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Measuring electron-positron annihilation radiation from laser plasma interactions

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Measuring electron-positron annihilation radiation from laser plasma interactions [a)]

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We investigated various diagnostic techniques to measure the 511 keV annihilation radiations. These include step-wedge filters, transmission crystal spectroscopy, single-hit CCD detectors and streaked scintillating detection. While none of the diagnostics recorded conclusive results, the step wedge filter that is sensitive to the energy range between 100 keV to 700 keV shows a signal around 500 keV that is clearly departing from a pure Bremsstrahlung spectrum and that we ascribe to annihilation radiation.

I. INTRODUCTION

Intense lasers have been shown to produce a large number (10^{10} – 10^{11}) of positrons [1] when irradiating gold targets. While a fraction of the positrons come out of the target forming a relativistic jet, a large portion of the positrons remains inside the solid gold target where they are annihilated by electrons. In general, annihilations occur either directly through two γ-ray photon process which produces ~511 keV radiations, and indirectly through the formation of positronium, resulting in photons with energies depending on the total spin of the positronium: 511 keV if the total spin is 0 (parapositronium), and <511 keV if it is 1 (orthopositronium). Because of the low probability of forming positroniums inside solid gold [2], annihilations inside the target will be dominant by direct annihilations. The annihilation line shape depends on the distribution of electrons and positrons when the annihilations occur which can provide insight physics inside the laser-irradiated target.

Extensive studies on the annihilation processes in plasmas have been carried out for the solar atmosphere [3,4], astrophysical relevant relativistic and magnetized plasmas [5]. But little is known in the context of high energy density interaction of intense laser-plasma interaction. Characterization of the annihilation radiation from laser-produced positrons is not only interesting in terms of physics, but also important for its potential applications. If sufficiently bright, this high-energy radiation would be useful for a variety of applications such as tomography and backlighting radiography.

The key issues for the annihilation radiation measurements are the lack of established diagnostics. Because of the high photon flux and high electromagnetic pulse environment from the picosecond time-scale laser target interaction, detectors used for high-energy photon measurements with high resolving power, such as high purity germanium detector, are not applicable. In this paper, we will discuss and present some preliminary results from the application of step-wedge filters, transmission crystal spectroscopy, single-hit CCD detectors, streaked scintillating detection and single-hit pulse-height measurement.

II. DIAGNOSTIC DESCRIPTION

The step wedge filter we implemented has a simple layout. It uses a set of tantalum filters of various thicknesses (from 0.1 to 10 mm) and an imaging plate as detector [6, 7]. The combination of the step-wedge filter transmission and the image plate sensitivity provides a low-resolution energy spectrum, but this diagnostic does not suffer from EMP and does not have pileup issues. Under the assumption that the functional shape of the photon emission is known to be of Bremsstrahlung nature, the x-ray spectrum can be recovered by a best fit of the exposure values relative to the different filter thicknesses in the step-wedge filter. Assuming the emission to be dominated by Bremsstrahlung, the conversion efficiency of the laser energy into the energy of continuum emission in specific energy bands can therefore be calculated by integrating the derived spectra over the region of interest. The efficiency of the diagnostic is calibrated using radioactive sources at discrete spectral lines and interpolated using the EGSNRC Monte Carlo code [8] simulating the filter material and the Imaging Plate. An annihilation spectrum is then derived from the differences between the measured spectrum and the best fitting Bremsstrahlung spectrum. If the 0.5 MeV annihilation radiations were substantial one would expect an increase of the photon flux in the region of annihilation energy with respect to a pure Bremsstrahlung emission.

The Gamma Crystal Spectrometer (GCS) setup is shown in Fig. 1. It is designed after the well-established transmission crystal spectrometer (TCS) that is routinely used on the Omega facility at LLE, Jupiter at LLNL and lasers at LULI laboratory [9]. The spectrometer uses a curved thick Ge (220) crystal (0.4 mm) with lattice spacing (0.200 nm), having Rowland circle with diameter of 965 mm. The spectrometer bandwidth includes the

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Au K-shell lines in the 67-80 keV range in the first diffraction order and the 511 keV region in the second order.

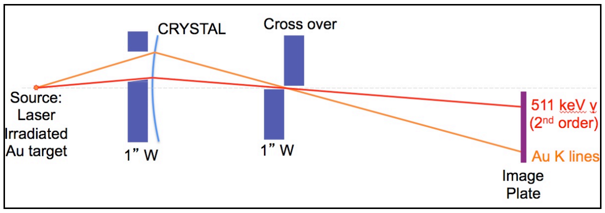

FIG. 1. GCS uses Laue geometry.

We tested two types of single-hit CCDs. One is a HAMAMATSU CCD detector [10, 11] that has 1700x1200 pixels with 20 μm pixel size coupled to a CsI scintillator. The instrumentation and calibration details have been described in Ref. [10]. The second single-hit diagnostic is the XRD 1620 digital x-ray detector [12]. It is based on a 16-inch amorphous silicon sensor operating as a two-dimensional photo-diode array with a pixel size of 200 μm and a total image size of 2048 x 2048 pixels.

Finally we tested a scintillator coupled to an optical streak camera. This diagnostic consists of an 18 cm long plastic scintillator (Pilot B), collecting optics and a HAMAMATSU streak camera. The main purpose of the diagnostic is to gate out the prompt radiation from laser-target interaction, and measure annihilation radiation by converting 511 keV photons to optical photons.

II. EXPERIMENTAL SETUP

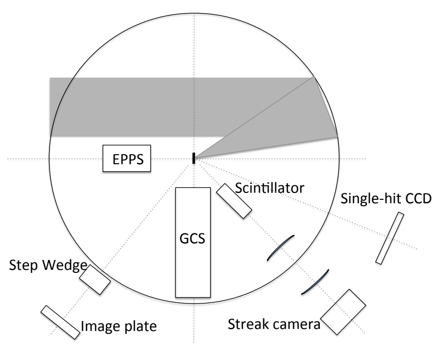

FIG 2: Annihilation diagnostic setup at Titan experimental chamber. Also shown is the electron-positron-proton spectrometer EPPS which provides direct measurement of positrons outside the target. Simultaneous measurements of all diagnostics enabled the data correlation.

The test experiments were carried out at the Titan laser at the Jupiter laser facility at the LLNL, using an s-polarized laser beam with a wavelength of 1054 nm. The pulse length of the short pulse was 10 ps, and the laser energy was about 300 J. The prepulse to main-pulse intensity contrast was less than 10^{-5}. An f/3 off-axis parabola provides a focal spot of about 8 μm containing about 68% of the total laser energy. The diagnostic setup is shown in Fig. 2. The short pulse was incident onto the targets at an angle of 18°, and the targets were 1-mm thick solid Gold and Europium discs, 2 mm in diameter.

III. RESULTS AND DISCUSSIONS

While none of the diagnostics recorded conclusive results, the step wedge filter shows a signal that is clearly departing from a pure Bremsstrahlung spectrum and that we ascribe to annihilation radiation.

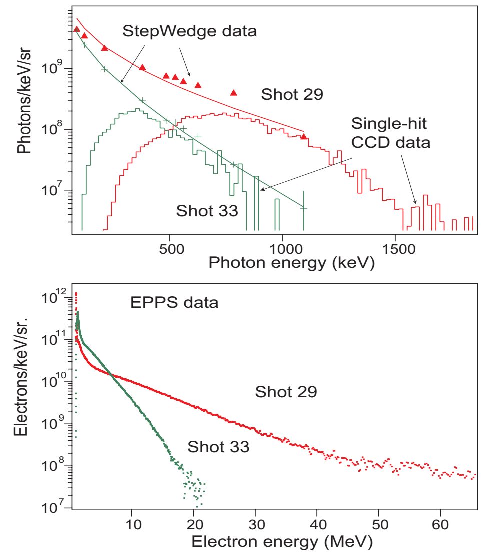

FIG. 3. Sample spectra from the Step Wedge Filter (triangles and crosses are the measurements, and the lines are fitted bremsstrahlung spectra), Single-hit CCD (HAMAMATSU) and Eelectron-positron-proton spectrometer (EPPS) for two shots. Shot 29 had Au target while Shot 33 had Eu target.

Figure 3 shows the photon spectra taken by the Step Wedge filter together with the best-fit bremsstrahlung spectra. A departure from the bremsstrahlung fit was observed for Shot 29, which used gold target and for which a large number of positrons were observed (Fig. 4) by the EPPS [13] diagnostic. This increase in photon flux, in the region between 500 keV and 700 keV is deemed to be from the annihilation radiation. Shot 33 had Europium target which has lower efficiency of producing positrons than gold target [1]. In this shot, the measured spectrum fits well to the bremsstrahlung spectrum and shows no hint of annihilation radiation. For comparison, the photon spectra from HAMAMATSU single-hit diagnostic [11] are plotted for these two shots. We observe a good agreement between the slope of the bremsstrahlung data, and therefore the inferred electron temperatures, from both diagnostics. Shot 29 had a hotter electron temperature as compared to Shot 33, as shown in the EPPS electron spectra, consistent with the higher photon energies detected by the Step Wedge filter as well as the Singe-hit CCD diagnostics.

Fig. 4 shows a comparison of the direct positron measurements from EPPS and the indirect measurement of annihilation radiation, which is the result of the differences between measured spectra and fitted bremsstrahlung spectra from the Step Wedge filter diagnostic and shows a good correlation between a high positron signal and indirect annihilation radiation signal. This correlation is a good indication of successful measurement of annihilation radiation from Step Wedge filter.

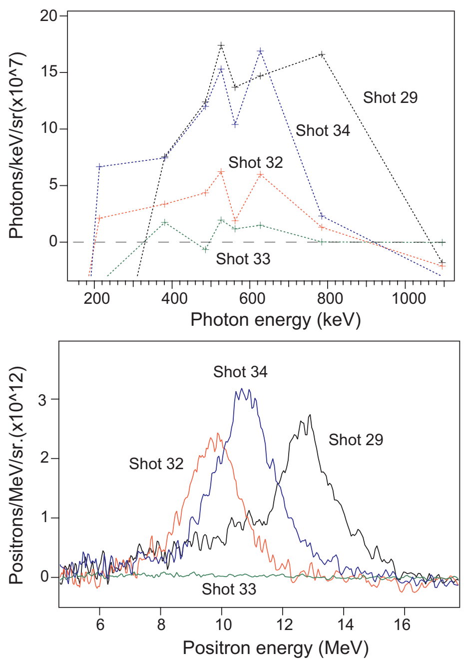

FIG. 4. Annihilation signals from the Step Wedge filter (top) from four shots. Shot 29, 32 and 34 had Au for targets while Shot 33 had Eu for target. The EPPS measured positron spectra for the same shots are shown in the bottom figure.

While the HAMAMATSU single-hit CCD diagnostic acquired bremsstrahlung spectra [11], no obvious signature was identified as annihilation radiation. The XRD detector was found to suffer from the background noise from the shots that prevented it from achieving single hit for high energy photons. It was found that while increasing distance between the target chamber and detector was helpful, additional methods (such as sophisticated filters) are needed as well as refinement in data analysis.

Although the system worked well, the streaked detector did not yield evidence of annihilation radiation. The streaked (with 200 ns time widow) photon traces appeared to be similar for shots with and without positron productions. This may be due to Pilot B plastic scintillators having poor temporal resolution (~10 ns) combined with little annihilation over a time scale of 100 ns due to the lack of orthopositronium production at the target. We believe a faster scintillator will help in this set up in future attempts to measure time gated annihilation radiation.

High quality spectra were obtained from GCS that showed strong K-shell lines of Au and Eu. However, the signature for annihilation is not conclusive, although there is a hint of signal [11] at photon energy around 255.5 keV, corresponding to the second order of 511 keV lines. Recent results from GCS recorded on the OMEGA EP laser are shown in Fig. 5, without evidence of annihilation emission. Extensive research is going on to improve GCS' detection efficiency as well as the signal-to-noise ratio.

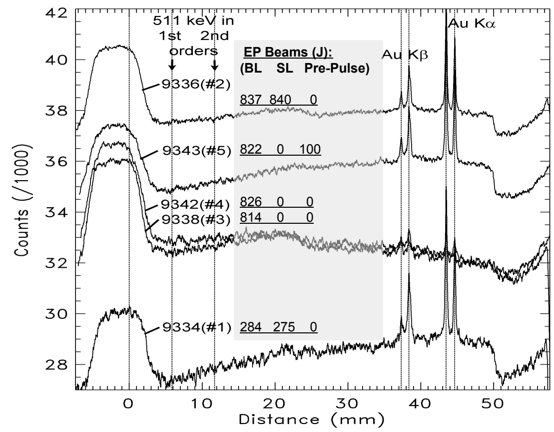

FIG. 5. Five shots of GCS test results on positron experiment on the OMEGA EP lasers. Three beams were used. Two were short pulse (10 ps): backlighter (BL) and sidelighter (SL), and one long pulse laser (3 ns) for pre-pulse generation.

IV. SUMMARY

Five diagnostic setups and test results on the annihilation radiation measurements for positrons produced during intense laser target interactions. While the Step Wedge filter diagnostic is showing evidence of annihilation radiation, four diagnostics (two single-hit type diagnostics, scintillator coupled streak camera, and gamma crystal spectrometer) did not have sufficient signal to provide evidence of annihilation detection. Further research is being carried out to improve the efficiency as well as the energy resolution of these diagnostics.

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