ADVANCED ACCELERATOR CONCEPTS (AAC)

JUL 26 – 31, 2026

Very high energy electrons from multi-Petawatt LWFA in a transitional regime

On behalf of **E50122** beamtime / collaboration

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26/07/2026

TEXAS
The University of Texas at Austin

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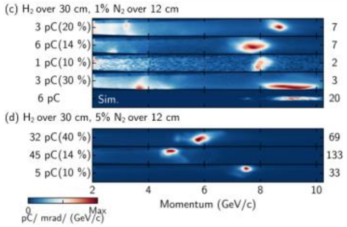
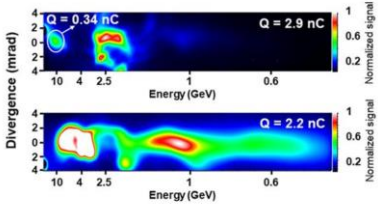
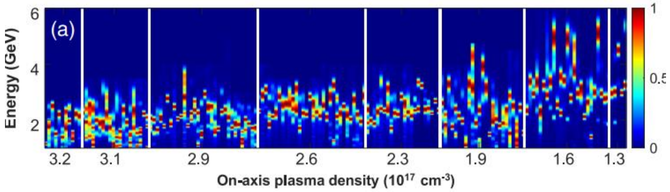
1.1 Introduction - experiment overview and motivation



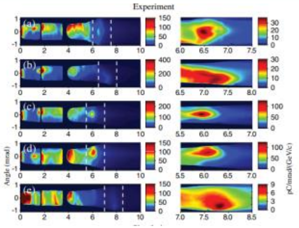
A. Picksley et al., Phys. Rev. Lett. Phys. Rev. Lett. 133, 255001 (2024)



C. Aniculaesei et al., Matter Rad. Extremes 9, 014001 (2024)



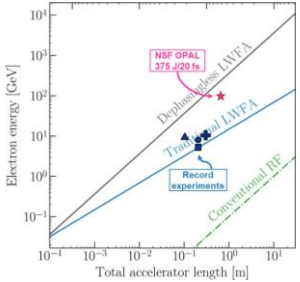
J.E. Shrock et al., Phys. Rev. Lett. 133, 045002 (2024)



A.J. Gonsalves et al., Phys. Rev. Lett. ***122****, 084801 (2019)*

8-10 GeV electron beam energies have been obtained – but the 10 GeV milestone is hard to surpass.

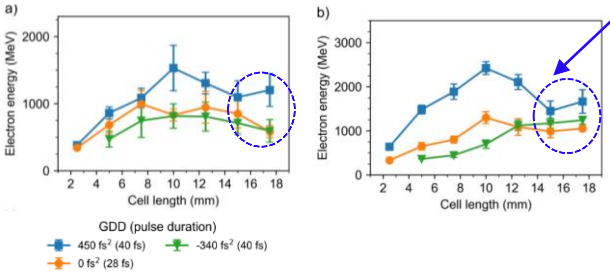
Requirements: guiding, beam shaping, nanoparticles.



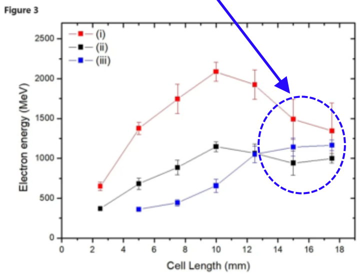
J. Shaw et al., Phys. Plasmas 32, 083107 (2025)

What happens if we just use the available laser energy for LWFA?

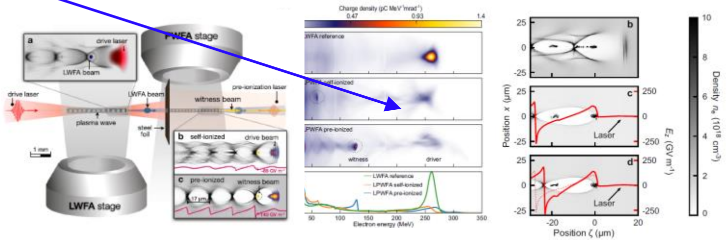
There were some clues …



J.H. Shin et al., Plasma Phys. Control. Fusion 60 (6), 064007 (2018)



H.T. Kim et al., Sci. Rep. 7 (1), 10203 (2017)



T. Kurz et al., Nat. Comm. 12, 2895 (2021)

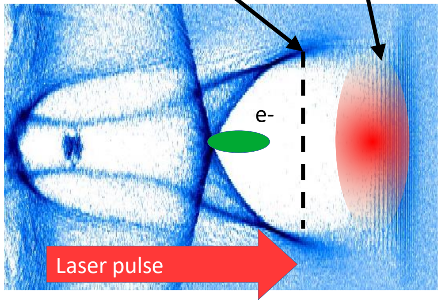
1.2 Introduction - experiment overview and motivation

Dephasing length

$$L_{dp} = \frac{4}{3}\frac{\omega_0^2}{\omega_p^2}\frac{\sqrt{a_0}}{k_p}$$

Pump depletion length

$$L_{pd} = \frac{\omega_0^2}{\omega_p^2} c\tau$$



Maximum energy gain:

$$\Delta E[GeV] \approx 1.7 \left(\frac{P[TW]}{100}\right)^{\frac{1}{3}} \left(\frac{10^{18}}{n_e[cm^{-3}]}\right)^{\frac{2}{3}} \left(\frac{0.8}{\lambda_0[\mu m]}\right)^{\frac{4}{3}}$$

Maximum charge:

$$N \approx \left(\frac{8/15}{k_0 r_e}\right)\left(\frac{P}{m_e^2 c^5/e^2}\right)^{1/2} \approx 2.5\times 10^9 \frac{\lambda_0[\mu m]}{0.8}\left(\frac{P[TW]}{100}\right)^{1/2}$$

W. Lu et al., Phys. Rev. ST Accel. Beams 10, 061301 (2007)

- Motivation

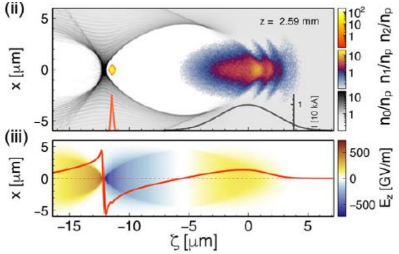
1) LWFA scaling expectations

1) ΔE = 10-14 GeV
2) L_{dp} = 262 mm
3) L_{pd} = 92 mm
4) Q_{max} = ~1 - 3 nC

[n_e = 2x10^{17}/cc, P~4 PW]

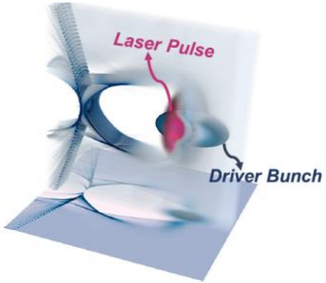
2) PWFA

$$\tilde{Q} = \frac{N_b k_p^3}{n_e} > 1 \text{ (equivalent of } a_0\text{)}$$



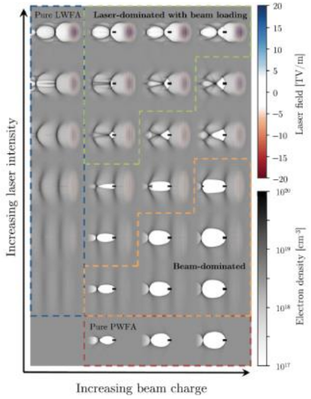
A. Martinez de la Ossa et al.,
*Trans. R. Soc. A **377,** 20180175.(2019)*

3) PWFA + LWFA = LEPA



T. Wang et al.,
Phys. Rev. Accel. Beams 23, 111304 (2020)

$$\left(\frac{\partial^2}{\partial t^2} + \omega_p^2\right)\frac{\delta n}{n_0} = \underbrace{-\omega_p^2 \frac{n_b}{n_0}}_{\propto \phi_{el}} + \underbrace{c^2 \Delta \frac{\vec{a}^2}{2}}_{\propto \phi_{pond}}.$$



J. Götzfried et al.,
Phys. Rev. X 10, 041015 (2020)

1.3 Introduction - collaboration

C. I. Hojbota (PI), O. Z. Labun, D. D. Phan, R. Sain, D. Stec, B.M. Hegelich

A. J. Franco-Altamirano, T. Araujo, R. Zgadzaj, M. C. Downer

B. Diaconescu (Co-PI/LER), L. Tudor, V. Nastasa, L. Neagu, S. Balascuta, K. Sphor, P.G. Bleotu, V. Phung Ling Jen, C. Ticos, S. Ter-Avetisyan, M. Patrascoiu, M. Gugiu, S. Popa, V. Popescu, D. Ursescu, A. Dumitru, L. Vasescu, A. Nazaru, D. Nistor, S. Rusnac, A. Lazar, R. Schmelz, I. Dancus, P. Ghenuche (Co-PI), V. Malka, C.A. Ur, et al.

B.Hidding, C. Aniculaesei, M. Cerchez, M. Osenberg, O. Bilen, T. Heinemann, E. Hartmann, N. Thomas, T. Wilson, A. Pukhov

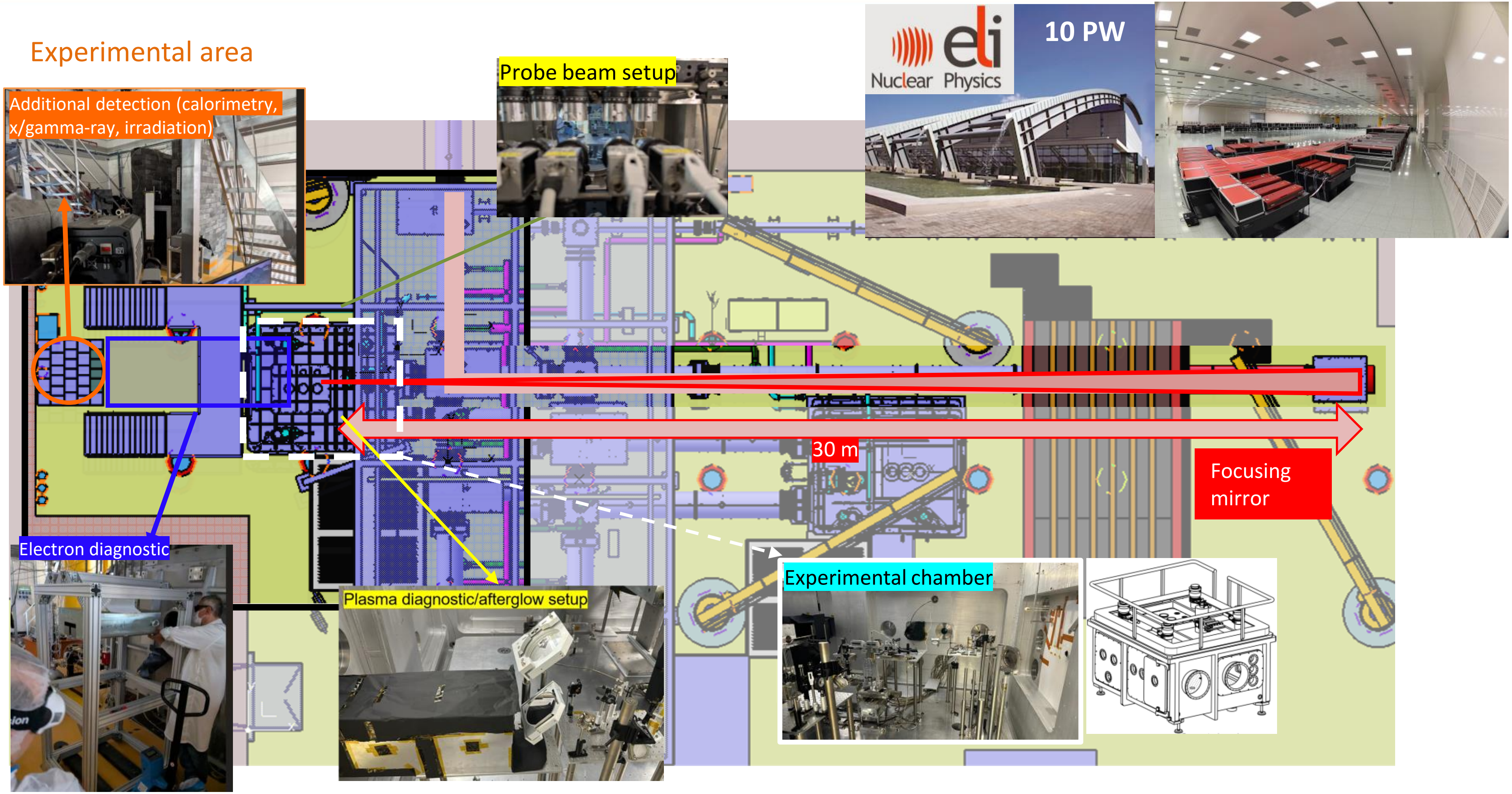
P. Franke, T. Ha, E. McCary, S. Milton, L. Labun, J. Paye, C. Neacsu, G. Tiwari, G. Plateau, H. Smith

V. Winter

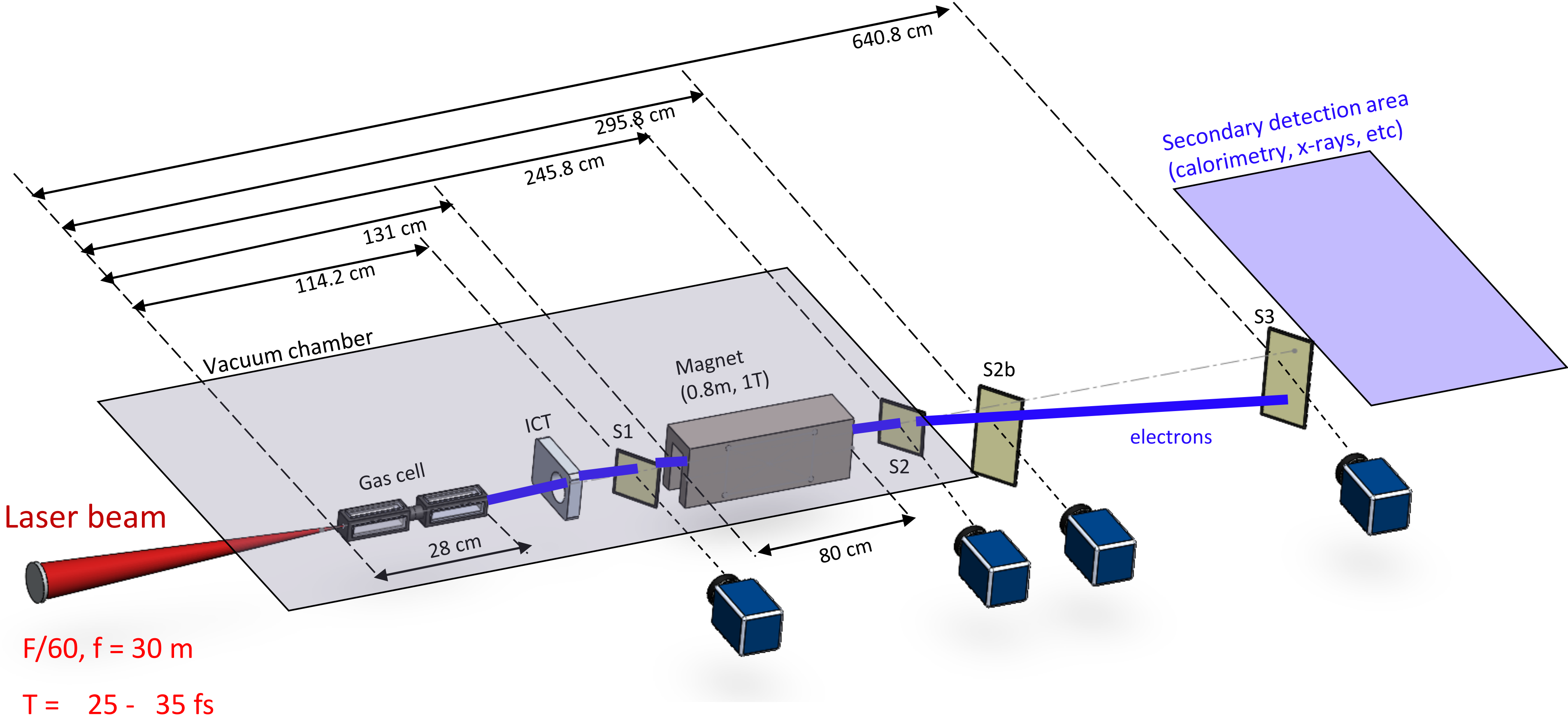
Funding: UT Austin - TAU Systems, Inc. SRA; UT Austin, Center for High Energy Density Science (CHEDS); EURO-LABS Transnational Access Funding (EURO-LABS-IFIN-HH-035);

2.1 Setup and conditions – target area (1)

Experimental area



2.2 Setup and conditions – target area (2)



F/60, f = 30 m

T = 25 - 35 fs

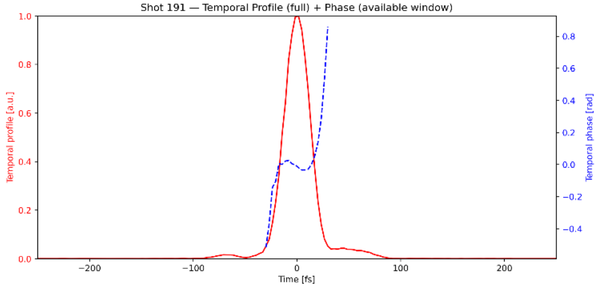
E = 240 - 300 J

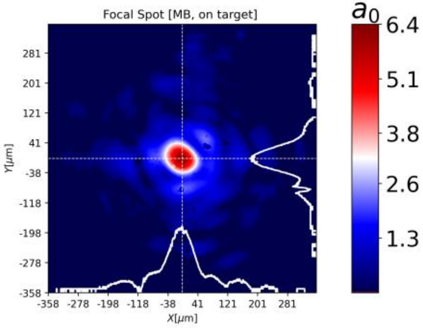
P_{target} = 4-6 PW

2.3 Setup and conditions - laser status

Operating regime:
$a_0 \sim 4 - 7$

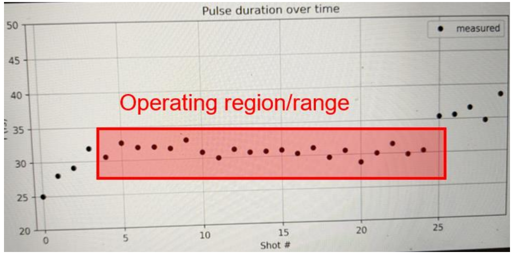
Beam waist:	w_0	$= 55.9 \pm 5.6\ \mu m$
Energy (high-power shots):	E	$= 275.2 \pm 6.06\ J$
Transmission efficiency:	$\eta_{\%}$	$= 0.614$
Energy on target:	E_T	$= 168.9 \pm 4.75\ J$
Pulse duration:	t	$= 33 \pm 3\ fs$
Encircled energy:	η_{airy}	$= 35 - 55\%$
F/#	60	
Laser wavelength:	$740 - 850\ nm\ [810\ nm]$	

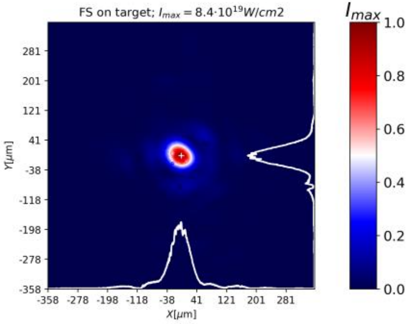


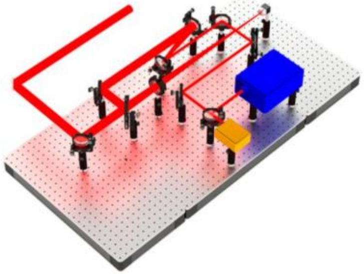


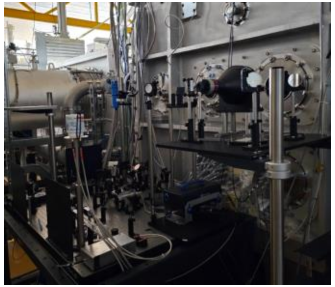
On-shot monitoring (pick-up):

- Temporal profile
- Spectral phase
- Energy
- Pointing
- Transverse profile

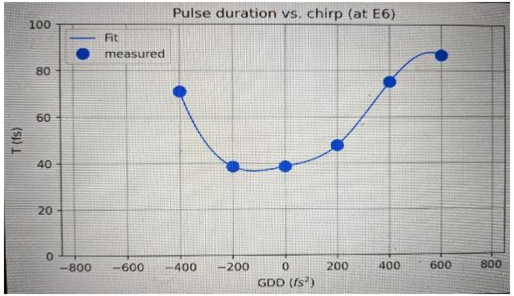




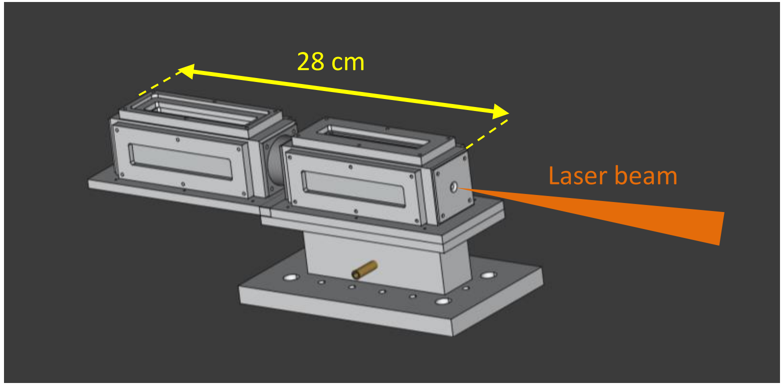


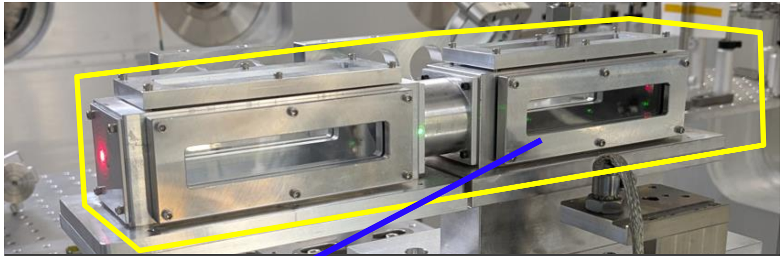


Online laser diagnostic setup



2.4 Setup and conditions - target



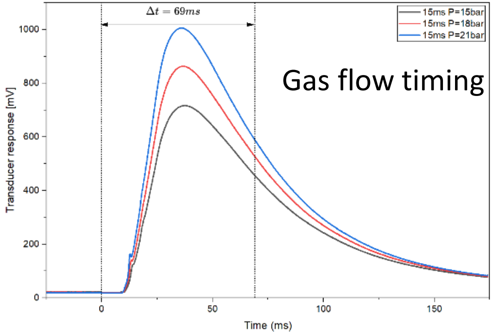


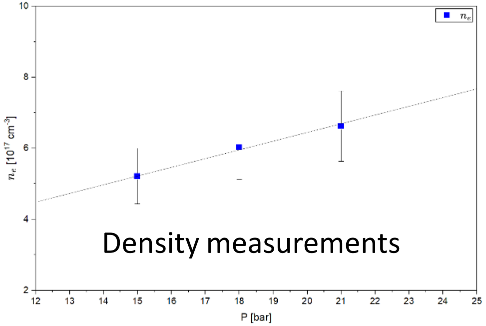
Double gas cell: 28 cm (2x12.5 cm + 3cm separator)

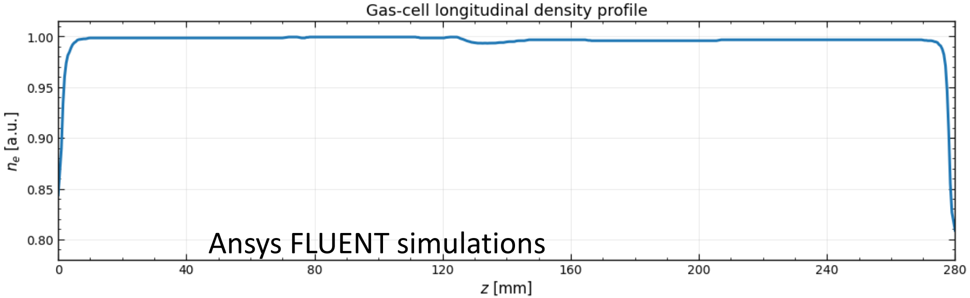
Single cell configuration

15.5 cm
(12.5 cm + 3cm extension)

Gas medium	He 97% / N_2 3%
He 100%	He 95% / N_2 5%
He 99% / N_2 1%	He 97% / Ne 3%

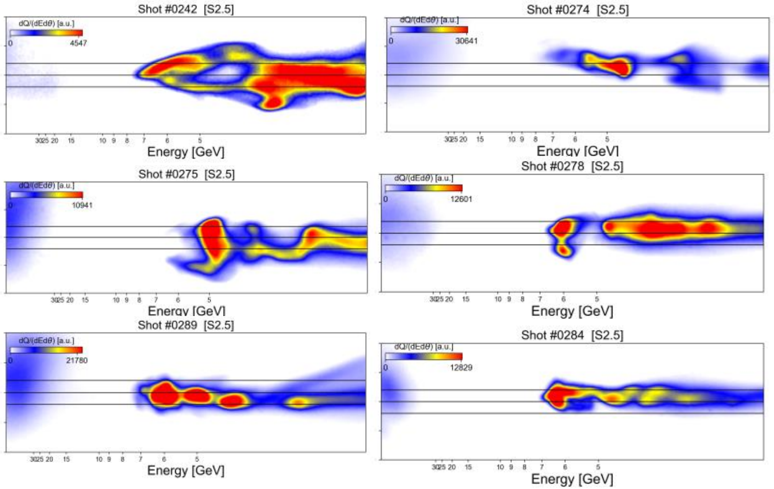




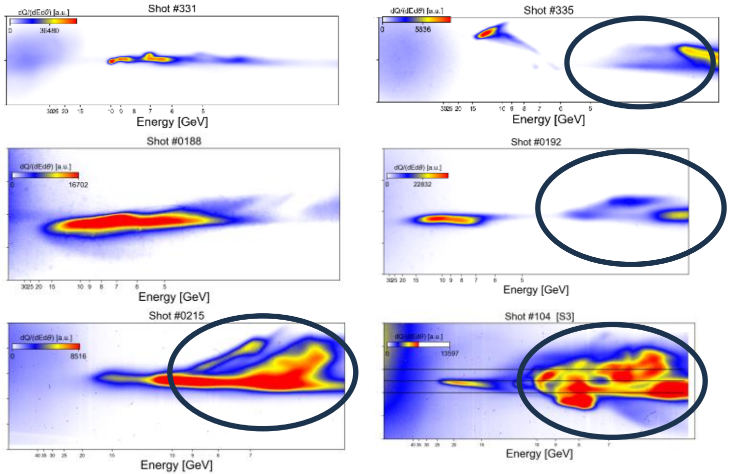


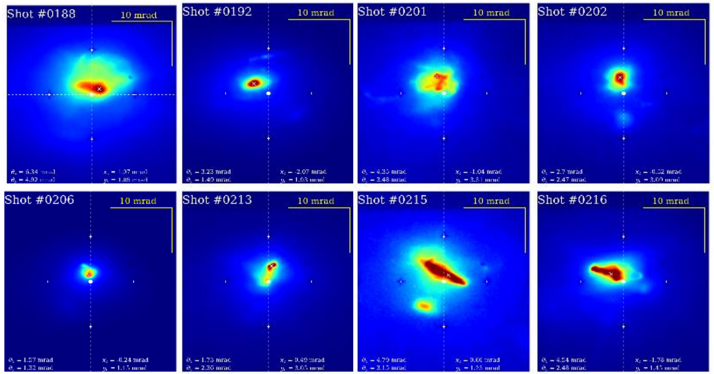
3.1 Results - overview

L_{acc} = 15.5 cm



L_{acc} = 28.0 cm



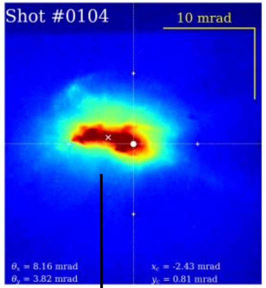


At 15.5 cm we regularly obtained 5-10 GeV

Very hard to go beyond 10 GeV …

When switching to L_{acc} = 28 cm, electron beam structure becomes more complex and the energies go beyond 10 GeV, surpassing 15 GeV multiple times

3.2 Results - experimental highlight: beyond 10 GeV

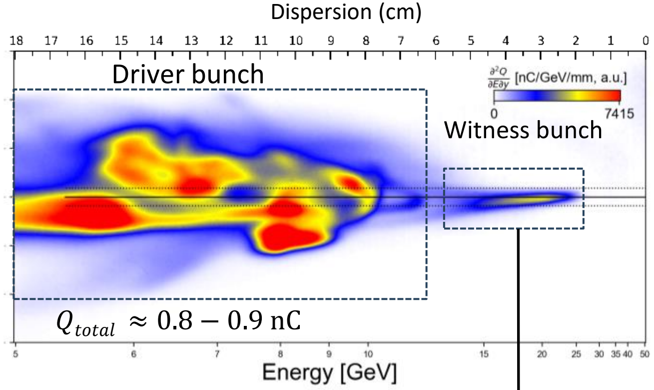


Low pointing offset!

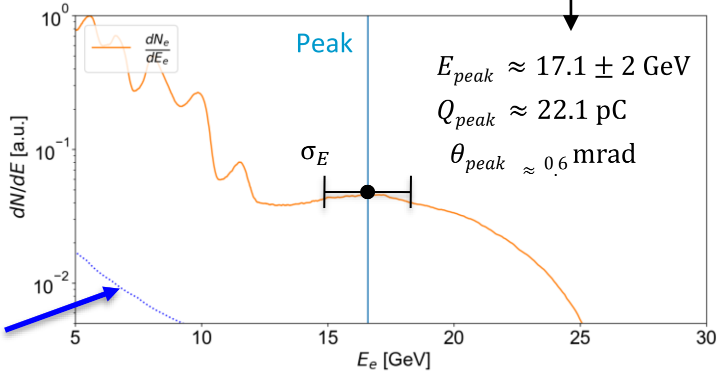
Beam profile at S1

$\theta_{fwhm} \approx 3.8\, mrad$

$\theta_y \approx 0.8\, mrad$



$Q_{total} \approx 0.8 - 0.9$ nC

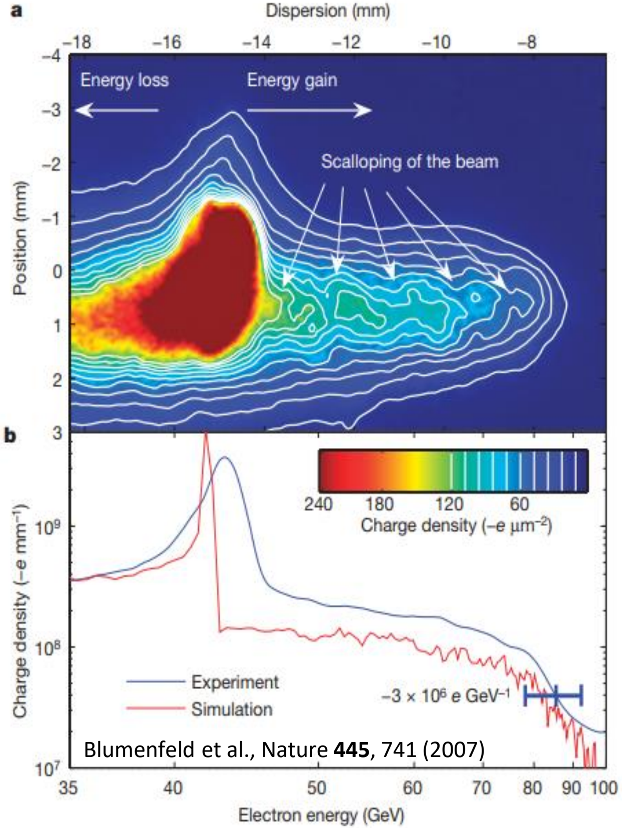


$E_{peak} \approx 17.1 \pm 2$ GeV

$Q_{peak} \approx 22.1$ pC

$\theta_{peak} \approx 0.6$ mrad

Detection limit

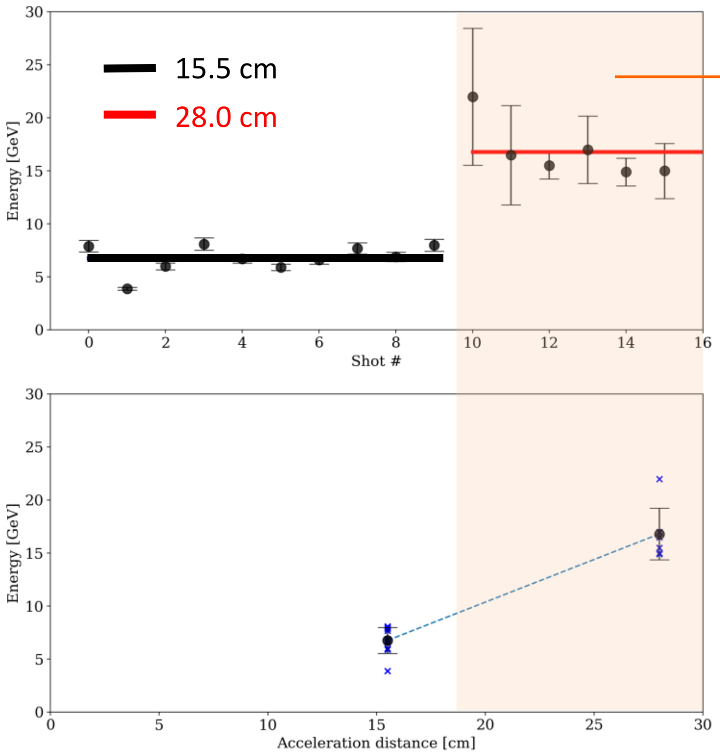


Blumenfeld et al., Nature **445**, 741 (2007)

Highest energy shot – peaking at **~17 GeV** with electron energy extending **beyond 20 GeV**

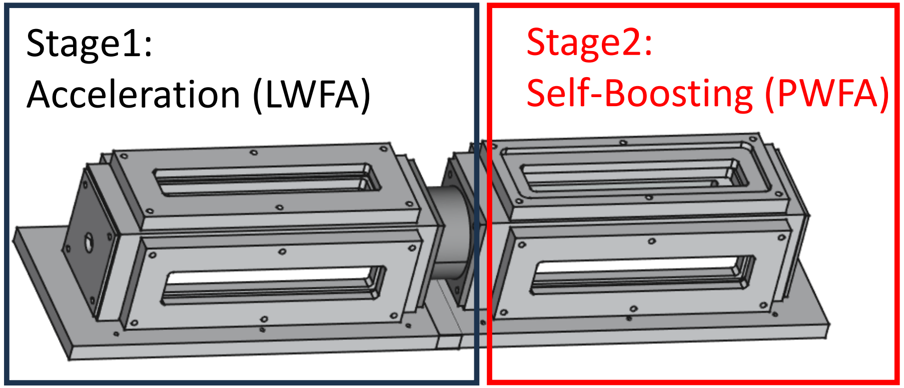
Feature comparison with a previous PWFA demonstration!

Maximum energy vs. acceleration distance



The energy is basically doubled when the 2nd cell is used

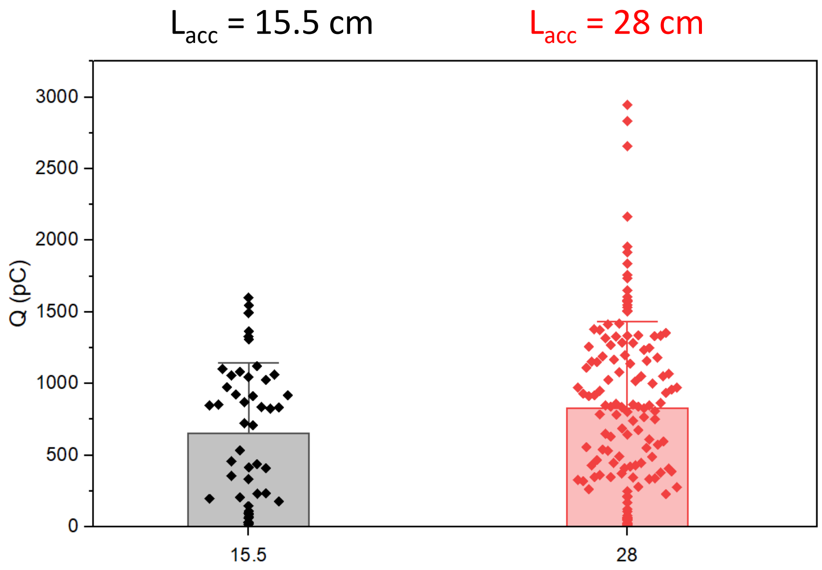
This is consistent with the following model:



Magnetic spectrometer
B = 0.9 – 1.0 T
L = 0.8 m

See reports of 8 GeV measurements on
D. Catana et al., Plasma Physics and Controlled Fusion 68 (4), 045001 (2026)

3.4 Results – charge enhancement



Charge injected for the two stages:

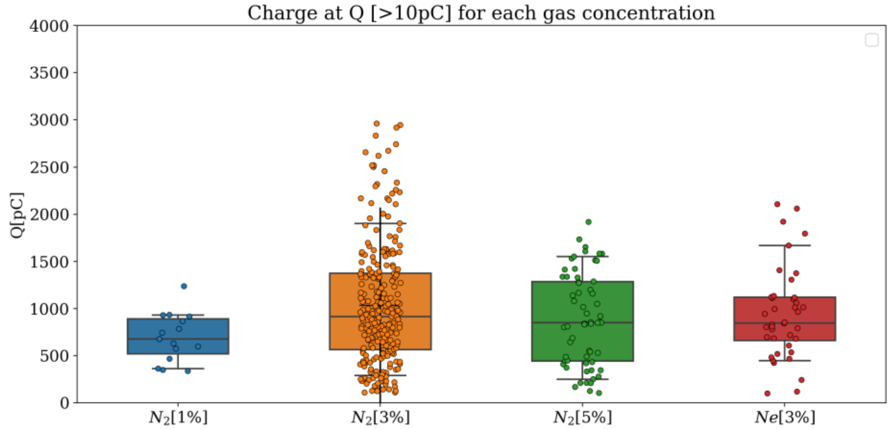
Single gas cell:
$\langle Q \rangle \approx 0.65\, nC$
$Q_{max} \approx 1.6\, nC$

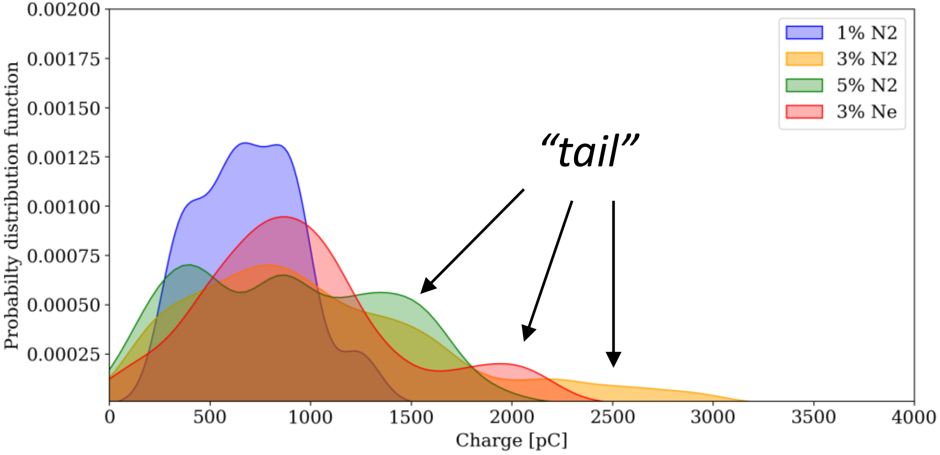
Double gas cell:
$\langle Q \rangle \approx 0.8\, nC$
$Q_{max} \approx 3\, nC$

Indication that charge injection still occurs after 15.5. cm! (i.e. in the second stage)

Likeliest scenario:
An additional witness beam gets injected into the wake and accelerated by the driver

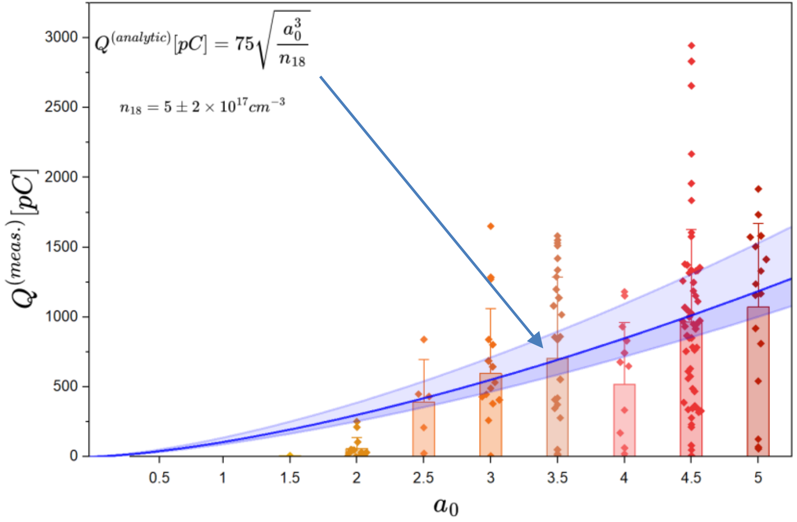
3.5 Results – gas species' effect on beam charge





Gas species have a clear effect on charge (3% N_2 produces highest charge)

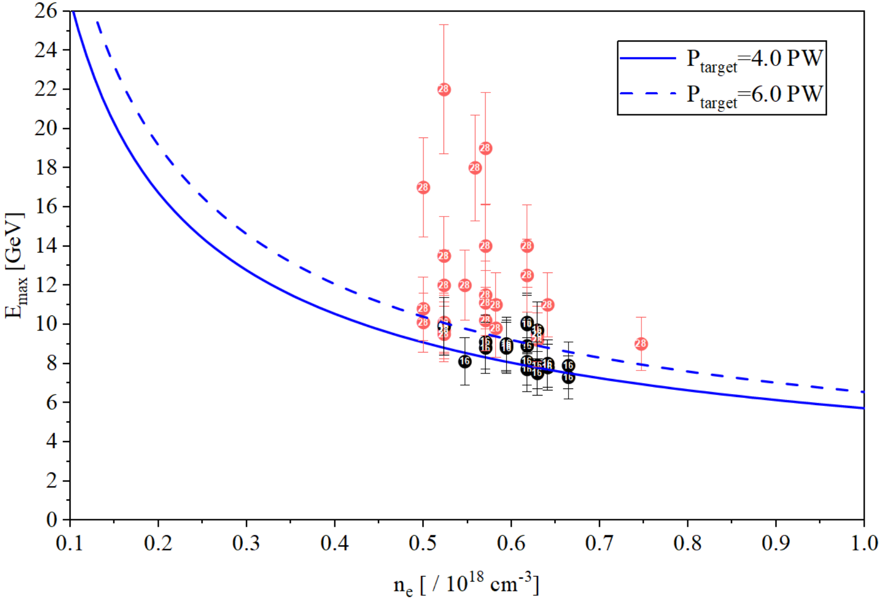
Scaling law is exceeded by measurements (instead of acting like an upper bound)



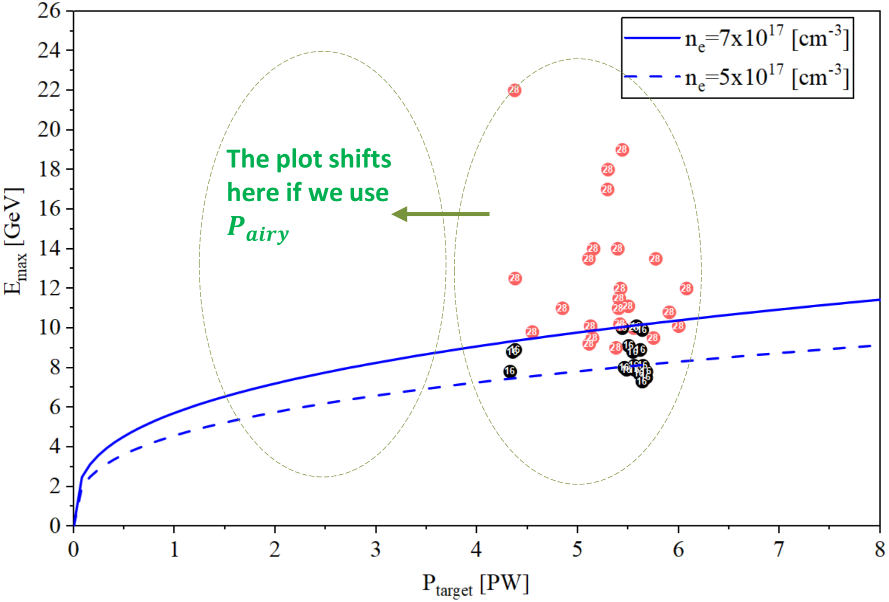
3.6 Results – scaling laws

$$\Delta E[GeV] \approx 1.7\left(\frac{P[TW]}{100}\right)^{\frac{1}{3}}\left(\frac{10^{18}}{n_e[cm^{-3}]}\right)^{\frac{2}{3}}\left(\frac{0.8}{\lambda_0[\mu m]}\right)^{\frac{4}{3}}$$

L= **28 cm** / 15.5 cm



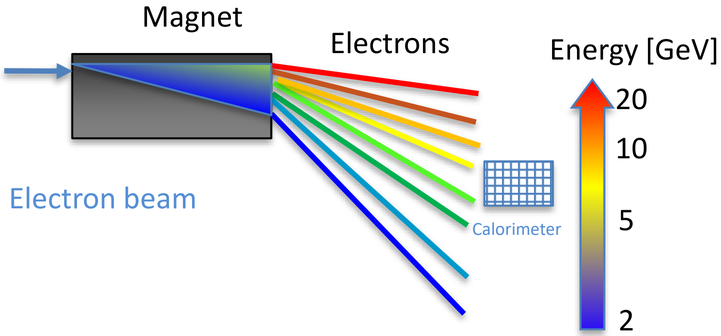
L= **28 cm** / 15.5 cm

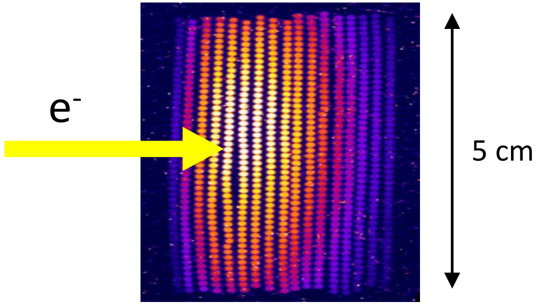


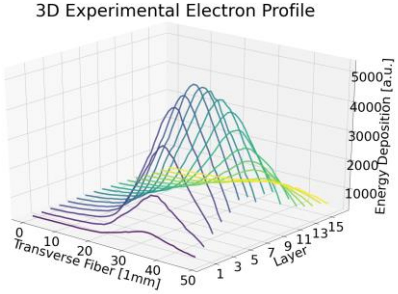
Final details of the analysis are in progress but conclusions will remain unchanged.

Maximum achieved energy goes beyond the typical LWFA scaling
Indication of a hybrid LWFA -> PWFA (HLPWFA) mechanism!

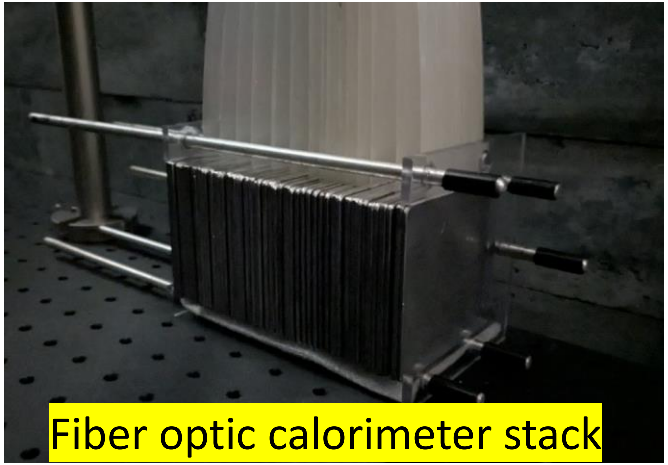
3.7 Results - calorimetric detection (electrons)

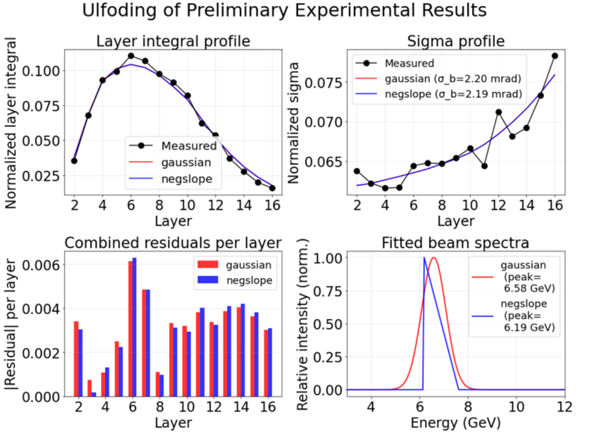






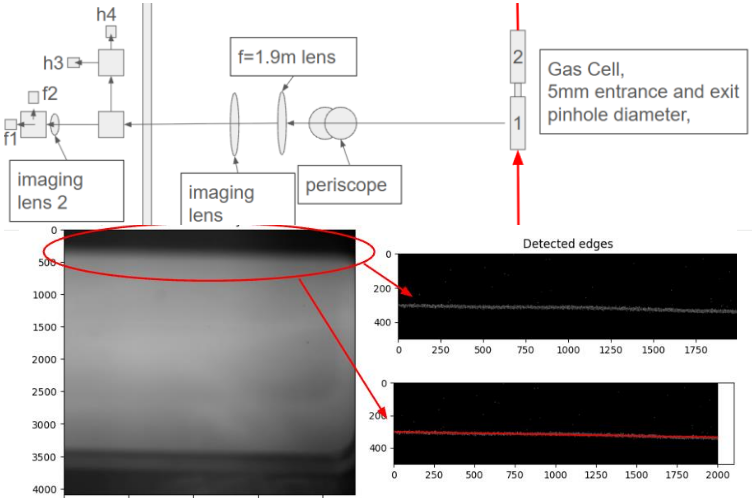
A. J. Franco-Altamirano

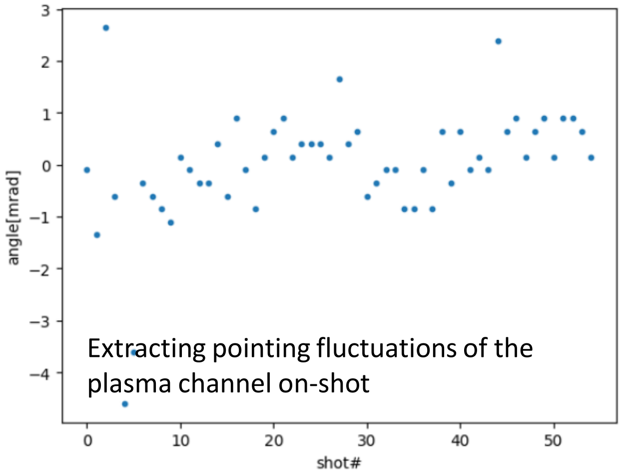




Preliminary results obtained at the 10PW beamline at ELI-NP indicate unfolded energy between 5GeV and 8GeV.

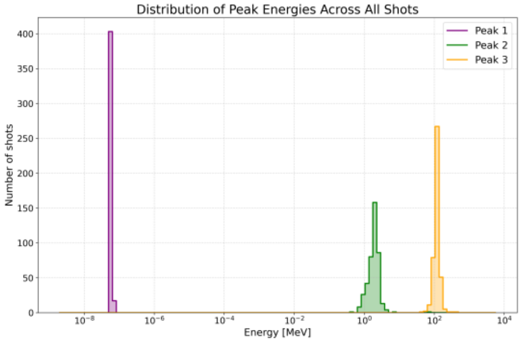
Plasma afterglow – a useful tool for diagnosing channel properties

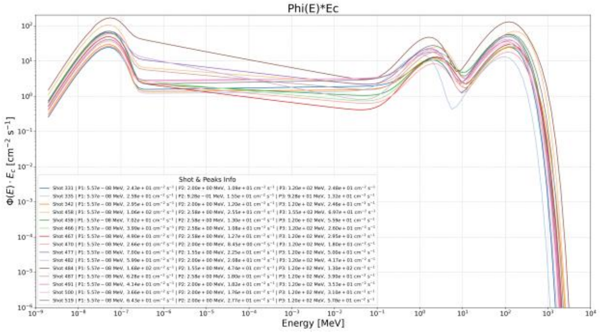


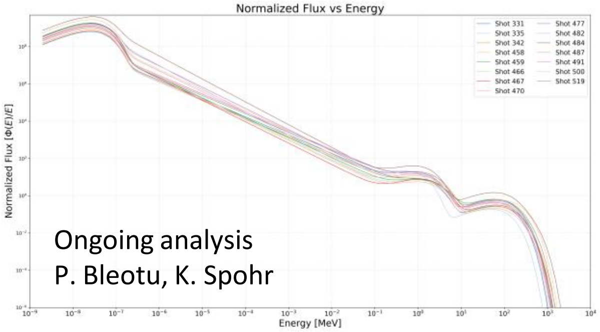


Ongoing analysis
O. Bilen et al.

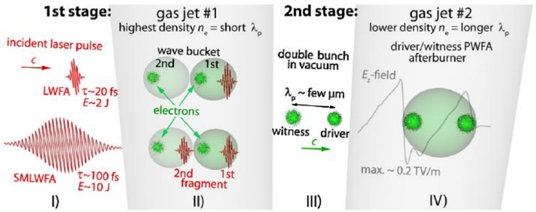
Observing spallation neutrons >100 MeV





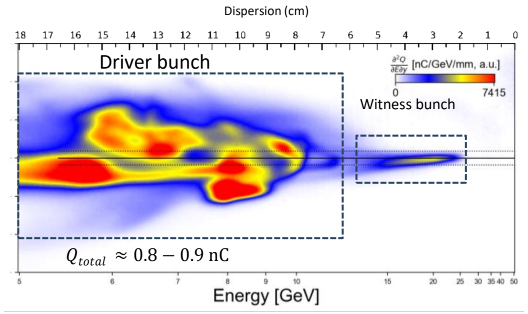


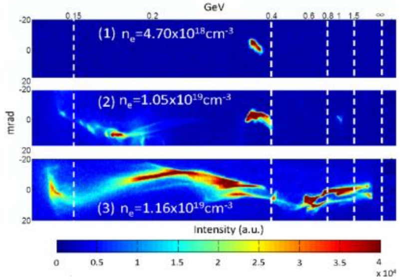
4.1 Discussion – Similar experiments



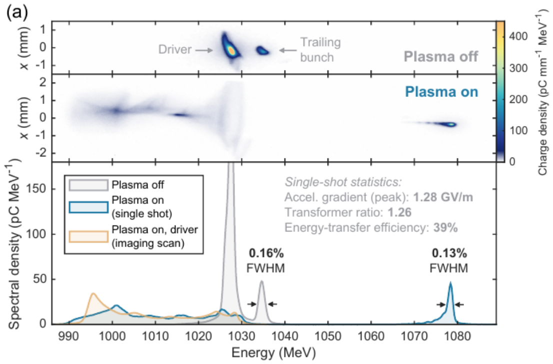
B. Hidding et al., Phys. Rev. Lett. 104, 195002 (2010)

Self-mode transition:
K.H. Pae et al., Phys. Plasmas, 17, 123104 (2010)

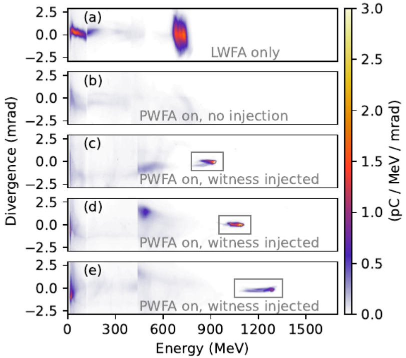




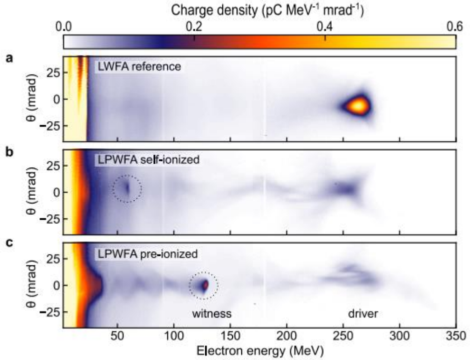
Masson-Laborde, P E et al., Phys. Plasmas 21, 123113 (2014)



C. A. Lindstrøm et al.,
Phys. Rev. Lett. 126, 014801 (2021)



F. M. Foerster et al.,
arXiv:2602.24107v1 (2026)



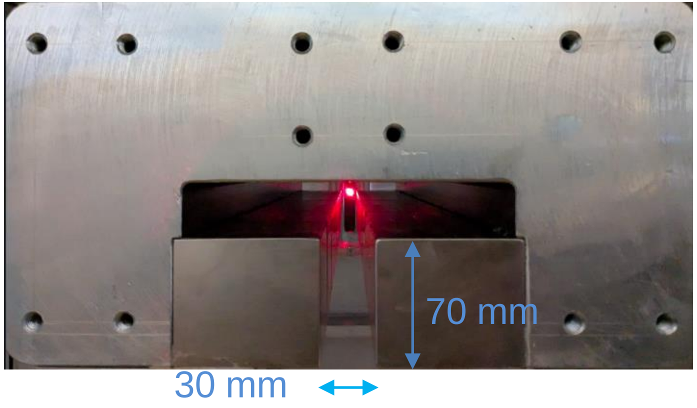
T. Kurtz et al., Nat. Comm. 12, Article number: 2895 (2021)

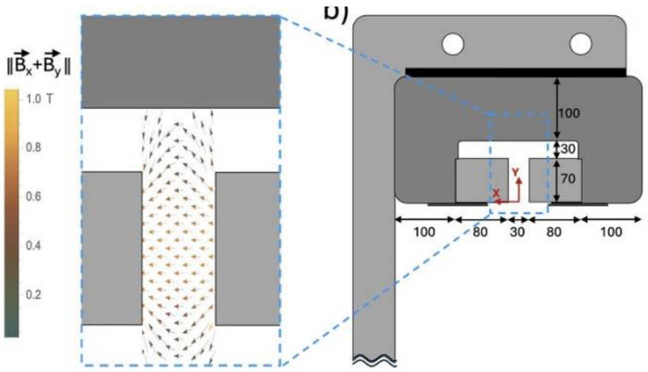
First demonstration of PWFA:
J.B. Rosenzweig et al., Phys. Rev. Lett. 61(1), 98 (1988)

Recent PWFA overview:
C. A. Lindstrømet al., arXiv:2504.05558v1 (2025)

Reviews of (H)LPWFA:
B. Hidding et al., Appl. Sci., 9(13), 2626, (2019)
B. Hidding et al., Photonics, 10(2), 99 (2023)

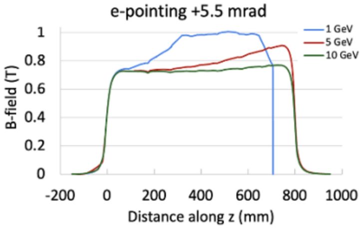
Magnetic spectrometer



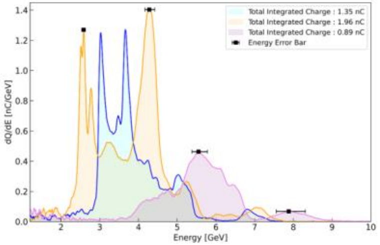


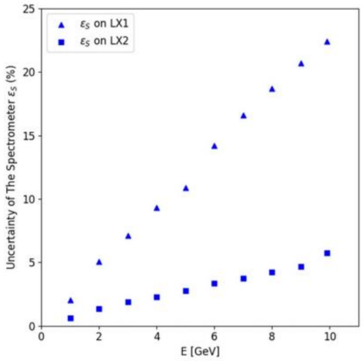
Acceptance angle ±14.5 mrad - Necessary!
Small acceptance angle would **not** distinguish PWFA features of the driver beam (beam breaking up, transverse divergence growth).

We use multiple screens after magnetic dispersion, and an entrance screen for pointing correction …



$$\varepsilon_S(y,\theta) = \sqrt{\left(\left|\frac{\partial E}{\partial y}\right|\frac{\Delta y}{|E|}\right)^2 + \left(\left|\frac{\partial E}{\partial \theta}\right|\frac{\Delta \theta}{|E|}\right)^2}.$$





B. B. Pollock et al., Proceedings of PAC09, 3035–3037 (2009)
H.J. Cha et al., Rev. Sci. Instrum. 83, 063301 (2012)
C.I. Hojbota et al., AIP Advances 9 (8), 085229 (2019)

$$\frac{\sigma_E}{E} \approx \frac{\theta\sqrt{(L_1^2+L_2^2)E}}{(L_1+L_2)eBc\,L_m} \times 100\ [\%]$$ Error: $\frac{\Delta E}{E} = \pm 2 - 15\%$

M.V. Ambat et al., Rev. Sci. Instrum. 96, 123303 (2025)

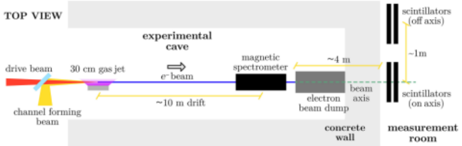
$$\boxed{Q[pC] = \frac{N_{PSL} Q_e \times 10^{12}}{a_{N_S} \times N_{PSL/e} \times f_{SR}(t) \times f_{En}(E)}}$$

D. Catana et al., Plasma Phys. Control. Fusion 68 045001(2026)

4.3 Discussion – future work

What should we do with these beams?

Generate muons! (for radiography and beyond)

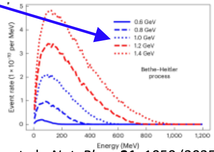


D. Terzani et al., *PRAB* **28** (2025)

Photoproduction: $\gamma Z \rightarrow \pi^{\pm} X \rightarrow \mu^{\pm} + \nu_{\mu} + X$

Bethe–Heitler: $\gamma Z \rightarrow \mu^{+}\mu^{-} Z$

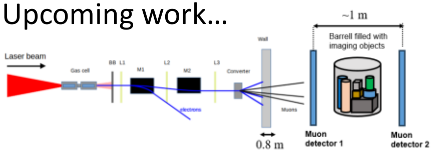
L. Calvin et al., PPCF **68**, 035015 (2026)
S. Ikram et al., arXiv:2605.13118 (2026)
K. Zhu et al., arXiv:2607.12984 (2026)

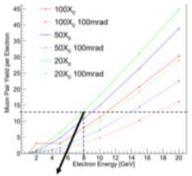


A. I. Titov, B. Kämpfer and H. Takabe, PRSTAB 12, 111301 (2009).

F. Zhang et al., *Nat. Phys.* **21**, 1050 (2025)

Upcoming work…



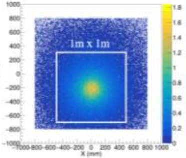


$\langle E_e \rangle = 8\ GeV$

$\eta \approx 1.3 \times 10^{-5}\ \mu/e^{-}$

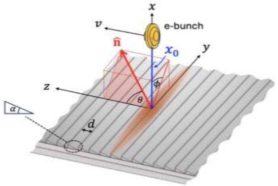
At Q= 400 pC, we get

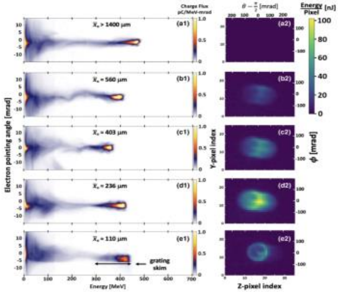
$N_{\mu} = 3.25 \times 10^{4}$ / shot



Diagnose them in compact setups!

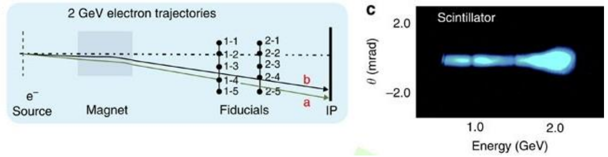
Smith-Purcell radiation





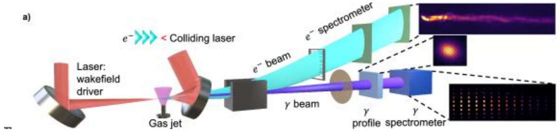
R. Rudzinsky et al., Optica 13, 5 (2026)

Fiducial wires

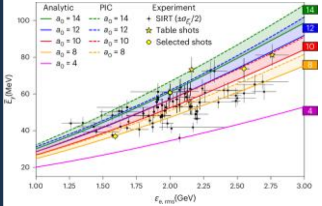


X. Wang et al., Nat. Commun. 4, 1988 (2013)

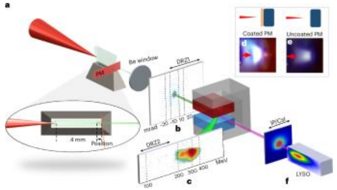
Strong-Field QED



E. Los et al., Nat. Commun. 17, 1157 (2026)



M. Mirzaie, C.I. Hojbota, D.Y.Kim et al., Nat. Photonics 18, 1212 (2024)



X. Hu et al., Nat. Photonics (2026)

5. Conclusions

- We observed electrons with peak energy of 17.1 ± 2.0 GeV, extending beyond 20 GeV

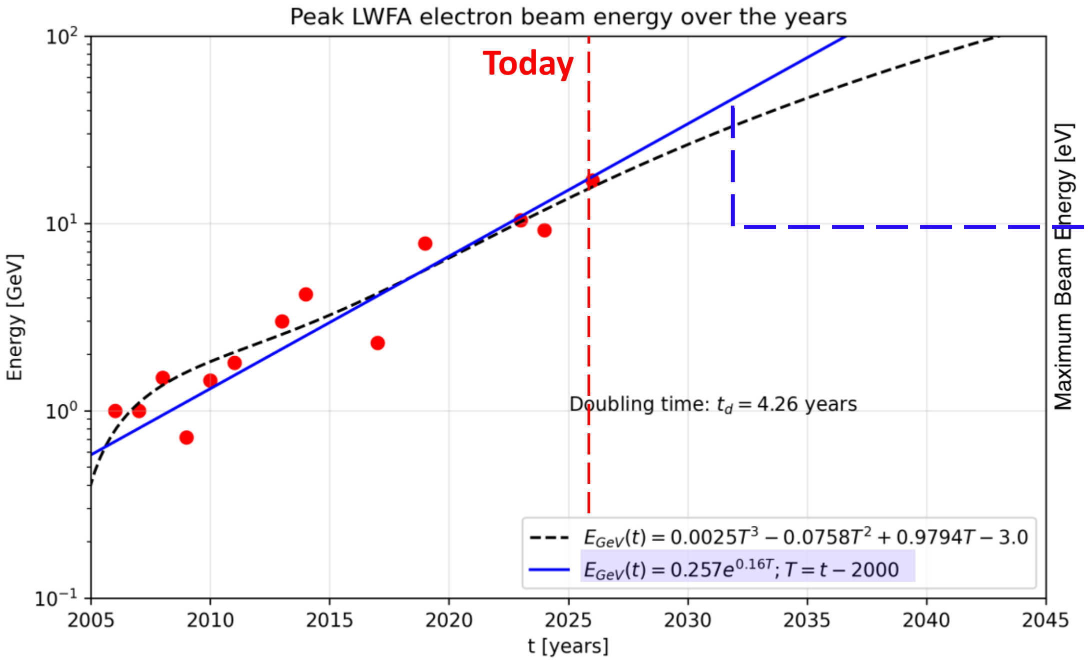
- Beams of up to Q = 3 nC were produced, with a clear gas species dependence

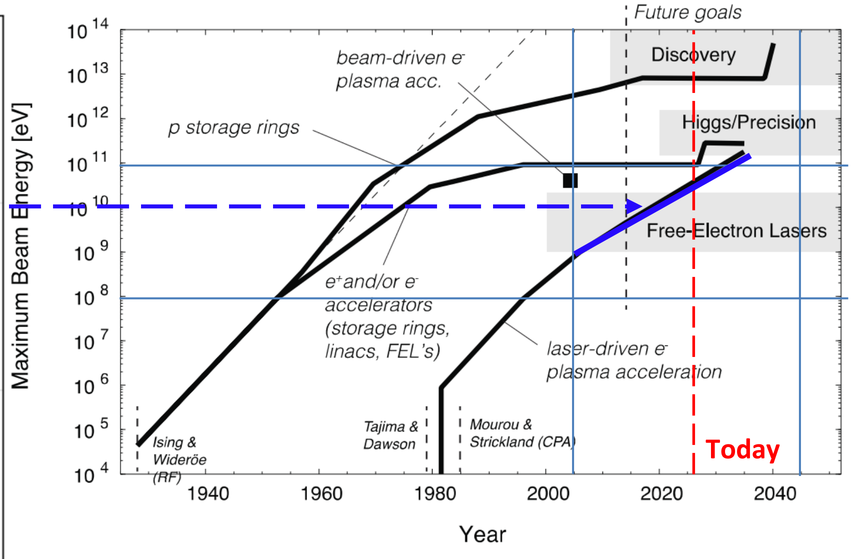
- We have strong evidence of a transitional (hybrid) regime:
  - (H)LPWFA = (1)LWFA + (2)PWFA
- The evidence is backed by:
  - electron spectra features
  - injection and acceleration in the 2^{nd} stage
  - departure from classical LWFA scaling

- We conducted plasma afterglow and neutron measurements

- Although not perfect (yet), the beam produced here can readily be used in:
  - Beam-target experiments (e.g. $\mu^+\mu^-$ production)
  - Laser-electron collisions (SFQED)
  - Measurement of electron bunch characteristics

☺ Food for thought ☺





R. W. Aßmann & J. Grebenyuk, Proc. IPAC'14, 961–964 (2014). doi:10.18429/JACoW-IPAC2014-TUOBB01

A. Cakir and O. Guzel arXiv:1908.07207v4 (2020)

Peak LWFA electron energy has doubled approximately every 4-4.5 years.
This trend has persisted for more than two decades.

We should expect 100 GeV from (*some form of*) LWFA within 10-15 years!