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Dynamics of neutralizing electrons during the focusing of intense heavy ions beams inside a heavy ion fusion reactor chamber *

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Abstract. The efficiency of a Heavy Ion Fusion reactor heavily depends on the maximum value for the density of energy (DoE) that can be deposited by the ion beams. In order to reduce the final beam radius, and thus to increase the DoE inside the target, the beam spatial charge has to be neutralized. Therefore the dynamics of the neutralizing electrons (DNE) play a central role in optimizing the DoE deposited in solid targets by the high current of the high energy heavy ion beams. We present results on some aspects of the DNE, which was performed using the Monte-Carlo 2D1/2 PIC code BPIC.

1. INTRODUCTION

High intensity beams of energetic heavy ions are valuable tools to study high-energy density physics (HEDP) for applications such as inertial fusion energy (IFE) or for basic research (i.e. astrophysics). The energetic ions, as produced by large accelerator facilities, can penetrate deep inside a dense target generating a homogeneous plasma of macroscopic size ($\approx \mathrm{cm} \times \mathrm{mm}^2$) well suited for measuring the properties of dense plasmas. The main problem to access HEDP with a heavy ion beam generated by a high energy accelerator is the level of intensity at the target. For a given energy of a bunch of ions, this intensity is inversely proportional to the duration of the bunch and to the square of the focus radius. A high energy ion beam cannot be manipulated as easily as a laser beam, in particular because of the electrostatic repulsion between the ions that tends to expand the bunch in the longitudinal and transverse dimensions during the acceleration and the focusing of the beam. The reduction of this electrostatic potential during the focusing of the beam up to the target is a central technical issue both for HEDP and IFE, and is presently addressed by several groups (see [1]).

When considering heavy ions, the dynamics during focusing is only sensitive to electrostatic interaction. The reduction of the electrostatic field between the beam ions (EFBI) is obtained by introducing a low density plasma as a neutralizing medium in the target chamber. Here we consider the propagation through a low density gas, with density $\left(\approx 10^{13}\,\mathrm{cm}^{-3}\right)$ comparable to the beam density. Numerical results are given for a standard IFE configuration. Simulations have shown that high gain

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can be obtained only if the radius of the beam at the target is less than a few milimeters, which cannot be reached without highly effective neutralization of the EFBI.

2. RESULTS

2.1 Propagation in vacuum

We consider a beam of radius r_b and define f as the neutralization degree of the beam, computed as the average charge (considering all species)/ion total charge [2]. The average is done over the region covered by the beam, so that even if the beam is globally neutral, f can be less than one. In particular f is a decreasing function of the transverse temperature of the beam electrons. We first consider the optimal case of an initially neutral beam. In Fig. 1 we have represented our results for a typical case of inertial fusion driven by heavy ions. Here, $1/r_b$ is chosen as the x-axis. As this quantity is increased, we follow the beam focusing inside the target chamber. The last point of the curve corresponds to the focal plane. We attribute the decrease of f observed on Fig. 1 in a vacuum chamber to the increase of the transverse temperature of electrons resulting from isentropic compression. The dotted line in Fig. 1 is calculated from the isentropic compression law. In [3] a simple expression was proposed: $r_e = r_b + 3\lambda_D$ **(1)**, where λ_D is the Debye length and r_e is the radius of the electron beam. We see in Fig. 1 that the isentropic law agrees quite well with the full numerical result (red curve). The two other curves on Fig.1 (green and blue), corresponding, respectively, to the cases where the chamber is filled with a low density ($7.5\times10^{12}\,\text{cm}^{-3}$) and high density ($5\times10^{13}\,\text{cm}^{-3}$) gas, demonstrate that a reservoir of cold electrons provides a cooling mechanism for the neutralizing electrons. The reduction of transversal electron temperature contributes to preserving the initial high degree of neutralization.

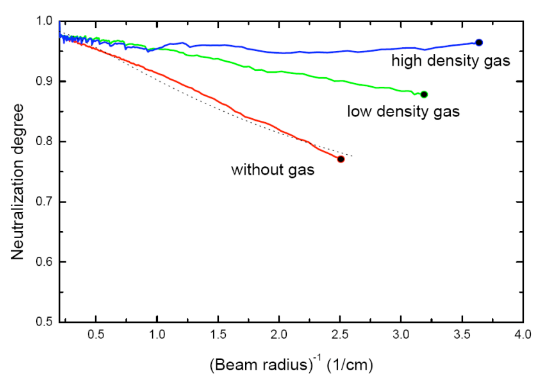

Figure 1 Average neutralization degree and transverse temperature for a 2.5 GeV, 3.8 kA -Xe+ beam focusing over 3 m in a vacuum or in a FLiBe gas. Initial points of the curve corresponds to the entrance of the beam in the chamber (5 cm radius), while the end points of the curves are at the target. The dotted curve was calculated using [3]. The beam is assumed to be initially fully neutralized.

2.2 Trapping of electrons and boundary conditions

We now turn to a more realistic situation where the beam is initially non-neutral. A discharge plasma preformed at the entrance of the chamber is used to neutralize the beam. The influence of boundary conditions in the longitudinal direction is clearly demonstrated in Fig. 2. The curves show a fast increase of f due to the capture of electrons from the discharge plasma. When the beam leaves the preformed plasma, a steep reduction of the neutralization degree takes place, because the external plasma traps some of the electrons close to the beam tail. Later on, the beam starts ionizing the background gas that fills the chamber. A fraction of the electrons in this plasma tail will be picked-up by the beam, thus resulting in an enhancement of the neutralization degree. Note that if the neutralization degree is close to 1, as in the previous section, the enhancement of the neutralization provided by the flux of plasma electrons cannot compensate the isentropic heating. The excess of positive charge in the plasma tail will limit the fraction of electron captured by the beam. By placing a direct connection between the gas chamber and the plasma discharge, the plasma at the tail of the beam are allowed to pick-up electrons from the discharge rather than from the beam. This process improves significantly the focussing.

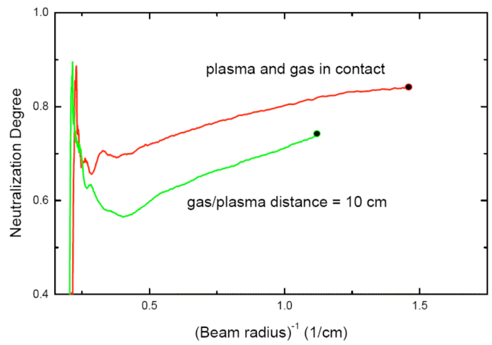

Figure 2 Same as Figure 1 but for different boundary conditions: A gas discharge is used to neutralize the beam (initially non neutral) before it penetrates the target chamber. Two configurations are compared. In the first one (red curve) the plasma discharge is in contact with the gas chamber. A current of electrons can thus exist between the plasma discharge and the background plasma created by the beam. In the second case (green curve) there is a gap of 10 cm between the plasma/discharge and the gas chamber, which prevents the exchange of electrons between the two plasmas.

3. Conclusions

We addressed the influence of the dynamics of the free electrons, created by ionizing of the gas atoms, on the efficiency of neutralisation. We showed two aspects of the electrons dynamics during the focussing. (i) The neutralization degree of an initially well neutralized beam decreases as the beam converges to the target due to the heating of the electrons moving with the beam. We showed that interaction with the background plasma can reduce this heating, thus improving the neutralization and the focusing. (ii) The competition between the beam potential and the plasma potential for trapping the electrons. Ionization of the background gas provides neutralizing electrons, but only a fraction of these electrons is captured by the beam. Without any specific boundary condition, as the beam traps plasma electrons, the plasma tail becomes positively charged. This positive charge will attract the beam electrons, limiting the neutralization. The beam neutralization is improved by placing an external electron source in contact with the plasma tail.

When considering a well neutralized incoming beam, with optimized boundary conditions, we have obtained quite high values for the average neutralization degree. Such values can only by explained by taking into account complex beam-plasma interactions in the longitudinal direction [4].

References

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