FACET-II
Facility for Advanced Accelerator
Experimental Tests

New proposal:

Laser Control and Collimation of Particle Beams for Higgs Factories

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Spencer Gessner, SLAC

FACET-II PAC Meeting
November 20, 2024

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

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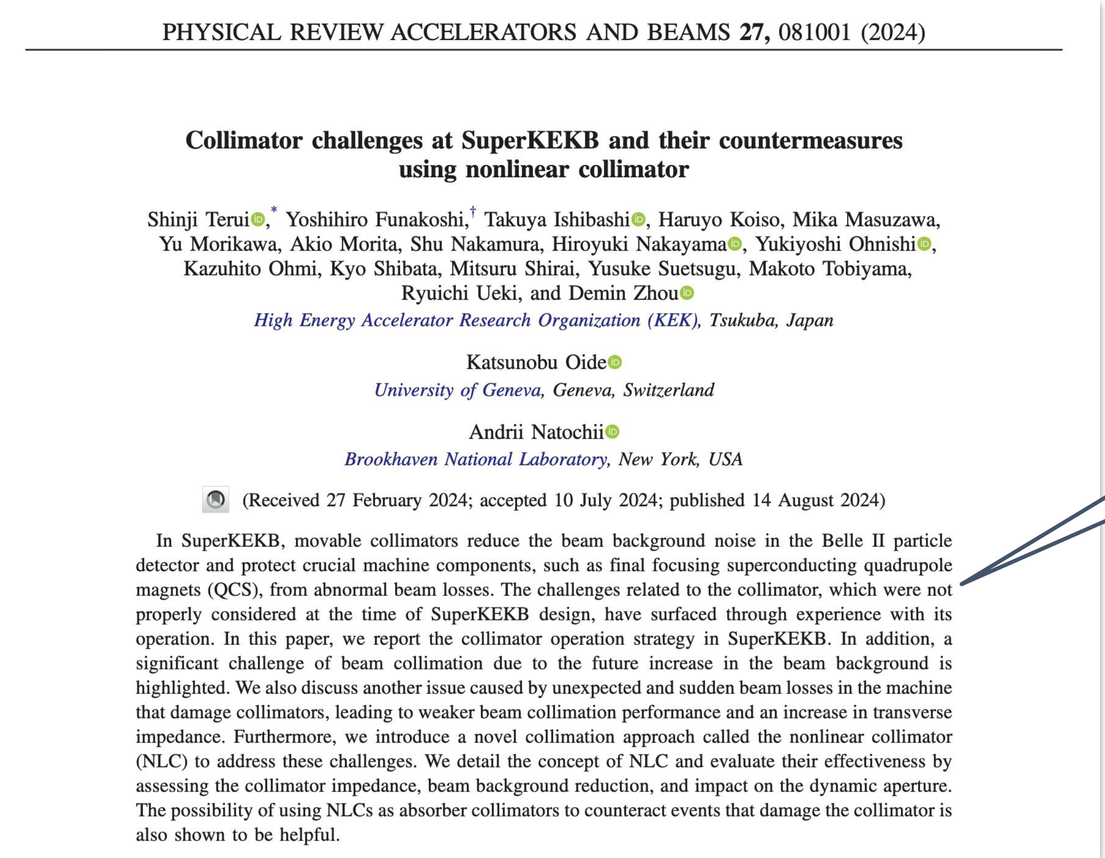
Collimation for Circular Colliders

Collimation of particle beams is a major challenge for high-luminosity colliders.



PHYSICAL REVIEW ACCELERATORS AND BEAMS **27,** 081001 (2024)

Collimator challenges at SuperKEKB and their countermeasures using nonlinear collimator

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In SuperKEKB, movable collimators reduce the beam background noise in the Belle II particle detector and protect crucial machine components, such as final focusing superconducting quadrupole magnets (QCS), from abnormal beam losses. The challenges related to the collimator, which were not properly considered at the time of SuperKEKB design, have surfaced through experience with its operation. In this paper, we report the collimator operation strategy in SuperKEKB. In addition, a significant challenge of beam collimation due to the future increase in the beam background is highlighted. We also discuss another issue caused by unexpected and sudden beam losses in the machine that damage collimators, leading to weaker beam collimation performance and an increase in transverse impedance. Furthermore, we introduce a novel collimation approach called the nonlinear collimator (NLC) to address these challenges. We detail the concept of NLC and evaluate their effectiveness by assessing the collimator impedance, beam background reduction, and impact on the dynamic aperture. The possibility of using NLCs as absorber collimators to counteract events that damage the collimator is also shown to be helpful.

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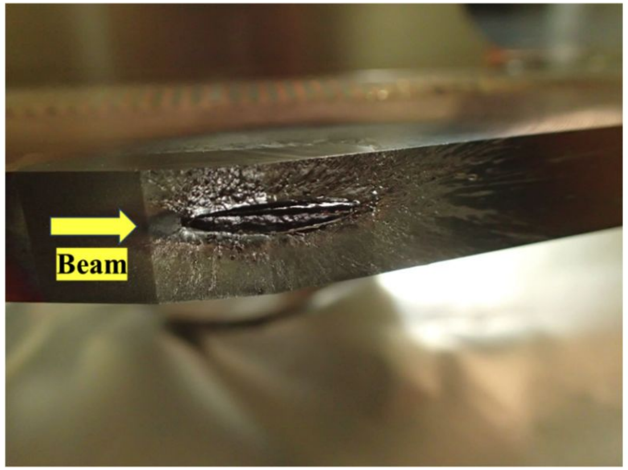
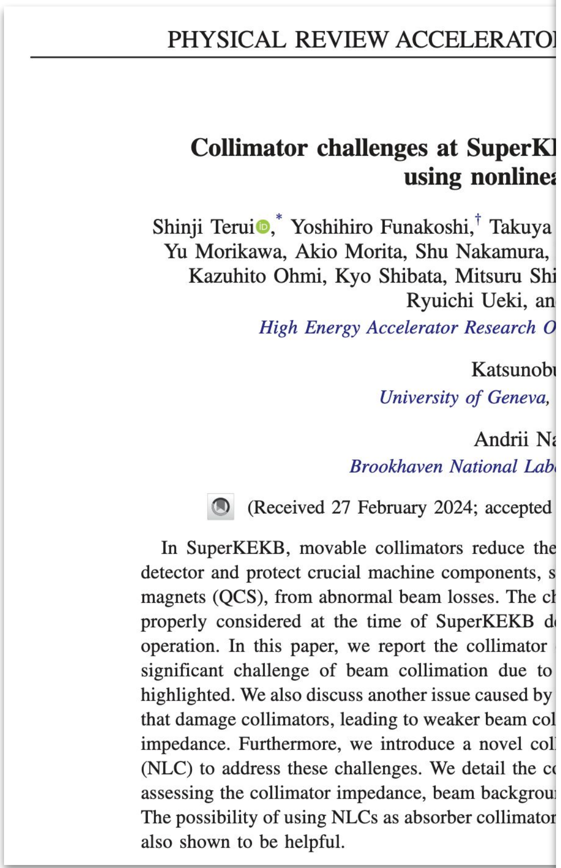


FIG. 5. Collimator jaw with a scar on the surface of the collimator head due to the passage of the abnormal beam.

Collimator design is critical to achieving the luminosity goals of a collider.

Collimation for Circular Colliders

Collimation of partic ty colliders.



PHYSICAL REVIEW ACCELERATO

Collimator challenges at SuperK
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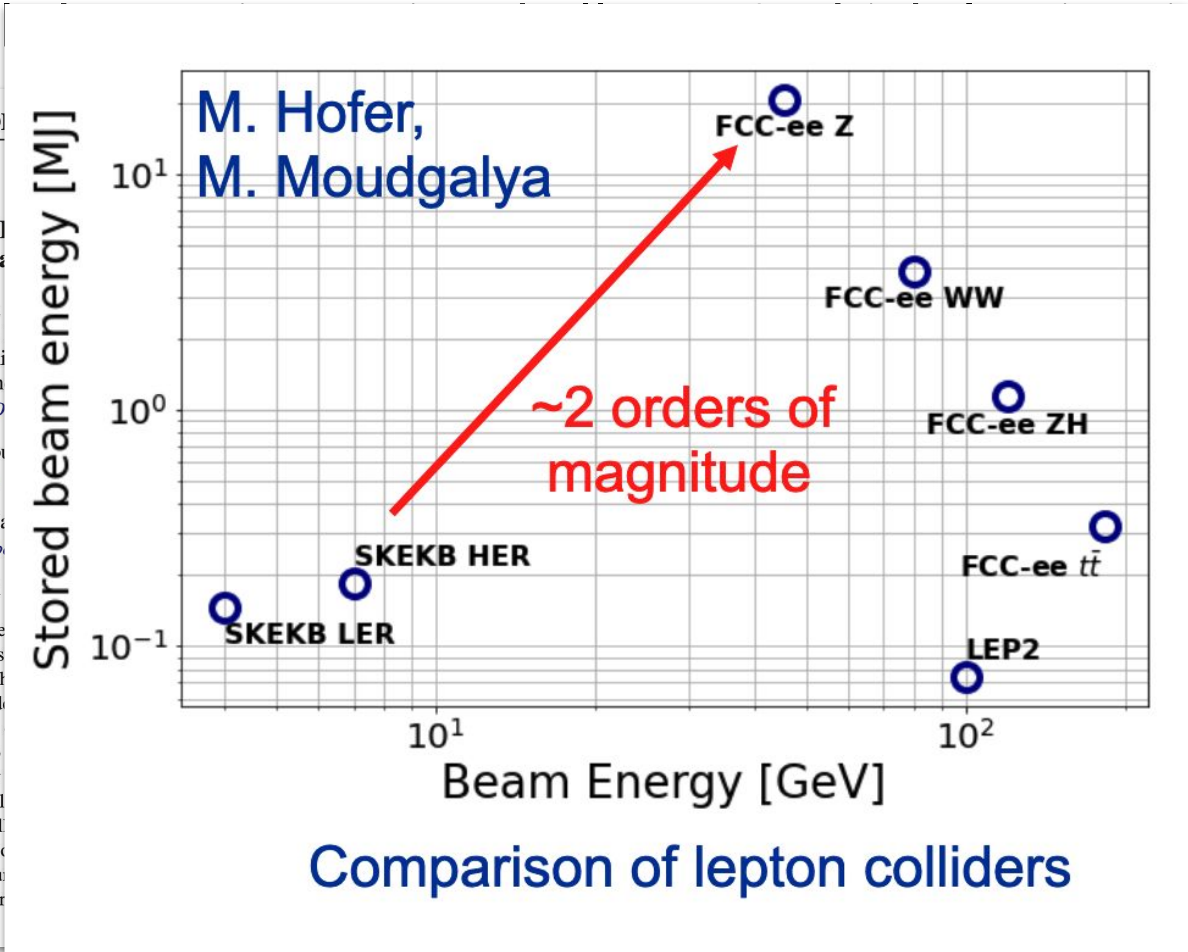

Comparison of lepton colliders

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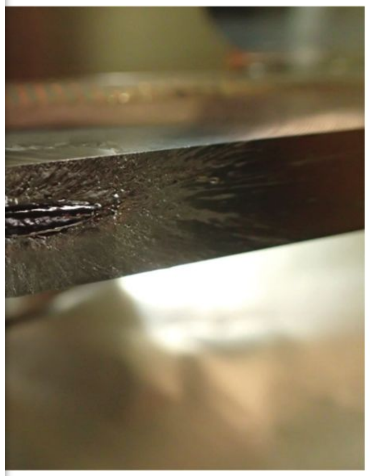
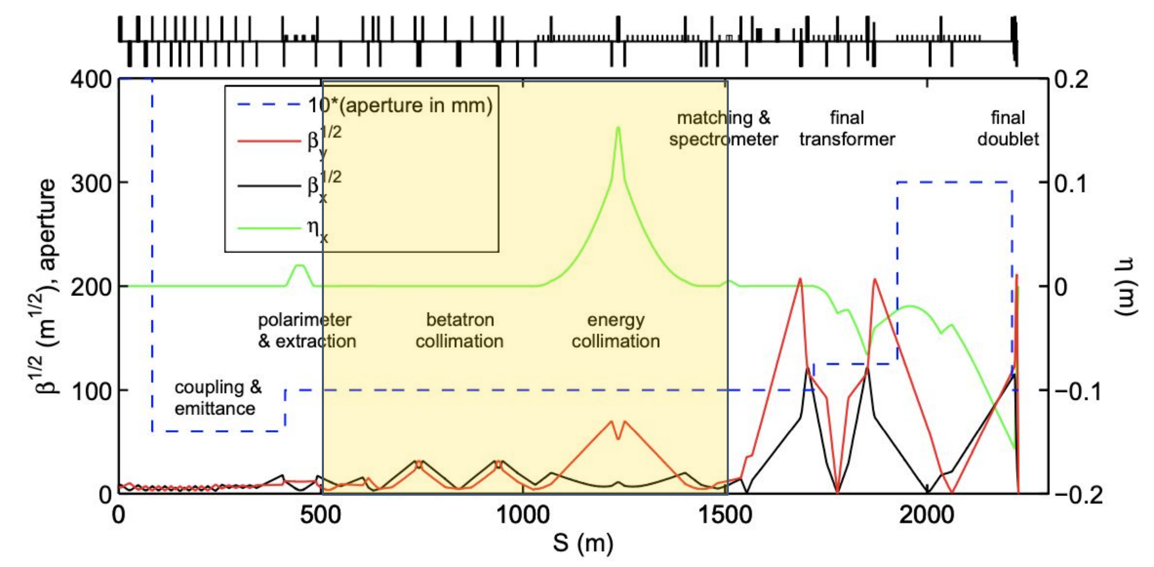


with a scar on the surface of the
passage of the abnormal beam.

Collimator design is critical to achieving the luminosity goals of a collider.

Collimation for Linear Colliders

Collimation of particle beams dominates the length of the Beam Delivery System.



ILC BDS: 1 km of collimation!

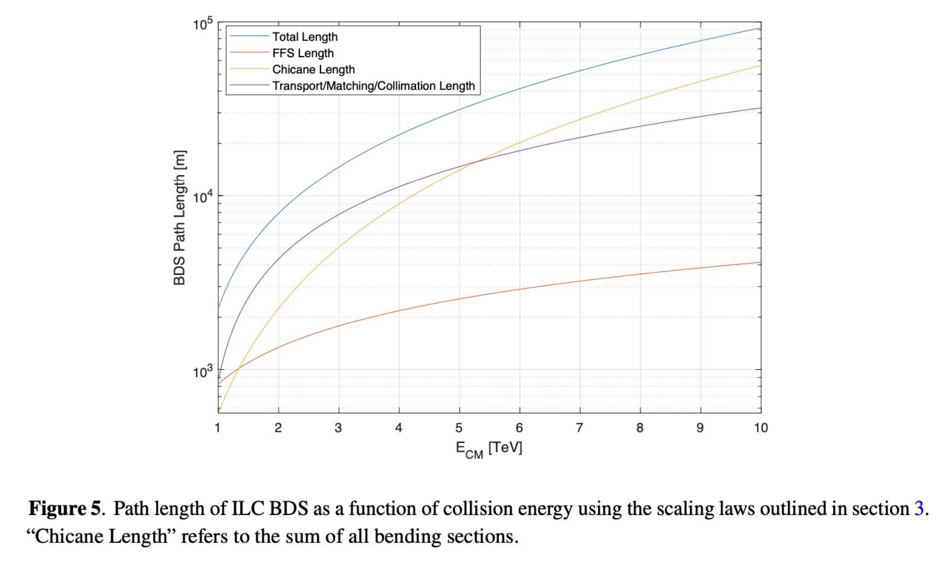


Figure 5. Path length of ILC BDS as a function of collision energy using the scaling laws outlined in section 3. "Chicane Length" refers to the sum of all bending sections.

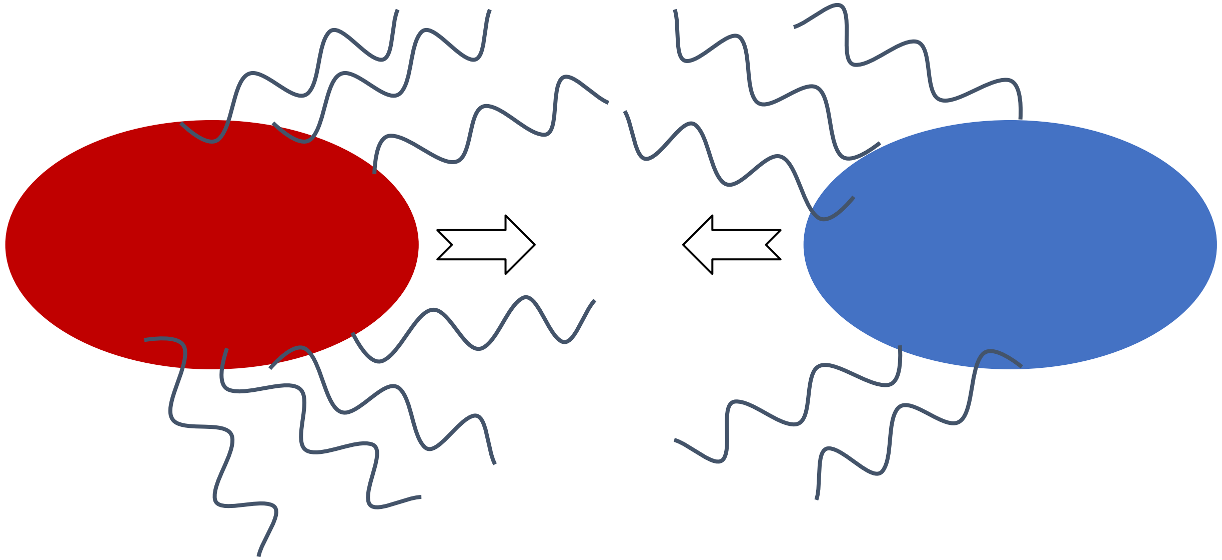
Barklow, Gessner et. al. "Beam delivery and beamstrahlung considerations for ultra-high energy linear colliders" JINST 18 P09022 (2023)

Novel collimation schemes will reduce cost of a Linear Collider Higgs Factory and enable a 10 TeV Wakefield Collider.

The Beam-Beam Flip-Flop Instability

Asymmetric scenario:

- “Weak” beam radiates more beamstrahlung photons than “Strong” beam.



$N = N_0 - \Delta$

$n_{\gamma BS}$ ↓

$\sigma_z = \sigma_{z0}$

$\xi = \xi_0$

$N = N_0 + \Delta$

$n_{\gamma BS}$ ↑

$\sigma_z = \sigma_{z0}$

$\xi = \xi_0$

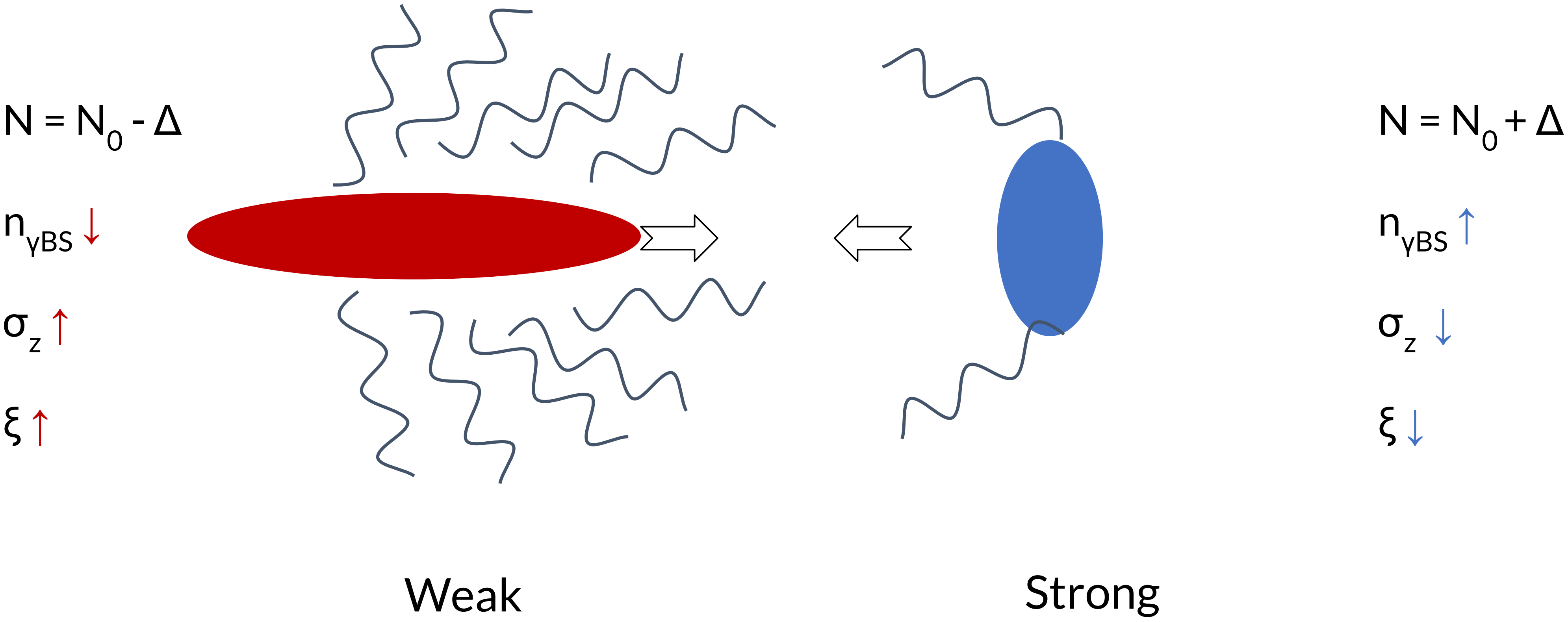
Weak

Strong

The Beam-Beam Flip-Flop Instability

Asymmetric scenario:

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



$N = N_0 - \Delta$

$n_{\gamma BS}$ ↓

σ_z ↑

ξ ↑

$N = N_0 + \Delta$

$n_{\gamma BS}$ ↑

σ_z ↓

ξ ↓

Weak

Strong

ξ_y may become very large for the weak beam. Charge and luminosity are lost.

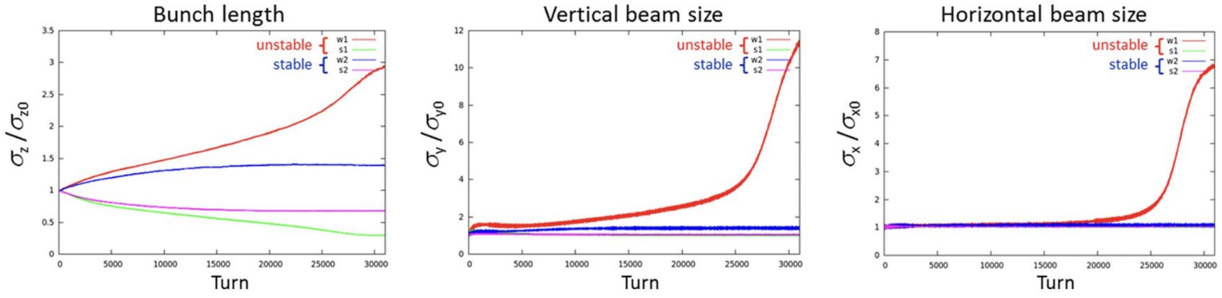
Beam-Beam Instabilities in the FCC-ee

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

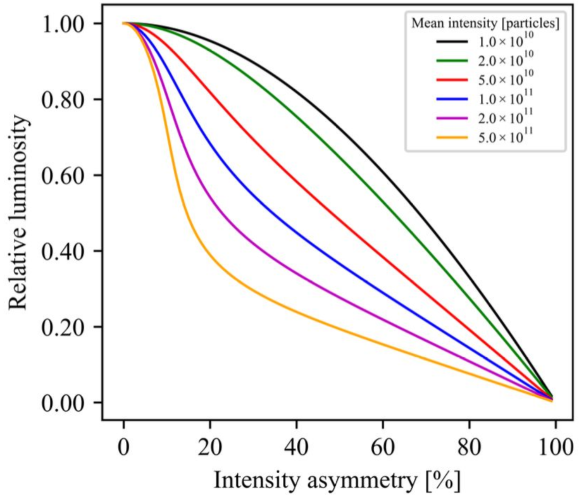
At the z-pole, a few percent intensity asymmetry is tolerable.

Asymmetries are balanced through top-up injection.

But the top-up rate is slower than the instability growth rate.



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

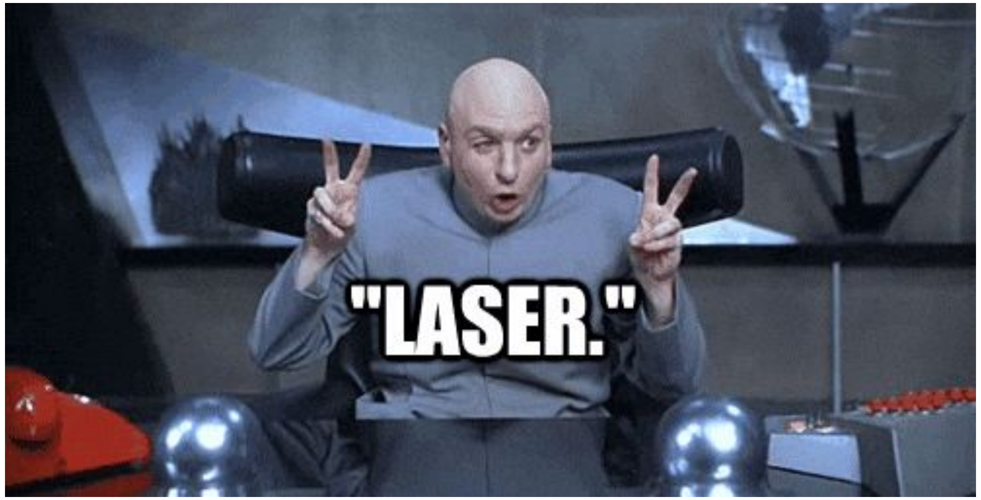


K. Nguyen et al. https://arxiv.org/abs/2404.09012

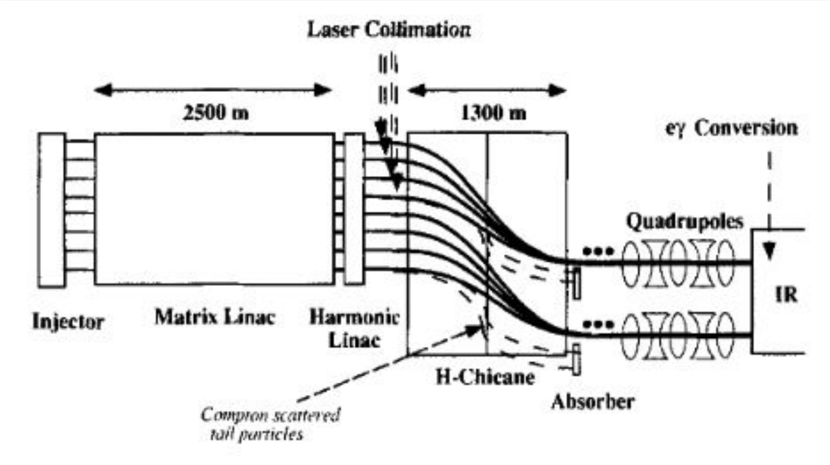
Is there a faster way to control the charge of the colliding bunches?

Science Drivers

1. Develop an “indestructible” collimator.
2. Reduce the length of the collimation system.
3. Provide bunch-by-bunch control of the beam charge.
4. Do all of that with the same tool?

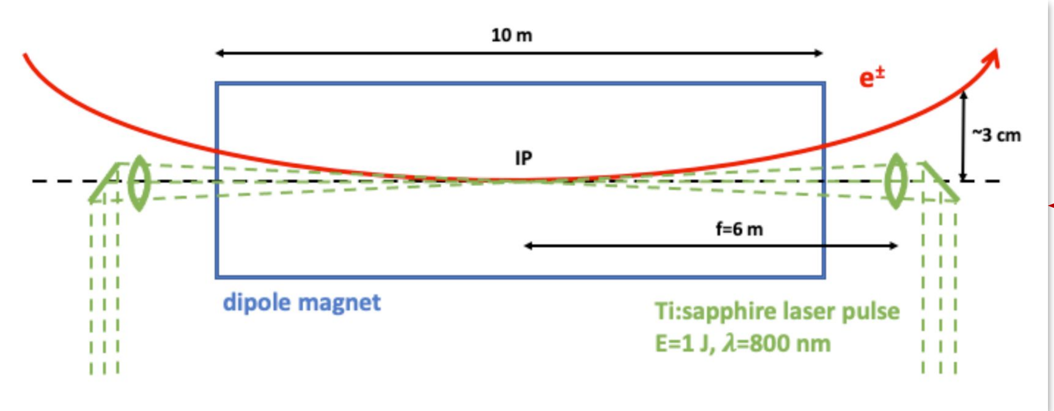


Proposal: Laser Control of Particle Beams



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

Laser collimation of Particle Beams for Multi-TeV Linear Collider



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

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

Shot-by-shot control of electron bunch intensity in FCC.

“A Ti:sapphire J-class kHz laser system is ready to be built today [7–9]. Specifically, we consider a laser system operating with 1 J pulses at 3 kHz (the revolution frequency), with an average power of 3 kW, which translates to the same average laser power as for LBNL’s k-BELLA initiative (3 J at 1 kHz) [10].”

E320 is the backbone of this proposal

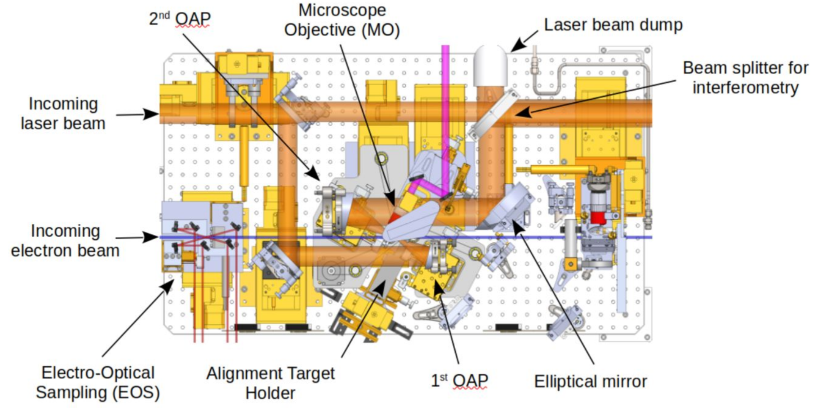
Leverage the E320 infrastructure at FACET-II to provide an R&D platform for:

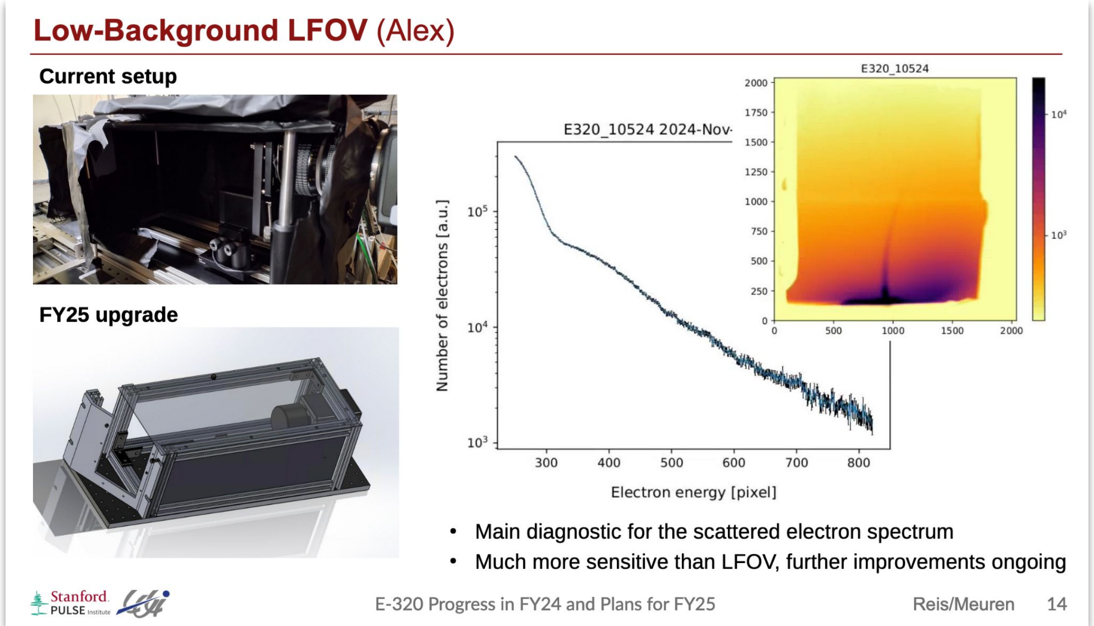
- Bunch-to-bunch laser intensity control.
- Halo collimation.
- Diagnostics to demonstrate collimation and control of high energy beams.

FACET-II is the only User Facility in the world that combines 10 GeV beams with high-power lasers to accommodate this type of R&D.

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





Low-Background LFOV (Alex)

Current setup

FY25 upgrade

- Main diagnostic for the scattered electron spectrum
- Much more sensitive than LFOV, further improvements ongoing

Stanford PULSE Institute

E-320 Progress in FY24 and Plans for FY25 Reis/Meuren 14

Linear Compton Scattering

Much of this R&D assumes *Linear* Compton Scattering.

We prefer long electron beams and stretched laser pulses (σ_z = 200 μm, σ_t = 0.66 ps)

Assume 100 mJ laser pulse energy.

$$x = \frac{4E_b E_\gamma}{m_e^2 c^4} \cos^2 \frac{\alpha_0}{2}$$

$$\sigma_0(x) = \frac{2\pi r_e^2}{x} \left(\left[1 - \frac{4}{x} - \frac{8}{x^2} \right] \ln(1+x) + \frac{1}{2} \left[1 - \frac{1}{(1+x)^2} \right] + \frac{8}{x} \right) .$$

The expected cross-section is 550 millibarn.

There are approximately 4 × 10^{17} photons per pulse.

The interaction probability is 10^{-3} - 10^{-2} depending on geometry.

Phase 1: Demonstration of a fast feed-forward system

Goals:

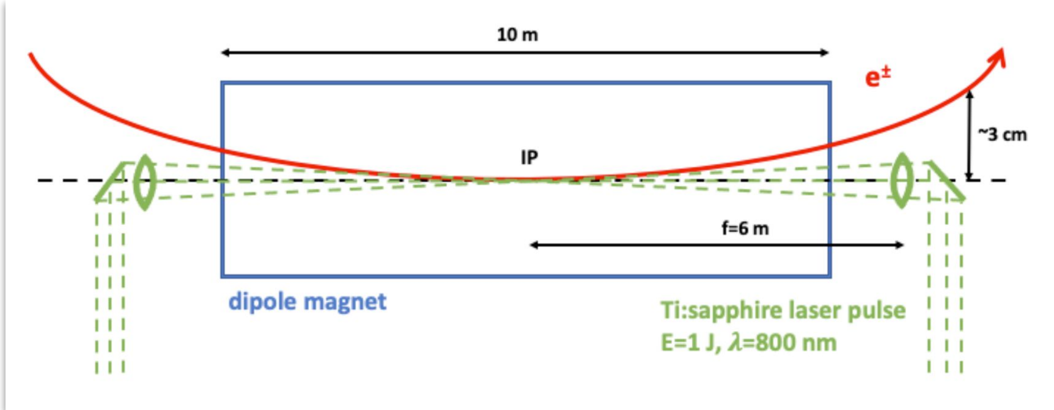
- Mimic feedback mechanism for FCC-ee by demonstrating shot-to-shot feed forward control.
- Deploy halo characterization diagnostic.

Hardware:

- No change to E320 setup.
- Electronics for fast Pockels cell control.
- AWAKE-style Halo Monitor.

Expected signal:

- 5×10^7 scattering events per pulse.



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

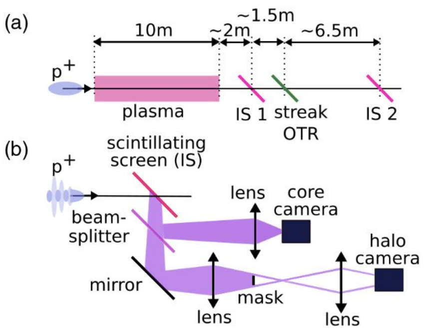
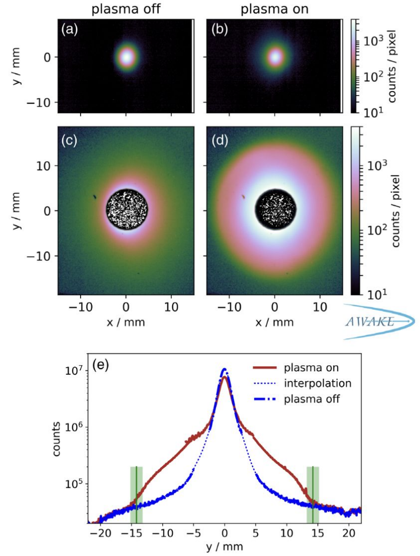


FIG. 1. (a) Schematic location of the imaging stations (IS1 and IS2) and of the OTR streak camera screen with respect to the plasma. The proton bunch moves from left to right. (b) Schematic drawing of the optical setup of the imaging stations.



M. Turner, et. al Phys. Rev. Lett. 122, 054801 (2019)

Phase 2: Halo Collimation

Goals:

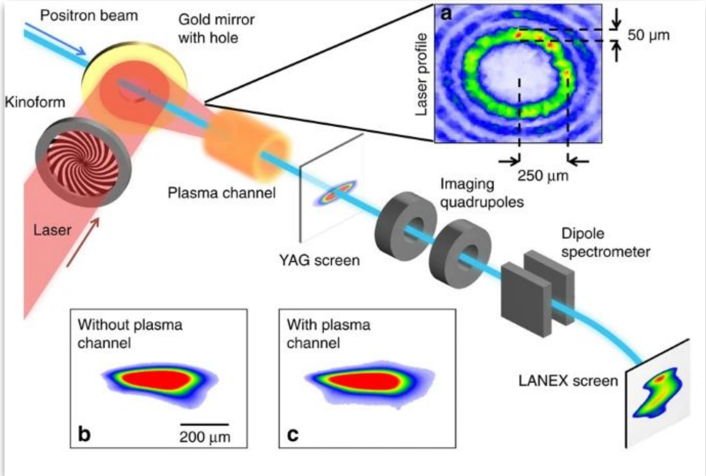
- Interact beam halo particles with an anular laser pulse.
- Measure jitter tolerances and effects.

Hardware:

- Laguerre-Gauss or High-Order Bessel Optics.
- Head-on laser interaction.
- LBG_LFOV or other sensitive detector.

Expected signal:

- 7✕ 10^3 scattering events per pulse.



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

LBG_LFOV upgrade (Knetsch)

Phase 3: Alternative Schemes

Goals:

- Reduce required laser pulse energy needed for collimation and control by utilizing nonlinear compton scattering and/or alternate geometries.

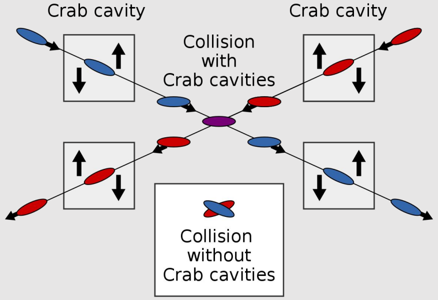
Hardware:

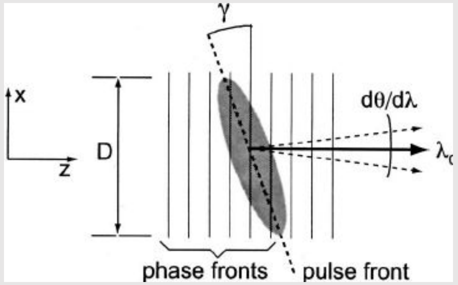
- 90° OAP
- Cylindrical lens
- Tilted phase front

Expected signal:

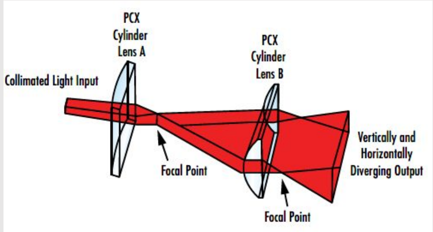
- Depends on scheme

Tilted Phase Front





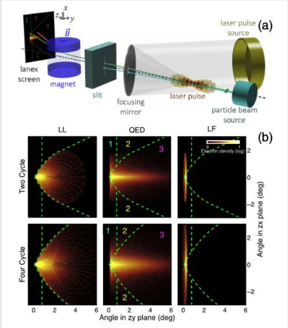
Cylindrical Lens



Nonlinear Quenched Regime

Operate in a nonlinear regime but still induce a binary interaction.

"Quantum Quenching of Radiation Losses in Short Laser Pulses." C. N. Harvey, et al. Phys. Rev. Lett. 118, 105004 (2017)



Conclusions

The R&D topics covered by this proposal have the potential to improve the performance and reduce the cost of future Higgs Factories, while paving the way towards a 10 TeV Wakefield Collider BDS system.

- The proposal is well-aligned with P5 Recommendations 2.c and 4.a.

The E320 experiment enables rapid implementation and a clear path to results for this proposal.

- The technical risk for Phases 1 and 2 is low.

The implementation of a Halo Monitor will be broadly useful for the facility.