Laser Produced Positron Research at Lawrence Livermore National Laboratory

Present to the 2nd Conference on Extremely High-Intensity Laser Physics,
September 5-8, 2017, Lisbon Portugal

Hui Chen

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Lawrence Livermore National Laboratory

Acknowledgement: Team member and Collaborations

N. Brejnholt, M-A. Descalle, A. Hazi, R. Heeter, A. Kemp, G. E. Kemp, A. Link, B. Pollock, E. Marley, S. R. Nagel, **J. Park**, M. Schneider, R. Shepherd, M. Sherlock, R. Tommasini, S. C. Wilks, **G. J. Williams** - ***Lawrence Livermore National Lab***

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G. Grigori **– *Oxford University***

E. d'Humieres, ***University of Bordeaux***

R. Fedosejevs, **S. Kerr** – ***University of Alberta***

F. Beg, **B. Edghill**, C. Krauland, C. Mcguffey, J. Peebles, M-S Wei - ***UCSD***

C. Kuranz, M. Manuel, L. Willingale – ***University of Michigan***

A. Spitkovsky - ***Princeton University***

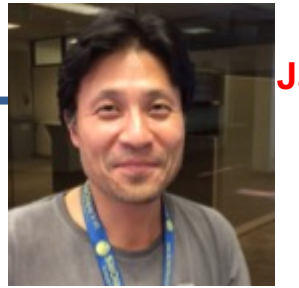
Y. Arikawa, H. Azechi, S. Fujioka, , H. Hosoda, S. Kojima, N. Miyanaga, T. Morita, T. Moritaka, T. Nagai, M. Nakai, T. Namimoto, H. Nishimura, T. Ozaki, Y. Sentoku, Y. Sakawa, H. Takabe, Z. Zhang - ***ILE, Osaka University***

P. Audebert – ***LULI, École Polytechnique***

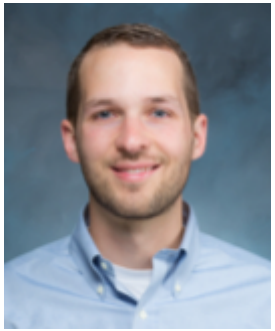
M. Hill, D. Hoarty, L. Hobbs, S. James - ***AWE***

***Complete list of names are included in the publications cited**

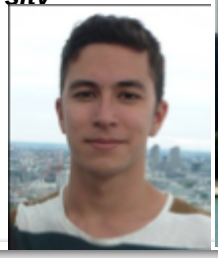
Many thanks to the JLF, Omega EP, LFEX and Orion laser facilities for their support.We acknowledge the LLNL LDRD funding (10-ERD-044 and 12-ERD-062, 17-ERD-010) for this project.



Jaebum Park



Jackson Williams



Brandon Edghill

Shaun Kerr

At LLNL, we have been investigating laser produced positrons through experiments and modeling

1. **Positron jet characterization:**
   - Absolute positron number and energies
   - Emittance
   - Yield dependence to laser & target

2. **Relativistic laser-plasma interaction physics:**
   - Sheath field acceleration
   - Effect of electromagnetic field

3. **Applications:**
   - Positron radiography – APS DPP 2017
   - Relativistic electron-positron pair plasma – APS DPP 2017

Simulation tools:

- Particle-in-cell: PICLS
- Particle code: GEANT4; EGS4
- Hydrodynamic code: HYDRA

- OSIRIS; LSP

Majority of experiments were performed on large laser facilities with 1-10 ps, 100 J to 1500 J energy per shot

Titan laser (LLNL)
1-10 ps, 100-350 J
5-10 shots/day

LFEX (ILE)
2-4 beams
1-2 ps,
~0.5-1 kJ/beam

Omega EP (LLE)
2 beams
1-10 ps
up to 1.3 kJ/beam
Up to 16 shots/day

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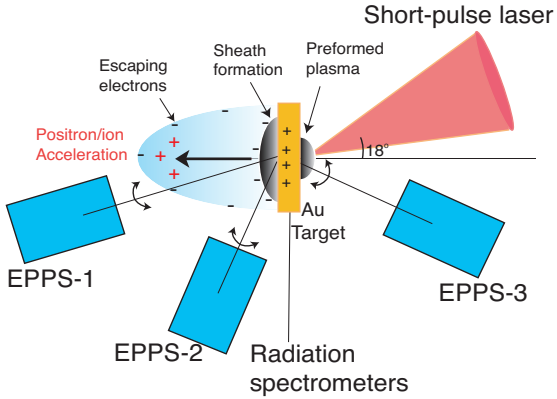
ORION (AWE)
2 beams
0.5-1 ps,
up to 500 J/beam

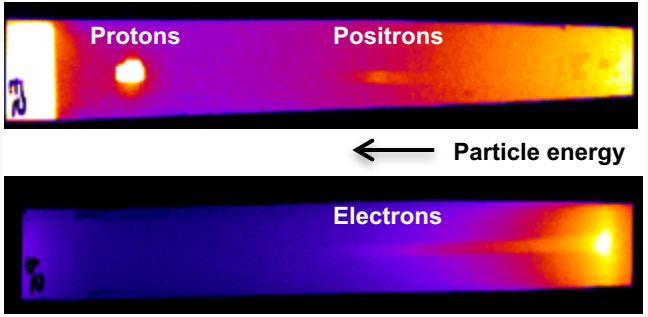
In each experiments, e-, e+, p+ and γ from gold targets were measured by various diagnostics

Experimental setup at Titan



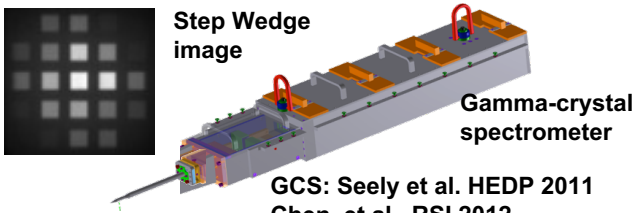
Electron positron proton spectrometer

EPPS raw images



EPPS: Chen, et al., RSI 2008

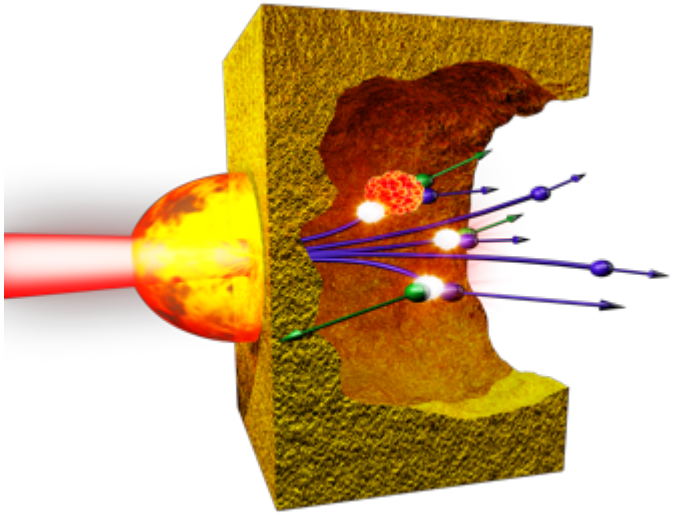
High-energy gamma diagnostics



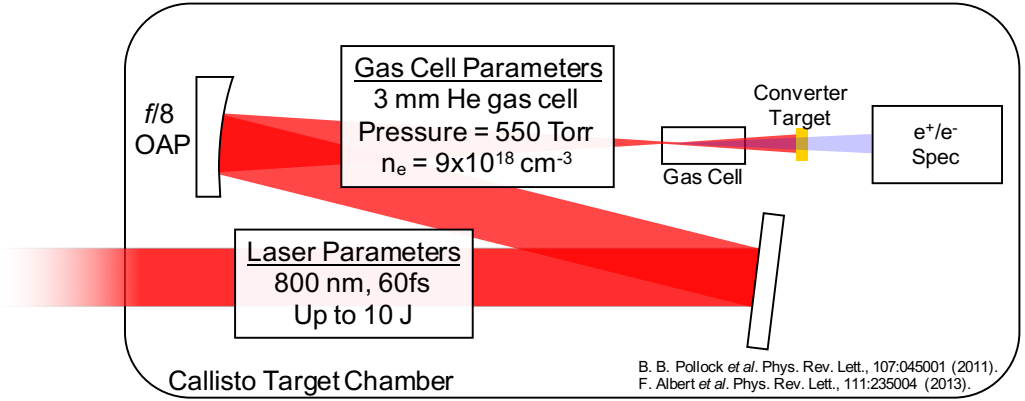
GCS: Seely et al. HEDP 2011
Chen, et al., RSI 2012

The laser intensities used experimentally were from 10^{18} to 10^{20} W/cm^2

Direct pair production
(laser on gold target)



Indirect pair production
(wake-field electrons on gold target)



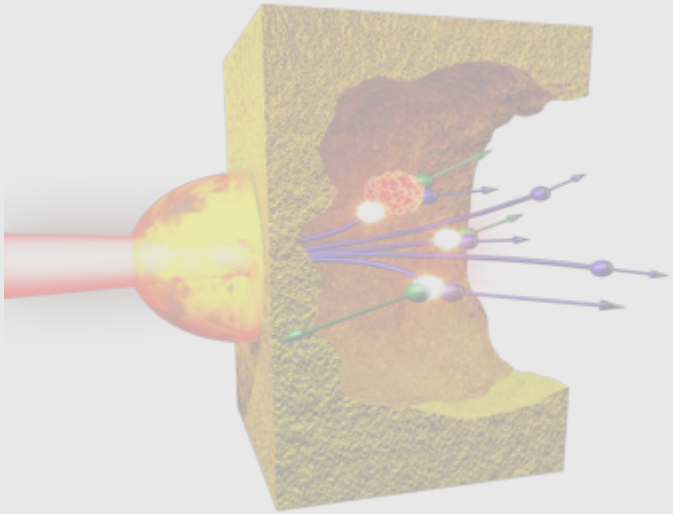
Williams et al. Physics of Plasmas (2015)

Prior experiment laser produced positrons:
T. Cowan et al., Laser Particle Beams (1999)

Prior references on making positrons using wake-field accelerated electrons:
Gahn et al. (2002) and Sarri et al., (2013)

We experimented with indirect pair production using wake-field generated electron beams

Direct pair production
(laser on gold target)



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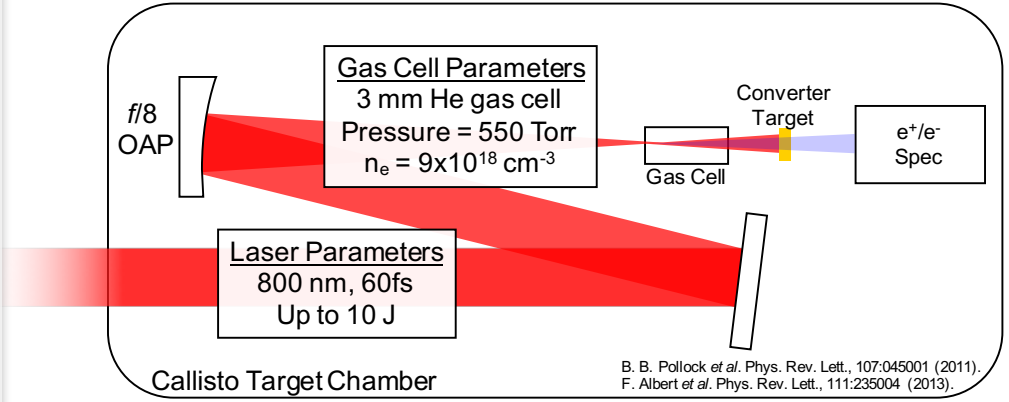
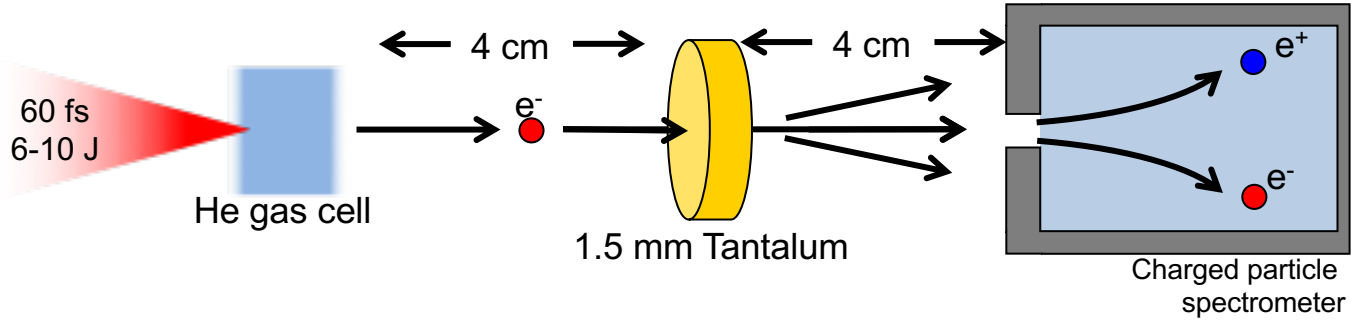


Williams et al. Physics of Plasmas (2015)

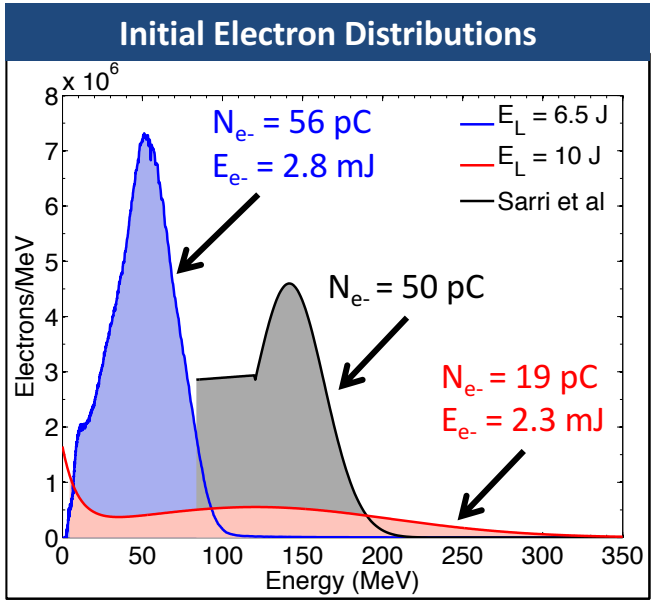
Prior references on making positrons using wake-field accelerated electrons: Gahn et al. (2002) and Sarri et al., (2013)

Electrons were accelerated and driven into a converter target to produce positrons



Williams, et al. Phys. Plasmas (2015)

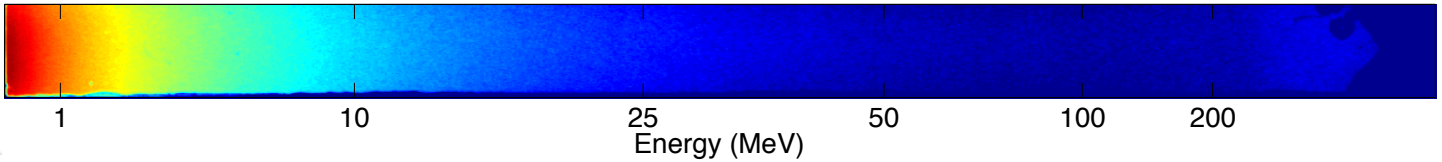
Positron signal was not observed for either a high energy or high flux electron source



Geant4 modeling may provide explanation of null result

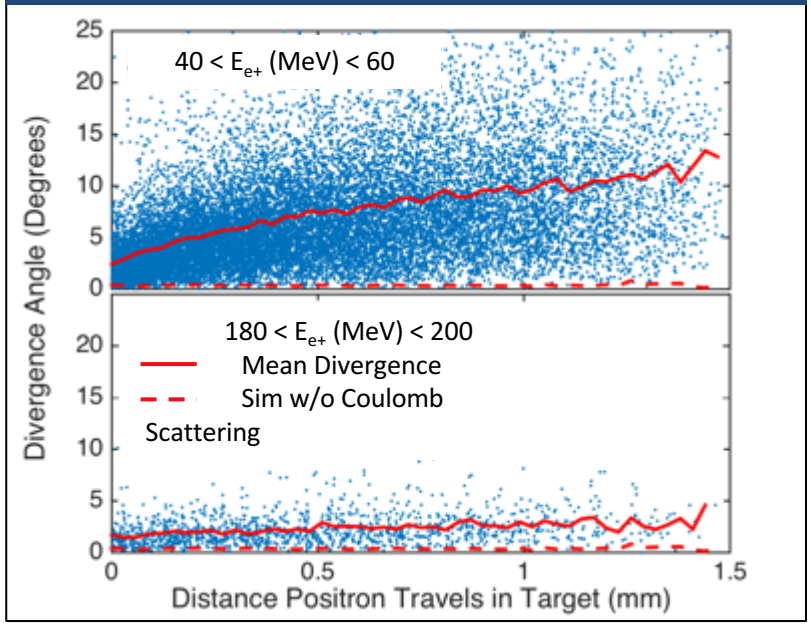
Williams, et al. Phys. Plasmas (2015)

Positive-side image plate for electron source in red curve



Beam divergence is larger than expected, and is dominated by Coulomb scattering

Energy-Resolved Divergence of Emitted Positrons



Williams, et al.
Phys. Plasmas (2015)

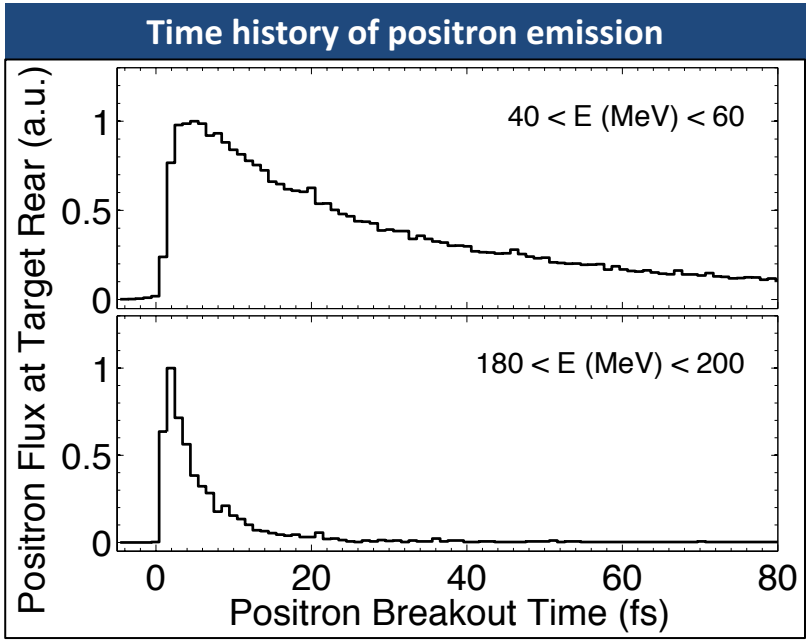
Initial electron divergence from LWFA sources is a negligible contribution

Simulation also shows that the positron beam is longer than the electron pulse due to straggling inside the target

Pulse duration of positrons can be significantly longer than electron source

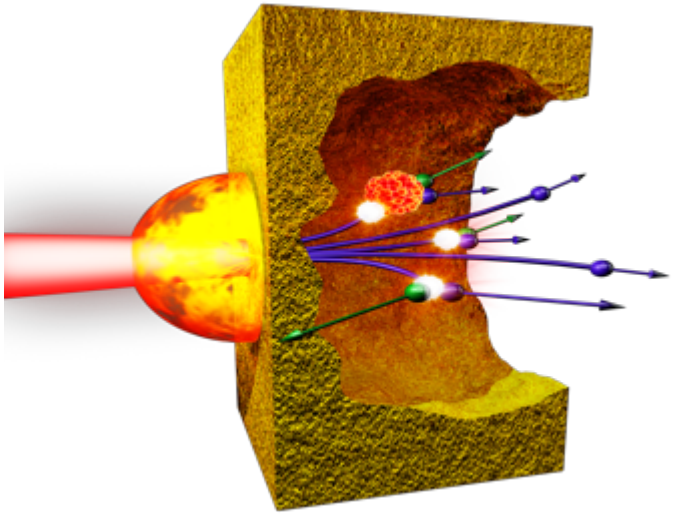
- $\tau_{e-} > 10$ fs
- $\tau_{e+} \geq 13\text{-}50$ fs

Williams, et al.
Phys. Plasmas (2015)



Direct pair production was investigated extensively for laser intensities from 10^{18} to 10^{20} W/cm^2

Direct pair production
(laser on gold target)



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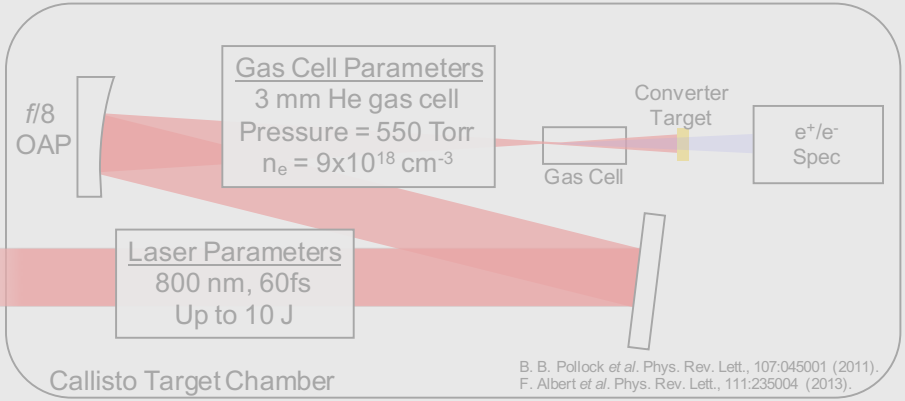
Indirect pair production
(wake-field electrons on gold target)

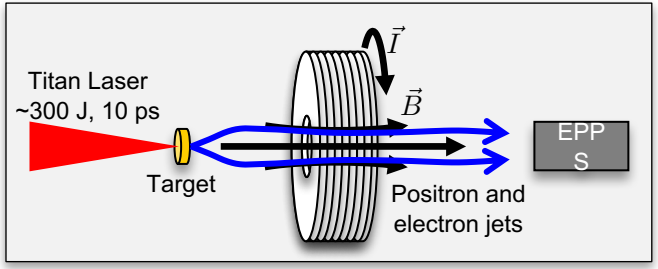


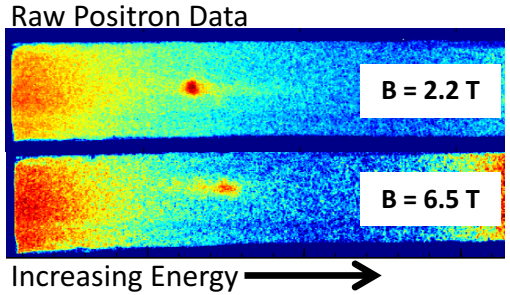
Williams et al. Physics of Plasmas (2015)

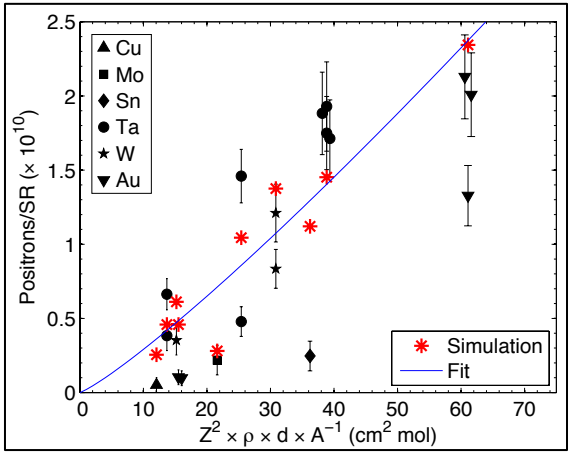
Prior references on making positrons using wake-field accelerated electrons:
Gahn et al. (2002) and Sarri et al., (2013)

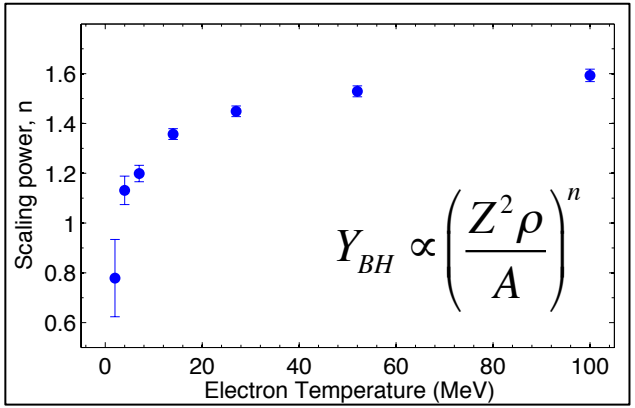
Bethe-Heitler process was verified as the dominant pair generation mechanisms through detailed measurements

Target dependence of laser-produced positrons were measured, aided by magnetic collimation of the pair jets







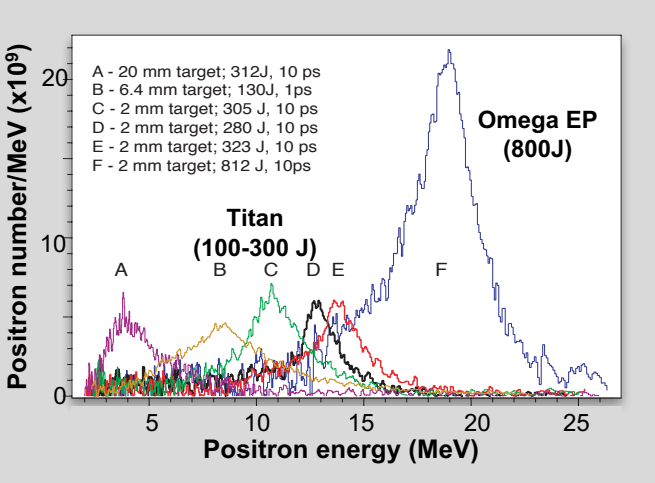


Bethe-Heitler has an effective scaling ~Z^2

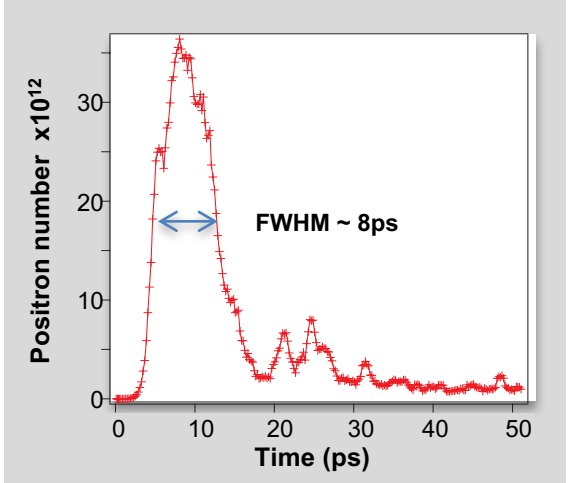
Williams et al.
Phys. Plasmas (2016)

Quasi-monoenergetic, high flux, relativistic positrons are produced in *ps* time scale

Titan and Omega EP positron data*



Sim. e+ width for 10 ps exp. (LSP)**



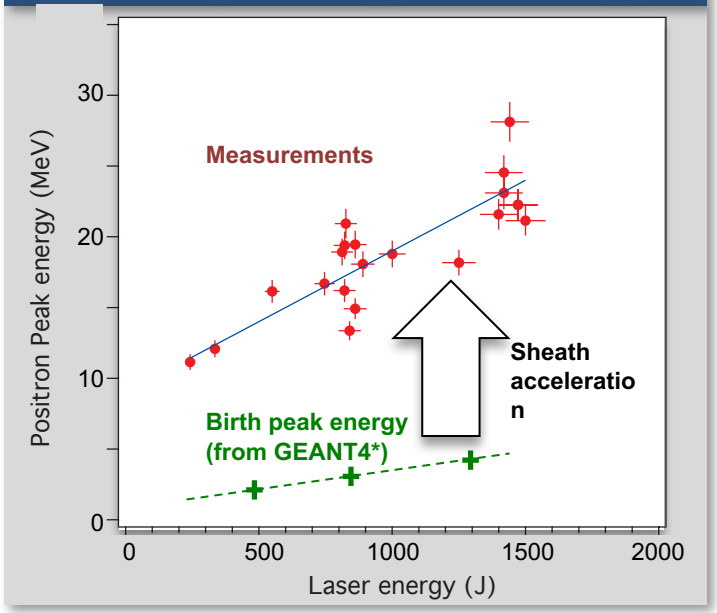
* More details see Chen *et al.*, PRL 2009, PRL2010, HEDP 2011

**Chen et al, POP 2015

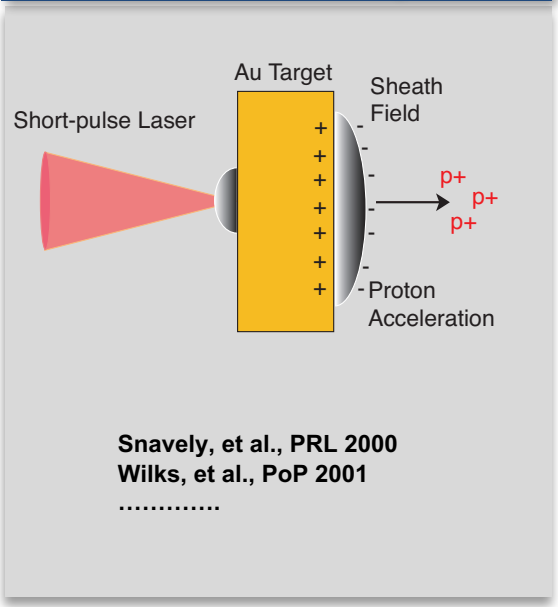
Pair number: $10^{10} – 10^{12}$	Peak energy: 4 - 30 MeV	Flux duration: ~10 - 100 ps
E conversion>$2x10^{-4}$	Pair rate: ~10^{22} /s	Peak flux: >10^{25} $cm^{-2}s^{-1}$

Positrons are accelerated to 10s' of MeV, which far exceed their birth energy

Positron peak energy vs laser energy



Sheath acceleration of protons



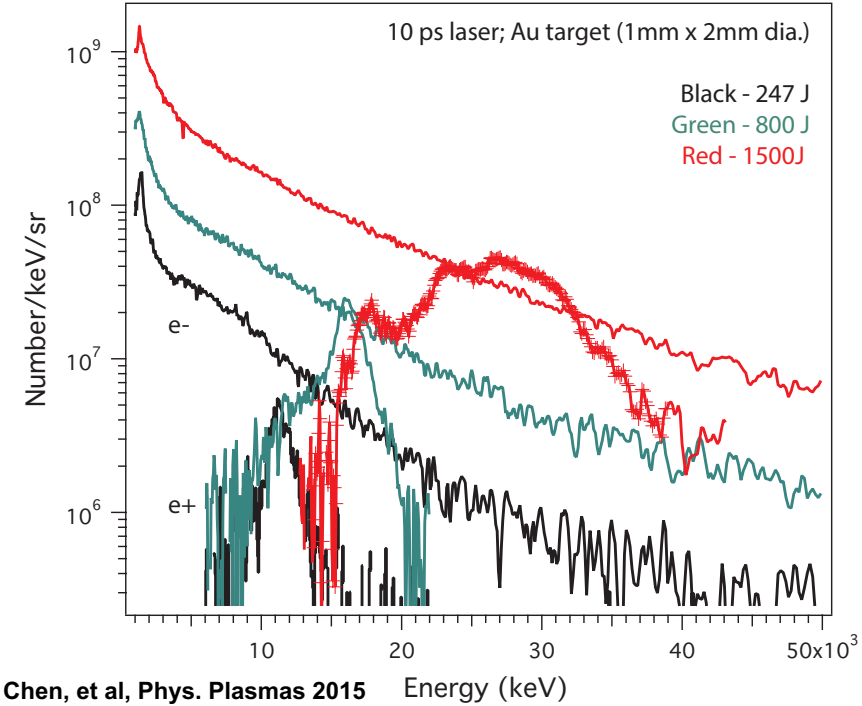
* Chen, et al, Phys. Plasmas 2015

* Particle code GEANT4 was developed by CEAN (www. geant4.cern.ch)

This feature is unique and it is the result of intense laser target interaction

Detailed positron spectrum reveals physics in sheath acceleration

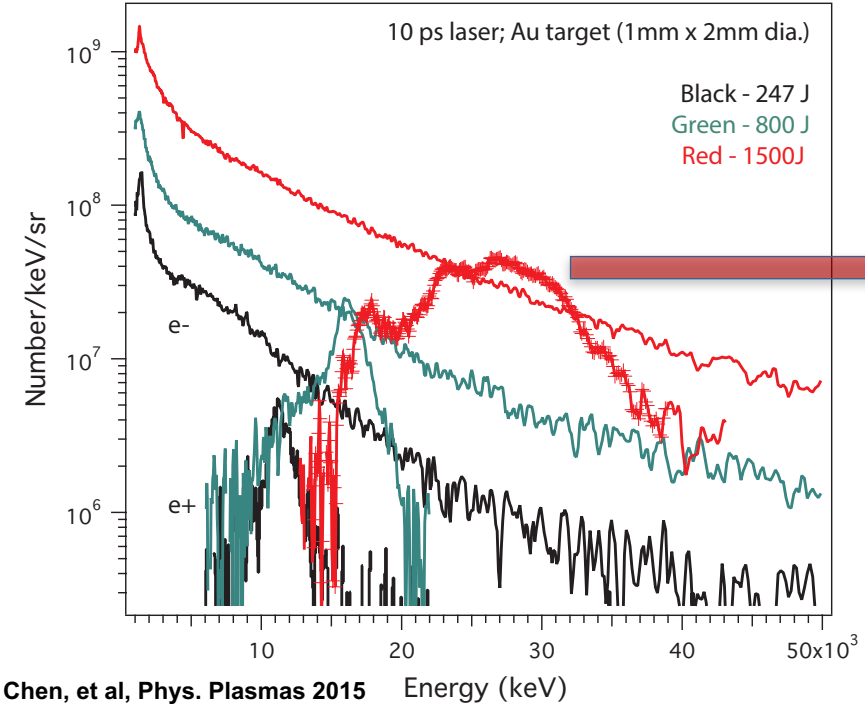
E&P pectra at 3 laser energies



* **Chen, et al, Phys. Plasmas 2015**

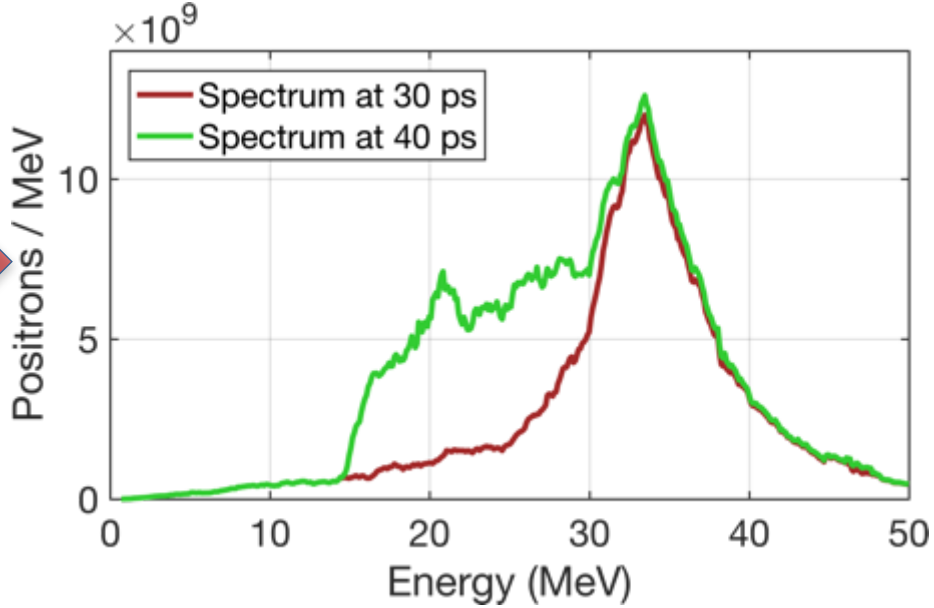
Detailed positron spectrum reveals physics in sheath acceleration

E&P pectra at 3 laser energies



* **Chen, et al, Phys. Plasmas 2015**

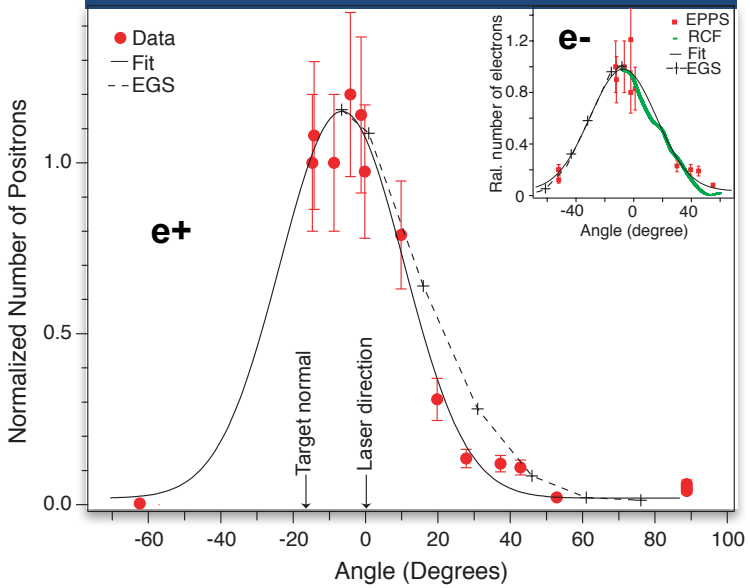
Time evolution of the spectrum (LSP)



Shaun Kerr, APS DPP 2017

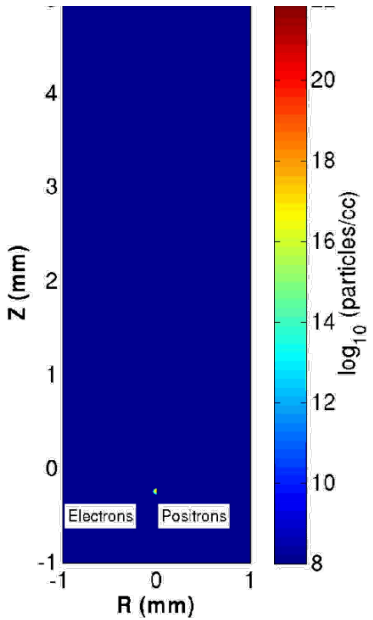
Laser produced relativistic pairs form jets at the back of the target

e+ and e- angular distributions



Chen *et al.*, PRL 2010

Jets simulated by LSP*

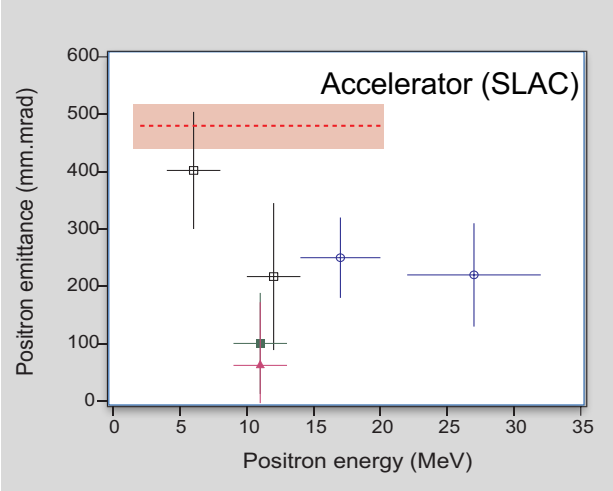


*Tony Link

Jet angular spread: 10-30 degrees. The jets are shaped by the E and B fields of the target. Its direction is controlled by the laser parameters and target.

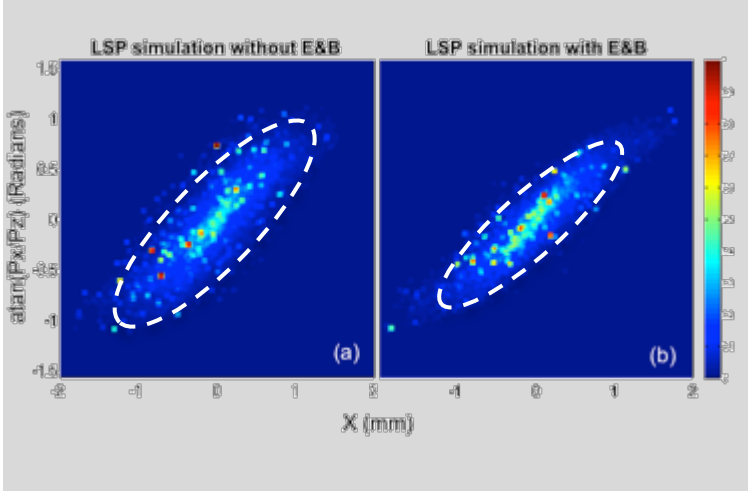
The emittance of laser-positrons is comparable to, or smaller, than that obtained on large accelerators

Measured positron emittance



Exp. on Titan & OMEGA EP, in collaboration with SLAC

Simulated positron emittance using LSP

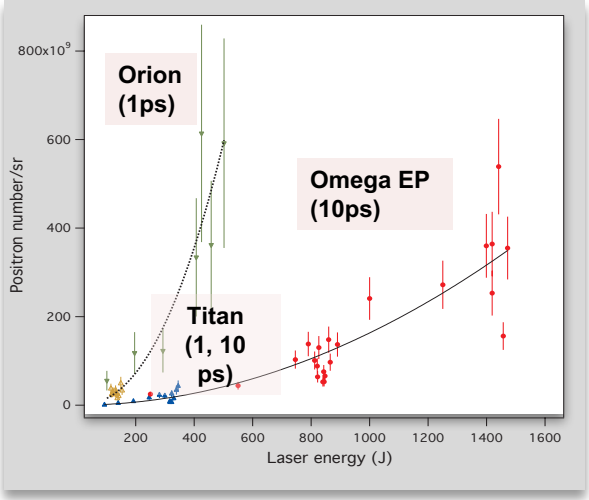


Chen, Sheppard, Gronberg et al., POP 2013

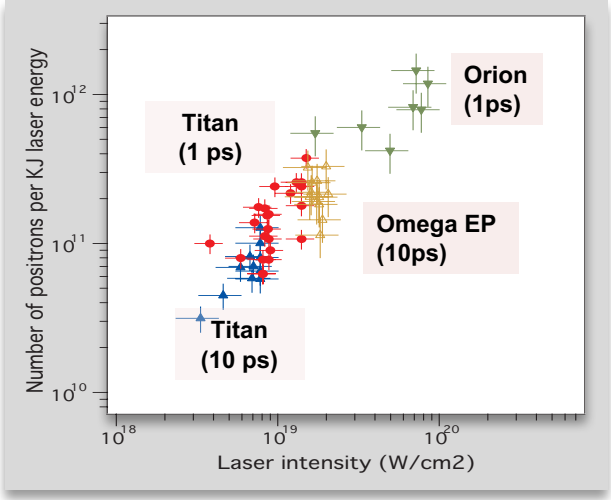
Our pairs can be called a jet; as they are not sufficiently collimated to be a ”beam”.

We found that the pair yield scales as ~E^2 based on data from Titan, EP and Orion experiments

Positron number ~ E^2



Norm. positrons ~ $I_{laser}^{1.1}$



Chen, Fiuza, Sentoku et al. PRL, 2015
Chen, Link, et al, PoP, 2015
Myatt, et al. PRE 2009

Positron number shows a ~E^2 dependence for both 1 ps and 10 ps shots.

Relativistic, non-neutral electron-positron plasma jets have been produced

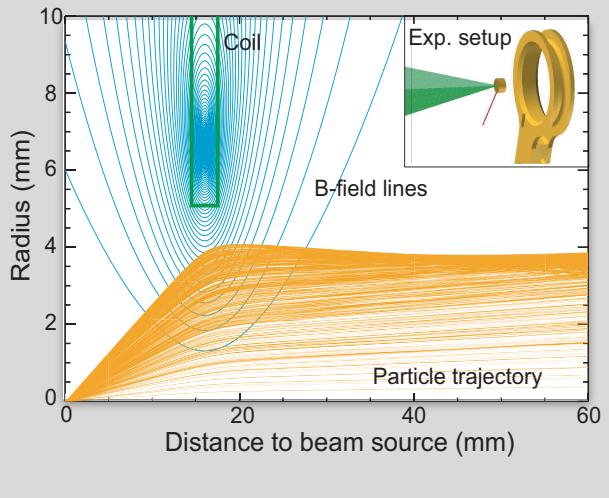
Parameter	Exp. Value*
$T_{//}$	0.5 - 4 MeV
$T_{\perp}$	0.2-1 MeV
n_{e+}	$\sim 10^{11\text{-}13}$ cm^{-3}
n_{e-}	$\sim 10^{12\text{-}15}$ cm^{-3}
τ_{Jet}	5 – 30 ps

*Chen, et al. PRL 2010; HEDP 2011; POP 2014

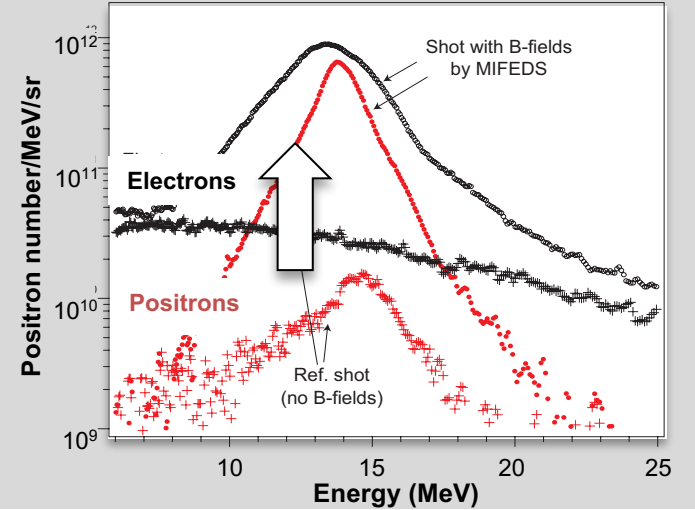
The most obvious needs are to (1) increase the density of the pair jets and (2) reduce the electron/positron density ratio.

We have demonstrated effective collimation of laser-produced relativistic electron-positron pair jets

MIFEDS setup on OMEGA EP



e- & e+ spectra after collimation

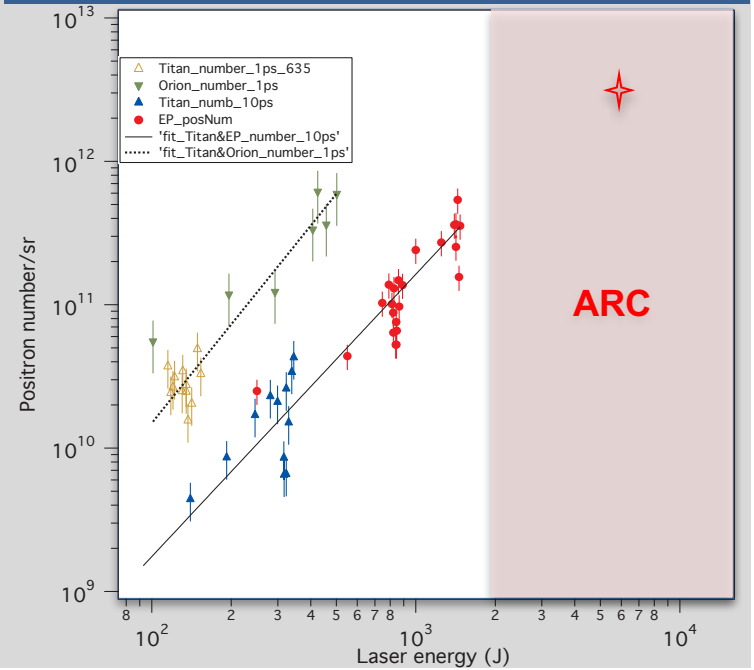


Chen, Fiksel, Barnak, et al., POP 2014

- The effective divergence of the beam reduced from 30 deg FWHM to 5 deg;
- The charge (e-/e+) ratio in the beam reduced from ~100 to 5.

The positron scaling indicates that ARC energy may provide very high positron yield

ARC energy results in high e+ yield



To determine the actual yield, we need:
(1) Laser intensity;
(2) Pulse contrast;
(3) Focal quality.

Furthermore, ARC is unique relative to the Titan, Omega EP and Orion lasers:

Titan parabola – f/3
Omega EP – f/2
Orion – f/3
NIF ARC – **f/60**

The long focal length parabola is favored by wake-field acceleration experiments; its effect to laser plasma interaction needs to be determined.

ARC results
Hui Chen, APS DPP 2017

We have been awarded NIF Discovery Science shot time using ARC – these questions will be answered soon.

Date Published	Primary Author	Laser	Energy/J	Intensity/ Wcm^{-2}	Pulse Duration/fs	Target	Diameter /mm	Thickness /mm	Best e^+/e^- ratio	Best e^+ Number	Best e^+ Density	Dominant Production Method
9/14/2015	E. Liang	Texas Petawatt	~100	$3\times10^{20} - 1.9\times20^{21}$	128-245	Au: Disk/Rod	2-4.5/2-3	0.1-5/4-10	15%/37%	$\sim1.8\times10^{10}$	$1.6\times10^{15}cm^{-3}$	Bethe-Heitler/Direct Process
						Pt: Disk/Rod	2-4.5/2-3	0.1-6/4-6	33%/52% $\pm$ 10%			
10/23/2000	C. Gahn	Table-Top at ATLAS	.22		130	Pb		2 (slab)		$\sim2\times10^{7}$		Bethe-Heitler/Indirect Process
3/15/2017	Yonghong Yan	XingGuang III laser facility	100-200	$\sim2\times10^{19}$	800	Ta	1-10	1		$2.8(\pm0.3)\times10^{9}\ str^{-1}$		Bethe-Heitler/Direct Process
3/12/2017	Yuchi Wu	XingGuang III laser facility					1-10			$2.8\times10^{9}\ str^{-1}$		
3/7/2016	Tongjun Xu	Petawatt at Shanghai Institute of Optics and Fine Mechanics	3.75	3.5×10^{19}	45	Cu and Pb		2-20	48%	3.5×10^{8}	$3\times10^{12}cm^{-3}$	Bethe-Heitler/Indirect Process
6/20/2013	G. Sarri	HERCULES at Center for Ultrafast Optical Science	0.8	6×10^{18}	30	Cu, Sn, Ta and Pb		1.4-6.4		3.5×10^{7}	$2\times10^{14}cm^{-3}$	Bethe-Heitler/
4/23/2015	G. Sarri	ASTRA-GEMINI at Rutherford Appleton Laboratory	14	3×10^{19}	42 ± 4	Pb		5-40	49% of the beam is e^+	3×10^{7}	$10^{15}cm^{-3}$	Bethe-Heitler/Indirect Process
12/23/2009	H. Chen	Titan at the Jupiter Laser Facility	120-250	$\sim1\times10^{20}$	700-10000	Au, Ta, Sn, Cu, Al	6.4	0.1-3.1		$2\times10^{10}s^{-1}$		Bethe-Heitler/Direct Process
7/1/2010	H. Chen	Titan at the Jupiter Laser Facility and OMEGA EP at the Laboratory for Laser Energetics	100-850	$1\times10^{19} - 5\times10^{20}$	1000-10000	Au	1-20	1		$10^{10} - 10^{11}$	$\sim10^{13}$	Bethe-Heitler/Direct Process
4/24/2014	H. Chen	OMEGA EP at the Laboratory for Laser Energetics	830 ± 30	5×10^{18}	10000	Au	2	1	$2.5=\frac{e^-}{e^+}$		1.9×10^{9}	Bethe-Heitler/Direct Process – Magnetic Collimation
1/31/2013	H. Chen	Titan at the Jupiter Laser Facility and OMEGA EP at the Laboratory for Laser Energetics	200-850	$5\times10^{18} - 6\times10^{19}$	10000	Au		1		$10^{10} - 10^{12}\ per\ bunch$		Bethe-Heitler/Direct Process
12/6/2016	G. Williams	Titan at the Jupiter Laser Facility	270	1.2×10^{19}	10000	Cu, Mo, Sn, Ta, W, Au	6.3	0.538-2.36		$\approx10^{7} - 10^{9}$		Bethe-Heitler/Direct Process – Target Dependence
10/21/2015	G. Williams	Calisto at the Jupiter Laser Facility	6.5-10		60	Ta		0.25-4.2		None Measured above background		Bethe-Heitler/Indirect Process

Brandon Edghill, APS DPP 2017

At LLNL, we have been investigating laser produced positrons through experiments and modeling

✓ **Pair jet characterization:**
- Absolute positron number and energies
- Emittance
- Yield dependence to laser & target

✓ **Relativistic laser-plasma interaction physics:**
- Sheath field acceleration
- Effect of electromagnetic field

➢ **Applications:**
- Positron radiography – APS DPP 2017
- Relativistic electron-positron pair plasma – APS DPP 2017

Simulation tools:

➢ Particle-in-cell: PICLS

✓ Particle code: GEANT4; EGS4

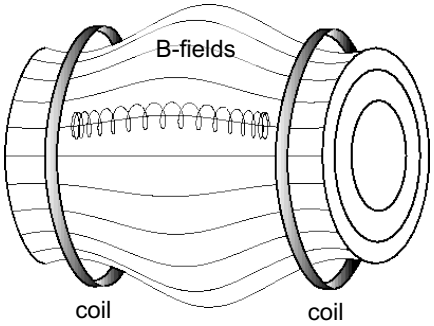
➢ Hydrodynamic code: HYDRA

✓ OSIRIS; LSP

Lawrence Livermore
National Laboratory

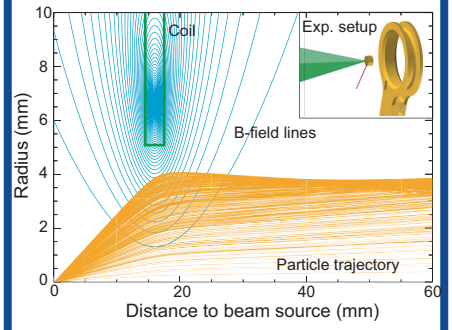
A relativistic pair plasma by pair confinement?

In theory mirror machine works for both charges



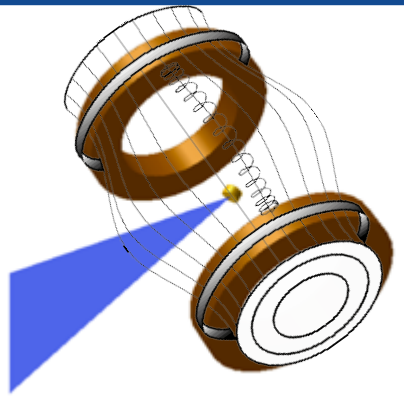
Gibson et al, PRL 1960
Pedersen et al, J. Phys. B 2003
Myatt, et al, PRE 2009

The first step: one coil has been demonstrated



Chen et al. PoP (2014)

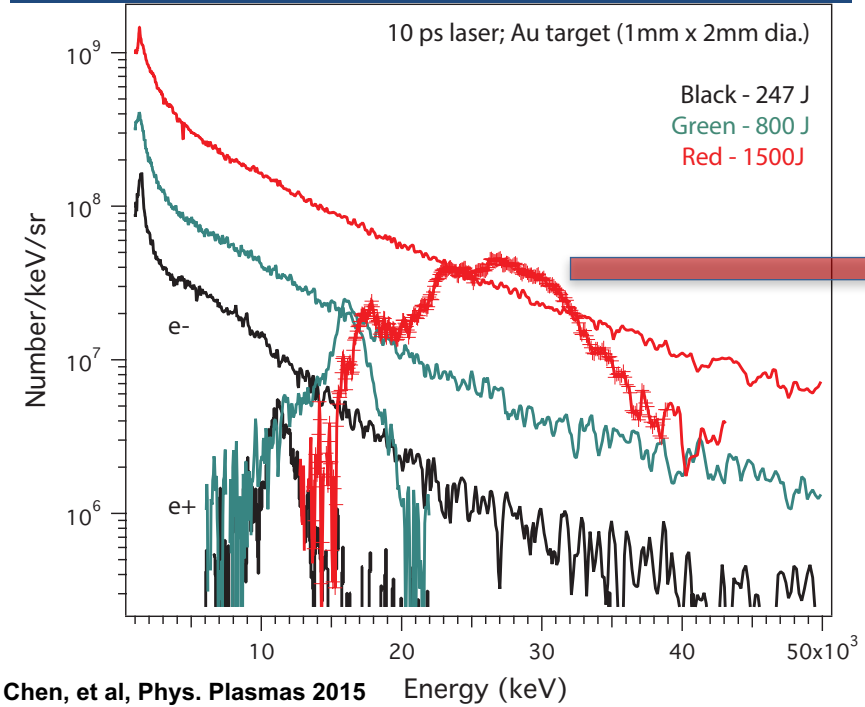
A double-coil system will form a mirror field



Theory and preliminary simulations show that using mirror fields, it is possible to trap MeV electrons and positrons produced from the laser-solid interactions.

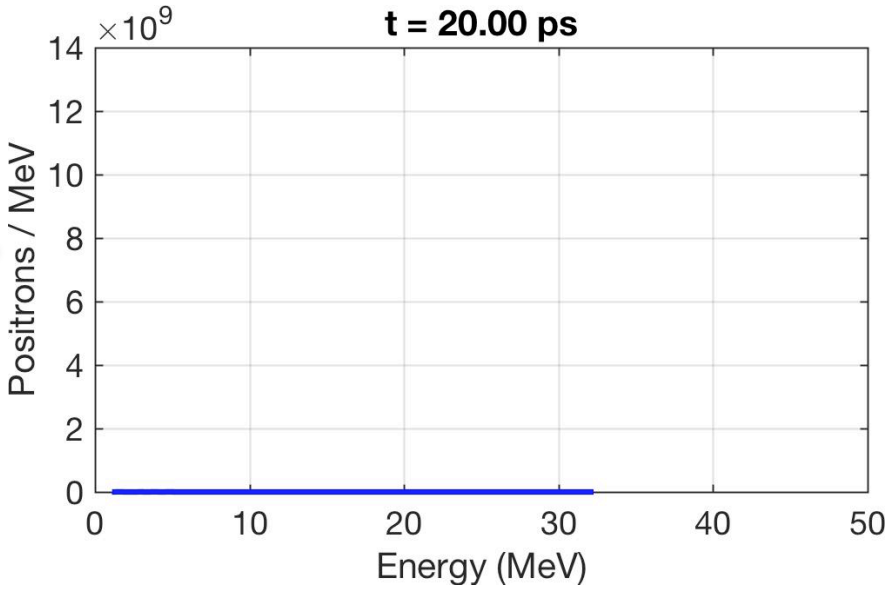
Detailed positron spectrum reveals physics in sheath acceleration

Positron spectra at 3 laser energies



* **Chen, et al, Phys. Plasmas 2015**

Time evolution of the spectrum (LSP)



Shaun Kerr, APS DPP 2017