A compact electron spectrometer for hot electron measurement in pulsed laser solid interaction

H. Chen,[a] P. K. Patel, D. F. Price, B. K. Young, P. T. Springer, R. Berry, R. Booth, C. Bruns, and D. Nelson
Lawrence Livermore National Laboratory, Livermore, California 94550-9234

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Ultraintense laser-matter interactions provide a unique source of temporally short, broad spectrum electrons, which may be utilized in many varied applications. One such, which we are pursuing, is as part of a diagnostic to trace magnetic field lines in a magnetically confined fusion device. An essential aspect of this scheme is to have a detailed characterization of the electron angular and energy distribution. To this effect we designed and constructed a compact electron spectrometer that uses permanent magnets for electron energy dispersion and over 100 scintillating fibers coupled to a 1024×1024 pixel charge coupled device as the detection system. This spectrometer has electron energy coverage from 10 keV to 60 MeV. We tested the spectrometer on a high intensity ($10^{17}-10^{21}$ W/cm^2) short pulse ($<$100 fs) laser, JanUSP, at Lawrence Livermore National Laboratory using various solid targets. The details of the spectrometer and the experimental results will be reported. © *2003 American Institute of Physics*. [DOI: 10.1063/1.1526929]

I. INTRODUCTION

The characterization of hot electrons produced by ultraintense laser-matter interactions is not only critical to the understanding of laser plasma physics,[1] but also important to many applications making use of the temporally short, broad spectrum of electrons. One of these applications, being pursued at Lawrence Livermore National Laboratory (LLNL) is a novel diagnostic for tracing magnetic field lines in a magnetic fusion device, such as a spheromak.[2] In this scheme a burst of hot electrons is produced by a short pulse laser incident on a solid object (such as an injected pellet), which, after propagating through the magnetic field environment of the fusion device, struck a wall and produced an observable x-ray signal. An essential aspect of this scheme is to understand the energy and angular distribution of the electrons produced, given certain laser parameters such as laser intensities and prepulse conditions. However, no sufficiently detailed information on the electron production from a thick solid target is presently available: to date, efforts made to obtain the electron production at various laser pulse length and intensities have produced diverse results. These include those measuring the secondary x rays[3–6] and those directly measuring electrons using magnet-based spectrometers.[7,8]

To obtain the required electron production data, we designed and constructed a Fiber Array Compact Electron Spectrometer (FACES). The spectrometer uses dipole magnets to produce a magnetic field to disperse electrons at different energies. This is the same approach as those direct electron measurements by Malka and Miquel[7] and Gahn, Tsakiris, and Witte.[8] In particular, Gahn and co-workers[8] also used scintillating fibers coupled to a charge coupled device (CCD) to detect electrons, which is of the same principle as our FACES spectrometer. The instrument reported here is designed to be more compact and versatile with higher energy resolution. In this article, we describe the design and assembly of the FACES spectrometer, as well as preliminary measurements of the electrons produced with the high intensity ultrashort pulse laser JanUSP at LLNL.

II. SPECTROMETER DESIGN

A schematic of the FACES spectrometer is shown in Fig. 1. Electrons collimated by the slit enter a magnetic field, there they are dispersed energetically along the side where the detection fibers are placed. Stray visible light is blocked by an aluminized Mylar foil (0.2 μm thickness Al on 0.5 μm thickness Mylar) covering the entrance slit (tantalum, width 8 mm). Fibers are also placed on the back of the spectrometer in the straight-through direction to pick up any signal produced by hard x rays and γ rays that are not dispersed by the magnetic field.

A uniform magnetic field is generated by permanent magnets sandwiched by two plates of cold rolled steel (area 10 cm by 5 cm). The spacing of the two plates is adjustable to produce an even magnetic strength (less than 5% variations) across the area of interest. We can vary the magnetic field by using magnets of different strengths; for example, magnetic field strengths from 100 to 1000 G will disperse electrons with energies of 10 keV up to several MeV.

For detection, we chose to use scintillating fibers routed to a CCD. This scheme has several advantages over other detection methods such as silicon diodes or scintillators coupled to photon multipliers. First, with fibers, the spectrometer can have many more channels (increasing the energy resolution). Second, scintillating fibers can be chosen to be relatively insensitive to x rays and γ rays. The scintillating fibers we employed are polystyrene-based fast green (emission at 492 nm) scintillator (BCF-20) with diameter of 0.5 mm, manufactured by BICRON Saint-Gobain Industrial

[a]Electronic mail: chenhui@llnl.gov

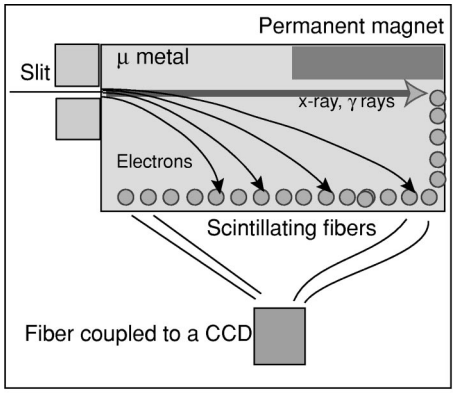

FIG. 1. Schematic diagram of the electron spectrometer.

Ceramics, Inc.[9] They were coated with extramural absorber to eliminate optical cross talk. Technical data including scintillating efficiency and transmission efficiency are available from the manufacturer. The fibers are placed 1 mm apart along the sides of the magnets. This corresponds to an energy resolution up to 1%.

We used a 16 bit, water-cooled, 1024×1024 pixel CCD designed and built at LLNL.[10,11] The CCD sensor is a SITe TK1024[12] with a 1:1 fiber-optical window built in.

A total of 120 individual fluorescing fibers transmit the photons from the electron spectrometer to the surface of the 1 in. square CCD. These were hand loaded and epoxied into a custom designed Delrin fiber array holder, then polished to 1 μm level smooth surface. This array was then attached to a spring loaded holder that allowed this polished fiber array to be carefully and accurately coupled to the surface of the CCD without applying any undue pressure to the fiber-optical surface at the CCD chip.

The housing of the spectrometer was designed so that the FACES package is as compact as possible. Figure 2

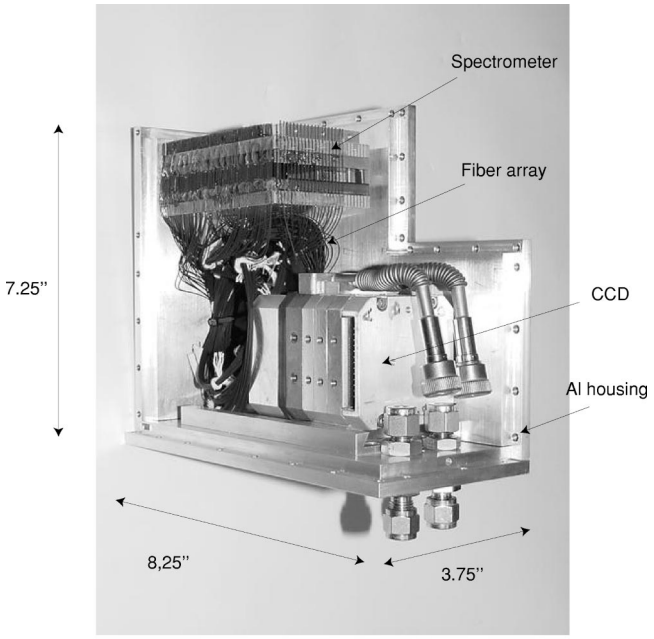

FIG. 2. Photograph of the Fiber Array Compact Electron Spectrometer (FACES). The dimensions are in units of inches.

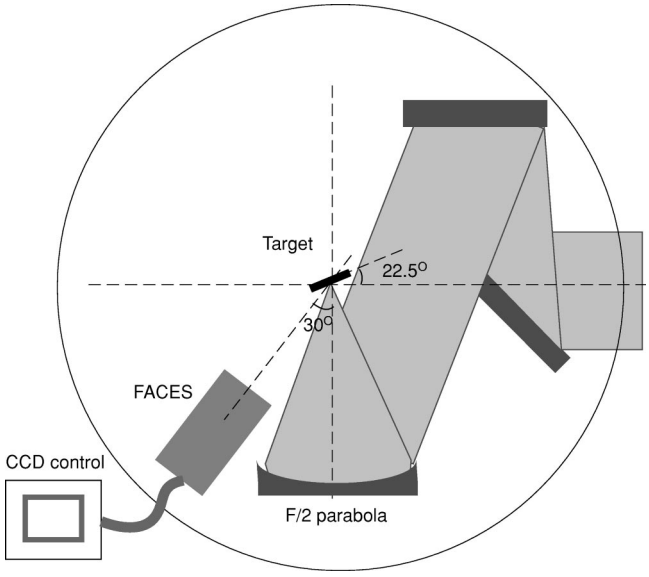

FIG. 3. Diagram of the FACES setup in the JanUSP vacuum chamber.

shows the assembly of the package. The whole spectrometer is placed in a light-tight 1/2-in.-thick aluminum box with outermost dimensions of 8.25 in.×7.25 in.×3.75 in. Extreme care has been taken in the design to ensure complete shielding of the spectrometer from possible laser-induced electromagnetic pulses. The aluminum enclosure is then plated with 0.125-in.-thick tantalum sheets. As an extremely dense high-Z metal, tantalum shields the spectrometer volume from the stray electrons, high-energy x rays, γ rays, and other energetic particles generated from the laser-target interactions. The water lines and CCD control are fed through the shielding.

III. EXPERIMENT ON THE JANUSP LASER

We performed experiments on the JanUSP Ti:sapphire laser.[13,14] It has a pulse length of 100 fs and delivers up to 10 J laser energy at 800 nm. The laser is focused with an f/2 parabola to a focus spot size of about 3.5 μm, and the laser intensity ranges from 10^{17} to 10^{21} W/cm^2. The experimental setup inside the JanUSP chamber is shown in Fig. 3. The target for the experiments was high purity iron slab (1 mm thick, 2 mm wide and 50 mm long). The laser is incident on the target at 22.5° off normal. The spectrometer slit is aligned 30° from the laser beam, i.e., 52.5° off normal, and 23 cm away from the target. The chamber is at a vacuum of $\sim 10^{-5}$ Torr during these experiments.

We operated the laser in the energy range from 10 to 150 mJ. The magnetic strength of the spectrometer was set to either 150 or 1000 G, to measure electron energies up to 1.3 and 60 MeV, respectively. After taking data at each laser shot, we took background data to account for the CCD thermal noise. The background was then subtracted from the signal during the data process. To ensure the fiber signals are from the electrons and not other sources, we inverted the magnetic field to deflect the electrons to the side opposite to the electron-dispersion fibers. Under this condition, we detected no signals from the fibers on the dispersion side. From the fibers placed on the side opposite to the entrance slit, in a

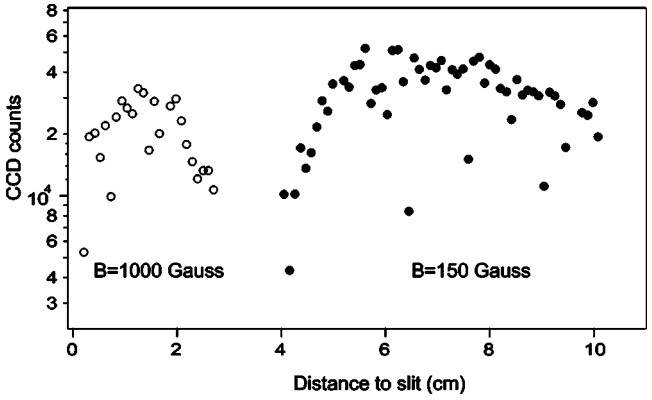

FIG. 4. Signals taken for Fe target at 120 mJ laser energies from two spectrometer magnetic strength setups: 1000 and 150 G.

shot with laser energy of 3 J, we detected a very weak signal from three fibers directly facing the slit. This signal is attributed to hard x rays and γ rays. There is no observable signal from x rays and γ rays at ~100 mJ laser shots. Further evidence for the spectrometer detecting electrons came from measurements from shots at the same laser energies but with different magnet strengths. As shown in Fig. 4, the signal (which is proportional to the number and energy of electrons) shifts along the dispersion plane, corresponding to the dispersion function for the two magnet strengths.

The data processing takes into account the energy absorption by the fibers at different electron energies using data from ESTAR.[15] Fiber scintillating efficiencies and transmission efficiencies are calculated using data provided by the manufacturer.[9] Finally, we took into account the CCD quantum efficiency (15%) and gain (3.7 electrons/count) to derive the number of electrons collected by each fiber whose location corresponds to a given energy. Figure 5 shows preliminary results from our measurements at a laser energy of 112 mJ. There are a couple of data points that are particularly low counts. This is due to their relatively low fiber efficiency. A more thorough calibration using a known electron source is planned, which will account for these fiber variations and validate the efficiency calculations.

IV. SUMMARY AND FUTURE PLAN

We have described a fiber-array-based compact electron spectrometer, FACES for measuring the hot electron distribution produced by intense laser-target interactions. Experiments on a short pulse laser prove that the spectrometer is sensitive to these electrons and insensitive to other forms of high energy radiation produced by the laser. It was designed to be flexible and easy to use and proved to be so. An absolute calibration of the spectrometer is planned which will use a newly built electron gun.[16]

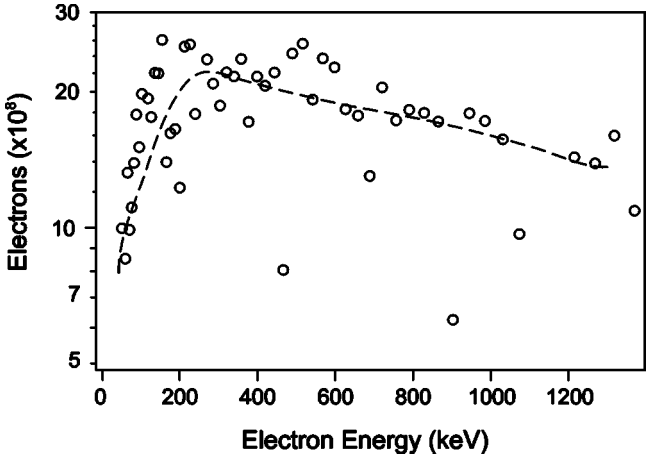

FIG. 5. Electron distribution from a Fe target at 112 mJ laser energy.

Detailed measurements are being obtained on the JanUSP laser, including systematic measurements of electron production from various target materials at different detection angles and laser intensities.

ACKNOWLEDGMENTS

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[1] P. Gibbon and E. Forster, Plasma Phys. Controlled Fusion **38**, 769 (1996).
[2] H. McLean, H. Chen, D. Hill, and D. Ruytov, Rev. Sci. Instrum. (to be published).
[3] G. D. Enright and N. H. Burnett, Phys. Rev. A **32**, 3578 (1985).
[4] M. Schnurer, R. Nolte, T. Schlegel, M. P. Kalachnikov, P. V. Nickles, P. Ambrosi, and W. Sandner, J. Phys. B **30**, 4653 (1997).
[5] K. B. Wharton, S. P. Hatchett, S. C. Wilks, M. H. Key, J. D. Moody, V. Yanovsky, A. A. Offenberger, B. A. Hammel, M. D. Perry, and C. Joshi, Phys. Rev. Lett. **81**, 822 (1998).
[6] G. Pretzler, Th. Schlegel, and E. Fill, Phys. Rev. E **62**, 5618 (2000).
[7] G. Malka and J. L. Miquel, Phys. Rev. Lett. **77**, 75 (1996).
[8] C. Gahn, G. D. Tsakiris, and K. J. Witte, Rev. Sci. Instrum. **71**, 1642 (2000).
[9] www.bicron.com
[10] A. D. Conder, J. Dunn, and B. K. F. Young, Rev. Sci. Instrum. **66**, 709 (1995).
[11] J. Dunn, B. K. F. Young, A. D. Conder, and R. E. Stewart, Proc. SPIE **2654**, 119 (1996).
[12] http://www.site-inc.com/
[13] J. D. Bonlie, F. Patterson, D. Price, B. White, and P. Springer, Appl. Phys. B: Lasers Opt. **70**, S155 (2000).
[14] F. Patterson, J. Bonlie, D. Price, B. White, and P. Springer, Ultrafast Optics 99 Conference, Ascona, Switzerland, 11–17 July 1999.
[15] http://physics.nist.gov/PhysRefData/Star/Text/ESTAR.html
[16] H. McLean (privite communications).