GEANT4 Monte Carlo Simulation of Pair Creation Using Petawatt Lasers

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Introduction

-Irradiating high-Z targets such as gold with ultra-intense lasers creates electron positron pairs.
-The laser creates a plasma on the surface of the target.
-The electro-magnetic fields of the laser accelerate electrons out of the plasma.
-The electrons possess sufficient energy to generate pairs.
-Incoming spectrum is modified by well-known processes.

-We can study this phenomenon using Monte Carlo simulation.

-CERN's Geant4 Monte Carlo code is used for this simulation.

Applications

-High Γ factors in long gamma ray bursts indicate a pair-plasma environment.

-Cygnus X-1 MeV flares show a signature indicative of pair annihilation.

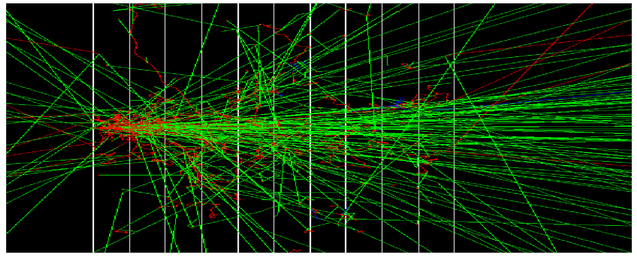
-Similar phenomena may occur in other suspected black holes.

-The laser production method can potentially produce positron densities in excess of 10^{18} cm^{-3}.

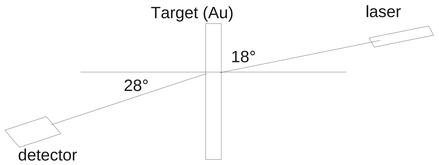
-This method produces pairs with much higher efficiency that accelerators.

-Hence, this method is preferable for studying the denser pair plasmas expected to exist in such astrophysical systems.

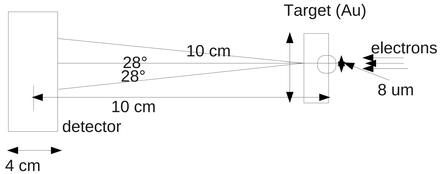
Diagram of a set of simulation shots. Electrons are red, gamma rays are green, and positrons are blue.



Titan experimental set-up.



Simulation set-up.



Spectra

-Spectra are taken near an angle of 28 degrees.

-We fit the high-energy tail of simulation electron spectra to Titan data.

-For instance, to the left we determine that this spectrum has an initial electron temperature (kT) of roughly 6 MeV.

-We then examine the positron spectrum and see that it matches in shape (to within the somewhat noticeable error) but not position.

Sheath Field

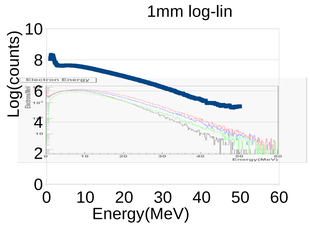
-The shift of the positron spectrum is a known effect.

-A build-up of positive ions on the surface of the target opposite the laser traps some of the escaping electrons, creating an electric potential.

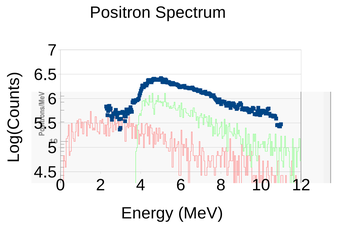
-This affects the electrons which have not already gone through (those with lower energies) and all of the positrons.

-Applying a simple electrostatic potential between target and detector roughly simulates this.

Comparison between experimental spectrum (top) and simulation with an incident kT of 5 MeV (black), 6 MeV (blue), 7 MeV (red), and 6 MeV after a sheath field has been applied (green). The fit at the low energy end improves slightly after application of the field.



Positron spectrum comparison at 1 mm 6 MeV before field application (red) and after application (green). The peak energy matches afterwards.



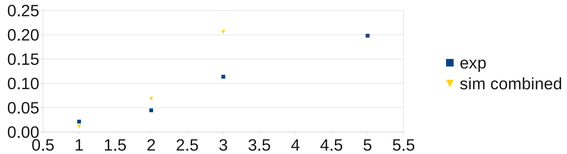
Scaling

-We examine scaling of the e+/e- ratio with thickness and the e+ yield with thickness.

-Based on the above, for the e+/e- ratio we consider only the region from 4-40 MeV.

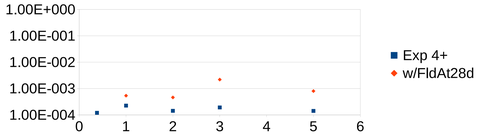
-Also based on the above, the electron count is determined by the simulation with the field below 20 MeV and by that without the field above 20 MeV.

-This results in some double-counting, but there are also some electrons not counted due to being out of the angle selection window when they would be in in were the field simulation more accurate. These effects are assumed to roughly cancel, though this is uncertain.



e+/e- ratio comparison. Thicknesses over 5 mm lack experimental data due to a high signal-to-noise ratio. Simulation ratio at 5 mm is > 1, demonstrating the shortcomings of the simple method of sheath field approximation used.

Right: Yield comparison. Note the 2 mm point has a lower initial electron temperature, causing the downward aberration. Note further that there are qualitative similarities in the trend. The higher deviation at higher thicknesses is suspected to be due to geometrical issues.

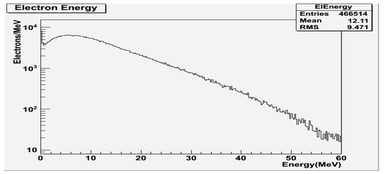


Texas Petawatt (TPW) Laser Experiments

-Similar experiments were recently carried out using the TPW.

-PIC simulations were used to obtain hot electron spectra for similar simulations.

-Processed data for comparison is forthcoming.



Electron spectrum obtain from putting the results of a PIC simulation using TPW parameters into the Monte Carlo code. For the final version, a similar PIC code will be used to apply the effects of the sheath field.

Conclusions/Future Work

-This method does partially reproduce the trends in e+/e- ratio, yield, and energy spectra for energies above 4 MeV.
-Below this energy, the simulation vastly under-predicts electrons.
-Use for relative, rather than absolute, trends should allow targets to be optimized for maximum e+ yield in future experiments.
-Particle-in-cell plasma simulations may enable extension into the low-energy region.
-A modified version of the same code will be used to simulate the response of spectrometers used in the TPW experiments using a fully 3D field geometry.

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