Interactions of Lasers and Electron Beams for Collider-Directed R&D at FACET-II

Spencer Gessner, SLAC

AAC24, Naperville
July 23, 2024

SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

Collaboration

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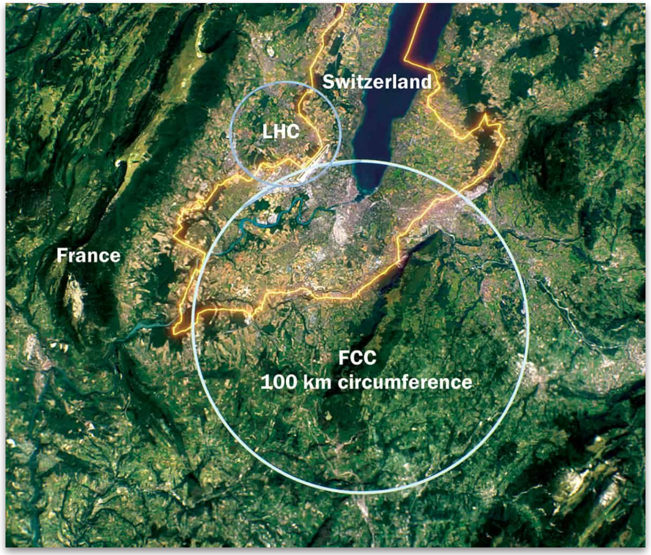
CERN: J. Keintzel, F. Zimmermann

ÉCOLE POLYTECHNIQUE: S. Meuren

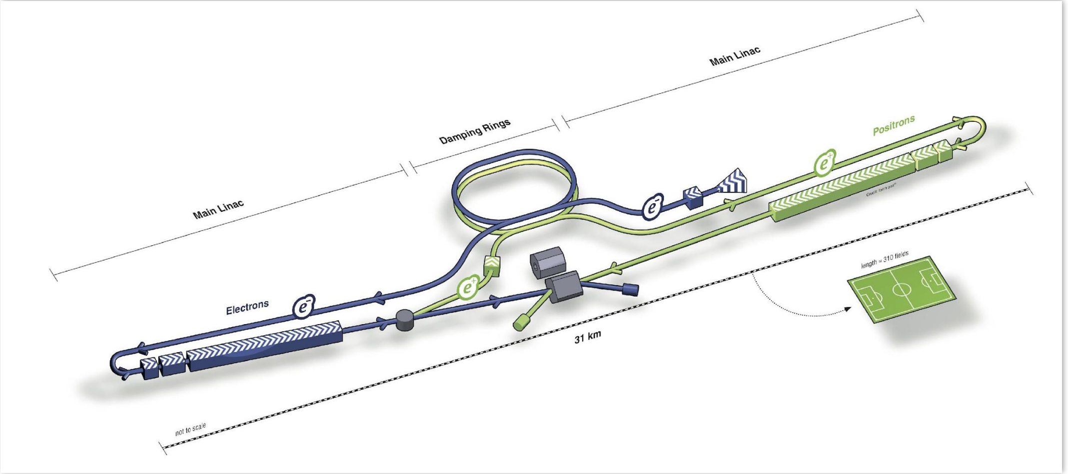
INFN: I. Drebot

Future Colliders

FCC-ee



ILC

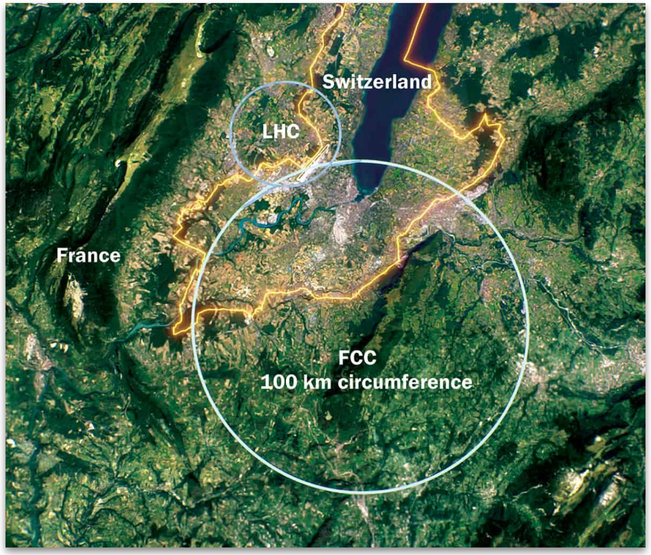


The P5 Report recommends:

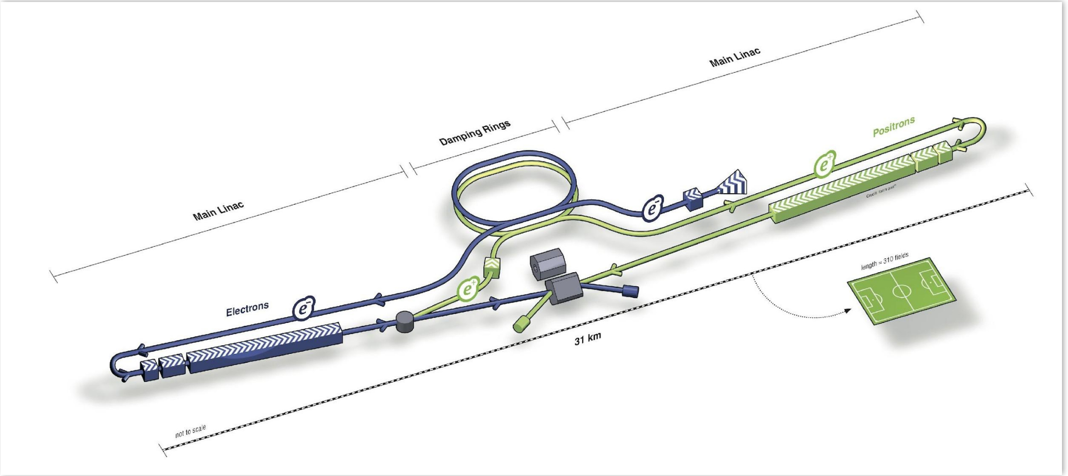
2.c) An off-shore Higgs Factory . . . The current designs of **FCC-ee** and **ILC** meet our scientific requirements.

Future Colliders

FCC-ee



ILC



The P5 Report recommends:

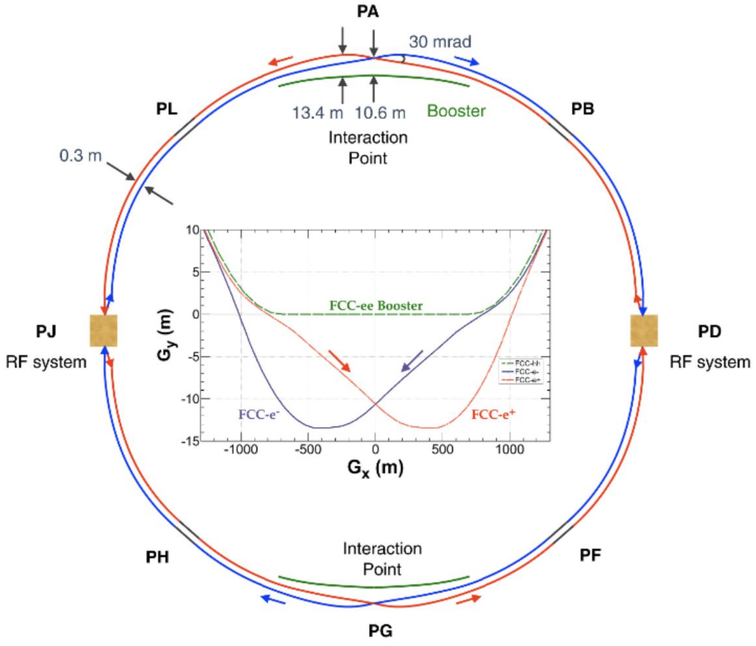
Area Recommendation 10) . . . collider accelerator R&D at the level of **$35M per year**. . .

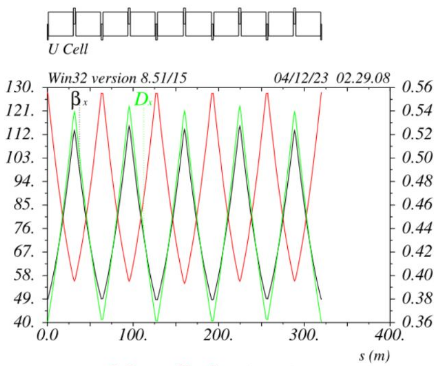
Higgs Factory Designs are Mature (Boring?)

The ILC TDR was published in 2013.

The FCC-ee Feasibility Study has robust accelerator design.

These machines *should* be boring. The experiment is particle physics, not accelerator physics.





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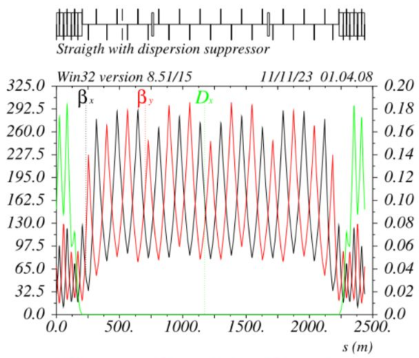
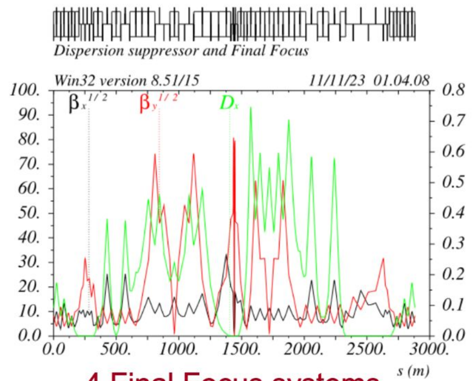


4 Long Straight Sections



4 Final Focus systems

P. Raimondi, FCC Week 2024

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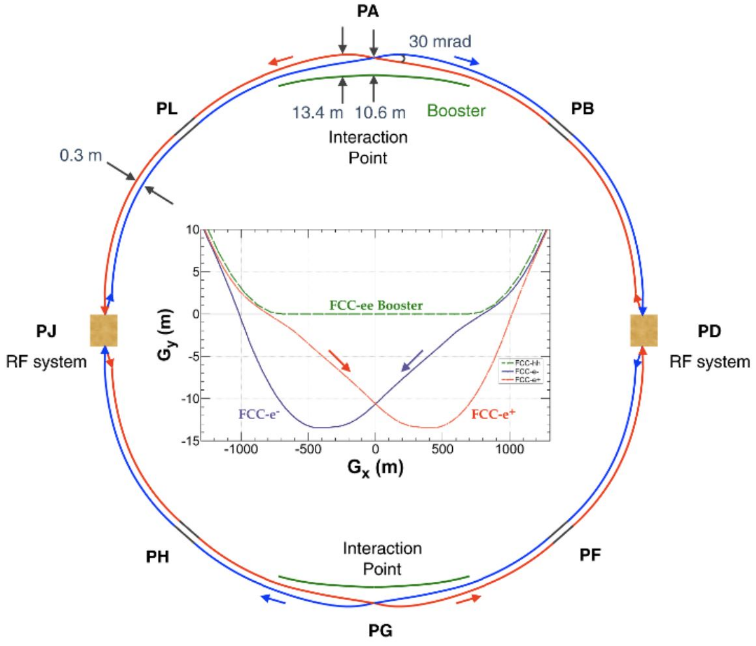
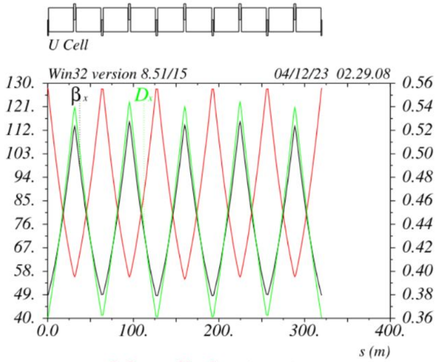


Is there anything left to do?



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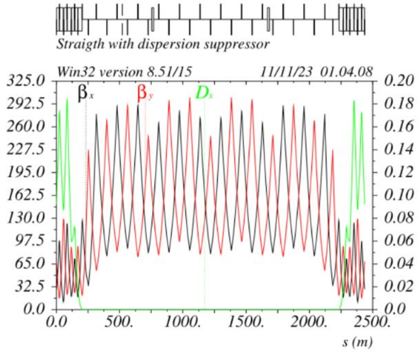

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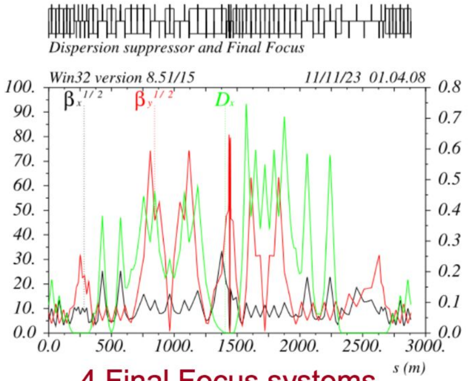

4 Final Focus systems

[P. Raimondi, FCC Week 2024]

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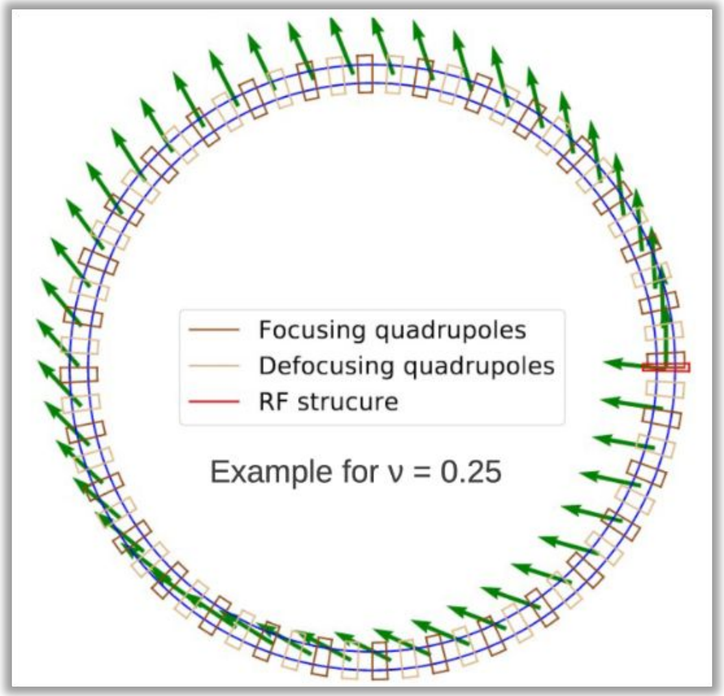
Pushing the Envelope

Yes! There is a lot left to do!

FCC-ee has an ambitious program to measure the beam energy at the Z-pole to one part in 10^{-6}!

It's not possible to measure the beam energy this accurately by varying the strength of the dipole magnets (10^{-4}-10^{-5}).

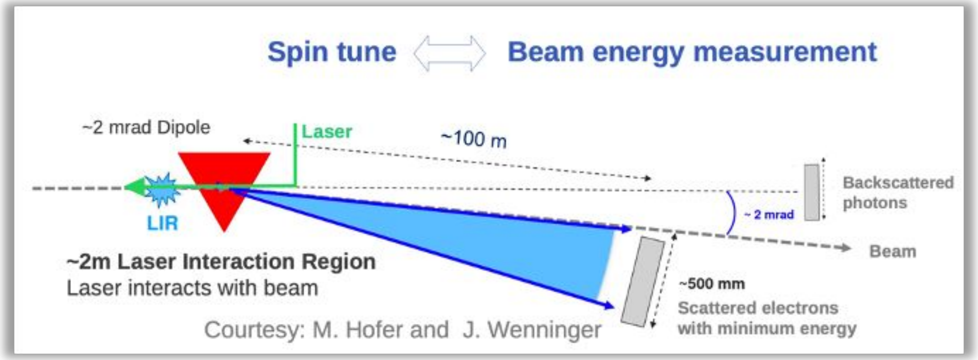
Instead, measure the spin tune.



https://arxiv.org/pdf/1909.12245

Table 15. Calculated uncertainties on the quantities most affected by the centre-of-mass energy uncertainties, under the final systematic assumptions.

Observable	statistics	$\Delta\sqrt{s}_{\rm abs}$ 100 keV	$\Delta\sqrt{s}_{\rm syst-ptp}$ **40 keV**	calib. stats. 200 keV/$\sqrt{N^i}$	$\sigma_{\sqrt{s}}$ 85 ± **0.05** MeV
m_Z (keV)	4	100	**28**	1	–
Γ_Z (keV)	4	2.5	**22**	1	**10**
$\sin^2\theta_W^{\rm eff} \times 10^6$ from $A_{FB}^{\mu\mu}$	2	–	**2.4**	0.1	–
$\frac{\Delta\alpha_{QED}(m_Z^2)}{\alpha_{QED}(m_Z^2)} \times 10^5$	3	0.1	**0.9**	–	**0.1**



FACET-II is unique

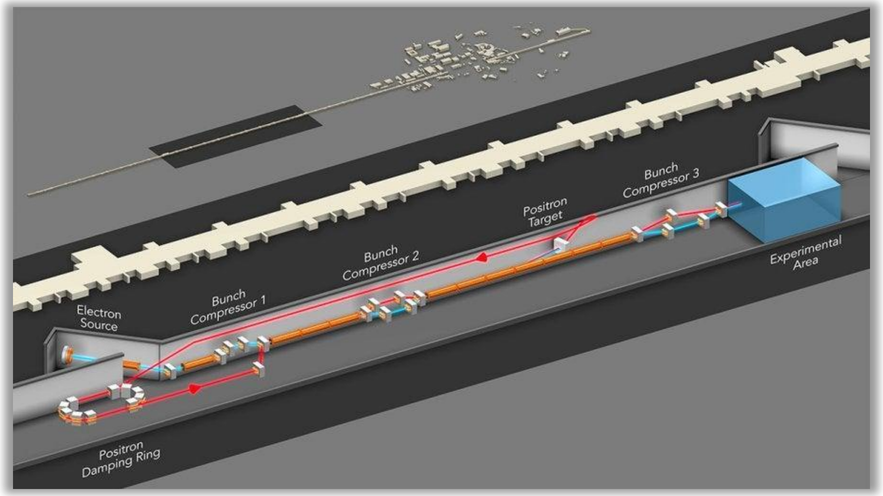
What role can FACET-II play in R&D for future Higgs Factories?

FACET-II is the only test facility in the world that provides a primary electron beam with energy greater than 10 GeV.

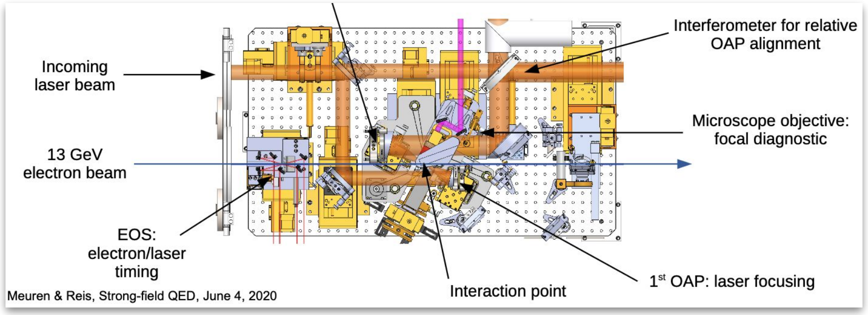
The electron bunch length may be controlled by adjusting the RF phase of the linac sections.

FACET-II has a high power laser with a laser-electron beam interaction point.

See Alex Knetsch's talk on E320 Strong Field QED Experiment in WG6 Tuesday at 5:40.



FACET-II facility layout



E320 Laser Interaction Point

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Collider R&D at FACET-II

We identify several challenges for FCC-ee and ILC that can be addressed at FACET-II:

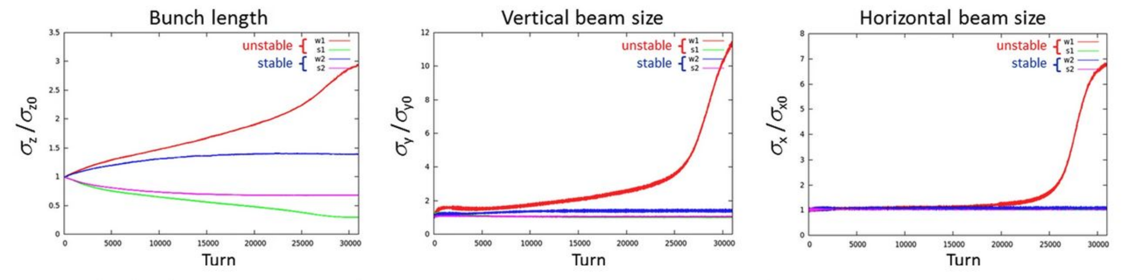
1. Laser control of electron bunch intensity for FCC-ee.
2. Laser collimation of electron beams for FCC-ee and ILC.
3. Compton polarimetry tests for the FCC-ee.
4. Experimental verification of strong-field QED models for beam-beam interactions at the ILC and beyond.

Bunch Intensity Challenge at FCC-ee

The FCC-ee bunch charge is controlled by top-up injection. The time between top-ups is roughly 1 minute.

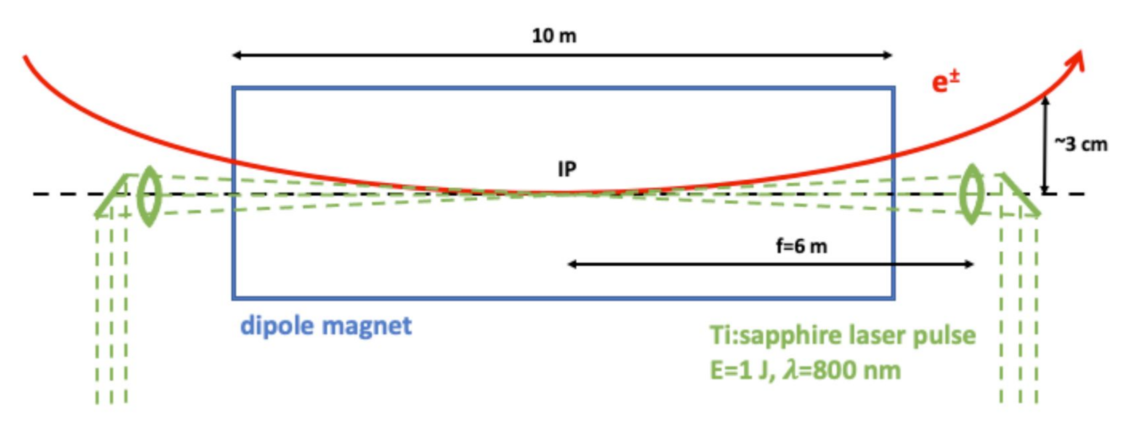
A beam-beam instability occurs if the charge difference between colliding bunches is greater than a few percent (flip-flop instability). This instability may develop on the few-second time scale.

Proposal: use Compton scattering to control the FCC bunch intensity on a fast timescale.



Example of 3D flip-flop: simulation results of a quasi-strong-strong model at low energy (45.6 GeV)

Shatilov, D. How to increase the physics output per MW.h for FCC-ee?. *Eur. Phys. J. Plus* **137**, 159 (2022).



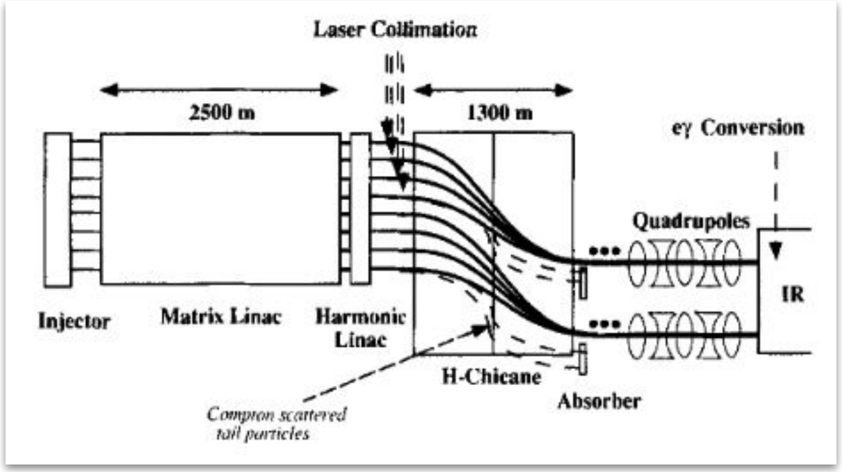
Zimmermann, F. Raubenheimer, T. CONTROLLING e+/e− CIRCULAR COLLIDER BUNCH INTENSITY BY LASER COMPTON SCATTERING. WEPOST010, IPAC22.

Collimation Challenge at Colliders

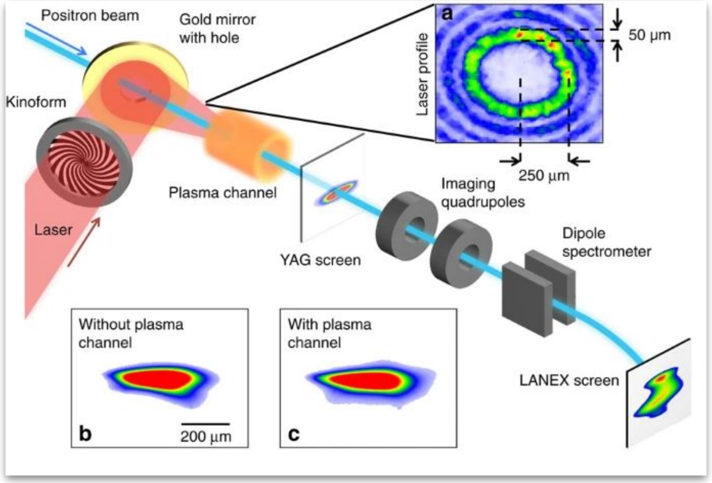
Collimation systems for linear and circular colliders have conservative designs: they must be able to withstand a complete mis-steering of the beam.

Collimation systems get damaged over time. They may fracture and produce dust in the beamline.

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



Zimmermann, 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.

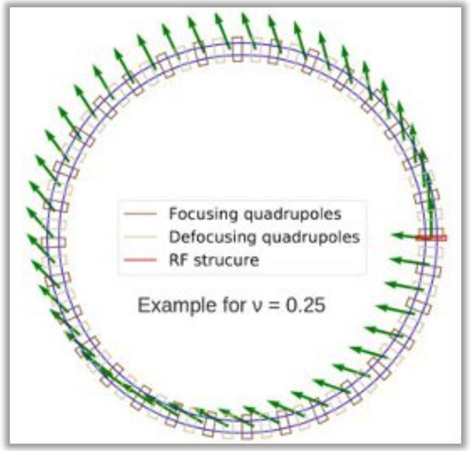
Compton Polarimetry Challenge at FCC-ee

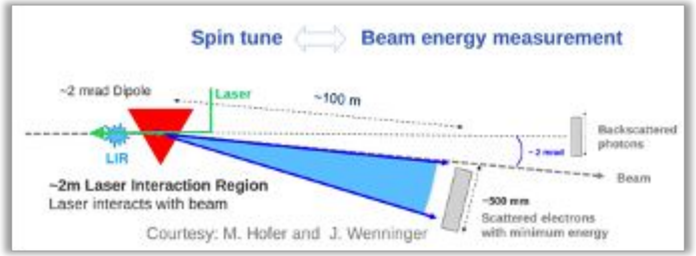
The electron beam energy must be measured at the level of 10^{-6} at FCC-ee in order to measure the width of the Z boson.

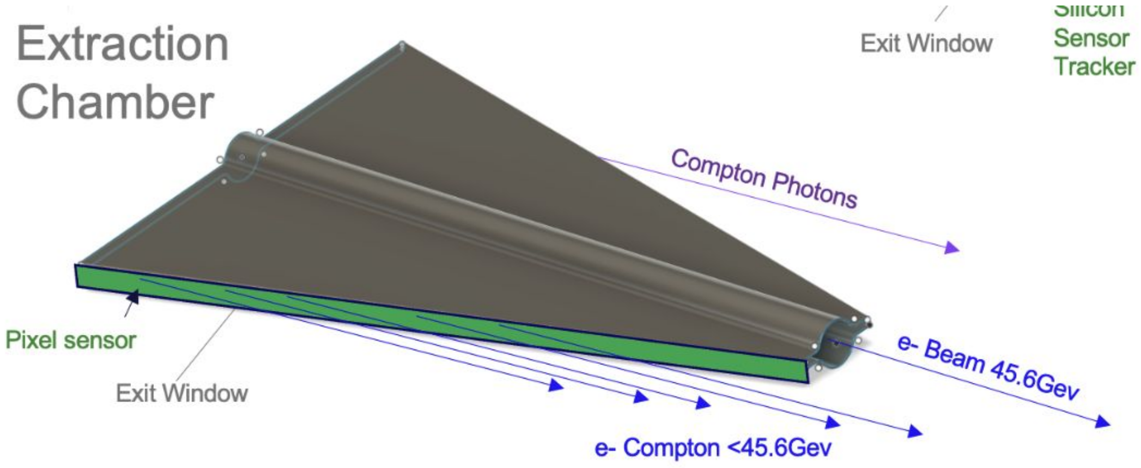
This is only possible with spin tune measurements, but the FCC bunches are not polarized.

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

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







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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 options for FACET-II.

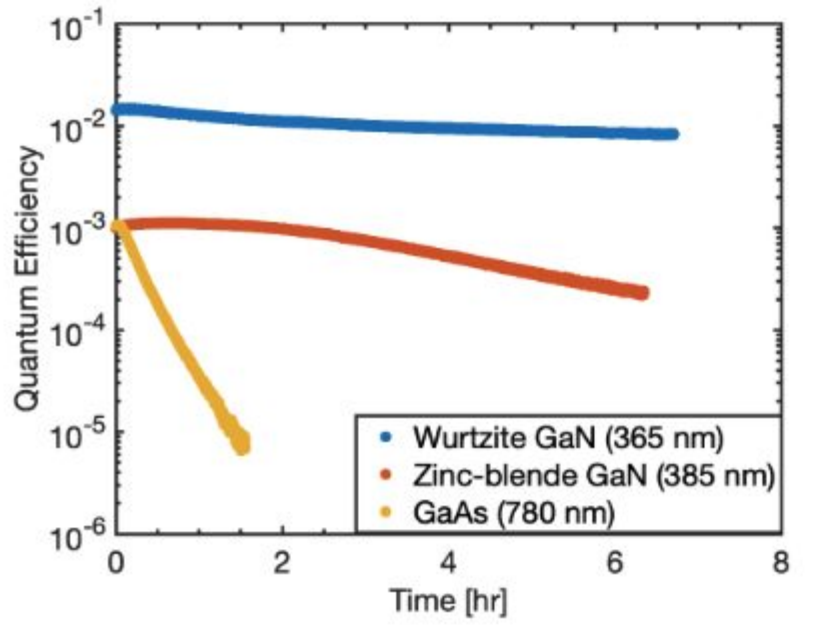

FIG. 2. Threshold lifetimes of the NEA W-GaN, ZB-GaN and GaAs photocathodes compared under similar vacuum conditions.

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

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Verification of Strong Field QED Models

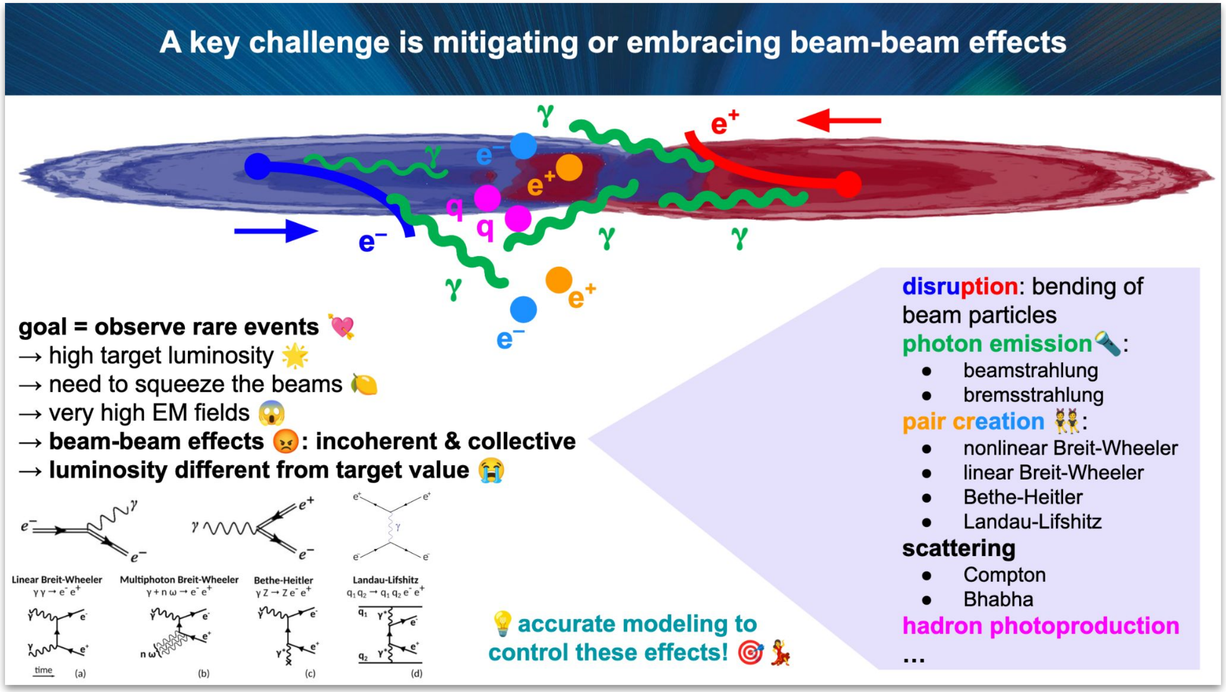
For high-energy upgrades of linear colliders, the beamstrahlung parameter Υ becomes very large. . .

We are developing the WarpX code as a high performance replacement of GUINEA-PIG and CAIN.

Neither GUINEA-PIG or CAIN include all of the physics relevant to extreme Υ scenarios.

With larger laser pulse energies, **E320 will be sensitive to non-perturbative QED effects**.

A. Formenti, LBNL



See Remi Lehe's talk on Beam-Beam modeling in WarpX in WG7 Thursday at 5:00.

Conclusion

A Future Higgs Factory is the top priority for the global accelerator-based HEP science.

R&D innovations have the potential to increase the luminosity of these machines.

The high beam energy and flexibility of FACET-II, plus the availability of a high power laser makes is an ideal facility for R&D activities that support Future Higgs Factories.

We will leverage the E320 experimental infrastructure in support of Collider Directed R&D at FACET.