Factors determining the choice of the laser-accelerated ions for fast ignition

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Abstract. Some problems related to fast ignition by the laser-accelerated ions of elements with the atomic numbers $6 \leq Z \leq 30$ are considered. It is shown that for these values of $Z$ the radiative losses from both the hot spot and the ion source and the ionization losses in the ion source are acceptable. The methods for cleaning the ion source of the fast ignition thermonuclear target from protons are proposed.

1. Introduction
Fast ignition can be realized when heating the compressed fuel by the laser-accelerated ions [1-11]. To provide the possibility and the high efficiency of such a scenario, the flux and, therefore, the source of the ions should obey several requirements. The intensity $I_{\text{bomb}}$ of bombardment of the hot spot should be sufficiently high, while the ranges $R$ of the ions in it should be sufficiently short [1-10,12]. The latter means that the typical kinetic energy $\varepsilon_{\text{typ}}$ of the ion should be sufficiently low [1-6]. Both $\varepsilon_{\text{typ}}$ and the intensity of the ion flux near the source increase with the intensity and, probably, duration of irradiation of the source [2,3,8,10]. Therefore, in some situations $I_{\text{bomb}}$ and $R$ will be acceptable only if the bombarding ions are focused [1,5-10]. The necessity of focusing results in the difficulties related to a decrease in $I_{\text{bomb}}$ due to the spread of the ion velocities and the divergence of the ion flux [1,5].

The necessity of focusing disappear when the atomic number $Z$ of the element, the ions of which heat the hot spot, is sufficiently high (here it is assumed that the compressed fuel density $\rho$ is of the order of 100 g/cm$^3$ or higher) [5,6,10]. The reason is that the main dependence of $R$ on $Z$ is being described by the factor that equals $Z^{-2}$ or is about this value (see Refs. [2,3,5,6] and below). The absence of the necessity to focus the ions will simplify space modulation of heating the hot spot [10]. Such a modulation may provide a substantial decrease in the energy necessary to heat the hot spot [13]. An increase in $Z$, at least up to about 6, will also improve the ion generation efficiency [3,5,10].

The maximum acceptable value of $Z$ is limited by the necessary to provide the sufficiently low radiative losses of energy [2,5,6] and other factors. Some of these factors and the problems related to the effective acceleration of the ions of elements with $Z > 1$ are considered below.

2. The acceptable typical kinetic energies of the laser-accelerated ions
It is convenient to begin the quantitative analysis of the problems, related to the choice of the laser-accelerated ions for heating the hot spot in the D-T fuel, from calculating the ion kinetic energy $\varepsilon$ corresponding to the condition
where $T_e$ is the electron temperature (see also Refs. [3,5,6,12]).

Let us describe the range of the ion of the isotope with the atomic mass $A$ in the D-T fuel by

$$R(\varepsilon, \rho, T_e = 12 \text{ keV}) = 1.2 \text{ g/cm}^2,$$

where $T_e$ is the electron temperature (see also Refs. [3,5,6,12]).

Equation (2) is similar to an equation presented in Ref. [3], the difference is that here $Z'$ can differ from $Z$. In many situations motion of the ion with $Z' \neq Z$ in the hot spot will result in its quick stripping [6]. It is possible that if $Z$ is sufficiently high, $Z' = Z'$ (or 2) during the whole process of deceleration of the ion in the hot spot, but this problem requires the special studies. In any case, (2) allows us to demonstrate that the possible difference of $Z'$ from $Z$ at the high $Z$ is not very important.

For several ions, the ion kinetic energies $\varepsilon_3$ and $\varepsilon_5$, corresponding to (1), (2) and $\rho$ of 300 or 500 g/cm$^3$, respectively, and the ratios $\varepsilon_{3(5)}/Z'$ are shown in table 1.

The real $R$ may differ from that being given by (2) (see also Refs. [14,15]). For the analysis of the importance of such a difference for the conclusion about the acceptability of the radiative losses, the ion kinetic energies $\varepsilon'$ and $\varepsilon''$, corresponding to (2), the condition $R(\varepsilon, \rho, T_e = 12 \text{ keV}) = 0.8 \text{ g/cm}^2$ and $\rho$ of 300 or 500 g/cm$^3$, respectively, are also shown in table 1. These energies can be considered as those corresponding to (1) and the assumption about a 1.5-fold underestimation of $R$ by (2).

### Table 1. Examples of $\varepsilon_{3(5)}$, $\varepsilon_{3(5)}/Z'$ and $\varepsilon'_{3(5)}$

| Ion   | $^{12}\text{C}$ | $^{23}\text{Na}$ | $^{27}\text{Al}$ | $^{28}\text{Si}$ | $^{39}\text{K}$ | $^{39}\text{Kr}$ | $^{65}\text{Zn}$ | $^{65}\text{Zn}$ | $^{65}\text{Zn}$ |
|-------|-----------------|-----------------|-----------------|-----------------|----------------|----------------|----------------|----------------|----------------|
| $\varepsilon_3$, MeV | 155 | 594 | 846 | 997 | 1416 | 1608 | 1804 | 1752 | 3665 | 3910 | 4154 |
| $\varepsilon_3/Z'$, MeV | 25.8 | 54.0 | 65.1 | 71.2 | 83.3 | 89.4 | 95.0 | 87.6 | 130.9 | 134.8 | 138.5 |
| $\varepsilon_3$, MeV | 143 | 549 | 784 | 927 | 1312 | 1496 | 1684 | 1601 | 3424 | 3661 | 3898 |
| $\varepsilon_3/Z'$, MeV | 23.8 | 50.0 | 60.3 | 66.2 | 77.2 | 83.1 | 88.6 | 80.0 | 122.3 | 126.3 | 130.0 |
| $\varepsilon'$, MeV | 75.8 | 314 | 463 | 559 | 794 | 927 | 1066 | 929 | 2263 | 2451 | 2642 |
| $\varepsilon''$, MeV | 69.1 | 286 | 422 | 510 | 722 | 845 | 975 | 833 | 2071 | 2449 | 2429 |

### 3. Radiative and ionization losses of energy

For the D-T fuel cooling by the inverse Compton effect (see, e.g., Ref. [16]) is not important. Therefore, the upper boundary of the bremsstrahlung radiation losses, related to “doping” the hot by the bombarding ions, can be found using the approximation of the optically thin plasma [5,6].

Let us consider the product of the bremsstrahlung radiation intensity $I_{br}^{\text{max}}$ that corresponds to one totally ionized immovable ion, immersed into the fuel with $T_e = 12$ keV, on the optimum time $t_{opt}$ of bombardment of the fuel. Using the times $t_{opt}(\rho = 300 \text{ g/cm}^3) = 21 \text{ ps}$ and $t_{opt}(\rho = 500 \text{ g/cm}^3) = 14 \text{ ps}$
(see Ref. [12]) and describing \( I_{br}^{max} \) in the Born approximation (see Refs. [5,17]), we obtain 
\[
(I_{br}^{max} t_{opt})(\rho = 300 \text{ g/cm}^3) [\text{MeV}] = 1.76 \times 10^{-2} Z^2, \quad (I_{br}^{max} t_{opt})(\rho = 500 \text{ g/cm}^3) [\text{MeV}] = 1.95 \times 10^{-2} Z^2.
\]

In many situations the acceptability of the radiative losses due to the bound-bound transitions in the bombarding ions immersed into the fuel can be demonstrated using the model taking into account only the 2p-1s transitions in the hydrogen-like ions [6]. The reason is that even these transitions turn out to be rather slow and, as a result, the emission power corresponding to them turns out to be relatively low. At least at \( Z \leq 30 \), “the reserve of smallness” of this power shows that both the changes of the bound state energies and transition rates due to the influence of the free electrons and binding of two or more electrons with one nucleus cannot result in a “catastrophic” increase in the radiative losses.

In a cavity filled with thermal radiation with the temperature \( T_R \), a hydrogen–like ion in the 2p state is a radiation source with the power \( P_z = P_z^{sp} [1 + 1/\exp(\Delta E/T_R)] \), where \( P_z^{sp} = Z^6 \times 1.01 \times 10^{-9} \text{ W} \) is the power of the spontaneous radiation and \( \Delta E = Z^2 \times 10.2 \text{ eV} \) [6] (see also Ref. [18]).

For elements mentioned in table 1, the values \( I_{br}^{max} t_{opt} \) and \( P_z(T_R = 12 \text{ keV}) t_{opt} \) are shown in table 2. Comparison of the sum of these values with \( \epsilon_{3(5)} \) and \( \epsilon'_{3(5)} \) shows that in all of the situations under consideration the radiative losses from the compressed fuel will be acceptable if \( \epsilon_{opt} \) corresponds to \( R(T_e = 12 \text{ keV}) = 1.2 \text{ g/cm}^2 \) and even to some lower values of \( R(T_e = 12 \text{ keV}) \). This conclusion is valid even if (2) underestimates \( R \) significantly. Note, however, that at least at \( Z \) up to about 6 the covariance of \( I_{bomb} \) with \( R(\epsilon = \epsilon_{opt}) \) is very strong [5] (see also Refs. [3,6]).

| Element | C | Na | Al | Si | K | Zn |
|---------|---|----|----|----|---|----|
| \((I_{br}^{max} t_{opt})(\rho = 300 \text{ g/cm}^3) , \text{ MeV}\) | 0.63 | 2.1 | 3.0 | 3.4 | 6.4 | 16 |
| \((I_{br}^{max} t_{opt})(\rho = 500 \text{ g/cm}^3) , \text{ MeV}\) | 0.70 | 2.4 | 3.3 | 3.8 | 7.0 | 18 |
| \(P_z(T_R = 12 \text{ keV}) t_{opt}(\rho = 300 \text{ g/cm}^3) , \text{ MeV}\) | 0.21 | 2.4 | 4.8 | 6.5 | 24 | 180 |
| \(P_z(T_R = 12 \text{ keV}) t_{opt}(\rho = 500 \text{ g/cm}^3) , \text{ MeV}\) | 0.14 | 1.6 | 3.2 | 4.3 | 16 | 120 |

The acceptability of the radiative losses from the ion source can be demonstrated describing the bremsstrahlung radiation, emitted by the electron with the kinetic energy \( \epsilon_e = \epsilon_{3(5)}/Z' \) or \( \epsilon'_{3(5)}/Z' \) in the Born approximation [5] (see also Refs. [3,17]). For example, this approximation yields that if the electron with \( \epsilon_e = (\epsilon_3 / Z') (^{64}\text{Zn}^{166}) = 138.5 \text{ MeV} \) (see table 1) moves in a solid zinc or zinc plasma with the same density, its radiative losses of energy on the path of 100 \( \mu \text{m} \) are about 1.1 MeV. Such radiative losses are quite acceptable. It is possible to show that at the lower \( Z \) the radiative losses from the ion source are less important.

Probably, for fast ignition by any laser-accelerated ions the losses of energy due to ionization of the material(s) of the ion source by the high-energy electrons will be low. For example, the ionization losses of energy of the electron with \( \epsilon_e = 138.5 \text{ MeV} \) in a solid zinc are about 15 MeV/cm [19].

4. **Some problems related to acceleration of the ions of elements with \( Z > 1 \)**

Usually, it is assumed that the effective acceleration of the ions of elements with \( Z > 1 \) by laser radiation is possible only when the region of the acceleration contains practically no protons [8,11,20]. To satisfy this condition in fast ignition target, the special measures will be necessary (see also Ref. [11]). For example, the following seems to be possible. Before assembling the target, the ion source can be cleaned from the light isotope of hydrogen and/or the chemical containing it and, if necessary,
influenced by D, or/and T, or/and the chemicals containing D or/and T. The later can probably prevent or at least delay sufficiently the “contamination” of the ion source by protons during the time period between its cleaning and use. Note that this period can be rather short. In some of the targets with two cones (see, e.g., Ref. [13]) one of the cones can provide the irradiation of the ion source by the “cleaning” laser beam(s) just before or/and during the implosion.

The effective cleaning of the ion source of the fast ignition thermonuclear target from a sufficiently small amount of protons can probably occur “spontaneously”. It is possible that the sufficiently long time of bombardment of the hot spot can be provided only by the successive irradiation of the different regions of the ion source [5]. The influence of the photons, electrons and ions, emitted by the hot spot, on the unused regions of the ion source can be both negative [1,2,5,6] and positive. The positive influence can be related, first of all, to an increase in the ionization stage of the ions of elements with relatively high Z at the stage of their acceleration. Cleaning the unused regions from protons may also be possible. Note that the plasma, arising from the unused region of the ion source due to the influence of photons from the hot spot, will expand during heating the hot spot on the distance of a few μm [6] or even less. Note also that at the relatively low \( T_e \) (for example, at \( T_e \leq 2.9 \text{ keV} \) for \( \rho = 500 \text{ g/cm}^2 \) or \( T_e \leq 3.5 \text{ keV} \) for \( \rho = 300 \text{ g/cm}^2 \)), heating the hot spot by the unfocused laser-accelerated protons, deuterons and tritons can be effective, i.e., both sufficiently high \( I_{\text{comb}} \) and sufficiently short \( R \) can be provided (see also Refs. [1,3]).

5. Conclusion
The optimum scenario of fast ignition of the D-T microexplosions by the laser-accelerated ions will probably include bombardment of the hot spot by the ions of the element(s) with Z of about 10 or even greater at least at the relatively high \( T_e \).

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