FACET-II

Facility for Advanced Accelerator Experimental Tests

Collider-Directed R&D at FACET-II

Mitigation of Beam-Beam Flip-Flop Instability

BB24 EPFL, Sep 2-5

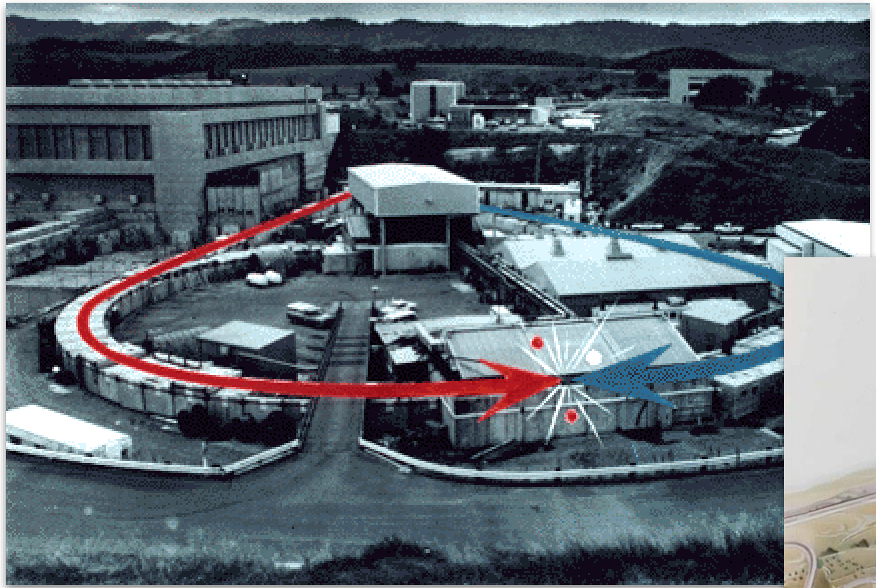
Spencer Gessner
Asst. Professor (Starting Oct. 1)
SLAC and Stanford University
sgess@slac.stanford.edu

SLAC NATIONAL ACCELERATOR LABORATORY

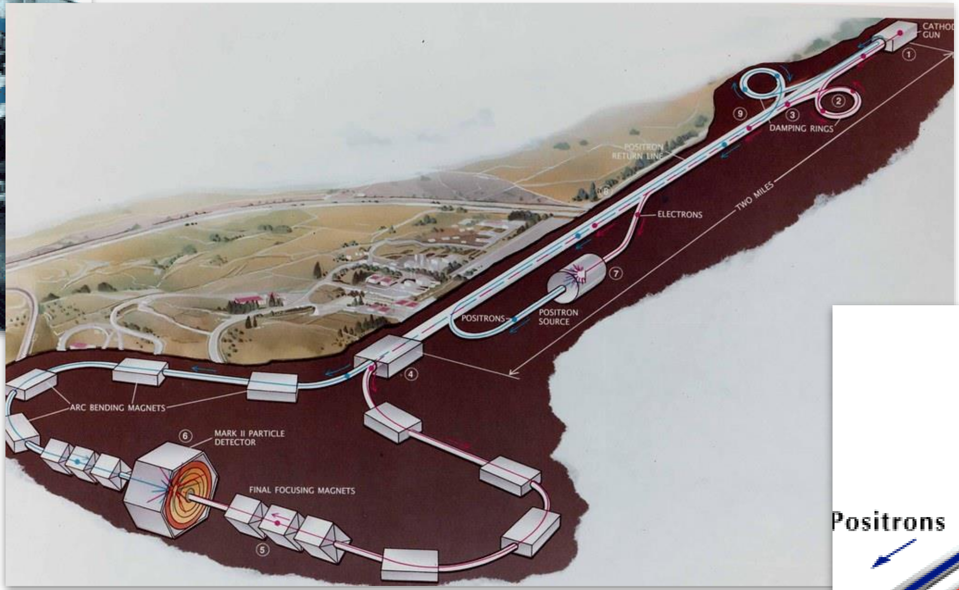
Stanford University | U.S. DEPARTMENT OF ENERGY

SLAC: Four Decades of Colliders

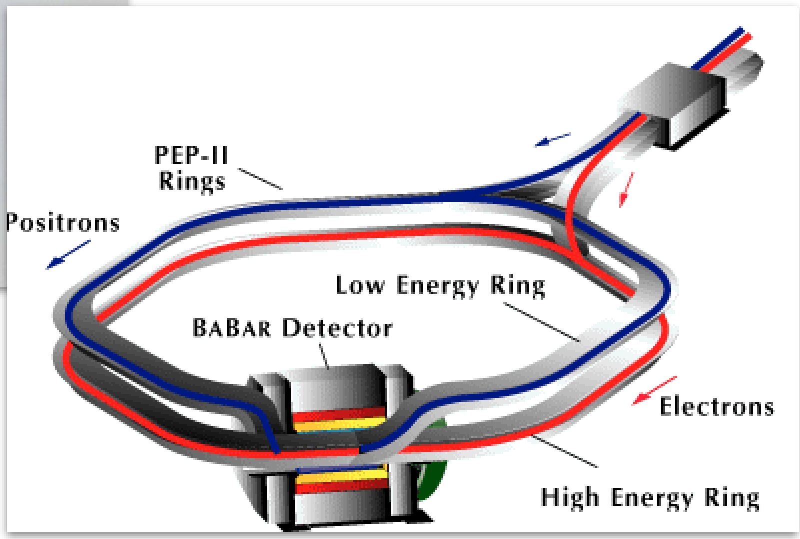
SLAC developed leadership in many areas of collider physics and continues to contribute expertise to the design and operation of colliders around the world.



SPEAR (1972-1990)



SLC (1988-1998)



PEP-II (1998-2008)

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FACET-II

Accelerator Beam Test Facility

LCLS-II

Highest Rate X-Ray FEL

LCLS

First X-Ray FEL

FACET-II provides *unique* beams

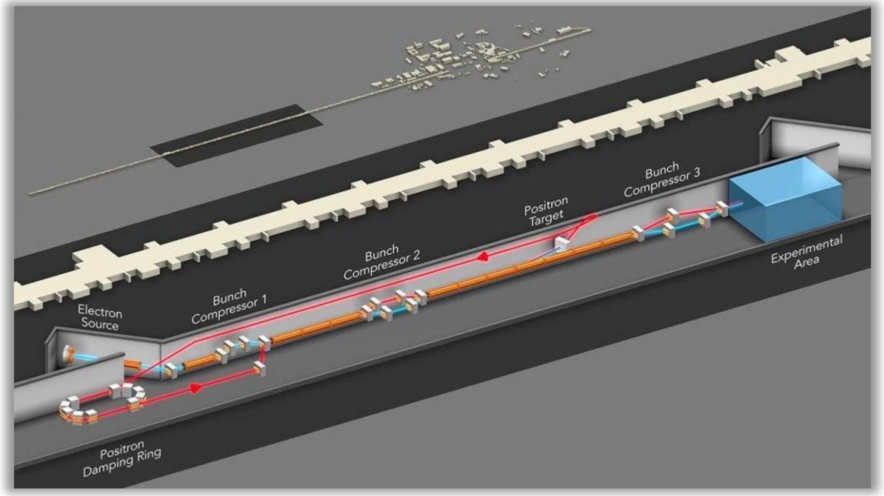
FACET-II delivers electron beams with nanocoulomb charge at 10 GeV energy.

FACET-II has three compressor chicanes to reduce the length of the bunch delivered to experiments.

The near term goal for FACET-II is to deliver beams with $\sigma_x \approx \sigma_y \approx \sigma_z < 10$ µm. The long term goal is 100 kA peak current beams.

The radial electric field of the electron bunch is about 100 GV/m in the lab frame!

FACET-II facility layout



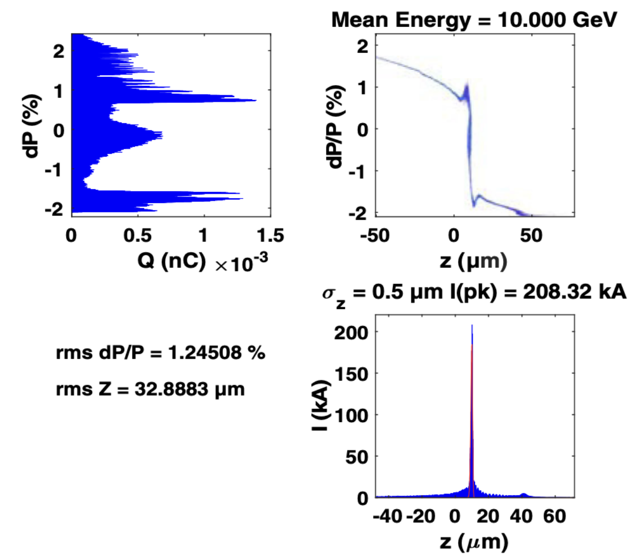


FIG. 4. Longitudinal phase space of the 2-nC electron bunch tracked to sector 20 at maximum compression.

https://doi.org/10.1103/PhysRevAccelBeams.22.101301

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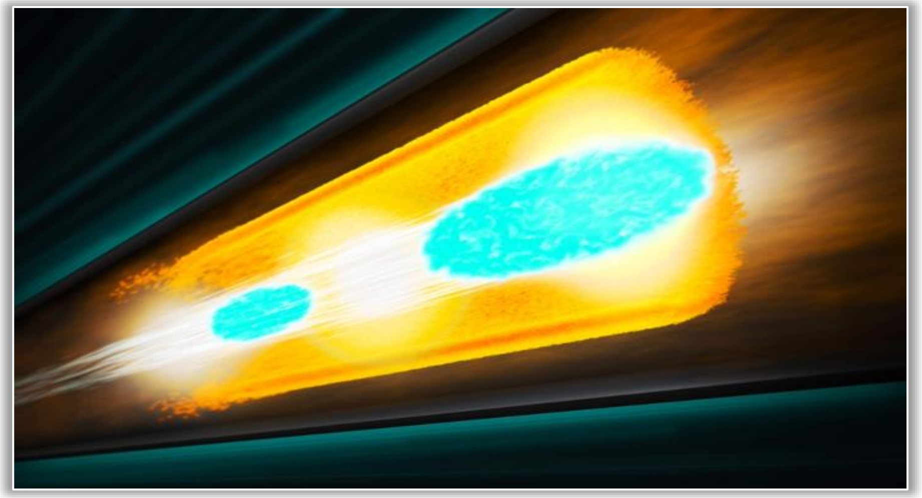
FACET-II: Extreme Beams

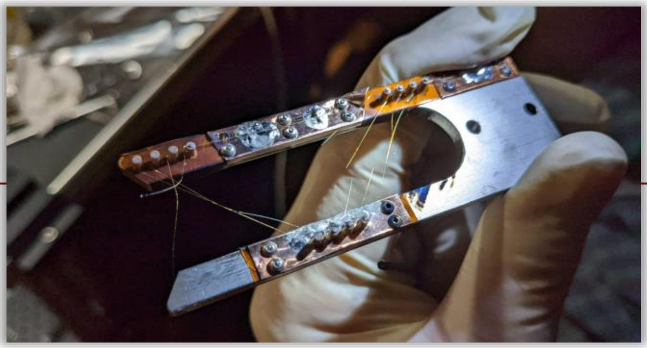
Ultra-high peak current bunches produce extreme fields!

The FACET beam eats intercepting diagnostics for breakfast.

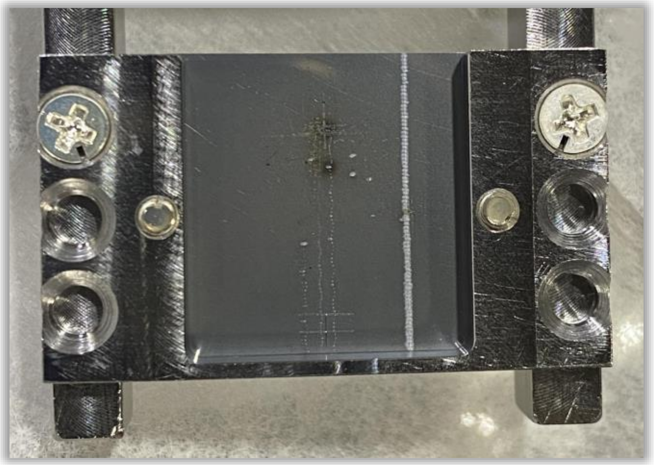
Beam-Driven Plasma Wakefield



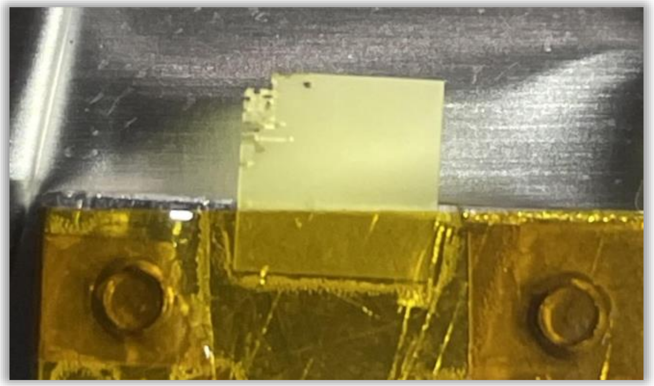
Extreme beams are required for the plasma wakefield acceleration program at FACET-II.



Wire scanner. . . shredded



OTR foil. . . drilled



YAG crystal. . . swiss-cheesed

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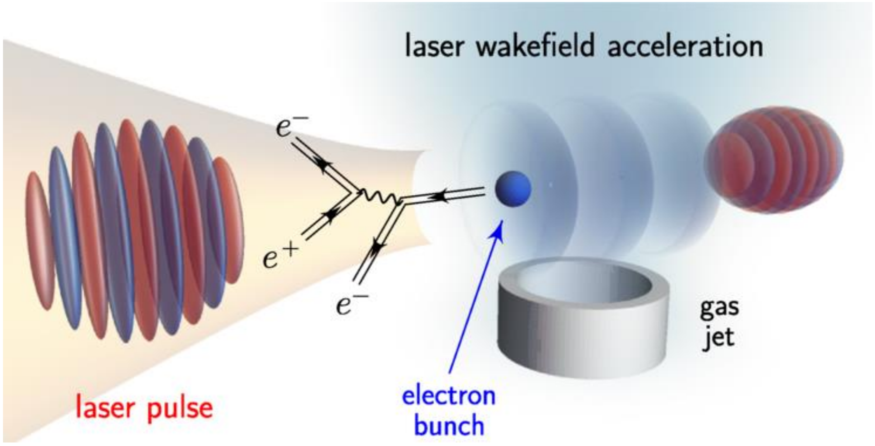
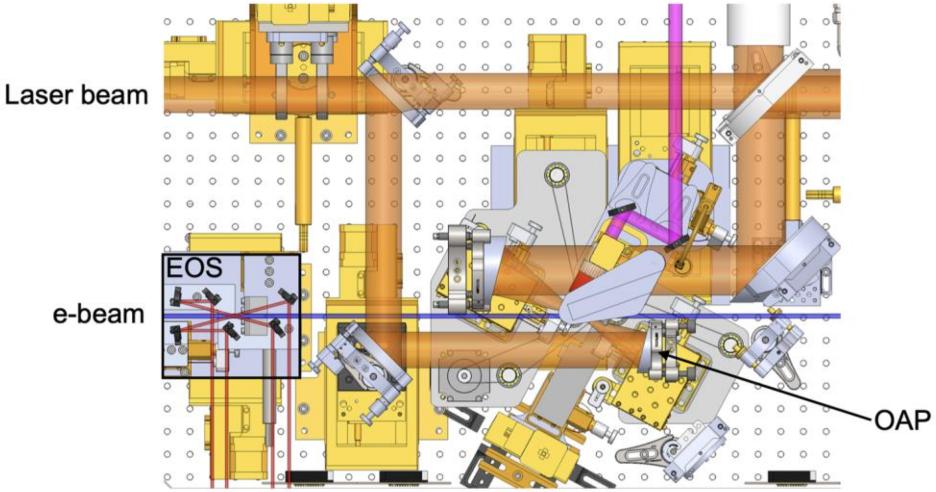
Strong Field QED at FACET-II

FACET-II has a 20 TW laser that can be used to collide with electron beam for inverse Compton scattering experiments.

The motivation for this research is to probe strong field QED effects:

- Nonlinear Compton scattering
- Coherent pair creation
- Trident cascade
- Violation of local constant field approximation





SLAC E320 Experiment

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P5 Report and Accelerator R&D Priorities

Recommendation 2: Construct a portfolio of major projects that collectively study nearly all fundamental constituents of our universe and their interactions, as well as how those interactions determine both the cosmic past and future.

c. An **off-shore Higgs factory**, realized in collaboration with international partners, in order to reveal the secrets of the Higgs boson. The current designs of **FCC-ee and ILC** meet our scientific requirements. The US should actively engage in feasibility and design studies.

Recommendation 4: Support a comprehensive effort to develop the resources—theoretical, computational, and technological—essential to our 20-year vision for the field. This includes an aggressive R&D program that, while technologically challenging, could yield revolutionary accelerator designs that chart a realistic path to a **10 TeV pCM collider**.

a. Support vigorous R&D toward a cost-effective 10 TeV pCM collider based on proton, muon, or possible **wakefield technologies**, including an evaluation of options for US siting of such a machine, with a goal of being ready to build major test facilities and demonstrator facilities within the next 10 years.

The FACET-II program will expand to include R&D for near-term

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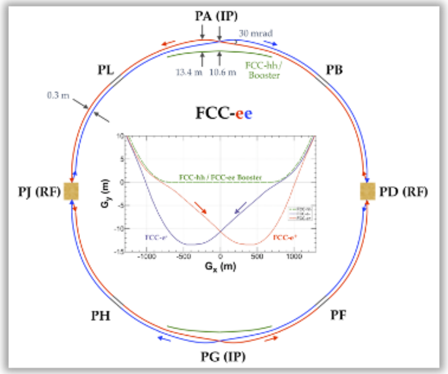
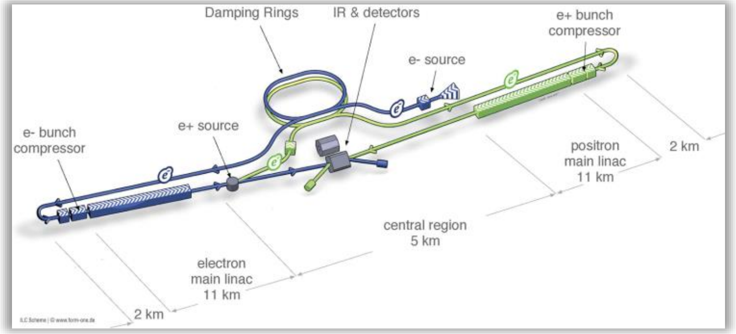
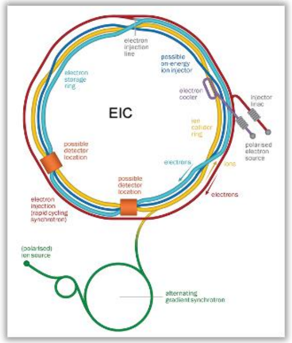
Collider-Directed R&D Opportunities at FACET-II



- Laser control of electron bunch intensity for FCC-ee.
  - For mitigating beam-beam flip-flop instability.
- FCCee injector studies.
  - Demonstrate fast charge variation from injector and wakefield verification.
- Compton polarimetry studies for FCCee.
  - Validate detector design and performance for ~10% polarization signal.



- Laser collimation of electron beams for ILC.
  - For "unbreakable" collimators.
- Experimental verification of strong-field QED models.
  - For high beamstrahlung regime collisions.
- ILC source studies (US-Japan grant).
  - Design and validation of very high power targets driven by electron beams.



- Coherent Electron Cooling at EIC.
  - Measure electron noise in the near-IR at the injector and test noise reduction.

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See backup slides for more information.

The Beam-Beam Flip-Flop Instability

Symmetric scenario:

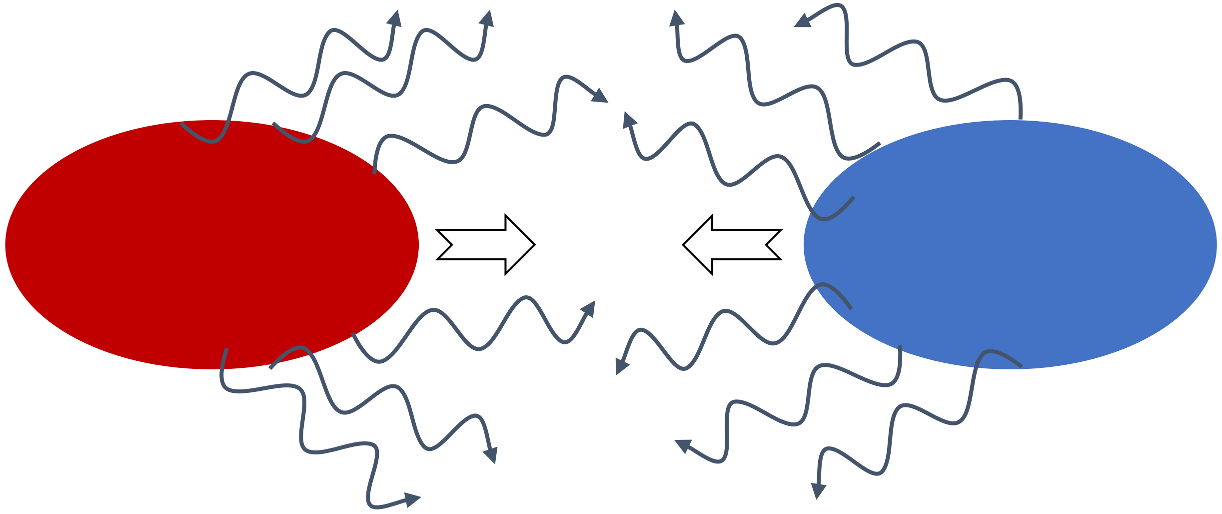
- Equal bunch intensities and equal beamstrahlung.

$N = N_0$

$n_{\gamma BS} = n_{\gamma BS0}$

$\sigma_z = \sigma_{z0}$

$\xi = \xi_0$



$N = N_0$

$n_{\gamma BS} = n_{\gamma BS0}$

$\sigma_z = \sigma_{z0}$

$\xi = \xi_0$

The Beam-Beam Flip-Flop Instability

Asymmetric scenario:

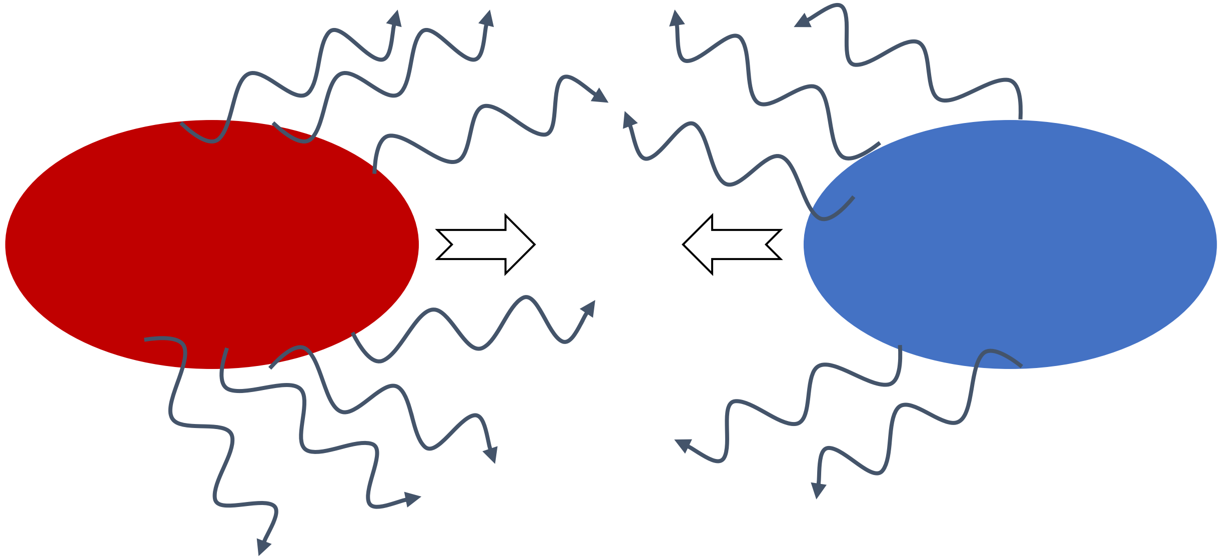
- "Weak" beam radiates more beamstrahlung photons than "Strong" beam.

$N = N_0 - \Delta$

$n_{\gamma BS}$ ↓

$\sigma_z = \sigma_{z0}$

$\xi = \xi_0$



$N = N_0 + \Delta$

$n_{\gamma BS}$ ↑

$\sigma_z = \sigma_{z0}$

$\xi = \xi_0$

Weak

Strong

The Beam-Beam Flip-Flop Instability

Asymmetric scenario:

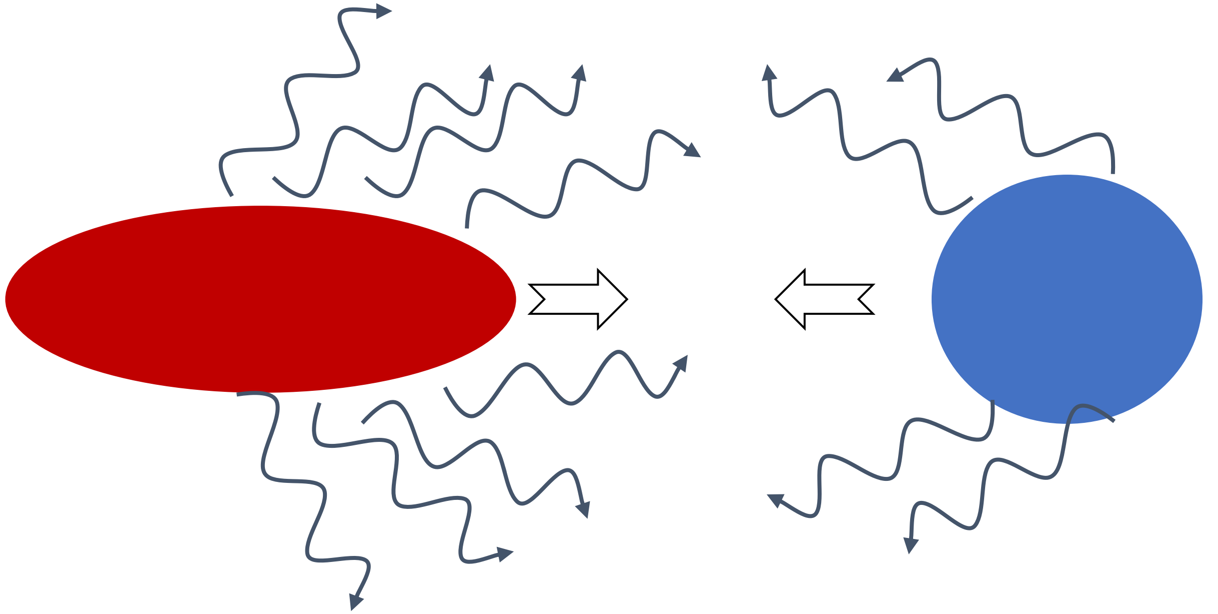
- More/less beamstrahlung radiation leads to longer/shorter bunch lengths.

$N = N_0 - \Delta$

$n_{\gamma BS} \downarrow$

$\sigma_z \uparrow$

$\xi = \xi_0$



$N = N_0 + \Delta$

$n_{\gamma BS} \uparrow$

$\sigma_z \downarrow$

$\xi = \xi_0$

Weak

Strong

The Beam-Beam Flip-Flop Instability

Asymmetric scenario:

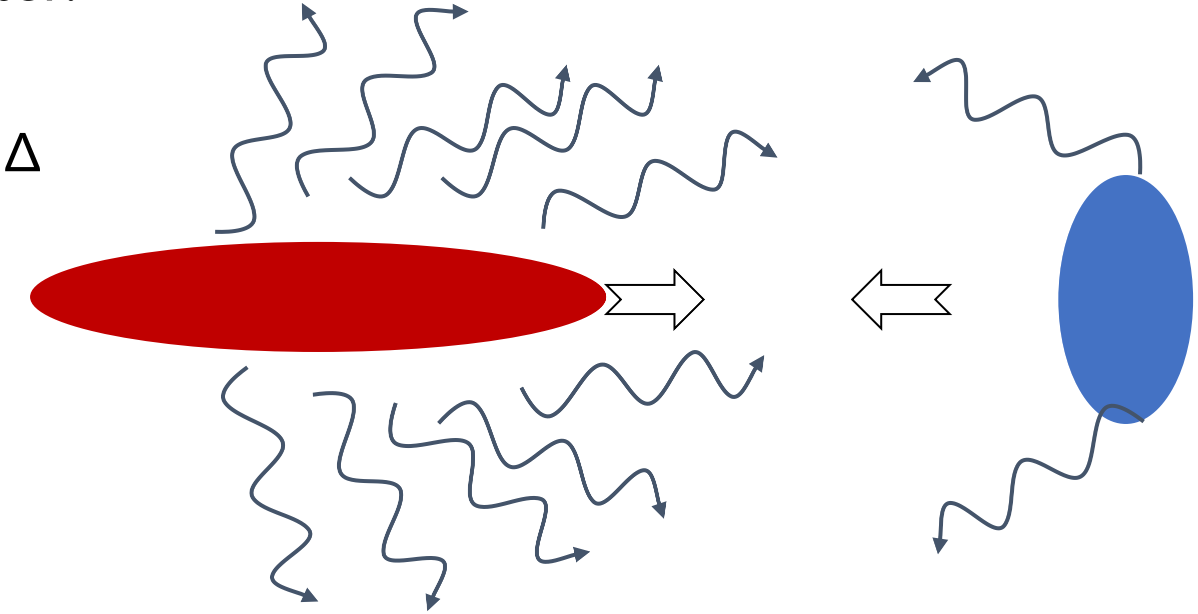
- Longer/shorter bunch lengths decrease/increase the beam-beam parameter.

$N = N_0 - \Delta$

$n_{\gamma BS} \downarrow$

$\sigma_z \uparrow$

$\xi \uparrow$



$N = N_0 + \Delta$

$n_{\gamma BS} \uparrow$

$\sigma_z \downarrow$

$\xi \downarrow$

Weak

Strong

ξ_y may become very large for the weak beam and it is lost.

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Growth Rate and Sensitivity to Asymmetries

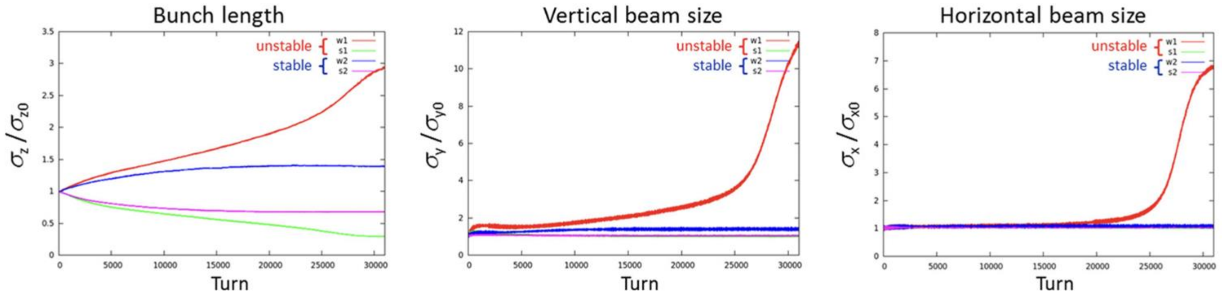
Simulations by Shatilov indicate growth rate of the instability over ~10000 turns.

At the z-pole, a few percent intensity asymmetry is tolerable.

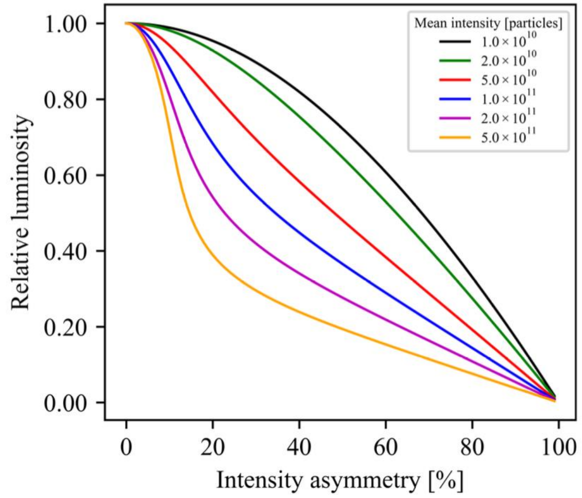
Asymmetries may be balanced through top-up injection.

The top-up rate is ever 15000-to-30000 turns.

Does the instability grow faster than the top-up rate?



D. Shatilov https://doi.org/10.1140/epjp/s13360-022-02346-x



K. Nguyen et al. https://arxiv.org/abs/2404.09012

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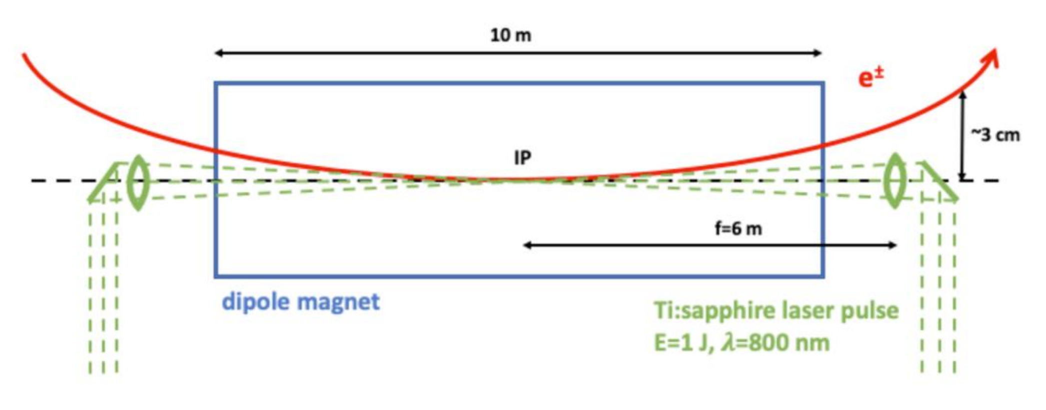
Fast-Feedback on Colliding Bunch Intensity

If the flip-flop instability develops faster than the top-up frequency, the FCC will require a fast feedback for bunch intensity control.

This can be achieved by Compton Back Scatter of individual bunches with high energy laser pulses.

The laser pulse energy is controlled on a bunch-by-bunch basis to compensate for intensity asymmetry between bunches.



F. Zimmermann, T. Raubenheimer IPAC 2022
https://accelconf.web.cern.ch/ipac2022/papers/wepost010.pdf

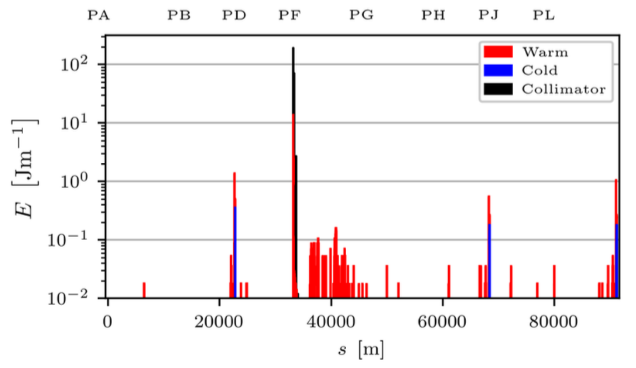


Figure 4: Single-bunch loss map after 500 turns with laser interaction for the Z operation mode and a laser spot size of 100 µm. Aperture losses in normal conducting magnets are shown in red, and losses on superconducting magnets are shown in blue.

I. Drebot, et. al IPAC 2023 https://doi.org/10.18429/JACoW-IPAC2023-MOPA074

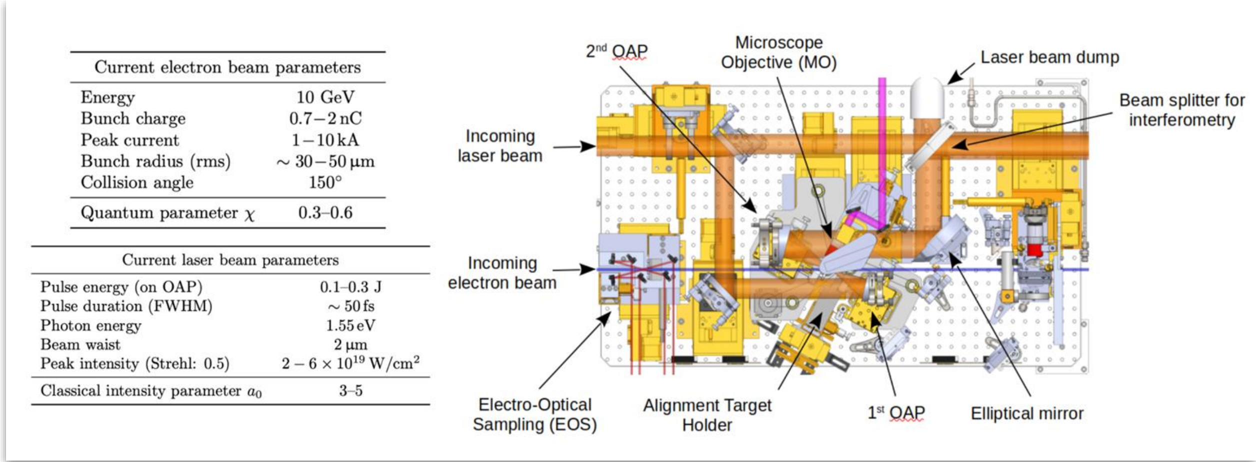
FACET-II Proposal

Proposal

With J. Keintzel and F. Zimmermann, CERN, I. Drebot, INFN, and E320 Team

Use the E320 infrastructure at FACET-II provides an R&D platform to demonstrate:

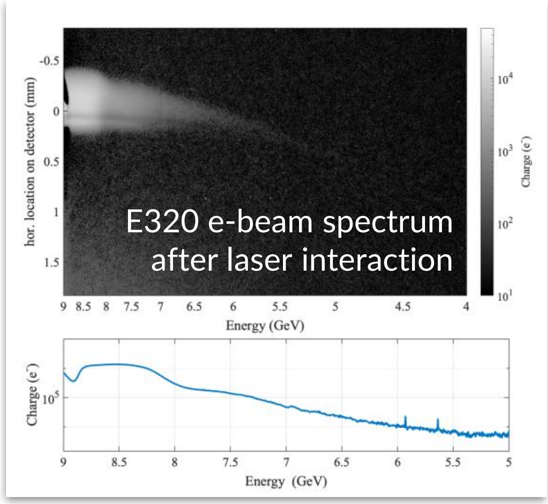
- Bunch-to-bunch laser intensity control.
- Performance and lifetime of laser optics in radiation environments
- Explore optimal geometries for maximizing interaction and minimizing laser power.



Current electron beam parameters	
Energy	10 GeV
Bunch charge	0.7 – 2 nC
Peak current	1 – 10 kA
Bunch radius (rms)	∼ 30 – 50 μm
Collision angle	150°
Quantum parameter χ	0.3–0.6

Current laser beam parameters	
Pulse energy (on OAP)	0.1–0.3 J
Pulse duration (FWHM)	∼ 50 fs
Photon energy	1.55 eV
Beam waist	2 μm
Peak intensity (Strehl: 0.5)	$2 - 6 \times 10^{19}$ W/cm^2
Classical intensity parameter a_0	3–5

Tatiana Smorodnikova, EPS 2024



Advertisement #1: Experimental Proposals for FACET-II

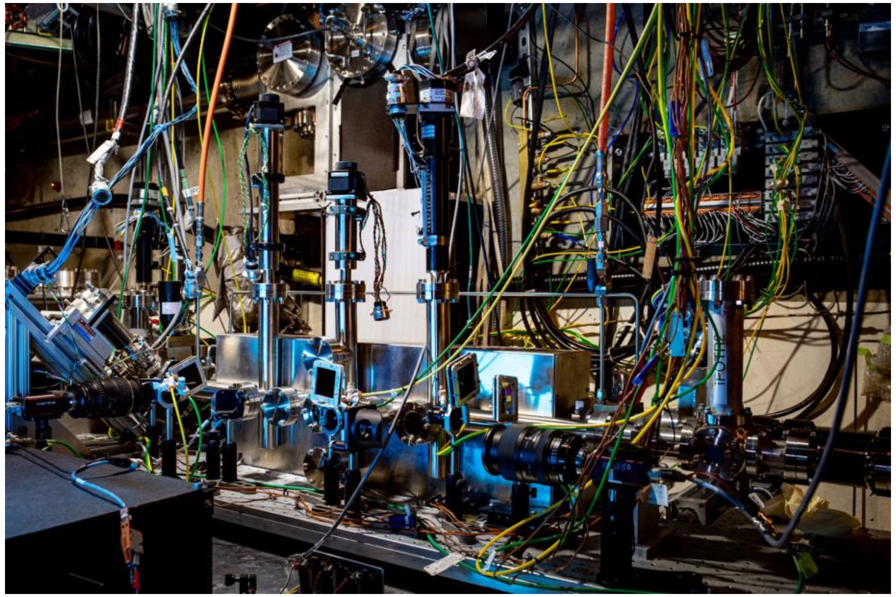
We are currently accepting proposals for experiments at FACET-II, especially proposals for Collider R&D topics.

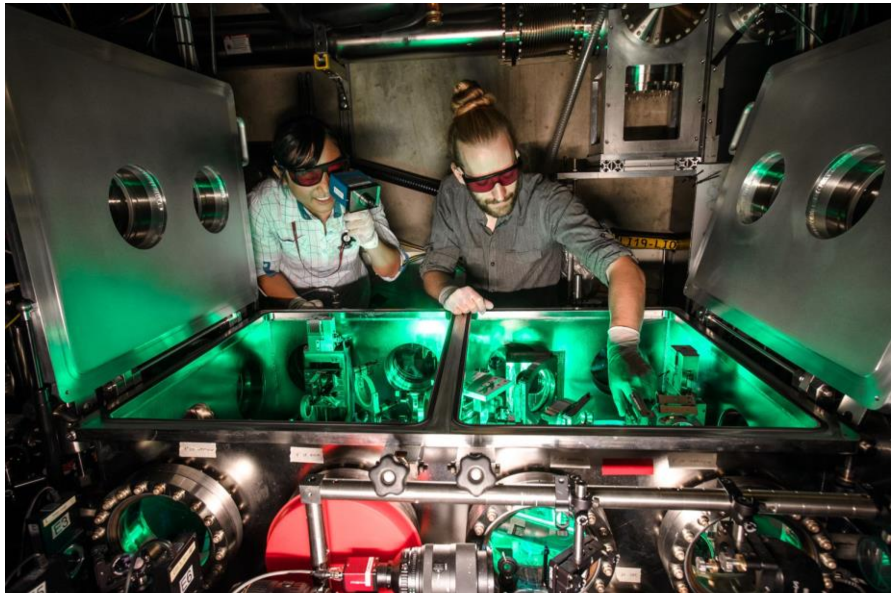
https://facet-ii.slac.stanford.edu/proposals

We want proposals to be successful!

Please contact myself or FACET managers before submitting your proposal:

- Ivan Rajkovic, FACET User Manager
- Mark Hogan, FACET Director





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Advertisement #2: Postdoc Positions at SLAC

Research Associate in Beam-Beam Effects for Circular Colliders

SLAC is seeking qualified scientists to contribute to beam-beam studies for the FCC-ee and EIC colliders. These studies will utilize state-of-the-art simulation tools including XSuite, WarpX, BeamBeam3D, BMAD, and the Blast toolkit. Study topics include the beamstrahlung-induced 3D flip-flop instability at FCC-ee and polarization preservation with beam-beam interactions at the EIC.

Research Associate in the 10 TeV Wakefiled Collider Design Study

SLAC is seeking qualified scientists to contribute to the design of a very high energy future collider based on wakefield accelerator technology. Study topics include staging of plasma accelerators, advanced beam delivery systems, beam-beam interactions with extreme beamstrahlung, and overall system optimization. Participation in the FACET-II experimental program is encouraged.

Postdoc positions will be posted in October. I will forward them to BB24 organizers.

Advertisement #3: Seminar at CERN

A&T Seminar

The 10 TeV Wakefield Accelerator Collider Design Study

by Spencer Gessner (SLAC)

Friday Sep 6, 2024, 11:00 AM → 12:00 PM Europe/Zurich

6/2-024 - BE Auditorium Meyrin (CERN)

Description

Abstract: From its inception, the Advanced Accelerator field has considered future colliders as the ultimate goal of high-gradient accelerator technology. In the decades that followed, there has been rapid experimental progress and a conceptual evolution of what future colliders based on Wakefield Accelerator (WFA) technology might look like. The recent P5 Report calls for "vigorous R&D toward a cost-effective 10 TeV pCM collider based on proton, muon, or possible wakefield technologies." Specifically, the P5 Report requests "the delivery of an end-to-end design concept, including cost scales, with self-consistent parameters throughout." In this presentation, I will outline the requirements and challenges for a 10 TeV WFA collider. The study will investigate the physics case for electron-positron, gamma-gamma, and electron-electron collisions at 10 TeV. The study will identify R&D topics that mutually benefit 10 TeV collider design and near-term Higgs Factories. Finally, I will describe a community-driven design based on working groups and performance metrics to produce a unified 10 TeV collider design concept, including a timeline with deliverables.

For those at CERN on Friday, I am giving a seminar on the 10 TeV Wakefield Collider, including Beam-Beam effects (extreme beamstrahlung).

https://indico.fnal.gov/event/59618/contributions/294346/attachments/179939/246829/The_10TeV_WFA_Study_v3.pdf

https://forms.gle/tLCYykFRdYus7CS86

Advertisement #3: Sem

A&T Seminar

The 10 TeV Wakefield Accelera

by Spencer Gessner (SLAC)

Friday Sep 6, 2024, 11:00 AM → 12:00 PM Europe/Zurich

6/2-024 - BE Auditorium Meyrin (CERN)

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Interest Form for 10 TeV WFA Study

This form is to express interest in participating in the 10 TeV WFA study, including participation in working groups and joining the e-mail list.

sgess@slac.stanford.edu Switch account

Not shared

* Indicates required question

Name *

Your answer

Email address *

Your answer

Which working groups are you interested in joining? *

- [ ] Sources
- [ ] Laser Driver
- [ ] Beam Driver - SWFA
- [ ] Beam Driver - PWFA
- [ ] LWFA Linac
- [ ] SWFA Linac
- [ ] PWFA Linac
- [ ] Beam Delivery Systems
- [ ] Beam-Beam Interactions
- [ ] Beam Diagnostics
- [ ] Machine-Detector Interface
- [ ] HEP Detector
- [ ] HEP Physics Case
- [ ] Environmental Impact
- [ ] Other:

For those at CERN on Friday, I am giving a seminar on the 10 TeV
including Beam-Beam effects (extreme beamstrahlu

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Thank you!

Backup

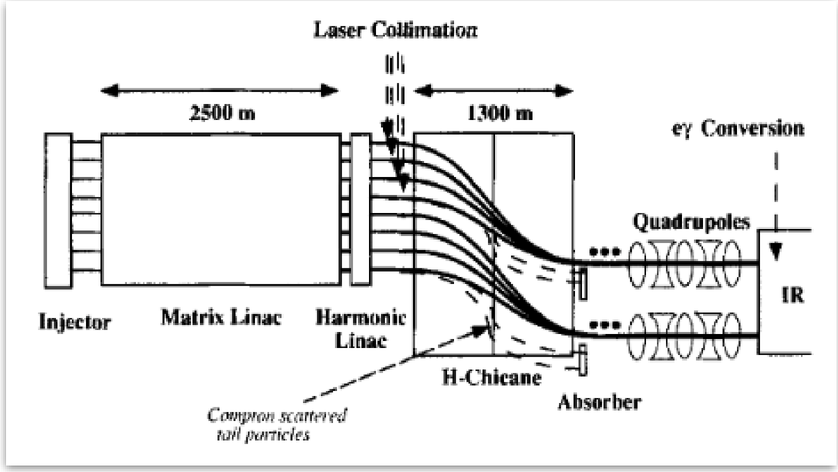
Collimation Challenge at Colliders

Collimation systems for linear and circular colliders have conservative designs: they must be able to withstand a complete mis-steering of the beam.

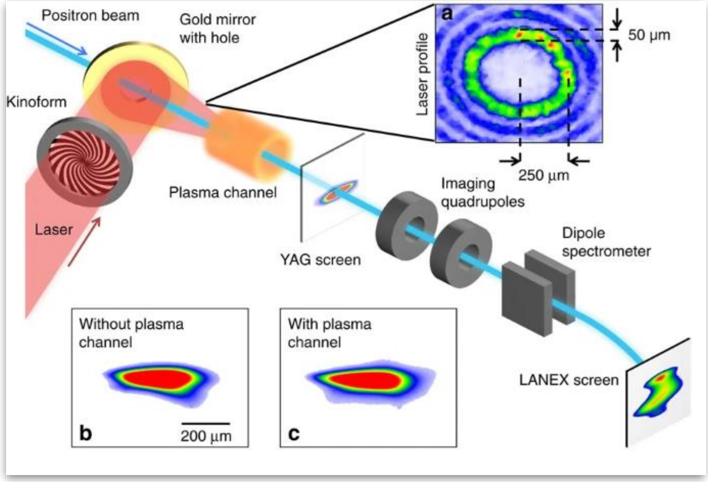
They can be destroyed in a single shot!

Proposal: use Compton scattering with shaped laser pulses for a robust, compact, and undamageable collimation system.

This programs leverages prior research by the E225 Experiment at FACET and E320 at FACET-II.



Zimmerman, F. New final focus concepts at 5 TeV and beyond. Eighth Advanced Accelerator Concepts Workshop. 1998.



Gessner, S. et al. Demonstration of a positron beam-driven hollow channel plasma wakefield accelerator. Nat. Comm. 2016.

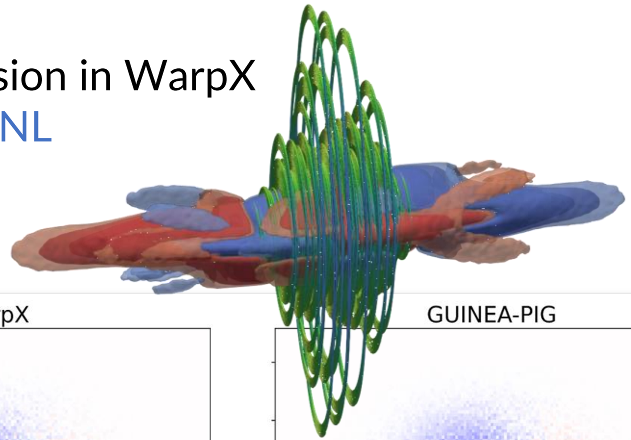
Verification of Beam-Beam Codes

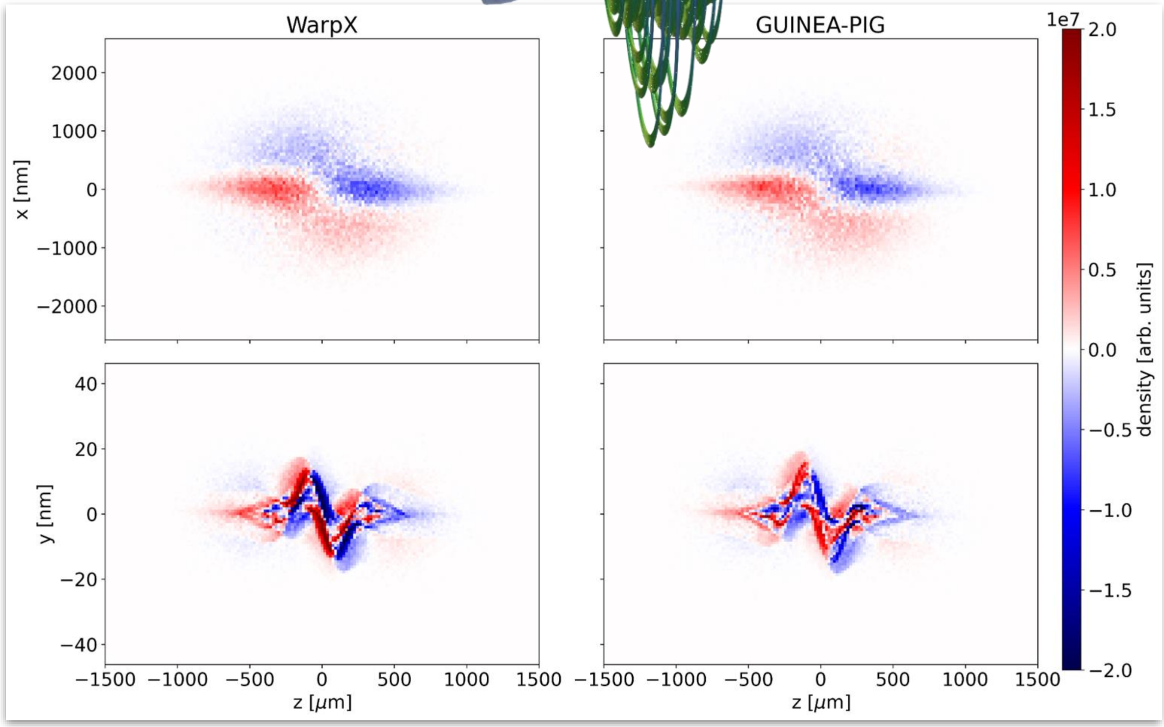
For high-energy upgrades of linear colliders, the beamstrahlung parameter Υ becomes very large.

With LBNL, we are developing the WarpX code as a high performance replacement of GUINEA-PIG and CAIN in the extreme beamstrahlung regime.

E320 provides a test bed to study the extreme beam physics relevant to large Υ regime.

ILC bunch collision in WarpX
A. Formenti LBNL





We are targeting WarpX towards EIC and FCC-ee applications for high-speed, "strong-strong" simulations.

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Brendan O’Shea, SLAC
Paolo Craievich, PSI

FCCee Injector Studies at FACET-II

- Study 1: FCCee requires arbitrary 0 - 5 nC at +/-5% charge variation inside pulse train from injector to prevent flip-flop instability
  - Prove design requirement of arbitrary bunch charge from injector, before engineering in 2029
- Study 2: Test wakefield models used to design FCCee injector linac at bunch spacings from 25 to 100 ns
  - Prove injector design before engineering in 2029
- Study 3: Test FCCee high temperature superconducting magnet at FCCee design beam power
  - Required to prove reliability required for FCCee

- Exploring three possible studies at FACET-II for March 2025 review
- Current studies at SwissFEL can show principles, but do not reach FCCee design parameters
- All three studies well aligned to FACET-II machine capabilities
  - FACET-II injector meets FCCee charge requirements
  - FACET-II linac can accommodate FCCee beam power
  - FACET-II has existing positron infrastructure and experience from FACET/FFTB/SLC

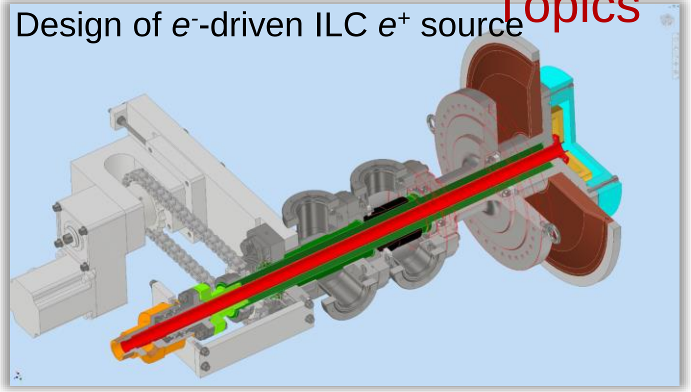
FACET-II capabilities are well-positioned to address FCCee injector R&D Topics

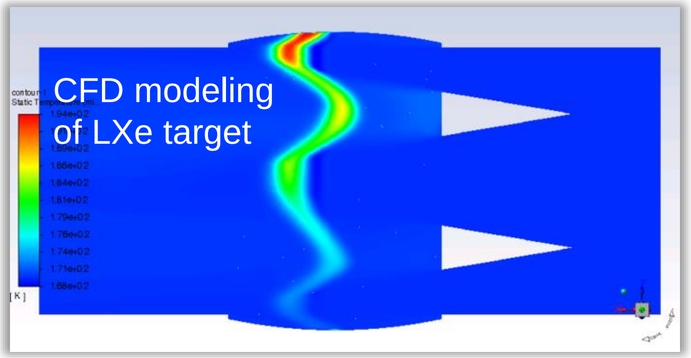
US-Japan Particle Sources Collaboration

The KEK, JLab, SLAC particle sources collaboration has been awarded two US-Japan grants.
FY24: Advanced Electron and Positron Source Concepts
FY25-26: Advanced Positron Source Concepts

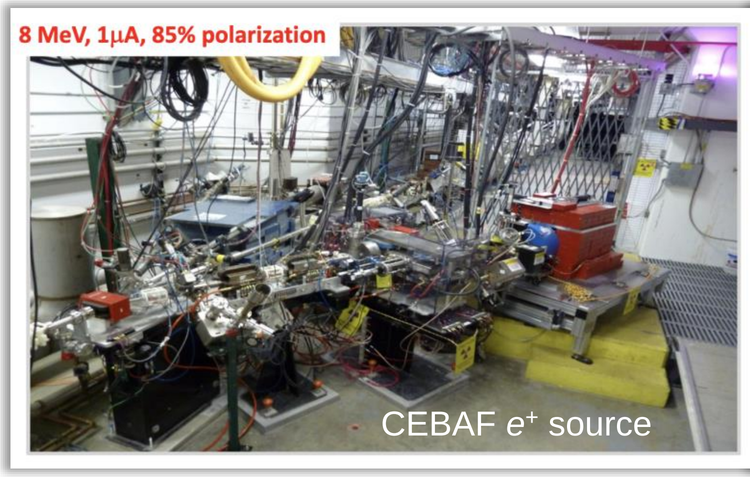
The *US-Japan Particle Sources Collaboration* addresses particle source R&D topics relevant to the ILC, EIC, CEBAF facilities, as well as advanced R&D for future ultra-high-power sources.

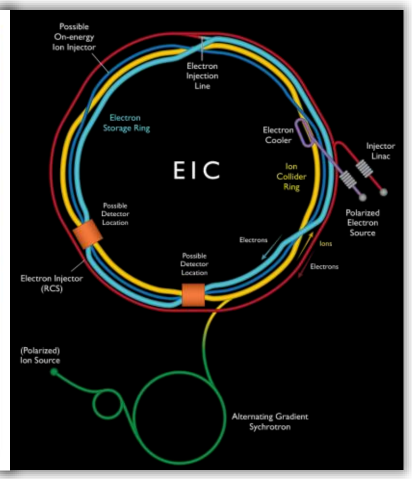
R&D Topics

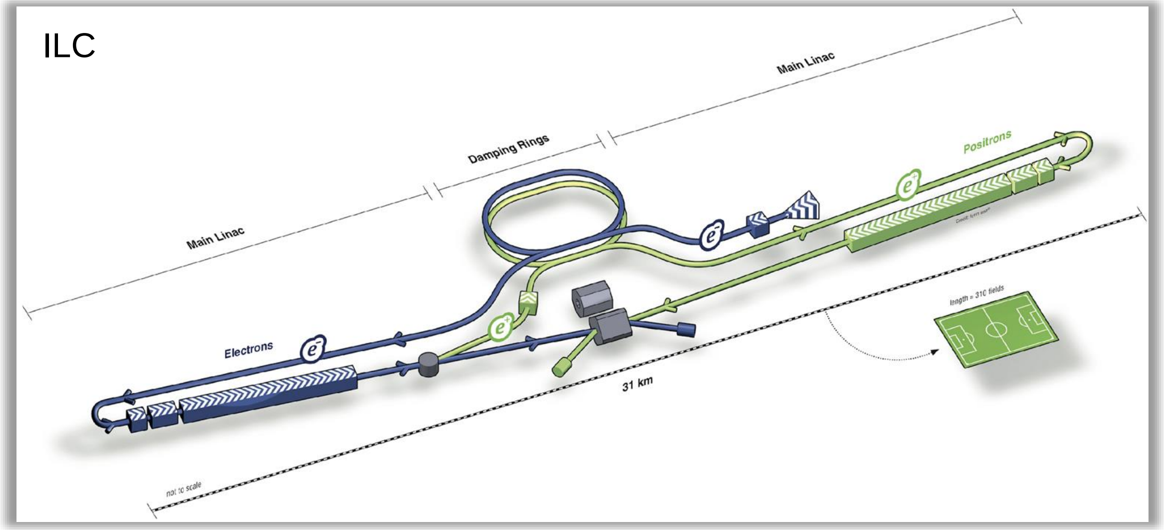




Colliders and Facilities







SLAC KEK-JAPAN Jefferson Lab

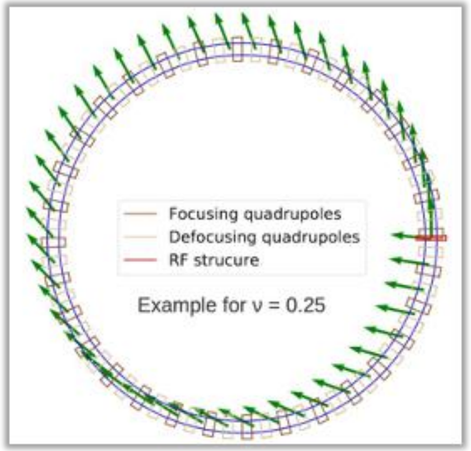
Compton Polarimetry Challenge at FCC-ee

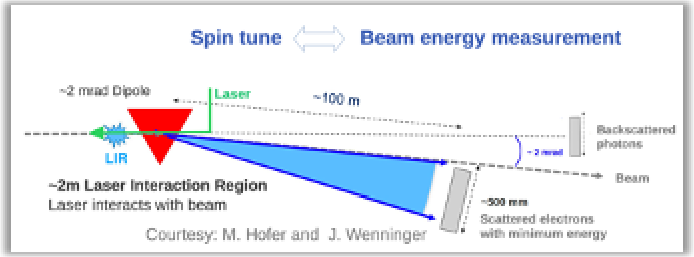
The electron beam energy must be measured at the level of 10^{-6} at FCC-ee in order to measure the width of the Z boson.

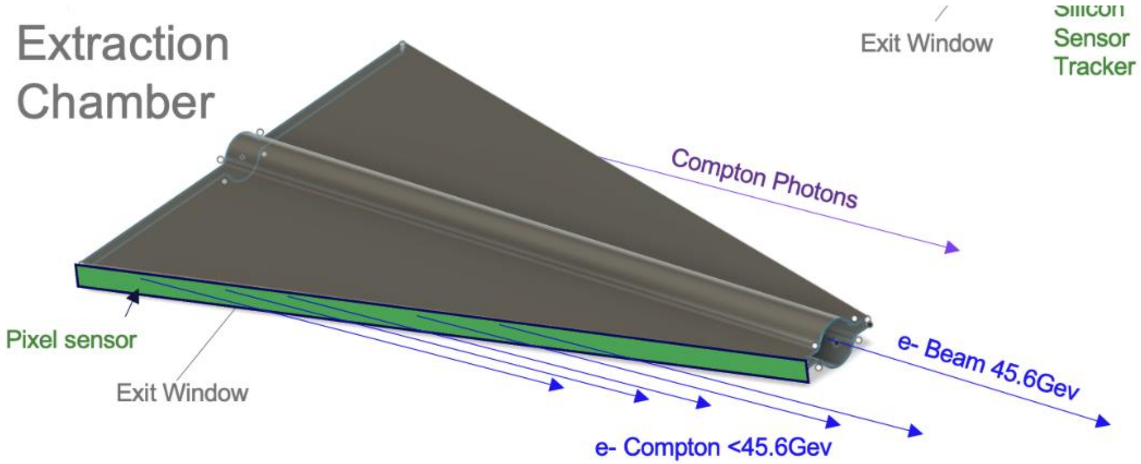
This is only possible with spin tune measurements, but the FCC bunches are not polarized.

The FCC plans to produced weakly-polarized (10%) pilot bunches for this measurement.

Proposal: test measurement strategies and detectors for weak Compton signals using E320 setup.







R. Kiefer, FCC Week 2024
https://indico.cern.ch/event/1298458/contributions/5977825/attachments/2877527/5039902/2024_06_13_Polarimeter_FCCweek_p.pdf

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Compton Polarimetry at FACET-II?

FACET-II does not produce polarized electrons.

In general, it is not possible to use polarized cathode (GaAs) in RF guns because they do not survive the poor vacuum compared to DC guns.

But new ideas are currently in development! We are working with:

- John Smedley, SLAC
- Joe Grames, JLab
- Jared Maxson, Cornell

to understand polarized source options for FACET-II.

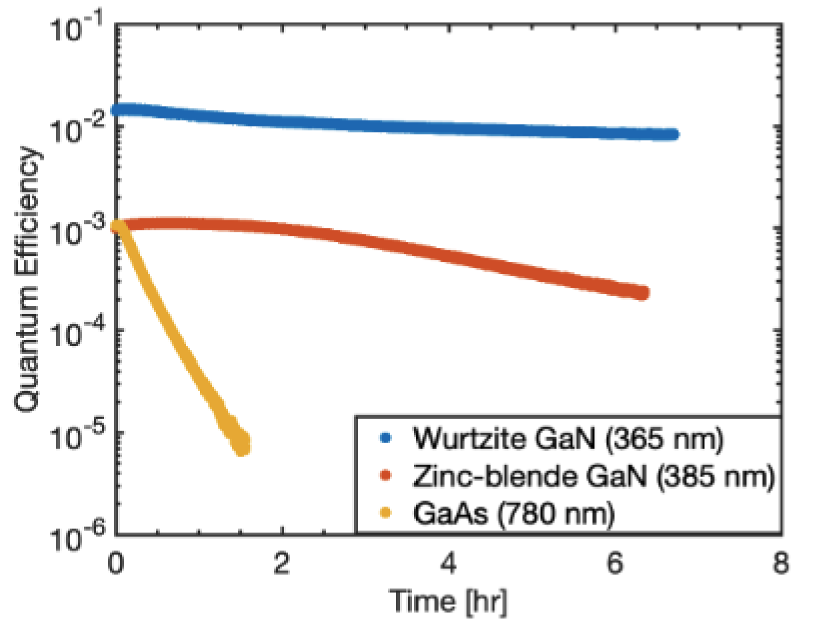

FIG. 2. Threshold lifetimes of the NEA W-GaN, ZB-GaN and GaAs photocathodes compared under similar vacuum conditions.

Levenson, S. Measurement of Spin-Polarized Photoemission from Wurtzite and Zinc-Blende Gallium Nitride Photocathodes. arXiv:2405.04481. 2024.

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Electron bunch noise measurement for EIC

Electron bunch structure measurements were performed at FAST as part of EIC Coherent Electron Cooling R&D.

Near-IR Noise in Intense Electron Beams, Kladov, et al. IPAC24.

FACET-II can continue this research (similar injector parameters) and it also benefits FACET-II ABP program to better understand microbunching instability.

Table 1: FAST and proposed CEC beam parameters.

Parameter	FAST	EIC
E_p, GeV		100 - 275
E_e, MeV	40 - 300	50 - 150
Bunch charge, nC	0 - 3	1
ϵ (rms, norm), μm	3 (at 1 nC)	2.8
Bunch length, mm	0.3 - 10	12 - 8
Drift section, m	80	100

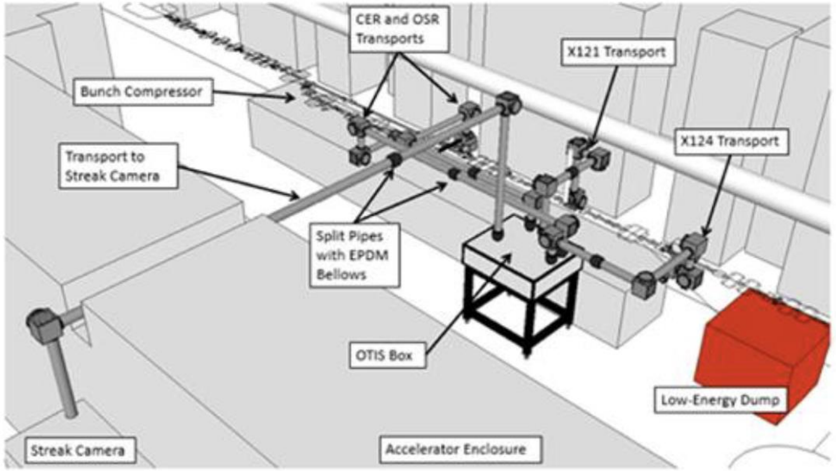


Figure 4: A schematic of the all-mirror optical transport from X121 to the streak camera and photodiode.

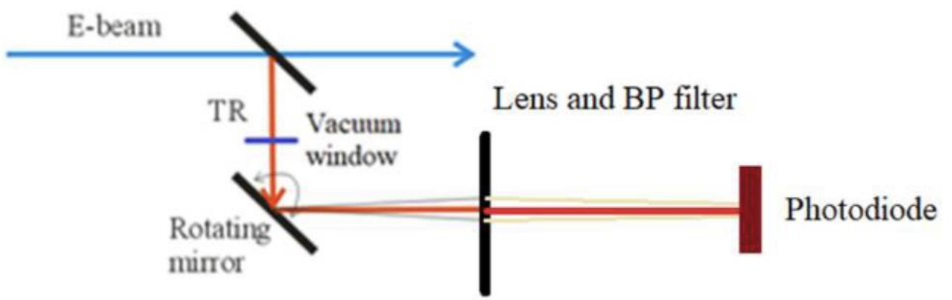


Figure 3: The proposed schematic of the TR spectrometer (BP is a band-pass filter).

Compact Positron Source (SLAC LDRD)

SLAC is funding a 2-year LDRD on the design of a Compact Positron Source.

The Compact Positron Source is based on a Penning-Malmberg trap and produces 100 nm emittances without a damping ring.

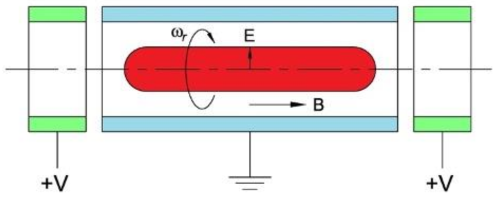
Extraction and compression of the beam from the trap is a major beam physics challenge!

The Compact Positron Source is being explored as a low-cost option for bringing positrons back to FACET. It achieves cost savings by eliminating the following systems:

- High-energy target
- Positron return line
- Positron damping ring

The design will start in FY25 and prototyping will start in FY26.

Penning-Malmberg Trap



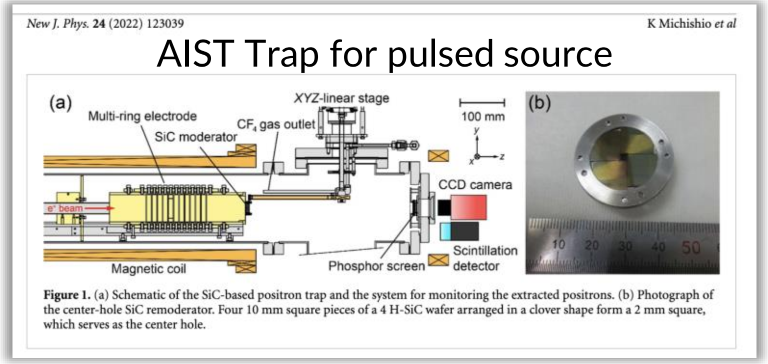
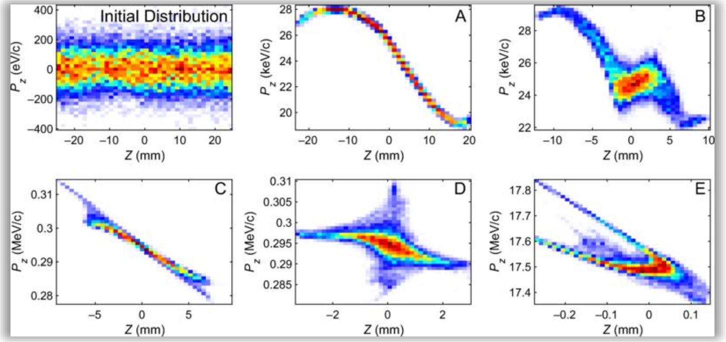
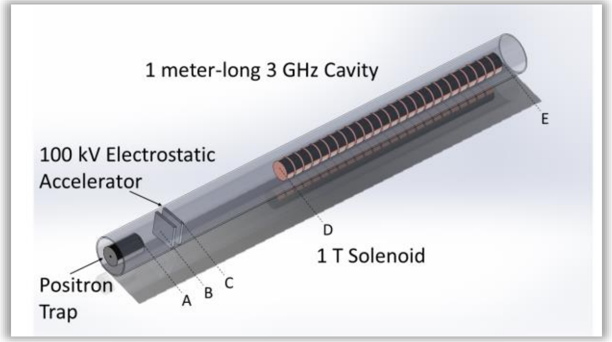


Figure 1. (a) Schematic of the SiC-based positron trap and the system for monitoring the extracted positrons. (b) Photograph of the center-hole SiC remoderator. Four 10 mm square pieces of a 4 H-SiC wafer arranged in a clover shape form a 2 mm square, which serves as the center hole.





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

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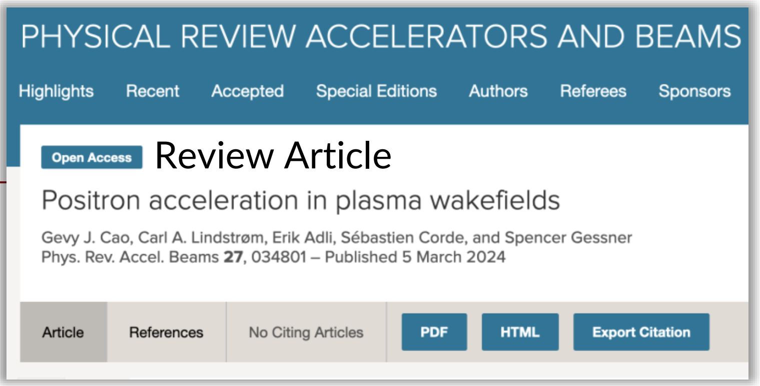
Positron PWFA Research at FACET-II

Positrons are desired for very high energy e^+e^- collisions, but there are challengers with accelerating positrons in plasma. We have a recent review article on this topic.

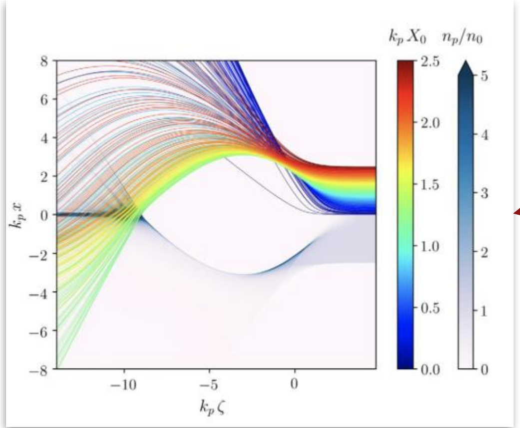
One concept stands out as the most promising for accelerating positrons: the finite-radius regime.

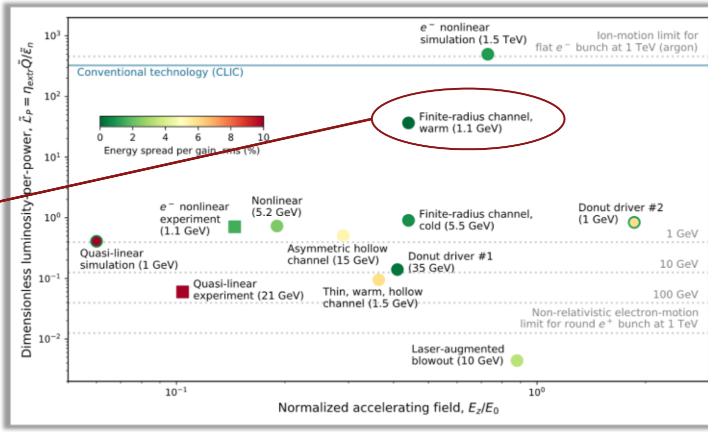
The E333 experiment at FACET-II is investigating the finite-radius regime while we wait for positron beams to become available. CU Boulder Ph.D. student is leading the experimental effort.

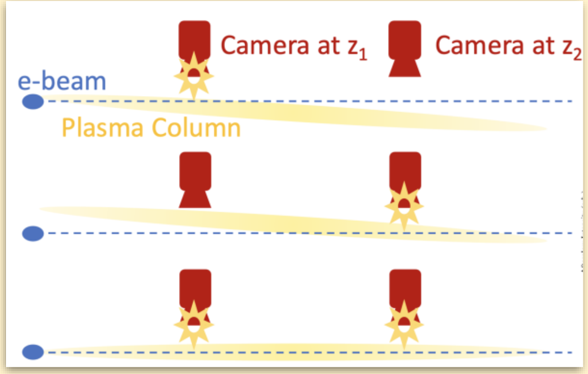
- Stage 1: Demonstrate finite radius plasma with axicon and multi-optic ionization.
- Stage 2: Demonstrate electron alignment to channel and guiding properties.
- Stage 3: Wakefield measurements with electron driver and electron witness.
- Stage 4 (when positrons are available): Demonstrate electron beam-driven acceleration of positrons.

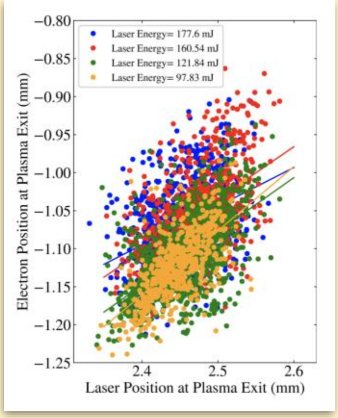


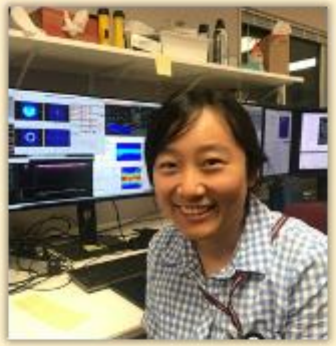
S. Diederichs, et al, “High-quality positron acceleration in beam-driven plasma accelerators,” PRAB, 2020.











CU Boulder Ph.D. Student Valentina Lee

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E333 Experiment at FACET-II, PI S. Gessner: Demonstration of finite-radius regime.