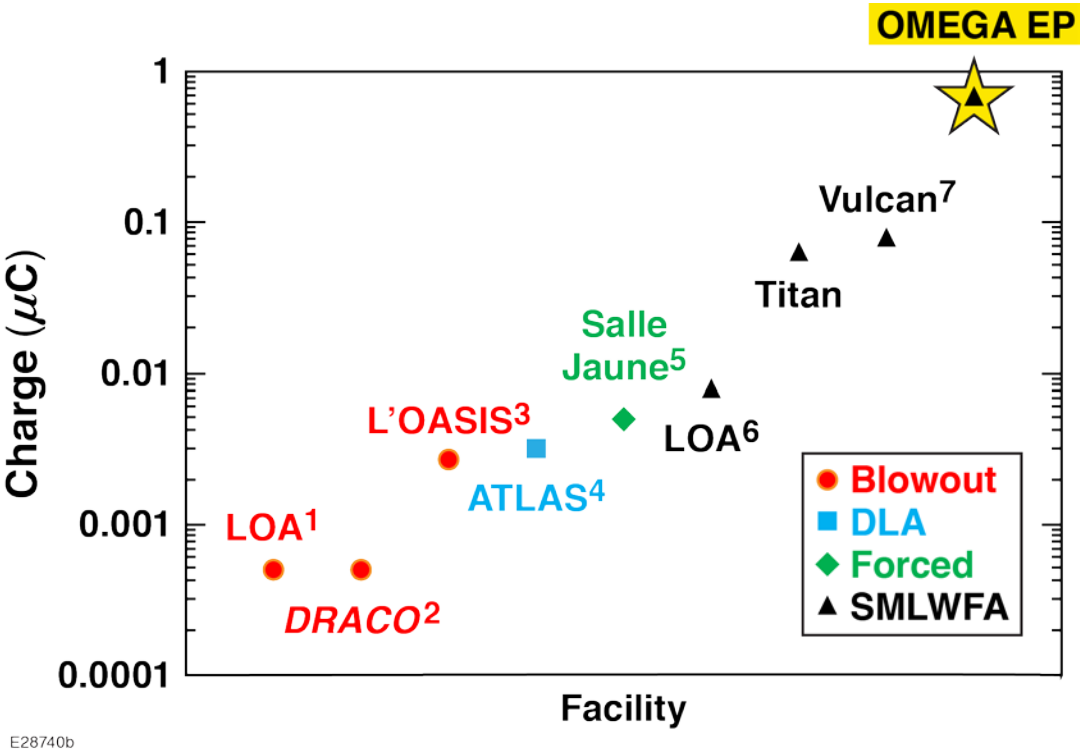
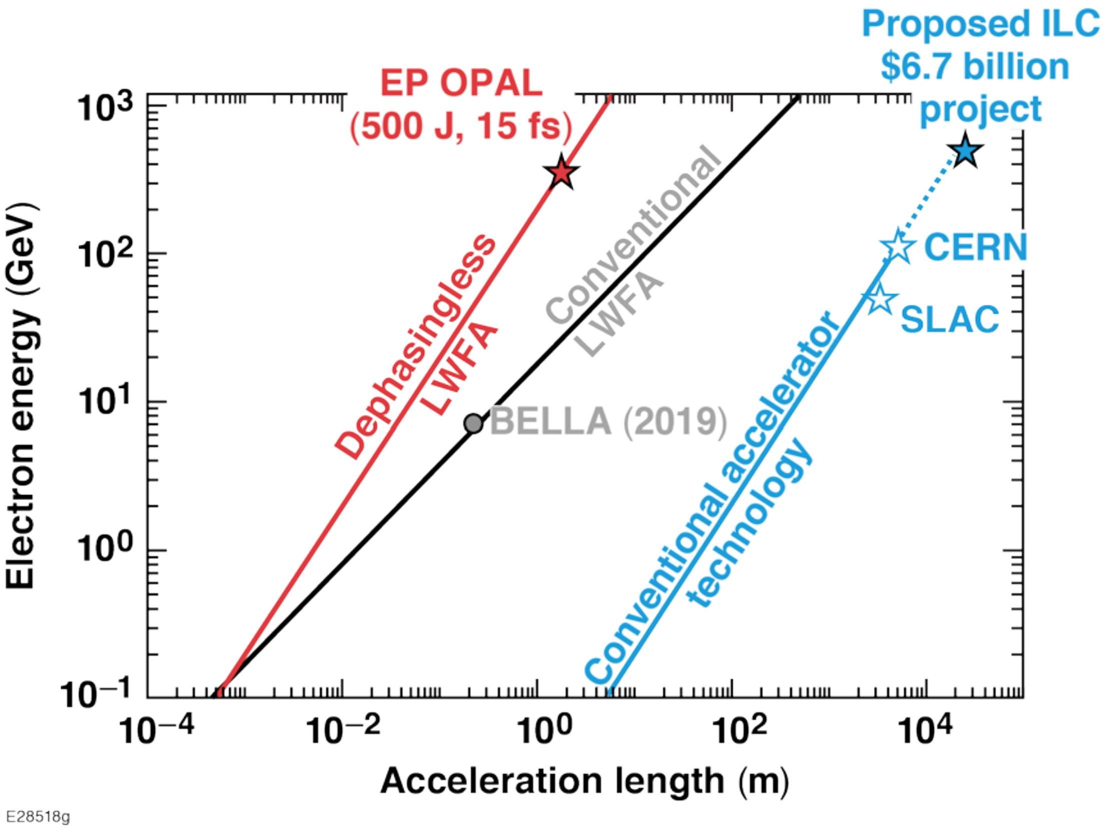
New Developments in Laser Wakefield Acceleration at the Laboratory for Laser Energetics





J. L. Shaw
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Laboratory for Laser Energetics

Hilary Seminar
ZOOM
25 January 2021

[1] J. Faure *et al.*, Nature 431, 541 (2004). | [2] J. P. Couperus *et al.*, Nat. Commun. 8, 487 (2017). | [3] C. G. R. Geddes *et al.*, Nature 431, 538 (2004). | [4] C. Gahn *et al.*, Phys. Rev. Lett. 83, 4772 (1999). | [5] Z. Najmudin *et al.*, Phys. Plasmas 10, 2071 (2003). | [6] M. I. K. Santala *et al.*, Phys. Rev. Lett. 86, 1227 (2001). | [7] V. Malka *et al.*, Phys. Plasmas 8, 2605 (2001).

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Summary

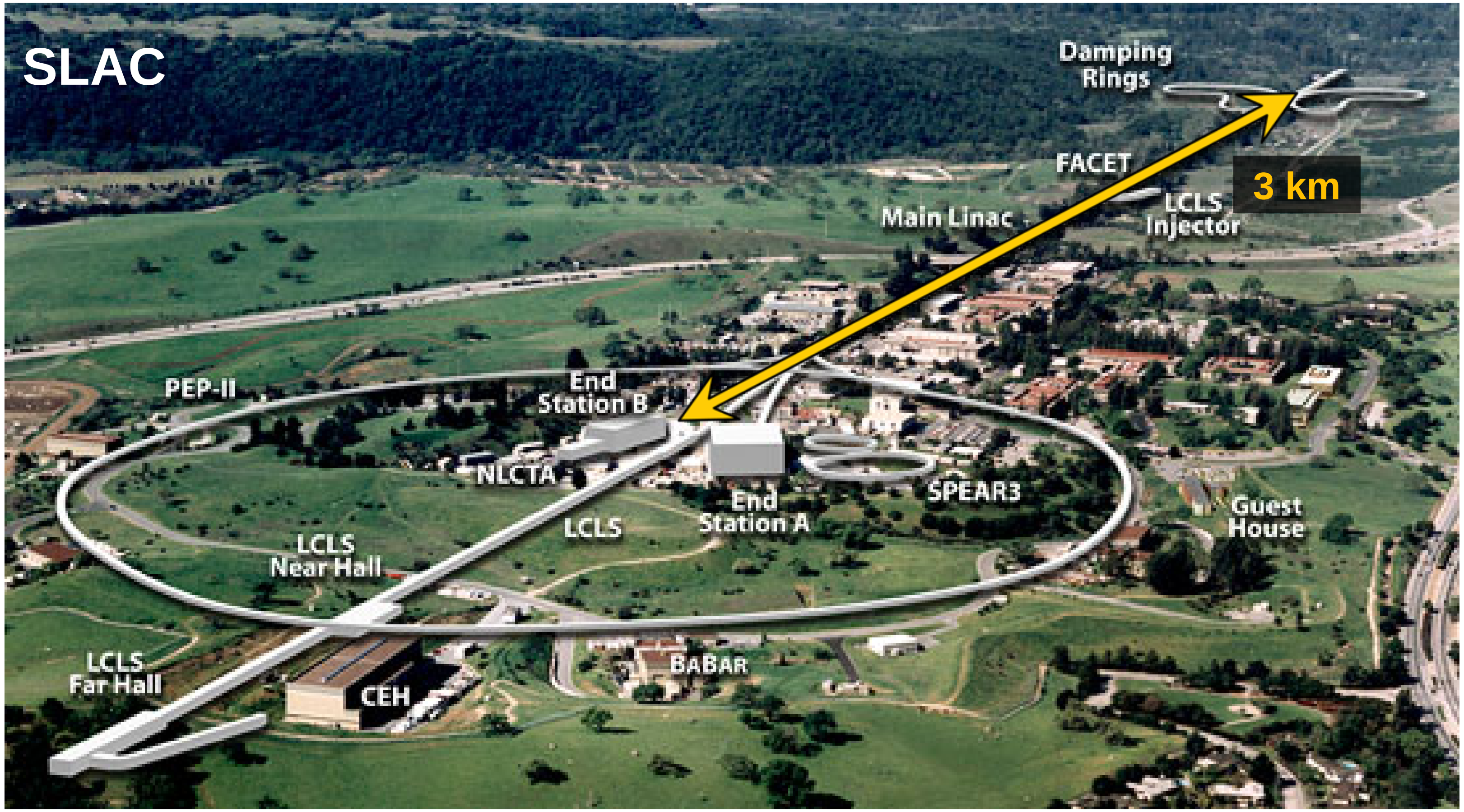
The Laboratory for Laser Energetics (LLE) is exploring novel means to advance the field and application of laser wakefield accelerators (LWFA)

- We have recently demonstrated record-breaking electron beam charge with the acceleration of a > 0.7 uC electron beam from a self-modulated LWFA driven by the OMEGA EP laser

- Our new “achromatic flying focus” concept, a method of spatiotemporally controlling laser propagation, shows promise as a means to circumvent the fundamental limitations of LWFA and offers a path to a single-stage 500 GeV LWFA

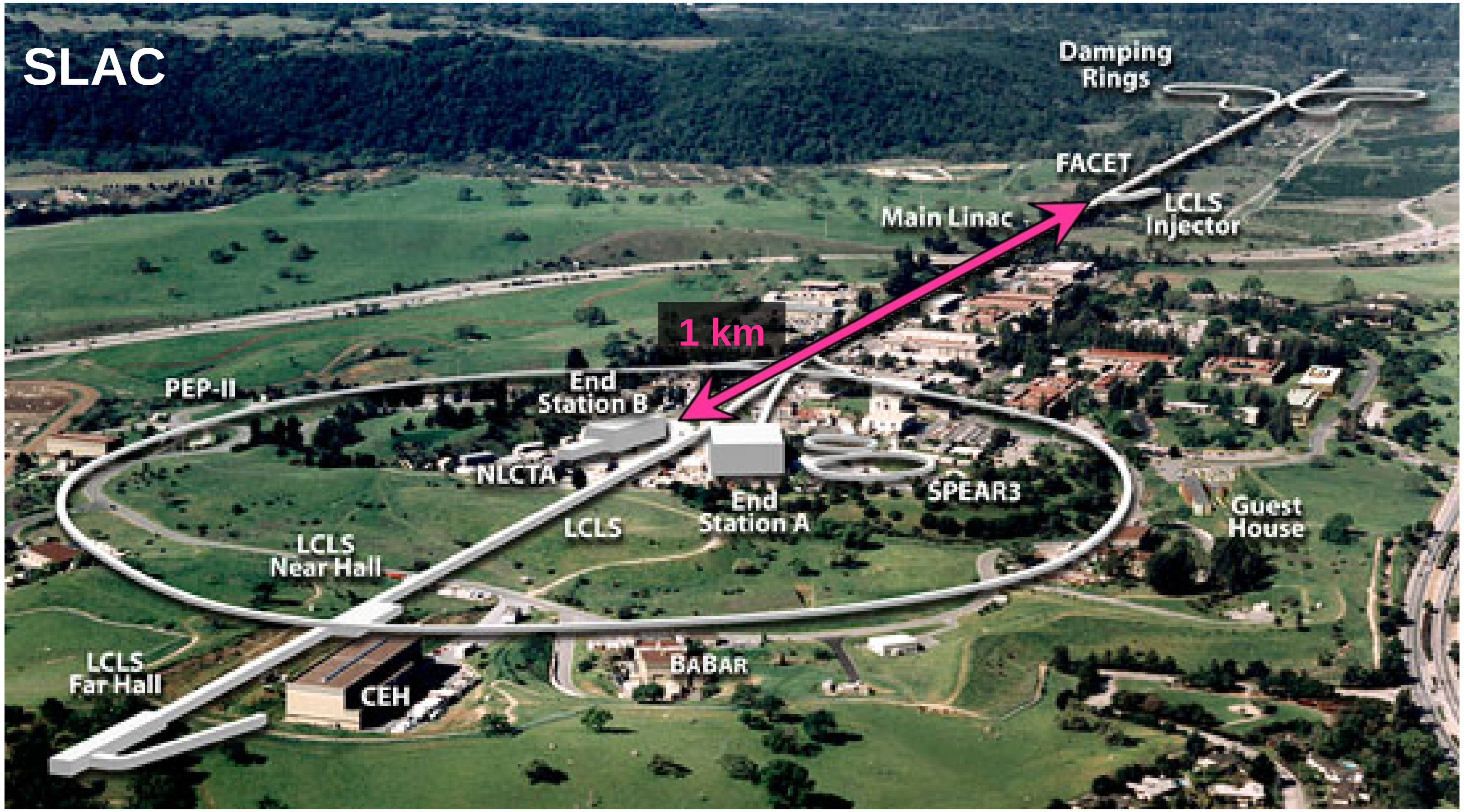
Why Plasma Accelerators?

Electron beams from conventional, radio-frequency accelerators are key scientific tools



http://www-group.slac.stanford.edu/com/images/gallery/general-lab.htm

Advanced x-ray sources also rely on kilometer-scale electron accelerators



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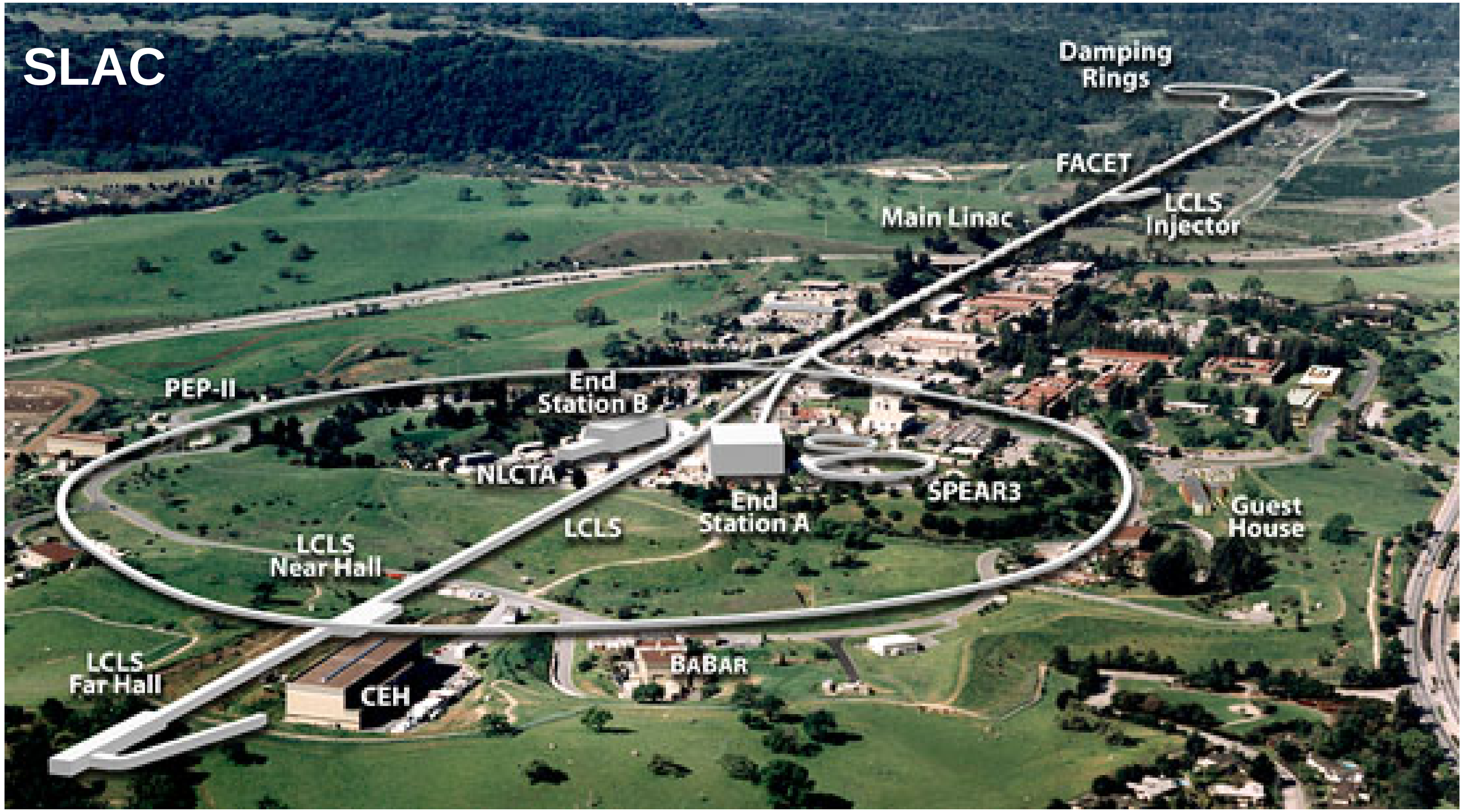
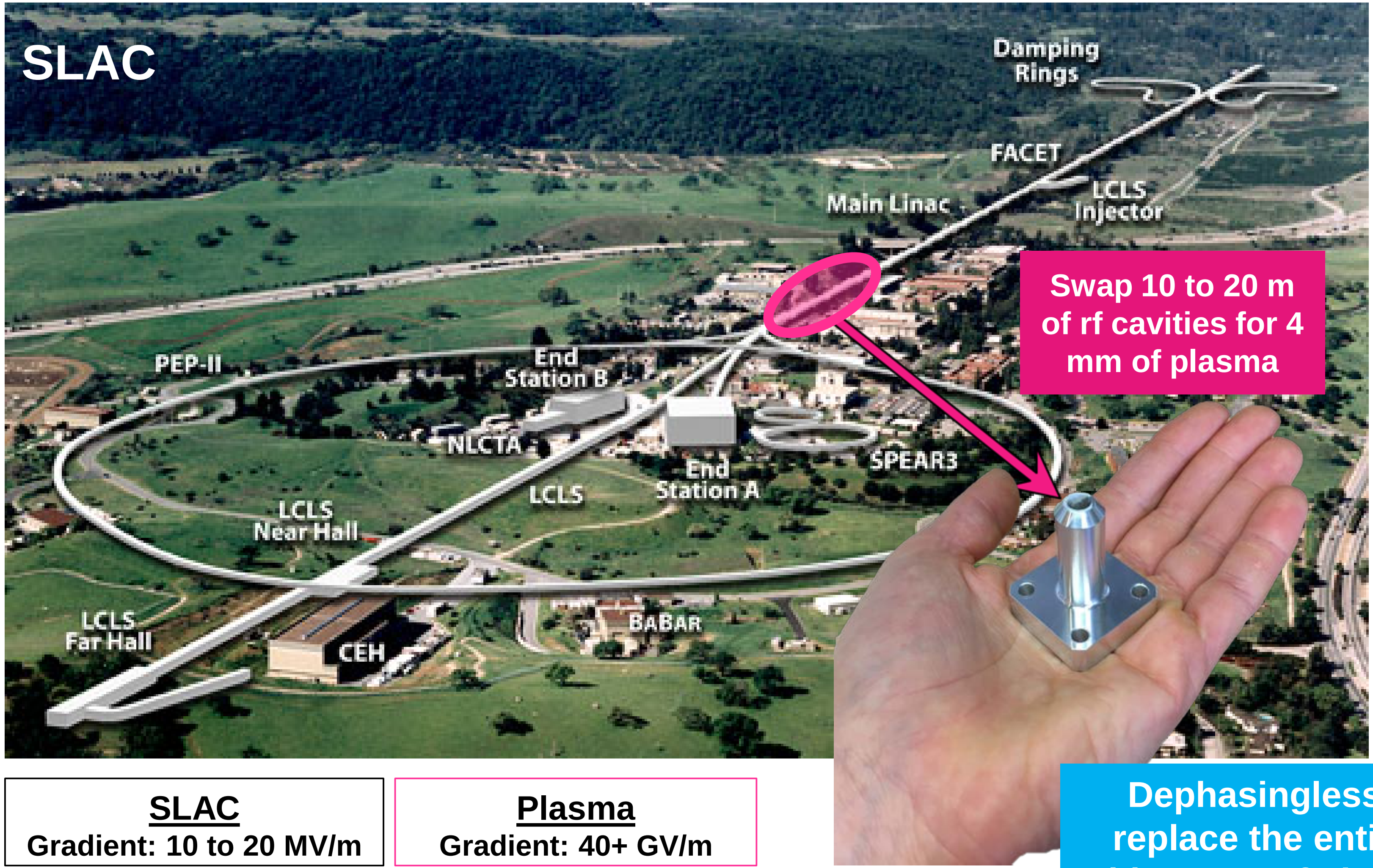
Can we develop a high-performing, compact electron and x-ray source?



SLAC	**Plasma**
Gradient: 10 to 20 MV/m	**Gradient: 40+ GV/m**

http://www-group.slac.stanford.edu/com/images/gallery/general-lab.htm

Can we put SLAC in your hand?



Swap 10 to 20 m of rf cavities for 4 mm of plasma

SLAC	Plasma
Gradient: 10 to 20 MV/m	Gradient: 40+ GV/m

Dephasingless LWFA could replace the entire SLAC linac with 25 cm of plasma accelerator

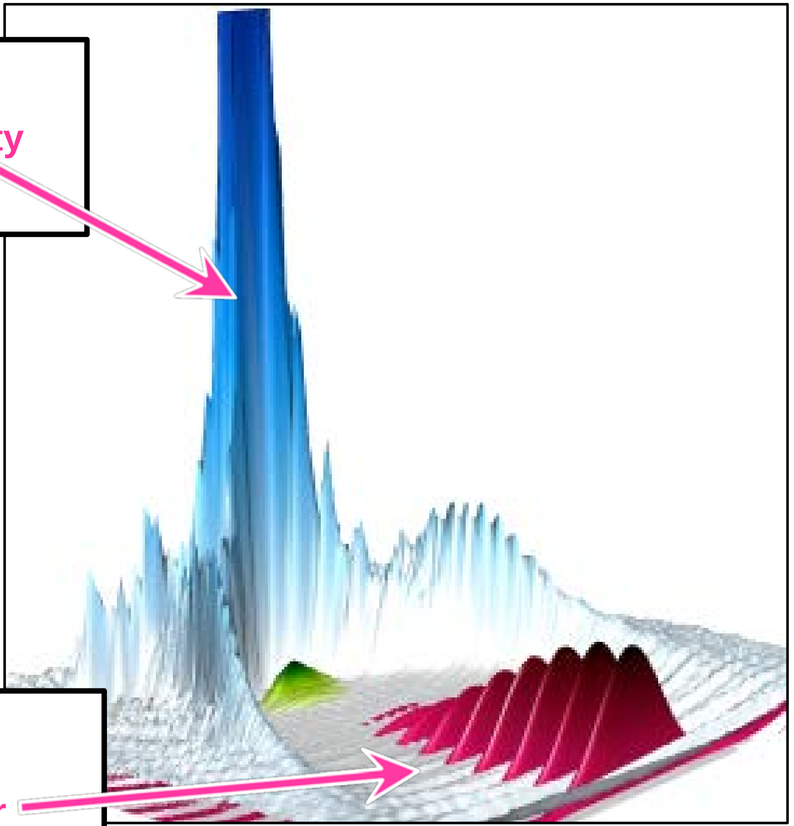
Physical Picture of LWFA

Physical Picture

LWFA is somewhat analogous to wakeboarding

Wake in water
meter scale

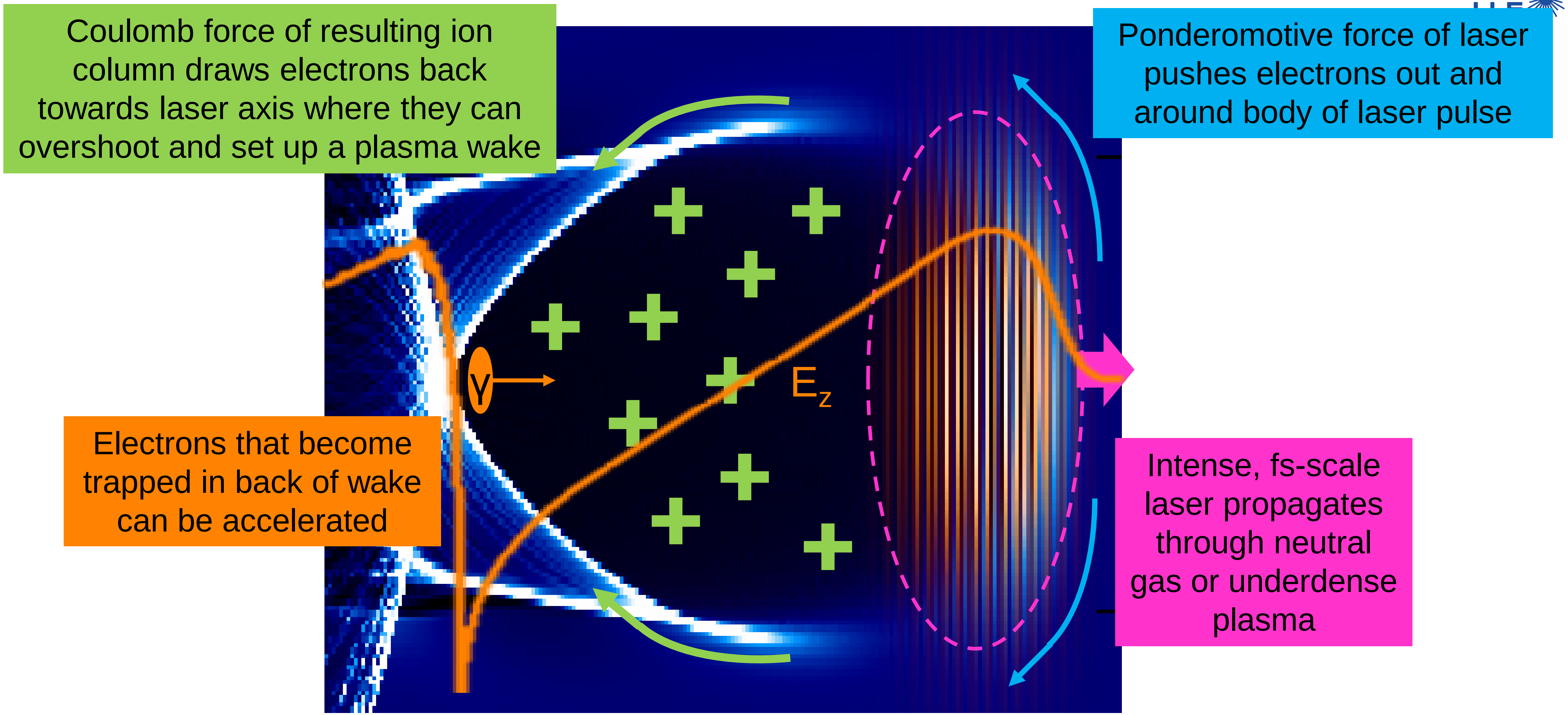
Wake in plasma
micron scale



Wakefield
Height versus Density modulations

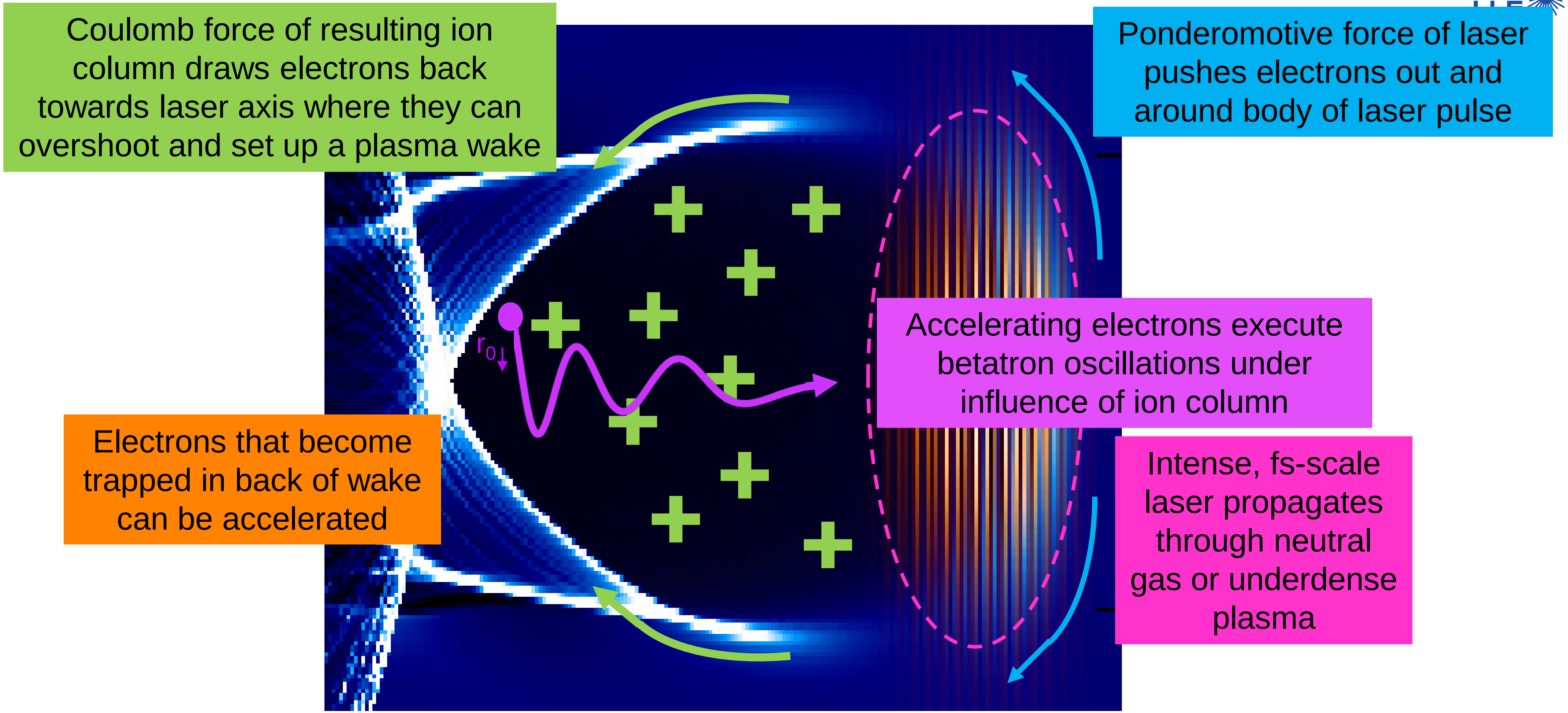
Wake driver
Boat versus Laser

LWFA in the Blowout Regime*



* W. Lu et al., Phys. Rev. Spec. Top. – Accel. Beams 10, 061301 (2007).

LWFA in the Blowout Regime*

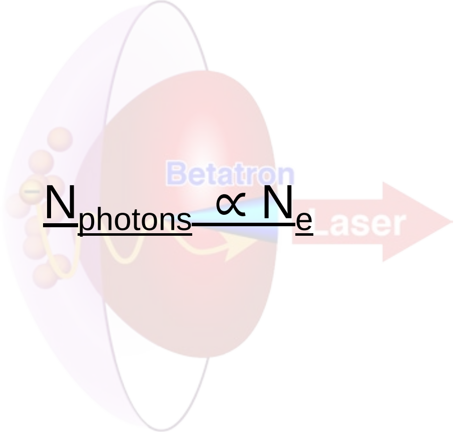


* W. Lu et al., Phys. Rev. Spec. Top. – Accel. Beams 10, 061301 (2007).

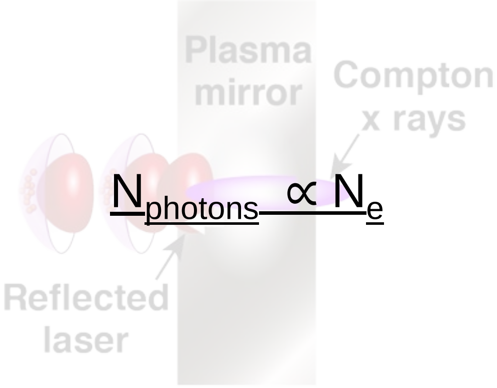
Project 1:

High-Charge Electron Beams from Self-Modulated LWFA (SMLWFA)

The high-energy electrons from LWFAs can provide compact sources for conversion to photons and positrons



$N_{photons} \propto N_e$



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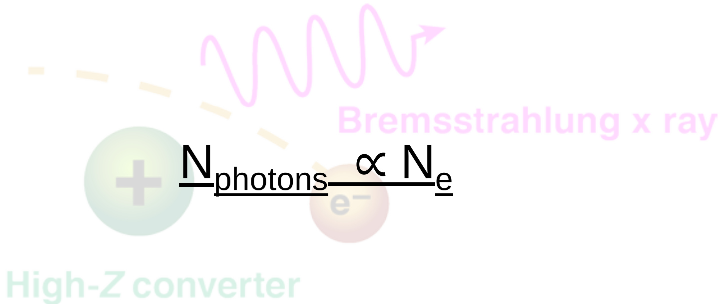

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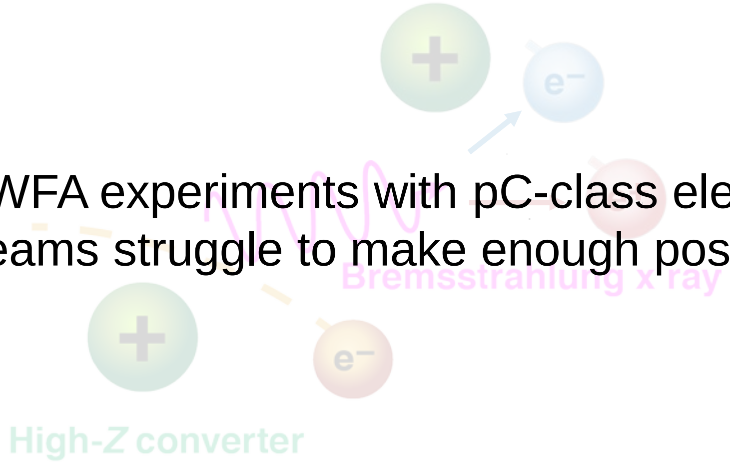


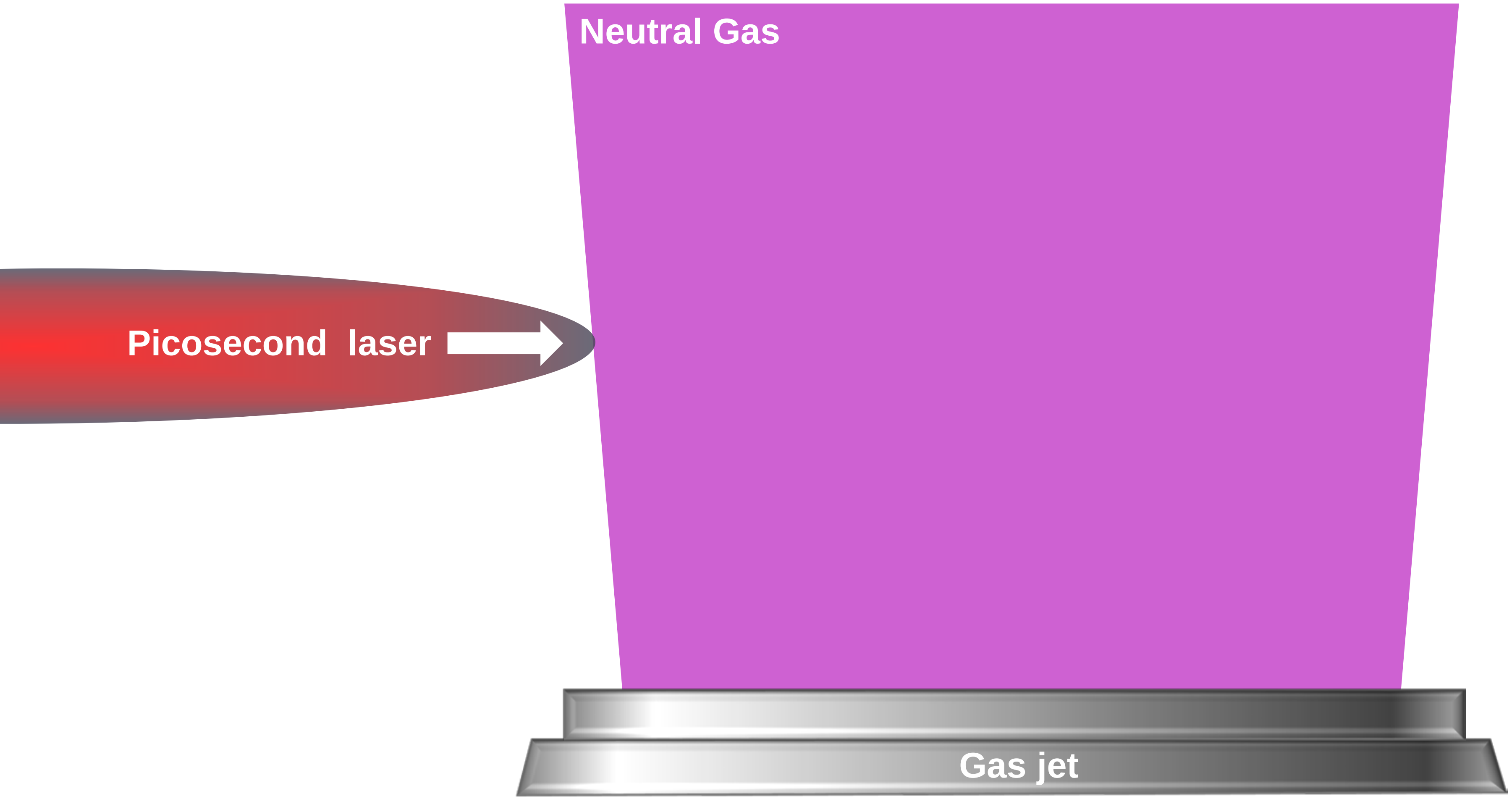
LWFA experiments with pC-class electron beams struggle to make enough positrons

Hard, Bright X Ray Sources

Positron Sources

Ps-scale, kJ-class lasers can drive self-modulated LWFA, which can produce sizably more charge

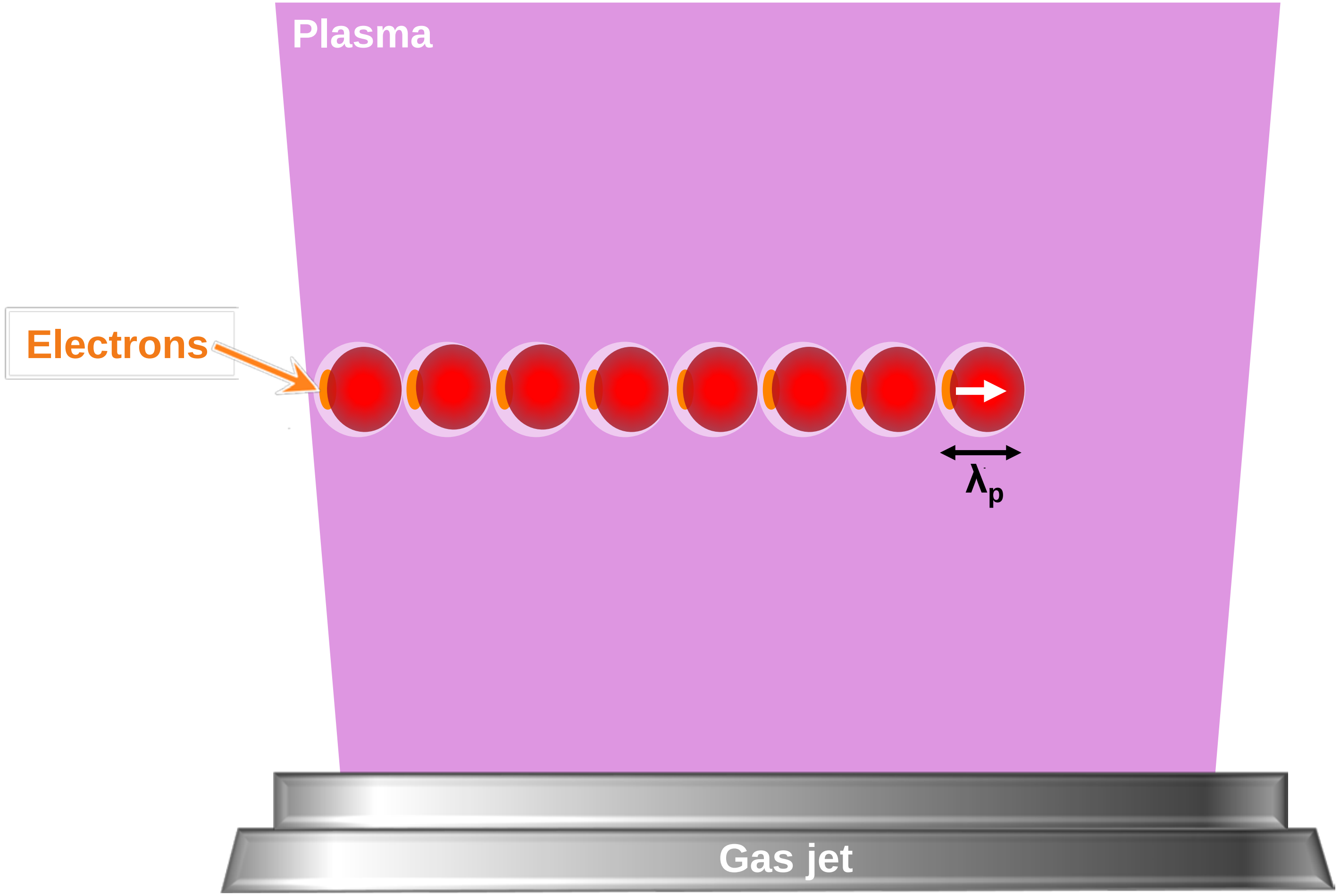
In SMLWFA, a laser pulse with cτ > λ_p enters a plasma and becomes modulated at λ_p via the Raman forward scattering* and/or self-modulation** instabilities



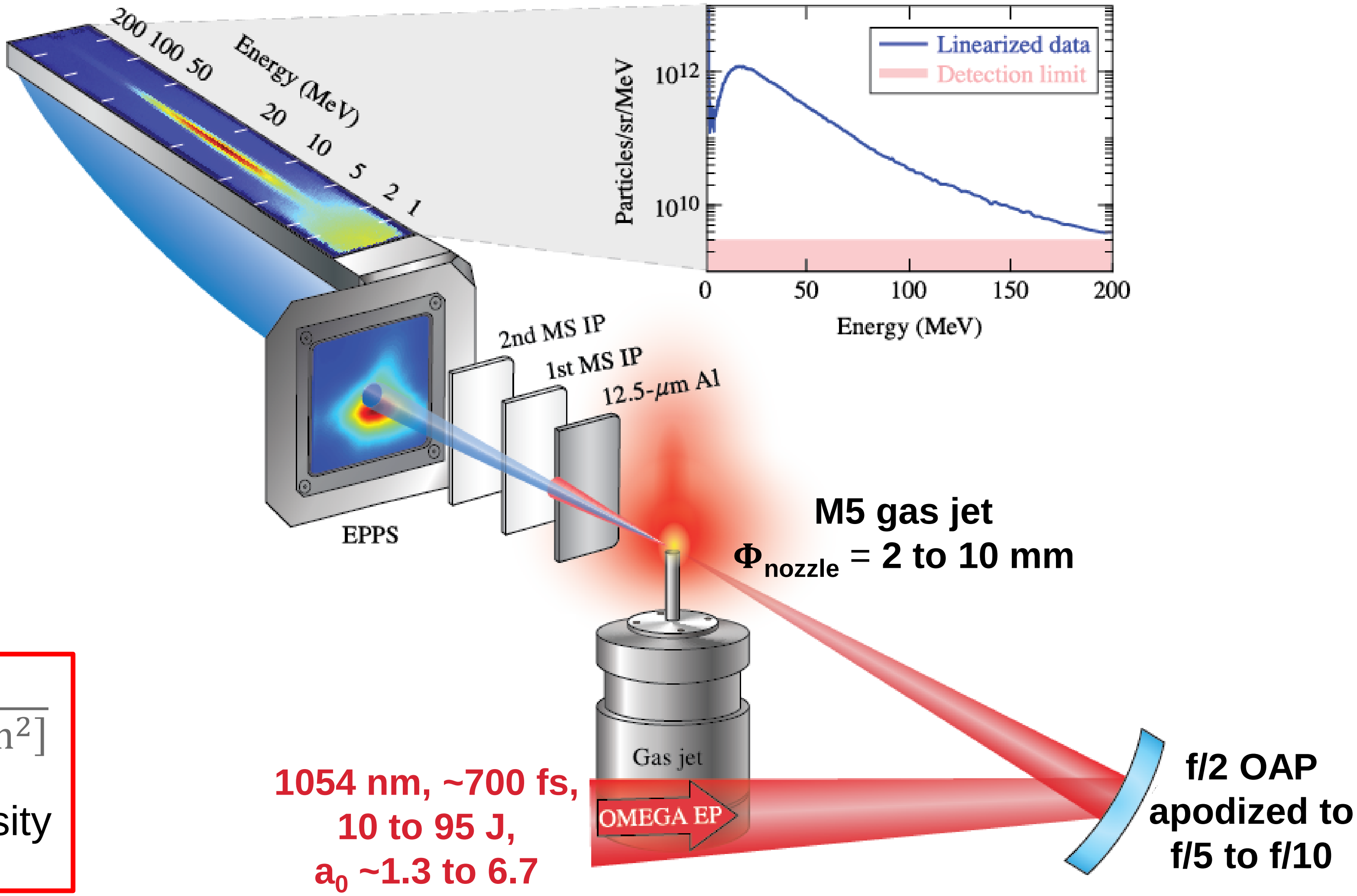
* A. Modena *et al*., Nature 377, 606 (1995).
C. Joshi *et al*., Phys. Rev. Lett. 47, 1285 (1981).

** E. Esarey *et al*., Phys. Rev. Lett. 72, 2887 (1994).
N. E. Andreev *et al*., Pisma Zh. Eksp. Teor. Fiz. 55, 551 (1992).
T. M. Antonsen and P. Mora, Phys. Rev. Lett. 69, 2204 (1992).
P. Sprangle *et al*., Phys. Rev. Lett. 69, 2200 (1992).

Modulations lead to a train of laser micropulses coherently driving plasma waves whose longitudinal electric fields trap and accelerate electrons to relativistic energies



SMLWFA experiments were performed on OMEGA EP

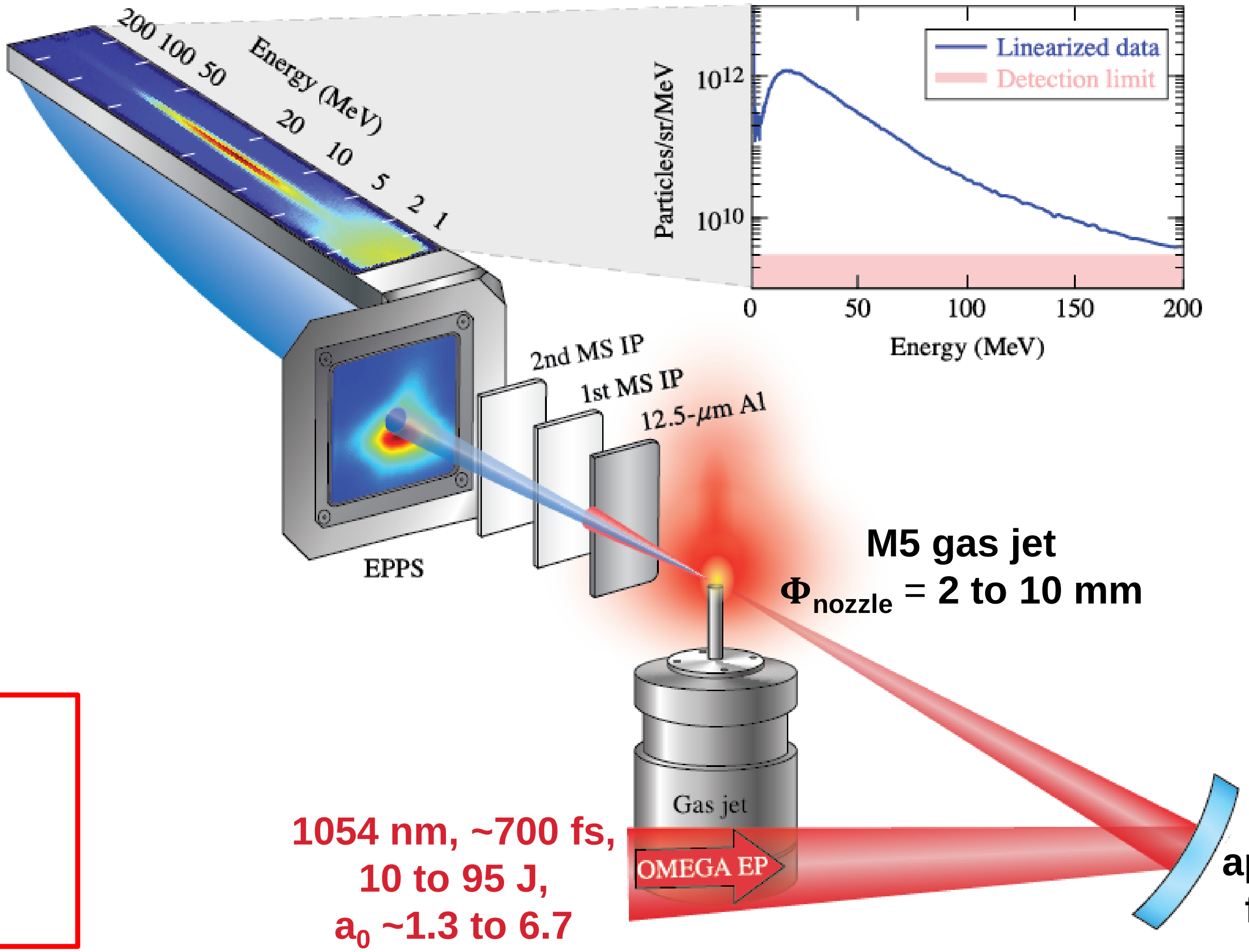


$$a_0 = \frac{eE_0}{mc\omega_0} \propto \sqrt{I_0[W/cm^2]}$$

I_0 = Peak laser intensity

EPPS: electron–positron–proton spectrometer
OAP: off-axis parabola

SMLWFA experiments were performed on OMEGA EP



a_0 ~ 2

↓

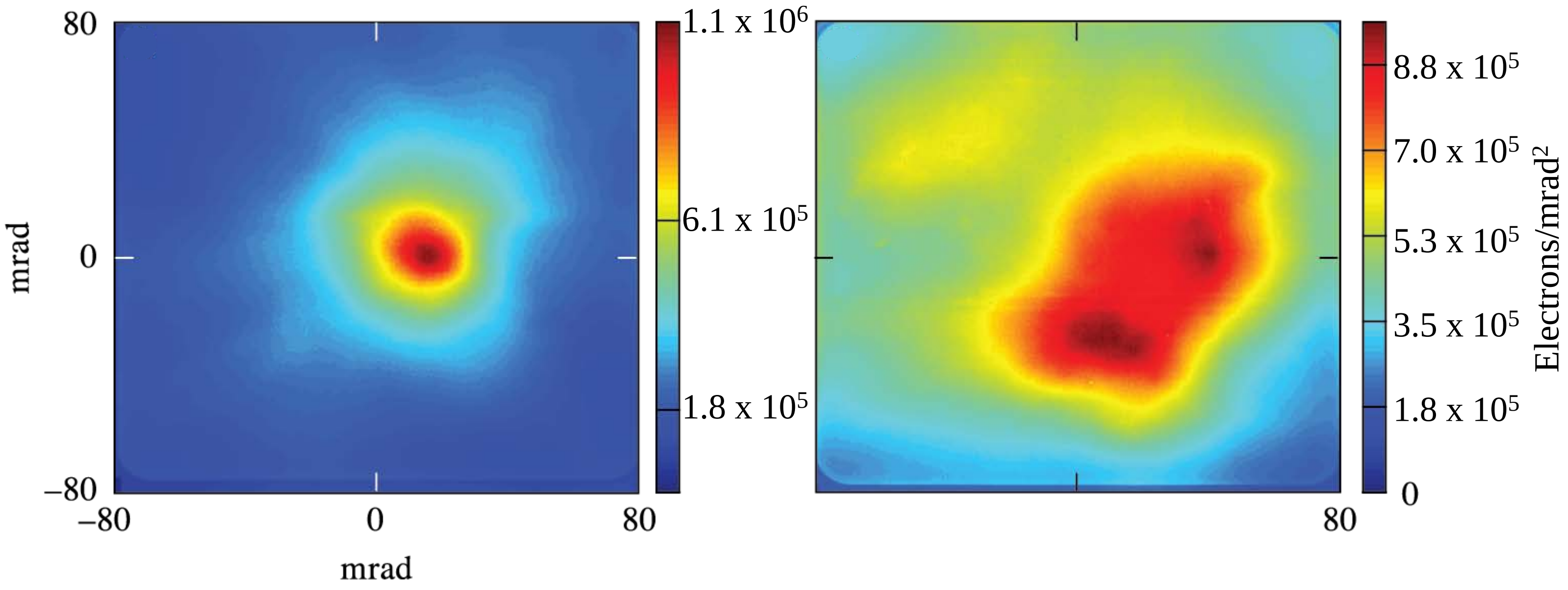
I_0 ~ 8 x 10^{18} W/cm^2

EPPS: electron–positron–proton spectrometer
OAP: off-axis parabola

Electron beams with divergences as low as 32 x 39 mrad were measured, which is significantly reduced from the next best SMLWFA divergence reported

Lowest-Divergence

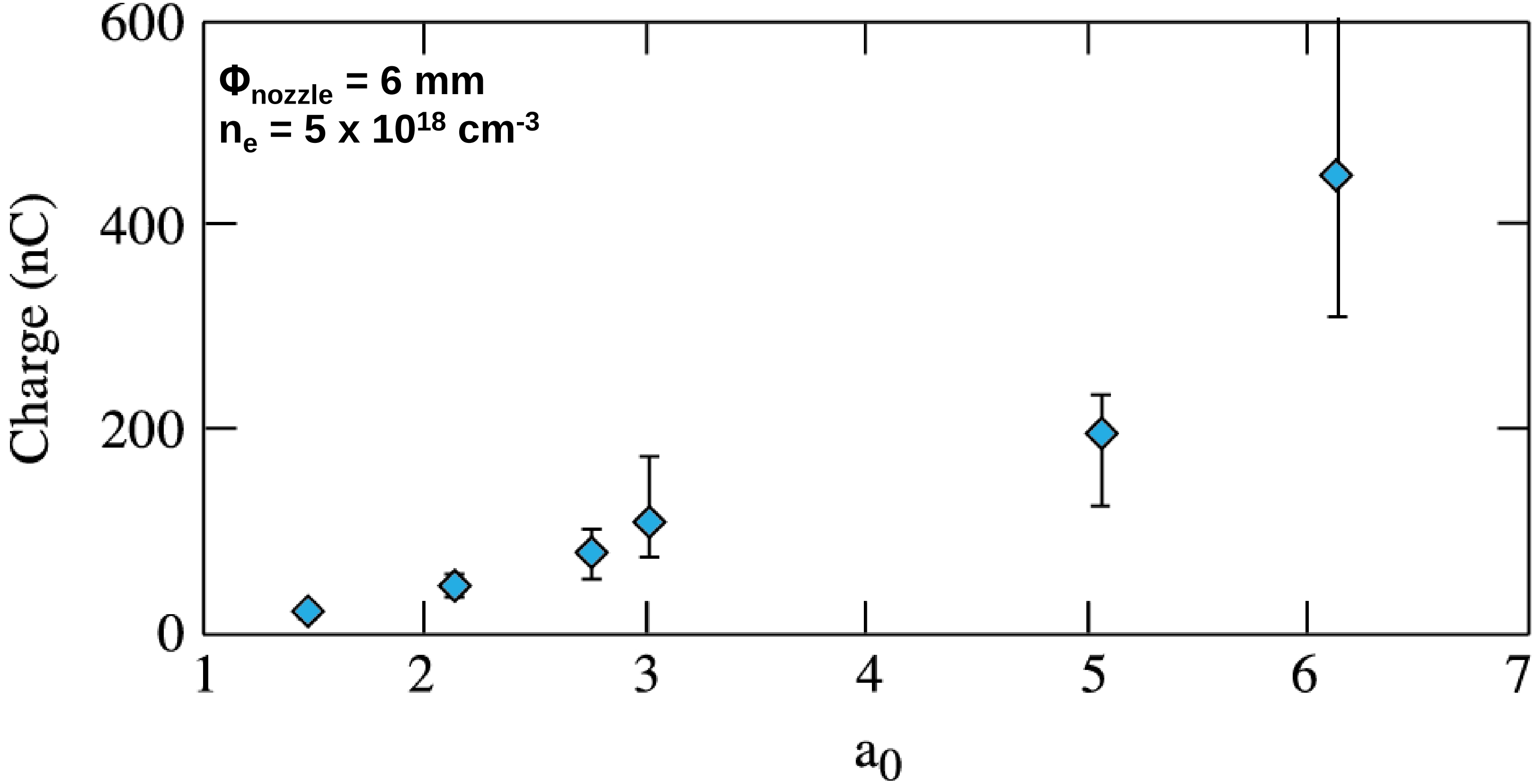
- $a_0 = 4.4$
- Φ_{nozzle} = 10 mm
- $n_e = 1.1 \times 10^{19}$ cm^{-3}
- Pointed 8 mrad



Highest-Charge

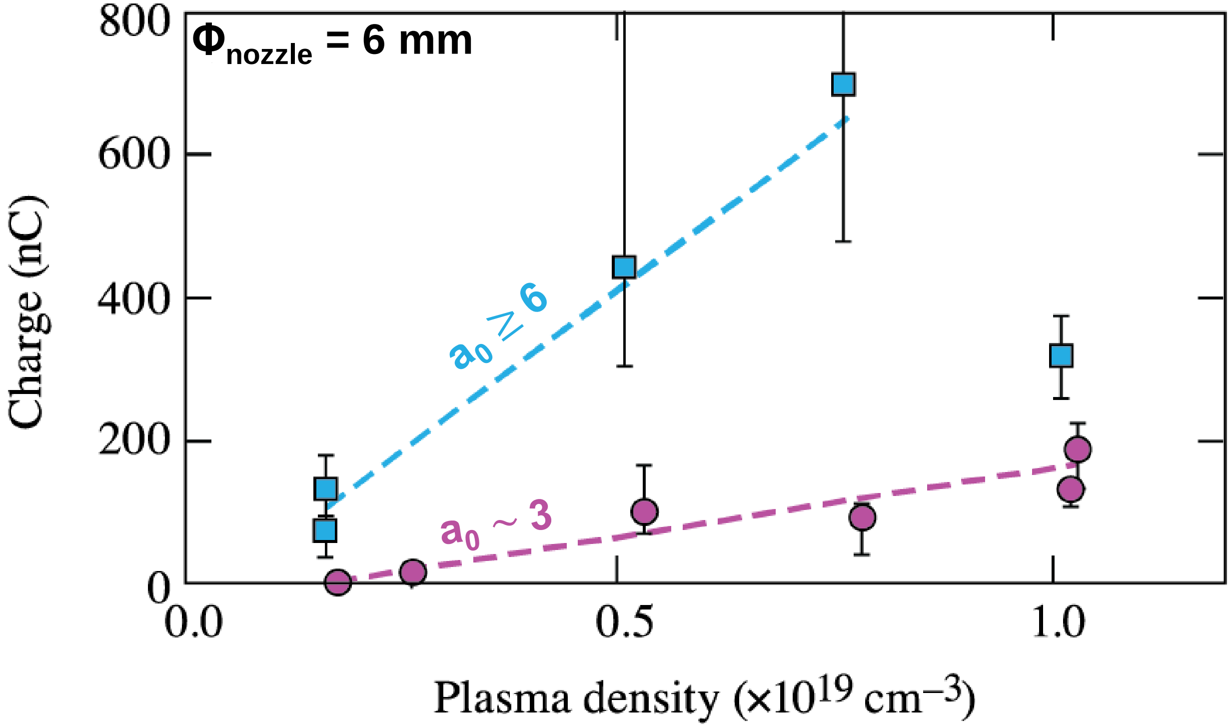
- $a_0 = 6.6$
- Φ_{nozzle} = 6 mm
- $n_e = 7.5 \times 10^{18}$ cm^{-3}

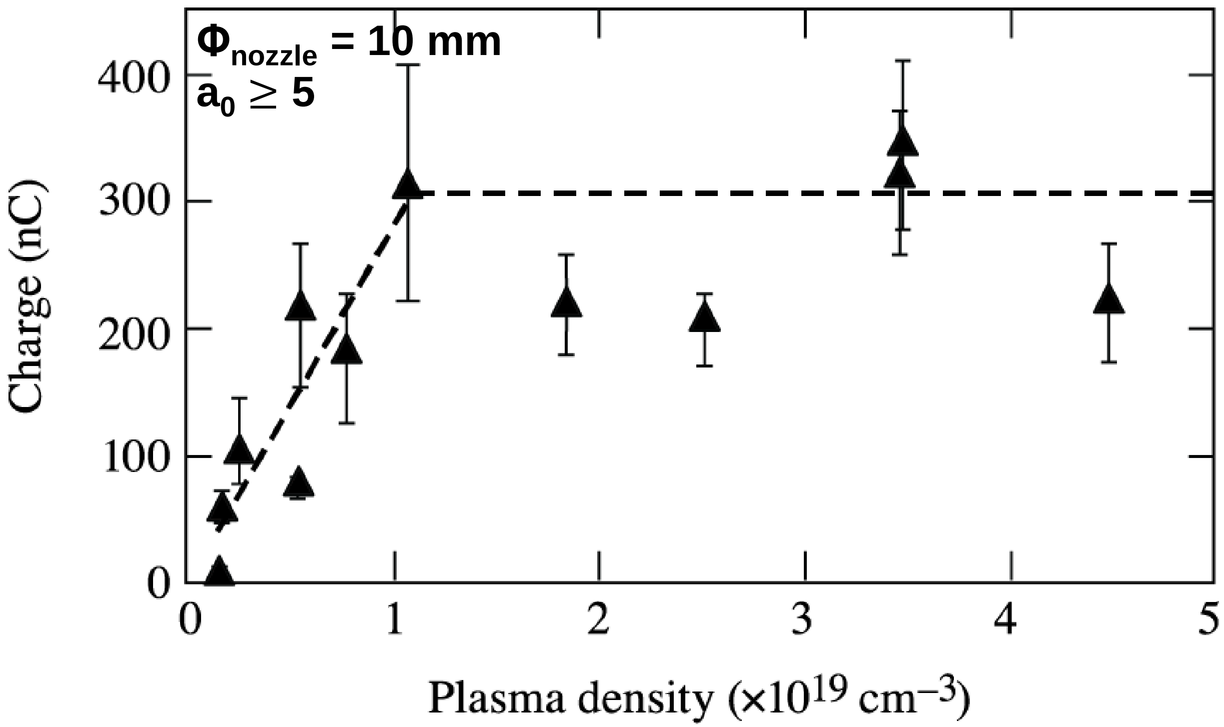
Total charge in the electron beams scales approximately linearly with a_0



Same trend was observed for:
- 6-mm-dia. nozzle at n_e = 1, 2, and 3 x 10^{19} cm^{-3}
- 4-mm-dia. nozzle at n_e = 1 x 10^{19} cm^{-3}
- 10-mm-dia. nozzle at n_e = 0.2, 0.5, 1, and 3.5 x 10^{19} cm^{-3}

The ideal regime for producing high-charge electron beams for this SMLWFA-based LPA is for $n_e \sim 1 \times 10^{19}$ cm^{-3} or less.



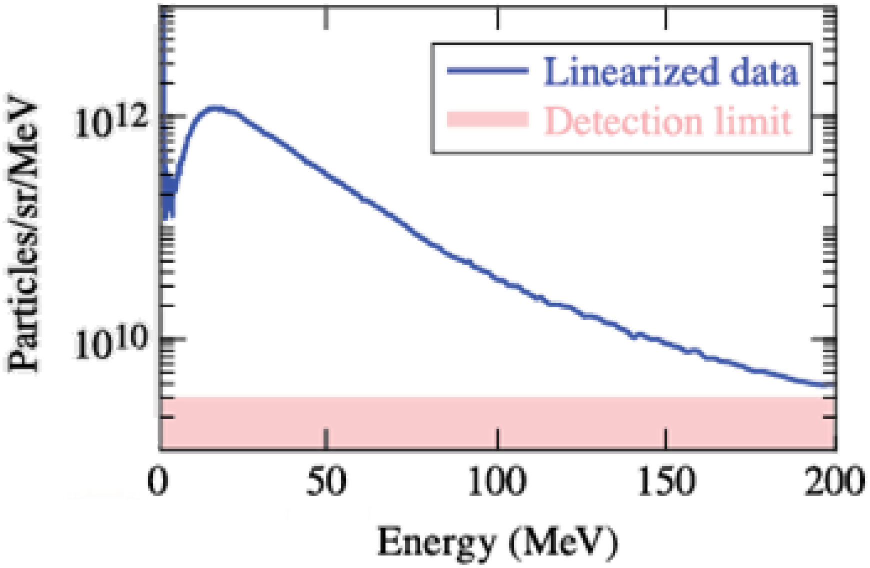


Electron beams with charges up to 707 ± 429/224 nC were measured

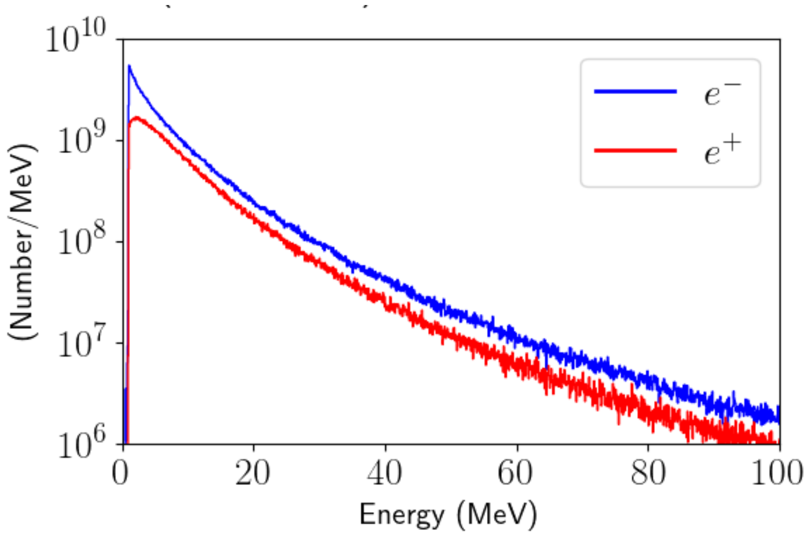
Laser-to-electron conversion efficiencies up to 11% were observed

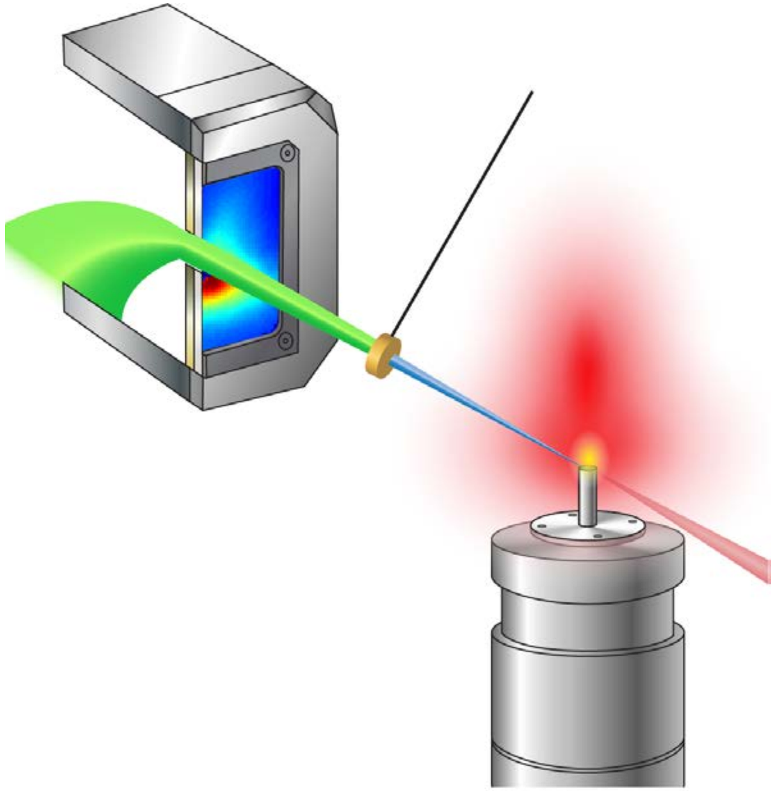
- **The weighted average electron energy of the representative electron spectrum from this experiment is 17.9 MeV**

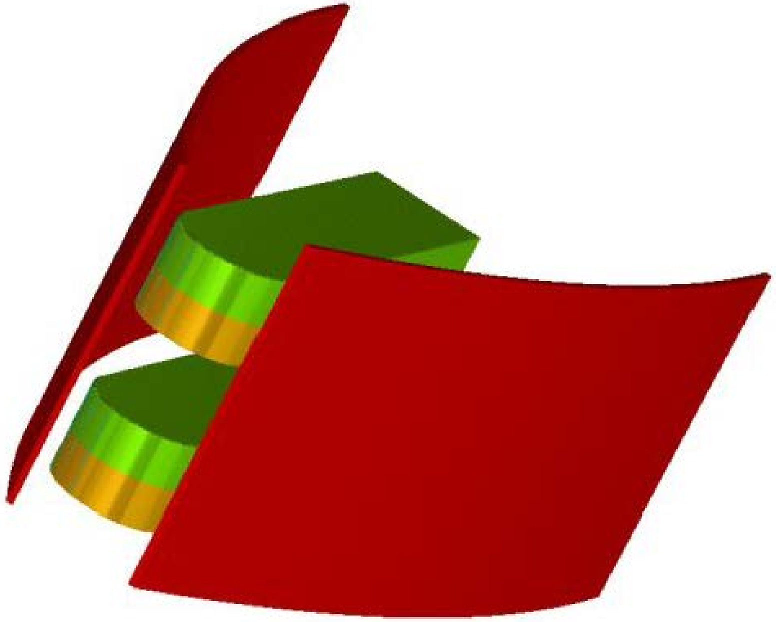
- **Using this energy, the 707 nC electron beam corresponds to a conversion efficiency from laser energy to electron energy of 11%**



Collaborative work between LLE, Oxford (Gregori), and RAL (Bingham) is exploring positron production using these high-charge electron beams







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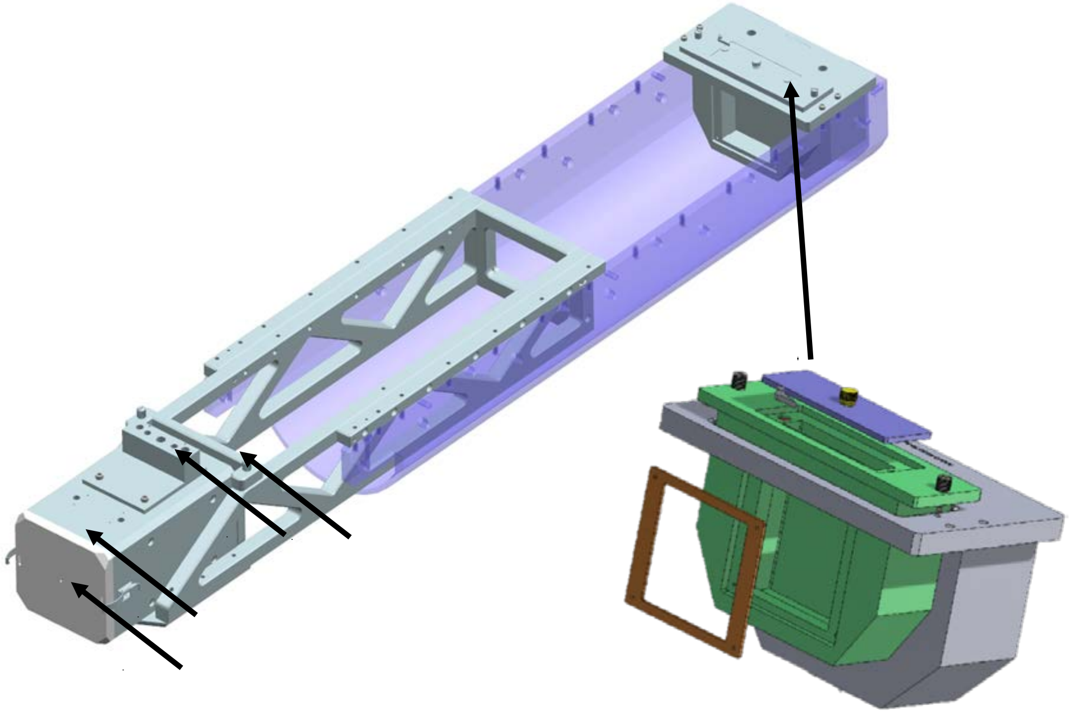
Calculated positron yields using a 200 nC electron beams in a 15 mm Pb converter peak at 10^9 e^+/MeV*

* Figure and calculation courtesy C. Arrowsmith

We are collaborating with LLNL (Albert) and Oxford (Gregori) to measure the betatron radiation produced by the high-charge electron beam



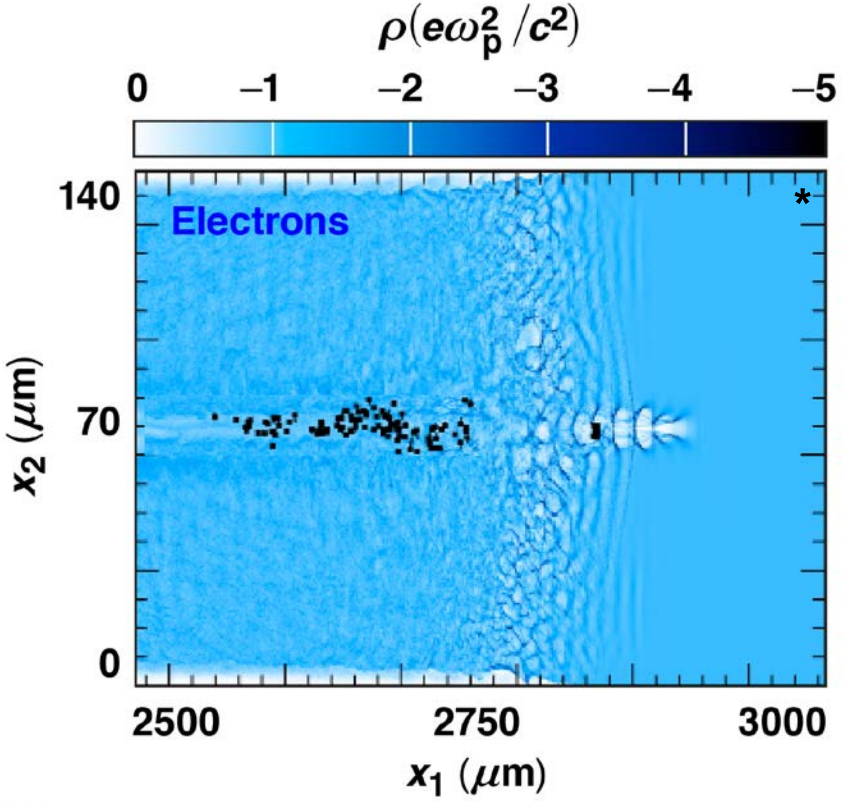
- **Previous Betatron Results from Titan:**
  - **10^9 photons/eV/Sr @ 6 keV from a 10 nC beam**
  - **E_{crit} up to 20 keV**

- **Predicted results from OMEGA EP**
  - **Similar energies, source size, and duration**
  - **~7 x 10^{10} photons/eV/Sr owing to 70x greater charge**

Bremsstrahlung and Inverse Compton Scattering sources will also be investigated

[redacted]

We are also collaborating with LLNL (Lemos) to radiograph the SMLWFA to verify two acceleration mechanisms



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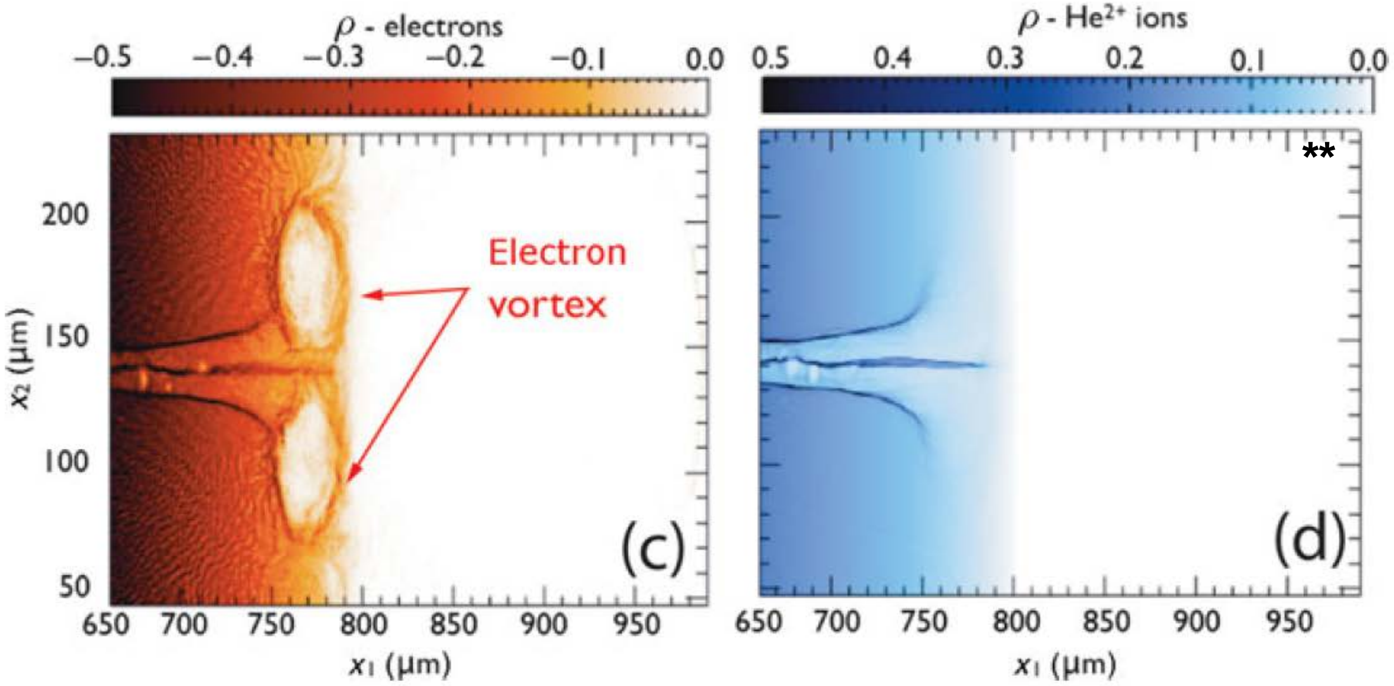
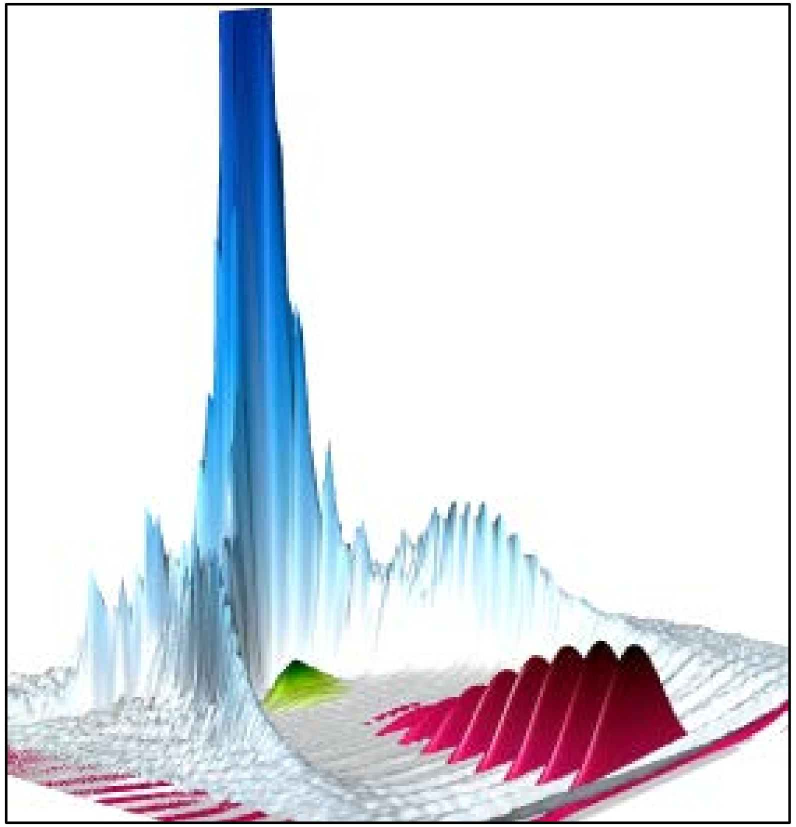


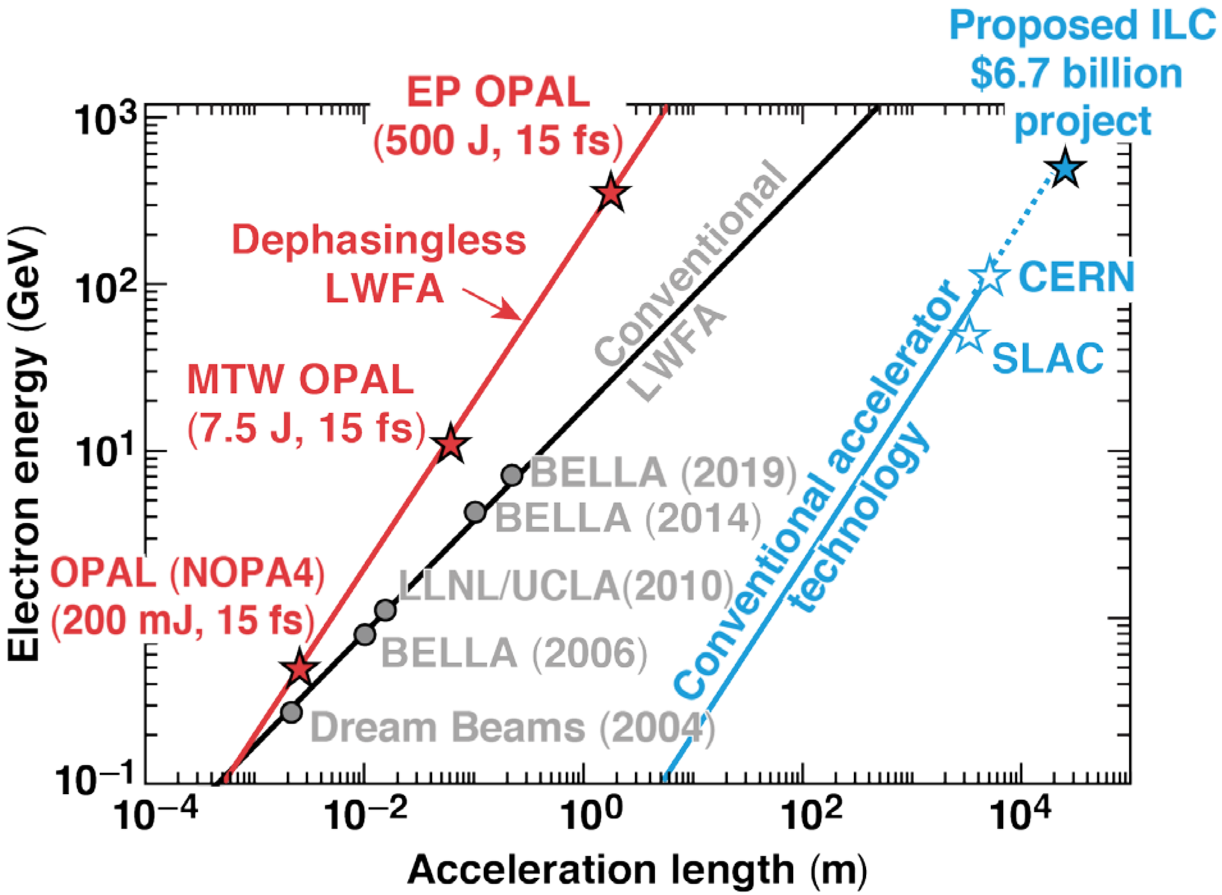
* Simulations and figure curtesy N. Lemos
** N. Lemos *et al.*, J. Plasma Physics 78 327 (2012)

Project 2:

Achromatic Flying Focus towards a Single-Stage 500 GeV LWFA

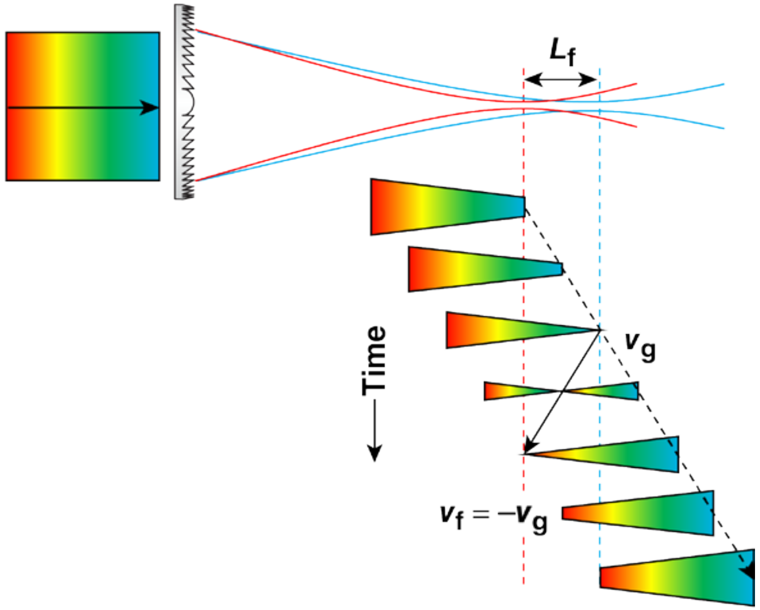
The dephasing of the accelerating electrons relative to the drive laser limits the maximum energy gain of the electrons in a conventional LWFA

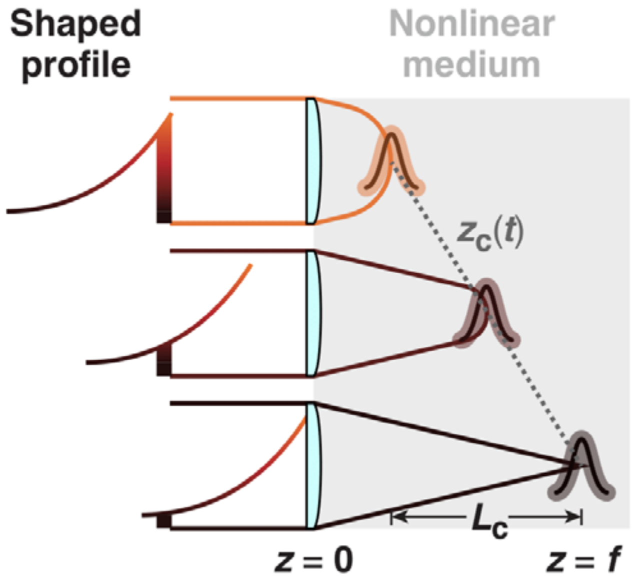


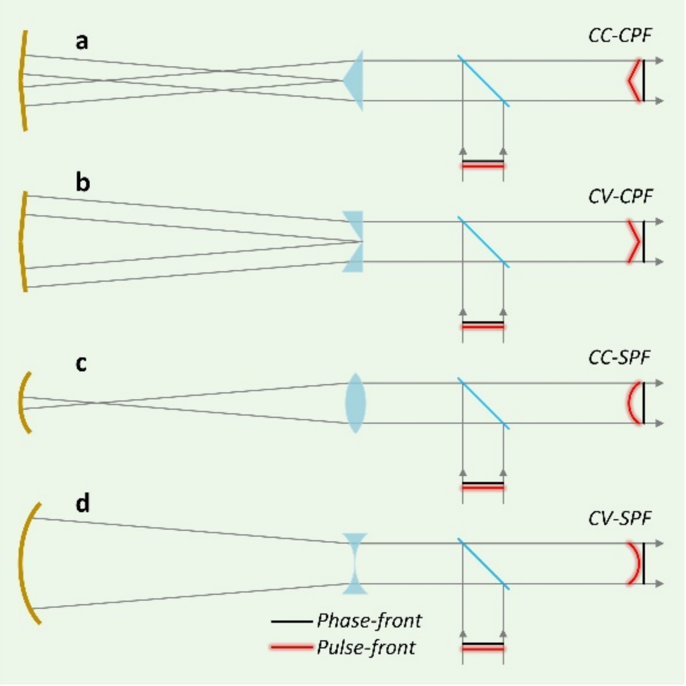


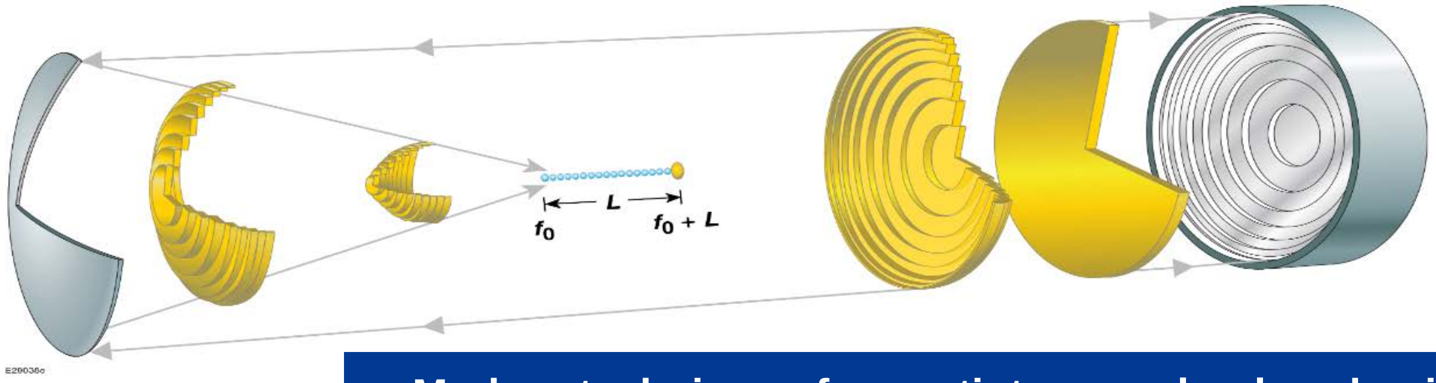
The production of an intensity peak that can move at the vacuum speed of light in plasma could eliminate dephasing in LWFA

We are studying various methods of spatiotemporal pulse shaping (flying focus), where we structure a laser pulse with advantageous space-time correlations that are tailored to a particular application









Modern techniques for spatiotemporal pulse shaping offer cylindrical symmetry, velocity control, and extended focal ranges

* A. Sainte-Marie *et al.*, Optica (2018)
D. Froula *et al.*, Nat. Photonics (2018)
** T. Simpson *et al.*, Submitted(2020)
† Z. Li *et al.*, Nat. Sci. Reports (2020)
‡ J. Palastro *et al.*, Phys. Rev. Lett. (2020)
C. Caizergues *et al.*, Nat. Photonics (2020)

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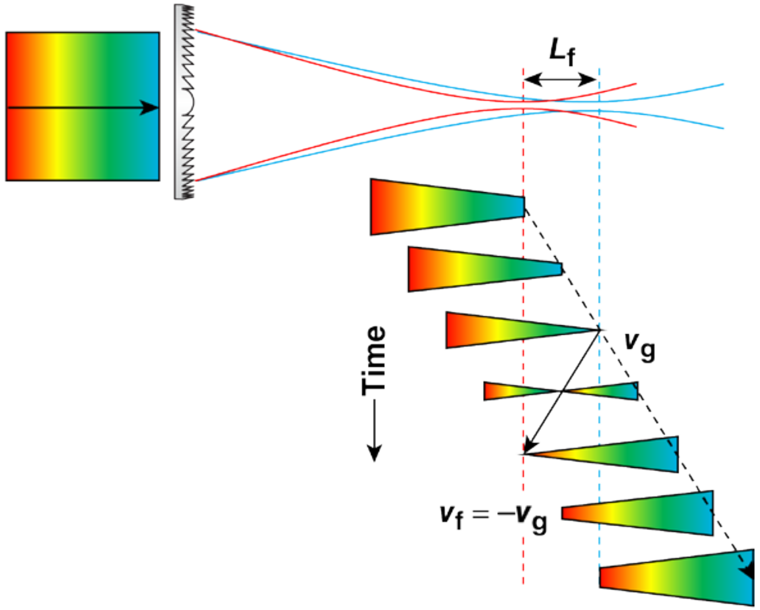

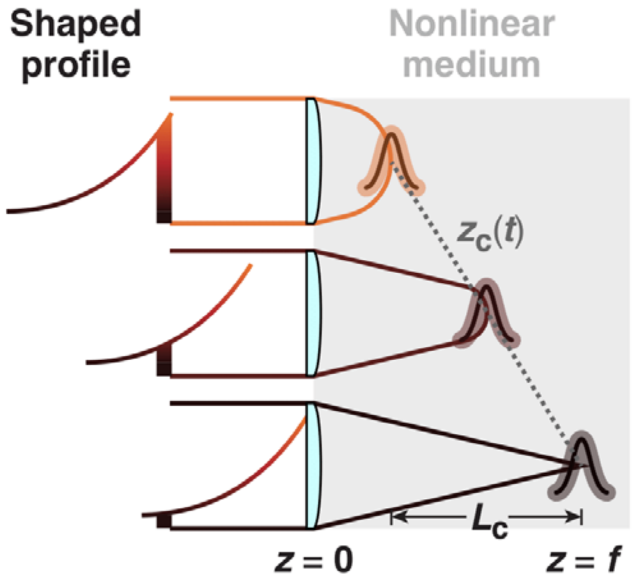

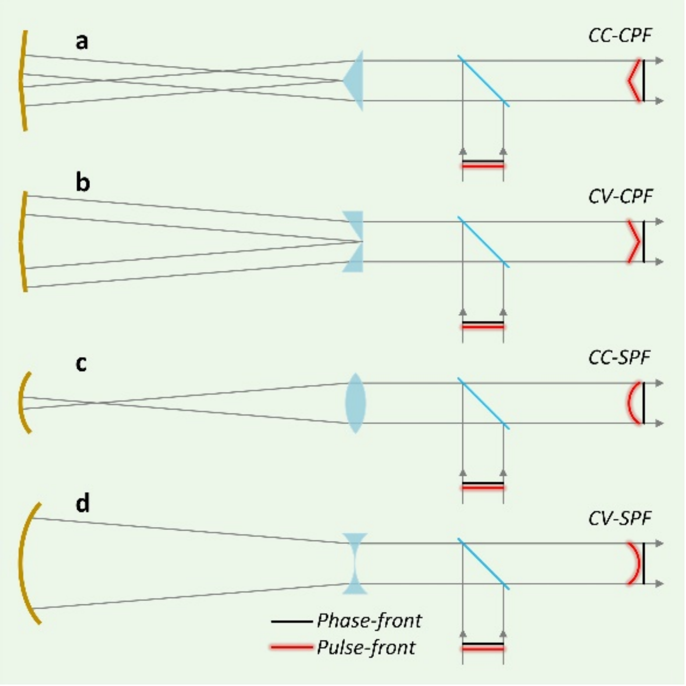

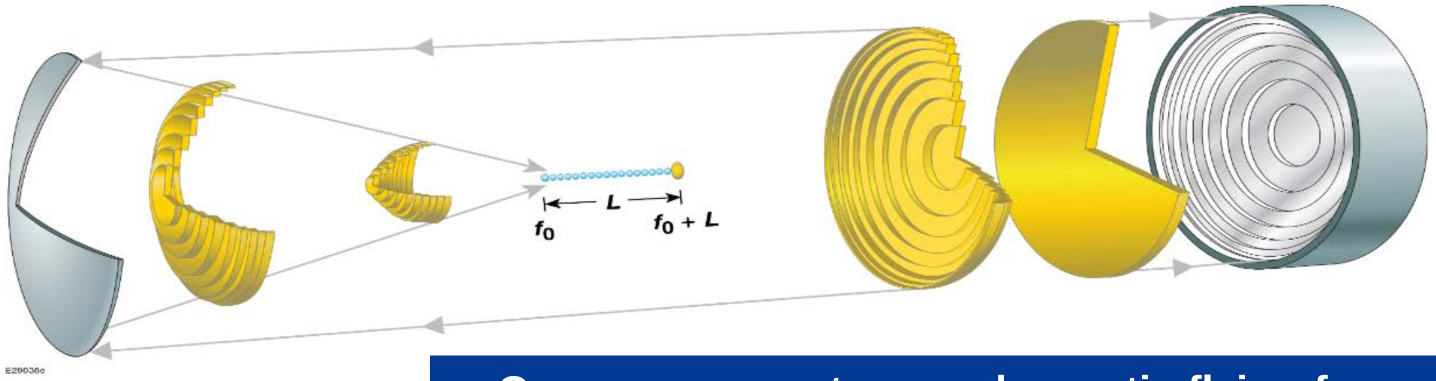

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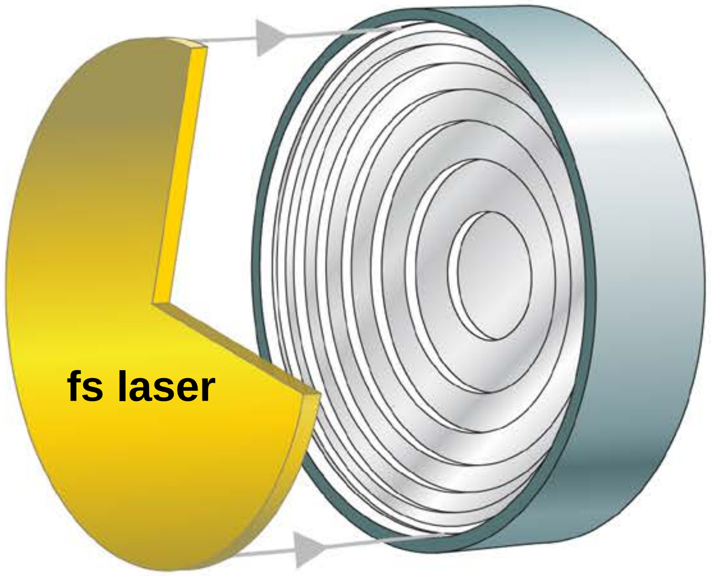
Our new concept—an achromatic flying focus (AFF)—could enable a new regime of LWFA

The AFF uses spherical aberration to create an extended focal region and a radial echelon to control the time at which rings of power reach their respective foci along the extended focal region

Axiparabola**

Radial Echelon*



* J. P. Palastro *et al.*, Phys. Rev. Lett.
** S. Smartsev et al. Opt. Lett. 44, 3414 (2019)

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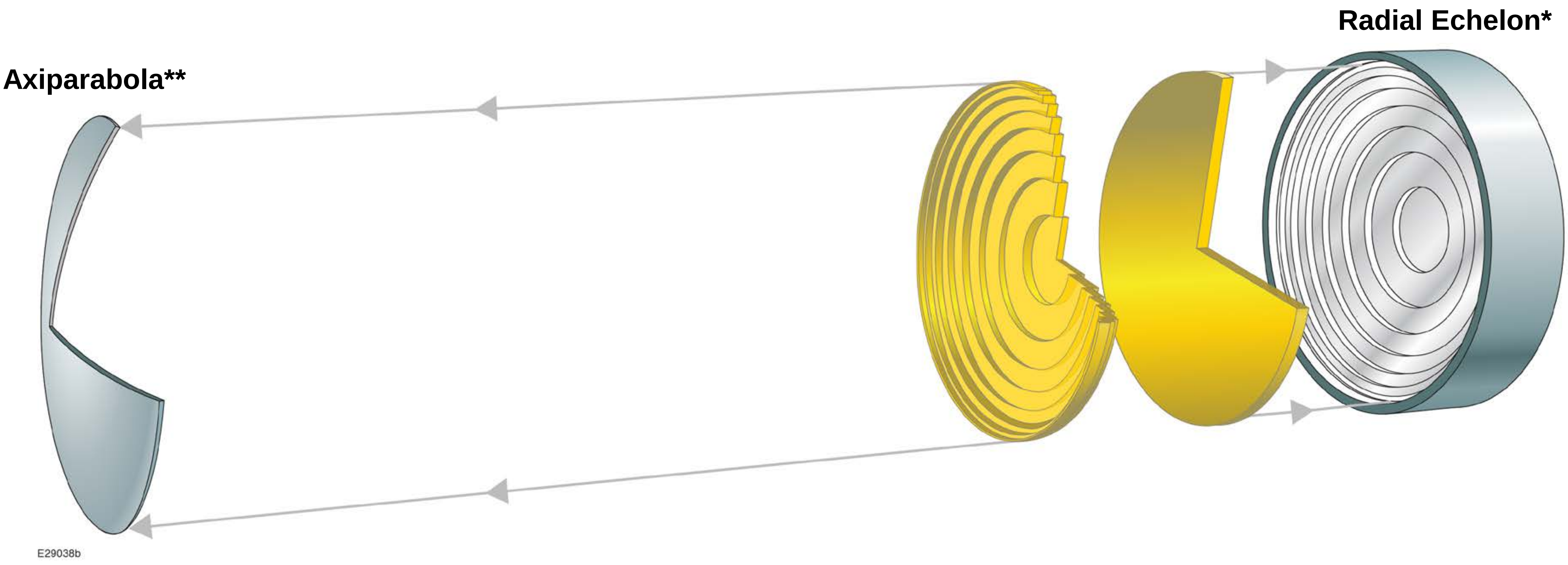

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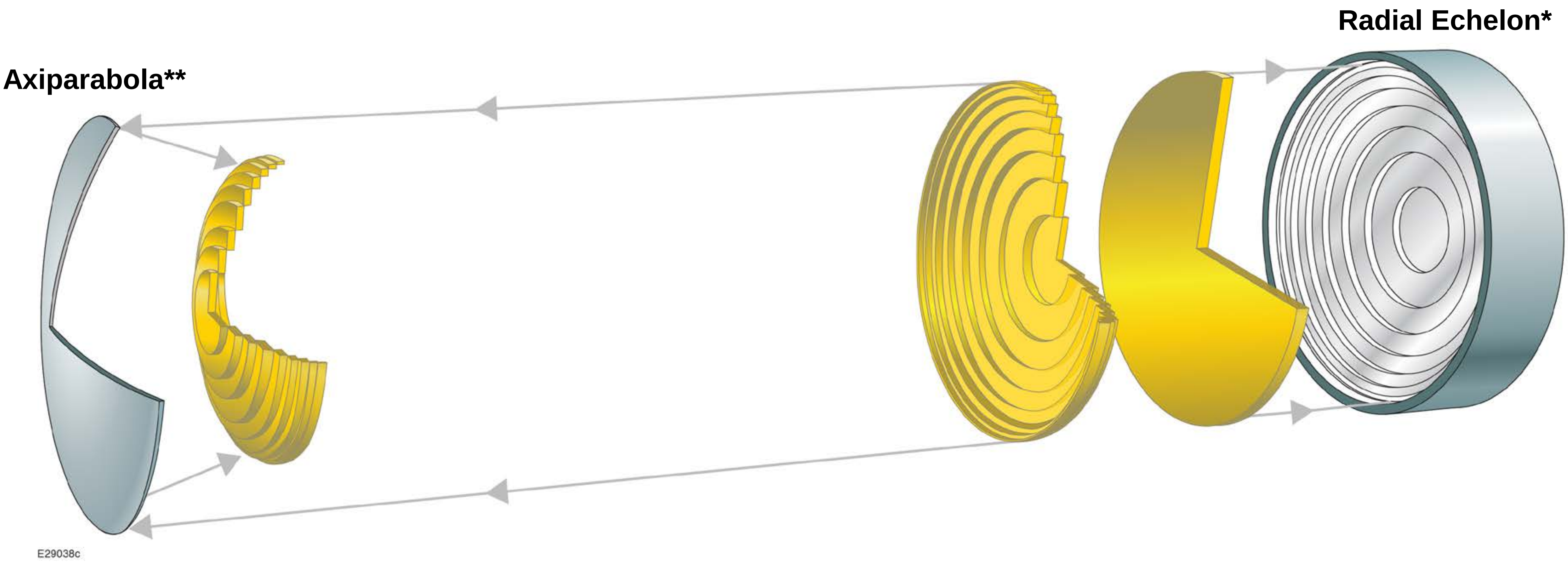

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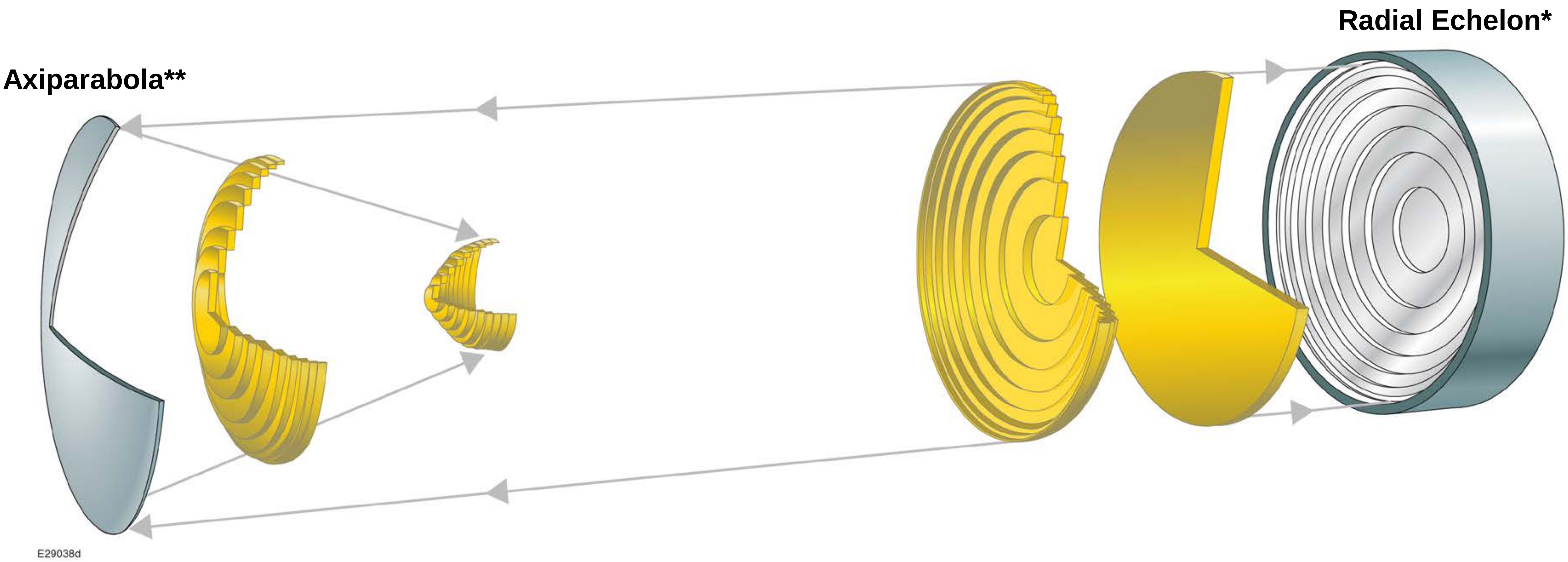

* J. P. Palastro *et al.*, Phys. Rev. Lett.
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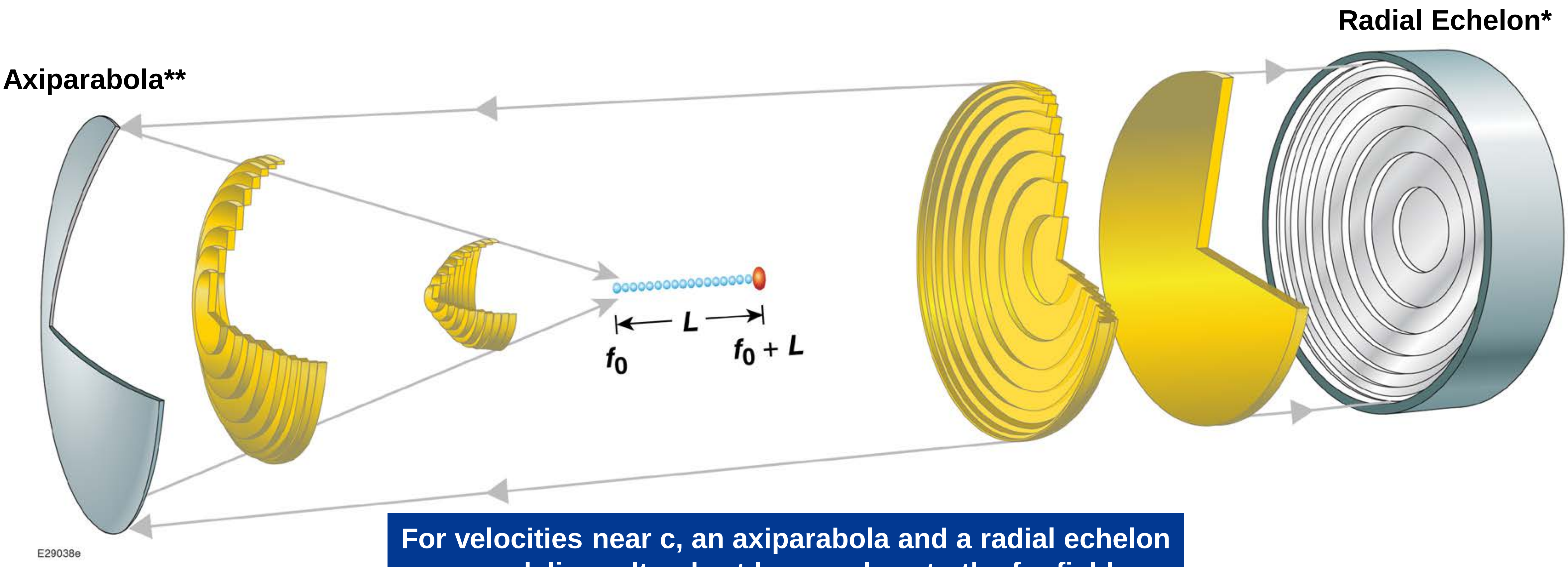
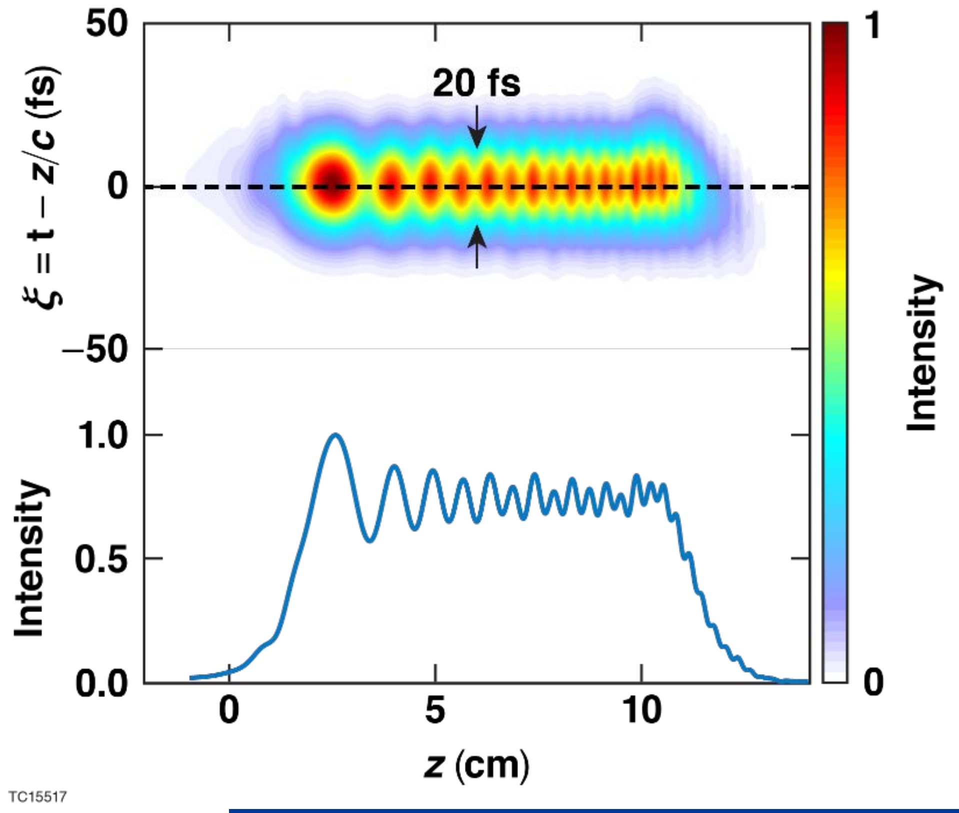
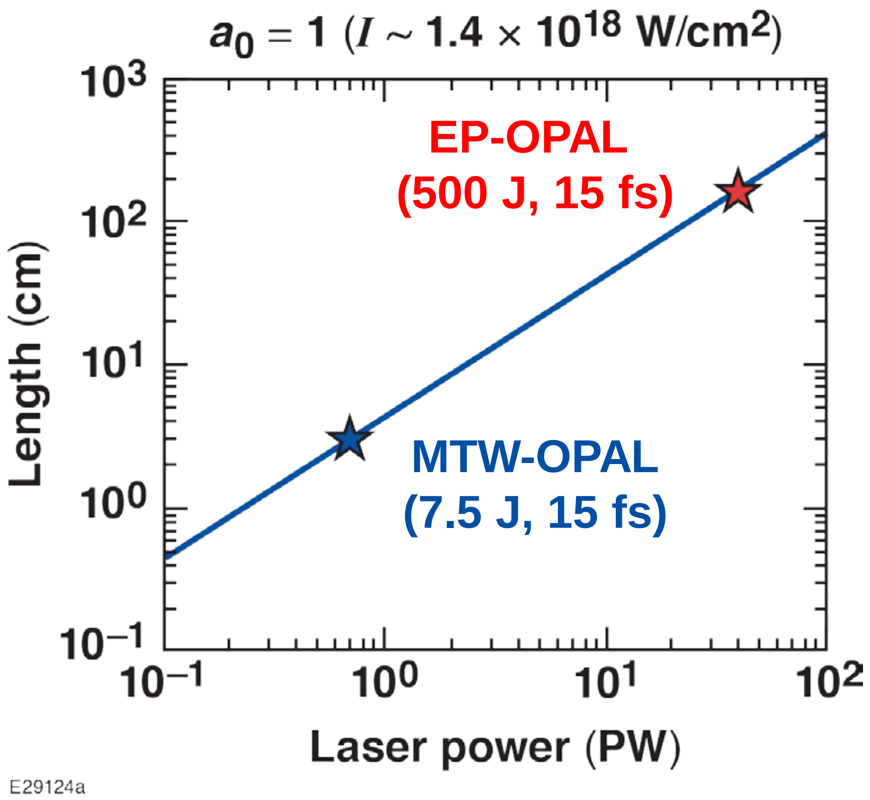


For velocities near c, an axiparabola and a radial echelon can deliver ultrashort laser pulses to the far field

* J. P. Palastro *et al.*, Phys. Rev. Lett.
** S. Smartsev et al. Opt. Lett. 44, 3414 (2019)

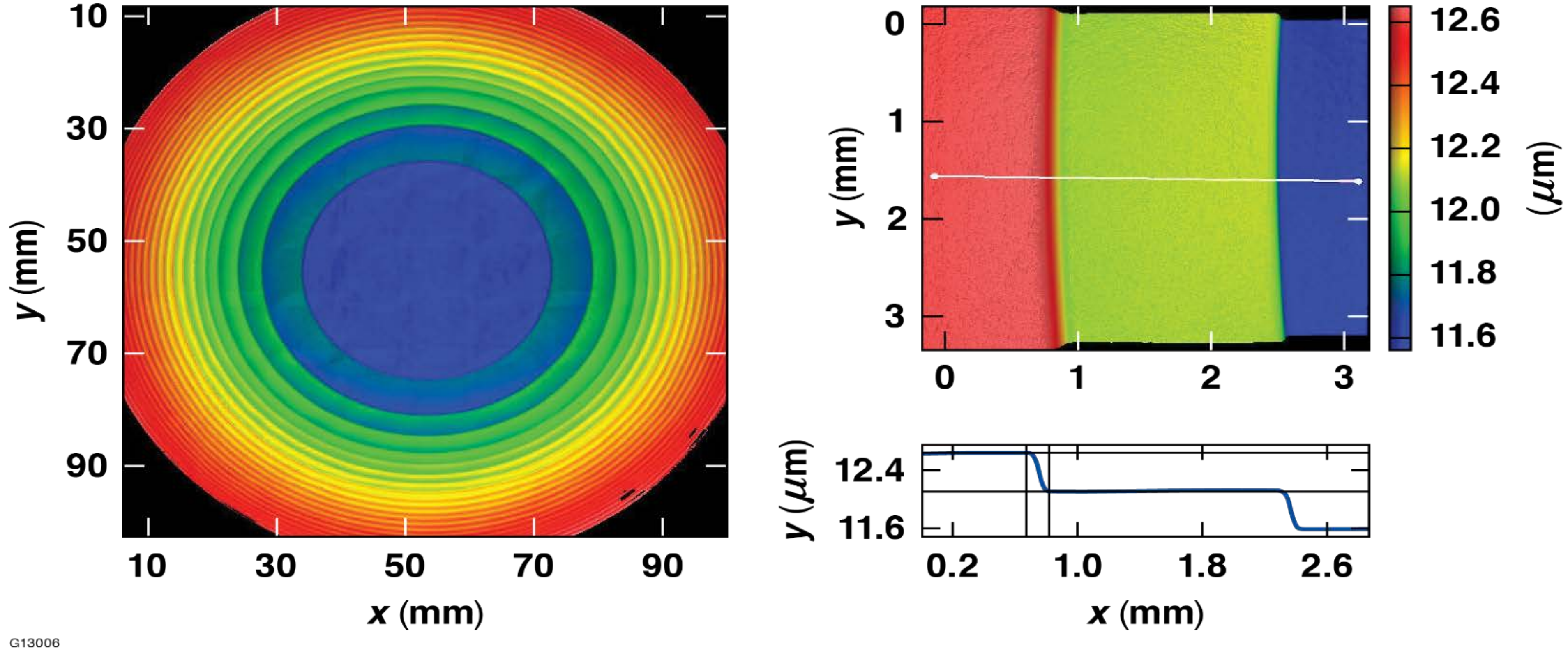
Wave propagation simulations demonstrate that the axiparabola and echelon can deliver a short pulse with a small spot over 10 cm





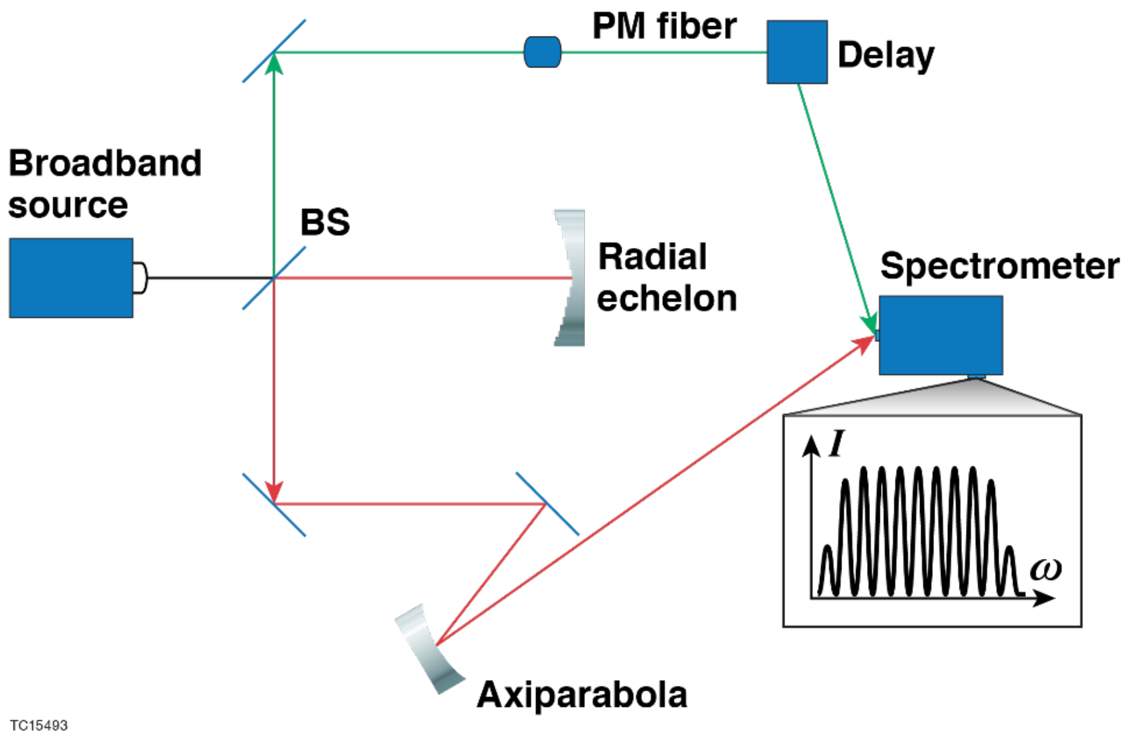
Emerging short-pulse laser systems provide the capability to produce relativistic intensities that propagate over centimeters to meters

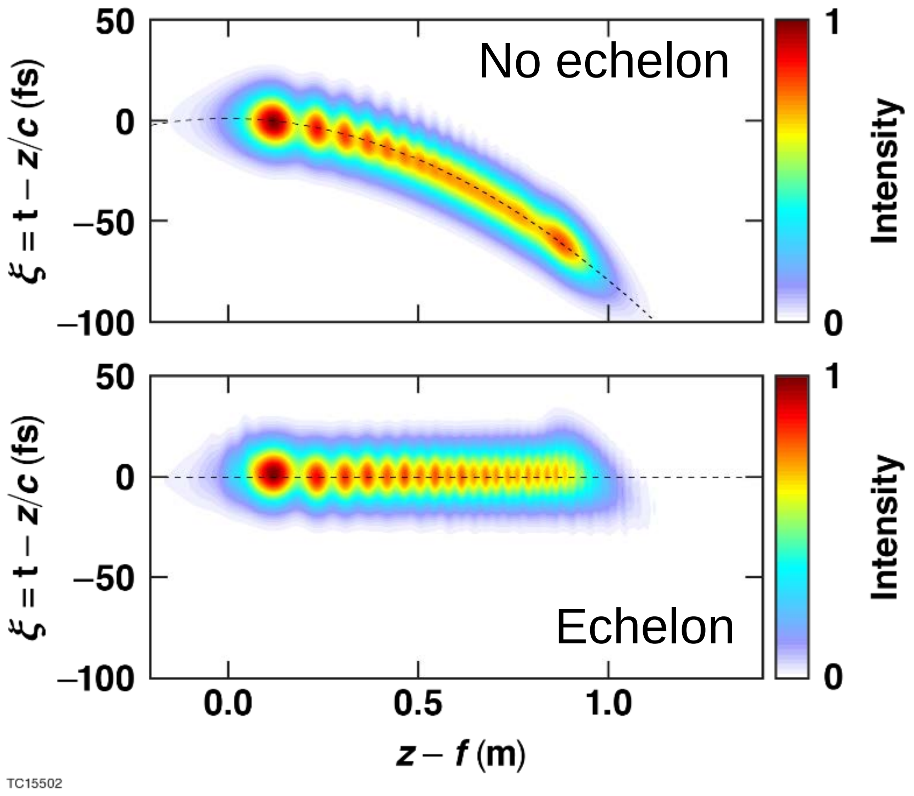
LLE has developed an in-house capability to fabricate radial echelons using electron-beam evaporation



White light interferometry measurements have ensured that the manufactured echelons meet the specs for upcoming experiments

Planned experiments will demonstrate velocity control using the axiparabola-echelon pair





The spectral interference of a reference pulse with the imaged far-field of the axiparabola-echelon provides the relative delay and velocity

The chromatic and achromatic flying focus, as well as other spatiotemporal control methods, can be applied to several applications beyond LWFA

UR LLE

- **Ionization Waves**
  - J. P. Palastro *et al.*, Phys. Rev. A 97, 033835 (2018)
  - D. Turnbull *et al.,* Phys. Rev. Lett. 120, 225001 (2018)
- **Photon Accelerators**
  - A. Howard *et al.,* Phys. Rev. Lett. 123, 124801 (2019)
- **Strong-field QED Phenomena in Compton Scattering**
  - A. Di Piazza, submitted
- **Attosecond Lighthouses**
- **Fermi Acceleration**
  - D. Ramsey, in preparation
- **Raman Amplification**
  - D. Turnbull *et al.,* Phys. Rev. Lett. 120, 024801 (2018)
- **Cherenkov Radiation**
- **Terahertz Radiation**
- **Direct Vacuum Electron Acceleration**
  - D. Ramsey, accepted Phys. Rev. E

The LLE is exploring novel means to advance the field and application of LWFA

- We have recently demonstrated record-breaking electron beam charge with the acceleration of a > 0.7 uC electron beam from a self-modulated LWFA driven by the OMEGA EP laser

- Our new "achromatic flying focus" concept, a method of spatiotemporally controlling laser propagation, shows promise as a means to circumvent the fundamental limitations of LWFA and offers a path to a single-stage 500 GeV LWFA

We are looking to add to our team!

Questions?

National Nuclear Security Administration