arXiv:2301.08368

A Compact, Low-Emittance Source of Positron Beams for Plasma Wakefield Accelerators

Spencer Gessner, SLAC
Rafi Hessami, Stanford University

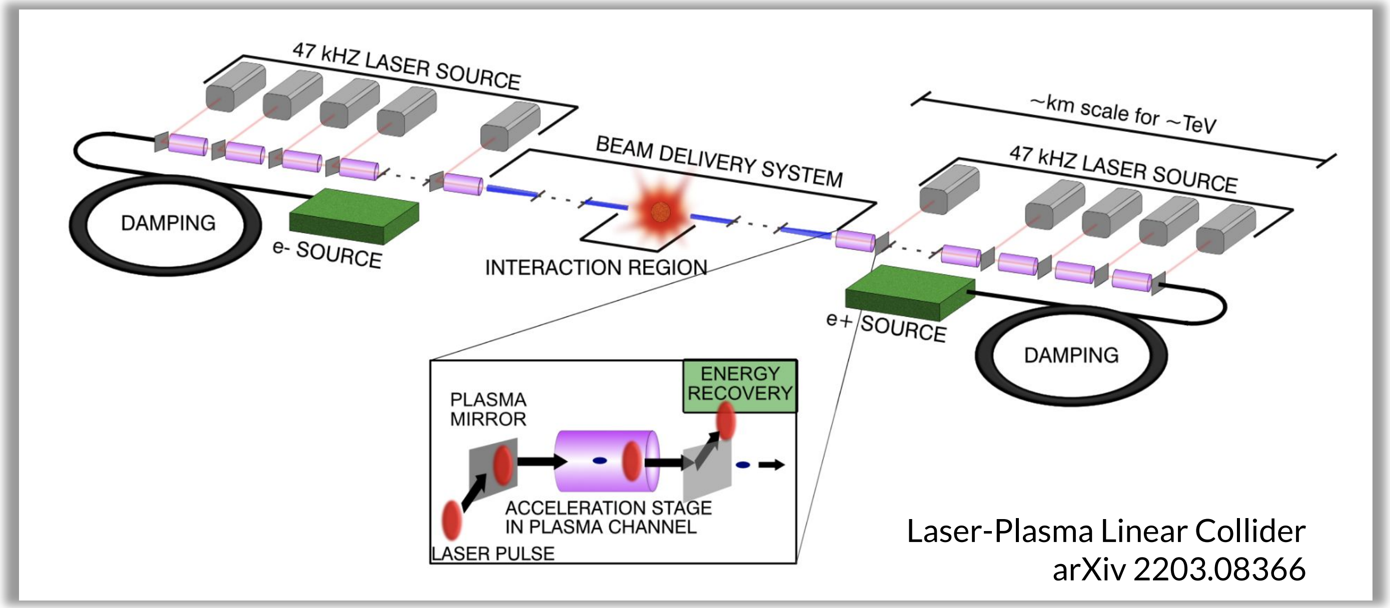
EAAC2023, Elba, Italy

September 20, 2023

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

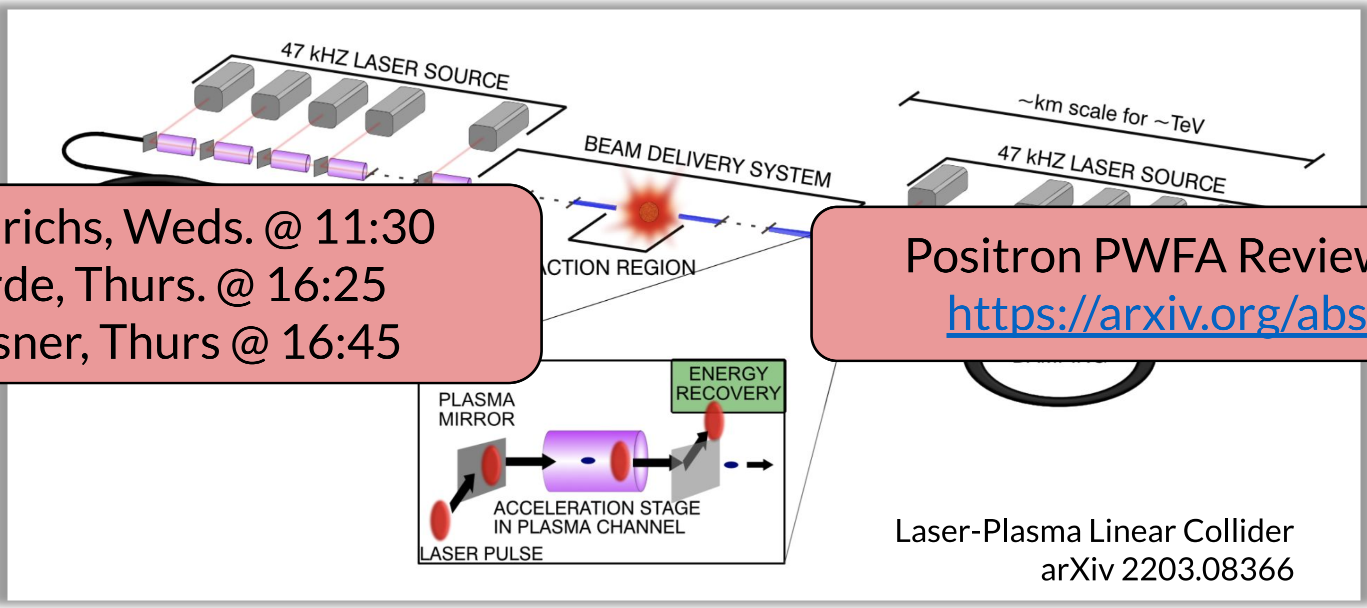
Plasma Linear Colliders



Laser-Plasma Linear Collider
arXiv 2203.08366

Challenge for our field: *How do we accelerate positron bunches in plasma?*

Plasma Linear Colliders



Laser-Plasma Linear Collider
arXiv 2203.08366

Talk by S. Diederichs, Weds. @ 11:30
Talk by S. Corde, Thurs. @ 16:25
Talk by S. Gessner, Thurs @ 16:45

Positron PWFA Review posted today!
https://arxiv.org/abs/2309.10495

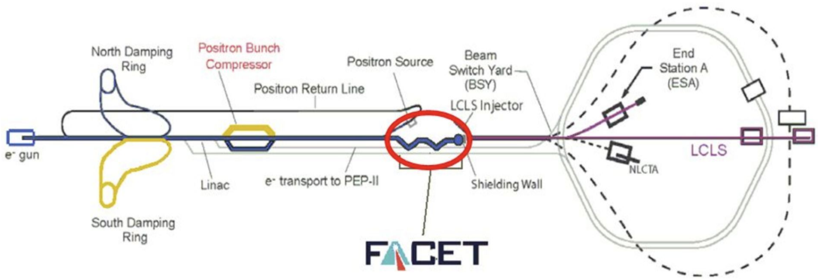
Challenge for our field: *How do we accelerate positron bunches in plasma?*

Positron PWFA Experimental Research (arXiv:2309.10495)

FFTB

M. J. Hogan et. al. *Phys. Rev. Lett.* 90 205002 (2003).
B. Blue et. al. *Phys. Rev. Lett.* 90 214801 (2003).
P. Muggli et. al. *Phys. Rev. Lett.* 101 055001 (2008).

FACET



S. Corde et. al. *Nature.* 524 442445 (2015).
S. Gessner et. al. *Nat. Comm.* 7 11785 (2016).
A. Doche et. al. *Nat. Sci. Rep.* 7 14180 (2017).
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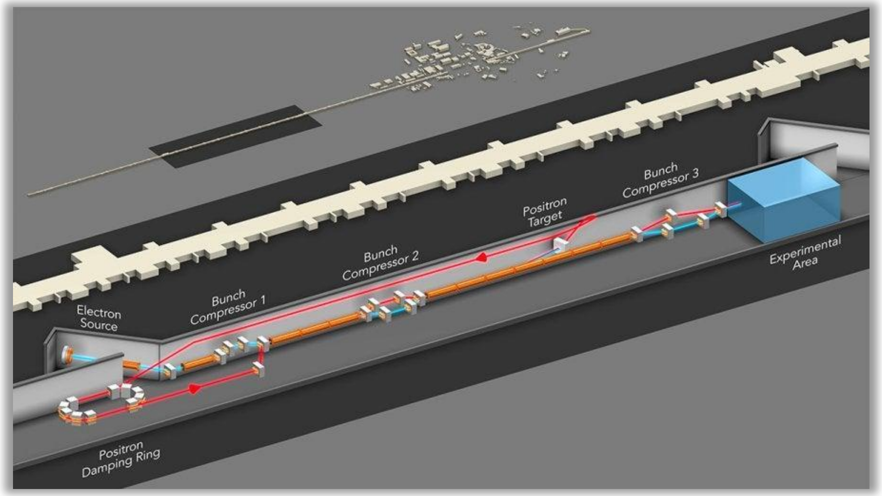
S. Gessner et. al. *arXiv:*2304.01700 (2023).

FACET-II*



*E333 experiment planned for filament regime positron PWFA.

Positron PWFA experiments have only taken place at SLAC using existing SLC infrastructure. *How do we expand access to positron beams?*

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Positron PWFA Experimental Research (arXiv:2309.10495)

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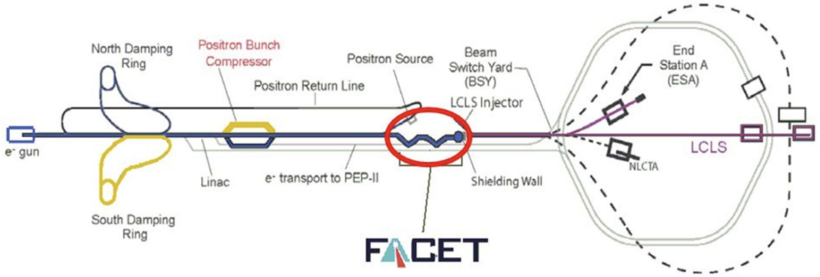

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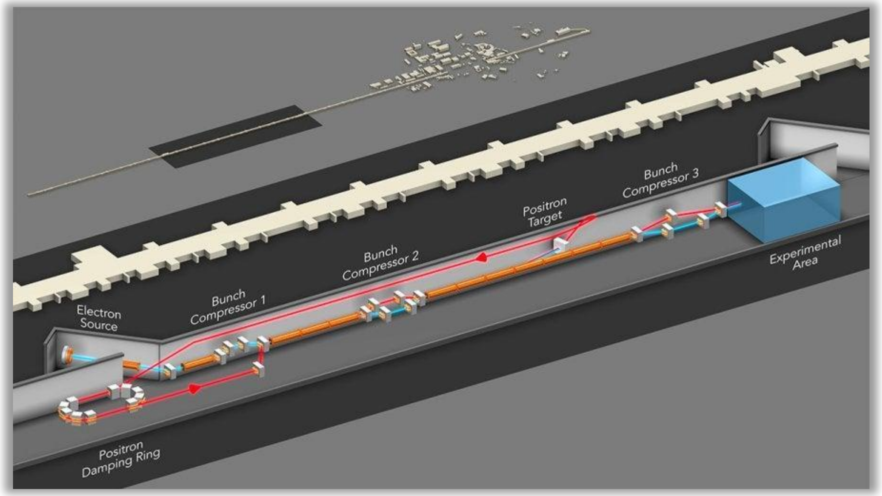

*E333 experiment planned for filament regime positron PWFA.

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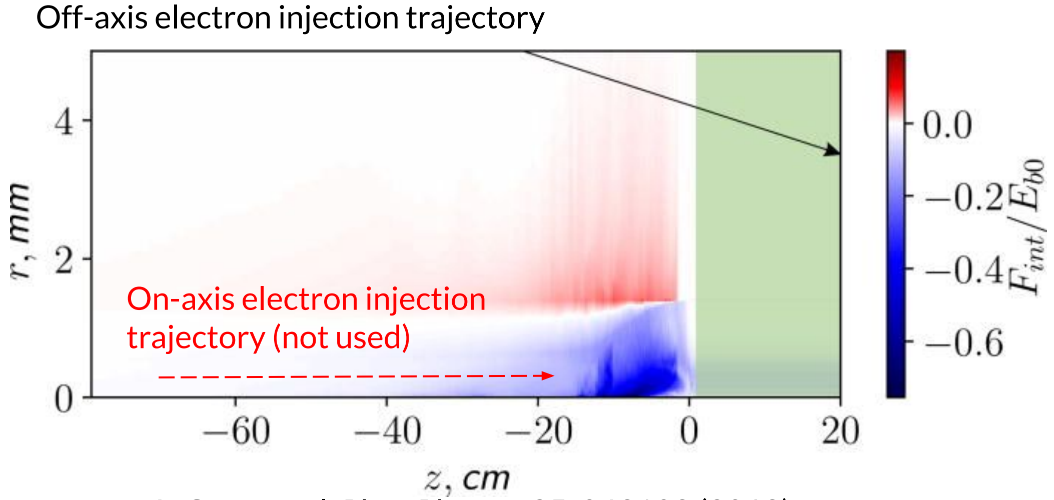
Talk by G. Sarri, Mon. @ 18:05

Seed of an Idea

- AWAKE experiment goal: electron acceleration in proton beam-driven wake.
  - Electron injection into the proton beam-driven plasma wakefield is challenging because on-axis beam electrons see a defocusing force during the plasma up-ramp.
  - Positron beams would be a useful diagnostic to characterize the injection process!



A. Gorn et. al. *Phys. Plasmas* 25, 063108 (2018)

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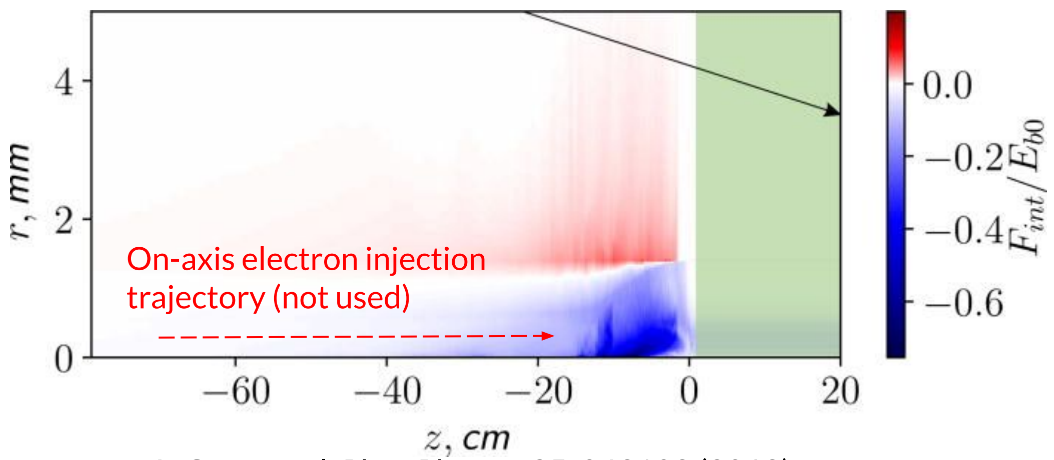
  - Positron beams would be a useful diagnostic to characterize the injection process!

Off-axis electron injection trajectory



A. Gorn et. al. *Phys. Plasmas* 25, 063108 (2018)

- But where to find a positron beam source compatible with AWAKE e^- injector footprint?

- CERN Antimatter Decelerator: low-energy positron beams for antimatter experiments.

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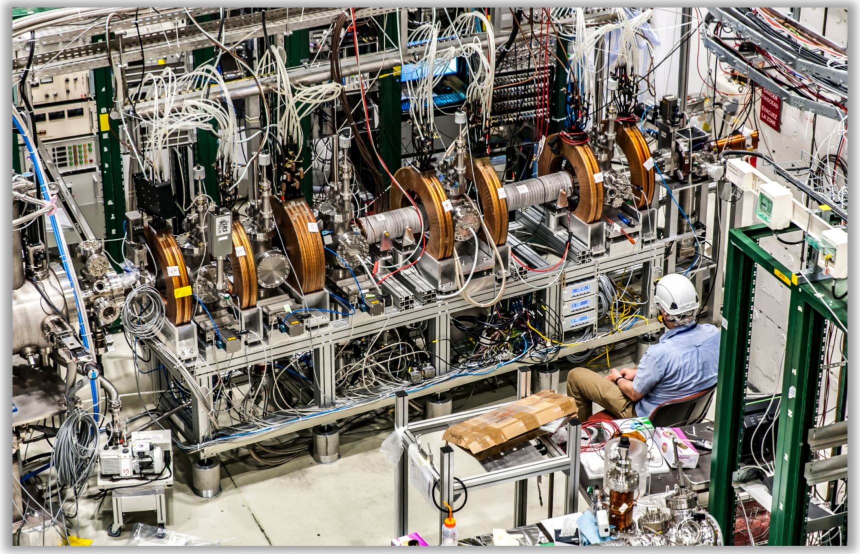
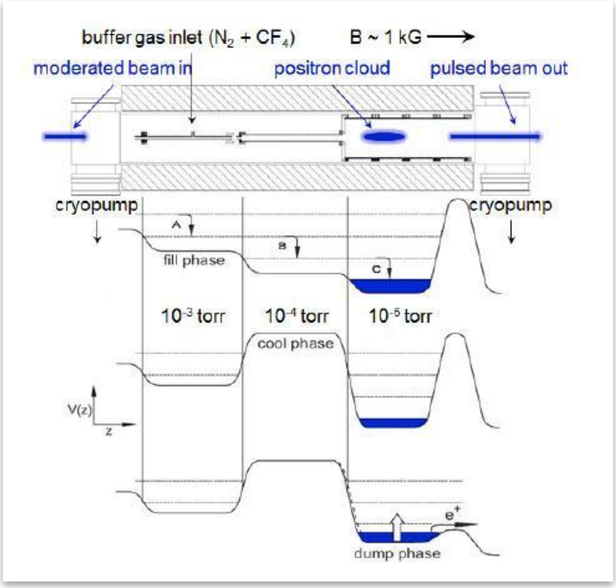
Positron Traps for Antimatter Experiments



GBAR Positron Source at CERN



Schematic for trapping and cooling positrons

A multi-cell trap for increasing positron beam rate
https://positrons.ucsd.edu/traps.php

Penning-Malmberg traps are well established technology for accumulating and manipulating low-energy positron beams.

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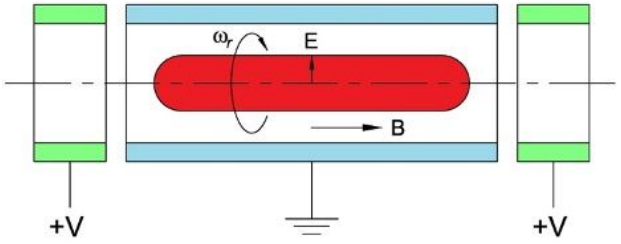
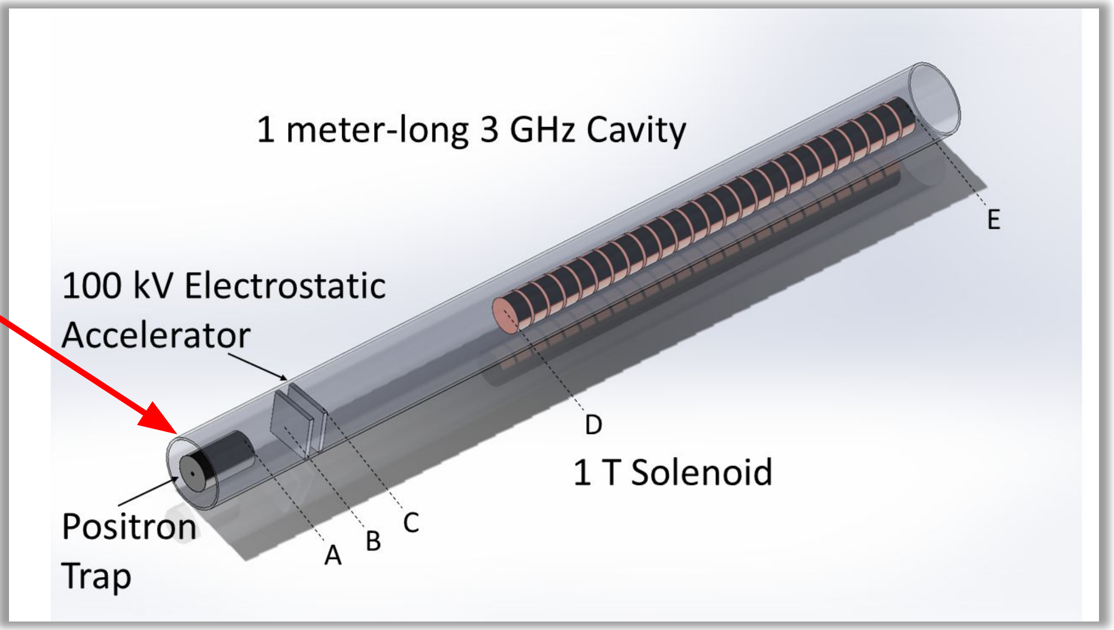
Penning-Malmberg Traps for Positron Beams

R. Hessami at CERN (2019)
Now Stanford Ph.D. student

Penning-Malmberg Trap



A Compact Source of Positron Beams with Small Thermal Emittance, R. Hessami and S. Gessner. https://arxiv.org/abs/2301.08368

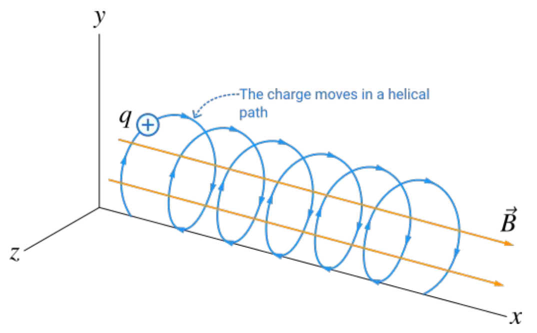


Are Penning-Malmberg traps viable sources of positron beams?

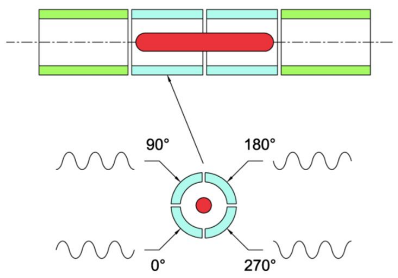
Penning-Malmberg Trap

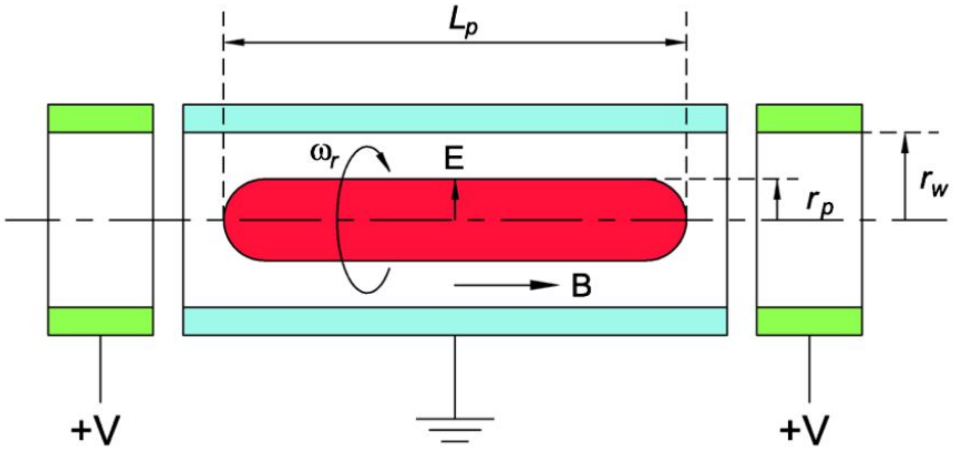
- The Penning-Malmberg Trap consists of a solenoidal magnetic field and two end-cap potentials to confine the non-neutral plasma.
- Individual particles drift back and forth between the end caps along a helical path.
- The non-neutral plasma produces a repulsive space charge. The plasma *rotates* due to the *E x B* which leads to an inward pointing *v x B* force.
  - The plasma is confined!

Single-Particle Trajectory



"Rotating Wall"





J.R. Danielson et. al. *Rev. Mod. Phys.* 87, 247 (2015)

Traps Provide Low Emittance Positron Beams

The equations of state for non-neutral plasma have an equilibrium solution. The non-neutral plasma forms a cylinder with a sharp radial boundary. The radius of the plasma cylinder depends on the rotation rate of the plasma ω_r.

Using the equations of state and the following definition of emittance:

$$\varepsilon_{n,\ \mathrm{rms}} = \frac{1}{m_0 c}\sqrt{\langle x^2\rangle\langle p_x^2\rangle - \langle x p_x\rangle^2}$$

We find (arXiv:2301.08368):

$$\epsilon_n = \frac{1}{mc}\sqrt{\frac{qNmk_BT}{8\pi\epsilon_0 B\omega_r L_p}}$$

for N positrons, B solenoid field, T temperature, and L_p trap length.

J.R. Danielson et. al. *Rev. Mod. Phys.* 87, 247 (2015)

Equations of State

$$n(r,z) = Ce^{-q\phi_{\mathrm{eff}}(r,z)/k_BT}$$

$$q\phi_{\mathrm{eff}}(r,z) = \tfrac{1}{2}m\omega_r(\Omega_c - \omega_r)r^2 + q\phi(r,z)$$

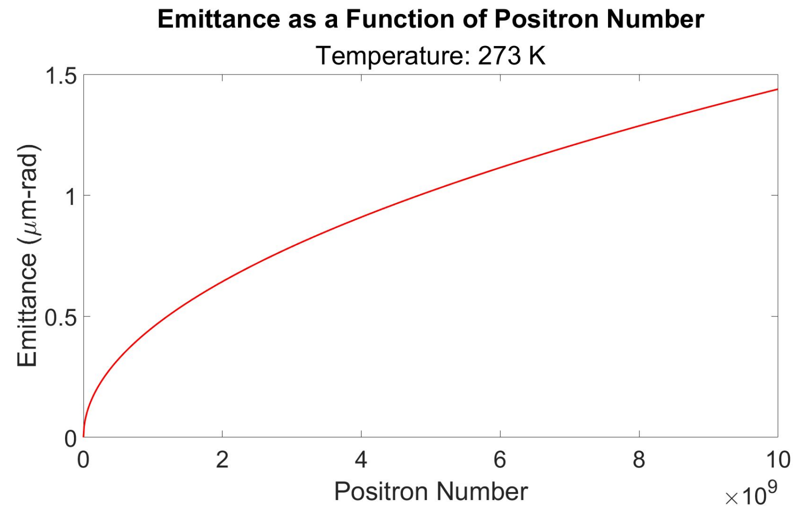
$$\frac{\partial^2\phi}{\partial r^2} + \frac{1}{r}\frac{\partial\phi}{\partial r} + \frac{\partial^2\phi}{\partial z^2} = -\frac{n(r,z)}{\varepsilon_0}$$

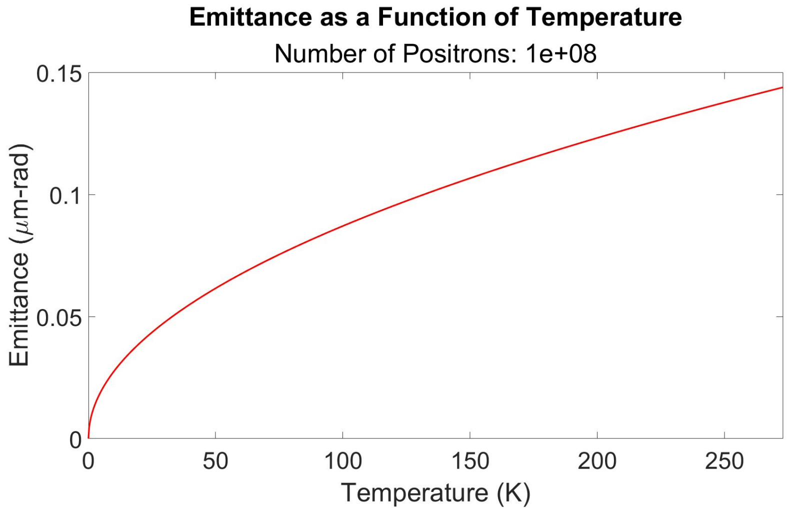
$$f_{\mathrm{eq}}(r,z,\mathbf{v}) = \frac{n(r,z)}{(2\pi k_BT/m)^{3/2}} \times \exp\left[-\frac{1}{2}m(\mathbf{v}+\omega_r r\hat{\theta})^2/k_BT\right]$$

Traps Provide Low Emittance Positron Beams

$$\epsilon_n = \frac{1}{mc}\sqrt{\frac{qNmk_BT}{8\pi\epsilon_0 B\omega_r L_p}}$$

Parameter	Symbol	Value
Trap radius	r_w	4 cm
Trap length	l_w	10 cm
Magnetic field	B	1 T
e^+ plasma radius	r_p	1.3 mm
e^+ plasma length	r_l	5 cm
Temperature	T	273 K
Number of positrons	N	10^8
Space charge potential	$\Delta\phi$	22.4 V
Debye length	λ_D	60.6 μm
Cyclotron frequency	Ω_c	175.6 GHz
Rotation frequency	ω_r	3.2 MHz
Transverse emittance	$\varepsilon_{x,y}$	0.11 μm-rad





Challenges

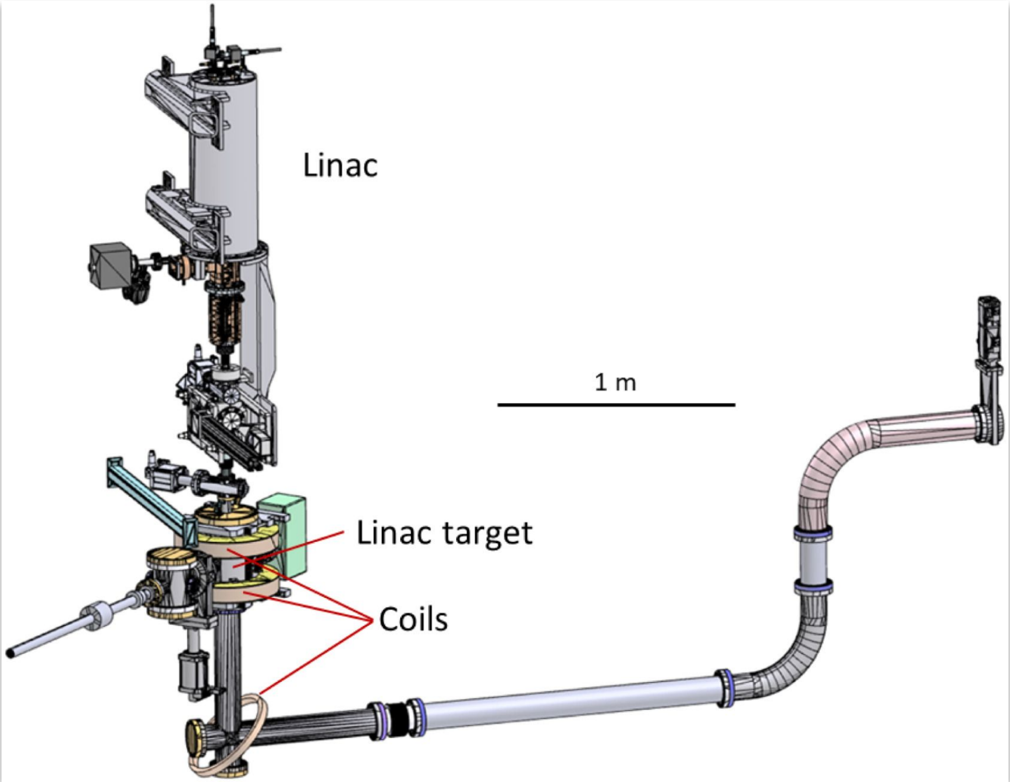
We identify 4 main challenges:

1. Positron source and source rate
2. Bunch compression
3. Emittance preservation
4. Intrinsic angular momentum

Challenge: Positron Source

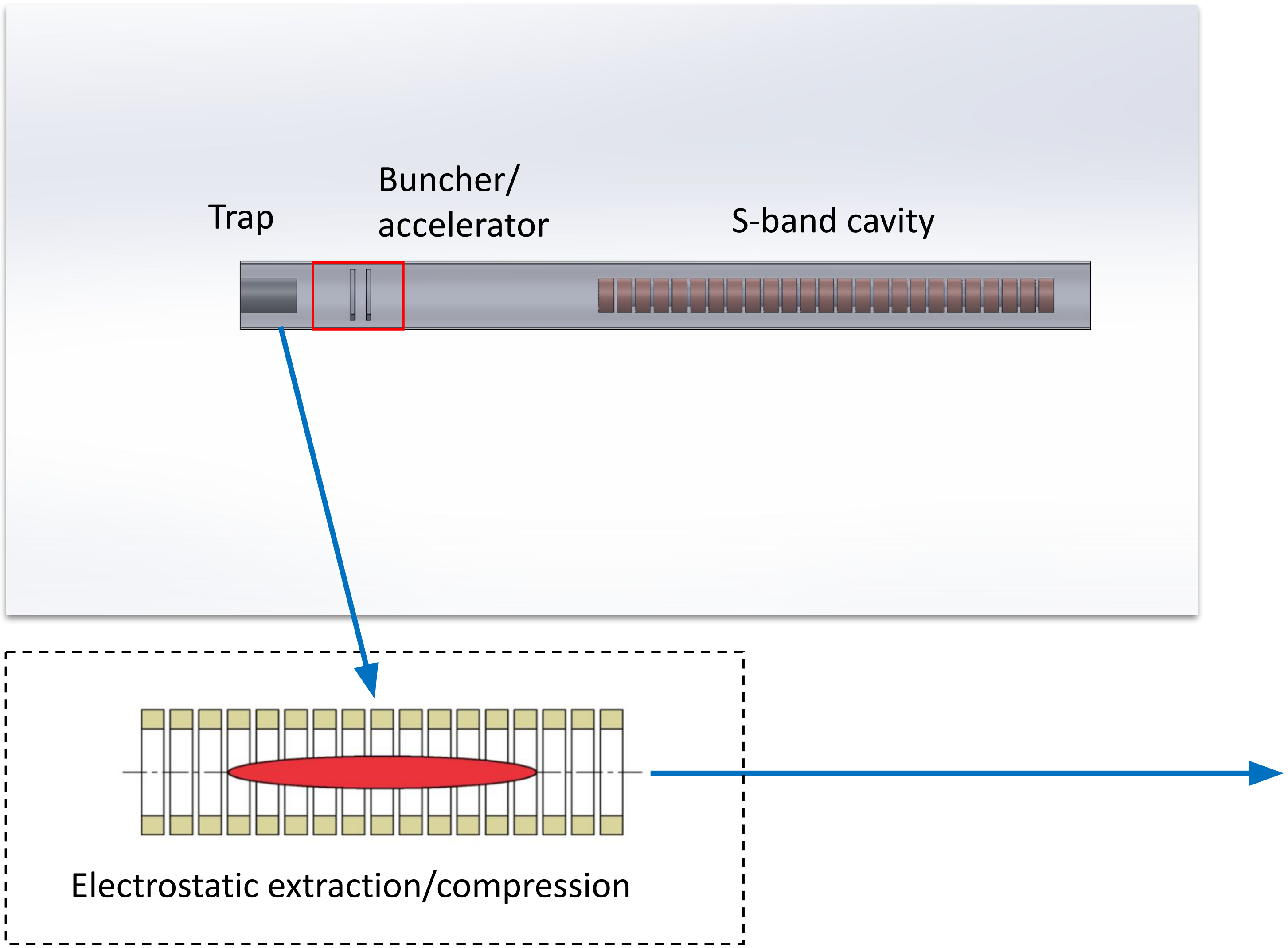
Fig. 3. The closed capsule (small design). The welding of the front ring is visible. The post has got a 6–32 UNC thread with a length of 6.3 mm.

Sodium-22 radioisotope source produces 1E7 e^+/s, but only 1E6 e^+/s enter the trap after passing through the neon moderator.

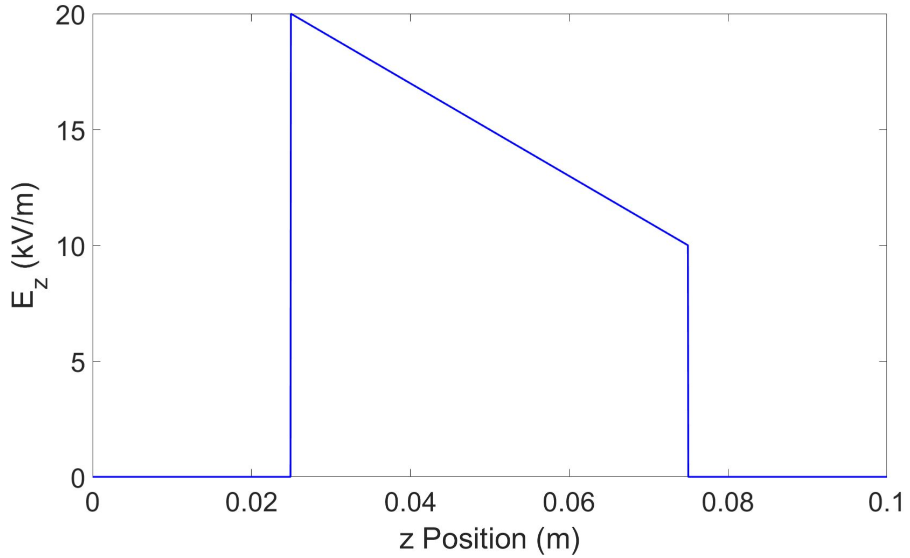


GBAR positron source is based on a 9 MeV electron beam. The electron-to-slow-positron efficiency is 3E-8. Only 5E7 e^+/s after passing through the neon moderator.

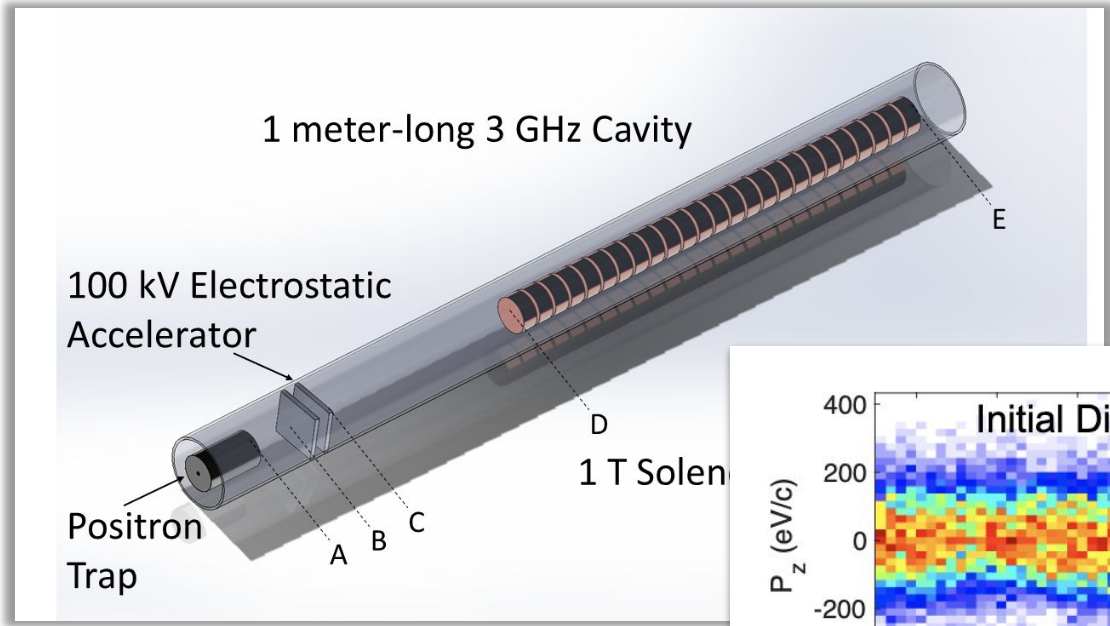
Challenge: Bunch Compression

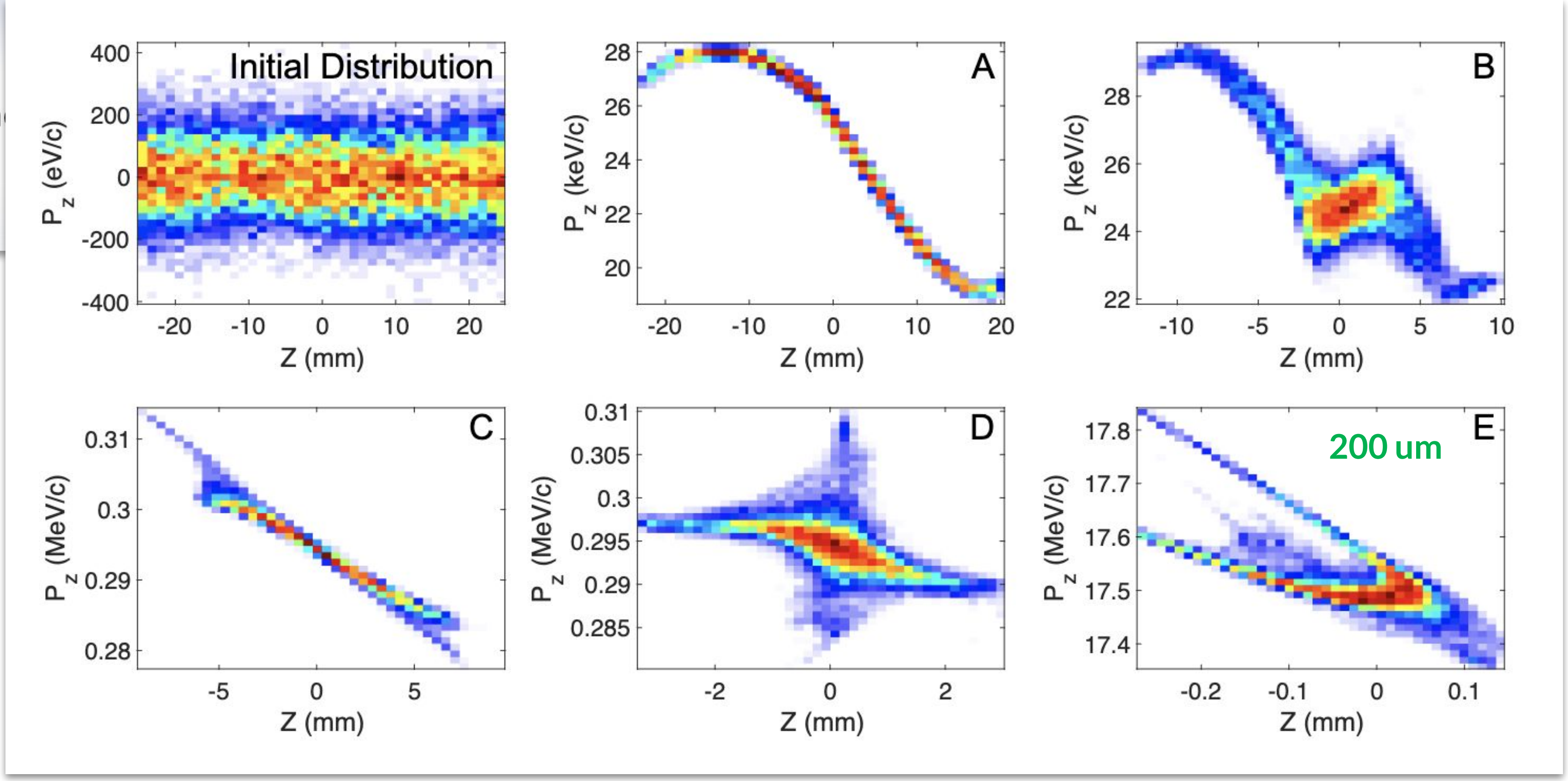


The bunch is several cm-long in the trap and must be reduced to 100 um-scale for injection in low-density plasma wakefield.



Multistage Compression - GPT Simulation

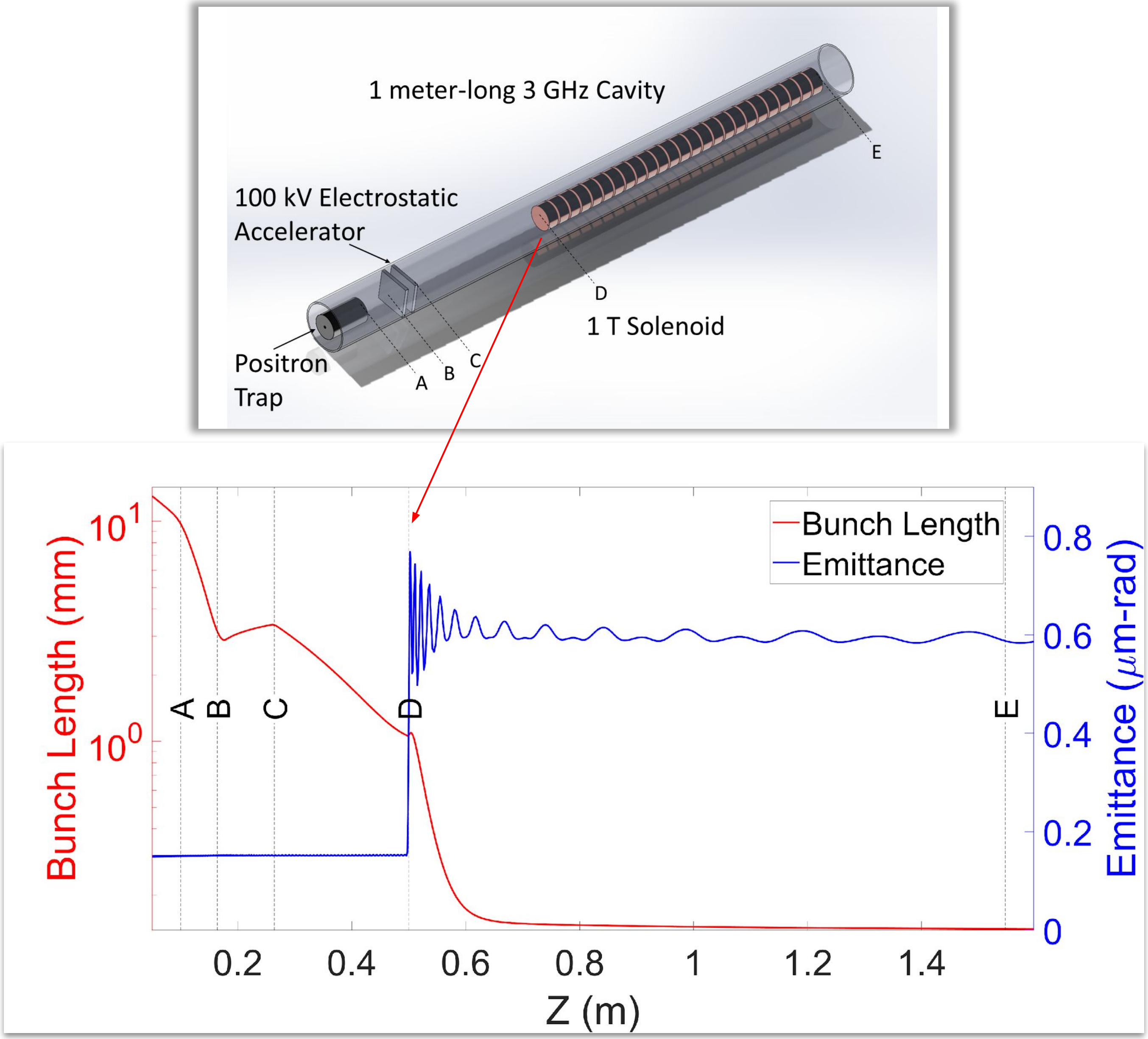




Challenge: Emittance Growth

The GPT simulation shows emittance growth occurs at the start of the RF cavity.

Solution (yet to be implemented): stronger focusing at entrance of s-band cavity.



Challenge: Intrinsic Angular Momentum

The positrons are cooled in the PM trap before being injected.

The cooling process means that the positrons are *born* in a solenoidal magnetic field. They have intrinsic angular momentum.

The intrinsic angular momentum is much greater than the thermal emittance of the beam.

$$\mathcal{L} \approx 250 \ \mu\text{m-rad}$$

$$\mathcal{L} = \frac{\langle x p_y - y p_x \rangle}{2} = \frac{e B \sigma_r^2}{2mc}$$

$$\Sigma_{4D} = \begin{bmatrix} \langle x^2 \rangle & \langle x p_x \rangle & \langle xy \rangle & \langle x p_y \rangle \\ \langle x p_x \rangle & \langle p_x^2 \rangle & \langle p_x y \rangle & \langle p_x p_y \rangle \\ \langle xy \rangle & \langle p_x y \rangle & \langle y^2 \rangle & \langle y p_y \rangle \\ \langle x p_y \rangle & \langle p_x p_y \rangle & \langle y p_y \rangle & \langle p_y^2 \rangle \end{bmatrix}$$

Solution: Round-to-Flat Beam Transformer

Damping-ring-free electron injector proposal for future linear colliders

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(Received 10 May 2022; accepted 13 December 2022; published 12 January 2023)

The current designs of future electron-positron linear colliders incorporate large and complex damping rings to produce asymmetric beams for beamstrahlung suppression. Here, we present the design of an electron injector capable of delivering flat electron beams with phase-space partition comparable to the electron-beam parameters produced downstream of the damping ring in the proposed International Linear Collider (ILC) design. Our design does not employ a damping ring but is instead based on cross-plane phase-space manipulation techniques. The performance of the proposed configuration, its sensitivity to jitter along with its impact on spin-polarization are investigated. The proposed paradigm could be adapted to other linear collider concepts under consideration and offers a path toward significant cost and complexity reduction.

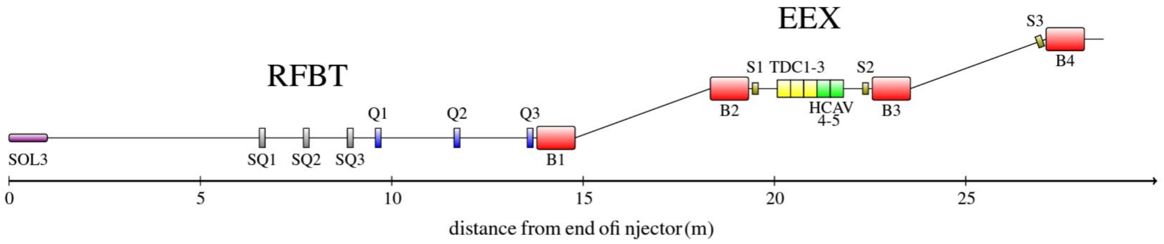


FIG. 2. Overview of the emittance manipulation beamline combining the RFBT (skew-quadrupole magnets SQ1, SQ2, and SQ3) and EEX (from dipole magnet B1 to B4) insertions. The label "SQ*i*" and "Q*i*" refer to skew- and normal-quadrupole magnets, "B*i*" and "S*i*" are dipole nd sextupole magnets. The elements "TDC*i*" and "HCAV*i*" refer to transverse-deflecting and 3.9-GHz SRF cavities; "SOL3" is a solenoidal magnetic lens.

Beams with intrinsic angular momentum can be partitioned such that the vertical emittance is small (same as thermal emittance) and the horizontal emittance is large (size of angular momentum term).

Round-to-flat beamlines use skew quadrupoles to transform the beam.

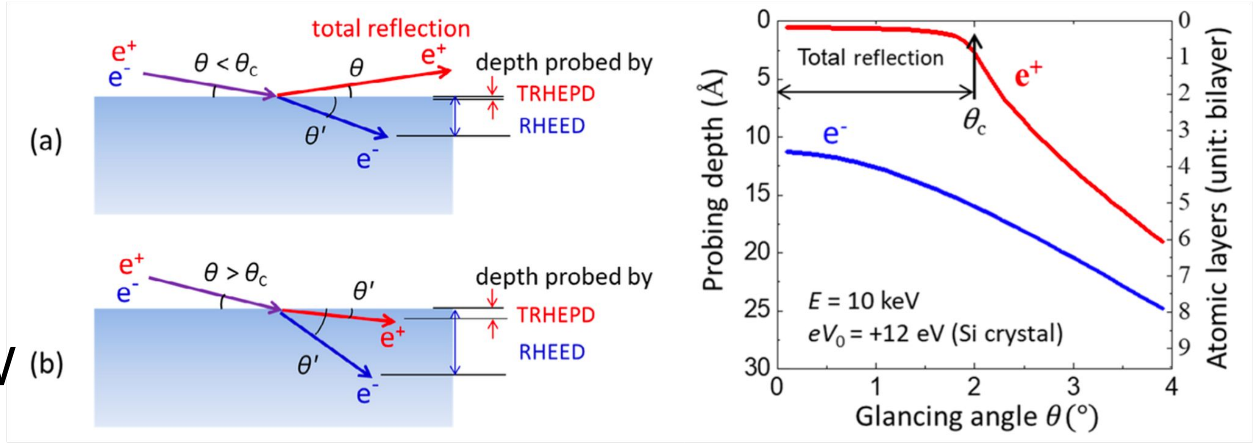
Beams with intrinsic angular momentum are proposed for "damping-ring-free" linear colliders.

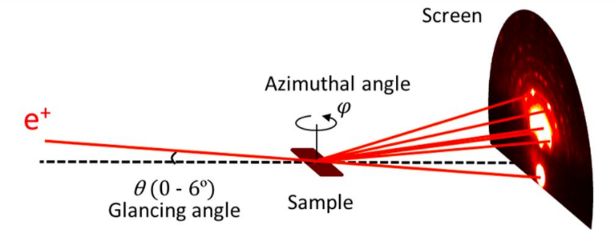
Other applications: Ultrafast Science with Positron Beams

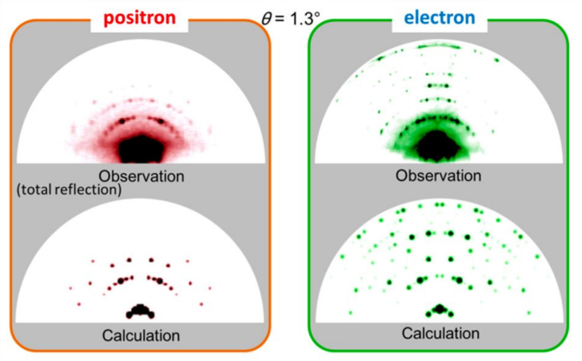
- Positron beams interact *differently* with the surface of materials than electron beams.
- This allows for direct probes of surface dynamics .
- Existing facilities (e.g. SPF in Japan) provide CW positron beams.
  - No time resolution.

Our positron source can provide temporally compressed positron bunches for pump-probe positron diffraction measurements.

Y. Fukuya, J. Phys. D: Appl. Phys. 52, 013002

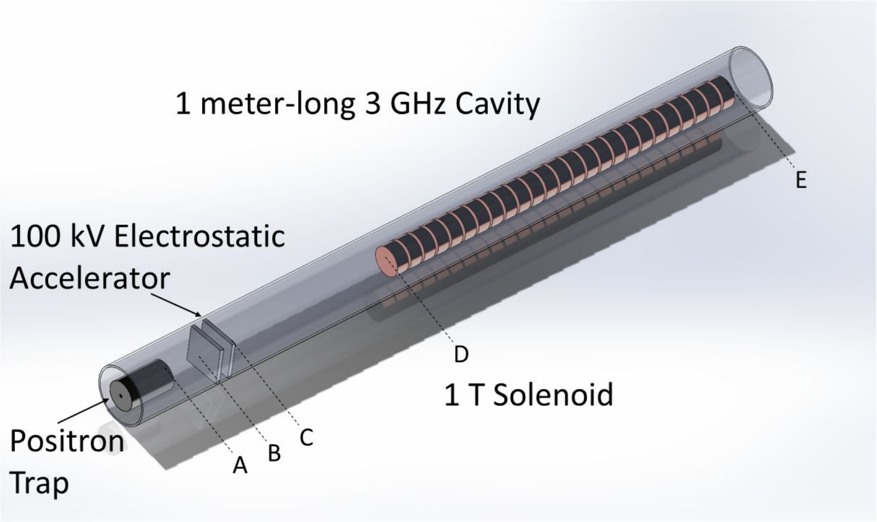






Final Bunch Parameters

- In our GPT simulation, we were able to compress and accelerate the positron beam with sub-micron emittance and sub-mm bunch length.



Beam parameter	Value
Beam energy	17.6 MeV
Beam charge	15.43 pC
Bunch length (rms)	190 μm
Energy spread (rms)	0.76%
Transverse emittance	0.60 μm-rad

TABLE II. Beam parameters at the end of the simulation.

Beam parameters at point E (no round-to-flat transformation)

Next Steps

1. Correct emittance growth at start of s-band cavity.
2. Add round-to-flat beam transformer line to the simulation.
3. Simulate injection of positron bunch into low density (1E15 cm^{-3}) plasma wakefield.
4. Tolerance studies.

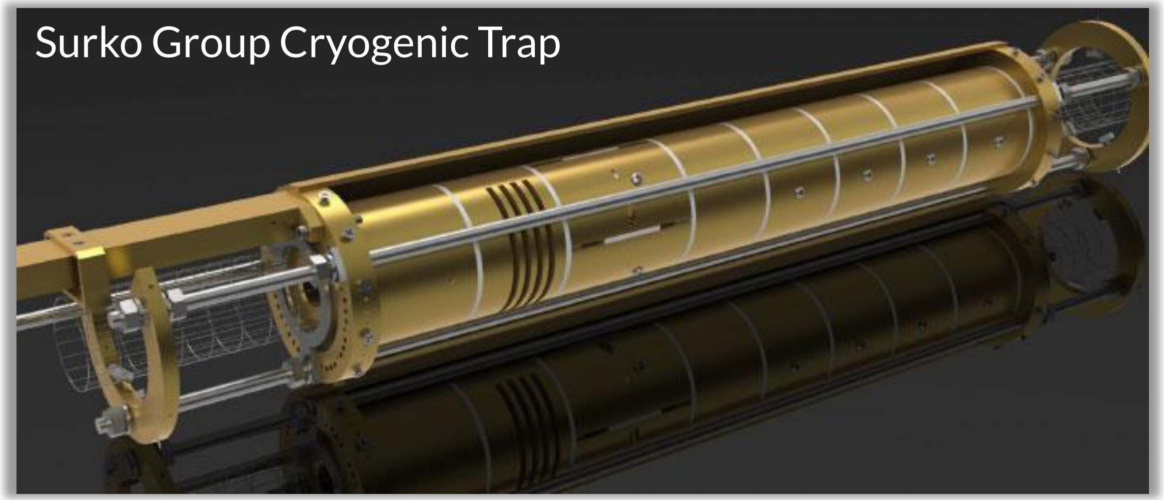
Acknowledgements

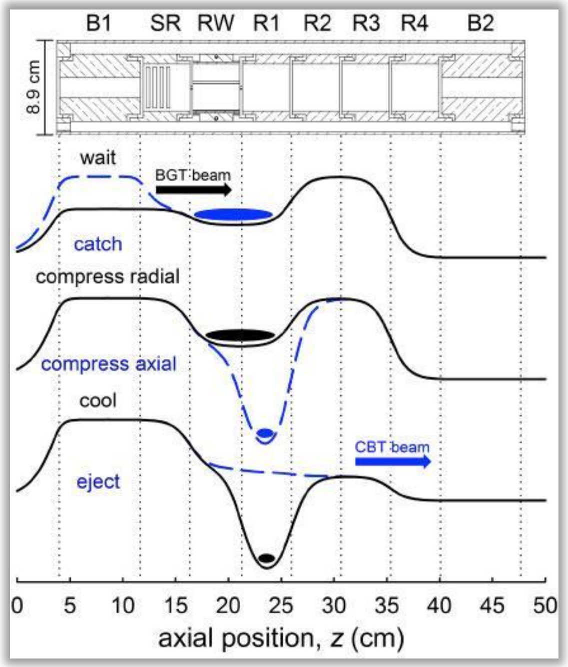
Many individuals helped to provide background on positron sources for this project. We thank Dirk Peter Van Der Werf, Samuel Niang, and Laszlo Liszkay for showing us the GBAR experiment at CERN. Thank you to David Cooke, David Cassidy, Allen Mills, and Cliff Surko for background on positrons from electrostatic traps. Thank you to Pietro Musumeci for background on UED systems. Klaus Floettman and Bas van der Geer provided input on simulations in ASTRA and GPT, respectively. Thank you to the AWAKE electron source group Seongyeol Kim, Mohsen Dayyani Kelisani, Steffen Doebert, and Edda Gschwendtner from CERN for their useful discussions and support.

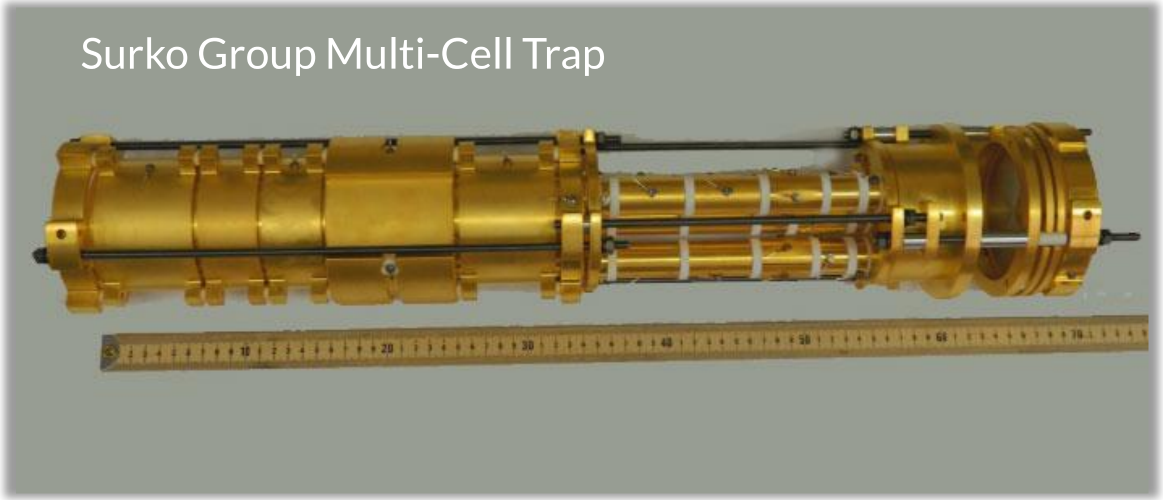
Backup

Alternative Traps

- We have purposefully selected conservative positron beam parameters for the first application.
- A path exists to go to nm-level emittances with cryogenic traps.
- Multi-cell traps can be used to increase beam rate.







Positrons at FACET-II

- Restoring the positron capabilities at FACET-II was reviewed at the CD-2 level before being descoped from the FACET-II project.
- Damping Ring magnet design was completed, and prototypes were procured as part of the project.
- User interest in positrons at FACET-II remains strong.