Generation of a hollow ion beam: Calculation of the rotation frequency required to accommodate symmetry constraint

A. R. Piriz
ETSI Industriales, Universidad de Castilla-La Mancha, 13071 Ciudad Real, Spain

N. A. Tahir
Institut für Theoretische Physik, Universität Frankfurt, 60054 Frankfurt, Germany

D. H. H. Hoffmann
Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany and GSI Darmstadt, Planckstrasse 1, 64291 Darmstadt, Germany

M. Temporal
ETSI Industriales, Universidad de Castilla-La Mancha, 13071 Ciudad Real, Spain
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A hollow intense heavy ion beam with an annular focal spot has many important applications. The Gesellschaft für Schwerionenforschung, Darmstadt is planning to develop a radio frequency wobbler that will rotate the beam at extremely high frequencies and thus create an annular (ring shaped) focal spot. In this paper, we present an analytical model that determines the minimum rotation frequency of the wobbler in order to achieve a high degree of irradiation symmetry (an asymmetry of a few percent) of the target. Estimates for a typical heavy ion imploded target are also presented.

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Intense heavy ion beams are an excellent tool to research the field of high-energy-density matter [1,2]. Heavy ion beams have a number of advantages over other drivers including lasers, light ions, high power explosives, gas guns, and diamond anvil cell [3–7]. The Gesellschaft für Schwerionenforschung (GSI), Darmstadt is a unique laboratory worldwide that has a heavy ion synchrotron which delivers intense beams of energetic heavy ions. The focal spot of these beams is either circular or elliptic and using these beams, important experimental work has been performed [8–11]. However, theoretical calculations have shown [12–14] that employment of a hollow beam which has an annular or ring shaped focal spot has numerous advantages. Using such a beam, one can achieve very high compression due to the convergence of the cylindrical shock wave at the target axis.

Another important experiment which requires such a beam focal spot is implosion of a multilayered cylindrical target shown in Fig. 1, which can be used for the cold compression of the enclosed sample material. The above figure shows the proposed configuration and it is seen that the target is composed of a solid hydrogen cylinder with a radius R_{h0}, which is enclosed in a thick shell of solid lead. The right face of the target is irradiated with an ion beam that has an annular or a ring shaped focal spot. The inner radius of the focal ring R_1 is assumed to be larger than R_{h0} which avoids direct heating of the hydrogen. The outer radius of the focal spot ring, R_2, is considered to be much less than the outer radius of the lead shell, R_e. The region $R_2 \leqslant r \leqslant R_e$ acts as a tamper limiting the outward expansion of the absorption region.

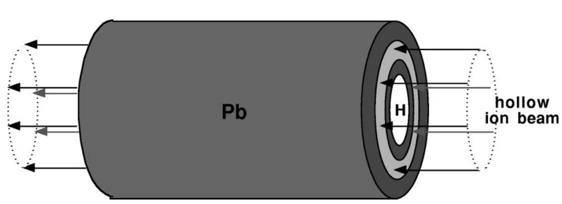

FIG. 1. Beam-target geometry.

It is assumed that the length of the target is much less than the range of the projectile particles so that the energy deposition along the particle trajectory is fairly uniform. A shell of heated material with a very high pressure is created in the absorber region lying between R_1 and R_2 with a mass m_a, while the region lying between R_{h0} and R_1 forms a cold payload shell having a mass m_{pl}. The hydrogen mass is denoted with m_h. In practice, one always has the condition $m_{pl} \ll m_a$ fulfilled and in the cases of interest, one also has $m_h \ll m_{pl}$.

The high pressure in the absorber generates a shock wave which travels through the payload and is then transmitted into the hydrogen. This shock travels along the radius of the hydrogen cylinder and is reflected at the axis. The reflected shock travels outward and is rereflected by the payload. This process of multiple shock reflection goes on while the payload continues to move inwards, slowly compressing the hydrogen. This leads to a low entropy or ‘‘cold compression’’ of the hydrogen layer. Numerical simulations have shown [2,12,13] that by using appropriate beam and target parameters, one can easily achieve the theoretically predicted physical conditions necessary for hydrogen metallization. These include a density of about 1 g/cm^3, a pressure of the order of 5 Mbar, and a temperature of a few thousand kelvin.

The generation of the annular focal spot used in this experiment design represents a challenging problem. At the

GSI Darmstadt, a high frequency rf wobbler is being designed which will rotate the beam with a rotation frequency of the order of GHz, which will generate the required shape of the focal spot [15]. The hollow beam rf wobbler design consists mainly of two radio frequency structures, excited at the resonance frequency of a transverse eigenmode. The transverse mode structures may be developed as split coaxial type [16,17] or as iris loaded waveguides [18], depending on the deflection efficiency. The challenging task is to get high homogenous transverse fields for ions traveling at about half the velocity of light, because the ion beam passing the deflectors is rather unfocused, with a transverse diameter in the millimeter regime. Each of the cavities deflects the beam in one plane, with a sine function time variation. Therefore, a phase-stable coupling of both transverse cavities with respect to the particle's velocity provides a perfect circular deflection. The resonance frequency of the structures is accurately determined by their geometrical dimensions.

To keep both cavities at exactly the same frequency, plungers will be utilized. They allow tuning of the resonance frequency by about 0.5%. Each of the cavities will be powered by its own power amplifier and to allow independent amplitude and phase control. Thus, elliptical beams may also be generated on targets without any hardware modifications. By adding more deflecting structures, which operate on integer harmonics or subharmonics, the wobbler could even provide lissajouslike transverse beam sweeps. We intend to install circulators between the structures and the amplifiers to protect the amplifiers from reverse rf power.

It is, however, very important to determine the value of the rotation frequency that will be needed for an acceptable symmetry (an asymmetry of the order of a few percent) in the driving pressure which is important for the symmetric compression of the hydrogen.

A simple estimation of the required rotation frequency can be done as follows by considering a box pulse of power P and duration τ_p. In such a case, a region in the absorber with a size of the order of the focal spot r_{fs} is heated by the rotating beam during a time of the order of t_c given by

$$t_c = \frac{r_{fs}}{\omega(R_1 + r_{fs})}, \tag{1}$$

where $\omega = 2\pi\nu$ is the angular velocity of rotation and ν is the frequency, as shown in Fig. 2. During this time, the pressure increases in this region by

$$\Delta p \propto \frac{P t_c}{r_{fs}^2}. \tag{2}$$

On the other hand, the maximum pressure p in the absorber is

$$p \propto \frac{P\tau_p}{(R_1 + 2r_{fs})^2 - R_1^2}. \tag{3}$$

Thus, the relative pressure asymmetry is

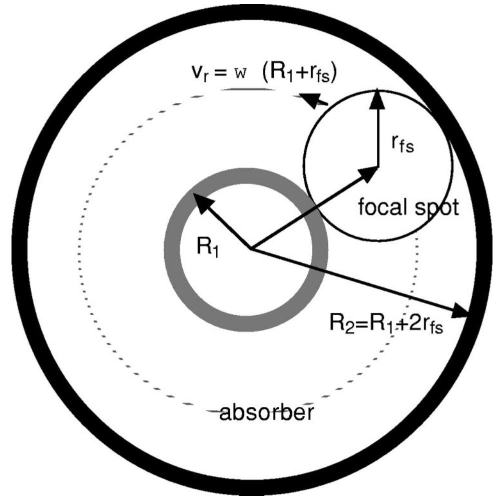

FIG. 2. Schematic diagram of a target heated by a rotating beam.

$$\frac{\Delta p}{p} \approx \frac{4}{\omega\tau_p}, \tag{4}$$

which is independent of the target size.

It may seem surprising that the degree of pressure symmetry on the payload surface is only determined by the pulse duration and the rotation frequency. However, it can be easily understood by noting that if t_c is the required time for raising the pressure by Δp in a region in the absorber with an area of the order of the focal spot $A_{fs} = \pi r_{fs}^2$, then the time required for raising the pressure in the whole absorber, which in fact is the rotation period T, by the same amount Δp must be

$$T \sim t_c \frac{A_a}{A_{fs}}, \tag{5}$$

where $A_a = \pi[(R_1 + 2r_{fs})^2 - R_1^2]$ is the absorber area. So we have

$$\Delta p \propto \frac{t_c}{A_{fs}} \sim \frac{T}{A_a}. \tag{6}$$

Taking into account that the maximum absorber pressure is reached when all the beam energy has been absorbed, we have

$$p \propto \frac{\tau_p}{A_a}. \tag{7}$$

Combining Eq. (6) with Eq. (7), we easily retrieve Eq. (4). In these calculations, we have neglected the hydrodynamic motion of the absorber because in the cases of interest, the beam rotation velocity ωR_1 is much larger than the sound speed c_0 in the absorber. In fact, for a typical target $R_1 = 0.05$ cm, the absorber is composed of lead and $c_0 \leqslant 7\times10^5$ cm/s [12–14]. Thus, for a rotation frequency $\nu \geqslant 0.4$ GHz [15], it turns out that $\omega R_1 > 2\times10^2 c_0$, for which hydrodynamic motion of the absorber should not play any role in determining the asymmetries on the payload surface.

As an example, let us require a pressure symmetry better than 5% and take $\tau_p \sim 30$ ns. In such a case, one gets $\nu \geqslant 0.4$ GHz or a rotation period of less than 2 ns. In the design presently considered at the GSI Darmstadt, the minimum value for the rotation frequency is close to 0.4 GHz with a maximum of few GHz [15]. Moreover, the technological constraints will limit the creation of a circular ring to an asymmetry of the order of 1%. This is an intrinsic asymmetry that will be inherent to this setup, independent of the rotation frequency. Therefore, by increasing the rotation frequency above a certain value (few GHZ according to the present calculation), one will not achieve any significant improvement of the symmetry. On the other hand, a much higher rotation frequency can spoil the symmetry along the target axis. In fact, because of the finite transit time t_T of the ions within the target, the angular position of the focal spot is progressively delayed as the ions travel in the axial direction. Then in order to keep the axial symmetry at the same level than in the azimuthal symmetry, we must require a maximum delay of the order of the rotation period T:

$$t_T = \frac{L}{v_i} \leqslant T = \frac{1}{\nu}, \tag{8}$$

where v_i is the ion velocity and L is the target length. For a typical situation $v_i \sim 0.1c$ (c is the light speed), $L \approx 2$ cm, and the previous equation yields $\nu \leqslant 1.5$ GHz. Therefore, we see that a rotation frequency $\nu \sim 1$ GHz can meet both, a good axial and a good azimuthal symmetry.

It is worth to consider how the pressure asymmetry given by Eq. (4) is translated to the inner face of the payload by a shock wave [14]. So, as a first approximation, we can write the following expressions:

$$\frac{\Delta p}{p} \approx 2\frac{\Delta \dot{R}_s}{\dot{R}_s} \approx 2\frac{\Delta R_1}{R_1}, \tag{9}$$

where $\dot{R}_s$ is the shock velocity. When the shock emerges from the payload, the velocity of its inner face is approximately doubled because of the large density difference between hydrogen and lead [19]. We can, therefore, consider that the perturbation amplitude is also doubled: $\Delta R_{ho} \approx 2\Delta R_1$, and that this amplitude is conserved up to the maximum compression. Therefore, the asymmetry of the compressed hydrogen is

$$\frac{\Delta R_{hf}}{R_{hf}} \approx \frac{\Delta p}{p} \frac{R_1}{R_{h0}}. \tag{10}$$

Since heat transport is practically negligible, we can consider that the main effect of this asymmetry is to reduce the effective radius of the compressed hydrogen.

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