Laser-driven generation of high-energy positron beams: the case of EuPRAXIA

Gianluca Sarri

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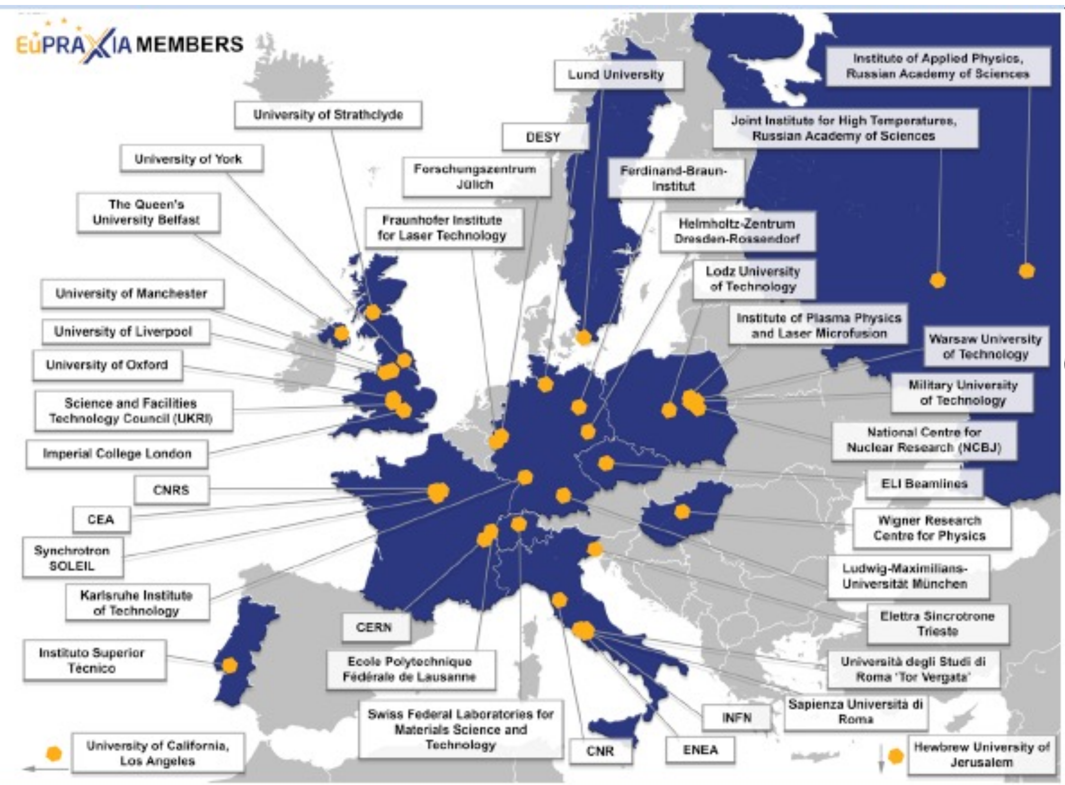
The EuPRAXIA facility

EuPRAXIA is the first accelerator user facility based on plasma acceleration technology.

The first ESFRI plasma accelerator project and their first accelerator project since 2016.



WP1 - Coordination & Project Management
R. Assmann, INFN & DESY
M. Ferrario, INFN

WP2 - Dissemination and Public Relations
C. Welsch, U Liverpool
S. Bertelli, INFN

WP3 - Organization and Rules
A. Specka, CNRS
A. Ghigo, INFN

WP4 - Financial & Legal Model. Economic Impact
A. Falone, INFN

WP5 - User Strategy and Services
F. Stellato, U Tor Vergata
E. Principi, ELETTRA

WP6 - Membership Extension Strategy
B. Cros, CNRS
A. Mostacci, U Sapienza

WP7 - E-Needs and Data Policy
R. Fonseca, IST
S. Pioli, INFN

WP8 - Theory & Simulation
J. Vieria, IST
H. Vincenti, CEA

WP9 - RF, Magnets & Beamline Components
S. Antipov, DESY
F. Nguyen, ENEA

WP10 - Plasma Components & Systems
K. Cassou, CNRS
J. Osterhoff, DESY

WP11 - Applications
G. Sarri, U Belfast
E. Chiadroni,U Sapienza

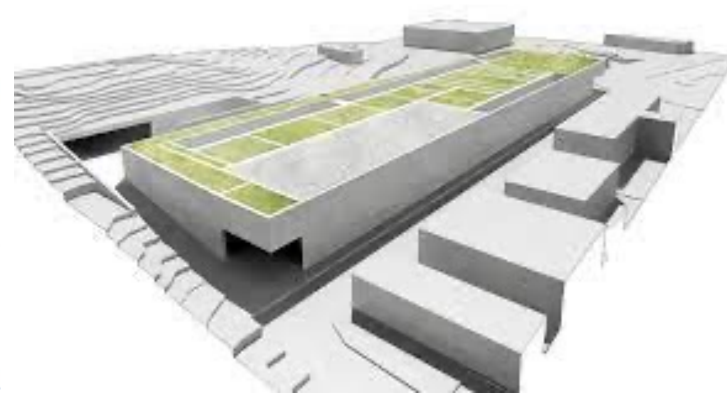
WP12 - Laser Technology, Liaison to Industry
L. Gizzi, CNR
P. Crump, FBH

WP13 - Diagnostics
A. Cianchi, U Tor Vergata
R. Ischebeck, EPFL

WP14 - Transformative Innovation Paths
B. Hidding, U Strathclyde
S. Karsch, LMU

WP15 - TDR EuPRAXIA @SPARC-lab
C. Vaccarezza, INFN
R. Pompili, INFN

WP16 - TDR EuPRAXIA Site 2
A. Molodozhentsev, ELI-Beamlines
R. Pattahil, STFC



EuPRAXIA Conceptual Design Report: R. Assman et al., Eur. Phys. J. Special Topics 229, SUPPL 1 (2020)

European Commission

EPSRC

AHIPS, December 2024

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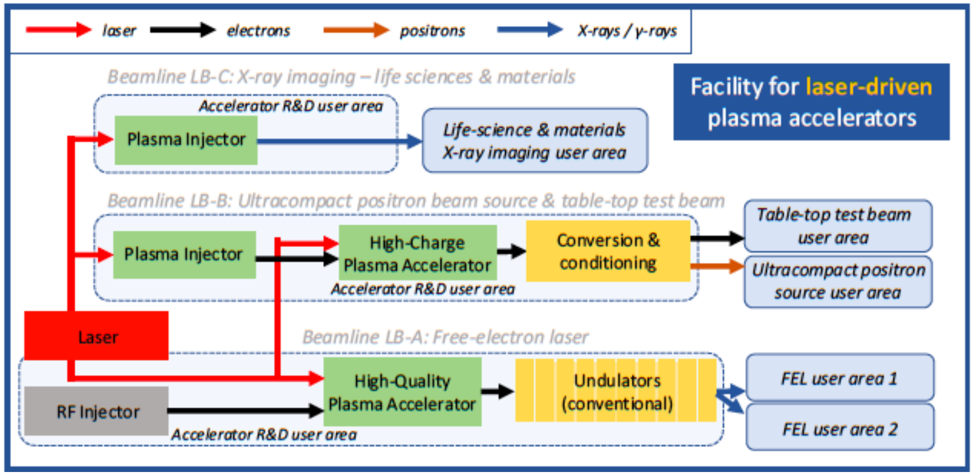

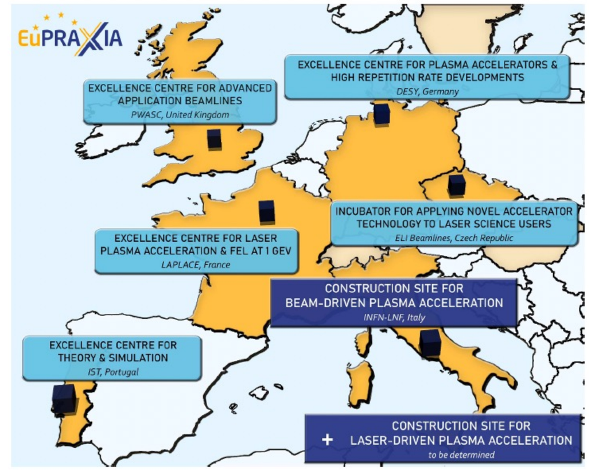

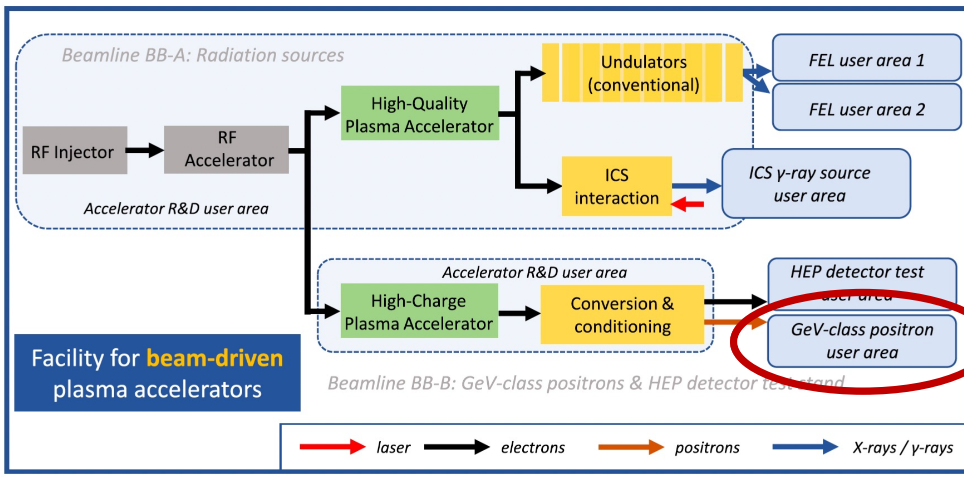

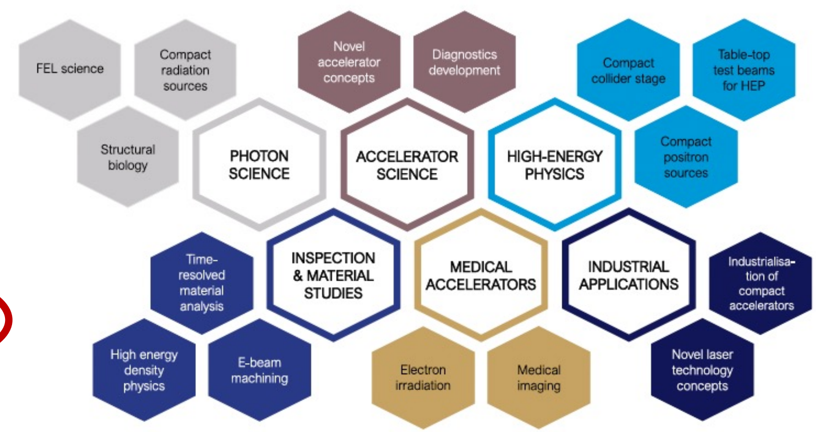

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Introduction

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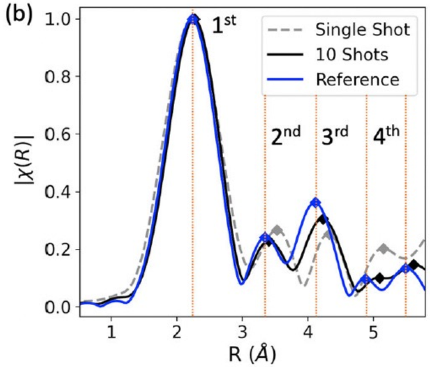
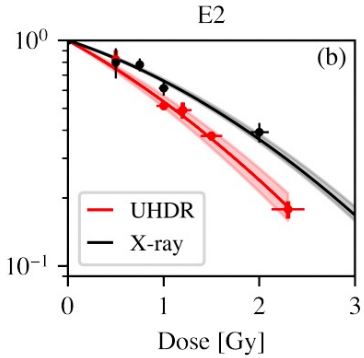


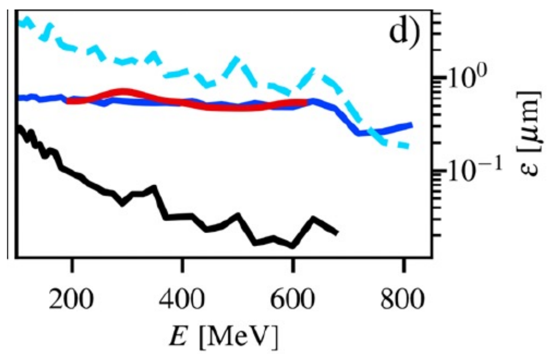
Communication Phys. 7, 247 (2024)

RADIOBIOLOGY



arXiv:2309.06870v2 (2024)

POSITRON SOURCES



Scientific Reports 64, 044001 (2024)

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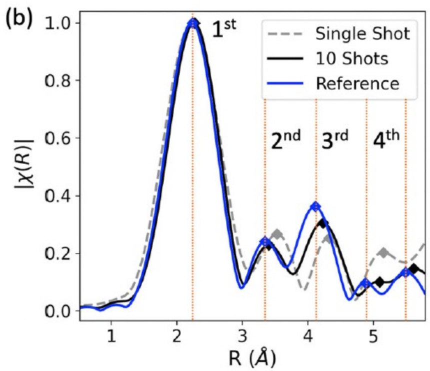

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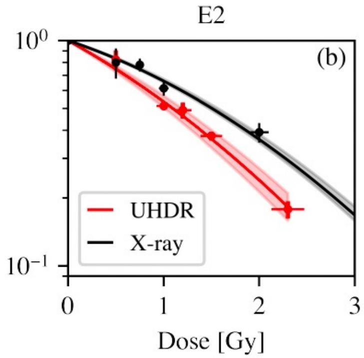

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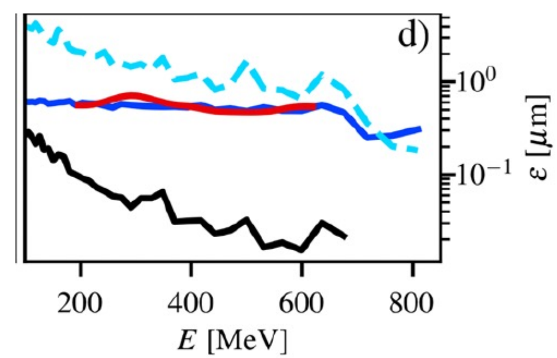
Flagship app. EuPRAXIA CDR

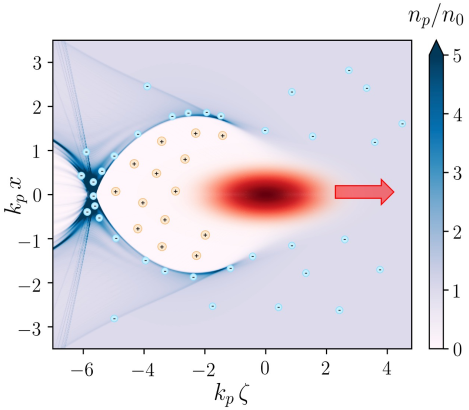
POSITRON SOURCES

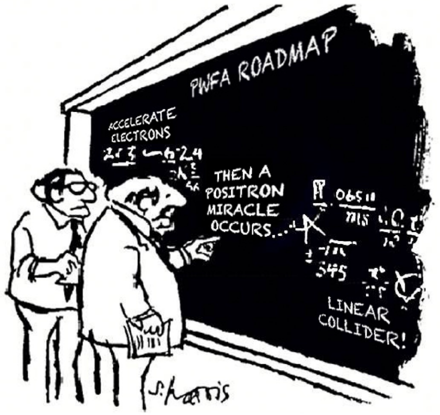


Scientific Reports 64, 044001 (2024)

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.





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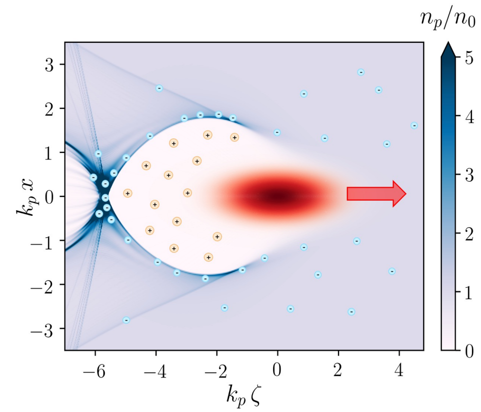
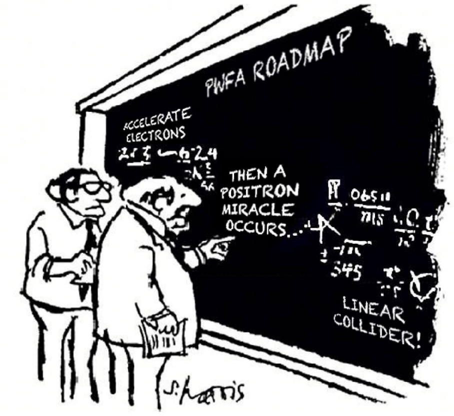
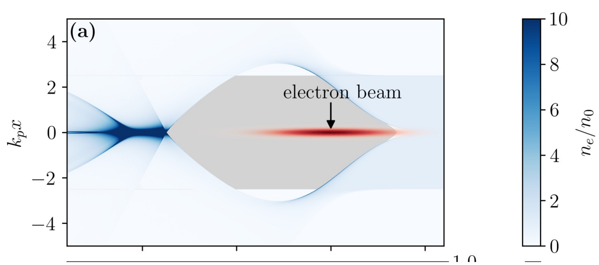
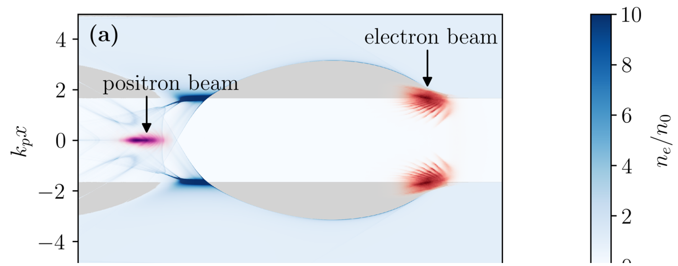




Several schemes have been numerically proposed in order to overcome this issue, including hollow plasma channels and finite plasma columns





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

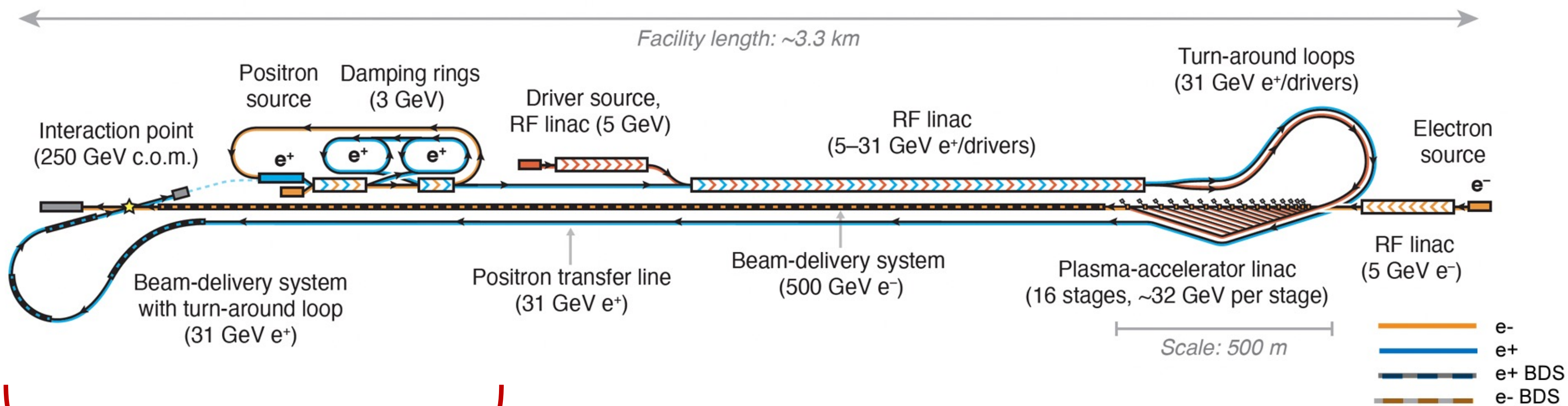
Phys. Rev. A. Beams 23, 121301 (2020)

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

Why positrons?

The issue is so complex that recent proposals for plasma-based colliders try to circumvent it with hybrid schemes

The Hybrid Asymmetric Linear Higgs Factory (HALHF) Concept



31 GeV positron beamline based on conventional technology

Is it possible to devise a long-term program to introduce plasma-based acceleration in the positron arm?

B. Foster et al., NJP 25, 093037 (2023)

A roadmap for a solution?

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

- short duration: $\sigma_z \sim$ 10s μm
- low normalized emittance: $\varepsilon_n \sim$ μm
- "reasonable charge": Q ~ 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)*

European Commission EPSRC

Disclaimer

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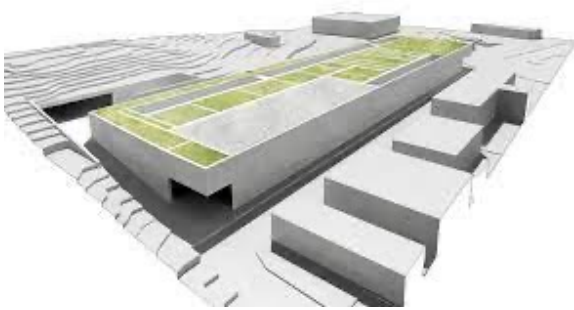
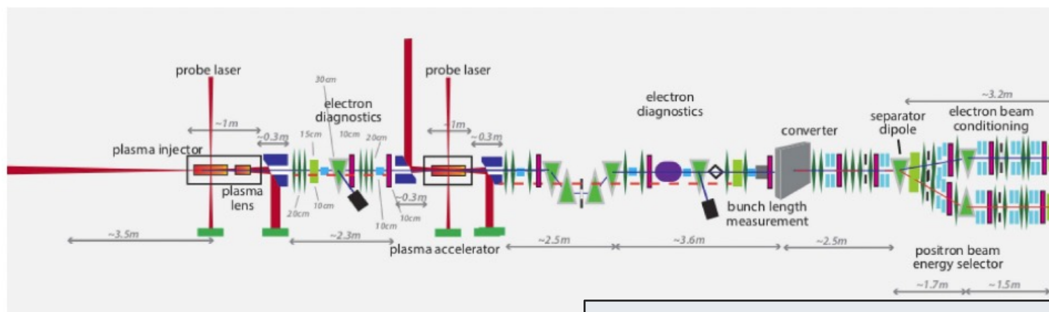
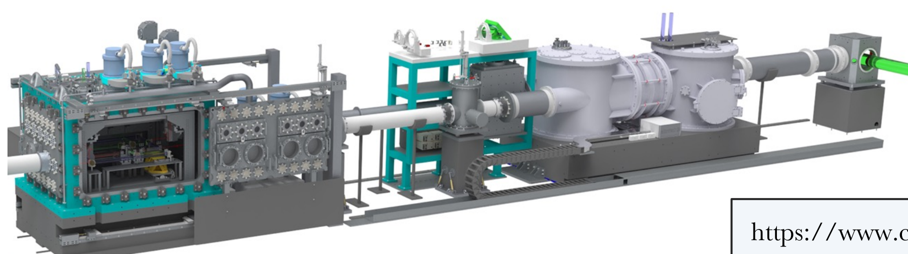




R. Assman et al., Eur. Phys. J. Special Topics (2020)

EPAC *Extreme Photonics Application Centre (UK)*

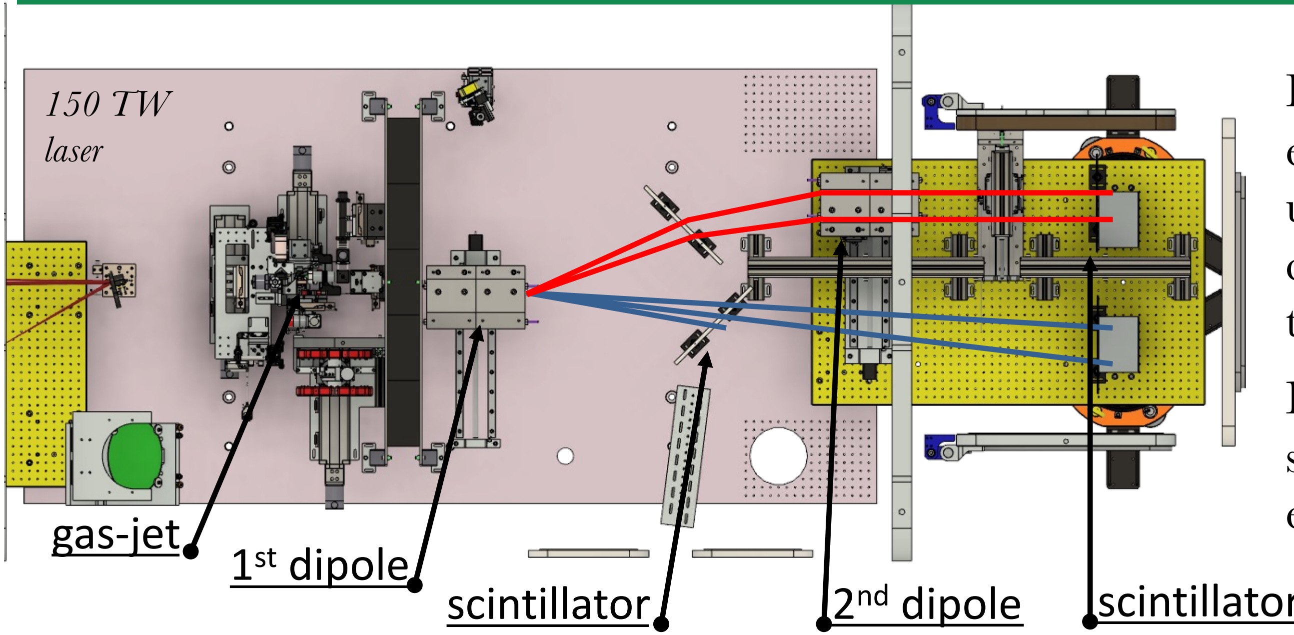


https://www.clf.stfc.ac.uk/Pages/EPAC.aspx

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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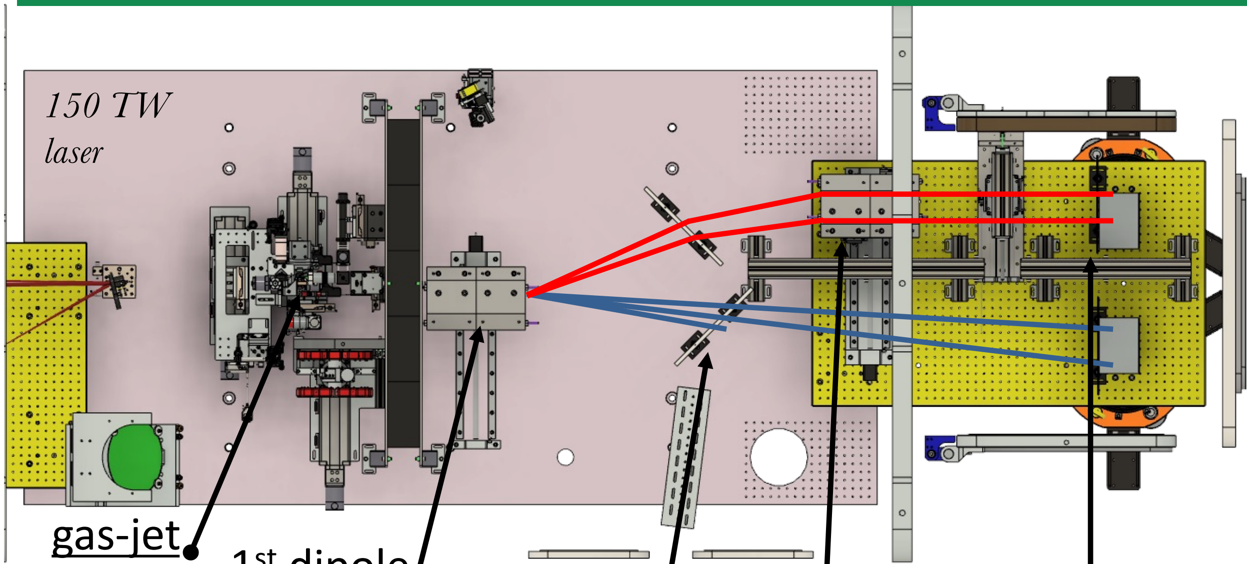

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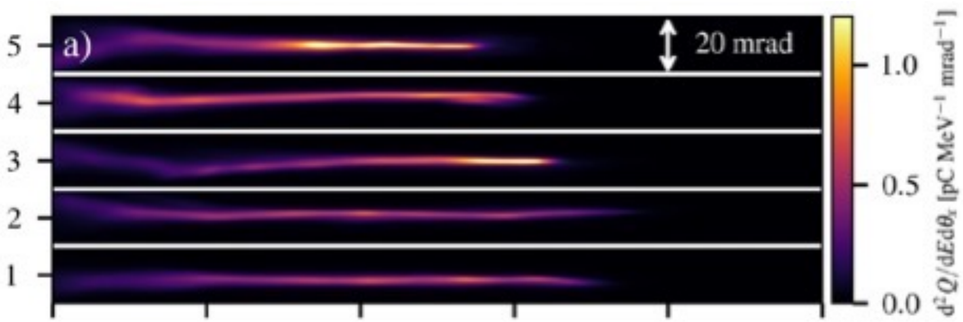

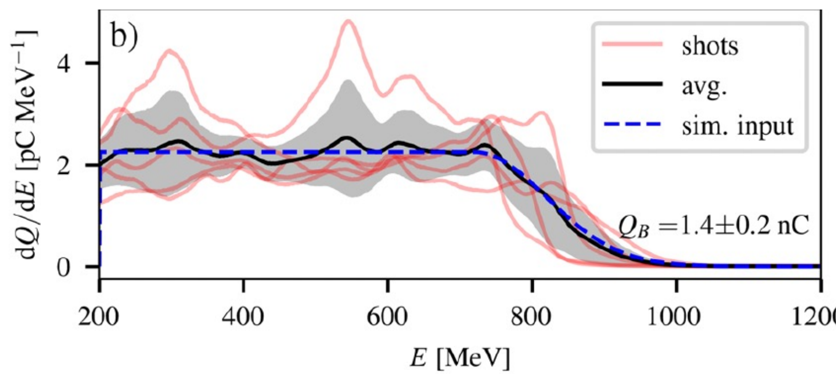

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Experimental results

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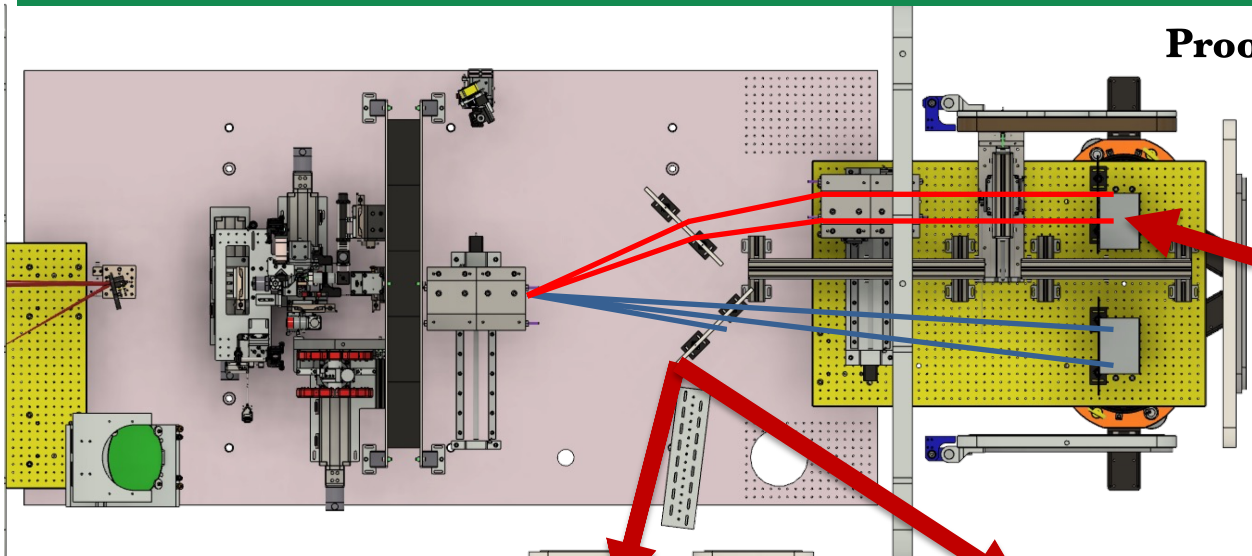
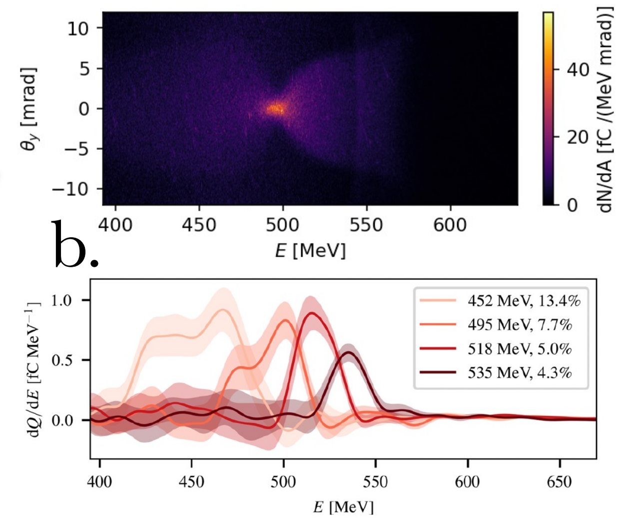
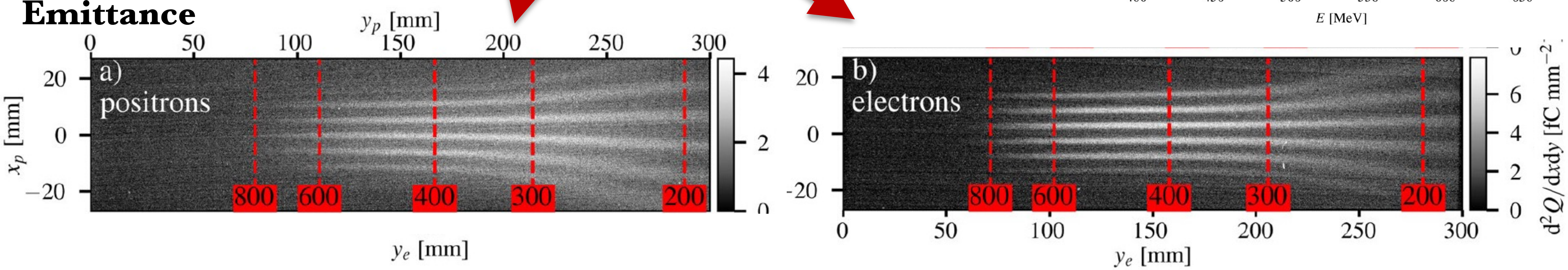


Proof-of-principle Energy selection



Emittance



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

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

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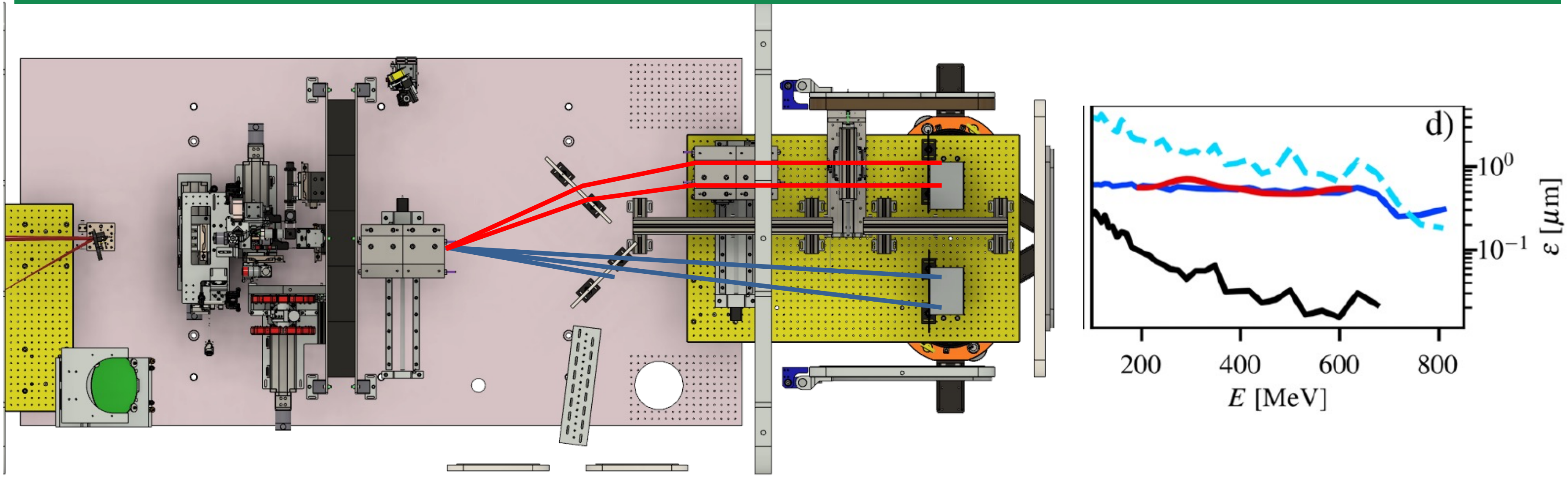


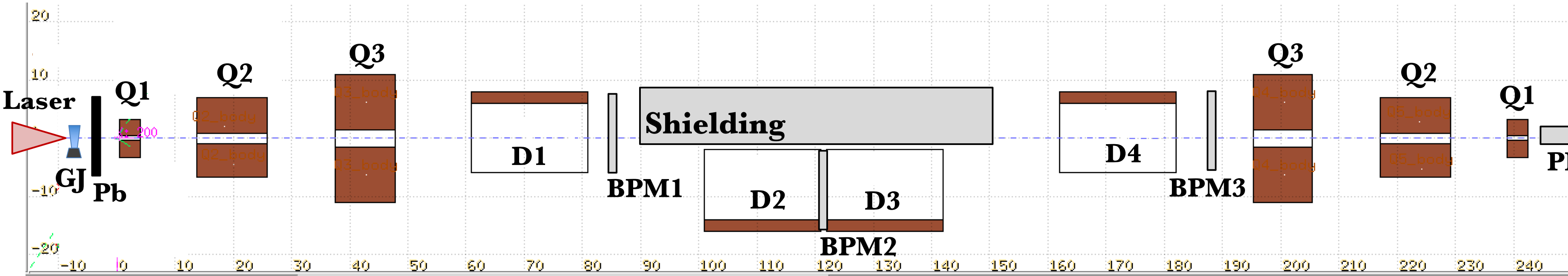
	CLF (2024)	Muggli et al.[22]	Corde et al.[23]	Gessner et al.[24]
E (GeV)	0.6	28.5	20.3	20.3
σ_x (μm)	2.7	25	$<$ 100	50
σ_z (μm)	$\lesssim$ 4*	730	30–50	35
ε (nm)	15	14 × 3	5 × 1	7
$\bar{\varepsilon}$ (μm)	18	390 × 80	200 × 50	300

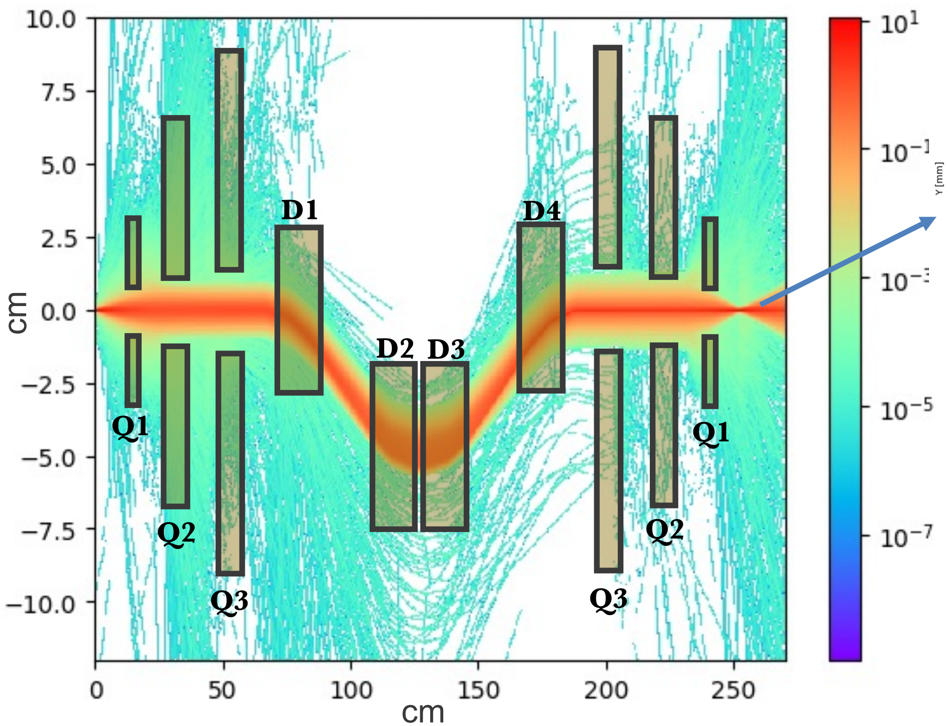
M. Streeter et al, Sci. Rep. 64, 044001 (2024)

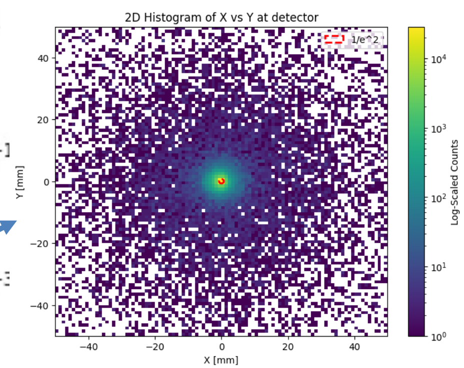
** Not measured, inferred from simulations*

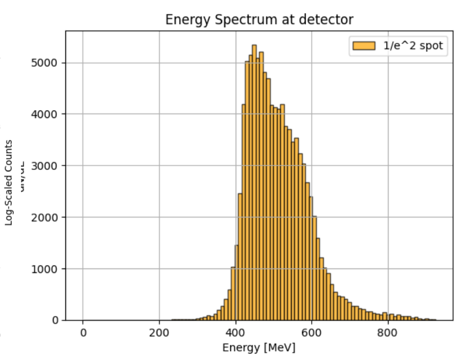
Positron sources @ EuPRAXIA

Start-to-end-simulations







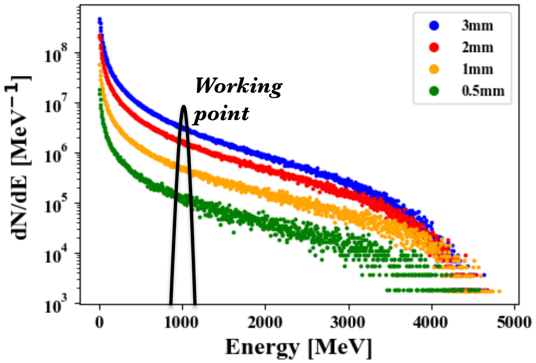


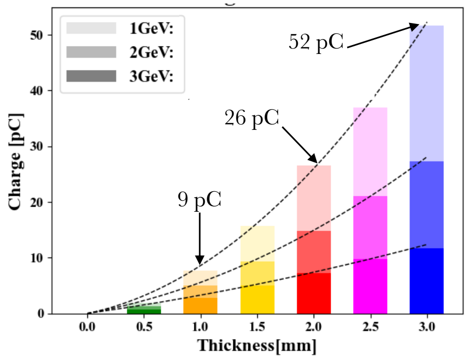
Positron energy:	460 ± 8% MeV
Positron charge:	2.1 pC
σ_z:	50 µm
σ_x,σ_y:	20 µm

Next steps and potential upgrades

Next steps

1. **10s of pC** are required for beam loading. This can be achieved with a PW-class laser





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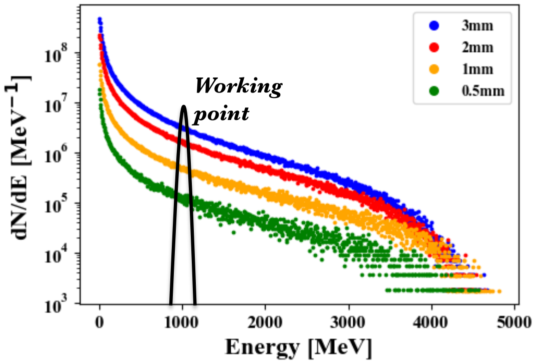

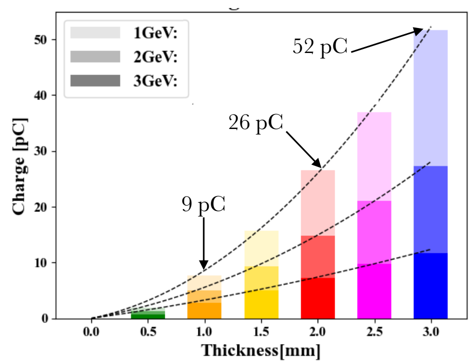

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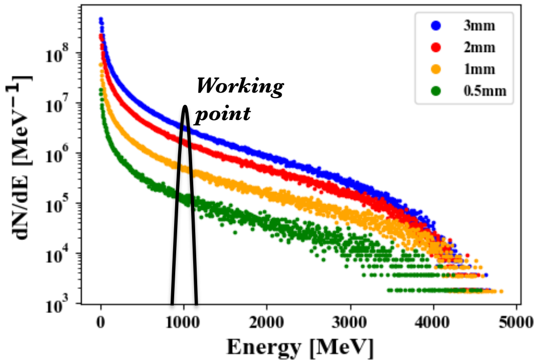

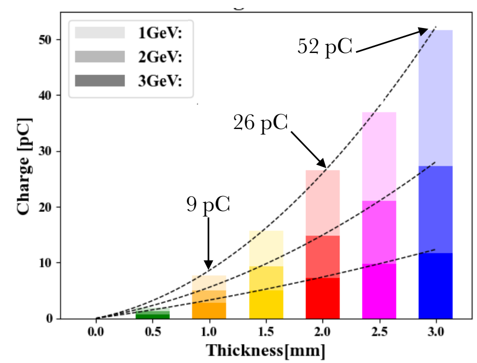

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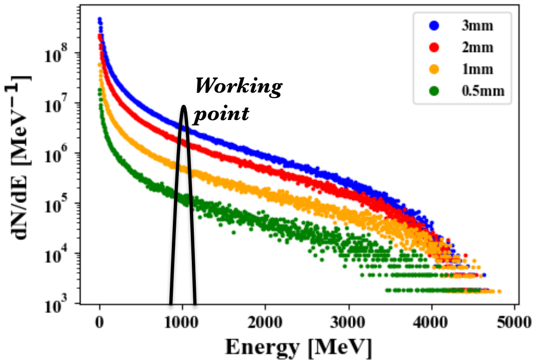

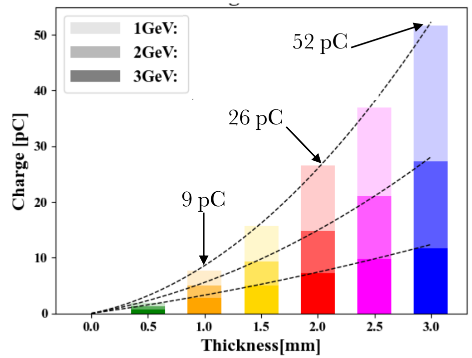

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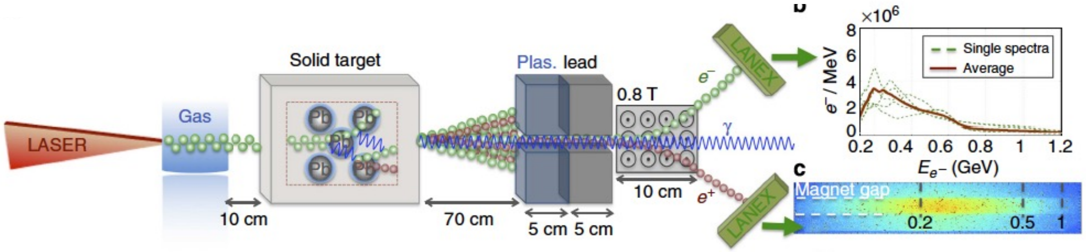
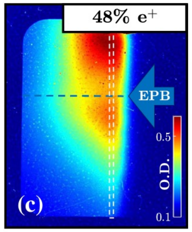
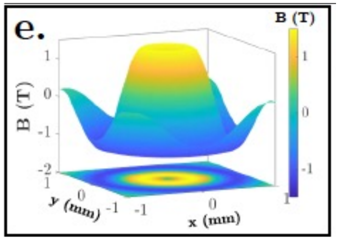
4. **Further optimization** of the positron beam characteristics (mainly higher charge and smaller size) using more complex beamlines currently under investigation

Other applications

1. Studies of the fundamental physics of **pair plasmas**





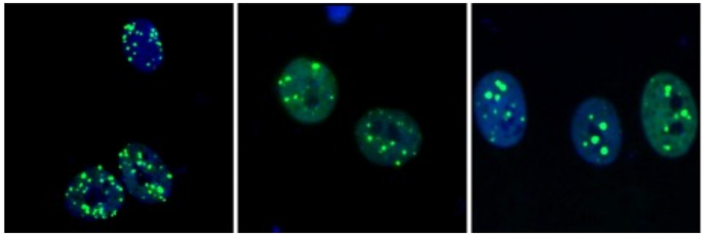


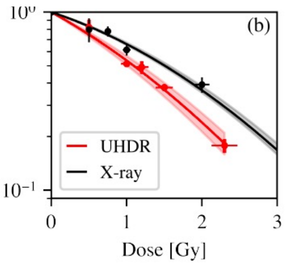
G. Sarri et al., Nature Comm. (2015)

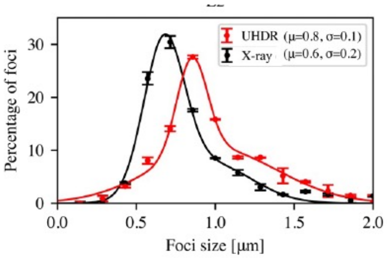
R. Warwick et al., Phys. Rev. Lett. (2017)

N. Shukla et al., J. Plasma Phys. (2018)

2. Radiobiology **at ultra-high dose-rates** at and beyond FLASH







C. McAnespie et al., IRJOBP (2024)

C. McAnespie et al., PRE (2024)

C. McAnespie et al., arXiv:2309.06870v2(2024)

3. High-flux **bremsstrahlung and Compton sources**

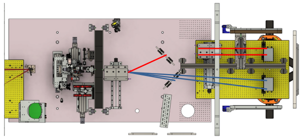
Conclusions

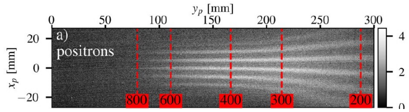
Conclusions

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

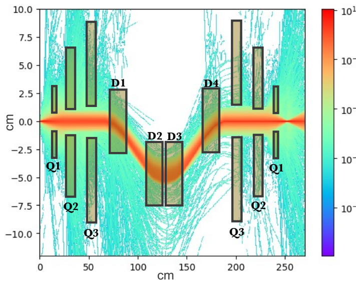
⇒ 100TW-scale lasers can provide narrowband (~5%) positron beams of **sufficient quality to be guided and accelerated in a plasma wakefield**

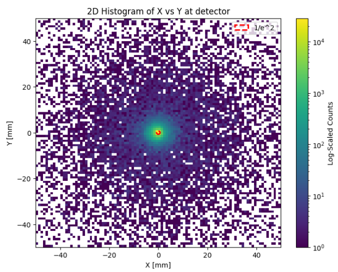
⇒ **First proof-of-principle experiments at 100 TW** validate the numerical expectations

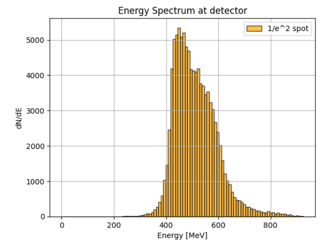




⇒ **Start-to-end simulations** confirm analytical expectations

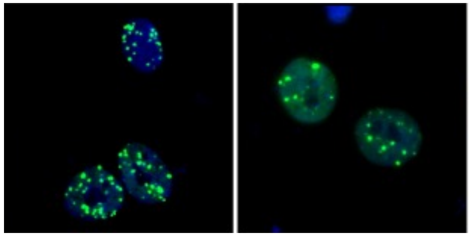


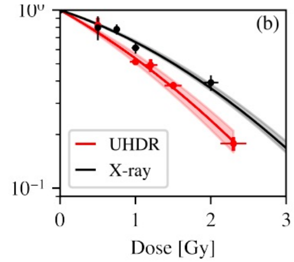




⇒ Extension to **10s of pC positron beams** possible with PW-scale lasers

⇒ Several other **key applications** of strong societal and scientific impact





Thanks for your attention!

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