SIMULATION STUDIES OF IMPACT OF SPS BEAM WITH COLLIMATOR MATERIALS*

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Abstract

Damage caused by full impact of one LHC beam on solid copper has been previously studied using two-dimensional hydrodynamic computer simulations [1, 2]. In the present paper we report numerical simulations that have been done to assess the damage caused to collimator materials due to impact of full SPS beam that comprises of 288 bunches of 450 GeV/c protons. This study considers a tungsten cylindrical target which has length of 50 cm and radius of 5 cm that is facially irradiated by the beam with two different focal spot sizes determined by σ = 0.088 and 0.88 mm, respectively. These simulations have shown that the target will be completely destroyed in both cases..

INTRODUCTION

The Super Proton Synchrotron, SPS is used as LHC injector, but also to accelerate and extract protons and ions for fixed target experiments and for producing neutrinos (CNGS). In particular the risks during the fast extraction of LHC and CNGS beams must be considered since any failure during this process can lead to serious equipment damage.

The SPS accelerator is 6.9 km long (circumference) and accelerates protons from 14 GeV/c or 26 GeV/c to a momentum of up to 450 GeV/c. It is a cycling machine with cycles having a length of about 10 s. The transverse beam size is largest at injection and decreases with the square root of the beam energy during acceleration. For the operation as a synchrotron, the beam size is typically of the order to 1 mm.

When the SPS operates as LHC injector, up to 288 bunches are accelerated, each bunch with about 1.1×10^{11} protons. The bunch length is 0.5 ns and two neighboring bunches are separated by 25 ns so that the duration of the entire beam is about 7 μs. The normalized emittance is 3.75×10^{-6}m. Assuming a beta function of 100 m, the beam size (σ of the Gaussian intensity distribution) is 0.88 mm. When the SPS was used as proton-antiproton collider, the luminosity was maximized by minimizing the beta function to 0.5 m. Assuming this value the beam size would be about 0.06 mm. We have carried out simulations considering three cases using σ = 0.088 mm, 0.28 mm and 0.88 mm respectively.

Although the energy stored in the SPS beam is less than 1 % of the LHC beam energy at 7 TeV/c, it still is sufficient to cause considerable damage in case of a failure. To assess the damage level caused by such an accident, limited experiments on target irradiation by the SPS beam have been done in a beam transfer line between the SPS and the LHC / CNGS target [3, 4]. This will not be possible in the years to come, whereas such studies will be required on regular basis. For this reason, a facility for tests with extreme thermo-mechanical shocks, named HiRadMat, is being constructed as part of the phased implementation for LHC collimators [5]. It will allow sending of several MJ energy beam in μs pulses to a dedicated target station that will be constructed. The main use of this facility will be to test the consequences of beam impact on beam absorbers, collimators and other objects, which is mandatory for the design of such devices to be installed in LHC and other future accelerator facilities like FAIR, at Darmstadt [6]. These experiments therefore will be very useful to validate simulations that have been previously done to estimate damage caused by an LHC beam in case of an accident [1, 2]. In addition to that, other areas of research including material sciences and High Energy Density (HED) states in matter will also benefit from these experiments. In this paper we present numerical simulations of hydrodynamic and thermodynamic response of a solid tungsten target that has been irradiated with full SPS beam. These simulations have shown that the target will be completely destroyed generating large samples of HED matter.

PROTON ENERGY DEPOSITION IN MATTER

It is well known that energetic heavy ions deposit their energy in the target as a result of Coulomb collisions, mainly with the target electrons [8, 9]. The 7 TeV protons, on the other hand, when incident on matter, will generate particle cascades in all directions and one needs to calculate the energy deposited by all these different particles in the target. For this purpose we have used the well known particle interaction and transport Monte Carlo code, FLUKA [10, 11]. This code is capable of calculating all components of particle cascades in matter from TeV energies down to that of the thermal neutrons. The energy

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deposition profile calculated by the FLUKA code is used as input to the BIG-2 code. The target geometry for the FLUKA simulations is considered to be a cylinder of solid tungsten that is 50 cm long and has 1 cm radius.

In Fig. 1 we plot the specific energy deposition along the beam axis (r = 0) by a single bunch that consists of 1.1×10^{11} protons, assuming three different values of σ of the Gaussian transverse intensity distribution, namely, 0.088 mm, 0.28 mm and 0.88 mm respectively. The focal spot sizes corresponding to these values are within the typical operational limits of the SPS proton antiproton collider. It is seen that a maximum specific energy of about 0.38 kJ/g is deposited at L = 10 cm.

Fig. 2 shows corresponding specific energy deposition profiles along target radius at L = 10 cm (point of maximum energy deposition)

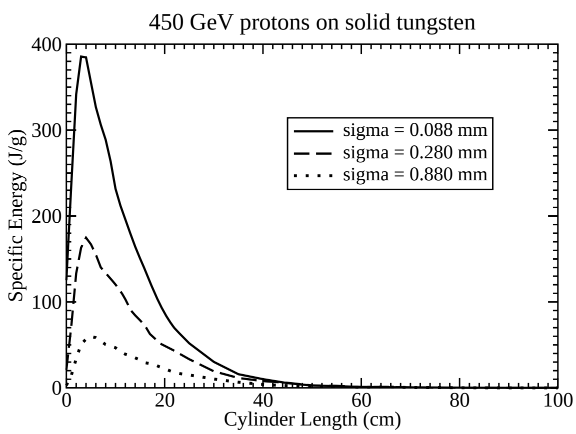

Figure 1: Specific energy deposition by a single bunch along beam axis (r = 0), using three different focal spot sizes.

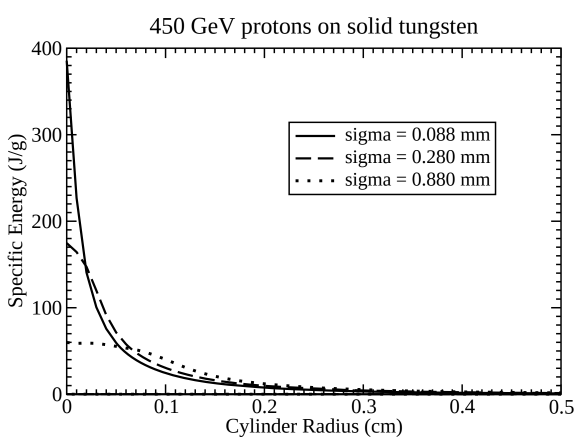

Figure 2: Specific energy deposition by a single bunch along radius at L = 5 cm (the point of maximum deposition), using three different focal spot sizes.

SIMULATION RESULTS

In this section we present numerical simulation results of thermodynamic and hydrodynamic behavior of a solid tungsten cylindrical target with radius = 5 cm and length = 50 cm that has been facially irradiated by the SPS proton beam. These simulations have been carried out using a two-dimensional hydrodynamic computer code, BIG-2 [7]. The beam focal spot in these calculations corresponds to a σ = 0.088 mm.

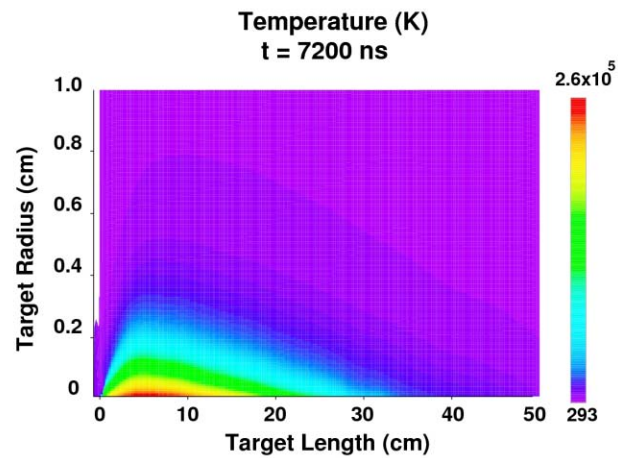

Figure 3: Beam incident from left-to-right: temperature on length–radius plane at t = 7200 ns, solid tungsten cylindrical target facially irradiated by 450 GeV/c SPS proton bunches, target length = 50 cm, target radius = 5 cm, Gaussian intensity distribution in transverse direction with σ = 0.088 mm, 288 bunches with each bunch composed of 1.1×10^{11} protons, bunch length = 0.5 ns, bunch separation = 25 ns (any significant temperature variation is localized to beam heated region so only the inner 1 cm radius is shown in this figure).

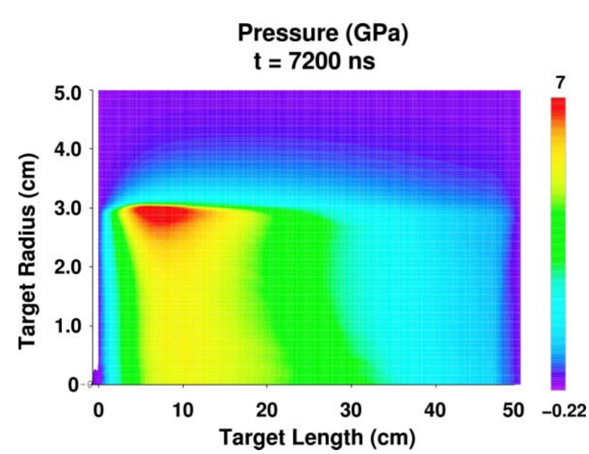

Figure 4: Pressure distribution corresponding to Fig. 3 (Propagation of shock wave generated by thermal pressure is clearly seen).

Figure 3 shows the temperature distribution in the target at the end of the pulse when all 288 bunches have been delivered. It is seen that a maximum temperature of 2.6×10^5 K has been generated in the target that means that the target material will be in a plasma state in this region.

The high temperature in the target gives rise to high pressure that generates shock waves in the material. A maximum pressure of about 32 GPa is generated at t = 200 ns (when only 8 bunches have been delivered) which launches a shock wave in radial direction. Figure 4 shows the pressure distribution in the target at t = 7200 ns. It is seen that by this time, the shock front has arrived at a radial position of 3 cm.

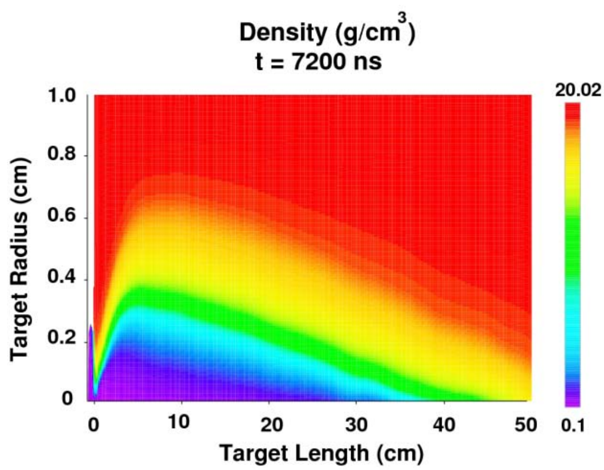

Figure 5: Density distribution corresponding to Fig. 3

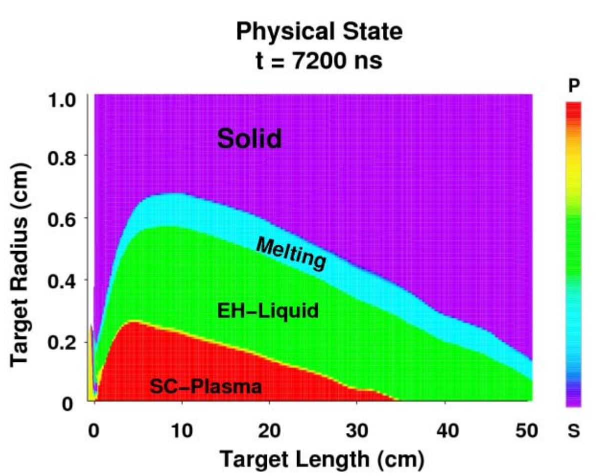

Figure 6: Target physical state corresponding to Fig. 3.

Figure 5 shows the density distribution in the target at the end of the pulse. It is seen that the density along the target axis has been substantially reduced and is less than 1 % of the solid tungsten density. This is because the shock wave moves material outward in radial direction that leads to a continuous reduction in the density. It has been seen in the simulations that the density decreases significantly after 1000 ns that means that the protons that will be delivered in subsequent bunches will penetrate deeper in the target. This ”tunneling” effect will have important implications on design of beam bump and sacrificial beam stoppers.

We note that target heating is a localized effect as electron heat conduction is not so effective on this time scale. We therefore only show inner 1 cm radius of the target for temperature distribution in Fig. 3. Pressure propagation, on the other hand, is not localized to the beam interaction region and therefore we show the target behavior within the full radius of 5 cm.

In Fig. 6 we show the target physical state at the end of the proton pulse at t = 7200 ns. It is seen that within inner 2 mm radius, a strongly coupled plasma state exists that is followed by an expanded hot liquid. The melting front is also seen propagating outwards. The physical states have been calculated using a sophisticated semi-empirical Equation-of-state (EOS) model described elsewhere [12]. These simulations clearly show that an SPS proton beam is capable of destroying solid targets that leads to generation of interesting HED states in matter. It will therefore be possible to perform dedicated HED experiments at the future HiRadMat facility at CERN.

Simulations with σ = 0.28 mm and 0.88 mm have shown that the target will be destroyed in these two cases as well.

REFERENCES

[1] N.A. Tahir et al., J. Appl. Phys. 97 (2005) 083532.

[2] N.A. Tahir et al., Phys. Rev. Lett. 94 (2005) 135004.

[3] V. Kain et al., CERN-LHC-Project-Report 822, Geneva, CERN (2005).

[4] R. Assmann et al., ”LHC Collimators: Design and Results from Prototyping and Beam Tests”, CERN-LHC-Project Report-850 (2005).

[5] R. Assmann, private communication.

[6] W.F Henning 2004 Nucl. Inst. Meth. A 214 211.

[7] V.E Fortov et al., Nucl. Sci. Eng. 123, 169 (1996).

[8] C. Deutsch, Ann. Phys. Fr. 11 (1986) 1.

[9] T.A. Mehlhorn, J. Appl. Phys. 52 (1981) 6522.

[10] A. Fasso et al., ”FLUKA: A Multi-Particle Transport Code”, CERN-2005-10, INFN/TC-05/11, SLAC-R-773 (2005).

[11] A. Fasso et al., ”The Physics Models of FLUKA: Status and Recent Developments”, Conf. on Computing in High Energy and Nuclear Physics, La Jolla, USA, March 24 - 28, 2003, arXiv:hep-ph/0306267.

[12] I. V. Lomonosov et al., 2007 Laser Part. Beams 25 567.