Positron Creation Using Ultra-intense Lasers

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Original goal of this work: Study basic plasma physics by creating dense pair plasmas and jets.

**Tokamaks**
- Theory only
- $N_{e^+} \approx 8 \times 10^{14}$
- $V \approx 2.7 \times 10^7 \text{ cm}^3$
- $3.3 \times 10^7 \text{ cm}^{-3}$

**Penning-Malmberg Traps**
- Experimental
- $N_{e^+} \approx 8 \times 10^7$
- $V \approx 6 \text{ cm x 1 mm(D.)}$
- $4 \times 10^9 \text{ cm}^{-3}$

**Ultra-intense Lasers**
- Titan laser
- $N_{e^+} \approx 10^{11}$
- $V \approx 1 \text{ mm x 1 mm(D.)}$
- $1 \times 10^{14} \text{ cm}^{-3}$

Could lasers create the highest density of positrons in the laboratory, by creating a large number in a short time (~ picosecond) ?
Simulations of ultra-intense laser-solid interfaces show that generation of mildly relativistic electrons was possible.

**Non-relativistic Case** (low laser irradiance $I \lambda^2 < 10^{18} \mu m^2 W/cm^2, v_{osc}/c < 1$)

\[ E_{laser} = E_0 \cos(kx - \omega t) \hat{y} \]

\[ \vec{F}_\perp = -e\vec{E}_{laser} = -eE_0 \cos \omega t \hat{y} \]

Electrons “wiggle” along surface, never penetrating into overdense.

**Relativistic Case** (high laser irradiance $I \lambda^2 > 10^{18} \mu m^2 W/cm^2, p_{osc}/m_0c > 1$)

Transverse component $\sim$ longitudinal component

\[ \vec{F}_{pond} = -\nabla\left[ (\gamma - 1)m_0c^2 \right] \hat{x} \]

\[ T_{hot} = \left( \sqrt{1 + \frac{I \lambda^2}{1.37 \times 10^{18}}} - 1 \right)m_0c^2 \]


Some electrons with enough excursion are non-adiabatically accelerated into solid.

Scaling verified by Particle-In-Cell simulations as well experiments on LLNL PetaWatt.

Multi-MeV electron energies are generated when ultra-intense pulses hit solids.
Important to realize that this is not a mono-energetic beam of electrons, but broad spectrum.

"Relatively low" energy electrons creating the pairs would mean that positron density in target would be high.
Estimates on the conversion efficiency of laser energy into hot electrons range from 15-50%.

**Current Ultra-intense Lasers**

1. RAL Petawatt – 600 J in 1 ps
2. Omega EP – 800 J in 10 ps
3. Titan – 120J in 1 ps
   - 250J in 10 ps

Typical use is Fast Ignition research.

Roughly, the fraction of $E$ converted to bremsstrahlung in a thick target:

$$I/E \sim 0.0007 \times Z \times T_{\text{hot}}$$

Example: Au, Omega EP, coupling 30% into 1.5 MeV hots $\Rightarrow$ 20 J of Bremsstrahlung!

A considerable amount of energy can be converted into photons, then pairs, in < 20 ps. Downside? Rep. rate measured in hours.
Prior art: Substantial theoretical studies, but very little experimental data existed.

### Theoretical/Modeling

- Shearer et al. 1973
- Liang et al. 1995, 1998
- Shkolnikov et al. 1997
- Gryaznykh et al. 1998
- Shen & Meyer-ter-Vehn, 2001
- Nahashima & Takabe, 2002
- Wilks et. al., 2005
- Berezhiani et al., 2007
- Myatt et al., 2009

Assume a $T_{\text{hot}}$, it was predicted for 100 J laser $10^7 - 10^9$ positrons would be produced (depending on mechanisms target Z, thickness, Laser parameter etc.)

### LLNL NOVA PetaWatt Exp.

- Cowan et al. (1999)

- <100 were detected
- $e^+/e^- \sim 10^{-4}$

### Accelerator Electron Beam

- Gahn et al. (2002)

- ~30/shot at 2 MeV
- $e^+/e^- < 10^{-3}$
Two main processes involved in laser positron creation in the presence of high-Z nucleus

1. Direct (Trident) pair production
   \[ e^- + Z \rightarrow 2e^- + e^+ + Z \]
   (Z: nucleus)

2. Indirect (Bethe-Heitler) pair production:
   \[ e^- + Z \rightarrow \gamma + e^- + Z \]
   \[ \gamma + Z \rightarrow e^- + e^+ + Z \]
   (\(\gamma\): Bremsstrahlung)

High energy (>MeV, relativistic) \(e\)'s are the key to both processes
Which mechanism dominates depends strongly on target thickness.

Laser Energy 280 J, Intensity $10^{20}$ W/cm$^2$

![Graph showing positron number vs. thickness of gold foil](Assuming no electron refluxing.)
How many pairs can be made when both trident and B-H mechanisms are considered?

Helpful guide to design an experiment

Positron yield/kJ of hots

Optimal thickness (Au)

J. Myatt, et. al., PRE 79 066409 (2009)

However, we find that there is an additional thing we can do to increase yield...
Maximizing the hot electron energy and number increases the positron production

\[ N_{e+} \propto \int N_{Au} N_{e}(E) \sigma_{eZ}(E)dE \]

Hotter electrons from underdense pls.

Measured super hot electrons

We found that maximizing pre-plasma increases positron signal.
We performed positron experiments on LLNL Titan laser in May and September 2008.

**Experimental setup**
- 2w, 50 - 150 J, 1-3 ns
- Spot: 600 um
- 1w, 120 - 250 J
- 0.7 - 10 ps
- Spot: 8-10 um

**Targets**
- Al, Cu, Sn, Ta, Au
- Thickness: 0.1 - 3.1 mm

**EPP Spectrometers**

Chen et al. RSI 08
Positron signal was observed and verified experimentally

Positron energy: ~3 to 20 MeV (relativistic)

Equivalent of about $10^6$ positrons were observed in the detector - 4 to 5 orders of magnitude more than previously observed.
First detailed positron energy spectra reveal important physics

- Super hot electrons (~9 MeV temperature)
- Colder positrons (~4 MeV)
- Positron/Electron ratio >$10^{-2}$ (about $10^{-4}$ from NOVA)

**EPP spectrometer data (target rear)**

**Laser**

**EPPS**

**1mm Au**

Cowan et al. (1999)
Modeling is used to confirm relative electron and positron signal levels seen in experiment.

**We employ EGS (NRC version).**

Steps taken to compare with experiments.

1. Generate an initial electron \( f_{in}(E) \).
2. Run it through target (e.g., 3 mm Au.)
3. Attempt match w/ observed \( f_{out}(E) \) signal.
4. Modify \( f_{in}(E) \) until \( f_{out}(E) \) match occurs.
5. Compare positron signal with exp’t.

Example. Electrons injected at 25 MeV (green \( \rightarrow \) e-, yellow \( \rightarrow \) photons, red \( \rightarrow \) e+)
First detailed positron energy spectra reveal important physics

EPP spectrometer data (target rear)

Observed ~ 1e10 from rear of target, 1e8 from front.

Explanation of the energy shift of positron peak:
The same acceleration field for protons (sheath field)

Chen, et al. PRL 2009
Recent experiments at Omega EP indicate nonlinear scaling with laser energy.

EPPS positron shot #5082 (812 J, 10ps)

- $\sim 2 \times 10^{11}$ positrons inferred.
- $\sim 3$ time more positrons than the linear scaling based on Titan 10ps shots predicted.
- High rate of positron production: $\sim 2 \times 10^{22}$ e+/s
- Near monoenergetic positron jet observed: due to large energy shift?
Interestingly, similar shift was observed in simulations by us and SLAC in 2006 for e+-e- jets.


Acceleration of positrons and de-acceleration of electrons seen in 3-D simulations of pair jets into both vacuum and plasma.
We attribute this to ion acceleration (via TNSA*) that is known to occur for ultra-intense laser-solid interactions.


Positron spectra was expected to shift to higher energies for thin targets. Could focusing also occur for the positrons?
This led to interesting idea: can we focus the positrons using a shaped target?

Initial target composition:
- Electron fraction: 1.001
- Ion fraction: 1.0
- Positron fraction: 0.001

Positrons are focused with the same electric field that is responsible for proton acceleration.

Results in a positron density that is 4 times higher than the initial positron density in the target.

Only a small, proof-of-principle simulation. More research required to confirm this.
The emittance was not measured experimentally, but estimates from the modeling give about 500 mm*mrad.

Emittance from EGS simulation of 1 mm Au target

Future experiments will attempt to measure emittance.
Higher Rep-rate short pulse lasers are being built and tested.

As of mid-2008, Mercury has been able to run continuously for several hours (300,000 shots), firing ten times a second at more than 50 joules per shot, each shot lasting just 15 nanoseconds (billionths of a second).
Summary

~120 J laser produced positrons

From the back of the target
~1\times10^{10} \text{ e+/shot}; \sim 10^{8} \text{ in the front}

Estimating the interaction volume with 20° half-angle and 1 mm thick target, V = 10^{-4} \text{ cm}^3, which gives \( n_+ \sim 10^{15} \text{ cm}^{-3} \) inside Au target

Observed positron: \sim 0.01 \text{ J} 
(EGS: escaping/total \sim 10\%)
Total produced positron: \sim 0.1 \text{ J}
Total positron E/Laser E: \sim 0.1\%