

FCC-EE ACCELERATOR DEVELOPMENTS FROM USASK

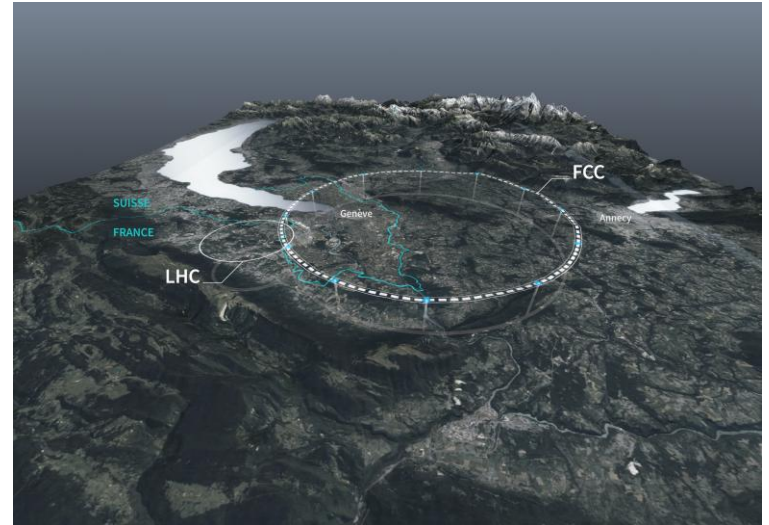
P. Hunchak, J. Keintzel, M. Boland

Overview

- Refresher on Future electron-positron Circular Collider (FCC-ee)
- Ongoing studies of non-linear field errors and their corrections
- A few other projects that USask is planning or actively involved in



<https://news.usask.ca/articles/research/2025/usask-ranked-among-canadas-top-research-universities.php>



<https://fcc.web.cern.ch/fcc-layout-aerial-view>

FCC-ee: The Collider

- The FCC-ee pushes to unprecedented energy and size for circular lepton colliders.
- The 91 km ring consists of thousands of magnetic elements, arranged to provide extremely focused beams at the interaction points for maximum luminosity.
- Reaching this target performance with realistic machine imperfections is a significant challenge being addressed by many collaborators.

"DEFINING THE NEW FCC-ee BASELINE OPTICS"
<https://indico.jacow.org/event/95/contributions/12429/>

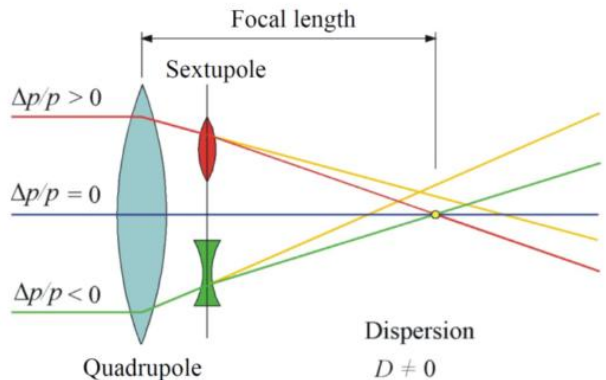
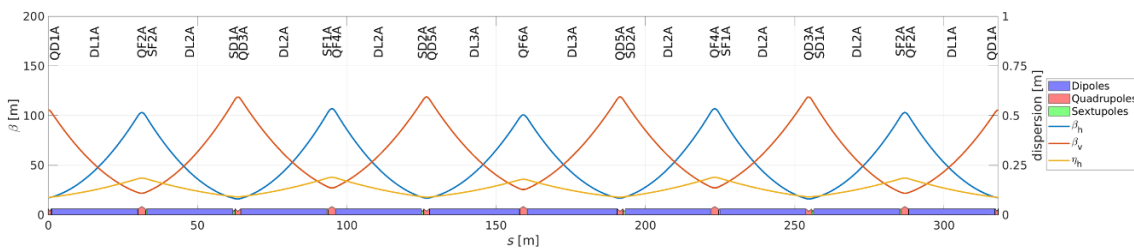
Optics Mode	LCC Z	LCC $t\bar{t}$
Beam Energy E (GeV)	45.6	182.5
Circumference C (m)	90644.816	
Energy Loss per turn W_0 (GeV)	0.035	9.01
RF momentum acceptance (%)	1	2
Transverse Tune Q_x/Q_y	194.16 / 170.20	346.19 / 262.27
Chromaticity Q'_x/Q'_y	12 / 5	0 / 0
Horiz. β -function at IP β_x^* (cm)	9	90
Vert. β -function at IP β_y^* (mm)	0.7	1.4
Horizontal emit. ε_x (nm)	0.70	2.10
Target vert. emit. in collision ε_y (pm)	1.40	2.11
Luminosity \mathcal{L} ($1 \times 10^{34} \text{ s}^{-1}/\text{cm}^2$)	150	1.45

Accelerators Simplified

The fundamental part of collider design is the arrangement of electromagnets that steer (dipoles) and focus (quadrupoles, sextupoles) the particle beams as they travel around the ring within the vacuum chamber, with particle energy being replenished each turn with RF cavities.

An ideal particle (on-axis, on-energy) has a specific path it takes within the machine, but a real beam has a spread both in position and in energy.

tt arc cell optics



Hillert, Wolfgang. (2021). Transverse Linear Beam Dynamics. 10.48550/arXiv.2107.02614.

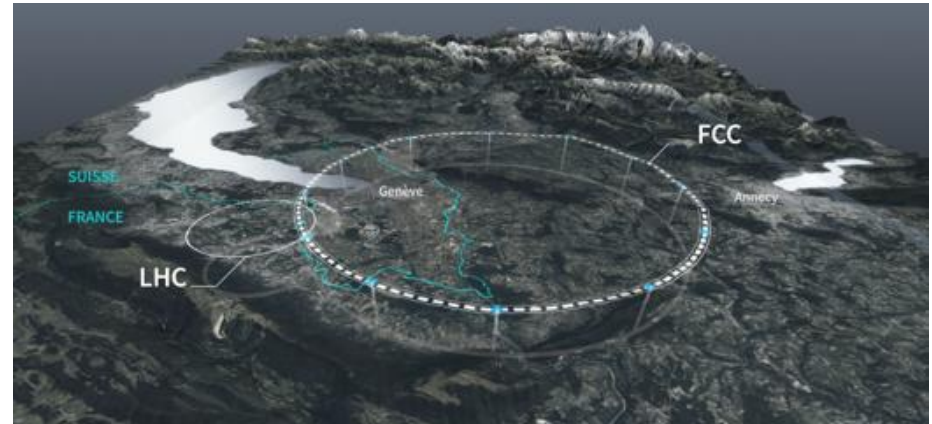
Challenge for FCC-ee

Along with variation in particle energy and trajectory, the machine itself will have imperfections. Magnets will have higher order field components from manufacturing, and misalignments introduce errors as well.

While these problems exist for previous/present machines the immense scale and energy of the FCC-ee intensify them.

We aim to transport particle beams that are tens of μm across around a 91km ring consisting of tens of thousands of elements.

The tuning of the machine in the presence of errors is crucial for success.

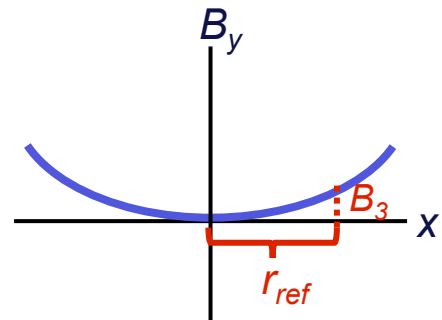


Field Errors and Misalignments

Many ongoing studies to ensure that the machine can be operated with realistic imperfections.

FCC-ee Optics Tuning – Towards the reference design (IPAC '26)

J. Keintzel et al. (incl. P. Hunchak & M. Boland) (<https://indico.jacow.org/event/95/contributions/14395/>)



Field Errors are defined by the relative size of the multipole relative to the nominal field.

For example a sextupolar error (B_3) on a dipole (B_1) would be defined as:

$$b_3 = \frac{B_3}{B_1} r_{ref}^2$$

Typically on the order 10^{-4} , $b_3 = 1 \cdot 10^{-4}$ is called 1 unit of b_3 .

Also, misalignments on the order of 1mm in each plane and 1000 μ rad rotations.

Estimated field error components for Arc Dipole magnets

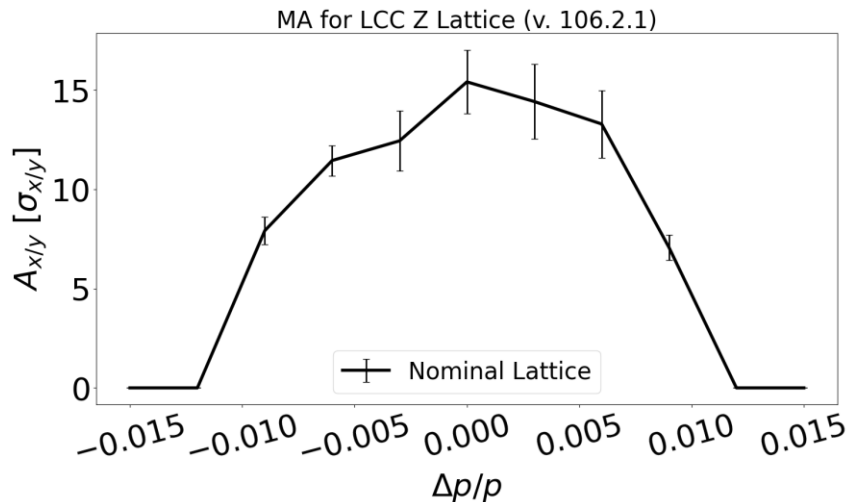
	Integrated field components at 10 mm	systematic (units)	r.m.s (units)
normal	B_1	-	10
	b_2	10	5
	b_3	0.5	0.5
	b_4	0.5	0.5
skew	a_2	1	2
	a_3	0.5	0.5
	a_4	0.1	0.1

Momentum Acceptance and Dynamic Aperture

Two of the key figures of merit for accelerator performance are the MA and DA.

Both are measures of what initial conditions for particles will be stored stably in the ring.

- MA scans momentum deviation and transverse amplitude
- DA scans transverse amplitude (x and y)



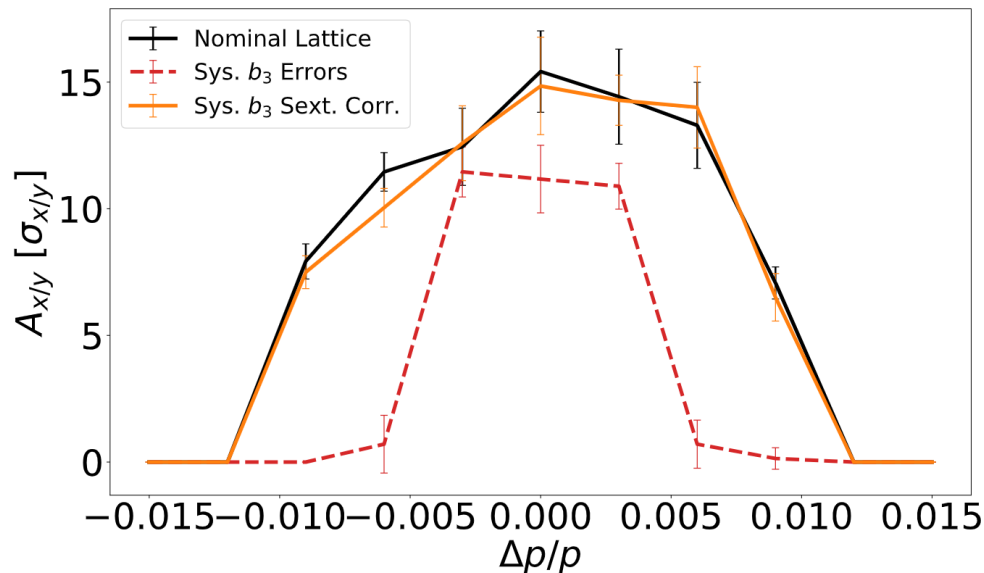
These metrics have direct correlation to beam lifetime and injection efficiency, both crucial for machine performance.

Previous studies show that even with good correction of linear optics, machine imperfections cause significant reduction in MA and DA.

Therefore, we look to non-linear effects.

Arc Dipole b_3 Errors - MA

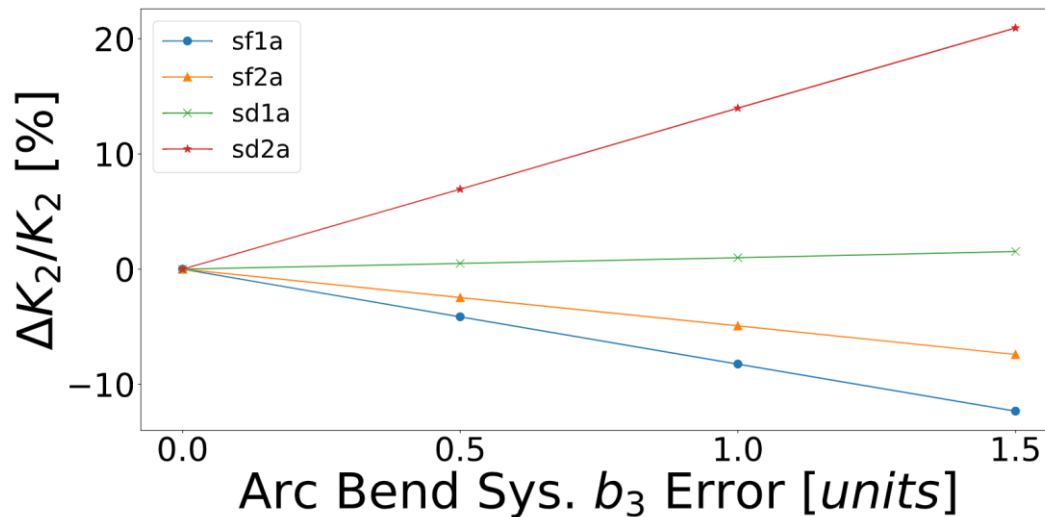
- In pursuit of complete non-linear correction scheme, examine imperfections in isolation.
- 0.5 units of systematic b_3 (sextupole) errors does reduce MA [10 tracking seeds averaged]



- Using four knobs to adjust the strengths of the four arc sextupole families and restore chromaticity (Q'_x, Q'_y) and amplitude detuning ($dQ_x/dJ_x, dQ_{x,y}/dJ_{y,x}$) to their design values, the MA is fully recovered.

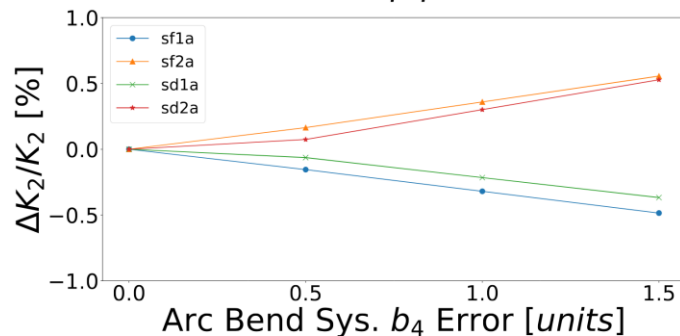
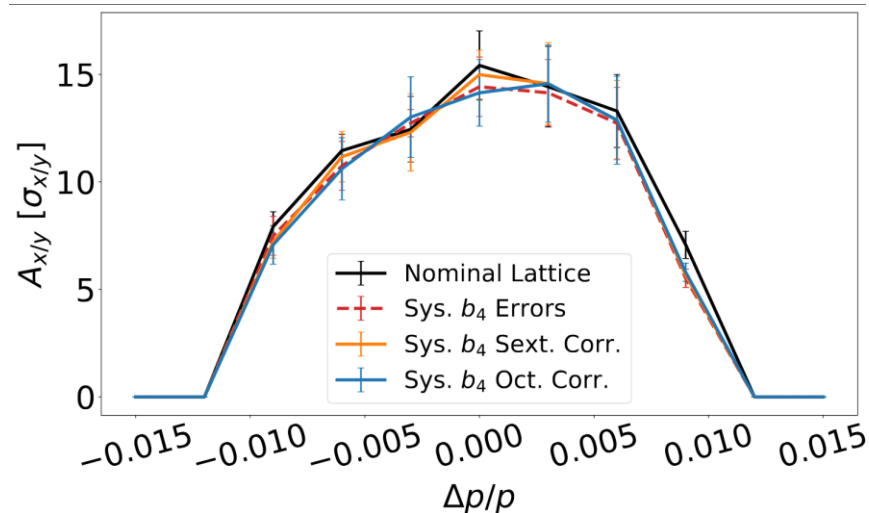
Arc Dipole b_3 Errors – Sextupole Strength

- To perform these corrections of 0.5 units sys. b_3 errors requires <7% adjustment of the arc sextupoles.
- Linear relationship with growing b_3 as expected.
- In $t\bar{t}$ sextupoles are close to their limit by design so this level of correction may require longer sextupoles.



Arc Dipole b_4 Errors – MA

- With 0.5 units sys. b_4 (octupole) errors there is negligible impact on MA [10 tracking seeds averaged]
- Very minimal change in the arc sextupole strengths required to restore design parameters (<0.5% change).
- Octupole fields can also be used to correct amplitude detuning and other high order terms.
- Exploring this further as possible enhancement of sextupole correction.



Orthogonal Octupole Corrector knobs

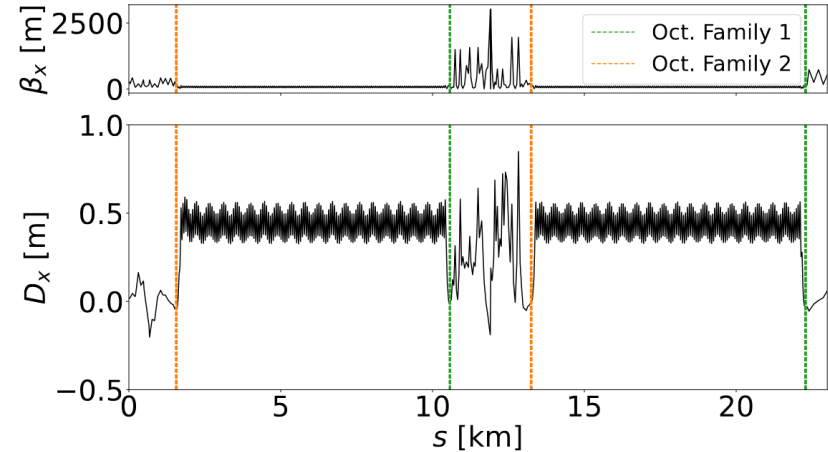
Octupoles most direct impacts on the optics are on amplitude detuning and 2nd-order chromaticity.

In order to correct amplitude detuning and minimize the impact on 2nd-order chromaticity, octupoles should be placed at locations where the machine optics maximize the factor:

$$F = \beta_x / (4D_x^2)$$

β -function (related to beam size) and dispersion, D_x (beam spread with energy deviation).

Locations at the start and end of each straight section were identified for octupole correctors in the FCC-ee, ongoing studies to see how well they can reduce the correction strength required in the sextupoles (especially at $t\bar{t}$ energy).

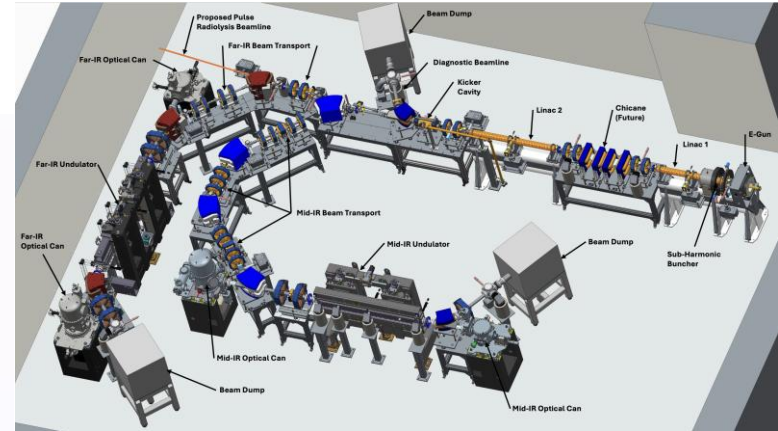
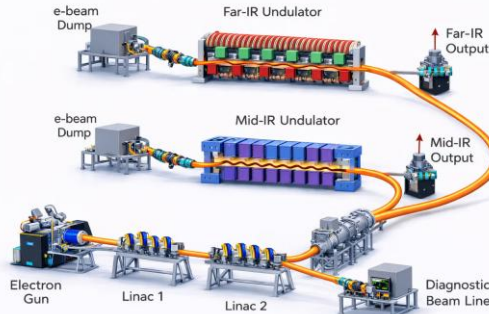


WaterFEL: IR Free Electron Laser lab in Canada



- National Lab for IR user experiments in spectroscopy and time resolved measurements.
- 90 keV electron source and 50 MeV linac.
- Two undulator lines to cover wavelengths 3-175 μm .
- Building under construction, commissioning in 2027.

The electron source and the creation and shaping of the initial electron bunch can be applicable for the FCC-ee injectors



Other Connections

Canadian Light Source

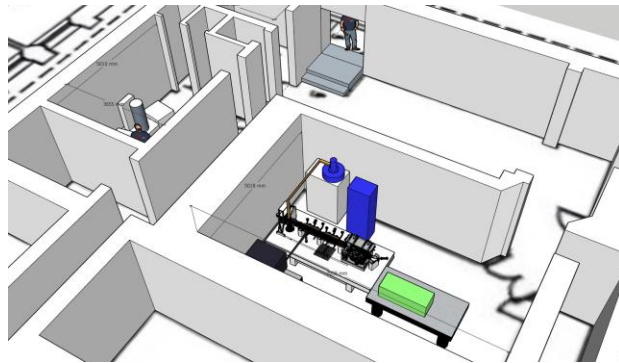
- Next talk (*E. Nebot Del Busto*)
- Opportunities for accelerator beamtime and measurements
- Light Source storage rings have been previously used as test beds for techniques and equipment used in colliders: including top-up injection and beam loss monitors.



Example works including E. Nebot Del Busto, M. Boland

<https://doi.org/10.1103/PhysRevSTAB.14.012804>

<https://jacow.org/IBIC2014/papers/WECZB3.pdf>



Proposed USask accelerator lab

- Early days of planning
- Other faculty at USask involved in planning and proposals

Conclusions

FCC-ee is a complex and challenging machine (91 km, 45.6-182.5 GeV)

- We are currently involved in the FCC tuning working group at CERN to address realistic imperfections in the design.
- Specifically working on correction of high order errors (b_3 and b_4) using sextupoles and octupoles (potential addition to the design).
- Collaborating with other tuning studies and working to produce a complete non-linear correction scheme to ensure best performance of the machine.

WaterFEL

- Some technological overlap with FCC-ee in the electron source/injector
- USask Master's student starting in the fall
- Commissioning in 2027

CLS, potential USask Accelerator Lab

*Thank you for
your attention.*

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