Plasma based positron sources for testing positron acceleration at EuPRAXIA

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Introduction

do we have low-hanging-fruit applications using high-charge lower-quality electron beams?

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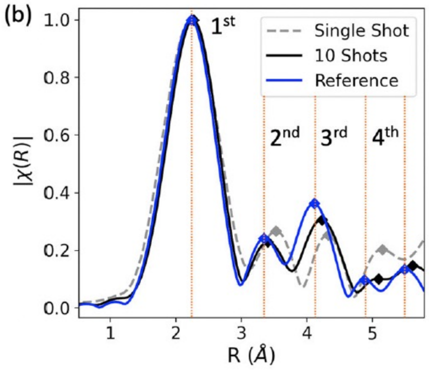
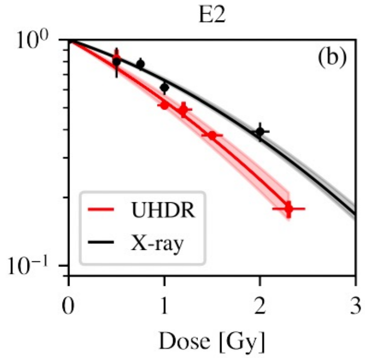
BETATRON SOURCES



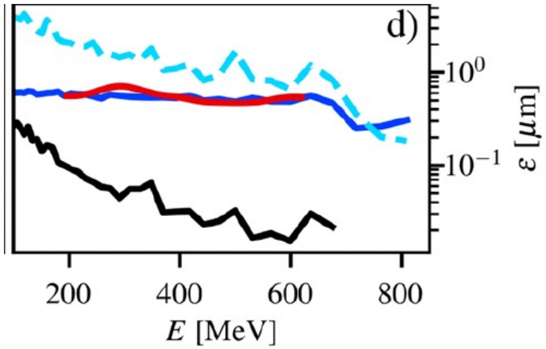
Communication Phys. 7, 247 (2024)

RADIOBIOLOGY



arXiv:2309.06870v1 (2024)

POSITRON SOURCES



Scientific Reports 64, 044001 (2024)

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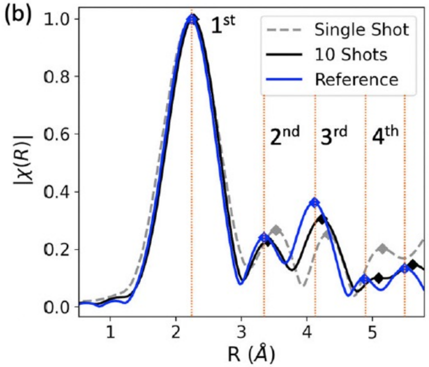

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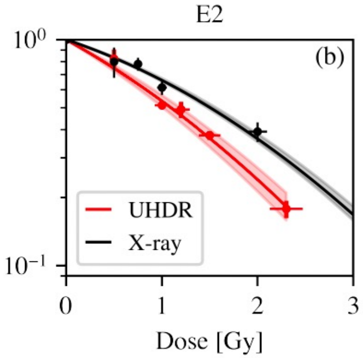

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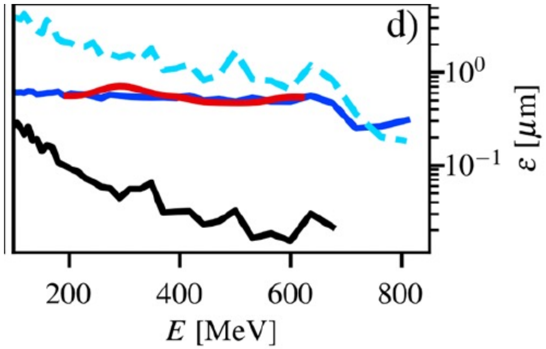

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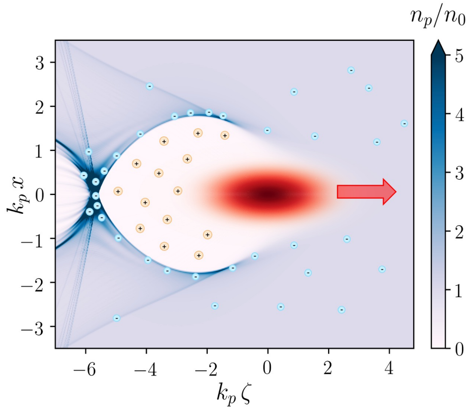
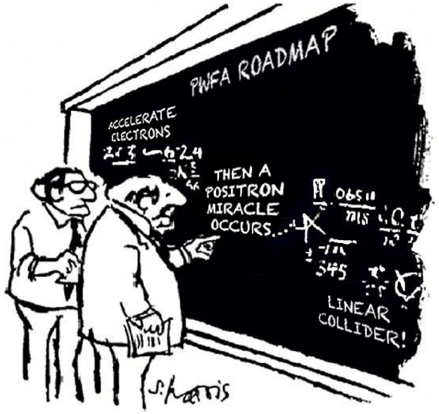
Why positrons?

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





See Jens' talk on Tuesday

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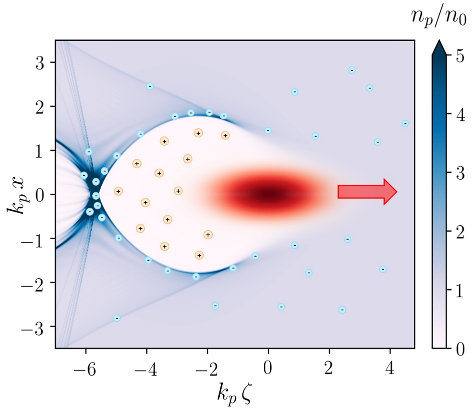

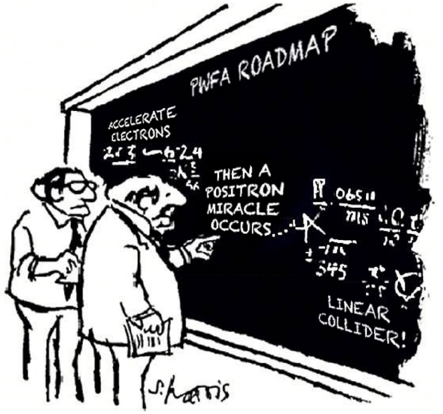

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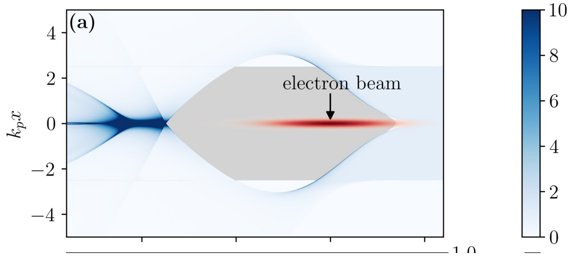
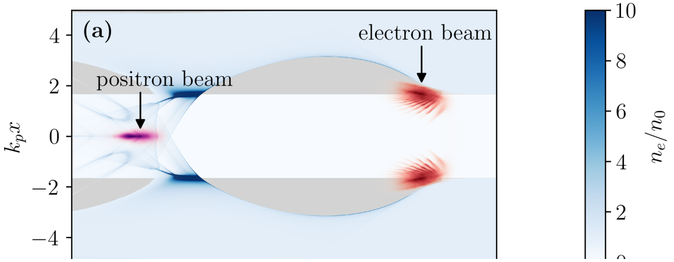
Several schemes have been numerically proposed in order to overcome this issue, including hollow plasma channels and finite plasma columns





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 FACET-II at SLAC will in principle be able to host plasma-acceleration experiments

A roadmap for a solution?

EPSRC

- Plasma-based positron acceleration is **a challenging task!**
- Most research has been carried out numerically
- In preparation for the design of a plasma-based (or plasma-assisted…) positron arm for a collider, **it is necessary to experimentally test** these accelerators, in order to identify the best and most practical ways to accelerate positrons in a plasma.
- **A first step** would thus be to provide positron beam facilities to the community

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For meaningful experimental studies, it is necessary to provide witness beams with remarkably demanding characteristics:

- short duration:	$\sigma_z \sim 10\ \mu\text{m}$
- low normalized emittance:	$\varepsilon_n \sim \mu\text{m}$
- "reasonable charge":	$Q \sim 0.1 - 20$ pC
- "reasonable energy":	E ~ 100s of MeV
- low energy spread:	ΔE/E ~ few %

- fs-scale synchronization and μm-scale overlap with driver beams

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A possible roadmap for the experimental development of high-quality positron beams could be:

1. **SHORT TERM** (5-10 years)	*Development of positron test beam facilities in Europe (e.g. EuPRAXIA, EPAC…)*
2. **MEDIUM TERM** (10 – 20 years)	*- Converging onto specific acceleration schemes* *- Experimental demonstration of 10s of GeV high-quality beams*
3. **LONG TERM** (>20 years):	*- ~100 GeV high quality beams in a hybrid scheme (conventional injector + plasma accelerating modules)*

Disclaimer

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

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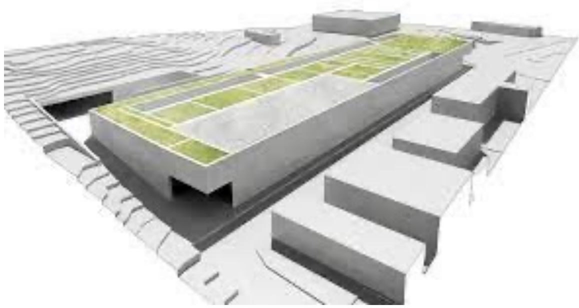
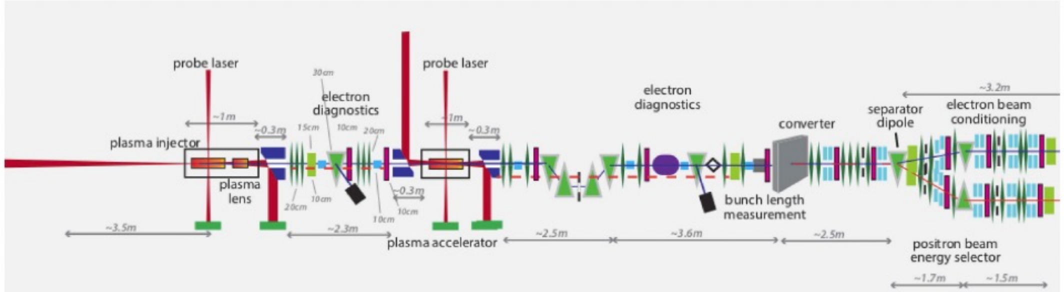
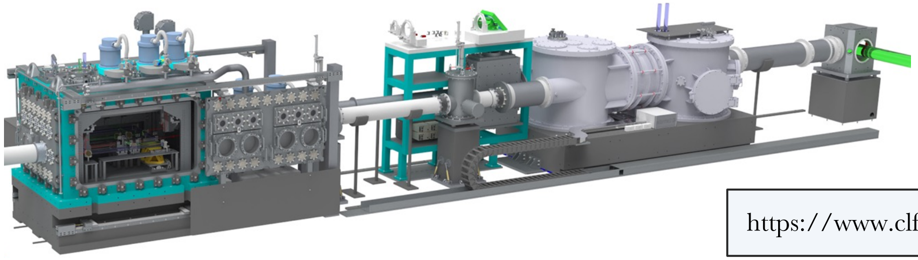
EuPRAXIA *the first ESFRI plasma accelerator project*





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

EPAC *Extreme Photonics Application Centre (UK)*

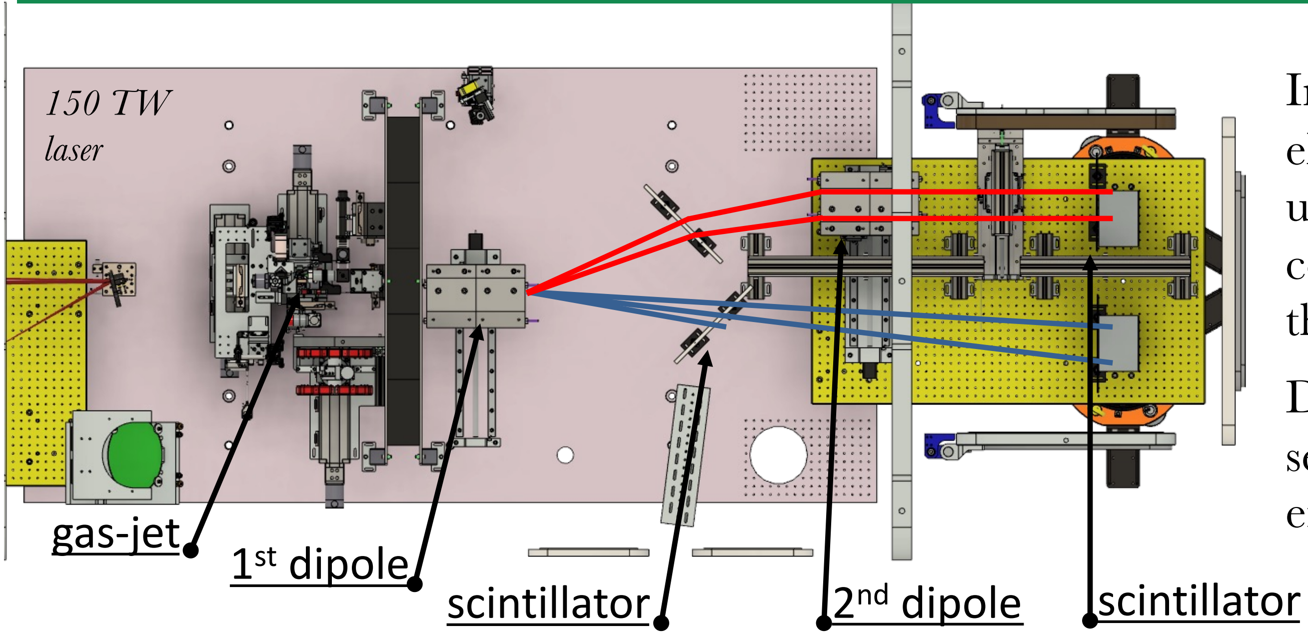


https://www.clf.stfc.ac.uk/Pages/EPAC.aspx

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. 64, 044001 (2024)

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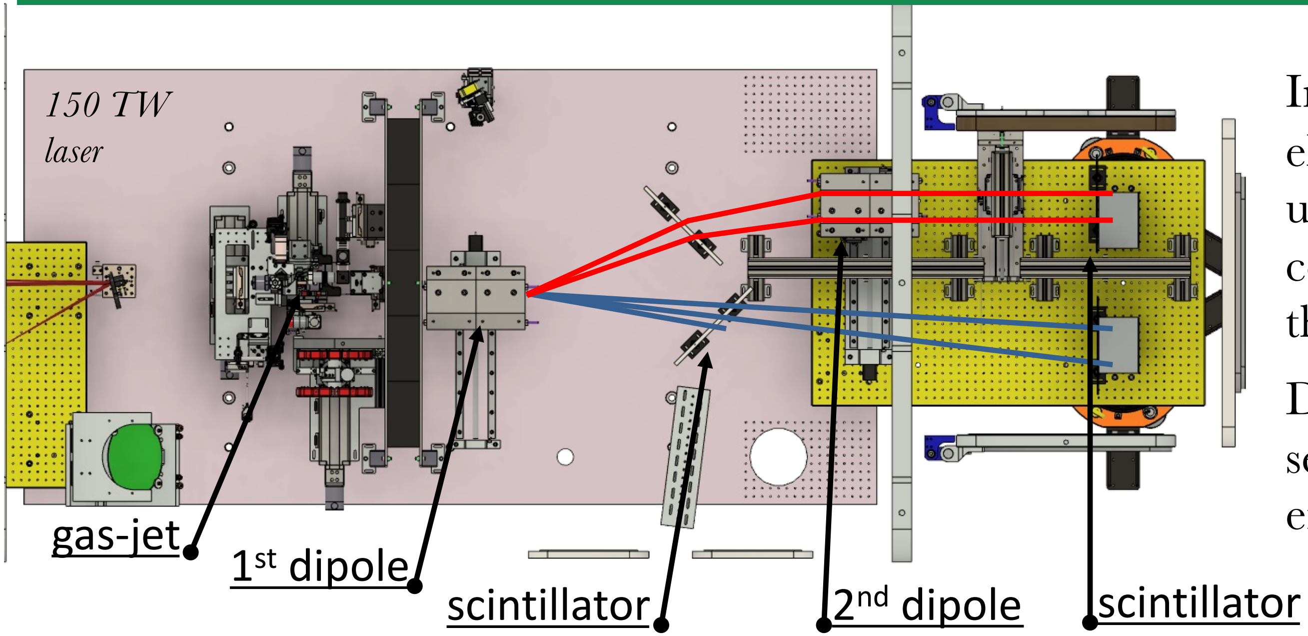

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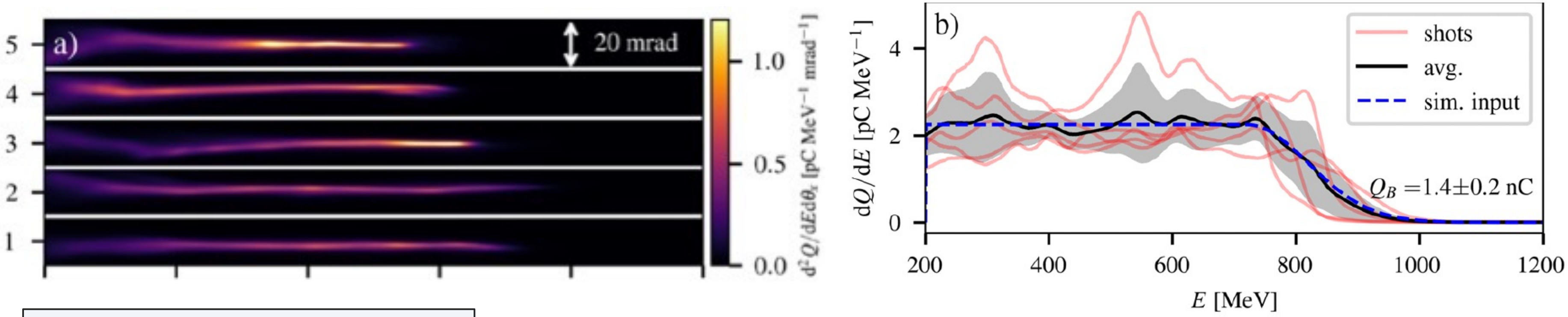

M. Streeter et al, Sci. Rep. 64, 044001 (2024)

Experimental results

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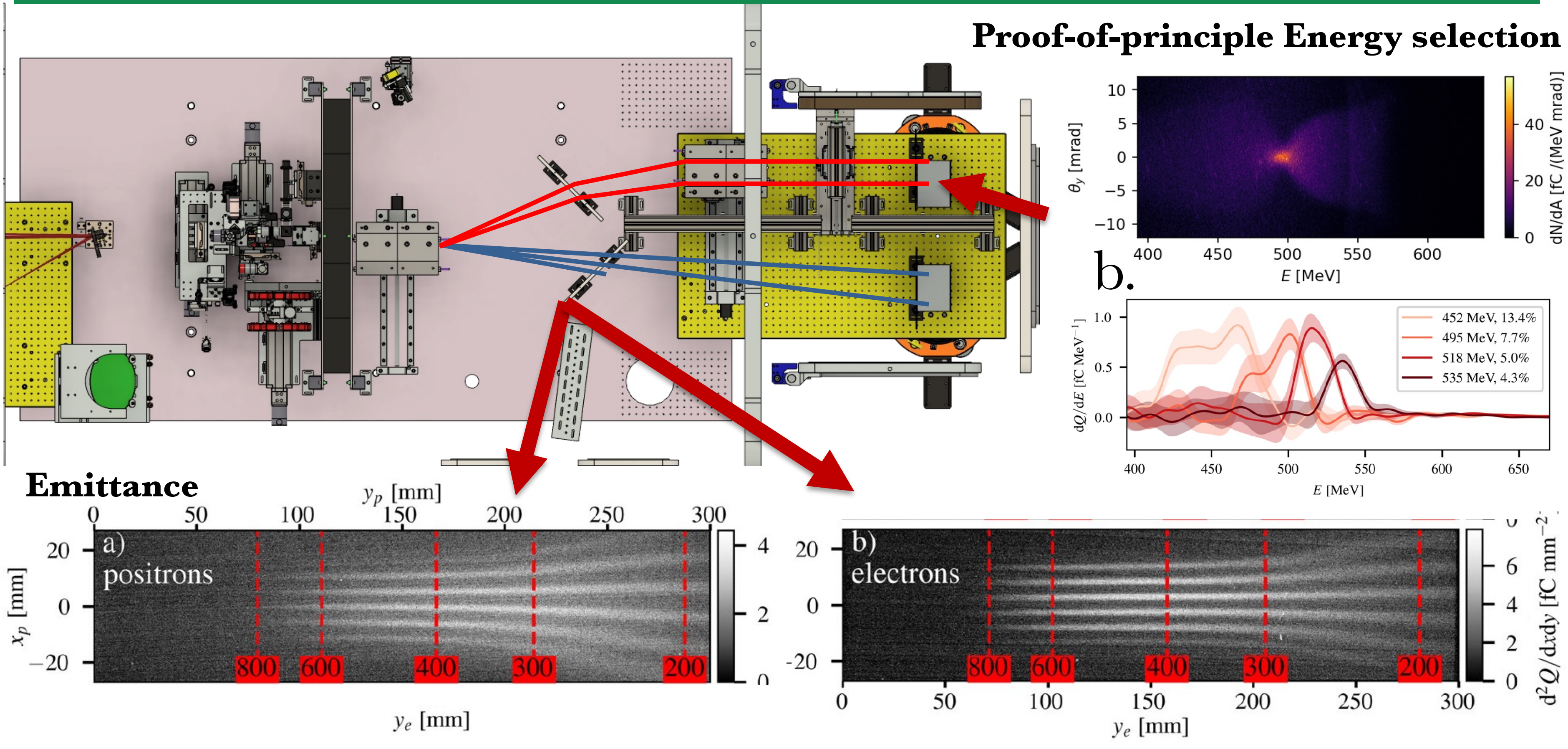

Proof-of-principle Energy selection

Emittance

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

M. Streeter et al, Sci. Rep. 64, 044001 (2024)

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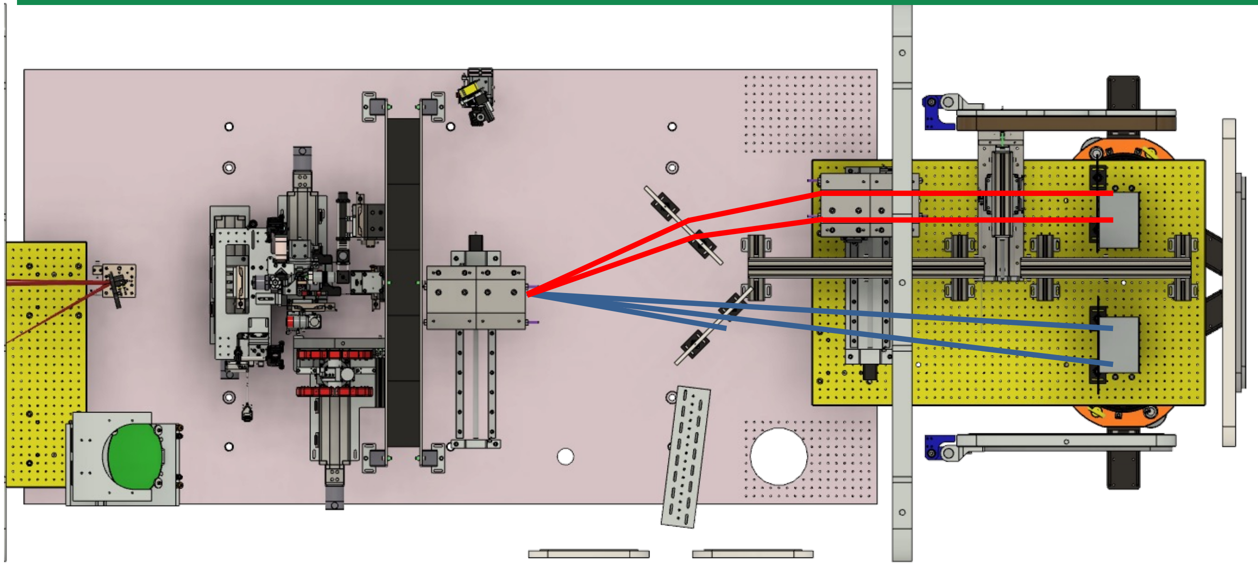
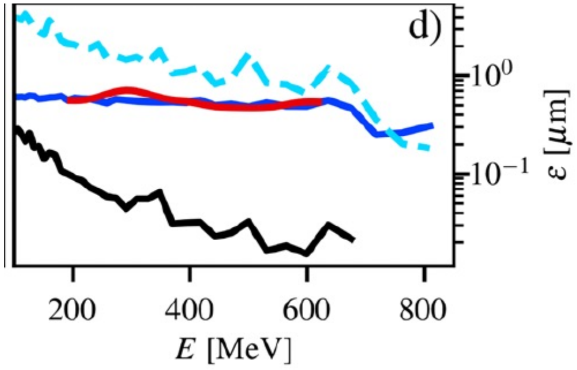




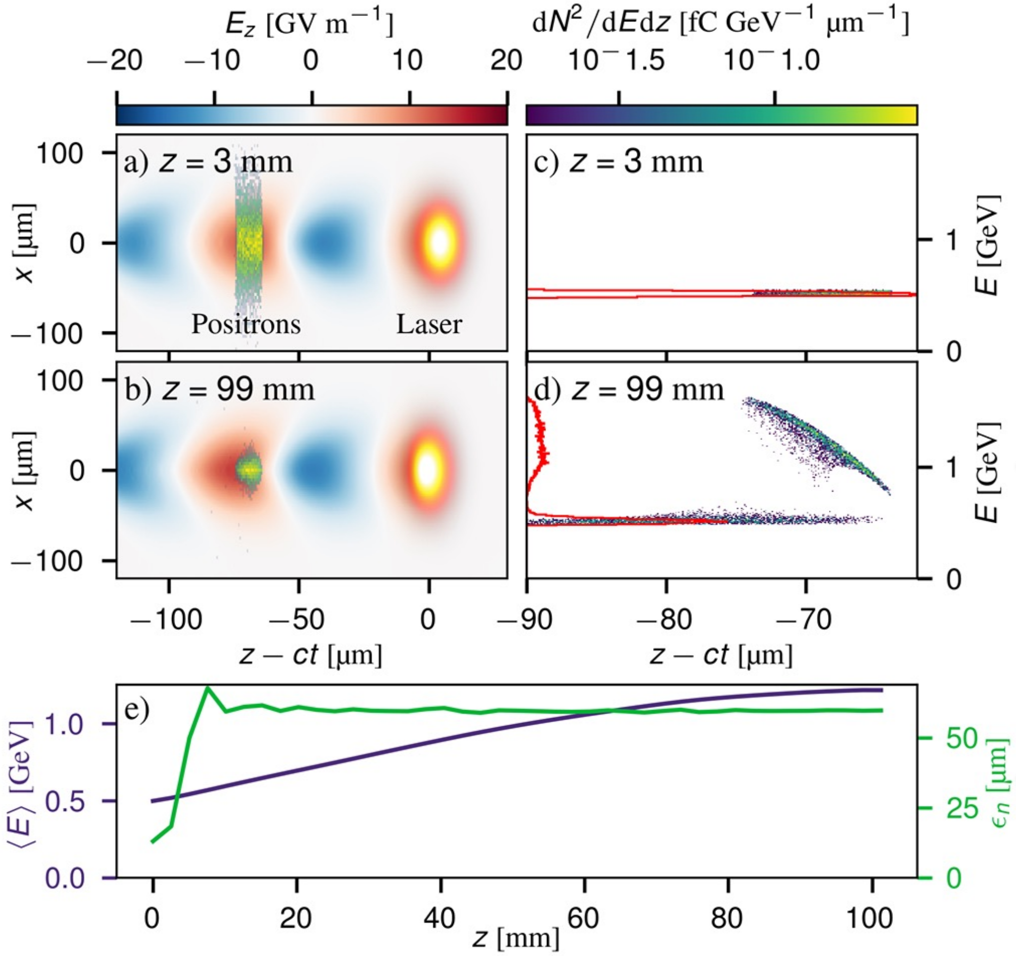
	CLF (2024)	**Muggli et al.**[22]	**Corde et al.**[23]	**Gessner et al.**[24]
E (GeV)	0.6	28.5	20.3	20.3
σ_x (μm)	2.7	25	$<$ 100	50
σ_z (μm)	$\lesssim$ 4*	730	30–50	35
ε (nm)	15	14×3	5×1	7
$\bar{\varepsilon}$ (μm)	18	390×80	200×50	300

M. Streeter et al, Sci. Rep. 64, 044001 (2024)

** Not measured, inferred from simulations*

Experimental results

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



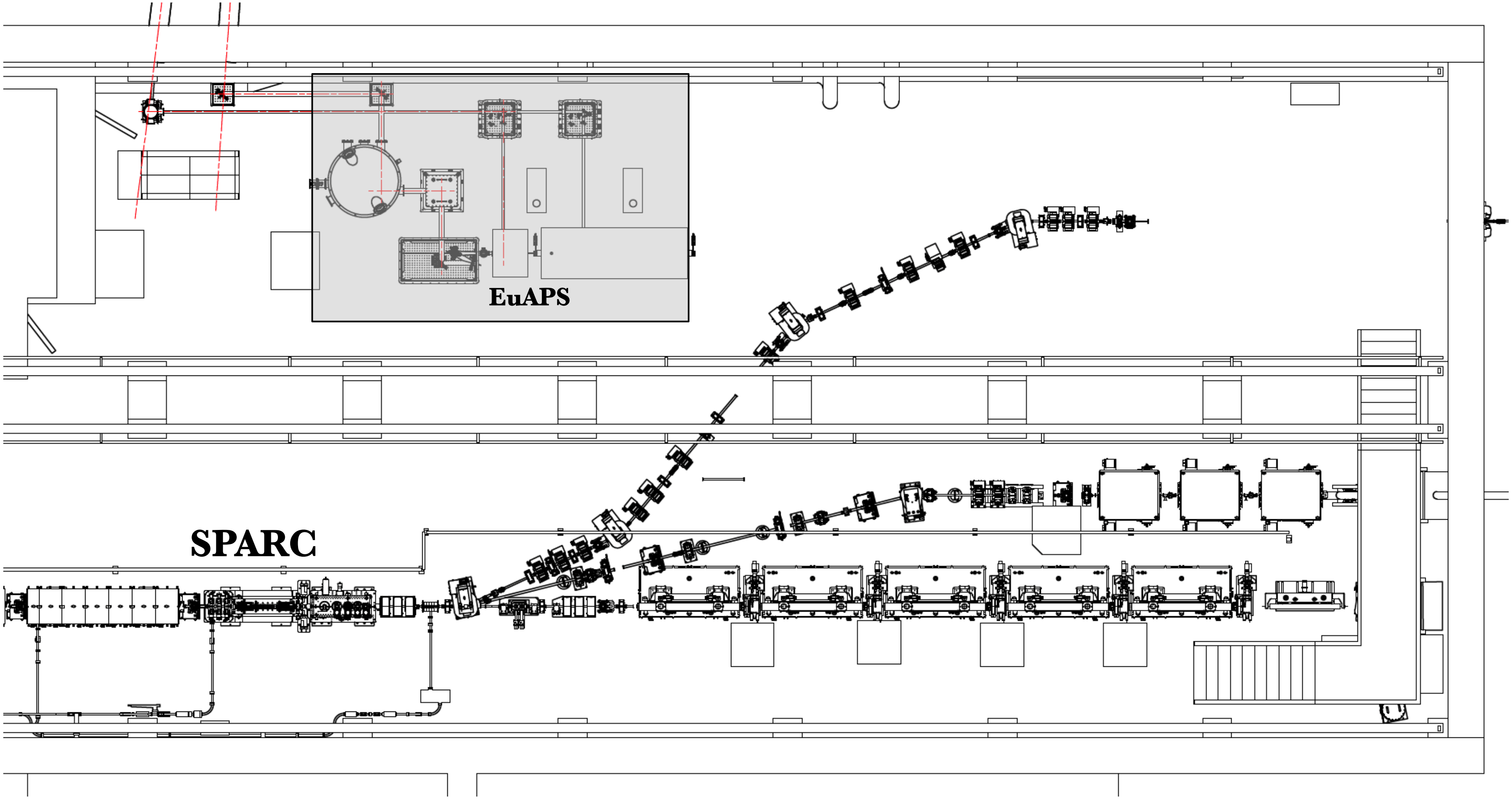
Positron beamlet (>50% of it) accelerated over 10 cm of plasma (n_e = 2 x 10^{17} cm^{-3}) up to an average energy of 1.2 GeV (E_{AV} ~ 7 GV/m).

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

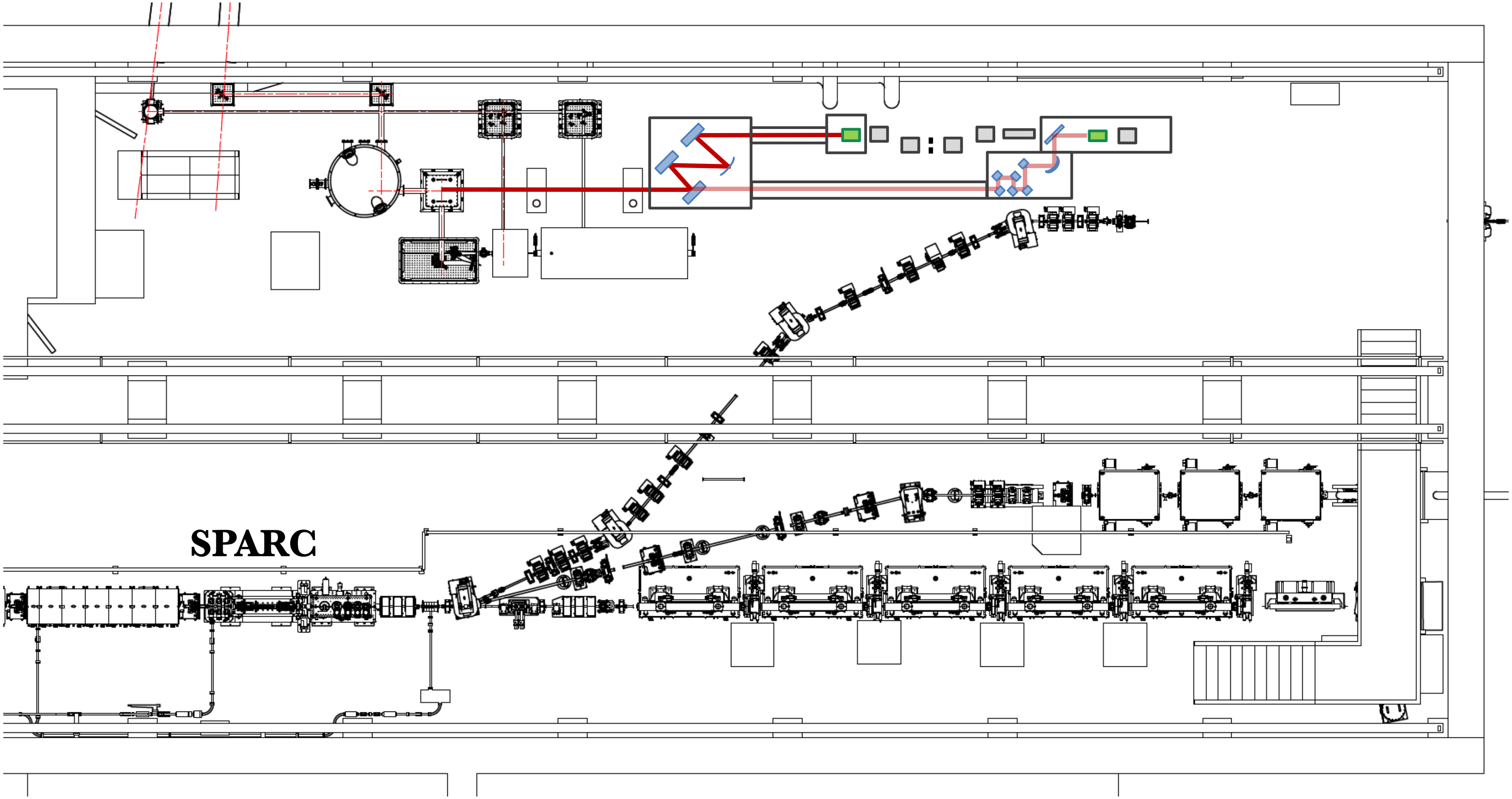
M. Streeter et al, Sci. Rep. 64, 044001 (2024)

Positron sources @ EuPRAXIA

The area and capability



The area and capability



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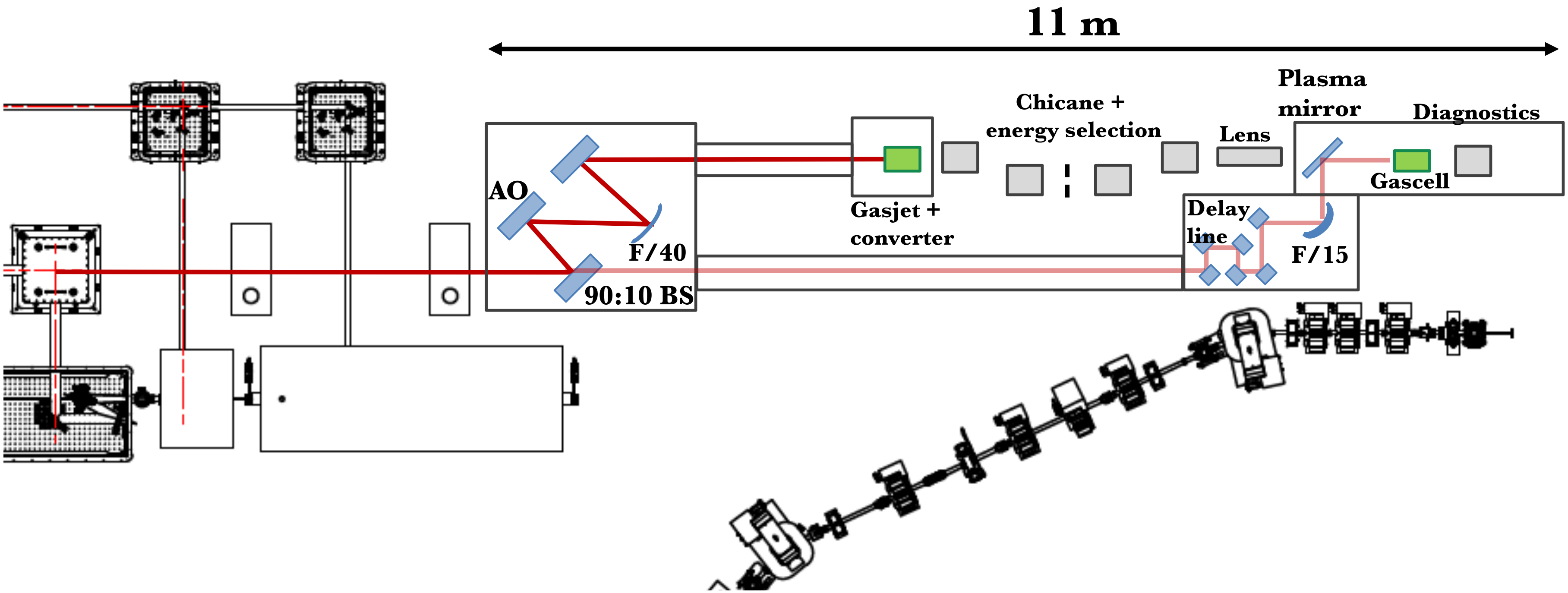

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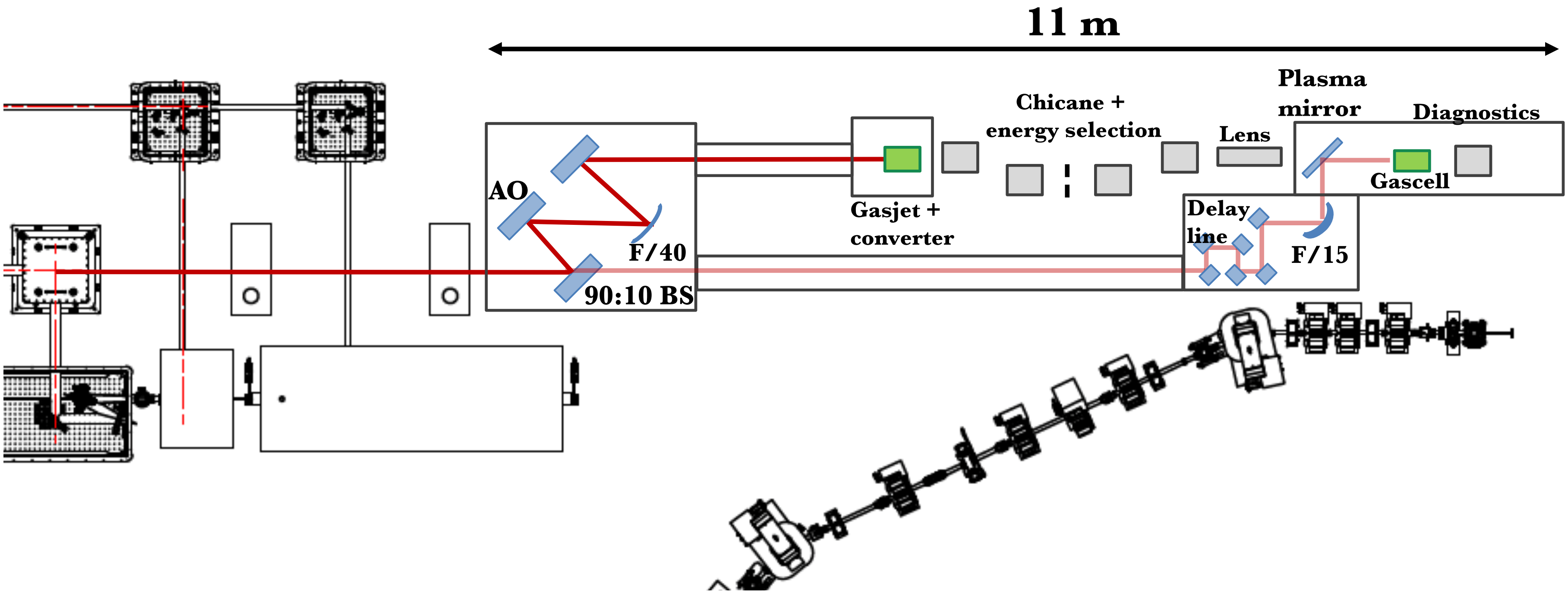


STEP 1: Generation of broadband GeV electron beams with nC total charge

STEP 2: Generation and characterization of the positron beam

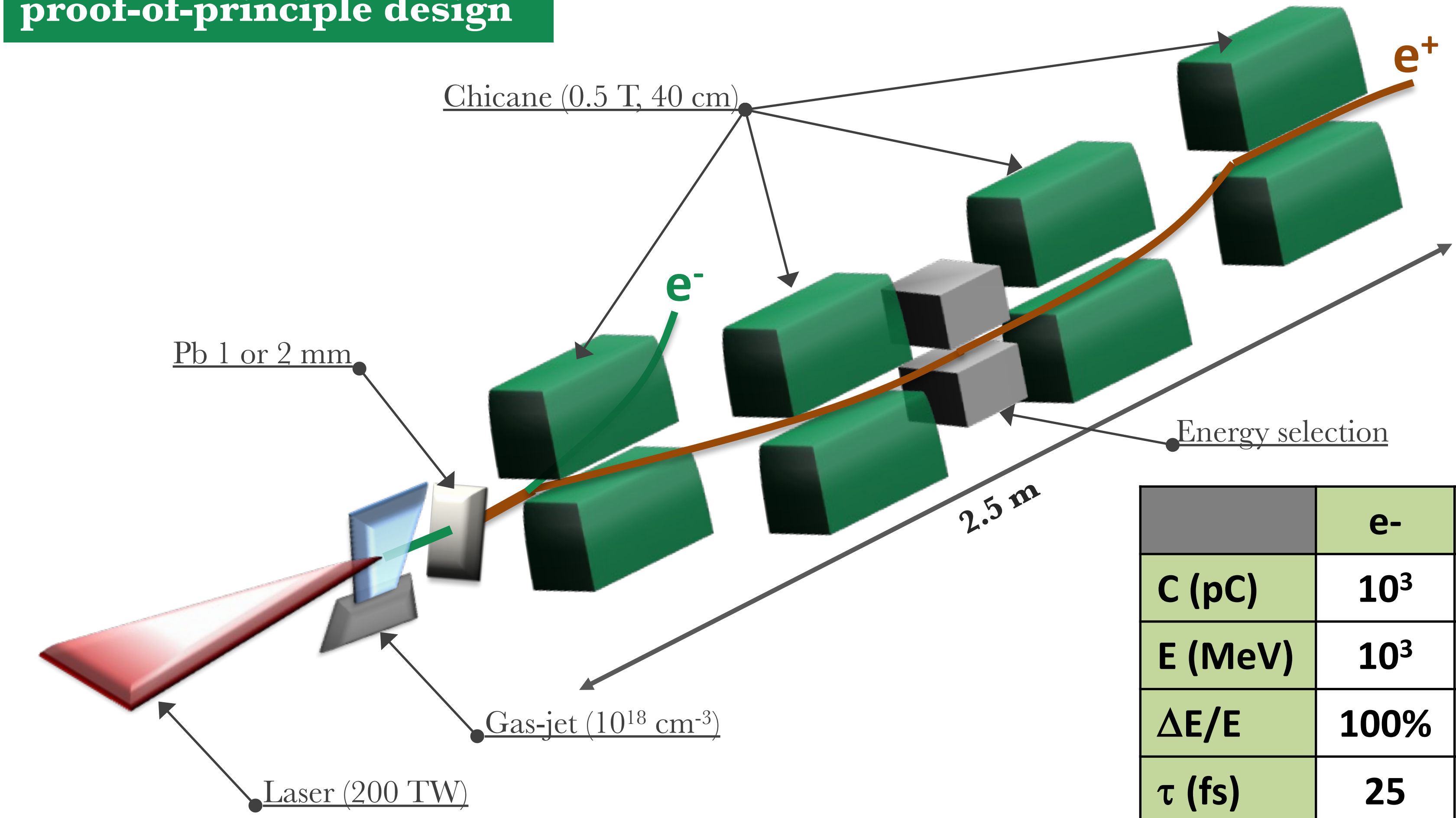
STEP 3: Transport and energy selection: demonstration of 500 MeV ±5% 1 pC charge e+

STEP 4: First demonstration of laser-driven positron wakefield acceleration

STEP 5: Coupling of the positron beam (witness) with SPARC (driver)

Proof-of-principle design

Start-to-end simulation of proof-of-principle design



Chicane (0.5 T, 40 cm)

e^+

e^-

Pb 1 or 2 mm

Energy selection

2.5 m

Gas-jet (10^{18} cm^{-3})

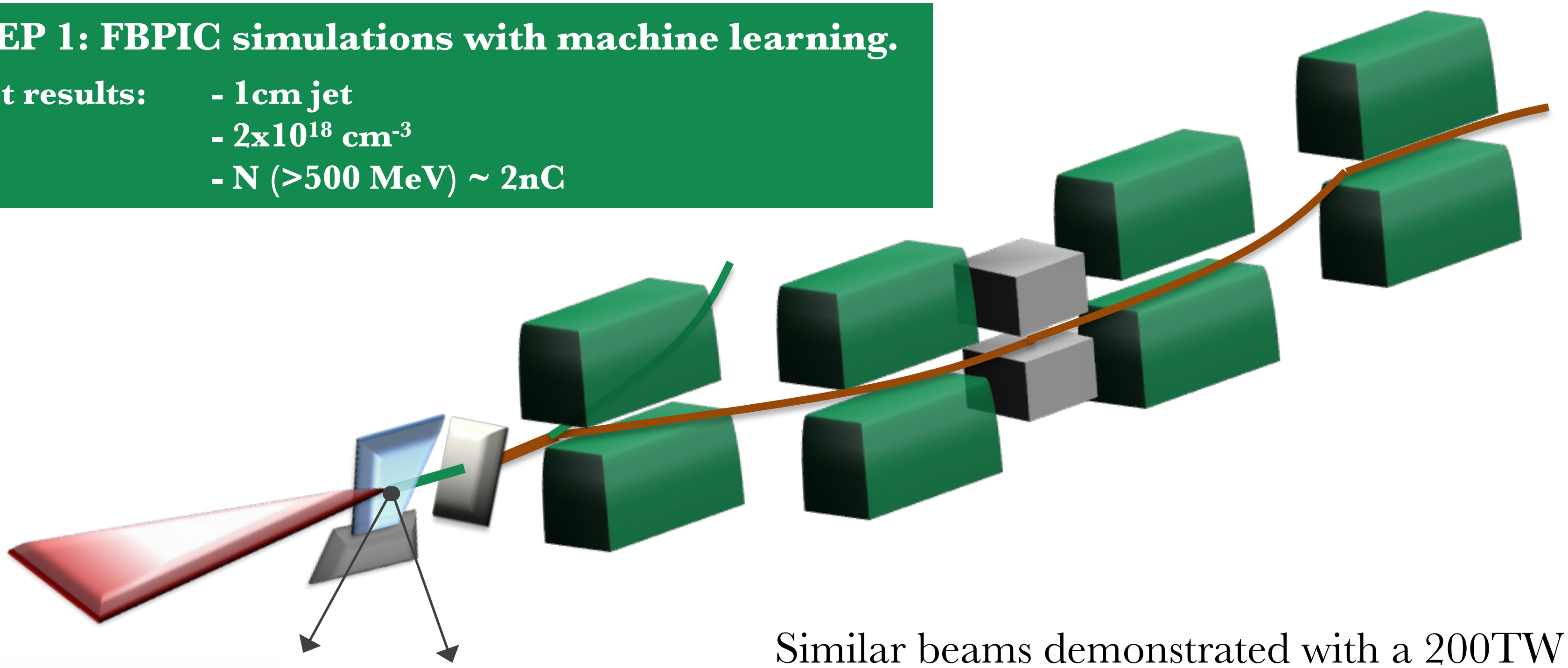
Laser (200 TW)

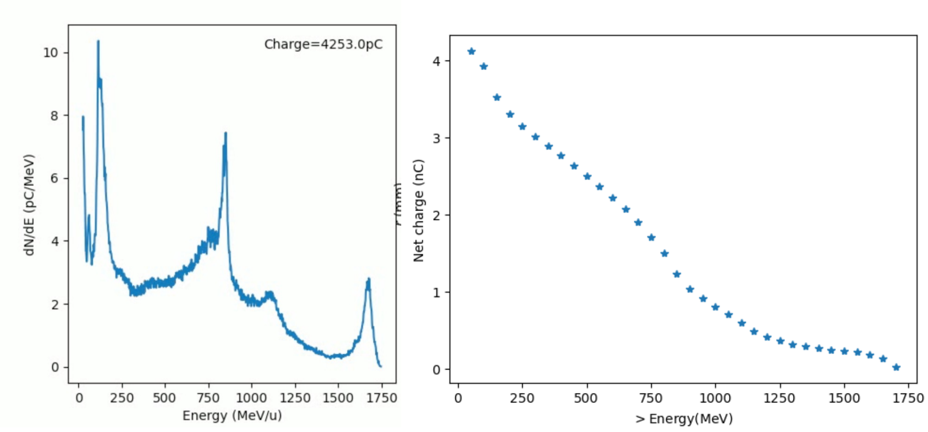
	e-	e+
C (pC)	10^3	1
E (MeV)	10^3	500
$\Delta E/E$	100%	10%
τ (fs)	25	30
ε_n (μm)	/	10

Simulation results

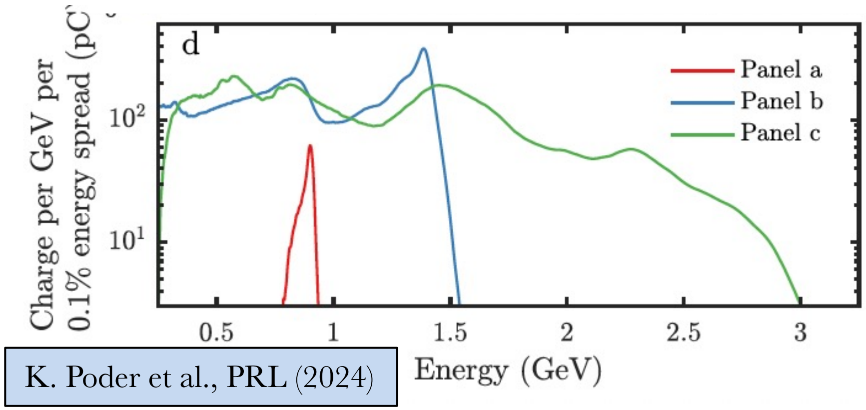
STEP 1: FBPIC simulations with machine learning.

Best results:
- **1cm jet**
- **2×10^{18} cm^{-3}**
- **N (>500 MeV) ~ 2nC**





Similar beams demonstrated with a 200TW laser

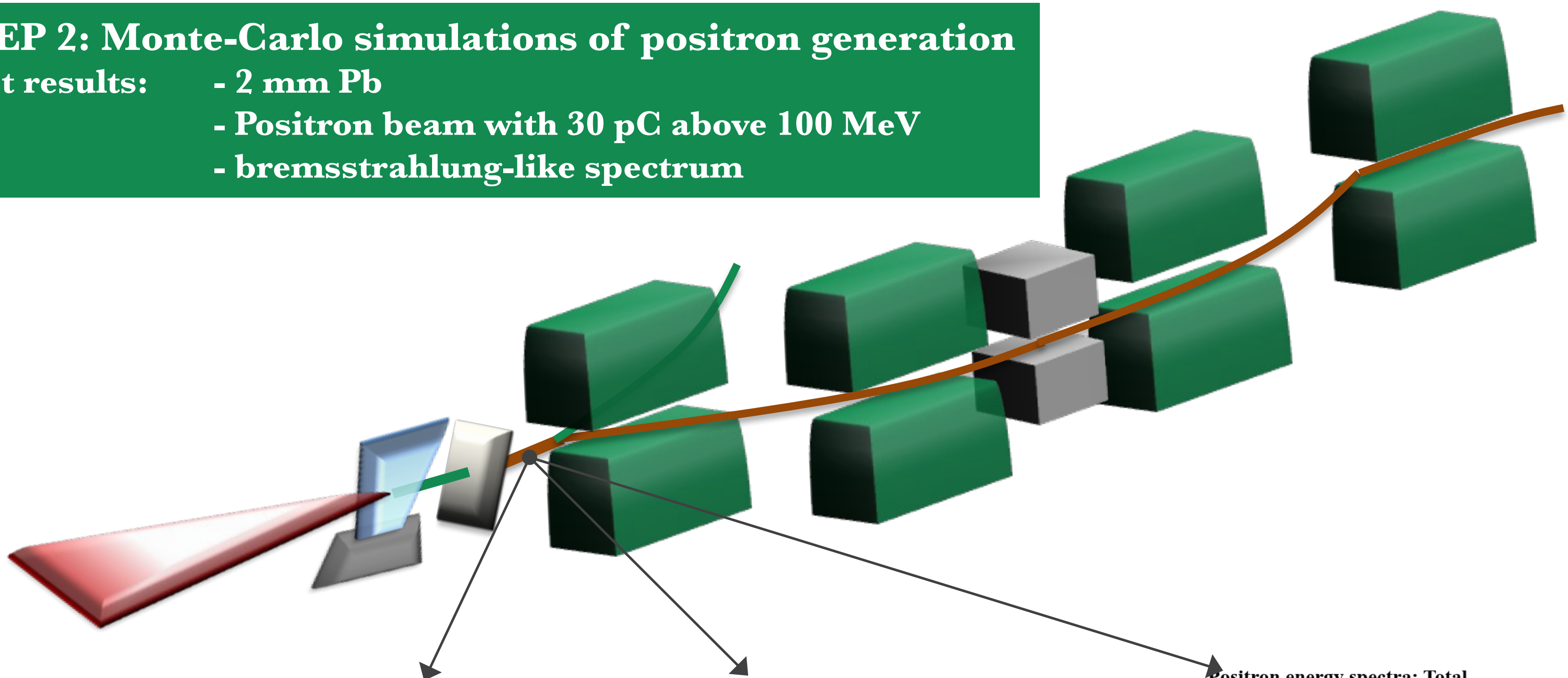


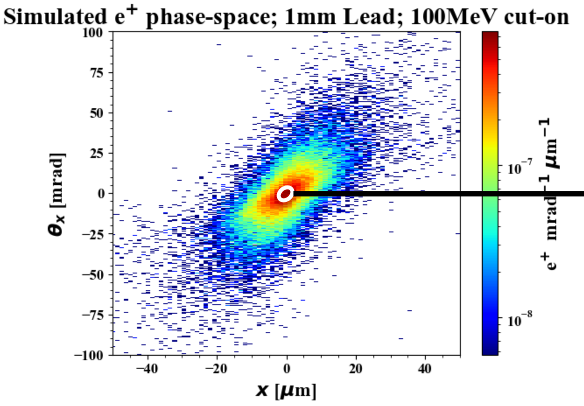
K. Poder et al., PRL (2024)

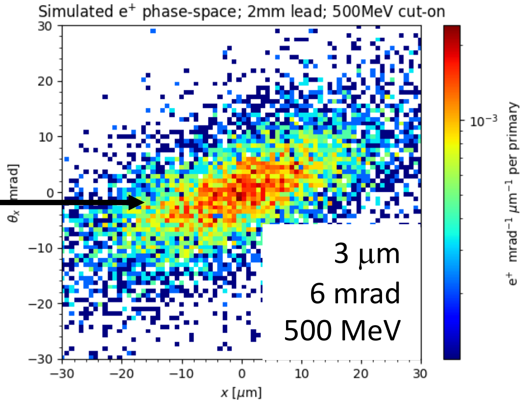
Simulation results

STEP 2: Monte-Carlo simulations of positron generation

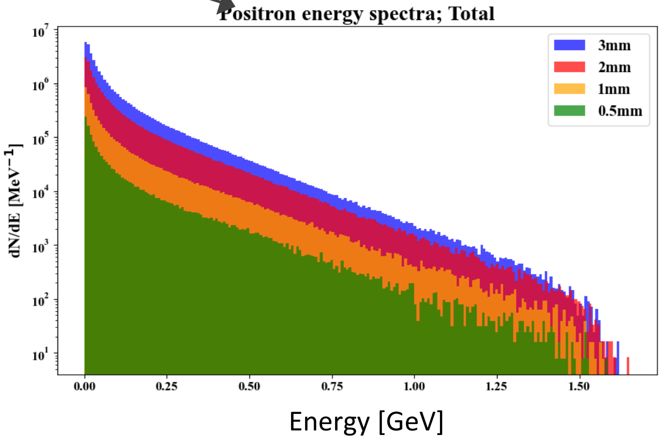
Best results:
- **2 mm Pb**
- **Positron beam with 30 pC above 100 MeV**
- **bremsstrahlung-like spectrum**




Simulated e⁺ phase-space; 1mm Lead; 100MeV cut-on


Simulated e⁺ phase-space; 2mm lead; 500MeV cut-on

3 µm
6 mrad
500 MeV


Positron energy spectra; Total

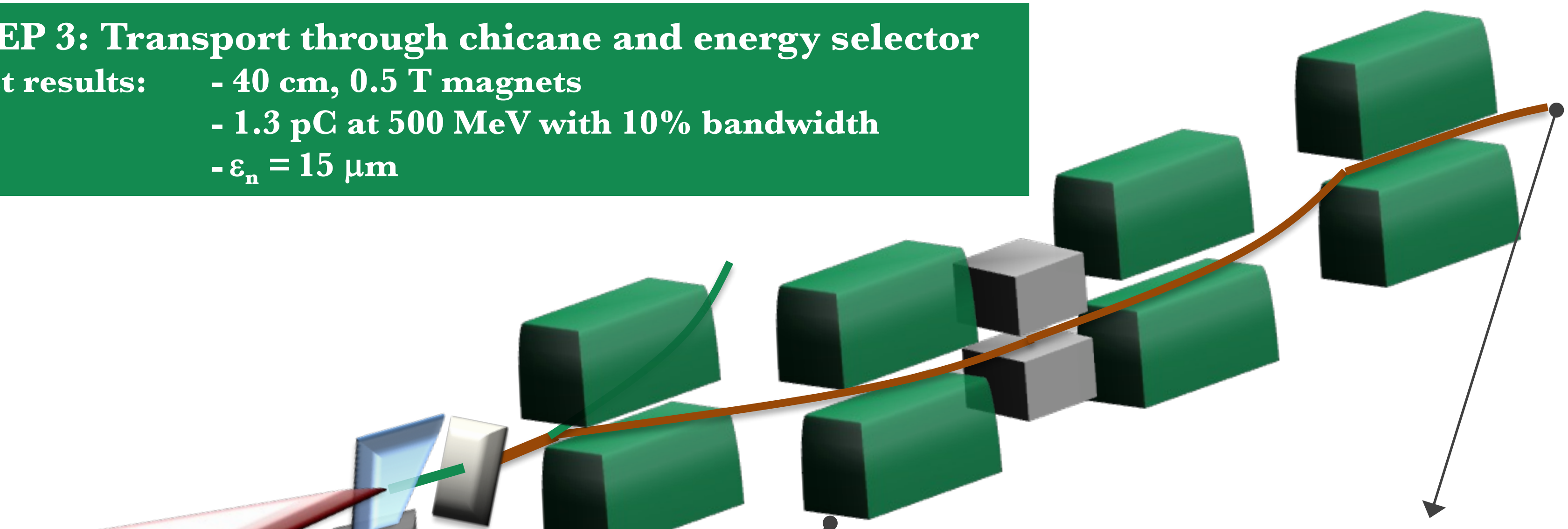
Gianluca Sarri

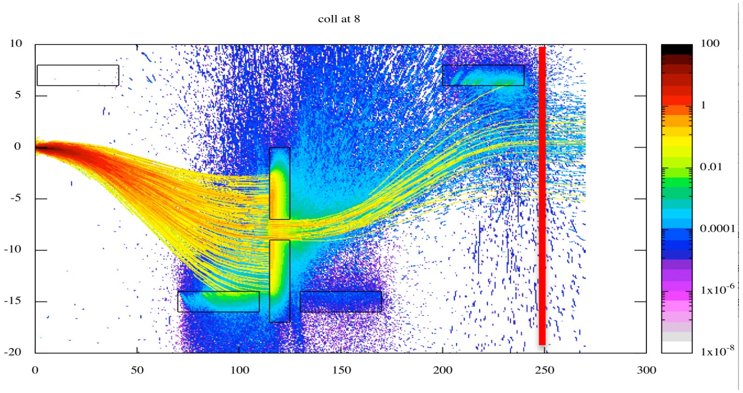
EuPRAXIA PP 2024

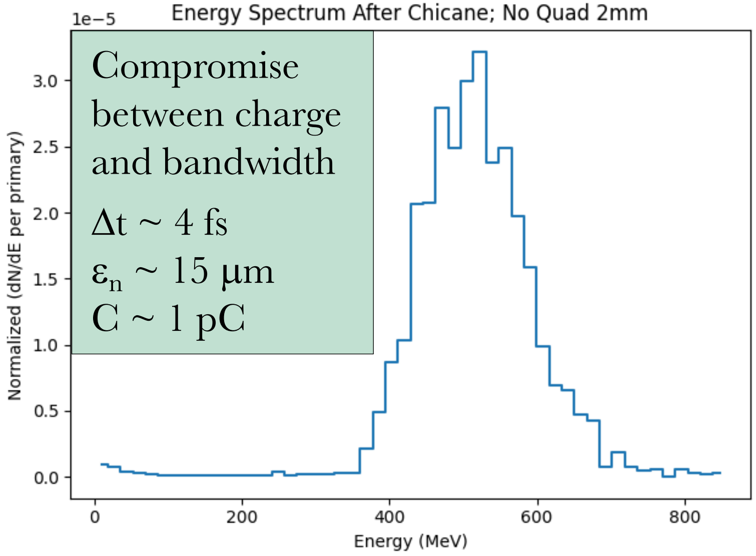
Simulation results

STEP 3: Transport through chicane and energy selector

Best results:
- **40 cm, 0.5 T magnets**
- **1.3 pC at 500 MeV with 10% bandwidth**
- **$\varepsilon_n = 15\ \mu m$**







Compromise between charge and bandwidth

$\Delta t \sim 4$ fs

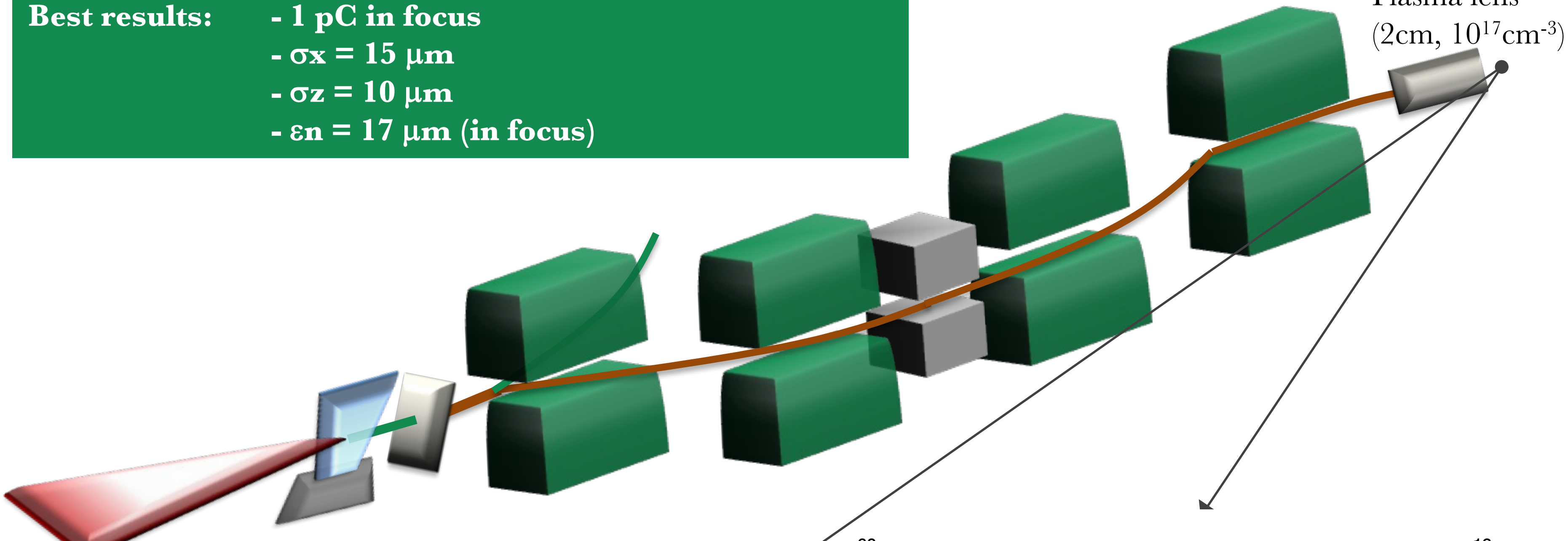
$\varepsilon_n \sim 15\ \mu m$

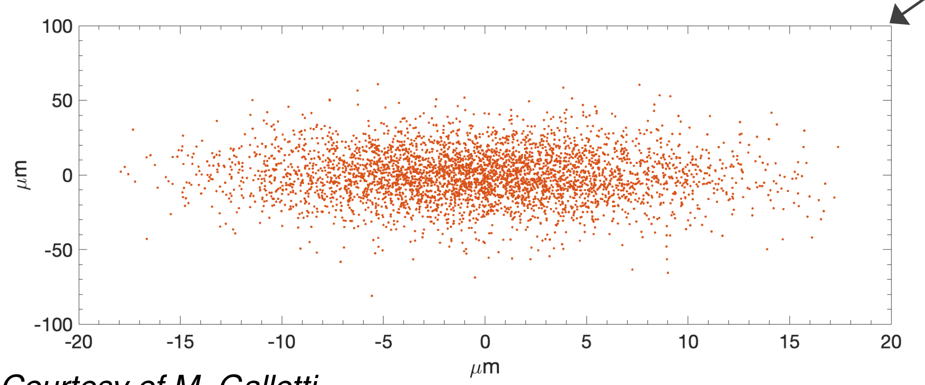
C ~ 1 pC

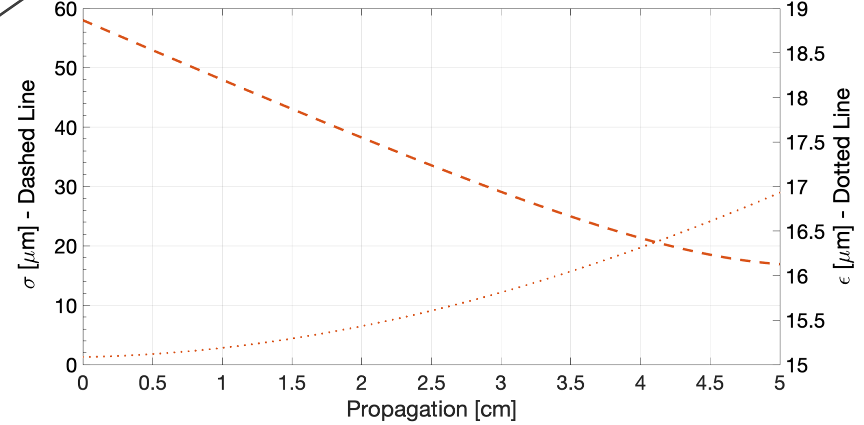
Plasma lens module

STEP 4: Refocus the positrons with a plasma lens

Best results:
- **1 pC in focus**
- **σx = 15 μm**
- **σz = 10 μm**
- **εn = 17 μm (in focus)**


Plasma lens (2cm, 10^{17}cm^{-3})



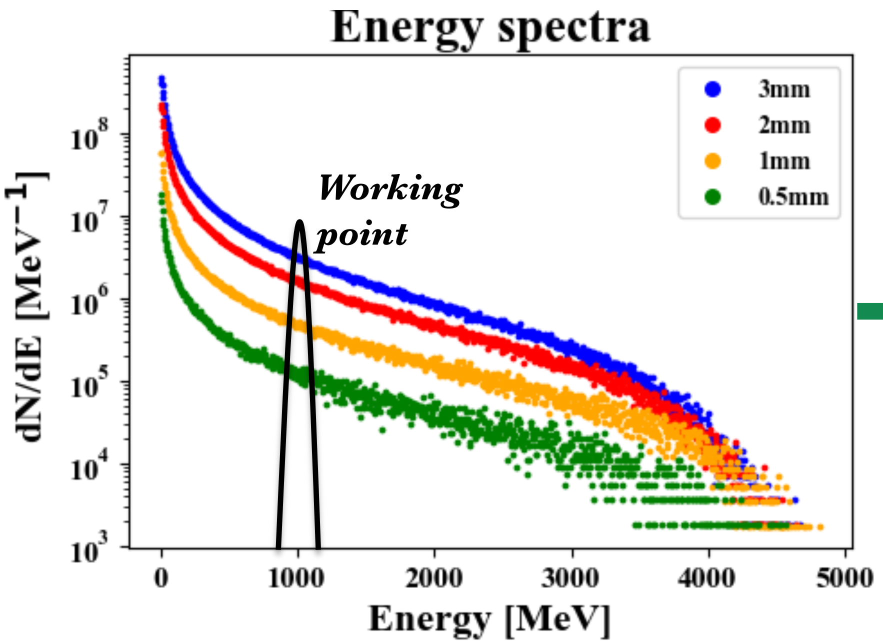


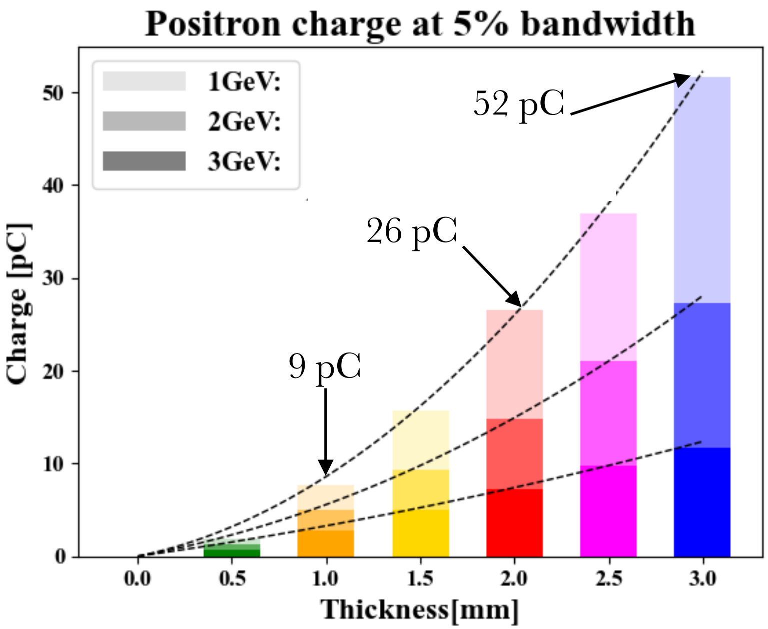
Courtesy of M. Galletti

Next steps and potential upgrades

10s of pC positron beams

10s of pC positron beams would be **obtainable with a PW laser.**


Energy spectra


Positron charge at 5% bandwidth

10 pC positron beams in a 5% bandwidth at the GeV level achievable using a ~5 GeV broadband electron beam with ~ nC charge. Requires a PW-scale laser

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

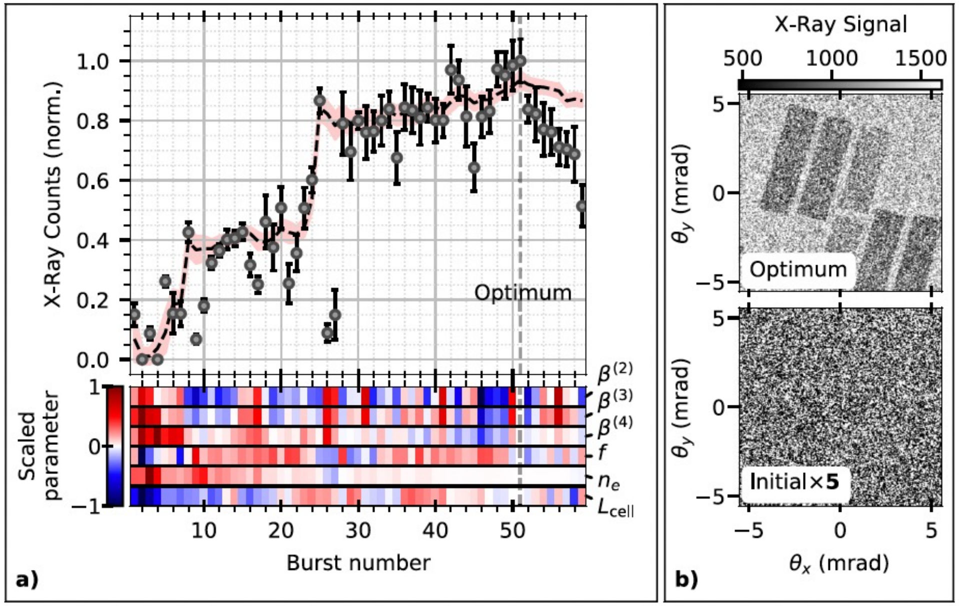
T. Foster et al., *in preparation* (2024)

Additional applications

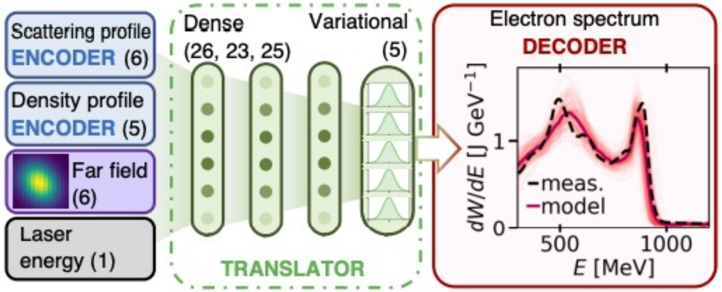
AI modelling of LWFA

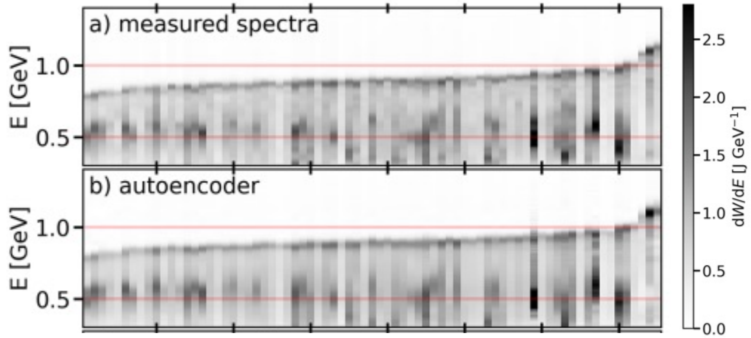
Machine-learning techniques now allows for active stabilization of LWFA and high-level of predictability

Baesyan optimization of laser and plasma parameters for betatron sources



Neural network predictions

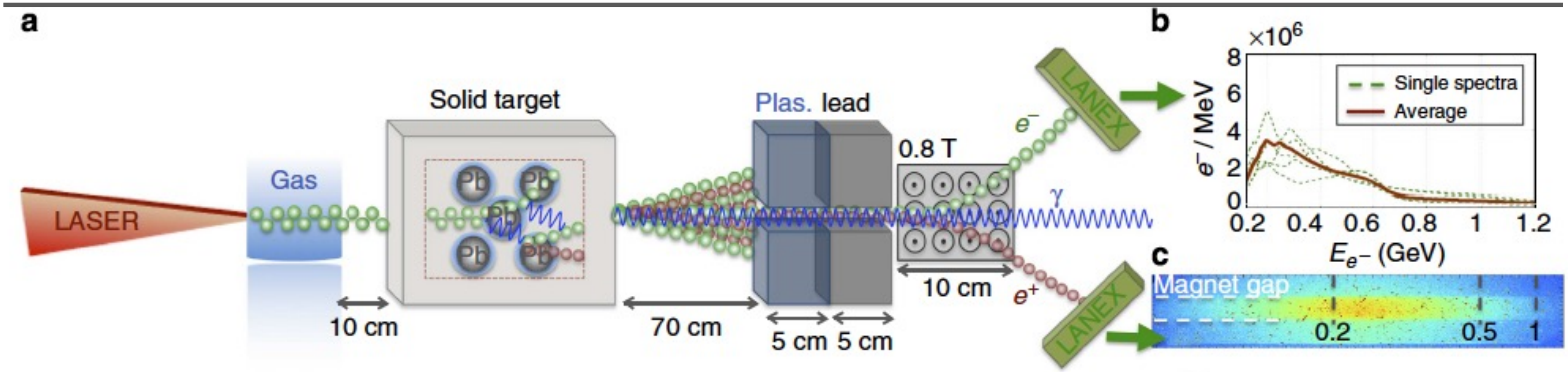


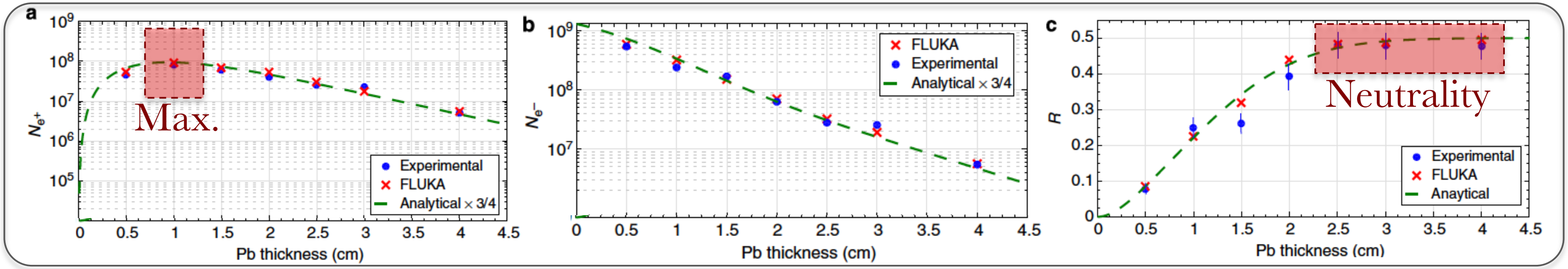


R. Shaloo et al., Nat. Comm. (2020)

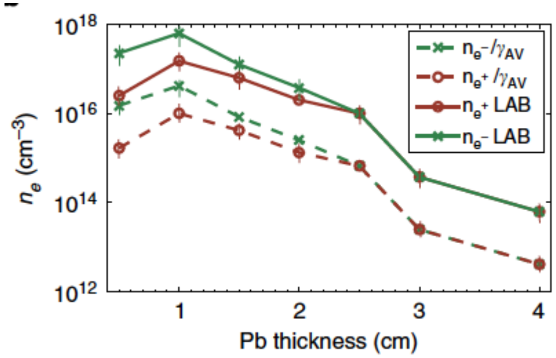
M. Streeter et al., HPLSE (2023)

Neutral beams



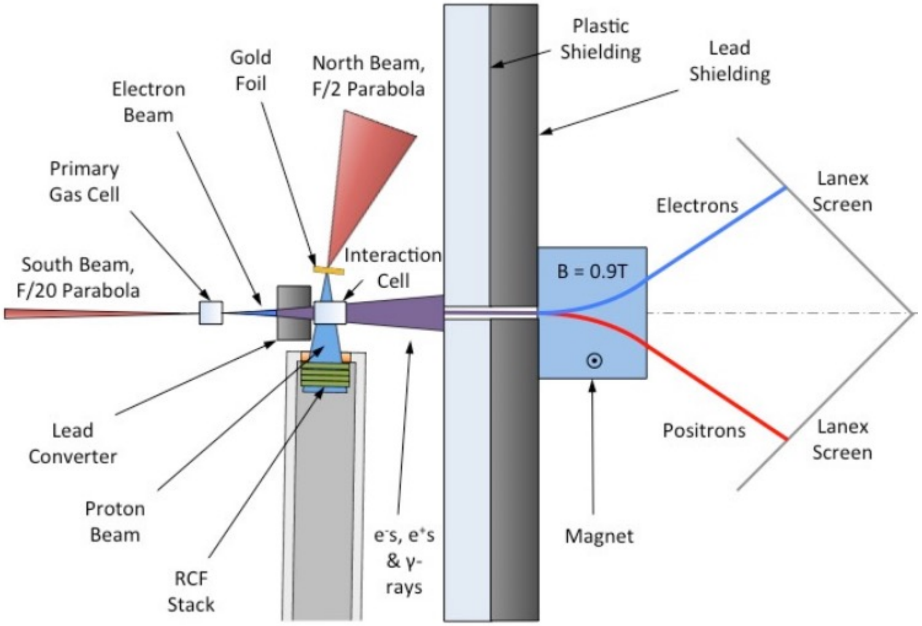


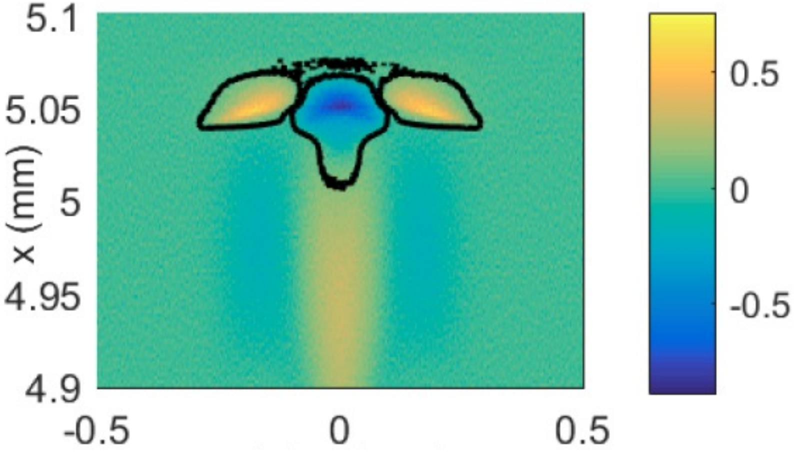
- ✓ Maximum positron yield at ~2 L_{RAD}
- ✓ ~48% of positrons at ~ 5 L_{RAD}
- ✓ Beam duration: ~ tens of fs
- ✓ Beam diameter: > c/ω_p
- ✓ Beam divergence: ~ tens of mrad

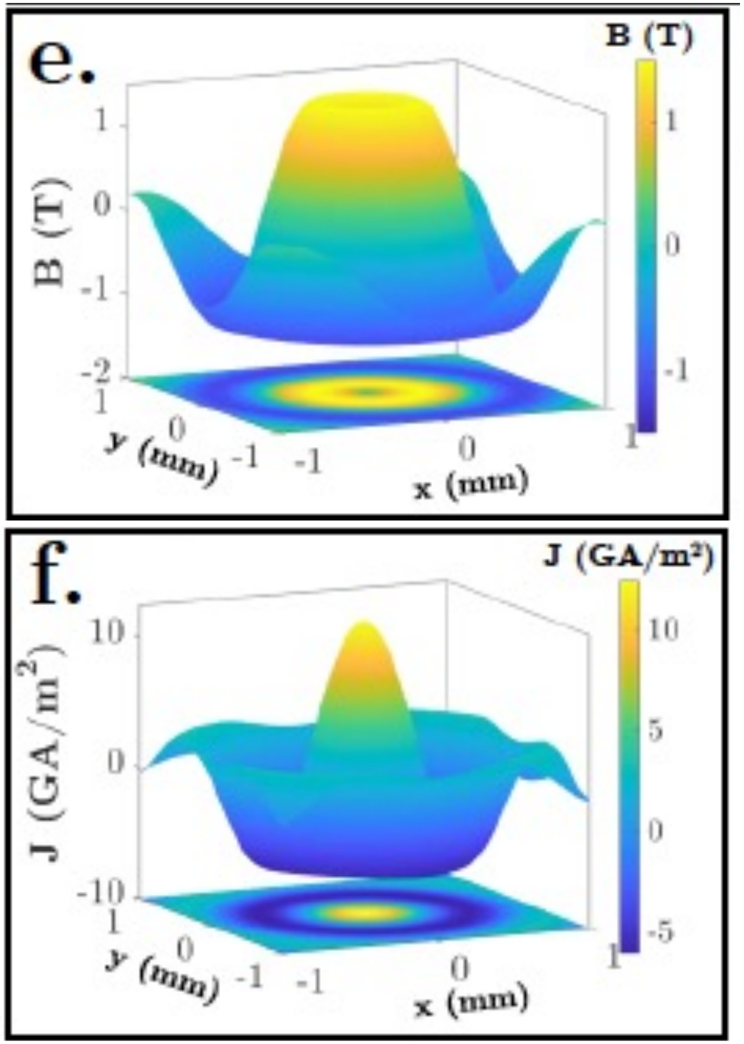


G. Sarri et al.,
Nature Comm. (2015)

Dynamics







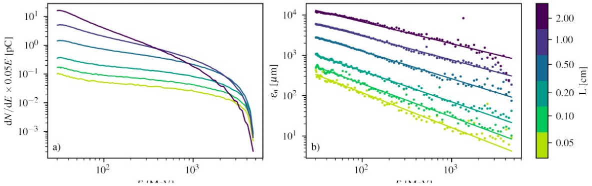
J. Warwick et al., Phys. Rev. Lett. (2017)

Conclusions

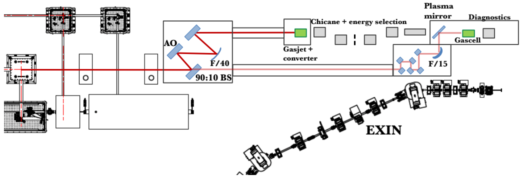
Conclusions

⇒ **Laser-wakefield** is a promising particle accelerator for electron beams.

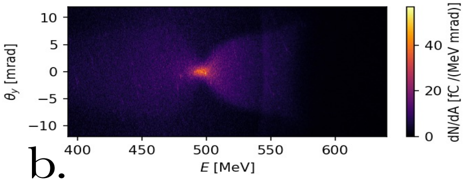
⇒ **Positron wakefield acceleration is significantly lagging behind,** mainly due to the lack of experimental facilities suited for these studies



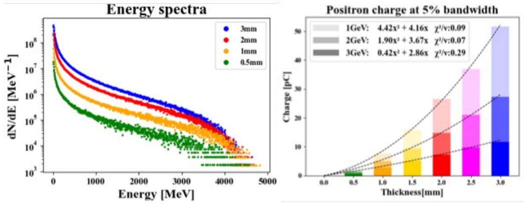
⇒ 100TW-scale lasers can provide narrowband (~5%) positron beams of **sufficient quality to be guided and accelerated in a plasma wakefield**



⇒ A first positron beamline is being cosidered **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 PW-class lasers**

M. Streeter et al, Sci. Rep. 64, 044001 (2024)

K. Poder et al., Phys. Rev. Lett. 132, 195001 (2024)

G. Sarri et al., Plasma Phys. Contr. F. 64, 04401 (2022)

Thanks for your attention!

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