BEAM STOP DESIGN AND CONSTRUCTION FOR THE FRONT END TEST STAND AT ISIS

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Abstract

A Front End Test Stand is being built at the Rutherford Appleton Laboratory in the UK to demonstrate a chopped H^- beam of sufficiently high beam quality for future high-power proton accelerators (HPPA). The test stand consists of a negative hydrogen ion source, a 3 solenoid LEBT, a 324 MHz four vane RFQ, a MEBT composed of rebunching cavities and choppers and a set of diagnostics ending with a beam stop. The beam stop, which has to accept a 3 MeV, 60 mA, 2 ms, 50 Hz (10% duty factor) H^- beam, consists of a coaxial double cone configuration where the inner cone's inner surface is hit by the beam and the inter-cone gap is cooled by high-speed water. In order to minimize both prompt and induced radiation pure aluminium is used, but the poor mechanical properties of pure aluminium are overcome by employing a metal spinning process that increases the yield strength to several times the original value of the non-deformed material.

INTRODUCTION

The progress of the FETS project of ISIS has been regularly reported in accelerator conferences since its first presentation in 2006 [1]. The beam stop is the "last" instrument of a series already described in those updates, the aim of which is to be used as a target that prevents the beam from damaging persons or devices in the surroundings of the facility.

There are a variety of solutions reported in the literature for proton beam stops both in terms of materials used and shapes designed. Different beam energies lead to different geometries. Radiation concerns and structural integrity limit the materials that can be applied for these type of devices. One of the first beam stops reported was the Low Energy Demonstration Accelerator LEDA [2] beam stop in the late 90's. This was an ogive shape electroformed Nickel instrument able to absorb a 6.7 MeV and 100 mA CW beam. Neutrons and gamma rays were stopped by a water (with boric acid) tank shielding around the cartridge containing the ogive beam stop. Because of activation concerns, a later development of the same LEDA beam stop proposed a carbon composite device integrated into the Nickel structure [3]. Similar conditions to the LEDA beam stop are found in a recent development proposed for the IFMIF-EVEDA accelerator [4], although in this case the beam stop was to be made of Copper and had a heat transfer optimised surface shape. A case closer to the one analysed in this paper, i.e., with a beam to be stopped of similar characteristics, was designed and manufactured for the SNS [5]. The geometry proposed was a 2 mm thick axysimmetric cone made of Nickel 200. No reference to neutron or gamma radiation issues was given.

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MATERIAL SELECTION

Radiation and neutron production is a primary concern at RAL, where the beam stop will be installed. Previous studies already referenced mention aluminium as a suitable material from the point of view of neutron and gamma production. The aluminium has a first threshold of neutron capture at 5.5 MeV and at 3 MeV the nuclear cross section is as low as 10^{-6} barn. Radiation, then, is only composed of X-rays, which are easily stopped by a thin aluminium foil.

The calculated stopping depth in aluminium is 80 μm. So, it is structural issues that determine the thickness of the beam stop since the radiation is quickly attenuated. Commercial pure aluminium is 99.5% pure, with impurities below 0.05% each (Cu, Mg, Mn, Ti, Zn, Si). However, in the case of Copper even that small amount can cause an unacceptable radiation dose, therefore, only ultra pure aluminium (99.99%) with a Copper content below 0.006% can guarantee the absence of radiation.

From the point of view of thermal conductivity, it is of vital importance that the choice of aluminium is again among the best possible. It has considerably larger conductivity than Nickel and, in addition, aluminium conductivity increases with temperature [6].

Clearly, mechanical properties are the main weakness of pure aluminium versus other materials: yield does not go beyond 10 MPa. Thus, only by cold forming can yield and tensile strength be improved. The amount by which these increase depends on the degree of deformation reached. In tests carried out in TEKNIKER using specimens extracted from metal spun pure aluminium, tension yields up to 70 MPa were obtained, although higher values, up to 110 MPa (H18 state), are also reported.

It is important with aluminium to keep temperature low enough in order not to affect mechanical properties. The yield starts decreasing with temperatures over 150ºC [7]. Another effect of temperature is that the cold hardened state returns to its annealed original if the material is kept at high enough temperatures for a certain period of time [8]. For example, yield strength of fairly pure aluminium (99.0%) can be reduced up to 10% by keeping it at temperatures around 175ºC for 5 hours, although hardly any effect is obtained after the first hour.

Considering that the beam stop is subjected to a pulsed beam, fatigue considerations are of the utmost importance due to the cyclic nature of the load. Fatigue curves for pure aluminium are hardly known since it is not used for structural applications. However, since the inner side of the cone tends to expand due to the heat transferred by the beam and the outer part is cooled by water (and so it is at a lower temperature and at a lower level of expansion) the cyclic stresses are compressive and the fatigue problem is a lot less severe if they had been tensile. In addition, the ultimate compressive stress showed in tests to be a lot larger (over 200 MPa) than the ultimate tensile stress.

DESIGN FEATURES

The basic parameters of the proposed beam stop and the FETS beam are presented in Table 1. The beam is assumed to be of Gaussian shape with maximum value at the centre equal to 380 W/cm^2, so that the total energy to be removed by cooling the beam stop is 18 kW.

Table 1 Beam Stop Parameters

Beam characteristics	
Operation Pulse (Hz)	50
Particle Energy (MeV)	3
Beam Current (mA)	60
Particle type	H^-
Duration (ms)	2
Duty factor (%)	10
Max. Av. Heat Flux (W/cm^2)	380
Physical Features	
ID (mm)	210
L (mm)	600
Beam Stop geometry	Axysimm. cone
Material	Al (99,99%)
Semicone angle (º)	9
Thermal Management	
Total heat removed (kW)	18
Coolant	Water 20ºC
Coolant Flow direction	Counterflow

Cone base diameter is set to fully accept the 100 mm (approx) beam diameter, with some space for the possibility of a wider and smaller maximum flux beam.

The beam stop is encapsulated on a parallel cone of commercial pure aluminium (99.5%), which leaves, approximately, a 5 mm gap for the cooling water to run from tip to base along the periphery of the beam stop cone outer surface (Figure 1). One end of the cone, the tip, is left free to move to avoid stresses due to thermal expansion.

Water is pressurised (2 bars) to overcome friction head losses of the circuit and the rather small likelihood of water boiling due to surface temperatures over 100ºC, although the latter will be always avoided by increasing water flow rate, if necessary.

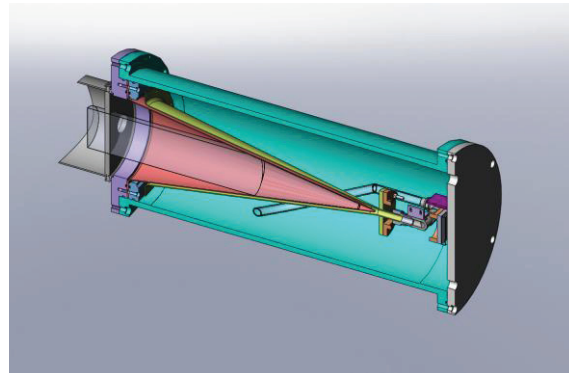

Figure 1: Beam Stop 3D model

ANALYSIS

With the material and basic parameters already defined by favourable properties and manufacturing constraints, the fluid mechanics and heat transfer problem coupled with mechanical stresses coming from the water pressure and vacuum effect is dealt with by varying a number of parameters, namely: cone wall thickness, water flow rate, tip inner radius and the beam maximum heat load.

In order to model heat transfer process between the beam stop walls and the cooling fluid a CFD program (Figure 2) was used for a number of cases, so that an expression for the heat transfer coefficient was derived as a function of fluid velocity, distance from the tip and wall outer temperature.

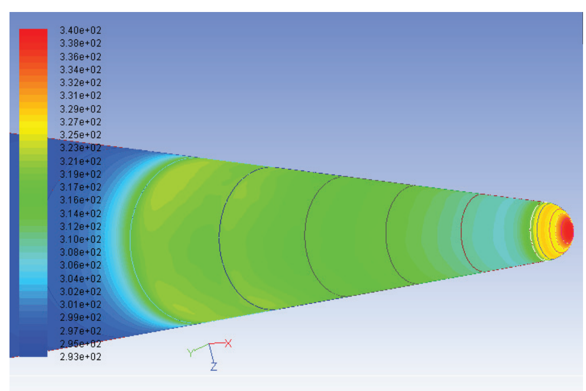

Figure 2: Cone wall outer temperature r_t=10 mm

Near the tip of the cone, the water jet has a higher velocity and the heat transfer coefficient takes very high values that rapidly decrease as water slows down at larger diameter, i.e., larger cross-section, zones.

As shown in Figure 2, maximum outer temperatures are generally found on the tip of the cone and are always kept below 100ºC. Inside the cone, the maximum temperatures are always in the tip and could exceed this temperature, although they stay far enough from temperatures that could change its hardened state.

The temperature of points on both the inner and outer surfaces of the cone varies with time and experience large temperature changes (Figure 3).

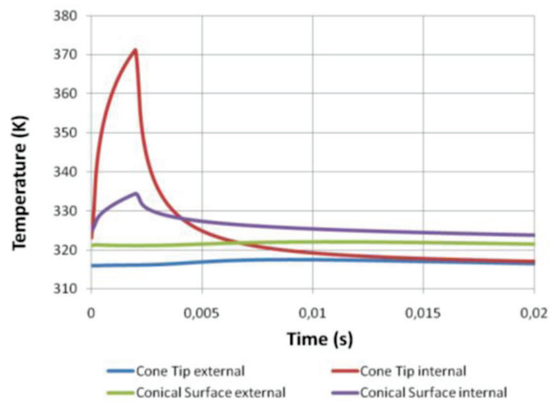

Figure 3: Temperature variation along the pulse

The conical part of the beam stop, as opposed to the radiused tip, is subjected to stresses well below the yield stress of the hardened material. Calculations reveal that wall thickness does not significantly affect the stress value.

Maximum stresses which, as already mentioned, are compressive, are concentrated on the radiused inner surface of the tip cone. The rest of the cone, the tapered surface is hardly affected. The smaller the tip radius, the smaller is the zone of high temperatures and stresses.

So, the tip of the cone is subjected to a pure compressive stress cycle that might lead to the formation of cracks. However, experiments show that even in the case of a crack formed at the tip, further propagation ceases eventually if pure compressive stress cycles are applied [10]. Crack propagation is arrested when the tip of the crack has grown out of the concentrated stress field at the tip. As a result, in order to guarantee the integrity of the beam stop for a long period of time, the design should consider minimising the tool tip radius and increasing the tip thickness in order that cracks are not given the chance to cross the beam stop wall.

MANUFACTURING

As already mentioned in the introduction, a metal spinning process is used to obtain the basic cone shape of the beam stop (Figure 4).

Figure 4: Metal Spinning Process of Beam Stop

Electroforming would not be an acceptable solution for the low yield of the pure aluminium. Only by cold forming can yield and tensile strength increase in this material. The semicone angle is the smallest possible by the spinning technique and the means available. In order to obtain the tip required for the beam stopping process, an optimum solution is to manufacture a separate piece of enough length with characteristics such as, for example, a tip inner radius smaller than 1 mm and tip thickness over 2 mm and the same cone angle. Tip and truncated cone will then have to be joined by Electron Beam Welding.

CONCLUSIONS

A beam stop design concept and its manufacturing were presented in this paper. The material selected was aluminium for its good radiation absorbing properties and the possibility of improving its poor mechanical properties by cold forming.

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