CHALLENGES OF LABORATORY EXPERIMENTS ON RELATIVISTIC PAIR PLASMAS

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Lawrence Livermore National Laboratory

Relativistic pair jets/plasmas are useful; but there are few questions we need to answer:

- What we are making?
  - Distribution in energy and space; scaling…
- It is a jet, a beam or/and a plasma?
- How dense and and how big a pair jet/plasma should be to make it useful for studying astrophysics problems in the laboratory?
- Any experimental methods that could be used for further development?

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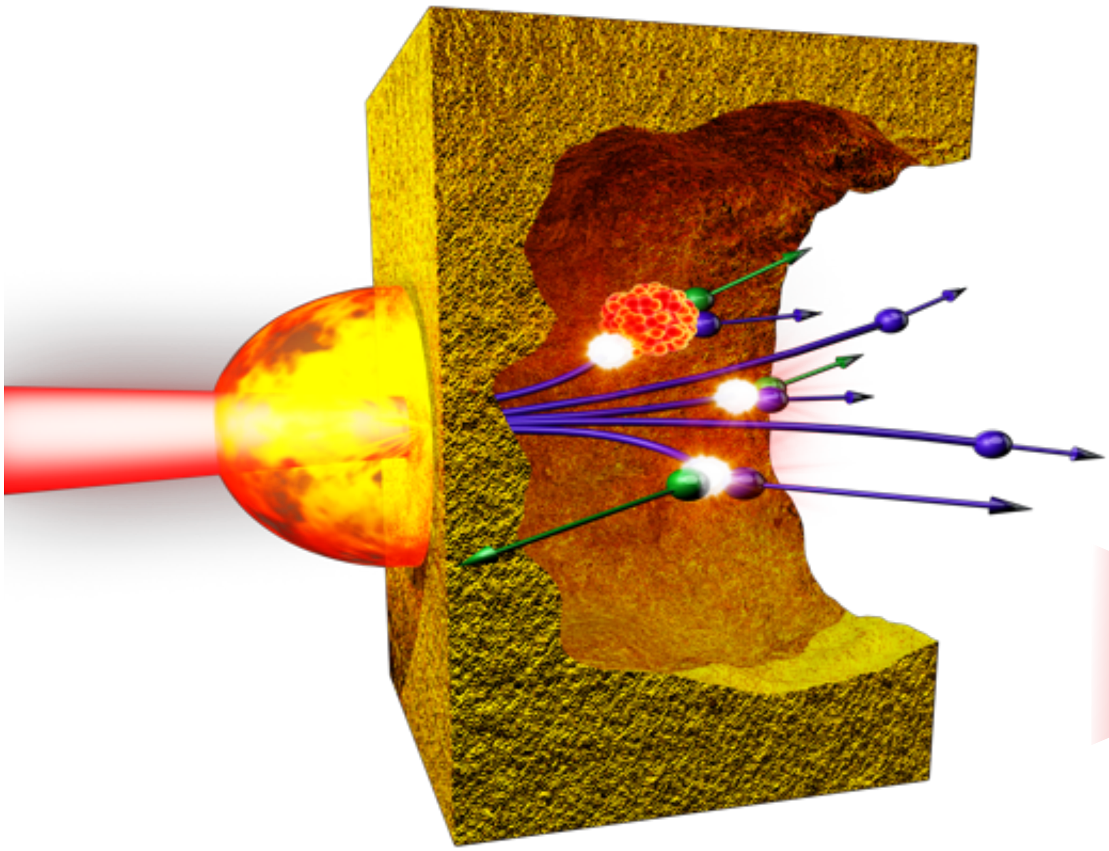
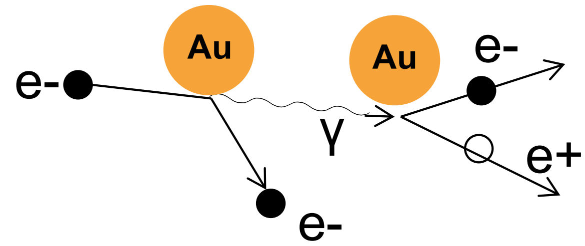
Lasers create positrons through the Bethe-Heitler process using targets with high atomic numbers

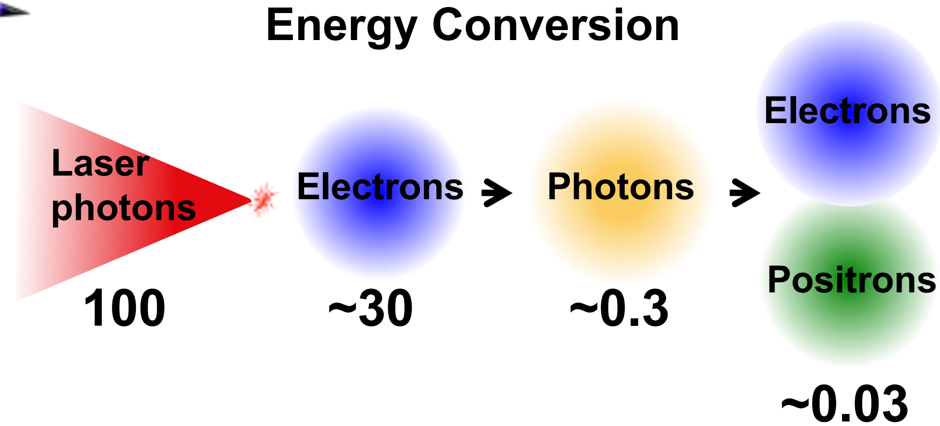


Making positrons using wake-field accelerated electrons:
Gahn et al. (2002), Sarri et al., (2013), Williams et al. (2015)

Bethe-Heitler diagram



Energy Conversion

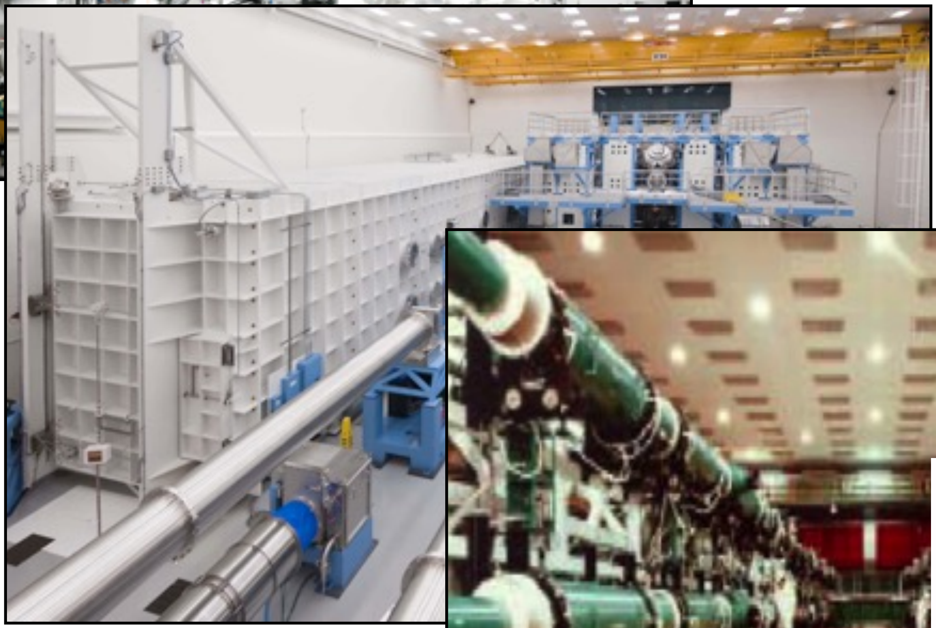


Prior experiment laser produced positrons:
T. Cowan et al., Laser Particle Beams (1999)

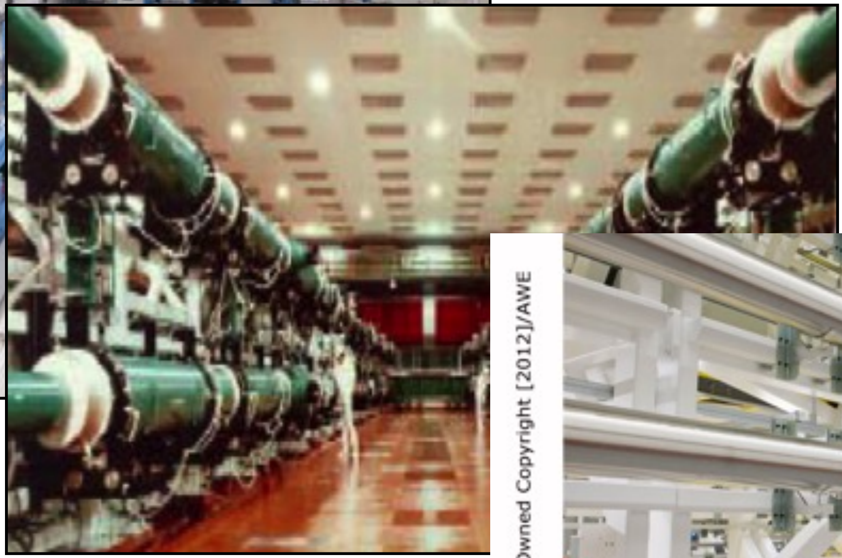
Laser-plasma interactions strongly affect the positrons – this is *unique.*

Experiments were performed on four laser facilities

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



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

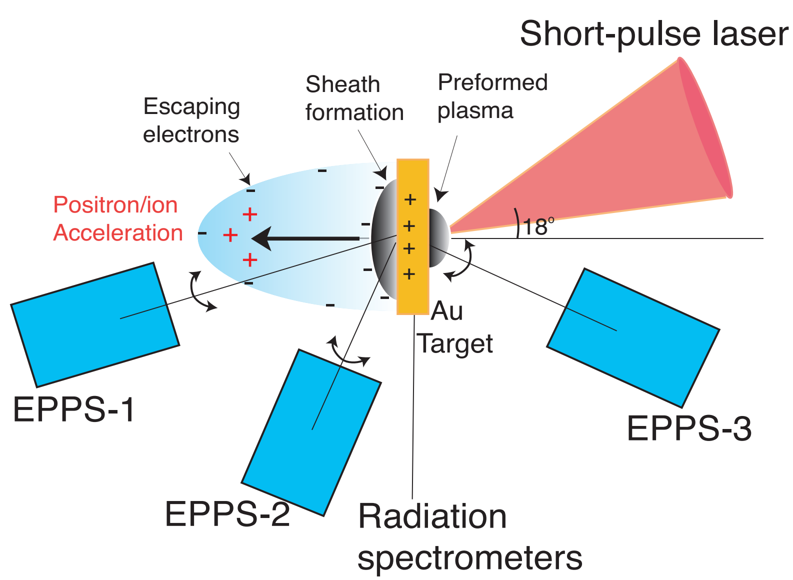


LFEX (ILE)
2-4 beams, 1 ps,
~1 kJ each beam

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

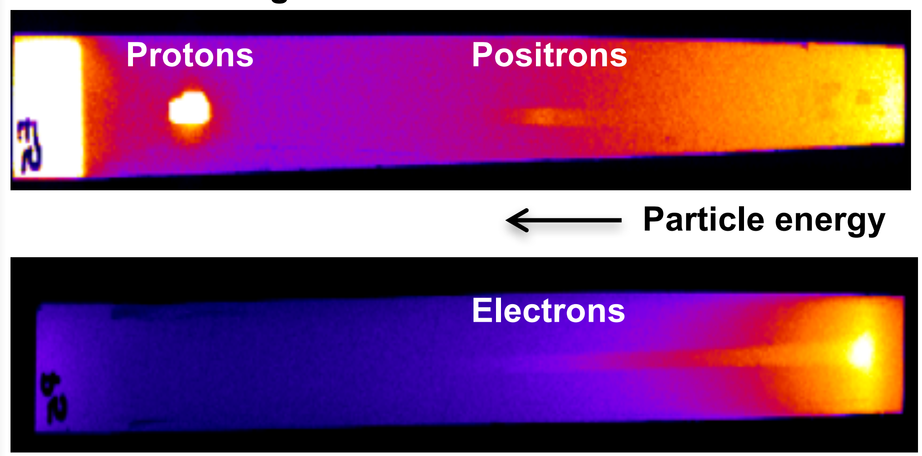
In the experiments, e-, e+, p+ and γ from gold targets were measured by various diagnostics

Experimental setup at Titan



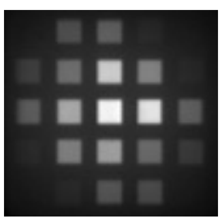
Electron positron proton spectrometer

EPPS raw images

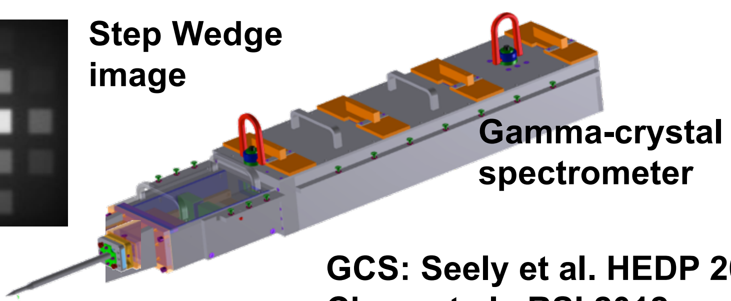


EPPS: Chen, et al., RSI 2008

High-energy gamma diagnostics



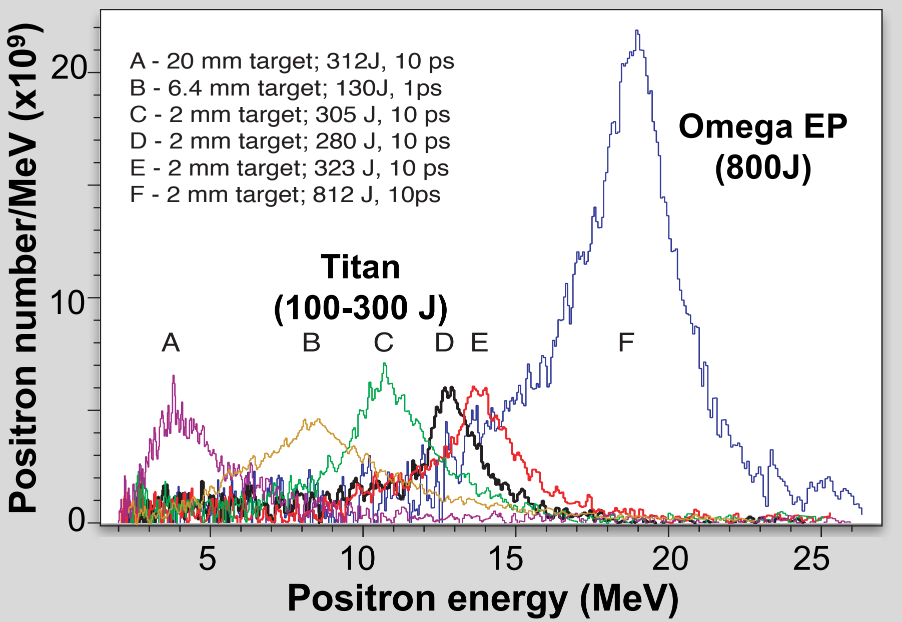
Step Wedge image



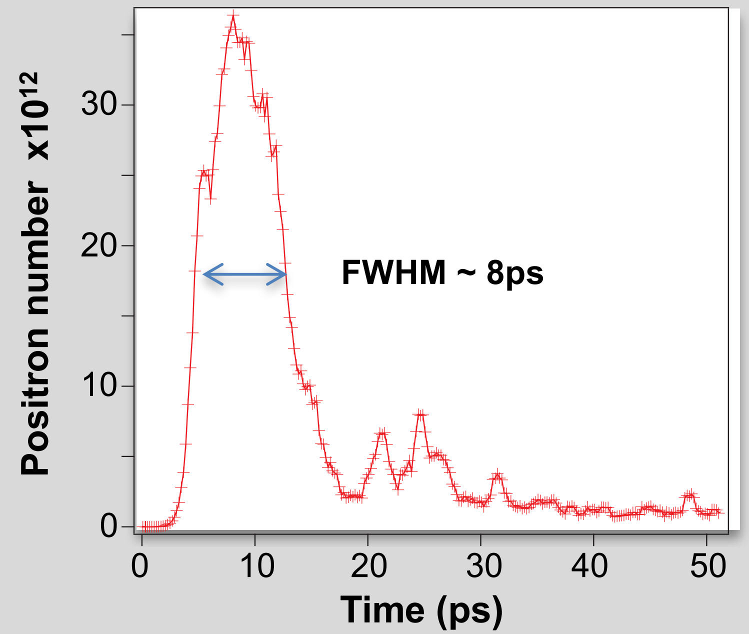
GCS: Seely et al. HEDP 2011
Chen, et al., RSI 2012

Lasers produce high-flux relativistic pairs in a very short time

Titan and Omega EP positron data*



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



* More details see Chen *et al.*, PRL 2009, PRL 2010, HEDP 2011

**Simulations by Tony Link

Pair number: $10^{10} – 10^{12}$ **Peak energy:** 4 - 30 MeV **Flux duration:** ~10 - 100 ps

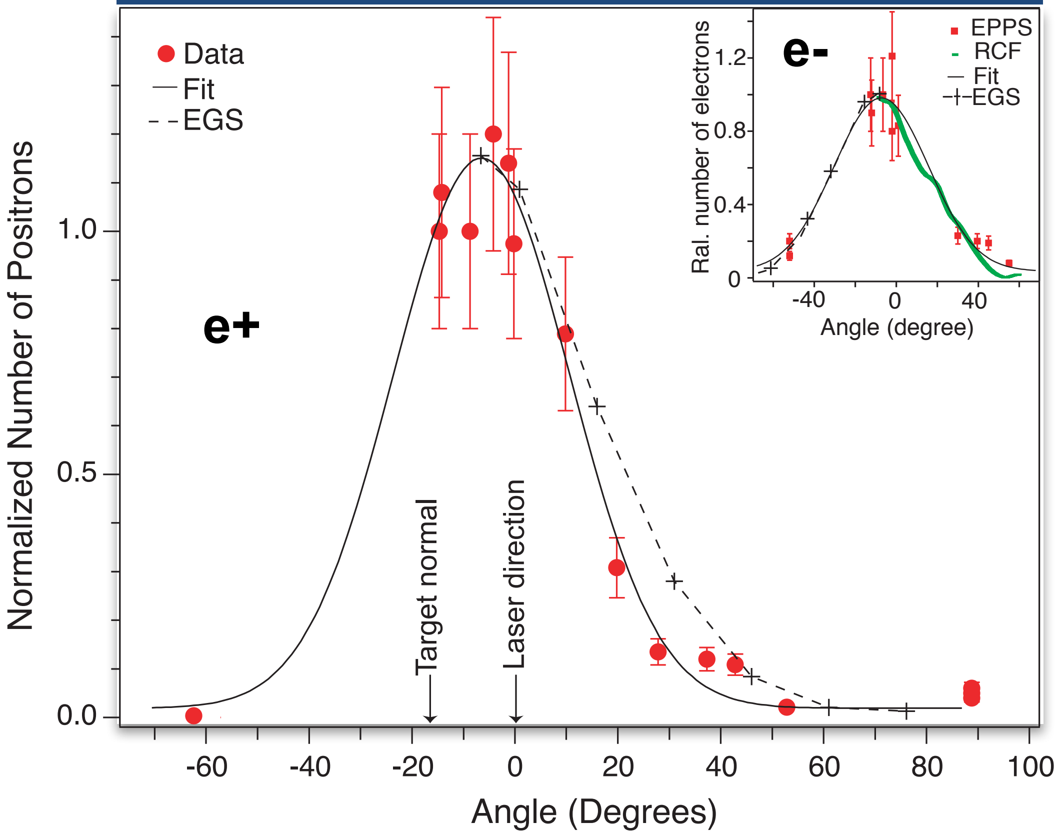
E conversion$>2\times10^{-4}$ **Pair rate:** $\sim10^{22}$ /s **Peak flux:** $>10^{25}$ $cm^{-2}s^{-1}$

In comparison, pair rate of the intense positron source* is about 10^6-10^9 /s.

* C. Hugenschmidt, “Positron sources and positron beams”, Proc. Inter. School of phys. “Enrico Fermi” Course CLXXIV

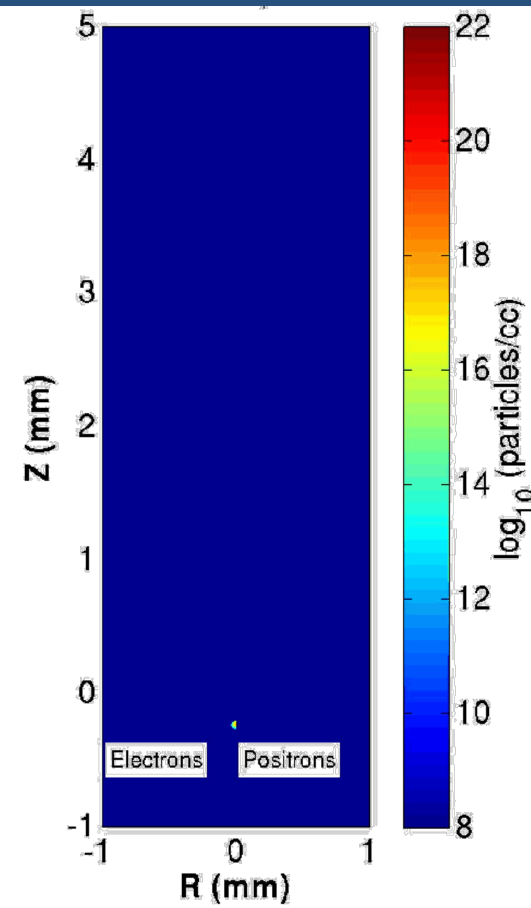
Laser produced relativistic pairs form jets at the back of the target

e+ and e- angular distributions



Chen *et al.*, PRL 2010

Jets simulated by LSP*

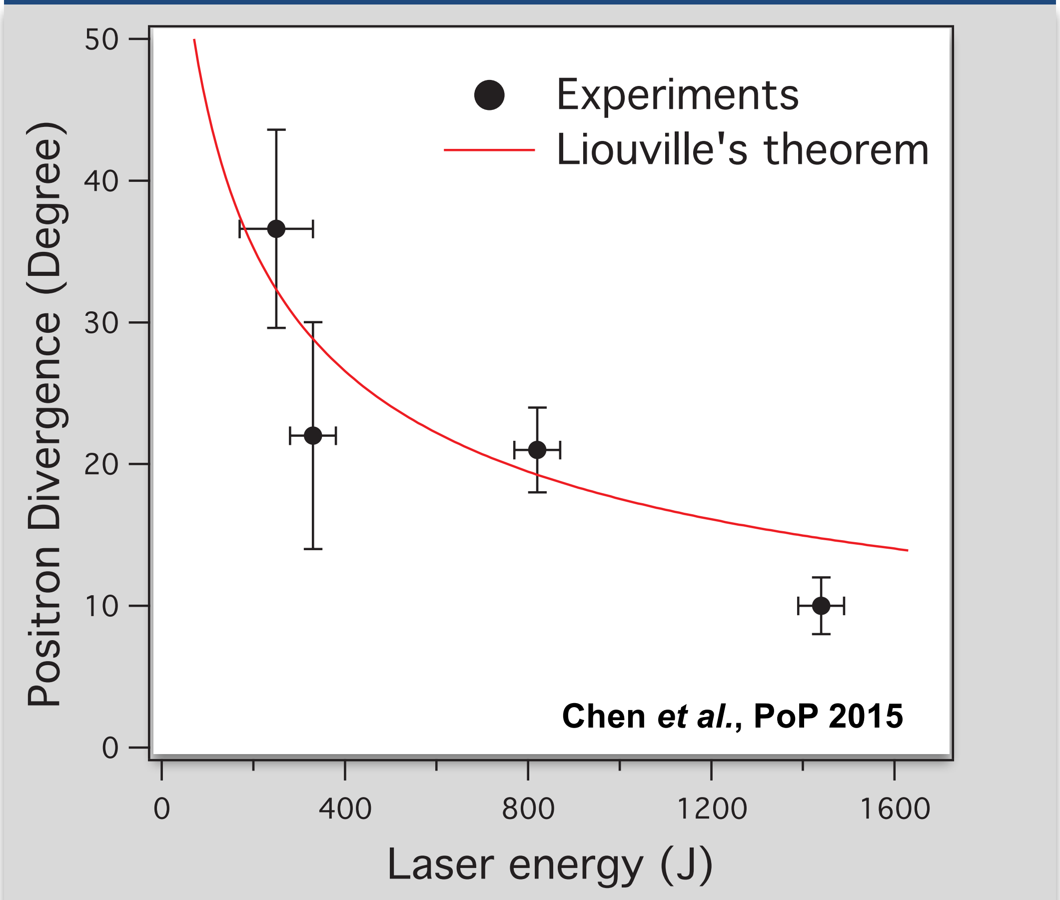


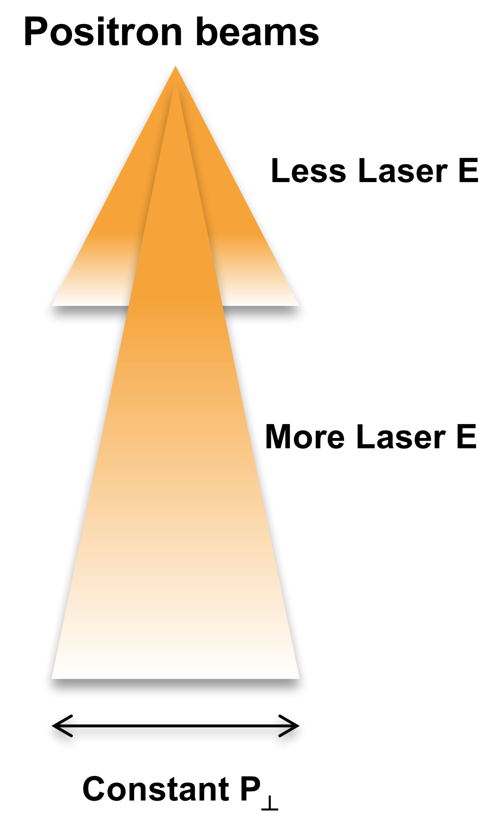
***Tony Link**

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 positron divergence depends inversely on the laser energy, agrees with Liouville's theorem for beam emittance

e+ FWHM angle vs laser E

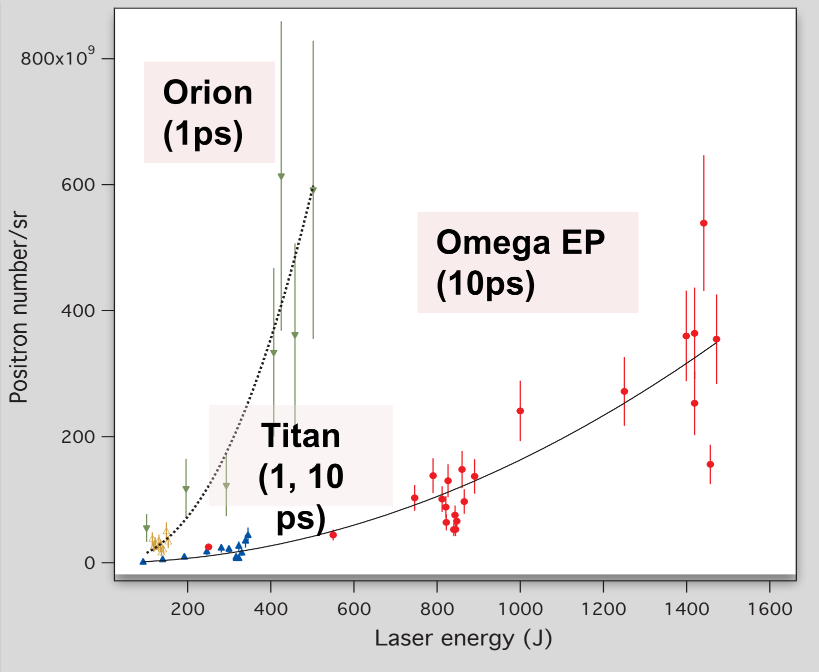




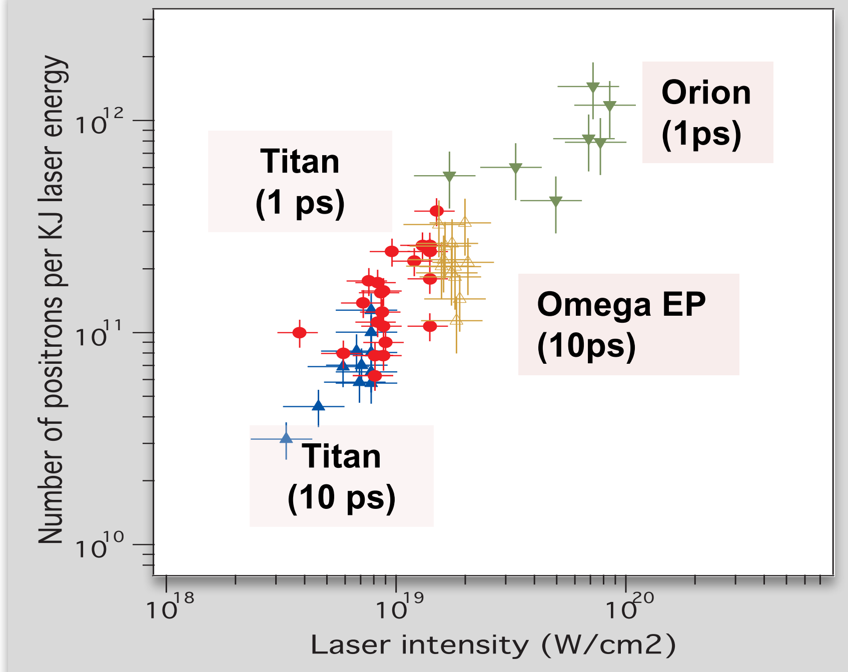
The data indicates that at 10 kJ laser energy, the jet divergence will reduce to 5 degree

This non-linear scaling was found in positron 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 pair jets/plasmas are useful; but there are few questions we need to answer:

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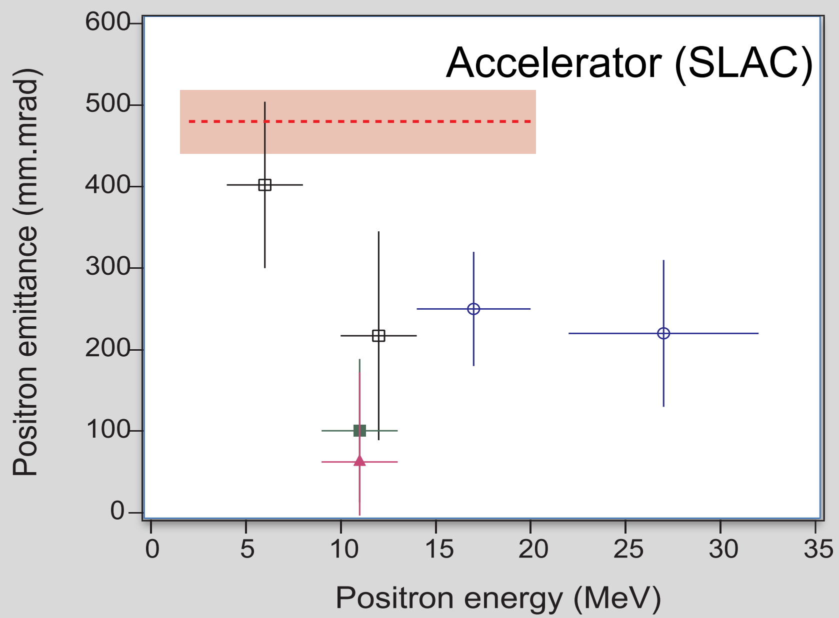
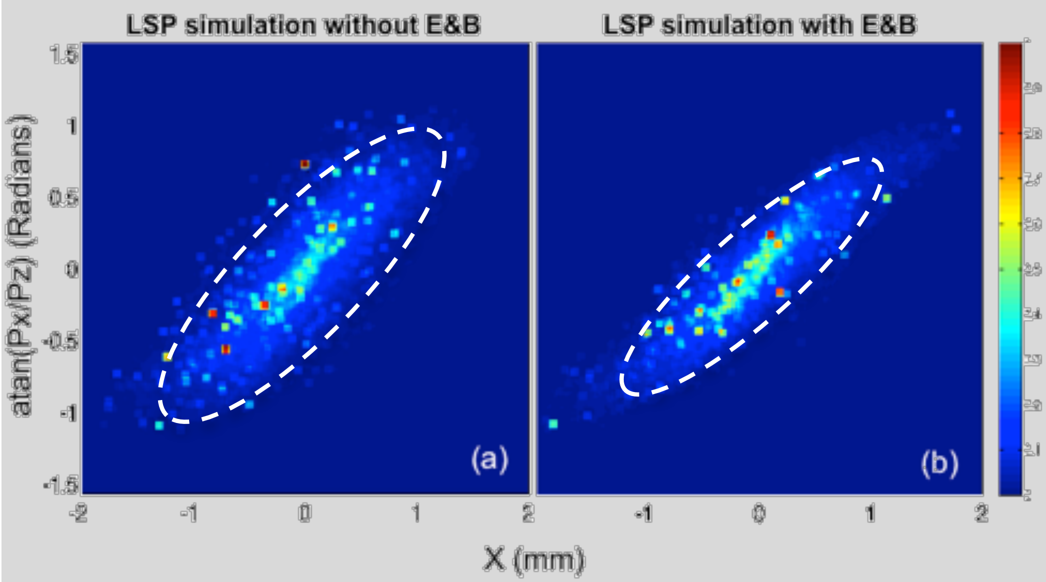
The emittance of laser-positrons is comparable to, or smaller than that obtained on large accelerators

Measured positron emittance



Simulated positron emittance using LSP



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

Chen, Sheppard, Gronberg et al., POP 2013

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

Pair ~~plasma~~ density is derived from the measured pair number and an estimated volume

Sarri, et al., 2015, JPP

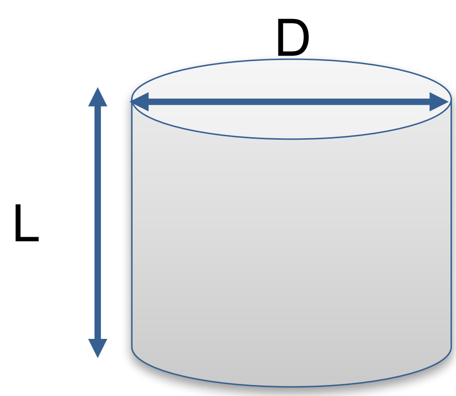
	$E_e{}^+$	$N_e{}^+$ MeV^{-1} Sr^{-1}	τ_{e^+}	θ_{e^+}	n_{e^+}	$n_{e^+}/(n_{e^-}+n_{e^+})$
Gahn et al. (2002)	2	10^4–10^5	0.13	/	/	/
Chen et al. (2009a)	10	10^8	1–10	350	1×10^{14}	5%–10%
Chen et al. (2010)	20	10^{10}	1–10	350	1×10^{13}	1%
Sarri et al. (2013b)	150	5×10^3	0.03	3	2×10^{14}	1%–10%
Sarri et al. (2015)	400	3×10^5	0.04	20	1×10^{17}	0%–50%

		Total number			
Chen et al., (2015)	**20-50**	**10^{12}**	**10**	**10^{14}**	
Liang et al., (2015)	**20 – 40**	**10^{10}**	**0.16**	**10^{13}**	**~50%**

$n = N_{e-/e+}$/Volume

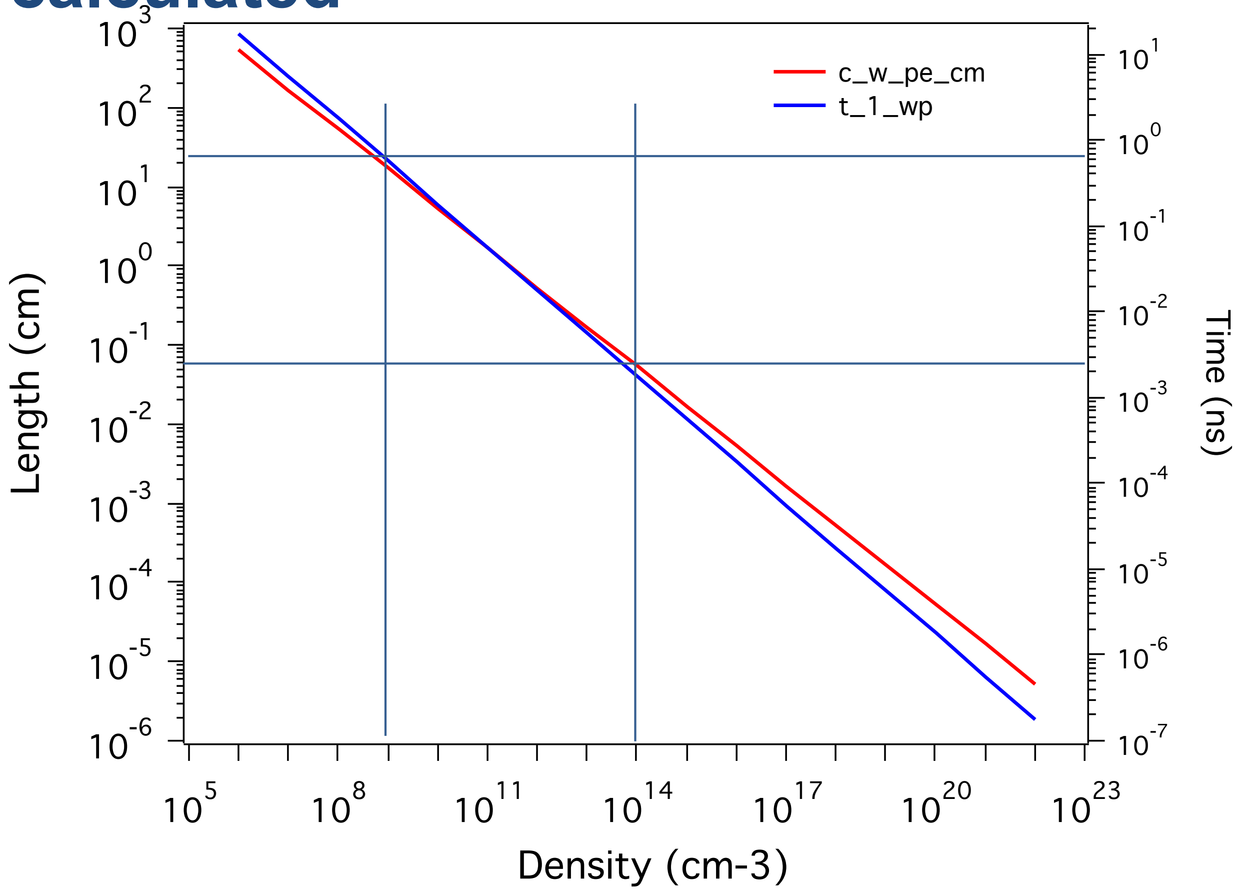
Reported pair ~~plasma~~ volume

Ref	Beam length L ($c*\tau$) in mm	Beam diameter D (mm)	Beam divergence (mrad)	Volume (cm^3)
Chen et al. 2015	**0.3 – 3**	**0.2**	~300	~1e-5 to 1e-4
	0.03	**0.4**	-	~1e-6
	~0.01	**0.2**	~3	~1e-7



Volume $= L * \pi (D/2)^2$

For a given density, the "skin depth" and plasma frequency can be calculated



For a pair density of 10^14 /cc, one need to meet the following as a "plasma":

Spatial scale: $L \gg c/\omega_p$ → a plasma size > 1 mm
Time scale: $t \gg 1/\omega_p$ → a time scale > 1 ps

Lasers-produced pair jets are approaching those needed for lab astro. experiments

Parameter	Exp. Value*	Desired for astro. relevant exp.**	
$T_{//}$	0.5 - 4 MeV	~ MeV	✔
$T_{\perp}$	0.2-1 MeV	~ MeV	✔
n_{e+}	$\sim 10^{11\text{-}13}$ cm^{-3}	$>10^{14\text{-}16}$ cm^{-3}	
n_{e-}	$\sim 10^{12\text{-}15}$ cm^{-3}	$>10^{14\text{-}16}$ cm^{-3}	✔
τ_{Jet}	5 – 30 ps	10-100 ps	✔

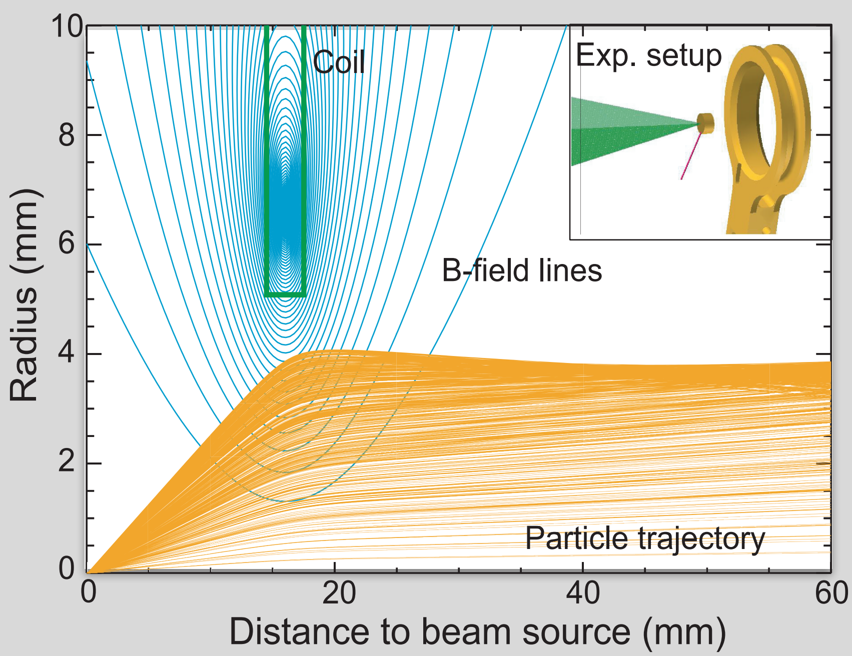
*Chen, et al. PRL 2010; HEDP 2011; POP 2014

**Fiuza et al., in preparation

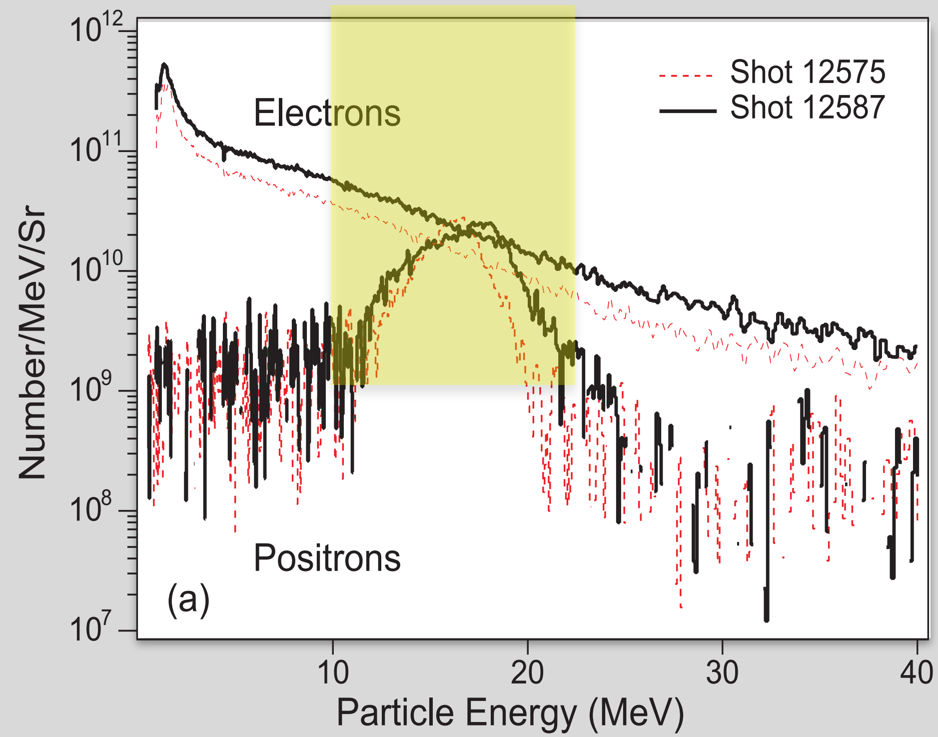
The most obvious needs are to (1) increase the density of the pair jets and (2) reduce the electron/positron density ratio.

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

MIFEDS setup on OMEGA EP



e- & e+ spectra before collimation



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

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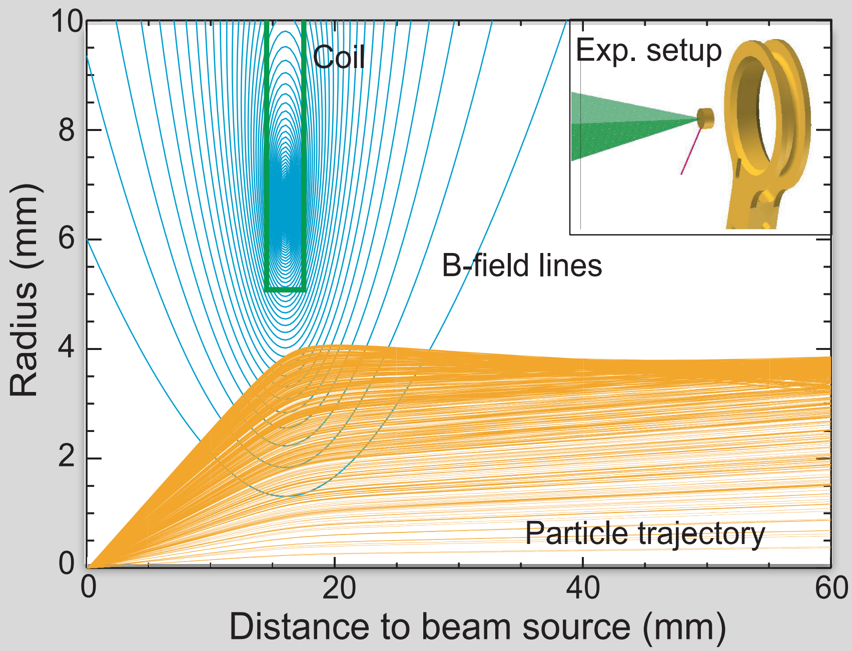

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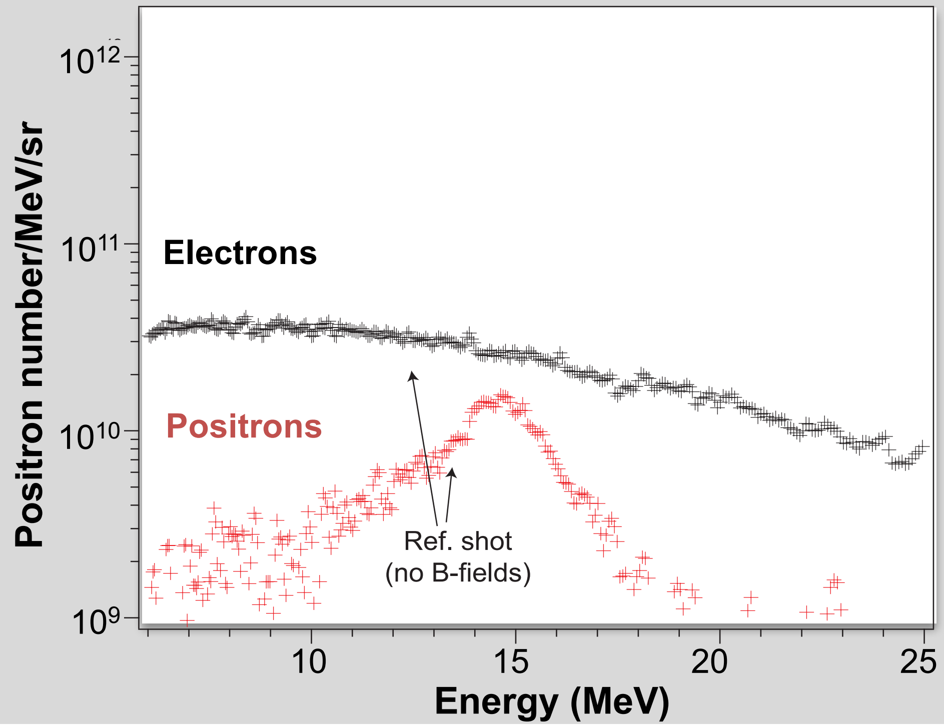

Chen, Fiksel, Barnak, et al., POP 2014

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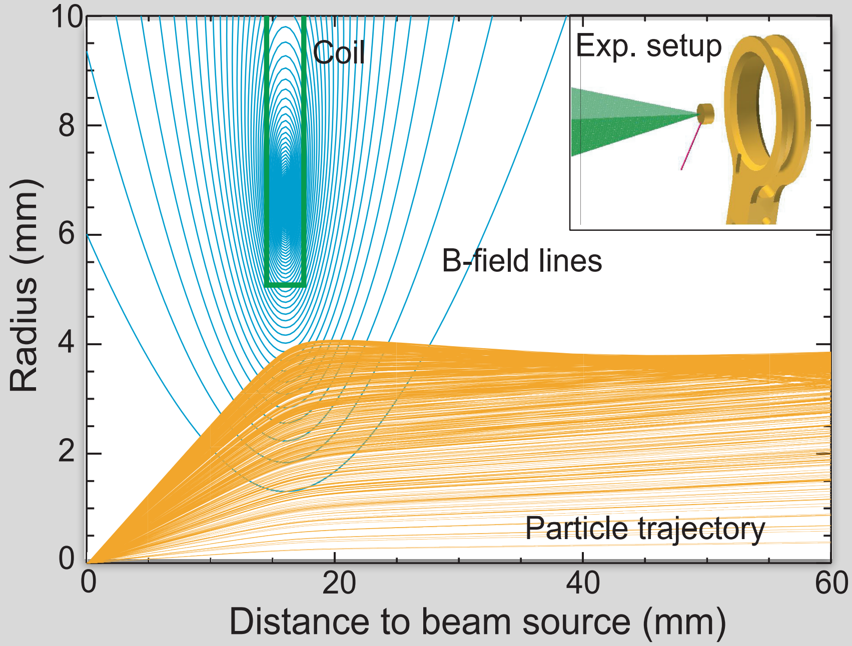
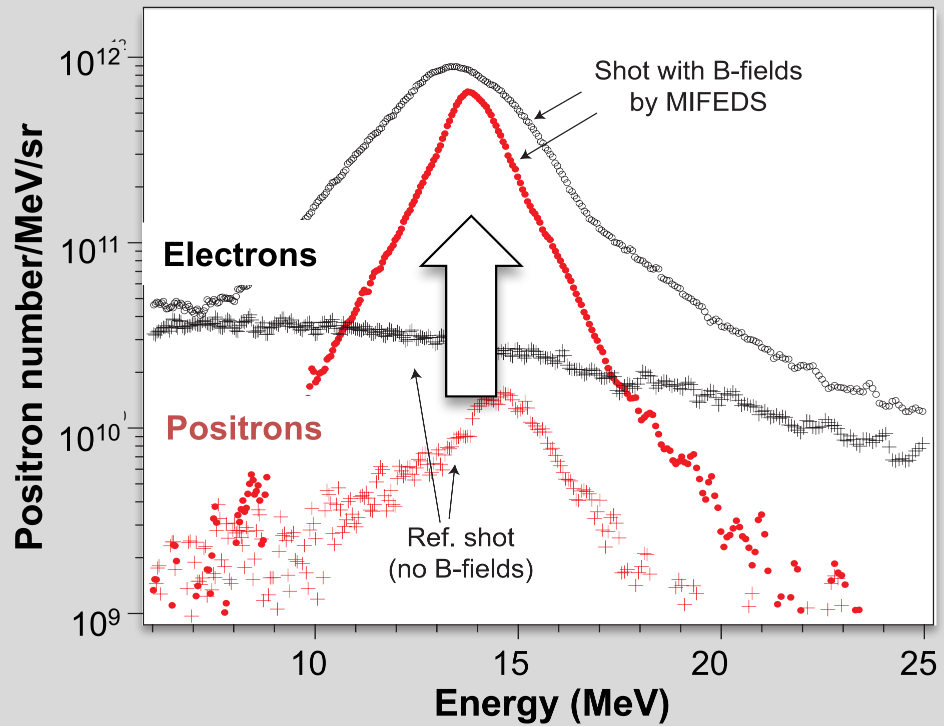


e- & e+ spectra after collimation



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.

Relativistic pair jets/plasmas are useful; but there are few questions we need to answer:

- What we are making?
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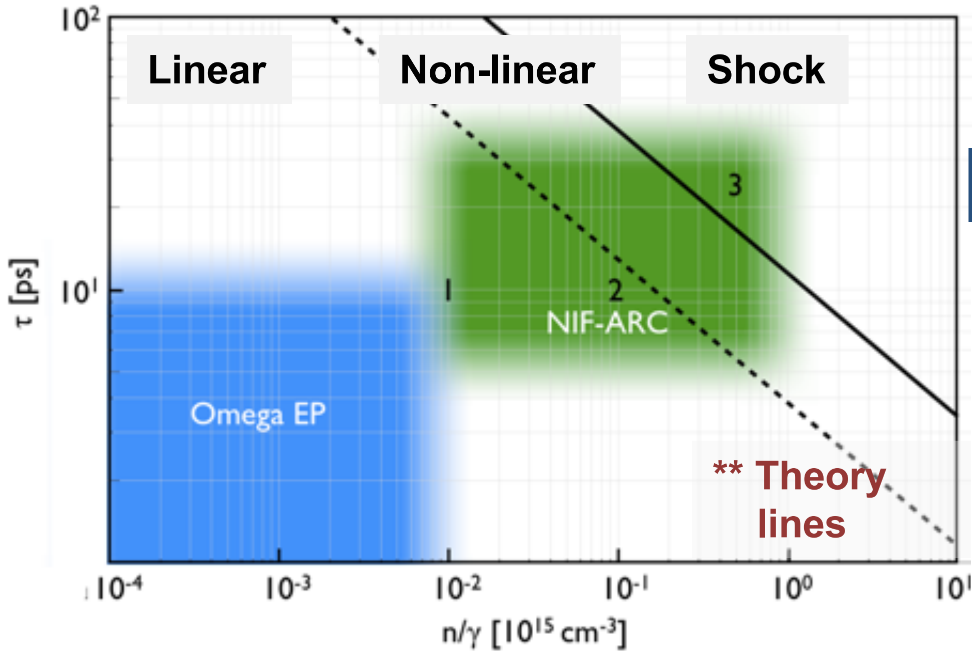
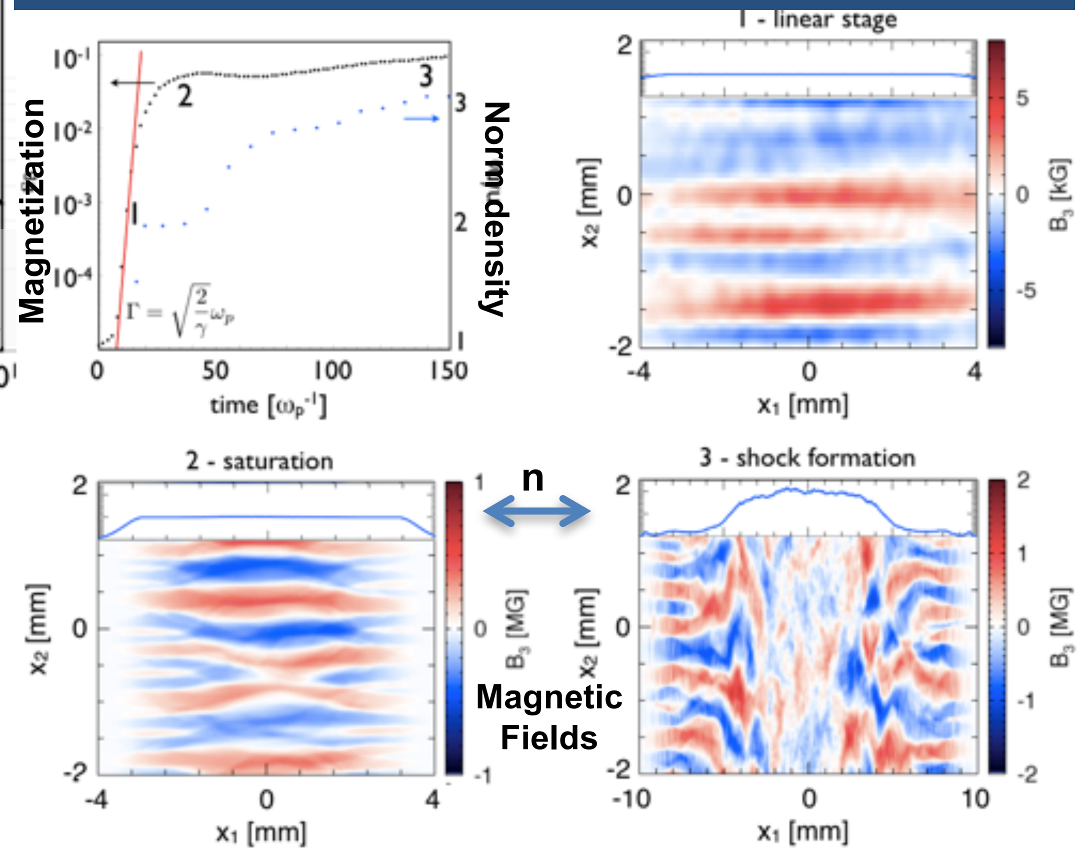
Laser-produced pair interactions can access the formation of astrophysical-relevant relativistic shocks in the lab

Relativistic shocks can be probed in the lab*



Experimental setup

Detailed study of rel. shock formation process*



* Simulations by F. Fiuza (in preparation)

** A. Bret, et al., PoP 2013, 2014

Pair plasma parameters needed for laboratory astrophysics experiments??

Spatial scale: $L >> c/\omega_p$

Time scale: $t >> 1/\omega_p$

For example in the PIC simulation by Caprioli & Spitkovsky 2014:

$L \sim (500 – 5000)*(c/\omega_p)$

$t*\omega_p \sim 200$

Pair plasma parameters needed for other laboratory astrophysics experiments??

Magnetic reconnection?

Relativistic pair jets/plasmas are useful; but there are few questions we need to answer:

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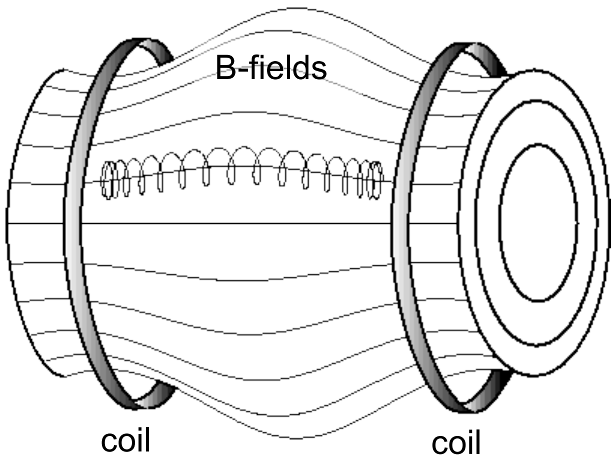
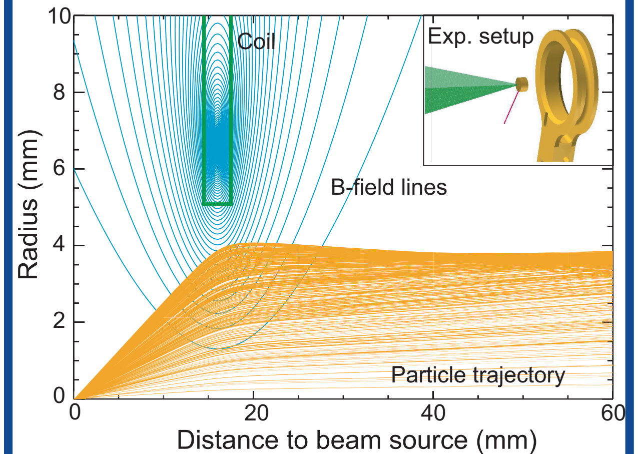
A relativistic pair plasma by pair confinement?

In theory mirror machine works for both charges



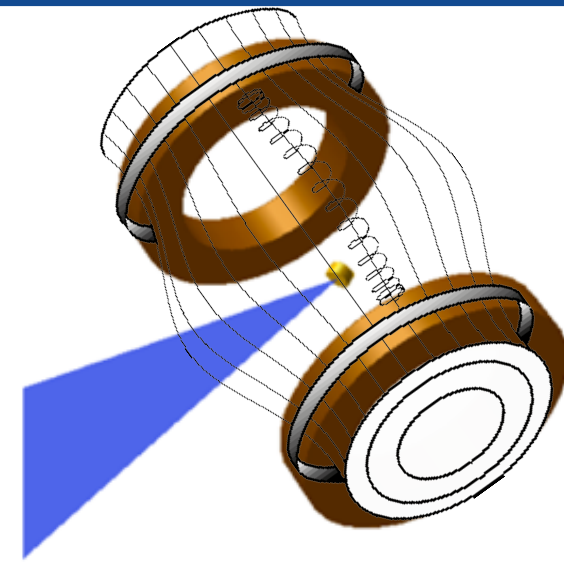
Gibson et al, PRL 1960
Pedersen et al, J. Phys. B 2003
Myatt, et al, PRE 2009

The first step: one coil has been demonstrated



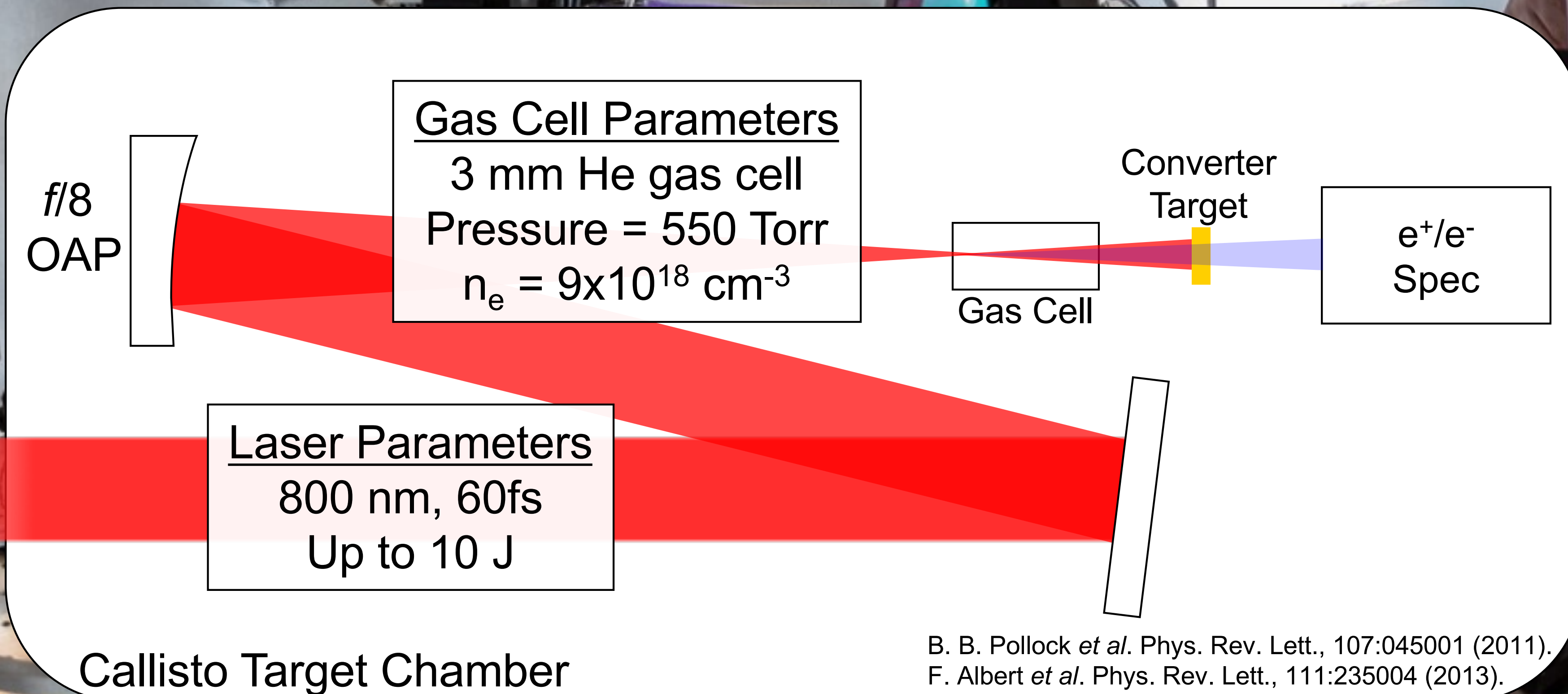
Chen et al. PoP (2014)

A double-coil system will form a mirror field



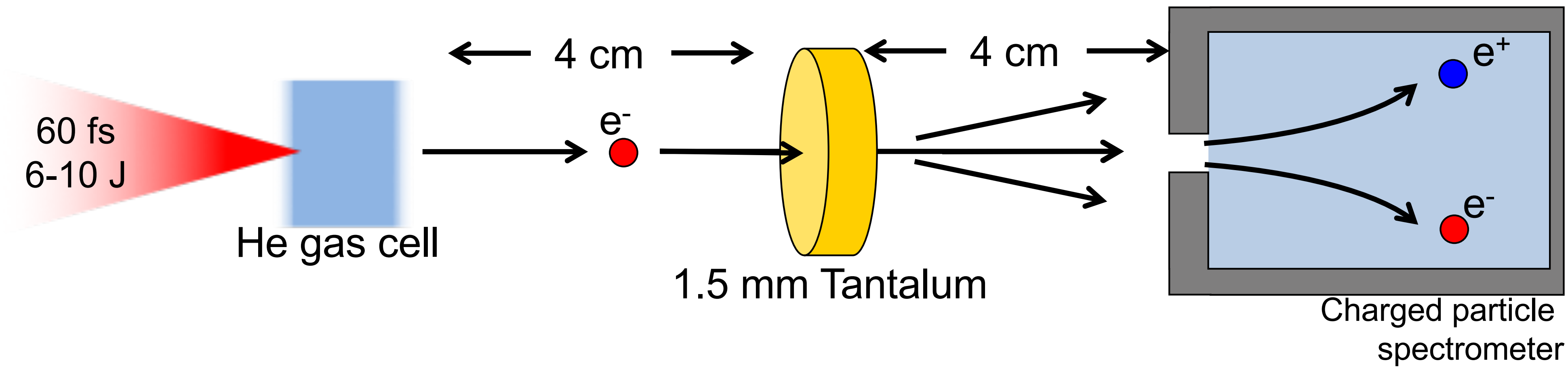
Theory and preliminary simulations show that using mirror fields, it is possible to trap MeV electrons and positrons produced from the laser-solid interactions.

We also tried wake-field driven pair production experiments using LLNL Callisto laser



B. B. Pollock *et al*. Phys. Rev. Lett., 107:045001 (2011).
F. Albert *et al*. Phys. Rev. Lett., 111:235004 (2013).

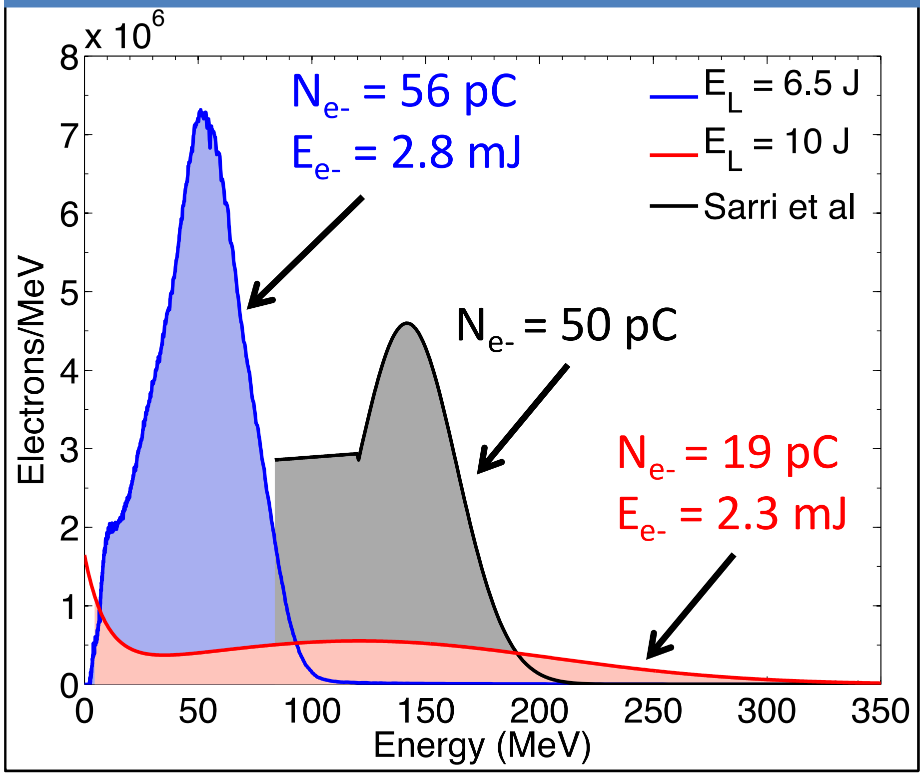
Electrons were accelerated and driven into a converter target to produce positrons



Detailed results were published on the Physics of Plasmas by G. J. Williams, et al. in 2015

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

Initial Electron Distributions

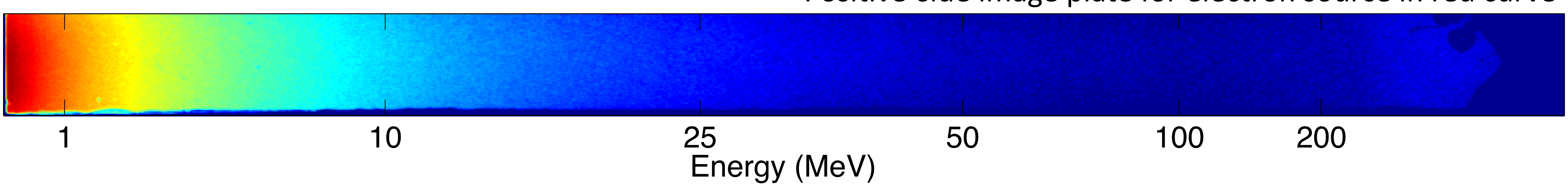


Hoped to see positron signal since charge and electron beam energy were similar to previous studies (Sarri, *et al.* PRL, 2013)

Why?

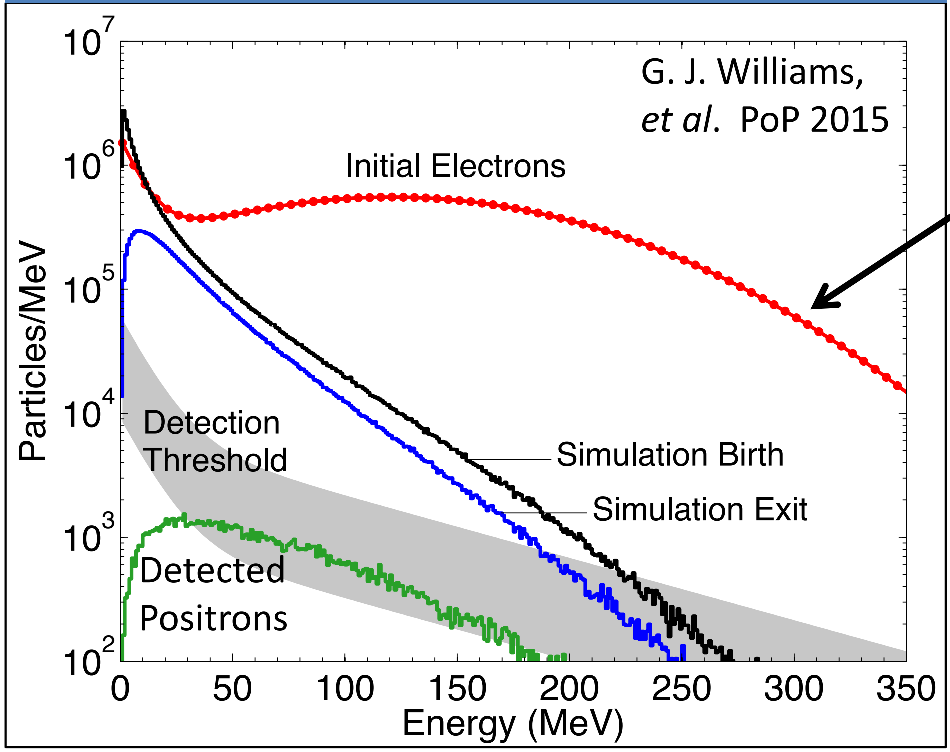
Geant4 modeling may provide explanation of null result

Positive-side image plate for electron source in red curve



Monte Carlo simulations show positron generation was below noise threshold

Upper bound electron source

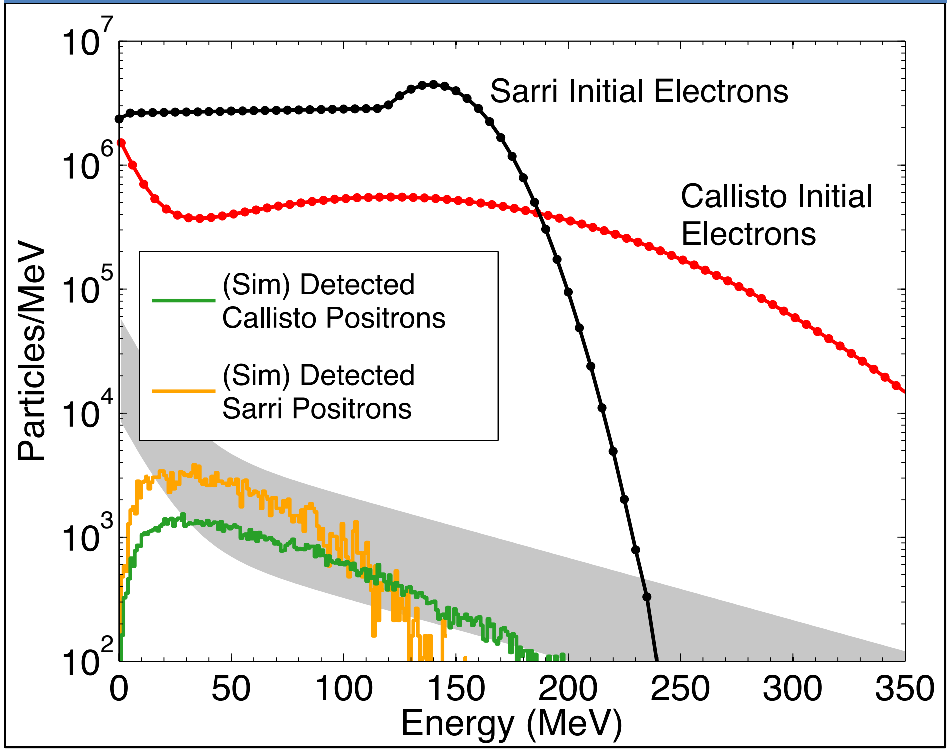


Experimental electrons
N_{e-} = 19 pC
E_{e-} = 2.3 mJ

Lower background noise or better detection efficiency is required to resolve positron signals for these electron sources

Using higher current, Sarri *et al,* electron source does not overcome our detection threshold

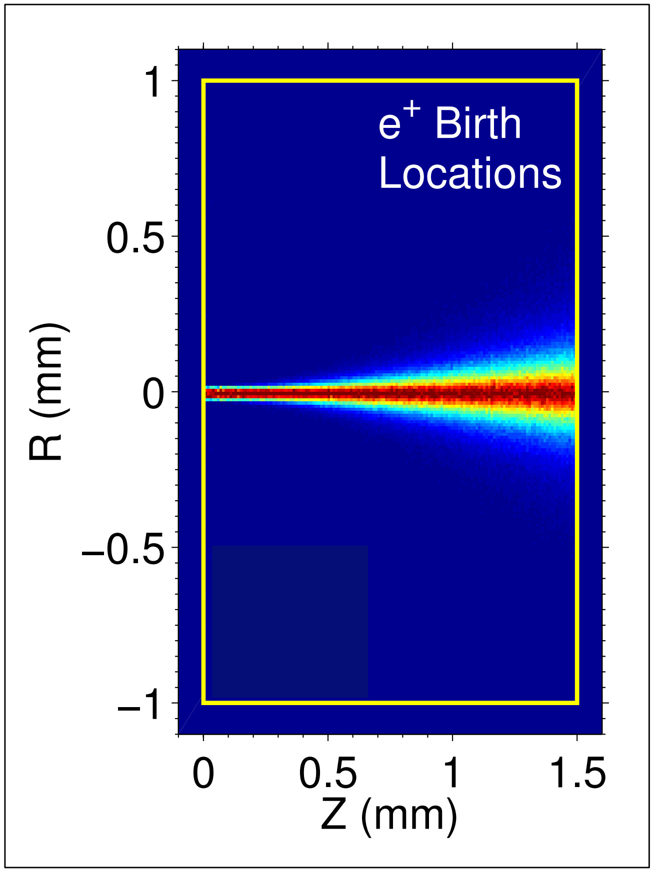
Upper bound electron source

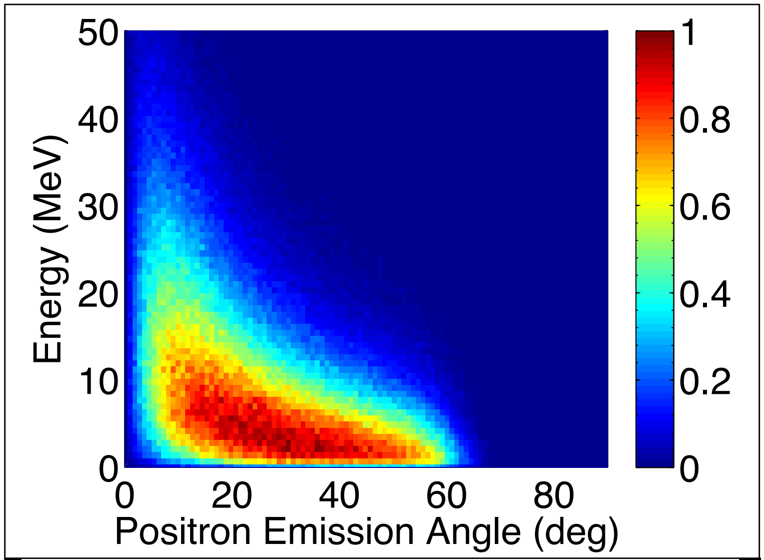


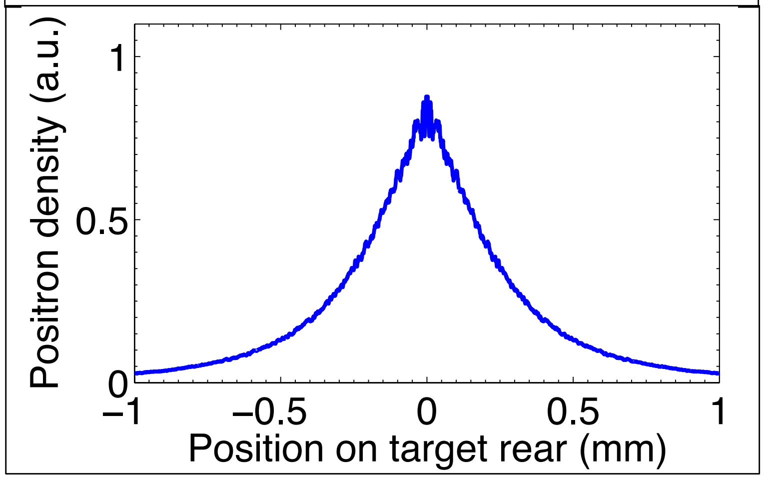
Most positrons are emitted into high angles and do not reach the detector

The issue is that positrons quickly lose energy and diverge in the target

G. J. Williams,
et al. PoP 2015







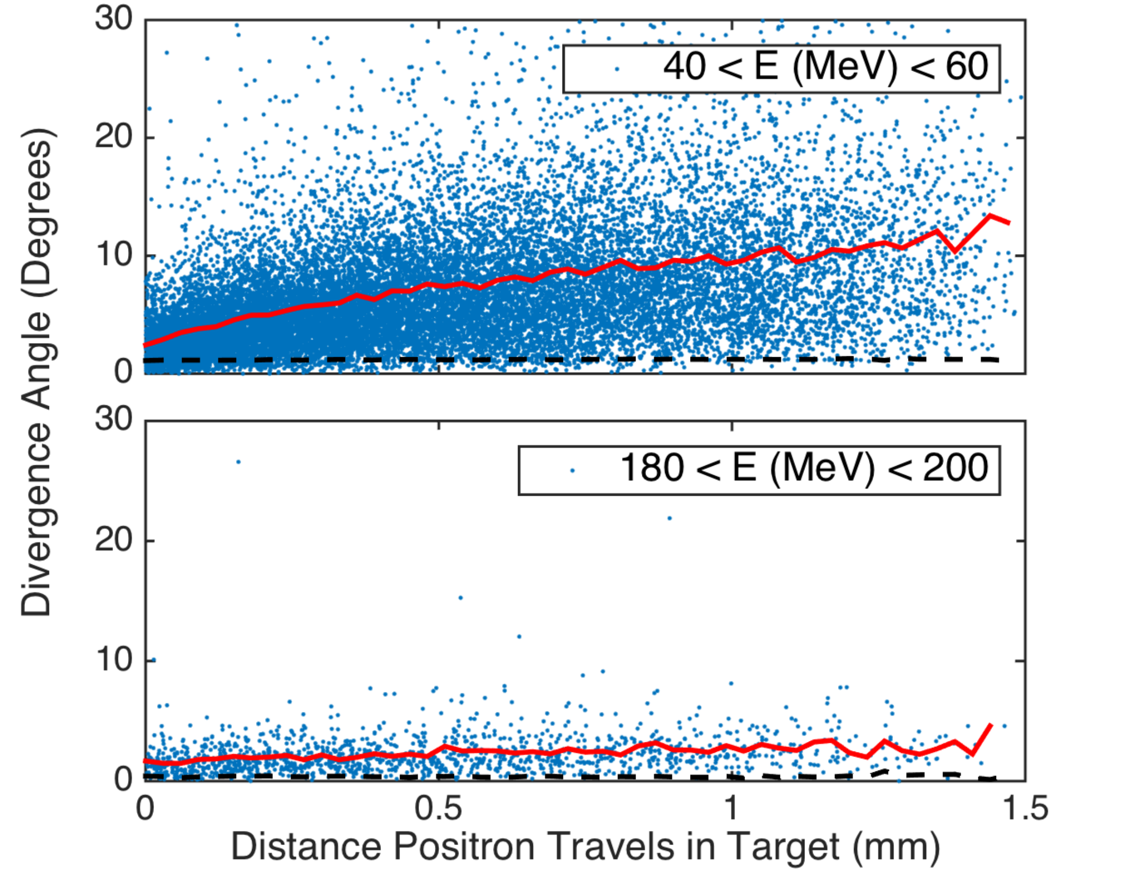
Even for a collimated electron beam, positrons are emitted into large angles

Beam divergence is dominated by Coulomb scattering

G. J. Williams,
et al. PoP 2015

Divergence angle of a few degrees for high energy positrons

Energy-Resolved Divergence of Emitted Positrons



Initial electron divergence from LWFA sources is a negligible contribution

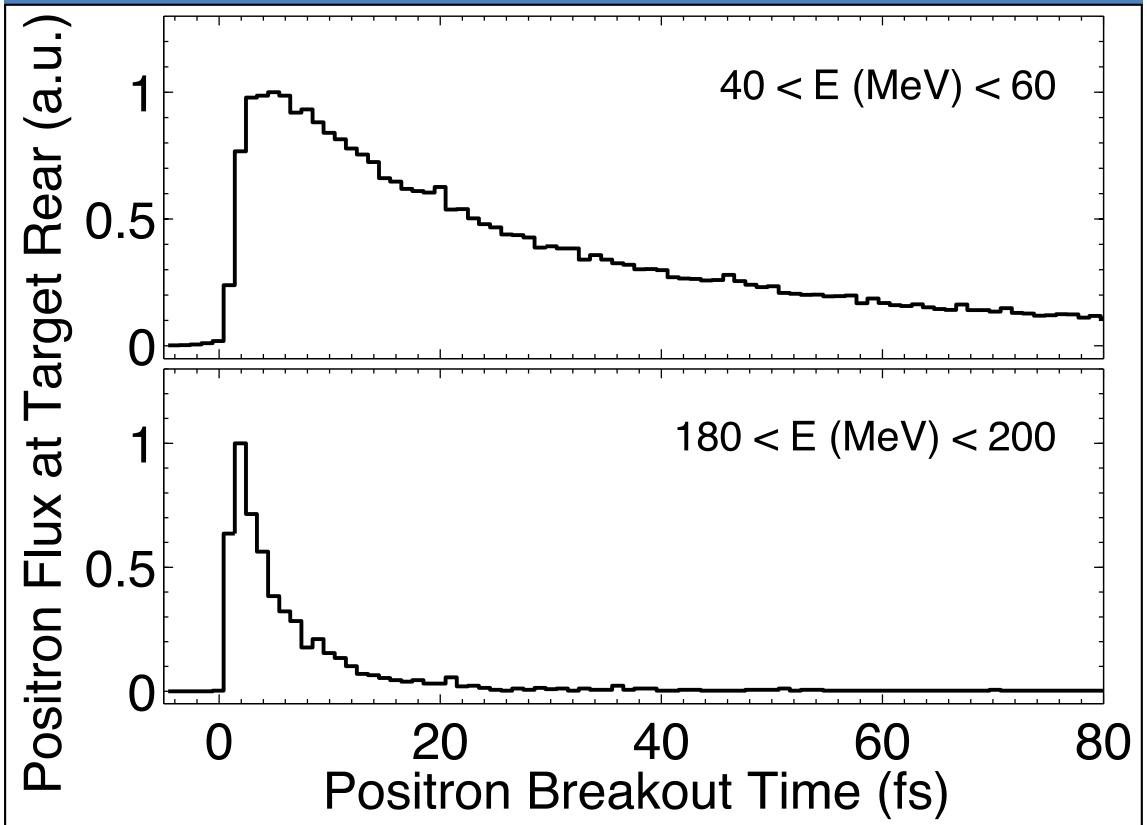
Straggling inside the target creates a chirped positron beam

Pulse duration of positrons can be significantly longer than electron source

- $\tau_{e-} \approx 10$ fs
- $\tau_{e+} = 13\text{-}50$ fs

G. J. Williams, *et al*. PoP 2015

Time history of positron emission



Maximum positron density is at rear surface = 4×10^{13} cm^{-3}.

Conclusion: I need your help and discussion to answer these questions…

- ✓ What we are making?
  - Distribution in energy and space; scaling…
- ➢ It is a jet, a beam or/and a plasma?
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Thank you!

Acknowledgement

Collaborators*:

F. Fiuza, J. Sheppard ***- SLAC***

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

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