Lawrence Livermore National Laboratory

# Positron Creation Using Ultra-intense Lasers

Scott C. Wilks

*Physics Division, LLNL*

*For presentation to*

*SLAC Workshop*

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# Acknowledgements

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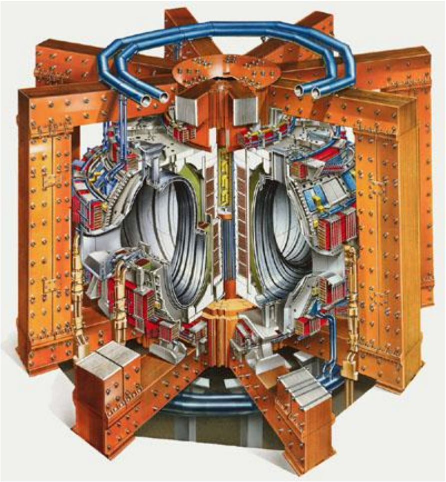
*Rice University*

Gianluca Gregori
*Oxford university*

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

## Tokamaks



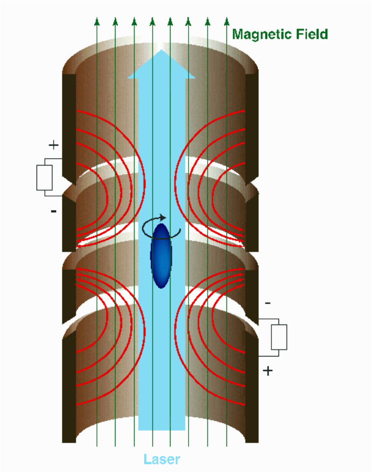
Theory only

$N_{e+} \sim 8x10^{14}$

$V \sim 2.7 \text{ x } 10^{7} \text{ cm}^{3}$

**$3.3 \text{ x } 10^{7} \text{ cm}^{-3}$**

## Penning-Malmberg Traps



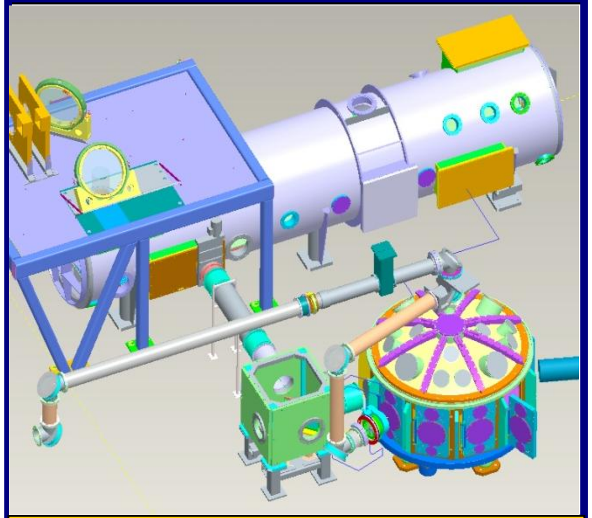
Experimental

$N_{e+} \sim 8x10^{7}$

V ~ 6 cm x 1 mm(D.)

**$4 \text{ x } 10^{9} \text{ cm}^{-3}$**

## Ultra-intense Lasers



Titan laser

$N_{e+} \sim 10^{11}$

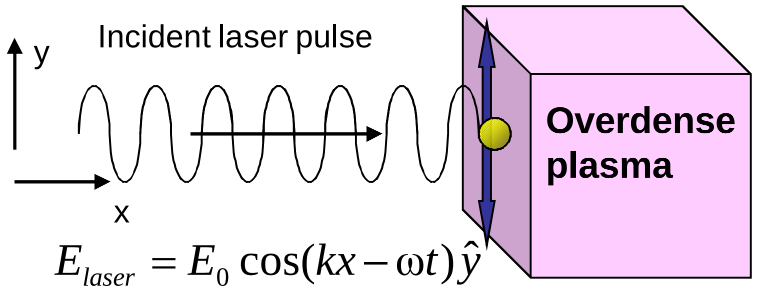
V ~ 1 mm x 1 mm(D.)

**$1 \text{ x } 10^{14} \text{ cm}^{-3}$**

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.

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



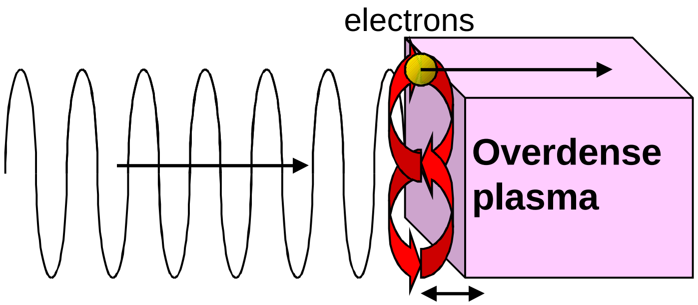
$$E_{laser} = E_0 \cos(kx - \omega t)\hat{y}$$

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

Electrons "wiggle" along surface, never penetrating into overdense.

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

Transverse component ~ longitudinal component



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

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

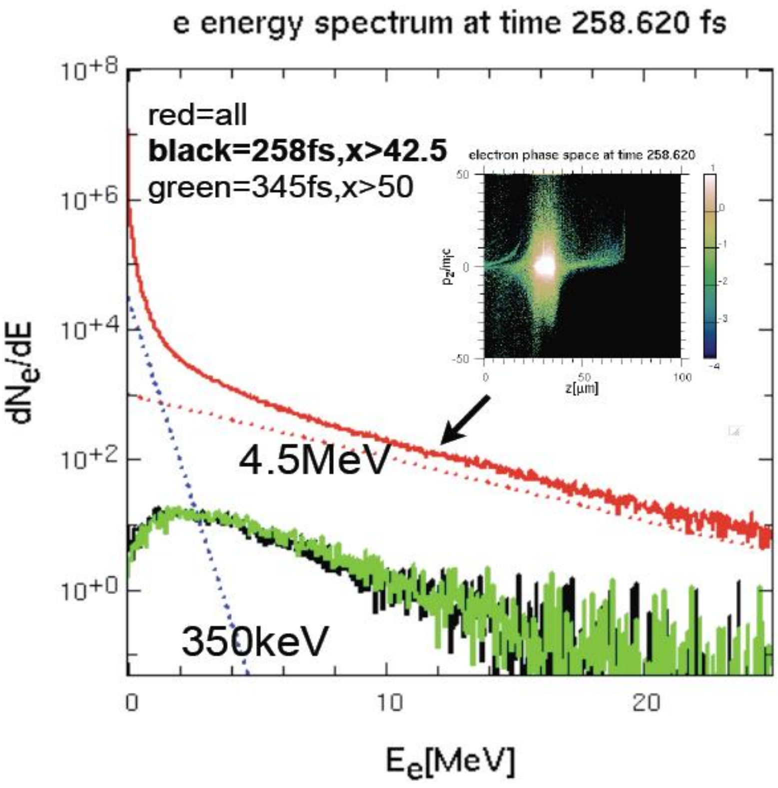
S. C. Wilks, et. al. Phys. Rev. Lett. (1992)

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

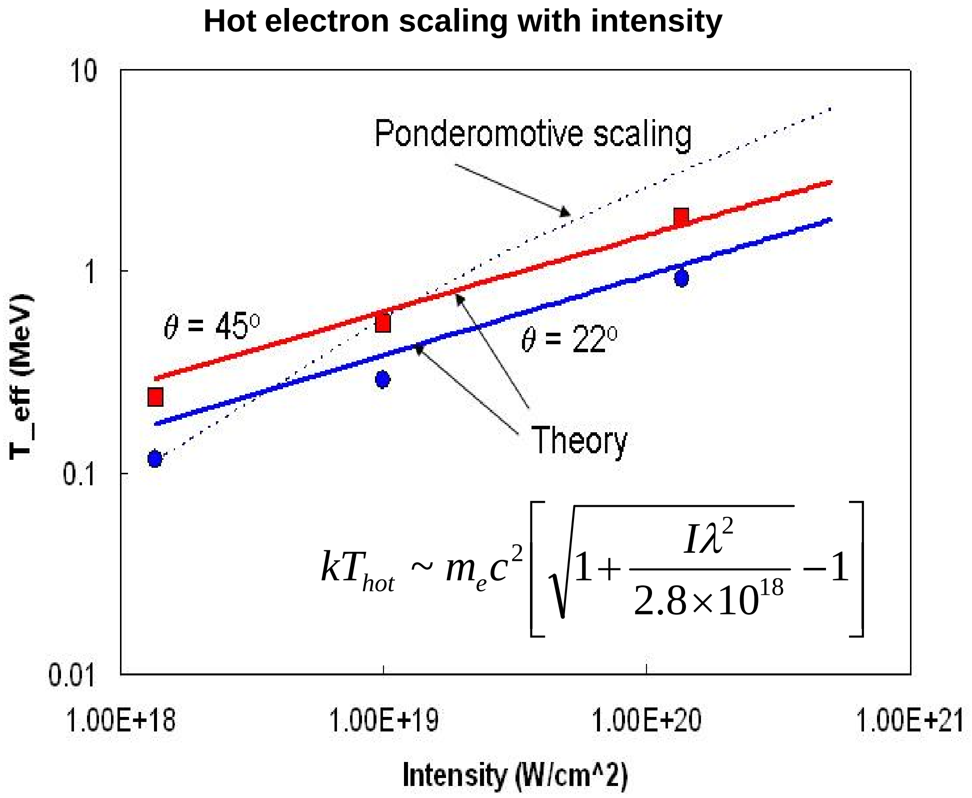
Scaling verified by Particle-In-Cell simulations as well experiments on LLNL PetaWatt.

**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.



e energy spectrum at time 258.620 fs



**Hot electron scaling with intensity**

$$kT_{hot} \sim m_e c^2 \left[ \sqrt{1 + \frac{I\lambda^2}{2.8\times10^{18}}} - 1 \right]$$

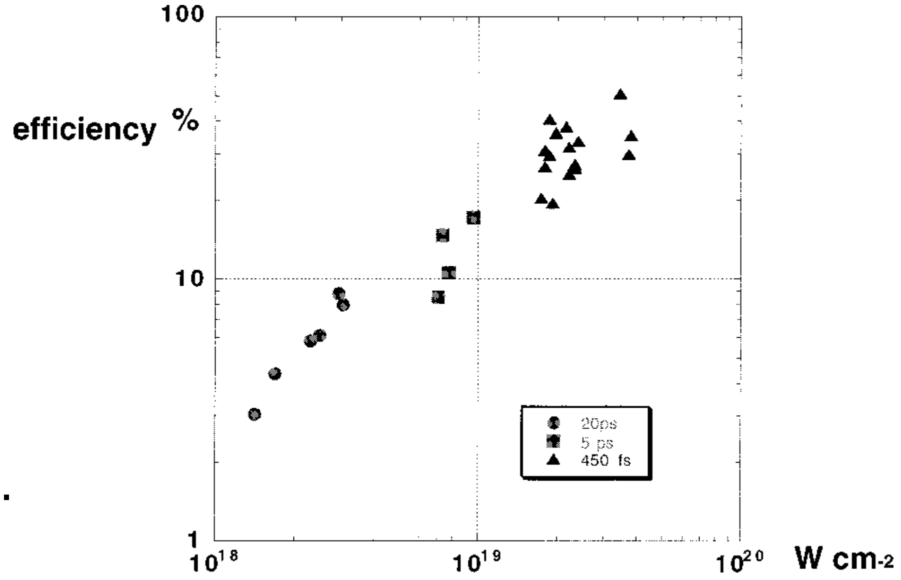
"Relatively low" energy electrons creating the pairs would mean that positron density in target would be high.

# Estimates on the conversion efficiency of laser energy into hot electrons range from 15-50%.

Currrent 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

Laser to Hot Electron Efficiency



"Hot electron production and heating by hot electrons in fast ignitor research" M. Key, et. al., Phys. Plasmas 5, 1966 (1998)

Typical use is Fast Ignition research.

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

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

Example: Au, Omega EP, coupling 30% into 1.5 MeV hots ➔ 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.

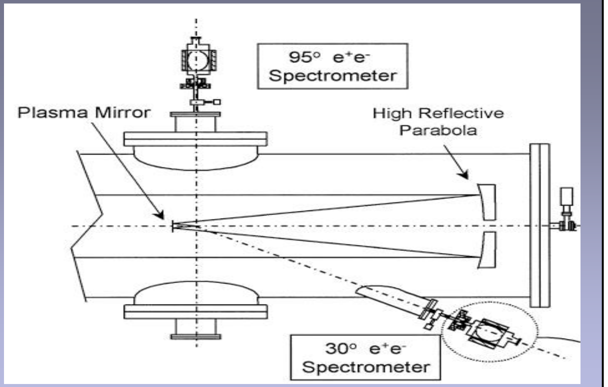
## Theoretical/Modeling

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

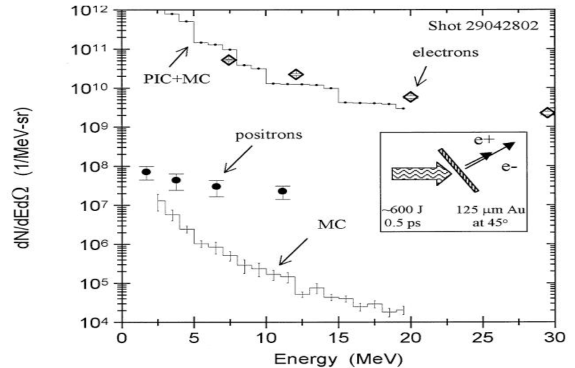
……

Assume a $T_{hot}$, 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.

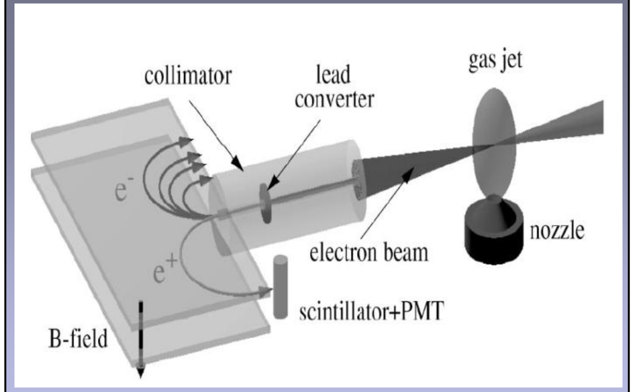


Cowan et al. (1999)

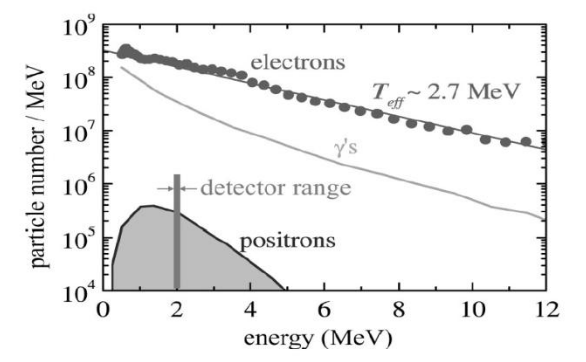


- <100 were detected
- e+/e- ~ $10^{-4}$

## 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

   $e^- + Z \rightarrow 2e^- + e^+ + Z$

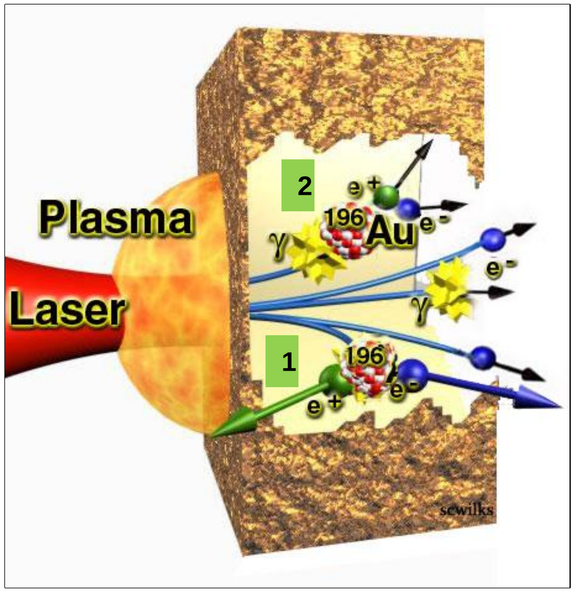
   ($Z$: nucleus)

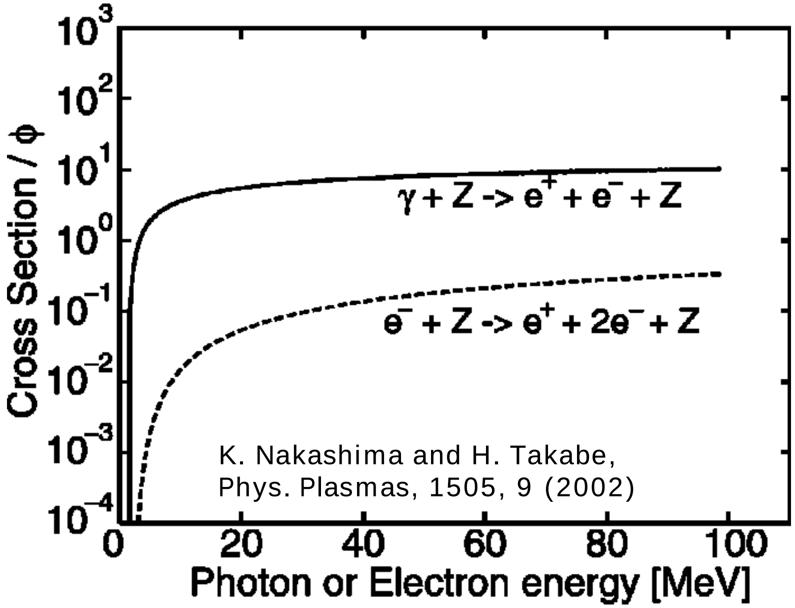
2. Indirect (Bethe-Heitler) pair production:

   $e^- + Z \rightarrow \gamma + e^- + Z$

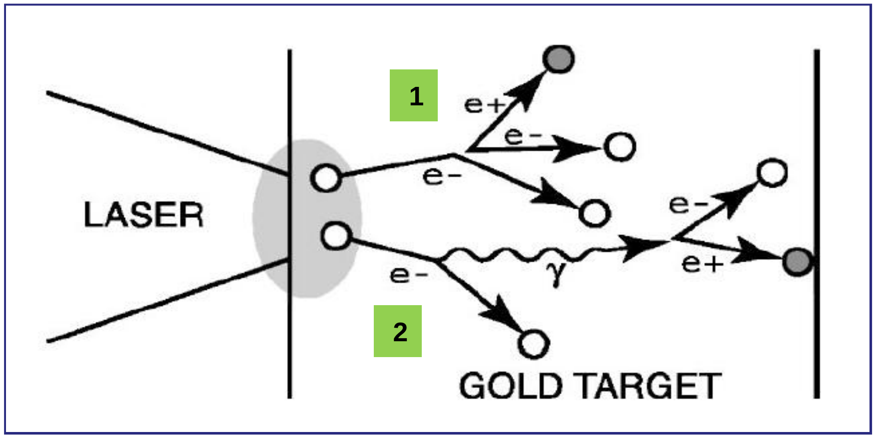
   $\gamma + Z \rightarrow e^- + e^+ + Z$

   ($\gamma$: Bremsstrahlung)





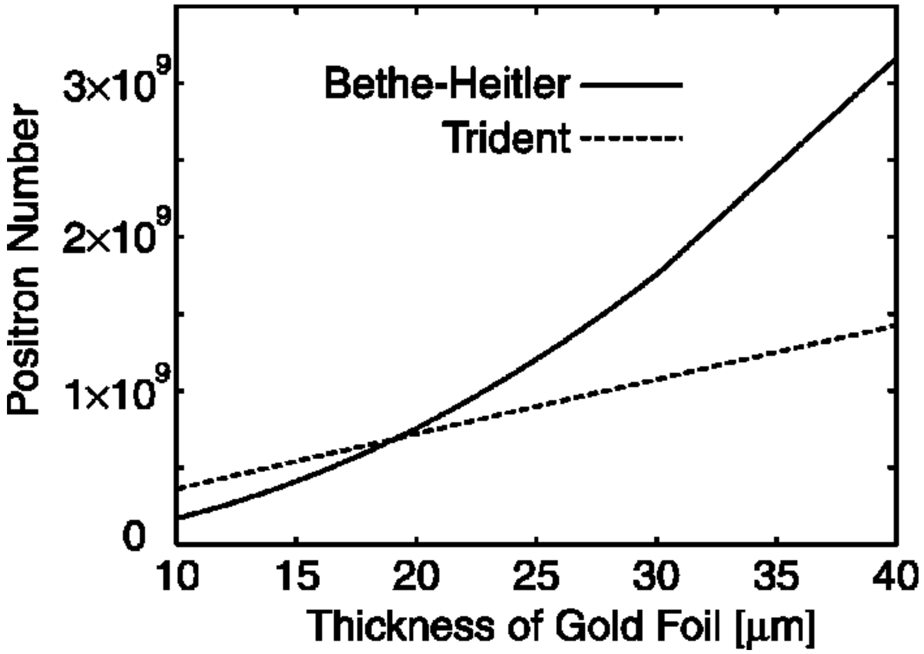
K. Nakashima and H. Takabe, Phys. Plasmas, 1505, 9 (2002)



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$^2$

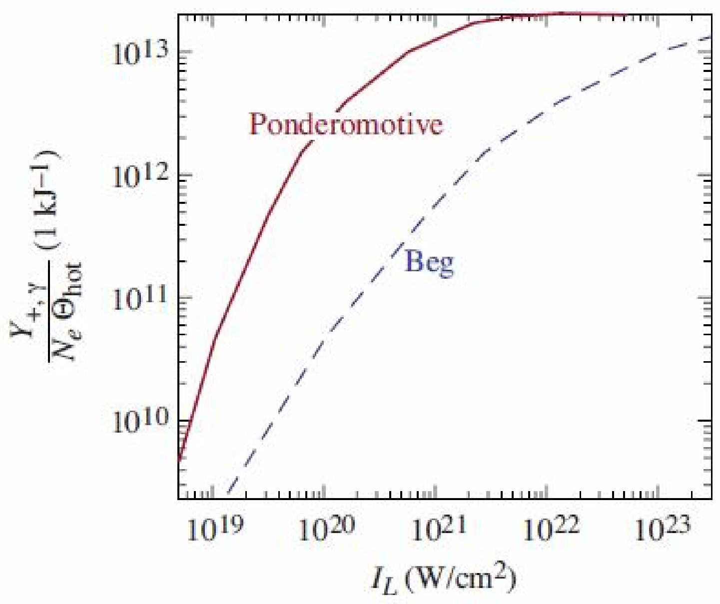


(Assuming no electron refluxing.)

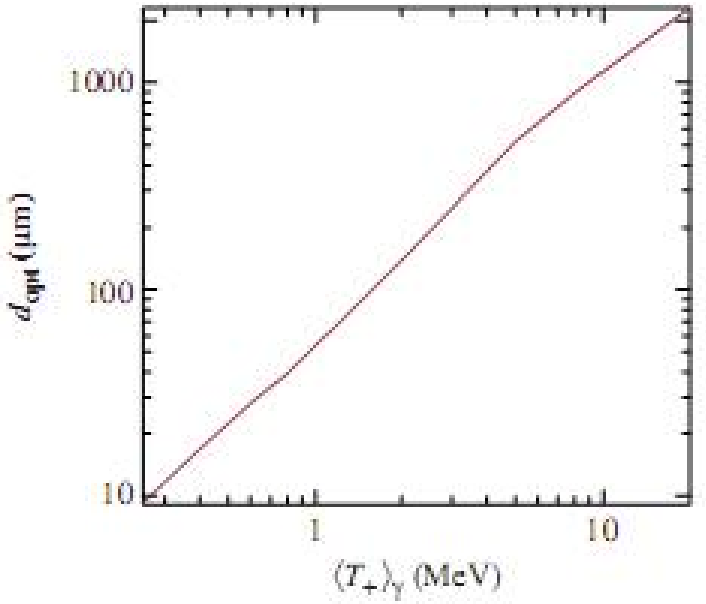
# How many pairs can be made when both trident and B-H mechanisms are considered?

Helpful guide to design an experiment

Positron yield/kJ of hots



Optimal thickness (Au)



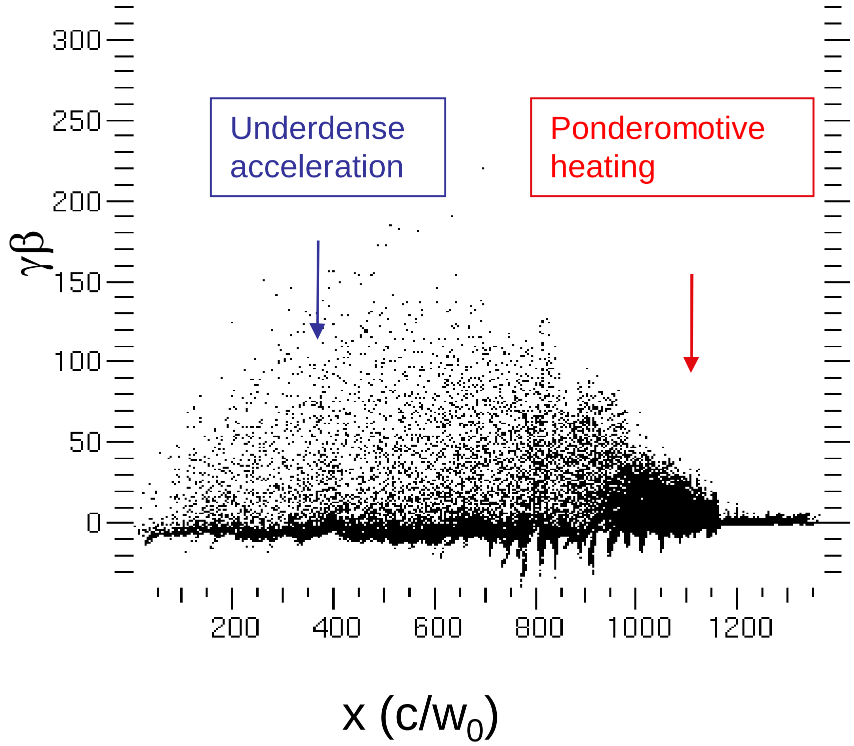
J. Myatt, et. al., PRE 79 066409 (2009)

However, we find that there is an additional thing we can do to increase yield…

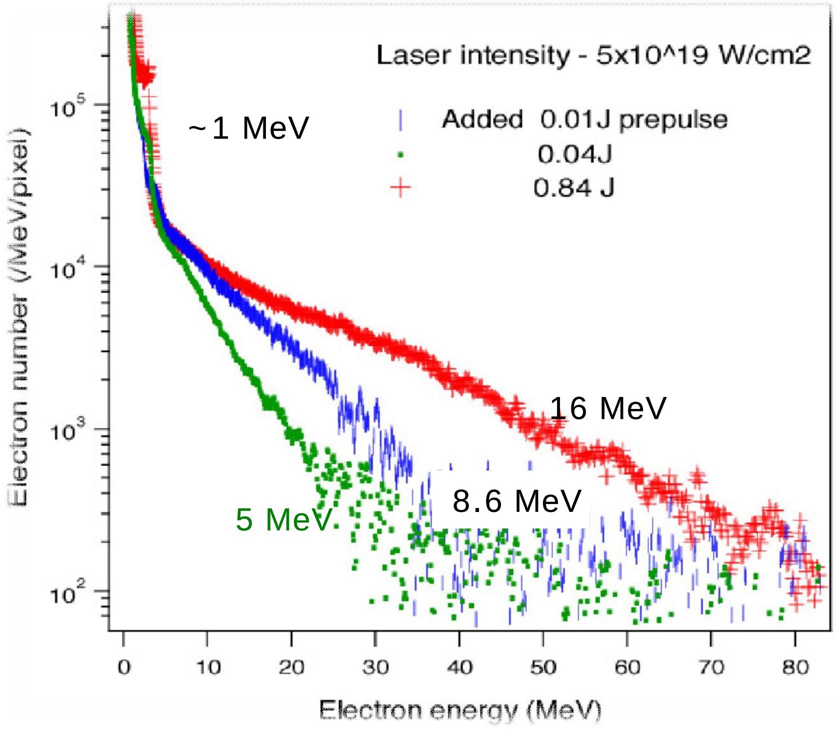
# Maximizing the hot electron energy and number increases the positron production

$$N_{e+} \propto \int N_{\mathrm{Au}} \boxed{N_e(E)} \sigma_{eZ}(E)\,dE$$

Hotter electrons from underdense pls.



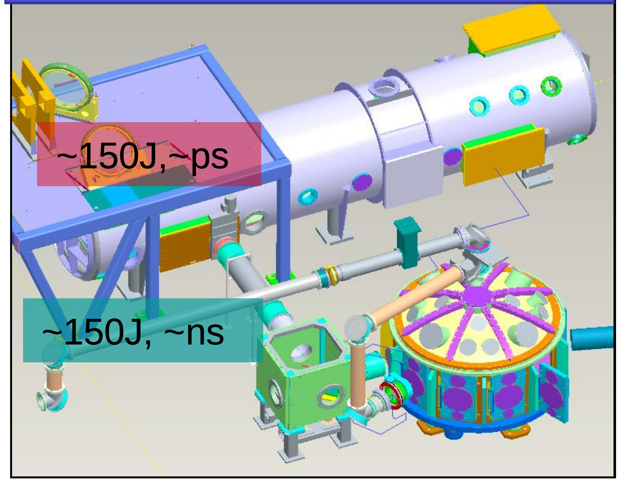
Measured super hot electrons



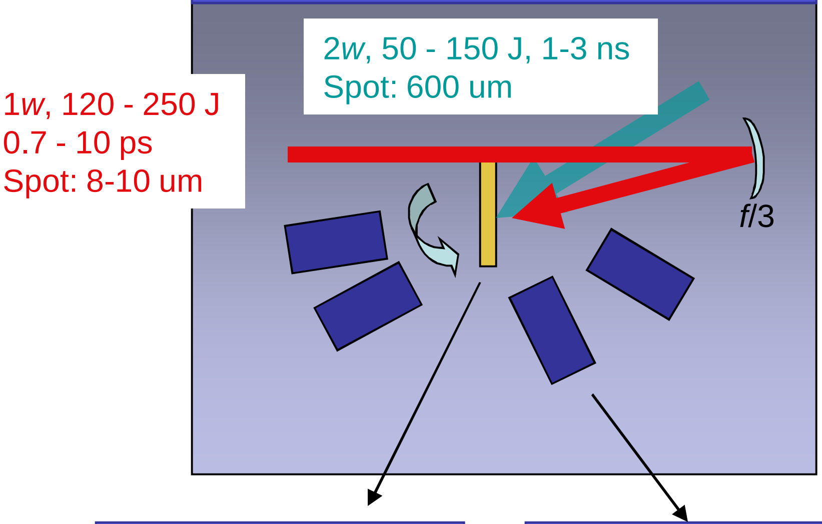
We found that maximizing pre-plasma increases positron signal.

# We performed positron experiments on LLNL Titan laser in May and September 2008

## LLNL Titan two-beam laser

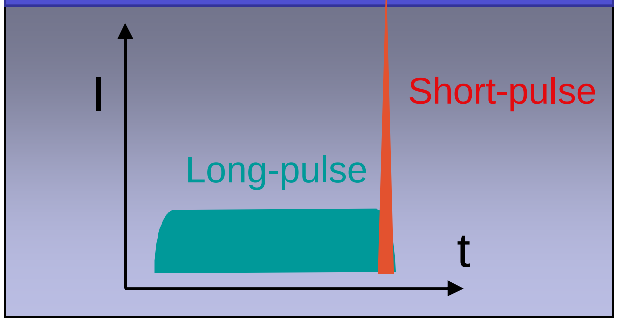


## Experimental setup


2*w*, 50 - 150 J, 1-3 ns
Spot: 600 um

1*w*, 120 - 250 J
0.7 - 10 ps
Spot: 8-10 um

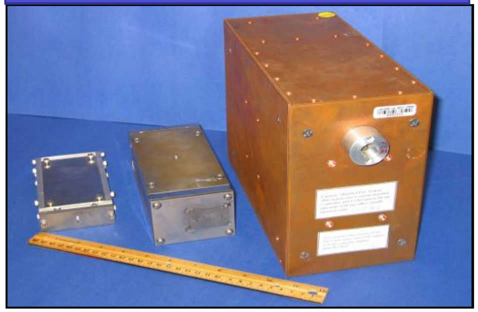
## Timing for the two beams



## Targets

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

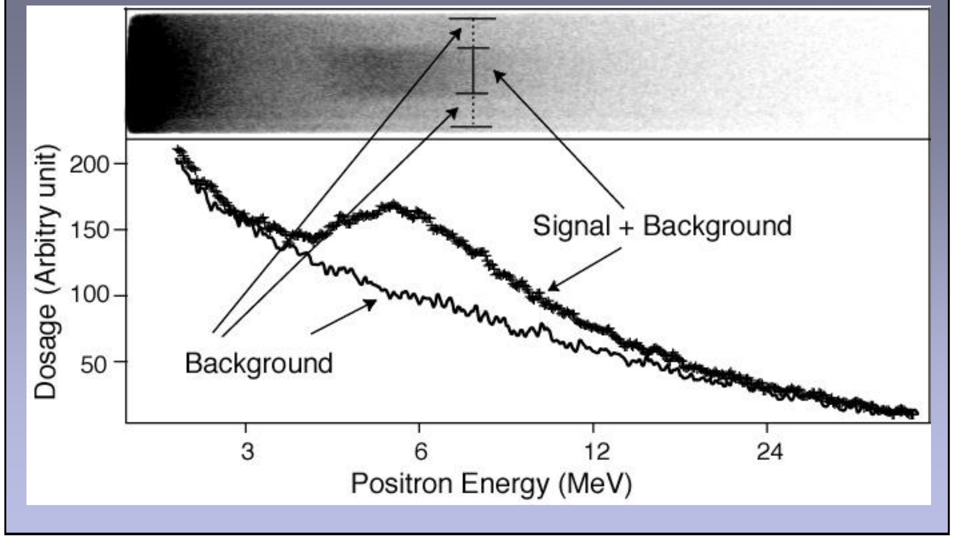
## EPP Spectrometers



Chen et al. RSI 08

# Positron signal was observed and verified experimentally

Raw positron data image (Au, 1mm)

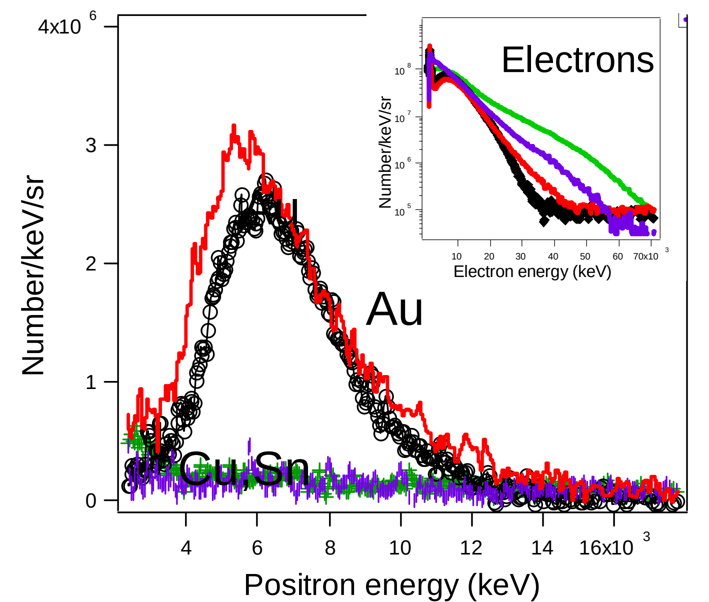


Positron energy: ~3 to 20 MeV (relativistic)

Equivalent of about $10^6$ positrons were observed in the detector - 4 to 5 orders of magnitude more than previously observed

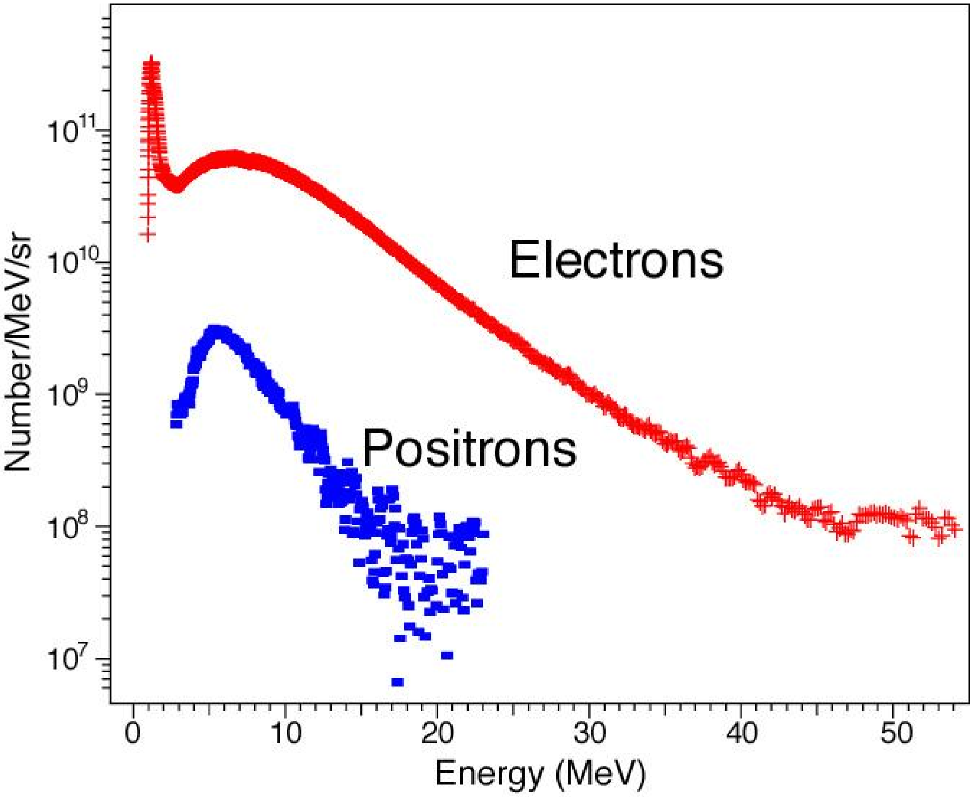
Positron signal was verified using various Z targets and thicknesses.

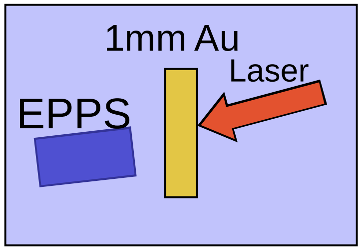
Positrons from lower Z undetected

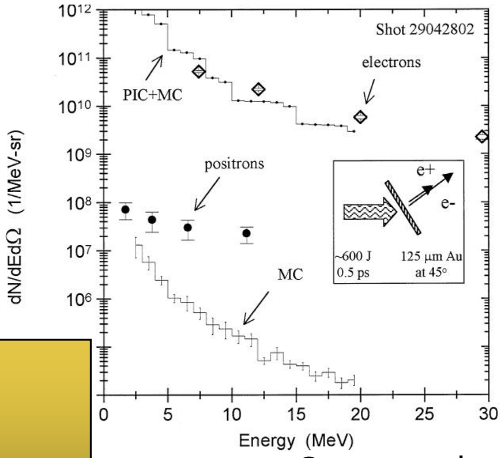


# First detailed positron energy spectra reveal important physics

EPP spectrometer data (target rear)







Cowan et al. (1999)

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

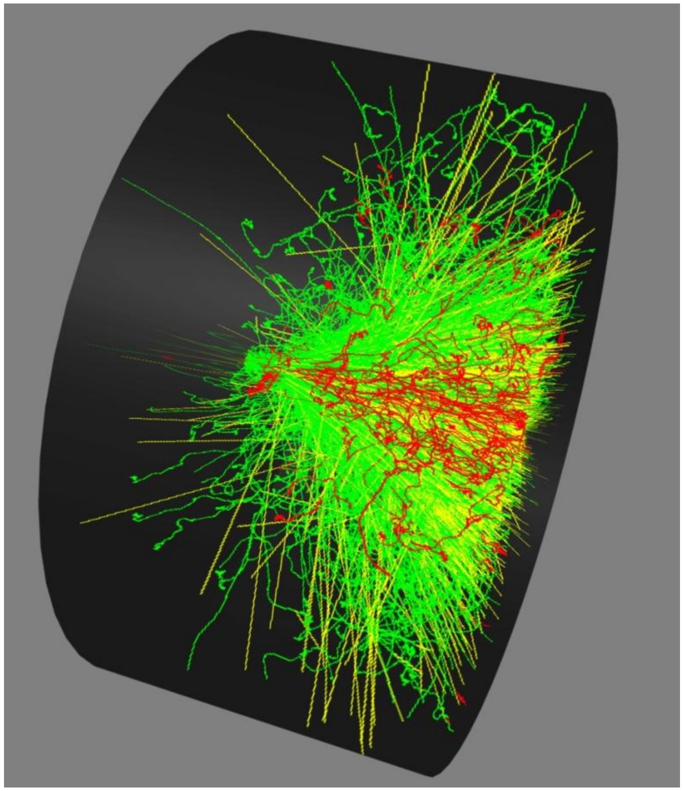
# Modeling is used to confirm relative electron and positron signal levels seen in experiment.

We employ EGS (NRC version).

Steps taken to compare with experiments.

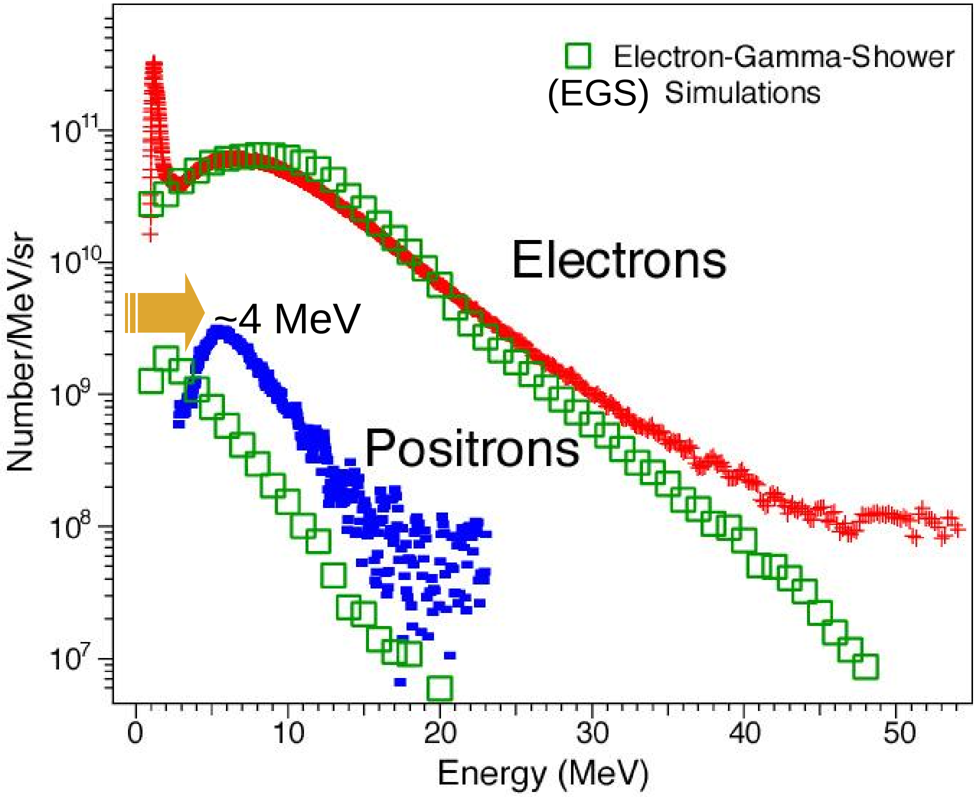
1. Generate an initial electron $f_{in}(E)$.
2. Run it through target (e.g., 3 mm Au.)
3. Attempt match w/ observed $f_{out}(E)$ signal.
4. Modify $f_{in}(E)$ until $f_{out}(E)$ match occurs.
5. Compare positron signal with exp't.

Example. Electrons injected at 25 MeV
(green ➔ e-, yellow ➔ photons, red ➔ e+)

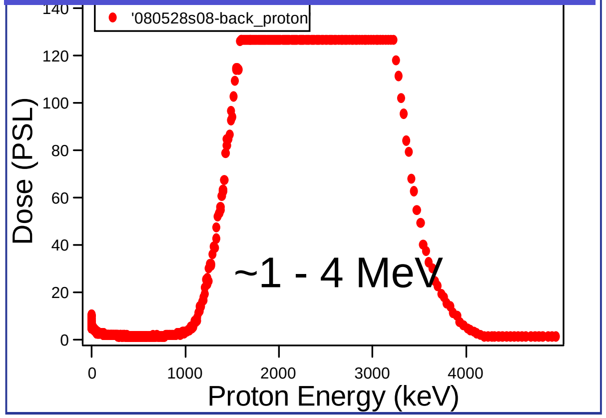


# First detailed positron energy spectra reveal important physics

EPP spectrometer data (target rear)



Proton spectrum

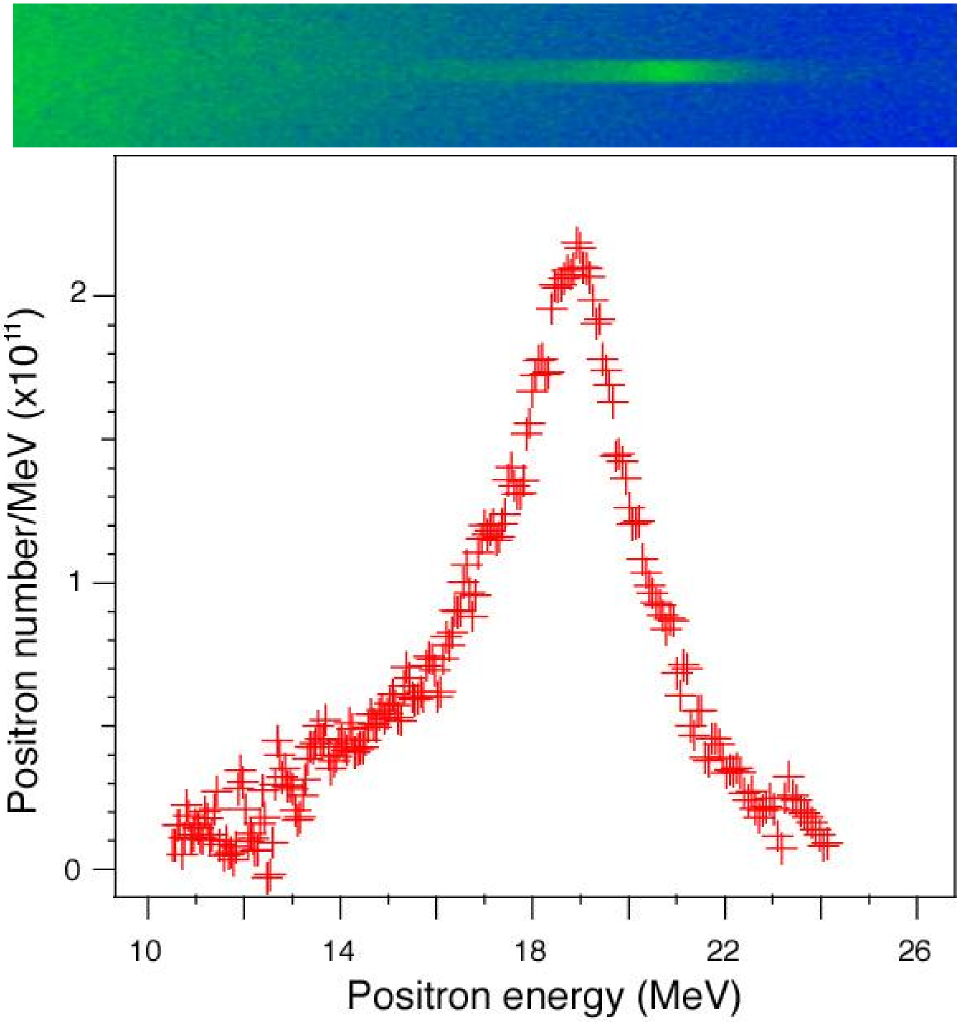


Chen, et al. PRL 2009

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)

# Recent experiments at Omega EP indicate nonlinear scaling with laser energy.

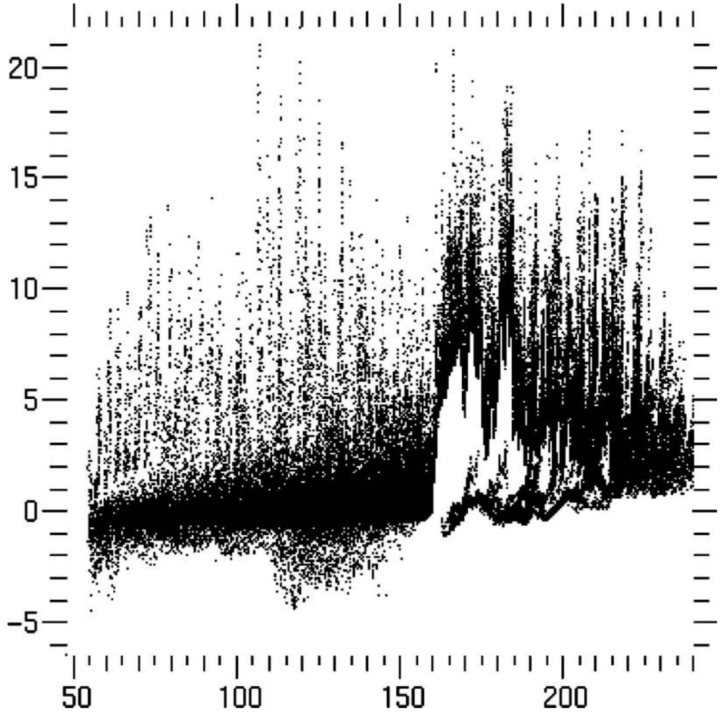
EPPS positron shot #5082 (812 J, 10ps)



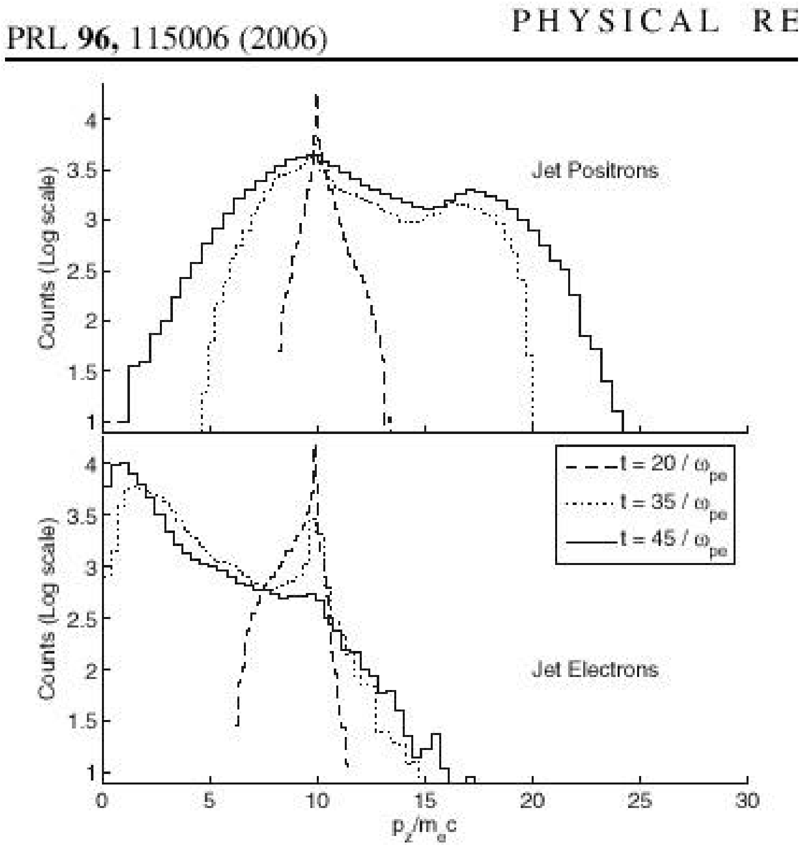
- ~2×10$^{11}$ positrons inferred.
- ~3 time more positrons than the linear scaling based on Titan 10ps shots predicted.
- High rate of positron production: ~ 2x10$^{22}$ e+/s
- Near monoenergetic positron jet observed: due to large energy shift?

# Interestingly, similar shift was observed in simulations by us and SLAC in 2006 for e+-e- jets.

*Figure 5. Positrons leaving the thin slab completely out the rear of the target.*



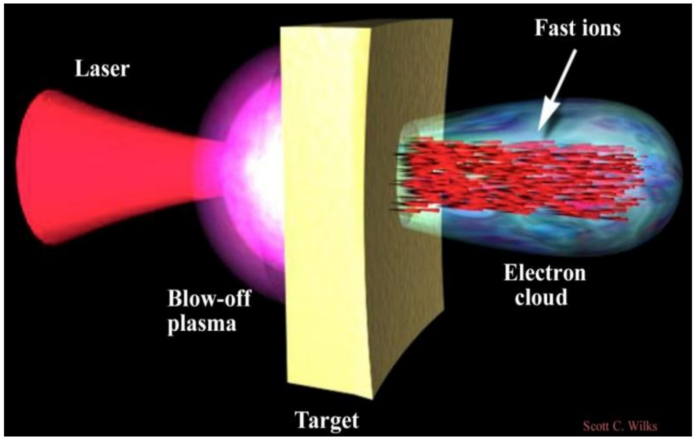
S. C. Wilks, et. al."Electron-Positron Plasmas Created by Ultra-Intense Laser Pulses Interacting with Solid Targets", *Astrophysics and Space Sciences*, 298, pp 347-355 (2005).



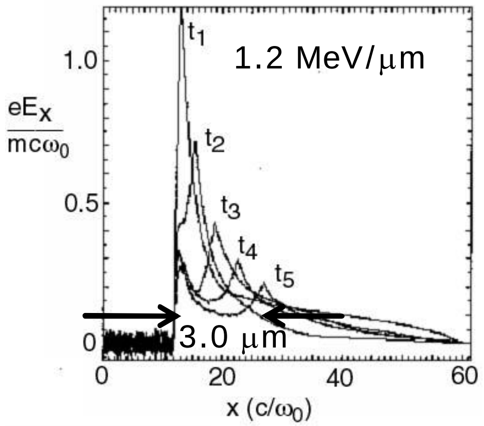
"Inductive and ES Acceleration in Relativistic Jet-Plasma Interactions", J. S. Ng and R. J. Noble, PRL 96, 115006 (2006).

Acceleration of positrons and de-acceleration of electrons seen in 3-D simulations of pair jets into both vacuum and plasma.

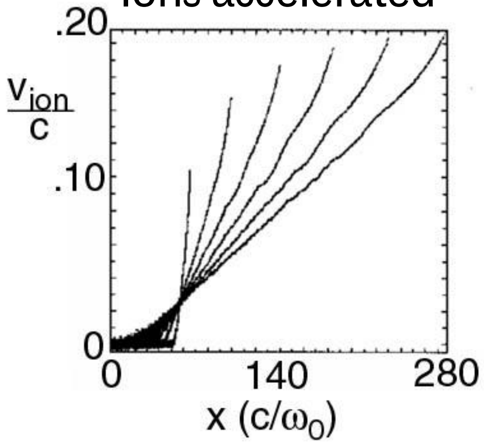
# We attribute this to ion acceleration (via TNSA*) that is known to occur for ultra-intense laser-solid interactions.



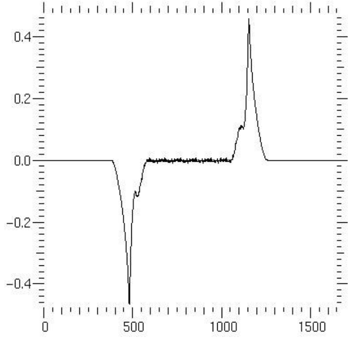
Accelerating field



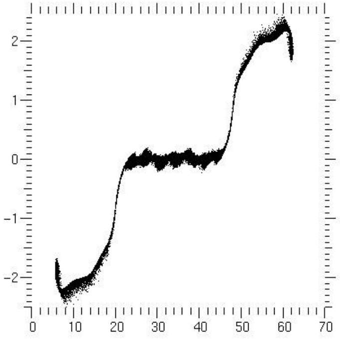
Ions accelerated



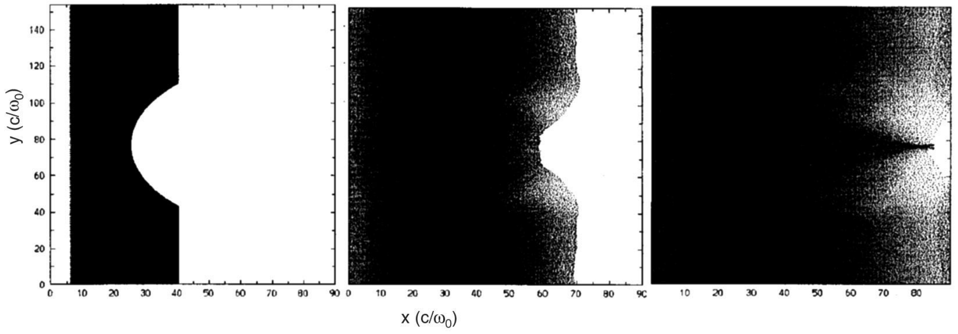
Accelerating field



Positron γβ



Ions can be focused by shaping target

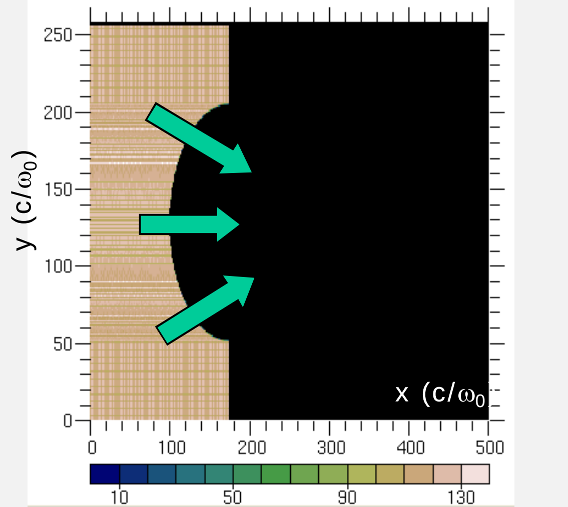


Positron spectra was expected to shift to higher energies for thin targets. Could focusing also occur for the positrons?

*S. C. Wilks, et. al., “Ion Acceleration Mechanisms in Ultra-Intense laser-Plasma Interactions”, *Physics of Plasmas*, 8, 542 (2001).

# This led to interesting idea: can we focus the positrons using a shaped target?

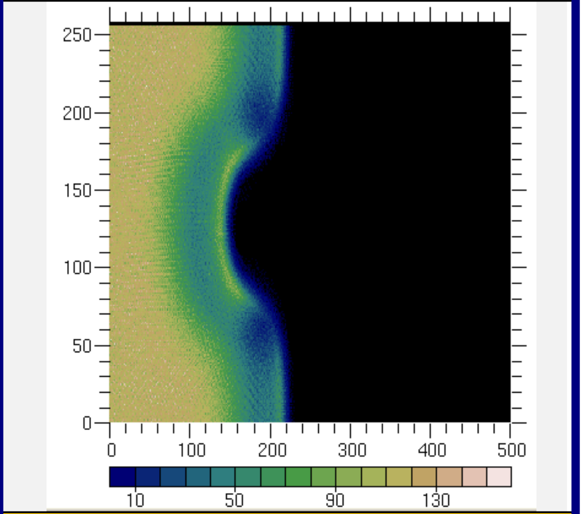
$t=0$



Initial target composition:

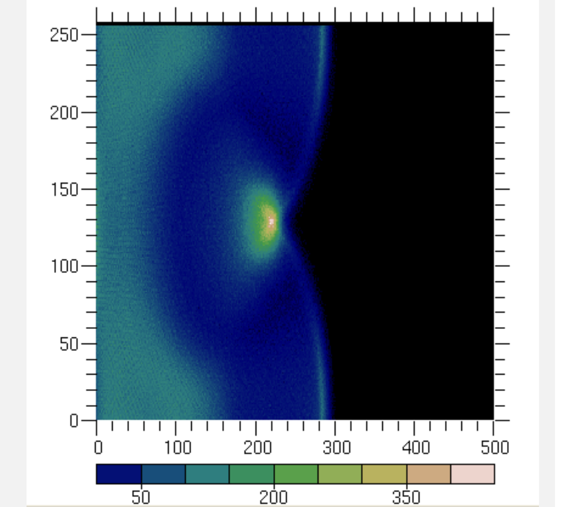
| | |
|---|---|
| Electron fraction | 1.001 |
| Ion fraction | 1.0 |
| Positron fraction | 0.001 |

$t=10\ \omega_0^{-1}$



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

$t=20\ \omega_0^{-1}$

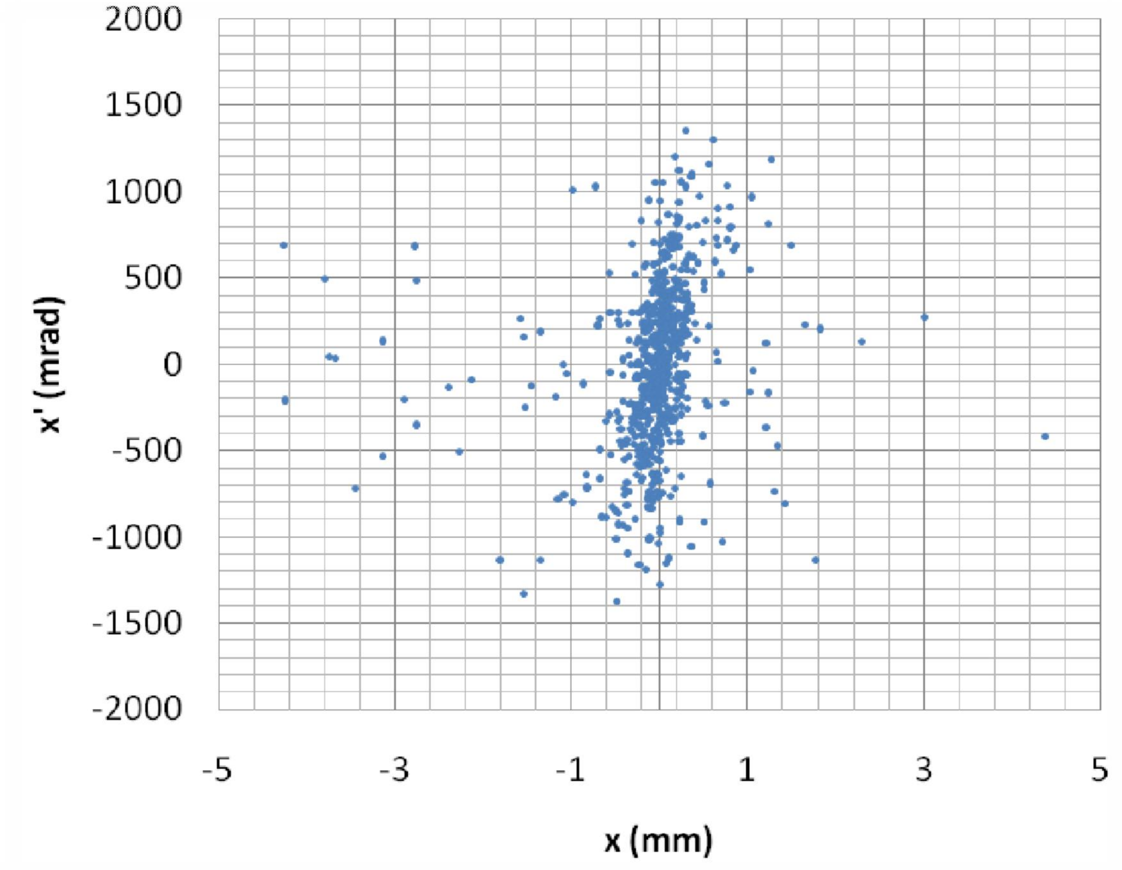


Results in a positron density that is 4 times higher than the initial positron density in the target.

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
~1×10$^{10}$ e+/shot; ~ 10$^{8}$ in the front

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

Observed positron: ~0.01 J
(EGS: escaping/total ~10%)
Total produced positron: ~ 0.1 J
Total positron E/Laser E: ~0.1%

## Other positron sources

Radioactive isotopes: 10$^{6\text{-}12}$/s
(High Flux requires reactor.)

Electron Linacs: 10$^{6\text{-}12}$/s
(ILC design: 10$^{10}$/bunch)