Laser-driven positron sources for applications in fundamental science and industry

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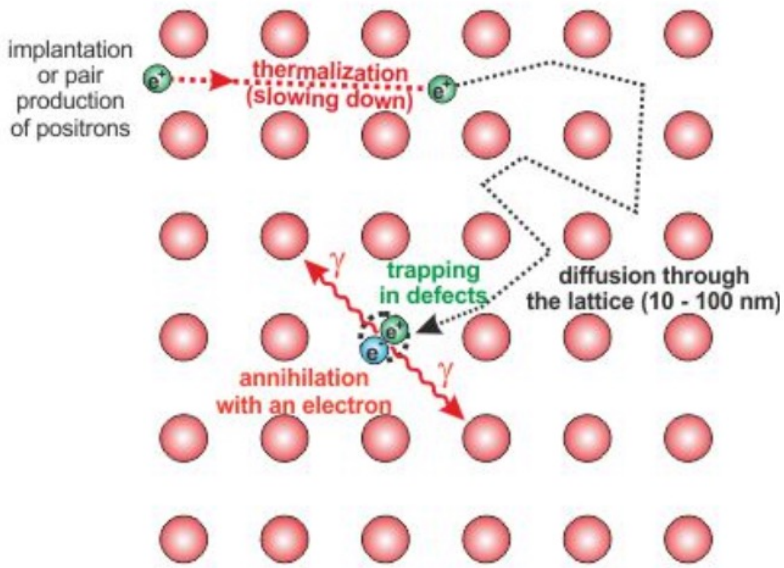
EAAC, September 2023, Isola d'Elba Italy

Low-energy positron sources

PALS

Low-energy positrons (~ keV - MeV) are used in a range of material characterisation techniques such as **Positron Annihilation Lifetime Spectroscopy (PALS).**



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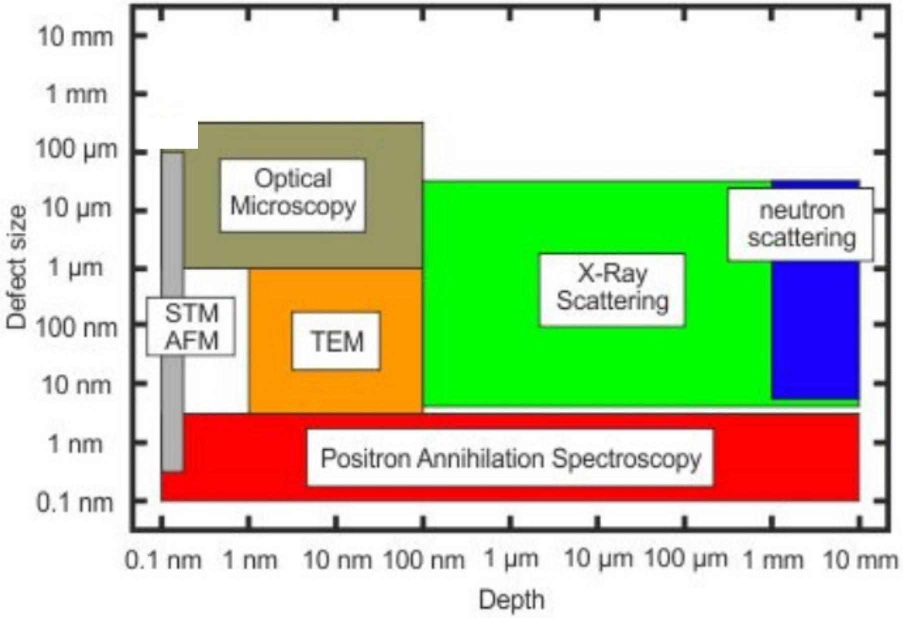


Conventional systems have two main limitations:

- X The positron energy is low (~ keV) and therefore only surface studies are possible
- X The positron duration is relatively long (>200 ps), limiting the resolution of the system

G. Sarri et al. PPCF 64,044001 (2022)

T. Audet et al., PRAB, 24,073402 (2021)

PALS

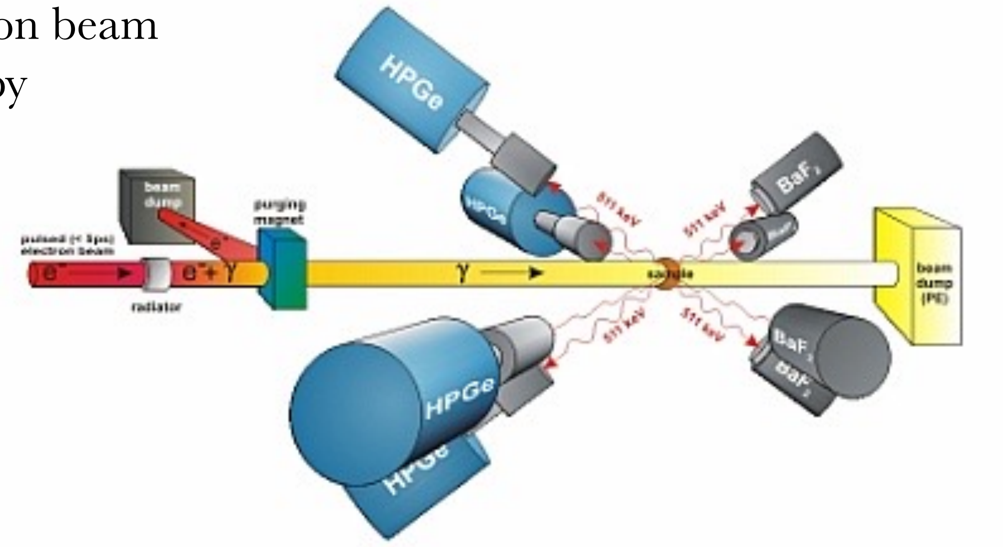
Conventional PALS machines use different positron sources, for example:

1. Na-22 radioactive source
2. Pair production from a LINAC electron beam
3. Gamma-induced positron spectroscopy

The localization of the positron at the defect site induces a longer lifetime:

$$\kappa_d = \mu_d[d] = I_2\left(\frac{1}{\tau_1} - \frac{1}{\tau_2}\right)$$

- κ_d: *rate of positron trapping*
- $[d]$: *defect concentration*
- τ_1: $\tau_1 < \tau_B$
- τ_2: *defect lifetime*



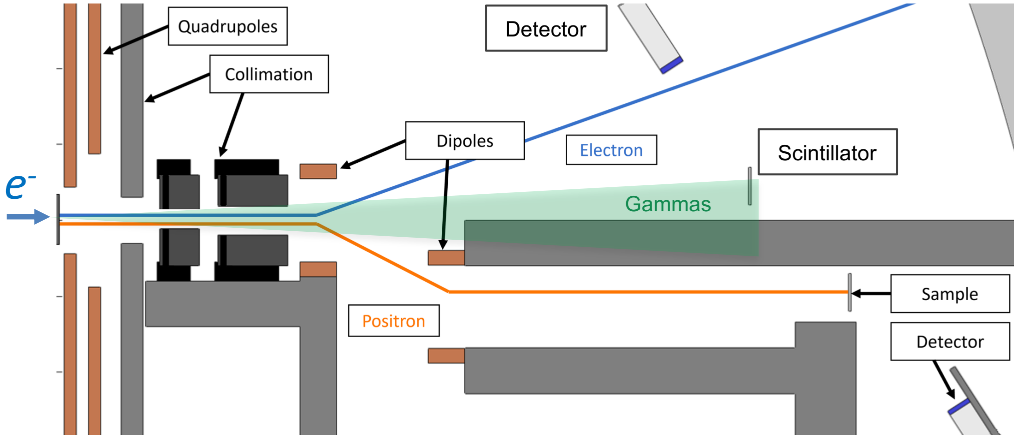
	ELBE	NEPOMUC	PLEPS	Fuji	NANOPOS	PULSTAR
flux (e+/s)	10^6	10^9	10^4	$5\text{x}10^2$	10^5	10^6 - 10^9
duration (ps)	250	/	260	300	/	300
energy (keV)	0.5 - 15	1	0.5 - 20	0.5 - 15	0.25 - 25	0.5 - 10

✗ relatively long duration (*comparable to the timescales to be studied*)

✗ low energy implies a short penetration depth (*surface studies only*)

Laser-driven positron generation

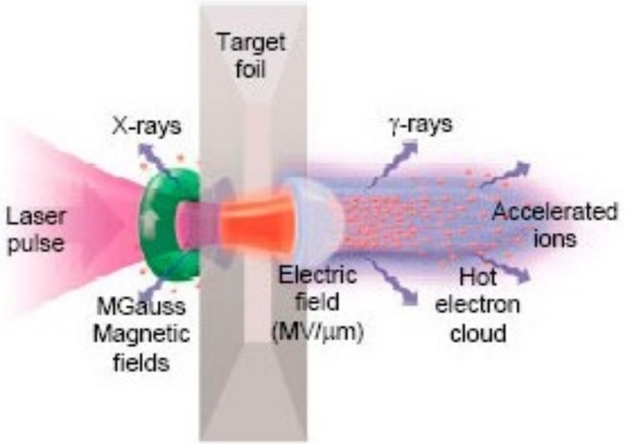
PALS configuration for a laser-driven positron source

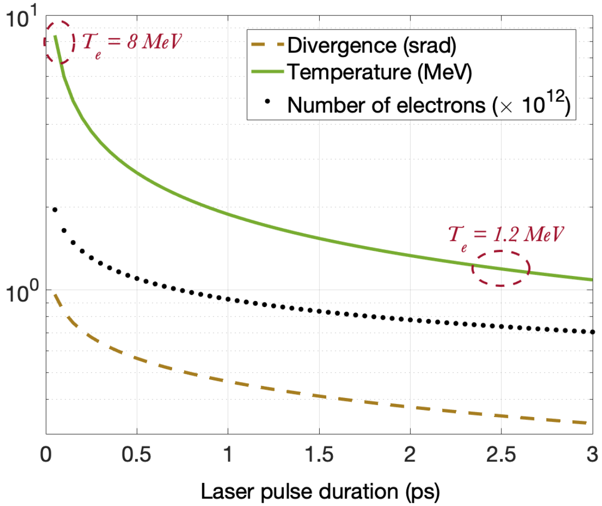


Main components

- ~ MeV-scale electron beams as a primary particle beam
- mm-scale high-Z converter
- 2 Hallbach magnets
- Collimation system
- Dog-leg configuration of two dipole magnets with slit for energy selection
- ~70ps scintillators and photomultipliers

Hot-electrons from direct laser-solid interactions





TYPICAL PARAMETERS

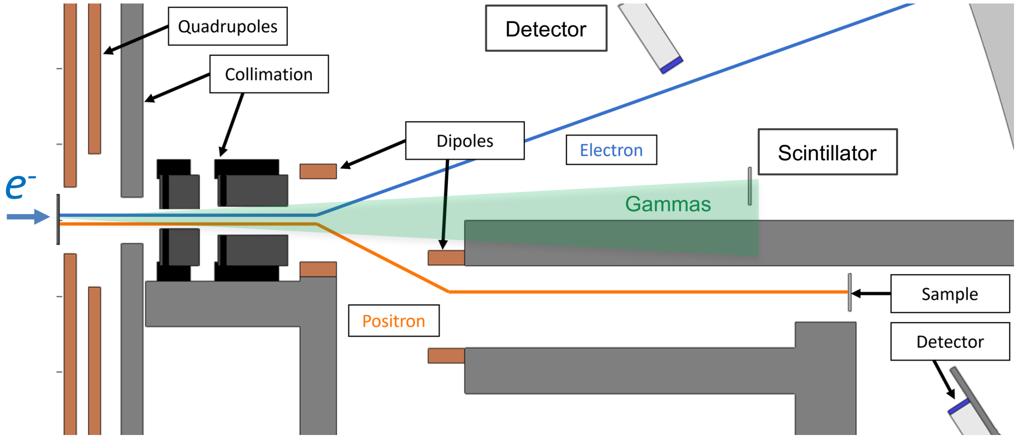
- μC electron beams
- ~ sr cone angle.
- ~MeV temperature.
- Electron beam duration ~ ps
- Electron to positron conversion ~ 10^{-3}

✗ **slow rep rate (~shot/min)**

G. Sarri et al. PPCF 64,044001 (2022)

Laser-driven positron generation

PALS configuration for a laser-driven positron source



Main components

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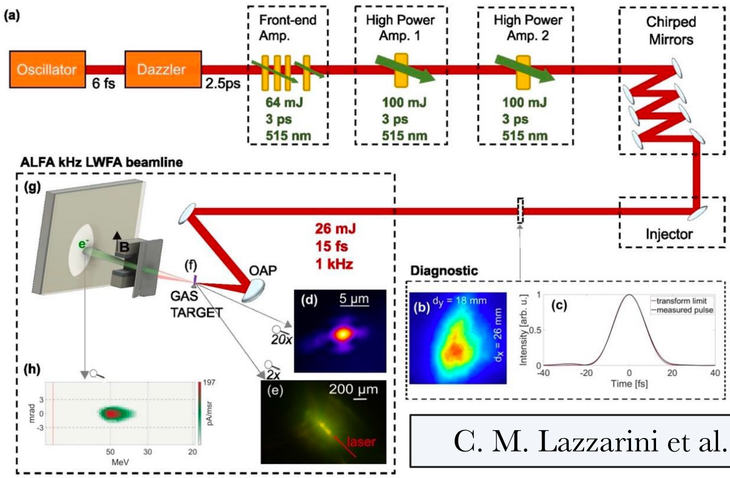
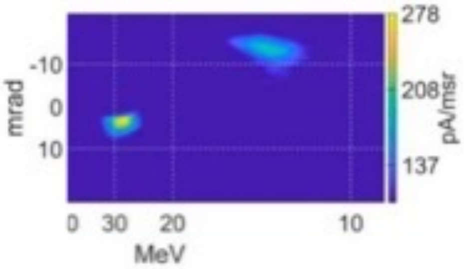
Laser-wakefield accelerated electron beams



C. M. Lazzarini et al., ArXiv (2022)



TYPICAL PARAMETERS

- pC electron beams
- mrad cone angle.
- 10-20 MeV temperature.
- Electron beam duration ~ fs
- Electron to positron conversion ~ 10^{-3}

✓ **high rep rate (~kHz)**

T. Audet et al., PRAB, 24,073402 (2021)

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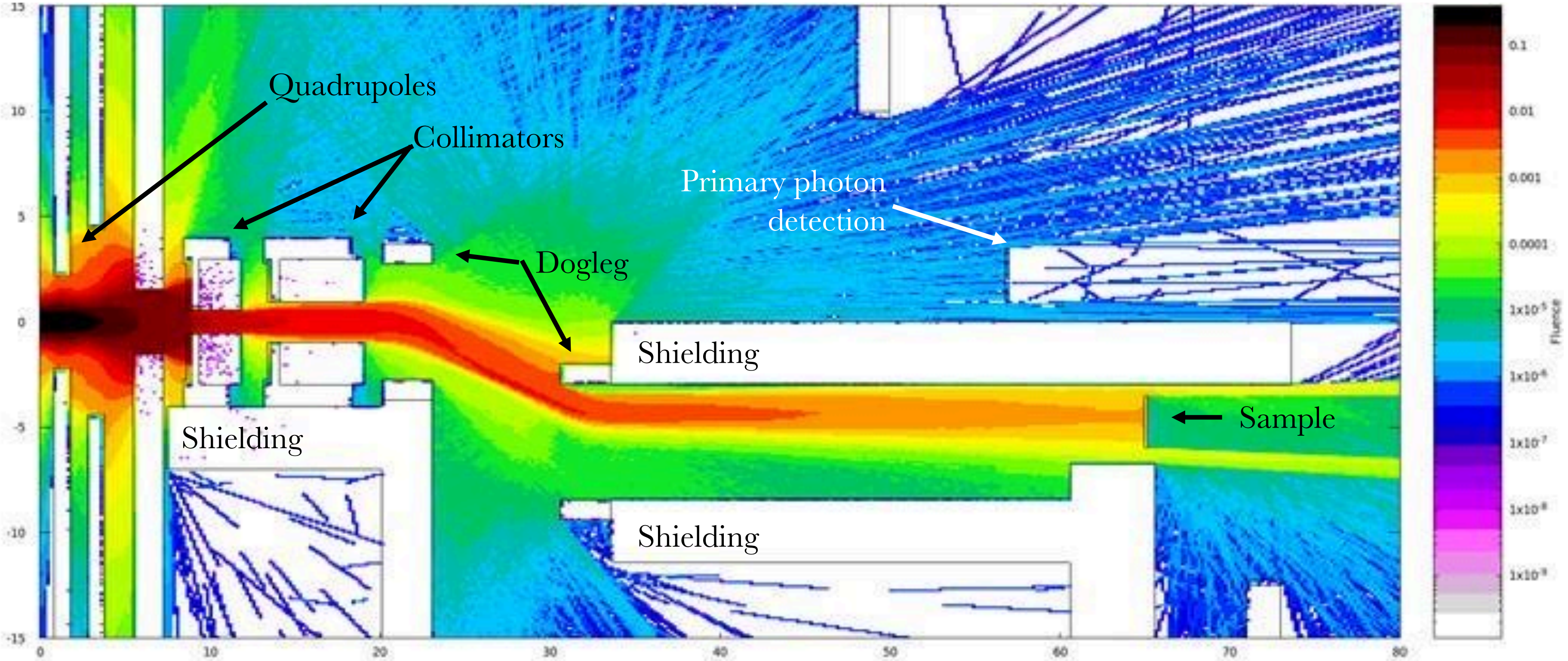
Simulation results

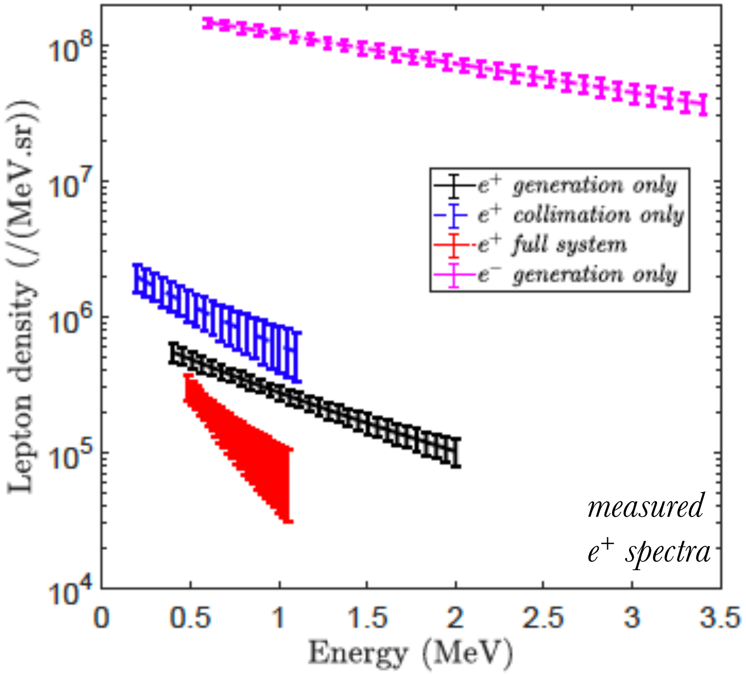


- Compact setup (~ 70 x 30 x 30 cm^3)
- Approximately 10^3 positrons per shot at sample plane
- At 100 Hz repetition rate, expected >10^6 e+/s
- Positron beam duration at sample of the order of 50 – 70 ps
- Energy tuneability between 0.3 – 5 MeV

T. Foster et al., *in preparation* (2023)

Experimental results

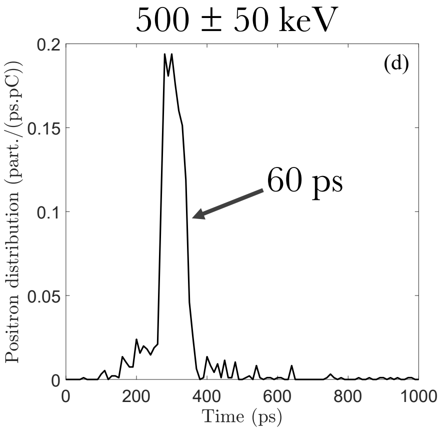
The system was first tested using the TARANIS laser directly irradiating the converter

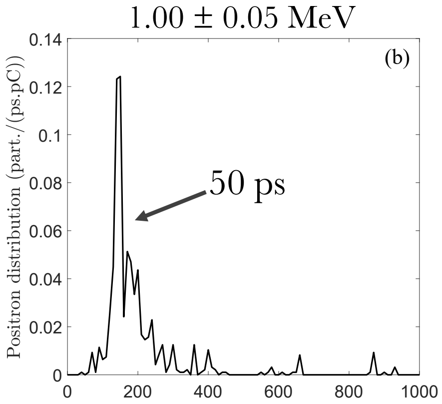


At source (generation): ~ $10^5 - 10^6$ e^+ / (MeV sr)

After quadrupoles (collimation): > 10^6 e^+ /(MeV sr)

After dogleg (full system): ~ 10^5 e^+ / (MeV sr)





	ELBE	NEPOMUC	PLEPS	Fuji	NANOPOS	PULSTAR	**Laser-driven positrons**
flux (e+/s)	10^6	10^9	10^4	5×10^2	10^5	$10^6 - 10^9$	**$10^5 - 10^6$**
duration (ps)	250	/	260	300	/	300	**50**
energy (keV)	0.5 - 15	1	0.5 - 20	0.5 - 15	0.25 - 25	0.5 - 10	**$0 - 10^3$**

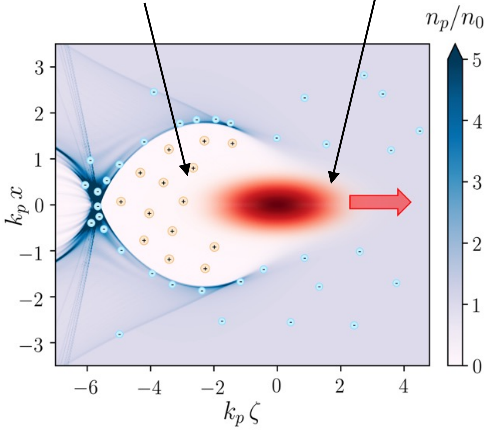
T. Audet et al., PRAB, 24,073402 (2021)

High-energy positron sources

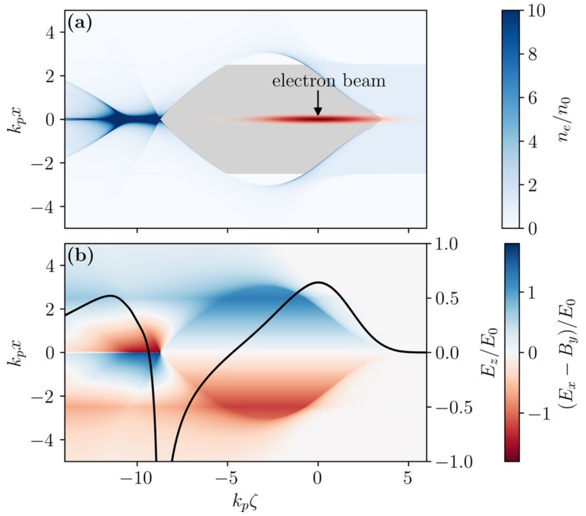
Plasma-based positron acceleration is challenging, but various new concepts have achieved promising results

ion background defocuses e^+

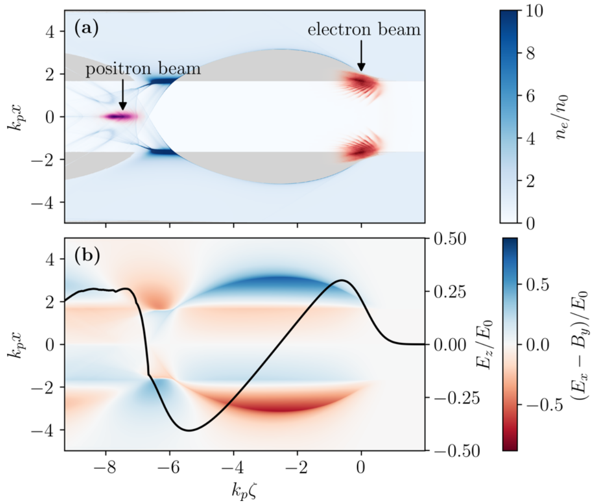
e^- drive beam



Finite plasma channels create electron filaments suitable for quality preserving e^+ acceleration



Asymmetric drive beams allow for stable e^+ acceleration in a hollow core plasma channel



A lot of progress in recent years:

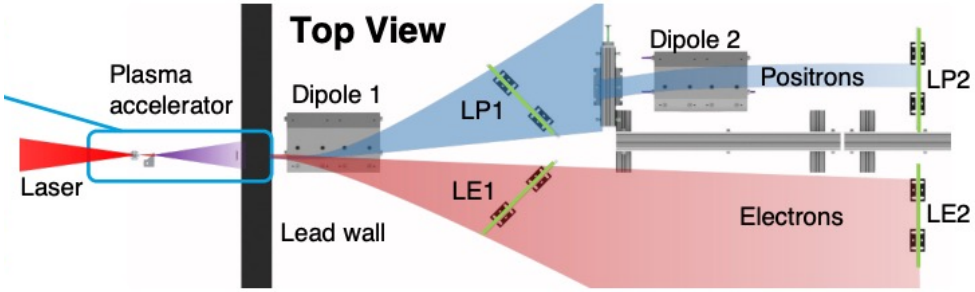
More concepts:
Lotov, PoP 14, 023101 (2007)
Zhou et al., arXiv:2211.07962v1 (2022)
Wang et al., arXiv. 2110.10290 (2021)
Liu et al., PRAppl 19, 044048 (2023)

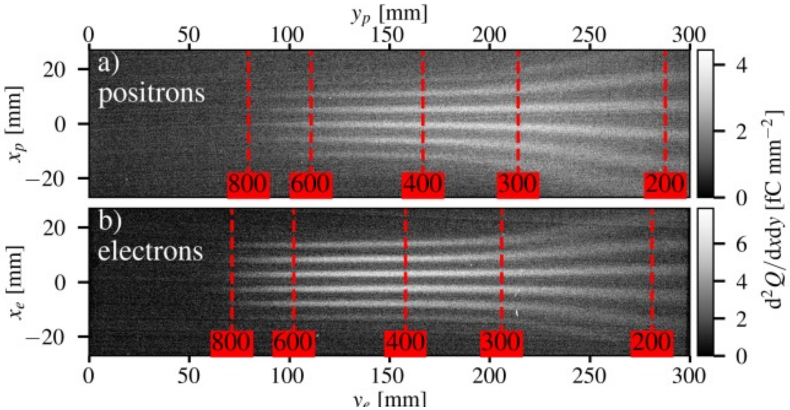
Finite plasma channels:
Diederichs et al., PRAB 22, 081301 (2019)
Diederichs et al., PRAB 23, 121301 (2020)
Diederichs et al., PoP 29, 043101 (2022)
Diederichs et al., PRAB 25, 091304 (2022)

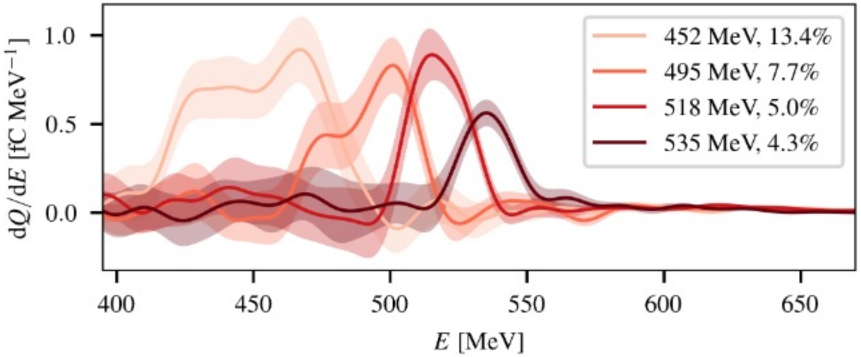
Hollow core plasma channels:
Zhou et al., PRL 127, 174801 (2021)
Zhou et al., PRAB 25, 091303 (2022)
Silva et al., PRL 127, 104801 (2021)

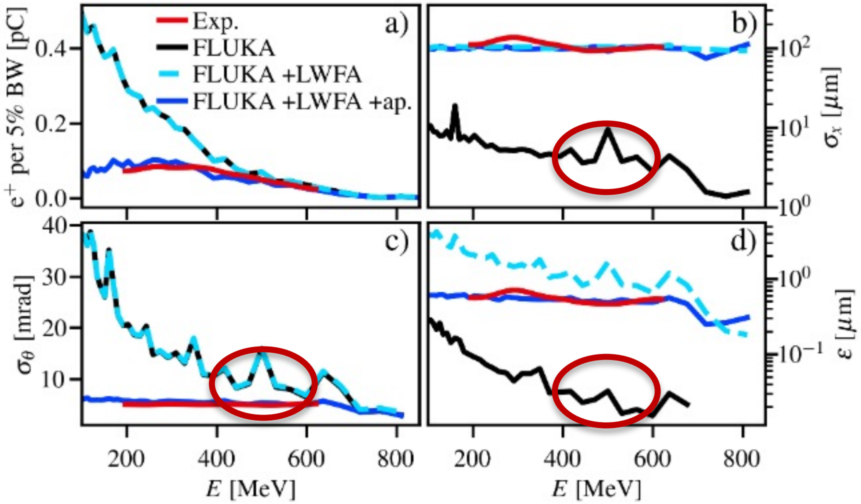
Courtesy of S. Diederichs

High-energy positron beams









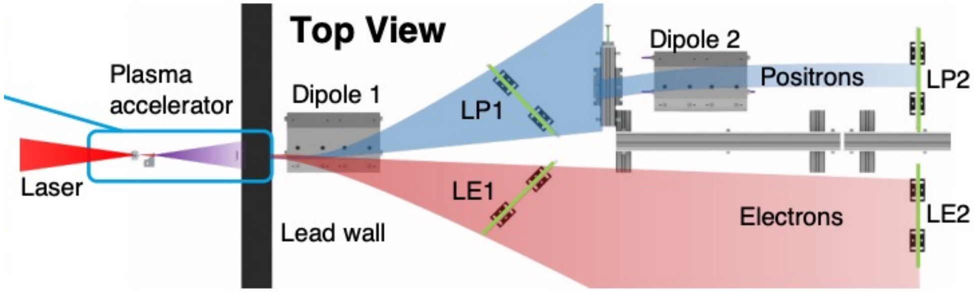
Obtained positron beam properties

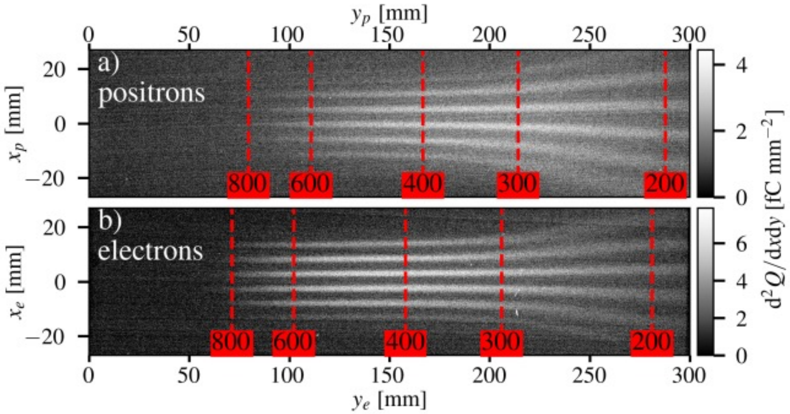
- Energy: 500 MeV
- Bandwidth: ΔE/E ~ 5%
- Charge: 0.2 pC
- Norm. Emit.: 15 µm
- Duration: < 50 fs

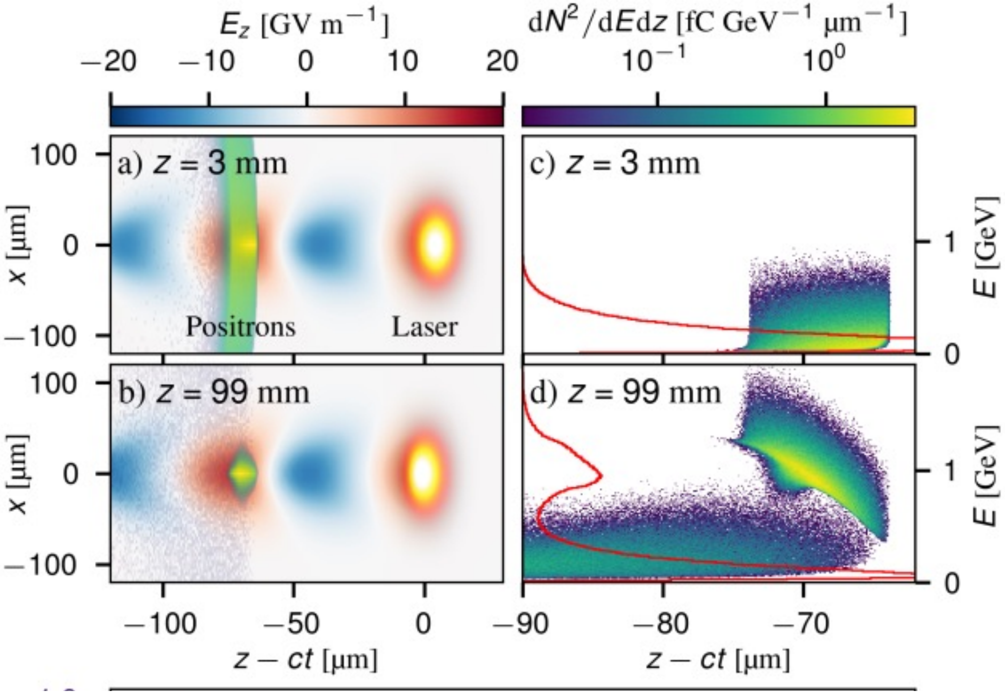
M. Streeter at al., ArXiv (2023)

G. Sarri et al., PPCF 64,044001 (2022)

High-energy positron beams







Laser-driven positron beams have sufficient spatial and spectral quality to be injected in further acceleration stages (plasma-based or conventional)

M. Streeter at al., ArXiv (2023)

G. Sarri et al., PPCF 64,044001 (2022)

EuPRAXIA

European Plasma Research Accelerator with Excellence in Applications

Gianluca Sarri

EAAC, September 2023, Isola d'Elba Italy

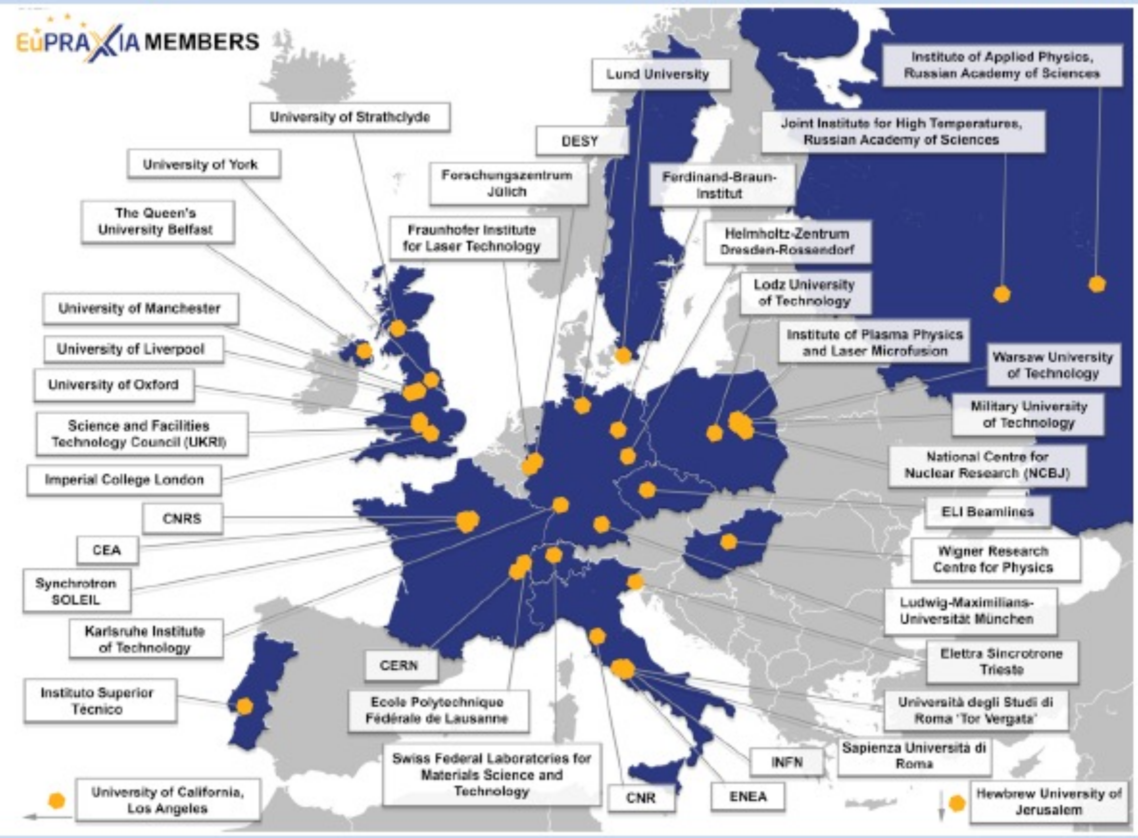
EuPRAXIA

Eupraxia is a European project for the first plasma-based particle accelerator of industrial quality and it is one of the facilities included in the ESFRI roadmap.

CONCEPTUAL DESIGN REPORT

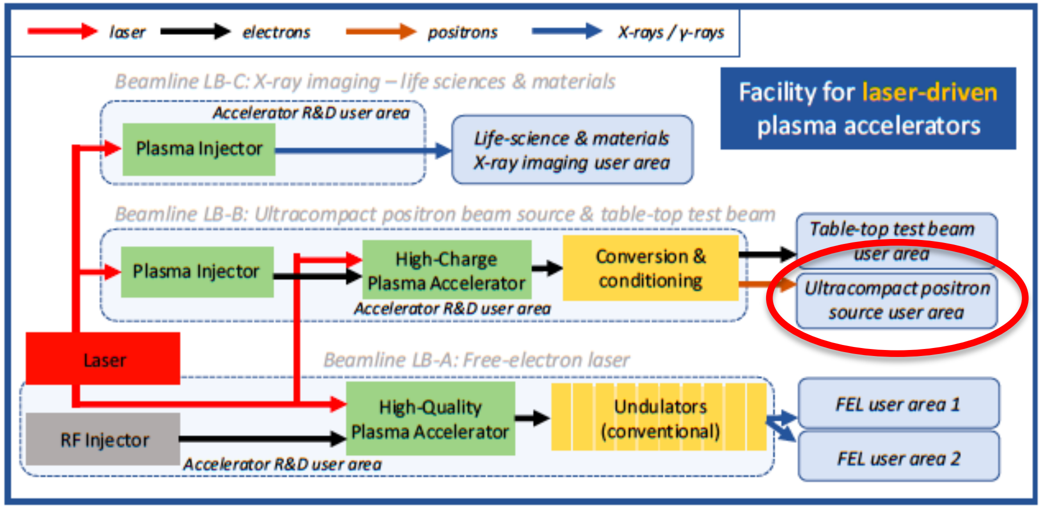
EuPRAXIA

European Plasma Research Accelerator with eXcellence In Applications



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

EuPRAXIA: low-energy positrons



laser
electrons
positrons
X-rays / γ-rays

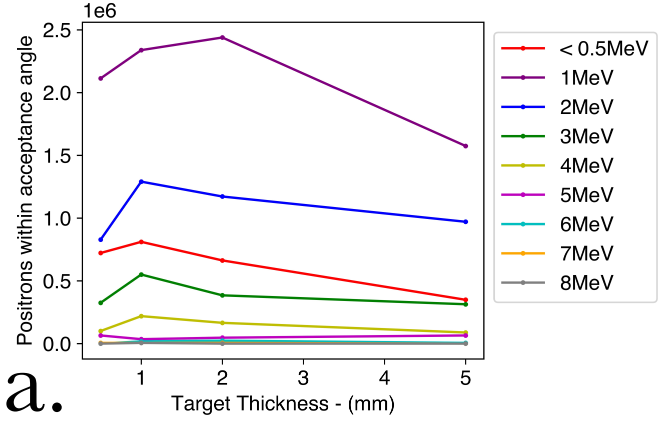
Facility for laser-driven plasma accelerators

Beamline LB-C: X-ray imaging – life sciences & materials
Accelerator R&D user area
Plasma Injector
Life-science & materials X-ray imaging user area

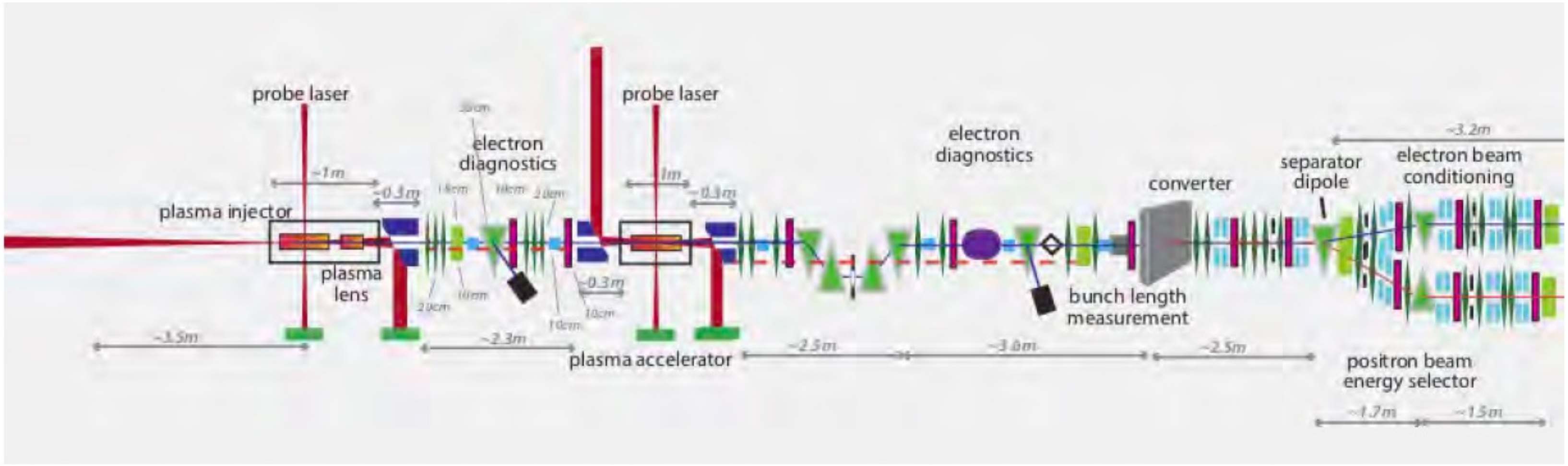
Beamline LB-B: Ultracompact positron beam source & table-top test beam
Plasma Injector
High-Charge Plasma Accelerator
Conversion & conditioning
Accelerator R&D user area
Table-top test beam user area
Ultracompact positron source user area

Laser

Beamline LB-A: Free-electron laser
RF Injector
High-Quality Plasma Accelerator
Undulators (conventional)
Accelerator R&D user area
FEL user area 1
FEL user area 2



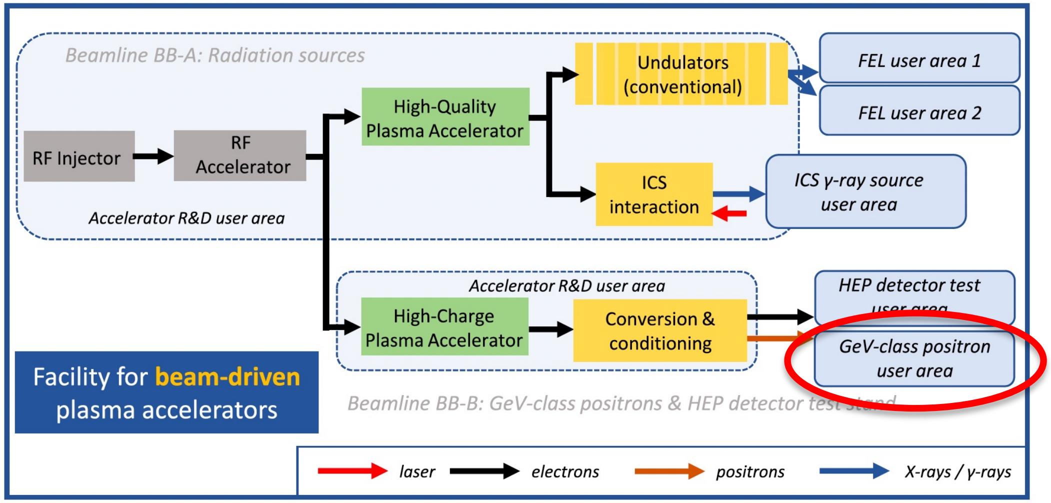
G. Sarri et al., PPCF 64,044001 (2022)



R. Assman et al., Eur. Phys. J. Special Topics 229, SUPPL 1 (2020)

G. Sarri et al., PPCF 64,044001 (2022)

EuPRAXIA: high-energy positrons



Beamline BB-A: Radiation sources

RF Injector

RF Accelerator

High-Quality Plasma Accelerator

Undulators (conventional)

FEL user area 1

FEL user area 2

ICS interaction

ICS γ-ray source user area

Accelerator R&D user area

Accelerator R&D user area

High-Charge Plasma Accelerator

Conversion & conditioning

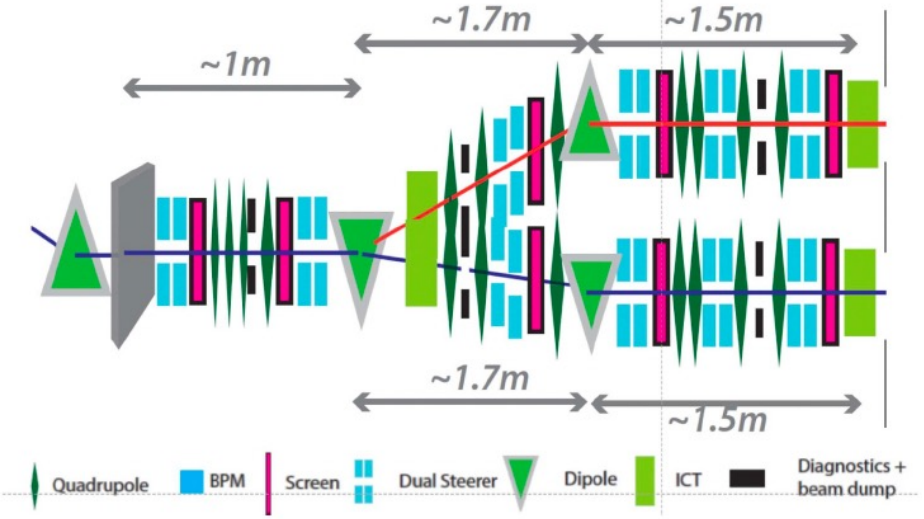
HEP detector test user area

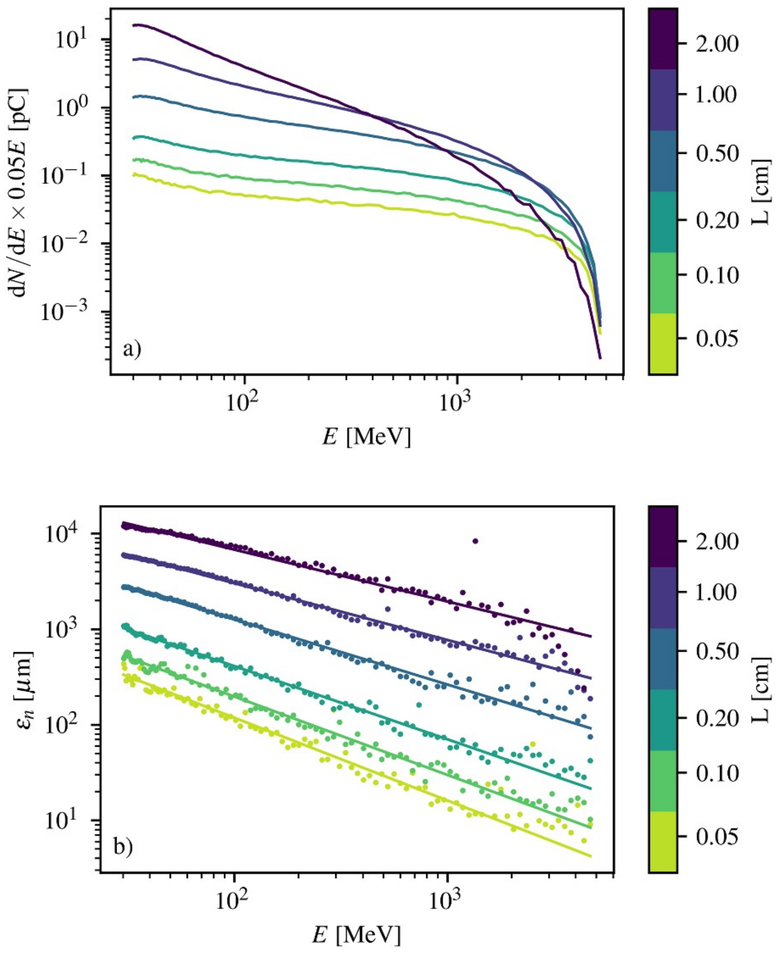
GeV-class positron user area

Beamline BB-B: GeV-class positrons & HEP detector test stand

Facility for **beam-driven** plasma accelerators

laser — electrons — positrons — X-rays / γ-rays





R. Assman et al., Eur. Phys. J. Special Topics 229, SUPPL 1 (2020)

G. Sarri et al., PPCF 64,044001 (2022)

Conclusions

⇒ **Laser-driven accelerators** can drive compact positron sources with unique characteristics for applications in both fundamental science and industry

⇒ **Low-energy positrons** (≤ MeV) with short duration (~50ps) and energy tuneability can provide high-resolution and volumetric scanning of materials

⇒ **High-energy positrons** (~ GeV) with good spatial and spectral quality (~micron-scale normalized emittance and pC-scale charge in a 5% bandwidth) have been produced and can be used as a seed in a wakefield accelerator

NEXT STEPS

⇒ Proof-of-principle PALS characterization	Dec 2023, TARANIS, QUB
⇒ Positron generation at the kHz level	May 2024, ELI-BL
⇒ Positron post-acceleration in a wakefield	second-half 2024 CLF

Thanks for your attention!

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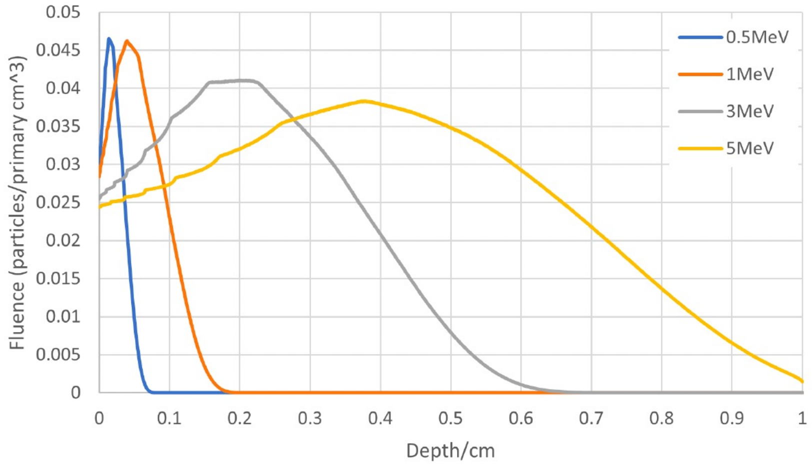
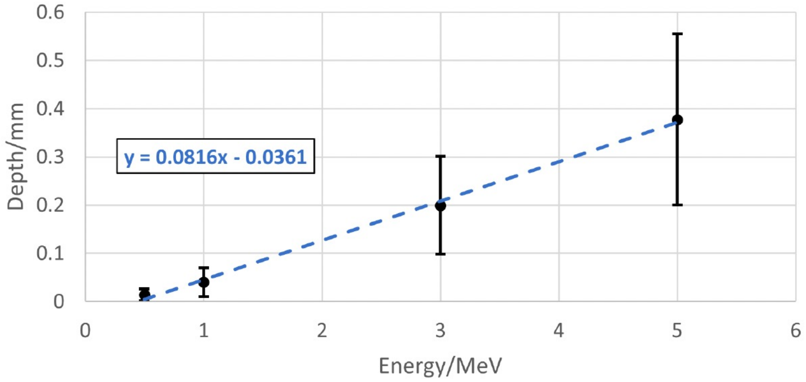
Back-up slide

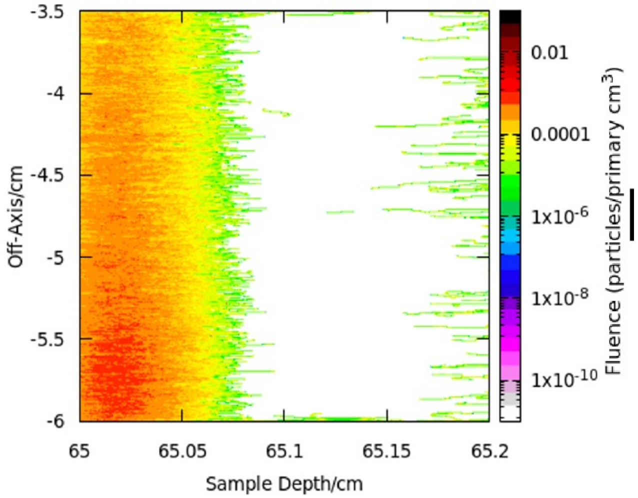
Comparison of Positron Energy



Peak Depth vs. Monoenergetic Positron Energy



Positron Depth Penetration for PALS



GammaSurvival Aluminium 511KeV 1E7 Stretched