation in the longitudinal direction which was ignored in the 2D analysis. That temperature gradient will cause thermal stresses of about 250 MPa as shown in Figure 6(b) and a maximum deformation of 208µm at the beam absorber ends as shown in Figure 6(c).

Despite that the thermal stresses exhibited in the 3D structure is smaller than the one obtained in the simplified 2D analysis it is still far higher than the 70 MPa yield stress of the copper. One way to decrease the stresses is to add an array of transverse slits along the structure.

For instance, Figure 7 demonstrates how an array of circular slits of 1 mm thickness, 20 mm radius with 4 mm step along the entire beam absorber could reduce the thermal stresses to 135 MPa, as shown in Figure 7(b), which is 46% less than for solid copper. On the other hand, the temperature of the hottest spot increased to 247° C as the heat flux is distributed relatively on smaller surface after cutting away the slits, as shown in Figure 7(a), giving a differential temperature of 182° between the top beam absorber surface and the cooling channels. Meanwhile, the deformation of the beam absorber ends decreased relatively to 162 µm. It worth noting, that the symmetry of the beam dump structure allowed us to simulate a quarter of the entire structure. It significantly reduced time of computations. Also the slit edges were blended with blend radius 0.5 mm to avoid any concentrated stresses on the edges.



(a) (b)

(c)

Figure 6. Simulation results of the proposed beam absorber. (a) Thermal profile with temperature in deg C. (b) Mechanical stresses (von Mises in MPa). (c) Displacement and projected deformation in µm.

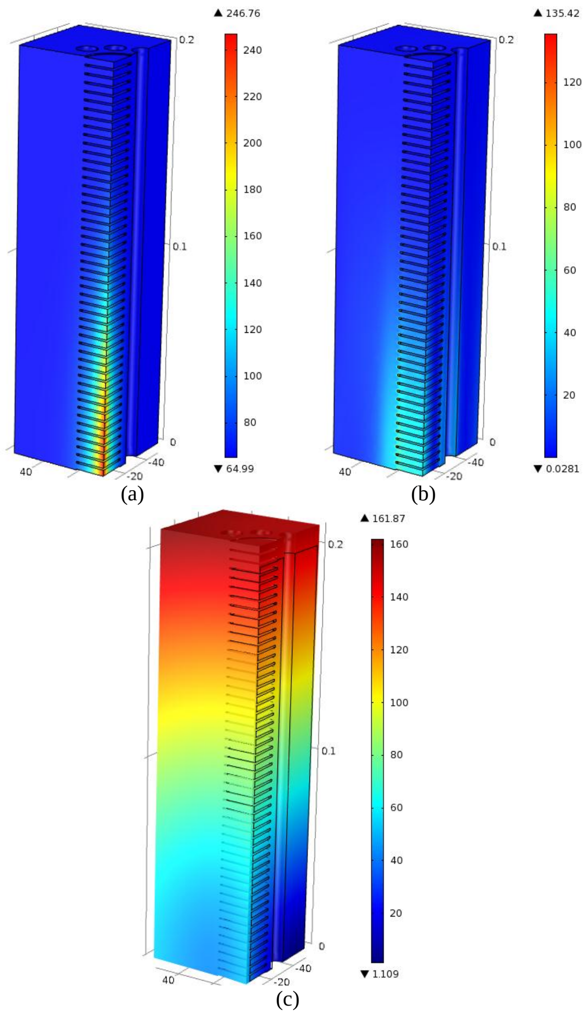


Figure 7. Simulation results of the proposed slitted beam absorber. (a) Thermal profile with temperature in deg C. (b) Mechanical stresses (von Mises in MPa). (c) Displacement and projected deformation in µm.

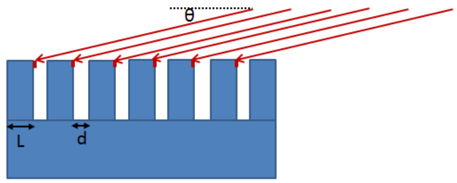
A serious problem that may arise with the operation of the slotted structure is that there would be a concentrated heat deposition on the slit side edges facing the beam as shown in Figure 8(a). In order to quantify the effect of this heat deposition, we have simulated part of the beam absorber and forced an increased heat flux P_2 distribution on these slit edges of length $d \cdot \tan(\theta)$ as $P_2 = \dfrac{P_1}{\tan(\theta)}$.

Figure 8(b) shows the simulated heat profile in this case where clearly the temperature is drastically increased to 494° on the slit edges causing thermal stresses of 320 MPa, as shown in Figure 8(c). The stresses are concentrated on the slit edges facing the beam. Clearly, the heat deposition would be a serious problem in the slotted structure unless taken care of.

One potential solution to the heat deposition problem is to corrugate the top surface of the beam absorber so that each slit lies in the shade of an inclined copper wall as shown in Figure 9 (a). The proposed corrugated surface would resolve the heat deposition problem with the heat flux distribution P_3 changed to:

$$P_3 = P_1 \frac{L+d}{\sqrt{L^2+h^2}} \quad .$$

Figure 9 (b)-(c) shows the thermal stresses of the corrugated beam dump with various slit shapes assuming d=1 mm, L= 4mm, h= 30µm, and blend radius= 0.5mm. Three different slit shapes were investigated namely; circular, elliptical, and modified custom slit shapes. The peak von Mises stresses of the three slit shapes are 97, 69, and 53 MPa for the circular, elliptical, and modified slits, respectively. Clearly, the stresses are reduced as larger slit area is achieved and so distributing the forces on larger area. That is why the stresses are reduced on going from the circular to the elliptical and then to the modified custom shape slit. However, the elliptical slits would lower the clearance between the slits and the cooling channels to 1.5 mm, which is undesirable. Thus the modified slits have been adopted despite that they would require additional fabrication steps. With the modified custom slit shape shown in Figure 9(c) the thermal stresses are 76% of the copper yield which makes the implementation of the required beam absorber for Project X possible using even conventional copper.



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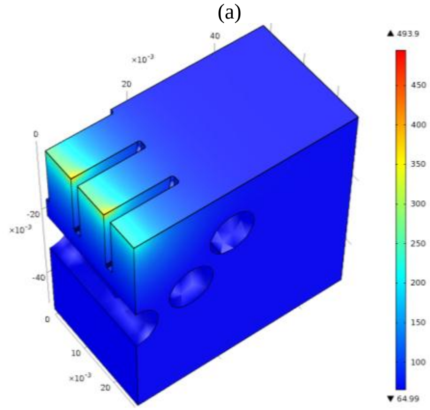

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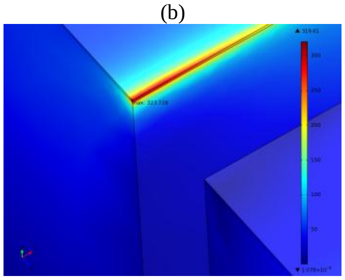

(c)

Figure 8. Heat deposition on slits of the beam absorber. (a) Sketch to depict the problem (b) Thermal profile with temperature in deg C. (c) Mechanical stresses (von Mises in MPa).

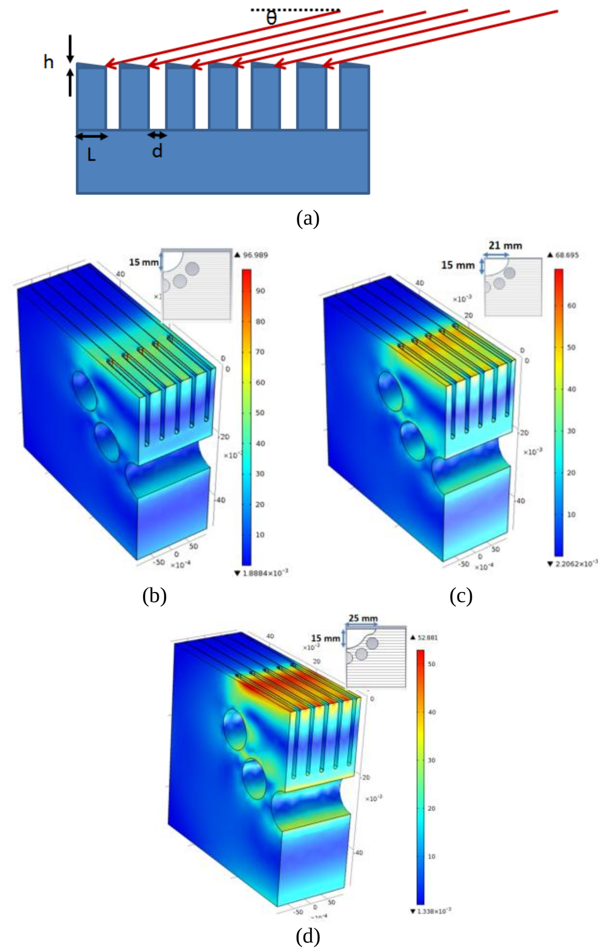

Figure 9. Corrugated beam absorber. (a) Sketch to depict the proposed corrugated beam absorber. (b) Mechanical stresses (von Mises in MPa) with circular slits. (b) Mechanical stresses (von Mises in MPa) with elliptical slits. (c) (b) Mechanical stresses (von Mises in MPa) with modified slits.

V. Conclusion

A MEBT beam absorber suitable for Project-X is proposed given the stringent requirements of dumping ~10 kW over limited space of 400 mm. Slitting the beam absorber is necessary to reduce the high thermal stresses expected with having a differential temperature of 180° C between the beam absorber top surface and the cooling channels. Moreover, corrugating the beam absorber top surface is needed to shield the slits' edges facing the beam from excessive heat deposition that would be concentrated on very narrow surfaces.

The proposed design with the corrugated surface would lower the stresses from 325 MPa, in case of bare surface, to about 100 MPa. Various slit shapes have been investigated, circular slits would decrease the stresses to about 97 MPa, while elliptical slits would even decrease the stresses to about 69 MPa, however they would lower the clearance between the slits and the cooling channels to 1.5 mm. A modified custom slit shape has been proposed and the simulation results has shown that it would successfully reduce the stresses to about 53 MPa corresponding to 76% of the copper yield, which makes the implementation of the required beam absorber for Project X possible using even conventional copper.

However there are still problems to be addressed before the final choice for the beam absorber design will be approved. The most pressing one is the blistering of copper surface under influence of proton beam which can force us to choose material other than copper.

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