

2022 Whitepaper on research opportunities in Inertial Fusion Energy

Title: Electron-driven fast-ignition approach to IFE

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1. Executive Summary

In the fast ignition (FI) scheme [Tabak1994] of inertial confinement fusion (ICF), the compression and ignition phases are separated, offering the possibility for higher efficiencies with significantly relaxed symmetry requirements and target design constraints. Ignition is triggered by a moderately short (10–20ps) high-power (multi-PW) laser which hits the pre-compressed fuel, generating a population of fast electrons that carries a fraction of the laser energy to the core of the fuel, where energy is deposited through collisions, heating and igniting the fuel. To achieve ignition, ~15–20 kJ of energy must be deposited over a radius of ~20 μm in the dense core [Atzeni1999]. The electron beam energy required at the source strongly depends on the divergence and spectrum of the fast electrons. In order to efficiently ignite the fuel, the generated fast electrons must have low divergence [Honrubia2009] and energies within 1–3 MeV to ensure that they can reach the dense central core and be stopped [Atzeni1999,Atzeni2009]. Numerical and experimental studies have shown that these conditions are difficult to meet. Direct irradiation of low-Z targets with petawatt laser pulses at relativistic intensity results in divergent electron beams with effective temperatures several times the desired range; this has led to megajoules of short-pulse laser energies necessary for ignition.

These obstacles might be overcome with experimental and numerical capabilities developed over the last decade. New developments in magnetic field generation and target design promise to reduce the required short-pulse laser energy to tens of kJ achievable with current laser systems. Externally applied magnetic fields, or self-generated fields that arise in imprinted resistivity gradients can actively reduce the electron beam divergence. In addition, dramatic improvements in computer performance and adaptation of simulation tools to GPU architectures allow us to model short-pulse-driven electron sources and transport to the dense core of an ICF target at full scale. The electron-driven approach to Fast Ignition is attractive due to its conceptual simplicity; a holistic assessment of IFE should include an updated assessment of its feasibility and cost. We propose the following three research questions:

- It is possible to generate and focus an electron beam with the characteristics required to heat a compressed ICF core?
- Can we design, build and demonstrate such an electron source in the Laboratory?
- Is it possible to assemble or maintain functionality of a focusing electron source in a realistic implosion?

2. Introduction

In the fast ignition (FI) scheme [Tabak1994] of inertial confinement fusion (ICF), the compression and ignition phases are separated, offering the possibility for higher efficiencies with significantly relaxed symmetry requirements and target design constraints. In its original conception, fast ignition is triggered by a moderately short (10–20ps) high-power (multi-PW) laser which hits the pre-compressed fuel, generating a population of fast electrons that carries a fraction of the laser energy to the core of the fuel, where energy is deposited through collisions, heating and igniting the fuel. To achieve ignition, $\sim 15\text{--}20$ kJ of energy must be deposited over a radius of ~ 20 μm in the dense core [Atzeni1999].

Laser-plasma interaction – The main approach to electron FI is to introduce a static high-Z cone into the fuel capsule before the implosion, in order to ensure that the laser deposits energy near the compressed core rather than having to propagate through the coronal plasma surrounding the imploding capsule. The electron beam energy that is required at the source strongly depends on the characteristics of the fast electrons, namely its divergence and spectrum. In order to efficiently ignite the fuel, the generated fast electrons must have low divergence [Honrubia2009] and energies within 1–3 MeV to ensure that they can reach the dense central core and be stopped [Atzeni1999, Atzeni2009]. Numerical and experimental studies have shown that these conditions are difficult to meet: direct irradiation of low-Z targets with petawatt laser pulses at relativistic intensity results in divergent electron beams with effective temperatures several times the desired range; this has led to near-Megajoules of short-pulse laser energies necessary for ignition. Figure 1 shows results of a numerical study of laser-plasma interaction under fast-ignition relevant conditions, i.e., a

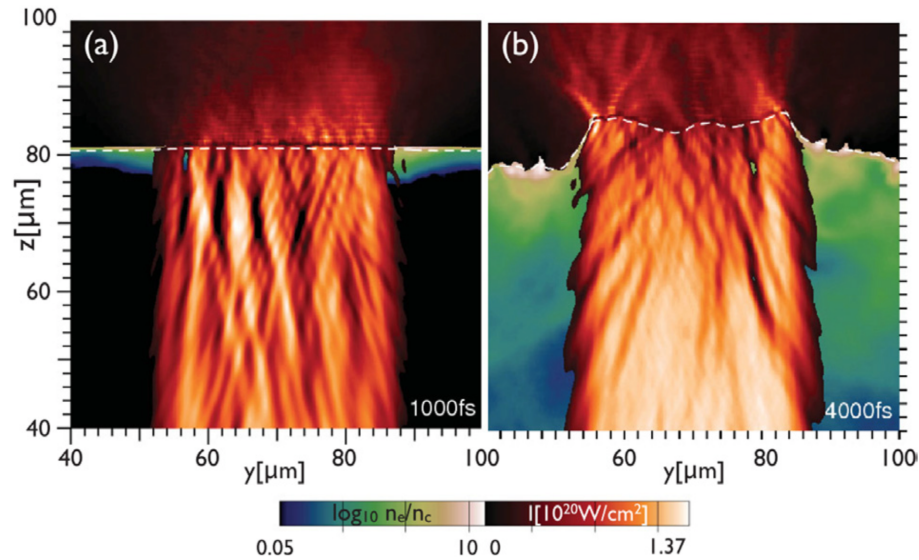


Figure 1. Modeling of fast electron source, relativistic petawatt laser pulse interacting with over-dense plasma. the laser pulse is injected at $z = 0$, and plasma is initially at $z > 80$ μm . Energy flux density along z (in red) shows continuously high conversion from the laser into a relativistic electron beam. The dashed line at $n_e = 10n_c$ shows deformation and motion of the absorption layer. Expansion of under-dense plasma into vacuum (in green) is evident. [Kemp et al (2014)]

40 μm wide multi-picosecond pulse with an intensity $I > 10^{20} \text{W}/\text{cm}^2$ irradiating a near-solid density target [Kemp2014].

The fast-electron transport aspect of FI is challenging for at least three reasons. Firstly, there is an issue that would exist even if fast electron propagation were purely ballistic. The size of the hot spot is comparable to the size of the fast electron source (i.e. the laser spot), but the two are separated by a distance which is several times their size. Therefore, any appreciable angular spread in the fast electrons must either be mitigated or controlled, as a reduction in the coupling efficiency will otherwise occur. Secondly there is the possibility that various instabilities might disrupt the beam propagation which in turn would impair the coupling efficiency. Thirdly, any solution to the first and second problem must be compatible with achievable fuel assemblies and the fast electron parameters required to achieve stopping in the hot spot. Yet another problem is the source characteristics as a function of the laser parameters: currently it would appear that the fast electron energy spectrum is too hard to allow for all the fast electrons to be deposited in an ideal hot spot. Transport simulations, see Fig.2 [Robinson2014,Strozzi2012], have shown that even under idealized conditions for an electron source with an artificially low divergence, the energy required for ignition is 130kJ; even assuming a 30% conversion efficiency between the laser and the electron source, this leads to several hundred kJ of short-pulse laser energy.

Broader context in IFE – Fast ignition has the potential to give high fusion gain at significantly relaxed symmetry requirements and target design constrains [Tabak1994, Shay2012]. In its original conception, laser-generated electrons deposit their kinetic energy in the dense core through collisions; alternative schemes consider laser-driven ion acceleration as an intermediate step to heating the target; shock ignition [Atzeni2014], which requires a sudden rise in laser intensity to heat the core through a shock wave; kinetic mechanisms like crossing of multiple relativistic electrons beams, driving plasma waves to heat the compressed core [Ratan2017].

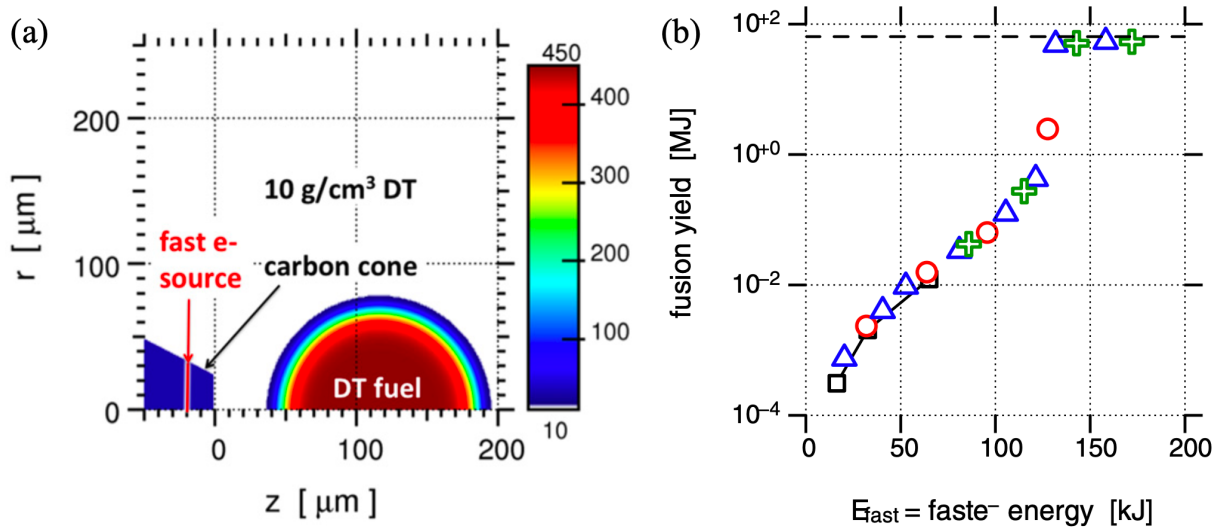


Figure 2. Modeling of fast electron transport. (a) Initial target set-up of the fast electron source in front of compressed core, density in g cm^{-3} . (b) Fusion yield versus total injected electron energy, using an artificially collimated source $\theta = 10^\circ$. $r_{\text{beam}} = 10 \mu\text{m}$ for black squares with solid line, $14 \mu\text{m}$ for red circles, $18 \mu\text{m}$ for blue triangles and $23 \mu\text{m}$ for green crosses. The blue triangle with $E_{\text{fast}} = 132 \text{ kJ}$ is the lowest value that can be deemed to be ignited. [Robinson et al (2014)].

3. Recent developments

Over the last decade, new developments in magnetic field generation and target design promise to reduce the required short-pulse laser energy to $\sim 150\text{kJ}$ achievable with current laser systems. Externally applied magnetic fields, or self-generated fields that arise in imprinted resistivity gradients can actively reduce the electron beam divergence. Recent experiments [Fujioka2016, Bailly-Grandvaux2018, Sakata2018] and separate simulations [Nagatomo2017] have demonstrated efficient guiding of laser-driven electron beams in $\sim\text{kiloTesla}$ external magnetic fields. On the other hand, resistivity gradients in laser-irradiated targets can self-consistently generate magnetic fields that will then reduce the divergence of the fast electron beam [Robinson2007, Kar2010, Vaisseau 2017, Li2020], see Fig.3.

Dramatic improvements in computer performance over the last decade, and adaptation of simulation tools to novel GPU architectures now allow us to model short pulse driven electron sources and transport to the dense core of an ICF target at full scale; however, integrated models of laser interaction, electron transport and hydrodynamics still don't exist. The separation of spatial and time scales between the various physics aspects of fast ignition including physics models like hydrodynamics and radiation transport on one end and kinetic physics on the other end is very challenging; a separate effort that connects various modeling approaches while ensuring their individual validity is necessary [M.Sherlock, separate whitepaper].

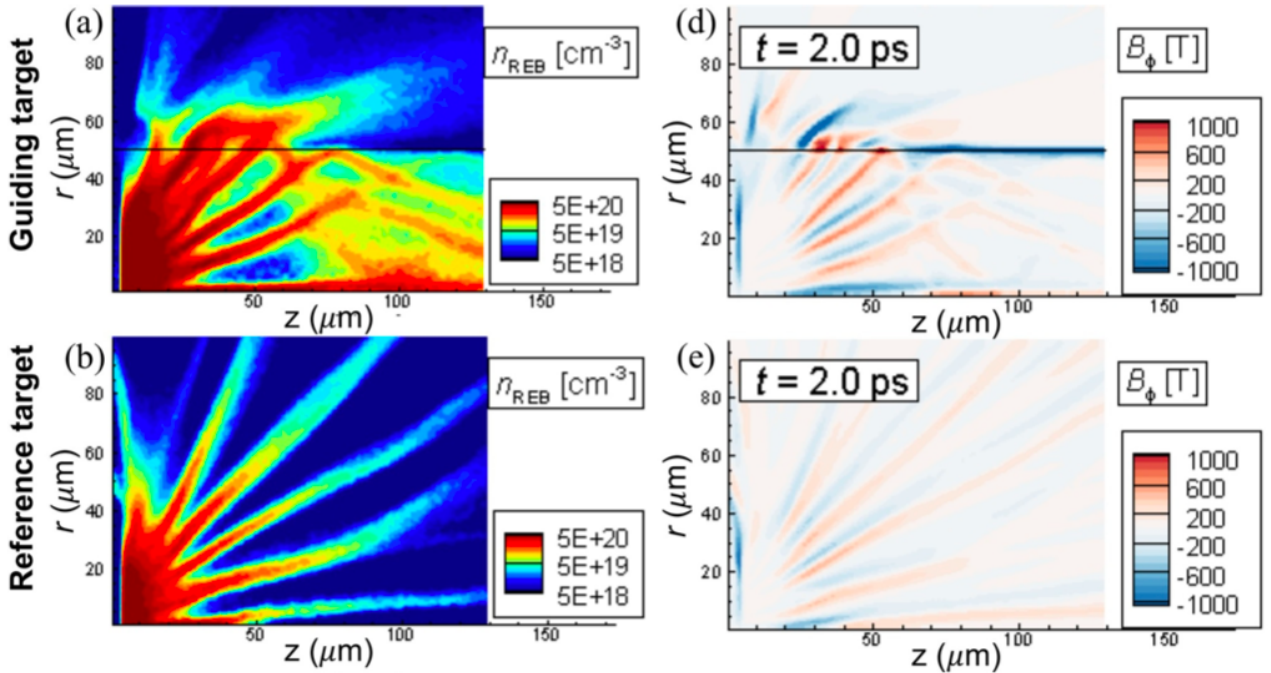


Figure 3. Guiding of relativistic electron beam in Al/CH (a,d) vs. CH-only reference case (b,e) by self-generated magnetic field at the interface between CH ($r < 50\mu\text{m}$) and Al ($r > 50\mu\text{m}$). [Li et al (2020)].

4. Research needs

We propose to investigate the electron-driven approach to fast ignition for IFE, leveraging recent advances in (a) experimental capabilities, such as magnetic field generation, (b) target design to optimize the formation of self-generated magnetic field, as well as (c) in computer modeling of laser-plasma interaction with large-scale particle-in-cell simulations and electron transport modeling with hybrid codes.

The following three key research questions need to be answered:

- It is possible to generate and focus an electron beam with the characteristics required to heat a compressed ICF core?
- Can we design, build and demonstrate such an electron source in the Laboratory?
- Is it possible to assemble or maintain functionality of a focusing electron source in a realistic implosion?

Key metrics: Combining the advantages of using magnetic field configurations in reducing the electron beam divergence with creating a softer electron spectrum, e.g. by using a reduced laser wavelength, it is conceivable to reduce the ignition energy by a factor three down to 50kJ, which could be achieved with the next generation of energetic short-pulse lasers.

Resources needed to address these questions include advanced modeling, i.e., kinetic descriptions of laser plasma interaction with particle-in-cell simulations, fast electron transport modeling with hybrid PIC / hydro models, as well as radiation hydrodynamic models of the underlying implosions. This requires access to large-scale computer facilities. Experiments on existing laser facilities like NIF-ARC, Omega-EP and LFEX need to address the second research question. The third question (assembly) can be addressed at the NIF laser, or in scaled experiments on Omega and GEKKO. Propagation of intense short pulse light through the IFE target chamber is similar to that of the implosion drive pulse [S.Wilks, separate whitepaper]. Our team effort will greatly benefit from the exceptional contributions by our US national and international university collaborators. Finally, there is strong overlap between the proposed fast ignition research and the US ICF program, both in terms of experimental and theoretical techniques, as well as workforce development.

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