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Scattering of carbon ions in the material of the protective membrane of a fast ignition, indirect compression target without cone

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Abstract

It is shown that scattering of the laser-accelerated carbon ions in the material of the protective membrane of a fast ignition, indirect compression target without cone can result in a significant increase in the hot spot radius and will complicate significantly or even prevent the effective shaping of the bombarded region of the compressed fuel.

Keywords: Fast ignition; Laser-accelerated ions; Scattering; Protective membrane

INTRODUCTION

The targets, proposed for fast ignition scenarios with heating of the hot spot by laser-accelerated ions, usually contain protective membranes or/and cones preventing damage of the ion source by plasma particles and radiation at the stage of compression of the fuel (Atzeni *et al.*, 2002; Barriga-Carrasco *et al.*, 2004; Borghesi *et al.*, 2006; Fernández *et al.*, 2009; Gus'kov, 2001; Honrubia *et al.*, 2009; Key, 2007; Key *et al.*, 2006; Logan *et al.*, 2006; Maynard & Barriga-Carrasco, 2005; Ramis & Ramírez, 2004; Roth *et al.*, 2001; Shmatov, 2003). For the sake of brevity, here and below a target with ion source protected by some region of the hohlraum wall (Ramis & Ramírez, 2004) is described as a target with a protective membrane. Passage of the ions through a protective membrane or/and cone will cause their scattering (Barriga-Carrasco *et al.*, 2004; Key *et al.*, 2006; Maynard & Barriga-Carrasco, 2005; Roth *et al.*, 2001). When these construction elements are partly or completely evaporated, the ions will also be scattered into the evaporated material (Barriga-Carrasco *et al.*, 2004; Maynard & Barriga-Carrasco, 2005).

Barriga-Carrasco *et al.* (2004) and Maynard and Barriga-Carrasco (2005) have shown that if the thickness of the gold membrane of the indirect compression target without a cone is on the order of 10 μm, scattering of protons in the material of the membrane will be very strong. This and the problems related to the gold membranes with the thicknesses on the order of 1 μm were considered as the factors corresponding to the expedience of the use of the targets with the cones.

Key *et al.* (2006) have presented the model according to which scattering of protons in a 10-μm-thick gold layer, placed at the distance $d = 100$ μm from the compressed fuel, does not cause the significant deterioration of the geometry of the hot spot.

Fast ignition scenarios with heating of the hot spot by laser-accelerated ions of some elements with the atomic numbers $Z > 1$ will be more effective than those with heating the hot spot by the laser-accelerated protons (Albright *et al.*, 2008; Fernández *et al.*, 2008, 2009; Gus'kov, 2001; Honrubia *et al.*, 2009; Shmatov, 2003, 2008, 2011). The upper boundary of Z will be determined, first of all, by the existence of the lasers for the sufficiently effective acceleration of the ions and, probably, will achieve at least six (Albright *et al.*, 2008; Fernández *et al.*, 2008, 2009; Honrubia *et al.*, 2009; Shmatov, 2003, 2008, 2011).

Below it is shown that scattering of the carbon ions in the material of the protective membrane of a fast ignition, indirect compression target without cone can be strong and, as a result, in some situations the use of such targets will be inexpedient.

THE LOWER BOUNDARY OF THE TYPICAL ANGLE OF SCATTERING OF IONS

Key *et al.* (2006) estimated the typical angle of scattering of ions in the material of the protective membrane by using the Molière theory. According to this theory, after passage of the

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completely ionized ions of element with the atomic number Z through the uniform foil consisting of atoms of one element with the atomic number Z_f and the atomic mass A_f, the angular distribution of the ions is determined by the parameter

$$\gamma_1[\mathrm{rad}] = \left[\frac{0.157 Z_f (Z_f + 1) Z^2 \times t_f[\mathrm{g/cm^2}]}{A_f \times (pv)[\mathrm{MeV}]}\right]^{1/2}, \qquad (1)$$

where t_f is the surface density of the foil or, in other words, its thickness measured in $\mathrm{g/cm^2}$, p and v are the ion momentum and the ion velocity corresponding to its average kinetic energy ε in the foil, and the parameter B that is the root of the equation $B - \ln B = b$, where

$$b = \ln\left[\frac{6680 \times t_f[\mathrm{g/cm^2}]}{\beta^2} \times \frac{(Z_f + 1) Z_f^{1/3} Z^2}{A_f (1 + 3.34\alpha^2)}\right], \qquad (2)$$

β is the ratio of v to the velocity of light, $\alpha = Z Z_f e^2 / (\hbar v)$, e is the absolute value of the electron charge, and $\hbar$ is the Planck constant (Bethe, 1953; Bichsel, 1963, 1968; Key *et al.*, 2006; Marion & Zimmerman, 1967; Molière, 1948). According to Bichsel (1963, 1968), the Molière theory is applicable at $B \geq 4.5$ (see also Bethe, 1953; Key *et al.*, 2006; Marion & Zimmerman, 1967).

Key *et al.* (2006) used the value $\gamma_0 = \gamma_1 \sqrt{B}$ as the typical angle of scattering of the ions. About 62 to 63% of the scattered ions will have the angle between the vector of the velocity and the initial direction of motion in the range from zero to γ_0, while about 73 to 75% of the scattered ions will have this angle in the range from zero to $1.2\gamma_0$ (Bichsel, 1963, 1968).

The Molière theory describes the situation when the stage of ionization of the material of the foil corresponds to the normal conditions (Bethe, 1953; Bichsel, 1963, 1968; Marion & Zimmerman, 1967; Molière, 1948). In fast ignition scenarios under consideration, the laser-accelerated ions will scatter either in a two-layer obstacle, consisting of the non-ionized and ionized material of the membrane, or, if the membrane is sufficiently thin, in the ionized material of the membrane (Barriga-Carrasco *et al.*, 2004; Maynard & Barriga-Carrasco, 2005; Ramis & Ramírez, 2004). Scattering in the ionized material is stronger than that in the non-ionized one with the same surface density. This can be demonstrated by using the Thomas-Fermi theory. According to this theory, ionization of the atom or an increase in the ionization stage of the isolated positive ion reduces the negative charge density ρ_e, corresponding to the bound electrons, in any space region (see, e. g., March, 1983). A decrease in ρ_e results in reduction of screening of the positive electric charge of the nucleus and, thereby, enhancing of the electric field scattering the moving charged particles. When the ions are placed in the plasma, the electric fields of the nuclei are also screened by the free electrons, but such screening is weaker than that by the bound electrons. Note that in the Molière theory the atoms of the scattering foil are being described within the framework of the Thomas-Fermi theory (Bethe, 1953; Molière, 1948). Note also that Maynard and Barriga-Carrasco (2005) presented the results of the computer simulation of the effects related to density and temperature of the foil scattering protons.

Thus, when the whole membrane or its layer is ionized and t_f is known, γ_0 can serve as the lower boundary of the typical angle of scattering of the ions in the material of the membrane.

When calculating t_f, it is convenient to use the formula $t_f = k_{ex}\, \rho_m\, l_\mathrm{m}$, where k_{ex} is a coefficient taking into account a possible decrease in the surface density of the ionized material due to its transversal expansion, ρ_m is the density of the membrane, and l_m is its initial thickness. Since the expansion of the membrane material will occur mainly in the direction that is perpendicular to the membrane surface, k_{ex} will probably not be less than 0.5 to 0.7 even if the special measures to reduce it are taken and in some cases will be close to unity (see Barriga-Carrasco *et al.*, 2004; Maynard & Barriga-Carrasco, 2005; Pert, 1979; Ramis & Ramírez, 2004; Taylor, 1987).

REQUIREMENTS ON COMPOSITION AND MINIMUM THICKNESS OF THE GOLD PROTECTIVE MEMBRANE OF THE TARGET WITHOUT CONE WITH THE EQUIMOLAR D-T FUEL

The protective membrane of the target without cone will be influenced by the compressing radiation (Albright *et al.*, 2008; Barriga-Carrasco *et al.*, 2004; Fernández *et al.*, 2008, 2009; Honrubia *et al.*, 2009; Maynard & Barriga-Carrasco, 2005; Ramis & Ramírez, 2004; Roth *et al.*, 2001). Making such a membrane of one or several low-Z elements or such elements and small amount of the high-Z element(s) is inexpedient. The main reasons are the following. The influence of the compressing radiation on such membrane would result in formation of a rather large plasma cloud (see, e. g., Eidmann *et al.*, 1995) and the necessity to prevent damage of the fuel capsule by this cloud. Also the motion of the non-evaporated part of the membrane toward the ion source under the influence of the ablative pressure would result in the necessity to place the ion source at the relatively long, on the order of 1 mm, distance d_1 from the membrane (see also Borghesi *et al.*, 2006; Ramis & Ramírez, 2004). When using at least some of the methods of acceleration of the ions, this would cause the strong deterioration of focusing of the ions on the ion source (see, e. g., Gus'kov, 2001; Shmatov, 2003).

Thus, the protective membrane being influenced by the compressing radiation should be made of the high-Z element(s). According to Borghesi *et al.* (2006) and Roth *et al.* (2001), if the material of the membrane has the usual solid-state density, l_m should be on the order of 10 μm (here and below the target parameters, which can depend on the composition of the fuel, correspond to the equimolar

D-T fuel). For example, Roth *et al.* (2001) described the gold membrane with $l_m = 30$ μm. Barriga-Carrasco *et al.* (2004) and Maynard and Barriga-Carrasco (2005) analyzed operation of the gold membranes with l_m from 1.5 to 46.5 μm. At $l_m = 3$ μm, the membrane side that faces the proton source would be heated to the temperature of about 190 eV and, as a result, d_1 must be at least of 7 cm (Barriga-Carrasco *et al.*, 2004). Such values of d_1 seem to be unacceptable, because they impose the very hard requirements on the smallness of spreads of the directions and absolute values of the initial ion velocities (see also Atzeni *et al.*, 2002; Barriga-Carrasco *et al.*, 2004; Gus'kov, 2001; Maynard & Barriga-Carrasco, 2005; Shmatov, 2003).

The requirements on the composition and minimum thickness of the protective membrane of the indirect compression target without cone seem to be close to those on these parameters of the layer confining radiation in hohlraum of this target. The results of computer simulation of operation of the walls of such hohlraums confirm that at least when the maximum compressing radiation temperature $T_{rad}^{\max}$ is about 300 eV, l_m of the gold membrane should be on the order of 10 μm. For example, Ramis and Ramírez (2004) have described the situation when $T_{rad}^{\max} = 329$ eV and evaporation of 30% of the material of the gold wall with the initial thickness of 40 μm occurs. Note that many of the parameters describing operation of the membrane, made of the low-Z element(s) or containing large amount of the low-Z elements, would be close to those describing operation of the ablators of the indirect compression targets.

EXAMPLES OF THE TYPICAL ANGLES OF CARBON ION SCATTERING AND THE IMPORTANCE OF THIS EFFECT

The examples of γ_0 for scattering of $^{12}\mathrm{C}^{+6}$ ions with 100 MeV $\leq \varepsilon \leq$ 825 MeV in the gold membranes with $\rho_m = 19.32\ \mathrm{g/cm^3}$ (see, e. g., Berdonosov, 1990) and k_{ex} $l_m =$ 10, 20, 30, and 40 μm are presented in Table 1. The chosen range of ε coincides approximately with the range of carbon ion kinetic energies in fast ignition scenarios considered by Albright *et al.* (2008), Fernández *et al.* (2008, 2009), Honrubia *et al.* (2009), and Shmatov (2003, 2008, 2011).

At $\gamma_0 \ll 1$ rad, the typical displacement Δ of the point of hit of the ion on hot spot due to scattering is about $\gamma_0 d$ (Key *et al.*, 2006).

According to Atzeni and Tabak (2005), the sum E_{hs} of the kinetic energies of the ions hitting the hot spot should obey the condition

$$E_{hs} \geq E_{hs}^{opt} \times \max(1, R/R_0) \times f_r(r_{hs}), \tag{3}$$

where E_{hs}^{opt} [kJ] $= 140(\rho\ /100\ \mathrm{g/cm^3})^{-1.85}$, ρ is the density of the fuel at the stage of heating the hot spot, R is the range of the ion in the hot spot, $R_0 = 1.2\ \mathrm{g/cm^2}$, r_{hs} is the hot-spot radius,

$$\begin{aligned} &f_r(r_{hs} \leq r_{opt}) = 1, f_r(r_{opt} \leq r_{hs} \leq 2.5r_{opt}) = r_{hs}/r_{opt}, \\ &f_r(r_{hs} \geq 2.5r_{opt}) = 0.4(r_{hs}/r_{opt})^2, \\ &r_{opt}[\mu\mathrm{m}] \approx 60[\rho/100\,\mathrm{g/cm^3}]^{-0.97} \end{aligned} \tag{4}$$

(see also Atzeni, 1999; Shmatov, 2011; Tabak *et al.*, 2006). Here it is assumed that the spread of the ion ranges is small, the hot spot is transversally uniform, and the ion stopping power in the hot spot is uniform.

The data from Table 1 and Eqs. (3) and (4) yield that in the scenarios with the transversally uniform hotspot, the importance of scattering of carbon ions in the protective membrane of the indirect compression target without cone at the realistic l_m, ε, and d depends strongly on ρ or, in some situations, on both ρ and the parameters of ion beam before its passage through the membrane.

Let us consider the examples with two values of ρ. Albright *et al.* (2008) and Fernández *et al.* (2008, 2009) described the scenarios with a relatively low ρ of $150\ \mathrm{g/cm^3}$, the fuel capsule radius $r_c = 730$ μm, the external and internal radii of the D-T ice in the fuel capsule of 580 μm and 330 μm, respectively, and bombardment of the compressed fuel by two counter-propagating beams of carbon ions with the energy spread of ±10%. The highest capsule gain corresponded to the average ion kinetic energy of about 440 MeV (Fernández *et al.*, 2009). The radius r_b^{main} of the main, i. e., high-density, region of the blob of the compressed fuel in the scenarios under consideration is about 60 μm. Let us assume that the thermal radiation compressing the fuel capsule is generated by the laser beams, the internal radius R_h^{int} of the hohlraum equals $2.56r_c \approx 0.187$ cm (Tabak *et al.*, 2006), the internal surface of the protective membrane coincides with the internal surface of the hohlraum wall, and

$$d \approx R_h^{\mathrm{int}} - r_b^{main} \approx 0.18\,\mathrm{cm} \tag{5}$$

Table 1. *Some values of* γ_0 [rad] *for scattering of* $^{12}\mathrm{C}^{+6}$ *ions in gold*

ε, MeV → k_{ex} l_m, μm ↓	100	150	200	400	500	825
10	2.54×10^{-2}	1.70×10^{-2}	1.28×10^{-2}	6.43×10^{-3}	5.17×10^{-3}	3.17×10^{-3}
20	3.78×10^{-2}	2.53×10^{-2}	1.90×10^{-2}	9.58×10^{-3}	7.70×10^{-3}	4.73×10^{-3}
30	4.76×10^{-2}	3.18×10^{-2}	2.39×10^{-2}	1.21×10^{-2}	9.69×10^{-3}	5.95×10^{-3}
40	5.60×10^{-2}	3.74×10^{-2}	2.81×10^{-2}	1.42×10^{-2}	1.14×10^{-2}	7.00×10^{-3}

Using Eqs. (4) and (5) and the data from Table 1, we obtain r_{opt} ($\rho = 150\ \mathrm{g/cm^3}$) ≈ 40 μm

$$\Delta(\varepsilon = 400 \text{ to } 500\,\mathrm{MeV},\ k_{ex} l_m = 10\,\mu\mathrm{m}) \approx 9 \text{ to } 12\,\mu\mathrm{m} \approx (0.23 \text{ to } 0.29) r_{opt}, \tag{6}$$

$$\Delta(\varepsilon = 400 \text{ to } 500\,\mathrm{MeV},\ k_{ex} l_m = 40\,\mu\mathrm{m}) \approx 21 \text{ to } 26\,\mu\mathrm{m} \approx (0.51 \text{ to } 0.63) r_{opt}, \tag{7}$$

According to Eq. (3), Eq. (6) describes a relatively weak scattering of the ions in the protective membrane, while the importance of scattering described by Eq. (7) depends on the transversal size of the ion source and the distribution of the directions of the ion velocities before passage of the ions through the membrane. This distribution is determined by the spread of the directions of the initial velocities of the ions accelerated in the regions with the small transversal sizes and, in some situations, by the measures undertaken to focus the ions (see also Borghesi *et al.*, 2006; Gus'kov, 2001; Key *et al.*, 2006; Roth *et al.*, 2001; Shmatov, 2003).

Ramis and Ramírez (2004) described the scenario with $\rho = 400\ \mathrm{g/cm^3}$, the D-T fuel mass of 0.8 mg, that corresponds to $r_b^{main} \approx 78\ \mu\mathrm{m}$, $R_h^{int} = 0.28$ cm and heating of the hot spot by the laser-accelerated protons passing through the 40-μm-thick gold hohlraum wall. Let us consider the scenario that is almost the same but the hot spot is heated by laser-accelerated carbon ions with ε ≈ 500 or 825 MeV.

Assuming that $d \approx R_h^{int} - R_b^{main} \approx 0.27$ cm, $k_{ex} \approx 1$ and using the data from Table 1 and Eq. (4), that yields $r_{opt}(\rho = 400\ \mathrm{g/cm^3}) \approx 16\ \mu\mathrm{m}$, we obtain

$$\Delta(\varepsilon = 500\,\mathrm{MeV}) \approx 31\,\mu\mathrm{m} \approx 2 r_{opt}, \tag{8}$$

$$\Delta(\varepsilon \approx 825\,\mathrm{MeV}) \approx 19\,\mu\mathrm{m} \approx 1.2 r_{opt}, \tag{9}$$

Eqs. (8) and (9) describe the important scattering of the ions in the protective membrane (see Eq. (3)).

Shaping the bombarded region of the compressed fuel can provide a significant decrease in the minimum acceptable value of E_{hs} compared with that corresponding to the transversally uniform bombarded region (Atzeni & Tabak, 2005; Temporal *et al.*, 2009). In the effective scenarios of such a kind, the difference between the typical outer and inner radii of the ring-shaped bombarded region should probably be about 10 μm (see, e.g., an example presented by Temporal *et al.* (2009)). This corresponds to the acceptable values of Δ for a few microns. The data from Table 1 and Eqs. (1), (2), (6)–(9) show that for the indirect compression targets without cones with heating the compressed fuel by carbon ions, the realization of such values of Δ will be difficult or even impossible.

SOME MEASURES TO MINIMIZE THE TYPICAL ANGLE OF SCATTERING OF IONS

In some situations the optimization of the ignition scenario can include the measures to minimize the typical angle of scattering of ions.

A decrease in γ_0 with increasing ε (see Eqs. (1), (2), (8), (9), and Table 1) can be one of the factors determining the optimum typical kinetic energies of the laser-accelerated ions. Note that other factors that can result in the expedience of acceleration of the ions to the relatively high kinetic energies were considered by Albright *et al.* (2008), Fernández *et al.* (2008, 2009), Honrubia *et al.* (2009), and Shmatov (2011).

The minimization of the typical angle of scattering of the ions by means of the optimization of composition and/or density of the protective membrane can also be expedient (see Callahan-Miller & Tabak, 2000; Rosen & Hammer, 2005; Wilkens *et al.*, 2007). For example, Wilkens *et al.* (2007) describe the hohlraum wall, the main region of which has the thickness of about 7 μm, and consists of 185 pairs of 30-nm-thick layers of uranium and 8.2-nm-thick layers of gold. The average composition of this "cocktail" wall region corresponds to the formula $U_{0.75}Au_{0.25}$ (Wilkens *et al.*, 2007). The sum of the thicknesses of the uranium and gold layers in this region are about 5.55 μm and 1.52 μm, respectively. Using Eqs. (1) and (2), it is possible to show that scattering of $^{12}C^{+6}$ ions with ε on the order of 100 MeV in the 5.55-μm-thick layer of uranium is being described by approximately the same value of γ_0 as scattering of such ions in the 5.79-μm-thick layer of gold. Thus, scattering of carbon ions in the "cocktail" layer under consideration is equivalent to that in the 7.3-μm-thick layer of gold. Note that for such a gold layer γ_0 ($\varepsilon = 500$ MeV) $\approx 4.3 \times 10^{-3}$ rad.

A decrease in the typical angle of scattering of the ions can also be achieved by means of increasing the atomic number of the element the ions of which heat the hot spot. For example, Eqs. (1) and (2) yield that for scattering of the $^{64}Z^{+30}$ ion with ε = 3900 MeV in the gold membrane with $k_{ex}\ l_m = 40\ \mu\mathrm{m}$, $\gamma_0 \approx 7.37 \times 10^{-3}$ rad. The chosen value of ε corresponds to $R \approx 1.2\ \mathrm{g/cm^2}$ at $\rho = 500\ \mathrm{g/cm^3}$ and the electron temperature $T_e = 12$ keV (Shmatov, 2008; here and below R is calculated according to the model of Bychenkov *et al.* (2001)). These values of R,ρ, T_e, and $k_{ex}\ l_m$ also correspond to ε ≈ 143 MeV, $\gamma_0 \approx 3.93 \times 10^{-2}$ rad for the $^{12}C^{+6}$ ions (see also Shmatov, 2008). However, it should be emphasized that the effective acceleration of the ions of elements with the relatively high Z, for example, with $Z \geq 20$, may be accompanied by the serious technical difficulties (see Albright *et al.*, 2008; Bychenkov *et al.*, 2001; Borghesi *et al.*, 2006; Fernández *et al.*, 2008; Honrubia *et al.*, 2009; Shmatov, 2008).

CONCLUSION

When using thermonuclear microexplosions for power production, scattering of the laser-accelerated carbon ions in the material of the protective membrane of a fast ignition, indirect compression target without cone will be acceptable only if ρ is relatively low, for example, about 200 g/cm^3 or less. For the scenarios with shaping the bombarded region of the compressed fuel, the problems related to scattering of the laser-accelerated ions of carbon and other elements in the protective membranes of the indirect compression targets are especially important.

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