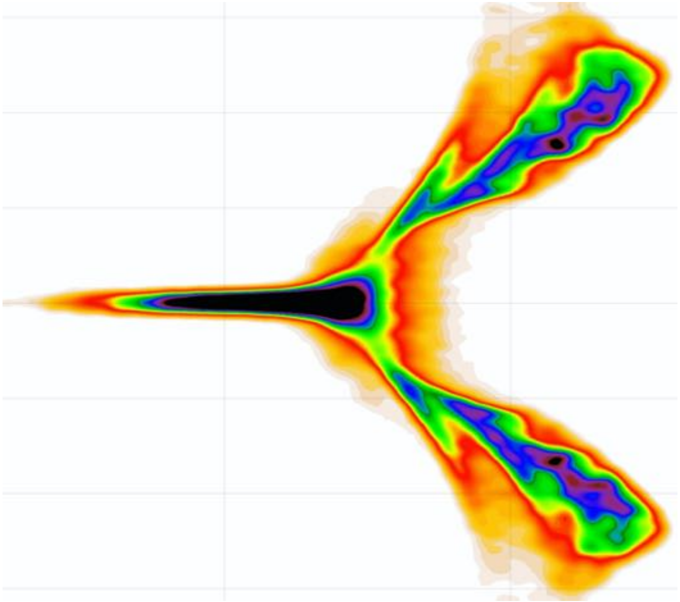
Tunable Laser Positron Source

A. Sahai (PI), V. Harid, M. Golkowski, University of Colorado
J. Cary, Tech-X, A. Thomas, Michigan,
S. Palaniyappan, LANL, H. Chen, LLNL
T. Tajima, UCI, V. Shiltsev, Fermilab



22nd Accelerator Test Facility (ATF) Users' Meeting
December 3-5, 2019 - Brookhaven National Laboratory

Funding source: DOE / NSF
Funding status: proposed

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Key Scientific Questions

- Can **tunable positron beams** be produced using laser wakefield accelerators ?

- Is it possible to **control the interaction** between
  ultrashort *positron-electron jets / showers* and *laser wakefield* plasma wave ?

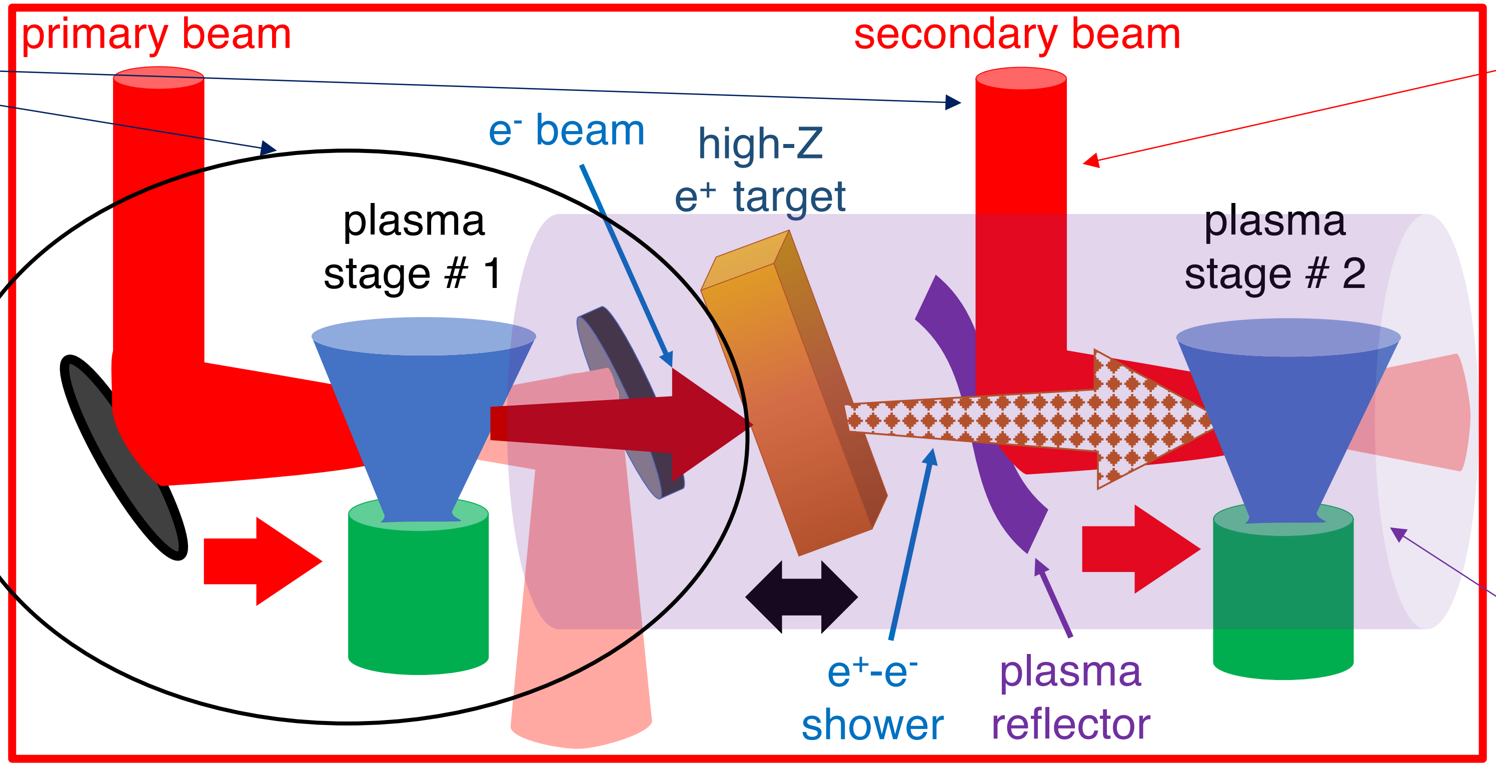
- What are the limits of the **range of tunability** of laser produced positron beams ?

- Which applications can benefit from an unprecedented ultrashort positron beam ?

BNL-ATF - Tunable Laser Positron Source

BNL-ATF
stable
synchronized
e-beam & CO_2 laser

BNL-ATF
sub-picosecond
1-5 Joule
CO_2 laser pulse



BNL-ATF
sub-picosecond
Nano-Coulomb
75 MeV e-beam

BNL-ATF
many Tesla
Superconducting
magnet

BNL-ATF laser, plasma and particle diagnostics

PHYSICAL REVIEW ACCELERATORS AND BEAMS **21,** 081301 (2018)

Quasimonoenergetic laser plasma positron accelerator using particle-shower plasma-wave interactions

Aakash A. Sahai*

Department of Physics and John Adams Institute for Accelerator Science, Blackett Laboratory, Imperial College London, SW7 2AZ, United Kingdom

Channeled Annihilation γ Imaging

PHYSICAL REVIEW B VOLUME 3, NUMBER 3 1 FEBRUARY 1971

Channeling of Positrons

J. U. Andersen* and W. M. Augustyniak
Bell Telephone Laboratories, Murray Hill, New Jersey 07974
and
E. Uggerhøj
Institute of Physics, University of Aarhus, 8000 Aarhus C, Denmark
(Received 7 July 1970)

IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979

CHANNELING RADIATION FROM POSITRONS

M. J. Alguard,* R. L. Swent,* R. H. Pantell,* B. L. Berman,† S. D. Bloom,† and S. Datz††

VOLUME 77, NUMBER 10 PHYSICAL REVIEW LETTERS 2 SEPTEMBER 1996

Increased Elemental Specificity of Positron Annihilation Spectra

P. Asoka-Kumar,[1] M. Alatalo,[1] V. J. Ghosh,[1] A. C. Kruseman,[2] B. Nielsen,[1] and K. G. Lynn[1]
[1]*Brookhaven National Laboratory, Upton, New York 11973*
[2]*IRI, Delft University of Technology, Mekelweg 15, NL-2629JB Delft, The Netherlands*

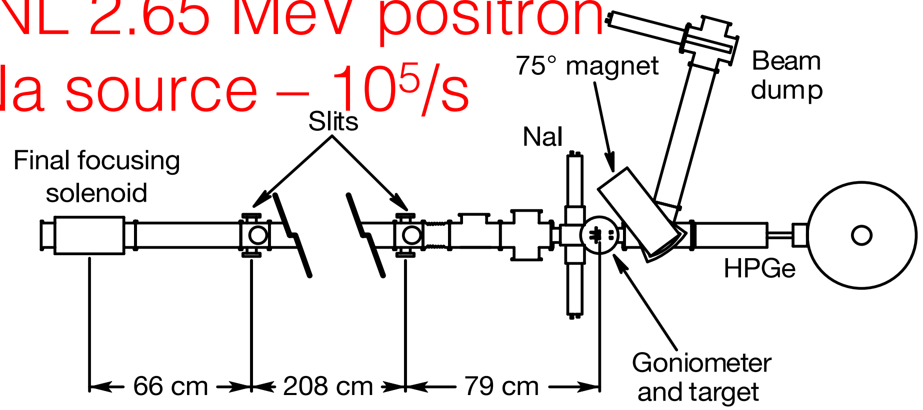
Spatial sampling of crystal electrons by in-flight annihilation of fast positrons

A. W. Hunt*†, D. B. Cassidy*†, F. A. Selim‡, R. Haakenaasen§, T. E. Cowan†, R. H. Howell†, K. G. Lynn‖ & J. A. Golovchenko*¶#

NATURE | VOL 402 | 11 NOVEMBER 1999

LLNL 2.65 MeV positron

^{22}Na source – 10^5/s



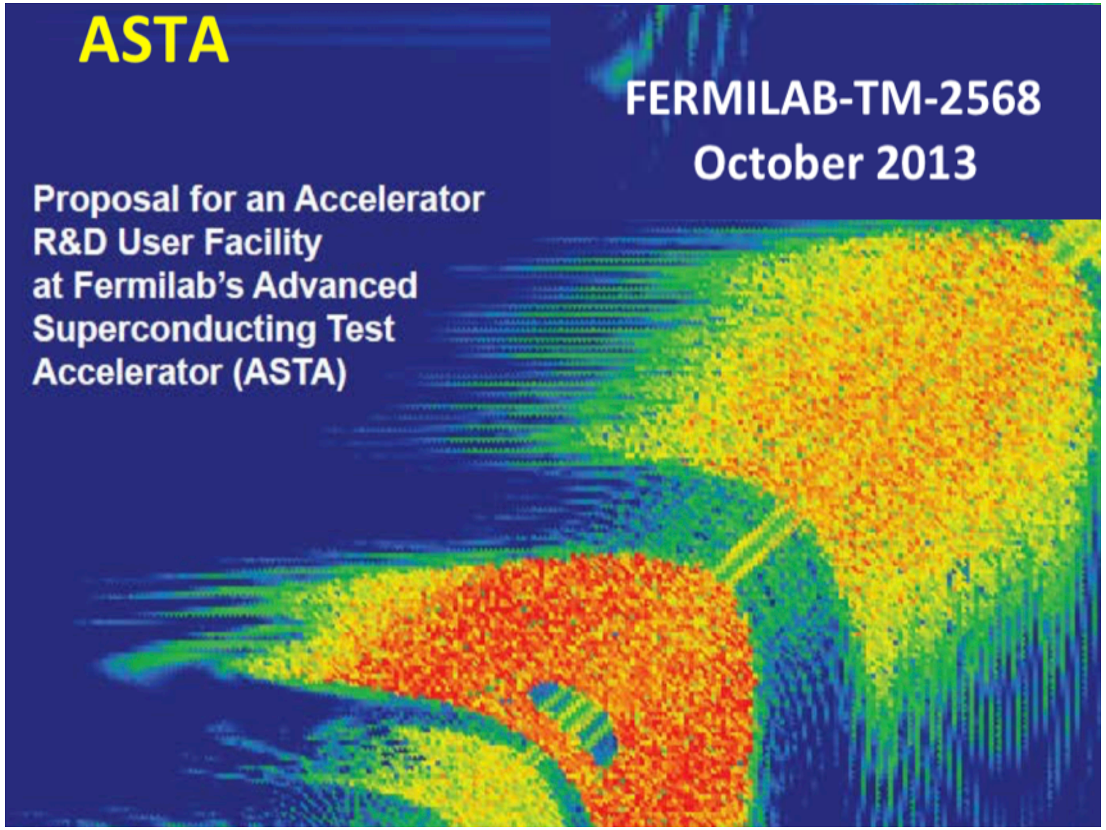
…development of practical atomic-scale channeling measurements of electronic spin densities, and momentum profiles in addition to valence and bonding e⁻ density maps.

Positron Channeling Radiation / Undulator

PHYSICS LETTERS Volume 57, number 1 17 May 1976

ON THE THEORY OF ELECTROMAGNETIC RADIATION OF CHARGED PARTICLES IN A CRYSTAL

M.A. KUMAKHOV



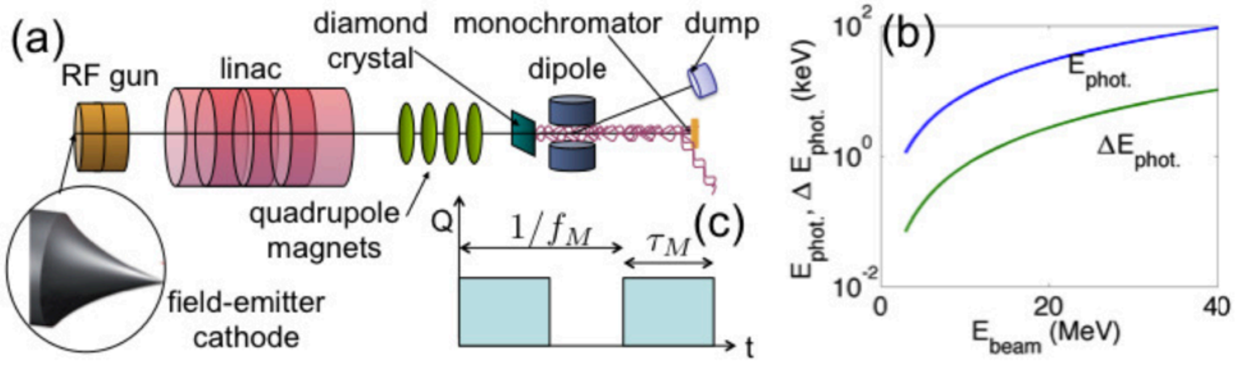


Figure 6: The layout of the X-ray channeling radiation source experiment in the 50 MeV area of ASTA [13].

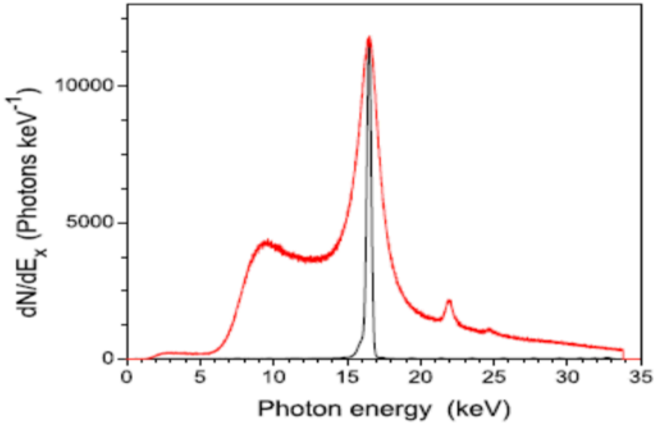


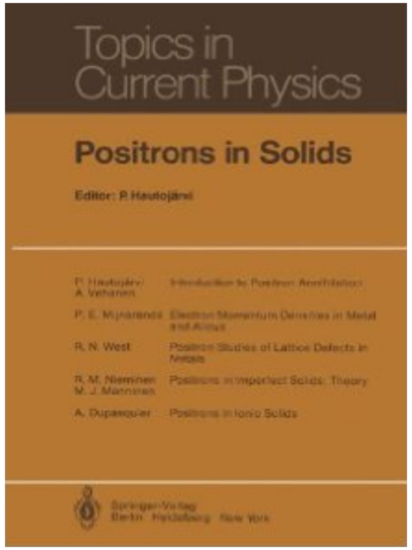
Figure 2: Observed spectrum of channeling radiation for transitions in (110) plane of diamond crystal at an electron energy of 14.6 MeV. Red: natural spectrum; black, monochromatized by Bragg reflection to remove the wings of the CR line and the Bremsstrahlung background [6].

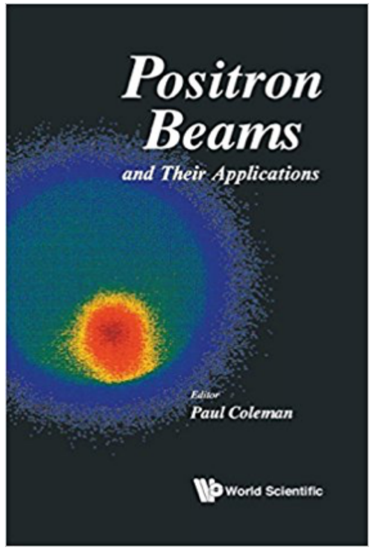
Further Applications

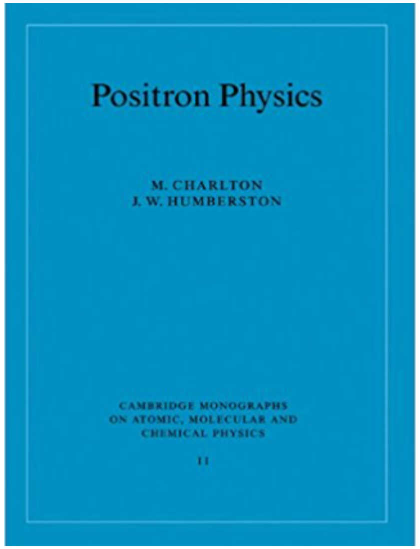
mostly MeV e^+

material science

annihilation spectroscopy







medicine / channeling undulators / anti-matter radiation reaction / anti-Hydrogen-Positronium etc …

Laser-Plasma Collider effort

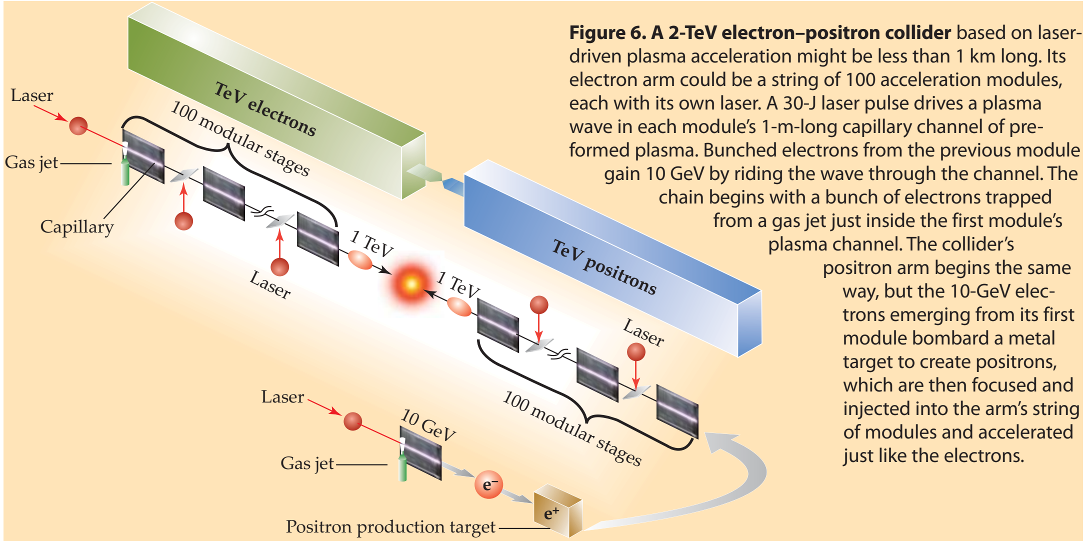
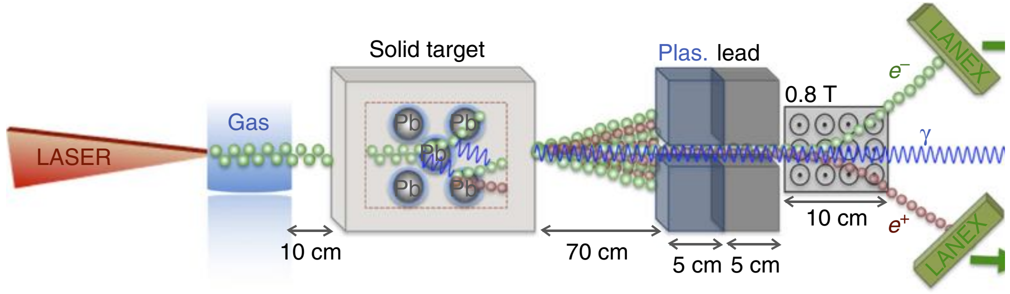


Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module's 1-m-long capillary channel of pre-formed plasma. Bunched electrons from the previous module gain 10 GeV by riding the wave through the channel. The chain begins with a bunch of electrons trapped from a gas jet just inside the first module's plasma channel. The collider's positron arm begins the same way, but the 10-GeV electrons emerging from its first module bombard a metal target to create positrons, which are then focused and injected into the arm's string of modules and accelerated just like the electrons.

Laser-driven plasma-wave electron accelerators
Wim Leemans and Eric Esarey
Citation: Phys. Today **62**(3), 44 (2009); doi: 10.1063/1.3099645
View online: http://dx.doi.org/10.1063/1.3099645

e+-e- shower / staging – tech is ripe !



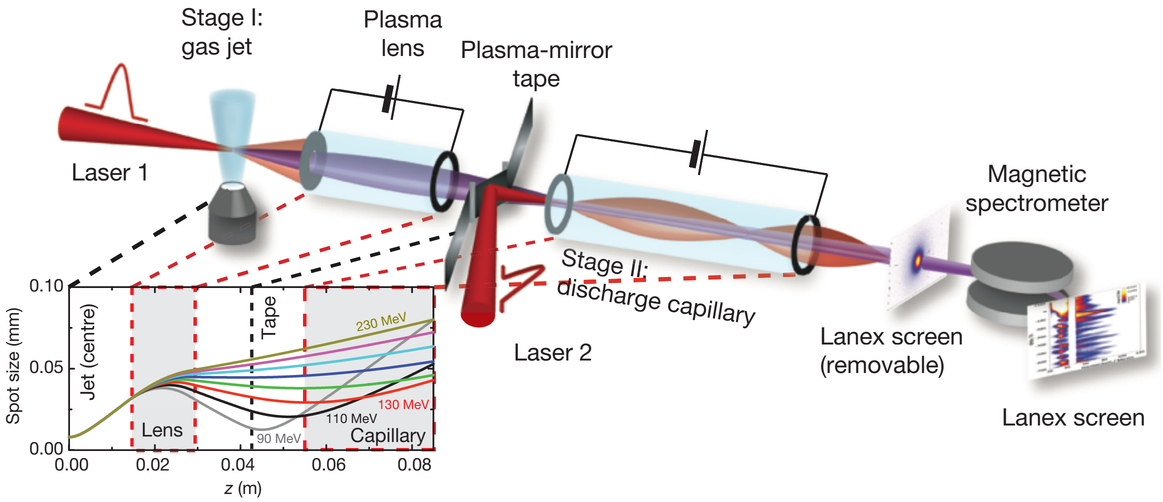
nature COMMUNICATIONS

ARTICLE

Received 4 Apr 2014 | Accepted 24 Feb 2015 | Published 23 Apr 2015 DOI: 10.1038/ncomms7747 OPEN

Generation of neutral and high-density electron–positron pair plasmas in the laboratory

G. Sarri[1], K. Poder[2], J.M. Cole[2], W. Schumaker[3,†], A. Di Piazza[4], B. Reville[1], T. Dzelzainis[1], D. Doria[1], L.A. Gizzi[5,6], G. Grittani[5,6], S. Kar[1], C.H. Keitel[4], K. Krushelnick[3], S. Kuschel[7], S.P.D. Mangles[2], Z. Najmudin[2], N. Shukla[8], L.O. Silva[8], D. Symes[9], A.G.R. Thomas[3], M. Vargas[3], J. Vieira[8] & M. Zepf[1,7]



LETTER

doi:10.1038/nature16525

Multistage coupling of independent laser–plasma accelerators

S. Steinke[1], J. van Tilborg[1], C. Benedetti[1], C. G. R. Geddes[1], C. B. Schroeder[1], J. Daniels[1,3], K. K. Swanson[1,2], A. J. Gonsalves[1], K. Nakamura[1], N. H. Matlis[1], B. H. Shaw[1,2], E. Esarey[1] & W. P. Leemans[1,2]

190 | NATURE | VOL 530 | 11 FEBRUARY 2016

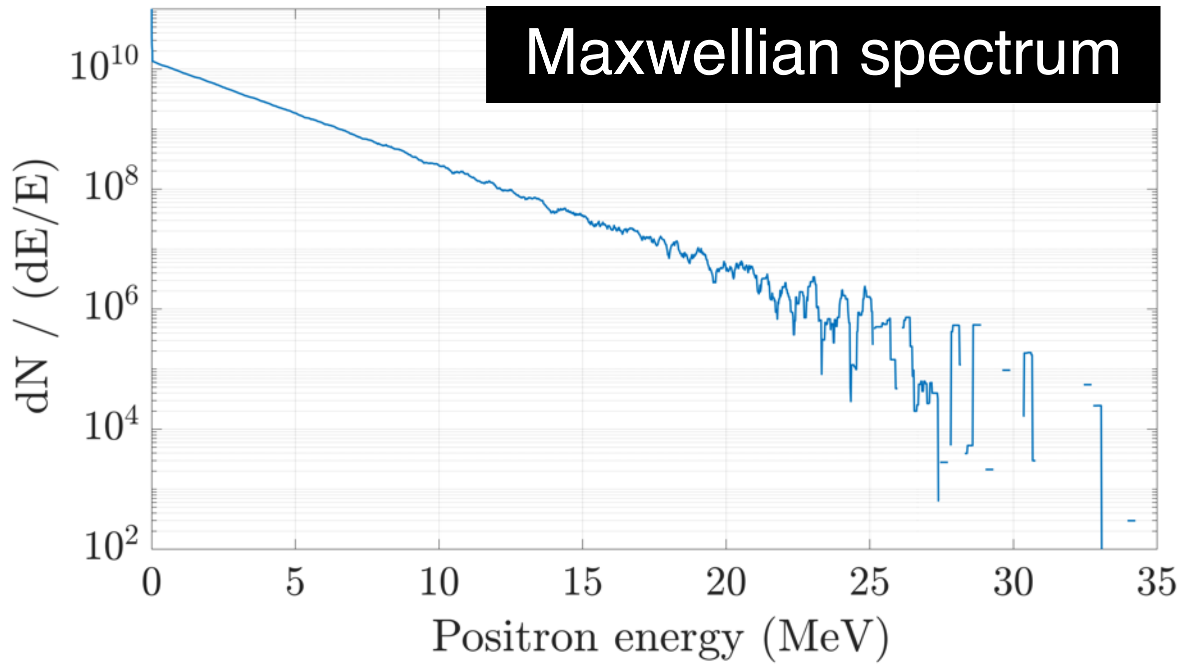
Recent progress in Laser-Plasma Accelerator tech

positron-electron showers

- showers – > MeV electrons on converter target
- although "some" authors have claimed so:

shower ≠ beam
pair-plasma ≠ beam

- positrons NOT isolated
- positrons still divergent
- un-localized in momentum space



orders-of-magnitude roll-off at high-energies

1st-stage – positron-production stage

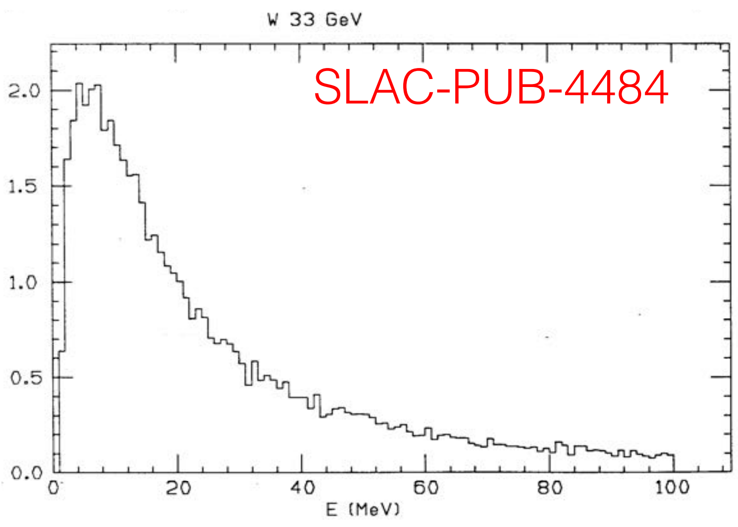


Fig. 3. Yield per 1–MeV energy (E) bin versus E at $z = 6$ radiation lengths.

anisotropic relativistic Maxwellian

$$f(\mathbf{p}) = C\ (p_\perp^2 + p_\parallel^2)\ \exp\left[-\beta_\perp \sqrt{1 + p_\perp^2 + A\ p_\parallel^2}\ \right]$$

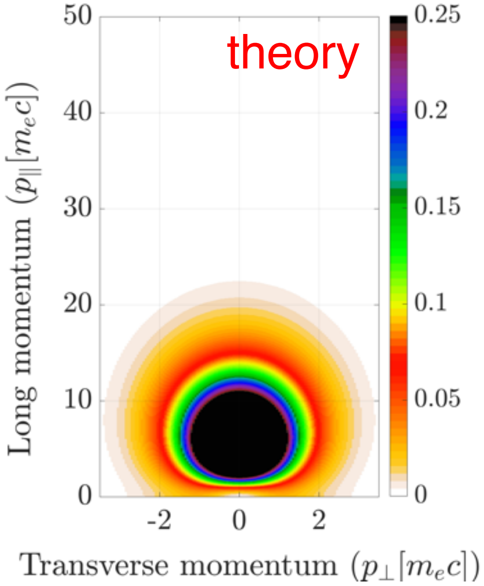
$$\beta_\perp = m_e c^2\ T_\perp^{-1},\ A = T_\parallel T_\perp^{-1}$$

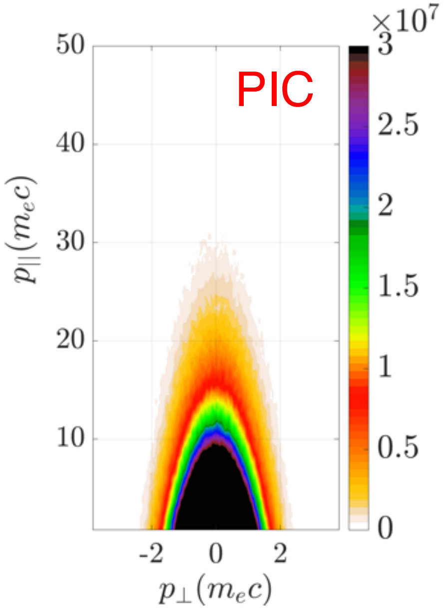
$$T_\perp = 0.2\ \text{MeV} \quad A = 25$$

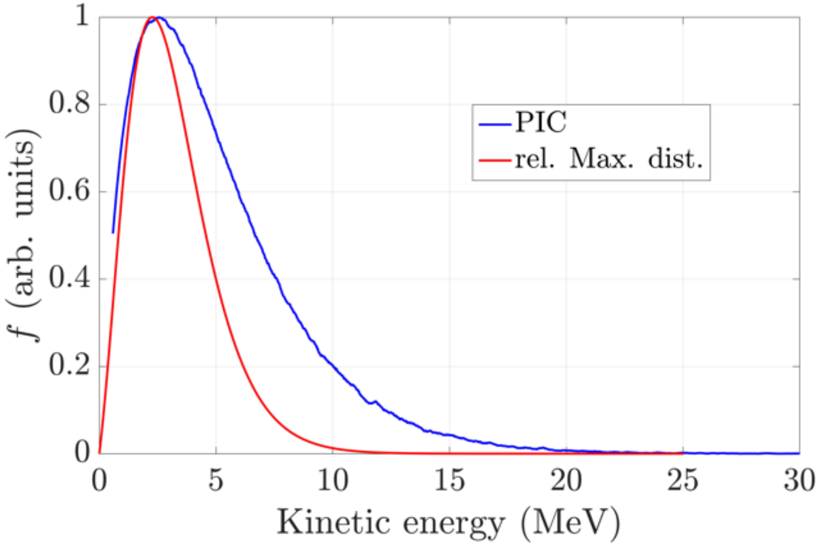
peak ~ 2.5 MeV

temperature ~ 200keV

shower e+ density $1\text{-}10 \times 10^{16}\ \text{cm}^{-3}$







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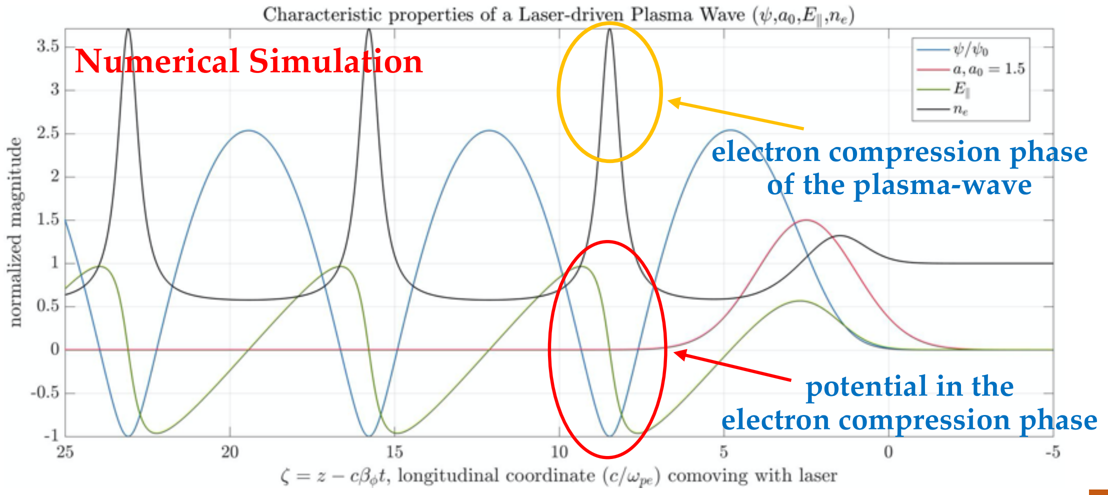
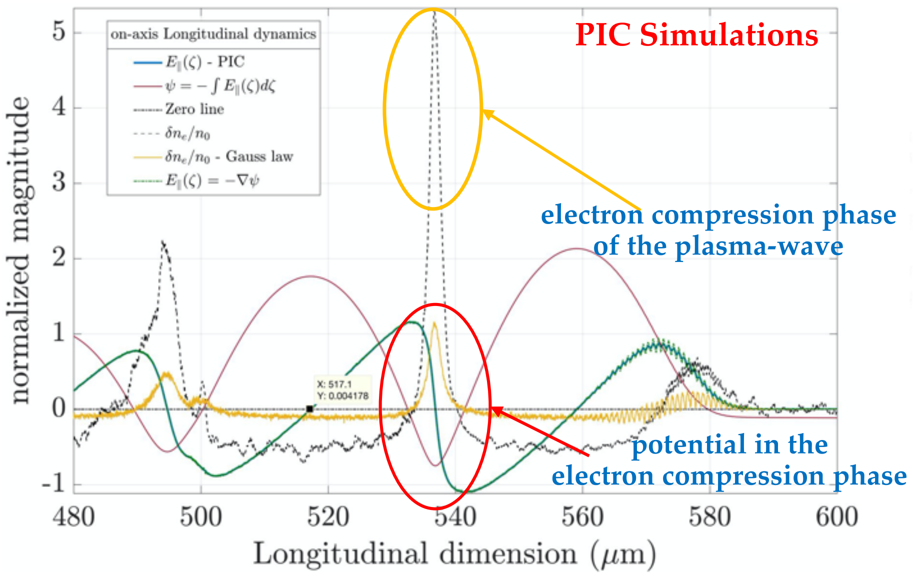
e+-LPA regime – controlling interaction

potential ~ 1 → steepening results in shortening of positron phase

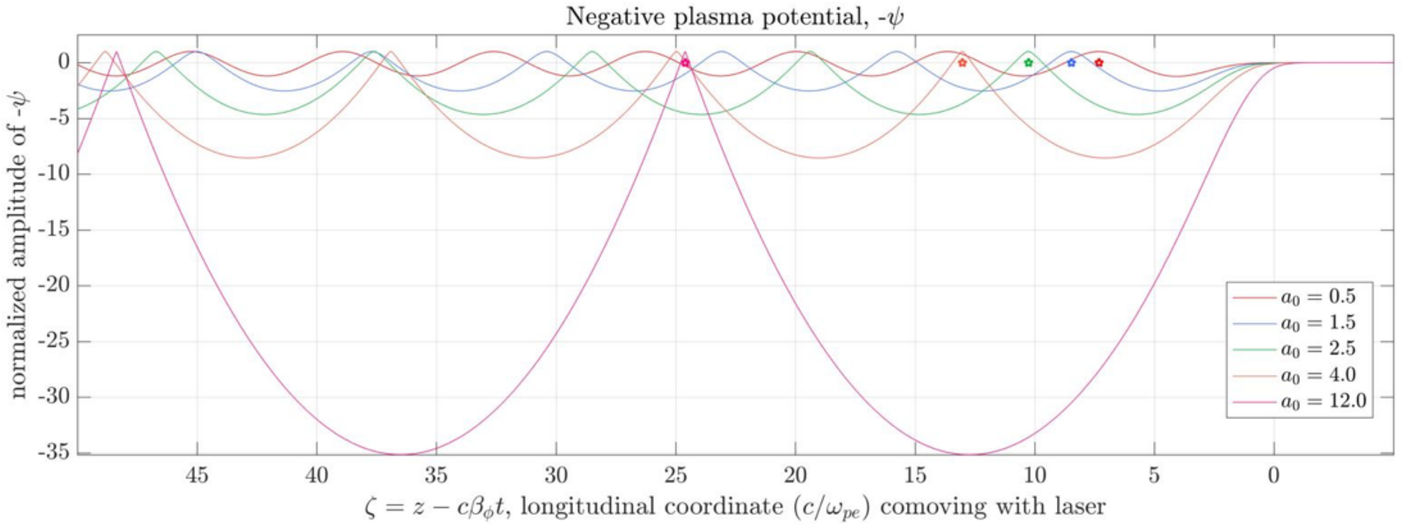


$$k_p^{-2}\frac{\partial^2 \phi}{\partial \xi^2} = \frac{(1+a^2)}{2(1+\phi)^2} - \frac{1}{2}$$

$$n/n_0 = \frac{\gamma_\perp^2 + (1+\phi)^2}{2(1+\phi)^2}$$



low a0 – self-modulated wakefield is USABLE



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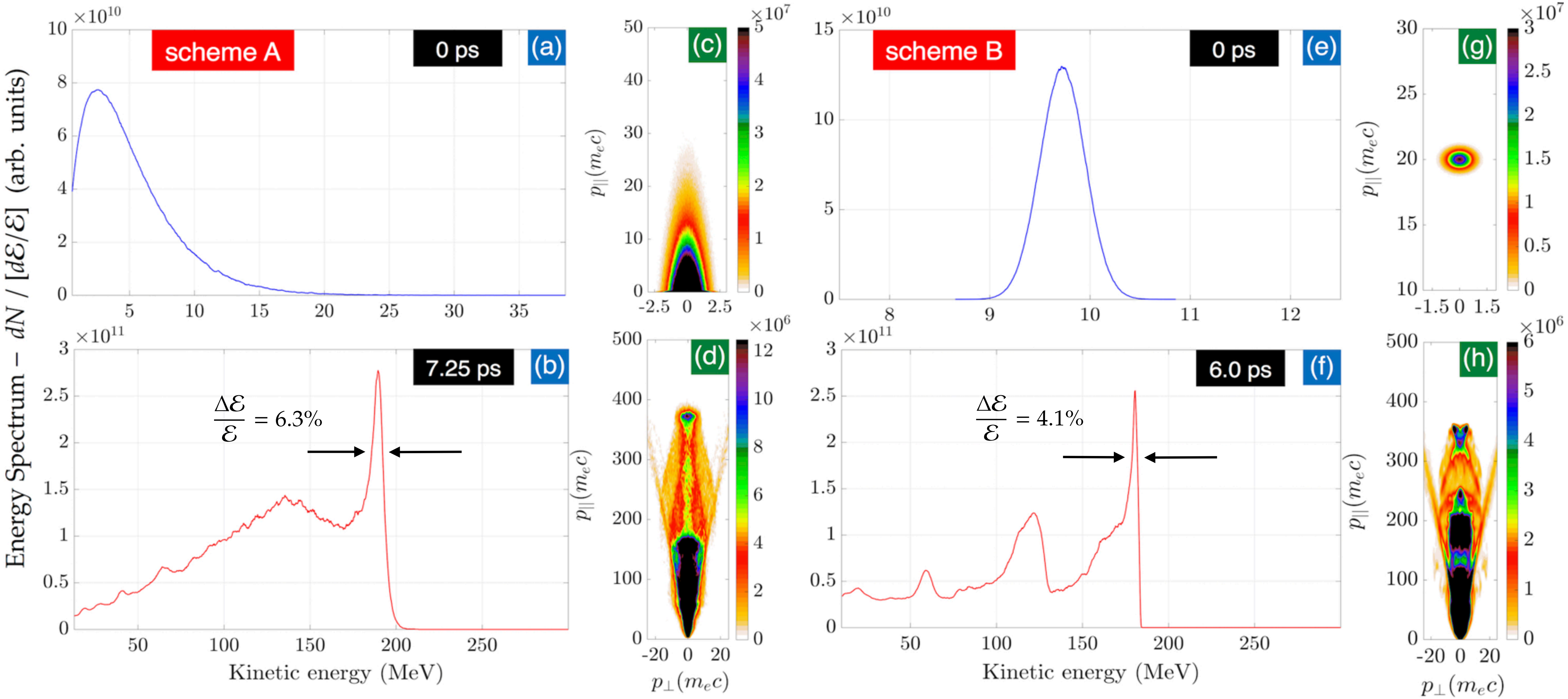
PIC-based – e+ acceleration results



$n_0 = 10^{18}\ cm^{-3}$, $E_L \sim 5\text{-}10J$, $w_0 = 40um$, $a_0 \sim 1.5$

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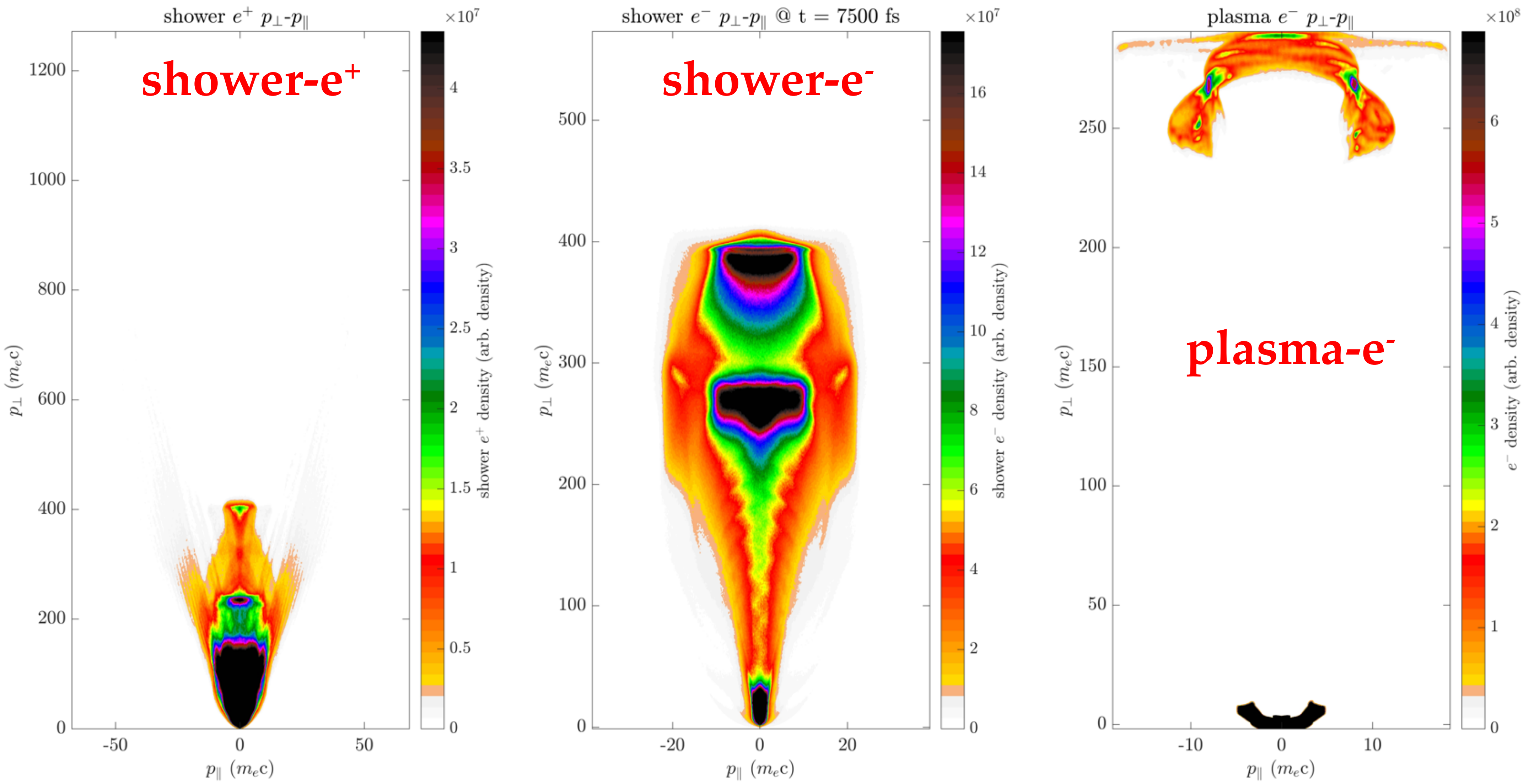
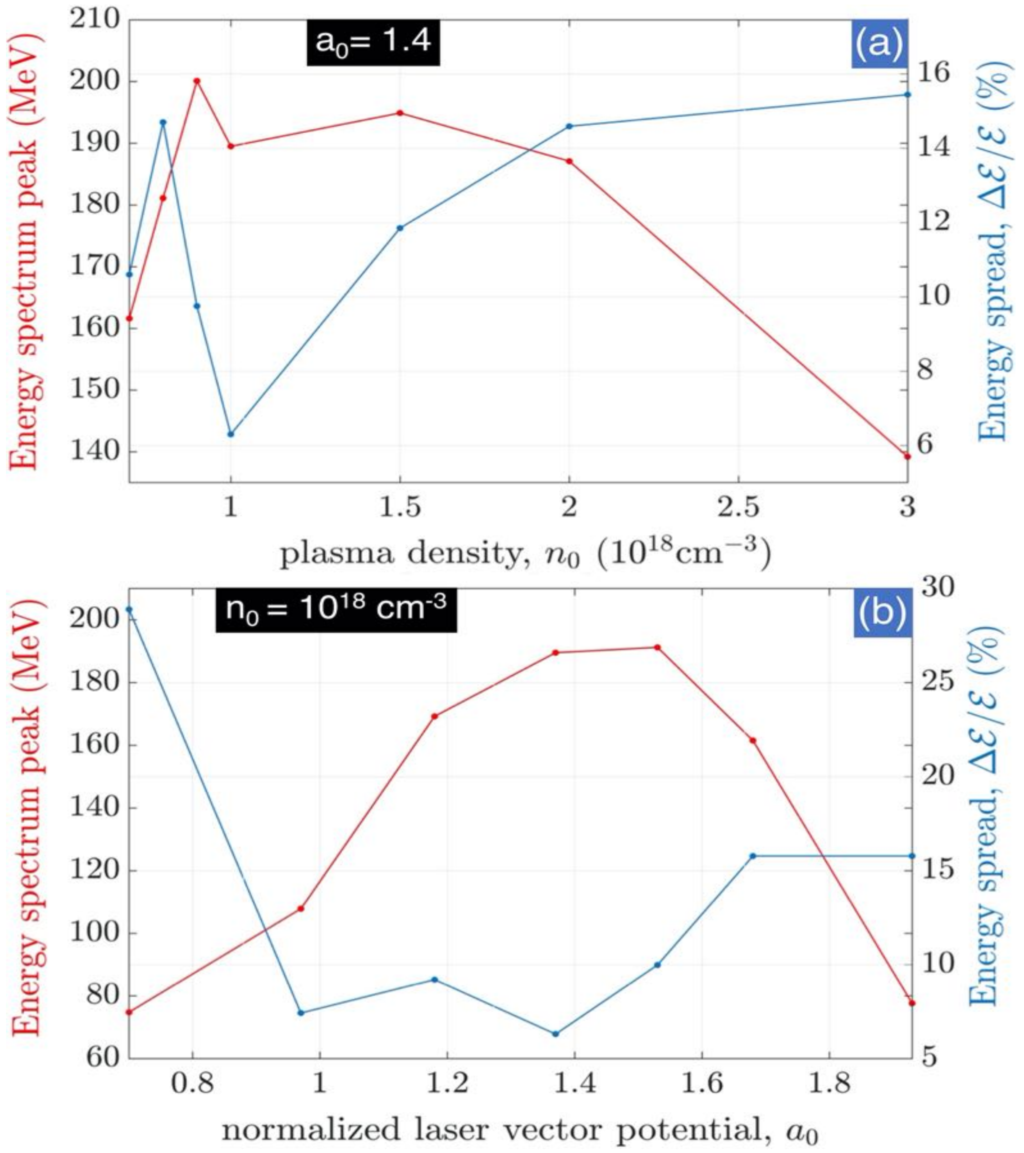
e+–LPA - PIC-based beam phase-space



Tunability - PIC-based parameter scan



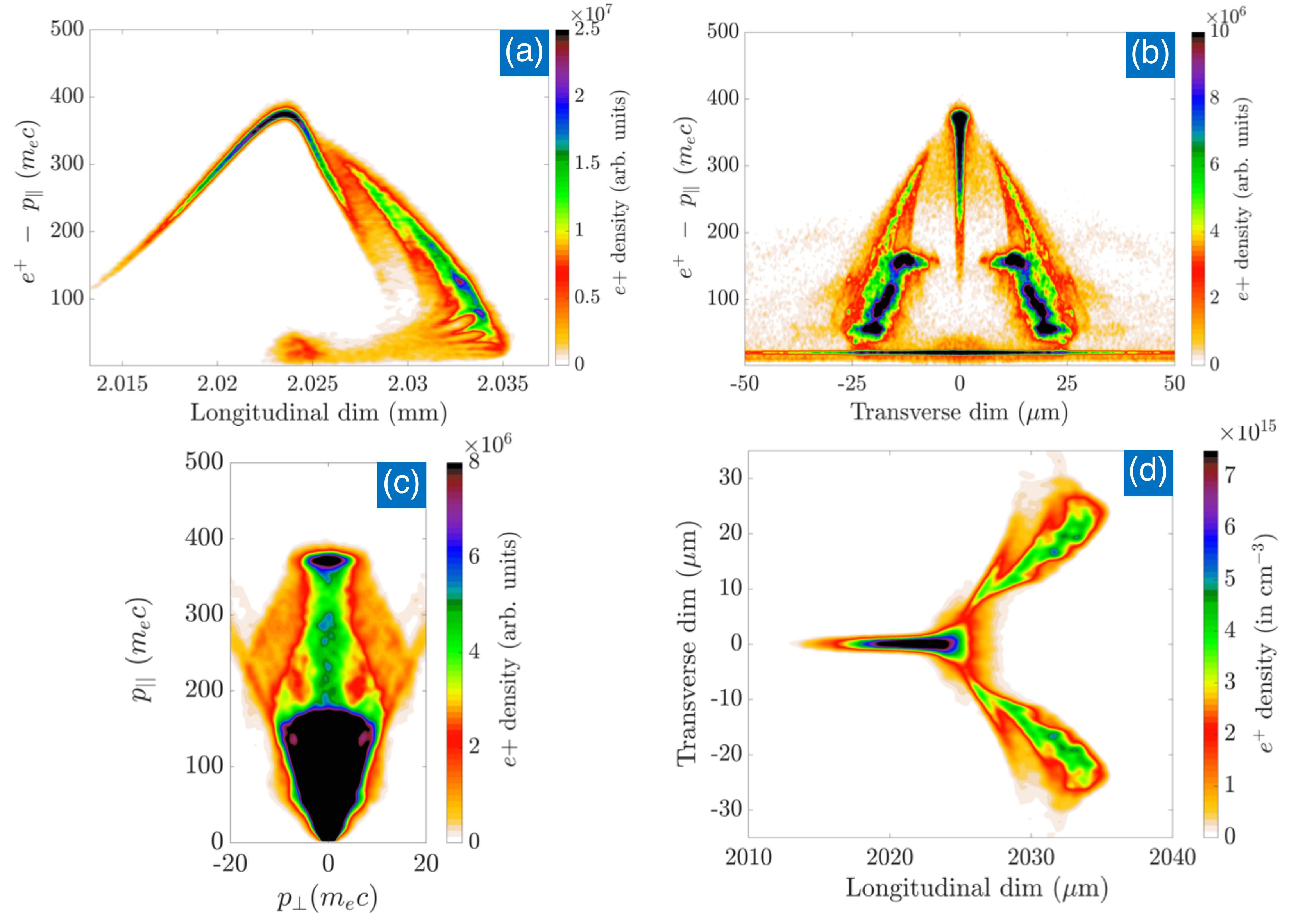
critical to understand shower-wave interactions

tuning of

e^+-beam spectral characteristics

with laser and plasma properties

PIC-based - positron beam characteristics



ultra-short positron bunch

~ $10^{7\text{-}8}$ - e+ / bunch

long. dim ~ 5 – 7.5 μm

tran. dim ~ 5 – 7.5 μm

open. angle ~ 5 – 10 mrad

Primary Challenges

Experimental challenges

- characterize ultrashort positron-electron shower produced by BNL-ATF beam
- control the interaction of shower and wave (coupling the laser)

Physics challenges

- Extending trapped charge – from shower to the beam
- Cooling the positron beam etc. – shower particles are divergent

Technological challenges

- Channeling undulators – couple the beam into sample
- Annihilation spectroscopy etc. - can the beam help in material science

Proposed Milestones

Yr. 1 – demonstration of positron-electron jet production in metal target, its characterization over the sub-ps electron beam parameter-space (spot-size, charge, current) and its interaction with laser-ionized plasma

Yr. 2 – demonstration of coupling high-power CO2 laser pulse within the plasma-cell simultaneously with positron-electron jets

Yr. 3 – demonstration of tuning of the characteristics of the positron beam by scanning over electron beam, CO2 laser and plasma properties.

Conclusions

- BNL-ATF facility is uniquely poised for the first demonstration of laser-driven tunable positron beam

- Applications of ultrashort positron beams can benefit atomic-scale material characterization.

- Collaboration between CUD, Tech-X, UMich, UCI, Fermilab, LLNL, LANL has been setup.
  Each collaborator brings a unique set of capabilities.

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Electron Beam Requirements

Parameter	Units	Typical Values	Comments	Requested Values
Beam Energy	MeV	50-65	*Full range is ~15-75 MeV with highest beam quality at nominal values*	*60-80*
Bunch Charge	nC	0.1-2.0	*Bunch length & emittance vary with charge*	*0.1-2.0*
Compression	fs	Down to 100 fs (up to 1 kA peak current)	*A magnetic bunch compressor available to compress bunch down to ~100 fs. Beam quality is variable depending on charge and amount of compression required.* *NOTE: Further compression options are being developed to provide bunch lengths down to the ~10 fs level*	*100-250, 500*
Transverse size at IP (σ)	μm	30 – 100 (dependent on IP position)	*It is possible to achieve transverse sizes below 10 um with special permanent magnet optics.*	*5-100*
Normalized Emittance	μm	1 (at 0.3 nC)	*Variable with bunch charge*	*1-3*
Rep. Rate (Hz)	Hz	1.5	*3 Hz also available if needed*	*1.5*
Trains mode	---	Single bunch	*Multi-bunch mode available. Trains of 24 or 48 ns spaced bunches.*	*Single bunch*

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CO_2 Laser Requirements

Configuration	Parameter	Units	Typical Values	Comments	Requested Values
CO_2 Regenerative Amplifier Beam	Wavelength	μm	9.2	*Wavelength determined by mixed isotope gain media*	
	Peak Power	GW	~3		
	Pulse Mode	---	Single		
	Pulse Length	ps	2		
	Pulse Energy	mJ	6		
	M^2	---	~1.5		
	Repetition Rate	Hz	1.5	*3 Hz also available if needed*	
	Polarization	---	Linear	*Circular polarization available at slightly reduced power*	
CO_2 CPA Beam	Wavelength	μm	9.2	*Wavelength determined by mixed isotope gain media*	*9.2*
Note that delivery of full power pulses to the Experimental Hall is presently limited to Beamline #1 only.	Peak Power	TW	5-10	*~5 TW operation is planned for FY21 (requires further in-vacuum transport upgrade). A 3-year development effort to achieve >10 TW and deliver to users is in progress.*	*0.1-10*
	Pulse Mode	---	Single		
	Pulse Length	ps	< 2		*2-0.5*
	Pulse Energy	J	~5	*Maximum pulse energies of >10 J will become available in FY20*	*0.1-2.5J (y1, y2), 5J (y3)*
	M^2	---	~2		*2*
	Repetition Rate	Hz	0.05		*0.05*
	Polarization		Linear	*Adjustable linear polarization along with circular polarization will become available in FY20*	*linear*

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Other Experimental Laser Requirements

Ti:Sapphire Laser System	Units	Stage I Values	Stage II Values	Comments	Requested Values
Central Wavelength	nm	800	800	*Stage I parameters should be achieved by mid-2020, while Stage II parameters are planned for late-2020.*	
FWHM Bandwidth	nm	20	13		
Compressed FWHM Pulse Width	fs	<50	<75	*Transport of compressed pulses will initially include a very limited number of experimental interaction points. Please consult with the ATF Team if you need this capability.*	
Chirped FWHM Pulse Width	ps	≥50	≥50		
Chirped Energy	mJ	10	200		
Compressed Energy	mJ	7	100		
Energy to Experiments	mJ	>4.9	>80		
Power to Experiments	GW	>98	>1067		

Nd:YAG Laser System	Units	Typical Values	Comments	Requested Values
Wavelength	nm	1064	*Single pulse*	
Energy	mJ	5		
Pulse Width	ps	14		
Wavelength	nm	532	*Frequency doubled*	
Energy	mJ	0.5		
Pulse Width	ps	10		

Special Equipment Requirements and Hazards

- Electron Beam
  - Plasma capillary discharge system – laser
  - Transverse deflecting cavity
  - Permanent magnet quadrupole
  - Stark-line shift measurement setup (plasma density vs. gas pressure)
  - Mask for beam splitting (beam-driven active plasma beam dump)

- CO_2 Laser
  - Mirror with hole delivery (5 J, sync. with e-beam) into the capillary / gas-jet
  - Tape reflector delivery (5 J, sync. with e-beam) into the capillary / gas-jet

- Superconducting Magnetic field
  - Can a superconducting magnet be setup on the beamline ?

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Experimental Time Request

CY2020 Time Request

Capability	Setup Hours	Running Hours
Electron Beam Only		
Laser* Only (in FEL Room)		
Laser* + Electron Beam	24	120

can run in time-shared mode with plasma beam dump experiment

Time Estimate for Full 3-year Experiment (including CY2020)

Capability	Setup Hours	Running Hours
Electron Beam Only		
Laser* Only (in FEL Room)		
Laser* + Electron Beam	72	360

* Laser = Near-IR or LWIR (CO_2) Laser

Diagnostics

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Full . Published Online: 31 October 2008 Accepted: May 2008

High performance compact magnetic spectrometers for energetic ion and electron measurement in ultraintense short pulse laser solid interactions

Review of Scientific Instruments **79**, 10E533 (2008); https://doi.org/10.1063/1.2953679

Hui Chen[1], Anthony J. Link[2], Roger van Maren[1], Pravesh K. Patel[1], Ronnie Shepherd[1], Scott C. Wilks[1], *and* Peter Beiersdorfer[1]

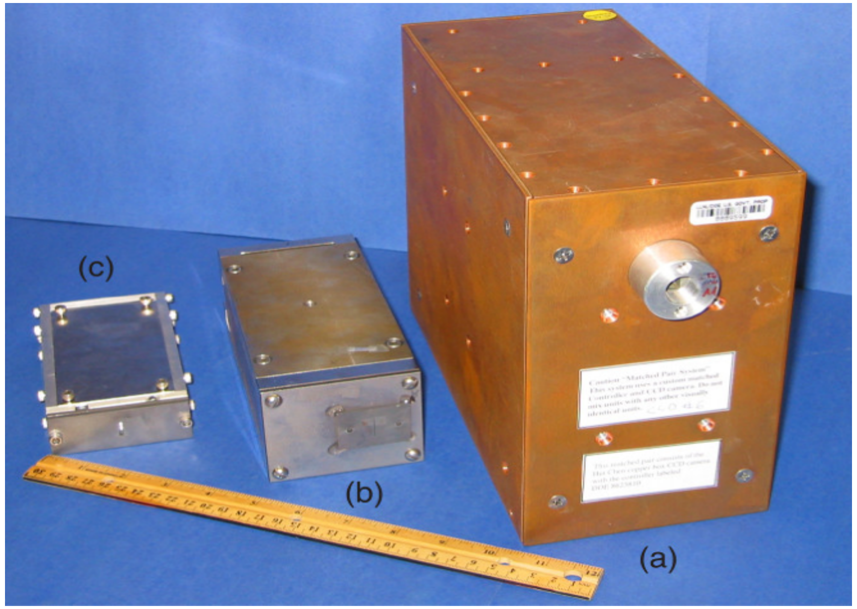

Figure 8: positron spectrometer & gamma-ray diagnostics

Laser and Particle Beams

cambridge.org/lpb

Research Article

MeV bremsstrahlung X rays from intense laser interaction with solid foils

S. Palaniyappan[1], D. C. Gautier[1], B. J. Tobias[1], J. C. Fernandez[1], J. Mendez[1], T. Burris-Mog[1], C. K. Huang[1], A. Favalli[1], J. F. Hunter[1], M. E. Espy[1], D. W. Schmidt[1], R. O. Nelson[1], A. Sefkow[2], T. Shimada[1] and R. P. Johnson[1]