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# Hot electron production using the Texas Petawatt Laser irradiating thick gold targets☆

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ABSTRACT

We present data for relativistic hot electron production by the Texas Petawatt Laser irradiating solid Au targets with thickness between 1 and 4 mm. The experiment was performed at the short focus target chamber TC1 in July 2011, with intensities on the order of several $\times 10^{19}$ W/cm$^2$ and laser energies around 50 J. We discuss the design of an electron-positron magnetic spectrometer to record the lepton energy spectra ejected from the Au targets and present a deconvolution algorithm to extract the lepton energy spectra. We measured hot electron spectra out to $\sim$50 MeV, which show a narrow peak around 10–20 MeV, plus high energy exponential tail. The hot electron spectral shapes appear significantly different from those reported for other PW lasers.

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## 1. Introduction

The study of relativistic hot electron production by ultra-intense laser irradiating solid targets is a timely topic important to many fields, from inertial fusion to laboratory astrophysics. Gamma-ray emission by relativistic electrons is critical to the understanding of many high-energy astrophysical processes including gamma-ray bursts, blazar jets, and pulsar winds. Recently, short-pulse lasers have advanced enough to allow these high-energy astrophysical processes to be studied in the laboratory. In addition to gamma-ray emission, relativistic electrons interacting with high-Z solid targets can produce copious electron-positron pairs in the multi-MeV range [1–3], which also have many laboratory astrophysics applications [7].

The recently commissioned Texas Petwatt Laser (TPW) at UT Austin is one of the world's most intense 100-J class short-pulse lasers [13]. In July 2011, we used the TPW to irradiate thick (1–4 mm) gold targets at the newly completed short-focus target chamber TC1 to study hot electron, gamma-ray and positron production. Even though no positron was convincingly detected due to the high background, this experiment allowed us to determine the background levels to improve our spectrometer designs for later positron experiments. This report focuses on the hot electron data and methodology. Gamma-ray data analysis is in progress and will be reported in a separate paper.

### 1.1. Hot electron and pair production

When an ultra-intense laser strikes a solid target, superthermal "hot" electrons are produced with characteristic energy approximated by Refs. [1,9]:

$$E_{\rm hot} = \left[\left(1 + I\lambda^2/1.4\times10^{18}\right)^{1/2} - 1\right]mc^2$$

where $I$ is the laser intensity in W/cm$^2$ and $\lambda$ is the laser wavelength in microns. Up to 30–50% of laser energy can be converted into hot electron energy [9,14]. If the incident laser intensity is such that $E_{\rm hot} > 2mc^2$), these hot electrons can then pair-produce inside a high-Z target [1]. Experimentally, the emergent hot electron spectrum is often quite complicated and depends on details of the target (Z, thickness, density etc) and laser properties (intensity, contrast, polarization, duration, incident angle, focal spot size etc, see Ref. [14] for review). Some experiments measuring mainly the low energy (<few MeV) spectrum show that the hot electron temperature $T_{\rm hot}$ may be more accurately approximated by $T_{\rm hot} \sim (I\lambda^2)^{0.34}$, consistent with the Beg scaling model [11], while other results

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seem to favor the ponderomotive scaling $T_{hot} \sim (I\lambda^2)^{0.5}$ above [1,9]. As we see in Section 5, the TPW hot electron spectrum cannot be described by simple exponentials.

The process of electron-positron pair production from hot electrons interacting with a high-Z nucleus can occur through two channels: the Trident process or the Bethe–Heitler (BH) process [3,10]. In the Trident process, electrons create pairs by directly interacting with the nucleus. This process dominates for thin foils <10's of microns [1]. We are using thick targets (1–4 mm) in our experiment, thus BH dominates: hot electrons first emit bremsstrahlung gamma-rays which then interact with the nucleus to create an electron-positron pair [3]. Both processes depend on $Z^2nL$ where $n$ = ion density and $L$ = target thickness. Hence BH scales as $Z^4n^2L^2$, strongly favoring thick Au ($Z = 79$) targets [1]. However, for $L >$ few mm, the pairs cannot escape from the target. Hence the optimal thickness for laser pair creation is around 3–4 mm [1].

When the laser-driven plus secondary electrons exit the target, they create a sheath electric field that can accelerate the positrons plus any surface protons. The sheath electric field forms on the order of a few tens of femtoseconds and can be very intense for high-$Z$ targets [12]. Most positrons may travel through this field, gain energy equal to the sheath potential and shift the peak energy of the observed positron spectrum up by several MeV [12]. This field also helps the positrons to form a narrow jet out of the target back [3], along an axis between the laser forward and target normal directions [12]. At the same time, the sheath potential likely reflux some of the low energy electrons back into the target and broaden the electron distribution, thus altering the detected electron spectrum. Detailed modeling of the emergent electron and positron spectra requires using a combination of PIC and particle physics Monte Carlo codes. So far there has been a lack of end-to-end simulations of the emergent electron and positron spectrum from first principles. Hence much more experimental data is critically needed to advance this field.

### 1.2. Texas Petawatt Laser

The experiment was conducted in TC1 of the Texas Petawatt Laser located on the University of Texas at Austin campus. The laser is based on an optical parametric chirped pulse amplification (OPCPA) design with mixed silicate and phosphorus Nd:glass amplification. Such a design allows a shorter pulse duration and higher intensity on target [6]. The design specifications of the laser give an estimated maximum energy on target of up to 200 J with a pulse duration of 150 fs and spot size of 5 microns [6]. The laser contrast is estimated to be around $10^7$ and perhaps as high as $10^{12}$ [13]. At full power, we expect a peak intensity of $I > 10^{21}$ W/cm$^2$. However, during our experiment, the laser was kept below maximum power to avoid damage to the f/3 focusing optics. Thus we saw an energy range of 40–60 J, and a longer pulse duration on the order of 200–300 fs, focused to a maximum intensity of $<10^{20}$ W/cm$^2$. We were assigned one week of shot time in July 2011, and carried out 14 shots.

## 2. Experimental set-up

The goal of the experiment is to measure hot electron, gamma-ray and positron production from an ultra-intense laser incident on thick Au targets. Au ($Z = 79$) is chosen because of its high-Z and high density. Motivated by theory and previous experiments [1–3], targets of 1–4 mm thickness were used.

To measure the spectra of laser-produced electrons and positrons, a magnetic spectrometer is designed and fabricated as the principle diagnostics device. The magnetic spectrometer was placed in the target normal position as indicated in Fig. 1. The spectrometer's designed energy range is ~1–50 MeV. To complement this high-energy spectrometer, a low energy weak-field spectrometer is borrowed from UT-Austin to cover the energy range <6 MeV. The data recording mechanism of both spectrometers is chosen to be phosphorus image plates (Fuji BAS SR2040). The plates do not require development and are reusable. In addition, the image plates can be read quickly via a computerized scanner and their response to deposited electrons has been well studied and calibrated [2,5]. These plates offer the benefit of a quick read time without complicated electronics inside the chamber. However, the data is wiped by visible light and degrades over time. Therefore the spectrometer case must be light-tight and image plates must be digitally recorded within 90 min or risk data loss [2].

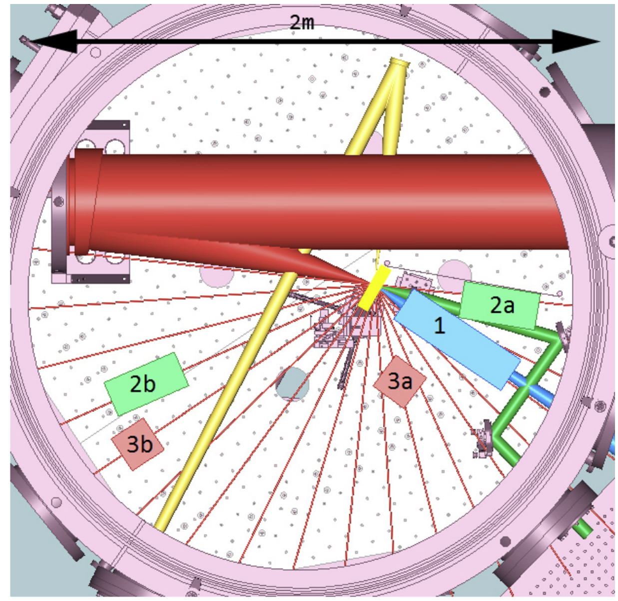


**Fig. 1.** The target chamber set-up for the TPW experimental run in July 2011 (the radial lines are in 10° increments about laser forward direction). The yellow central box indicates the orientation of our targets at 17° from laser forward. (1) The high energy e$^+$/e$^-$ spectrometer was placed at a variable distance of 9–22 cm at target normal. (2) The low energy e$^+$/e$^-$ spectrometer was first placed at (a) 4° outside laser forward and later placed at (b) the front of the target. (3) The filter-stack gamma-ray spectrometers: (a) looking at the high energy spectrometer positron side and (b) various other locations looking directly at the target. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

## 3. The e$^+$e$^-$ spectrometer

### 3.1. Design

Our primary diagnostic is a magnetic e$^+$e$^-$ spectrometer fabricated at Rice University. The magnetic field necessary to give the desired energy range (1–50 MeV) is ~0.6$T$. Since image plates are sensitive to X-rays, a major effort of the design is to reduce the X-ray background via optimal shielding. The spectrometer consists of three components: the outer case, the inner spectrometer, and the shielding. Because the response of the spectrometer could not be determined prior to the experiment beyond Monte Carlo simulations, the spectrometer is designed to be adaptable. The outer case is designed to be light tight, because the image plates used in the spectrometer are wiped by visible light.

The inner spectrometer consists of two 2″ wide × 6″ long neodymium-iron-boride (Nd–Fe–B) magnets separated by a distance of 1.4 cm to achieve peak magnetic field strength of approximately 0.6$T$ in the gap. The magnets are separated by Fe yokes to contain the magnetic field. so that the electrons will not be

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