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Overview of Recent Progress in US Fast Ignition Research*†

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Abstract. The Fast Ignition Program in the United States has enjoyed increased funding in various forms from the Office of Fusion Energy Sciences of the Department of Energy. The program encompasses experiments on large laser facilities at various world-wide locations, and benefits enormously from collaborations with many international scientists. The program includes exploratory work in cone-target design and implosion dynamics, high electron current transport measurements in normal density materials, development of diagnostics for heating measurements, generation of protons from shaped targets, theoretical work on high gain target designs, and extensive modeling development using PIC and hybrid codes

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1. INTRODUCTION

The fast ignition concept is attractive to the Inertial Fusion Community for a simple but fundamental reason: it in principle requires less total energy input to achieve ignition. Figure 1 outlines the fundamental differences between "hot spot" ignition and fast ignition [1]:

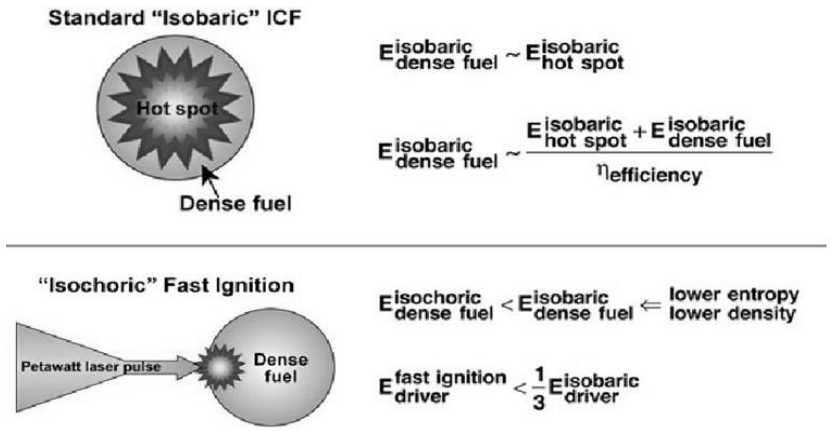


Figure 1: Concept of Fast Fusion

Current US programs and projects are developing new capabilities for Short Pulse HED Science and Fast Ignition : There are currently 3 funded projects from the Office of Fusion Energy Sciences in the US Department of Energy: (1) FI Concept Exploration (LLNL,GA ,UCD,OSU); (2) Fusion Science Center for Extreme States of Matter and FI (LLE, OSU, UCSD,, UR , UT, MIT, LLNL); and (3) FI Advanced Concept Exploration (LLNL,GA, LLE, OSU, UCSD, UR). There are, in addition, substantial resources derived from LLNL's Short Pulse S&T Initiative. The major US facilities to support FI research that currently are in use, or will be on line within the next 5 years, are LLNL's Jupiter facility, Sandia's Z and ZPW, Rochester's Omega and Omega EP, and ultimately LLNL's NIF.

This presentation was in the last Plenary Session of IFSA-2005, and served largely as a summary of oral and poster presentations from many US scientists at IFSA-2005. This paper makes reference to those presentations to guide the reader to the papers where the technical work is presented in detail. There are 6 sections: (1) Concept; (2) Relativistic electron transport and isochoric heating; (3) Modeling; (4) Proton isochoric heating and possible role in FI; (5) Fuel Compression-hydro design and experiments; and (6) Future Prospects.

2. TECHNICAL WORK

2.1 Concept

Figure 2 shows the three essential elements of fast ignition[2]

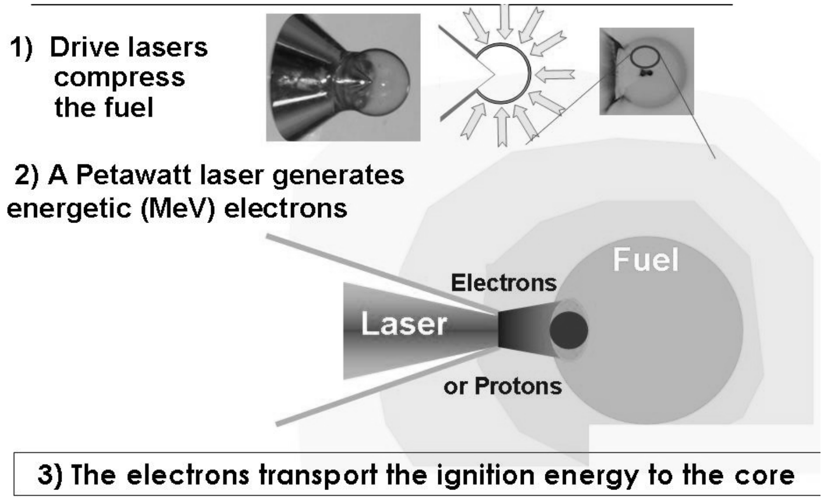
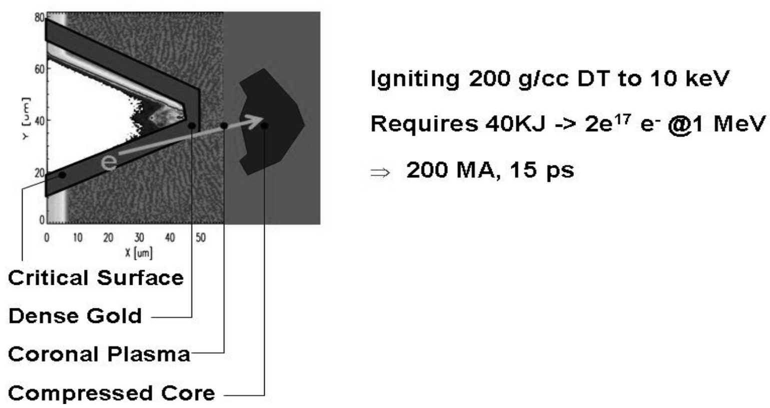


Figure 2 Three essential elements of Fast Ignition

The targets are imploded to an isochoric density as much as several hundred times normal density, a high energy, short pulse laser is guided near to the core of the imploded shell where the energy is converted into high energy electrons, and these electrons must traverse an extreme density gradient through the plasma surrounding the core, and then deposit their energy in the core. The targets will likely require a cone insert to enable the laser to get close enough to the core before converting its energy into fast electrons such that there can be a reasonable chance that fast electrons will remain collimated enough.

The scale of the currents involved and the complex path the fast electrons must travel are indicated on Figure 3 [2]:



αα

Figure 3 Ignition conditions and fast electron path in an FI target

2.2 Relativistic Electron Transport and Isochoric Heating

Initial studies have investigated large current flows in normal density materials induced by high energy, short pulse lasers. Diagnostics have been developed to record 2-D image K_α radiation from Cu and XUV radiation at 68 eV and 270 eV; and single-hit CCD spectrometers have been used to record the spectra of the K_α radiation as well as determine the absolute intensities. Observations have been made of electron transport through slabs of normal density metals and through wires and cones. In general, we find (a) that the fast electrons generated by the laser spread in slabs with an opening angle of nearly 40 degrees, independent of the intensity of the laser; (b) that the electrons appear to have a stopping length determined largely by potentials due to resistance experienced by the return current; (c) that there is a thin (~ 1 μm) layer on the front of the targets that reaches considerably higher temperatures than the bulk material; (d) that many of the presumably lower energy electrons spread rapidly on the surface of the target; and finally (e) there is no indication in any of these experiments of magnetic collimation, or self-pinching of the fast electrons.

The anomalous thin layer heating on the front surface is suppressed by application of a ~1μm over coating of another material, as shown in Figure 4[2]

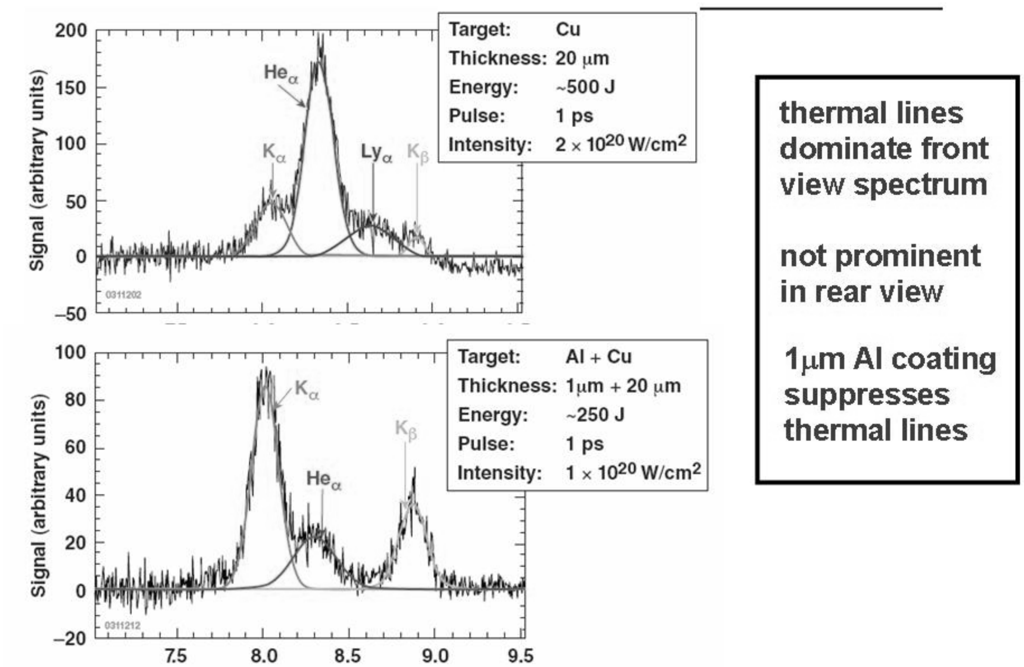


Figure 4: Extreme heating observed in initial layer of slab targets.

The origin of this anomalous heating layer is not completely understood, but may be related to Weibel-like instabilities: this phenomenon is a subject of current investigation.

2.3 Modeling

Modeling is at three main levels [3]:

1. 2D and 3D Radiation /hydrodynamic modeling to define the initial conditions for the short pulse interaction and also the post short pulse hydrodynamics
2. 2D and 3D explicit particle in cell modeling at densities <50 N_c to model the laser plasma interaction and the electron beam generation
3. 2D and 3D hybrid PIC modeling of the electron transport in dense plasma and the isochoric heating

Integration of these three modeling modes is under development in order to develop a full ab initio code for a design of a full Proof-of-Principle FI experiment. As part of the thrust to develop reliable predictive codes, we have begun to benchmark a well known hybrid-PIC code, LSP, against our experiments. Figure 5 shows an example in which LSP models the electron transport through 100 µm of Al for conditions of experiments with the RAL 100 TW laser; In this simulation, the electron injection is derived from a heuristic model; further refinements will include ab initio modeling of the fast electron generation and intial phase space directly from the laser fields.

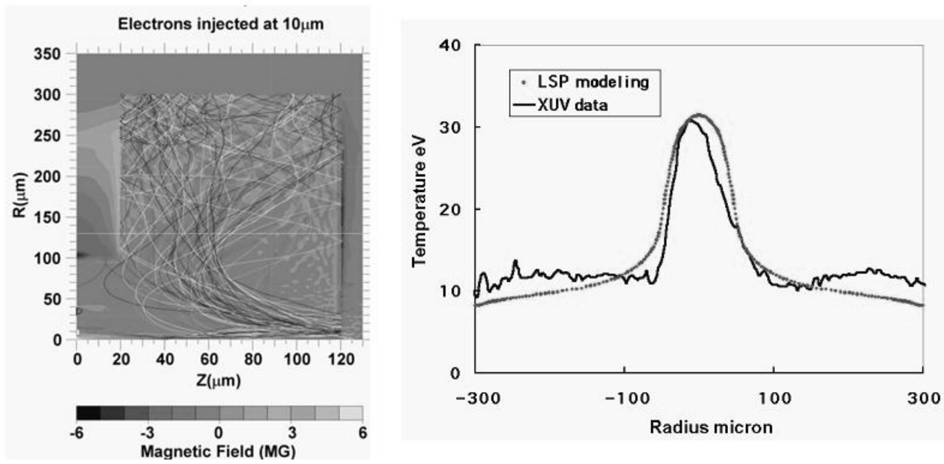


Figure 5: LSP modeling of electron transport and heating on a 100

LSP has also recently successfully reproduced K_{α} emission from Low Mass targets as well as from buried layer fluors.

2.4 Proton Isochoric Heating and Possible Role in FI [4]

Since the discovery of protons accelerated from the back surface of a relatively thin target struck by a ultra-intense laser pulse by Snavely et al. in 2000 [PRL, **85**, 2954], there has been an ever increasing interest in this phenomenon, and IFSA-2005 had many papers representing investigations into its uses. We have studied the generation of protons from shaped targets in an attempt to focus the proton beam, and to efficiently heat targets with these focused protons. This experimental effort has met with some real success, with clear indications of improved isochoric heating using protons compared to electrons. Further, it appears possible to focus the protons with considerable accuracy. Figure 6 shows some results of these types of measurements, and there have been theoretical analyses that suggest that the electron to proton conversion efficiency may be increased dramatically by correctly preparing the back surface of the laser target. This work has led to serious suggestions of making targets for FI which actually use the fast electrons, which appear to be difficult to spatially control, to generate focused proton beams to carry the laser energy through the surrounding plasma into the core. [11]

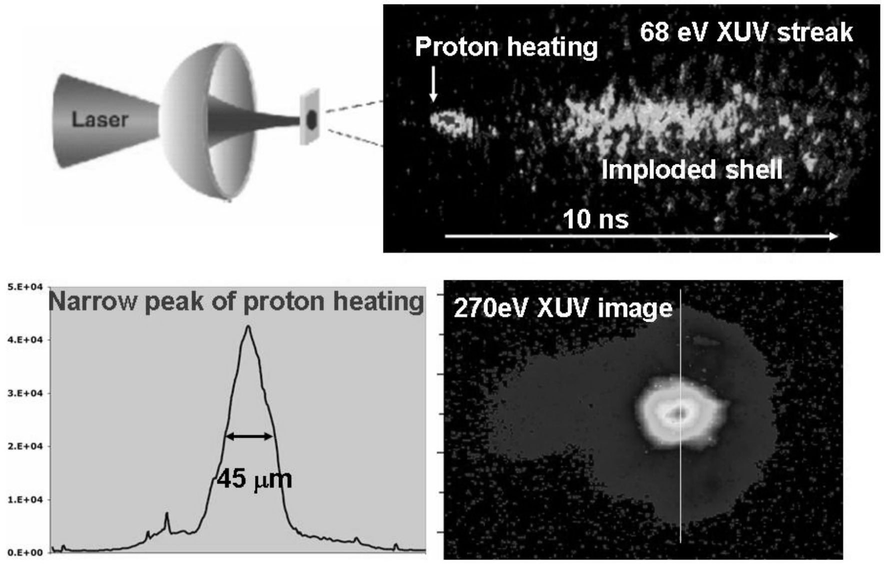


Figure 6: Focusing of protons accelerated from a shaped surface and the resulting heating

2.5 Fuel Compression-Hydro Design and Experiments[2, 5, 12]

The design requirements for a FI target are complex, as Figure 7 illustrates.

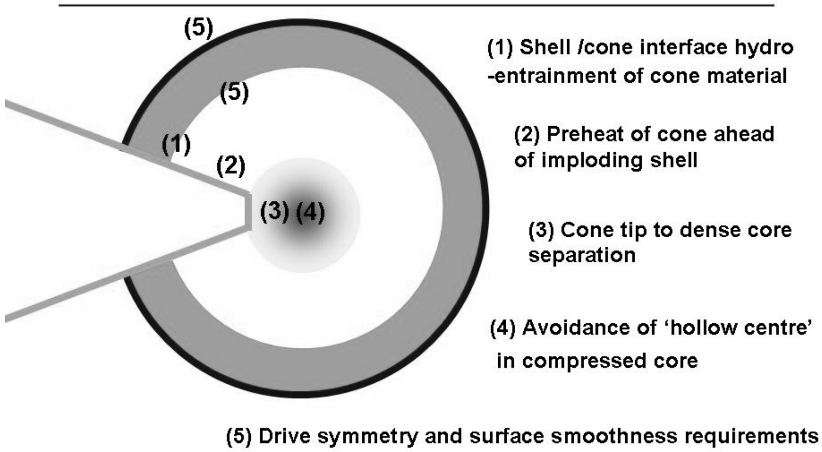


Figure 7: The essential elements and physical constraints of an FI target with cone.

We are experimentally validating our compression design codes with experiments on Omega, with gratifying results as shown in Figure 8 [10]

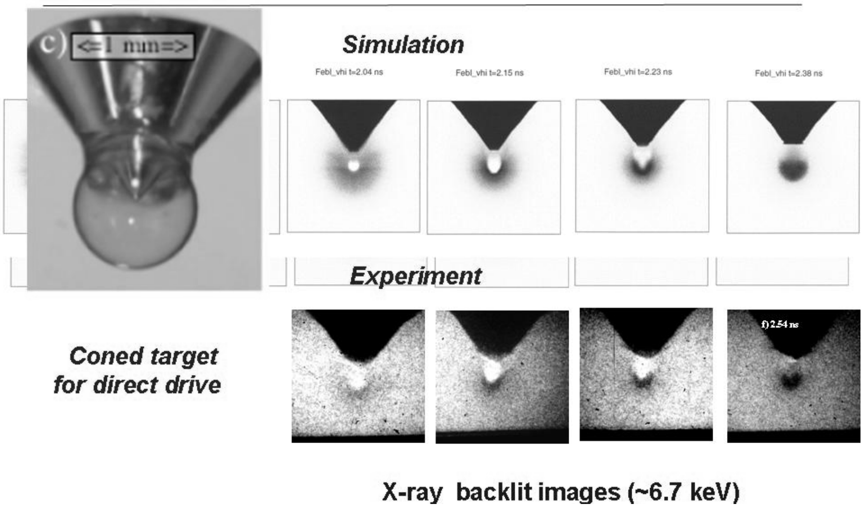


Figure 8: Simulation and experimental results of compression of FI target

The significance of these results is that direct drive at Omega gives well simulated results with no significant ablated /entrained Au near tip of cone, suggesting that these re-entrant cone designs are useable.

Another topic of research is the design of high gain targets for FI: As Figure 9 shows, it is possible to design thick wetted-foam , low adiabat, low velocity targets with high ρ, high ρR and small hot spot. Such targets concepts are essential for any proposed Proof-of-Principle (PoP) experimental demonstration of FI fusion[5]

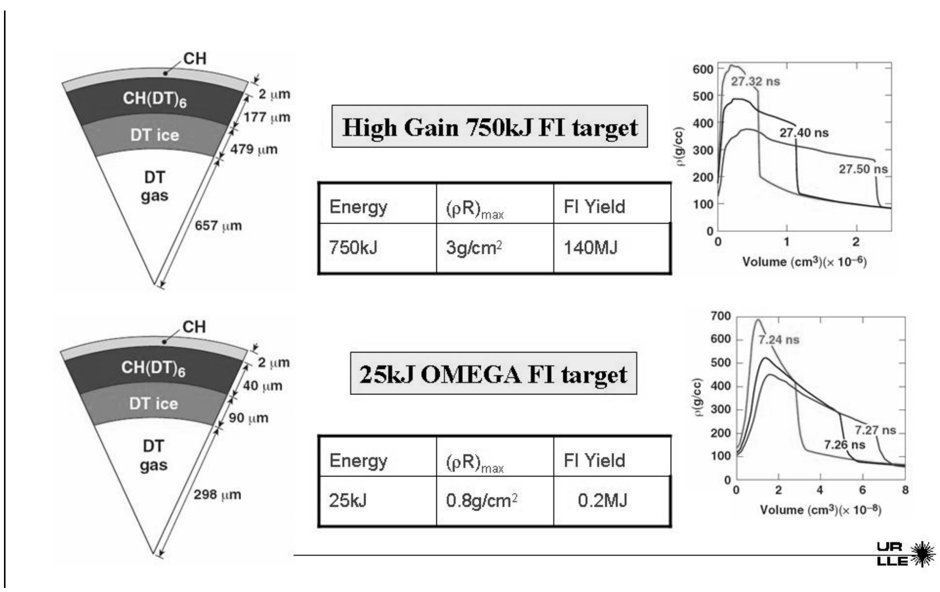
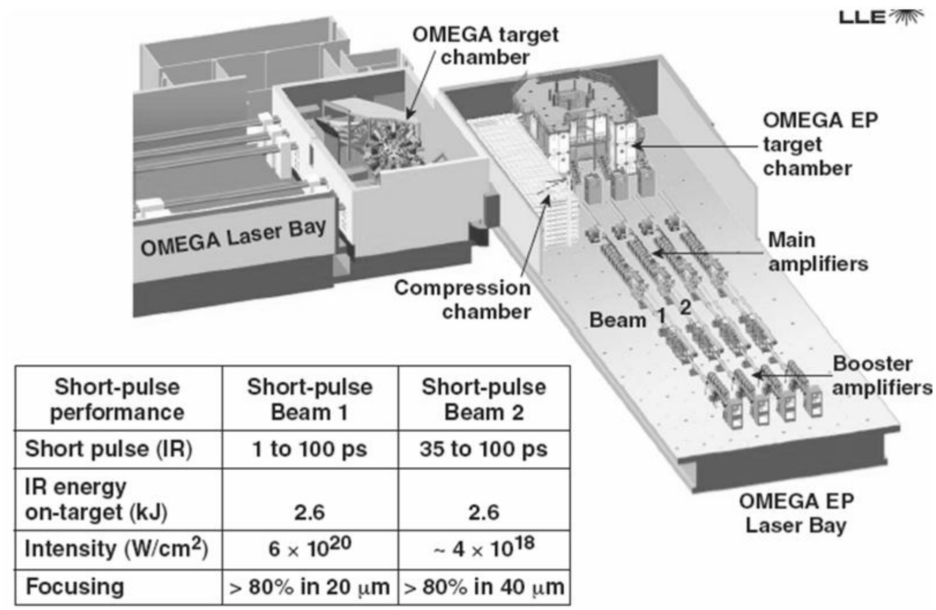


Figure 9 Proposed high gain target for FI.

3. Future Prospects

The future research in FI in the US is dependent upon the completion of facilities capable of compression of targets to high enough density, with energetic enough short pulse lasers. The current plan calls for sub-PoP experiments to be carried out on the Omega EP facility, now under construction at LLE, and due for completion in 2007. The essentials of the Omega EP facility are shown in Figure 10[6]



Short-pulse performance	Short-pulse Beam 1	Short-pulse Beam 2
Short pulse (IR)	1 to 100 ps	35 to 100 ps
IR energy on-target (kJ)	2.6	2.6
Intensity (W/cm^2)	6×10^{20}	$\sim 4 \times 10^{18}$
Focusing	> 80% in 20 μm	> 80% in 40 μm

Figure 10: The Omega EP facility to be used for sub-PoP FI experiments

Assuming that there is success with the sub-PoP experiments, the proposed plan calls for a full demonstration on the NIF sometime after the 2010-12 time frame, with a possible alternative being the Z-pinch facility at Sandia.

The medium term, the program will wok concentrate on "Integrated Experiments"; that is, combining as many of the aspects of the FI concept together in one experiment, and to continue to advance our modeling capabilities with a goal towards a full ab-initio FI code. Figure 11 shows the main components of planned integrated experiments, all aimed at the sub-PoP demonstration on Omega EP:

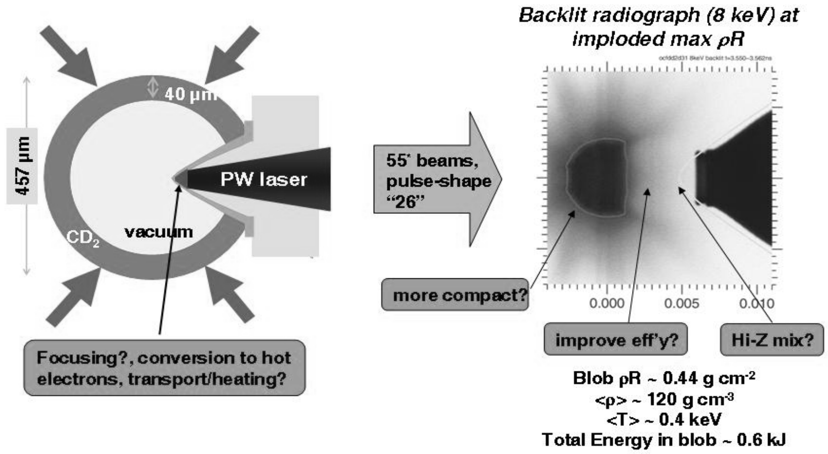


Figure 11: The physical concepts to be examined in preparation for the sub-PoP experiments

In the shorter term, the program continues to work on an ever increasing complex set of diagnostics in anticipation of the more aggressive experimental program. Figure 12 shows an example of the kinds of diagnostics that the US program is working on[1,8]

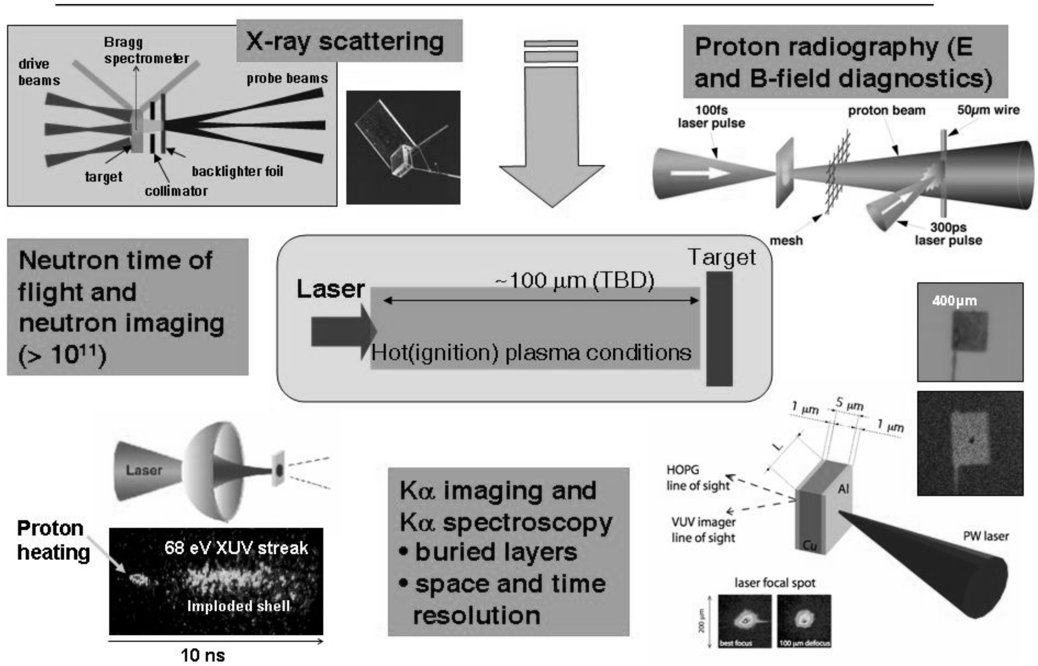


Figure 12: A representation of a partial list of diagnostics to be developed for the sub-PoP experiments.

Summary

The US Fast Ignition program is composed of a collection of University efforts, combined with support from NNSA facilities in LLE, LLNL, and Sandia. Its mission is to understand the fundamental physics issues confronting FI, and to develop the codes and diagnostics necessary to field a sub-PoP FI integrated experiment on Omega EP in the 2007-2008 time-frame. Assuming success at Omega

EP, the program plan calls for a full PoP experiment on the NIF[7] or perhaps Z-R[9] in the 2010-2012 time frame.

References

[1] See the link http://fsc.lle.rochester.edu/
[2] See R. Stephens et al., "High energy electron transport in solids", this volume #M01.1
[3] See H. Ruhl, "Collisional transport of fast electrons through solide density materials"#Tu011.4; T. Melhorn "Simulation of heating –compressed fast-ignition cores by petawatt laser generated electrons"#F027.2; S. Wilks. et al.,"On the use of reduce mass targets to obtain high temperature solid density materials using petawatt lasers for astrophysical applications"#Tu06.3, all this volume.
[4] See M. Key et al. "Study of electron and proton isochoric heating for fast ignition", this volume #M01.4
[5] See R. Betti, "Low-adiabat implosions for hot-spot and fast-ignition direct-drive inertial confinement fusion", this volume #M01.5
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[7] See E. Moses, "The National Ignition Facility: Path to Ignition in the Laboratory", this volume #Wp3.2
[8] D. Meyerhofer, LLE, Rochester, NY., Personal Communication
[9] See J. Porter, et al., "Understanding and control of time-integrated P2 and P4 radiation asymmetry in double z-pinch driven hohlraums", this volume #F023.2.
[10] See K. Akli et al.,, "Modeling of the elcetro eating of an imploded core in an integrated fast ignition experiment", this volume #MPo1.1
[11] See D. Hey et al., "A Monte Carlo Code for Modeling Proton Heating in Fast Ignition Targets", this volume #MPo1.9
[12] See Max Tabak, "Capsule optimization techniques for Fast Ignition", this volume #MPo1.19