GA–A26078

A CONCEPT EXPLORATION PROGRAM IN FAST IGNITION INERTIAL FUSION

Final Report for the Period September 1, 2000 Through March 1, 2008

by

PROJECT STAFF

A collaborative project between General Atomics and Lawrence Livermore National Laboratory with participation from The Ohio State University, UC San Diego, UC Davis, and Princeton University

Prepared under
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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 compression and ignition pulses allow ignition with less compression, resulting in (potentially) higher gain. Exploiting this concept effectively requires an understanding of the transport of electrons in prototypical geometries and at relevant densities and temperatures. Our consortium, which included General Atomics (GA), The Ohio State University (OSU), the University of California, San Diego (UCSD), University of California, Davis (UC-Davis), and Princeton University under this grant (~$850K/yr) and Lawrence Livermore National Laboratory (LLNL) under a companion grant, won awards in 2000, renewed in 2005, to investigate the physics of electron injection and transport relevant to the FI concept, which is crucial to understand electron transport in integral FI targets. In the last two years we have also been preparing diagnostics and starting to extend the work to electron transport into hot targets. A complementary effort, the Advanced Concept Exploration (ACE) program for Fast Ignition, was funded starting in 2006 to integrate this understanding into ignition schemes specifically suitable for the initial fast ignition attempts on OMEGA and National Ignition Facility (NIF), and during that time these two programs have been managed as a coordinated effort.

This result of our 7+ years of effort has been substantial. Utilizing collaborations to access the most capable laser facilities around the world, we have developed an understanding that was summarized in a *Fusion Science & Technology* 2006, Special Issue on Fast Ignition. The author lists in the 20 articles in that issue are dominated by our group (we are first authors in four of them). Our group has published, or submitted 67 articles, including 1 in *Nature*, 2 *Nature Physics*, 10 *Physical Review Letters*, 8 *Review of Scientific Instruments*, and has been invited to give numerous talks at national and international conferences (including APS-DPP, IAEA, FIW).

The advent of PW capabilities – at Rutherford Appleton Lab (UK) and then at Titan (LLNL) (2005 and 2006, respectively), was a major step toward experiments in ultra-high intensity high-energy FI relevant regime. The next step comes with the activation of OMEGA EP at LLE, followed shortly by NIF-ARC at LLNL. These capabilities allow production of hot dense material for electron transport studies. In this transitional period, considerable effort has been spent in developing the necessary tools and experiments for electron transport in hot and dense plasmas. In addition, substantial new data on electron generation and transport in metallic targets has been produced and analyzed.

Progress in FI detailed in §2 is related to the Concept Exploration Program (CEP) objectives; this section is a summary of the publications and presentations listed in §5. This work has benefited from the synergy with work on related Department of Energy (DOE) grants, the Fusion Science Center and the Fast Ignition Advanced Concept Exploration grant, and from our interactions with overseas colleagues, primarily at Rutherford Appleton Laboratory in the UK, and the Institute for Laser Engineering in Japan.

2. Program Results

This section summarizes our work over the last 7+ years, starting with the CEP by itself and continuing through its coordination with the ACE (starting in August 2005). The CEP and ACE programs were managed as a coordinated effort. We discuss below the aspects of our work relating to the CEP statement of work (SOW): The majority of our work has been summarized in an extensive set of articles published in 2006 in a special issue of *Fusion Science & Technology* devoted to Fast Ignition. In this special edition, edited by R.R. Freeman from OSU, E.M. Campbell of GA and K.A. Tanaka of ILE, our work is not only fully explored, but is also placed in context with the world-wide contributions of the many scientists working on fast ignition, and illustrates the leading role we have played. Here we outline our progress in the context of the goals for the CEP program. It is evident from our publications that we work closely with the worldwide FI research community, and make a special effort to integrate the published results of our international colleagues into our strategic planning. Moreover, some of the progress noted below derives directly from independent work done by our colleagues. In this and following sections we take care to mark those references to efforts that have a significant component of ACE or CEP funding in **bold**; all of these references are listed in the bibliography of ACE/CEP funded publications in §5.

2.1. Understand Physics of FI by Electron Ignition

Objective. To investigate the physics of the creation and transport of relativistic electrons in dense materials with a goal of enabling conceptual designs for FI relevant experiments on OMEGA and NIF.

Electron ignition requires the generation of a very high flux of 1-3 MeV electrons directed toward the compressed fuel. Previous studies showed 20%-40% conversion of laser energy into this electron energy band for intensities greater than 10^{19} W cm^{-2} [Wharton98,Yasuike01], the intensity range needed to produce the proper electron energies according to Beg scaling [Beg97] from data at ~10^{18} W cm^{-2}.

Our work over the years has considerably refined that picture. We have shown the beam-like nature of the electron current, and an adequate range, with some electron pooling at the laser plasma interface, and find the temperature of the electron spectrum is lower than expected from Beg scaling; this last allowing higher intensity ignition pulses that should more effectively generate electrons in the target.

Our pioneering use of buried fluorescent layers to probe hot electron behavior in dense plasmas (Fig. 1) [**Stephens04,Freeman06**] has shown that the electrons spread through metal substrates with a half-angle of ~40 deg. The current has a 1/e decay length of ~100 μm, largely determined by the Ohmic resistance of the "cold" metal (temperature <30 eV). Simple scaling arguments for the resulting electron energy and calculations of the necessary ignition energy [Atzeni99] suggest this will be marginally sufficient for demonstrating FI. But the laser intensity needed, after accounting for experimental electron behavior and realistic implosions [**Solodov07**,Atzeni07] was found to be quite high (>10^{20} W cm^{-2}) and the electrons produced by that laser beam, based on the Beg scaling law (for intensities < 10^{19} W cm^{-2}) [Beg97] would be too energetic to be useful unless the wavelength of the short pulse laser were converted to a harmonic ($\lambda < 0.5$ μm) to provide the necessary electrons. Recent calculations [**Sentoku06**] have suggested that for intensities in excess of 10^{20} W cm^{-2} the photon radiative pressure will substantially sharpen the plasma gradient at the critical surface and change the relationship between intensity and the mean energy of the resulting fast electrons. Consequently the mean energy of electrons produced at $I_{laser} > 10^{20}$ W cm^{-2} will be far lower than predicted (proportional to the increased plasma density slope at the critical density). This allows more efficient and quicker production of the necessary 1-3 MeV electrons.

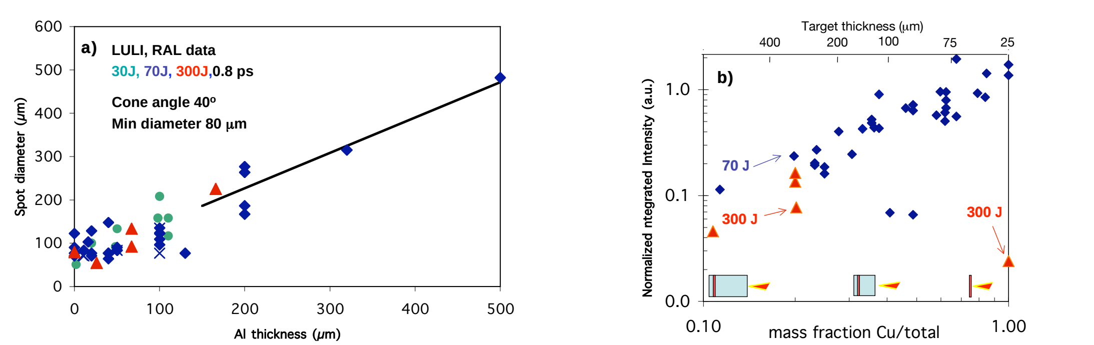

Fig. 1. (a) FWHM spot diameter as a function of propagation distance in aluminum for 30 J (LULI – green dots), 100 J (RAL – blue diamonds and x's), and 300 J (RAL – red triangles). b) Integrated K_α fluorescence intensity normalized to laser pulse energy as a function of the fraction of Cu in the target.

Accurate assessment of the electron energy spectrum is critical to this work. Early work used the model of Bell and Kingham [Bell03] to estimate the electron distribution slope temperature, T_{hot}, from electron propagation length [**Key06b**]. With Titan experiments (best facility presently available) we are working with laser irradiance only slightly >10^{20} W cm^{-2} with 0.7 ps pulses. This is where we expect the ponderomotive steeping effects start to play a role to affect T_{hot}. Recent work has consistently shown a T_{hot} lower than expected by ~2X [**King07**]. A major focus of the present experimental campaigns, then, is the evaluation of T_{hot} in as relevant a range as feasible with existing laser facilities. For the first time we are using an electron spectrometer in combination with bremsstrahlung spectrometer to obtain T_{hot} of electrons inside the target and those escaping from the rear surface. This is the first time that such a measurement has been performed. This diagnostic will be used for accurate measurement of T_{hot} on OMEGA EP experiments (see diagnostic section). The OMEGA EP, with irradiance >1x10^{20} at 10 ps pulse, will be required to fully explore this effect. When OMEGA EP facility becomes available in FY09 we will be positioned (in the ACE program) to extend these essential studies to near FI conditions.

Our early studies had given hints of a thin, hot surface layer at the laser-plasma interface. We examined this possibility by layering targets with thin fluorescing layers at various depths [**Akli08**] (Fig. 2). HOPG spectrometers collected simultaneous Mo and Ni spectra viewed from the front and back. Highly ionized He_α and Ly_α lines only appeared in the first micron of the surface. An optically thick collisional, radiative model (SCRAM [Hansen07]) using 0.1 μm thick axial slices was used to simulate this experiment. Fitting this model to the data indicates <10% fraction of K_α emitting area (that is approximately the area directly within the fwhm of the laser beam) was heated to ~6 keV with axial e-folding in 0.4 μm. While impressively hot, this area only contains about 2% of the total laser energy. Our analysis suggests that it is formed because of the shock of the ultra-intense ignitor beam (a side effect of the plasma interface steepening discussed above. Full scale FI will require intensities ~10X larger than used in this experiment and correspondingly larger shocks; this effect will be much stronger on OMEGA EP and this subject will be a major focus of our experiments there.

For the case of extreme current densities involved in realistic FI gives rise to the possibility of

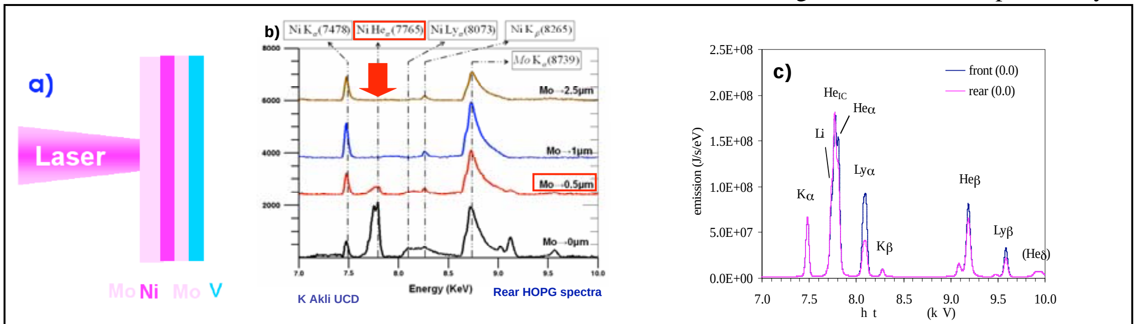

Fig. 2. (a) Multilayer fluorescence target (b) Ni fluorescence for different layer depths (c) Modeled spectra by S. Hansen, LLNL.

collective effects such as focusing fields and instabilities that would limit electron propagation in hot plasmas. Initial analyses [**Malkin02**] suggested that such instabilities would stop very energetic (>>MeV) electrons in the dense core. However, more recent calculations suggest that these instabilities are collisionally damped above 100 n_c [Kemp06]. This means that the critical component for our work is the relatively low-density hot plasma region near the cone tip. Experiments have been designed to investigate this region [**Pasley06**].

2.2. Understand Physics of FI by Proton Ignition

Objective. To understand the physics of proton production, particularly conversion efficiency and focusing, and consider its utility as an alternate ignition path.

This objective was a consequence of observations on the increase in proton energy for thin targets [**Mackinnon02**]. 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 [**Snavely07**]. 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. Sub-scale modeling by M. Foord, LLNL, using hybrid PIC LSP to model a hemi with radius of curvature, r_c = 50 μm shows that the proton focus improves when the laser beam is spread from 10 μm to 50 μm diameter (Fig. 3). 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, approximately suitable for Fast Ignition [**Key06**].

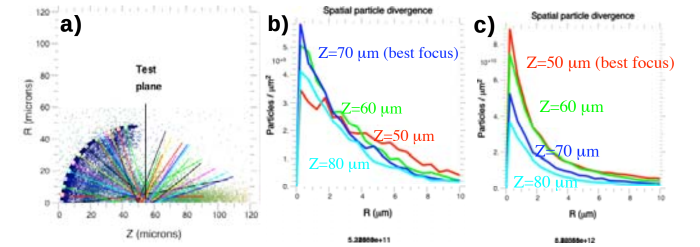

Fig. 3. (a) LSP simulation of 100 μm diameter hemi-shell 3.3 ps after 0.1 ps injection of 1.3 MeV hot electrons showing evolved proton density and typical paths. (b) Transverse proton concentration at various test planes for a 10 μm laser focus. (c) Transverse proton concentration for a 50 μm diameter laser focus.

Conversion efficiency to protons of energy >3MeV is also key research area in proton FI (Fig. 4). An analytic model was developed [**Key06**] along with modeling [**Foord07**] that suggested laser energy to proton energy conversion efficiencies up to 20% for high contrast laser pulses, thin, low scattering targets, high Z back surface, and adequate supply of protons. Experimental data shows the expected trend (Fig. 10), but to date conversion efficiency has not exceeded 10% of the laser energy. 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.

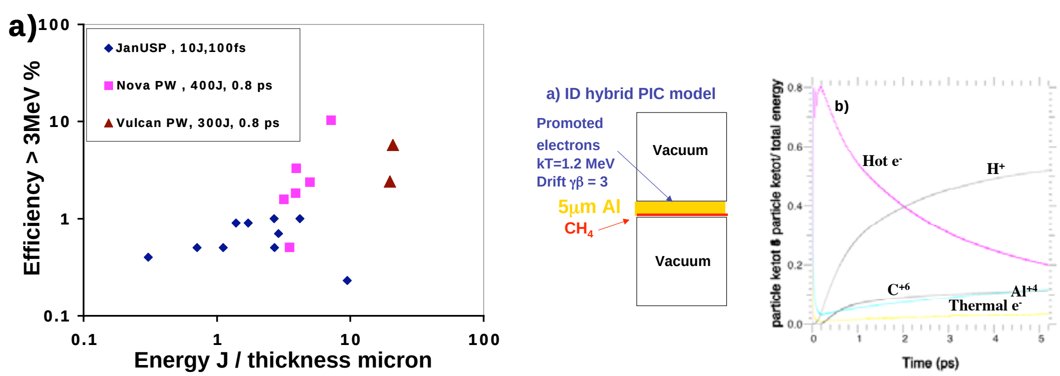

Figure 4: a) Conversion efficiency as a function of foil thickness b) model structure

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. 5), 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 [Atzeni02].

A prototype of such a proton source was built (Fig. 5b) 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 inside the cone was 125 μm in diameter, so could only produce about a quarter of the protons seen from a hemi-shell; electrons could flow sideways off that surface to the cone wall and presumably produced refocusing sheath fields along it. Those fields could change the proton focus [Toncian06]. That was enough to demonstrate focused heating of a Cu foil target (Fig. 5). Experiments to explore the effects of metal walls on the proton yield and focus will be included in a separate ion-oriented proposal.

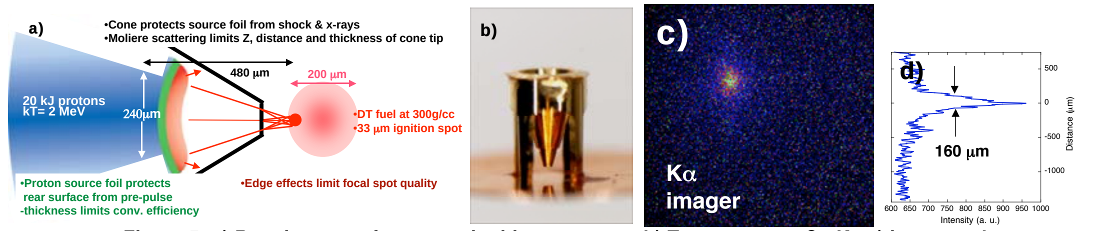

Figure 5: a) Requirements for proton ignition structure. b) Test structure Cu K_α c) image and d) line-out of spot heated by focused protons

Work will continue on determining the optimal efficiency of laser light conversion to proton kinetic energy, as well as determination of adequate models and verifying experiments to determine optimal focusing characteristics of the protons. Future proton work will be proposed as part of a developing light ion beam effort at the Los Alamos National Laboratory rather than within this electron-mediated ignition effort.

2.3. Diagnostic Development

Objective. To understand relevant diagnostic techniques in use by scientists in this field worldwide and adapt them as appropriate to our experiments; to develop specialized capabilities that are unique to our experimental efforts.

Probing phenomena inside dense plasmas in the face of the radiation and EMP blast caused by ultra-intense, short-pulse laser plasma interactions has been challenging. At NOVA PW experiments just prior to the beginning of this work, electronic diagnostics failed a majority of the time, and when they did work, data analysis was obscured by a background of energetic particles. Since those modest beginnings we have developed a wide arsenal of tools for both target and laser diagnostics, with new ones added as the laser energies and target temperatures increase.

Our diagnostic development work began, under the original CEP grant, with development of x-ray fluorescence imaging of Ti and Cu dopants [**Koch03**], expanded later for radiography [**King05**]. Stephens, et al. [**Stephens04**, **Lancaster07**] used this technique to study the divergence angle of electron transport in solid density plasmas. Later we also used the laser driven MeV proton beams for radiography of an implosion (Fig. 6) and for electromagnetic field measurements in plasmas [**Mackinnon06b, Mackinnon04**]. As we dealt with more energetic beams and hotter targets, we employed increasingly sophisticated techniques to characterize the plasma. Spectroscopic techniques gave information about plasma temperature and density [**Stoeckl04, Theobald06, Akli07**], and we also developed XUV diagnostics (68 and 256 eV) to extract temperatures [**Gu06**]. Thermal plasma temperatures were also measured using K α line shifts [**Gregori05, Chen07**]. These temperatures agreed qualitatively with the 256 eV XUV technique although this work is still in progress. We have spent considerable effort on laser diagnostics for the lasers at the facilities we have used. Knowing the specifics of the laser pulse *for each shot* continues to be a major effort. We have developed a technique for getting the true intensity [**Link06**] of a high intensity laser at the focal spot. Our efforts have resulted in the routine availability of laser prepulse data and equivalent plane images in the most recent Titan run. That information substantially improved our knowledge of the laser-pulse interaction, and showed substantial shot-to-shot variation. This information will be incorporated into our modeling and

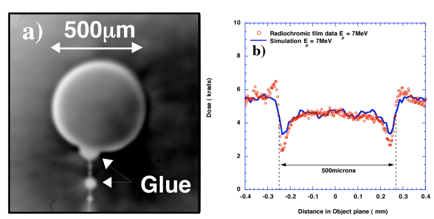

Figure 6: a) Proton image of imploding shell recorded with radiochromic film and b) compared to profile from a Monte-Carlo simulation and scattering theory

analysis and should reduce the substantial variation in shot-to-shot measurements (see for example Fig. 1) and will accurately benchmark numerical codes with experiments.

3. Summary

Good progress has been made in understanding electron and proton generation and its implications for the Fast Ignition concept within the capabilities of existing equipment.

1. Electron transport is now well understood in accessible regimes (relatively low temperature dense plasmas) in which the current transport is limited by Ohmic inhibition.
2. We have shown bottlenecking in electron generation at the front surface of targets. Although this bottlenecking generates high temperatures, it is restricted to a small region of space that does not hold up a significant fraction of the electron energy.
3. We have developed semi-integrated modeling packages (using, in various combinations, self-consistent hot electron generation, scattering, and x-ray fluorescence with hybrid PIC codes) to guide our experimental efforts. These tools are critical to our evaluation of laser_interaction/particle_transport options.
4. Diagnostics have been developed to characterize in-situ electron behavior to enable the experiments to date. New diagnostics – including new bremsstrahlung and electron spectrometers – have been developed to enable the higher energy hot plasma experiments to be performed in the next few years.

As a result of this work, Fast Ignition research is well positioned for the next step up in energy made possible by the new facilities coming on-line. Major issues for the coming year are: 1) Maximizing electron current injection from a cone geometry into a hot, dense plasma and controlling its spread and 2) Investigating the effect of profile steepening on conversion efficiency and hot electron spectrum at the multi-kJ, 10 ps conditions close to the requirements for FI. (3) Maximizing proton beam production efficiency and minimizing focus aberrations within the constraints of its protective case – thus providing firm basis for new ion/proton proposal to start in FY09.

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Submitted/Accepted manuscripts

1. K.U. Akli et al., "Laser heating of solid matter by light pressure-driven shocks at ultra-relativistic intensities," to be published in *Phys. Rev. Lett.* (2008).
2. T. Ma et al., "Extreme ultraviolet imaging of electron heated targets in Petawatt laser experiments," to be published in 5th special issue of *IEEE Transactions on Plasma Science on Images in Plasma Science* (2008).
3. J. Pasley et al., "Laser driven relativistic electron transport in wires," to be published in 5th special issue of *IEEE Transactions on Plasma Science on Images in Plasma Science* (2008).
4. M.S. Wei et al., "Study of relativistic electron beam production and transport in high intensity laser plasma interaction with a wire target by the integrated LSP modeling," submitted to *Phys. of*

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5. M. Nakatsutsumi et al., "Space and time resolved measurements of the heating of solids to ten million Kelvin by a PetaWatt laser," submitted to *J. New Physics* (2008).
6. J.A. King et al., "Studies of the transport of high intensity laser-generated hot electrons in cone coupled wire targets," to be published in *Phys. Rev. Lett.* (2008).
7. J. Pasley et al., "Laser driven relativistic electron transport experiment in shock heated warm dense matter," to be published in *J. Phys. D* (2008).

<u>A selection of invited conference presentations</u>

1. Applications of high field and short wavelength sources IX, OSA topical meeting , Palm Springs , Oct. 2001.
   a. M.H. Key, "Laser generated relativistic electrons – the key to fast ignition and hard x-ray sources."
2. Japan/US FI workshop – R. Stephens US Co-chair. 25-27 March 2002 Ritsumeikan University, Kusatsu, Shiga, Japan. It was held concurrently with Japan Physical Society meeting, in which we gave a FI symposium. The invited US talks at the JPS symposium were:
   a. M. Key, "Progress in fast ignition: a review of recent results in USA."
   b. R. Stephens, "Asymmetric targets suitable for fast ignition designs and tests."
   c. T. Cowan, "The role of fast protons in fast ignition and other applications."
3. 10th Intl. Workshop on the Radiative Properties of Hot Dense Matter, 16-20 Sept. 2002, St Malo, France
   a. R. Freeman, et al., "Understanding the role of fast electrons in the heating of dense matter: experimental techniques and recent results,"
4. International Conference on Multi-Photon Physics, October 02, Crete.
   a. R. Freeman, et al, "High intensity lasers and controlled fusion"
5. Workshop on Complex Systems of Charged Particles, Moscow, 20 April, 2006.
   a. L. Van Woerkom, "Energy transport in ultraintense laser-solid interactions."
6. Optical Society of America, Frontiers in Optics. 10-14 October, 2004, Rochester N.Y.
   a. M.H. Key, Tutorial Review, "Fast Ignition."
7. International Conference on Ultrahigh Intensity Lasers. 3-7 October, 2004, Lake Tahoe, CA
   a. M.H. Key, Keynote presentation, "Fast Ignition."
8. 46th Annual Meeting of the Division of Plasma Physics, Savannah, GA, November 15-19, 2004:
   a. M. Tabak, "Review of progress in Fast Ignition."
9. International Conference on Plasma Science, Traverse City, MI 4-8 June 2006
   a. L. Van Woerkom, "Electron transport in ultraintense laser-solid interactions"
   b. A.J. MacKinnon, "Studies of proton generation and focusing for fast ignition applications"
10. Laser Physics Workshop, Lausanne, Switzerland 24 July, 2006.
    a. L. Van Woerkom, "Energy transport in ultraintense laser-solid interactions."
11. 21st IAEA Fusion energy conference, Chengdu, China, 16-21 October 2006
    a. A.J. Mackinnon, "Studies of electron and proton isochoric heating for fast ignition"
12. APS-DPP 2006, Philadelphia PA: 30 Oct. – 3 Nov. 2006
    a. M.H. Key, "Status and prospects for the fast ignition inertial fusion concept"
13. 9th International Fast Ignition Workshop, Cambridge, MA, 3-5 Nov. 2006
    a. A.J. MacKinnon, "Studies of proton generation at focusing for fast ignition applications."
    b. F.N. Beg, "Electron Transport in Wire Targets"
14. APS-DPP 2007, Orlando, FL: 12 – 16 Nov. 2007
    a. L.D. Van Woerkom, "Intense laser interactions on the road to fast ignition"
15. 28th International Conference on Physics at High Energy Density in Matter, Herschegg, Austria: 27 Jan – 1 Feb
    a. F.N. Beg, "Transport of high intensity laser-generated hot electrons in cone coupled wire targets"
16. HEDLA, St. Louis, MO, 11-15 April 2008.
    a. F.N. Beg, "Transport of high intensity laser-generated hot electrons in fast ignition relevant targets"
    b. P. Patel, "Creating high energy density matter with intense laser driven proton beams"
17. ANS 18th Technology of Fusion Energy: 28 Sept. – 2 Oct. 2008
    a. R.B. Stephens, "Toward the design of a fast ignition target"

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