Necessity of bunch compression for heavy-ion-induced hydrodynamics and studies of beam fragmentation in solid targets at a proposed synchrotron facility

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This paper presents two-dimensional numerical simulations of hydrodynamic response of a solid lead cylindrical target that is irradiated by an intense uranium beam having a particle energy of 1 GeV/u and that consists of 10^{12} particles. Different time profiles have been considered for the beam power that include a case where the beam consists of five identical parabolic bunches with equal separation between neighboring bunches as well as a beam that consists of a single bunch. For the single bunch case we consider two different values for pulse length, namely, 1000 and 50 ns, respectively. Moreover we allow for two different values for the beam radius that is 0.5 and 1.0 mm, respectively. These calculations show that in order to achieve a high degree of beam-target coupling, it is absolutely essential to use a single bunched beam that has a reasonably short pulse length, which is 50 ns in this case. Such a large beam-target coupling efficiency is highly desirable for creating high-density strongly coupled plasmas as well as for studies that involve fragmentation of the projectile ions as the beam passes through solid matter. If the pulse length is assumed to be too long, substantial hydrodynamic expansion of the target material occurs during the early stages of irradiation that leads to significant reduction in the energy deposition by the ions that are delivered in the later part of the pulse. In case of the five-bunch configuration, heating caused by the first bunch is so strong that the target is completely distorted. As a result, the ions that are delivered in the later four bunches pass through the target without any interaction.

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I. INTRODUCTION

The Gesellschaft für Schwerionenforschung (GSI), Darmstadt is a unique laboratory that has a synchrotron (SIS-18) facility that delivers intense beams of energetic heavy ions. The SIS-18 facility has a magnetic rigidity of 18 Tm. Currently, this facility is being upgraded by introduction of a powerful rf buncher and a new high-current injector that is based on a radio frequency quadrupole and an interdigital H-mode structure [1–3]. The high-current injector has already become operational and has so far provided about 3×10^{10} particles of 300 MeV/u argon and about 10^9 particles of 200 MeV/u uranium in separate operations. The pulse length at present is about 300 ns that will be reduced to 50 ns when the buncher will become operational. The beam intensity of the SIS-18 is expected to increase steadily due to further optimization of the accelerator parameters and the total number of 200 MeV/u uranium particles is expected to increase to 2×10^{11}. This upgrade will be completed by the end of the year 2001, which will open up the possibility of creating high-energy-density matter at the GSI Darmstadt. Such samples of matter will be used to investigate the equation-of-state properties of matter under such extreme conditions.

Employing a two-dimensional hydrodynamic simulation model, BIG-2 [4] and using the upgraded SIS-18 beam parameters, we previously provided optimized designs for a number of beam-matter interaction experiments that will be carried out at this facility by the end of the year 2001. These studies involve simulation of hydrodynamic and thermodynamic response of ''subrange'' [5] as well as ''super-range'' [6] solid lead cylinders that are irradiated with the future SIS-18 beam. In the former type of targets, the target length is smaller than the ion range so that the Bragg peak does not lie inside the target. This leads to an almost uniform energy deposition along the particle trajectory, which results in uniform heating of the deposition region. This in turn generates a uniform pressure profile and the problem can be approximated to that of a one-dimensional shock propagation along the radial direction and one can simulate such an experiment by using a one-dimensional model like MEDUSA-KAT [7].

In the second type of targets, on the other hand, the target length is considered to be larger than the ion range. The Bragg peak then lies inside the target that leads to a nonuniform energy deposition along the beam trajectory. This nonuniform energy deposition generates a nonuniform pressure profile in the deposition region. In this case one requires at least a two-dimensional simulation model and we have used the BIG-2 [4] code to design this type of experiments.

We have also studied interaction of an ion beam having an annular (ring shaped) focal spot with a solid as well as a hollow lead cylinder [8]. Moreover, we designed an experiment that will be carried out to study if metallization of hydrogen may be achieved by imploding a multilayered cylindrical target that contains a layer of frozen hydrogen [9].

GSI is also discussing to extend its accelerator facilities by introduction of a synchrotron ring (SIS-200) that has a much higher magnetic rigidity of 200 Tm. According to the initial design considerations, this facility will provide a uranium beam having at least 10^{12} ions with a particle energy of 1 GeV/u. There are two possibilities under consideration for the time profile of the beam power. One is to generate a beam consisting of a series of five identical bunches while the second is to use a single-bunch beam. Another question is whether one can live with a long pulse having a duration τ of the order of hundreds of nanoseconds or strong bunch compression is essential that would reduce τ to about 50 ns. These questions are of great importance if one is interested to create high-density plasmas using heavy ion beams as well as if one wishes to study the fragmentation of heavy ions while passing through solid matter. For either of these experiments, a very high degree of beam-target coupling is required that demands that there is no significant hydrodynamic expansion during the irradiation. Otherwise the target density becomes too low to interact with the incoming projectile ions that leads to a reduction in the absorbed energy as well as a reduction in the fragmentation cross section. A reduction in the absorbed energy makes the plasma physics experiments inefficient while a reduction in fragmentation rate would effect the latter type of experiment. A natural consequence of the decrease in level of beam-target coupling is that the energy of the particles in the secondary beam (beam that escapes the target after interaction) increases with time. The fragment separator can tolerate an energy variation of a few percent. If this variation is too large, the secondary beam will no longer be directed toward the fragment separator, but will be completely lost.

Moreover, the resolving power of the fragment separator is given in first order by

$$R=\frac{(X,P)}{2r_b(X,X)}, \tag{1}$$

where (X,X) and (X,P) are the elements of the transfer matrix and describe the final dispersion and the magnification of the system, and r_b is the initial beam spot radius at the target. Therefore, in order to achieve a good resolving power, the focal spot radius on the target should be as small as possible. In addition, a small beam radius is necessary to restrict the transverse emittance growth due to scattering suffered by the beam in the target.

Our simulations show that in case of the five-bunch beam, the hydrodynamic expansion due to the heating caused by the first bunch is so strong that the particles in the remaining four bunches pass through the target without any significant interaction. In this case, each bunch has a duration of 140 ns and a bunch separation of 140 ns as well, so that the total pulse length is 1260 ns. This configuration therefore is not very useful.

We also considered a beam that consists of a single parabolic bunch having a duration of 1000 ns. It has been found that such a long beam is not very favorable for our purpose either because it also leads to substantial hydrodynamic expansion during the first 100 ns. We found that the most suitable beam configuration is that of a single bunch with a duration of 50 ns and a beam radius of 1.0 mm because the hydrodynamic expansion is negligible during this time.

The above simulations have been carried out using the BIG-2 [4] code and the beam-target arrangement is shown in Fig. 1. The beam is incident on the right face of the target that is 5-mm long. The range of 1 GeV/u uranium ions in cold solid lead is about 15.5 mm according to the SRIM code [10,11]. The ions therefore lose a fraction of their energy in the target that is about 25% initially and emerge with a reduced energy from the left face of the cylinder.

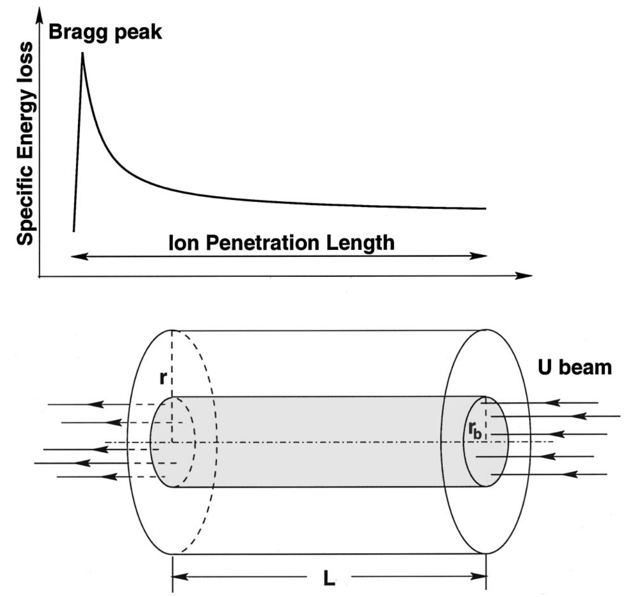

FIG. 1. A ''subrange'' solid cylindrical lead target irradiated with 10^{12} particles of uranium 1 GeV/u.

In Sec. II we present some useful basic range-energy relations as well as the beam and target parameters. The simulation results are discussed in Sec. III while the conclusions drawn from this work are noted in Sec. IV.

II. RANGE-ENERGY RELATIONS AND BEAM-TARGET PARAMETERS

In this section we describe some basic range-energy relations as well as target and beam parameters that have been used in these calculations.

A. Range-energy relations

In case of ion-beam matter interaction studies, one of the most important parameters that determines the maximum achievable temperature in the target is the specific power deposition P_s. This parameter is defined as follows:

$$P_s=\frac{E_s}{\tau}, \tag{2}$$

where τ is the pulse duration and E_s is the specific energy deposition given by

$$E_s=\frac{(1/\rho)(dE/dx)N}{\pi r_b^2}. \tag{3}$$

In the above equation, $(1/\rho)dE/dx$ is the specific-energy loss due to a single ion, ρ is the target-material density, x is the coordinate along the particle trajectory, N is the total number of particles in the beam, and r_b is the beam radius.

It is seen that P_s depends on a number of factors, some of which have opposite influences on the specific energy deposition. For example, if the ion energy (particle energy/u) is increased, $(1/\rho)dE/dx$ decreases while the transverse beam emittance improves. This in turn improves the focusing capability of the beam that allows one to reduce the focal spot radius. Since E_s is inversely proportional to the square of r_b, the specific-energy deposition could be increased significantly. However, if r_b becomes too small, the hydrodynamic expansion time scale becomes so fast that a shorter pulse is required. Otherwise the target material will expand due to the hydrodynamic motion during irradiation and a significant fraction of the beam energy will be lost. One therefore needs to determine an optimized set of parameters to maximize the specific energy deposition.

B. Beam parameters

We consider a uranium beam with a particle energy of 1 GeV/u while the total number of ions in the beam is 10^{12}. Power deposition profile along the radial direction is considered to be a Gaussian given by

$$P(r)=P_0 \exp\left[-\frac{r^2}{2\sigma^2}\right], \tag{4}$$

where σ is the standard deviation of the distribution. The full width at half maximum (FWHM) of this Gaussian distribution could be considered as the effective beam radius.

In these calculations we studied two cases with different beam radii, namely, with FWHM of 0.5 and 1.0 mm, respectively.

The time profile of the beam power is assumed to be parabolic given by

$$P(t)=-\frac{6E}{\tau^3}[t^2-rt], \tag{5}$$

where r is the pulse duration and E is the total energy in the beam that is about 38 kJ.

We consider two different cases for the time profile of the beam power. In the first case we assume a chain of five identical bunches that are equally spaced in time. Each bunch consists of 2×10^{11} particles and the bunch length as well as the bunch separation is 140 ns. In the second case we assume a single bunch with a pulse duration τ and we consider two values for τ, namely, 1000 and 50 ns, respectively.

C. Target parameters

The target is a solid lead cylinder that has a length $L=5.0$ mm and a radius $r=3.0$ mm. The range of 1 GeV/u uranium ions in cold solid lead is 15.5 mm. It is therefore a ''subrange'' target, the ions will deposit a fraction of their energy in the target material and emerge from the opposite face of the cylinder with a reduced energy. Our calculations show that in this beam-target configuration, the ions will initially lose about 25% of their energy in the target. As the material expands due to the hydrodynamic motion, the energy deposition is reduced substantially that leads to a significant increase in the energy of the ions that escape from the opposite face of the cylinder.

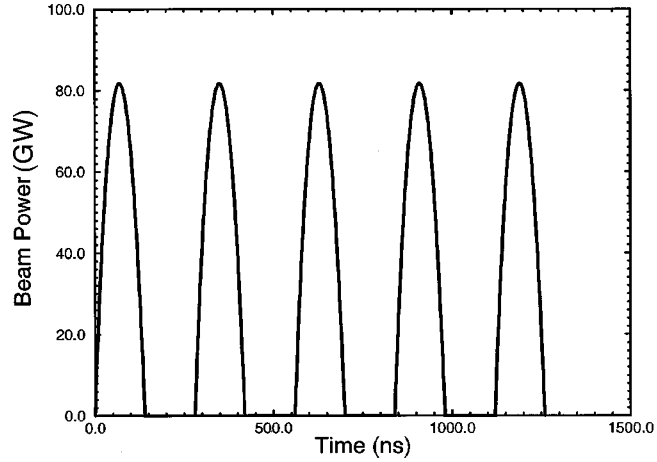

FIG. 2. Time profile of a beam consisting of five identical parabolic bunches, bunch duration $=140$ ns, bunch separation $=140$ ns, number of particles in each bunch $=2\times10^{11}$, and beam deposition profile along the radial direction is assumed to be a Gaussian.

III. SIMULATION RESULTS

In this section we present our detailed numerical simulation results of the hydrodynamic response of a solid lead target that is irradiated by an intense uranium beam whose parameters are given in Sec. II B. These simulations have been carried out using a two-dimensional hydrodynamic computer code BIG-2 [4]. The beam-target geometry is shown in Fig. 1.

A. Five identical parabolic bunches in a series

Figure 2 shows the beam power profile in time in case of five equally spaced identical parabolic bunches. Each bunch consists of 2×10^{11} particles of uranium with a particle energy of 1 GeV/u and the bunch length is 140 ns. Separation between every two neighboring bunches is also 140 ns that leads to a total pulse length of 1260 ns.

For the beam radius we consider two different cases, namely, a FWHM of the Gaussian equal to 0.5 and 1.0 mm, respectively. The results are presented below.

1. Beam radius 0.5 mm

As the beam is switched on, particles from the first bunch enter the target from the right face and deposit a fraction of their energy in the target along their trajectory. These particles emerge from the left face of the cylinder with a reduced energy. Since the particle range is about 15.5 mm in cold solid lead while the target is only 5 mm long, the Bragg peak does not lie inside the target. This leads to an almost uniform energy deposition along the particle trajectory as shown by Fig. 3(a) where we plot the specific-energy deposition on a length-radius plane at $t=150$ ns that shows a maximum value of $E_s=95$ kJ/g along the cylinder axis where the maxima of the Gaussian distribution occurs.

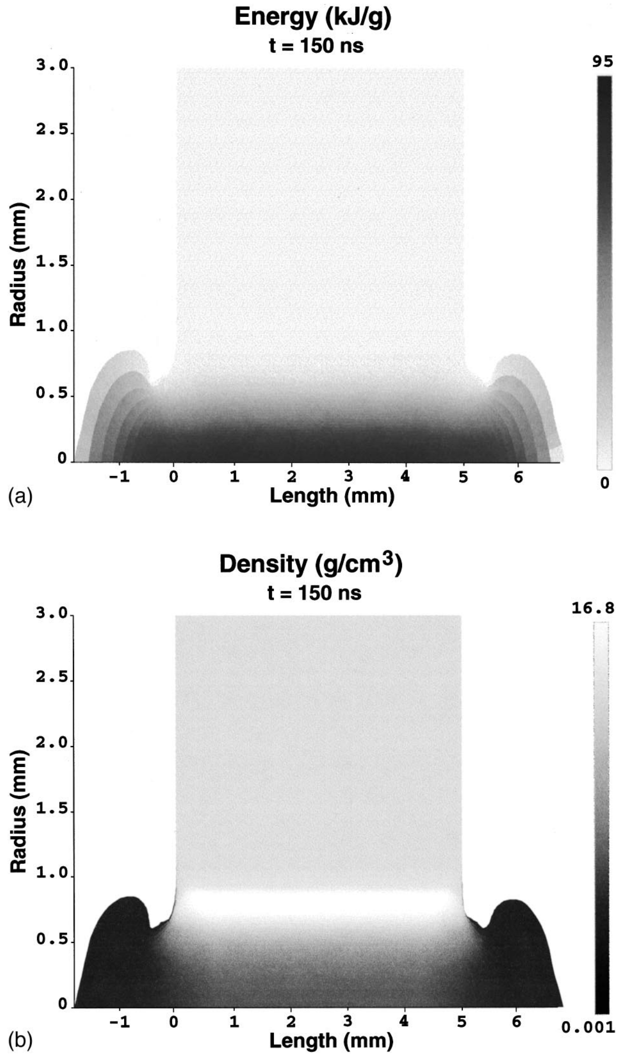

FIG. 3. (a) Specific energy deposition and (b) target density, on a length-radius plane at $t=150\,\text{ns}$, using bunch profile shown in Fig. 2 and a beam radius (FWHM of Gaussian distribution) $=0.5\,\text{mm}$.

It is seen that a cylinder of hot material that has a radius of 0.5 mm is created inside the target. The high pressure in this hot region drives a strong shock wave outwards along the radial direction as well as the material expands along the axial direction, as shown in Fig. 3(b), where we plot the target density on a length-radius plane at $t=150\,\text{ns}$. Figure 3(b) shows that as a result of this, the target density has been substantially reduced in the absorption region during the time of the first bunch.

To have a quantitative view of the calculations, we plot in Figs. 4(a)–4(c), respectively, the temperature, pressure, and the density, respectively, along the cylinder axis (at $r=0.0\,\text{mm}$) at different times. It is seen that at $t=50\,\text{ns}$, the temperature along the target axis is about 8 eV and the corresponding pressure is about 1.4 Mbar. The density at this time has become 10 g/cm^3. At $t=100\,\text{ns}$, it is seen that the temperature has increased approximately to 9 eV, but the pressure has been reduced to 1.15 Mbar because the density has become too small and is below 6 g/cm^3. At $t=150\,\text{ns}$, the density has been reduced to below 3 g/cm^3.

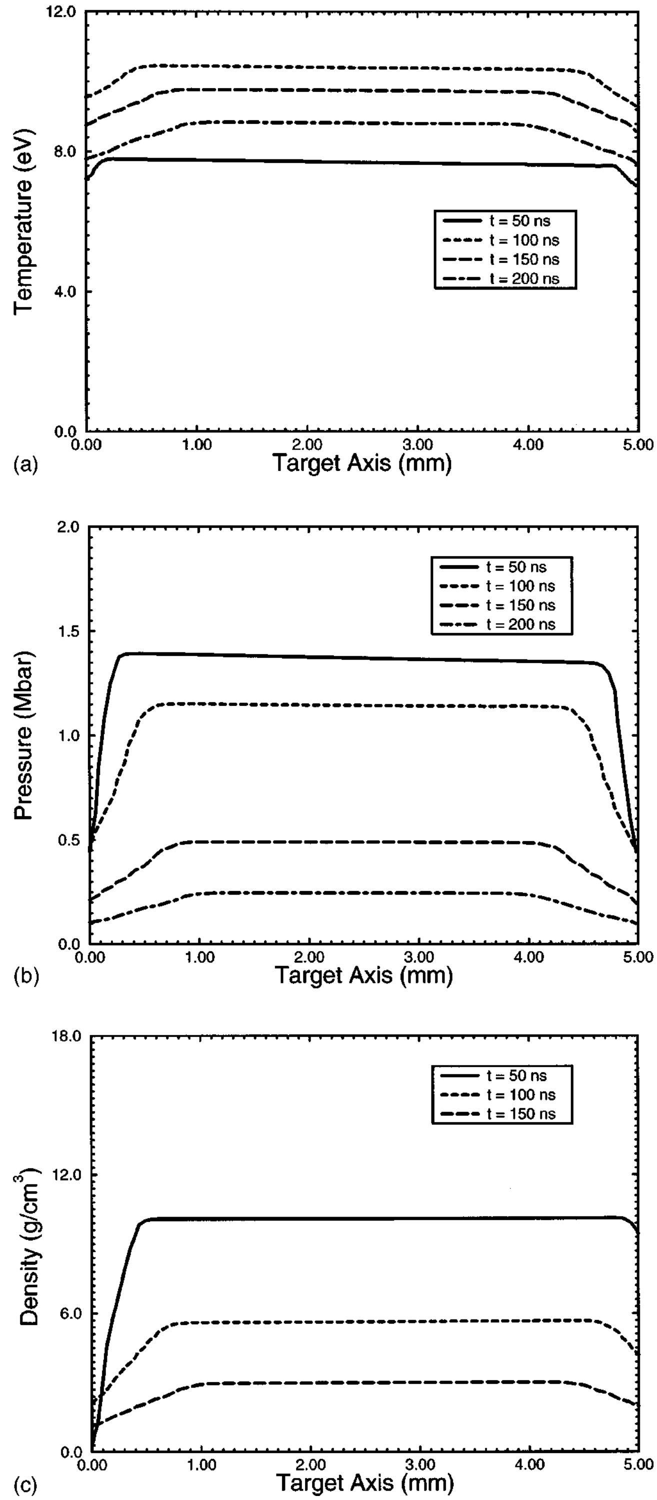

FIG. 4. (a) Temperature, (b) pressure and (c) density along cylinder axis ($r=0.0\,\text{mm}$) at different times using the beam profile shown in Fig. 2 and a beam radius of 0.5 mm.

Although the bunch is switched off at $t=140\,\text{ns}$, the heated material continues to expand, and at $t=280\,\text{ns}$ when the second bunch starts, the target density is so low that the particles escape without any interaction with the material. This is seen in Fig. 5 where we plot the fraction of the ion

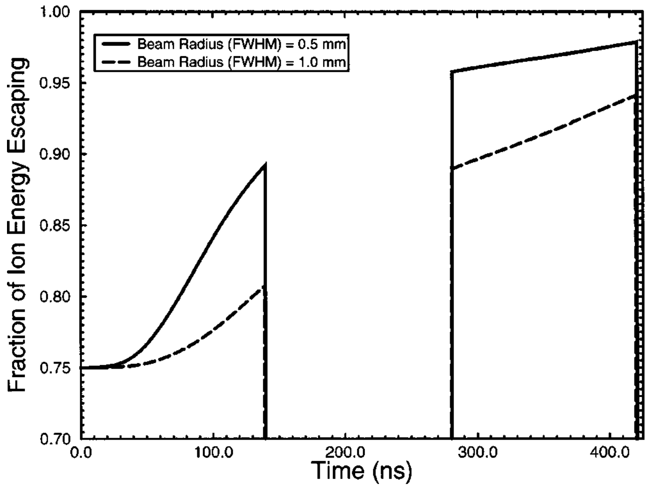

FIG. 5. Fraction of ion energy as a function of time that escapse the target along the axis ($r=0.0$ mm) for the case plotted in Fig. 4.

energy that escapes the target as a function of time. Initially, 75% ion energy escapes the target but as a result of reduction in the density due to material expansion, the fraction of the ion energy escaping the target increases and becomes about 90% at $t=140$ ns. At $t=280$ ns when the second bunch starts, about 99% ion energy escapes through the target. It is also clearly seen that at $t=80$ ns, during the target irradiation by the first bunch, the particle energy in the secondary beam has increased from an initial value of 75% to about 80%. This energy variation may result in a substantial beam loss. This configuration is therefore totally unsuitable for our purpose.

The target configuration at $t=300$ ns is shown in Fig. 6 where we plot the target density on a length-radius plane at $t=300$ ns.

2. Beam radius 1.0 mm

In Fig. 7 we plot the target density along the axis (at $r=0.0$ mm) at different times using the five-bunch beam configuration shown in Fig. 1 and using a beam radius (FWHM)

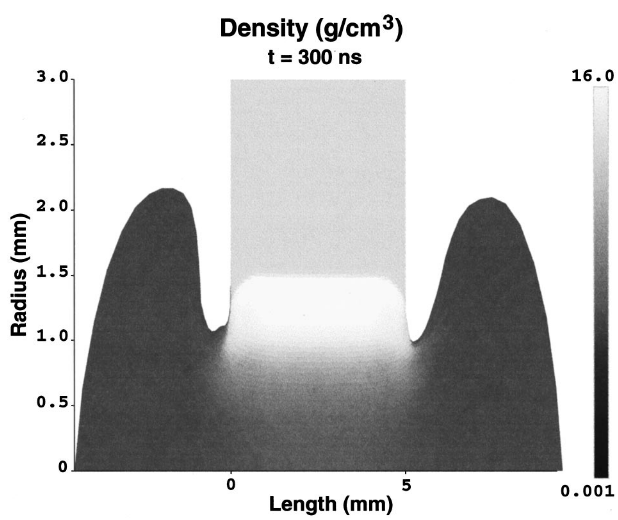

FIG. 6. Same as in Fig. 3(b), but at $t=300$ ns.

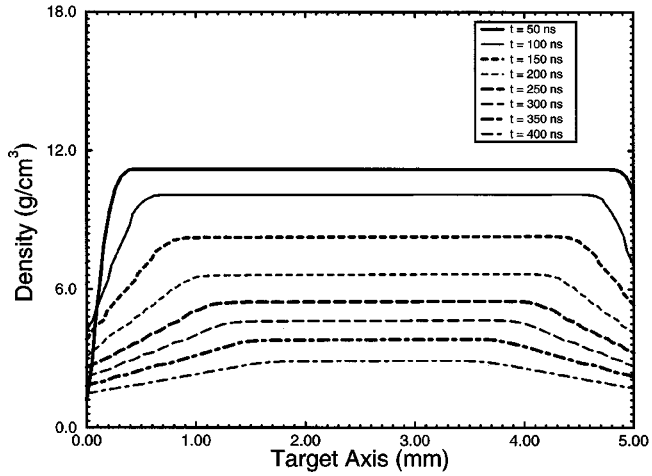

FIG. 7. Target density along axis (at $r=0.0$ mm) at different times using the beam profile and parameters considered in Fig. 2, but assuming a beam radius of 1.0 mm.

of 1.0 mm. In this case the beam radius is two times larger than the previous case and since according to Eq. (3), the specific-energy deposition is inversely proportional to the square of the beam radius, the specific-energy deposition in the present case is about four times less than in the previous case. As a consequence, the target temperature and in turn the pressure is significantly lower than that using a beam radius of 0.5 mm. This leads to a slower hydrodynamic expansion of the heated material. However, the hydrodynamic expansion is still rapid enough such that the target expands substantially during the first bunch.

The fraction of the ion energy that escapes the target as a function of time is shown in Fig. 5. It is seen that at $t=140$ ns, when the first bunch has just delivered its total energy, about 82% ion energy escapes the target. However, at $t=280$ ns when the second bunch starts, due to the continued material expansion, the amount of the escape energy is about 90% that increases to about 94% at $t=420$ ns when the second bunch is switched off. This means that about half of the particles in the second bunch and those in the remaining three bunches will not interact with the target. Moreover, the variation in the particle energy of the secondary beam becomes large enough at about $t=100$ ns to result in substantial beam losses. This configuration is therefore also very unattractive for the type of experiments we are interested in.

B. A single parabolic bunch

In this section we report results that have been achieved using a single parabolic bunch and we consider two different cases, namely, having a pulse length of 1000 and 50 ns, respectively.

1. A single bunch with duration 1000 ns

In Figs. 8(a) and 8(b) we plot the target density along the axis (at $r=0.0$ mm) at different times assuming a beam radius (FWHM of the Gaussian) $=0.5$ and 1.0 mm, respectively.

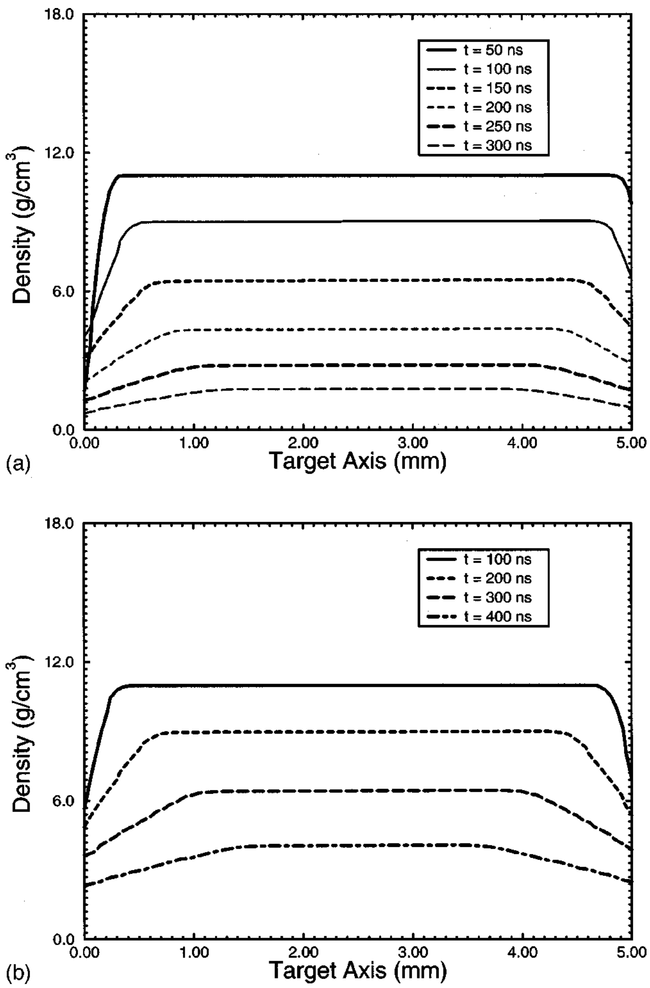

FIG. 8. Density along target axis (at $r=0.0$ mm) at different times, assuming a parabolic power profile and a pulse length $=1000$ ns, total number of 1 GeV/u uranium particles in the bunch is 10^{12}, using a beam radius, (a) 0.5 mm and (b) 1.0 mm.

It is seen from Fig. 8(a) that the density has been substantially reduced at $t=200$ ns, which means that particles that come afterwards and represent bulk of the beam will pass through the target without any significant interaction. This is seen from Fig. 9 where we plot the fraction of the ion energy that escapes the target as a function of time for the above two cases. It is seen that for the case corresponding to Fig. 8(a), the increase in the energy of the ions in the secondary beam becomes over 5% at $t=100$ ns. This will lead to substantial losses of particles in the secondary beam. This configuration is therefore totally unsuitable for beam-target interaction experiments of this type.

Figure 8(b) shows that if one uses a bigger beam radius, the expansion is slower compared to the previous case. However, Fig. 9 shows that still the expansion is rapid enough and at $t=200$ ns the fraction of escape energy becomes about 80%, which may not be tolerable for the fragment separator. These results show that even a single bunch with such a long duration is highly unsuitable for achieving a high beam-target coupling.

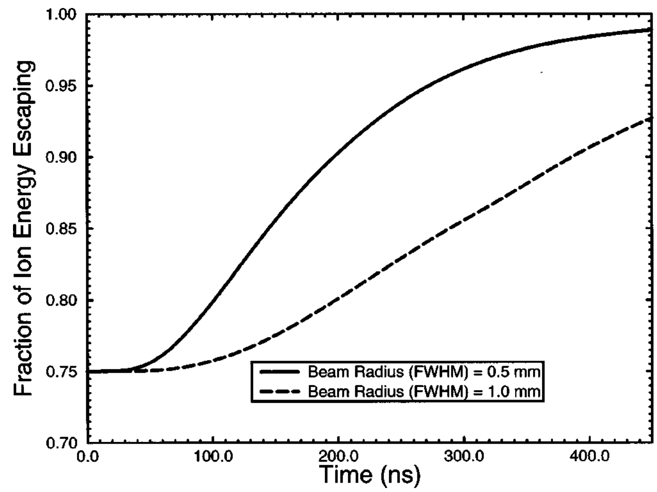

FIG. 9. Fraction of the ion energy that escapes through the target along the axis as a function of time for the two cases presented in Figs. 8(a) and 8(b), respectively.

2. A single bunch with duration 50 ns

We now report our results-using a single bunch that has a duration of only 50 ns. In Figs. 10(a) and 10(b) we plot the target density along the cylinder axis ($r=0.0$ mm) at different times using a beam spot radius (FWHM of the Gaussian) of 0.5 and 1.0 mm, respectively. It is seen from Fig. 10(a) that reduction in the density becomes significant only at $t=40$ ns. Figure 11 shows that in this case the ion escape energy is about 88% at $t=40$ ns. The pulse is switched off at $t=50$ ns. Due to the parabolic shape of the ion pulse the number of ions that is delivered in the last 10 ns of the pulse in quite small. This configuration therefore is reasonably good for the beam-matter interaction studies related to plasma physics. However, Fig. 11 shows that at $t=25$ ns, the increase in the energy of the escaping ions becomes of the order of 5%, which means that the beam delivered in the later half of the pulse will not be received by the fragment separator and will be lost. This configuration therefore is also not very good for fragment separation experiments.

Figure 10(b) shows that using a beam radius (FWHM of the Gaussian) of 1.0 mm, there is hardly any expansion in 50 ns. Correspondingly, Fig. 11 shows that there is no significant increase in the ion escape energy in this case. This beam configuration is therefore ideal for achieving a maximum beam-target coupling in the proposed plasma physics as well as fragment separation experiments.

IV. SUMMARY AND CONCLUSIONS

With the help of two-dimensional hydrodynamic simulations, it has been shown in this paper that bunch compression is essential for achieving a high beam-target coupling in ion-beam-matter interaction experiments. These experiments include creation of heavy-ion-beam generated plasmas as well as studies of fragmentation of the projectile ions while passing through solid matter. We considered a pulse that consists of five identical parabolic bunches of uranium 1 GeV/u ions with equal separation between two neighboring bunches.

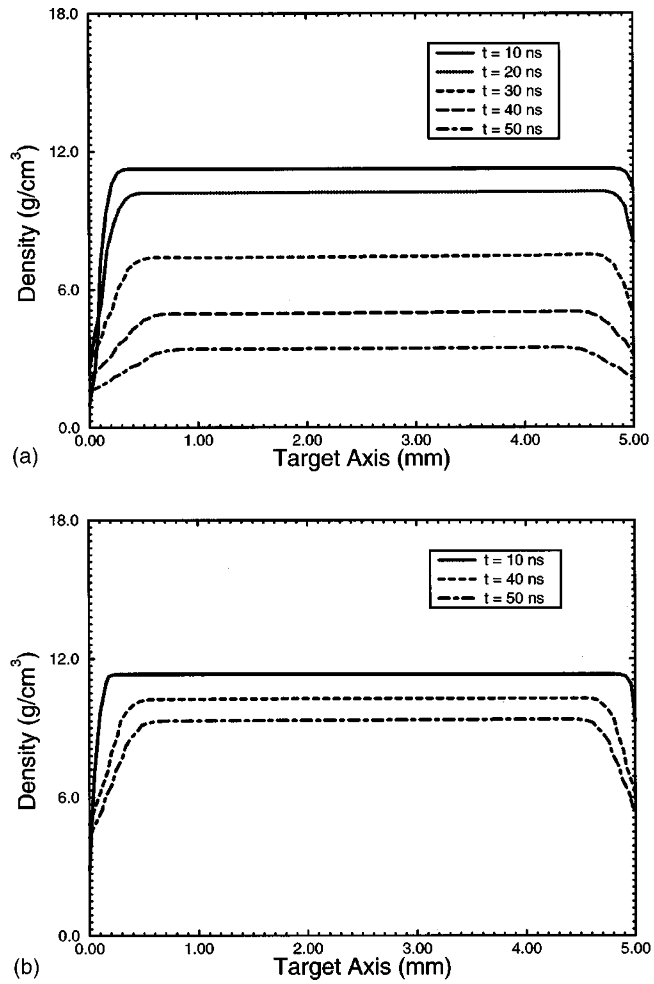

FIG. 10. Density along target axis (at $r=0.0$ mm) at different times, assuming a parabolic power profile and a pulse length=50 ns, total number of 1 GeV/u uranium particles in the bunch is 10^{12}, using a beam radius, (a) equal to 0.5 mm and (b) equal to 1.0 mm.

Each bunch contains 2×10^{11} ions and has a duration of 140 ns. The bunch separation is also 140 ns so that the total pulse length is 1260 ns. A solid lead cylinder was irradiated by this beam and two different cases were considered for the beam radius (FWHM of the Gaussian), 0.5 and 1.0 mm, respectively. In the former case, the specific-energy deposition is about 95 kJ/g and in the later case is 24 kJ/g along the target axis where the maxima of the Gaussian distribution lie. Consequently, the hydrodynamic expansion of the target is slower in the latter case compared to the former. However, despite this the energy deposited in both cases just by the first bunch is large enough to cause considerable expansion. By the time the second bunch starts, the density is so low that there is hardly any interaction between the particles and the target material. This shows that it is not a good idea to use this type of beam configuration.

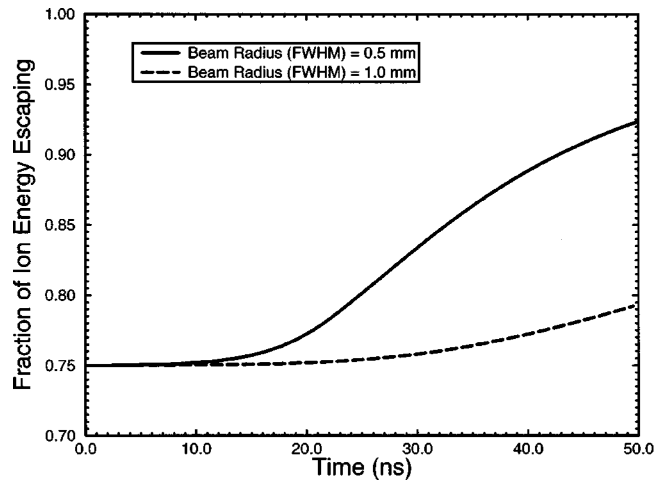

FIG. 11. Fraction of ion energy escaping the target as a function of time for the two cases presented in Figs. 10(a) and 10(b), respectively.

As an alternative, we have considered two cases using a single bunch with pulse duration of 1000 and 50 ns, respectively. Again we have allowed for a beam radius (FWHM of the Gaussian) of 0.5 and 1.0 mm, respectively for each of the above two cases. It is seen that the long pulse does not suit our purpose and considerable expansion of the target material occurs during the early phase of the target irradiation. This results in a substantially reduced ion-target interaction for the bulk of the ions.

The shorter pulse of 50 ns with a beam radius of 1.0 mm has been found to be very suitable for the proposed plasma physics as well as fragment separation experiments.

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