Plasma-based positron sources for testing positron acceleration at EuPRAXIA

Gianluca Sarri, T. Foster, J. Sarma, M. Galletti, L. Verra

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Introduction

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

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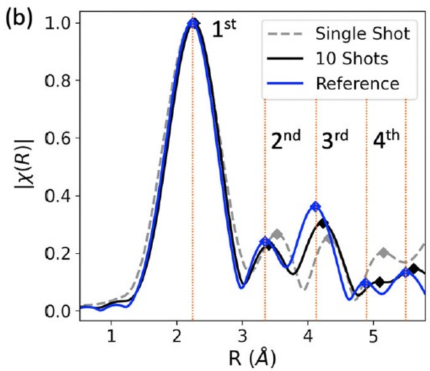
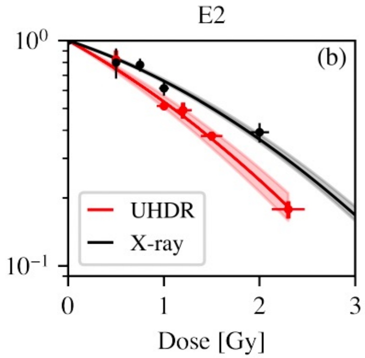
BETATRON SOURCES



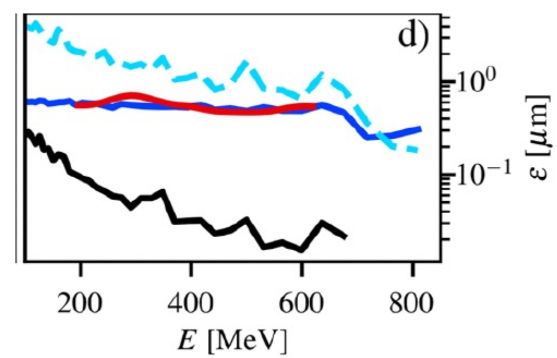
Communication Phys. 7, 247 (2024)

RADIOBIOLOGY



arXiv:2309.06870v2 (2024)

POSITRON SOURCES



Scientific Reports 64, 044001 (2024)

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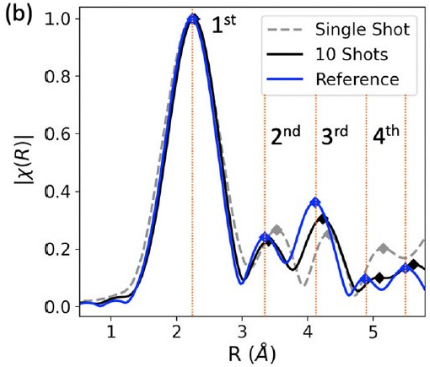
do we have low-hanging-fruit applications using high-charge lower-quality electron beams?

Flagship app. EuPRAXIA CDR

BETATRON SOURCES



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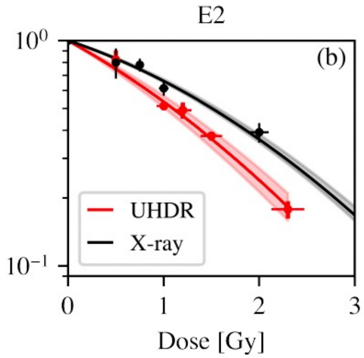

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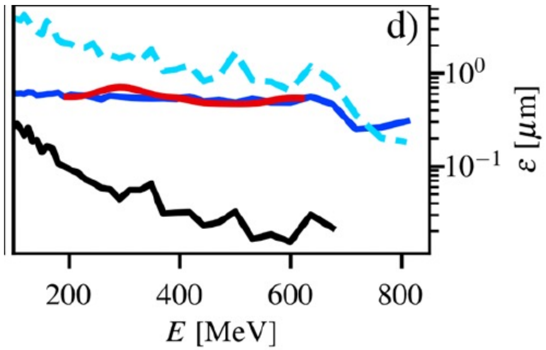

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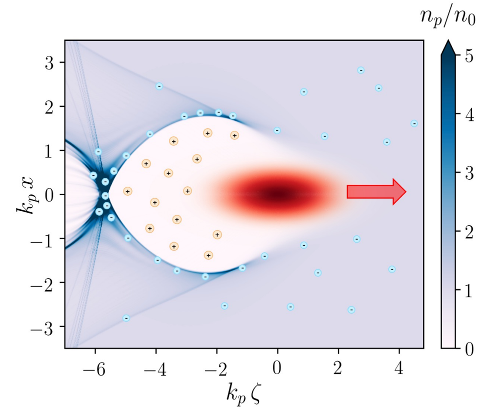
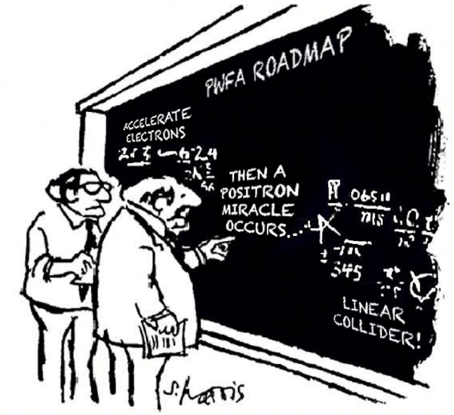
Why positrons?

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.





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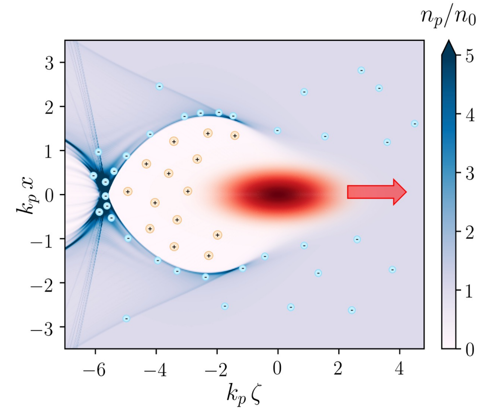
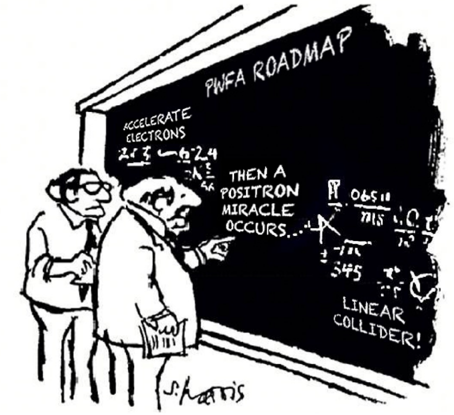
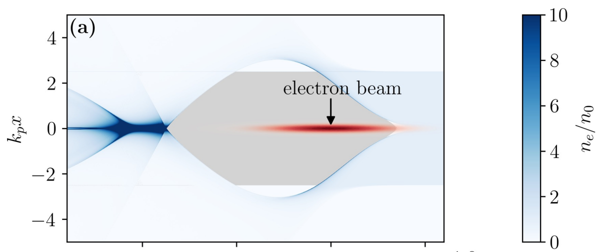
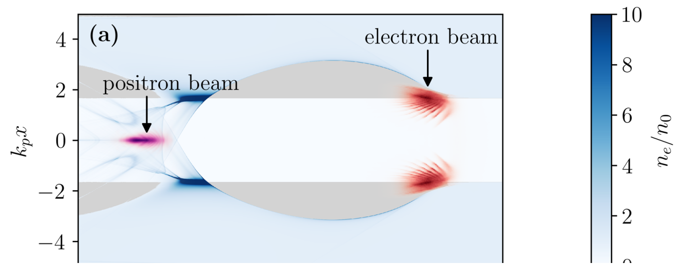




Several schemes have been numerically proposed in order to overcome this issue, including hollow plasma channels and finite plasma columns





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

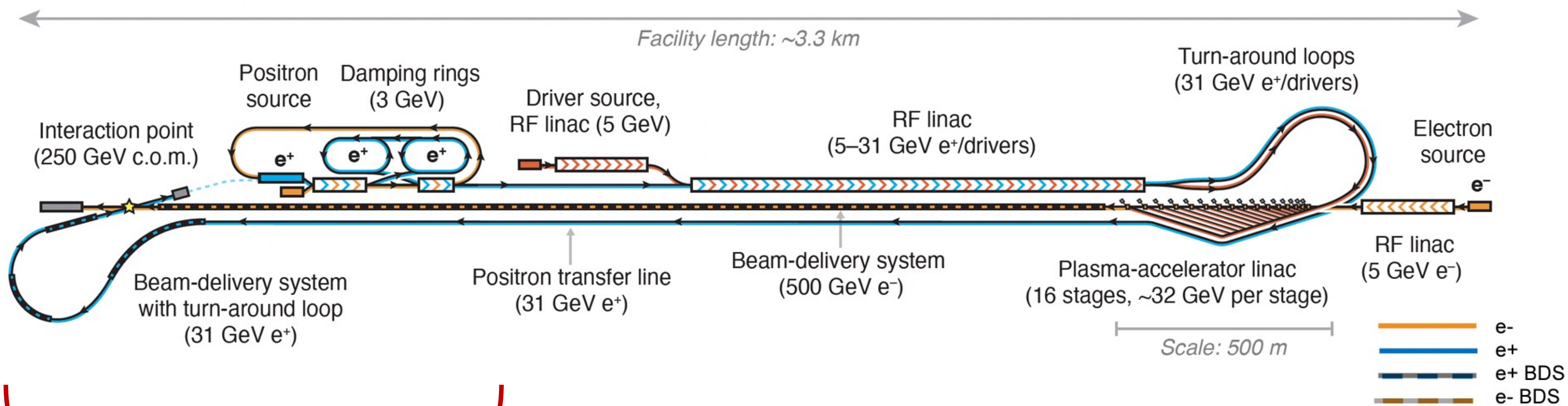
Phys. Rev. A. Beams 23, 121301 (2020)

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.
- **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: $\sigma_z \sim$ 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)*

Disclaimer

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

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

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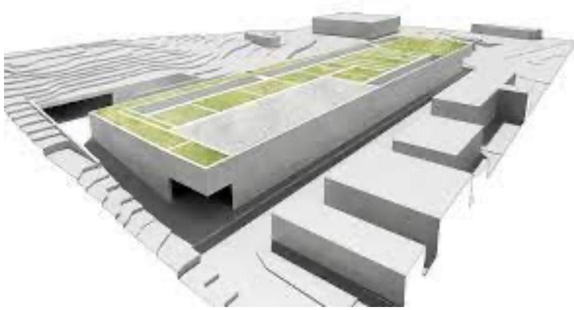
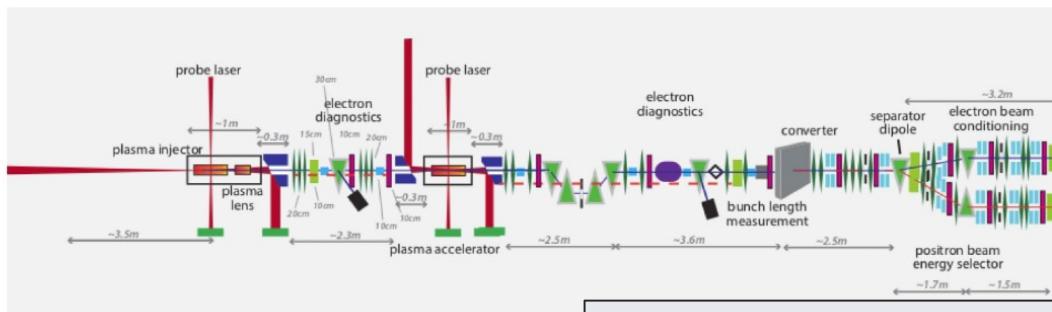
EuPRAXIA *the first ESFRI plasma accelerator project*





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

EPAC *Extreme Photonics Application Centre (UK)*

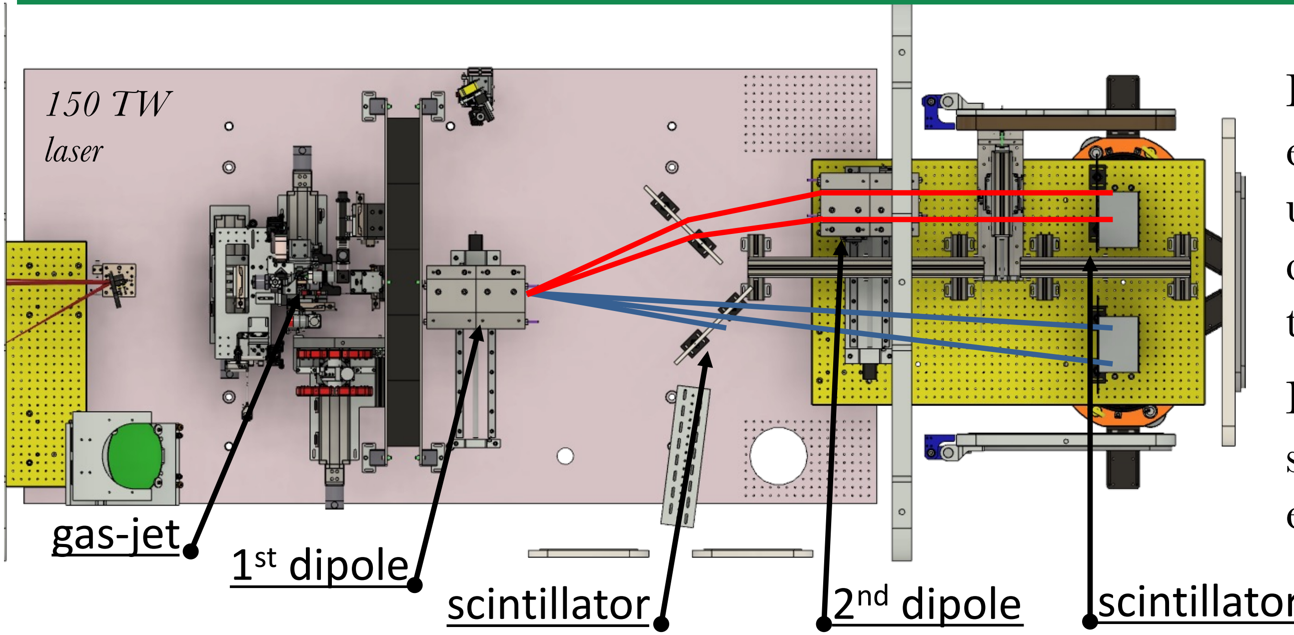
https://www.clf.stfc.ac.uk/Pages/EPAC.aspx

EPSRC

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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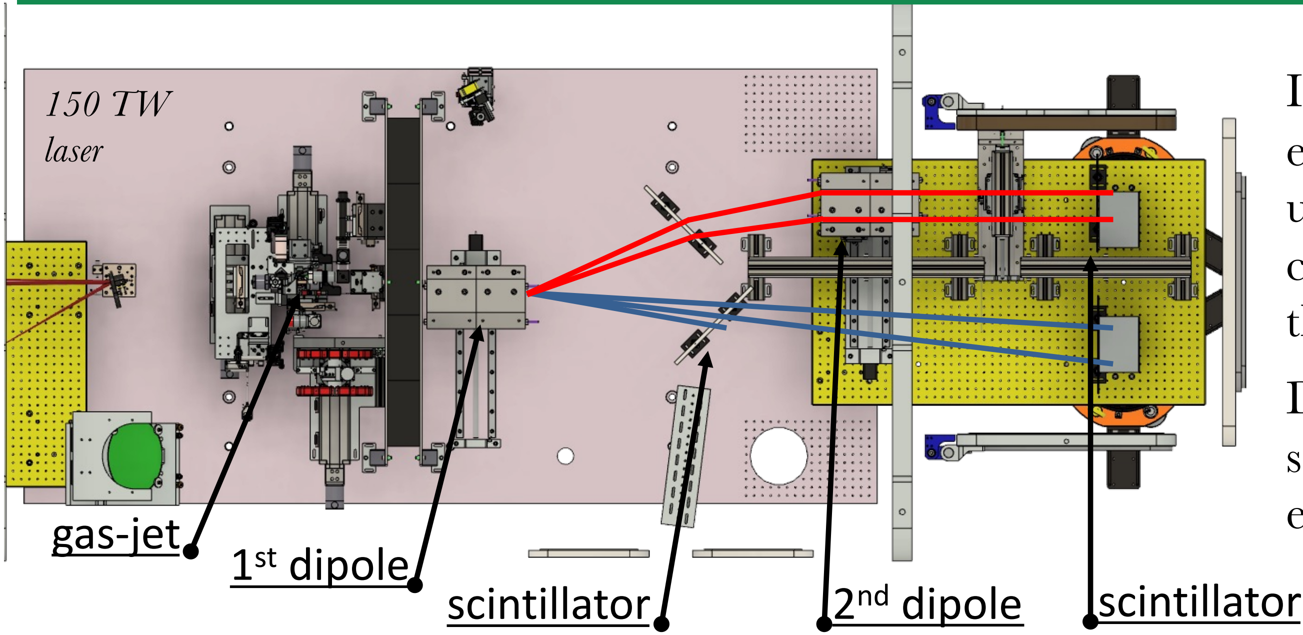

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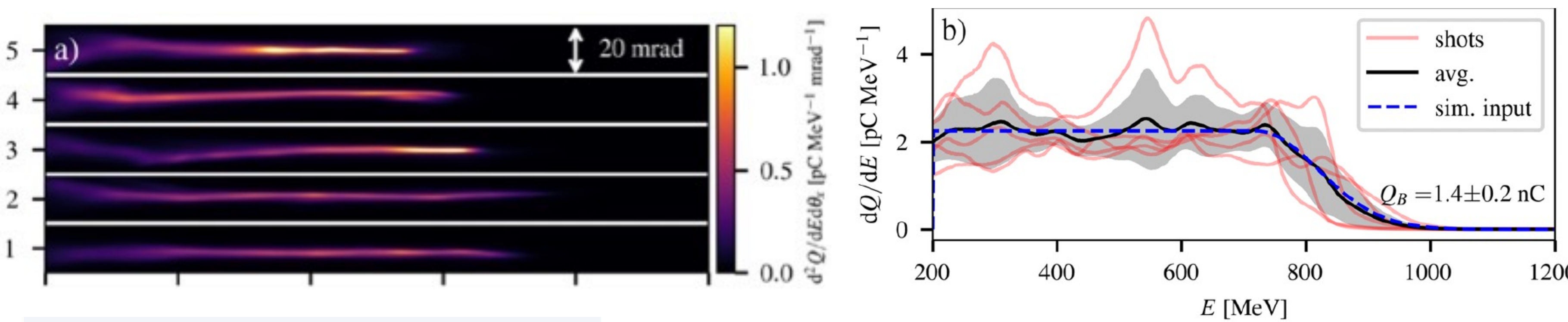

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Experimental results

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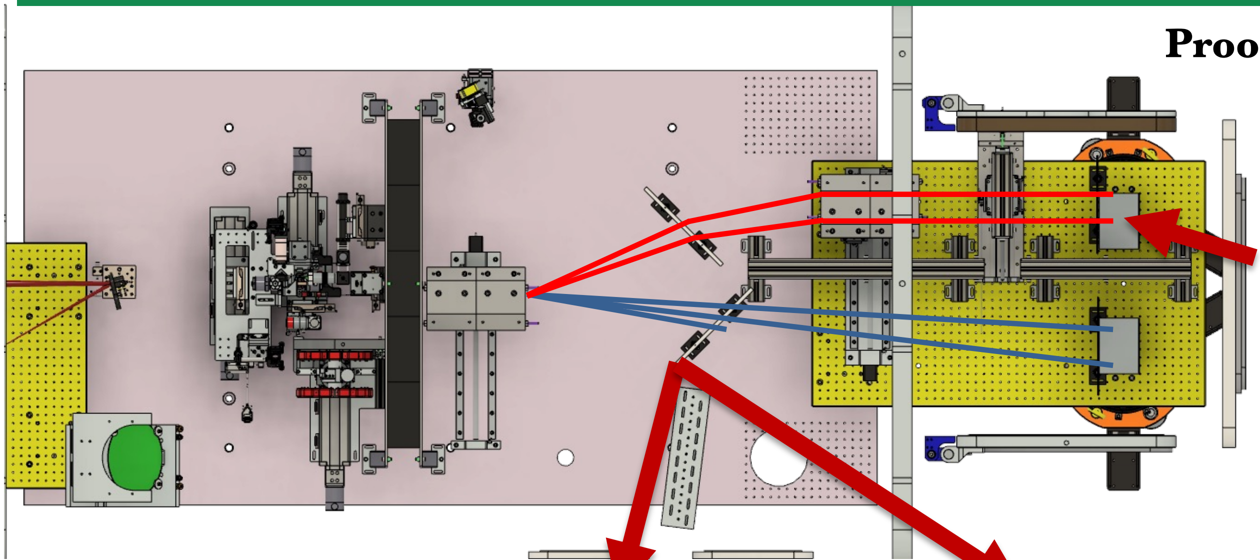
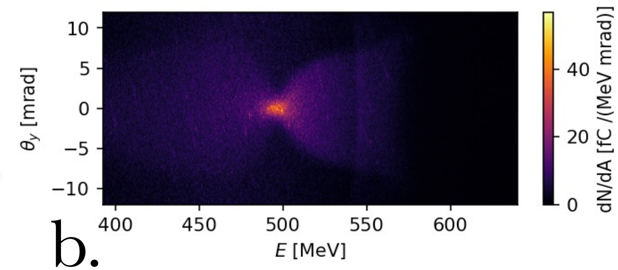
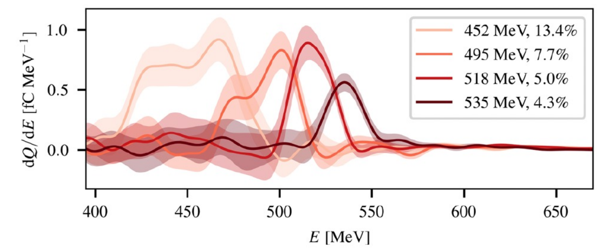


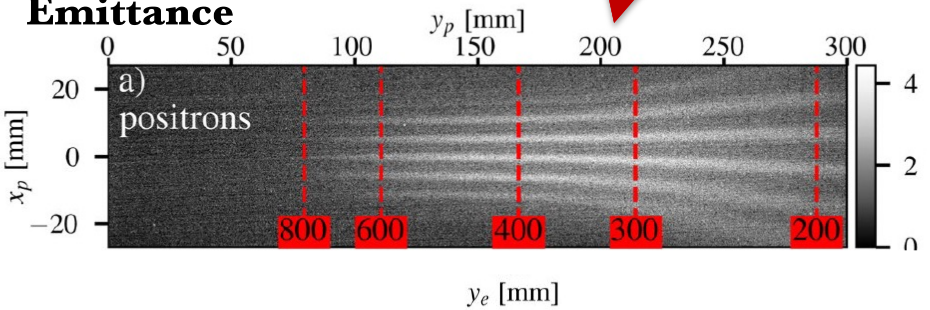
Proof-of-principle Energy selection

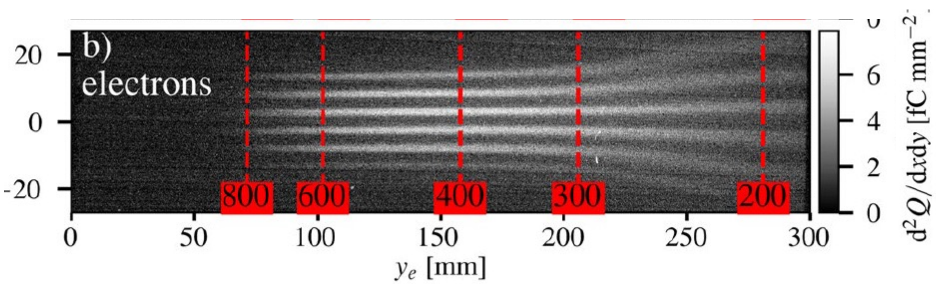


b.



Emittance





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

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

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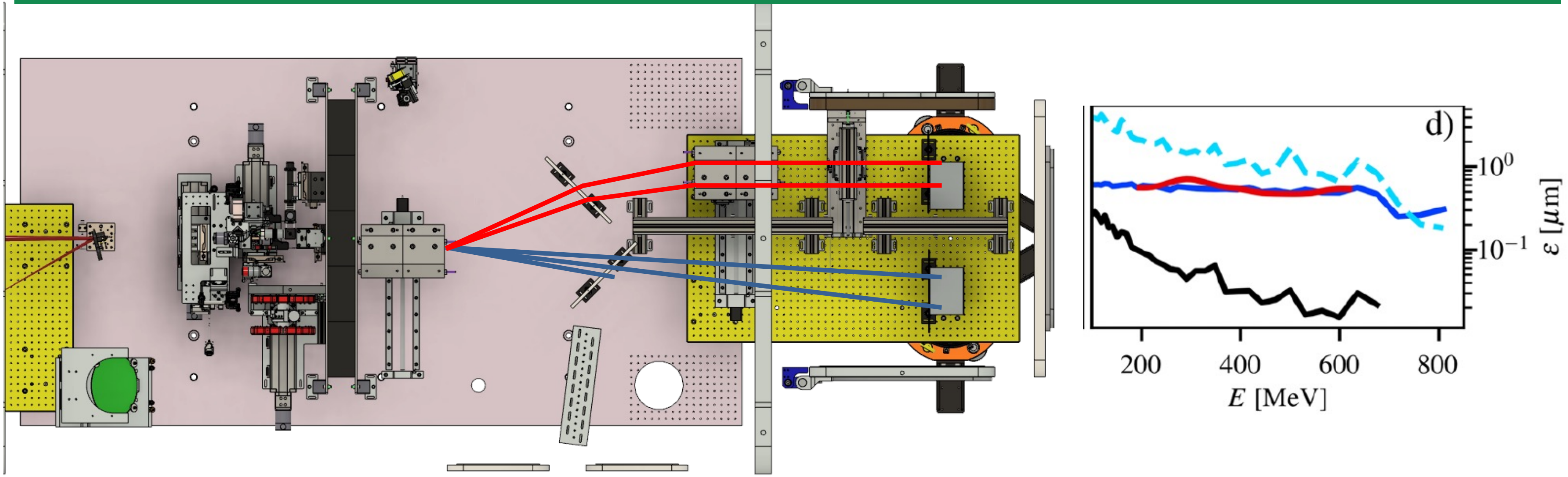


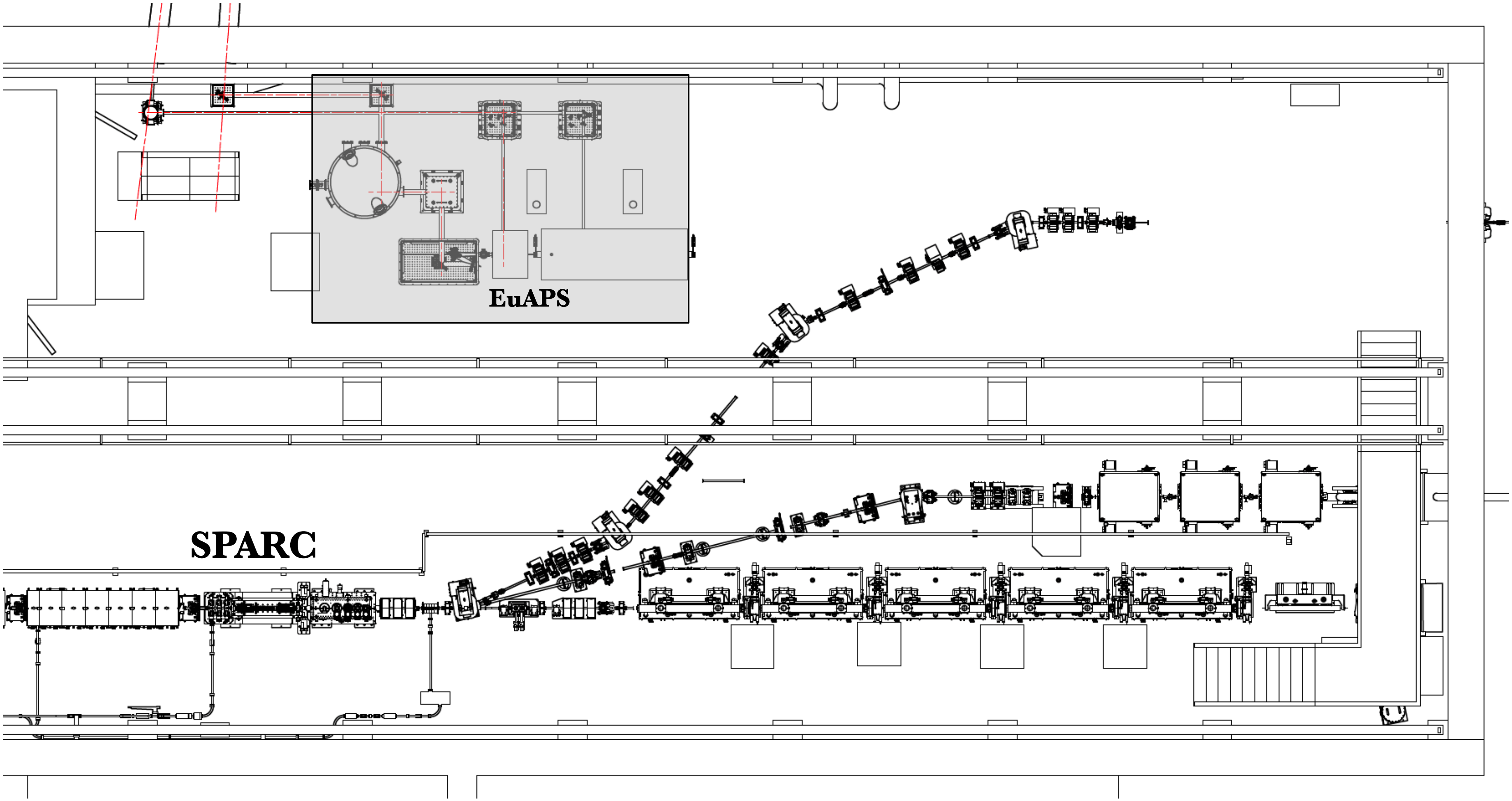
	CLF (2024)	Muggli et al.[22]	Corde et al.[23]	Gessner et al.[24]
E (GeV)	0.6	28.5	20.3	20.3
σ_x (μm)	2.7	25	$<$ 100	50
σ_z (μm)	$\lesssim$ 4*	730	30–50	35
ε (nm)	15	14 $\times$ 3	5 $\times$ 1	7
$\bar{\varepsilon}$ (μm)	18	390 $\times$ 80	200 $\times$ 50	300

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

** Not measured, inferred from simulations*

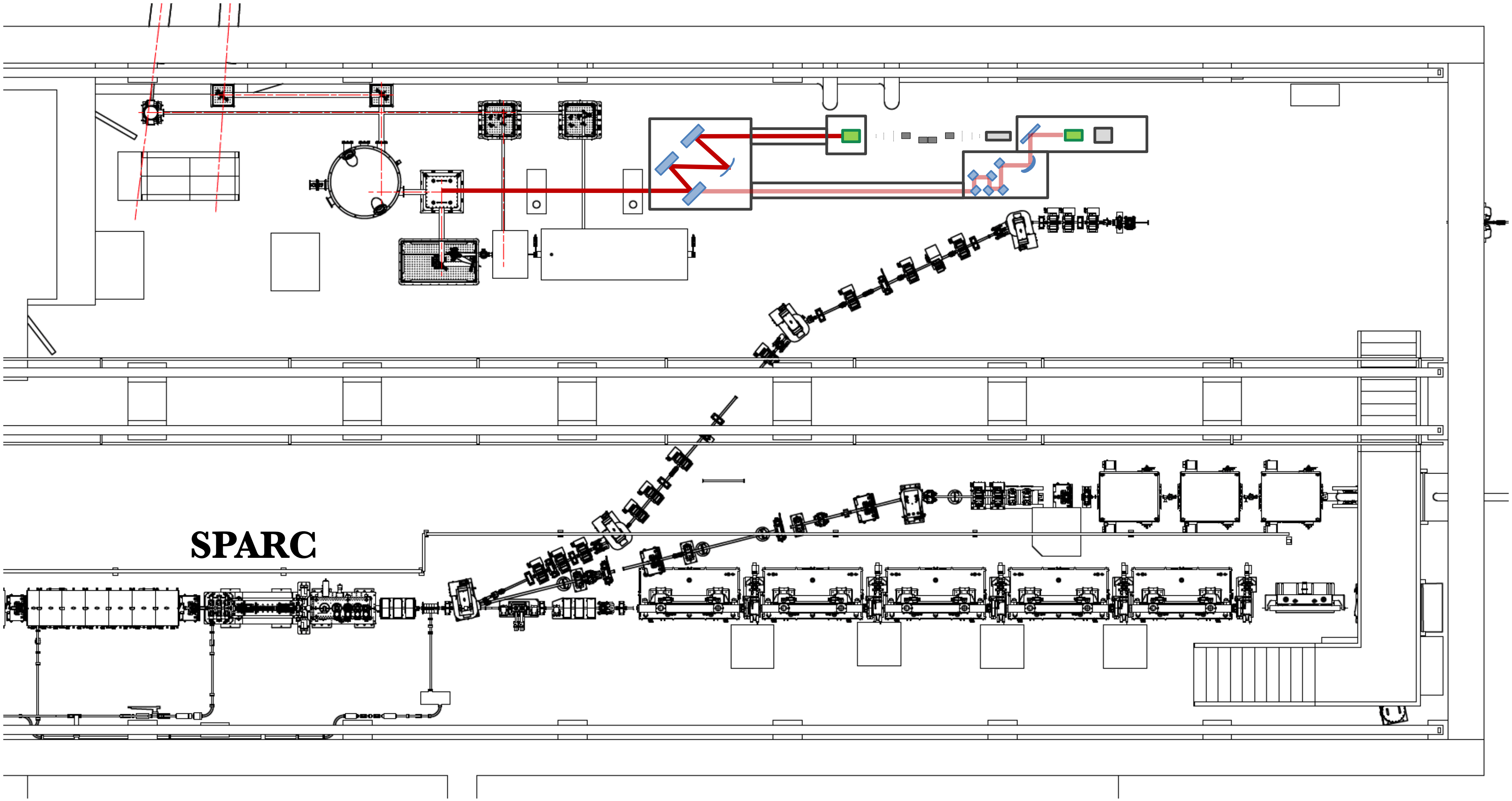
Positron sources @ EuPRAXIA

Proof-of-principle at 200 TW



EPSRC

The area and capability



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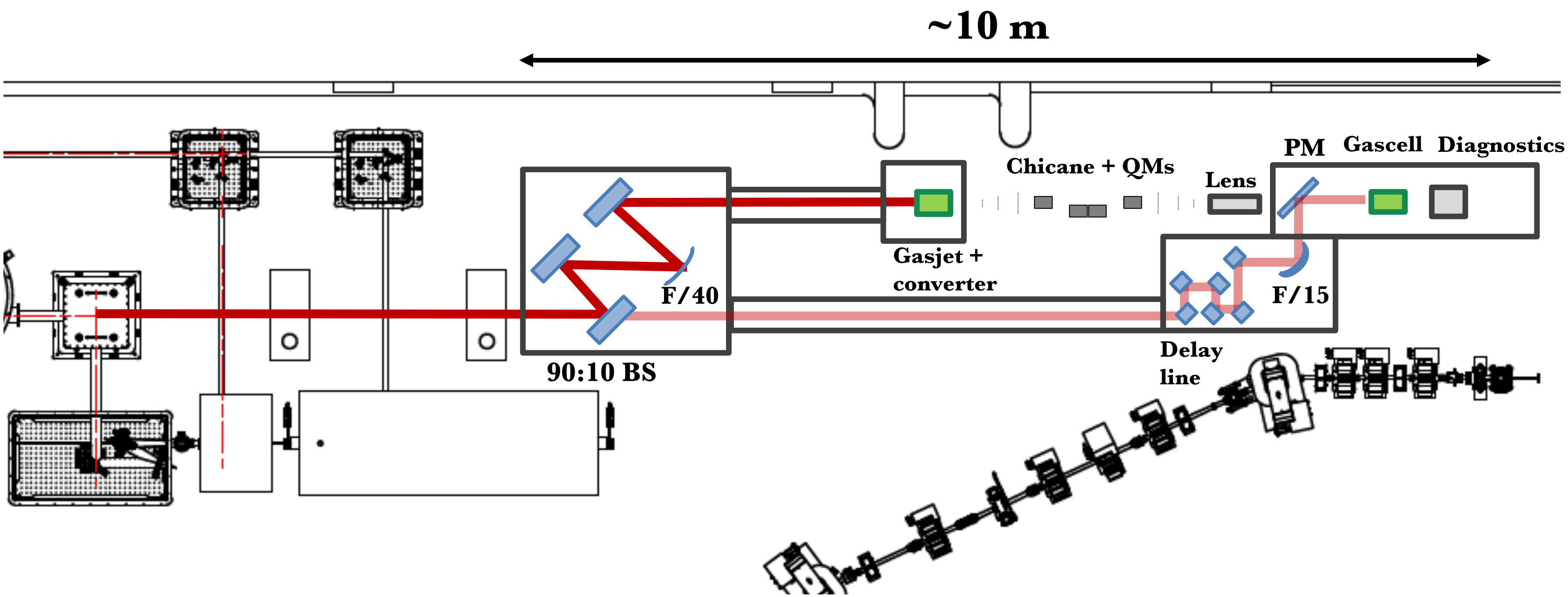


STEP 1: Generation of broadband GeV electron beams with nC total charge

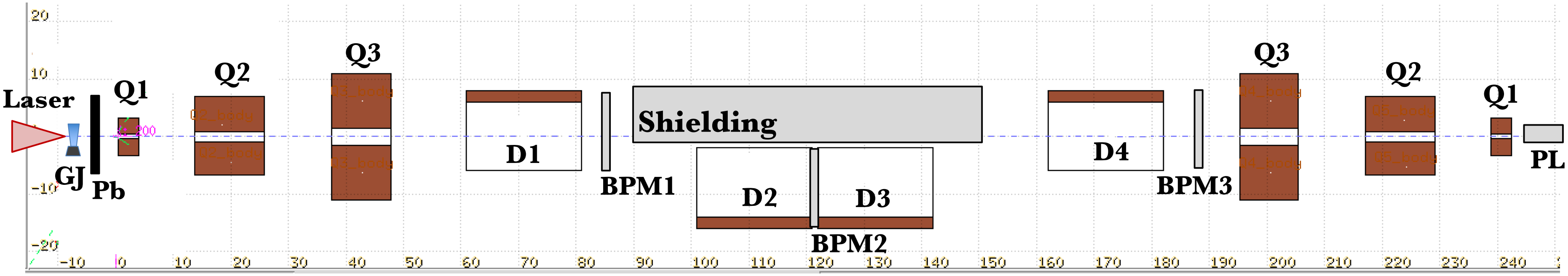
STEP 2: Generation and characterization of the positron beam

STEP 3: Transport and energy selection: demonstration of 500 MeV ±10% 3 pC charge e+

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

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

Start-to-end-simulations



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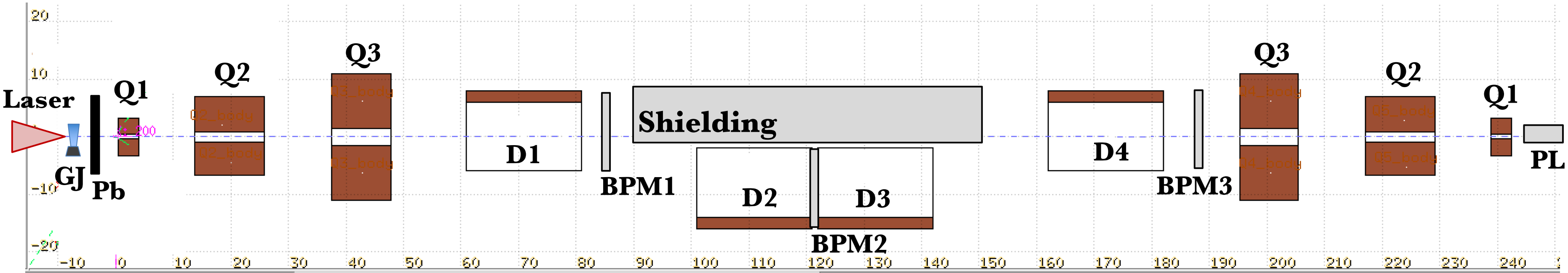

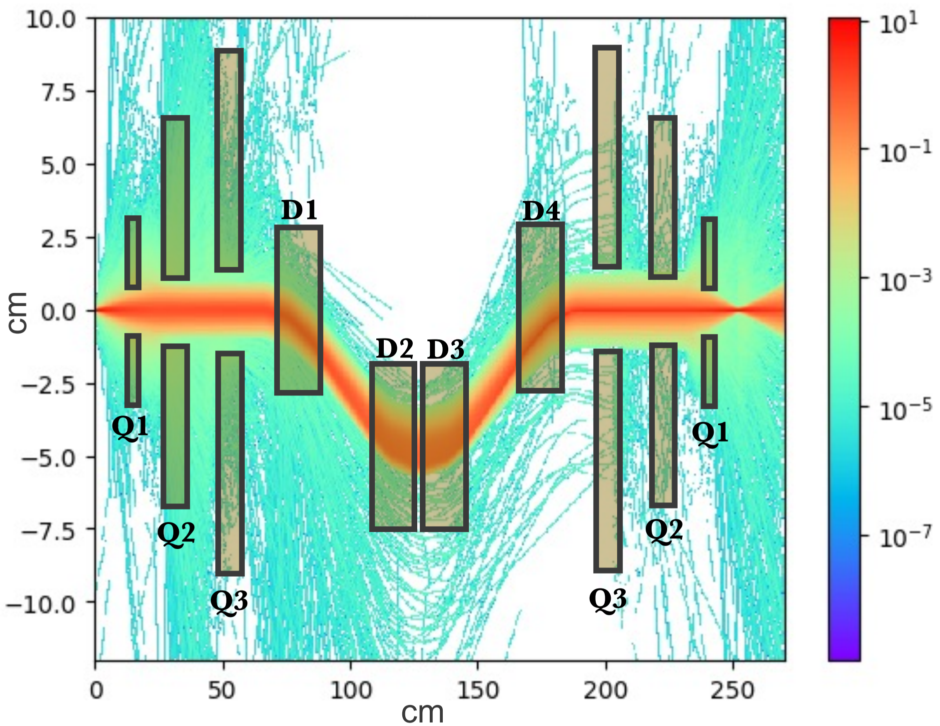

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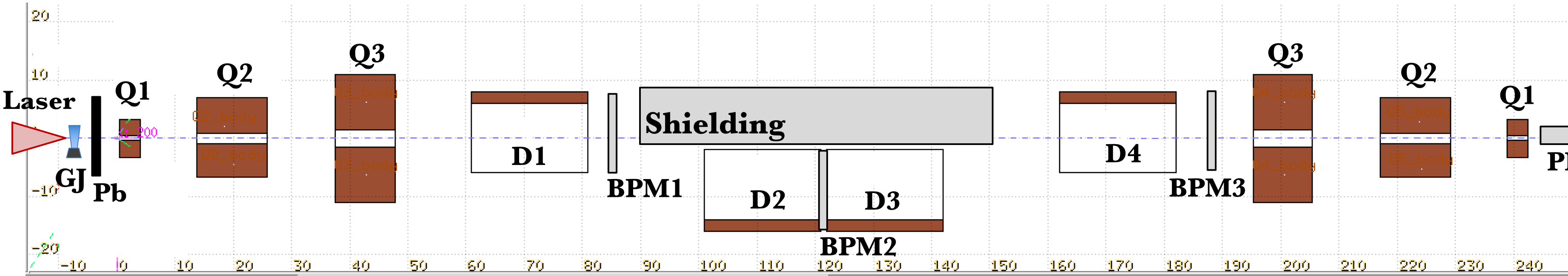

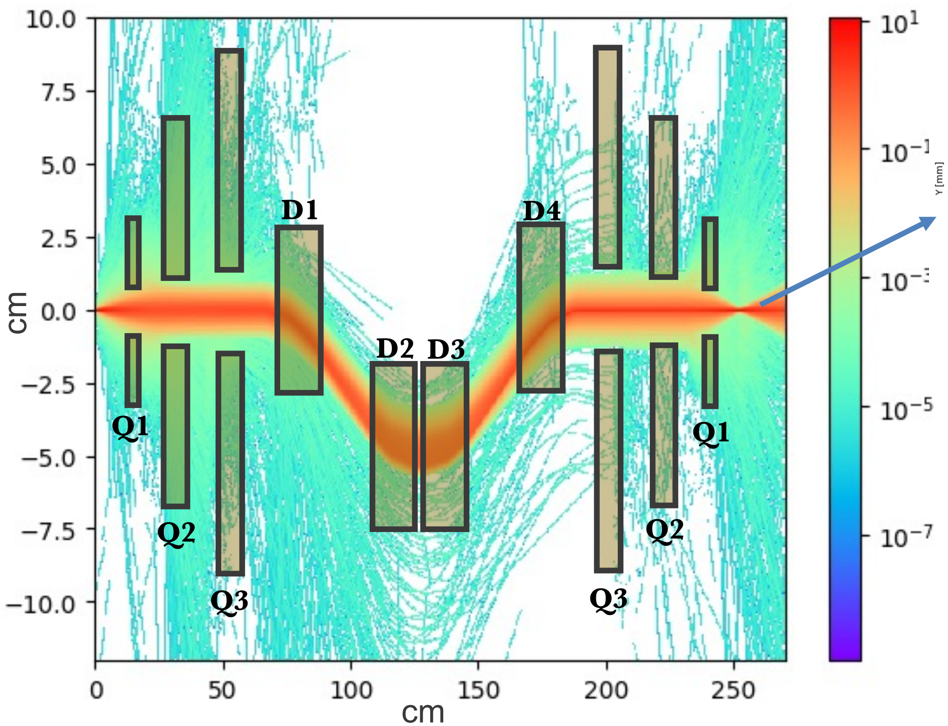

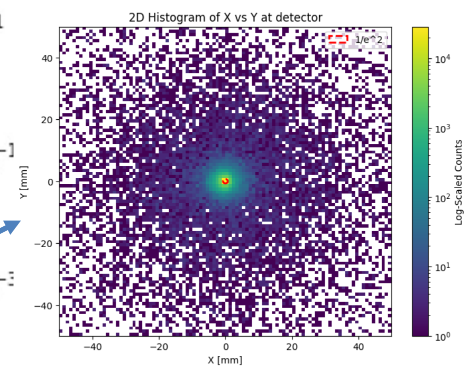

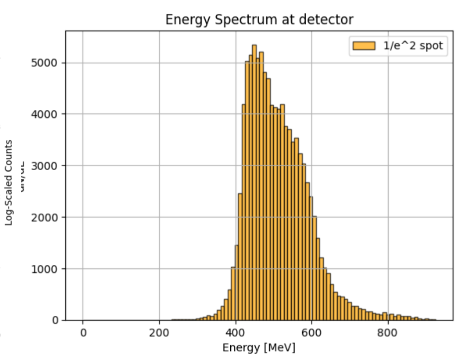

Positron energy:	460 ± 8% MeV
Positron charge:	2.1 pC
σ_z:	50 μm
σ_x, σ_y:	20 μm

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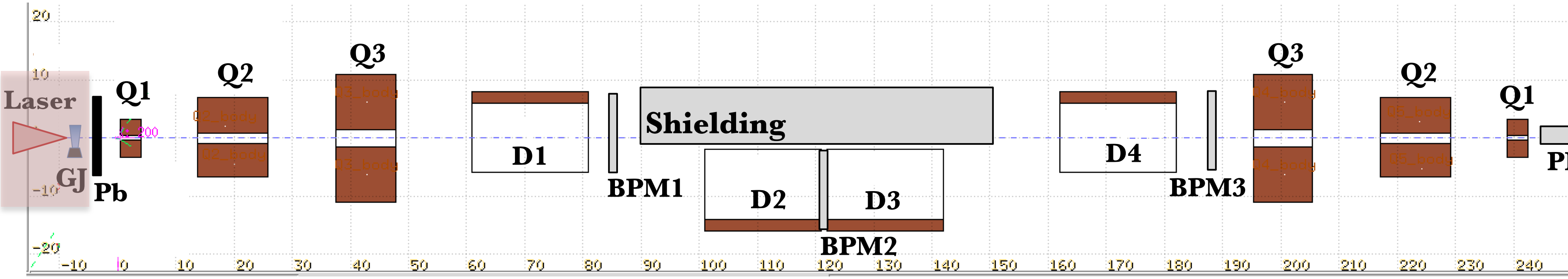

STEP 1: FBIC simulation with Bayesian optimization for charge above 500 MeV

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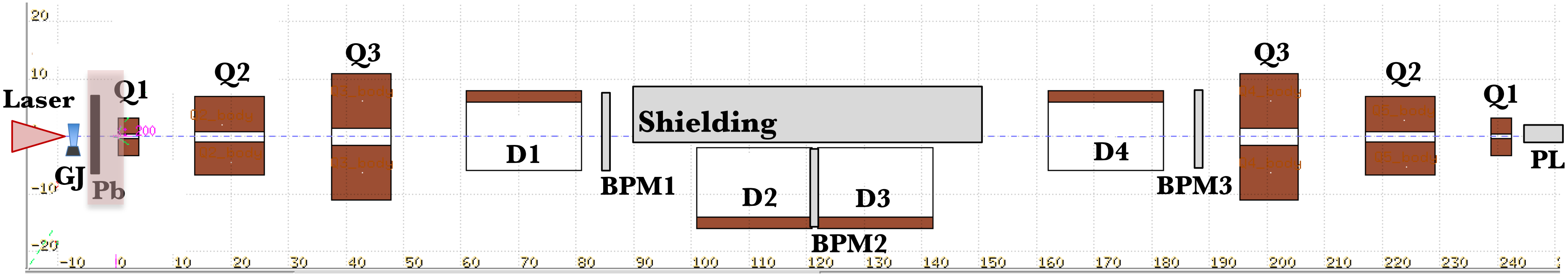

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STEP 2: FLUKA simulations of the positron beam characteristics at source (Pb converter)

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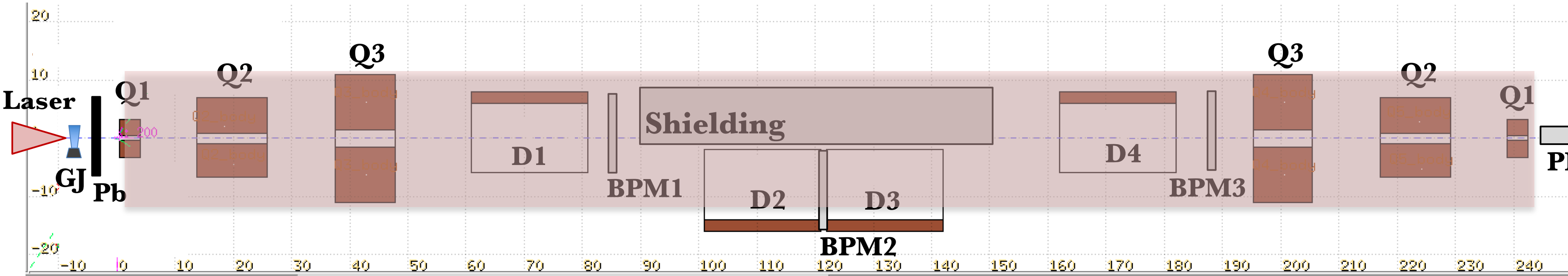

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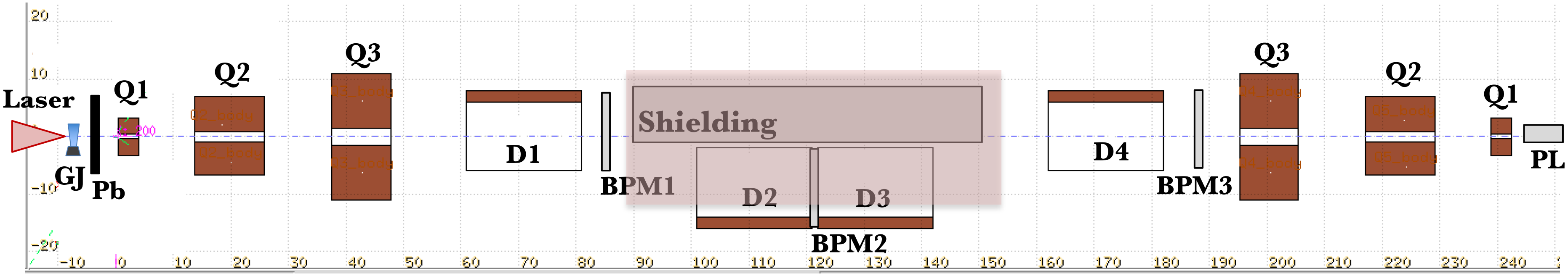

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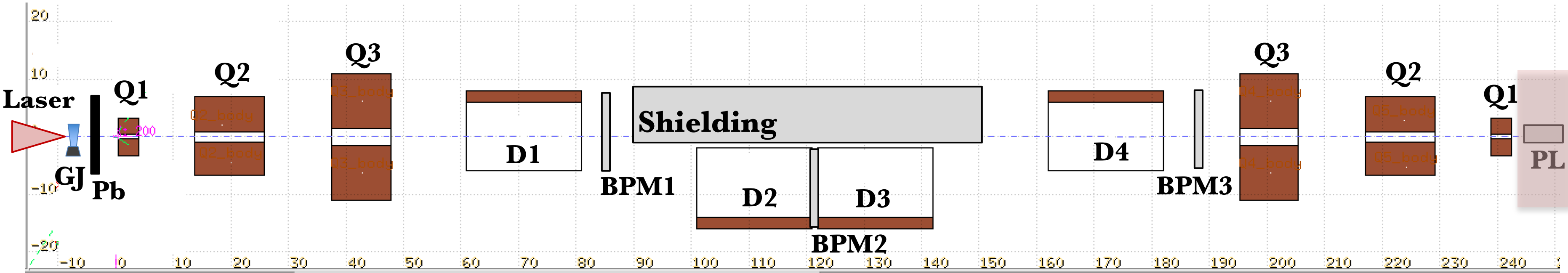

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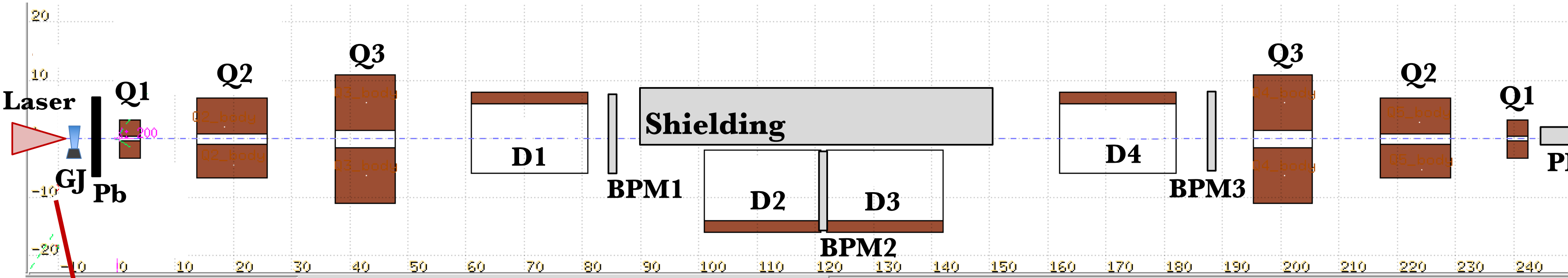
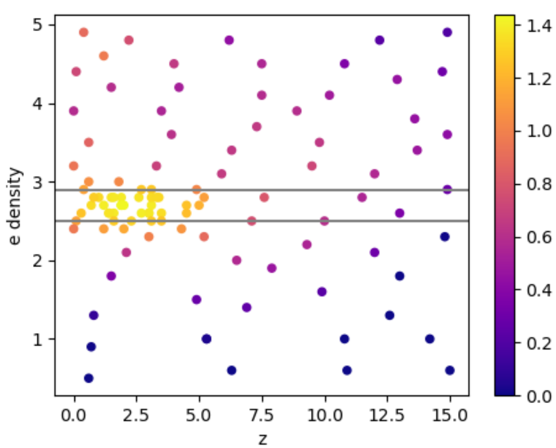
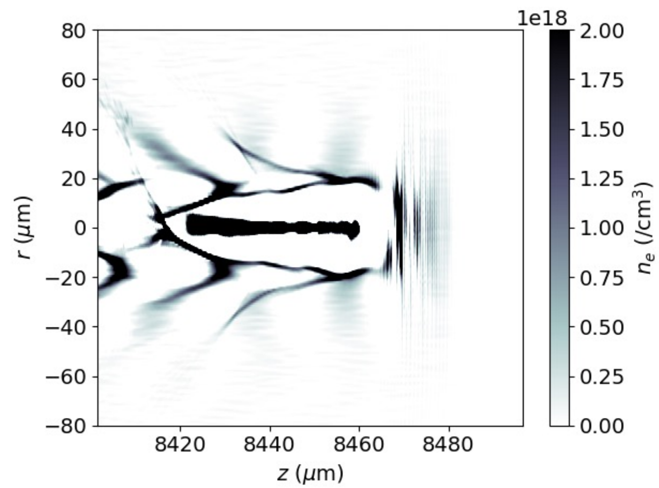
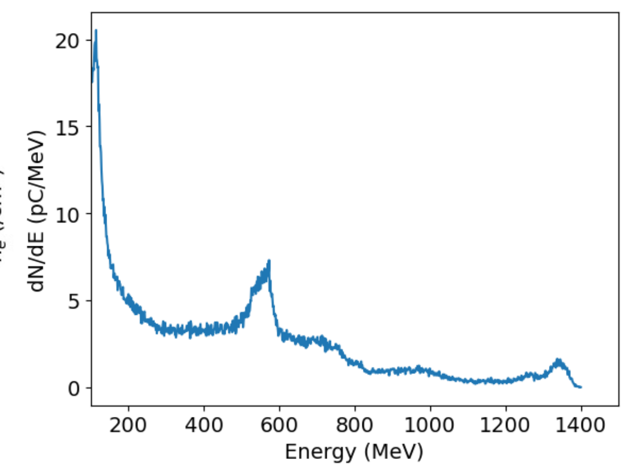
STEP 5: Plasma lens simulation

FB-PIC simulations



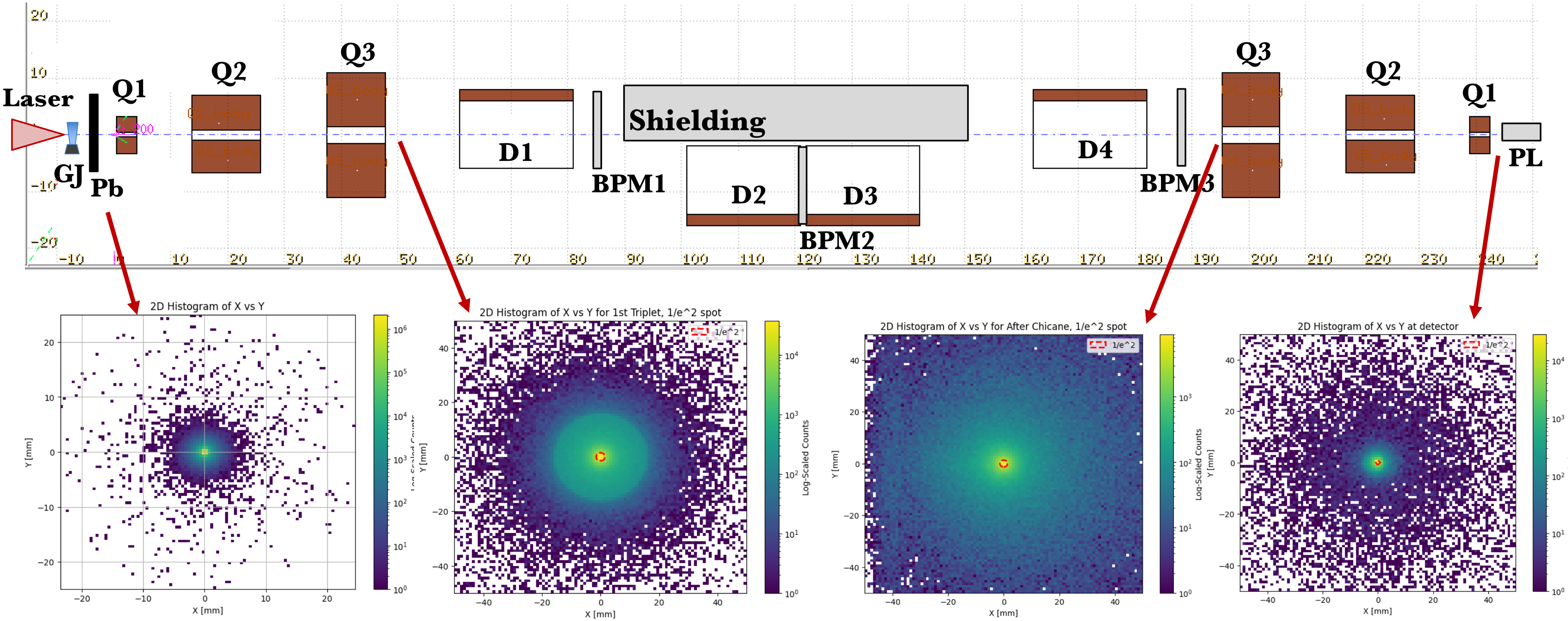


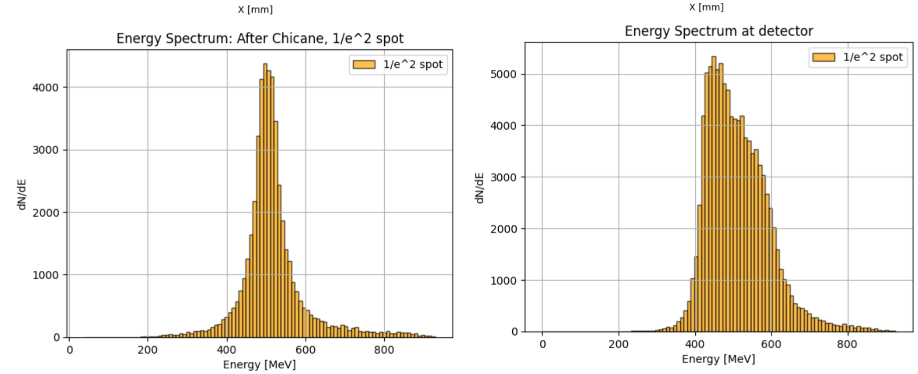




Electron beam duration:	150 fs
Charge > 500 MeV:	1.4 nC
Max. Energy:	1.4 GeV

FLUKA simulations





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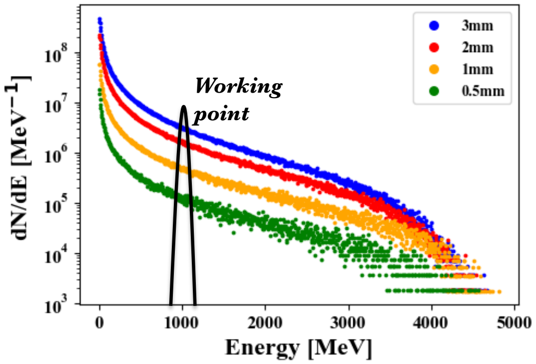
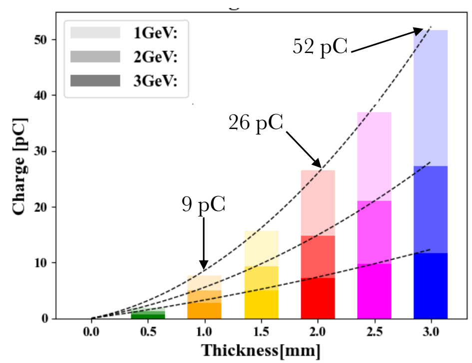
Next steps and potential upgrades

Next steps

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





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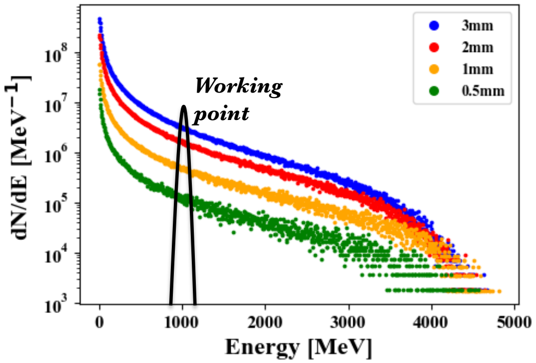

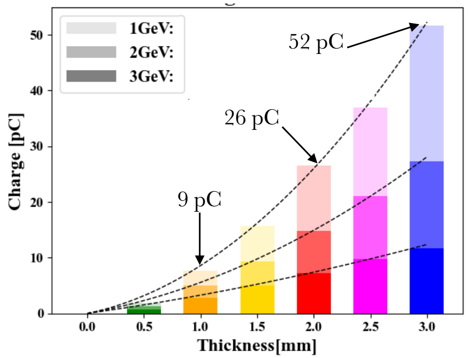

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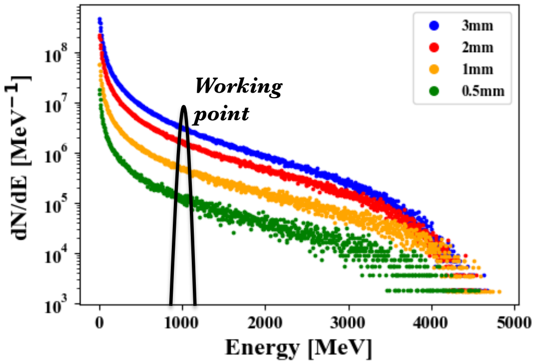

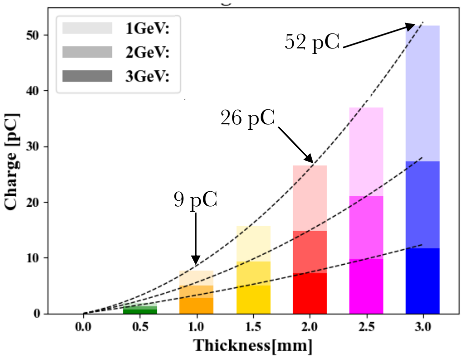

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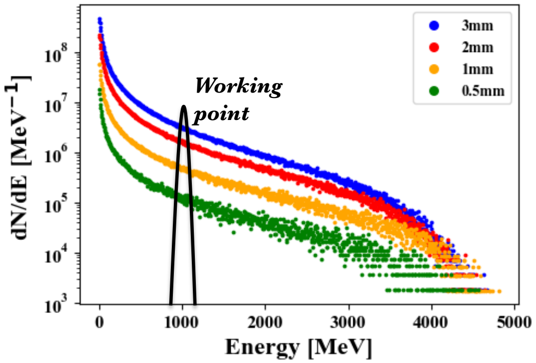
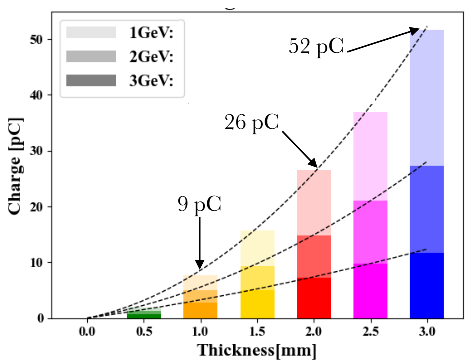
3. At the moment, line designed for laser-driven wakefield studies. The line is tantalizingly close to the Exin line of SPARC. Coupling it for **beam-driven studies** is complex, but not impossible

Next steps

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





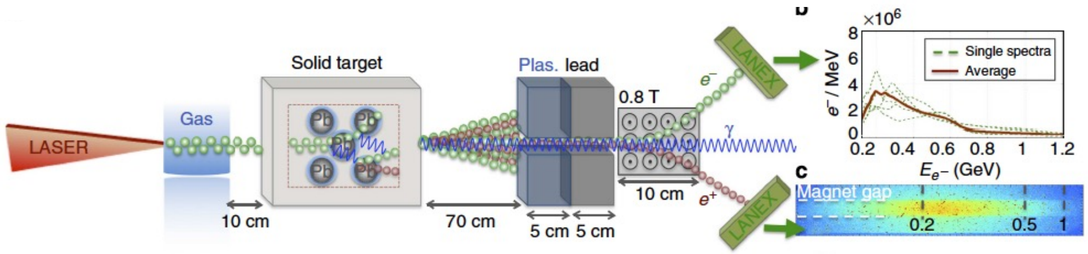
2. **Energy selection** (currently line designed for 500 MeV) possible with electromagnets

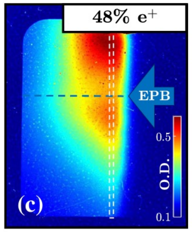
3. At the moment, line designed for laser-driven wakefield studies. The line is tantalizingly close to the Exin line of SPARC. Coupling it for **beam-driven studies** is complex, but not impossible

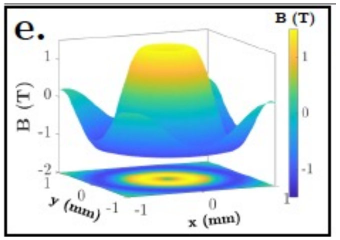
4. **Further optimization** of the positron beam characteristics (mainly higher charge and smaller size) using more complex beamlines currently under investigation

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)

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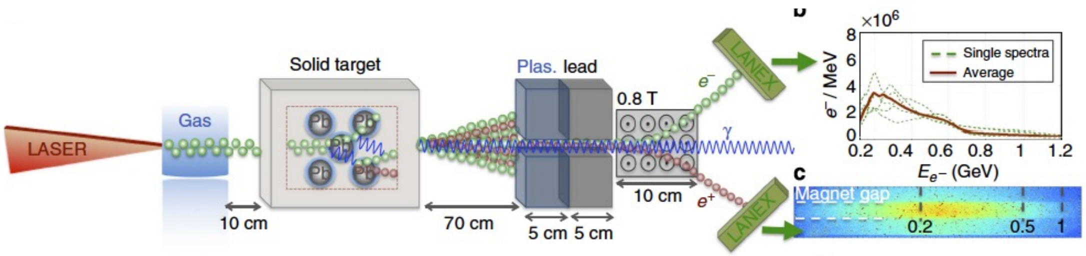

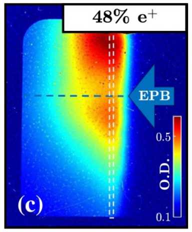

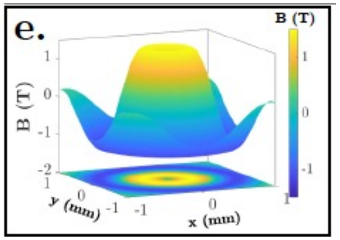

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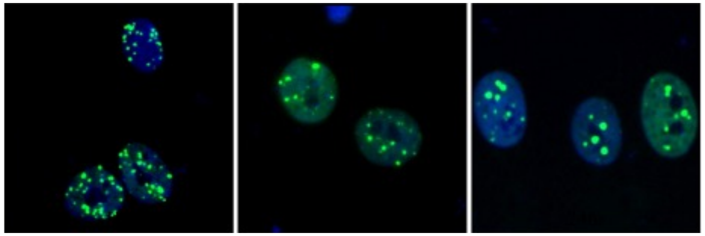
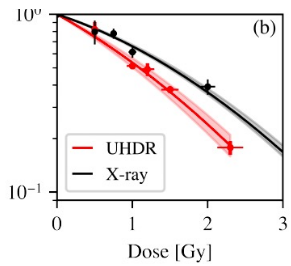
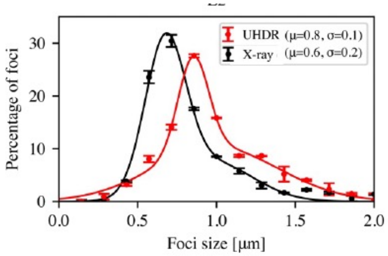
2. Radiobiology **at ultra-high dose-rates** at and beyond FLASH







C. McAnespie et al., IRJOBP (2024)

C. McAnespie et al., PRE (2024)

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

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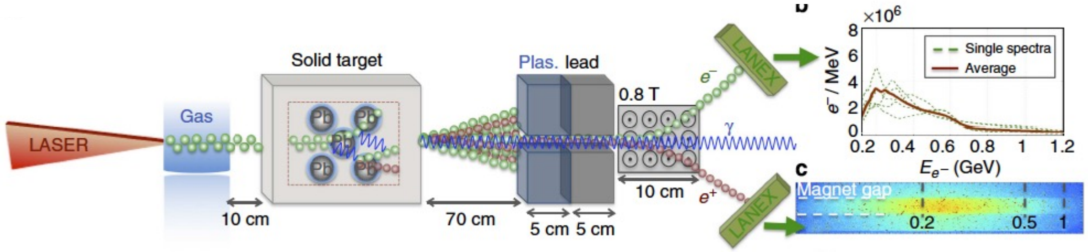

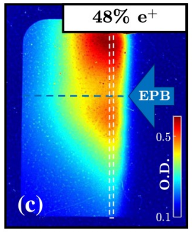

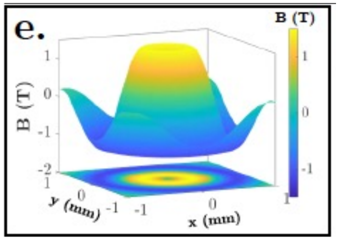

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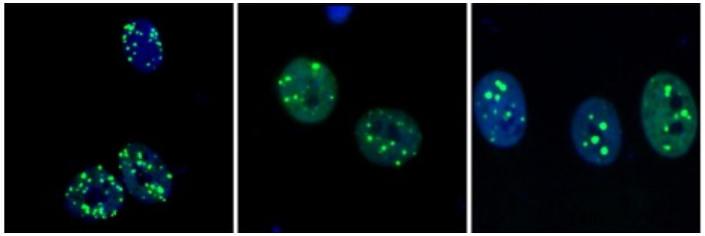
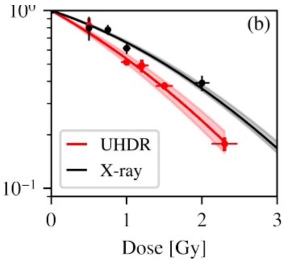
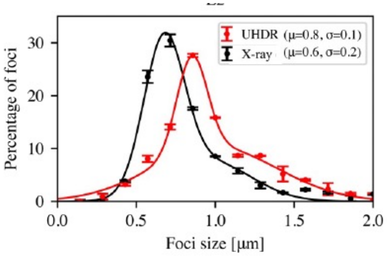






C. McAnespie et al., IRJOBP (2024) | C. McAnespie et al., PRE (2024) | C. McAnespie et al., arXiv:2309.06870v2(2024)

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

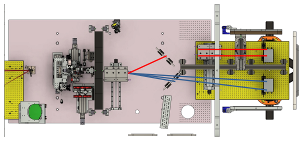
Conclusions

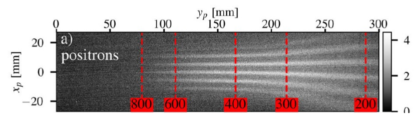
Conclusions

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

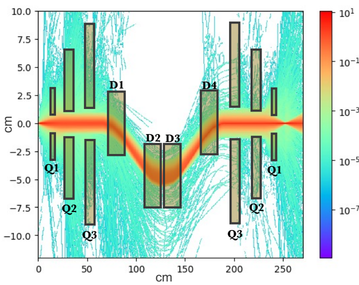
⇒ 100TW-scale lasers can provide narrowband (~5%) positron beams of **sufficient quality to be guided and accelerated in a plasma wakefield**

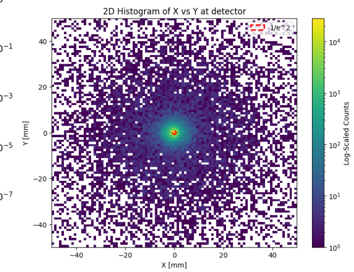
⇒ **First proof-of-principle experiments at 100 TW** validate the numerical expectations

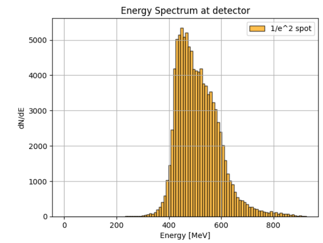




⇒ **Start-to-end simulations** confirm analytical expectations

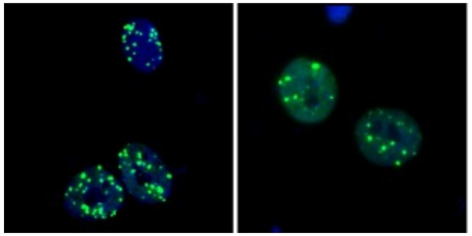


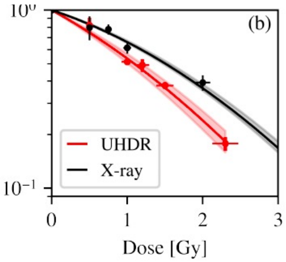




⇒ Extension to **10s of pC positron beams** possible with PW-scale lasers

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





Thanks for your attention!

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