Experimental demonstration of key parameters for Ion-Based Fast Ignition

B. M. Hegelich 1), 2), B. J. Albright 1), J. C. Fernandez 1) , D. C. Gautier 1), C. Huang 1), D. Jung 1), 2), T. J. Kwan 1), S. Letzring 1), S. Palaniyappan 1), R. C. Shah 1), H.-C. Wu 1), L. Yin 1), A. Henig 2), R. Hörlein 2), D. Kiefer 2), J. Schreiber 2), X.Q. Yan 2), D. Habs 2), B. Dromey 3) M. Temporal 4) and J.J. Honrubia 4)

1) Los Alamos National Laboratory, Los Alamos, United States of America
2) Ludwig-Maximilian-Universität München, Germany
3) Queens University Belfast, Belfast, UK
4) Grupo Interuniversitario de Fusión Inercial, Universidad Politécnica de Madrid, Spain

E-mail contact of main author: hegelich@lanl.gov

Abstract. Research on fusion fast ignition (FI) initiated by laser-driven ion beams has made substantial progress in the last years. Compared to electrons, FI based on a beam of quasi-monoenergetic ions has the advantage of a more localized energy deposition, and stiffer particle transport, bringing the required total beam energy close to the theoretical minimum. Due to short pulse laser drive, the ion beam can easily deliver the 200 TW power required to ignite the compressed D-T fuel. Our recent integrated calculations of ion-based FI include high fusion gain targets and a proof of principle experiment. The simulations identify three key requirements for the success of Ion-driven Fast Ignition (IFI): 1) the generation of a sufficiently high-energetic ion beam (≈ 400-500 MeV for C), with 2) less then 20% energy spread at 3) more than 10% conversion efficiency of laser to beam energy. This paper describes new experimental results, demonstrating all three parameters in separate experiments. Using diamond nanotargets and ultrahigh contrast laser pulses we were able to demonstrate >500 MeV carbon ions, as well as carbon pulses with <20%. First measurements put the total conversion efficiency of laser light into high energy ions on the order of 10%. Furthermore we are presenting simulation results towards the integration of all three parameters and towards focusing these ion beams.

1 Introduction

This paper summarizes significant recent progress, in experiments and modeling, towards the realization of high-gain fusion using the fast ignition (FI) approach [1] to inertial confinement fusion (ICF), made possible by the invention of high-power (~kJ), short pulse (<ps) lasers. Specifically, we discuss progress on the special Ion-driven Fast Ignition (IFI) variant of this approach using laser-driven ion beams to ignite the fuel. Within the Fast Ignition concept, such a high-power (~PW) laser is used to deliver sufficient power density (~10^{23} W/cm^3) to the DT fusion fuel at the time of stagnation at maximum compression (~10s of ps), to isochorically heat a spot in the fuel to ~10keV.

1.1 Electron Fast Ignition (EFI)

The standard (electron based) variant of fast ignition seeks to deliver the energy via fast electrons (~MeV), accelerated in the laser-fuel interaction [2,3]. To overcome challenges of laser-beam transport to the dense fuel core regions, this scheme was later modified by the addition of a re-entrant cone to ensure laser-plasma interaction close to the compressed core [4], but beam transport through plasma due to prepulse induced cone filling and electron transport to the hot spot due to large divergence of the electron beam remain the key challenges for electron fast ignition.

1.2 Proton Fast Ignition (PFI)

A possible alternative became feasible with the demonstration of proton acceleration from high power lasers at the Petawatt laser at Lawrence Livermore National Laboratory. Using the so-called "Target Normal Sheath Acceleration" (TNSA) mechanism [5], LLNL was able to accelerate protons to up to 60 MeV in an exponential spectrum [6]. Together with excellent emittance of the ion beam [7,8], which enables ballistic focusing via a shaped target [9], laser-driven electrostatic lenses [10] or miniature magnetic quadrupoles [11] to micron focal sizes, this in principle enables its use as a fast ignitor, first suggested by Roth et al in 2002 [12] and refined since then [13,14]. The main challenges of the proton fast ignition (PFI) concept as currently envisioned lie a) in the maxwellian nature of the TNSA produced proton spectra, b) the low particle energy and c) the relatively low demonstrated conversion efficiencies of laser-light into protons. A) spectral shape: the non-mono-energetic nature of the proton spectrum causes significant time-of-flight spread in the proton beam over longer distances and therefore requires the proton source to be situated close (~1mm) to the target, in turn requiring re-entrant cones and protection foils with all the added complications for target design, laser transport and particle transport. B) particle energy: the required particle energies for proton fast ignition are in the range of 5-15 MeV to achieve stopping at the right range in the fuel. Since the energy per particle is low, a very large number of protons ($>10^{16}$) is required to carry the necessary energy of ~10kJ. From current experiments it is not clear yet, if such a large number of protons can be supported by the proton target and efficiently accelerated by the laser. C) conversion efficiency: demonstrated conversion efficiencies for proton acceleration are currently at the 1-3% level, requiring several hundred kJ to MJ lasers to produce the required 10kJ of protons. Such a system would not represent significant savings over a standard (non-FI) IFE facility at the MJ level. Efficiencies of at least 10% are required to make any of the FI concepts feasible.

1.3 Ion Fast Ignition (IFI)

Using heavier ions than protons to achieve ignition is advantageous primarily due to the stiffer transport characteristics of a heavy ion beam and the enhanced stopping power of heavier ions, which would allow a much more precise deposition of all the energy in the hotspot volume [15, [16]]. Furthermore, due to the increased stopping, the particle energy to penetrate a given plasma to a specific depth has to be higher than for protons, meaning each particle will deliver more energy, allowing the total number of particles to be a lot smaller. This in principle eases a lot of target design problems. Our recent simulations were able to identify the key parameters for a carbon-based fast ignition scheme: on the order of 10^{14} carbon ions with energies of ~440±50 MeV, or 37 MeV/nucleon have to be focused into the ~$20\mu m^3$ hot spot [17,18]. However, exactly these characteristic makes TNSA based IFI impossible. Due to their enhanced stopping heavier ions not only benefit from, but require a monoenergetic spectrum, albeit a fairly broad one ($\Delta E/E$~20%). While efficient TNDA acceleration for heavier ions has been demonstrated [19,20], obtaining a sufficiently narrow carbon spectrum using the TNSA mechanisms has been shown only at lower efficiencies of ~0.1% [21], which makes it infeasible for ion fast ignition. However, the recent discovery of new ion acceleration mechanisms in large-scale PIC simulations has changed this paradigm. Specifically the Break-Out Afterburner (BOA) mechanism [22,23] and Radiation Pressure Acceleration (RPA) [24,25] seem to be well suited to deliver the required parameters for ion fast ignition. In contrast to TNSA, these variants of light pressure acceleration act predominantly on the high-Z ions, transferring most the laser energy to the high Z ions rather than the protons, making them ideal candidates for IFI. The challenge is in the experimental realization of these mechanisms: To reach the required regimes on current laser systems, that are 2-3 orders of magnitude smaller than a full FI laser, requires ultrathin (~nm) targets and therefore ultrahigh contrast of the laser pulse. Until recently, these requirements were out of range for all existing laser facilities. However, with the recent ultrahigh contrast upgrade of the Trident laser [26] and the development of robust, free-standing ultrathin Diamond-Like

Carbon (DLC) foils at LMU Munich, we could now conduct a first serious of experiments to investigate the feasibility of ion fast ignition.

2 Experimental setup

2.1 Laser system and contrast

The experiments were performed at the Trident laser at Los Alamos National Laboratory [27]. The shortpulse arm of the Trident laser delivers routinely 80J on target with a pulse duration of 500-600fs in a 1.5x diffraction limited spot using an F/3 off-axis parabola, resulting in an average spot intensity of ~2x10^{20} W/cm^{2} and a peak intensity of ~5x10^{20} W/cm^{2}. Trident employs a nonlinear filter technique to improve its pulse contrast [28,], which is a key parameter for all chirped pulse amplification systems (CPA) [29]. The contrast describes how fast the pulse turns on. Due to the nature of CPA, where a short sub-ps laser pulse is stretched in time (ns) then amplified and then recompressed to its original short duration, the short high intensity pulse sits on a ns pedestal of incompressible noise. In addition reflections in the system can also cause short prepulses before the main pulse and imperfect stretching/compression will induce ps “shoulders” into the pulse shape. The laser contrast is ratio of the pedestal/prepulse intensity at a given point in time to the peak intensity of the main pulse. For a typical ultrahigh intensity system that ratio is on the order of one millionth (10-6) at ~1ns before the 500fs main pulse. If the focused main pulse intensity is ~10^{20} W/cm^{2}, the prepulse intensity will be ~10^{14} W/cm^{2}, i.e. more than enough to create a plasma and to destroy the target before the main pulse can interact with it. For the advanced ion acceleration schemes to work at 10^{20} W/cm^{2} intensities, it is imperative that the initially only 5-50nm thick target is still overdense at the peak of the pulse. Therefore, at peak intensities above 10^{20} W/cm^{2} very good contrast ratios of better than 10^{-12} at ~ns are required. To realize these extreme, ultrahigh contrast conditions, we developed a new cleaning system based on Short Pulse Optical Parametric Amplification (SPOPA) [26]. Using an additional compressor stretcher pair and exploiting two quadratic nonlinearities we obtain cubic cleaning performance at great stability at modest intensity, realizing a contrast good enough to ensure main pulse interaction with an overdense target. The thus realized contrast currently is below the detection threshold of our optical diagnostics at 0.5ns. Damage threshold measurements on the used targets put it as low as <2x10^{-12} for a 1.2ns pedestal and <5x10^{-10} for 0.5ps prepulse. Closer in the contrast is measured to be <10^{-9} @ 50ps and <10^{-7} @ 5ps. Figure 1 shows the full aperture backscatter images of a 100nm target shot with the old frontend and contrast of ~10^{-7} @ ns and a 30nm target shot with the improved contrast values. Whereas the 100nm target shows a clear whole in the center, burned through by the prepulse, the 30nm target shows a strong central reflection from an overdense plasma. Targets as thin as 3nm where successfully shot on Trident, remaining overdense during a large part of the interaction.

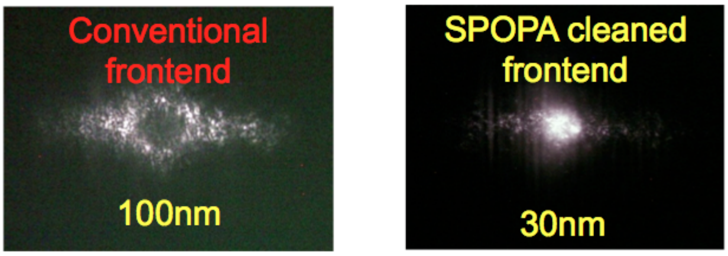

Figure 1: Full backscatter images from 100nm and 30nm targets shot with the conventional and ultrahigh contrast system, respectively.

2.2 Targets

The second requirement to successfully reach the BOA/RPA regime at ~10^{20} W/cm^{2} are nanometer targets. We employed nm-thin Diamond Like Carbon (DLC) foils, developed at the Kurchatov institute in Moscow and perfected for this application and produced LMU Munich using a specialized cathodic arc discharge [30]. DLC is a metastable form of amorphous carbon. Due to their high content of sp3 bonds, 50-75% for the targets used, the foils possess an exceptional mechanical robustness. Furthermore they are very transparent, making them less susceptible to laser prepulses, resulting in a high optical damage threshold.

2.3 Diagnostics

The Trident North Target Area was used for the experiments and a variety of different diagnostics was employed simultaneously. The exact diagnostics setup changed and evolved over the four experimental campaigns but a typical setup is shown in Figure 2. The main diagnostics consist of a suite of Thomson parabola ion spectrometer at different angles, ranging from compact low resolution spectrometers to a next generation, high resolution Thomson parabola specifically developed for these experiments [31], with an energy resolution of >2 GeV for carbon ions and charge state resolution C6+/C5+ at > 1 GeV. As secondary diagnostic several compact electron spectrometers are employed at different angles with energy resolution in the 10-100 MeV range. To analyze the pulse transmitted through the target during relativistic transparency (see below) we use a optical spectrometer, a single shot 2nd order autocorrelator and a specially developed single shot FROG device [32].

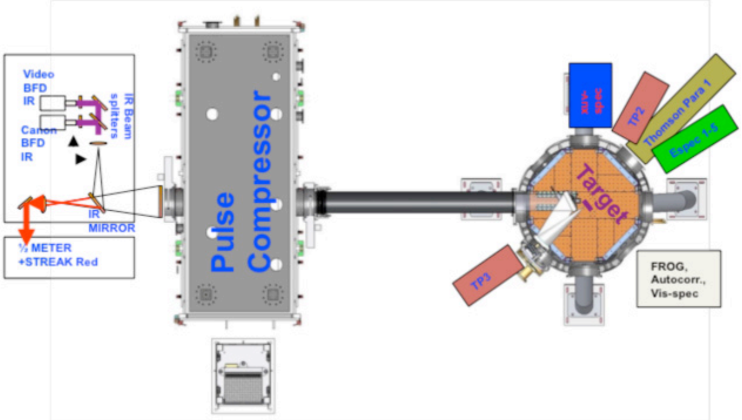

Figure 2: Figure 2: Typical experimental setup for ultrathin foil experiments on Trident: The target chamber (right) is outfitted with a variety of particle and optical diagnostics. A second diagnostic station to analyze the backscattered light is setup on the other side of the pulse compressor, looking at leakage of backscattered light through the compressor mirror with imaging and spectroscopical diagnostics.

3 Experimental results

Up to date, four experimental campaigns investigating laser-driven ion acceleration for ion fast ignition have been conducted on the Trident laser. Interacting the Trident laser pulse at normal incidence with a range of different thickness DLC targets, the optimal target parameters for Trident conditions could be determined, resulting in the first demonstration of >0.5 GeV carbon ions from laser acceleration [33]. This range of experimental data and the comparison to large-scale 2D and 3D simulations using our VPIC code on the LANL Roadrunner supercomputer let to a detailed understanding of the underlying physics [33] and the development of a reduced analytical model [34]. When the laser pulse hits an overdense nanometer target, it heats up the targets electrons while the target starts to expand. If the laser and target parameters are chosen correctly, the electrons will heat faster than the target is expanding, resulting in the condition $n_e/\gamma\ n_{cr}$ 1~, with $n_e >> n_{cr}$. Here, n_e is the electron density, n_{cr} the critical density for the laser wavelength and γ is the relativistic gamma factor of the electrons. In such a situation the target becomes relativistically transparent though still classically overdense, and the laser can penetrate the target and propagate within, volumetrically interacting with all target electrons. This leads to coherent, laser-driven electron motion, which sets up charge separation fields and kinetic instabilities with the slower ion population that can effectively transfer energy from the electrons to the ions [35].

The energy lost by the electrons is immediately replenished by the superimposed laser, making this mechanism very efficient for ion acceleration.

3.1 Ion Energies

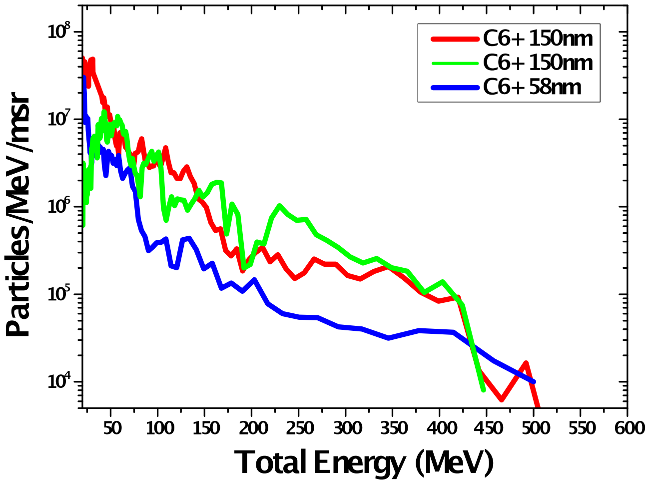

Figure 3: Laser-accelerated ion spectra for different DLC target thickness, measured at different angles with respect to the laser (and target normal) direction: 0° (blue), 8.5° (red) and 22.5° (green).

At the optimal thickness for Trident conditions, between 50 – 150 nm, we were able to demonstrate energies as high as 500 MeV, i.e. the required energies for IFI. Figure 3 shows example of ion spectra which were measured at different angles for target thicknesses within the optimal range, using Thomson parabola spectrometers at 0°, 8.5°, 22.5° and 45° as well as beam profiling monitors. The spectra show an exponential decaying distribution, with a real (not instrument induced) low energy cutoff, a remnant from a mono-energetic shape in an earlier acceleration phase. We could verify an approximate beam angle of ~22.5°, after which the energy declines steeply. The beam angle is related to the used focusing optics (F/3) and observed to decrease with a slower (F/8) optic and predicted to increase with a faster F/1 optic by simulations and theory (experiment scheduled).

3.2 Conversion efficiency

Preliminary estimates of laser energy to ion energy conversion efficiency ε can be done under the assumption of a homogenously distributed beam within a 22.5° cone angle as suggested by the measured ion spectra. Integrating the energy contained in the spectra in an energy range from 20 – 300 MeV, i.e. underestimating the total converted energy we arrive at a figure of approximately 8-10%, depending on the exact shot conditions. This is the right order of magnitude for ion fast ignition, achieved at conditions far from optimal. PIC simulations suggest that temporal and spatial pulse shaping will improve both the efficiency as well as the spectral distribution of the ion beam. Similar efficiencies were obtained in measurements at the Max-Born-Institute in Berlin, using a much small Ti:Sapphire laser with 0.7 J, 45 fs, 5x10^{19} W/cm^{2} and correspondingly thinner, 5nm targets [36]. Whereas the Trident experiments are the first experimental demonstration of the BOA regime, here the first onset of RPA acceleration could be observed [37].

3.3 Spectral shape:

The spectra shown in Figure 3 show only weak remants of mono-energetic shapes in their dropping low energy side and a slight increase/plateau at the high energy end. Obviously they are nowhere close to the required <20% energy spread for fast ignition. This is mainly due to the fact that we need every bit of laser intensity to achieve the 500 MeV required energies. Since a real fast ignition laser has to be orders of magnitude larger for pure energetics reasons, this allows us to trade of some of the intensity for spectral shaping. As we could show in experiments, the use of circular polarization can lead to more mono-energetic spectra

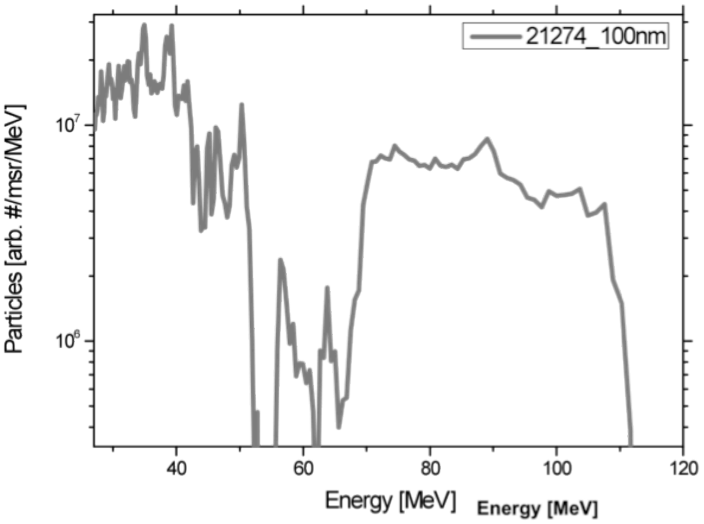

Figure 4: Mono-energetic carbon spectrum from BOA acceleration using a F/8 long focal range off-axis parabola.

[38]. By reducing the initial target expansion it is possible to seed a tight ion density spike, an ion-soliton, that will keep its distribution of accelerating electrons during the BOA phase and thus preserve local charge neutrality, preventing its dispersion. A different example of how such a spectrum can be obtained is shown in **Fehler! Verweisquelle konnte nicht gefunden werden.**. Here we use a long focal length off-axis parabola (F/8), projecting a larger focal spot. This reduces the on-target intensity and therefore the initial target expansion as well as the maximum ion energies. However, due to the longer Raleigh range the interaction length increases, off-setting the effect on maximal energies slighty. We obtain a peaked ion spectra at 90 MeV mean energy with an energy spread of roughly 20%, i.e. in the ballpark of Ion Fast Ignition. Narrower energy spreads (at ~40 MeV) could be obtained using circular polarization and will be published separately [39].

4 Conclusion

Recent experiments have for the first time shown the successful exploitation of the transparent-overdense regime of Break-Out Afterburner acceleration. In the course of the experiments we demonstrated carbon energies from laser-accelerators as high as 500 MeV/nucleon at laser-to-ion energy conversion efficiencies approaching 10%. We could further demonstrate spectral shaping in the 20% ΔE/E range by a variety of mechanisms, e.g. circular polarization or spatial pulse shaping. All pulse shaping methods employed today, reduce theintensity on target, leading to lower energies for the demonstrated mono-energetic spectra. However, since a real fast ignition laser has to be many orders of magnitude more powerful due to simple energetics requirements this does not present a conceptual problem. These results demonstrate three of the four key requirements of ion-based fast ignition, leaving only focusing left. The next grand challenge will be to unify all the separate characteristics in one beam. The recent experimental progress on laser-driven ion acceleration enabled us to considerably advance the theory, too, and develop a reduced model that is in excellent agreement with both experiments and simulations. This model enables rapid-turn-around design estimates for future experiments and massively parallel 3-dimensional PIC simulations requiring weeks of runtime on thousands of cores. Being able to optimize initial conditions for both, enables a steady progress in understanding and optimization of the ion source. We can thereby identify the temporal and spatial pulse parameters required to successfully obtain all three beam parameters at once. In the worldwide absence of a laser system fulfilling all required parameters at once, we have therefore performed numerical experiments using our benchmarked and validated VPIC code, to show that it is indeed possible to laser-accelerate carbon ions that will fulfill all three requirements simultaneously. These results are paving the way for a suitable, quasi-monoenergetic ignitor ion beam, which in turn enables feasible and much simpler targets that do not require a capsule with a reentrant cone. Ion-based FI is emerging as the variant with the most separability of its basic elements: (1) DT fuel compression to a mass density ρ = 300–500 g/cc, areal density ρ r ≈ 3 g/cm2; (2) generation of a ~ 10 kJ, ~450 MeV, quasi-monoenergetic ignitor carbon beam, achieved via the interaction of a high-power, high-energy short-pulse laser with a nano-target that is well separated from the imploded fuel capsule, and; (3) the deposition of the beam energy in a relatively small "hot spot" volume (~ 25 μ m)3, within τ ~ 20 – 50 ps, which ignites the fuel. Besides the obvious engineering advantages, this separability enables more rapid and cost-effective scientific progress and development in each area. With the recent progress in both theory and experiments, ion-based fast ignition can be considered as a serious alternative to the classical FI concepts.

This work is sponsored by the US DOE and the LANL LDRD program office and by the German DFG and LMUexcellent.

---

[1] Tabak M, Hammer J, Glinsky ME, Kruer W L, Wilks SC, Woodworth J, Campbell E M, Perry MD and Mason R J Phys. Plasmas (1994), 1, 1626
[2] Wilks, S.C.et al., 1992 Phys. Rev. Lett. 69, 1383
[3] Beg, F.N. et al., 1997 Phys. Plasmas 4, 447
[4] Kodama R et al. 2001 Nature 412 798
[5] Hatchett S. et al. 2000 Phys. Plasmas 7 2076
[6] Snavely, R. et al., 2000 Phys. Rev. Lett. 85 2945
[7] Schreiber, J. et al., 2004 Appl. Phys. B 79, 1041
[8] Cowan, T. et al., 2004 Phys. Rev. Lett. 92, 204801
[9] Patel, P.K. et al., 2003 Phys.Rev.Lett. 92 125004
[10] Toncian T. et al 2006 Science 312 410
[11] Schollmeier M. et al 2008 Phys. Rev. Lett. 101 055004
[12] Roth, M. et al., Phys. Rev. Lett. 86 (2001), 436
[13] Atzeni S, Temporal M and Honrubia J J 2002 Nucl. Fusion 42 L1;
[14] Temporal M, Honrubia J J Atzeni S 2002 Phys. Plasmas 9 3098
[15] Fernandez J.C., et al., Journal of Physics: Conference Series 112 (2008) 022051
[16] Shmatov, M., 2007 Fus. Sci. Techn. 52, 116
[17] Honrubia, J.J. et al., 2009 Phys. Plasmas 16, 102701
[18] Fernandez, J.C. et al., 2009 Nucl. Fusion 49, 065004
[19] Hegelich, B.M. et al., 2002 Phys. Rev. Lett. 89, 085002
[20] Hegelich, B.M. et al., 2005 Phys. Plasmas 12, 056314
[21] Hegelich, B M, et al., 2006 Nature 439, 441
[22] Yin L, et al., 2006 Lasers Part. Beams 24 291
[23] Albright B.J. et al., 2007 Phys. Plasmas 14 094502
[24] Macchi A. et al 2005 Phys. Rev. Lett. 94 165003
[25] Robinson A.P.L. et al., New Journal of Physics 2008 10 013021
[26] Shah, R. et al., 2009 Opt. Lett. 34, 2273
[27] Batha, S.H., et al., 2008 Rev. Sci. Instr. 79 10F305
[28] Wang and B.Luther-Davies JOSA B, 11: 1531 (1994)
[29] Mourou, G.A., Umstadter, D., 2002 Scient. Amer., 286.
[30] Liechtenstein, V.K. et al., 1997 Nucl. Instrum. Methods Phys. Res., Sect. A 397, 140
[31] Jung, D., et al., submitted to Rev. Sci. Instrum. 2010

[32] Palaniyappan, S. et al., 2010 Rev. Sci. Instrum. 81, 1
[33] B.M. Hegelich et al., submitted to Nature Physics (2010)
[34] Yan, X., et al., 2010 Appl. Phys. B 98, 711
[35] Yin L., et al., 2007 Phys. Plasmas 14 056706
[36] Steinke, S. et al., 2010 Las. Part. Beams 28, 215
[37] Henig, A. et al., 2009 Phys. Rev. Lett. 103, 245003
[38] Jung, D. et al., 4th International Conference on Ultra-Intense Lasers, Watkins Glen NY, US, September 26-30 2010
[39] Jung, D. 2010 in preparation