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# Progress and prospects for an FI relevant point design

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**Abstract.** The physics issues involved in scaling from sub ignition to high gain fast ignition are discussed. Successful point designs must collimate the electrons and minimise the stand off distance to avoid multi mega-joule ignition energies. Collimating B field configurations are identified and some initial designs are explored.

Fast ignition (FI) is an advanced concept for inertial confined fusion (ICF) that has the potential to deliver gain ~100x for a driver energy ~1MJ. It is attractive for the development of inertial fusion energy (IFE) because target performance in this regime would be most effective for an IFE power plant. It is less attractive for IFE than central hot spot ignition (CHS) in the short term because it lacks a credible point design for high gain.

Experimental research on FI and much of the numerical modeling effort have been focused on near term sub ignition scale FI experiments that are accessible with current laser facilities. The issues arising with scaling up to high gain have had less attention. High gain requires rhoR ~3 $gcm^{-2}$ whereas rhoR values in leading FI experiments (e.g.FirexI and Omega EP cone guided electron FI studies) are an order of magnitude smaller.

Increase of rhoR is obtained by self similar scaling of the hydrodynamics of the target. This brings two difficulties which lead to reduced coupling efficiency of laser energy to the ignition hot spot. Distances scale in proportion to rhoR so that the stand off between the cone tip and the dense fuel is increased and the coupling efficiency is reduced for a divergent électron source. The thickness of the cone tip when scaled up in a self similar fashion increases the energy loss and scattering of the electrons and reduces the coupling efficiency.

Measurements of the divergence of the electrons in initially cold solid targets showed typically $40^o$ cone angle [e.g. Stephens et al ] but , include significant self-collimation by azimuthal B fields and therefore under estimate the true source divergence. The more recent availability of large scale PIC modeling has indicated high source divergence with a normalized integrated solid angle ~5 steradians. [Kemp ] While the conclusions of the PIC modeling lack adequate validation by experimental bench marking, they are currently the best available guides to the source characteristics.

It is shown here that in the absence of collimation of the electrons, the ignition energy scales as (stand off distance x source divergence angle)$^4$ and that this leads to unacceptable multi-megajoule ignition energies. A high gain point design for fast ignition must therefore minimize the stand off distance and achieve collimation of the electrons. This paper discusses the status of our efforts to accomplish this.

We use the modeling capability and methodology deployed in developing the indirect drive CHS point design for the national ignition campaign (NIC), in particular the Lasnex and Hydra codes. Indirect drive is also used for our FI designs. We have also developed a 3D/2D PIC code,PSC [ Cohen] and have used it for large scale modeling of the laser plasma interaction and the electron source [Kemp]. Electron transport is modeled with a new hybrid PIC code, Zuma [ Larson] and it has been integrated with Hydra to model ignition and burn [ Marinak] . An important corollary of the code development is experimental studies aimed at benchmarking the PIC and hybrid PIC modeling [Patel] .

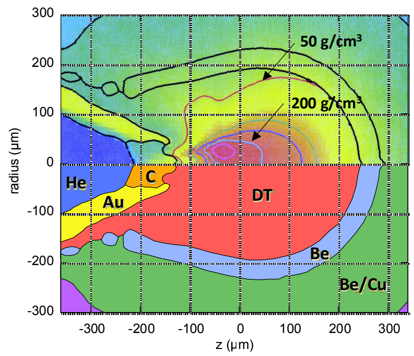


Figure 1

Figure 1 illustrates a 2D hydro design of an ignition scale target with an Au cone and diamond cone tip. [Shay to be published ] It has 2.75 mg of DT fuel and is driven with a 1.75 MJ laser pulse at 0.35 micron wavelength . If ignited it gives 277MJ of fusion energy (gain 150x neglecting the ignitor energy). There is however 110 micron of stand off distance between the inner surface of the cone and the dense fuel .This stand off is already reduced relative to a symmetric implosion by using a 50 µm of P1 asymmetry in shell radius to cause the implosion to arrive earlier at the center from the cone side . The peak fuel density reaches 300g/cc, which is suitable for FI, but the stand off distance is large enough to present major problems for electron ignition.

In studying electron ignition we use analytic fits to PIC modeling results from PSC to define the divergence and the energy spectrum of the electron source injected in Zuma and we scale the energy spectrum with the laser intensity in proportion to the ponderomotive potential as discussed in these proceedings by Strozzi et al. The Zuma /Hydra coupled codes have been used to study ignition and burn. An idealized spherical DT fuel mass is assumed with a $12^{th}$ power super-gaussian density profile of 450 g/cc peak density and 70 µm radius. There is an underlying uniform density of 10g/cc of DT . A solid C cone of density 20 g/cc with a 50 µm diameter tip and a $60^{o}$ cone angle is placed 70 µm from the fuel mass. An electron source is launched in a plane 20 µm inside the cone tip. Ignition occurs at 3.5 MJ laser energy with a 50-micron source diameter, a 15 ps pulse duration and 0.53-micron laser wavelength.

This unacceptably large ignition energy is due to the large source divergence and stand off distance. It can be simply understood by recognizing that very large divergence suppresses any auto-induced collimation by azimuthal B fields. Simple geometrical calculation of the electron flux density on axis and its absorption efficiency in the 1.2 $gcm^{-2}$ of the ignition hot spot can be used in conjunction with published results on the absorbed electron energy flux density needed for ignition[ Atzeni ] , to define the ignition energy.

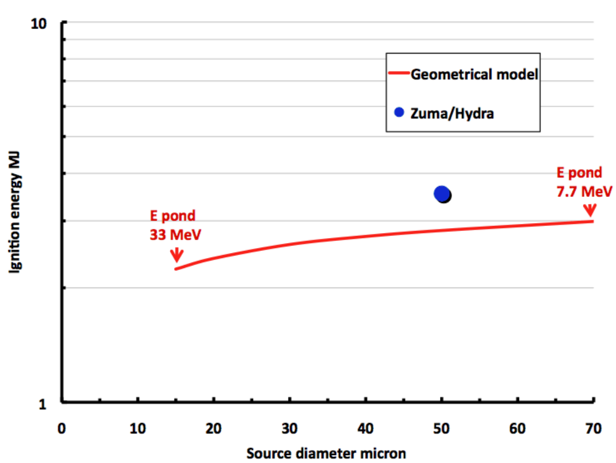


Figure2 Ignition energy 450 g/cc DT, 0.53 mm laser , 15 ps pulse and 70 µm stand off.

Figure 2 shows both the previously described Zuma Hydra calculation and simple geometrical modeling results. The underlying scaling follows from using the normalized integrated solid angle Ω to define the beam intensity on axis $I(0)= P/(\Omega z^2)$ and noting that the coupled fraction scales as the electron energy $E^{-1}$ therefore as laser $(I\lambda^2)^{0.5}$. The ignition power therefore scales as $(\Omega z^2)^2$ or as stated earlier as (stand off distance x divergence angle) $^4$.

An effective way to collimate electrons is to use an axial magnetic field in which the electron Larmor radius is smaller than the ignition hot spot radius so that electrons spiral along the field lines from the laser focal spot to the ignition hot spot. This approach is presented detail in these proceedings by Strozzi et al. The required B field strength is >50MG and ignition energies at 450 g/cc are reduced to ~260 kJ of 0.53 micron laser energy. Preformed 50 kG fields can be compressed in the FI implosion to >50MG but unfortunately not inside the FI target cone tip [ Tabak]. The consequence is that electrons must travel from a low axial B field to a high field and encounter mirror reflection. Efficient escape thro the mirror requires a mirror loss cone angle as large as the source cone angle and analytic estimates suggest this limits the B field increase to <30%. Numerical modeling results [Strozzi et al. ibid ] confirm a strong increase in ignition energy for B field increases >50%. This avenue of electron collimation is therefore blocked by mirror reflection.

An alternative collimation method is use of a B field with hollow pipe geometry such that electrons are reflected and confined within the pipe, which guides them to the ignition hot spot. The reflection condition for angle θ and field thickness L is : $BL > (\gamma_e v_e m_e/e)(1-\cos\theta)$. A converging configuration could force the beam into a smaller area allowing a lower intensity and cooler electron temperature at the source to improve coupling efficiency, but conservation of emittance implies that the beam solid angle at the exit would increase inversely with the beam area . In addition for steep convergence angles, electrons are reflected back to the source after a few reflections. Converging configuations are therefore not helpful.

There are two possible routes to hollow fields. One is compression of an axial B field around an cylinder of dense material that resists compression as suggested by Strozzi et al. The other is auto-generation of an azimuthal B field by the electron beam using a radial change of resistivity η in current density j where $dB/dt \sim \nabla\eta \times j$ . [Robinson et al] We have explored the latter in more detail . Ohmic heating limits B field growth by reducing resistivity so that the achieved B field scales as $B \sim j^{-1}$ in a time $t \sim \eta^{-1} j^{-2}$ A Zuma /Hydra model calculation shows in figure 3, a 30 micron diameter source in an idealized cone/fuel configuration, which achieves ignition at 1.6 MJ with a 20 ps of 0.53 μm wavelenth. The cone tip is 35 micron from the fuel and the source is 35 micron inside the cone tip. The 15 MG B field at the edge of the cone is not an ideal collimator , being strong enough only to reflect <3MeV électrons while the ponderomotive potential is 32 MeV.

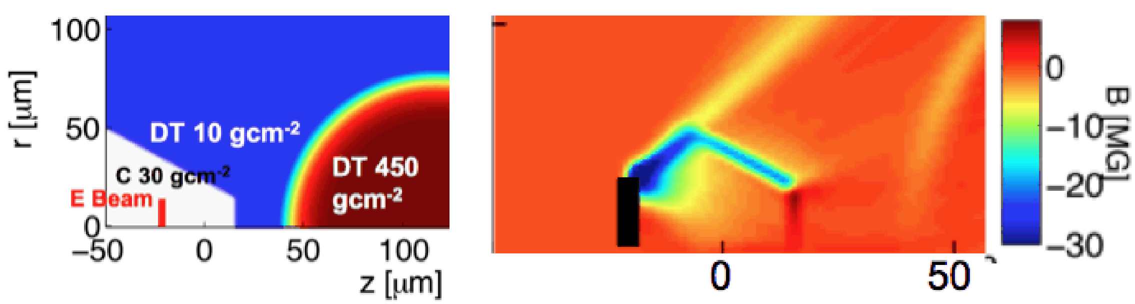


Figure 3 Left : initial conditions. Right : B field detail in cone tip

Stronger B fields are generated with higher Z materials which have higher resistivity and we have begun hydro design studies to explore how best to create cone tip protrusions that will generate strong azimuthal B fields. A design with an Au protruding tip produced only a 20 μm stand off in DT but it had the defect that the Au is compressed and had in addition to its high Z, an axial rhoL of 4.4 $gcm^{-2}$ . Scattering and absorption therefore prevented effective propagation of the electrons. Figure 4 shows a compromise using Cu as the cone tip material. Here the axial rhoZ is smaller at 1.4 $gcm^{-2}$ and the stand off distance from the Cu to the dense DT is 50 μm.

This example has been used to test the full Hydra /Zuma capability by injecting electrons at the perpendicular source plane shown in figure 4. The planar source is idealized since a source created by a laser it would be located on the non planar inner surface of the cone tip. Injection of up to 2.2 MJ in 20 ps with a source diameter of 50 micron and 0.53 µm laser wavelength did not however produce ignition indicating the inadequacy of this design. Use low z materials in the cone tip, which have low density results in excessive push back by the hydro jet from the implosion core . We are exploring how to optimize this scheme.

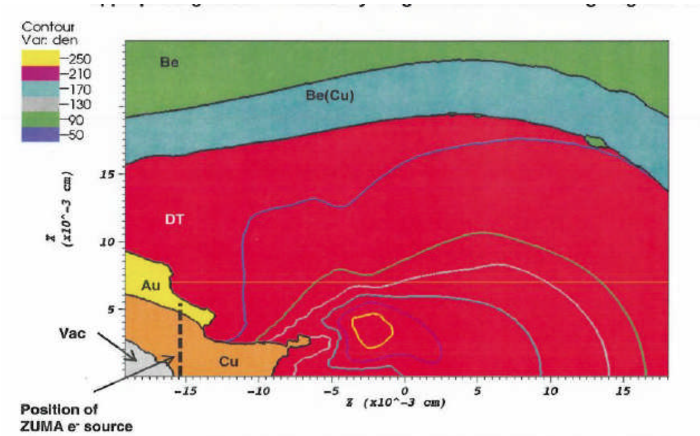


Figure 4 Hydra 2D target design with a protruding Cu tip showing the location of the Zuma electron source used for Hydra /Zuma modeling of electron transport and heating

The current status of our point design effort is that no satisfactory design has yet been found. We are however at an early stage in our use of well adapted design tools and there is a huge design space that we have yet to explore. It is also important to ensure that the source divergence is correctly specified. The PIC modeling is still without adequate bench marking nor has it been fully explored. Recent PIC simulations with longer 5 ps pulse duration suggest reduced divergence for the higher energy electrons. Development of an adequate point design for fast ignition remains a crucial requirement. It is a large task and will require time and effort commensurate with its scale. Fast ignition has had only a tiny fraction of the desi gn effort used to develop the CHS point design for the NIC.

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