Plans for the Compact Positron Source at SLAC

Spencer Gessner, Rafi Hessami, Aaron Lindenberg,
Chris Adolphsen, Joel England, Mark Hogan, SLAC

LCWS2024, Tokyo
July 10, 2024

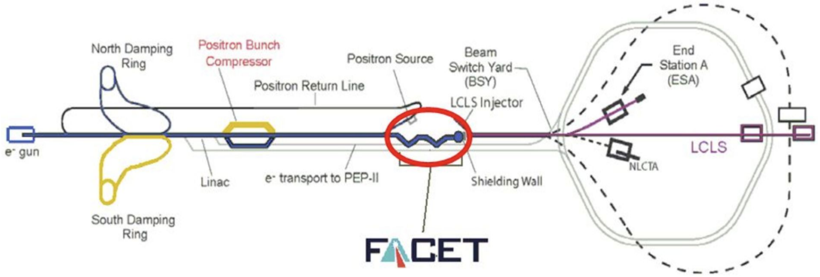
SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

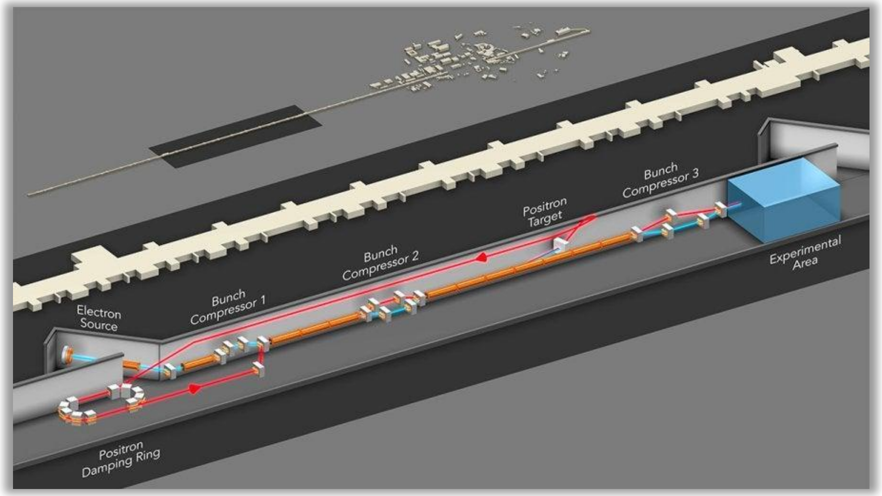
Motivation: Access to Positron Beams for Accelerator R&D

FFTB

FACET



FACET-II*



M. J. Hogan et. al. *Phys. Rev. Lett.* 90 205002 (2003).
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S. Corde et. al. *Nature.* 524 442445 (2015).
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S. Gessner et. al. *arXiv*:2304.01700 (2023).

*E333 experiment planned for filament regime positron PWFA.

Positron PWFA experiments have *only* taken place at SLAC by using existing SLC infrastructure.

Motivation: Access to Positron Beams for Accelerator R&D

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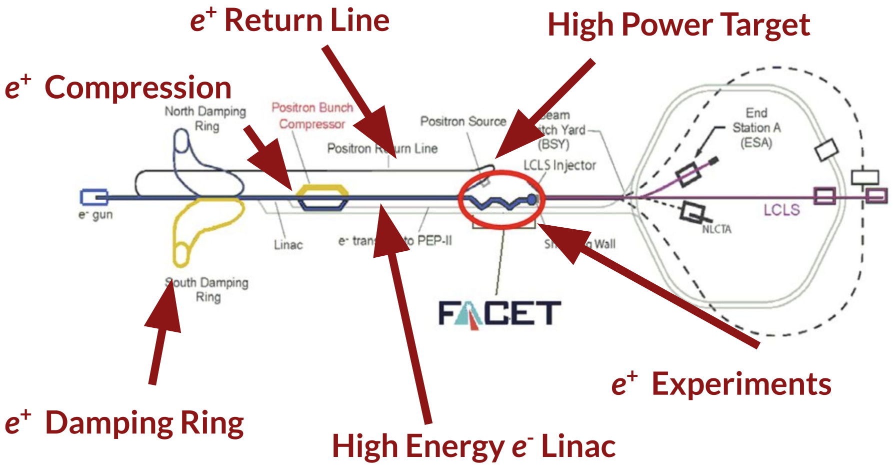
FACET



S. Corde et. al. *Nature.* 524 442445 (2015).
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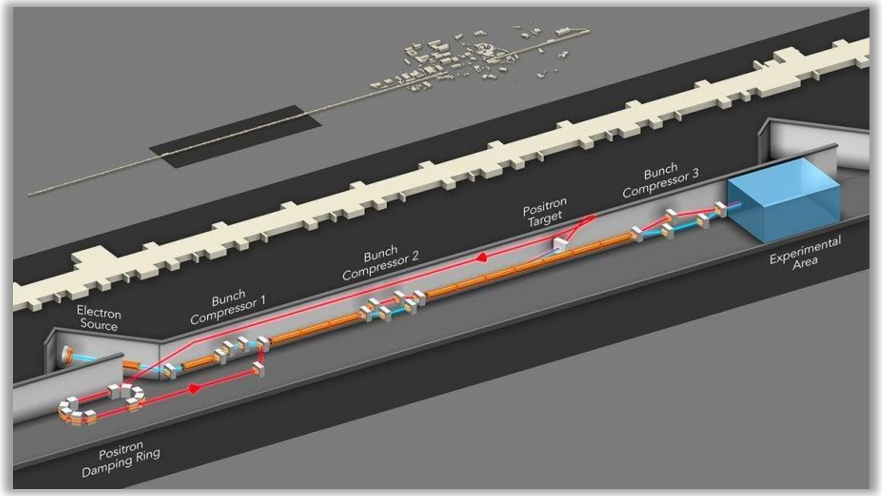

*E333 experiment planned for filament regime positron PWFA.

Approximately $50M to return e^+ capabilities to FACET-II

> Positron PWFA experiments have *only* taken place at SLAC by using existing SLC infrastructure.

Motivation: Multi-Disciplinary Science

Accelerator R&D

Exploring the Quantum Universe

Pathways to Innovation and Discovery in Particle Physics

Report of the 2023 Particle Physics Project Prioritization Panel

Executive Summary

An upgrade for FACET-II e⁺ is uniquely positioned to enable study of positron acceleration in high-gradient plasmas.

A strategic plan for the High Energy Physics Advisory Panel

Advanced Accelerator Physics

PHYSICAL REVIEW ACCELERATORS AND BEAMS

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Open Access **Review Article**

Positron acceleration in plasma wakefields

Gevy J. Cao, Carl A. Lindstrøm, Erik Adli, Sébastien Corde, and Spencer Gessner

Phys. Rev. Accel. Beams **27**, 034801 – Published 5 March 2024

Article | References | No Citing Articles | PDF | HTML | Export Citation

Laboratory Astrophysics

Physics of Plasmas | PERSPECTIVE | scitation.org/journal/php

Review Article

Perspectives on relativistic electron-positron pair plasma experiments of astrophysical relevance using high-power lasers

Cite as: Phys. Plasmas **30**, 020601 (2023); doi: 10.1063/5.0134819
Submitted: 14 November 2022 · Accepted: 19 January 2023 ·
Published Online: 24 February 2023

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[a)]Authors to whom correspondence should be addressed: chen33@llnl.gov and fiuza@slac.stanford.edu

Ultrafast Materials Science

Article | Open access | Published: 22 June 2022

Many-body theory of positron binding to polyatomic molecules

Jaroslav Hofie...

Nature 606, ...

7359 Access...

PHYSICAL REVIEW LETTERS **130**, 263001 (2023)

Many-Body Theory Calculations of Positron Scattering and Annihilation in H_2, N_2, and CH_4

C. M. Rawlins,...
Centre for Light-M...

Available online at www.sciencedirect.com

ScienceDirect

surface science reports

Surface Science Reports 71 (2016) 547–594

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Positrons in surface physics☆

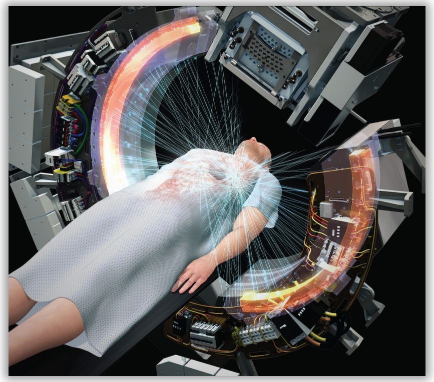
Christoph Hugenschmidt

FRM II and Physik-Department E21, Technische Universität München, Lichtenbergstraße 1, 85748, Germany

Received 9 June 2016; received in revised form 9 June 2016; accepted 24 September 2016
Available online 4 October 2016

Stanford Medicine first to try out novel tumor-targeting radiation therapy machine

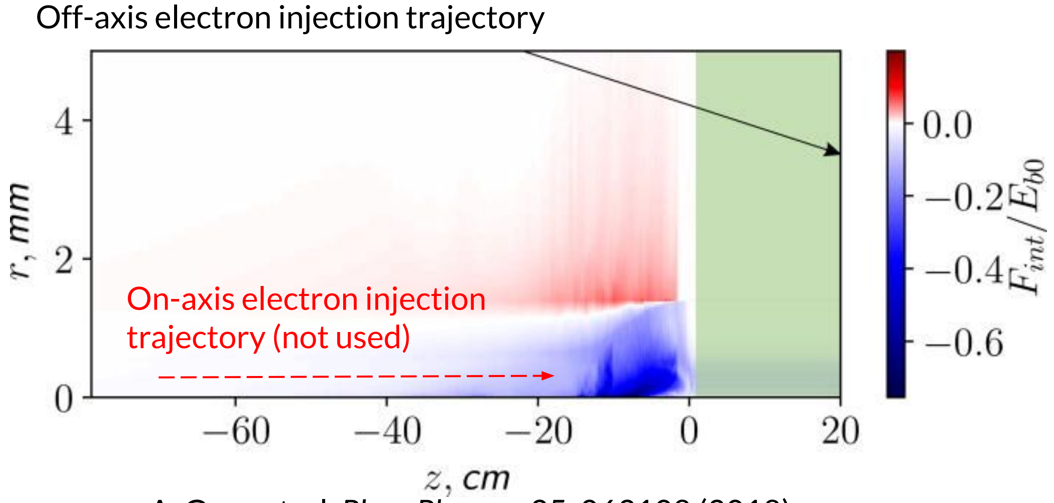
Novel Treatment Modalities



SLAC is *uniquely positioned* to deliver positron beams available nowhere else in the world for high-impact research.

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)

Seed of an Idea

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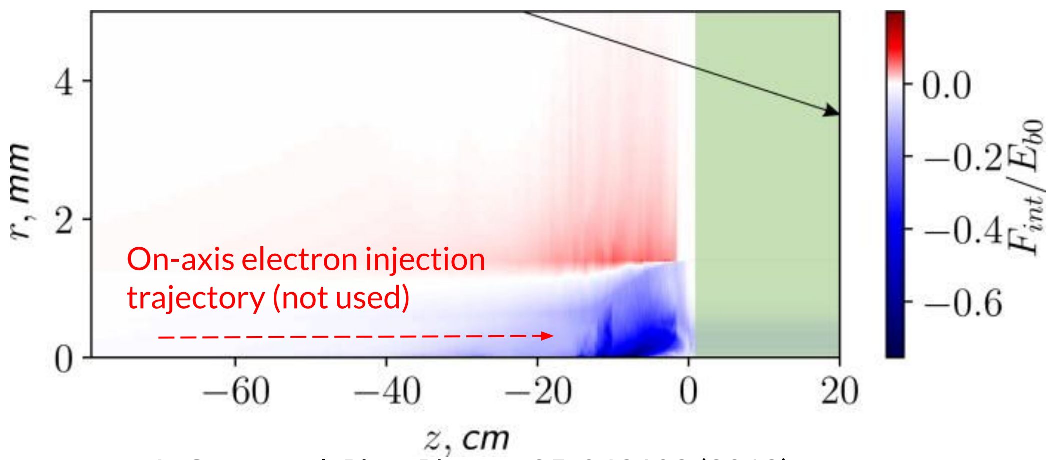
Off-axis electron injection trajectory

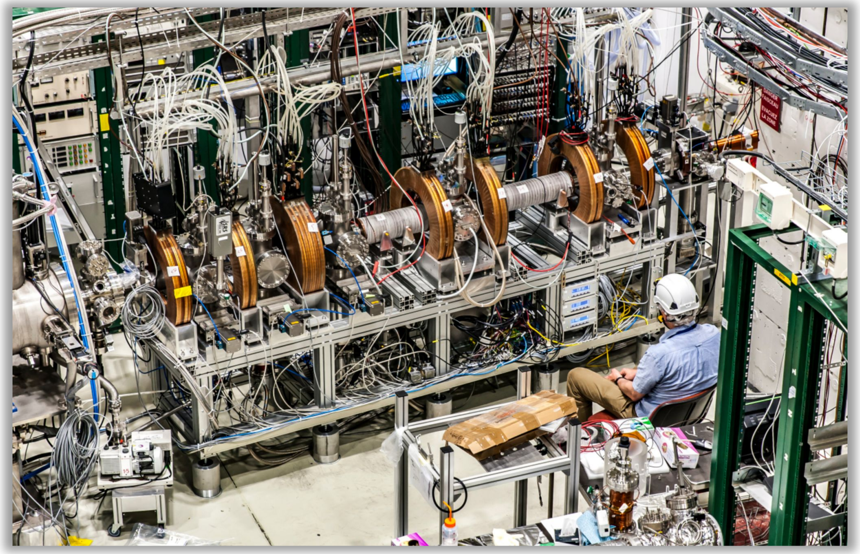


A. Gorn et. al. *Phys. Plasmas* 25, 063108 (2018)

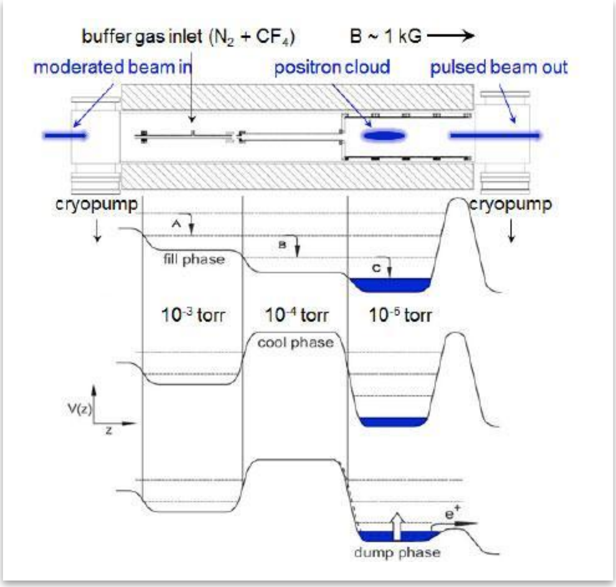
- But where to find a positron beam source compatible with AWAKE e^- injector footprint?

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

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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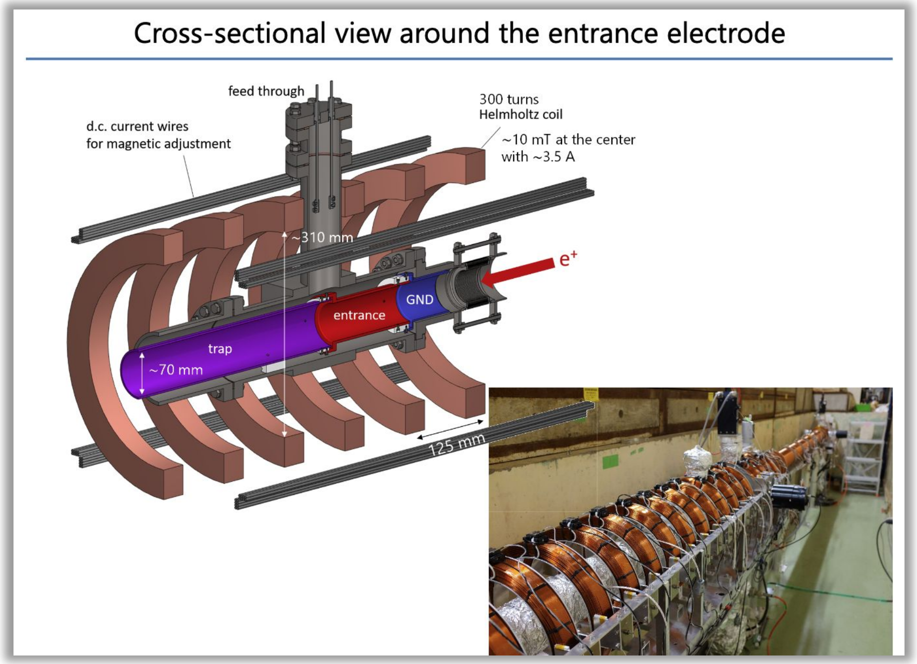
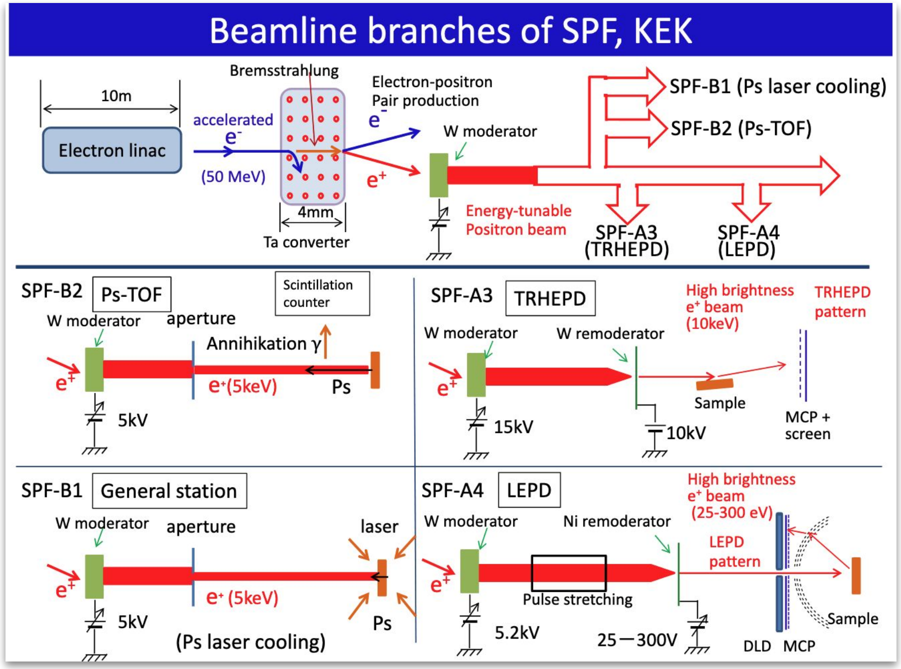
Low-Energy Positron Beams for Materials Science

KEK Slow-Positron Facility





Low-energy positron beams are probes for materials science research and are a particularly useful tool for studying surfaces.

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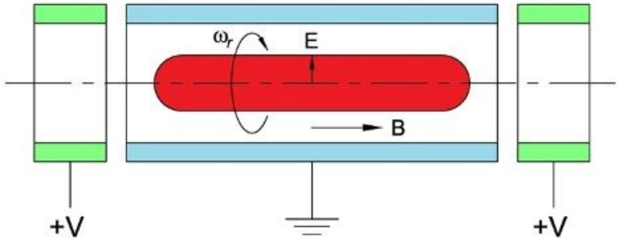
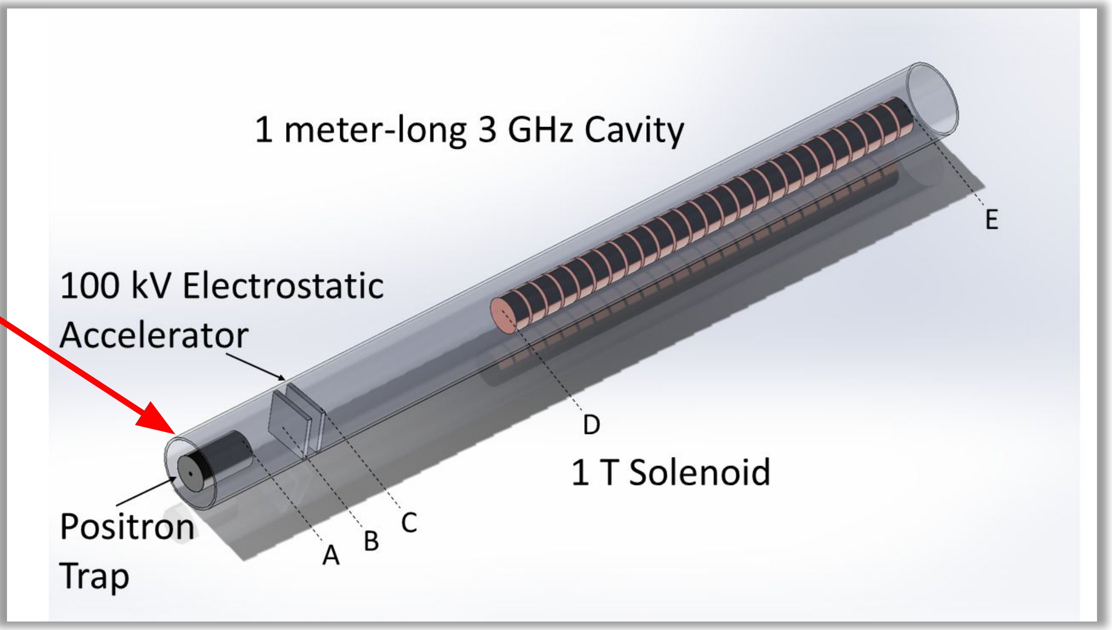
Penning-Malmberg Traps for Positron Beams

Penning-Malmberg Trap



Compact Source of Positron Beams with Small Thermal Emittance,
R. Hessami and S. Gessner. Phys. Rev. Accel. Beams 2023.



Are Penning-Malmberg traps viable sources of positron beams?
100 nm emittance!

Challenges

Challenge #1

Produce high quality positron bunches at high rate

Challenge #2

Compress and accelerate positrons from trap while preserving the beam quality.

Production Rate Challenge

The positron trap provides high-quality beams, but at relatively low rate. The current state-of-the-art is around $1 \times 10^8\ e^+/s$.

The FACET-II positron source based on the SLC target system with a new damping ring can provide $3 \times 10^{10}\ e^+/s$.

We can purse high-impact accelerator R&D with only $1 \times 10^9\ e^+/s$, a ten-fold improvement over the current state-of-the-art.

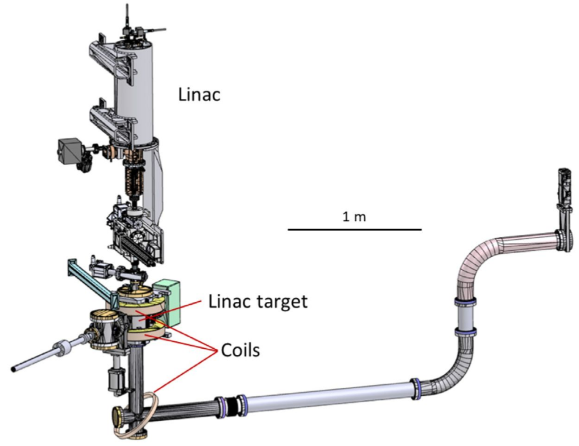
Nuclear Inst. and Methods in Physics Research, A 985 (2021) 164657

Table 1
Performance of linac-based positron sources.

Linac	e^- energy MeV	e^- beam power W	Slow e^+ flux $10^7\ e^+/s$	Efficiency $10^{-7}\ e^+/e^-$
Oak Ridge [33]	180	55 000	10	0.53
Livermore [34]	100	11 000	1000	16
ETL, Japan [35]	75	300	1.0	6
KEK [36]	55	600	~~5~~ 10	7.3
Ghent [37]	45	3800	2	0.4
Giessen [38]	35	3500	1.5	0.2
Mitsubishi, Japan [39]	18	16	0.077	1.35
GBAR, CERN	9	2500	5	0.28
Saclay, CEA [40]	4.3	300	0.2	0.05

M. Charlton, J.J. Choi, M. Chung et al.

GBAR Source



A 100 MeV electron beam with 1 kW power will produce 10^9 slow positrons per second.

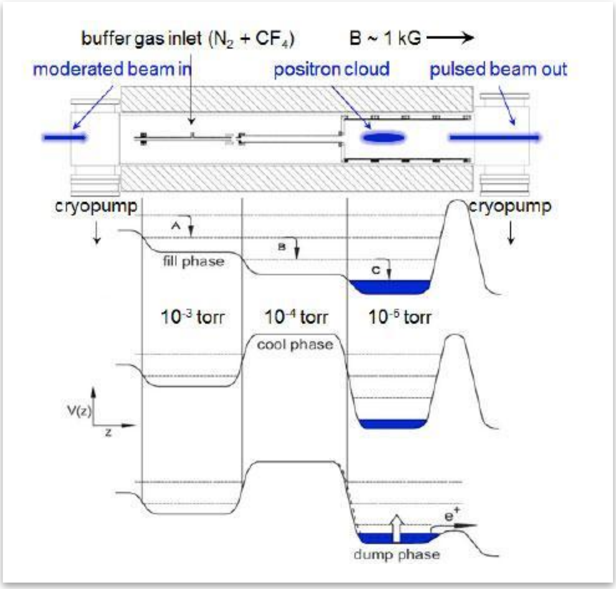
Positron Capture

The traditional method for capturing and cooling positrons is with a buffer gas trap.

The positrons in the trap cool faster than they annihilate with the gas.

But it takes a long time to accumulate enough positrons. . .

Positrons are lost while we wait to accumulate.



Schematic for trapping and cooling positrons

Efficient Positron Capture

The AIST group in Japan has developed a novel method for trapping positrons that is optimized for linac sources (New Jour. Phys, 24, 123039 2022).

The technique takes advantage of the pulsed nature of the linac source (as opposed to CW radionuclide sources).

The potentials inside the trap are synchronized with the incoming positron beam.

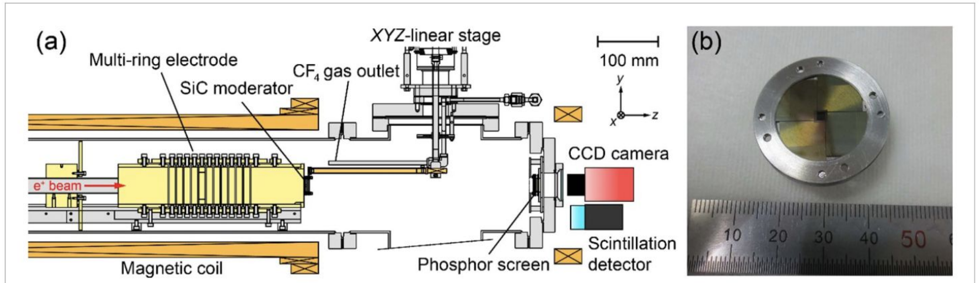

New J. Phys. **24** (2022) 123039 K Michishio *et al*

Figure 1. (a) Schematic of the SiC-based positron trap and the system for monitoring the extracted positrons. (b) Photograph of the center-hole SiC remoderator. Four 10 mm square pieces of a 4 H-SiC wafer arranged in a clover shape form a 2 mm square, which serves as the center hole.

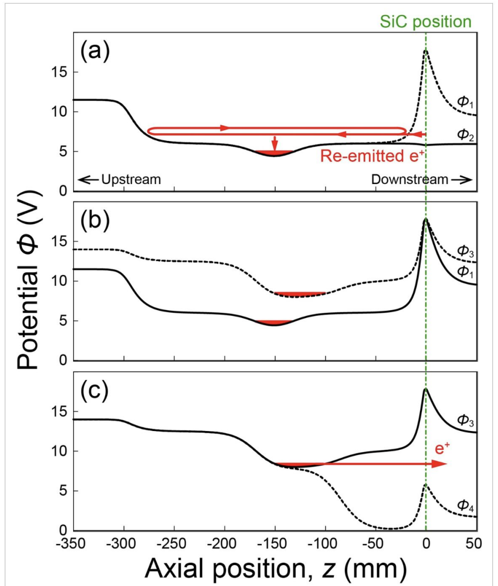


Figure 2. Electrostatic potential on the trap central axis for each operation: (a) accumulation stage of positrons re-emitted from the SiC remoderator ($\Phi_1 \rightarrow \Phi_2 \rightarrow \Phi_1$), (b) potential floating stage ($\Phi_1 \rightarrow \Phi_3$), and (c) pulse-extraction stage ($\Phi_3 \rightarrow \Phi_4$). The green dashed line at $z = 0$ mm denotes the position of the SiC remoderator surface.

The AIST technique is a 5X improvement over traditional BGT with pulsed beams.

Challenges

Challenge #1

Produce high quality positron bunches at high rate

Producing 10^9 e^+/s is challenging but possible with state-of-the-art techniques and 100 MeV e^- driver.

Challenge #2

Compress and accelerate positrons from trap while preserving the beam quality.

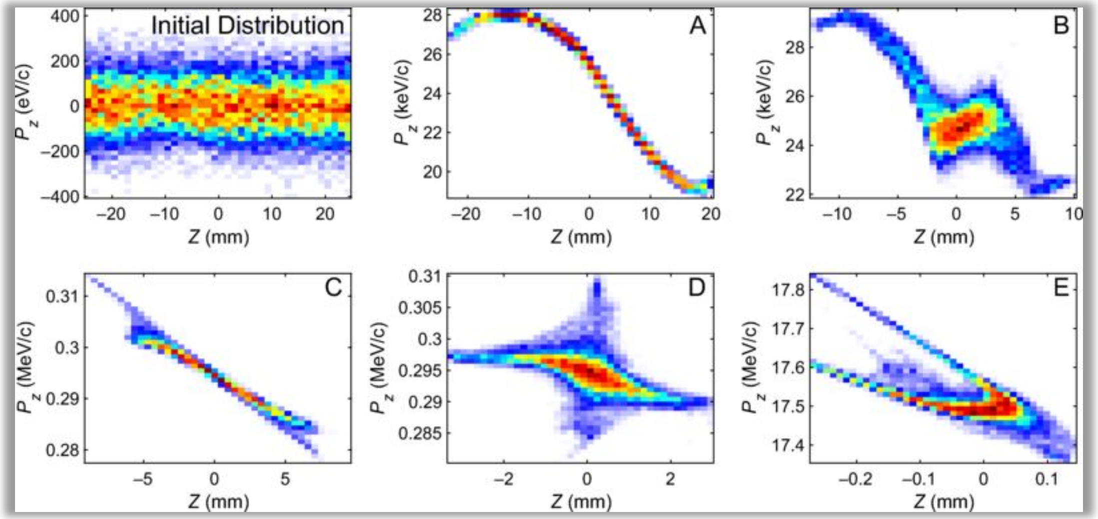
Compression and Acceleration

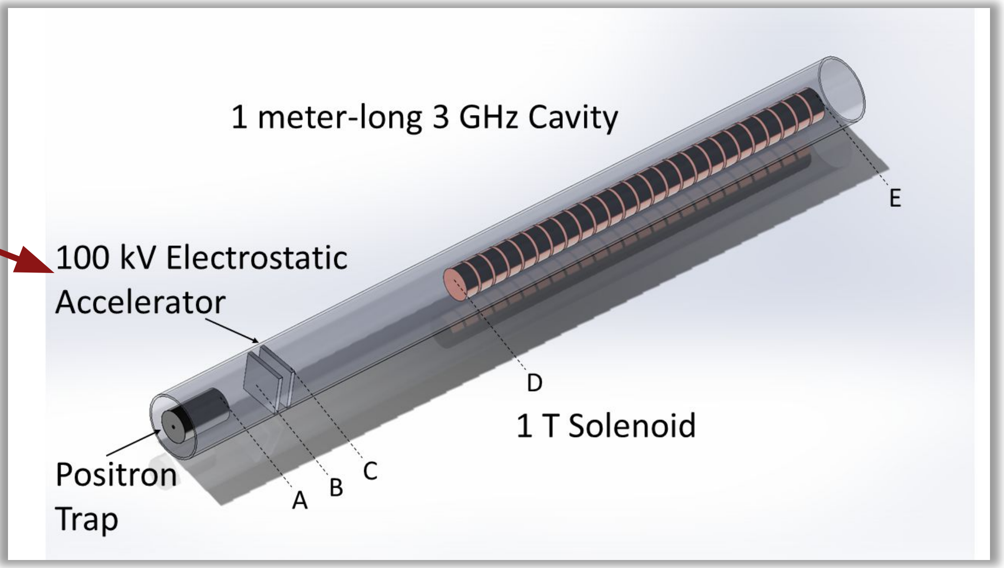
The beam inside the trap is *cold* and *at rest.*

The beam must be extracted from the trap, accelerated, and compressed in time.

Our PRAB paper explored electrostatic bunching, but we have not performed a detailed study of realistic devices.

Compact Source of Positron Beams with Small Thermal Emittance, R. Hessami and S. Gessner. Phys. Rev. Accel. Beams 2023.

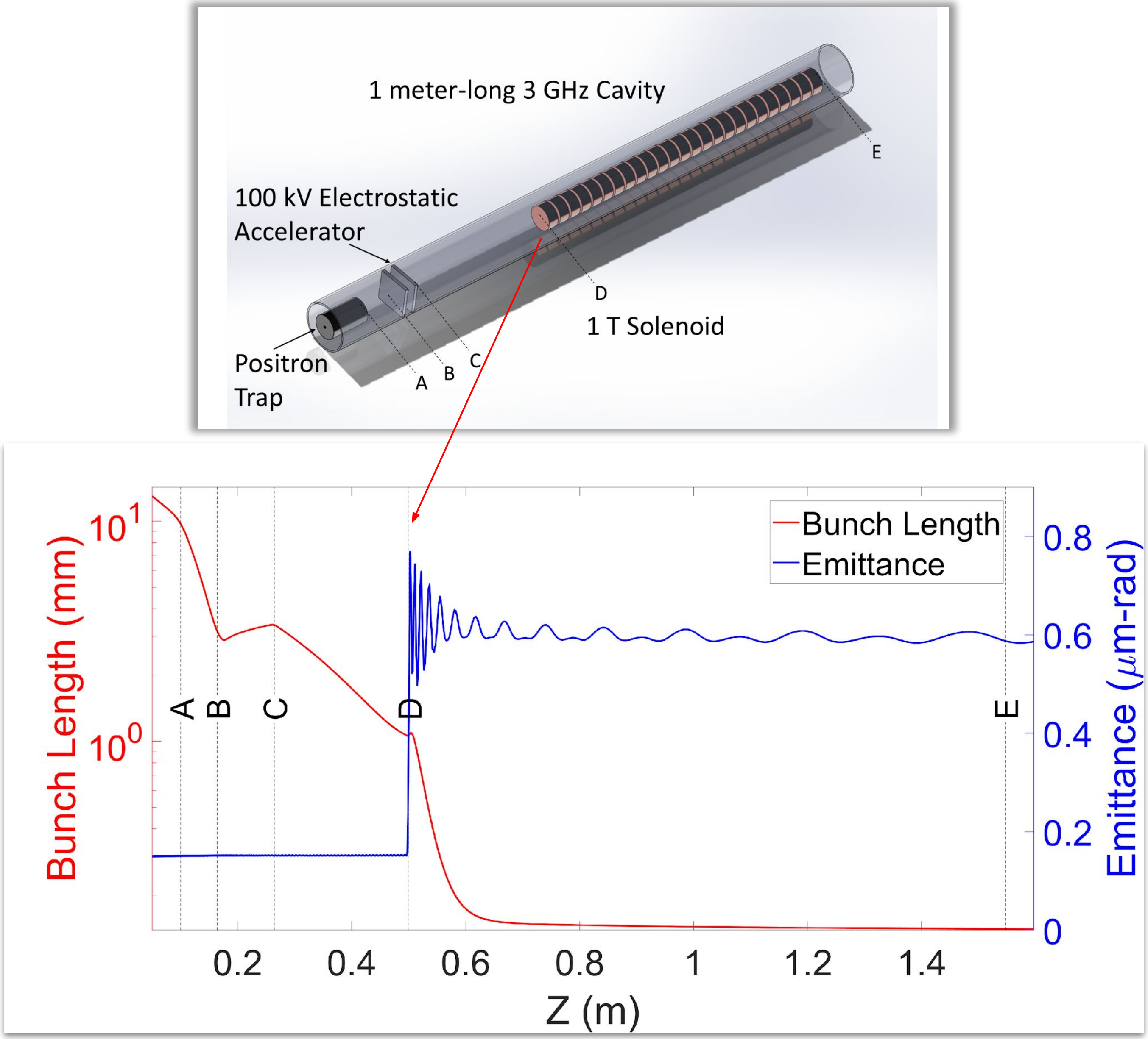




Emittance Growth

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.



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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.

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

$$\mathcal{L} = \frac{\langle xp_y - yp_x \rangle}{2} = \frac{eB\sigma_r^2}{2mc}$$

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

Solution: Round-to-Flat Beam Transformer

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

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[1]*Northern Illinois Center for Accelerator & Detector Development and Department of Physics, Northern Illinois University, DeKalb, Illinois 60115, USA*

[2]*Hiroshima University, Higashi-hiroshima, Hiroshima, Japan 739-8527*

[3]*Argonne National Laboratory, Lemont, Illinois 60439, USA*

(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.

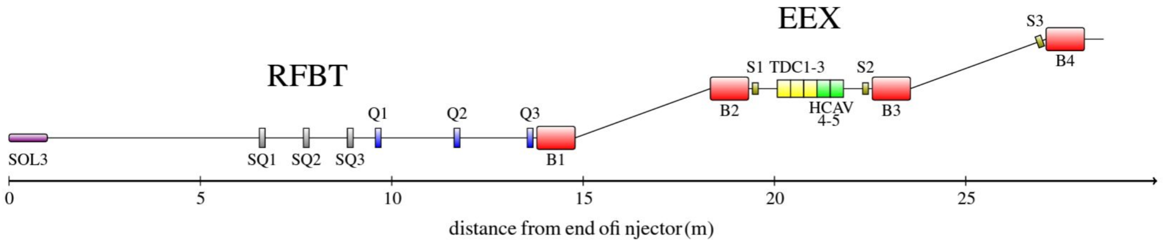


FIG. 2. Overview of the emittance manipulation beamline combining the RFBT (skew-quadrupole magnets SQ1, SQ2, and SQ3) and EEX (from dipole magnet B1 to B4) insertions. The label "SQ*i*" and "Q*i*" refer to skew- and normal-quadrupole magnets, "B*i*" and "S*i*" are dipole nd sextupole magnets. The elements "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.

Challenges

Challenge #1

Produce high quality positron bunches at high rate

Producing 10^9 e^+/s is challenging but possible with state-of-the-art techniques and 100 MeV e^- driver.

Challenge #2

Compress and accelerate positrons from trap while preserving the beam quality.

Solutions exist at conceptual level, but detailed models and beamline simulations are still needed.

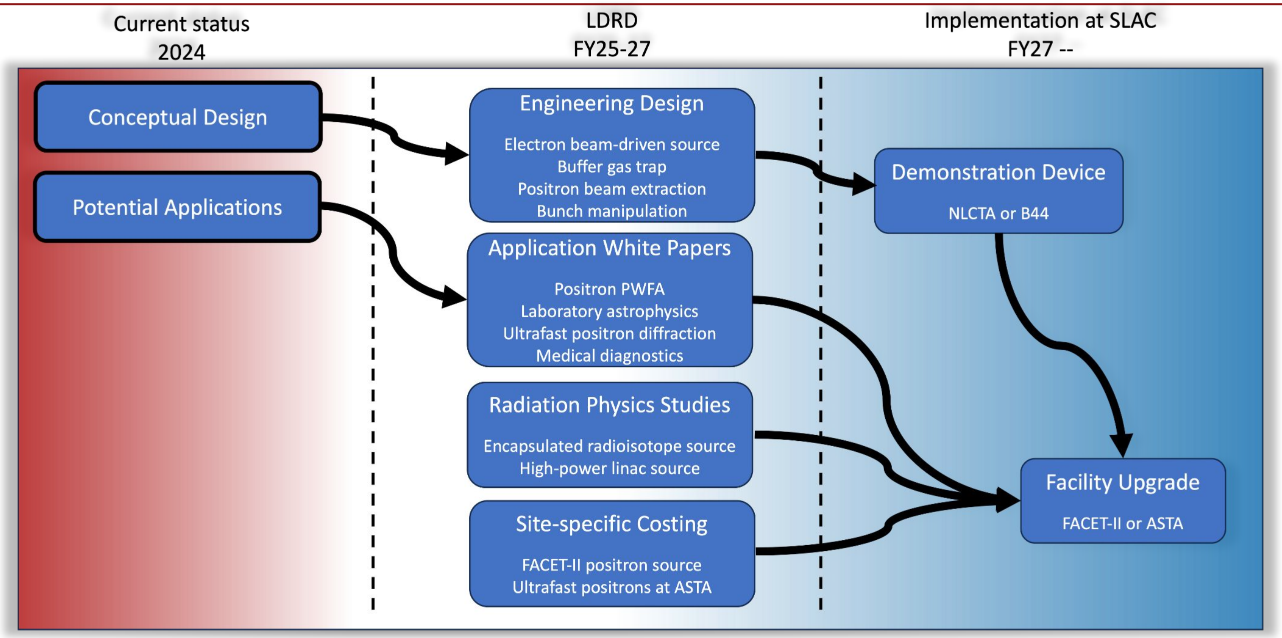
Plan at SLAC

We have requested $500k LDRD funding to pursue a *technical design* of the compact positron source:

- Compact 100 MeV e^- linac using C^3 technology.
- Cooled tungsten target with moderator for 1 kW beam.
- Shielding and Radiation Protection Considerations.
- AIST trap technique plus accumulator trap.
- Pulsed extraction and compression using fast rise-time components.
- RF acceleration.
- Round-to-flat beamline.
- Integration in FACET-II.
- Modeling with GPT, Impact-T, CST, ACE3P.

We will pursue a demonstrator at SLAC (NLCTA) or through collaboration with universities.

Research Roadmap



We anticipate that by the end of the LDRD, we will have already applied for funding such that construction and implementation of the compact positron source can begin in FY26 or FY27.

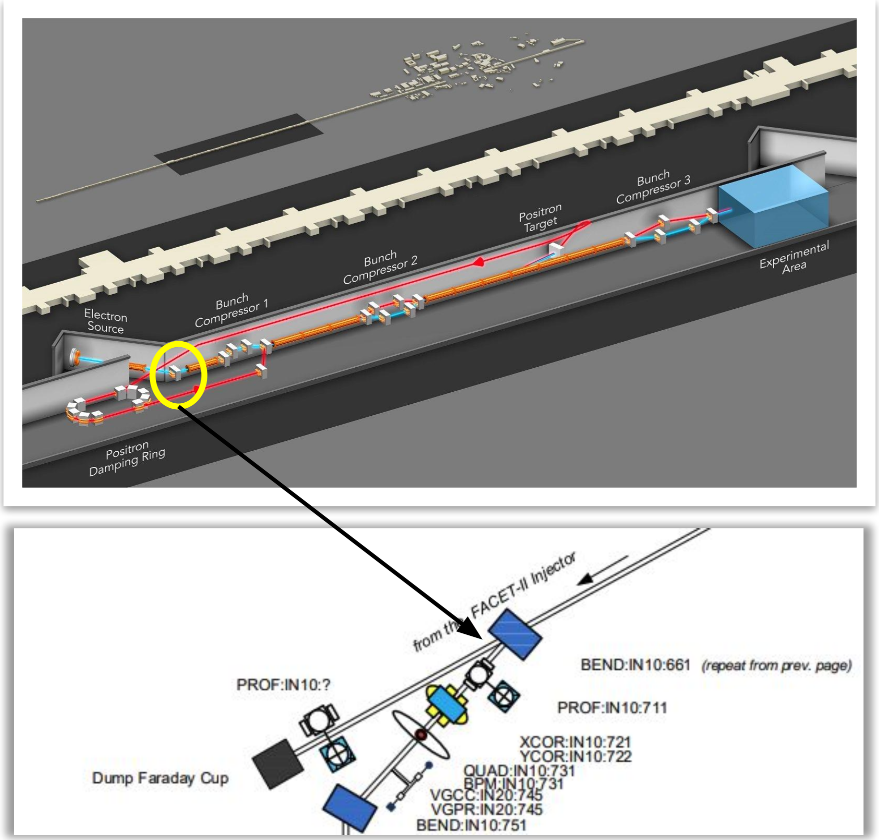
A stand-alone system could be installed at NLCTA or B44 or at a university in support of beam physics R&D, first materials science studies, and first tests of positron tracer beams for radiation therapy.

An integrated system could be deployed at FACET-II, consistent with LAF downtimes and constraints from LCLS-II. Science with positron beams could begin in FY28.

Backup

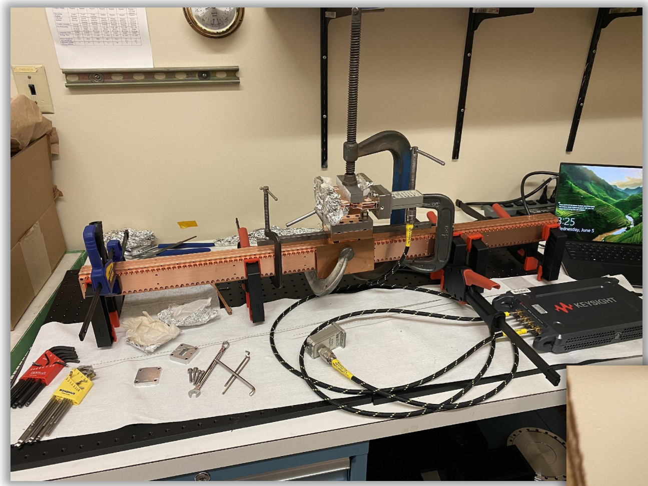
Approach: Linac Source

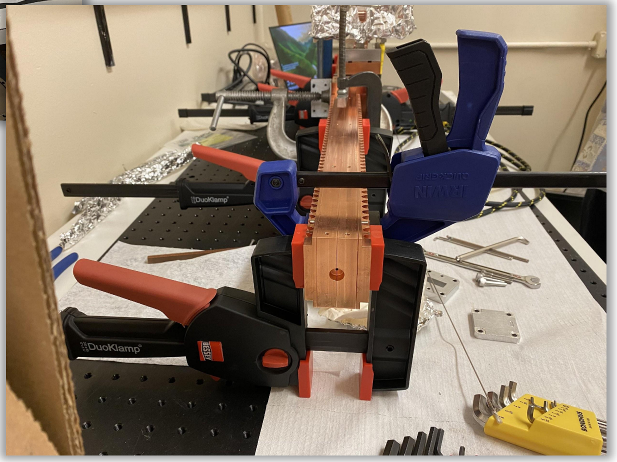
FACET-II



Replace switchable dipole with kicker to select 125 MeV electron bunches for positron target. This is compatible with FACET operation: 30 Hz at injector with 10 Hz for experiment and 20 Hz for positron generation.

Stand-alone System





Meter-scale, cryo-cooled, distributively coupled RF structure produces 100 MeV beams with 2.5 kW beam power. **A compact solution using C^3 technology!**

Approach: Targetry and Radiation Protection

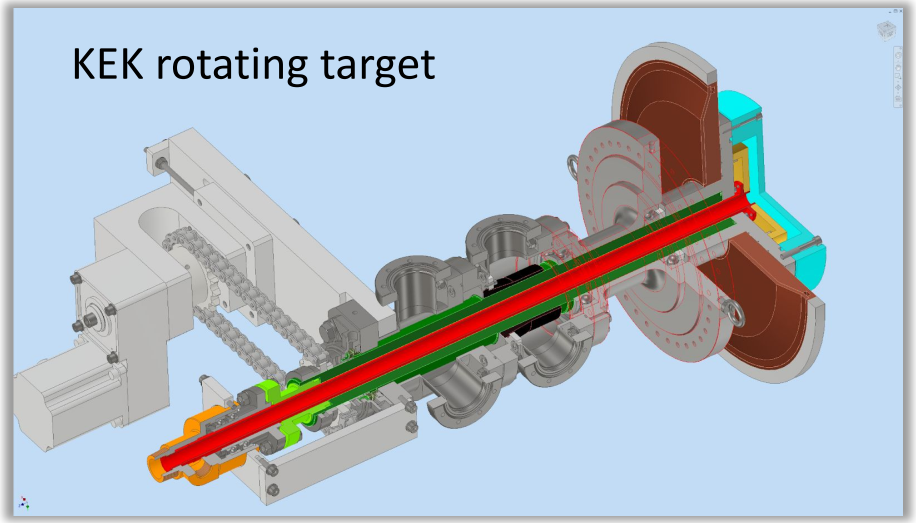
The target must withstand 1 kW of incident beam power.

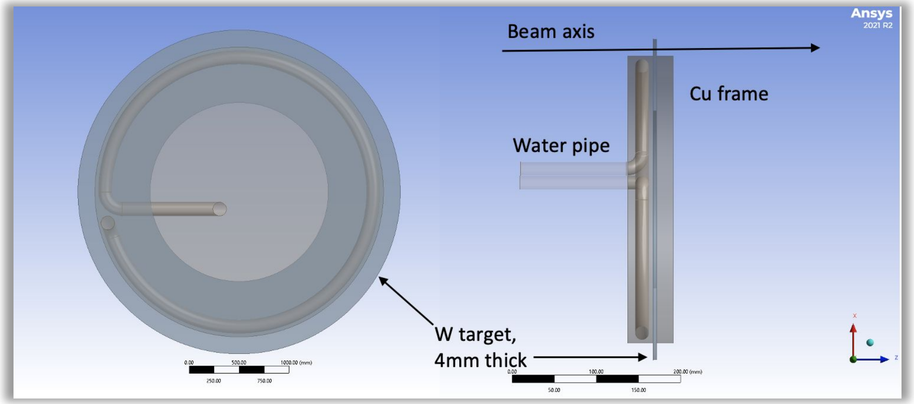
We will leverage our existing collaboration with KEK and JLab through the “Advanced Electron and Positron Sources” US-Japan grant.

A thin (1 mm), rotating tungsten target with water cooling is likely sufficient for our needs.

We will work with Radiation Protection to develop a compact shielding solution for 1 kW of losses at 125 MeV beam energy.

We just learned that our follow-on grant “Advanced Positron Sources” will be funded.





Approach: Beam Extraction and Modeling

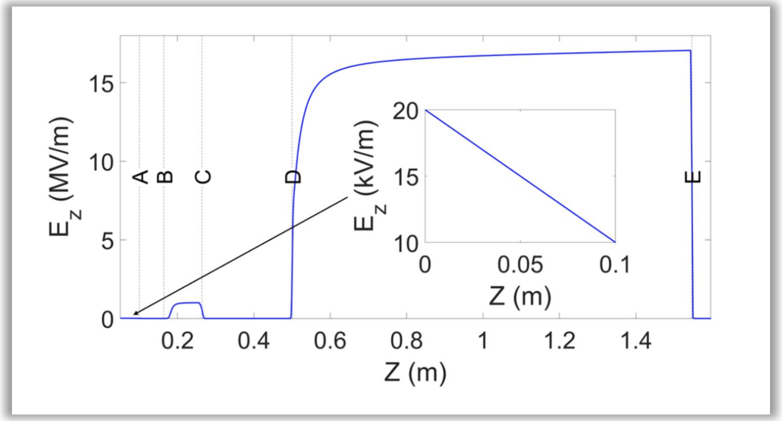
Our PRAB paper modeled the acceleration and compression of the beam with the GPT code.

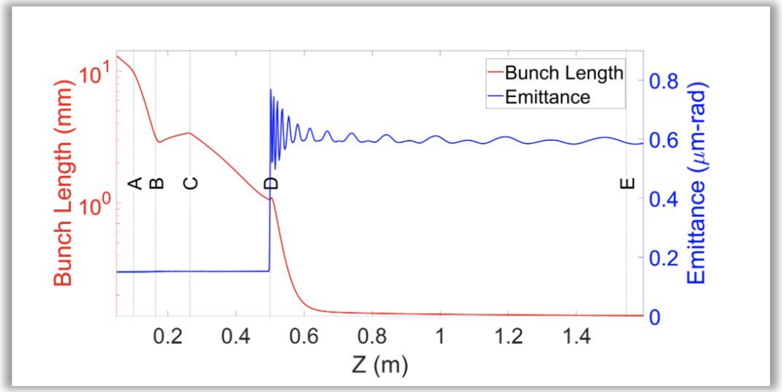
We observe a blow-up in emittance at the entrance of the s-band accelerator structure. We aim to address this issue with iterative beam dynamics studies.

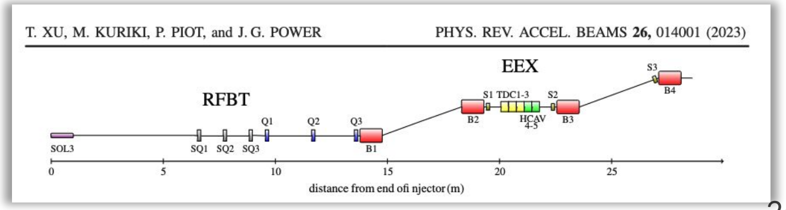
After initial acceleration, the beam undergoes a round-to-flat transformation with a skew quadrupole lattice. The round-to-flat lattice should be as compact as possible.

The LDRD will fund a postdoc to carry out a detailed study of open beam physics questions.

Compact Source of Positron Beams with Small Thermal Emittance, R. Hessami and S. Gessner. Phys. Rev. Accel. Beams 2023.







Ultimate Parameters

[Compact Source of Positron Beams with Small Thermal Emittance, R. Hessami and S. Gessner. Phys. Rev. Accel. Beams 2023.]

Our study will establish the expected performance parameters for a system to be built and demonstrated at SLAC. Performance parameters include:

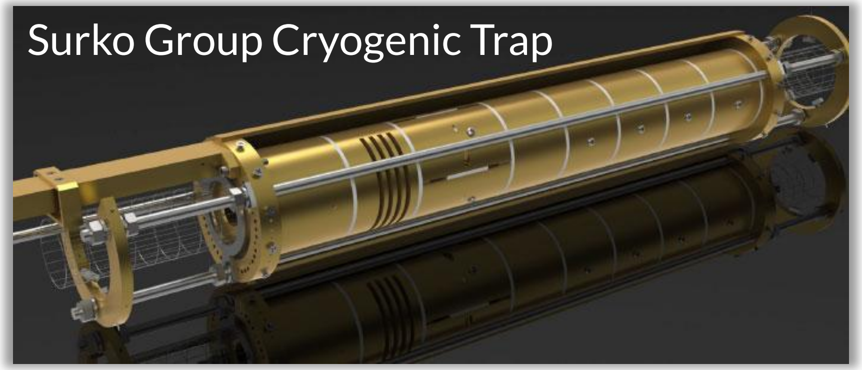
- Bunch rate
- Bunch charge
- Emittance
- Bunch length

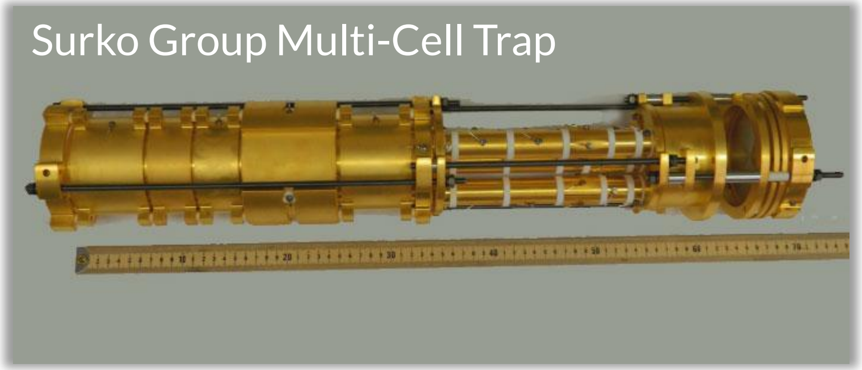
Our study will also provide a roadmap for future R&D and upgrades that will extend the capabilities of the trap to provide even higher quality beams. Future R&D directions may include:

- A cryogenic trap for even lower emittance beams.
- A multiplexed trap to increase the beam rate.

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

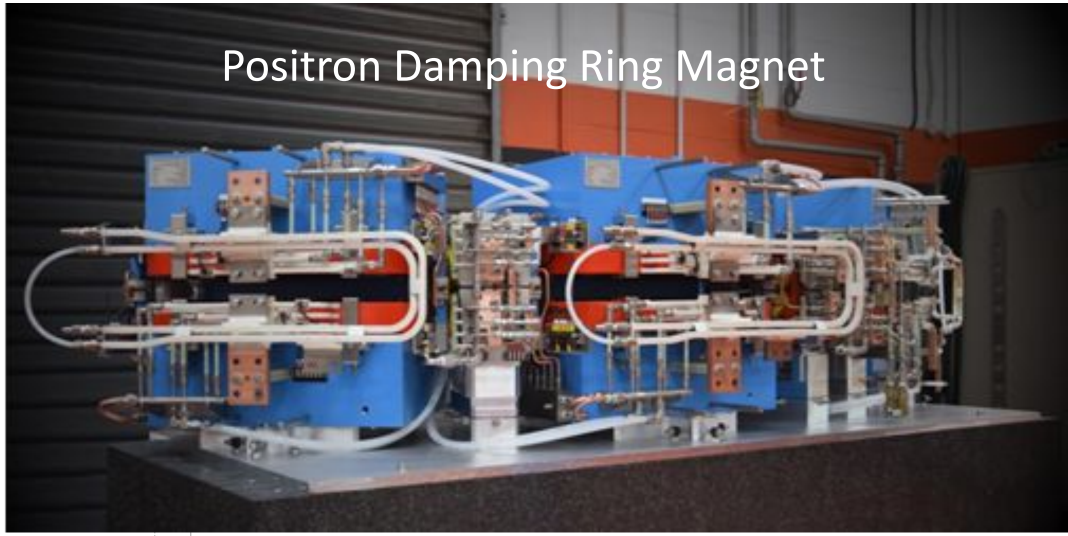
Beam parameter	Value
Beam energy	17.6 MeV
Beam charge	15.43 pC
Bunch length (rms)	190 μm
Energy spread (rms)	0.76%
Transverse emittance	0.60 μm rad

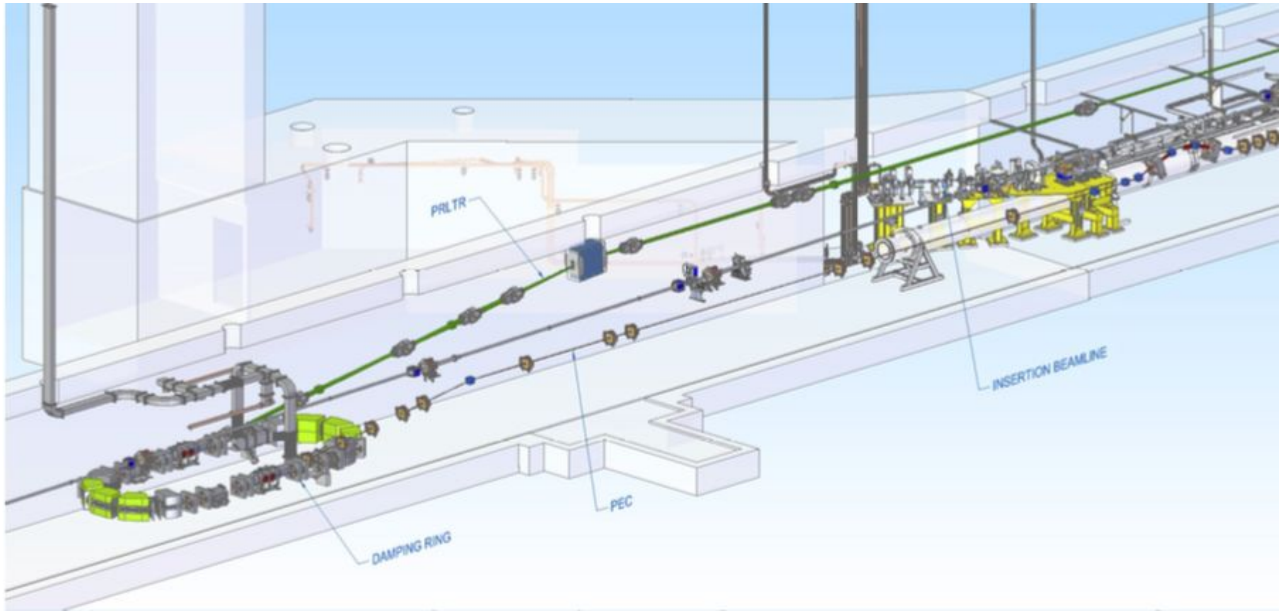


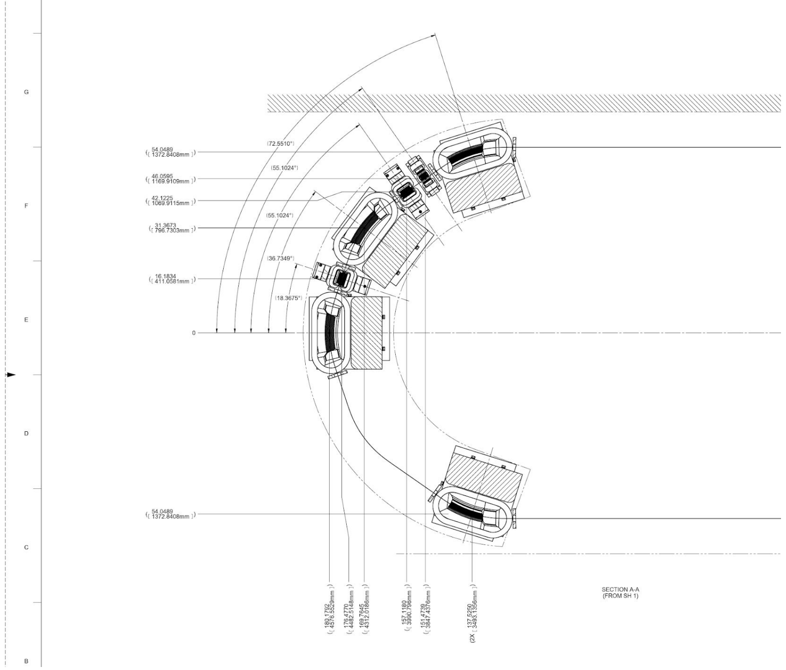


Positrons at FACET-II

- 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.







Sodium-22 Source

A ^{22}Na positron source for use in UHV

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Abstract

A source capsule for ^{22}Na isotope sources for use in UHV positron beam systems is described. The capsule is suitable for a source strength up to 0.1 Ci (3.7×10^{9} Bq).

PACS: 78.70.Bj
Keywords: Positron annihilation; Positron source; Positron beam; ^{22}Na isotope

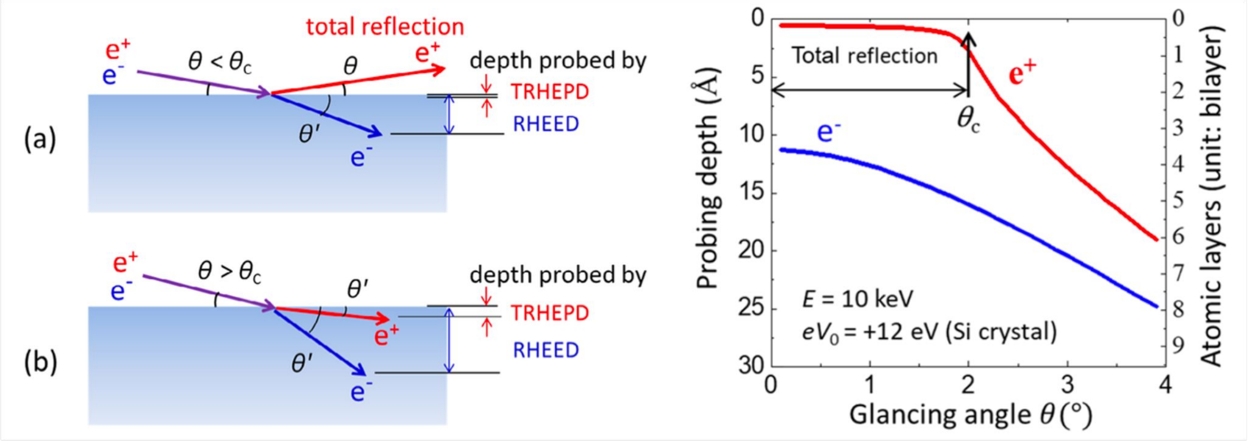
https://doi.org/10.1016/j.nimb.2004.03.049

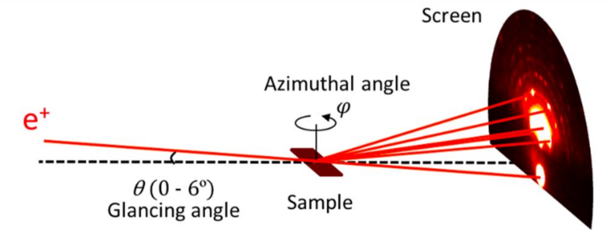
Fig. 3. The closed capsule (small design). The welding of the front ring is visible. The post has got a 6–32 UNC thread with a length of 6.3 mm.

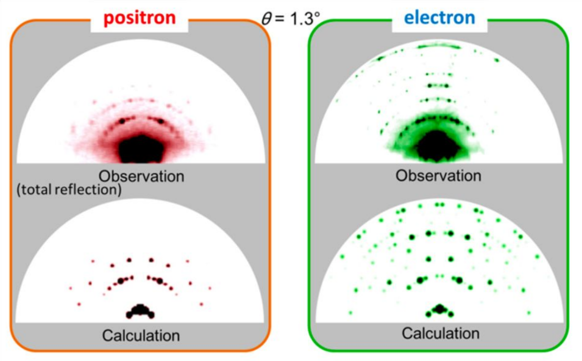
Questions: Ultrafast Science with Positron Beams

- Positron beams interact *differently* with the surface of materials than electron beams.
- This allows for direct probes of surface dynamics .
- The existing Slow Positron Source is just that, slow!

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

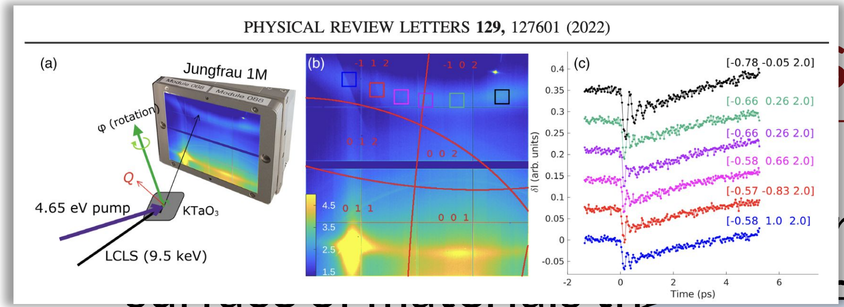




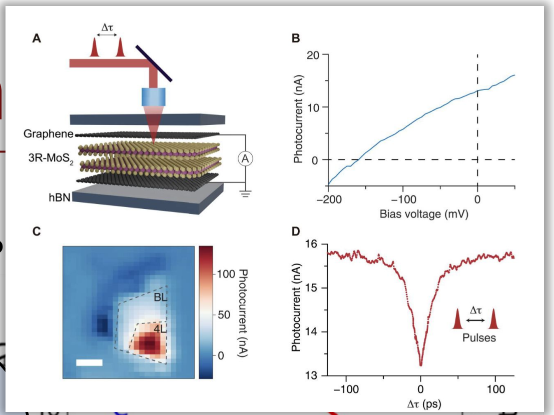


Can we compress positron bunches from PM traps to sub-picosecond direction and synchronize it with external laser probe?

Ferroelectrics, Krapivin et al, PRL (2022)



Heterostructures, Wu et al, Sci, Adv. (2022)

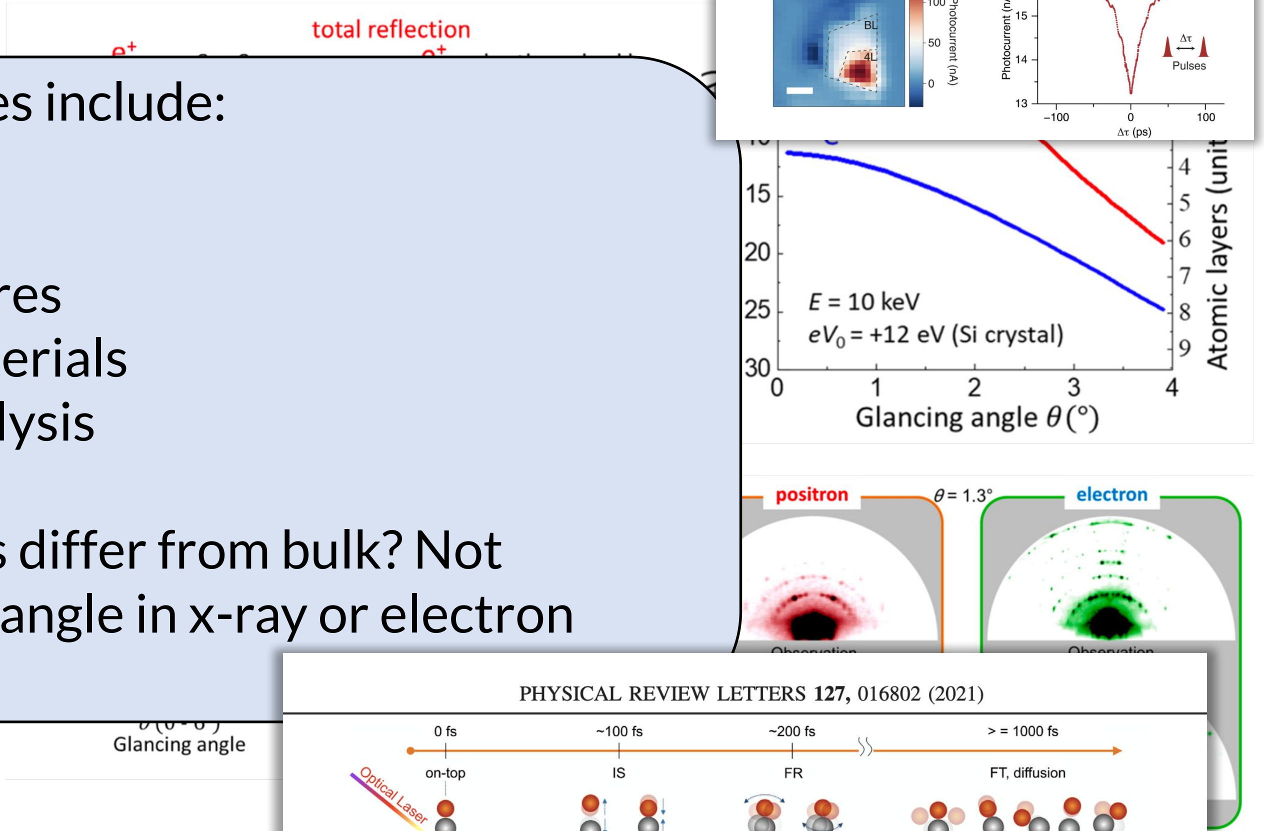


...st Science with Positron Beam...

...*ntly* with the
...surface of materials th... ...on beams

- This allows for direc... dynamics .
- The existing Slow P... slow!

Y. Fukuya, J. Phys. D: Appl. P...

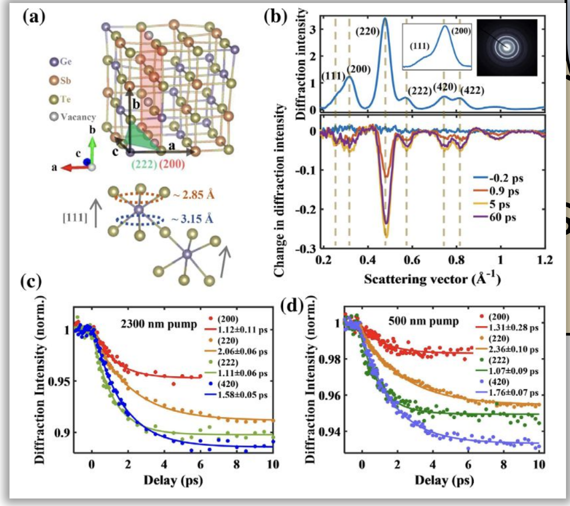


First science opportunities include:

- Ferroelectrics
- 2D heterostructures
- Phase change materials
- Materials for catalysis

How do surface dynamics differ from bulk? Not straightforward to disentangle in x-ray or electron scattering experiments.

...to sub-picosecond
...synchronize it with
...laser probe?



Phase Change Materials, Qi et al, PRL (2022)

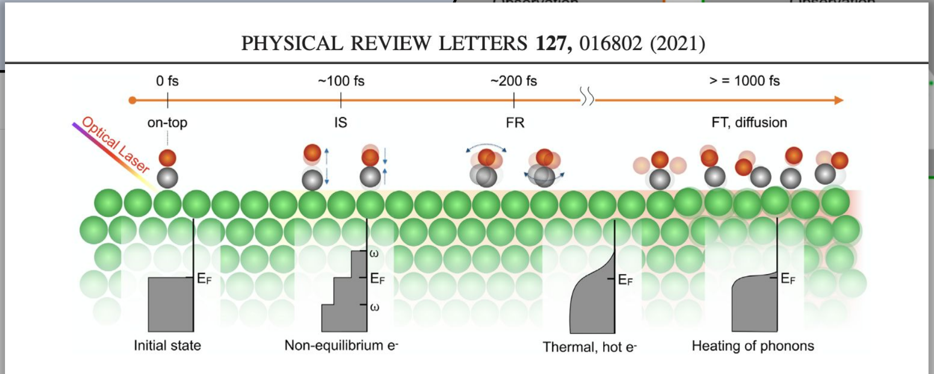


FIG. 3. Sketch of the system evolution during the first picosecond. Atom colors: O, red; C, gray; Ru, green.

Catalysis, Diesen et al, PRL (2021)