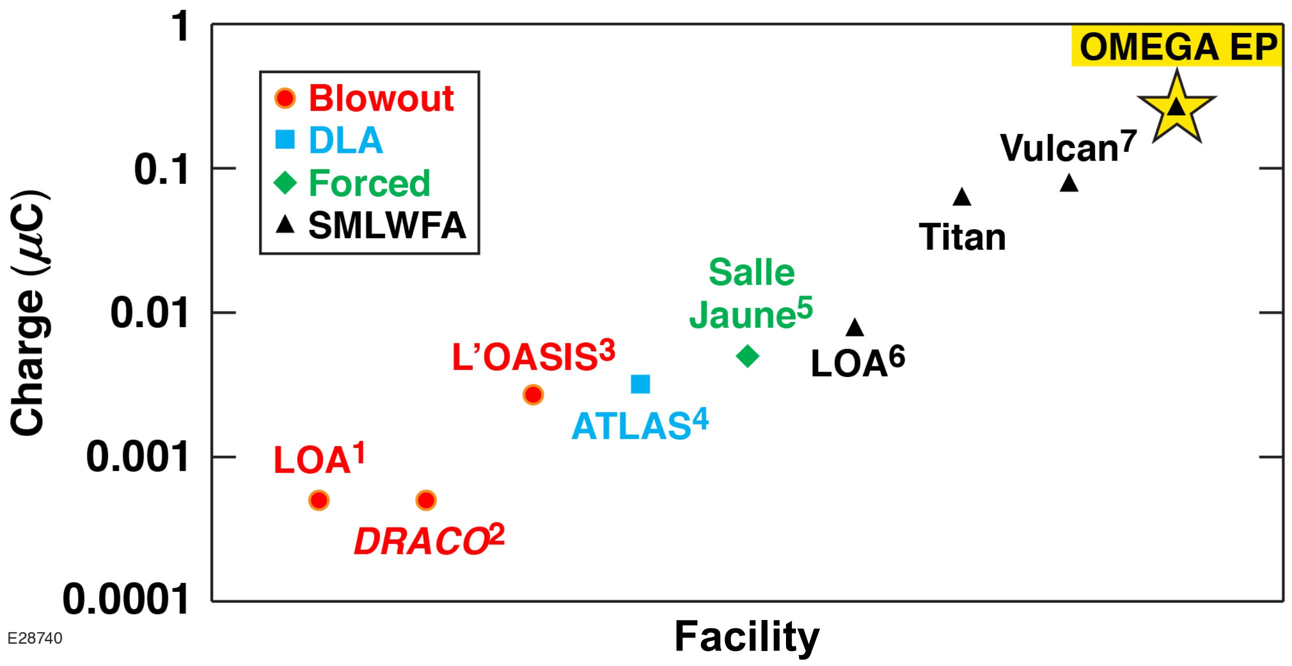
Microcoulomb-Class Self-Modulated Laser Wakefield Accelerator on OMEGA EP



[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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61st Annual Meeting of the
American Physical Society
Division of Plasma Physics
Fort Lauderdale, FL
21–25 October 2019

Summary

Self-modulated laser wakefield acceleration at OMEGA EP has demonstrated electron beams with charge exceeding 270 nC

- **A platform for self-modulated laser wakefield acceleration (SMLWFA) has been established on the OMEGA EP laser at the Laboratory for Laser Energetics**

- **Platform development at OMEGA EP required new target, laser, and diagnostic capabilities**

- **Initial experiments have demonstrated electron beams with maximum energies greater than 200 MeV and charge exceeding 270 nC, which is > 3X times higher than the next best result**

- **Current scalings suggest that higher-energy and higher-charge electron beams are possible**

Collaborators

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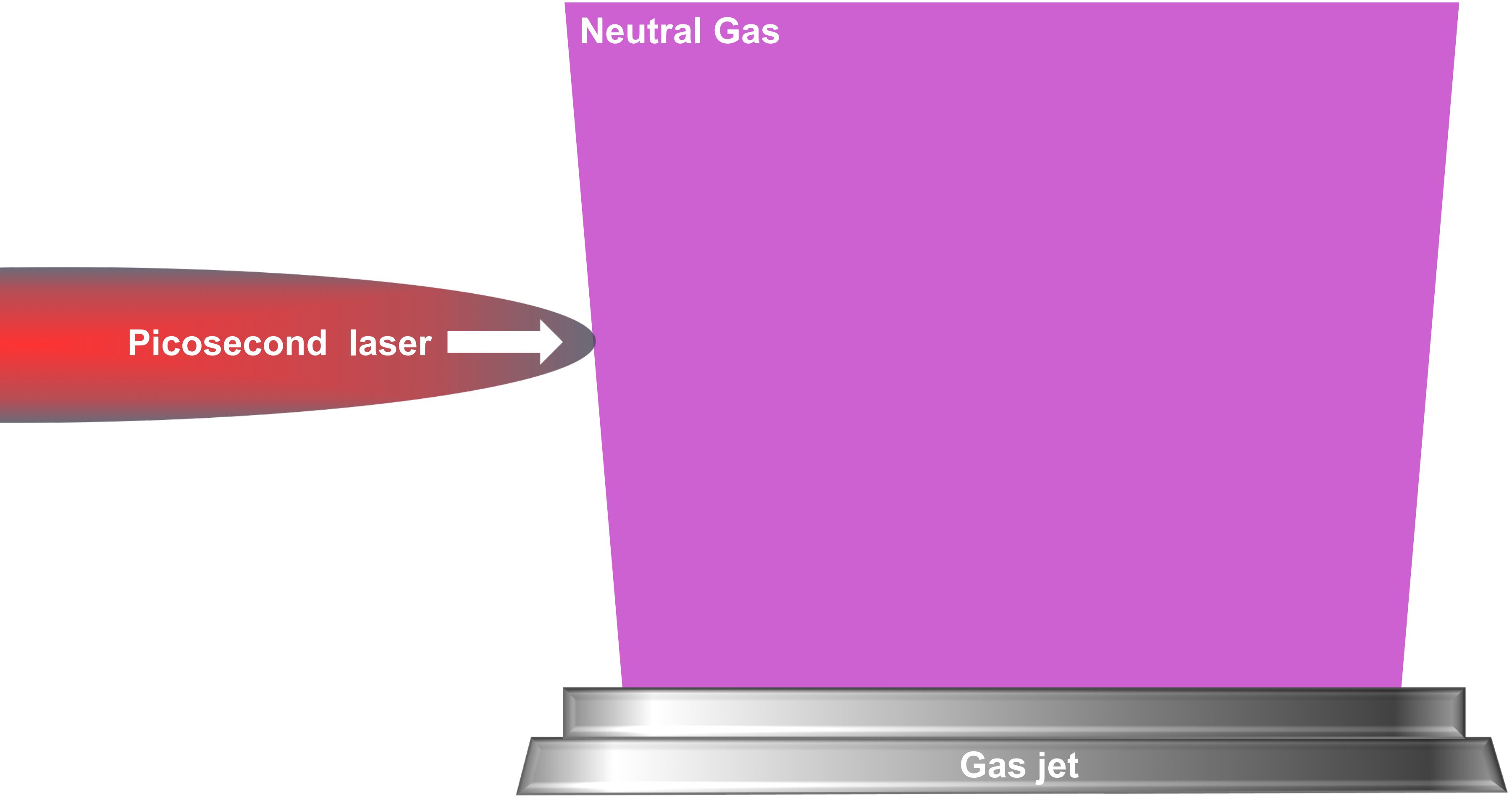
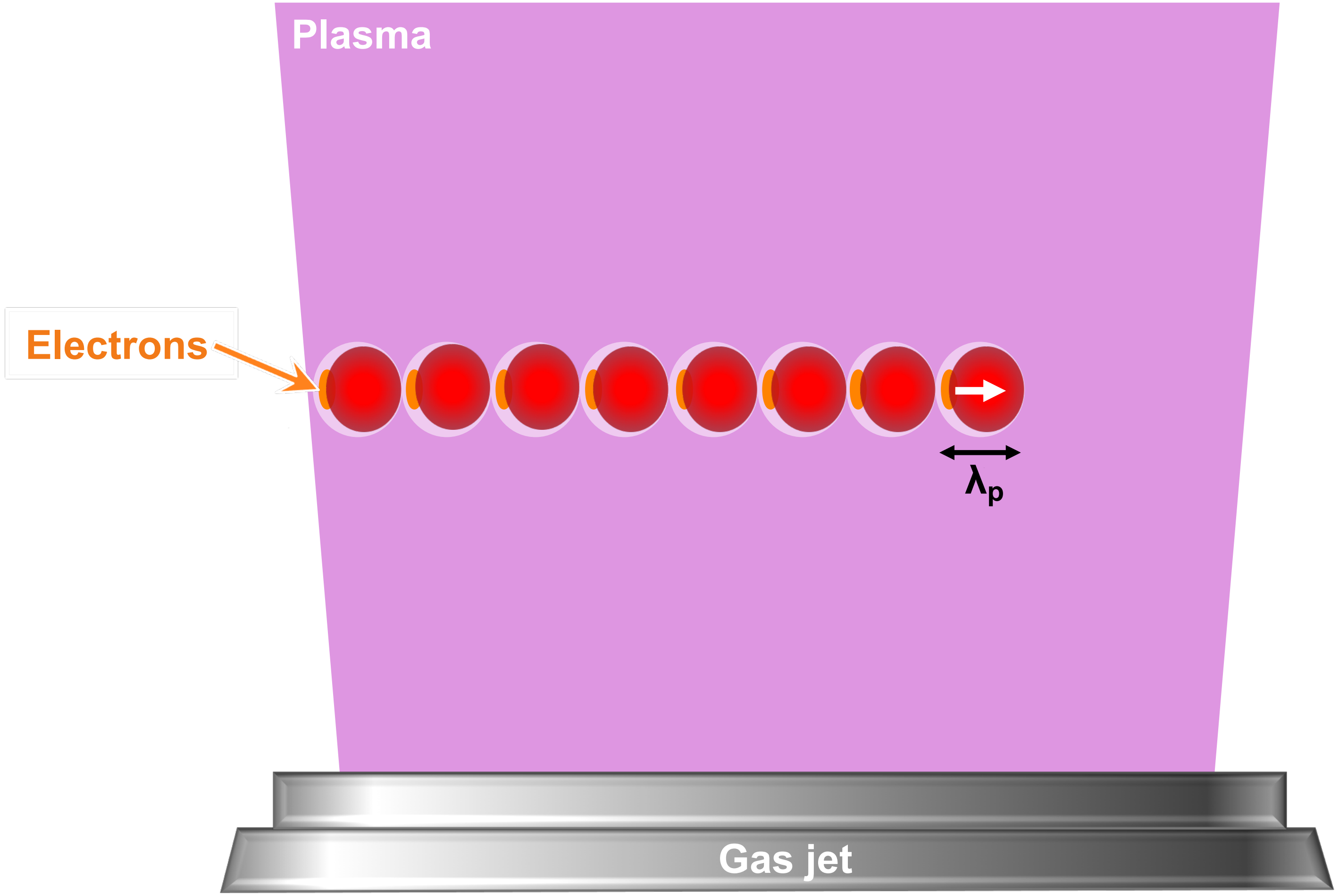
Lawrence Livermore National Laboratory

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

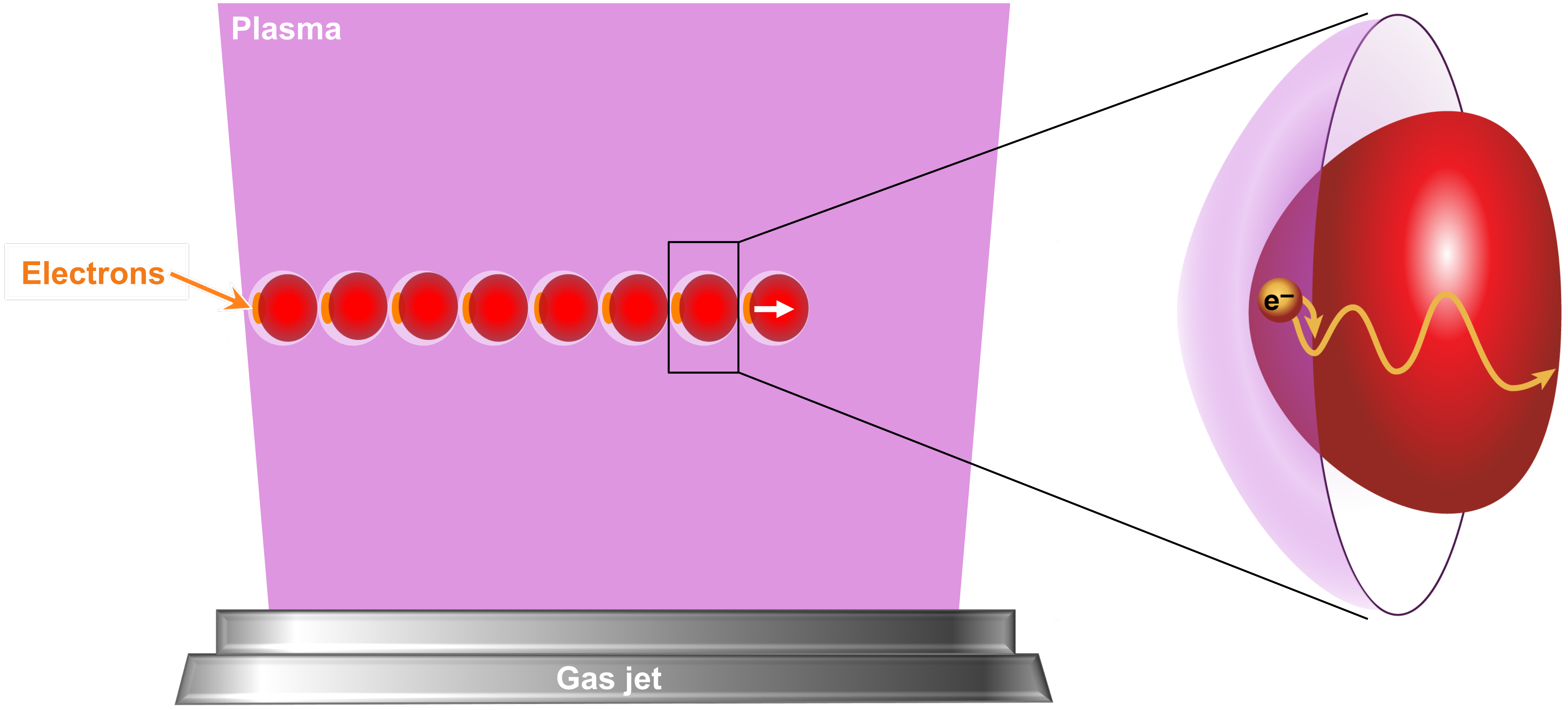


* A. Modena *et al.*, Nature 377, 606 (1995).
C. Joshi *et al.*, Phys. Rev. Lett. 47, 1285 (1981).
** E. Esarey *et al.*, Phys. Rev. Lett. 72, 2887 (1994).
N. E. Andreev *et al.*, Pisma Zh. Eksp. Teor. Fiz. 55, 551 (1992).
T. M. Antonsen and P. Mora, Phys. Rev. Lett. 69, 2204 (1992).
P. Sprangle *et 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

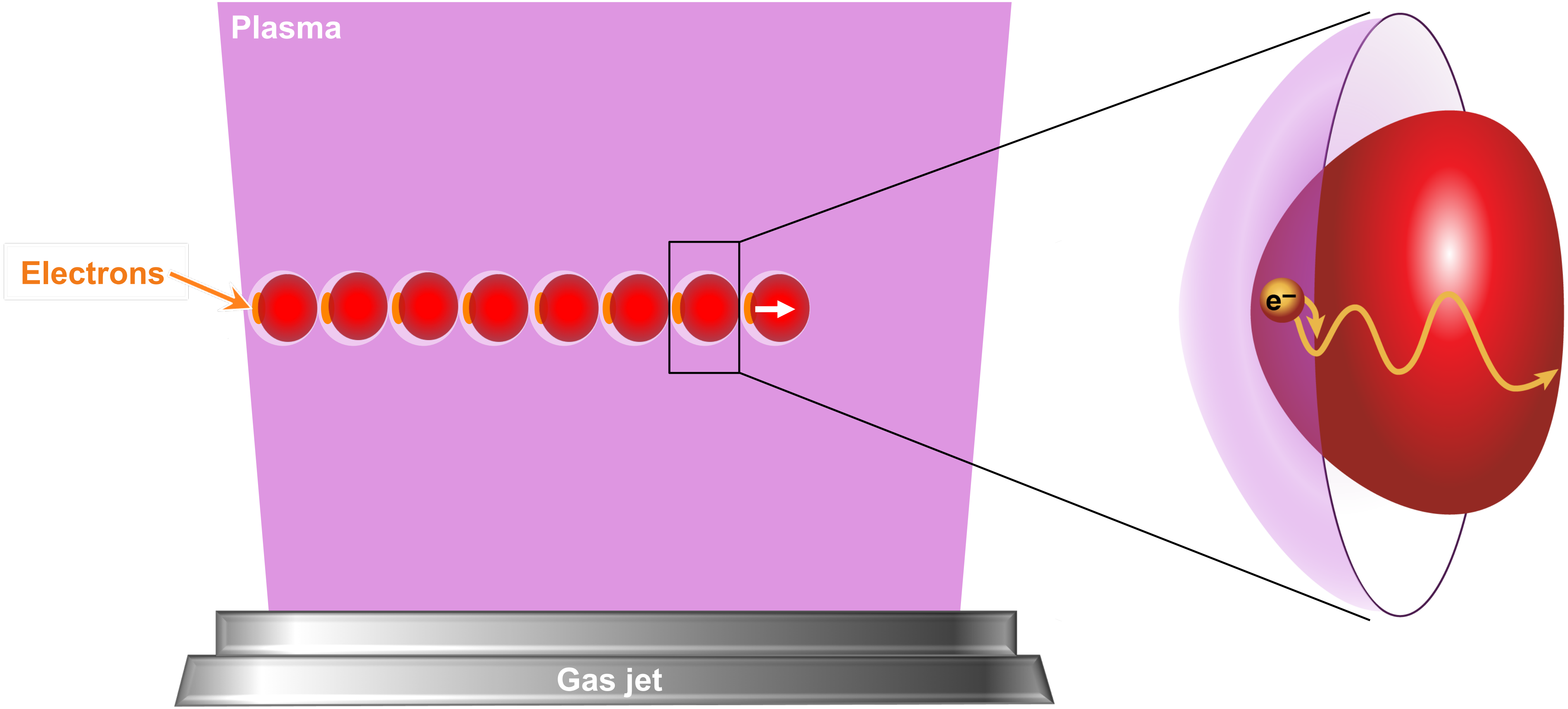


Because the laser overlaps the trapped electrons, electrons can gain energy from direct laser acceleration (DLA) in addition to SMLWFA



Physical Picture

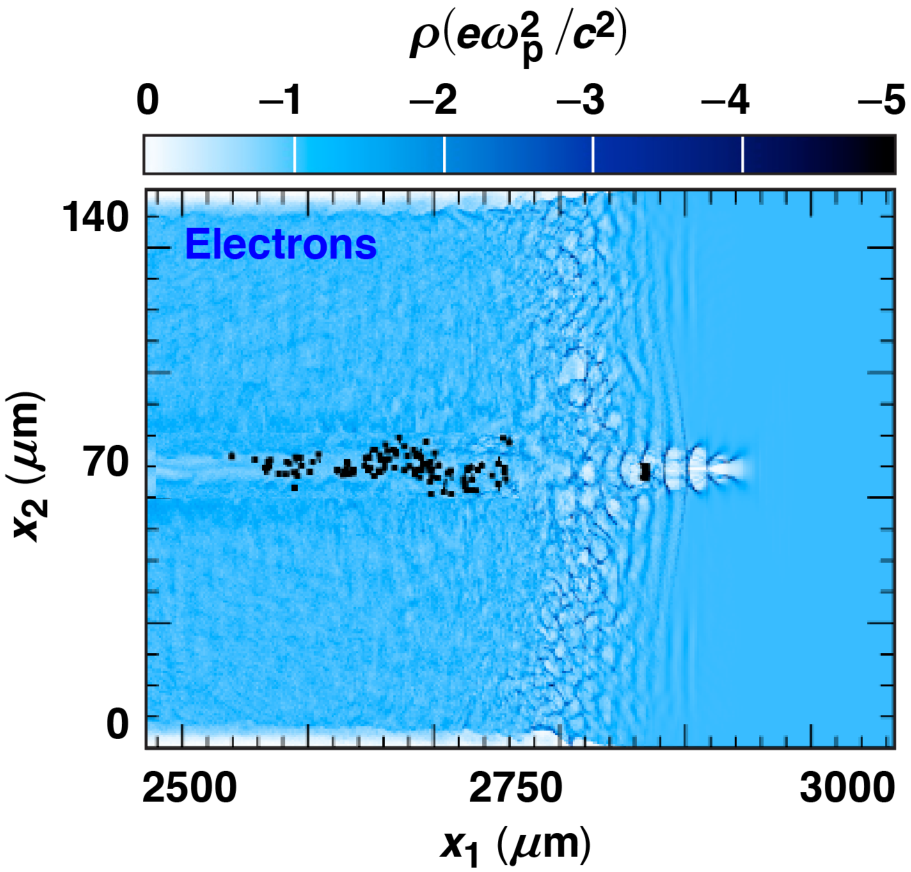
Because the laser overlaps the trapped electrons, electrons can gain energy from direct laser acceleration (DLA) in addition to SMLWFA



Simulations* show that for a_0 values ~1.5, both SMLWFA and DLA play an equally important role in electron acceleration, but by a_0 of ~3, DLA is the dominant energy-gain mechanism.

* N. Lemos *et al.*, Plasma Phys. Control. Fusion 58, 034018 (2016).

Dominant mechanism of energy gain of the electrons depends on their location in the wake structure



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* Simulations and figure curtesy N. Lemos

Motivation

SMLWFA driven by kJ-class lasers can provide compact sources of high-energy electrons for conversion to photons and positrons

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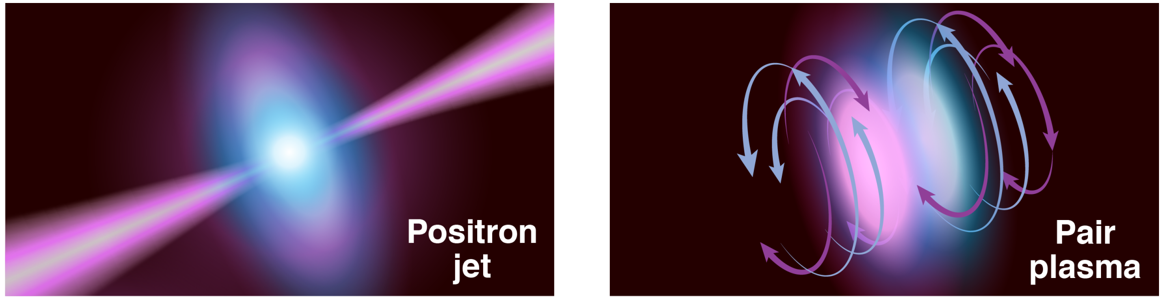
$\underline{N_{photons}} \propto N_e$

10 nC→1.5x10[12] photons/keV/Sr @ 6.5 keV*

$\underline{N_{photons}} \propto N_e$

10 nC→10[10] photons/shot @ 10-250 keV†



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Calculations for proof-of-principle experiments using electron beam from OMEGA EP predict up to 10^9 e^+/MeV/sr

$\underline{N_{photons}} \propto N_e$

10 nC→10^9 photons/keV/Sr @ 0.8-2 MeV**

Resolution of discrepancy in existing data^

Hard, Bright X Ray Sources

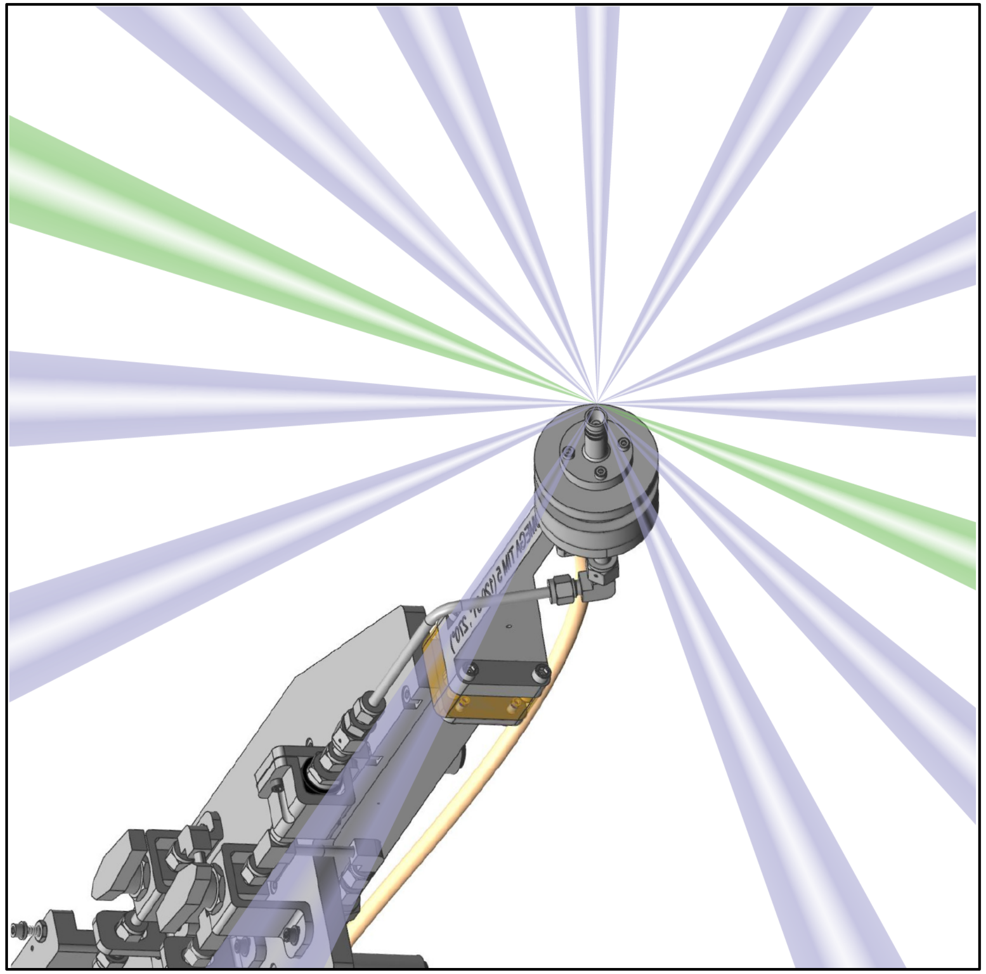
Positron Sources

*F. Albert *et al*., Phys. Rev. Lett. 118, 134801 (2017)
** N. Lemos *et al*., Plasma Phys. Contr. Fusion 60, 054008 (2018).
†N. Lemos *et al*., Submitted to Phys. Rev. Lett.
‡Calculation courtesy G. J. Williams
^ Comments by Williams *et al*., on G. Sarri *et al*., Phys. Rev. Lett. 110 255002 (2013). Accepted by Phys. Rev. Lett. June 2019.

SMLWFA experiments required the development of an ultrafast gas-jet system* for OMEGA EP

- **The gas-jet system was specifically designed to limit gas release in case of failure to protect sensitive electronics in the OMEGA EP compressor**
  - **Maximum gas release in the event of total failure: 30 cm^3**

- **The gas-jet valve is fast opening; the gas jet opens and closes in ~100 μs**

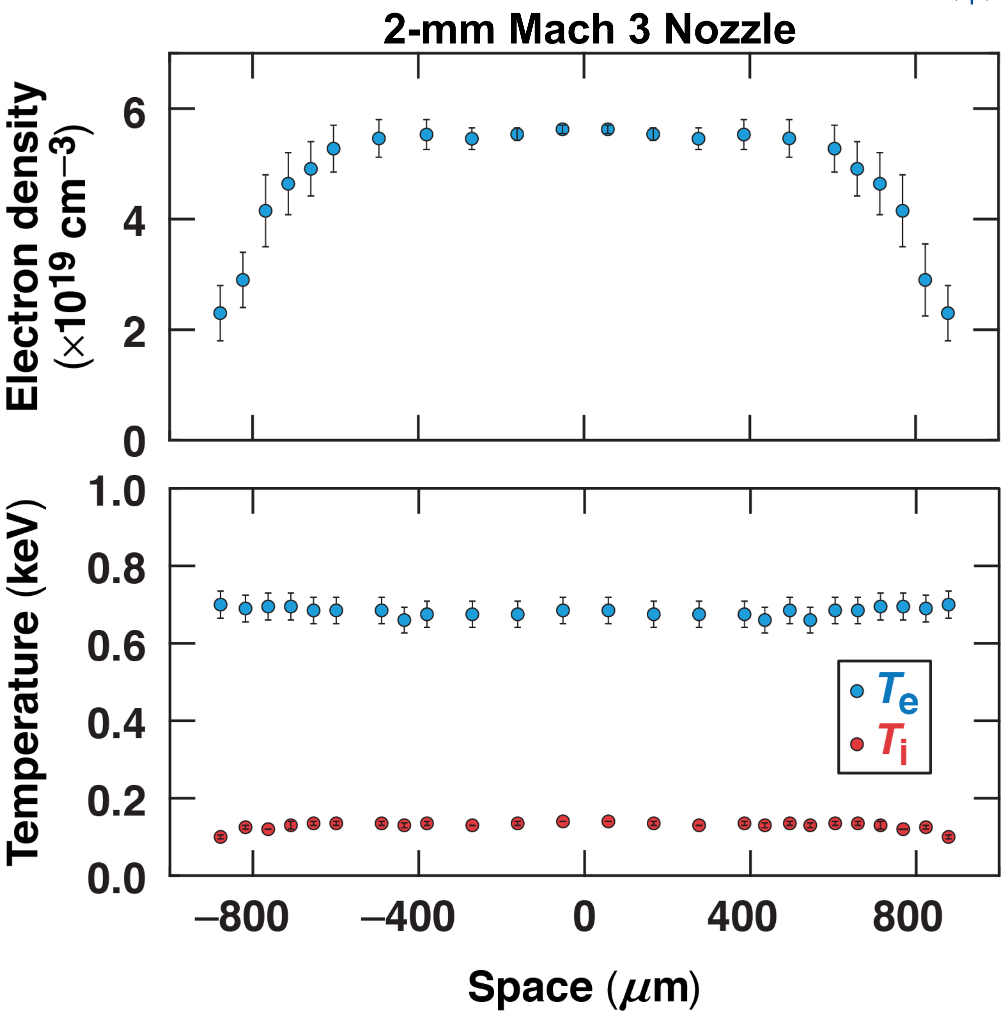


* A. M. Hansen *et al.*, Rev. Sci. Instrum. 89, 10C103 (2018)

The gas jet was activated on OMEGA and OMEGA EP

Parameter	Value
Systems	OMEGA EP (long* and short** pulse) OMEGA (long† pulse)
Mach numbers	3 to 6
Nozzle diameters	500 μm to 10 mm
Gas fills	H_2, He, N_2, Ar, Ne, Kr, Xe, CO_2
Fill pressures	Up to 720 psi (Demonstrated densities up to 4×10^{20} cm^{-3}) 1500 psi available starting January 2020

Gas jet system is now routinely available to users on OMEGA and OMEGA EP



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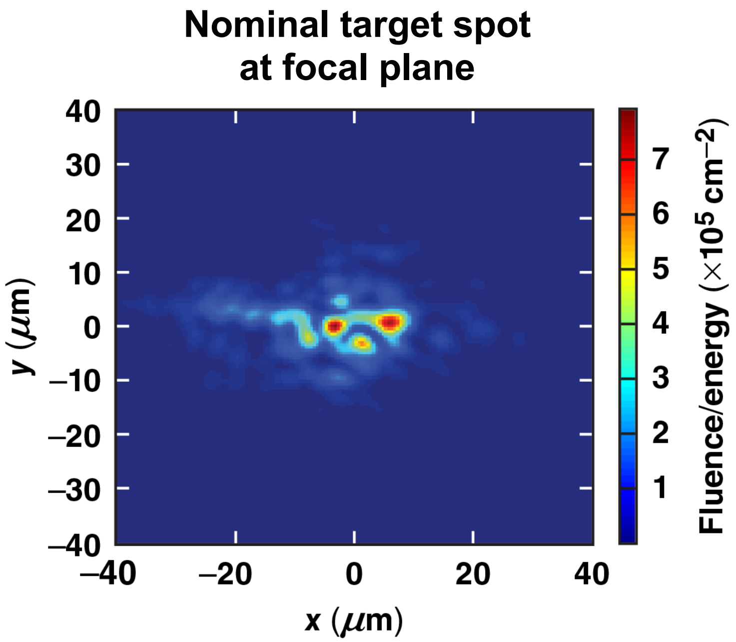
* PI: D. Haberberger
** PI: J. L. Shaw
† PI: A. Hansen

SMLWFA experiments required modification to the focusing capabilities of OMEGA EP

Standard OMEGA EP *f*/2 focus



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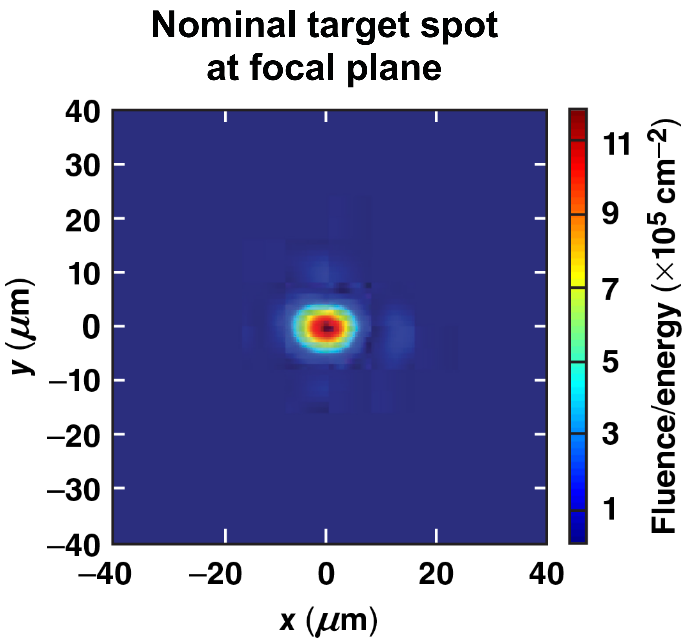
Max energy: 500 J*

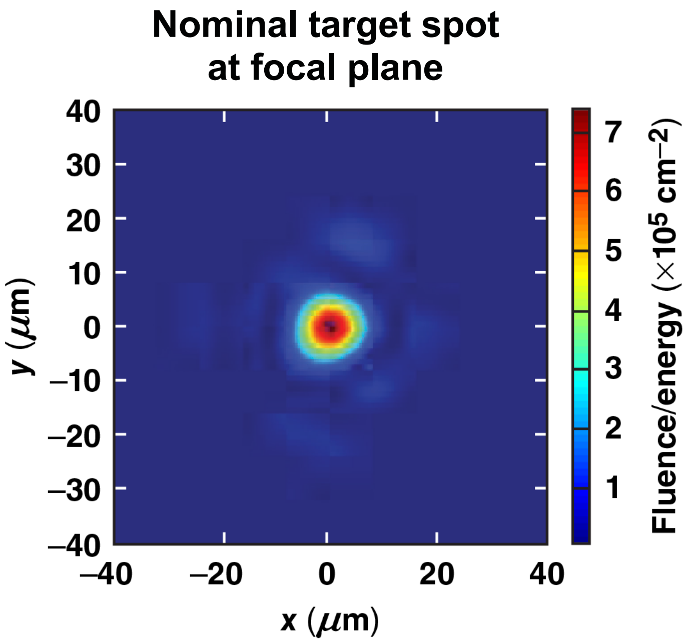
f/6 apodizer



E28126b

Max energy: 95 J*

f/8 apodizer

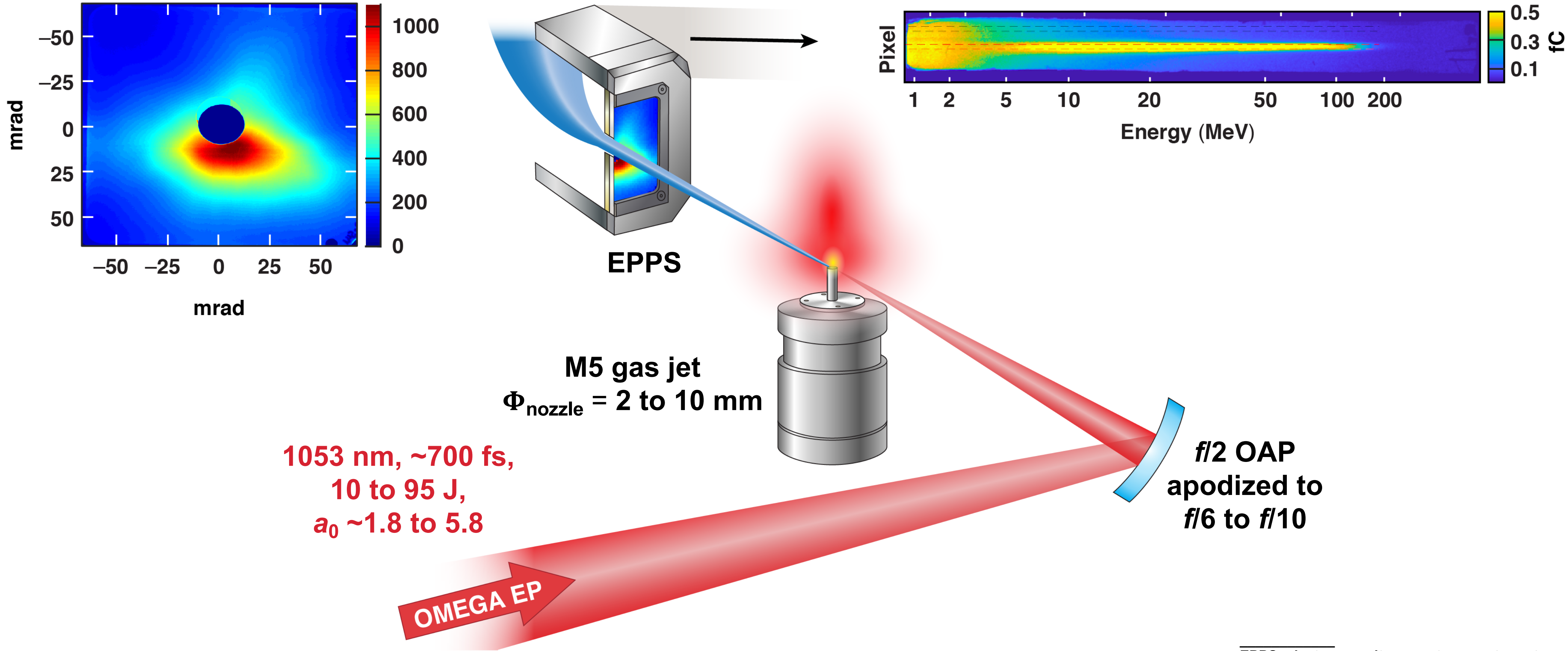


E28126c

Max energy: 55 J*

* In 700 fs

The experimental setup for SMLWFA shots utilized new laser and target capabilities of OMEGA EP as well as a new diagnostic capability



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

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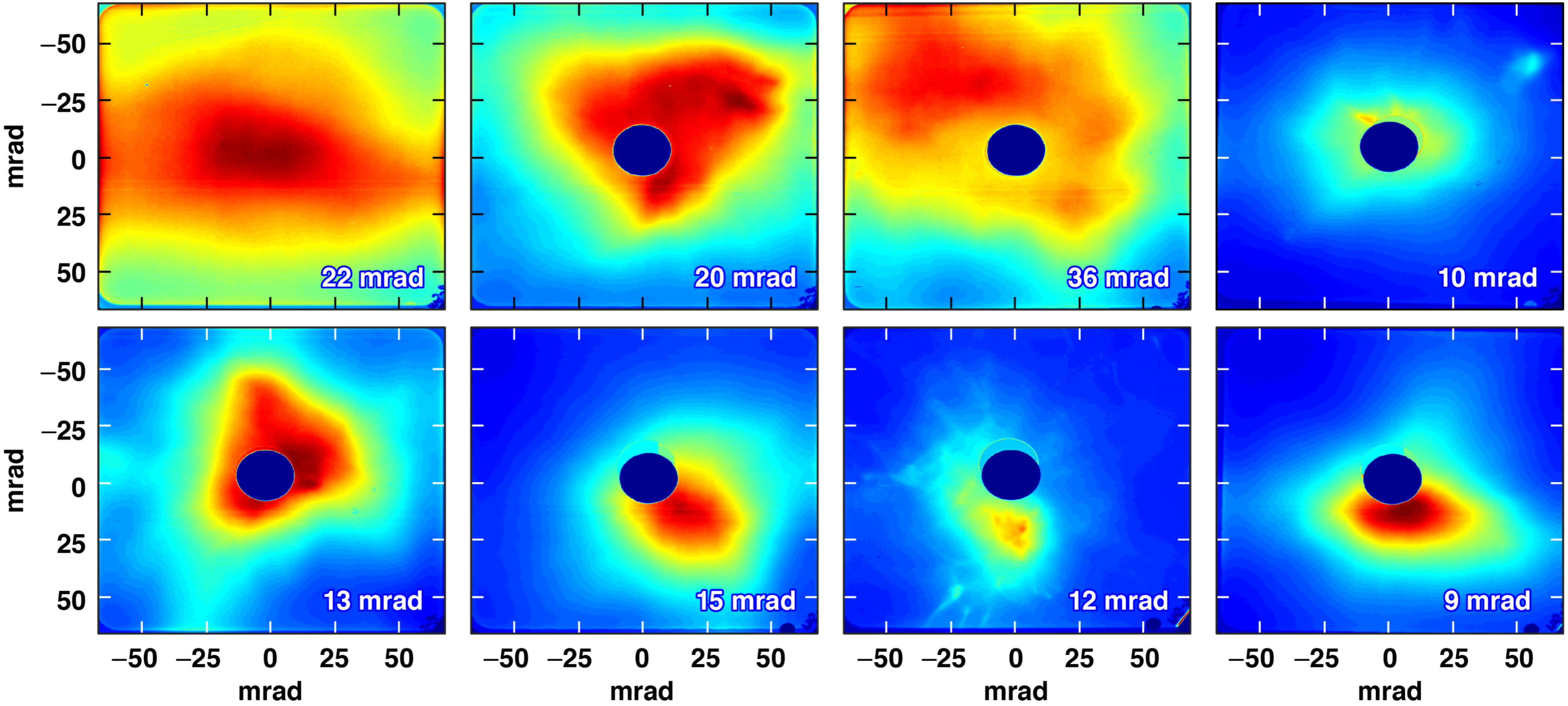
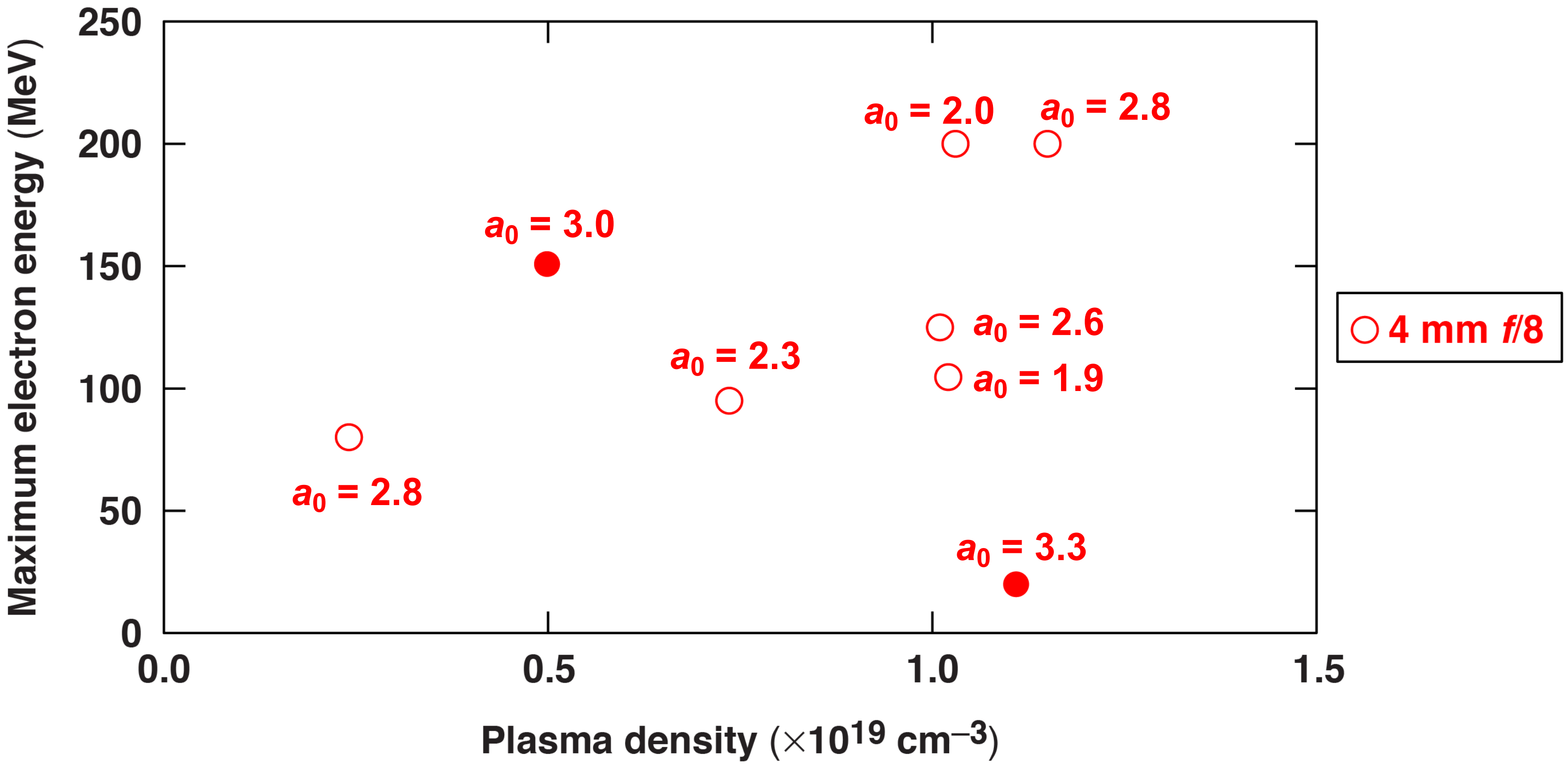
Pointing of electron beams jitters up to 36 mrad with respect to the EPPS axis



Since most energetic electrons are typically at the center of the beam, maximum energies are often not represented.

Results

For typical SMLWFA parameters, there is no clear trend between maximum electron energy and n_e or a_0



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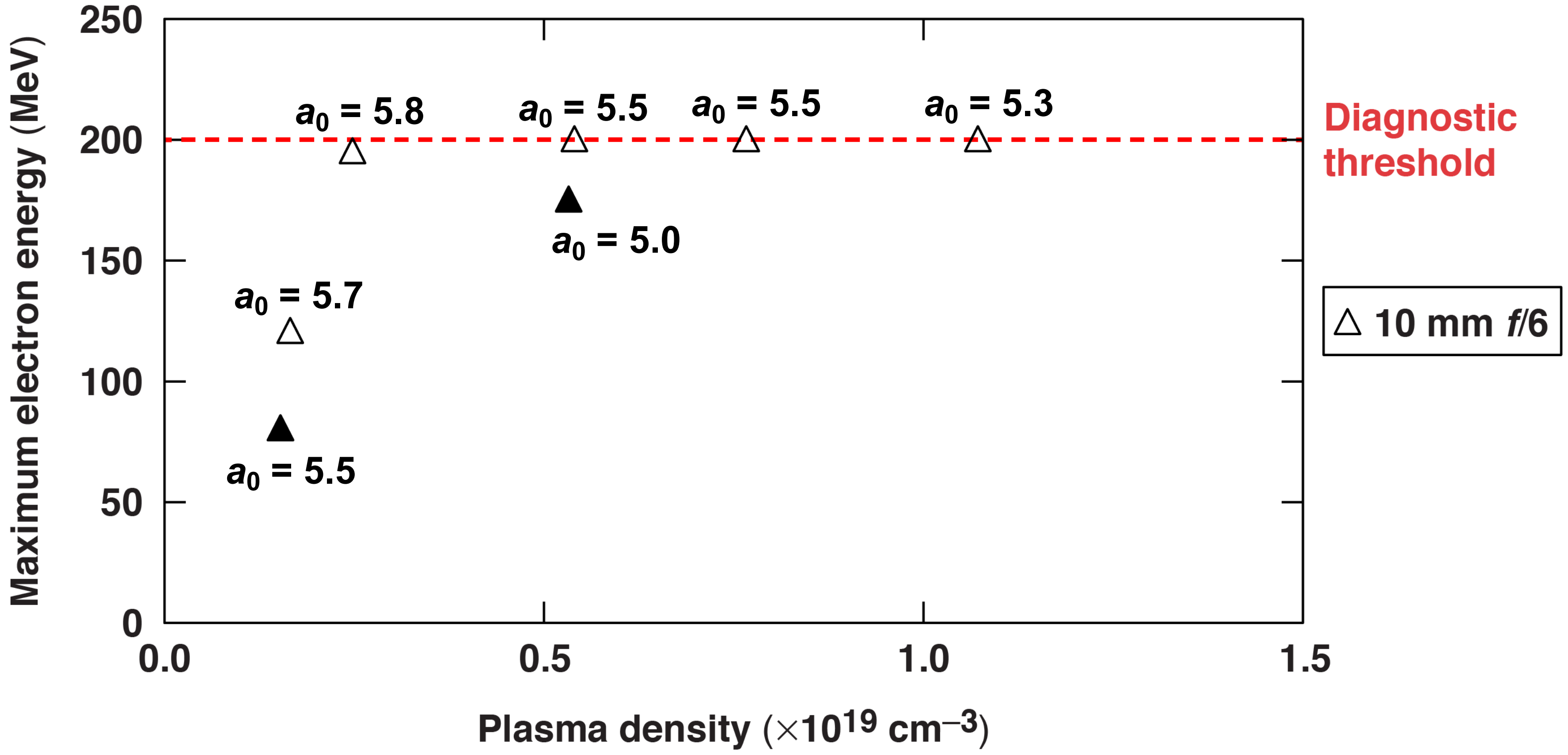
Scatter in data arises due to the majority of the electron beam centroids not falling on the axis of EPPS.

For higher a_0 values, the maximum electron energy rises rapidly with density and a_0 until exceeding the diagnostic threshold



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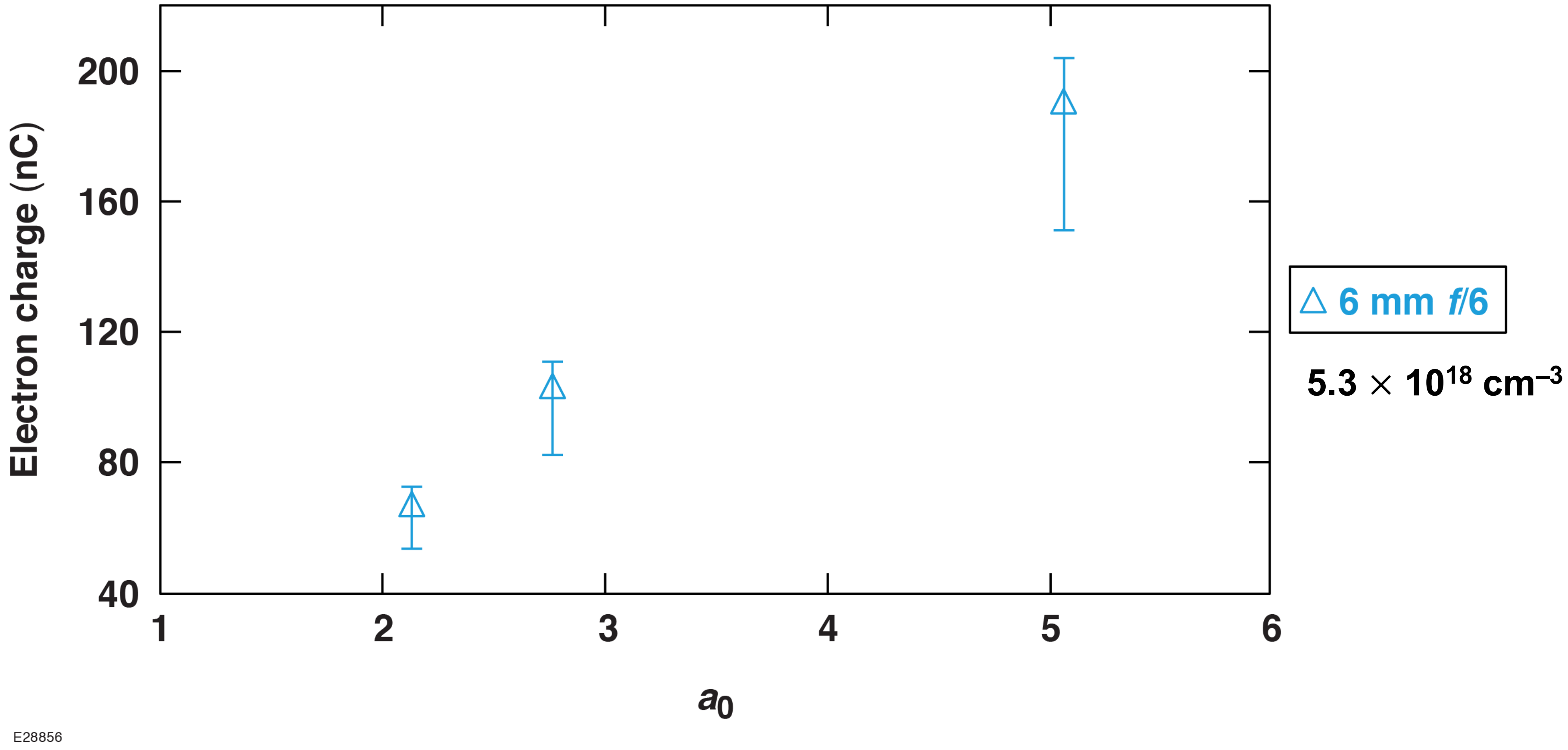
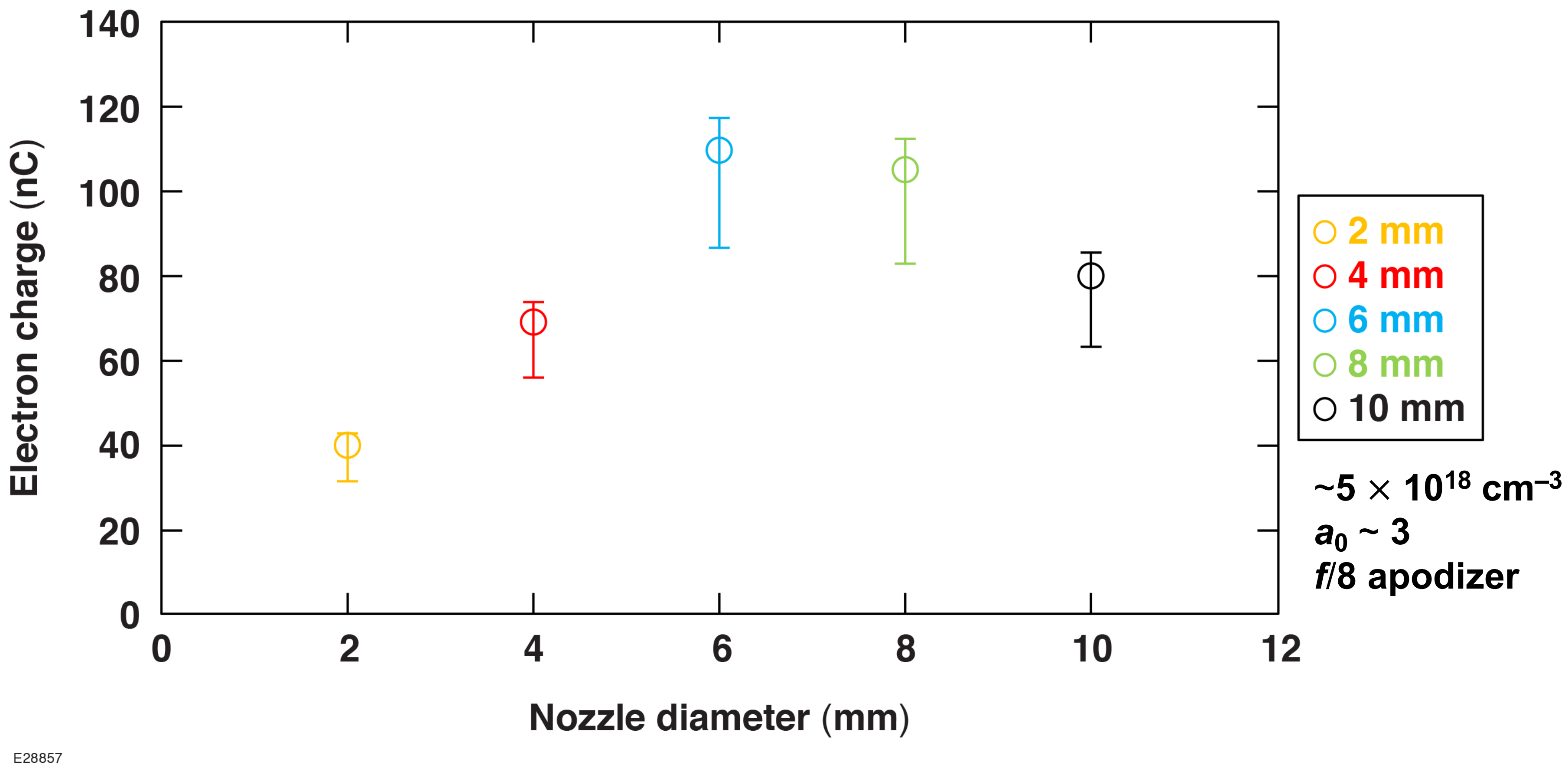
Because the 1/γ scaling does not hold when DLA is the dominant acceleration mechanism, maximum electron energy measurements in higher a_0 cases are less sensitive to alignment

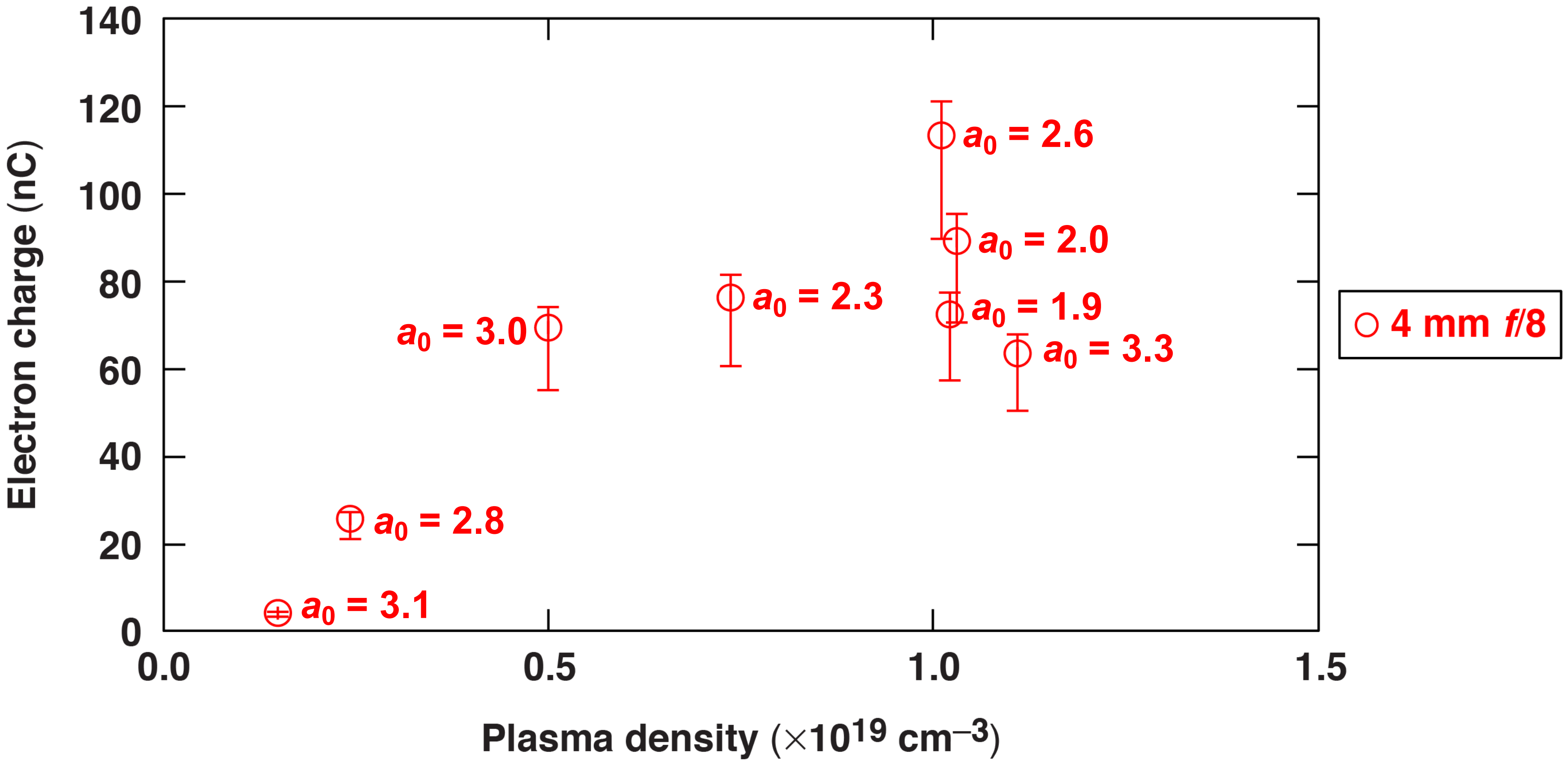
The total electron charge scales with a_0



For typical SMLWFA parameters, 6-mm-diam nozzle produces the highest charge



For a 4-mm diam nozzle with an *f*/8 apodizer, the total electron charge increases with density until ~5 × 10^{18} cm^{-3}, then approximately plateaus



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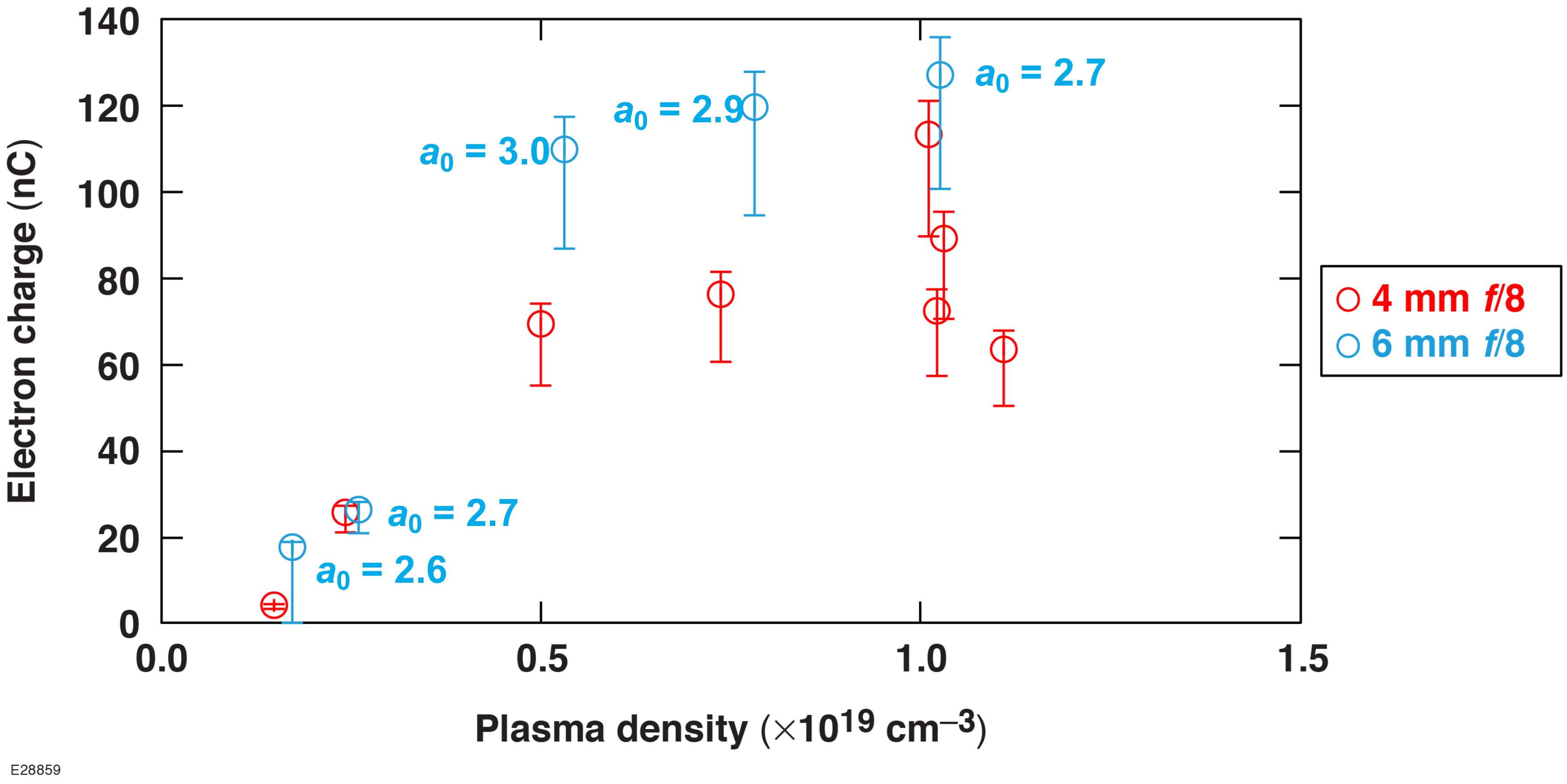
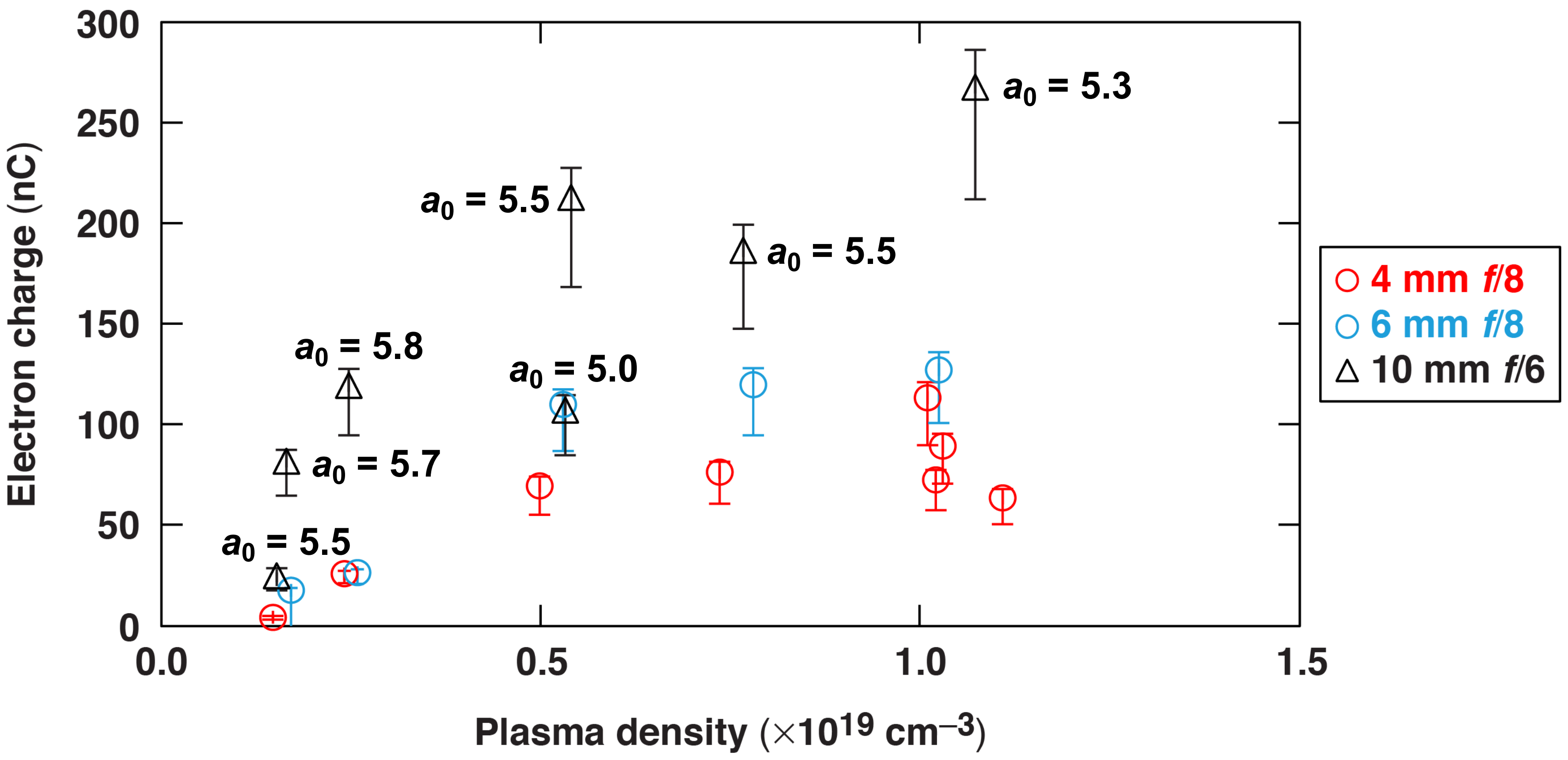
A 6-mm-diam nozzle with an f/8 apodizer shows a similar trend to the 4-mm-diam nozzle



The plateau is higher for a longer nozzle.

Results

Converting to an *f*/6 apodizer allowed higher a_0s, which produced a strong charge scaling with density



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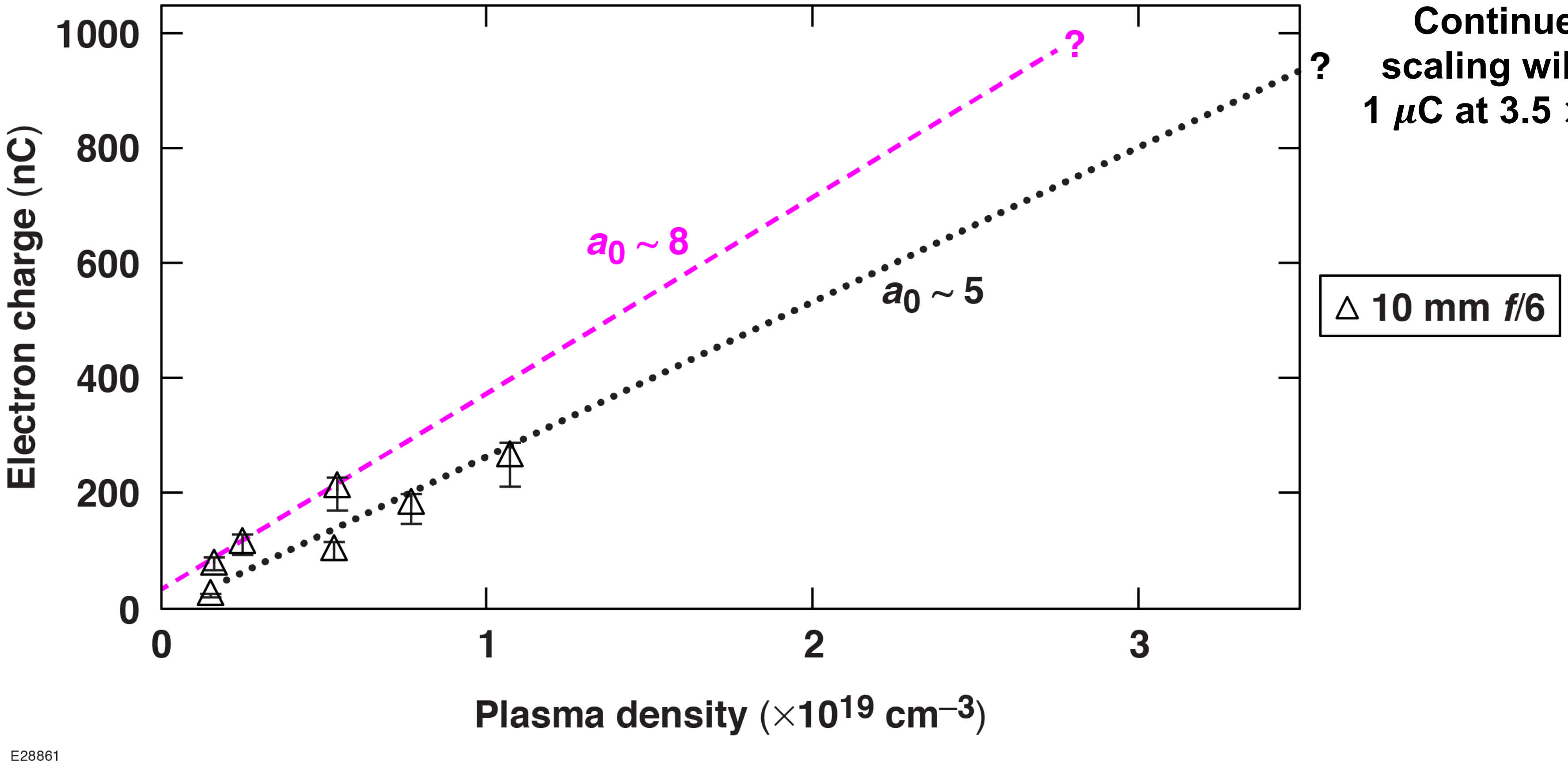
An electron charge of 270 nC has been measured, and scaling indicates further gains are possible.

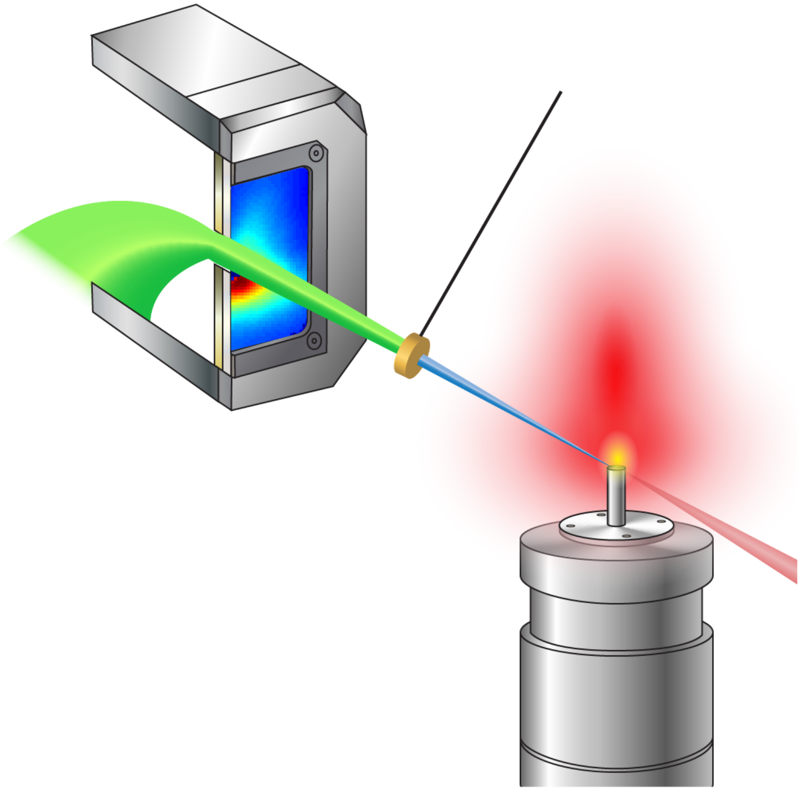
Future experiments will investigate how the electron charge scales with a_0 and n_e

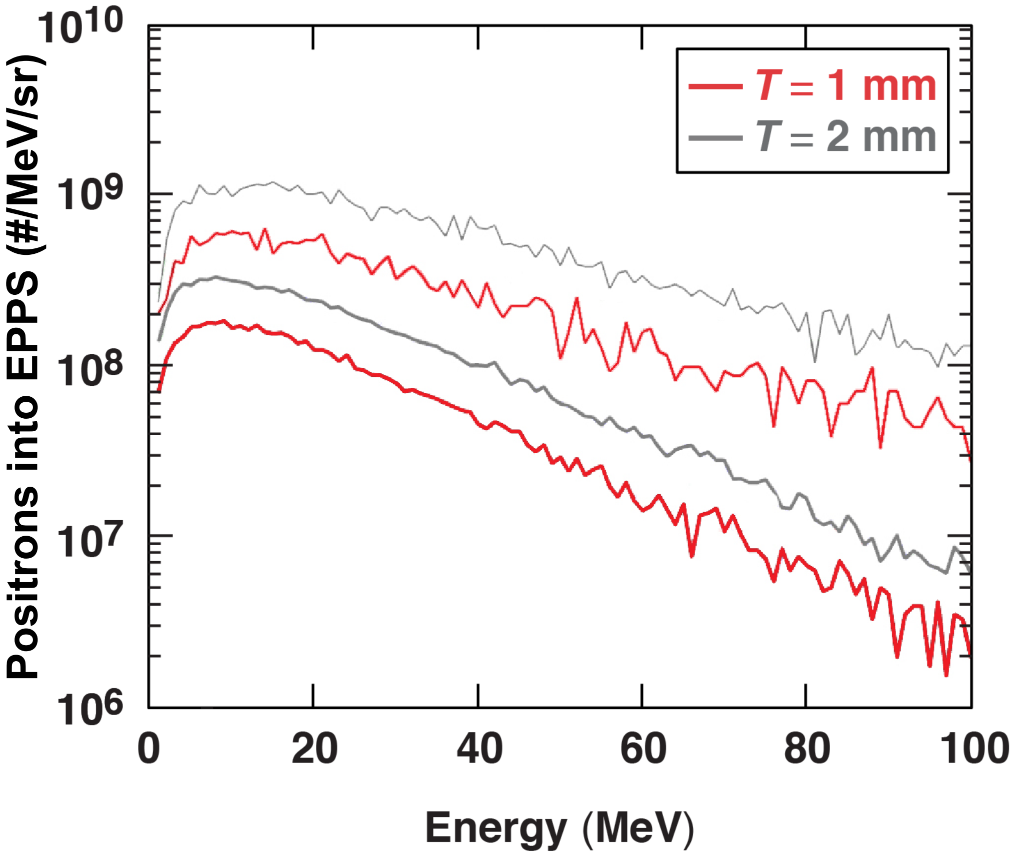


Continued linear scaling will produce 1 μC at 3.5×10^{19} cm^{-3}

Campaign scheduled for October 29, 2019

Future experiments will test positron production using 270 nC electron beam





* Calculations courtesy G. J. Williams

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This material is based upon work supported by the U.S. Department of Energy under Award # DE-SC0017950, the National Science Foundation under Award # PHY-1705224, and by the Department of Energy National Nuclear Security Administration under Award Number # DE-NA0003856.