Interaction Physics of the Fast Ignitor Concept

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The interaction of relativistic electrons produced by ultrafast lasers focusing them on strongly precompressed thermonuclear fuel is analytically modeled. Energy loss to target electrons is treated through binary collisions and Langmuir wave excitation. The overall penetration depth is determined by quasielastic and multiple scattering on target ions. It thus appears possible to ignite efficient hot spots in a target with density larger than 300 g/cm^3. [S0031-9007(96)01191-X]

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Since its inception [1] in 1994, the so-called fast ignitor scenario (FIS) proposed to ease the indirect drive approach to inertial confinement fusion [2] of hollow pellet containing the thermonuclear fuel deuterium + tritium (DT) has been the object of many intensive investigations.

Most of them, conducted through numerical simulations [3–5], have already addressed basic issues concerning the capability of ultrafast lasers with irradiance $I \geq I_{18} \equiv 10^{18}$ W/cm^2, to bore a channel in the corona of the precompressed target fuel. The latter is expected to be prepared through powerful lasers [2] or intense heavy ion beams [6] suitably synchronized. This novel and time segmented scenario [1] has to be appreciated as the latest sophistication elaborating upon the already overexploited disparity between the cheap compression cost ($\sim n^{2/3} \sim 1.1 \times 10^7$ J/g) of strongly degenerate Fermi electrons and the high toll requested for plasma heating ($\sim 6 \times 10^8$ J/g). In these regards, a very significant improvement previously introduced is the hot spot ignition of a small fraction (a few percent only) of the cold compressed fuel [2].

Our main concern in the present work is to investigate analytically within a simple model the coupling [7] to a precompressed target of the relativistic electron beams (REB) in the MeV energy produced by the ultrafast lasers currently under development with a supercompressed DT fuel [8]. More specifically, we intend to critically investigate the REB capabilities to igniting hot spots well localized within the overall spherically, supercompressed DT.

Following recent numerical simulations [3–5], we take it for granted that the REB propagation may be approximated in a cylindrical geometry on an acceleration distance $\sim$200 μm through a very steep density gradient [9]. Nonetheless, we shall work our model in a homogeneous approximation with a fixed beam density n_b and a target plasma density n_p. Here we are striving for proof of principle arguments rather than for quantitative accuracy.

The REB interaction physics contemplated here looks like a remake of a very similar one envisioned in the mid seventies [10] for a REB direct driven compression. However, the present targets are at least 500 times more dense than the former ones. In order to coordinate their proposal, Tabak *et al.* [1] advocate a 6 μm range for 1 MeV electrons fully stopped in 300 g/cm^3 DT fuel. Such a value looks reasonable for igniting a hot spot much smaller than the surrounding dense compressed DT core. However, the uncertainties still plaguing the REB direct drive approach [10–12], through a solid density target, make it compulsory to pay a thorough attention to similar issues encountered in the present scenario. The REB energy range considered is fixed by the laser irradiance through the relationship ($\lambda_\mu = 1$ μm) [13]

$$T(\text{MeV}) = 0.511\left\{\left[1 + 0.7\left(\frac{I}{I_{18}}\right)\lambda_\mu^2\right]^{1/2} - 1\right\}, \quad (1)$$

with $1 \leq I/I_{18} \leq 20$ so $0.152 \leq T(\text{MeV}) \leq 1.44$.

FIS prescriptions [1] recommend a 3 kJ REB energy at 1 MeV for hot spot ignition. This amounts to a current $\sim 3 \times 10^8$ A. Considering a compressed core radius $\sigma \equiv$ 50 μm a plausible channel radius $a = \sigma/4$ yields an average beam density $n_b \sim 1.3 \times 10^{22}$ e cm^{-3}. It should also be noticed that a 300 g/cm^3 DT core at the usual 5 keV temperature [2] appears as a fully ionized and weakly coupled ($\Lambda \sim 5 \times 10^{-3}$) hydrogenic plasma with $n_p \sim 10^{26}$ e cm^{-3}.

As far as the REB propagation is concerned, we consider a monochromatic beam. Any transient collective modes excited in the channel are expected to be instantaneously collisionally damped according to (T_p = target temperature) [12]

$$\frac{n_p(\text{cm}^{-3})}{T_p^3(\text{eV})} \geq 10^{11}, \quad (2)$$

easily fulfilled in the present situation.

A noticeable exception might be afforded by the electromagnetic filamentation (Weibel) through transverse modes, one thus encounters a situation quite germane to the filamentation of intense ion beams [6]. However, the presently produced REB within compressed core do not have to satisfy the same stringent focusing conditions. Moreover, very recent 2D numerical simulations [14] make it clear that the REB velocity is mostly axial for the first 20–25 fs. Then, the beam starts also a lateral expansion, which is likely to stabilize the filamentation process [6].

Moreover, some insight into the REB axial velocity distribution may be gained from 2D simulations [14] showing it as a superposition of a low velocity plateau flanked with a high and narrow velocity component. So, the first part might be used for uniform channel heating while the second one is essentially modeled by the monochromatic beam considered here which penetrates the dense compressed core.

This huge current is expected to pinch the REB through an azimuthal magnetic field $B_0 \sim 4.8 \times 10^{10}$ G. Nonetheless, the linear beam density is still able to secure a very high space charge with Budker parameter $\geq 10^3$, so the standard Alfven-Lawson limit is easily overcome. Such enormous B_0 values could *a priori* be a concern for the REB-target interaction itself.

Fortunately, the resulting target electron Larmor radius $\sim 3.8 \times 10^{-8}$ cm still remains much larger than the corresponding Debye length $\sim 5 \times 10^{-9}$ cm and the mean particle interdistances $\sim 1.35 \times 10^{-9}$ cm in a DT compressed at 300 g/cm^3 and 5 keV temperature.

As a consequence, it is the target density which takes responsibility for shaping the energy loss and multiple scattering processes which we consider now.

The ratio $n_b/n_p \leq 10^{-4}$ demonstrates that in spite of its huge current the REB should be taken dilute in the overcompressed target with a mean electron interdistance larger by a good order of magnitude compared to that in the target. The REB-target interaction is then reducible to that of a linear superposition of isolated charges. Focusing attention on the most significant stopping mechanisms, we include binary electron-electron collisions through a plasma-adapted Møller expression [15]

$$-\frac{dE}{dx} = \frac{2\pi n_p e^4}{m_e \beta^2 c^2}\left[\ln\frac{1}{2\tau_{\min}} + 0.125\left(\frac{\tau}{\tau+1}\right)^2 - \frac{(2\tau+1)}{(\tau+1)^2} + 1 - \ln 2\right], \quad (3)$$

with $\tau_{\min}$ the ratio of projectile electron wavelength $\lambda\!\!\!^{-}_e$ to target Debye length λ_D, $\tau = \gamma - 1$ in terms of the usual Lorentz parameters $\beta = V/c$, $\gamma = (1-\beta^2)^{-1/2}$, and the excitation of Langmuir collective modes [16]

$$-\frac{dE}{dx} = \frac{2\pi n_p e^4}{m_e \beta^2 c^2}\ln\left[\frac{V}{\omega_p \lambda_D}\left(\frac{2}{3}\right)^{1/2}\right]^2, \quad (4)$$

in terms of the target electron plasma frequency ω_p.

We are entitled to restrict ourselves to a continuous slowing down approximation because large and sudden energy losses are likely to happen very rarely. This point is well documented by the fact that a bremsstrahlung contribution comparable to the above ones would request a beam energy $\sim 800/(Z+1)$ MeV much larger ($Z = 1$) than those considered here. Also, electron-position pair production remains totally negligible below 10 MeV [17]. However, in contradistinction to the simpler ion stopping [18] case we have to give up the straight line approximation for the projectile trajectory. Due attention has now to be paid to the quasielastic and highly erratic motion of the relativistic electrons experiencing multiples scattering on target ions. Such a process is essentially quantified by the square average deflection per unit path length ($Z = 1$, $A = 2$) [19]

$$\lambda^{-1}(\mathrm{cm}^{-1}) = 8\pi\left(\frac{e^2}{m_e c^2}\right)^2 \frac{Z(Z+1)}{A\beta^4}(1-\beta^2) \times \left[\ln\left(\frac{137\beta}{Z^{1/3}(1-\beta^2)^{1/2}}\right) + \ln(1.76) - \left(1 + \frac{\beta^2}{4}\right)\right]. \quad (5)$$

Putting together the stopping contributions (3) and (4) allows us to compute a continuous range for a 90% energy loss of 1 MeV electrons as

$$R = \frac{m_e c^2}{4\pi n_p c^4} \times \int_{0.3025}^{0.8836} \frac{dV}{(1-V)^{3/2}} D(V)^{-1} = 42.66\ \mu\mathrm{m}, \quad (6)$$

with

$$D(V) = \ln(68.53V) + \ln(68.026V^{1/2}) + \frac{(1-\sqrt{1-V})^2}{8} - (2\sqrt{1-V} + V - 1) + 1 - \ln 2$$

for a stopping target with 300 g/cm^3 and 5 keV. It should be noticed that the range (6) in a hot target with classical electrons is larger than the corresponding one at $T = 0$ with fully degenerate ones. The latter being notoriously less responsive to the projectile field [20].

This R value is comparable with the core extension σ. So, we really need an efficient packing mechanism to wind the projectile trajectories within a much smaller domain in the compressed core. This winding process is easily quantified by the maximum penetration depth ℓ_0 of the given REB.

The precise calculation of this parameter has been for many years the hard core of that subfield of nuclear and particles physics devoted to particle detection [21]. In the present context, we find it very useful to use a classical result due to Hemmer and Farquar [22] which is based on stochastic arguments summarizing a great deal of previous efforts. So, considering a slab thickness containing every projectile trajectory whatever their orientation with respect to beam axis is, one gets the simple relationship

$$R = \ell_0 + \frac{1}{2}\frac{\ell_0^2}{\lambda} + \frac{1}{2}\frac{\ell_0^3}{\lambda^2}, \quad (7)$$

between the continuous winded range R and the maximum penetration depth ℓ_0.

Figure 1(a) features simultaneously R and ℓ_0 for the energy range $0.5 \leq T(\mathrm{MeV}) \leq 15$. In order to qualify the FIS as a coherent ignition scenario, we have also to request a sufficiently short stopping time

$$t_{\mathrm{stop}} = \frac{1}{c} \int_{E_{\max}/10}^{E_{\max}} \frac{1 + E/m_e c^2}{[(E/m_e c^2)(E/m_e c^2 + 2)]^{1/2}} \times \frac{dE}{dE/dx}, \quad (8)$$

which allows for an adequate hot spot extension highlighted by $4 \leq \ell_0 \leq 18$ μm.

The corresponding $t_{\mathrm{stop}} \sim 10^{-13}$ sec exhibited in Fig. 1(b) seems compatible with further equilibration time between hot electrons and thermonuclear ions in ignited target.

Those results are indeed putting the interaction physics of the FIS on serious grounds. However, other related issues such as the conversion efficiency of the laser light into energetic REB have also to be positively addressed. Such concerns are motivating some authors [9] to advocate an even more precompressed DT core. This explains that we investigate on Fig. 2, the target density dependence of the above results for a 1 MeV REB and a target density between 300 and 1000 g/cm^3. Then, we really witness a drastic reduction of R, ℓ_0, and t_{stop}.

On the other hand, we also proceeded to a systematic variation of the target temperature between 1 and 5 MeV. The above results are then left practically unchanged. Large T variations remain below 2.5%.

In summary, we have demonstrated through a simple but efficient analytical modeling of the laser produced REB in interaction with the supercompressed DT core that the fast ignitor scenario is actually able to yield thermonuclear ignition. Additional insight should be gained by incorporating realistic boundary conditions to the REB propagation scheme.

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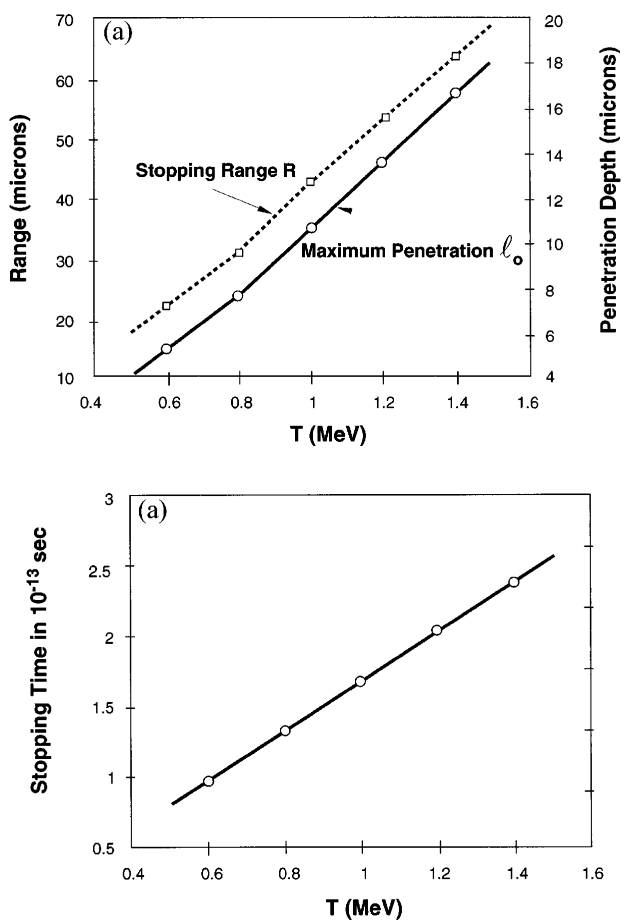

FIG. 1. (a) REB range R (μm) and maximum penetration depth ℓ_0 (cm) in a 300 g/cm^3 DT target at 5 keV and $0.5 \leq T \leq 1.5$ MeV. (b) Corresponding stopping time t_{stop}.

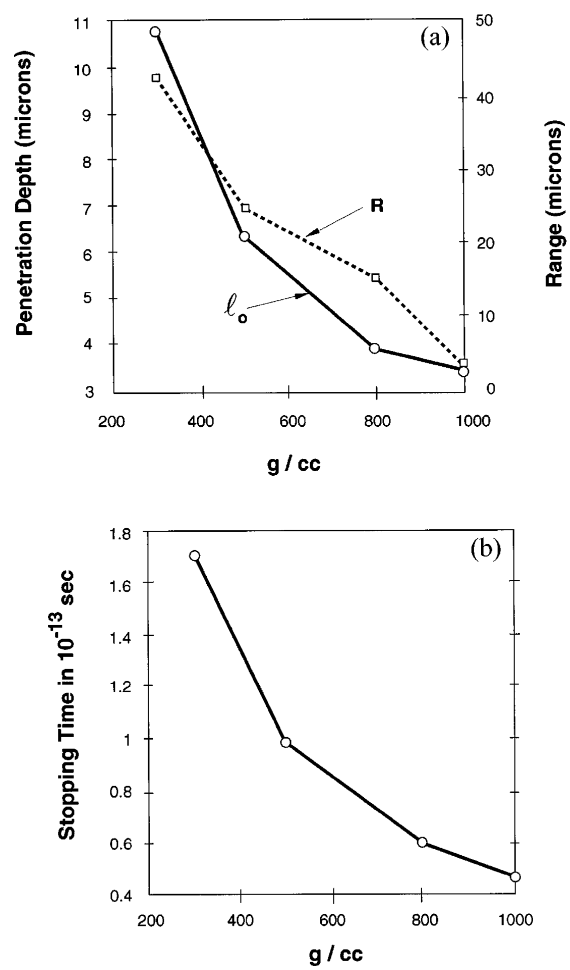

FIG. 2. (a) R and ℓ_0 for $T = 1$ MeV, and target density ranging from 300 up to 1000 g/cm^3, with 5 keV temperature. (b) Corresponding stopping time t_{stop}.

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