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The essentials of generation and transport of high energy electrons in over dense materials: the prospect for "conventional" fast ignition concepts

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The physical outlines of Fast Ignition Fusion (FI) are well known.[1] A solid D-T target is assembled (compressed) to a density of ~ 200 gm/cm^3, with either high energy, nanosecond pulse length lasers (in direct or indirect drive mode), with heavy ions, or "Z" pinch systems. Unlike conventional "hot spot" ICF, the target is ishochorically compressed, that is, there is no low density portion of the target. After the material is assembled (that is, compressed), an UHI laser bores through the lower density plasma surrounding the target, and at the relativistic critical density surface[2]roughly 40% of its energy is converted into electrons of approximately 1 MeV average energy In the FI concept, these 1 MeV electrons are envisioned as traversing a density gradient on the order of 10^{24} grams/cm^3/μm in a well-defined narrow column, subsequently depositing their energy in the compressed core[3].

Figure 1 shows a cartoon of the FI concept. The laser beam is shown as penetrating in well beyond the classical value of the critical density, due to the intensity of the laser fields forcing the electrons away from the high intensity portions of the beam. The laser finally terminates this "hole boring" at the relativistic critical density.

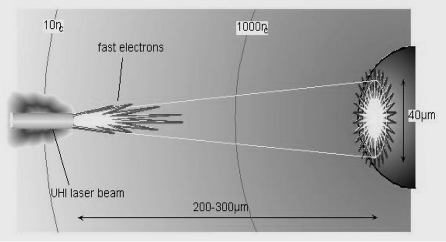


Figure 1

The key physical concept in (FI) is that the fast electrons, once produced, will penetrate through the plasma from critical density (n_c) up to as much as 10^4 times n_c in a collimated manner over distances of 10's of μm. It is this essential element of the fast ignition concept that is the least explored, either theoretically or experimentally. Figure 2 indicates the nature of the physics question: the fast electrons are produced at the critical density (n_c) in some distribution, and then must transverse a gradient of more than 10^{24}grams/cm^3/µm in some orderly fashion to reach the dense core. The Figure indicates the crucial physics questions:

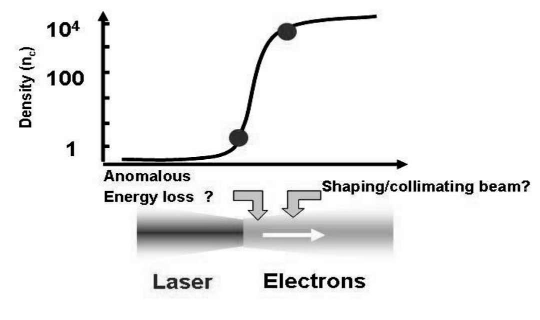
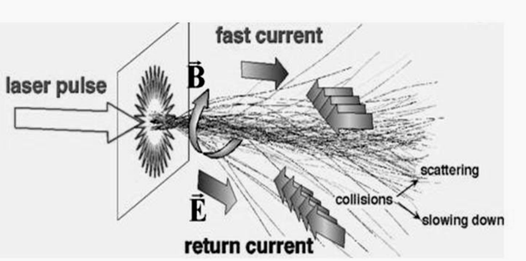


Figure 2

- What is the nature of the conversion process of laser energy to fast electrons;
- what are the possible energy loss mechanisms at or near the point where the fast electrons are produced;
- and do the electrons that are directed towards the core travel in a collimated fashion, influenced as they are by various mechanisms, including binary collisions, collision-less anonymous resistivity, electric potentials, and self-induced magnetic fields.

Figure 3[4]. illustrates the extremes within the target material as the fast electrons attempt to propagate: (a) whereas overall charge neutrality of the target yields refluxing of the fast electrons globally, local charge neutrality requires that the fast electrons be replaced essentially instantaneously by larger numbers of slower moving background electrons (so-called return current); (b) the fast electrons undergo some degree of binary scattering with ions and background electrons, (yielding x-rays and/or γ rays), with a resulting tendency to spread transversely;(c) the slower moving return current electrons undergo much more pronounced scattering, resulting in a inhibition that is reflected in large electric fields that must develop consistently with the total current flow to establish local charge neutrality; (d) the fast electrons current, *and* the return current each have a self-consistent B field, which although oppositely directed are *not*, in general, co-located in space; (e) the total E and B fields must satisfy Maxwell's equations locally, as well as globally, at all times.



Hybrid PIC model (Paris) (C Toupin et al. In Inertial Fusion Science and Applications 99 Publ. Elsevier p471 (2000)

Figure 3

It was recognized early[5] that heating of the target material is due to the *return current* of the very large number of background thermal electrons (in comparison to the number of fast electrons). Not only is the number of returning electrons very large, these electrons are moving at a much slower velocity than the laser generated fast electrons, and therefore undergo much more effective energy exchange with the background ions. That is, these electrons heat the material precisely because they are sensitive to the resistivity of the material, and produce local heating which is proportional to $\rho(T)\bullet\left(j(\bar{r})_{\text{return}}\right)^2$ This heating, which is explicitly dependent upon the space and time dependent temperature of the material, as well as the spatial distribution of the return current, is the source of the so-called "isochoric" heating of the target induced by a high intensity laser pulse.

The role of the Ohmic electric field arising from the return current in the dynamics of the fast electron transport is only recently become widely recognized in modeling and analysis. This significance arises from the fact that contrary to conventional wisdom, materials do not linearly increase their conductivity with increasing temperature. Quite to the contrary: the resistivity of nearly all materials, and certainly metallic materials, rises as function of temperature nearly 3 orders of magnitude from its room temperature value to a "universal maximum" around 10 eV, and then begins to drop rapidly with further increases in temperature.[6]

The return current is not only responsible for the heating of the material, it is also the source of an often over-looked stopping mechanism for fast electrons as they transverse the material, *even when the fast electrons themselves suffer few if any collisions with the ions or electrons of the material*. Noting that $j_{\text{return}} \cong j_{\text{fast}}$ at all spatial locations-at all times-during the fast electron transit, and that j_{return} is affected directly by the resistivity of the material, there necessarily exists an Ohmic potential within the material; the gradient of which is an electric field whose direction is precisely that to act to slow the fast electrons. Expressing this as an Ohmic stopping scale length[7] over which the potential change is equal to the mean energy of the fast electrons, one has a measure of a mechanism that can actually terminate the fast electron penetration into the material. The scale length depends upon (a) the mean energy of the fast electrons, (b) the number of fast electrons produced by the laser, and (c) the average value of the resistivity. The full computational modeling of this effect is extremely complicated for many reasons, not the least of which is that all of the controlling elements are functions of space and time throughout the fast electron pulse. Hence the concept of a single valued stopping length assigned to a material is highly over simplified.

It is the physical requirement that all E and B fields within the material satisfy Maxwell's equations at all points in space at all times that makes the physics of electron transport extremely difficult to understand in separated parts: processes such as the scattering vs self pinching B fields, for example, are connected self consistently,. The simultaneous Maxwell requirements that $\vec{\nabla}\times\vec{B}=\vec{j}+\partial\vec{E}/\partial t$ and $\vec{\nabla}\times\vec{E}=-\partial\vec{B}/\partial t$ give rise to a form of self generating dynamo effect, since the E field is the total electric field, and is not curl-less. This Maxwell requirement-at all locations in space and at all times-is at the source of several predicted non-linear behaviours in the development of possible transport modes, including the splitting of the fast electron beam into smaller beams below the Alfven limit[8].

We have performed measurements that demonstrate this non-local stopping of the 1 MeV electrons launched by the laser. We find that under circumstances in which the temperature of the target material is less than 100 eV, the forward momentum of the fast electrons is rapidly attenuated, with a resultant rapid spreading of the electron beam. Figure 4 shows recent unpublished results obtained by K_α imaging. The fast electrons appear to be rapidly attenuated in the forward diredtion, but rapidly spread transversely

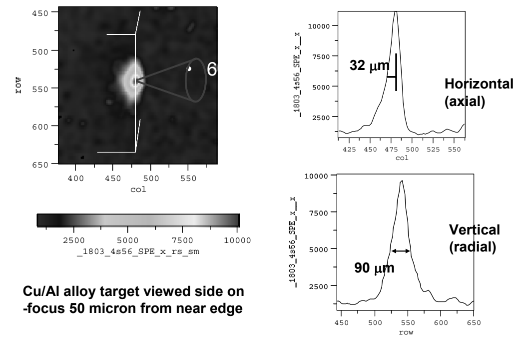


Figure 4

We conclude that electron transport measurements relevant to FI must be done in the resistive region appropriate to actual fusion energy: ~1keV.

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