Expansion of Dense Plasma Formed on Solid Target Exposed to Focused Electron Beam

D.I. Skovorodin[1,2,a)], Yu.A. Trunev[1,2], A.S. Arakcheev[1,2], V.T. Astrelin[1,2], A.V. Burdakov[1,2], V.V. Danilov[1,2], V.V. Kurkuchekov[1,2], D.A. Starostenko[1,2], S.S. Popov[1,2] and S.L. Sinitskiy[1,2]

[1] *Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia*
[2] *Novosibirsk State University, Novosibirsk 630090, Russia*

[a)] Corresponding author: dskovorodin@gmail.com

Abstract. Performance of flash radiography units implies a high spatial resolution. Thus, focused electron beams are utilized to produce bremsstrahlung x-ray at the solid target. Strong heating of the target up to 1-10 eV temperature and formation of dense plasma can lead to beam disruption. In case of multi-pulse operation mode of radiography unit the plasma produced by the first pulse can strongly affect subsequent pulses. In present work we utilize the model of Zeldovich and Raizer to estimate the electron density in the target plasma. The typical parameters of radiography units based on linear induction accelerators is considered. It is shown that electron density in plasma expanding after first pulse is high enough to affect subsequent electron beams.

INTRODUCTION

Flash radiographic units based on linear induction accelerators (LIA) are widely used to study fast processes [1, 2, 3]. Basic principles of flash radiography is illustrated in figure 1. The hard x-ray is produced by converting electron beams on high-Z target. Performance of flash radiography implies a high spatial resolution which requires point-like x-ray source. LIA provide high quality electron beams which can be focused to sub-millimeter spots on the x-ray converters.

One of the major issues in preservation of spot size is interaction of the beam with a target plasma. The target material is strongly heated by an electron beam with power deposition of order of $1kJ/mm^3$. The highly-ionized plasma with density of solid material is formed during the pulse of a accelerator. The plasma can emit positive ions which are extracted by high negative potential of the beam. The ions propagate upstream thus neutralizing the electron beam. It results in strong self-focusing and instabilities development of the incident beam. Several techniques as barrier foils and electrostatic gapping have been suggested to mitigate negative effect of back-streaming ions [4].

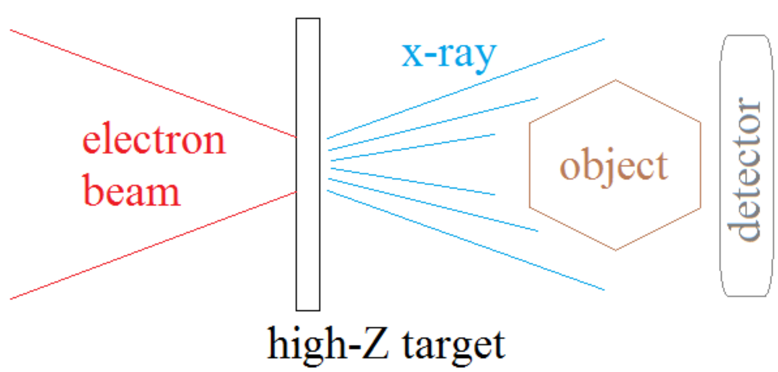

FIGURE 1. Basic principles of flash radiography.

The plasma expands into vacuum after the pulse of electron beam. In case of multi-pulse operation mode of radiography unit the plasma produced by the first pulse can strongly affect subsequent pulses. The interaction of electron beam with plasma cloud strongly depends on its electron density. Although the plasma is highly ionized at first moment it cools down adiabatically during expansion. Thus the plasma should recombine rapidly according to Saha equation. However the recombination rate decreases because of plasma expansion and the degree of ionization could be frozen. Recombinetion kinetic of plasma formed on the target of radiografic unit has been considered earlier [5]. However, in that paper calculations was limited by short time interval about of 2 μs corresponding to DARHT-II parameters. At the same time the regime of long delay between the pulses could be interesting [1]. In present work we utilize the model of Zeldovich and Raizer [6] to estimate the electron density in the target plasma after tens microseconds delay. The typical parameters of radiography units based on linear induction accelerators is considered.

HEATING AND EXPANSION OF TARGET

Interaction of electrons with target material is dominated by multiple scattering, ionization losses and bremsstrahlung. Energy deposition of the beam was calculated using GEANT4 toolbox. The target consist of tantalum with thickness of 0.5 mm was considered. Figure 2 shows depth profile of energy deposition in the target. For electrons with energy of 20 MeV the profile is almost uniform with average deposition of $2.2\frac{MeV}{mm}$. In case of 2 MeV electrons the deposition is concentrated in the first half of target depth with average value of $2.9\frac{MeV}{mm}$.

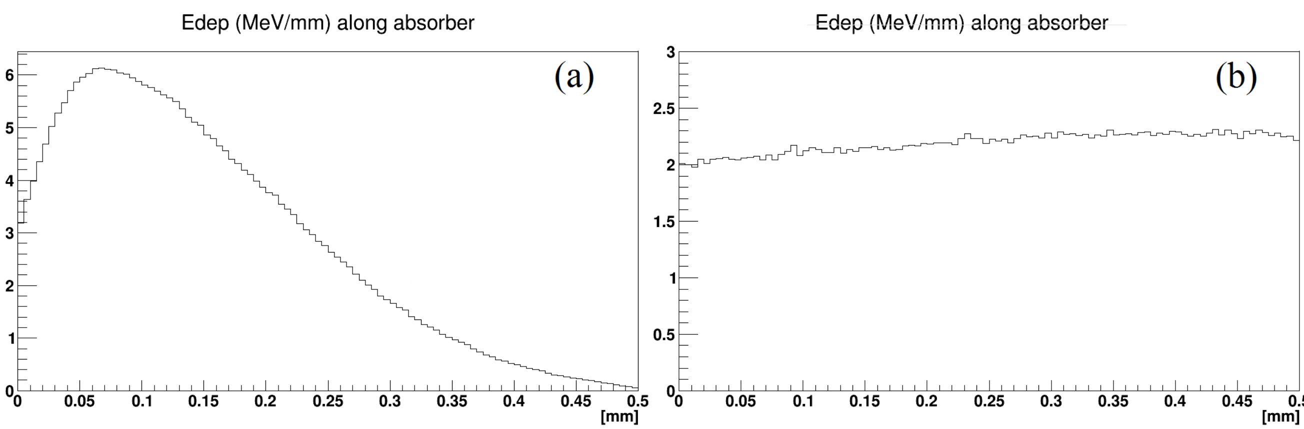

FIGURE 2. Depth profile of energy deposition in tantalum plate irradiated by electrons with energy 2 MeV (a) and 20 MeV (b)

The fact is that the state of target material depends on energy deposition per material atom which depends on the spot size of the beam. Figure 2 illustrates this dependency for the case of 2 MeV accelerator [1, 2]. Despite of the lack of reliably measured beam profiles on the target it is shown that energy deposition of order of $100\frac{eV}{atom}$ can be achieved in radiographic units. Energy deposit is much more than specific heat required for target evaporation. Thus, so high energy deposition results in transition of material to the state of dense plasma [6, 5].

The plasma expands into vacuum because of acceleration by pressure gradient. Comprehensive hydrodynamic modeling have showed that the stage of plasma acceleration occupies few tenths of microseconds [7]. Thus plasma expansion becomes inertial one rapidly. Almost all internal energy of plasma has been transformated to kinetic one. This allows calculating average velocity of plasma expansion:

$$v = \sqrt{\frac{2Q}{m_a}}, \tag{1}$$

where m_a is mass of target material atom. From the equation (1) we obtain velocity of $10^4 \frac{m}{s}$ for $Q = 100\frac{eV}{atom}$. Using this result we can calculate the characteristic dimension of plasma cloud after time interval t as $r(t) \approx v \cdot t$. After the $10\,\mu s$ average plasma dimension is about of $0.1m$ which is comparable with spacing between the target and final focus magnet [4, 1]. As plasma expansion is three-dimensional one we could estimate the density of the cloud using next

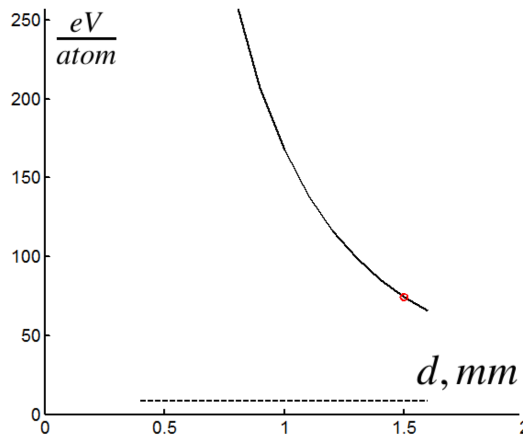

FIGURE 3. Energy deposition Q per material atom vs. spot size of the beam. Dashed line represents specific heat required for target evaporation.

expression:

$$n \approx n_0 \left(\frac{r_0}{v \cdot t} \right)^3, \tag{2}$$

where n_0 is density of solid tantalum, r_0 is characteristic dimension of heated area of the target. Solid line on the Fig. 4 (a) illustrates the dependence of cloud density on the time after beam impact.

FROZEN PLASMA

We use the model of Zeldovich and Raizer to estimate the density of expanded plasma [6]. The model is based on next suggestions:

- the plasma expands inertially after rapid acceleration thus $n \sim t^{-3}$;
- on the first stage of the expansion plasma obey thermodynamical equilibrium;
- the polytropic process equation is used to determine plasma temperature;
- the value of heat capacity ratio $\gamma \approx 1.3$ is used because of rapid recombination of plasma electrons;
- the Saha equation is used to determine equilibrium degree of ionization on this stage;
- after plasma departs from local thermodynamic equilibrium its temperature is low enough to neglect ionization process;
- on this stage the density is still so high that impact (three-body) recombination dominates plasma kinetic;
- at the moment of violation of thermodynamic equilibrium there are not multiple charged ions in the plasma.

The model of Zeldovich and Raizer is based on the next kinetic equation:

$$\frac{d\alpha}{dt} = -bn\alpha^2, \tag{3}$$

where α is degree of ionization, n is total density of atoms and ions and b is recombination constant. The constant b strongly depends on the plasma temperature $b \sim T^{-\frac{9}{2}}$. Thus, asymptotic value for α depends on the plasma cooling regime. If the colling is slow enough α does not tend to zero in the limit $t \to \infty$ and plasma does not totally recombine (so called regime of "frozen of plasma"). If plasma is cooled faster than $T \sim t^{-\frac{10}{9}}$ degree of ionization α tends to zero and plasma completely recombines. The model of Zeldovich and Raizer takes into account plasma heating by recombination itself thus it becomes nonlinear one. Both modes can be implemented depending on the initial conditions.

In present work we use finite-difference method to solve equations of the model. Figure 4 (a) shows the density of plasma electron for $Q = 100\frac{eV}{atom}$ and $30\frac{eV}{atom}$. In first case the density of plasma is still higher then the density of electron beam even after 100 μs after the first pulse. Subsequent pulses injected in plasma cloud likely to be disrupted because of neutralization and instabilities. At the same time decreasing of Q three times cause three order of magnitude reduction of n_e. Figure 4 (b) illustrates dependence of electron density at the moment 20 μs after beam impact on the energy deposition Q. Considered value of Q is close to threshold of "frozen plasma" mode.

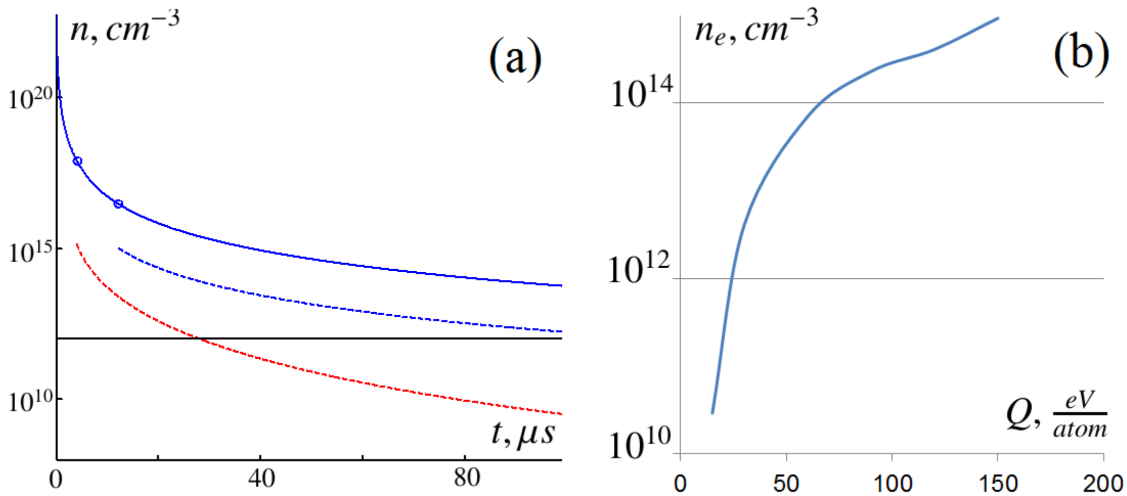

FIGURE 4. Figure (a) shows the density of the cloud vs. time after beam impact. Solid line, blue dashed line and red dashed line represent total density of atoms and ions, electron density for $Q = 100\frac{eV}{atom}$ and for $Q = 30\frac{eV}{atom}$ respectively. Black line illustrates characteristic density of electron beam between the target and final focus magnet. Figure (b) illustrates dependence of electron density at the moment 20 μs after beam impact on the energy deposition Q.

CONCLUSIONS

- It is shown that electron density in plasma expanding after first pulse is high enough to affect subsequent electron beams for the typical parameters of radiography units based on linear induction accelerators.
- The density of expanded plasma strongly depends on initial conditions. There are threshold value of energy deposition per atom of target material for plasma to be frozen. Energy deposition of $Q = 100\frac{eV}{atom}$ is slightly above the threshold.

ACKNOWLEDGMENTS

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