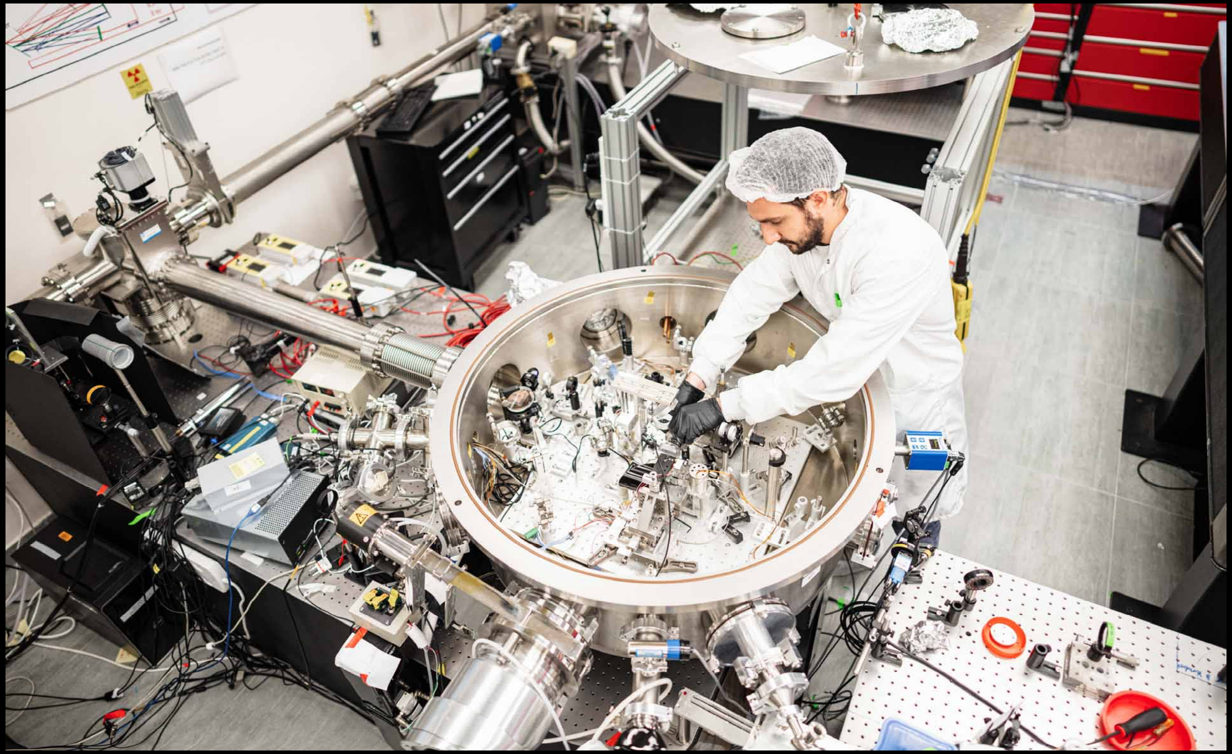
Plasma Guided Compton Source



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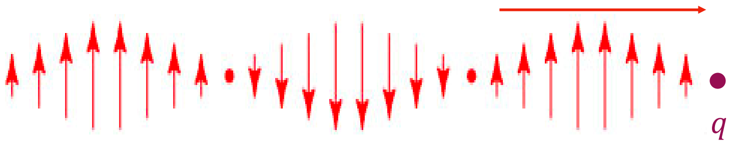
ACCELERATING CHARGED PARTICLES USING LIGHT

Single electron under the force of an EM plane wave

$\vec{A} = A_0 cos(kx - \omega t)\hat{y}$



$a_0 \equiv \frac{eA_0}{m_e c^2}$

$\gamma_0 \equiv \sqrt{1 + a_0^2/2}$

$kx = \frac{a_0^2}{8\gamma_0} sin2\phi$

$ky = -\frac{a_0}{\gamma_0} sin\phi$

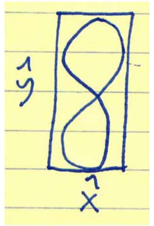


Figure-8 motion in some moving frame of reference

no net energy coupling *"Lawson-Woodward Theorem"*

The ponderomotive force

Add a slowly changing spatial envelope $\vec{\tilde{E}}$ to the plane wave

$\vec{E}(\vec{r},t) = Re\{\vec{\tilde{E}}(\vec{r},t)e^{-i\omega t}\}$

Separate the charge position to an oscillating and a slow component

$\vec{r}(t) = \vec{r}_o(t) + \vec{r}_s(t)$

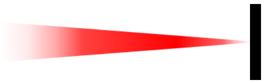
$\langle \vec{r}_o(t) \rangle = 0$

$\langle \vec{r}(t) \rangle = \langle \vec{r}_s(t) \rangle = \vec{r}_s(t)$

$\vec{f}_p \equiv m_e \frac{d}{dt}\langle \vec{v} \rangle = -\frac{e^2}{2m_e\omega^2}\nabla\langle \vec{E}^2(\vec{r}_s(t),t)\rangle$

$\xrightarrow[\gamma>>1]{} -m_e c^2 \nabla\sqrt{1 + \langle a^2 \rangle}$

Focusing / defocusing beam: acceleration / deceleration

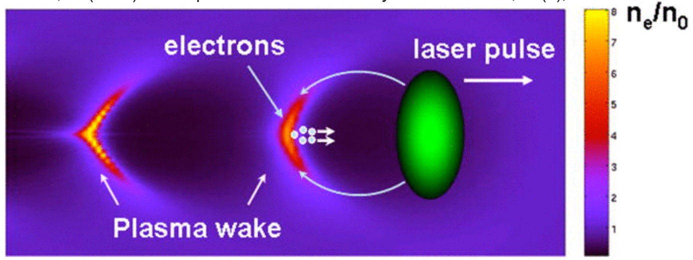


Employ the plasma's collective response, for example: laser wakefield acceleration

Use the ponderomotive force to excite plasma waves

Electrons are trapped and accelerated in the wake

Malka, V. (2012). Laser plasma accelerators. *Physics of Plasmas*, *19*(5), 055501.



State-of-art:

Energies as high as 8 GeV

Reasonable control over spectral features

Only nanocolumb charge

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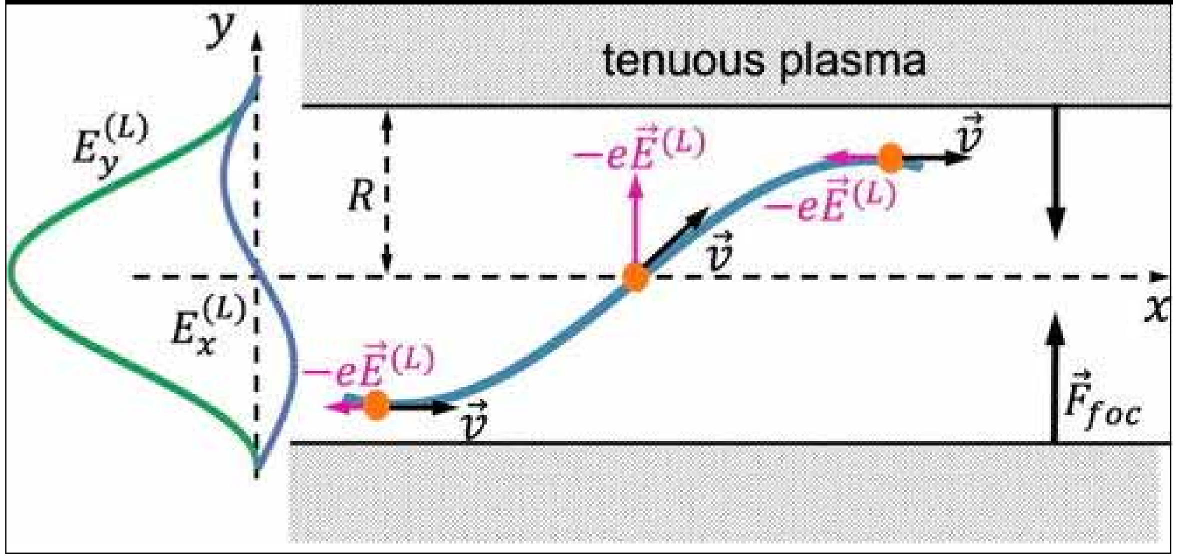
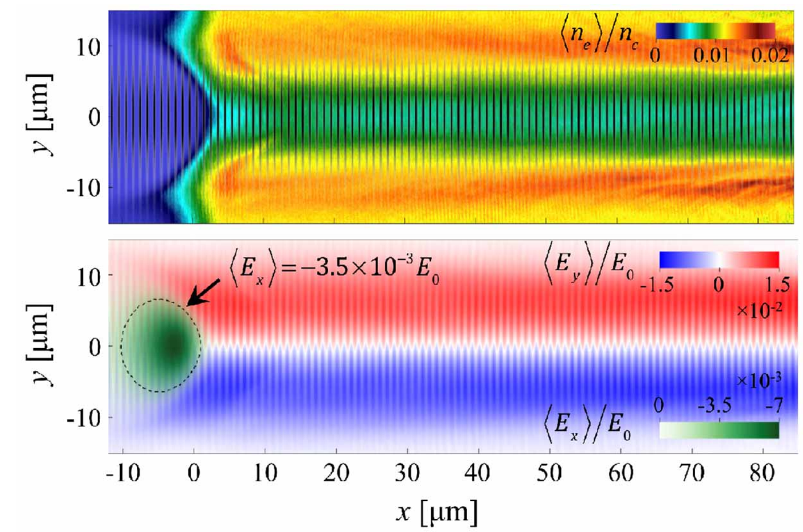
DIRECT LASER ACCELERATION (DLA)

- The ponderomotive force of the leading part of the laser pulse expels electrons and forms a slowly evolving quasi-stationary ion channel
- The laser electric field transfers energy into transverse (betatron) oscillations
- This energy is redirected by the magnetic field of the laser into the longitudinal direction


WANG ET. AL, POP 26, 083101 (2019)

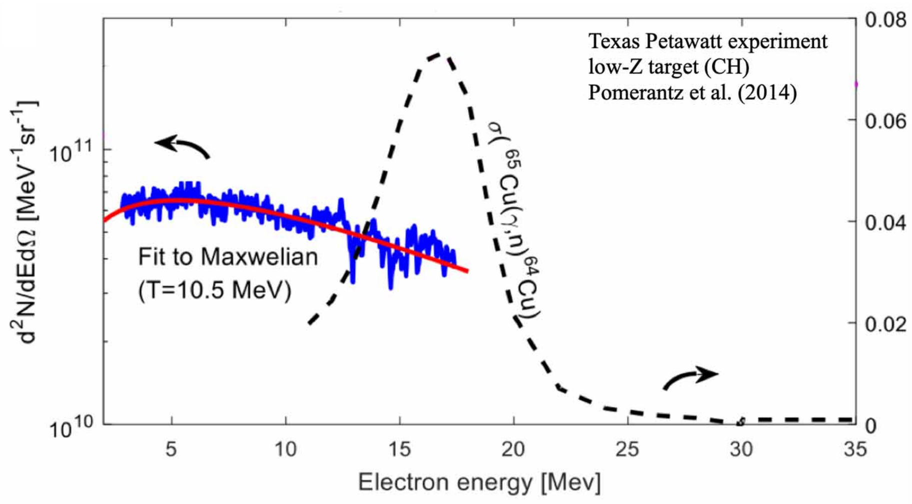

AREFIEV ET. AL, POP 23, 056704 (2016)

DIRECT LASER ACCELERATION (DLA)

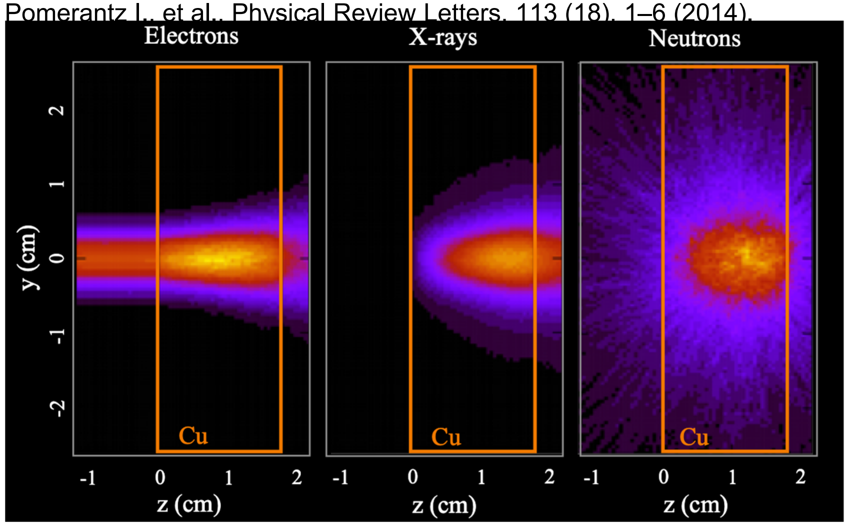
- DLA has been observed in experiments for 25 years
- These experiments used low-Z targets (plastic foils or gas jets)

- DLA produce MeV-level, continuous electron spectrum
- Reported conversion efficiency of laser energy to electrons of over 25%
- An ideal method for generating a large number of photo-nuclear reactions

Malka, G., et al., Physical Review Letters, 79 (11), 2053 (1997).
Malka, G., et al., Physical Review Letters, 78 (17), 3314 (1997).
Gahn, C., et al., (1999). Physical Review Letters, 83 (23), 4772–4775.
D. Giulietti, et al., Phys. Rev. E 64, 15402 (2001).
D. Giulietti, et ak., Phys. Plasmas 9, 3655 (2002).
Willingale, L., et al., New Journal of Physics,15 (2), 025023 (2013).
Rosmej O. N., et al, New Journal of Physics, 21 (4), 043044 (2019).
Rosmej O. N. , Plasma Phys. Control. Fusion 62, 115024 (2020).
Shaw, J.L., et al., Sci Rep 11, 7498 (2021).
Gorlova, et al. (2022). Laser Physics Letters, 19 (7), 075401.
Gunther, et al., (2022). Nature Communications 2022 13:1, 13 (1), 1–13.



Pomerantz I., et al., Physical Review Letters, 113 (18), 1–6 (2014).



Pukhov scaling prediction: $T_e \propto \sqrt{I} \propto a_0$ Pukhov et al, PoP 6, 2847 (1999)

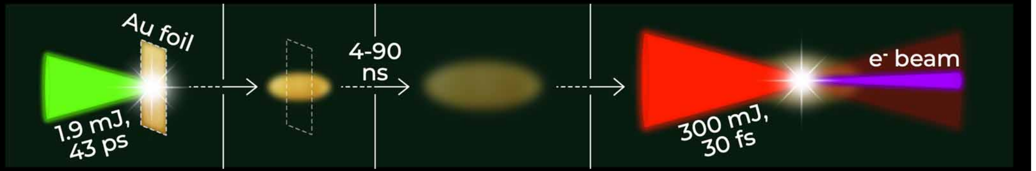
STUDYING DLA IN DETAIL @TEL-AVIV U.

Itamar Cohen

Main pulse: 100-500 mJ / 25 fs

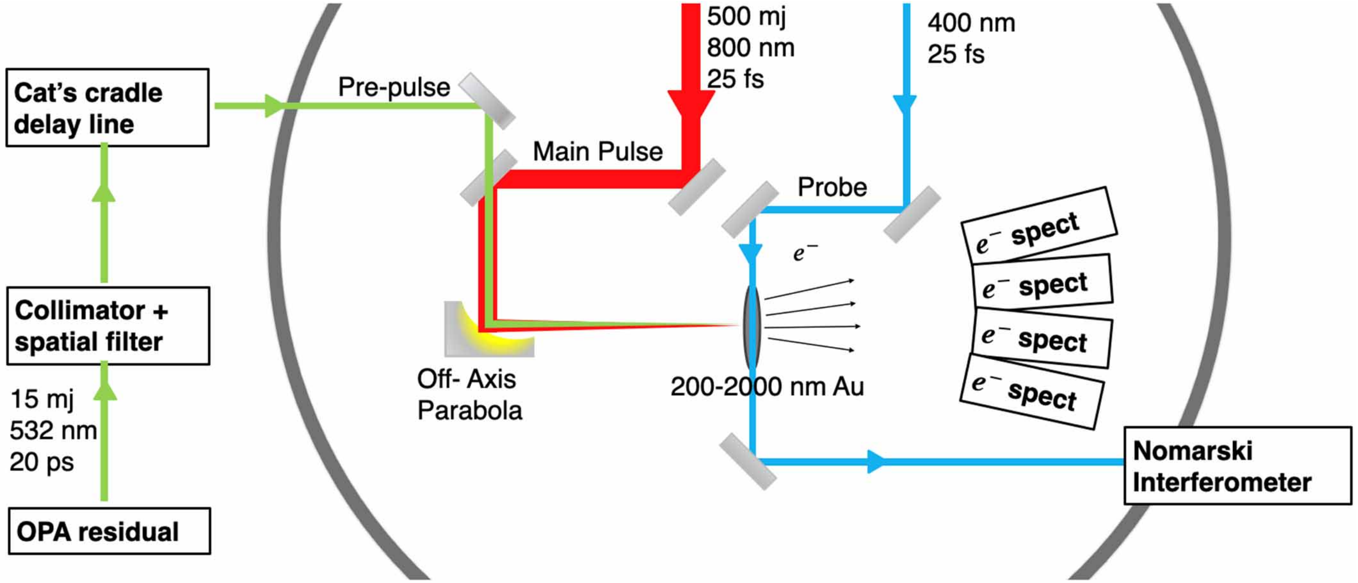
Parametric scan of:

- Target thickness and composition
- Pre-pulse energy
- Pre- to main-pulse delay



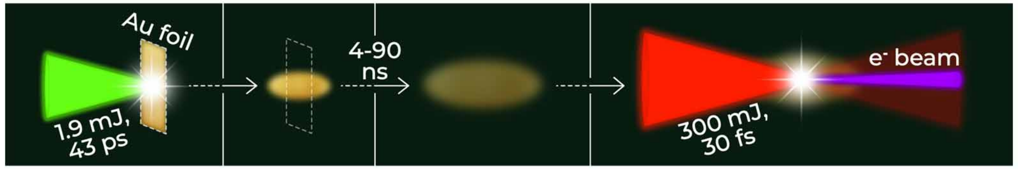
For each shot we record:

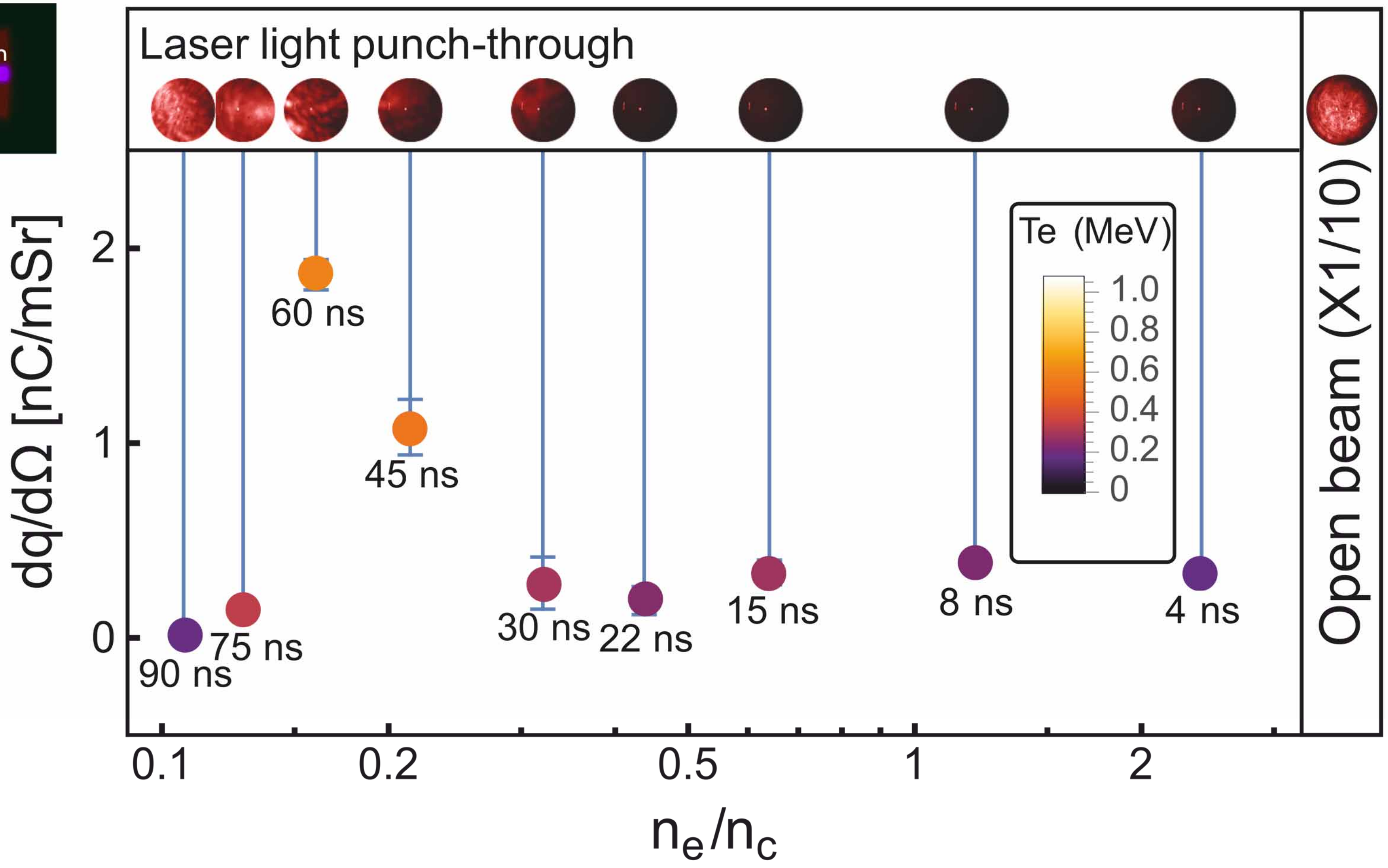
- Electron spectrum
- Plume’s density profile
- NF image of light punching through the plasma



FINDING THE OPTIMAL PLASMA PLUME DENSITY PROFILE

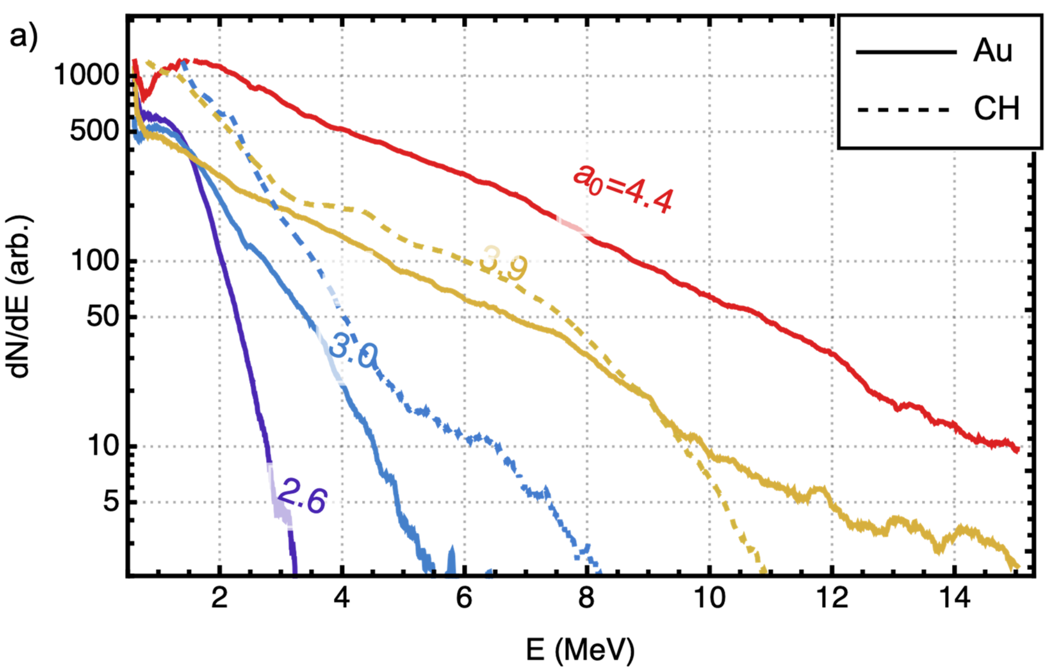
EXAMPLE PRE-PULSE DELAY SCAN AT FIXED MAIN PULSE AND PRE-PULSE INTENSITIES

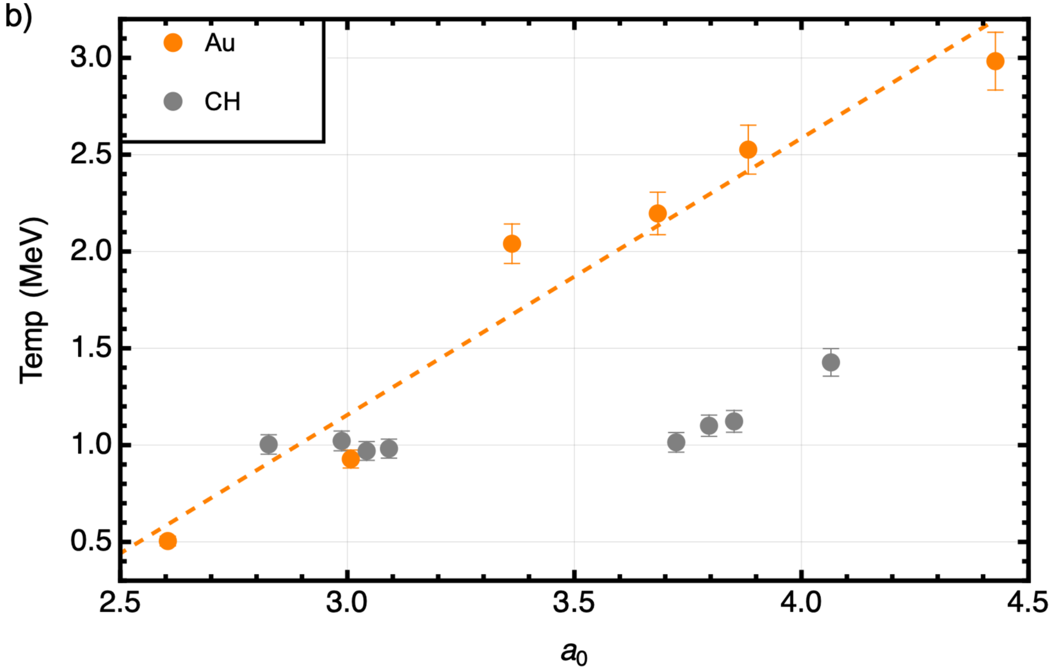




DLA: A LOW-Z VS. HIGH-Z PLASMA TARGET

- We generated DLA electron beams from high-Z plasma targets (Au)
- For each plasma type, the plume's density profile was optimized to yield a beam with a maximal electron temperature





- DLA from Au plasma maintains Pukhov scaling, CH plasma does not.

Why?

$$a_0 \equiv \frac{eA_0}{m_e c^2}$$

$$T_e \propto \sqrt{I} \propto a_0$$

AN ANALYTICAL MODEL FOR THE EXPANSION OF A THIN DISK OF PLASMA

$$n = n_{i0}\frac{R_0^2\frac{1}{2}df(\alpha)}{R(t)^2L(t)}\overbrace{\exp\left(-\frac{r^2}{R(t)^2}\right)}^{\text{RADIALLY GAUSSIAN}}\overbrace{\exp\left(-\frac{|z|}{L(t)}\right)}^{\text{LONGITUDINAL EXPONENTIAL}}\overbrace{\left(1+\alpha\frac{|z|}{L(t)}\right)^{1/\alpha}}^{\text{SHAPE FACTOR}}$$

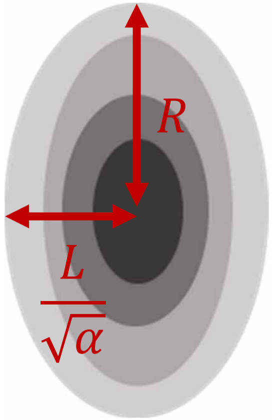
Velocity: $\vec{u} = \frac{\dot{R}(t)}{R(t)}\vec{r} + \frac{\dot{L}(t)}{L(t)}\vec{z}$ **Normalization:** $f(\alpha) = \frac{\alpha^{-\frac{1}{\alpha}}\exp(-\alpha)}{\Gamma\left(1+\frac{1}{\alpha},\frac{1}{\alpha}\right)}$

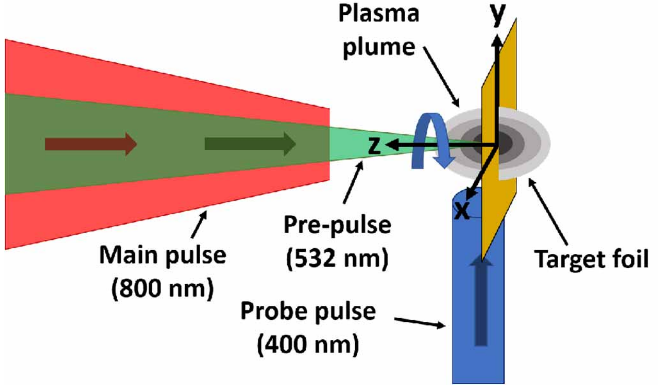
An approximate solution to the plasma EOM when $\alpha \ll 1$.

The plume evolution in time is then:

$$\begin{cases} \ddot{L} = \dfrac{\alpha c_s^2}{L} \\ \ddot{R} = \dfrac{2c_s^2}{R} \end{cases} \qquad c_s^2 = c_{s0}^2\left(\frac{R_0}{R}\right)^{\frac{4}{3}}\left(\frac{L_0}{L}\right)^{\frac{2}{3}} \propto T_e$$

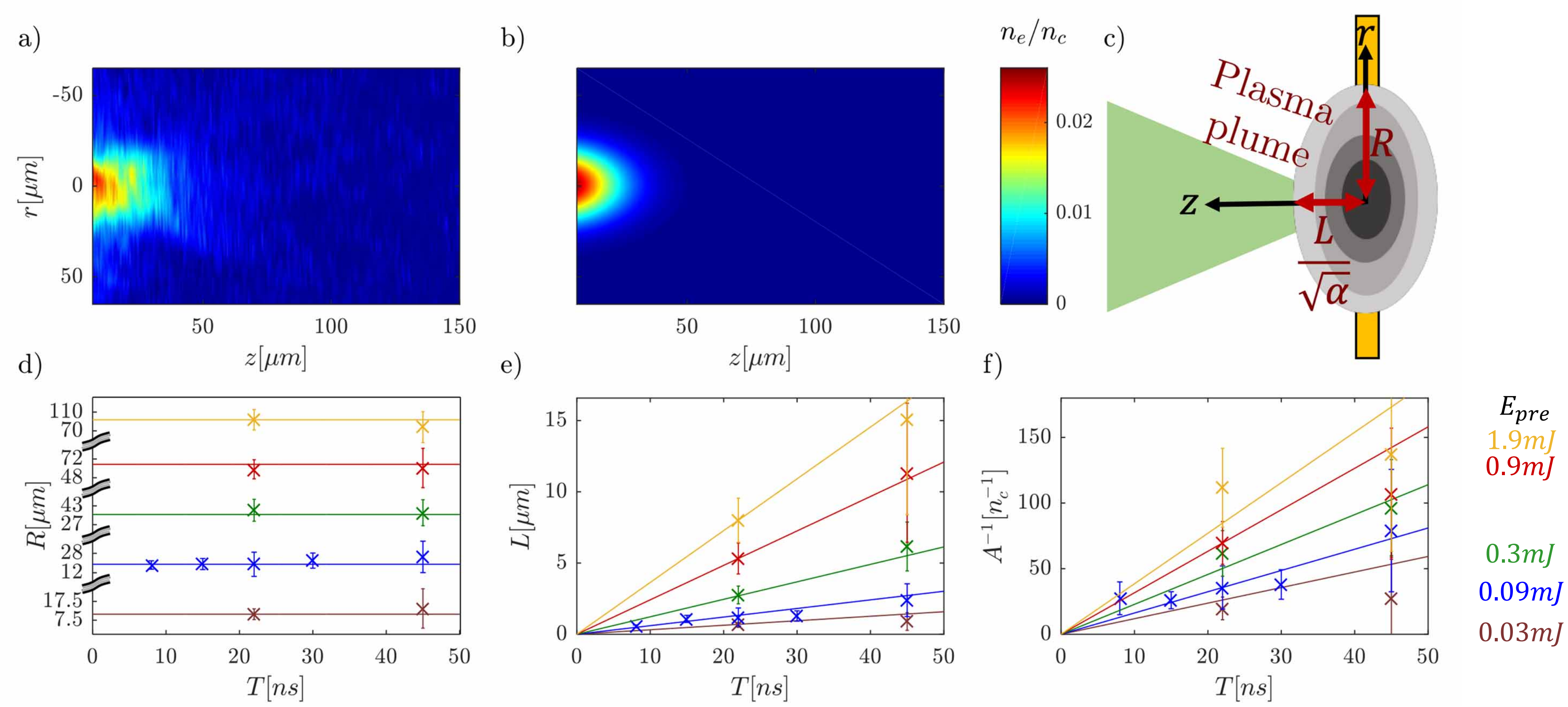
PLASMA PLUME





FITTING THE THIN DISK MODEL TO THE MEASURED PLASMA PLUME EVOLUTION

$$n = n_{i0}\frac{R_0^2\frac{1}{2}df(\alpha)}{R(t)^2L(t)}\exp\left(-\frac{r^2}{R(t)^2}\right)\exp\left(-\frac{|z|}{L(t)}\right)\left(1+\alpha\frac{|z|}{L(t)}\right)^{1/\alpha}$$



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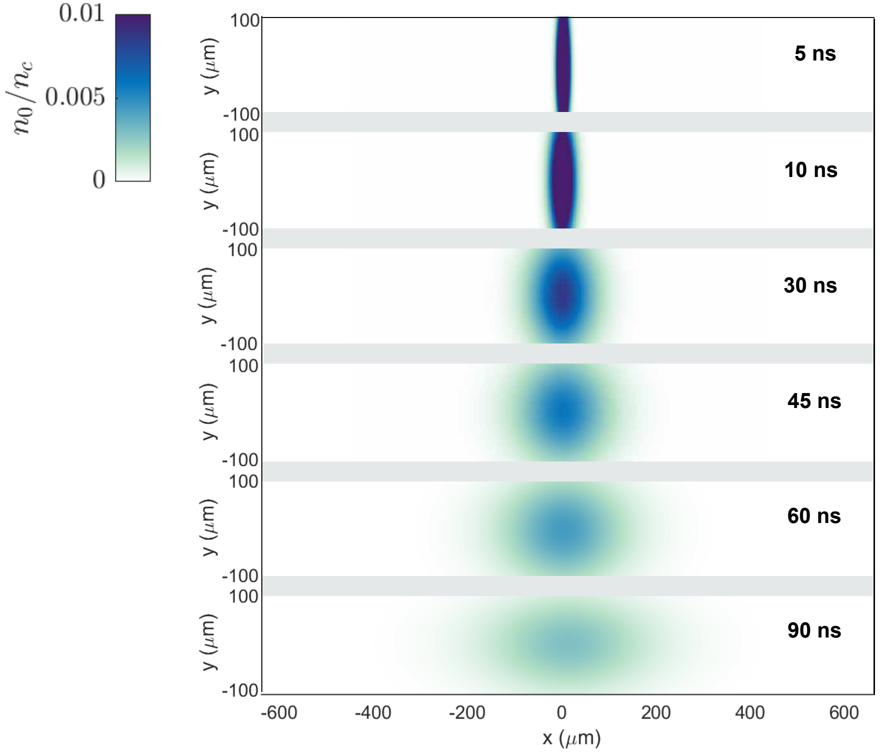
SIMULATION

Talia Meir

- Using the EPOCH-2D code
- Running on Lonestar6
  (ranked world 13th supercomputer)
- Measured plasma plume profiles serve as initial inputs
- Field ionization is implemented in the code

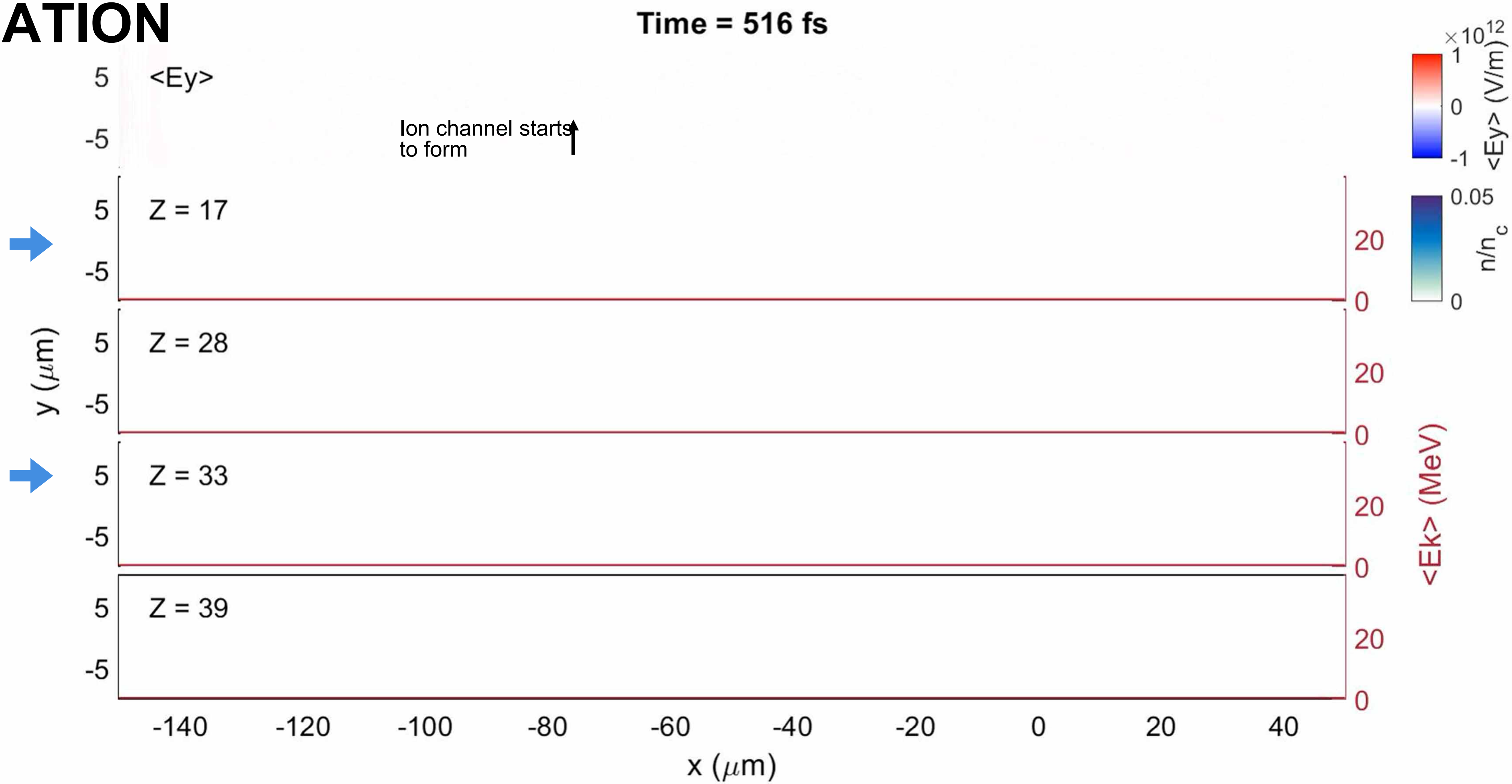
INPUT PLASMA PROFILES (FROM MEASUREMENT)



SIMULATION

Low-Z electrons are ionized prematurely, before the ion channel is formed

High-Z electrons are ionized later when the channel is already formed



For low-z targets, the target is depleted from all of its ionization electrons too early, resulting in inefficient DLA

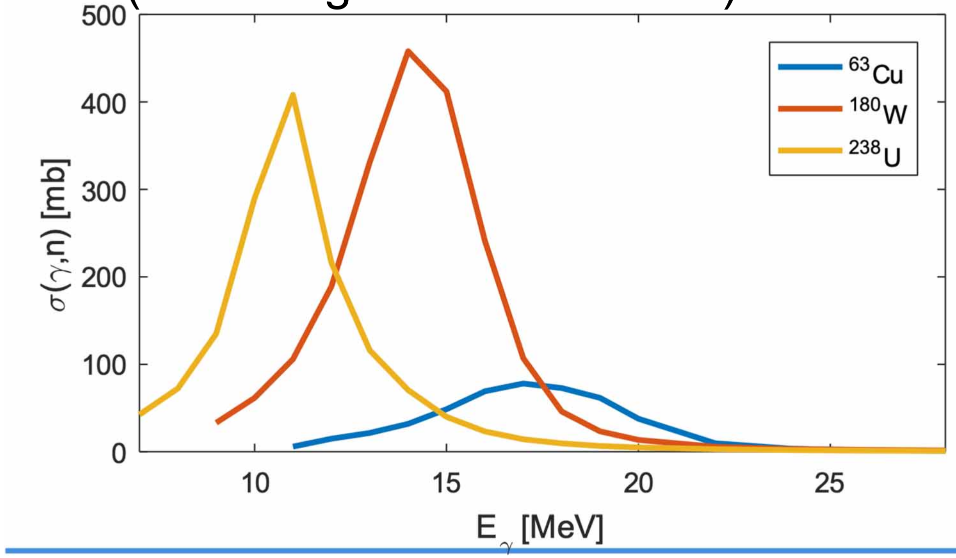
ELECTRON AND NEUTRON YIELDS

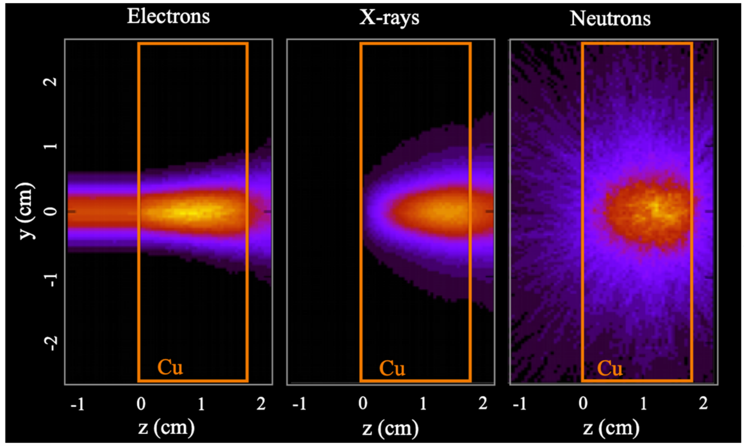
Highest performance with a_0 = 4.5, 800 nm thick Au targets, pre-pulse of 1.9 mJ at t= -60 ns

- >20% conversion efficiency from laser energy to E>0.5 MeV electrons

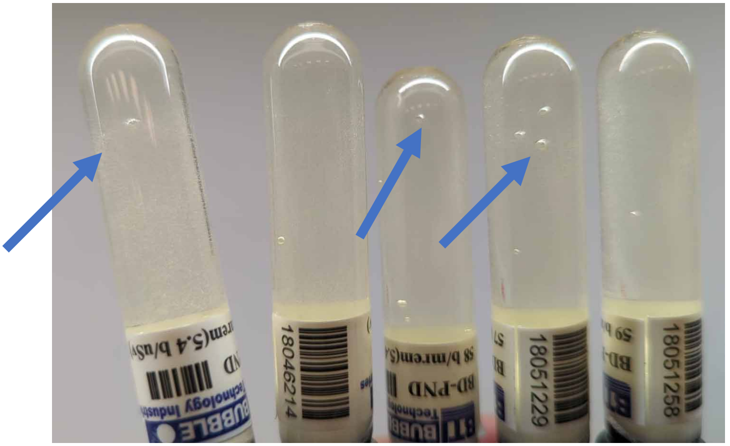
- We used the electron beam to generate neutrons
  - 1 cm thick ^{238}U converter
  - 3×10^5 neutrons per shot

(assuming a 4π distribution)





BUBBLES DOSIMETERS

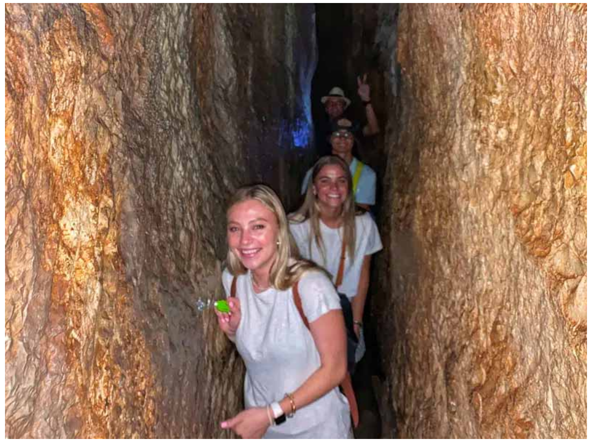


A PLASMA GUIDED COMPTON SOURCE

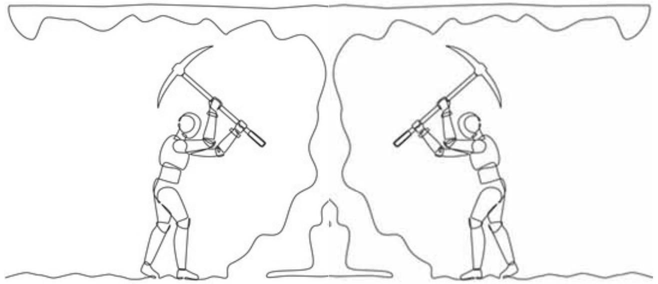
SILOAM TUNNEL

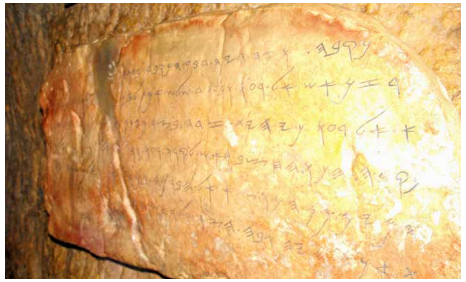
A water tunnel that was carved within the City of David, during the reign of Hezekiah of Judah, 7th century BC

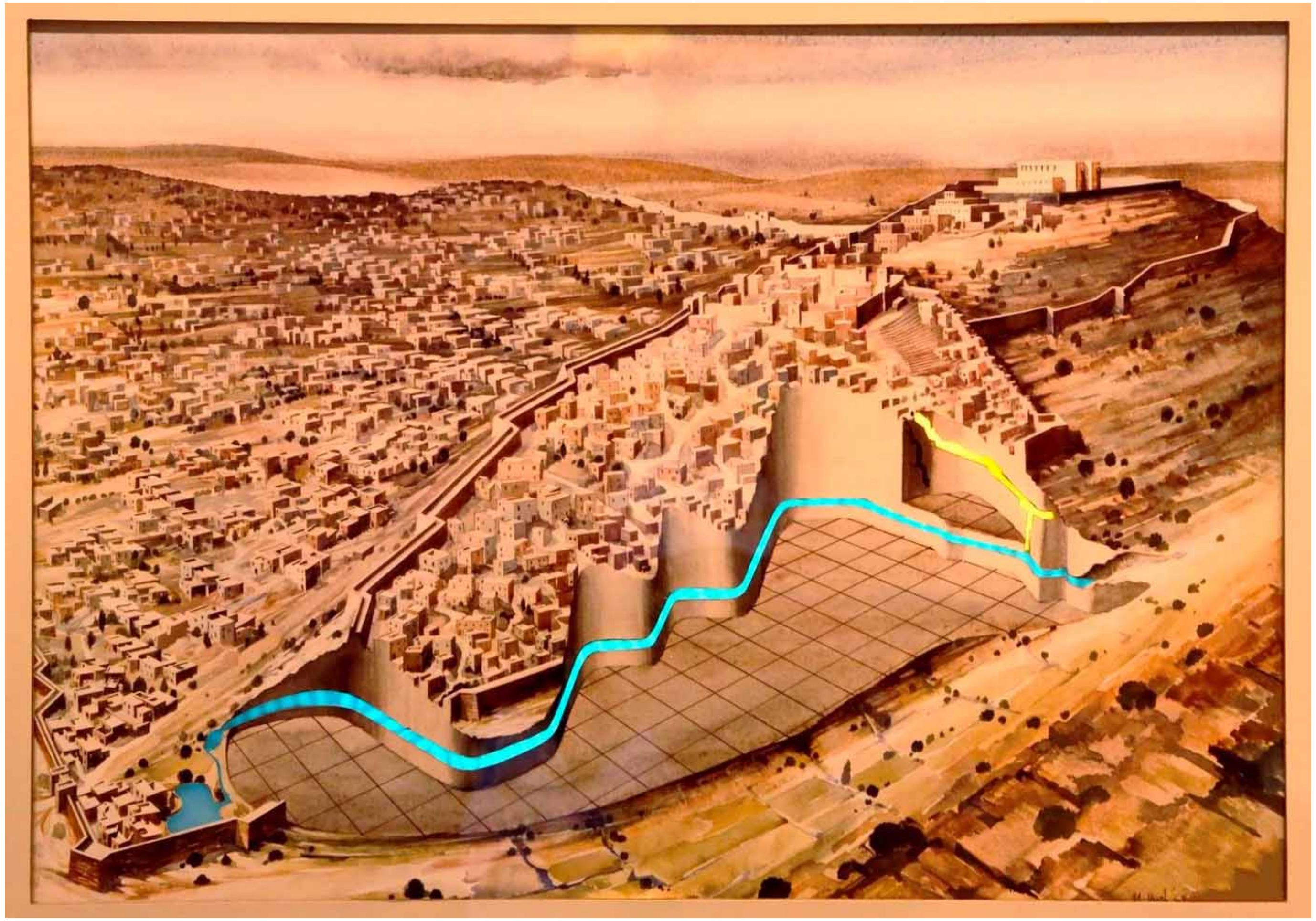
- One of Jerusalem’s best tourist attractions (in Summer)



- Engineering marvel: The tunnel was carved from both direction. The workers met in the middle.







PLASMA GUIDED COMPTON SOURCE

Generate Compton photons by two counter propagating DLA channels

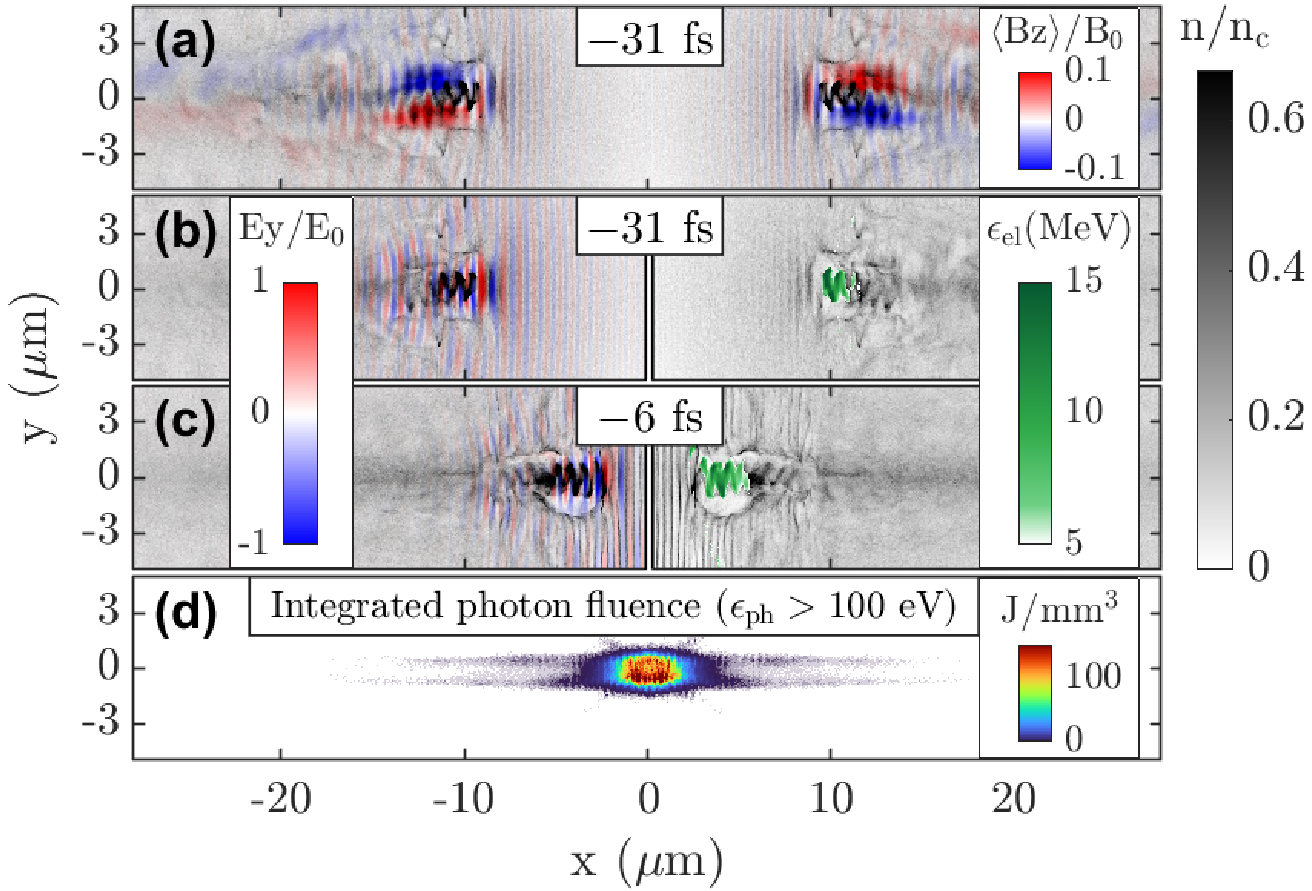
- Take advantage of:

  (1) Increased E fields resulting from self-focusing in the plasma

  (2) Sub-µm electron source-size

  (3) High electron charge

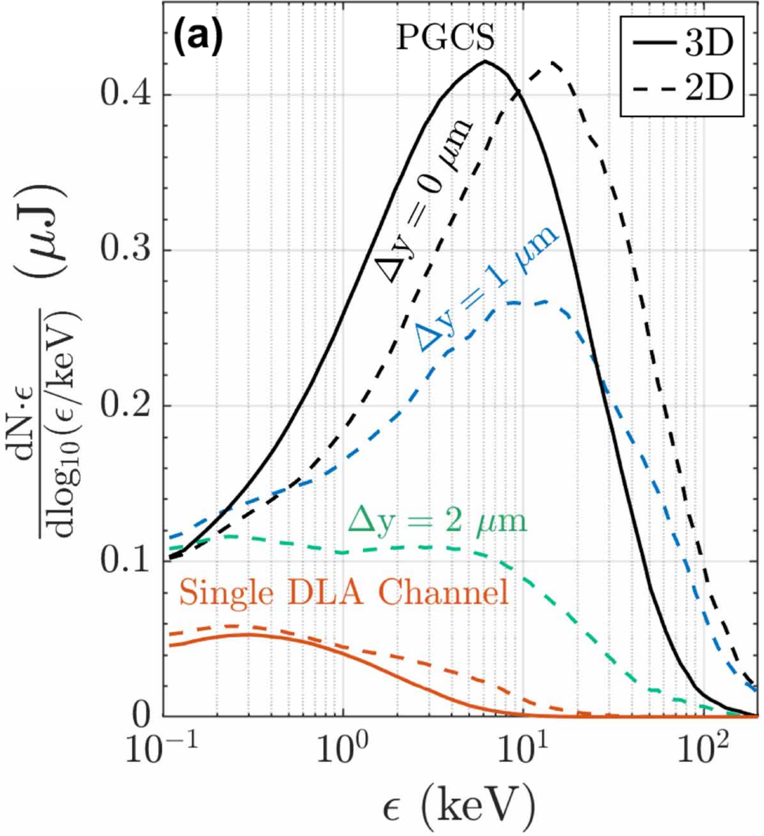
Simulations for a table-top 1J / 30 fs laser



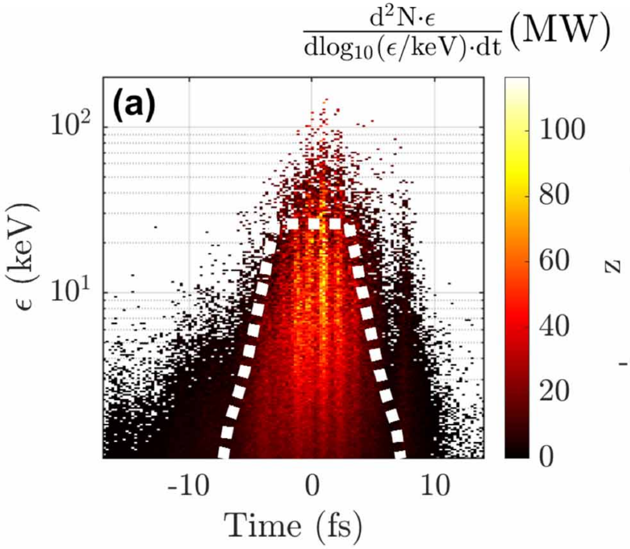
PLASMA GUIDED COMPTON SOURCE

Generate Compton photons by two counter propagating DLA channels

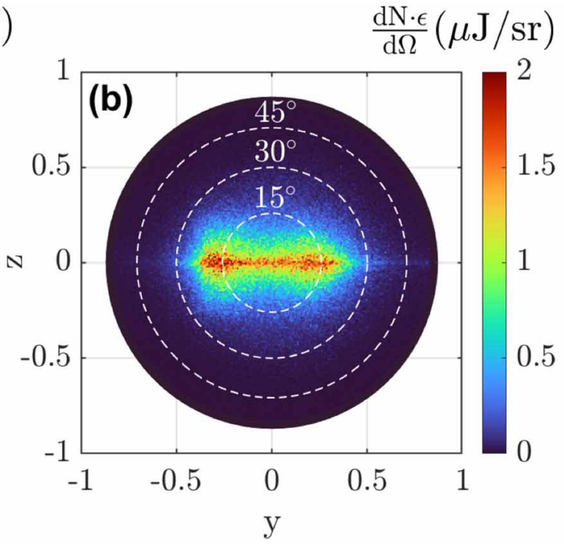
Spectral peak: 5 keV



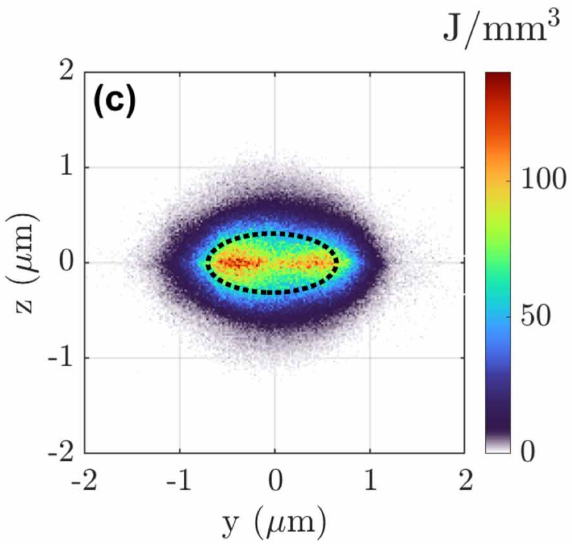
Duration: ~12 fs



Divergence: 20˚

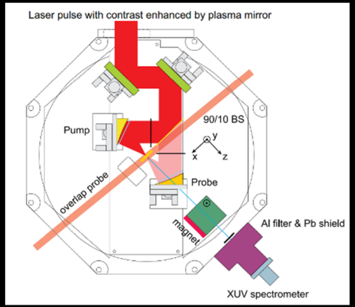


Source size: ~1.6 μm



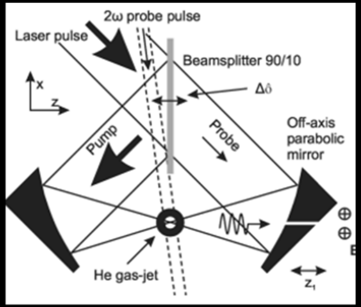
COMPARISON TO OTHER LASER-PLASMA COMPTON SOURCES

Two beams interacting with a solid foil



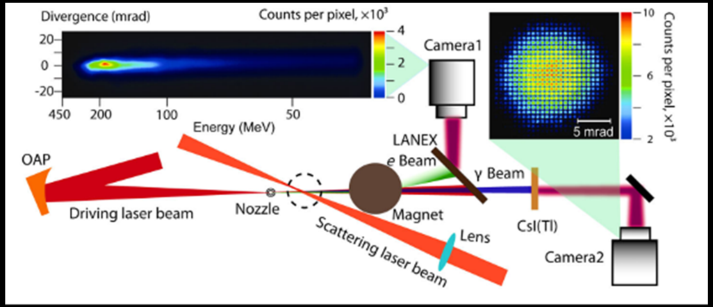
A Paz (2012)

Two beams interacting in a gas jet



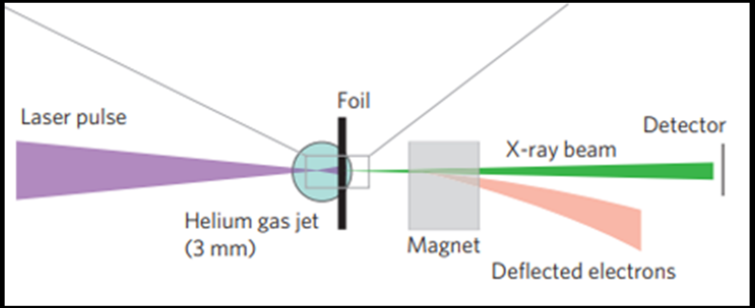
H. Schwoerer (2006)

Compton scattering off LWFA electrons



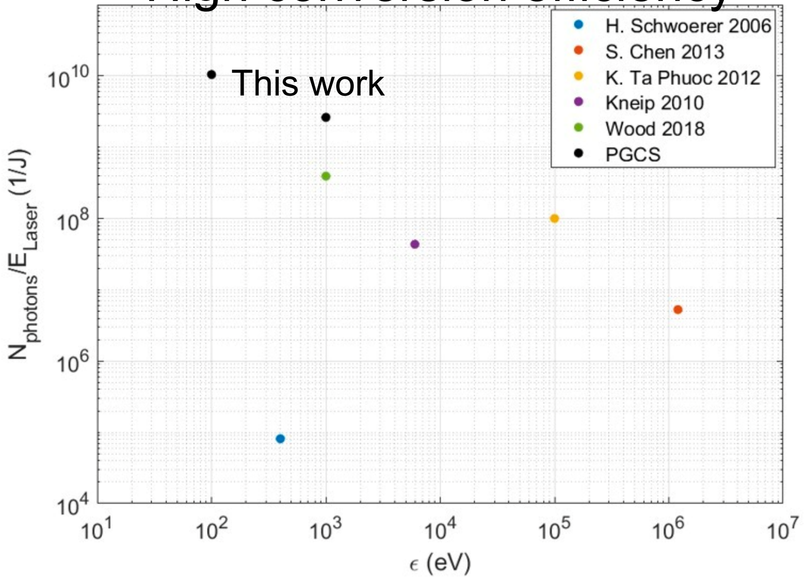
S. Chen (2013)

Compton scattering off LWFA electrons with reflection off a Plasma Mirror

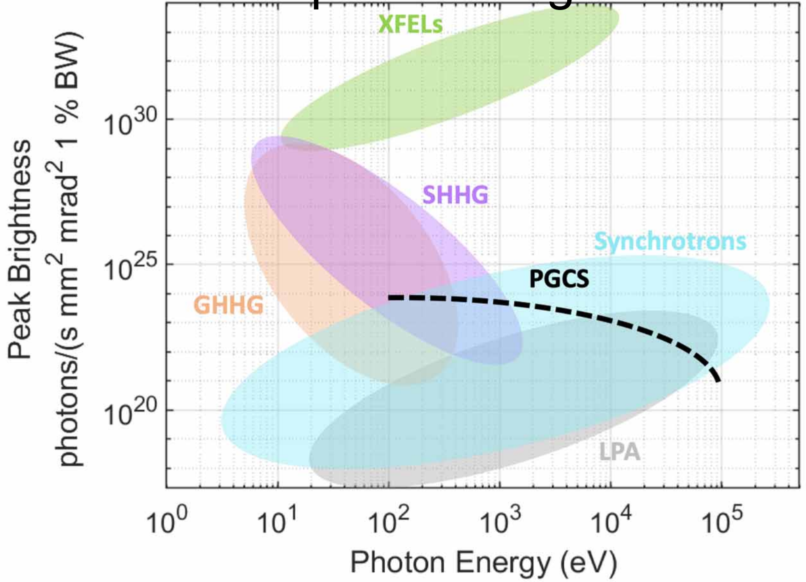


K. Ta Phuoc (2012)

High conversion efficiency

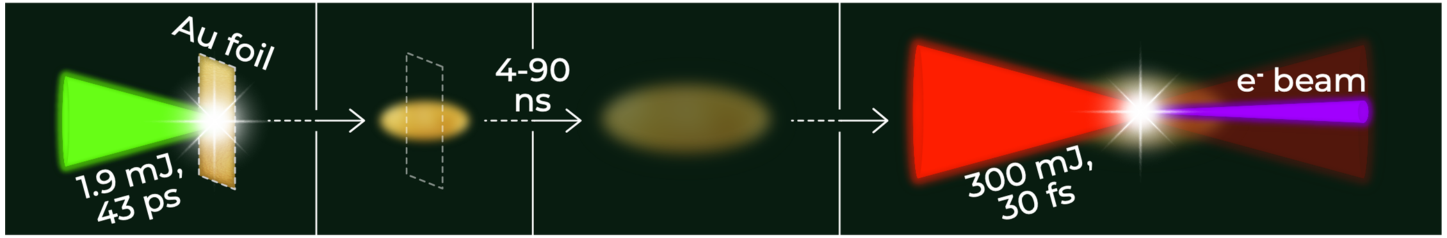


Competitive Brightness

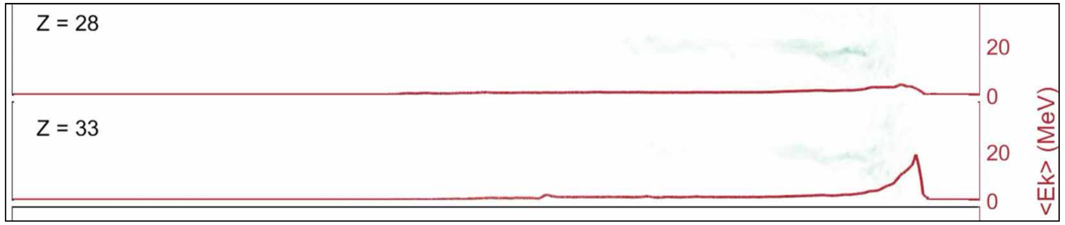


SUMMARY

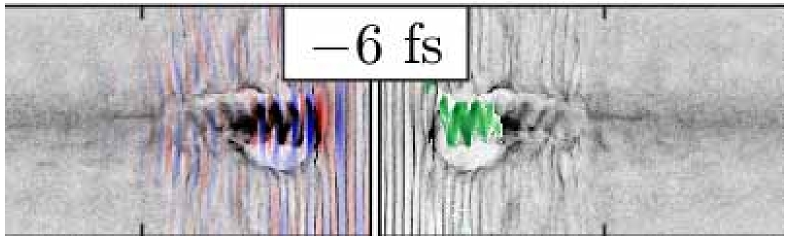
- Direct laser acceleration - Efficient conversion of eV photons to MeV electrons



- Target's atomic number must be matched with the laser intensity for efficient acceleration



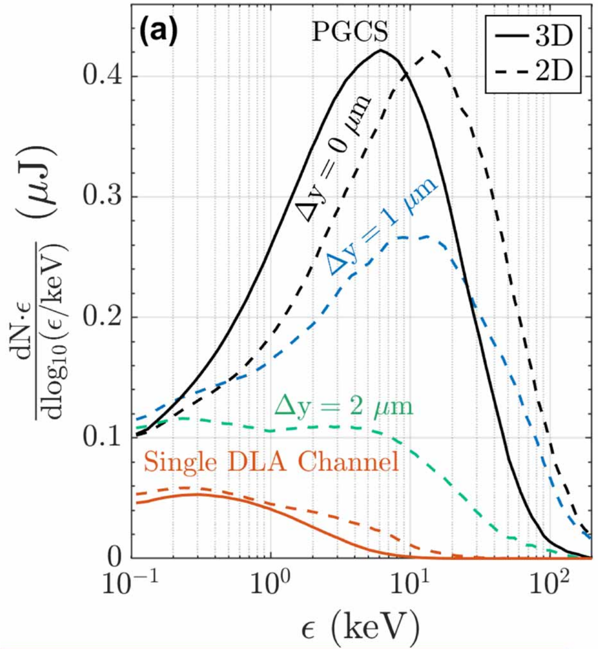
- A bright Compton source formed by two DLA channels (PIC study)



1J / 30 fs laser:

~5 KeV photons

10^{23} photons/ s mm^2 mrad^2 1% BW



- 2024: Experimental realization at TAU

THANK YOU