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Abstract
Isochoric heating of inertially confined fusion plasmas by laser driven MeV electrons or protons is an area of great topical interest in the inertial confinement fusion community, particularly with respect to the fast ignition (FI) proposal to use this technique to initiate burn in a fusion capsule. Experiments designed to investigate electron isochoric heating have measured heating in two limiting cases of interest to fast ignition, small planar foils and hollow cones. Data from Cu K_α fluorescence, crystal x-ray spectroscopy of Cu K shell emission, and XUV imaging at 68eV and 256 eV are used to test PIC and Hybrid PIC modeling of the interaction. Isochoric heating by focused proton beams generated at the concave inside surface of a hemi-shell and from a sub hemi-shell inside a cone have been studied with the same diagnostic methods plus imaging of proton induced K_α. Conversion efficiency to protons has also been measured and modeled. Conclusions from the proton and electron heating experiments will be presented. Recent advances in modeling electron transport and innovative target designs for reducing igniter energy and increasing gain curves will also be discussed.

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1. Introduction

The Fast Ignition (FI) approach to Inertial Confinement Fusion (ICF) holds particular promise for fusion energy because the independently generated ignition pulse allows ignition with less compression, resulting in (potentially) higher gain. Designing targets able to exploit the FI scheme efficiently requires an understanding of the transport of electrons in prototypical geometries and at relevant densities and temperatures. We present an overview of recent research designed to investigate proton and electron isochoric heating in regimes of interest to fast ignition. This work, which is part of the US Fusion Energy Program, has been conducted through international collaborative experiments carried out on the Callisto and Titan laser facilities at LLNL in the USA, at the Vulcan laser facility in the UK and at the ILE Osaka Gekko PW facility in Japan. In the near term the goals of this program are to test theoretical models of isochoric heating with well diagnosed experiments. In the longer term we aim to carry out tests of the integrated problem where short pulse lasers isochorically heat shock-compressed materials. Finally we plan to carry out fast ignition experiments on ignition scale plasmas on the National Ignition Facility.

In cone coupled electron fast ignition the fuel capsule is imploded onto the tip of a hollow cone. The short pulse laser is focused through the cone and relativistic electrons (of a few MeV average energy) are transported from the cone tip over a distance of the order of 100 μm into the assembled DT core at about 300 gcm^{-3} and confined within a diameter <40μm. The total energy deposited in the hot spot is about 20kJ in 10 ps. Overall coupling efficiency between laser energy and thermal energy in the ignition hot spot should exceed 10% and preferably reach 20% (as seen in the first small scale integrated experiments) to make the scheme practically attractive.

Modeling of the laser accelerated electron sources, the transport of energy by electrons and the consequent isochoric heating have advanced considerably (studies into the sensitivity of the electron transport to the incident electron distribution are currently underway, while a number of new target concepts that may reduce the ignition energy and increase the gain curve are also under active investigation) but there is still no well established modeling capability to enable extrapolation from small scale experiments to full scale FI. The processes are complex and challenging from both experimental study and modeling aspects. We have recently used two limiting cases, which address specific issues in electron transport and offer good opportunities for comparison with modeling.

(1) Thin foils of small area constrain electrons to reflux between the surfaces in a time short compared to the laser pulse duration so that there is always approximate cancellation of the net injected current by reflux current thus eliminating the effect of Ohmic heating by the return current of cold electrons, which is a dominant effect in initially cold solid targets in the absence of refluxing. (2) In the opposite limit a hollow cone couples the laser to a long thin wire and provides a situation where there is 100% compensation of the fast electron injection into the wire by the cold electron return current thus maximizing Ohmic effects. The geometry is simple in that the area of the current flow is constant and equal to the cross sectional area of the wire.

Protons offer an alternative means of isochoric heating with very different physical constraints. The requirement is similar to that for electrons; to deliver about 15kJ to <40 μm with a proton axial temperature of about 3MeV. Conversion efficiency to protons should exceed 15% assuming the beam is focused to < 40 μm. Cone geometries similar to the designs used for electron fast ignition are currently envisioned. For proton FI, the cone must protect the proton source foil from rear surface plasma formation induced by the implosion but it should not cause Molieré scattering outside the required <40μm hot spot. The source foil should be thick enough to protect its rear surface from pre-pulse shock modification but thin enough to allow adiabatic energy loss to acceleration of protons to dominate over collisional energy loss for the refluxing electrons. The laser irradiation should produce sufficiently high temperature electrons uniformly across the source foil to make collisional losses relatively insignificant and to result in a sheath axial development that is spatially uniform giving radial proton focusing to a spot size <40 μm. The laser pulse length should be short enough to limit edge effects on the sheath to optimize focusing of the protons. Following successful initial studies of focusing protons with hemi shell targets, using a 10 J 100 fs laser we extended the study to higher energy and longer pulses using PW class lasers at the RAL Vulcan, ILE Gekko and LLNL Titan facilities. Proton focusing was significantly aberrated in these experiments where a relatively small laser focal spot produced a central maximum in the sheath extension giving radial components to the acceleration. This paper will describe recent theoretical and experimental progress in this area.

2. Electron isochoric heating and transport

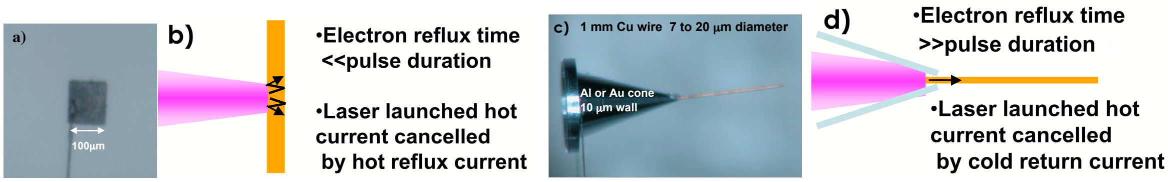

Figure 1: Targets for electron transport studies. a,b) low mass foil which maximizes hot electron refluxing. c,d) wire that has no refluxing.

Studies and modeling of the laser accelerated electron sources, the transport of energy by electrons and the consequent isochoric heating have advanced considerably but there is still no well established modeling capability to enable extrapolation from small scale experiments to full scale FI. The processes are complex and challenging from both experimental study and modeling aspects.

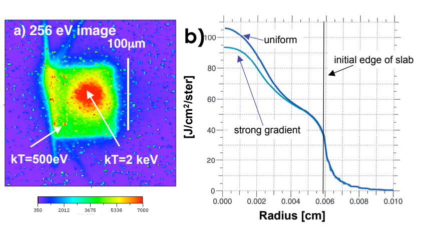

Figure 2: a) experimental XUV image and b) Lasnex model of heated foil.

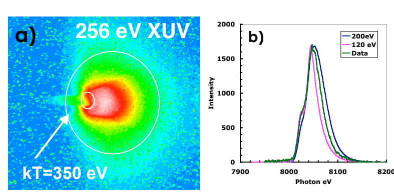

Figure 3: a) experimental XUV image and b) Cu-K_α emission from a heated cone-wire target

We have recently used two limiting cases (Fig. 1), which address specific issues in electron transport and offer good opportunities for comparison with modeling.

Thin foils of small area constrain electrons to reflux between the surfaces in a time short compared to the laser pulse duration so that there is always approximate cancellation of the net injected current by reflux current thus eliminating the effect of Ohmic heating by the return current of cold electrons, which is a dominant effect in initially cold solid targets in the absence of refluxing. The isochoric phase of target heating is shown by 256 eV x-ray imaging (Fig. 2). An absolute image fit via 2D LASNEX modeling shows a 2 keV peak temperature and a 4:1 radial temperature variation in 100x100x5 μm^3 target. The modeling shows that electron thermal conduction equalizes front/back temperature during the XUV emission in thin targets and that 12% of the laser energy is converted to thermal energy in the target.

In the opposite limit a hollow cone couples the laser to a long thin wire and provides a situation where there is 100% compensation of the fast electron injection into the wire by the cold electron return current thus maximizing Ohmic heating by the return current. The geometry is simple in that the area of the current flow is constant and equal to the cross sectional area of the wire. For this target, thermal emissions were imaged in the XUV at 256 eV and energetic electron current from its 8 keV Cu-K_α spectroscopy (Fig. 4). LASNEX modeling of the XUV emission gives a maximum temperature of 350 eV, while the Cu-K_α line width gives a temporal mean temperature of 160 eV [Greg05]. (The K_α emission is linear with current, and presumably also with temperature so gives mean temperature, while XUV emission varies as fourth power of temperature, so is heavily weighted toward the max wire temperature.) The electron propagation along the wire is shown by the Cu-K_α imaging system to have a 1/e attenuation length of ~ 100 μm (Fig. 4). Both the temperature and propagation length results are in reasonable agreement with LASNEX model and the analytic model by Bell and Kingham [Bell03] (Fig. 5).

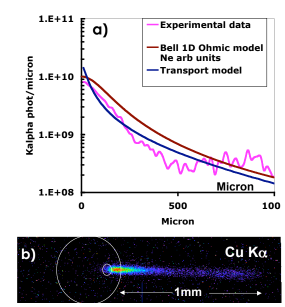

Figure 4: a) Image and b) line-out of Cu K_α emission from heated target.

Other features of the cone-wire experiments are still in need of interpretation. Electron propagation along the wire is observed by the Cu-K_α imaging system to have a much longer range component (l>1mm) about 2% of the peak. The cone-laser interaction also produces complications since this geometry is 3D and prone to modification by the laser pre-pulse. Both of these effects are being addressed in ongoing experiments. Experimentally, we have two approaches: 1) 'nail' targets that provide a flat surface for coupling the laser to the wire, and 2) flat plates set at glancing laser incidence angle to emulate the laser-cone interaction. In simulations we are investigating the role of pre-pulse in modifying the cone geometry. Results from this work will be presented elsewhere.

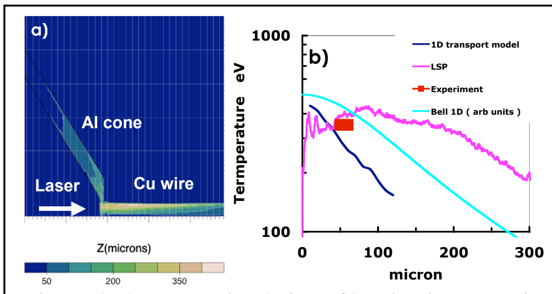

Figure 5: a) Lasnex simulation of heating in cone-wire target. b) Experimentally observed maximum temperature compared to simulation and expectation from model of Bell & Kingham.

2.3. Proton heating

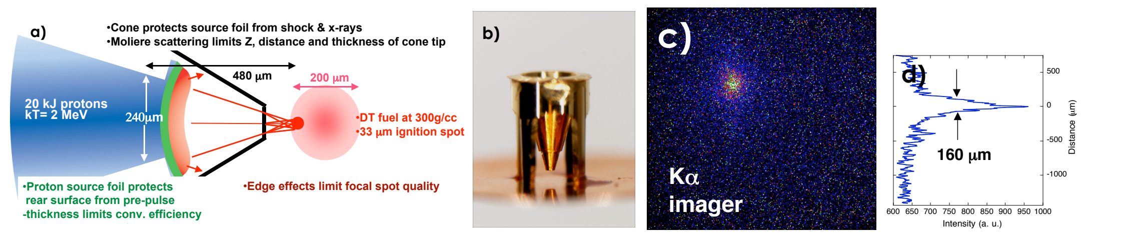

Figure 6: a) Requirements for proton ignition structure. b) Test structure Cu K_α c) image and d) line-out of spot heated by focused protons

Protons offer an alternative means of isochoric heating with very different physical constraints. The requirement is similar to that for electrons: i.e to deliver ~15kJ to a less than 40 μm diameter spot with a proton axial temperature of about 3 MeV. Conversion efficiency to protons should exceed 15% assuming all the beam is focused within this spot. Cone geometries similar to the designs used for electron fast ignition are currently envisioned. For proton FI (Fig. 6a), the cone must protect the proton source foil from rear surface plasma formation induced by the implosion but it should not cause Moliére scattering outside the hot spot. The source foil should be thick enough to protect its rear surface from pre-pulse shock modification but thin enough to allow adiabatic energy loss to acceleration of protons to dominate over collisional energy loss from the refluxing electrons. The laser irradiation should produce sufficiently high temperature electrons uniformly across the source foil to make collisional losses relatively insignificant and to result in a sheath axial development that is spatially uniform giving radial proton focusing to a spot size <40 μm. The laser pulse length should be short enough to limit edge effects on the sheath to avoid significant loss of well focused protons. The protons must also deliver their energy in a short time; because of their velocity spread, the proton generating foil must be quite close to the core – ≤2 mm depending on details [Atzeni02].

A prototype of such a proton source was built (Fig. 6b) to test our capabilities and its performance. It was sized to appropriately for the 500 μm diameter shells used on Omega and Gekko. The accelerating surface in inside the cone was 125 μm in diameter, so could only produce about a quarter of the protons seen from a hemi-shell; electrons flowed off that surface and presumably produced sheath fields along the walls of the cone. Those fields could change the proton focus [Toncian06]. That was enough to demonstrate focused heating of a Cu foil target (Fig. 6c,d). Upcoming experiments are planned to explore the effects of metal walls on the proton yield and focus.

Following successful initial studies of focusing protons with hemi shell targets, using a 10 J 100 fs laser [Patel03] we extended the study to higher energy and longer pulses using PW lasers at the RAL Vulcan and ILE Gekko facilities. Proton focusing was significantly aberrated in these experiments where a relatively small laser focal spot produced

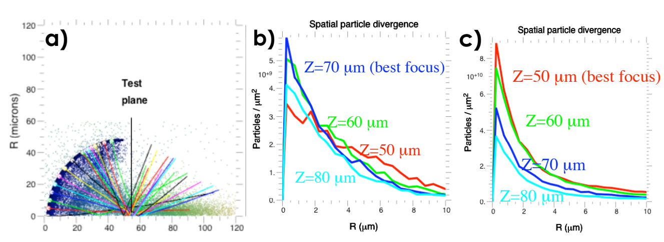

Figure 7: a) LSP simulation of 100 μm diameter hemi-shell 3.3 ps after 0.1 ps injection of 1.3 MeV hot electrons showing evolved proton density and typical paths. b) transverse proton concentration at various test planes for a 10 μm laser focus. c) transverse proton concentration for a 50 μm diameter laser focus.

a central maximum in the sheath extension giving radial components to the acceleration. Sub-scale modeling by M. Foord, LLNL, using hybrid PIC LSP to model a hemi with radius of curvature, r_c = 50 μm shows considerable reduction in proton focus aberration occurs when the laser beam is spread from 10 μm to 50 μm diameter (Fig. 7). The focus for the former occurs at 1.4r_c while the latter is at 1.0r_c, as expected for an unaberrated beam. In addition, the focus is more compact; 6 μm vs. 4 μm for the 1/e diameter. Self-similar scaling of these results to full FI scale (960 μm diameter shell) gives a focused beam ~38 μm diameter, on track for Fast Ignition.

Conversion efficiency to protons of energy >3MeV is also key research area in proton FI. Analytic models and hybrid PIC modeling are being developed to obtain better understanding of how to optimize for proton fast ignition. From analytic methods it is clear that collisional losses in refluxing electrons in the foil should be minimized, the electron temperature should be maximized to reduce collisional losses, depletion of the supply of protons should be avoided by proving a sufficiently thick proton rich layer (adsorbed hydrocarbon monolayers may be insufficient), and the proton to other ion ratio in the source layer should be as high as possible. Recent 1D numerical modeling with the hybrid PIC code LSP are beginning to show promising results, namely >50% conversion of electron energy to proton energy > 3MeV.

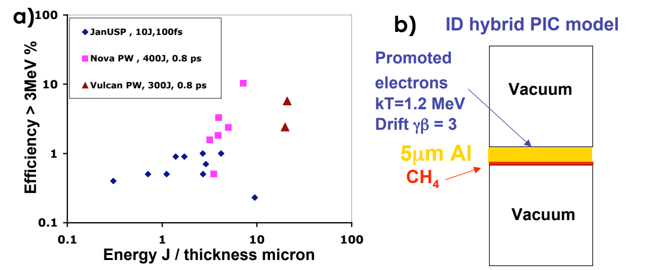

Figure 8: a) Conversion efficiency as a function of foil thickness b) model structure

2.4. Fuel Assemblies for Fast Ignition

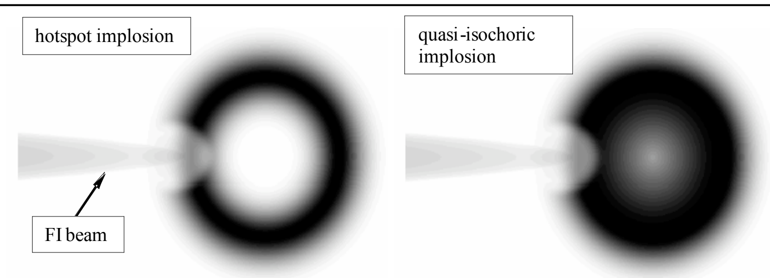

Figure 9: Schematic comparison of fast ignition of a typical hotspot implosion and a quasi-isochoric implosion.

Another area or research relevant to FI is the design of optimized implosions for assembling the compressed fuel. The hydrodynamics of FI implosions deserve separate attention since, with their externally supplied ignition sources, FI implosions optimize with different imploded fuel configurations than their conventional counterparts. In particular, while the conventional ICF approach is fundamentally dependent on the formation of a robust hotspot to ignite, this central hotspot is in fact a liability in FI. Since ignition occurs effectively from the outside of the fuel assembly in FI, the fusion burn wave in a FI target would propagate predominantly around the edge of a hotspot fuel assembly where the fuel density is high. In a high aspect ratio hotspot implosion, this would amount to nearly two-dimensional burn front propagation. It is evident that if a near-uniform density, or isochoric, fuel assembly could be arranged, the burn wave would propagate much more efficiently through the fuel, namely directly through the center of the implosion in a more three-dimensional manner. Indeed, the gain models which have been proposed for FI target design (and cited to demonstrate its advantages over conventional hotspot ignition) typically assume a near-uniform spherical assembly as a starting point [Atzeni99, Tabak06]. A challenge in realizing the potential of FI is then whether and how such quasi-isochoric implosions can actually be realized. Fig. 9 schematically contrasts a conventional hotspot and a quasi-isochoric fuel assembly in FI.

Quasi-isochoric ("hotspot-less") implosion designs will clearly differ markedly from the high-velocity, robustly-igniting hotspot implosions traditional in ICF. One approach to designing such implosions is to appeal to the classical self-similar solutions of ideal hydrodynamics as first described by [Guderley42]. A peculiarity of these solutions is that a particular sub-family of solutions represents the implosion of a spherical shell into a nearly uniform density imploded core. Such an implosion is precisely the isochoric assembly sought as a FI target. Using these idealized, self-similar implosions as a guide, a laser power history can be designed to mimic the self-similar implosion of a shell of frozen DT fuel into a compact quasi-isochoric mass of the necessary density for FI. Fig. 10 illustrates an example of such a laser history and the resulting quasi-isochoric imploded core from a 1D numerical simulation. The remarkably small hotspot volume and near uniformly dense imploded core are evident.

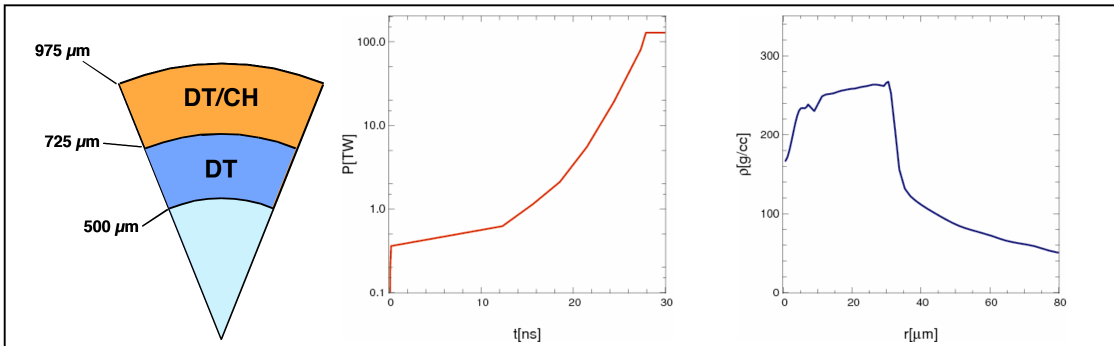

Figure 10: Radial target build, laser power history, and the resulting imploded DT core for an example quasi-isochoric FI target.

3. Summary

In conclusion, for typical we have studied two limiting cases of electron isochoric heating with and without dominant refluxing and we are using these as benchmark cases for developmental hybrid PIC modeling. We have also measured heating by focused proton beams using both hemi-shell and most recently sub-hemi-shell–in-cone targets. We find that better control of the accelerating sheath geometry is needed to reduce the focal spot size to that need for FI. Conversion efficiency modeling suggests that efficiencies higher than so far obtained and meeting the need for FI should be possible with suitable design optimization, experiments on the Titan and Vulcan laser systems are planned to confirm these predicted trends.

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