On application of wobbler in experiments with cylindrical targets

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Abstract. For the experiments with irradiation of cylindrical targets by intense heavy ion beams which are actual for fundamental and applied researches (laboratory astrophysics, heavy ion inertial fusion, ion therapy, industry) it is necessary to shape the driver beam with hollow geometry. The wobbling method is of interest for such experiments. In the paper one of the problems of the method is considered leading to possible symmetry violation. The results of the simulation of the rotated beam dynamics are presented.

1. Introduction

Laboratory study of astrophysical plasma provide good understanding of the physics and peculiarities of the phenomena due to the reproducibility and high level of controllability of such experiments. For these experiments the cylindrical targets are of a special interest [1-6]. Cylindrical target implosion and low-entropy compression of the sample or substance placed inside the target provide the high pressures (MBars) at the axis with relatively low temperatures. Distinguished pressure 3-15 MBar at 3000-10000 K corresponds to the regime of the laboratory modeling of the interior of the giant planets. The same regime corresponds to the conditions of the hydrogen metallization. The higher temperatures correspond to the regime of heavy ion inertial fusion (HIIF) [7]. The experiments with cylindrical targets are important for the applied research too (for example, [8]).

For the experiments with cylindrical targets irradiated by intense ion beams it is necessary to shape the irradiating beam with appropriate (hollow) geometry. There are various methods of hollow beam formation ([8-11]). The method based on the blocking of the central part of the irradiating beam by the absorber requires very high intensity of the initial beam to provide the necessary energy deposition at the target (tens kJ of deposited energy per cm and higher). It results in the problem of initial beam formation and is too much expensive and non-effective. Another method is to apply the plasma lenses to shape the quasi-Bennet distribution of the particles in a beam cross-section. In comparison with the
plasma lens method the wobbling method [8,9] has the advantages of the best experiment condition stability and easy beam control and manipulation. The basic idea of the wobbling method is to apply the deflecting plates with crossed electromagnetic fields which create the beam centroid rotation at the target. In the case of appropriate relation between the angular velocity of the beam centroid rotation and the temporal characteristics of the processes inside the target arising from the target irradiation the beam may be considered as hollow one. In this paper one of the problem of wobbling method application is considered, the results of the beam dynamics simulation are presented.

2. Common principles of the experiment

In dependence on the goal of the experiment and the approach to the target heating (direct or indirect [13]) the various types of the targets are applied, some of which are shown at Figures 1 and 2. The beam-driven heavy ion fusion may be realized with near-relativistic ion beam (the beam energy > 0.5 GeV/u). Heavy-metal (as a rule, Pb) shell, or liner, should be applied to compress the D+T compound (see Figure 1). Multi-layered targets shown at Figure 2 are proposed for the experiments for hydrogen metallization (see, for example, [5]) and extreme matter state research [6,7].

At Figure 3 the principle of wobbling is illustrated ([8]). The harmonically changing electromagnetic field applied to the plates deflects the beam so the beam draws the curve of 2nd order at the target. The energy of the beam, the geometry of the wobbling line and the phase shift between the fields at the field plates determine the shape of the curve. For the specific physical task the combination of parameters exists corresponding to circular motion of the beam centroid at the target.
In all the experiments (HIIF, astrophysical plasma modeling and high density physics) as well as in medical applications (hadron and ion therapy) the following requirements must be fulfilled, namely, the energy deposition at the target must have the azimuthal symmetry as well as axial and longitudinal uniformity [14-16]. These requirements affect the choice of the beam shaper parameters.

3. Dynamics simulation

The symmetry and uniformity of the energy deposition at the target are studied earlier (for example, [17]). Among the studied factors affecting the symmetry and uniformity violation the factor of the field frequency mismatch is found to be of importance [12]. In this Section the results of careful beam dynamics simulation are presented, taking into account the wobbler field frequency mismatch. For the study the following parameters of the target are accepted: the thickness of the irradiated area is 1,0 mm, the radius of irradiated area is 1,6 mm with respect to the target axis (see Figure 2). The parameters of heavy ion beam used for the beam dynamics simulation are presented at the Table 1. Two types of the beam ions are considered with different beam energy with fulfillment the condition of near-relativistic regime: $^{28}_{\text{238}}\text{U}^{2+}$ and $^{59}_{\text{27}}\text{Co}^{27+}$ with 1 GeV/u and 450 MeV/u respectively. The parameters of the beamline are presented at the Table 2. The channel aperture is equal to 100 mm. The maximum field amplitude is taken in accordance with the Kilpatrick limit [18]. Modeling of the dynamics is carried out with the help of TRANSIT code [19]. The basic elements of the beamline simulated are: RF-deflectors and simplest focusing system (triplet of quadropole electromagnetic lenses).

At Figures 4-7 the results of the beam dynamics simulation are presented. At Figures 4 and 5 the transverse beam phase portraits and radial intensity distribution at the focal plane are shown for the case of mismatch frequency absent.

| Table 1. Beam parameters |
|--------------------------|
| Type of the ions         | $^{28}_{\text{238}}\text{U}^{2+}$ | $^{59}_{\text{27}}\text{Co}^{27+}$ |
| Beam energy, MeV/u.      | 1000                          | 450                          |
Particle per bunch (ppb) $10^{12}$ $2 \times 10^{11}$
Normalized effective x-emittance, mm*mrad 25 8
Normalized effective y-emittance, mm*mrad 8 8
Initial beam radius, mm 50 40
Momentum spread, % ±0.5 ±0.5
Particle distribution Gaussian (decoupled) Gaussian (decoupled)
Pulse length, ns 50 120

Table 2. Beamline parameters for the case of $^{27+}_{59}$Co ions with energy 450 MeV/u

| Element       | Length, m | Field amplitude |
|---------------|-----------|-----------------|
| X-deflector   | 1.472     | 1.5 MV/m        |
| Drift         | 0.184     | -               |
| Y-deflector   | 1.472     | 1.5 MV/m        |
| Drift         | 0.800     | -               |
| Lens 1        | 0.400     | 16.34 T/m       |
| Drift         | 0.160     | -               |
| Lens 2        | 0.800     | 15.37 T/m       |
| Drift         | 0.160     | -               |
| Lens 3        | 0.400     | 18.76 T/m       |
| Drift         | 0.194     | -               |
At Figures 6 and 7 the transverse beam phase portraits and the radial intensity distribution at the focal plane are shown for the case of the mismatch between the frequency of the 1st and 2nd deflectors. The value of the “ellipticity” and the ellipse turn angle value depend on the sign and the value of the frequency deviation. At Figures 6 and 7 the case of “negative” mismatch (the frequency of 1st deflector is 297 MHz, the frequency of 2nd 295.5 MHz) is illustrated. Parameter of the “ellipticity” grows linearly with mismatch increase in the range of parameters actual for the experiment. The beam begins to irradiate the external shell and the pusher. It results in the asymmetry of the shock wave formation which converge to the “interval” in transverse plane instead of the “point”, so the experiment requirements (conditions for the beginning of thermonuclear reaction, particularly) may be violated. Additionally, the experiment radiation safety may be violated too.

Fig.4. Transverse beam portrait in the focus plane at the target. RF-frequency of 1st deflector -297.0 MHz, 2nd - 297.0 MHz

Fig.5. Particle distribution in radial direction. RF-frequency of 1st deflector -297.0 MHz, 2nd - 297.0 MHz

Fig.6. Transverse beam phase portrait in the focus plane at the target. RF-frequency of 1st deflector -297.0 MHz, 2nd - 295.5 MHz.

Fig.7. Particle distribution in radial direction. RF-frequency of 1st deflector -297.0 MHz, 2nd - 295.5 MHz.
4. Conclusions

The problem of the beamline creation for the goals of application in experiments with cylindrical targets is discussed. Sharply focused quasi-hollow intense beam may be formed by means of the beamline consisting from two deflectors with harmonic field and focusing optics. During the beamline development possible deflector frequency mismatch appearance should be taken into account to avoid the irradiation symmetry violation which is important for the extreme matter state research and ignition experiments, as well as to avoid the non-effective illumination and radiation safety violation both in fundamental and applied researches.

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