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The Large Hadron Collider and the Super Proton Synchrotron at CERN as Tools to Generate Warm Dense Matter and Non-Ideal Plasmas

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The largest accelerator in the world, the Large Hadron Collider (LHC) at CERN, has entered into commissioning phase. It is expected that when this impressive machine will become fully operational, it will generate two counter rotating 7 TeV/c proton beams that will be made to collide, leading to an unprecedented luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Total energy stored in each LHC beam is about 362 MJ, sufficient to melt 500 kg copper. Safety of operation is a very critical issue when working with such extremely powerful beams. It is important to know the consequences of an accidental release of the beam energy in order to design protection system for the equipment. For this purpose we have carried out extensive numerical simulations of the interaction of one full LHC beam with copper and graphite targets which are materials of practical importance. Our calculations have shown that the LHC protons will penetrate up to about 35 m in solid copper and 10 m in solid graphite. A very interesting outcome of this work is that the impact of the LHC beam on solid matter will generate Warm Dense Matter (WDM) and Strongly Coupled Plasmas (SCP).

The beams for the LHC are pre-accelerated in the SPS (Super Proton Synchrotron) to 450 GeV/c and transferred to LHC via two beam lines. Several SPS cycles are required to fill the LHC, in one cycle a batch with up to 288 bunches can be accelerated. From the safety point of view it is also very important to study the damage caused to the equipment in case of an accident involving an uncontrolled release of the SPS beam. For this purpose we have also carried out detailed numerical simulations of the impact of the full SPS beam on solid copper and tungsten targets. These simulations have shown that the targets are severely damaged by the beam. It is also interesting to note that also in this case, a large part of the target material is converted into WDM and SCP. This study, therefore, shows that the LHC and the SPS have the potential to be used for studying these important fields of research. However, to achieve this goal, it is necessary to advance this work by designing dedicated experiments. This work is in progress.

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1 Introduction

The Large Hadron Collider (LHC) at CERN is the most sophisticated accelerator complex in the world. It is expected to generate two counter rotating, bunched beams of 7 TeV/c protons with each bunch comprised of 1.15×10^{11} particles. The total number of protons in each beam, therefore is about 3.2×10^{14} . Bunch length is 0.5 ns and separation between two neighboring bunches is 25 ns while the total length of the beam is about 89 μs . The transverse intensity profile in the beam is Gaussian with typically $\sigma = 0.2 \text{ mm}$ [1]. In the center of the experiments the beam size is about 10 times smaller. The total energy stored in each LHC beam is 362 MJ which is sufficient to melt 500 kg of copper. Special care is required during the operation with such powerful beams

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because any accidental release of even a very small fraction of the beam energy can cause considerable damage to the equipment.

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). 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 μ s. Although the energy stored in the batch is less than 1% of the LHC beam at 7 TeV, it is enough to cause considerable damage in case of failure. Protection must start during acceleration in the SPS and must be efficient at the moment of extraction from the SPS towards the LHC throughout the LHC cycle.

A worst case scenario for the LHC as well as the SPS is in which the entire beams of the two machines, respectively, are lost at a single point due to system failure. Fortunately the likelihood of such an accident to happen, is very remote. Nevertheless, one should know the consequences of an accident of this magnitude in order to design the necessary protection system. For this purpose, we have carried out extensive numerical simulations of the full impact of the LHC beam on solid copper and solid graphite cylindrical targets and that of the SPS beam on solid copper and solid tungsten cylinders, respectively. The particle energy loss in the target in both cases, is calculated using a well known fully integrated particle physics and multi-purpose MonteCarlo simulation package capable of simulating all components of the particle cascades in matter up to TeV energies, named, FLUKA [2, 3]. This data is used as input to a two-dimensional hydrodynamic computer code, BIG2 [4], to study the hydrodynamic and the thermodynamic response of the target. These simulations have shown that the target is severely damaged in both cases [5–11]. A very interesting and important outcome of this work has been that a large part of the target is converted into Warm Dense Matter (WDM) and Strongly Coupled Plasma (SCP) which suggests an additional application of the above two machines.

Another very important project that has been approved at CERN, is the **HiRadMat (High Radiation on Materials)** facility which will provide a test stand to carry out fixed target experiments to study the impact of the SPS beam on solid materials. 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 [12]. These experiments therefore will be very useful to validate our simulations [5–11] that have been done for the LHC and the SPS beams. In addition to that, other areas of research including material sciences and High Energy Density (HED) states in matter including WDM and SCP [13–15, 17–26, 33, 34] will also benefit from these experiments.

In this paper we present a brief overview of this work emphasizing the recent results. In Sec. 1 we discuss the simulations of interaction of the LHC beam with solid matter while similar calculations using the SPS beam, are presented in Sec. 3. Conclusions drawn from this work are noted in Sec. 4.

2 Target Simulations Using the LHC Beam

In this section we present numerical simulations of target heating by the LHC beam which have been carried out using a two-dimensional hydrodynamic computer code, BIG2 [4], which is based on a Godunov type scheme. The energy loss of the 7 TeV/c protons and of the shower is calculated using the FLUKA [2, 3] code and this data is used as input to the BIG2 code. Different physical states through which the target material passes during irradiation, are treated using a semi-empirical equation-of-state model described elsewhere [27, 28]. We considered respectively, solid copper and solid graphite as target material and the results are discussed below.

2.1 Solid Copper Target

2.1.1 Energy Loss Calculations

The target considered for the FLUKA calculations was a solid copper cylinder with a radius = 1 m, a length = 5 m that was facially irradiated by the LHC beam. The energy deposition was obtained using a realistic two-dimensional beam distribution, namely, a Gaussian beam (horizontal and vertical $\sigma_{rms} = 0.2$ mm). In Fig. 1, is

plotted the energy deposition in GeV per proton per unit volume. It is seen that a peak energy deposition of 1200 GeV/p/cm³ is obtained at a longitudinal position of 16 cm.

Fig. 1 Energy deposition per proton per unit volume in solid copper as a function of the depth into the target and the radial coordinate. (Online colour: www.cpp-journal.org).

In Fig. 2 we present the specific energy deposition by a single bunch along the axis ($r=0.0$) that shows a peak specific energy deposition of about 2.3 kJ/g at $l = 16$ cm. In Fig. 3, is plotted the specific energy deposition along the radial direction at four different positions along the axis, namely, 8, 16, 24 and 36 cm.

Fig. 2 Specific energy deposition along the axis ($r=0.0$) by one bunch with 1.15×10^{11} protons.

Fig. 3 Specific energy deposition by one bunch along the radial direction at four different points along the axis.

2.1.2 Hydrodynamic Simulations

In previous calculations [5,6], we used the FLUKA energy loss data presented in Figs. 2 and 3 as input to the hydrodynamic code, BIG2, and studied the hydrodynamic and the thermodynamic response of the target along the cross section at given positions along the cylinder axis. These simulations were very helpful in understanding the level of target heating, generation of high pressure, propagation of shock waves and the damage caused to the target by these effects. However, this model did have some limitations. For example, the specific energy deposited by a few tens of bunches generates very high pressure (few tens of GPa) that drives an outgoing radial shock wave which leads to a reduction in the density along the cylinder axis. As a consequence, the protons that are delivered in subsequent bunches penetrate deeper into the target, thereby leading to a substantial lengthening of the projectile range. This very important effect can not be seen in this model. Nevertheless, these simulations were very helpful in developing analytic estimates of the proton penetration depth and it was concluded that the LHC protons can penetrate between 10 – 40 m in solid copper, although Fig. 1 shows that the range of the 7 TeV/c protons in solid copper under static conditions is of the order of 1 m. It is therefore absolutely essential to take into consideration this important effect when designing a sacrificial beam stopper.

Fig. 4 Specific energy deposition along the axis (at $r=0.0$) at different times during irradiation; time interval between two consecutive lines is $1 \mu s$.

Fig. 5 Target temperature along the axis (at $r=0.0$) at different times during irradiation; time interval between two consecutive lines is $1 \mu s$.

Fig. 6 Target pressure along the axis (at $r=0.0$) at different times during irradiation; time interval between two consecutive lines is $1 \mu s$.

Fig. 7 Target density along the axis (at $r=0.0$) at different times during irradiation; time interval between two consecutive lines is $1 \mu s$.

Recently, we developed a more realistic model in which a solid copper cylindrical target is considered that has a radius = 5 cm and a length = 5 m that is facially irradiated by the LHC beam. In these simulations we consider the target in the $r - Z$ geometry. We note that the energy loss data presented in Figs. 1 – 3 is obtained assuming a solid target density. In practice, the material density in the beam heated region continuously decreases due to the onset of hydrodynamics that leads to a reduction in the energy loss in that region and deeper penetration of the projectiles into the target. It is difficult to obtain a quantitative dependence of energy loss on the density. However, to take care of these effects we normalize the specific energy deposition with respect to the line density along the axis in every simulation cell at every time step. This is a reasonable approximation and the results thus obtained have provided a very good insight into this problem. However, to get a fully quantitative picture of this problem, it is necessary to run the BIG2 and the FLUKA codes iteratively. This work is in progress.

We plot in FIG. 4 the specific energy deposition along the target axis (at $r = 0.0$) at different times during the irradiation. It is seen that at $t = 500$ ns, the maximum specific energy deposition, E_s is about 20 kJ/g and the peak lies at about $L = 16$ cm. The curve labeled with $t = 1500$ ns shows that the maximum value of E_s has increased to about 29 kJ/g and the position of the peak and the foot of the distribution have shifted towards the right. As the protons penetrate deeper and deeper into the target, the volume over which energy deposition occurs increases. It is seen that at $t = 8500$ ns, the energy deposition becomes uniform over a large part of the target and

has a value of about 25 kJ/g. This amount of the specific energy deposition is comparable to that which could be achieved [16, 17, 21–25] at a dedicated accelerator facility, like FAIR [12]. Therefore the level of specific energy deposition that is achieved by the LHC is sufficient to perform important experiments on HED physics studies.

Temperature profiles corresponding to FIG. 4 are plotted in FIG. 5. It is seen that the temperature shows behavior similar to the energy deposition. It is seen from curve labeled with 9 which is plotted at $t = 8500$ ns, that in a large part of the target, the temperature is very uniform and is of the order of 40000 K.

Pressure profiles along target axis at different times are plotted in FIG. 6. It is seen that at $t = 500$ ns, a maximum pressure of about 30 GPa is generated at the location of the peak in the energy deposition. The following curves show that the maxima of pressure continuously shifts towards the right because of the extension of the energy deposition range. However, the magnitude of the pressure peak decreases with time due to reduction in the target density in this region.

The corresponding density profiles are shown in FIG. 7. Curve 1 which is plotted at $t = 500$ ns shows that a minima in the density (about 4 g/cm^3) is generated at the axis at $L = 16$ cm, where the maxima of specific energy deposition and pressure occur. This is due to the fact that the radial shock wave is strongest at this position. As the protons penetrate deeper into the target in axial direction, a density depletion surface is seen moving towards the right. The depletion front moves with an average speed of $0.35 \text{ m}/\mu\text{s}$. This means that the LHC protons will penetrate up to 35 m in solid copper, which is quite close to our previous estimates [5]. This information is very important when designing a sacrificial beam stopper to be used in case of an uncontrolled loss of the beam.

2.2 Solid graphite Target

Graphite is also a very important material that is widely used in the construction of collimators, jaws and beam dump. In the following we present simulations of the full impact of the LHC beam in a solid graphite target that have been done employing the BIG2 code. The EOS data for graphite provided in [29], has been used in these calculations.

2.2.1 Energy Loss Calculations

Fig. 8 Energy deposition per proton per unit volume in solid graphite as a function of the depth into the target and the radial coordinate. (Online colour: www.cpp-journal.org).

For the fLUKA calculations we consider a solid graphite cylinder with a radius = 1 m and length = 5 m that is facially irradiated with the LHC beam which has a Gaussian intensity distribution with a horizontal and vertical $\sigma_{rms} = 0.2$ mm. Fig. 8 shows the energy loss by a single proton per unit volume as a function of depth into the target and the radial coordinate. It is seen that a peak deposition of about $30 \text{ GeV/proton/cm}^3$ is obtained at a longitudinal position of 1.5 m. This is a very different behavior from that for the solid copper (see Fig. 1). Moreover, the distribution of the energy is more spread out in case of graphite compared to that in copper. These huge differences in the two distributions are due to the marked difference in the densities of the two materials. The specific energy deposition by a single proton bunch along the axis and along the radial direction (at different longitudinal positions) are shown in Figs. 9 and 10, respectively. It is seen that the specific energy deposition is significantly lower in graphite compared to copper.

Fig. 9 Specific energy deposition along the axis ($r=0.0$) by one bunch with 1.15×10^{11} protons.

Fig. 10 Specific energy deposition by one bunch along the radial direction at four different points along the axis. (Online colour: www.cpp-journal.org).

2.2.2 Hydrodynamic Simulations

A cylindrical solid graphite target with a radius = 5 cm and a length = 10 m that is facially irradiated with the LHC beam, is considered for the hydrodynamic simulations done by the BIG2 code.

Fig. 11 Specific energy deposition profiles along the axis (at $r=0.0$) at different times during irradiation.

Fig. 12 Temperature profiles up to $5 \mu s$, along the axis (at $r=0.0$) at different times during irradiation.

Fig. 11 shows the specific energy deposition along the axis at intervals of $10 \mu s$. It is seen that the specific energy deposition increases with time and one achieves an average specific energy deposition of about 40 kJ/g in a large part of the target at the end of the pulse. It is also seen that the peak of the distribution and the point where the specific energy deposition goes to zero, continuously move towards the right in the longitudinal direction. This is a direct consequence of the lengthening of the proton range due to density reduction.

The corresponding temperature profiles are shown in Figs. 12 and 13. It is seen from Fig. 12 that the temperature increases to above 4000 K at $t = 3 \mu s$, but at $t = 5 \mu s$, the top of the curve becomes flat. This is because the target material enters into a two-phase liquid-gas region which limits the temperature increase. This is further seen in Fig. 13 where we plot the temperature profiles along the axis at later times. It is seen that at $t = 15 \mu s$ the two-phase region extends up to about 4 m in the longitudinal direction and a small hump appears just before $L = 2$ m which represents the fully gaseous state. Curves plotted at later times show that the position of the two-phase liquid-gas region continuously shifts towards the right and to the left of this region, more and more material becomes gaseous and the temperature in this region continues to increase as more and more energy is

deposited by the beam. At the end of the pulse, we achieve a maximum temperature of about 10000 K in the target and the protons penetrate the entire length of the target.

Fig. 13 Temperature profiles after $5 \mu\text{s}$, along the axis (at $r=0.0$) at different times during irradiation.

Fig. 14 Density profiles along the axis (at $r=0.0$) at different times during irradiation.

Figure 14 shows the corresponding density profiles that show substantial density decrease and propagation of the density depletion front towards the right during the beam irradiation. These simulations show that using this dynamic model, the 7 TeV/c LHC protons will penetrate about 10 m into solid graphite where the range of these protons in the solid target is about 3.5 m.

3 Target Simulations Using the SPS Beam

Fig. 15 Specific energy deposition by one SPS bunch (1.15×10^{11} protons) in solid tungsten along axis ($r=0.0$), for three different values of $\sigma = 0.088$ mm, 0.28 mm and 0.88 mm, respectively.

Fig. 16 Specific energy deposition by one SPS bunch (1.15×10^{11} protons) in solid tungsten along radius, for three different values of $\sigma = 0.088$ mm, 0.28 mm and 0.88 mm, respectively.

For the SPS beam we consider three different values of $\sigma = 0.088$, 0.28 and 0.88 mm, respectively. Other parameters are the same as noted in Sec. 1. Cylindrical targets made of copper and tungsten have been used in the study. In the present paper, we present the calculations for a tungsten target and calculations for a copper target can be found elsewhere [7, 9].

3.1 Energy Loss Calculations

A solid tungsten cylindrical target with radius = 1 m and a length = 1 m which is facially irradiated by the beam, has been considered for the energy loss calculations using the FLUKA code. This data is converted into specific energy deposition that is plotted in Figs. 15 and 16, for three different values of σ . In Fig. 15 we present the specific energy deposited by one proton bunch along the target axes ($r=0.0$). It is seen that the range of the protons and the shower in the longitudinal direction is about 50 cm. The maxima of the three curves lie at a longitudinal position of 6 cm into the target. The maximum value of the specific energy deposition for $\sigma = 0.088$, 0.28 and 0.88 mm is 400, 180 and 70 J/kg, respectively. The specific energy deposition in the target by one bunch in the radial direction at the longitudinal position of 6 cm is plotted in Fig. 16.

3.2 Hydrodynamic Simulations

For the hydrodynamic simulations we consider a solid tungsten cylinder with a radius = 5 cm and a length = 2 m which is facially irradiated by the SPS beam. In the following we present the simulation results that have been obtained using the BIG2 code.

In Fig. 17 we plot the specific energy deposition profiles in the target along the axis for the different values of σ at $t = 7.2 \mu\text{s}$ (end of the beam). It is seen that the specific energy deposition is comparable in all the three cases which is in strong contrast to our previous calculations [7,8] where the specific energy deposition was substantially higher for the smaller beam focal spot size. This difference due to the fact that in the latter calculations we considered a static model where the range lengthening was not included and all the bunches deposited their energy at one point. It is also seen that the beam with smaller focal spot penetrates much deeper into the target in the longitudinal direction.

Fig. 17 Profiles of specific energy deposition along target axis at $t = 7.2 \mu\text{s}$ for three different values of $\sigma = 0.088$, 0.28 and 0.88 mm. (Online colour: www.cpp-journal.org).

Fig. 18 Temperature profiles corresponding to Fig. 17. (Online colour: www.cpp-journal.org).

The corresponding temperature profiles are shown in Fig. 18. It is seen that a maximum temperature of 40000 K is generated in the case of $\sigma = 0.088$ mm. Moreover, it is seen that in all the three curves, there is a region of constant temperature on the right hand side that represents melting of the material. The pressure profiles are shown in Fig. 19 which show that at the end of the pulse, high pressure exists in the target.

In Fig. 20, are plotted the density profiles in the three cases. It is seen that the protons have penetrated up to 150 cm in the longitudinal direction at the end of the beam in case of $\sigma = 0.088$ mm and in the beam heated region the density has been reduced to about 2 % of the solid density. The penetration depth in case of $\sigma = 0.28$ mm and $\sigma = 0.88$ mm is 120 cm and 70 cm respectively. It is therefore concluded that the target will be severely damaged by the SPS beam. Moreover the density and the temperature values show that a large part of the target will be converted into a SCP.

In Fig.21 we plot the coupling parameter, gamma, for a tungsten plasma vs temperature for four different values of density, namely, 1 %, 5 %, 10 % and 20 % of the solid density. This data has been calculated using the code SAHA-IV code [30–32] which is specially designed for calculations of thermodynamic properties of

Fig. 19 Pressure profiles corresponding to Fig. 17. (Online colour: www.cpp-journal.org).

Fig. 20 Density profiles corresponding to Fig. 17. (Online colour: www.cpp-journal.org).

Fig. 21 Plasma coupling parameter vs temperature for different values of density in a tungsten plasma. (Online colour: www.cpp-journal.org).

multicomponent plasma with strong interparticle interactions. The calculational procedure is based on a chemical picture of the plasmas [30,31]. Coulomb interaction of charged particles, short range repulsion of atoms and ions at close distances, degeneracy of free electrons, stages of ionization up to 20 were taken into account. Further details can be found in [32]. The density and temperature range used in these calculations corresponds to that achieved in the hydrodynamic simulations. It is seen from Fig. 21 that one can generate a strongly coupled tungsten plasma with a coupling parameter on the order of 5. Similar results have been achieved for the LHC beam.

4 Conclusions

Extensive numerical simulations of the hydrodynamic and thermodynamic response of solid targets of different materials of interest that are irradiated by the LHC and the SPS beams, respectively, have been carried out using a two-dimensional hydrodynamic computer code, BIG2. The energy loss of the protons in the target has been calculated using the FLUKA code. The data generated by the FLUKA code has been used as input to the BIG2 code. This study has shown that the targets are severely damaged by the proton beams and a large part of the target is converted into a huge sample of HED matter with fairly uniform physical conditions. This work has suggested an additional very interesting application of the LHC and the SPS. However, further work is needed to design suitable experiments for this purpose and this work is in progress.

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