3D PIC simulation of ion debris mitigation by B-field for LPP-EUV source

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Abstract. In laser produced plasmas (LPP) for EUV light source, the maximum ion kinetic energy sometime exceeds 10 keV. Such fast ion debris from LPP may cause damage on a collecting mirror of the light source. Therefore the mitigation of the fast ions is one of the critical issues that should be overcome for the practical use of LPP as EUV source for lithography. We have investigated both free plasma expansion and plasma expansion in an external magnetic field by using 3D particle simulation. The maximum ion energy in free expansion is essentially determined from the ratio of initial target radius to initial Debye length. Based on this relation we discuss the possibility to reduce the maximum ion energy. We show that the maximum ion energy perpendicular to the magnetic field is also reduced and that the ion radial flight distance becomes less than the gyro diameter estimated from the maximum energy. We also show that generated electric field causes the interchange instability of the plasma, but the instability is limited within a certain radial region. Simulation results indicate that the fast ions can be efficiently exhausted along the magnetic field without causing crucial damage on an EUV collecting mirror with the use of a single magnetic coil.

1. Introduction
EUV lithography is the most promising technology for producing next generation microprocessors [1], and laser produced plasma (LPP) is an attractive candidate for the light source [2]-[8]. In the scheme of LPP-EUV source, we use radiation of 13.5 nm wavelength from target materials, such as tin and xenon. However fast ion debris from LPP may cause damage on a collecting mirror of the light source. The maximum ion kinetic energy sometime exceeds 10 keV. Therefore mitigation of fast ion debris is one of the most critical issues that should be overcome for the practical use of LPP-EUV source. As a scheme for the mitigation of the fast ion debris, we here consider magnetic field shield (B-field shield). In magnetic field, charged particles perform gyro motion along magnetic field lines. For example, in the case of tin ions with the charge state of $Z = 1$, the energy of $E_i = 10$ keV and the magnetic field of $B = 3$ T, the Larmor radius is $R_{Li} = \sqrt{2m_iE_i/ZeB} \approx 5$ cm. Its diameter is comparable to the distance between the plasma source and the collecting mirror ($\approx 10$ cm). In LPP, since the initial plasma pressure is very large compared with the magnetic field pressure, the interchange instability may be induced during the plasma expansion. In this work, we investigate plasma expansion dynamics by using 3D particle-in-cell (PIC) method. We first study the maximum ion energy in free expansion of a spherical plasma and discuss its dependence on plasma parameters. Secondary we discuss the validity of B-field shield concept in LPP-EUV source.
2. Free expansion and reduction of the ion maximum energy

In LPP, electrons are mainly heated and expand into vacuum. Ions are then accelerated due to the electric field generated by expanding electrons. An analytic model of spherical plasma expansion was presented by using self-similar solution [10], which agreed with experimental results [11]. From the model, the maximum of ion kinetic energy is given by

$$E_{\text{max}} \simeq 2\langle Z \rangle T_e \ln \left( \frac{\Lambda^2}{2} / \ln \frac{\Lambda^2}{2} \right),$$

where $\Lambda = R_0/\lambda_D$ is a plasma size parameter, $R_0$ is initial plasma size and $\lambda_D$ is Debye length, $\lambda_D = (\varepsilon_0 k T_e/n_0 e^2)^{1/2}$, and $n_0$ and $T_e$ are initial density and temperature of electrons. We evaluated the maximum ion kinetic energy for a spherical plasma with uniform density $n_0$ and finite electron temperature $T_e$ and zero ion temperature $T_i = 0$ with the use of 3D PIC. Here we have used the ion-electron mass ratio of $m_i/m_e = 100$ to reduce the simulation time. It should be noted that even if we use a present super computer, it is still very difficult to simulate plasma expansion using real ion-electron mass ratio and real plasma size parameter. Therefore we use here fictitious values with keeping important physics to be the same. By choosing various combinations of the initial $T_e$, $n_0$ and $R_0$, we observed dependence of the maximum ion energy on the plasma size parameter as shown in Fig. 1. The maximum energy is observed at normalized time of $c_{\text{so}} t/R_0 = 1$. Simulation results of the maximum ion energy agree well with the model prediction.

If we consider a spherical target with $4\pi n_0 R_0^3/3 = C$, the plasma size parameter $\Lambda$ is proportional to $(C/R_0)^{1/2}$. It can be thus possible to reduce the maximum ion energy by choosing small $C$ and large $R_0$. It can be realized with the use of a small droplet with the minimum mass for emitting enough EUV power, and a double laser pulse irradiation scheme. The small droplet expands by a prepulse laser irradiation. A main laser pulse is irradiated to heat the preformed plasma after its size reaches large diameter, but small enough to satisfy the etendue limitation (about 1 mm in diameter) for the EUV light source. We can expect that the maximum ion energy can be reduced at least within a few keV with the use of this scheme. Details of the scheme will be discussed elsewhere.

![Figure 1](image1.png)  
**Figure 1.** Comparison of the maximum ion kinetic energy between simulations and the analytic model. Solid line presents the analytical model and triangles are simulation results.

![Figure 2](image2.png)  
**Figure 2.** A snapshot of ion motion. Points show ion positions and a ring represents the single magnetic coil.

3. Plasma expansion in magnetic field

To simulate the expansion of LPP in a magnetic field, we also consider the spherical plasma with the plasma size parameter of $\Lambda \approx 62$ at the center of an external magnetic field generated by a single coil. The ratio of the initial electron pressure to the magnetic pressure is chosen to be $p_{e0}/p_B = n_0 k T_e/(\mu_0 B_0^2/2) \simeq 14$ at the center of the coil. In the study of the plasma expansion...
in a magnetic field, the important physical scales of the problem are the relations among the gyro radii of electrons and ions and initial plasma radius, and also the ratio between the initial plasma pressure and the magnetic pressure. In the application of LPP for EUV light source, the relations of $R_{Le} < R_0 < R_{Li}$ and $p_0/p_B \gg 1$ are hold, where $R_{Le}$ and $R_{Li}$ are electron and ion Larmor radii, respectively. The relations are also satisfied in the simulations.

3.1. Suppression of radial expansion

Fig. 2 shows a snapshot of ion motion at time $c_0 t/R_0 = 7.8$. From the figure, we see that ions move along the magnetic field lines, and are exhausted in the direction along the magnetic field axis. Fig. 3 shows the ion energy spectra divided into two components perpendicular and parallel to the magnetic field at the same time as shown in Fig. 2. We also show the ion energy spectrum in the case without magnetic field for comparison. We can see that the maximum perpendicular energy is reduced, while the maximum parallel energy becomes higher compared with that without magnetic field. With the use of the single coil, most of ions are accelerated along the magnetic field, and the perpendicular energy is reduced.

![Figure 3](image3.png)

**Figure 3.** Energy spectra, spectrum without B-field (dotted line), energy component along the magnetic axis (solid line) and that perpendicular to the magnetic field (dashed line).

![Figure 4](image4.png)

**Figure 4.** Ion radial distributions for $B = 1B_0$ (light gray), $2B_0$ (dark gray) and $3B_0$ (black). Dashed lines correspond to maximum ion gyro diameters $R_D$.

Fig. 4 shows ion radial distributions near the center within the distance $\pm R_0$ along the magnetic axis for different magnetic field intensities of $B = 1B_0$, $2B_0$ and $3B_0$. The radial distributions are observed at time $c_0 t/R_0 = 7.8$ for the case of $1B_0$, 4.3 for $2B_0$ and 3.2 for $3B_0$, when the perpendicular ion energy reaches the maximum value for each case. The dashed line in Fig. 4 corresponds to the gyro diameter $R_D = 2R_{max}$, where $R_{max}$ is the ion maximum Larmor radius estimated from the maximum perpendicular energy for each case. The ion radial flight distance near the center is less than the gyro diameter corresponding to the maximum perpendicular energy. We have observed that the fractions of the ions that flight beyond 90% of the gyro diameter are 0.039%, 0.019% and 0.016% for the cases of $B = 1B_0$, $2B_0$ and $3B_0$, respectively. Therefore the radial flight distance of most of ions is limited to 90% of the maximum gyro diameter.

3.2. Influence of interchange instability

The interchange instability generally occurs during the expansion of high pressure plasmas in a magnetic field [12]. Since the relation of $R_{Le} < R_0 < R_{Li}$ is hold in LPP, electrons perform $E_r \times B$ drift motion, where $E_r$ is the radial electric field induced by ions expanding ahead in the radial direction [13]. Therefore the instability is caused by angular electric field $E_\theta$ generated by the electron drift. Fig. 5 shows the angular distributions of ions and angular electric field $E_\theta$ for the inner radial region ($R < R_{max}$) and the outer radial region ($R > R_{max}$) within a
region of $\pm R_0$ along the magnetic axis. There exists a large angular disturbance of ion density and corresponding angular electric field is generated in the inner region due to the interchange instability. However, no visible disturbances have been observed in the outer region for both ion density and $E_\theta$. Therefore the instability occurs only in the inner region, but not in the outer region. The instability may not be thus crucial problem in the B-field mitigation scheme, if we put a collecting mirror away from the magnetic axis with the distance longer than the maximum ion Larmor diameter.

![Graph](image)

**Figure 5.** Ion angular distributions of ions (a) and angular electric field $E_\theta$ (b) within inner region of $R < R_{\text{max}}$ (black) and in outer region $R > R_{\text{max}}$ (gray) in the case of $B = 1B_0$, where $R_{\text{max}}$ is the maximum ion Larmor radius. Ion distributions in outer region with 100 times magnified scale.

4. Summary
We have investigated plasma expansion dynamics with and without an external magnetic field with the use of 3D PIC simulations, related to the laser produced plasma for EUV light source. The maximum ion energy is shown to be determined from the plasma size parameter. We have also discussed the possibility to reduce the maximum ion energy with the use of a minimum mass droplet target and double laser pulse irradiation scheme. We show that the ion radial flight distance is reduced less than the maximum gyro diameter by applying an external magnetic field. The interchange instability of the expanding plasma occurs only in the inner radial region. Therefore the instability may not cause crucial damage on a collecting mirror, if the mirror locates away from the magnetic axis with the distance longer than the maximum ion gyro diameter. The fast ions can be exhausted along the magnetic field lines efficiently with the use of a single magnetic coil.

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