Laser-driven production of ultra-short high quality positron beams

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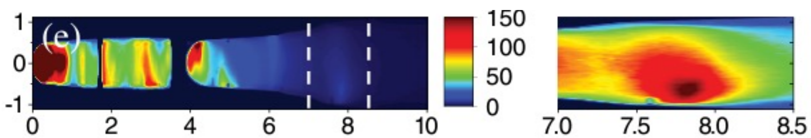
Introduction

The problem

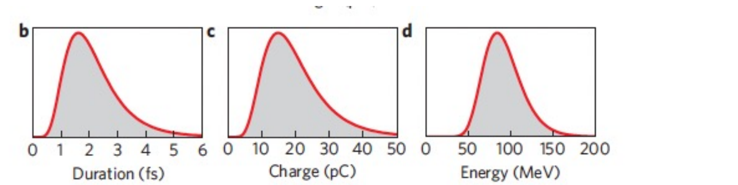
Plasma-based electron acceleration at a relatively mature stage, with landmark results achieved

>8 GeV electron beams



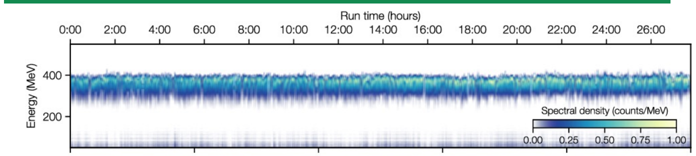
A. J. Gonsalves et al., Phys. Rev. Lett. 122, 084801 (2019)

Femtosecond-scale duration



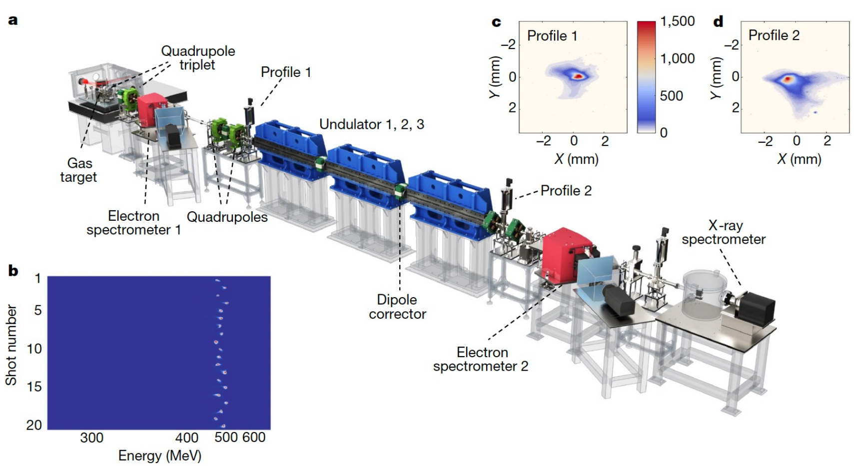
O. Lundh et al., Nat. Phys. 7, 219 (2011)

Long-term stable operation



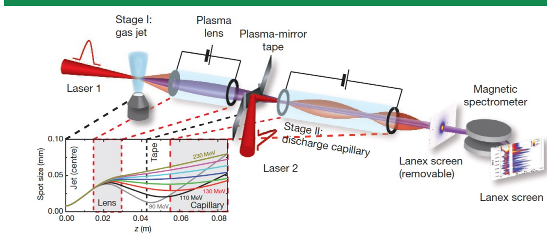
A. R. Maier et al., Phys. Rev. X 10, 031039 (2020)

Small energy spread



W. Wang et al., Nature 595, 516 (2021)

Proof-of-principle staging

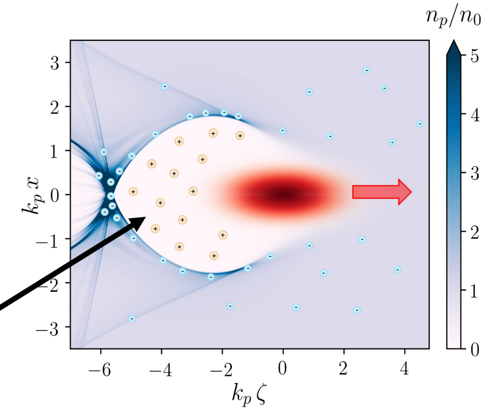


S. Steinke et al., Nature 530, 190 (2016)

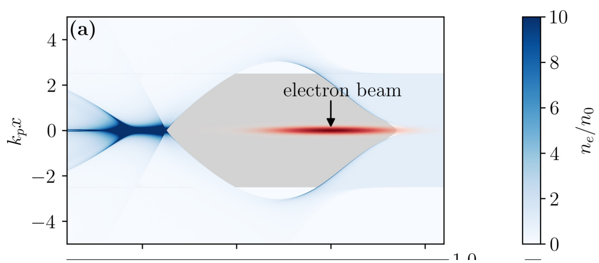
The problem

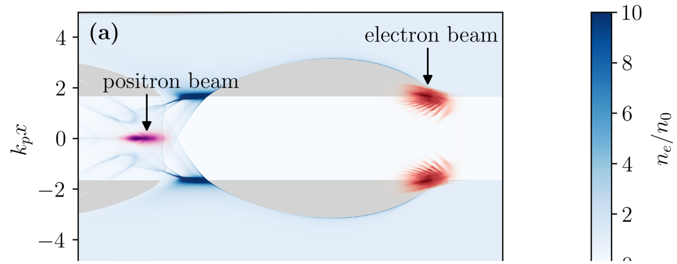
Plasma-based acceleration of positron is significantly lagging behind, due to inherent structure of the wake fields, which would normally be defocussing and decelerating for a positively charged particle.

ion background defocuses e^+



Several schemes have been numerically proposed in order to overcome this issue, including hollow plasma channels and finite plasma columns





Phys. Rev. Lett. 127, 104801 (2021)

Phys. Rev. A. Beams 23, 121301 (2020)

Programmatic experimental work currently not possible due to the lack of suitable facilities
Only SLAC could in principle host plasma-acceleration experiments

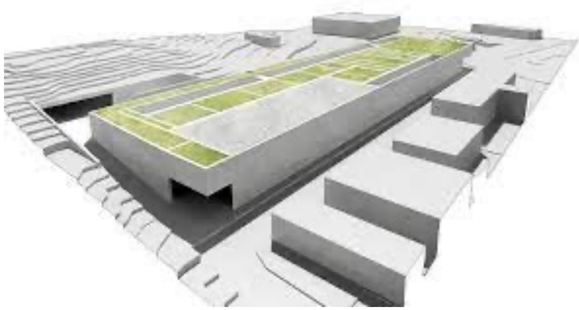
Disclaimer

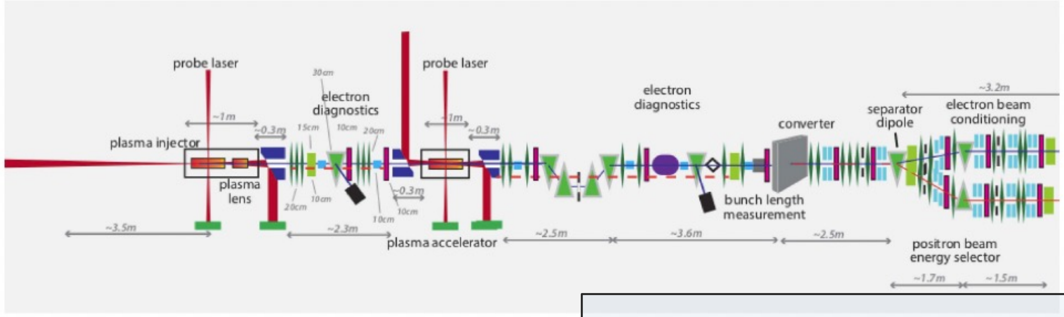
I am NOT proposing that we can build a fully plasma-accelerated positron beam with collider-like characteristics!

Rather, we are exploring the possibility of delivering positron beams of sufficient quality to be injected and accelerated in plasma accelerating cavities.

Several plasma-based facilities are currently considering this option, e.g.:

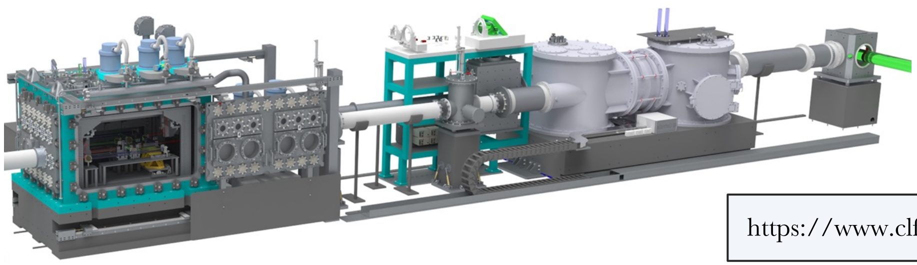
EuPRAXIA *the first ESFRI plasma accelerator project*





R. Assman et al., Eur. Phys. J. Special Topics (2020)

EPAC *Extreme Photonics Application Centre* (*UK*)

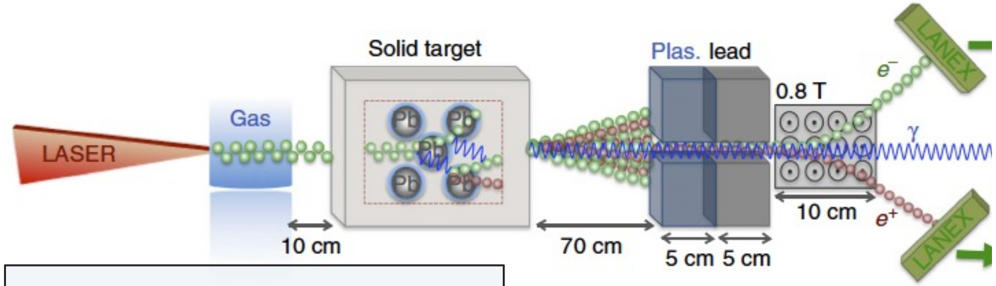


https://www.clf.stfc.ac.uk/Pages/EPAC.aspx

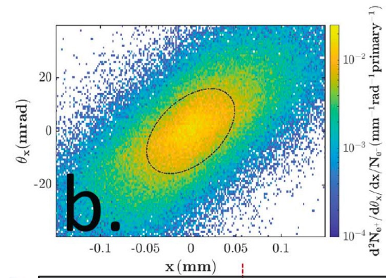
Expected output with a PW-scale laser

Numerical modelling

The simplest option to generate short positron beams (~fs) is to propagate a laser-wakefield electron beam through a high-converter target.



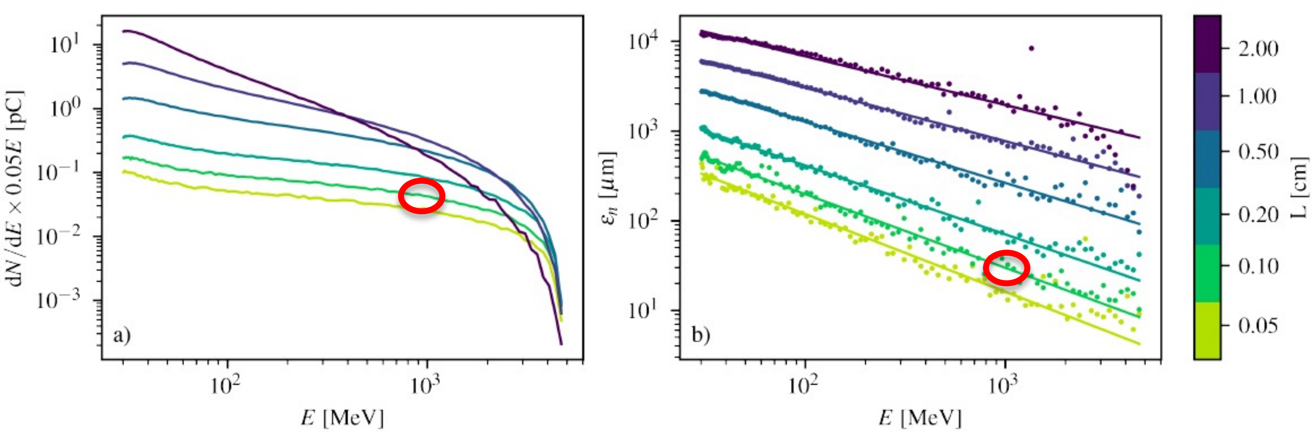
G. Sarri et al., Nat. Comm. 6, 6727 (2015)



Start-to-end simulations using PIC (FB-PIC) and Monte-Carlo (FLUKA)

A. Alejo et al., Plasma Phys. Contr. F. 62, 055013 (2020)

For example, if one considers a PW-scale laser (5 GeV electron beam with nC-scale charge)



G. Sarri et al., Plasma Phys. Contr. F. 64, 044001 (2022)

For a 100 μm converter

E (GeV)	2	1
ΔE/E (%)	5	5
Q (pC)	1	2
ε (nm)	5	20
$\bar{\varepsilon}$ (μm)	18	30
τ (fs)	~20	~20

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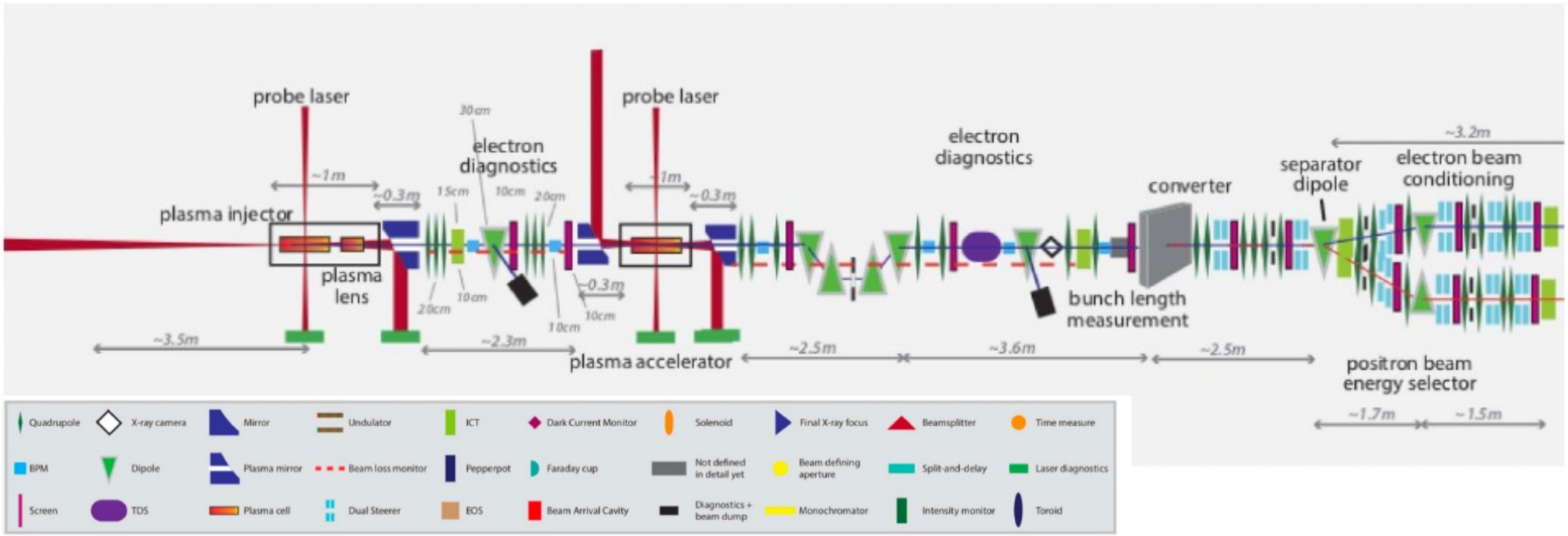
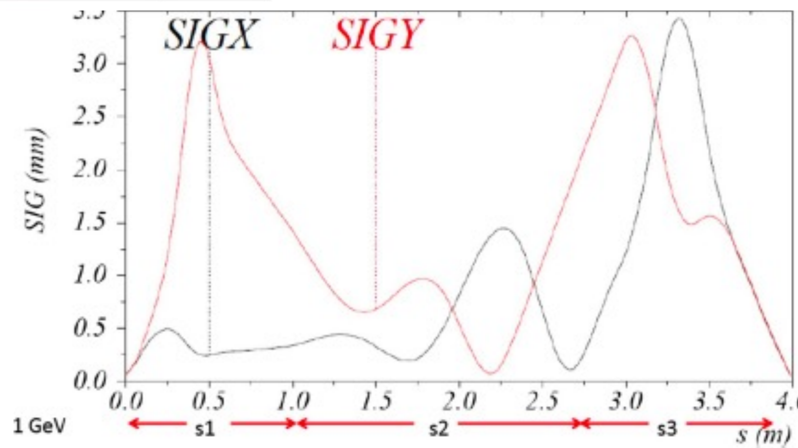
Capture and transport

EPSRC

First proof-of-principle design for the capture and transport of these positron beams in EuPRAXIA



Selection of 1 GeV beamlets with 5% energy spread, ~ pC charge, and focused down to 20 µm. Possibility of synchronised electrons and positron beams as a test facility

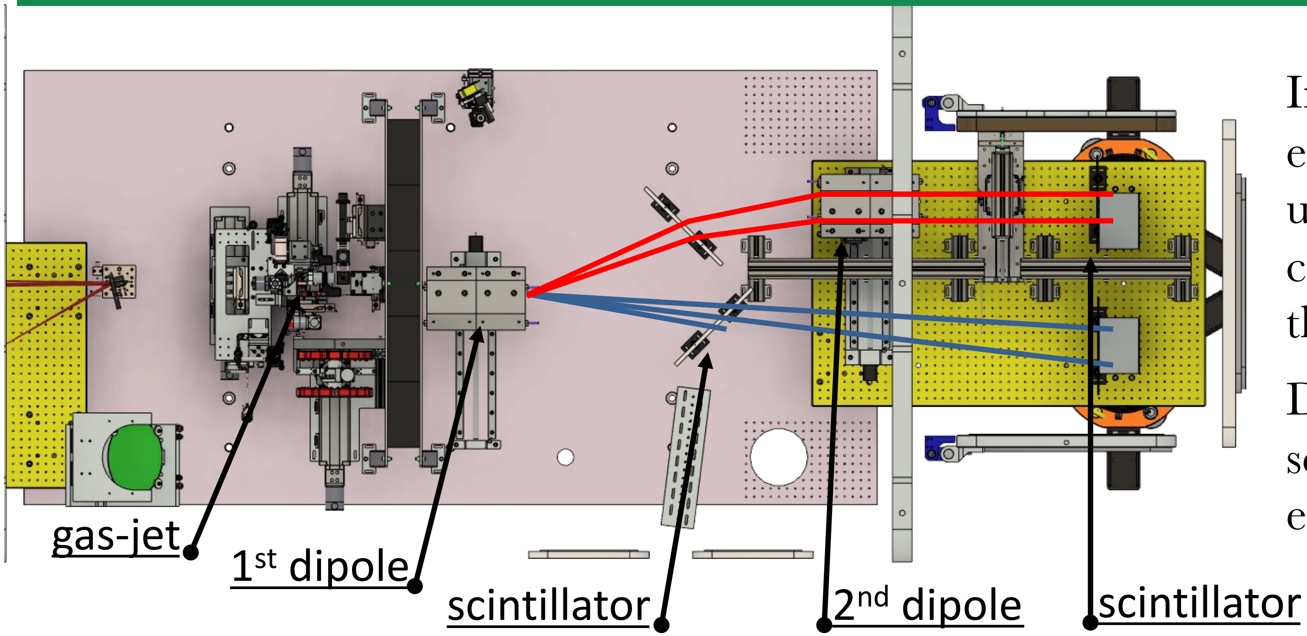


R. Assman et al., Eur. Phys. J. Special Topics (2020)

Proof-of-principle experiments

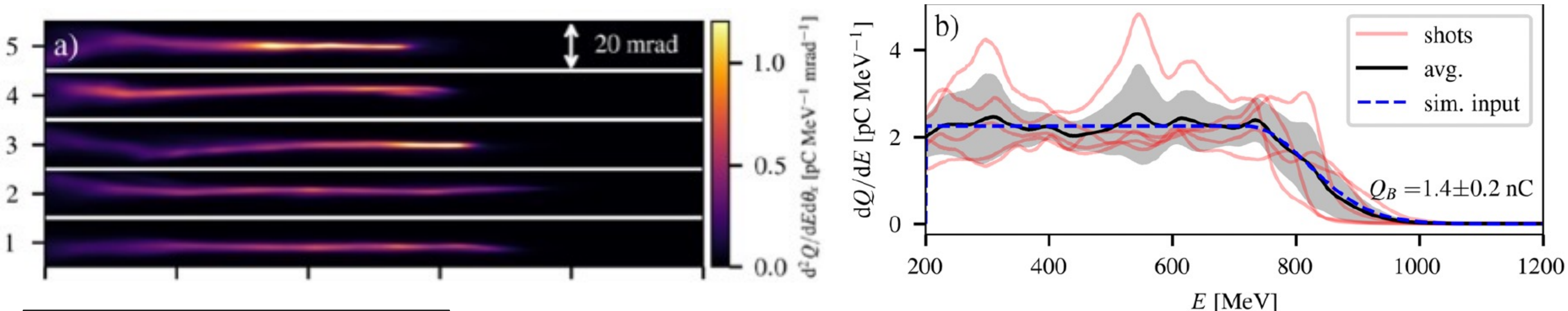
Setup

First proof-of-principle experiment carried out using the Gemini laser at the Central Laser Facility



Interaction of ~ 1.4 nC electron beam with energy up to 800 MeV with a lead converter target of thickness 1 < L <25 mm.

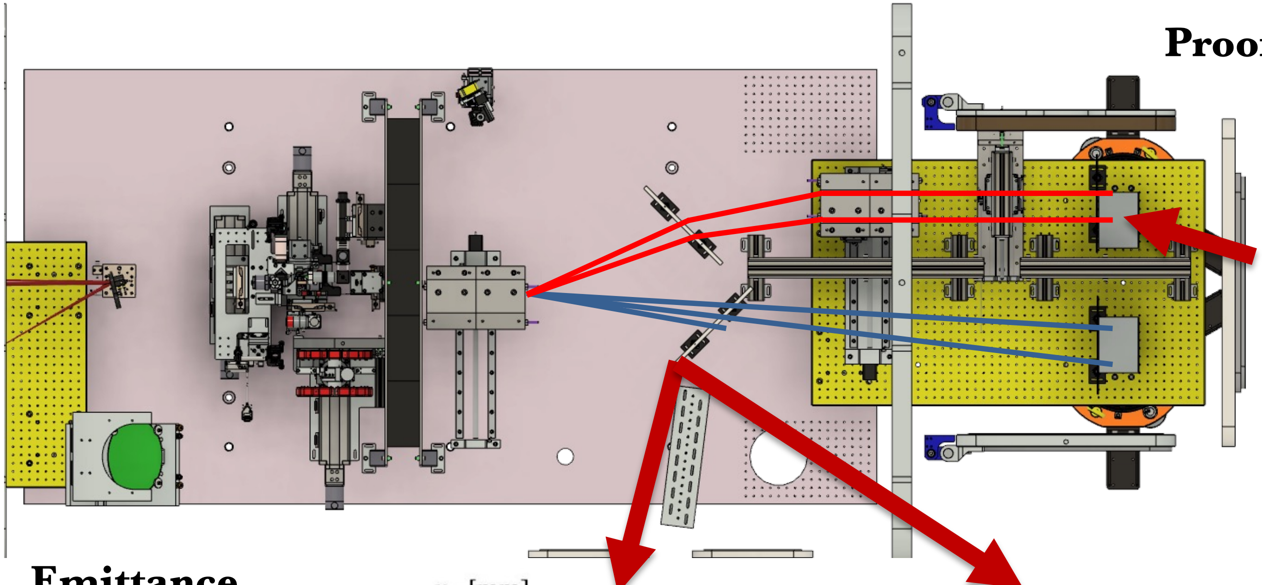
Dog-leg configuration to separate the positrons and emittance mask



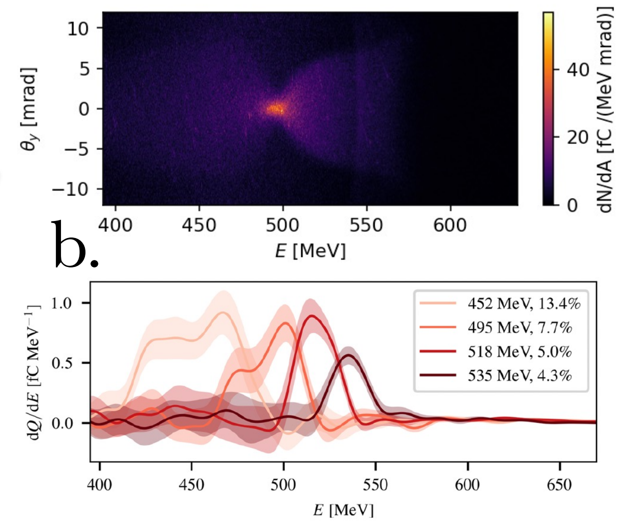
M. Streeter et al, Sci. Rep. 14, 6001 (2024)

Experimental results

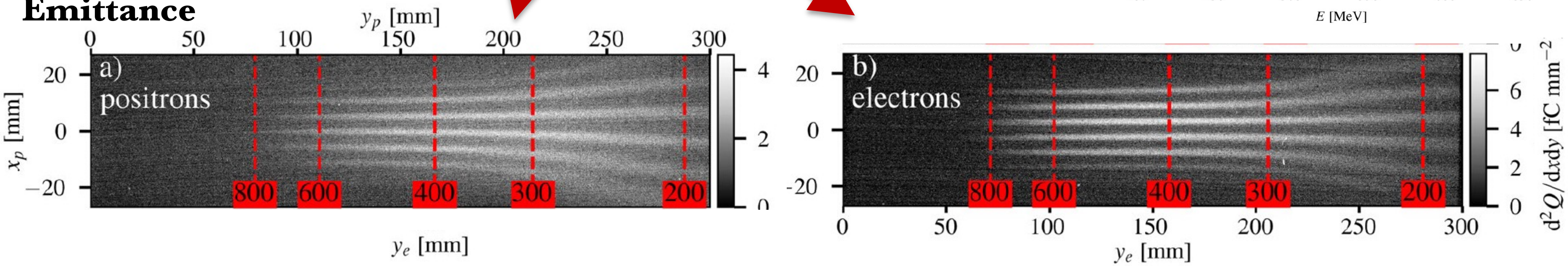
First proof-of-principle experiment carried out using the Gemini laser at the Central Laser Facility



Proof-of-principle Energy selection



Emittance



Simultaneous measurements of energy-dependent source size, divergence, and emittance

M. Streeter et al, Sci. Rep. 14, 6001 (2024)

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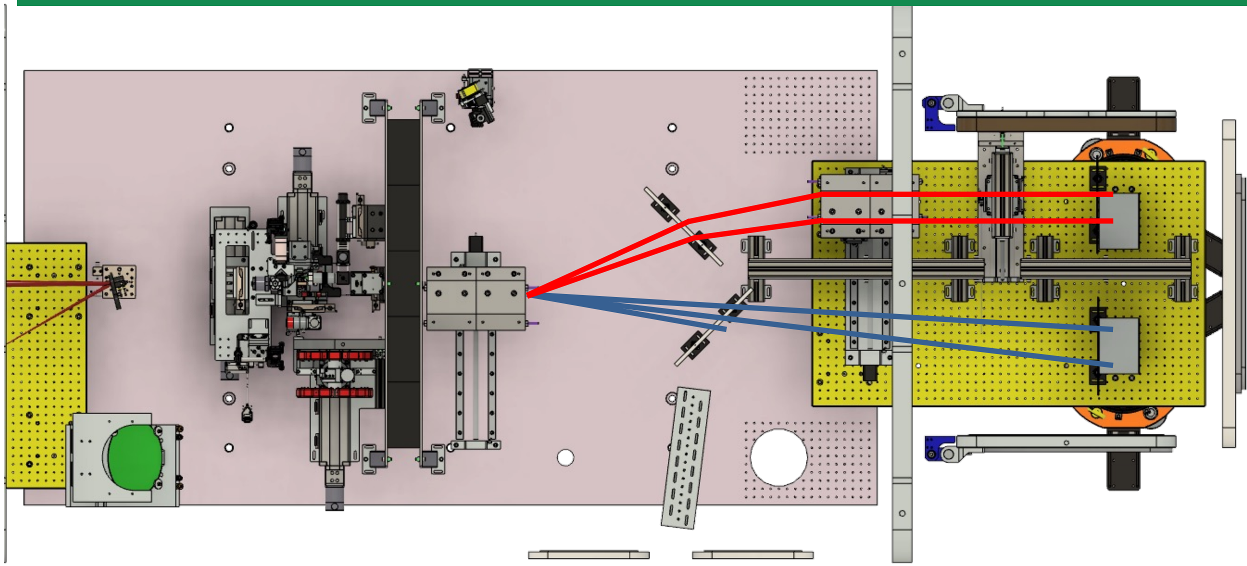
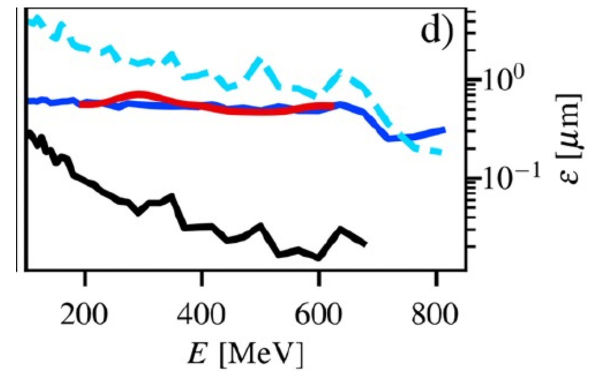
Experimental results

EPSRC

First proof-of-principle experiment carried out using the Gemini laser at the Central Laser Facility



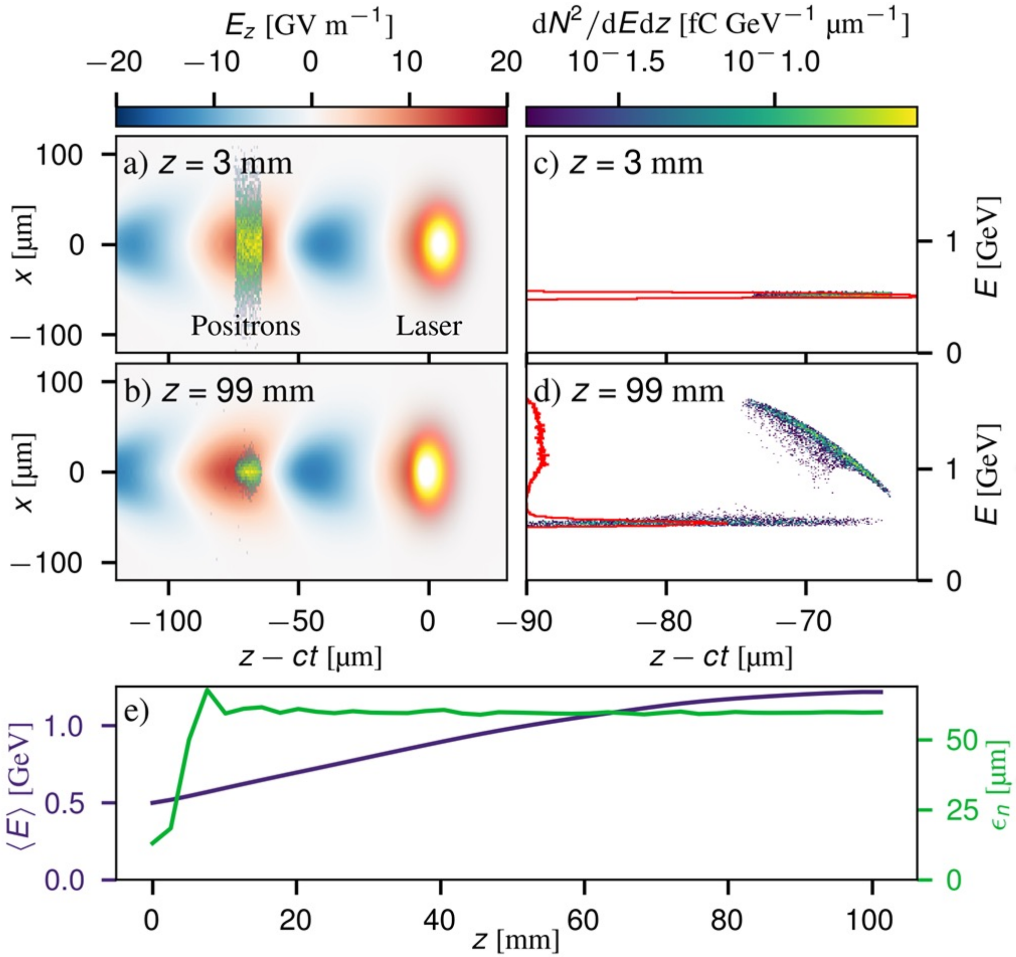


	CLF (2024)	Muggli et al.[22]	Corde et al.[23]	Gessner et al.[24]
E (GeV)	0.6	28.5	20.3	20.3
σ_x (μm)	2.7	25	$<$ 100	50
σ_z (μm)	$\lesssim$ 4*	730	30–50	35
ε (nm)	15	14×3	5×1	7
$\bar{\varepsilon}$ (μm)	18	390×80	200×50	300

M. Streeter et al, Sci. Rep. 14, 6001 (2024)

Experimental results

Even at this low energy and moderate spatial quality, the positron beamlet can be accelerated



Positron beamlet (>50% of it) accelerated over 10 cm of plasma ($n_e = 2 \times 10^{17}$ cm^{-3}) up to an average energy of 1.2 GeV ($E_{AV} \sim 7$ GV/m).

Initial increase in emittance due to mismatch with plasma (to be optimized), then constant over 10 cm of plasma

M. Streeter et al, Sci. Rep. 14, 6001 (2024)

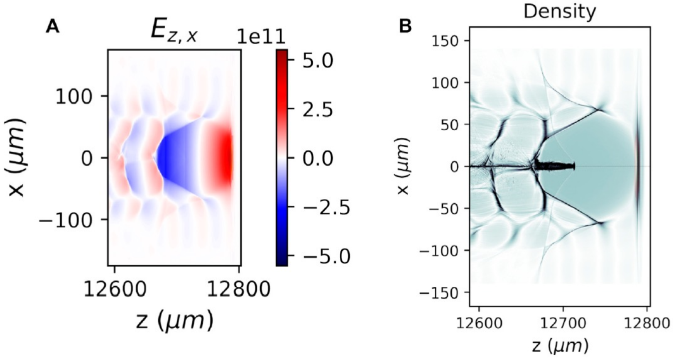
Multi-PW lasers: expected performance

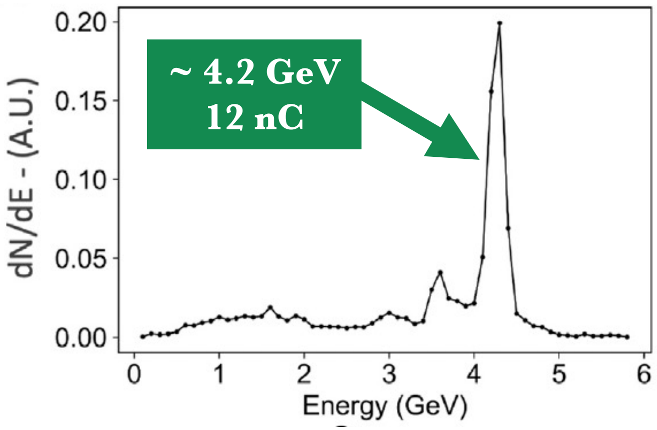
The issue of beam-loading

It would be desirable to have a beam capable of beam-loading, but this requires 10s of pC

10s of pC positron beams would require a ~ 10 nC primary electron beam, which is not practically achievable with PW-scale lasers. However, **these are obtainable with 10PW lasers.**

In collaboration with ELI-NP staff, we are running the first commissioning experiment on laser-wakefield acceleration using the 10PW laser





L. Calvin et al., Front. Phys. 11:1177486 (2023)

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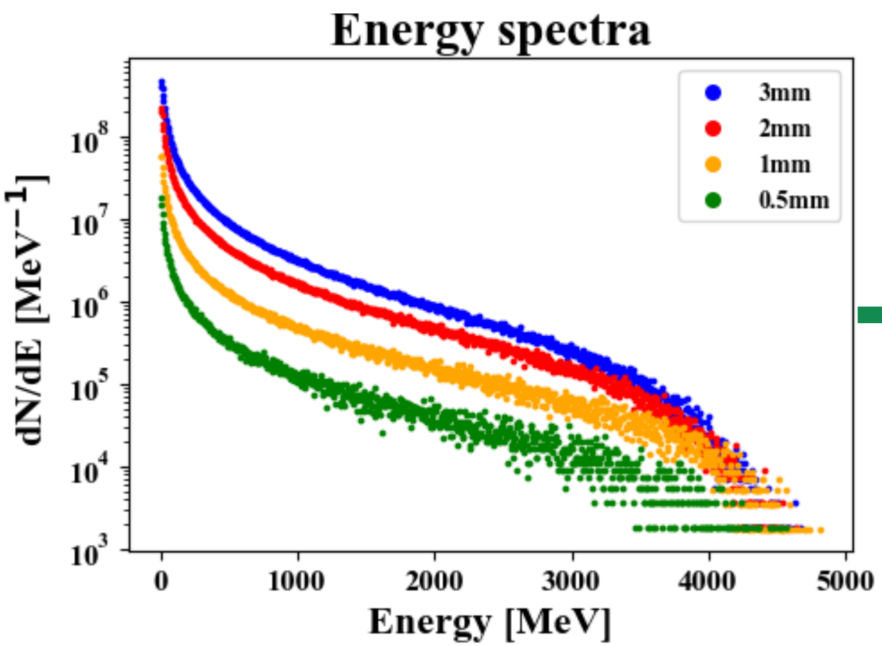
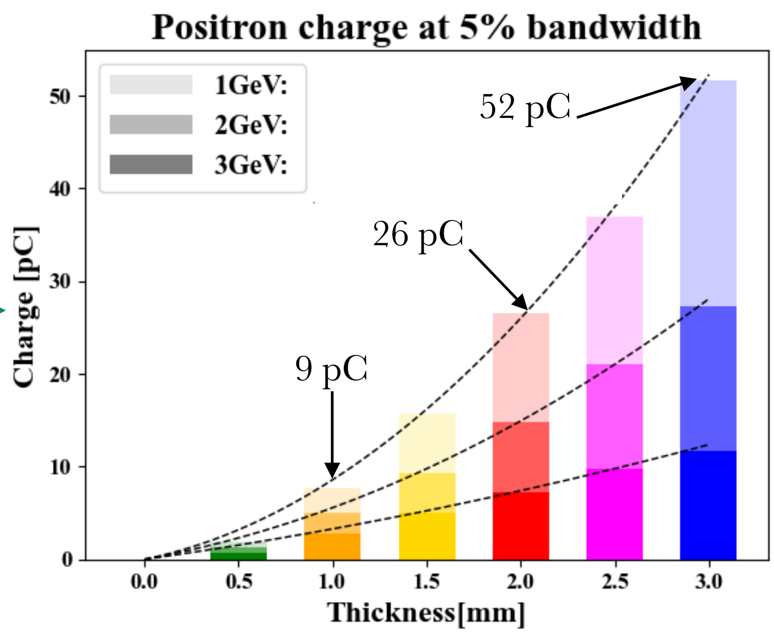


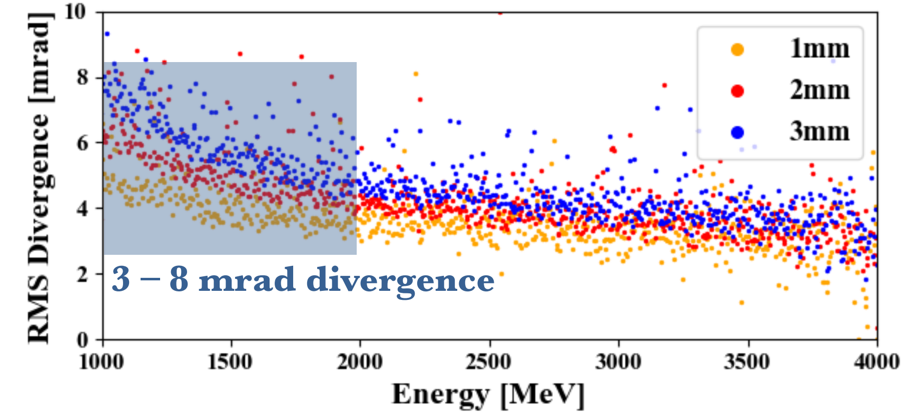


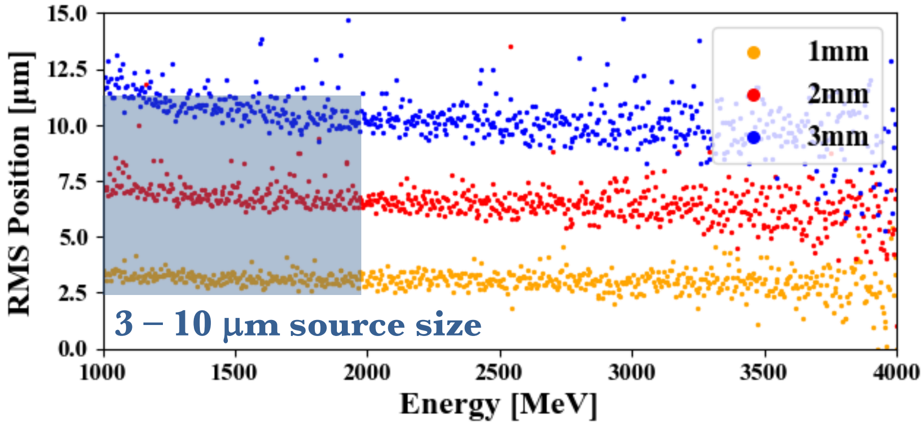
10-50 pC positron beams in a 5% bandwidth at the GeV level can be produced during the propagation of ~10 nC electron beams through mm-scale converter targets

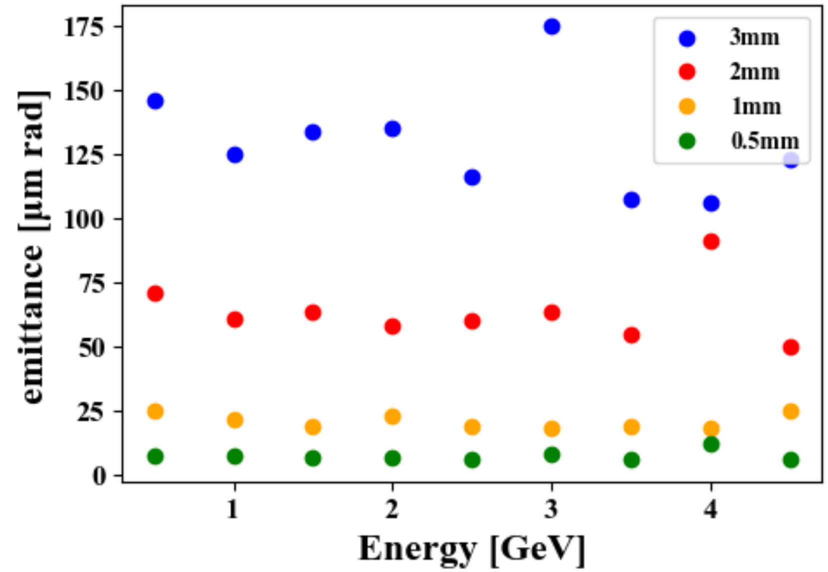
T. Foster et al., *in preparation* (2024)

10s of pC positron beams

These beams have femtosecond-scale duration and micron-scale normalized emittance







Trade-off between charge and emittance

	1 mm	2 mm
C (pC)	9	26
E (GeV)	1	1
ΔE/E (%)	5	5
τ (fs)	< 30	< 30
ε (nm)	10	30
$\bar{\varepsilon}$ (μm)	20	60

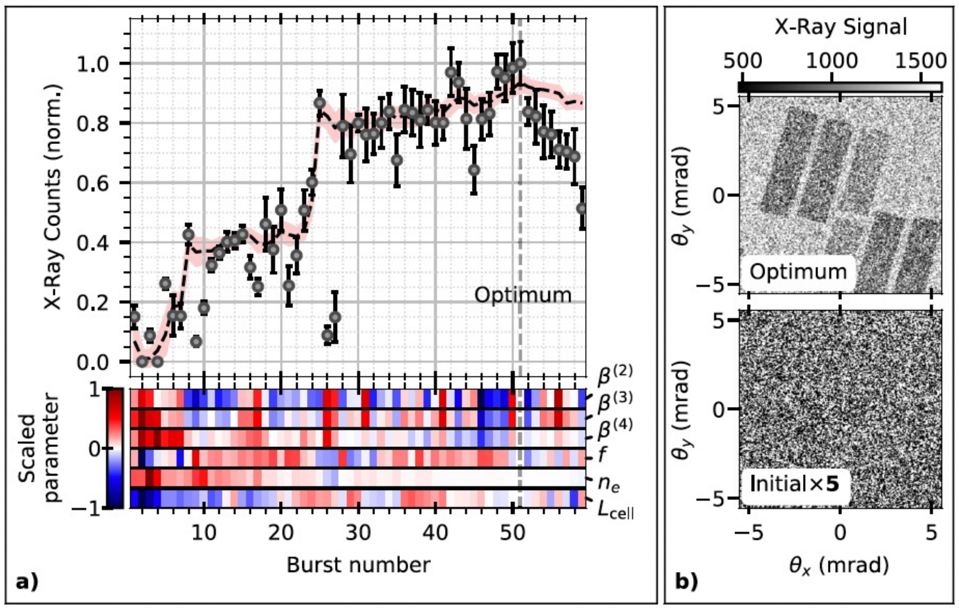
T. Foster et al., *in preparation* (2024)

Extras

AI modelling of LWFA

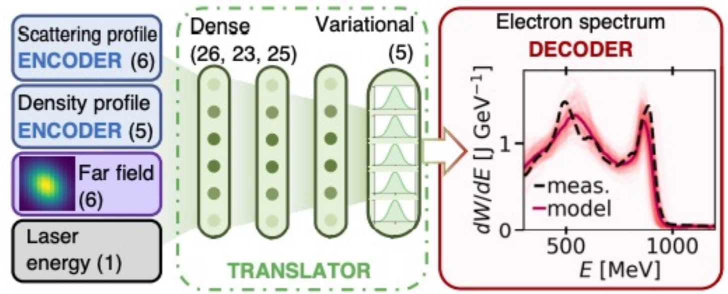
Machine-learning techniques now allows for active stabilization of LWFA and high-level of predictability

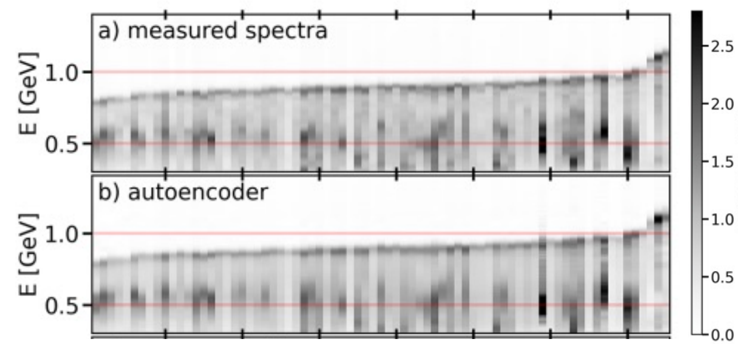
Baesyan optimization of laser and plasma parameters for betatron sources



R. Shaloo et al., Nat. Comm. (2020)

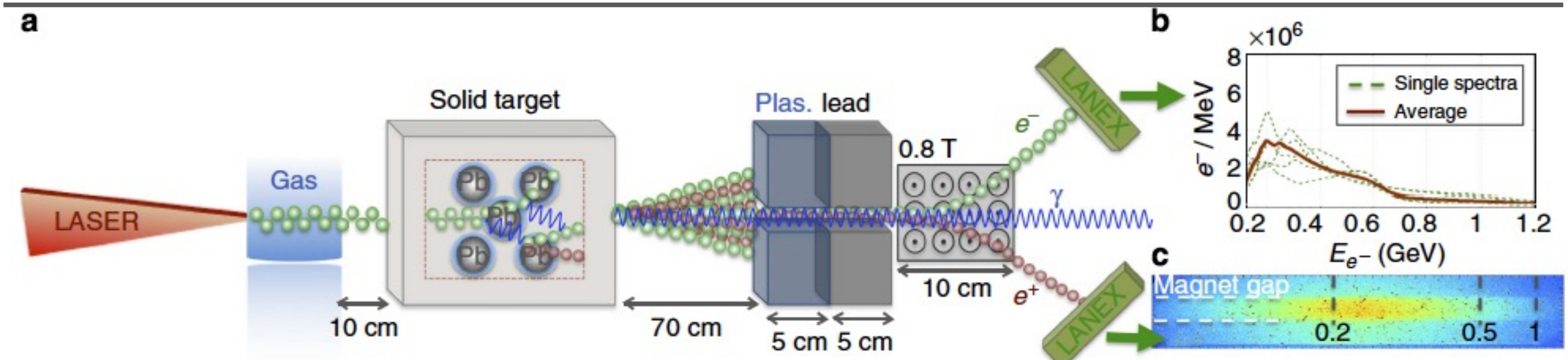
Neural network predictions

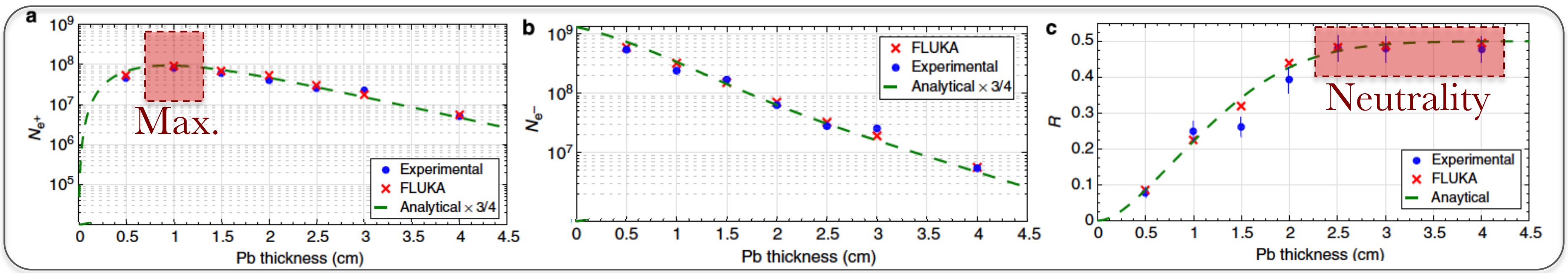




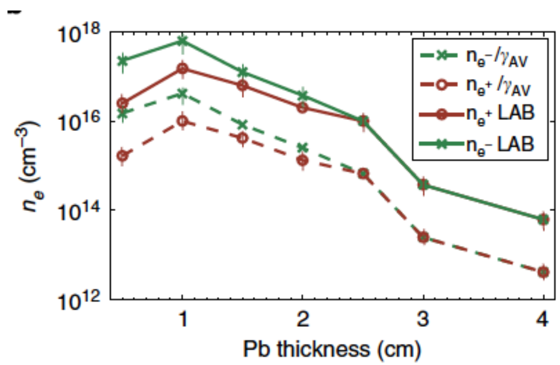
M. Streeter et al., HPLSE (2023)

Neutral beams



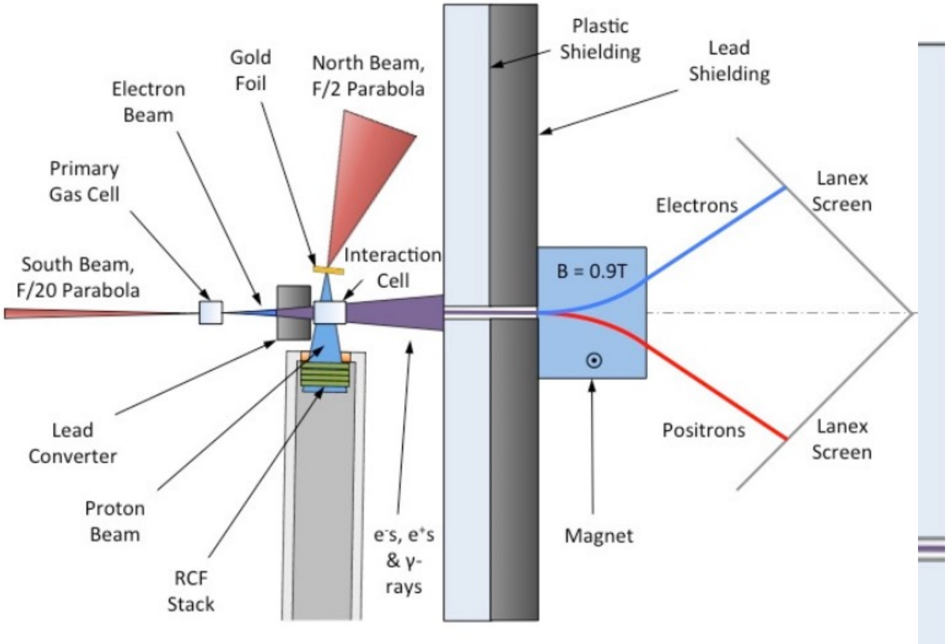


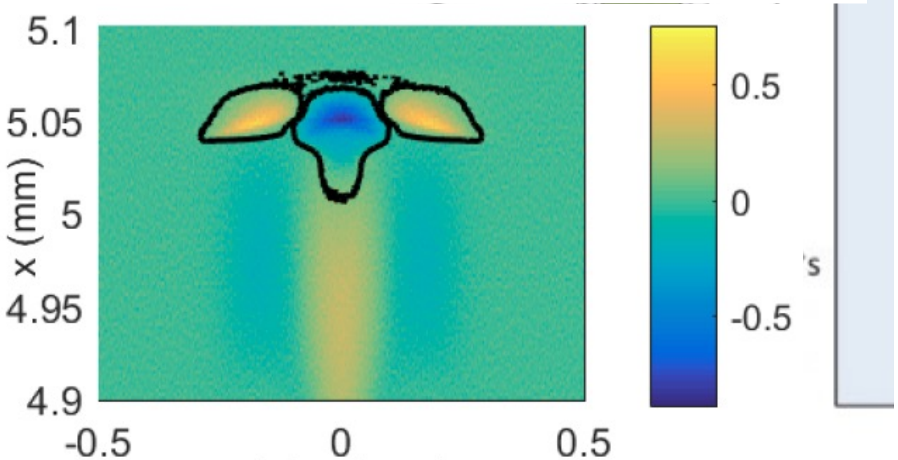
- ✓ Maximum positron yield at ~2 L_{RAD}
- ✓ ~48% of positrons at ~ 5 L_{RAD}
- ✓ Beam duration: ~ tens of fs
- ✓ Beam diameter: > c/ω_p
- ✓ Beam divergence: ~ tens of mrad

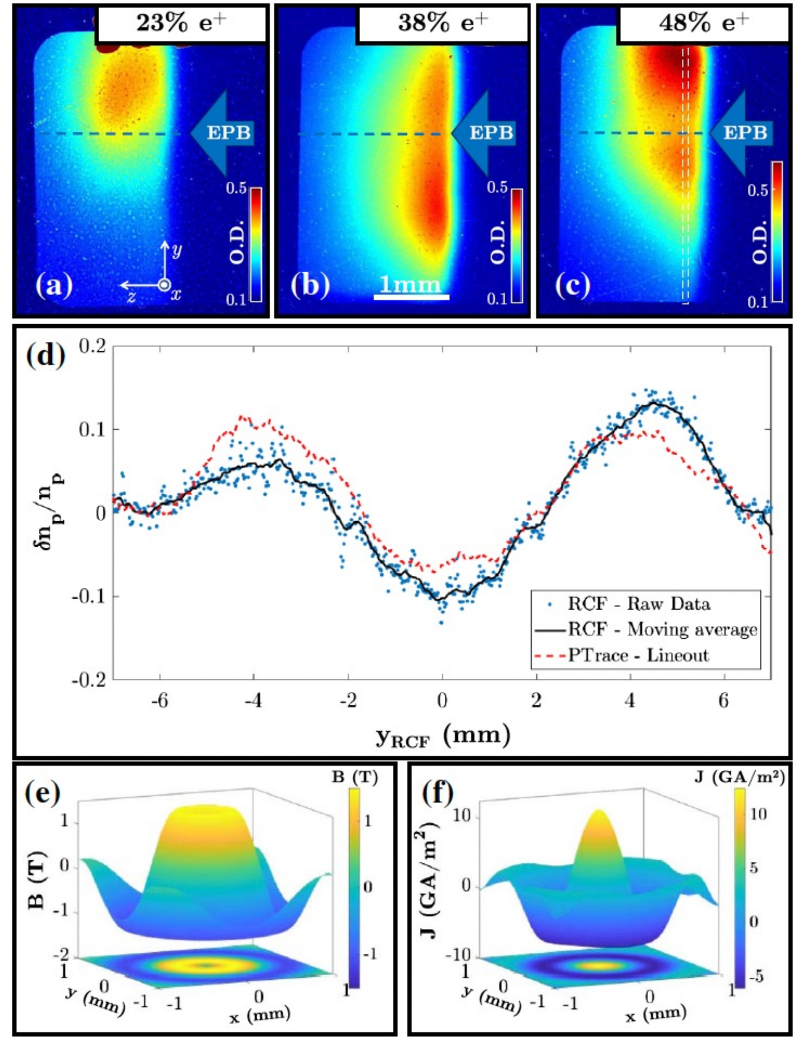


G. Sarri et al.,
Nature Comm. (2015)

Dynamics



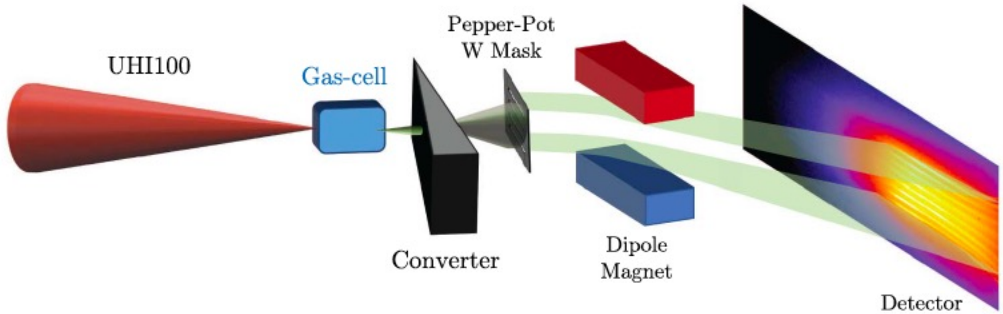


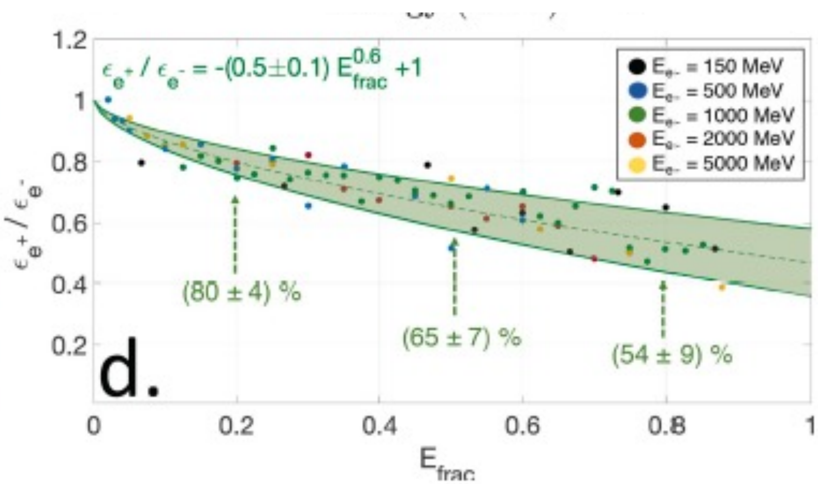


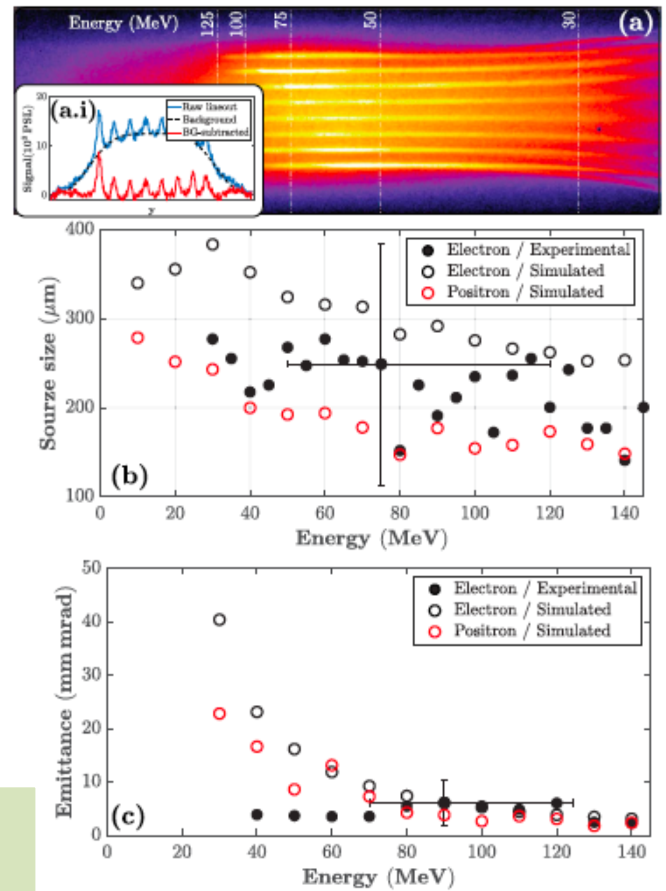
J. Warwick et al., Phys. Rev. Lett. (2017)

Non-invasive characterisation

First proof-of-principle experiments with ~ 50 TW laser producing ~ 100 MeV positrons







- Close correlation between e^- and e^+ properties
- **Live, simultaneous, and non-invasive** measurement of spectrum, source size, total charge, and energy-resolved emittance

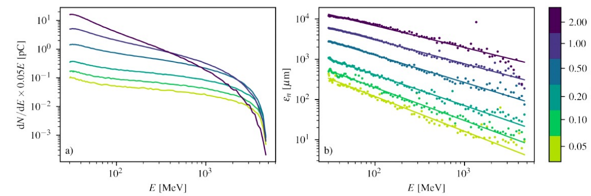
A. Alejo et al., PPCF 62, 055013 (2020)

Conclusions

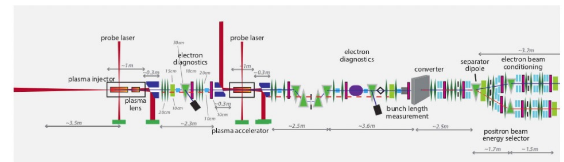
Conclusions

⇒ **Positron wakefield acceleration is significantly lagging behind,** mainly due to the lack of experimental facilities suited for these studies.

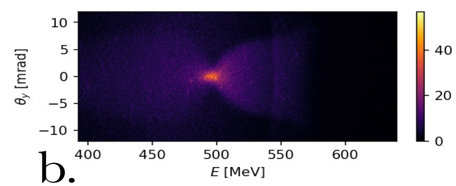
⇒ PW-scale laser can provide narrowband (~5%) GeV-scale positron beams of **sufficient quality to be guided and accelerated in a plasma wakefield.**



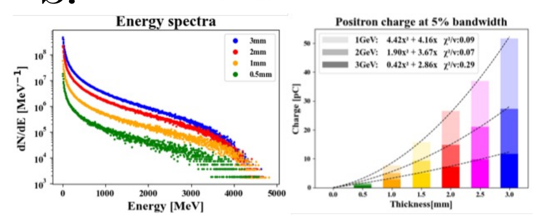
⇒ A first positron beamline has been designed **for the EuPRAXIA facility.**



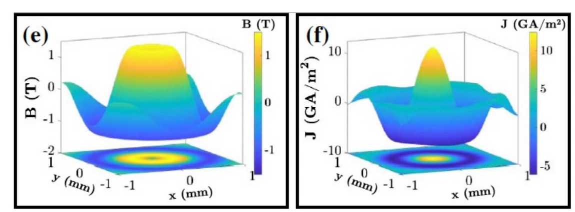
⇒ **First proof-of-principle experiments at 100 TW** validate the numerical expectations.



⇒ Numerical simulations indicate **high-charge positron beams obtainable with ~10 PW lasers.**



⇒ Laser-driven positron sources useful also for **many other applications!**
(detector testing, laboratory astrophysics, material science…)



Thanks for your attention!

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