

Large Hadron Collider at CERN: Beams generating high-energy-density matterN. A. Tahir,¹ R. Schmidt,² A. Shutov,³ I. V. Lomonosov,³ A. R. Piriz,⁴ D. H. H. Hoffmann,⁵ C. Deutsch,⁶ and V. E. Fortov³¹*Gesellschaft für Schwerionenforschung, Planckstraße 1, 64291 Darmstadt, Germany*²*CERN-AB, 1211 Geneva 23, Switzerland*³*Institute of Problems of Chemical Physics, Russian Academy of Sciences, Institutskii pr. 18, 142432 Chernogolovka, Russia*⁴*E.T.S.I. Industriales, Universidad de Castilla-La Mancha, 13071 Ciudad Real, Spain*⁵*Institut für Kernphysik, Technische Universität Darmstadt, Schlossgartenstraße 9, 64289 Darmstadt, Germany*⁶*LPGP, Université Paris-Sud, Orsay, France*

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This paper presents numerical simulations that have been carried out to study the thermodynamic and hydrodynamic responses of a solid copper cylindrical target that is facially irradiated along the axis by one of the two Large Hadron Collider (LHC) 7 TeV/c proton beams. The energy deposition by protons in solid copper has been calculated using an established particle interaction and Monte Carlo code, FLUKA, which is capable of simulating all components of the particle cascades in matter, up to multi-TeV energies. These data have been used as input to a sophisticated two-dimensional hydrodynamic computer code BIG2 that has been employed to study this problem. The prime purpose of these investigations was to assess the damage caused to the equipment if the entire LHC beam is lost at a single place. The FLUKA calculations show that the energy of protons will be deposited in solid copper within about 1 m assuming constant material parameters. Nevertheless, our hydrodynamic simulations have shown that the energy deposition region will extend to a length of about 35 m over the beam duration. This is due to the fact that first few tens of bunches deposit sufficient energy that leads to high pressure that generates an outgoing radial shock wave. Shock propagation leads to continuous reduction in the density at the target center that allows the protons delivered in subsequent bunches to penetrate deeper and deeper into the target. This phenomenon has also been seen in case of heavy-ion heated targets [N. A. Tahir, A. Kozyreva, P. Spiller, D. H. H. Hoffmann, and A. Shutov, *Phys. Rev. E* **63**, 036407 (2001)]. This effect needs to be considered in the design of a sacrificial beam stopper. These simulations have also shown that the target is severely damaged and is converted into a huge sample of high-energy density (HED) matter. In fact, the inner part of the target is transformed into a strongly coupled plasma with fairly uniform physical conditions. This work, therefore, has suggested an additional very important application of the LHC, namely, studies of HED states in matter.

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I. INTRODUCTION

The start of commissioning with beam of the Large Hadron Collider (LHC) in September 2008 at CERN is very unique in the accelerator field. Novel experiments that will be carried out at this impressive machine will allow access to unexplored realms of several areas of basic and applied physics. When working at its full capacity, LHC is expected to generate two extremely powerful counter-rotating beams of 7 TeV/c protons, with an energy of about 360 MJ per beam which is sufficient to melt 500 kg of copper [1].

Ensuring safe operation of the machine with such powerful beams is an extremely important and challenging problem. Any uncontrolled release of the beam energy could cause serious damage to the equipment. A rapid loss of even 0.002% of the 7 TeV/c beam at one spot could already damage a high-Z material such as copper. A worst case scenario is the possibility of the full LHC beam being lost at one place. Although the probability of an accident of this magnitude is extremely small, nevertheless it is important to have full knowledge of the consequences if it ever happens. This information is essential in order to design the protection systems of the machine correctly, to set admissible risk levels, and to determine the inventory of the spare parts needed to possibly replace the damaged equipment.

Previously, we simulated the response of a solid copper cylindrical target that was facially impacted by the full LHC

beam [2] along the axis. These simulations were done using a two-dimensional hydrodynamic computer code, BIG2 [3]. The energy deposition by the 7 TeV/c protons in copper was calculated employing the FLUKA code [4,5] and these data were used as input to the BIG2 code. In these simulations we studied the target behavior along the cross section at a fixed point on the axis ($L=16$ cm), where the maximum energy deposition occurs. This study showed that the high pressure produced in the deposition region after energy deposition by only 100 proton bunches generated a radially outgoing shock wave that led to a substantial reduction in density at the center. In practice, the protons that will be delivered in subsequent bunches will penetrate much deeper into the target. However, due to the limitations of the model used in the previous calculations, this effect could not be simulated. The penetration depth of 7 TeV/c protons in solid copper was calculated using analytical estimates based on the simulations. It was predicted that the LHC protons can penetrate between 10 and 40 m in solid copper. A very interesting and important outcome of this study was that the target was converted into a sample of high-energy density (HED) matter, which could be an additional very important application of the LHC [6].

In the present study, we consider a 5-m-long solid copper cylinder which has a radius of 5 cm that is facially irradiated with one LHC beam. The simulations have been carried out in the length-radius plane assuming axial symmetry. The en-

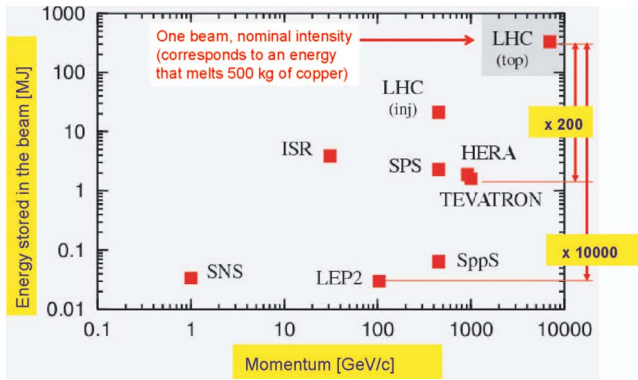


FIG. 1. (Color online) Energy stored in the beams of different accelerators as a function of the particle momentum.

ergy deposition in the target material is normalized with the line density along the axis. This allows us to simulate deeper penetration of the protons into the target due to the density reduction. These simulations show that the penetration front will move with an average speed of about $0.35 \text{ m}/\mu\text{s}$ which means that the protons will penetrate up to about 35 m in solid copper. This study has also shown that a large central part of the target will be in a strongly coupled plasma state with fairly uniform physical conditions. In Sec. II we describe some of the special features of the LHC and its beam parameters. The problem of energy deposition by energetic protons is discussed in Sec. III and the hydrodynamic simulation results are given in Sec. IV. Further discussion of the results is presented in Sec. V and the conclusions drawn from this work are noted in Sec. VI.

II. LARGE HADRON COLLIDER AT CERN

The motivation to construct the LHC at CERN comes from fundamental questions of particle physics. The LHC has been installed in a tunnel with a circumference of 26.8 km that was previously used for the Large Electron Positron (LEP) Collider. Two counter-rotating proton beams will circulate in separate beam pipes and will be accelerated to particle energies of 7 TeV. The protons in the two beams will then be made to collide at a center-of-mass energy of 14 TeV. In order to achieve the required collision rate, each beam will consist of a bunch train with each bunch consisting of 1.15×10^{11} protons. The total number of bunches in each beam will be 2808, so that the total number of protons per beam will be about 3×10^{14} . The bunch length will be 0.5 ns and two neighboring bunches will be separated by 25 ns while intensity distribution in radial direction will be Gaussian with a standard deviation, $\sigma=0.2 \text{ mm}$. In the center of the physics detectors the beam will be focused to a much smaller size, down to a σ of $20 \mu\text{m}$. The total duration of the beam is on the order of $89 \mu\text{s}$.

The LHC enters into a new domain. In particular the energy stored in each beam is larger by about 2 orders of magnitude with respect to other hadron machines, such as Super Proton Synchrotron (SPS), Hadron Electron Collider Anlage (HERA), TEVATRON, or Relativistic Heavy Ion Collider (RHIC) as shown in Fig. 1. Handling beam with such huge

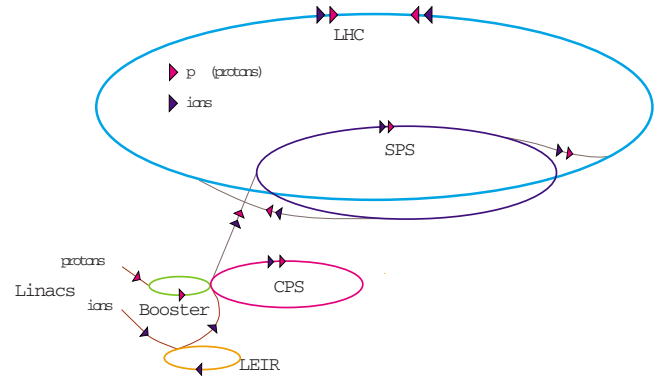


FIG. 2. (Color online) Large Hadron Collider injector complex, with the SPS as preinjector, and the CERN Proton Synchrotron (CPS) complex to prepare the beams for injection into the SPS.

energy will be a significant challenge. Machine protection becomes vital, in particular in the presence of superconducting magnets that quench in case of beam losses on the order of a few mJ.

The beam is prepared at the CERN injector complex that comprises several accelerators, linacs, booster, Proton Synchrotron (PS), and finally the SPS, as shown in Fig. 2. In the SPS the beam is accelerated to the LHC injection energy of 450 GeV and then transferred via about 3-km-long transfer lines. One beam pulse from the SPS includes up to 288 bunches; therefore, filling LHC requires about 10 SPS cycles for each beam.

After a lengthy period of commissioning of all technical systems, beam operation started in September 2008. Initial beam commissioning went quite smoothly and after only a few days, one of the two beams could be stored with a lifetime of several hours. During the tests, one bunch was injected with an intensity of up to 5×10^9 protons.

Due to an incident during the tests of the powering system preparing for a run at 5 TeV, the machine had to be switched off 10 days later for repair in one of the eight sectors and beam operation will restart in 2009. However, it will take time until nominal beam parameters will be achieved.

For each of the two LHC beams there is a beam dumping system that extracts the beam after nominal operation as well as in the case of equipment failure. The extracted beam is transferred through a 700-m-long beam line to a graphite beam dump block. The extraction is fast and all bunches are extracted within one turn. Along the beam dump line the beam size increases. The particle density is further reduced using two pulsed magnets that deflect each bunch differently to reduce the energy density to an acceptable level. The beam dumping system is one of the important safety systems required during the LHC operation. During the initial beam tests the machine protection systems interlocks and the beam dumping system performed as expected.

III. ENERGY DEPOSITION BY PROTONS IN MATTER

Relativistic protons impinging on the studied sample material produce particle cascades which deposit their energy in matter that leads to an increase in the temperature. The en-

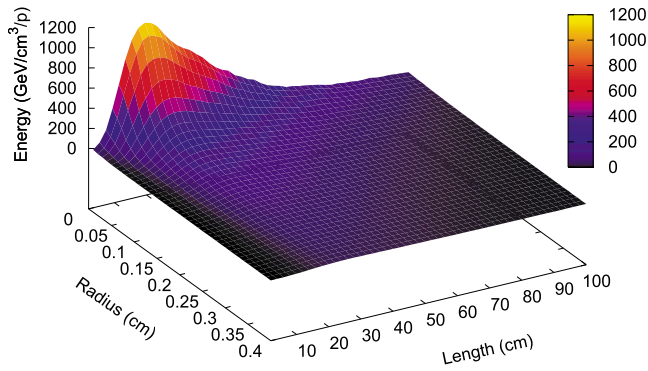


FIG. 3. (Color online) Energy deposition in a solid copper cylinder by a single 7 TeV proton per unit volume.

ergy deposited by the 7 TeV/c LHC protons in a solid copper cylinder has been calculated using the FLUKA code [4,5]. This is a fully integrated particle physics and multipurpose Monte Carlo simulation package capable of simulating all components of the particle cascades in matter up to multi-TeV energies. Further details can be found elsewhere [4,5].

For the study presented in this paper, the geometry for the FLUKA calculations was a cylinder of solid copper with radius=1 m and length=5 m. The energy deposition is obtained using a realistic two-dimensional beam distribution, namely, a Gaussian beam (horizontal and vertical $\sigma_{\text{rms}}=0.2$ mm) that was incident perpendicular to the front face of the cylinder.

In Fig. 3 we present energy deposition in GeV per proton per unit volume in solid copper as a function of the depth into the target and the radial coordinate. These data are converted into specific energy deposition, in kJ/g, which is deposited in the target to study heating and hydrodynamic expansion of the material using a two-dimensional code, BIG2 [3].

In Fig. 4(a) we present specific energy deposition profile of one bunch (1.15×10^{11} protons) in axial direction (at $r=0.0$) corresponding to the data plotted in Fig. 3. It is seen that a peak of energy deposition occurs at about 16 cm and the deposited energy is a factor 1250 higher than that at about 1.5 m. Energy deposition profiles along the transverse direction at four different points along the length, namely, 8, 16, 24, and 36 cm are plotted in Fig. 4(b).

IV. HYDRODYNAMIC SIMULATION RESULTS

In this section we present simulation results of hydrodynamic and thermodynamic responses of a solid copper cylindrical target that is facially irradiated along the axis with one of the LHC beams. The LHC beam parameters are described in Sec. II while the cylinder has a length=5 m and a radius=5 cm. These simulations have been carried out using a two-dimensional hydrodynamic code BIG2 [3] that is based on a Godunov-type scheme. The energy deposition data generated by the FLUKA code, which is presented in the previous section, are used as input to the BIG2 code. This code can handle complicated multilayered targets and different phases of matter are simulated using a well-known sophisticated

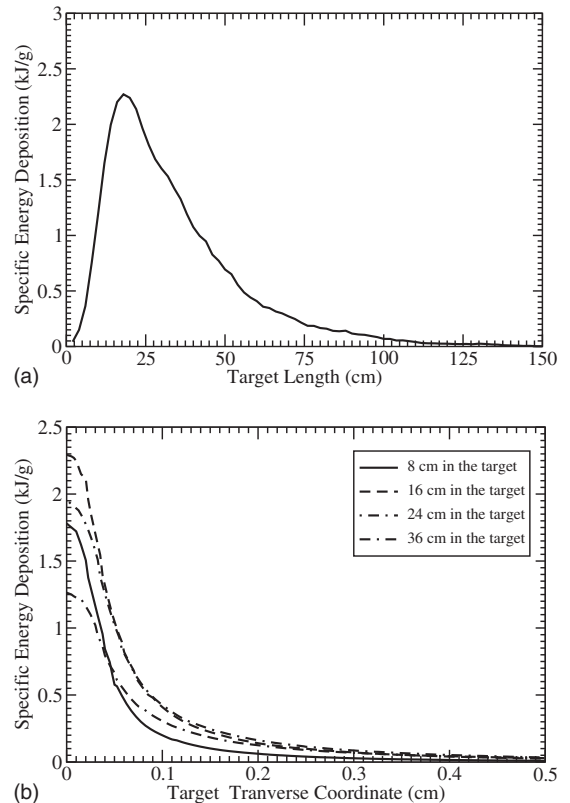


FIG. 4. Specific energy deposited by one LHC bunch in a solid copper cylinder: (a) along the axis ($r=0.0$ at $t=1$ ns) and (b) along the transverse coordinate at different longitudinal positions ($L=8, 16, 24,$ and 36 cm at $t=1$ ns).

semiempirical equation-of-state (EOS) model [7–9].

Figures 5(a)–5(c) show the specific energy deposition in the target on a length-radius plane at three different times, namely, 500, 4500, and 9500 ns, respectively. Since the energy deposition is localized, we show only the inner 2 cm radius of the target. It is seen in Fig. 5(a) that, when only 20 out of 2808 proton bunches have been delivered, a maximum specific energy deposition of 19 kJ/g is deposited in the target.

The target temperature and pressure corresponding to Figs. 5(a)–5(c) are shown in Figs. 6(a)–6(c) and Figs. 7(a)–7(c), respectively. It is seen in Fig. 6(a) that at $t=500$ ns, a maximum temperature of 3.47×10^4 K is achieved that generates a maximum pressure of about 29 GPa [see Fig. 7(a)]. This high pressure launches an outgoing radial shock wave that leads to a reduction in the density at the target center, as shown in Fig. 8(a). The density at the axis by this time has been reduced by a factor of 2 compared to the solid copper density.

Due to the continuous reduction in the density along the target axis, the protons that are delivered in subsequent bunches penetrate further and further into the target. This so-called “tunneling effect” leads to a substantial increase in the range of the projectile particles. In the present simulations, this effect has been taken into account by normalizing the specific energy deposition with respect to the line density along the target axis.

Figure 5(b) is plotted at a time when about 180 out of 2808 bunches have been delivered. It is seen that the maxi-

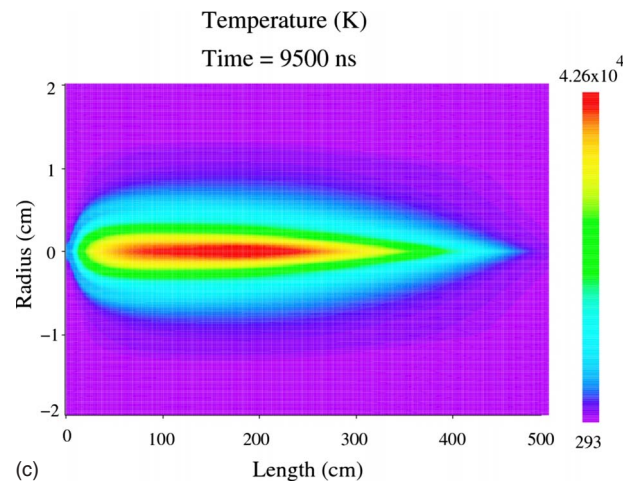
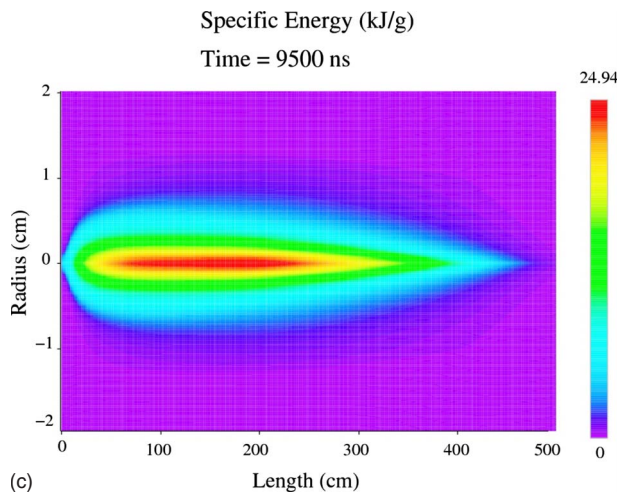
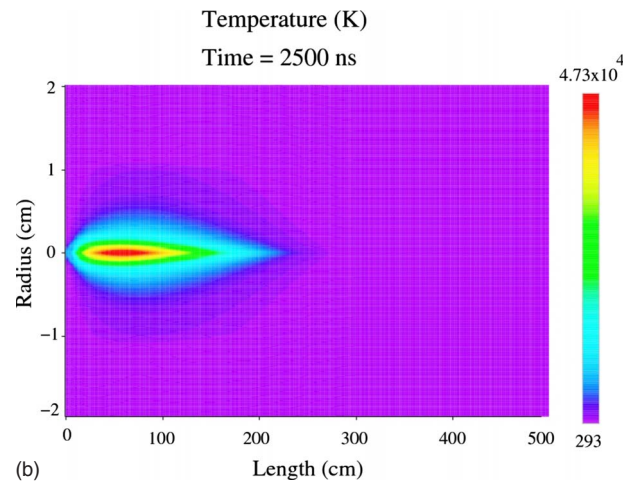
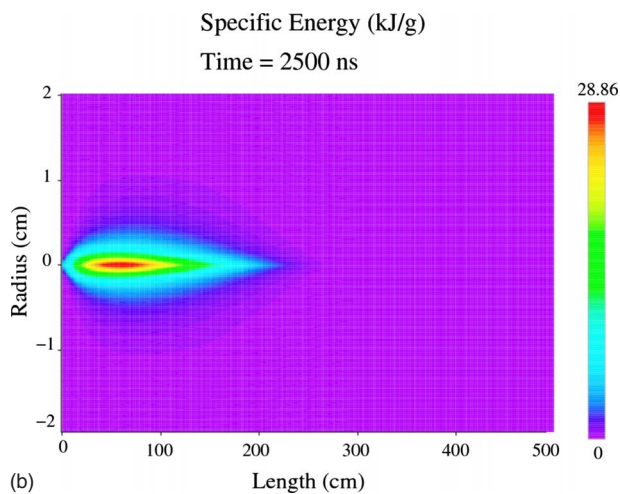
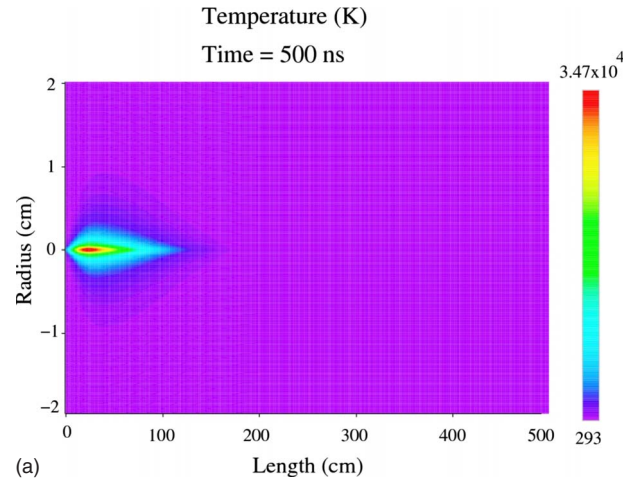
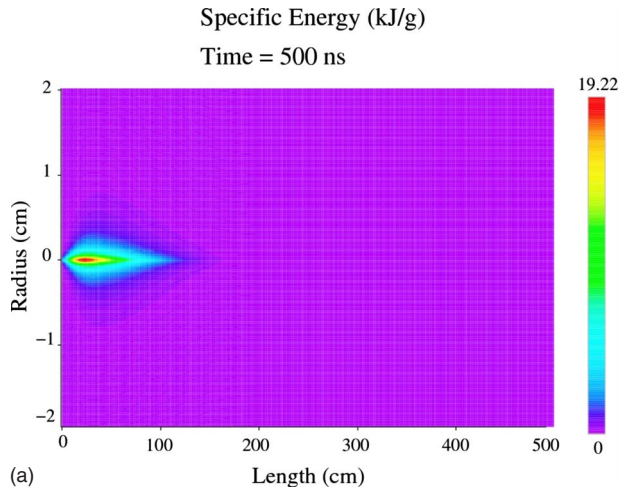
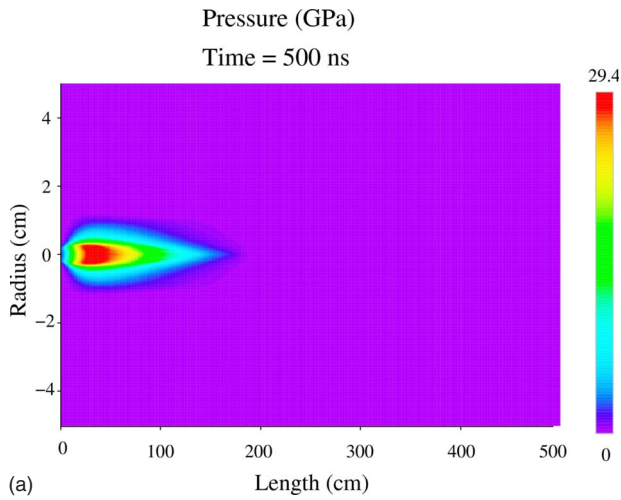


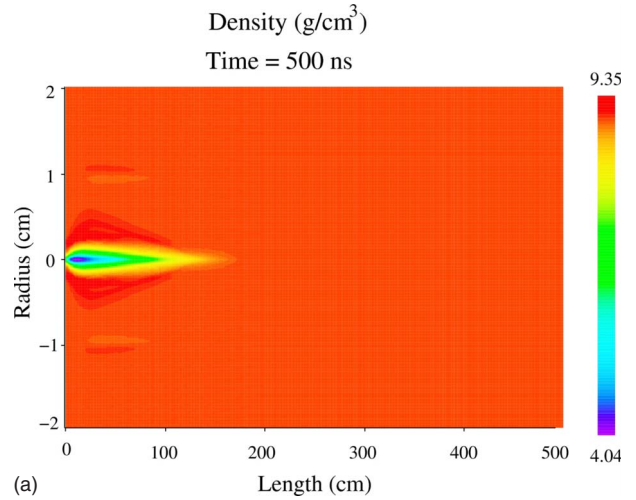
FIG. 5. (Color online) Specific energy deposition by one LHC beam in a solid copper cylinder with length=5 m and radius=5 cm; each bunch consists of 1.15×10^{11} 7 TeV/c protons, bunch length=0.5 ns, two neighboring bunches are separated by 25 ns, and transverse intensity distribution is Gaussian with $\sigma=0.2$ mm; energy deposition is a localized phenomenon so only the inner 2 cm radius of the target is shown (maxima lie at the center): (a) at $t=500$ ns (about 20 out of 2808 bunches delivered), (b) at $t=4500$ ns (about 180 out of 2808 bunches delivered), and (c) at $t=9500$ ns (about 380 out of 2808 bunches delivered).

FIG. 6. (Color online) Target temperature corresponding to Fig. 5 (maxima lie at the center).

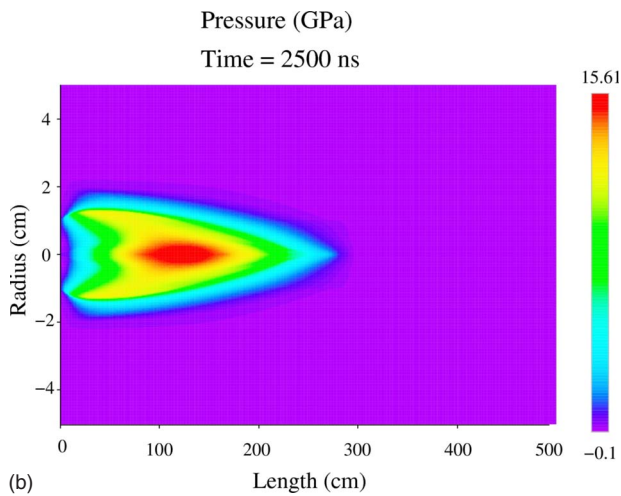
imum specific energy deposition is 27.7 kJ/g. A comparison between Figs. 5(a) and 5(b) shows that the maximum value of the specific energy deposition does not increase linearly with the number of bunches. This is a direct consequence of the tunneling effect as the energy is successively distributed over larger volumes. This is clearly seen in Fig. 5(b) where the deposition region extends to $L=3$ m compared to about 1 m in Fig. 5(a). The target temperature at $t=4500$ ns is



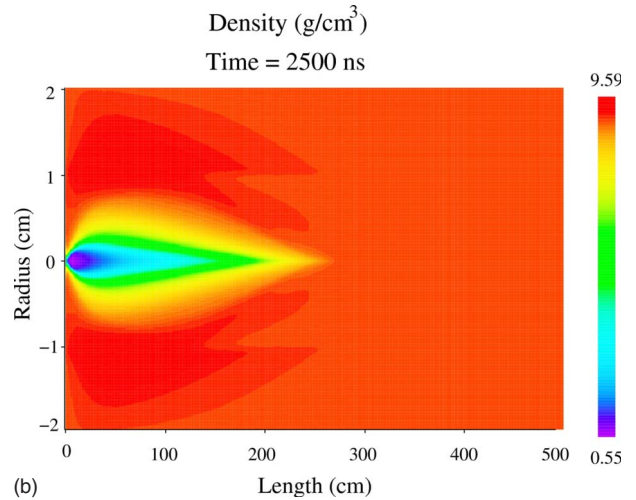
(a)



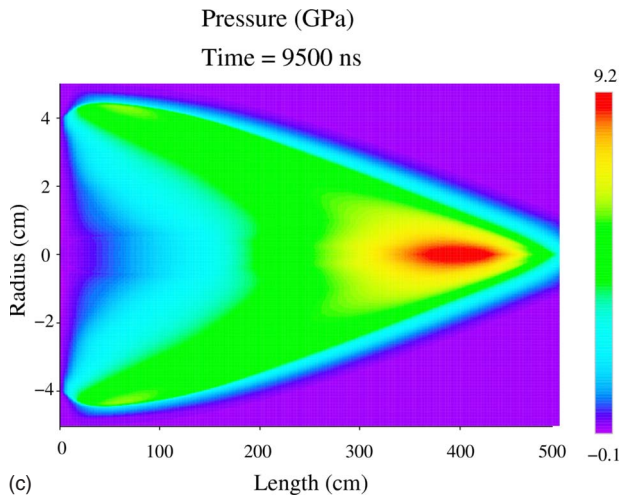
(a)



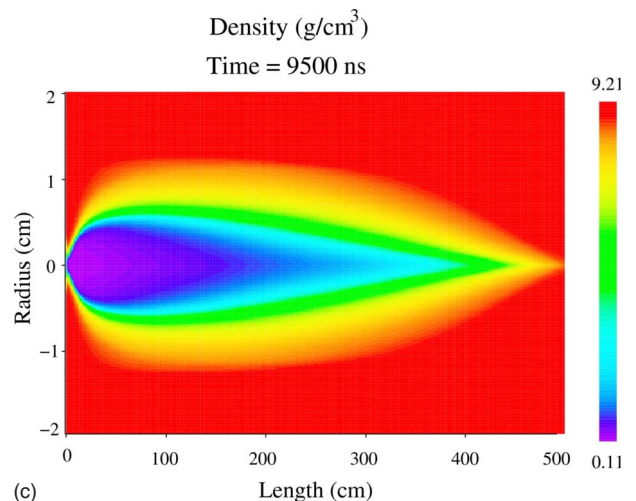
(b)



(b)



(c)



(c)

FIG. 7. (Color online) Target pressure corresponding to Fig. 5; since shock propagates from the beam heated region into the surrounding part of the target, we show the full 5 cm radius of the cylinder (maxima lie at the center).

FIG. 8. (Color online) Target density corresponding to Fig. 5 (minima lie at the center).

shown in Fig. 6(b). It is seen that the maximum temperature is now 4.6×10^4 K and a larger volume of the target has been heated as compared to that shown in Fig. 6(a). The corresponding pressure in the target is presented in Fig. 7(b)

which clearly shows propagation of the shock wave in the radial direction. It is to be noted that due to the cylindrical geometry, the maximum pressure has now decreased to 12.2 GPa. Figure 8(b) shows a strong reduction in the density at the target center in the beam heated region (0.25 g/cm^3)

compared to the solid density of 8.93 g/cm^3 . It is also seen that, in the shock compressed region, there is a slight increase in the density due to compression.

Figure 5(c) is plotted at a time when about 380 out of 2808 bunches have deposited their energy. It appears that the specific energy deposition has reached an equilibrium value of about 25 kJ/g while the deposition region now extends over the entire length of 5 m . It is also seen in Fig. 6(c) that an equilibrium temperature on the order of $40\,000 \text{ K}$ is achieved in the beam heated region, while the temperature distribution in the target follows the same behavior as the specific energy deposition.

The pressure, on the other hand, displays a very different pattern at later times as shown in Fig. 7(c). It is seen that the pressure has increased significantly over the large part of the target in radial direction due to the propagation of the shock wave.

The density at $t=9500 \text{ ns}$ is plotted in Fig. 8(c) showing that the protons have now penetrated through the entire length (5 m) of the target and there is a large volume of the target where the density is extremely low.

To show the variation in physical parameters in the target quantitatively, we plot in Fig. 9(a) the specific energy deposition along the axis (at $r=0.0$) at different times. It is seen that at $t=500 \text{ ns}$, the maximum specific energy deposition E_s is about 20 kJ/g and the peak lies at about $L=16 \text{ cm}$. The curve labeled with $t=1500 \text{ ns}$ 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 toward 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 $t=8500 \text{ ns}$, 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 [10–15] at a dedicated accelerator facility, such as Facility for Antiprotons and Ion Research (FAIR) [16] at Darmstadt. Therefore the level of specific energy deposition that is achieved in a target that is heated by the LHC beam is sufficient to perform important experiments on HED physics. Temperature profiles corresponding to Fig. 9(a) are plotted in Fig. 9(b) showing a behavior similar to that of the specific energy deposition.

Pressure profiles along target axis at different times are plotted in Fig. 10(a). It is seen that at $t=500 \text{ ns}$, 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 shift toward 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. 10(b). Curve 1 which is plotted at $t=500 \text{ ns}$ shows that a minima in the density (about 4 g/cm^3) is generated on the axis at $L=16 \text{ cm}$, 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 curve is seen moving toward the right.

It is seen in Fig. 4 that according to the FLUKA code, the

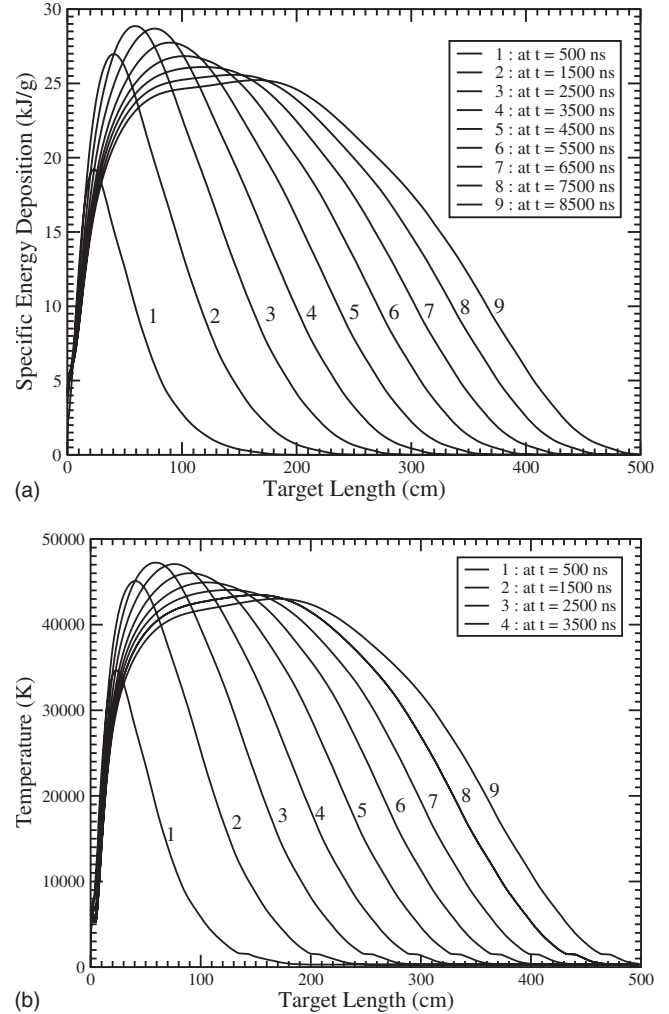


FIG. 9. (a) Specific energy deposition and (b) temperature, along the axis (at $r=0.0$) at different times during irradiation; the time interval between two consecutive lines is $1 \mu\text{s}$.

energy deposition range in a static model is about 1.25 m . Our hydrodynamic simulations show that at $t=1 \mu\text{s}$, the density has decreased significantly at the target center to up to $L=2 \text{ m}$. The density depletion surface moves to a position $L=5 \text{ m}$ at $t=8.5 \mu\text{s}$. 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. This information is very important when designing a sacrificial beam stopper to be used in case of an uncontrolled loss of the beam.

It is also seen that the inner beam heated part of the target is converted into a sample of HED matter with fairly uniform physical conditions. This work has suggested that LHC can also be used as a tool to study HED states in matter, which is an additional very important application of this impressive machine. To further illustrate this point, we show in Fig. 11 the physical state of the target at $t=9500 \text{ ns}$. It is seen that a plasma state exists up to 3 m length of the cylinder that is surrounded by a compressed hot liquid region.

Figure 12 shows a three-dimensional pressure-temperature-volume equation-of-state surface of copper based on the semiempirical model described in [7–9]. This

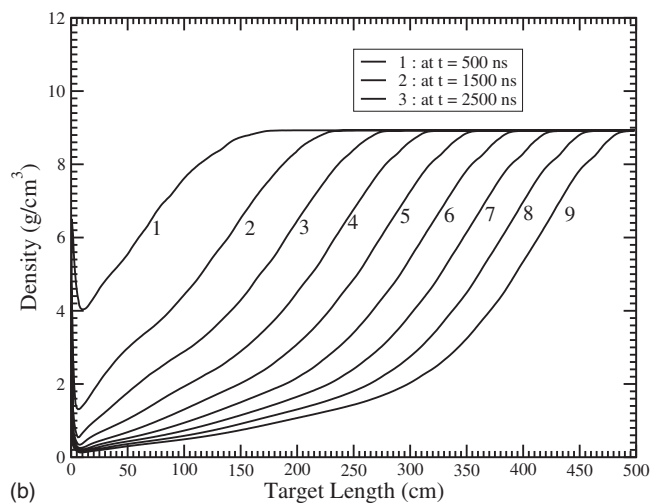
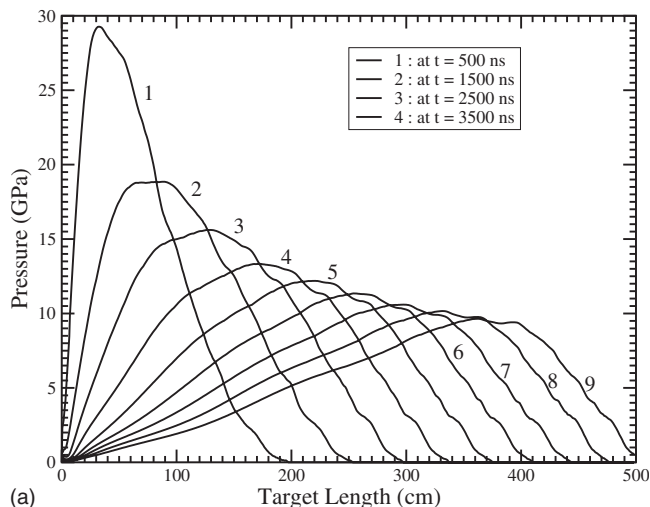


FIG. 10. (a) Pressure and (b) density, along the axis (at $r=0.0$) at different times during irradiation; the time interval between two consecutive lines is $1 \mu\text{s}$.

includes all the experimental data obtained using different experimental techniques noted in the figure caption. The thermodynamic path of the target material in the beam heated region corresponding to the parameters plotted in Figs. 9 and 10 is also shown in Fig. 12. It is seen that one can access the very interesting but unexplored strongly coupled plasma state using the LHC beam.

V. FURTHER ANALYSIS OF THE RESULTS

In Fig. 4(a) is plotted the specific energy deposited by one bunch along the axis which shows that the maxima lie at $L = 16$ cm. Figure 4(b), on the other hand, shows the same parameter along radius at four different positions on the axis, namely, $L=8, 16, 24,$ and 36 cm, respectively. In the previous work [2,6], we studied the problem in the target cross section and carried out separate simulations at these four points on the axis, using the respective radial specific energy deposition profiles as input to the BIG2 code. These calculations were very useful as they demonstrated the target heating by the LHC beam and propagation of the shock in the

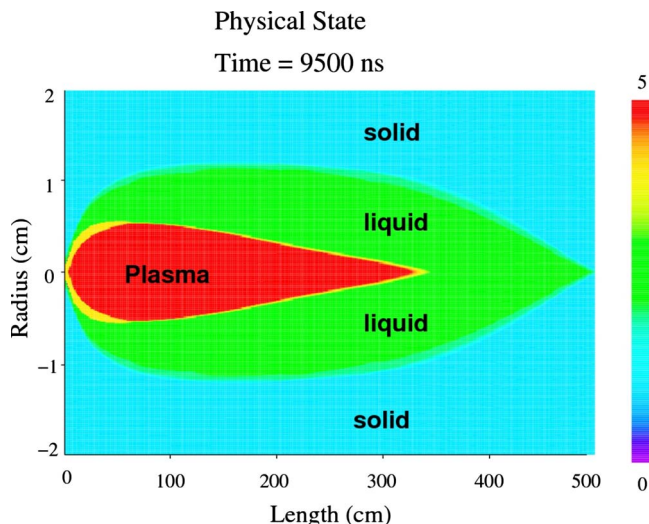


FIG. 11. (Color online) Physical state of the target at $t = 9500$ ns.

radial direction leading to strong reduction in density at the target center. This decrease in density as a function of time allowed us to estimate the penetration depth of the protons in the target that was between 10 and 40 m, although in this model, we could not simulate the proton tunneling effect directly. It was also found that the target will be heated to a few eV and the material will be converted into a sample of HED matter by first 100 bunches.

In the present study we consider the target in length-radius geometry assuming axial symmetry. The energy loss

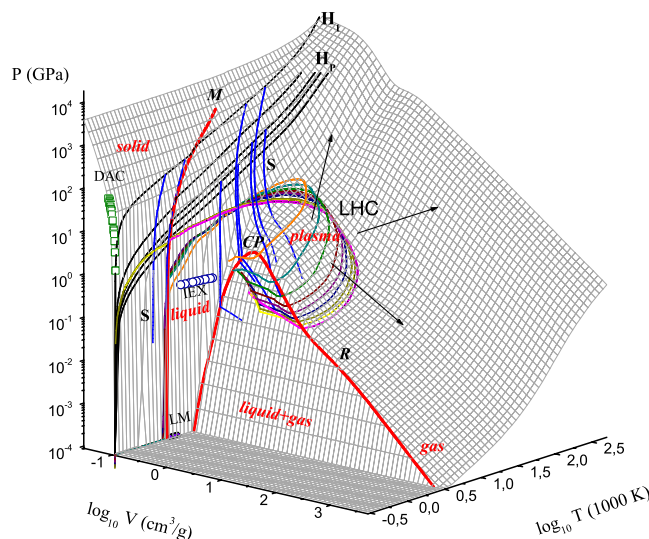


FIG. 12. (Color online) Three-dimensional (3D) pressure-volume-temperature surface for copper. M, melting region; R, evaporating region with the critical point, CP; solid, liquid, gas, liquid+gas, and plasma (arrows indicate the decrease in plasma nonideality parameter), physical states; H_1 and H_p , principal and porous Hugoniot; S, release isentropes of shock-compressed metal; IEX, isobaric expansion (“exploding wires”) data; DAC, static compression in diamond anvil cells; LM, density of liquid metal at room pressure; and LHC, states generated in copper by the LHC beam covering strongly coupled plasma region.

data shown in Fig. 3 are coupled to the BIG2 code in tabular form. The specific energy deposition in the target is normalized with respect to the line density along the axis at every time step. This allows one to simulate the deeper penetration of the protons as a result of density reduction caused by the radial shock wave. It has been found that the penetration occurs at an average speed of about $0.35 \text{ m}/\mu\text{s}$ that means that the protons will penetrate about 35 m during the pulse time of $89 \mu\text{s}$. As the protons penetrate into the target, a fairly uniform specific energy density distribution is generated along the target length which is about 25 kJ/g . This leads to a temperature of $40\,000 \text{ K}$ and the target in this region is in a strongly coupled plasma state. Such huge samples generated by the LHC beam can be used to study HED states in matter.

It is to be noted that in the present calculations, we use the energy deposition data calculated by the FLUKA code assuming solid copper density. However, our simulations show that the target density changes significantly in the beam heated region even after a few tens of the proton bunches are delivered. This density reduction has two effects on the protons that are delivered in subsequent bunches. First, the rate of production of the secondary particles (shower) in this low-density part is significantly decreased that leads to a substantial reduction in the energy deposition in that region. Second, the protons penetrate further and further into the target that leads to a much longer range of the protons compared to that under static conditions. In the present model, although we use the FLUKA energy loss data calculated assuming a solid target density, we normalize the specific energy deposition in each simulation cell at each time step according to the line density (ρR) along the target axis. To a reasonably good approximation this compensates for the reduction in energy deposition that should be caused due to decrease in the density. This model also allows one to study the deeper penetration of the protons into the target. The simulations that we carried out using this model have provided a very good physical insight into this problem. Nevertheless, to obtain

full quantitative information, it is necessary to couple the FLUKA code with the BIG2 code and this work is in progress.

VI. CONCLUSIONS

Numerical simulations of interaction of one LHC beam with a copper cylindrical target have been carried out. These calculations have been performed in two steps. In the first step, energy deposition by the LHC protons and the shower in the target is calculated using the FLUKA code [4,5]. In the second step, these data are used as input to a two-dimensional hydrodynamic code, BIG2 [3]. A full self-consistent treatment of this problem requires coupling of the FLUKA code with the BIG2 code. This work is currently in progress. The energy deposited by first few tens of bunches generates a very high pressure along the axis that launches a radial shock wave outward. This leads to depletion in the density at the central part of the target and the protons that are delivered in later bunches therefore penetrate deeper into the target. This effect was observed before in case of ion beam heated targets [17]. The density reduction in the beam heated region and the deeper penetration of the protons continues within the pulse duration. This so-called tunneling effect has important implications on the consequences of an accidental beam loss as well as for the design of a sacrificial beam stopper. In our study we simulate this effect by normalizing the specific energy deposition in the target with respect to the line density along the axis at every time step. Our simulations show that the protons will penetrate up to about 35 m in solid copper.

It is also interesting to note that the target is severely damaged by the beam and a huge sample of HED matter is generated. Due to the importance of this subject to numerous areas of basic and applied physics and due to its great potential for very useful industrial applications, HED physics has been a very active field of research over the past decades. Our work has shown that the LHC could be an additional tool to research this important branch of science.

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