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Petawatt Laser Data Analysis and Technology Development

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1. Introduction

The Petawatt (PW) laser beam line at the LLNL Nova laser facility was unique in the world in supplying an order of magnitude higher power (1PW in pulses of 500 fs duration) than lasers elsewhere. Focussed to intensities reaching $3x10^{20}$ Wcm^{-2}, it opened up a new regime of experimental science where free electron energies in the light wave are strongly relativistic. After full operational capability of the PW beam-line was reached, close to 25% of the operation of the Nova facility was dedicated to PW shots for two years, prior to the shut down of Nova in May 1999. A wealth of novel scientific data was obtained and it motivated the primary objective of this June 1 to Oct. 1,1999 LDRD, which was to complete systematic analysis of the PW laser data. This was done by the team, which had conducted the experiments working with associated experts in theoretical modeling of the complex physical phenomena. A second objective was to develop a key new technology of large area transmission gratings needed for the next step to higher energy PW laser development. This work was done by the team, which developed the reflective grating technology.

2. Scientific importance and spin off

The scientific results obtained with the PW laser had considerable impact and led to numerous presentations including keynote, plenary and invited talks at international conferences (see list V1 to V8 and appended copies), technical reports and publications (see list P1 to P21 and appended copies). There was significant public relations value, the results being featured, for example, on the scientific highlights web site at the 1999 APS DOP meeting and in the LLNL Science and Technology Review [P20]. A record of invention was filed for a novel ion beam source for which a patent application is in progress. Future exploitation of the science was assured by the creation of a new 4 year multi – institution collaborative research program in "exploration of fast ignition", supported by the DOE office of fusion energy sciences. The technical R&D on transmission grating development was at the forefront of diffraction grating technology and is a key enabling technology for future higher energy PW lasers.

3. Analysis of experiments

Analysis of the PW data has yielded outstandingly interesting scientific results, which can be summarized under the headings of:

- Intense collimated high-energy proton beams
- Relativistic electrons, multi Mev photons and photo-nuclear and pair production phenomena
- Fast ignition

3.1. Intense collimated high energy proton beams

One of the most interesting discoveries was the least expected. In studies aimed at characterizing the source characteristics of relativistic electrons generated by irradiating solid targets in vacuum, it was observed that an intense highly collimated beam of protons with energies up to 55 MeV was emitted perpendicular to the rear surface of the target [P5, P4, P16]. This was first seen as a sharply defined beam in an image recorded by radiochromic film (which changes color in proportion to the dose of ionizing particles or radiation). Quantitative analysis demonstrated that as much as 7% of the laser energy was converted to >20MeV protons [P16]. A magnetic deflection spectrometer showed a sharp cut off in the energy spectrum, which was at up to 55MeV on axis, and at lower energies for more off axis angles. The emittance of the beam was comparable to that used in proton accelerators. Nuclear activation through the (p, n) process in Ti gave confirmation of the angular pattern of the proton beam by autoradiography and confirmed the estimated conversion efficiency. The acceleration mechanism was identified and modeled analytically [P4] and numerically [P21]. It is due to a sudden formation by relativistic electrons of a Debye sheath at the solid vacuum interface creating accelerating fields for ions leaving the target of many MeV per micron. The ion beam has significant applications potential, which is now being explored and a record of invention has been filed.

3.2. Relativistic electrons, multi Mev photons and photo -nuclear and pair production phenomena

The relativistic electron source with energies up to 100MeV[P3] and typically 4 MeV "temperature" enables generation of an intense continuum of multi MeV x-ray photons through the process of Bremsstrahlung. Gold targets 1 mm thick emitted x-rays in a broad 100° forward cone angle in the direction of the laser. Conversion to MeV photons was 3% (implying >40% conversion to relativistic electrons) and dose levels as high as 2 rads at 1m were recorded [P6, P4]. Radiographs of sub mm resolution were obtained via as much as 15 cm of Pb. The application to dynamic radiography in the stockpile stewardship program requires even higher source intensities, which would be obtained if the cone angle of the source could be narrowed, which is an area of ongoing investigation.

Scientifically exciting byproducts of this work included the opening up of study of laser induced photonuclear processes [P2]. Photons at energies >10MeV induce (g, xn) nuclear activation, which was observed in Au for x=1 to 7 and used to measure the photon spectrum at energies up to 70 MeV in addition to the angular pattern of emission [P13, P19]; photo dissociation of Uranium was similarly induced [P2]. The first observations of e+e- pair production with lasers were also achieved [P3] and the data suggested that, in addition to pair production through absorption of photons interacting with high z matter, there was evidence of electron collisional production of pairs, which opens the way to laboratory study of the astrophysically significant electron positron plasma.

3.3. Fast Ignition

The Fast Ignition (FI) Inertial Fusion Energy (IFE) Concept is recognized as having the potential to improve the attractiveness of IFE reactors. FI ignites pre-compressed fuel pellets with a separate laser pulse, achieving much higher gain than is otherwise feasible. This higher gain and other advantages in the target, driver and ignition system lead to a more attractive power plant [P5, P17].

The scientific basis for the ignition spark energy and the fusion gain is well-established, [P5] but there is significant uncertainty in the efficiency of energy transfer from the ignitor laser to the ignition spark. In the most developed scenario, the laser beam must penetrate sub-critical density plasma and create a directed beam of relativistic electrons, which carries the ignition energy to the ignition spark. The proton beam discovered in our work also created a novel possibility for fast ignition in which a beam of ballistically focused protons more easily penetrates the peripheral plasma and heats the ignition spark [P14]. There is uncertainty in the energy transfer physics in both these scenarios and the physics involved is complex and relatively unexplored.

The transport of energy from the laser beam into solid density material by relativistic electrons was studied in our experiments. The heating effect of the electrons in solid targets was measured in two ways. Evidence of temperatures in the range 0.5 to

1keV was obtained from observation of a narrow DD thermonuclear fusion peak superimposed on an intense broad background from (γ, n) and (p, n) processes, in neutron energy spectra [P5]. Data were recorded from targets of CD_2 with a front layer of CH or Cu. Further evidence was obtained from x-ray spectra of emission from Al sensor layers buried up to 20 μm deep in CH targets. Temperatures of about 300 eV and density of 0.6 g/cc were recorded [P8, P9]. Of particular interest, were pinhole camera images of the x-rays from the Al, which showed an annular pattern of heating with an 80 μm diameter. Images from the rear side of targets having Al layers up to 100 μm from the front surface showed a similar annulus. This data strongly suggest heating in a collimated pattern as predicted by recent theoretical modeling of magnetically guided energy flow. The high temperature and density at distances more than 10x the focal spot diameter has never been seen before and this work is, therefore, significant in the quest for fast ignition.

4. Transmission grating development

The development at LLNL of 1 m diameter reflective diffraction gratings used for pulse compression, was the key technology for the PW laser. The limiting factor on the laser power is damage to the gold coatings of the gratings.

The objective of this LDRD was to demonstrate fabrication of a large aperture fused silica grating used in transmission. Such transmission gratings operate without damage at much higher energy per unit area. Highlights of this work [P20] and a detailed technical report [P1] are appended.

Computational modeling was used to define the required groove pattern for high efficiency operation in Littrow m=-1 order with 90° deflection of the beam. The grating grooves have 0.75 μm spacing and are very deep relative to their width. A test of the process at 5 cm aperture had earlier been shown to give 95% diffraction efficiency. A significant technology step addressed in this LDRD was the adaptation of the reactive ion beam etching (RIBE) process used in the grating manufacture to produce a 65 cm aperture grating on a fused silica substrate.

The grating fabrication process begins with coating the substrate with a resist. The resist is then exposed to a fringe pattern of the required spacing in the same large aperture laser interferometer that was used in manufacture of the reflection gratings. Chemical etching of the resist produces the required exposed pattern of bare fused silica and finally, the RIBE process is used to create the required groove depth in the fused silica before the residual resist is dissolved and washed off.

The major technology goal is to obtain a spatially uniform etch rate in the RIBE process at large aperture. Modifications were made to a 30 cm aperture RIBE system and a rotating mask technique was developed to give 5% uniform etch rate (except in a small fraction of the area near the center). This was verified with test pieces placed at different radii.

During the 4 month period of this LDRD one 65cm substrate was put through the full process. The RIBE etch depth measured in a small area near the edge was initially found to be too low and the grating was returned to the machine for further etching. Optical tests showed that in some areas high efficiency diffraction was obtained, but that overall the efficiency was lower and not spatially uniform. Tests showed that the additional etching had not increased the groove depth. This was attributed to a malfunction of the RIBE, due to incorrect gas feed during the etching process.

Despite this technical problem, significant progress was made towards large aperture transmission grating fabrication. In future work, the RIBE machine can be operated with improved gas feed control to rectify the problem. High diffraction efficiency over large aperture transmission gratings should then be achieved and should enable generation of up to 3 kJ laser pulse energies where the present PW laser limit is about 0.75 kJ. Further work will be needed to develop methods to fabricate and mount gratings with thin (<5mm) substrate thickness while maintaining adequate planarity.

This technology will be a key factor in any next generation high-energy PW laser.

5. Acknowledgements

This work was accomplished with the help of many colleagues whose names appear in the listed publications

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