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Three–dimensional simulations of a solid graphite target for high intensity fast extracted uranium beams for the Super–FRS

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Abstract

This paper presents three–dimensional numerical simulations of thermodynamic and hydrodynamic response of a wheel shaped solid graphite production target for the super conducting fragment separator (Super–FRS) that is irradiated with a fast extracted high intensity uranium beam. These fragment separator experiments will be carried out at the future Facility for Antiprotons and Ion Research (FAIR), at Darmstadt. Previously, we reported simulation results that were carried out using two–dimensional computer codes which showed that one can use a solid graphite target for the Super-FRS for the highest intensity (5×10^{11} ions per spill) of the fast extracted uranium beam. Present results, however, have shown that due to three–dimensional effects the maximum intensity that can be used with such a target is 3×10^{11} ions per spill. A detailed comparison between two–dimensional and three–dimensional results is presented in this paper.

Keywords: Elastic plastic behavior; FAIR; Fragment separator; High energy density physics; Intense heavy ion beams; Radioactive beams

1. INTRODUCTION

Construction of a superconducting fragment separator (Super–FRS) (Geissel *et al.*, 2003), is one of the most important parts of the international project, Facility for Antiprotons and Ion Research (FAIR) (Henning, 2004), at Darmstadt. Availability of a robust and stable production target that survives over an extended period of time during the experimental campaign, which will be carried out at a repetition rate of 1 Hz, is absolutely essential for the success of these experiments. Designing a viable Super–FRS production target for the highest intensities of fast extracted heavy ion beams at FAIR, is not a trivial problem. This is due to the fact that the specific power deposited by these beams in the target will be so high that the target may be destroyed in a single experiment. This is very much desirable in case of high energy density (HED) physics studies (Tahir *et al.*, 1999, 2000*a*, 2000*b*, 2001*a*, 2001*b*, 2003*a*, 2005*a*, 2005*b*, 2005*d*, 2005*e*, 2006, 2007*a*, 2007*b*, 2007*c*, 2008*a*; Piriz *et al.*, 2002, 2003, 2005, 2006, 2007*a*, 2007*b*; Temporal *et al.*, 2003, 2005; Lopez Cela *et al.*, 2006; Hoffmann *et al.*, 2005), but must be avoided in case of the Super–FRS at all costs.

Significant progress has been made over the past years to design a solid graphite Super–FRS target for fast extracted beams (Tahir *et al.*, 2003*b*, 2005*c*, 2007*d*, 2008*b*, 2008*c*). Graphite is an attractive material for target fabrication because it has a high sublimation temperature of 3925 K and has already been successfully used in construction of production targets for continuous beams (Heidenreich, 2002). Although such target design has never been developed and employed for fast extracted beams.

The new heavy ion synchrotron, SIS100 at FAIR, will deliver high quality particle beams including uranium with very high intensities. It is expected that in case of uranium, about 5×10^{11} particles per spill will be delivered, whereas for light and medium heavy elements, the intensities would be even higher. A wide range of particle energies (400 MeV/u–2.7 GeV/u) will be available while the beam could be focused to a spot of

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1 mm radius. Both, fast and slow extraction options will be available for the beam. In the former case, the bunch length will be on the order of 50–100 ns, while in the latter case, one will have a quasi-uniform beam power.

Theoretical investigations carried out over the past years have shown (Tahir *et al.*, 2003*b*, 2005*c*, 2007*d*, 2008*b*, 2008*c*) that it will be possible to employ a solid production target for the Super–FRS for high intensity heaviest ion beams (uranium). However, this work was carried out using two–dimensional (2D) simulations models. In the present paper, we report numerical simulations that have been performed using a three–dimensional (3D) computer code, and a comparison between the previous and the recent calculations is presented.

In Section 2, we discuss the general aspects of the problem while simulation results are presented in Section 3. Conclusions drawn from this work are noted in Section 4.

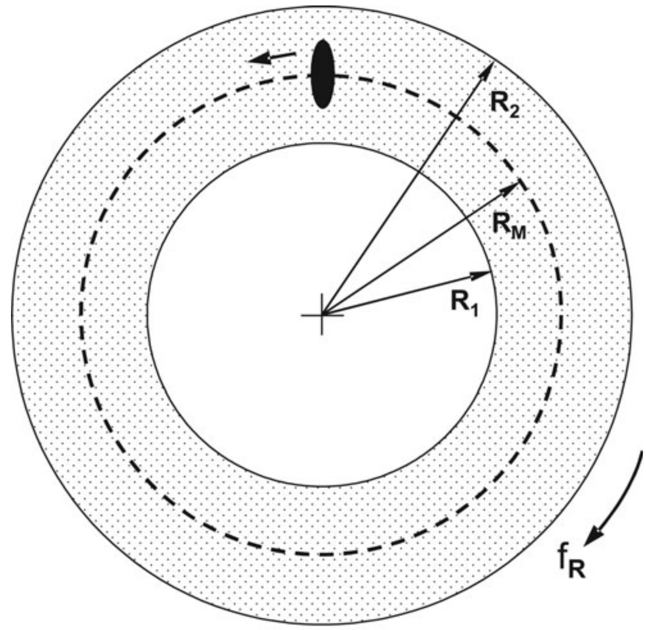
2. GENERAL DISCUSSION OF THE PROBLEM

Numerical simulations have shown that in the Super–FRS experiments, about 25% beam energy will be deposited in the target. In case of full intensity of the uranium beam (5×10^{11} ions per spill), the level of specific power deposition will be so high that it will destroy a solid graphite target in a single experiment (Tahir *et al.*, 2003*b*). One can reduce the specific power deposition to an acceptable level by increasing the focal spot area. However, the spot size can not be increased arbitrarily as it is restricted by requirements of good isotope resolution and sufficient level of transmission of the secondary beam through the fragment separator.

Since the Super–FRS experiments will be carried out at a repetition rate of 1 Hz, accumulation of residual heat in the target from successive experimental shots must be avoided. This requires that the deposited energy is efficiently transported away from the heated region before that particular spot is irradiated the second time. It has been suggested to use a wheel shaped target that is rotated at a suitable frequency so that the same target spot is not irradiated consecutively (see Fig. 1). By the time that particular target region is irradiated again, sufficient cooling would take place due to heat conduction and radiation loss and a steady state is achieved. Detailed numerical simulations have shown (Tahir *et al.*, 2005*c*) that such a configuration can be successfully used for the Super–FRS.

It is to be noted that in the above work, we were only interested to study the problem of heat conduction in the target and we therefore excluded hydrodynamics in these calculations. However, the energy deposition induces high thermal pressure that generates thermal stress in the target. If the induced stress level exceeds a *critical value*, such that the value of the so called von Mises parameter approaches 1, the target will be plastified or even break in case of a brittle material like graphite. To take care of this problem, in the above study, we considered low beam intensities and used a relatively large focal spot so that the induced stress level was low.

In the work reported (Tahir *et al.*, 2008*b*), we performed 2D numerical simulations of thermodynamic and hydrodynamic



$$R_M = \frac{R_1 + R_2}{2}$$

Fig. 1. Beam-target configuration for a multiple shot rotating solid carbon target.

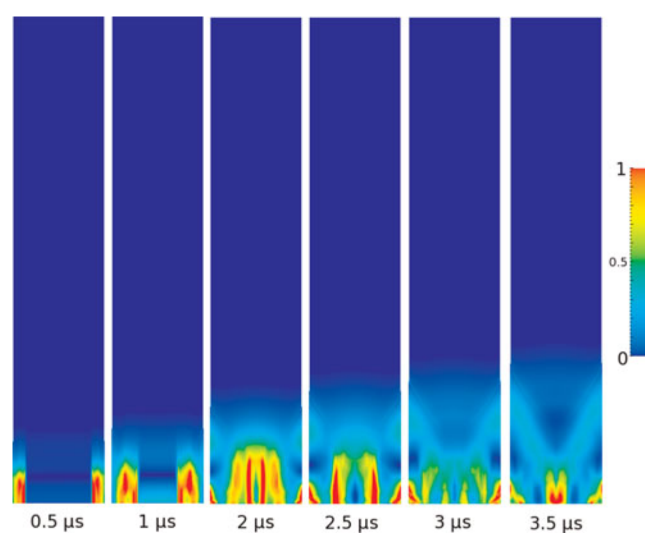


Fig. 2. (Color online) von Mises parameter, M at four different times, namely 1 μs, 2 μs, 3 μs, 4 μs. Solid graphite cylinder, radius = 8 cm, thickness = 1.5 cm, irradiated with a uranium beam, $N = 10^{11}$ ions per bunch, bunch length = 50 ns, particle energy = 1 Gev/u, Gaussian intensity distribution in transverse direction with $\sigma = 4$ mm. Beam is incident from left to right along the target axis.

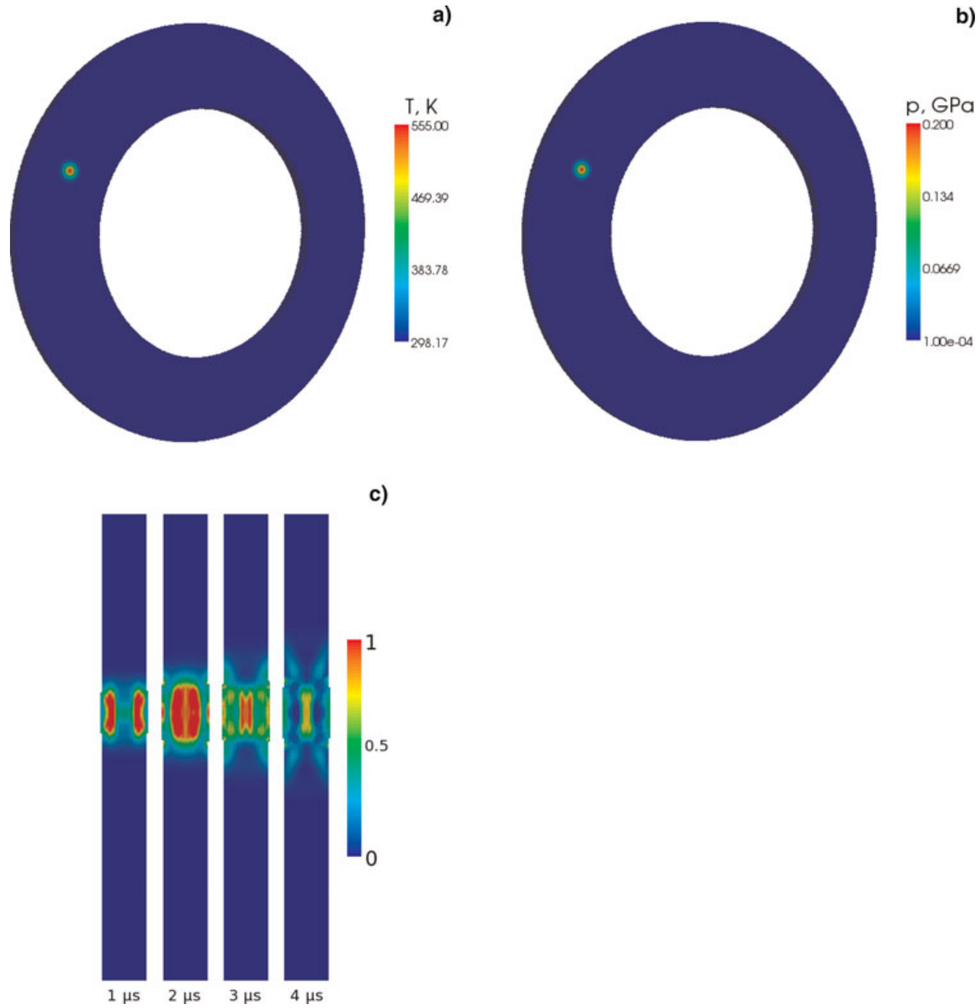


Fig. 3. (Color online) Wheel shaped solid graphite target, $\rho = 2.28\ g/cm^3$, inner radius = 13.5 cm, outer radius = 22.5 cm, thickness = 1.3 cm, irradiated with 1 GeV/u uranium ions, $N = 10^{11}$, bunch length = 50 ns, circular focal spot with $\sigma = 4$ mm, initial target temperature = 300 K, yield strength = 70 MPa; (**a**) Temperature at t = 50 ns, (**b**) pressure at 50 ns, (**c**) von Mises parameter at along cross section at different times.

response of a solid graphite cylinder that was irradiated with a high intensity uranium beam, directed along the target axis. The purpose of this work was to study the level of thermal stresses generated in the target by different beam intensities and different focal spot geometries. An important outcome of this work was that a circular focal spot induces minimum stress compared to anelliptic one and the stress level increases with the ellipticity of the spot. It is therefore advantageous to use a circular beam spot as far as possible.

In the work published (Tahir *et al.*, 2008*c*), we reported 2D numerical simulations of a wheel shaped solid graphite target (Fig. 1) that was irradiated with a high intensity uranium beam. In these calculations, we assumed an inner target radius, $R_1 = 13.5$ cm and an outer radius, $R_2 = 22.5$ cm. This work showed that one may use such a production target even for the highest intensity (5×10^{11} ions per spill) of the uranium beam using a relatively large focal spot that would still fulfill the conditions of achieving good isotope resolution and sufficient secondary beam transmission.

In the present paper, we report 3D numerical simulations of the above target. It has been found that these results are somewhat less optimistic compared to the 2D simulations as described in the next section.

3. SIMULATION RESULTS

In this section, we present numerical simulation results that have been obtained using a 3D particle-in-cell code, FPIC3D (Fortov *et al.*, 2006). Equation of state data has been used from Kerley (2001). The target geometry is shown in Figure 1 and it is madeof solid graphite. The inner radius of the wheel, $R_1 = 13.5$ cm, the outer radius, $R_2 = 22.5$ cm, and the thickness is 1.3 cm. It is reported elsewhere (Carbon, 2006, Private Communication) that the yield strength of graphite increases significantly with temperature. At room temperature, the yield strength, $Y = 70$ MPa whereas at 2000 K, it becomes 100 MPa. It has been suggested (Tahir *et al.*, 2008*c*) that one may benefit from

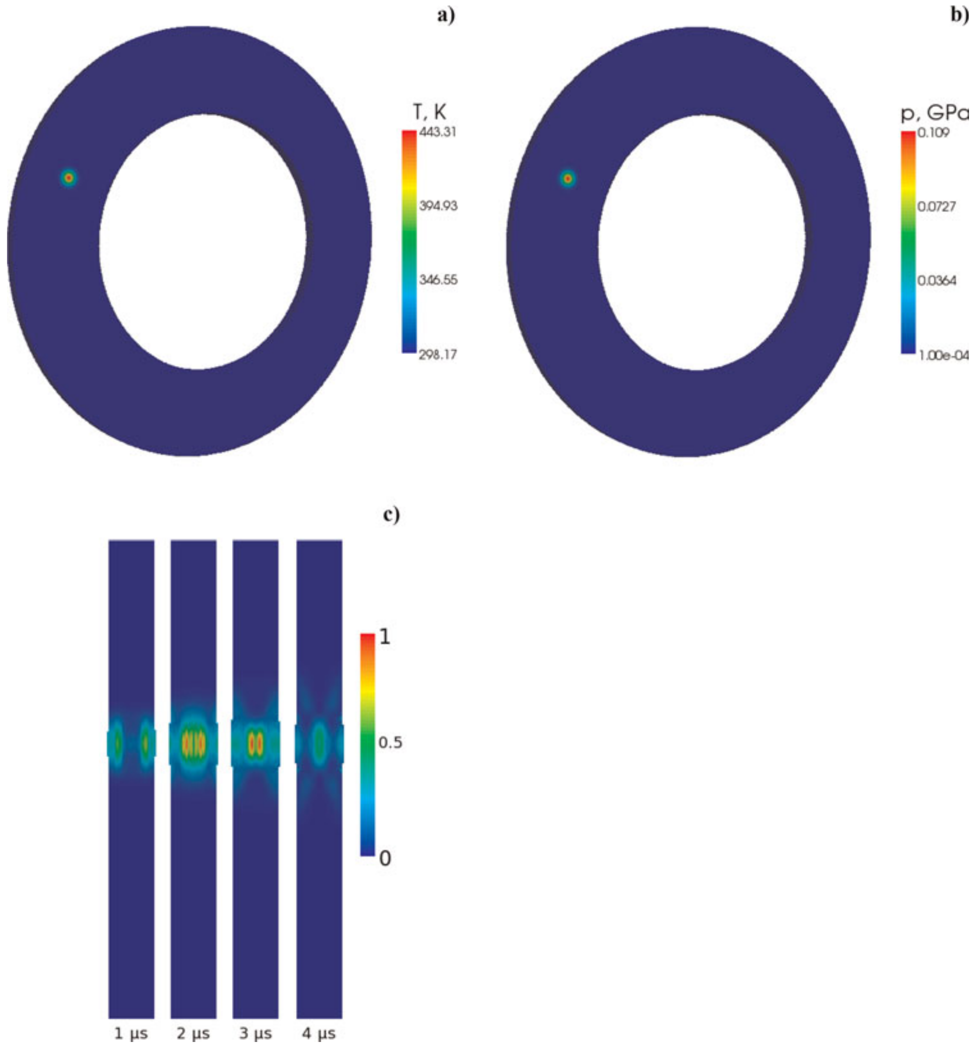


Fig. 4. (Color online) Wheel shaped solid graphite target, $\rho = 2.28$ g/cm^3, inner radius = 13.5 cm, outer radius = 22.5 cm, thickness = 1.3 cm, irradiated with 1 GeV/u uranium ions, $N = 5 \times 10^{10}$, bunch length = 50 ns, circular focal spot with $\sigma = 4$ mm, initial target temperature = 300 K, yield strength = 70 MPa; (**a**) Temperature at t = 50 ns, (**b**) pressure at 50 ns, (**c**) von Mises parameter at along cross section at different times.

this effect by preheating the target with a defocused ion beam. In the work reported in the present paper, we therefore have also done a few simulations assuming an initial target temperature of 2000 K.

3.1. Target at Room Temperature

In the previous 2D simulation studies (Tahir *et al.*, 2008*b*, 2008*c*), generation and propagation of stress waves was studied in the cross sectional geometry of the two type of targets. In this configuration, one can only simulate propagation of the stress waves in the radial direction. To study this problem in the longitudinal direction, we have now carried out 2D simulations of a solid graphite cylindrical target on a length–radius plane (assuming axial symmetry), and the results are presented in Figure 2. In these calculations, the target is initially assumed to be at room temperature so that the yield strength, $Y = 70$ MPa. The cylinder radius = 8 cm and has a length = 1.5 cm. A uranium beam with an intensity of 10^{11} ions per spill, is directed along the target axis. The bunch length is assumed to be 50 ns and the beam intensity in transverse direction is assumed to be a Gaussian with $\sigma = 4$ mm.

In Figure 2, we show the von Mises parameter, M, in the target at six different times. It is seen that at $t = 0.5$ μs, the value of M is on the order 1 at the target boundaries. This is due to the rarefaction waves that are generated at the two opposite faces of the cylinder. As the rarefaction waves move inwards, the value of M increases and approaches 1 in those regions (see Fig. 2 at $t = 1$ μs). These rarefaction waves arrive at the target center at $t = 2$ μs and then reflect at the center. This is seen from the following figures plotted at later times. This simulation shows that the target will not survive with the above beam parameters. Our previous study (Tahir *et al.*, 2008*b*), on the other hand, showed that a cylindrical target will survive the radial stress

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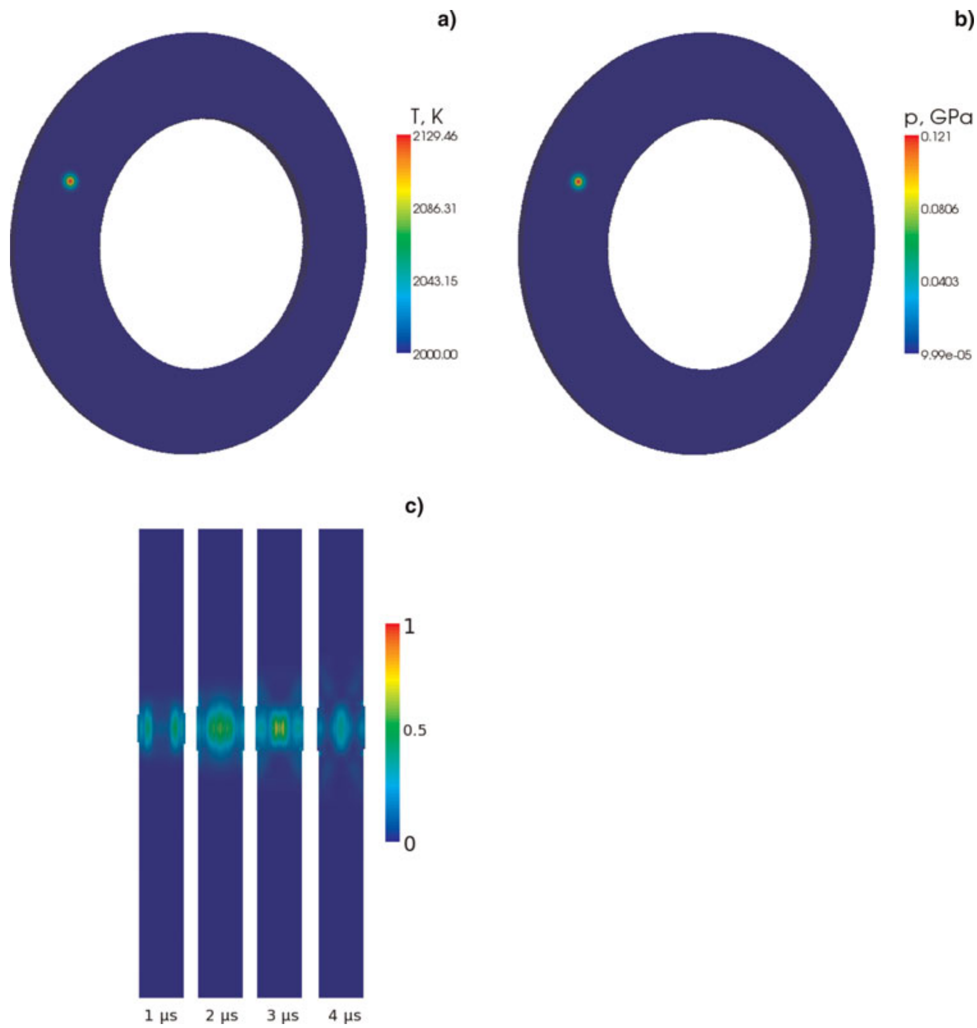

Fig. 5. (Color online) Wheel shaped solid graphite target, $\rho = 2.28\ \mathrm{g/cm^3}$, inner radius = 13.5 cm, outer radius = 22.5 cm, thickness = 1.3 cm, irradiated with 1 GeV/u uranium ions, $N = 10^{11}$, bunch length = 50 ns, circular focal spot with $\sigma = 4$ mm, initial target temperature = 2000 K, yield strength = 100 MPa; (**a**) Temperature at t = 50 ns, (**b**) pressure at 50 ns, (**c**) von Mises parameter at along cross section at different times.

waves generated by a beam with above parameters. Our present simulations have shown that a cylindrical target can tolerate up to 5×10^{10} ions per spill (a factor of 2 less than predicted by the previous study) while the rest of the beam parameters are kept constant. This is due to the fact that longitudinal stress is included in the 3D simulations.

To study this effect in a wheel shaped Super–FRS target, we consider a target with an inner radius, $R_1 = 13.5$ cm, $R_2 = 22.5$ cm, and a thickness = 1.3 cm. The target is irradiated with a 1 GeV/u uranium beam having an intensity of 10^{11} ions per bunch that is 50 ns long. The focal spot size is characterized with $\sigma = 4$ of a Gaussian intensity distribution in the transverse direction. In Figures 3a and 3b, we present the temperature and pressure profiles respectively at $t = 50$ ns. It is seen that a maximum temperature of 555 K and a maximum pressure of 200 MPa is achieved. In Figure 3c, we plot the von Mises parameter, M, in the beam heated region in the longitudinal direction at four different times. It is seen that at $t = 1\ \mu$s, M is on the order of 1 at the opposite faces of the wheel in the beam heated region. As the stress waves move inwards, M becomes on the order of 1 in the inner part of the target as well. This shows that the target will lose its elastic properties due to the stress waves generated in the longitudinal direction.

It has been shown (Tahir *et al.*, 2008*c*) that σ_X is restricted to a value of 4 mm due to requirements of good isotope resolution and if one would like to use a circular focal spot, then beam intensity is the only parameter that one can reduce. Our recent simulations have shown that this beam–target configuration will survive a maximum beam intensity of 5×10^{10} ions per spill, which is a factor of 2 less than that reported in our previous publications (Tahir *et al.*, 2008*c*). Figure 4 shows the 3D simulations where in Figures 4a and 4b, we plot the target temperature and pressure, respectively. In this case, the maximum temperature is about 440 K while the pressure is 100 MPa. Figure 4c shows the time evolution of M and it is seen that it achieves a maximum value of about 0.9 which implies that the material will remain in an elastic phase and the target will survive.

It is therefore concluded from this study that assuming all other parameters are kept constant, the maximum tolerable beam intensity for the Super–FRS target predicted by 3D simulations is about a factor 2 lower than that obtained by 2D calculations (Tahir *et al.*, 2008*b*, 2008*c*).

3.2. Target Preheated to 2000 K

In this section, we present 3D simulation results of the wheel shaped Super–FRS target that is preheated to an initial temperature of 2000 K so that the yield strength of the material is $=100$ MPa. First, we consider a 1 GeV/u uranium beam with an intensity of 10^{11} ions per spill with a bunch length = 50 ns. A circular focal spot is considered with $\sigma = 4$ mm. The results are presented in Figure 5. Figure 5a shows that the temperature increases from an initial value of 2000 K to 2129 K while a maximum pressure of 120 MPa is achieved. Figure 5c shows that M remains well below 1, which implies that this beam–target configuration will work.

As noted (Tahir *et al.*, 2008*c*), maximum value of σ_X allowed by requirement of good isotope resolution is 4 mm and of σ_Y determined by reasonable transmission (Tahir *et al.* 2003*b*) is 12 mm. Therefore, one may use an elliptic focal spot with $\sigma_X = 4$ mm and $\sigma_Y = 12$ mm. We carried out simulations using this focal spot size to determine the maximum beam intensity that can be used in the Super–FRS experiments. Our simulations have shown that one can use 3×10^{11} ions per spill. The results are plotted in Figure 6. It is seen that the maximum value of M is on the order of 0.9 and therefore the target will remain in an elastic state.

One may conclude that even in the case of a preheated target, the maximum beam intensity allowed according to

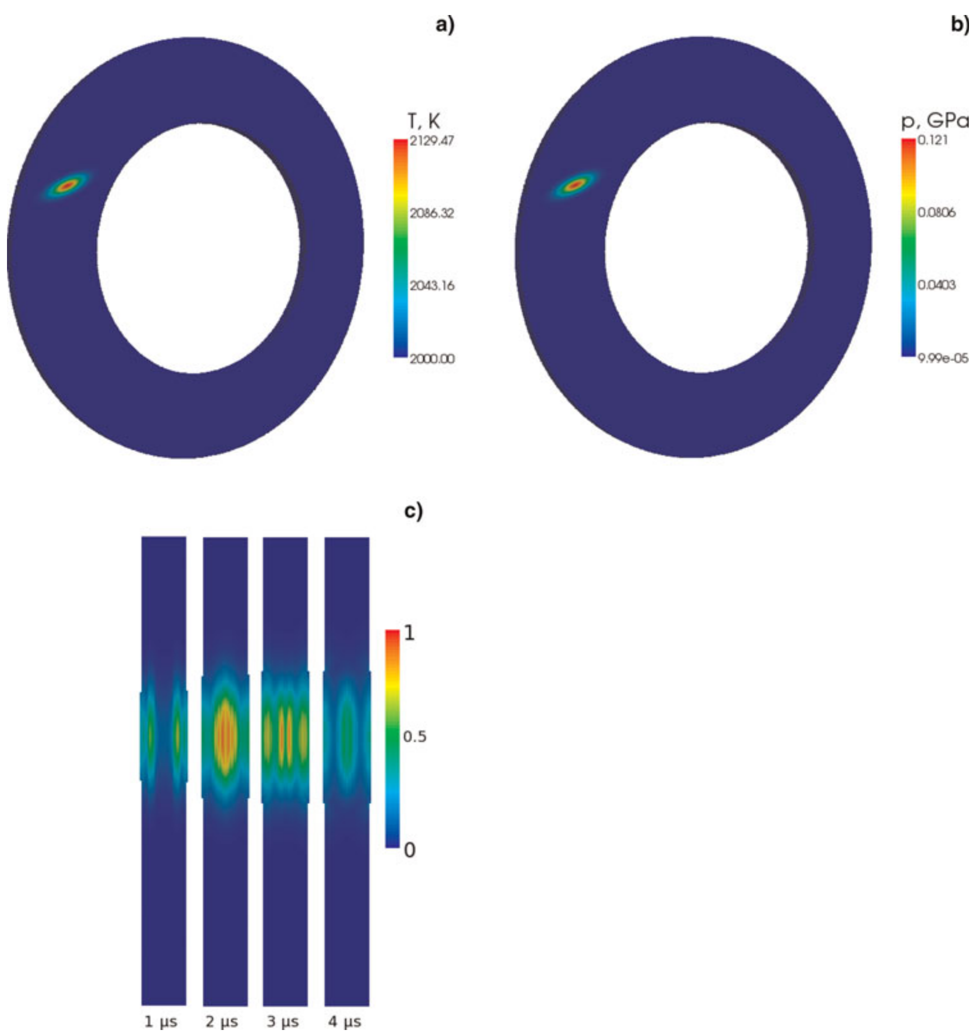

Fig. 6. (Color online) Wheel shaped solid graphite target, $\rho = 2.28$ g/cm^3, inner radius = 13.5 cm, outer radius = 22.5 cm, thickness = 1.3 cm, irradiated with 1 GeV/u uranium ions, $N = 3 \times 10^{11}$, bunch length = 50 ns, circular focal spot with $\sigma = 4$ mm, initial target temperature = 2000 K, yield strength = 100 MPa; (**a**) Temperature at t = 50 ns, (**b**) pressure at 50 ns, (**c**) von Mises parameter at along cross section at different times.

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3D calculations is approximately two times less than that predicted by 2D simulations.

4. CONCLUSIONS

In previous publications (Tahir *et al.*, 2003*b*, 2005*c*, 2007*d*, 2008*b*, 2008*c*), we reported 2D numerical simulations of a solid graphite target for the Super–FRS. The production target is one of the central features of the fragment separator and it should survive over a long period of time during an experimental campaign that will be carried out at FAIR at a repetition rate of 1 Hz. If the specific energy deposition by the beam is not controlled correctly, the target could be destroyed due to melting (or sublimation) in a single experiment (Tahir *et al.*, 2003*b*). The temperature should therefore always remain well below the melting (or sublimation) temperature of the target material. Graphite is therefore a very attractive material for designing production targets as it has a high sublimation temperature of 3925 K.

The target can also be destroyed by beam induced thermal stress if the stress level exceeds a critical value so that the von Mises parameter attains a value of 1. It is therefore very important to control the stress level that results from the pressure gradient generated in the target by the ion beam. In (Tahir *et al.*, 2008*b*), we studied this problem in a cylindrical target that was irradiated along the axis with a 1 GeV/u uranium beam. We studied the stress generated by different geometries including a perfect circular and elliptic focal spot. It has been found that a circular focal spot is the most useful as it generates minimum stress compared to an elliptic one with the same area. Moreover, the stress level increases with ellipticity of the spot.

It is to be noted that the Super–FRS experiments will be carried out at a repetition rate of 1 Hz. This may result in accumulation of heat if the energy is not transported efficiently from the beam heated region. This could lead to a substantial increase in temperature after a certain number of experimental shots that may eventually destroy the target. To overcome this difficulty, it has been proposed to use a wheel shaped target that is rotated at a suitable frequency such that different parts of the target that lie on a circle are irradiated successively. Numerical simulations have shown (Tahir *et al.*, 2005*c*) that in case of the Super-FRS target, strong cooling takes place due to heat conduction and the temperature of a given spot is substantially decreased before it is irradiated second time and a steady state is achieved.

Generation and propagation of stress waves in a wheel shaped Super–FRS target were studied using a 2D computer code and it was found that one can employ a solid graphite target for the highest intensity (5×10^{11} ios per spill) of the heaviest (uranium) ions at FAIR (Tahir *et al.*, 2008*c*). In the present paper, we report calculations that have been done using a 3D simulation model. These calculations have shown that the maximum intensity that one can use is somewhat lower, namely, 3×10^{11} ions per spill. This is due to the fact that in the 3D simulations, we include stress waves produced in the longitudinal direction due to the rarefaction waves generated at the target surface.

It is therefore concluded that one can use a solid graphite target for the fast extracted heavy ion beams at the Super–FRS target and it may not be necessary to develop a liquid jet target (Tahir *et al.*, 2007*e*).

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