INJECTION TRACKING STUDIES IN THE FCC-EE COLLIDER RING

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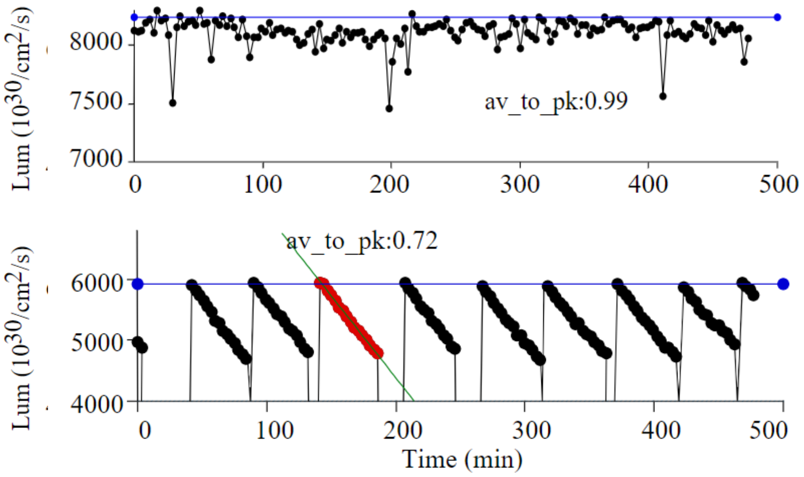
Top-up Injection for FCC-ee

Top-up injection is necessary to maximize the integrated luminosity of the collider.

Regular injection from the full-energy booster to maintain the beam current in the collider ring.

Proven at many other accelerators.

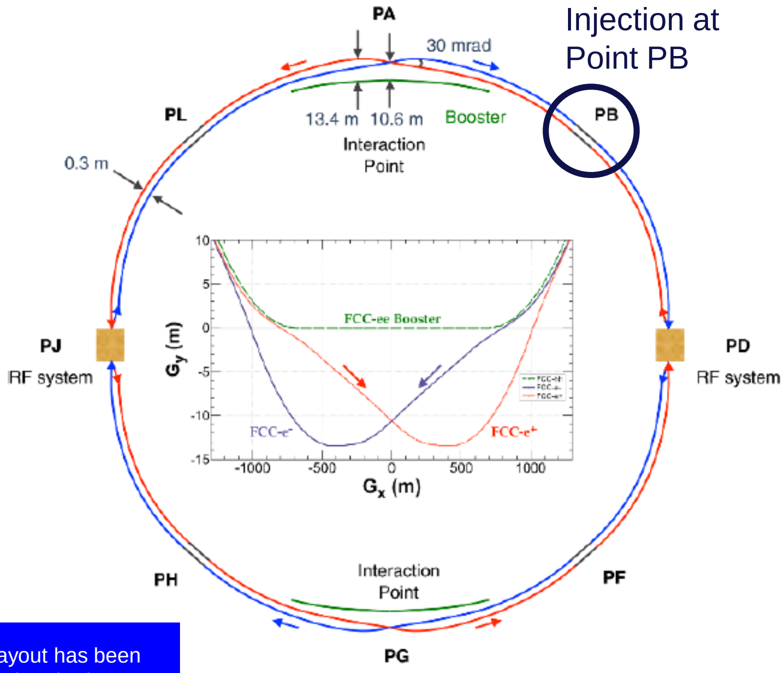
Four viable modes have been identified for FCC-ee in the past, we now look into follow-up studies of these approaches.



Wienands, U. "Lepton Collider Operation with Constant Currents". Proceedings of the 2005 Particle Accelerator Conference. doi:10.1109/pac.2005.1590385

M. Aiba et al. "Top-up injection schemes for future circular lepton collider". In: *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 880 (Feb. 2018), pp. 98–106. DOI: 10.1016/j.nima.2017.10.075. URL: https://doi.org/10.1016%5C%2Fj.nima.2017.10.075.

The FCC-ee Ring



Injection at Point PB

Layout has been updated. Shorter Circumference, longer injection straight.

Four operation modes (Z, WW, ZH, & $t\bar{t}$) ranging in beam energy from 45.6 to 182.5 GeV.

Z-mode examined first for machine protection aspect (high stored beam energy).

Z-mode operation Parameters

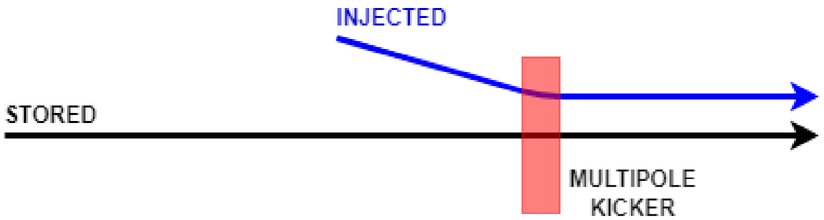
Beam energy (GeV)	45.6
Beam current (mA)	1390
Horizontal emittance ϵ_x (nm · rad)	0.27
Vertical emittance ϵ_y (pm · rad)	1.0

A. Abada et al. "FCC-ee: The Lepton Collider". In: *The European Physical Journal Special Topics* 228.2 (June 2019), pp. 261–623. ISSN: 1951-6401. DOI: 10.1140/epjst/e2019-900045-4. URL: https://doi.org/10.1140/epjst/e2019-900045-4.

Injection Options

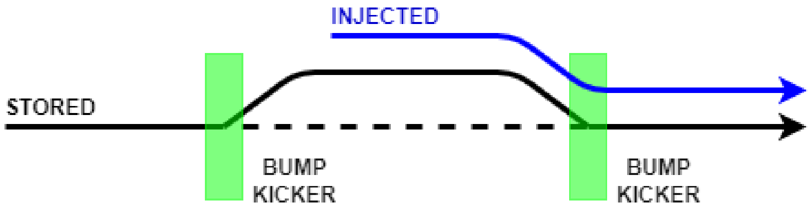
Multipole Kicker Injection (MKI)

- Off-axis injected beam
- Kicker has minimal on-axis field (stored beam)
- Kicker has significant off-axis field (injected beam)



Conventional Orbit Bump Injection

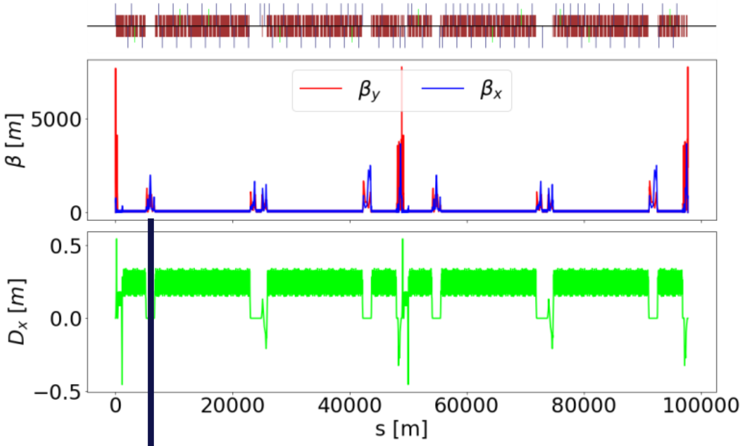
- Dipole kickers create a one turn orbit bump
- Reducing the effective amplitude of off-axis injected beam
- Bump is closed quickly to avoid septum on subsequent turns.



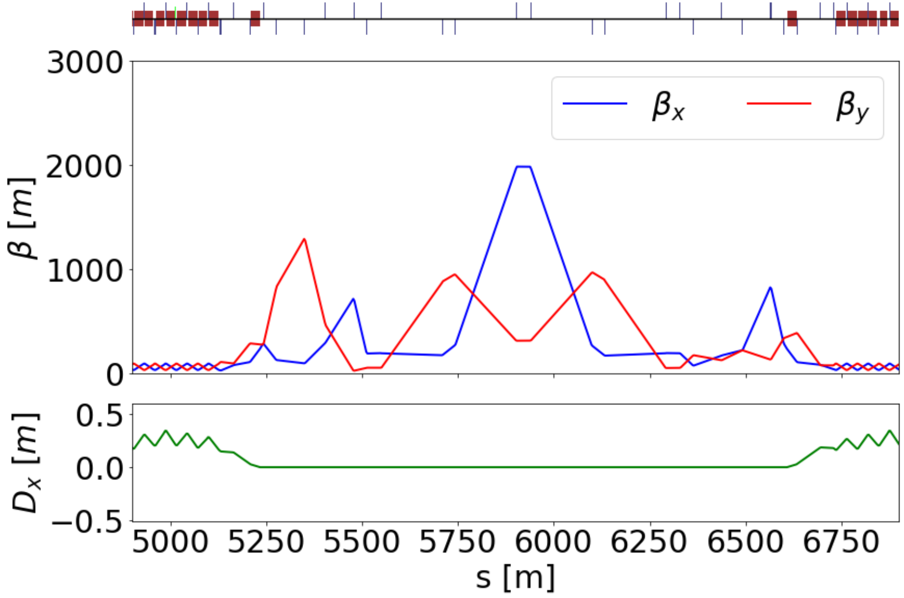
Both modes also work off-momentum, with dispersion allowing on-axis injection.
For all cases we’ve chosen to look into the horizontal plane.

Machine Parameters

Z Optics Full Machine



PB Injection Section

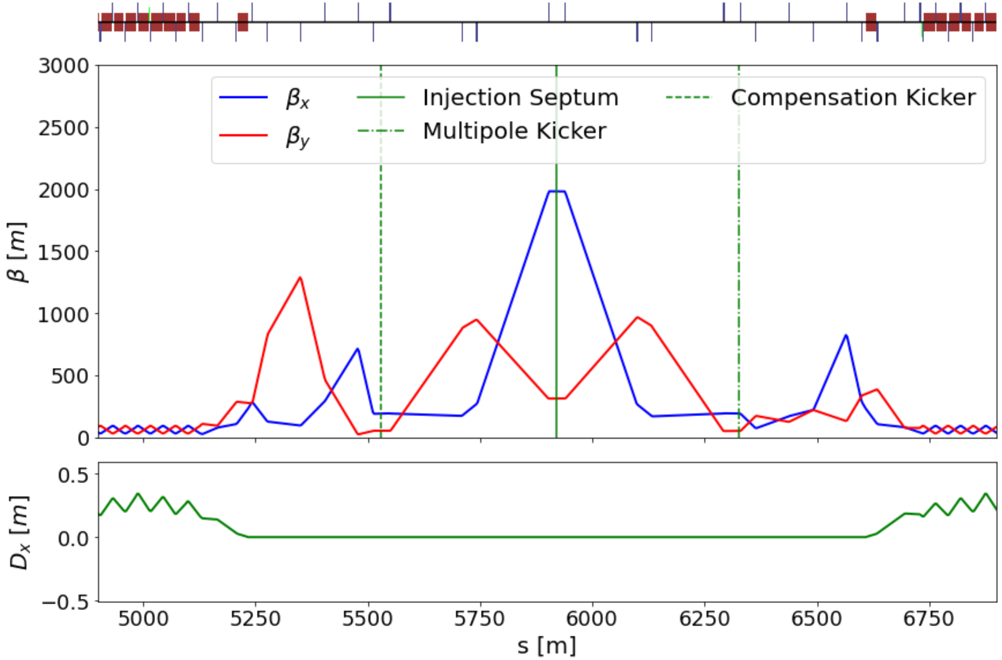


Optics matched (M. Aiba) to allow for both orbit bump and MKI on momentum. Large β_x at injection point to minimize effective size of the septum.

MULTIPOLE KICKER INJECTION

On-momentum

Placement of Injection Magnets



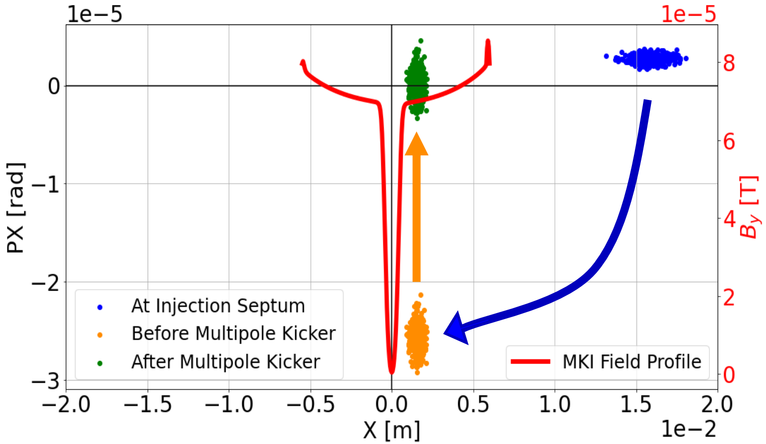
- MKI is a 90° phase advance after the septum.
- Compensation kicker (MKIC) is 90° ahead of the septum.
- Locations of the two identical kickers share similar β_x. (191m vs 193m)
- DA checks on ideal machine show no issues. (>15σ_x)
- Assume injected emittance = stored emittance.
  - $\varepsilon_x = 0.27\ nm \cdot rad$
  - $\varepsilon_y = 1.0\ pm \cdot rad$

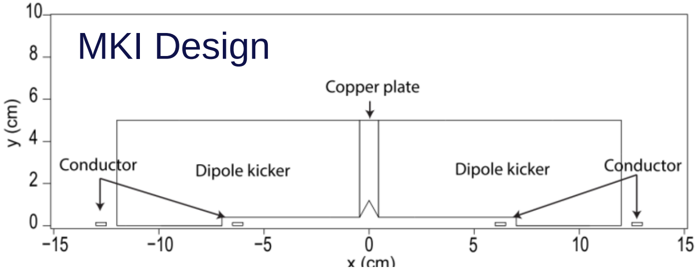
Simulating Injection

Injection at 20° horiz. phase, beam is off-axis at MKI. (90° phase advance)

MKI kicks injected beam and reduces its angle.

No losses during injection, with preliminary aperture model (no collimators included).





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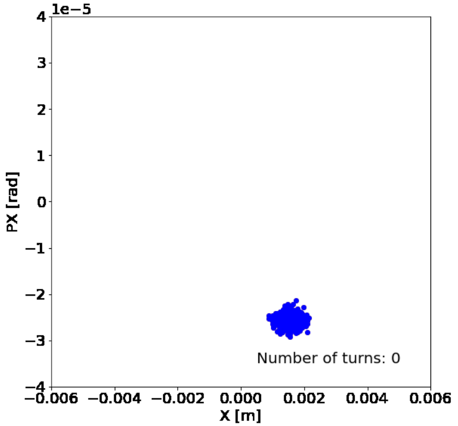
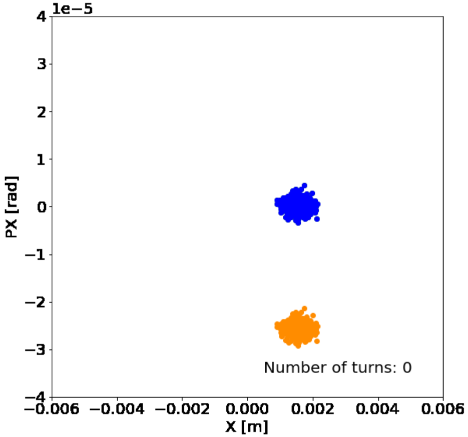
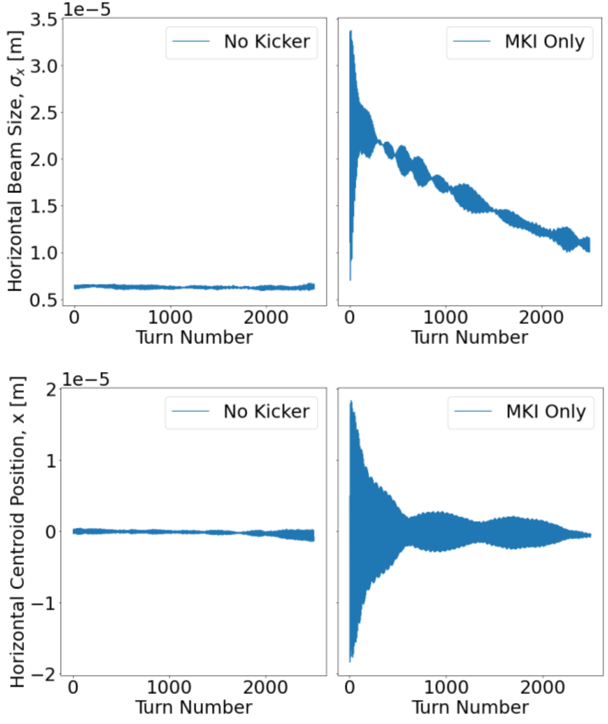




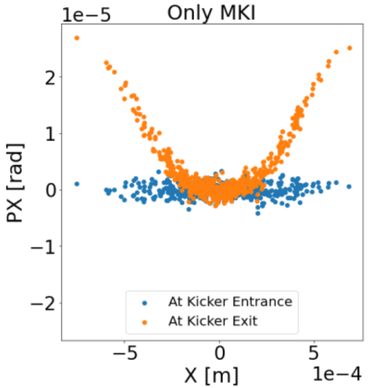
Injection Effect on Stored Beam at Interaction Point

Without MKIC, increase in σ_x would result in factor of ~5 decrease in luminosity.

Stored beam at IP



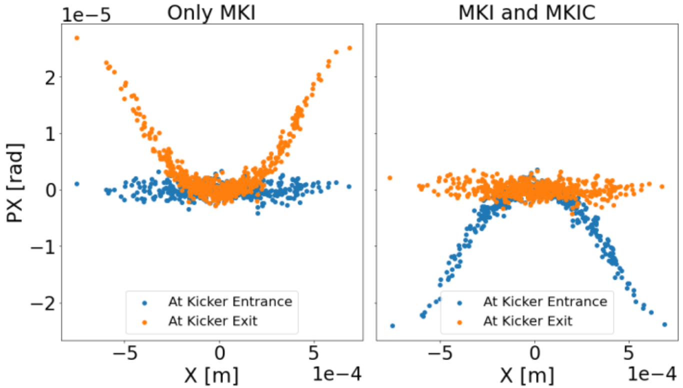
Stored beam at MKI location



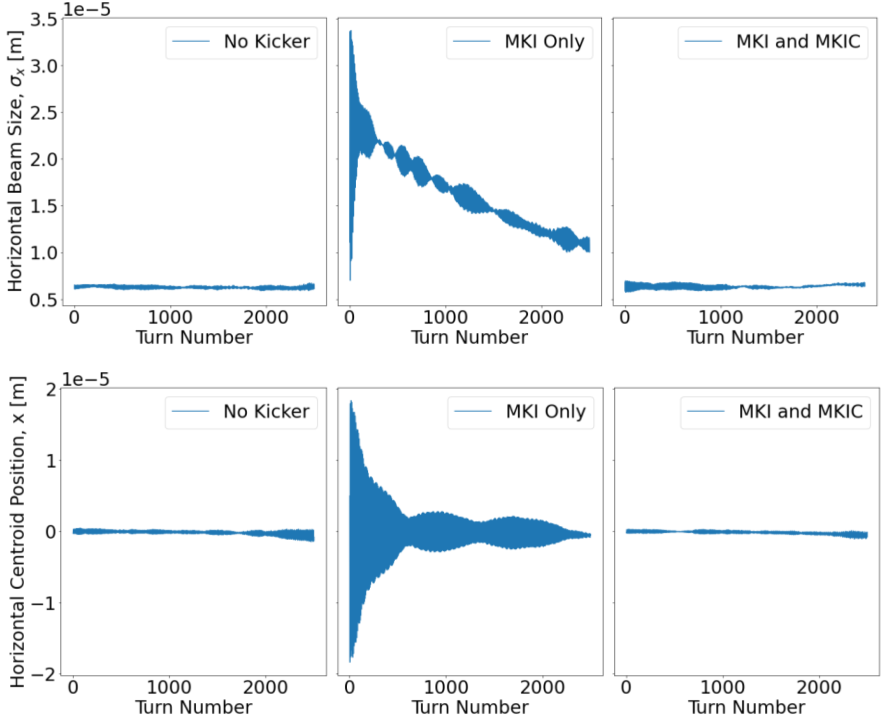
Injection Effect on Stored Beam at Interaction Point

Without MKIC, increase in σ_x would result in factor of ~5 decrease in luminosity.
180° phase advance from MKIC to MKI allows for '-I transformation' which counters effect on stored beam.

Stored beam at MKI location



Stored beam at IP



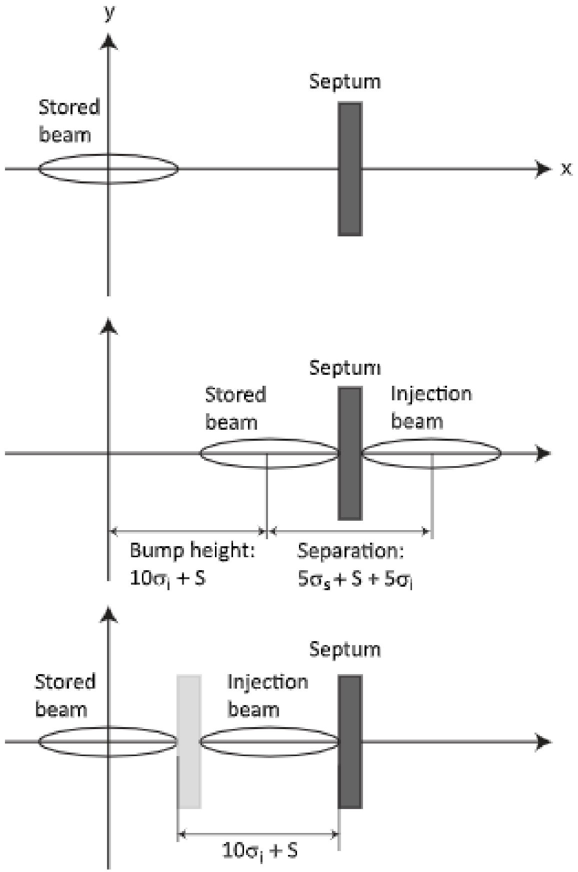
CONVENTIONAL ORBIT BUMP

On-momentum

Conventional Orbit Bump

- Two kickers used to create a temporary bump in the orbit.
- This brings the stored and injected beams close together.
- Bump is then closed.

Bump height needs to be $5\sigma_s + 5\sigma_i + S$ to allow the injected beam to clear the septum on subsequent turns



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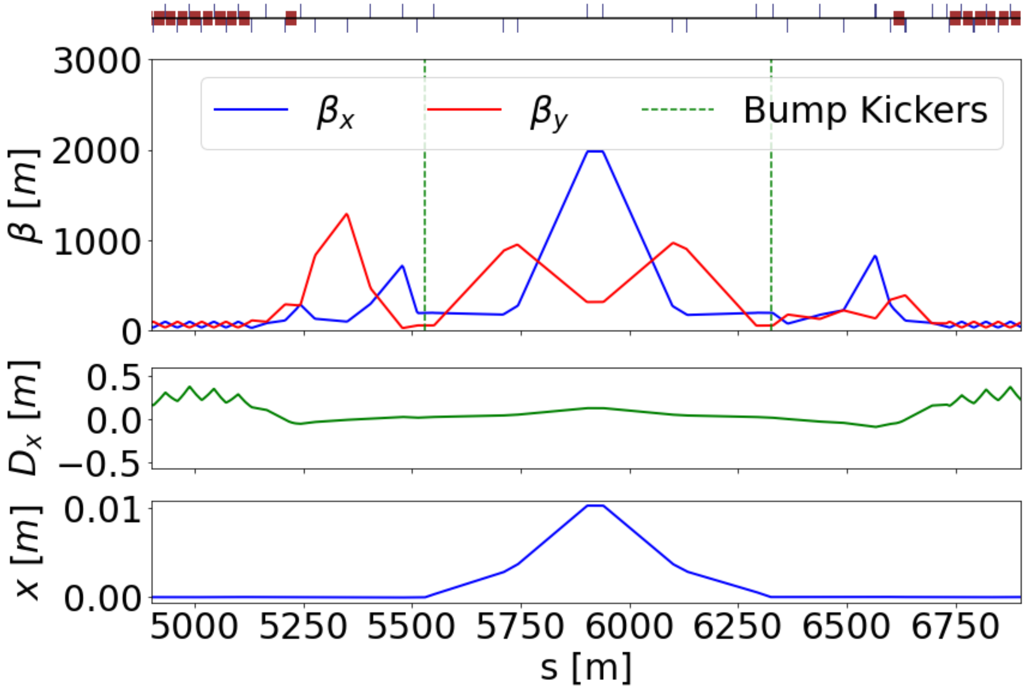
Injection Straight Optics - Bump Kickers Active



In both cases (MKI/Bump), the next step is error studies to see what closed orbit distortions we get and what injection efficiencies are achieved.

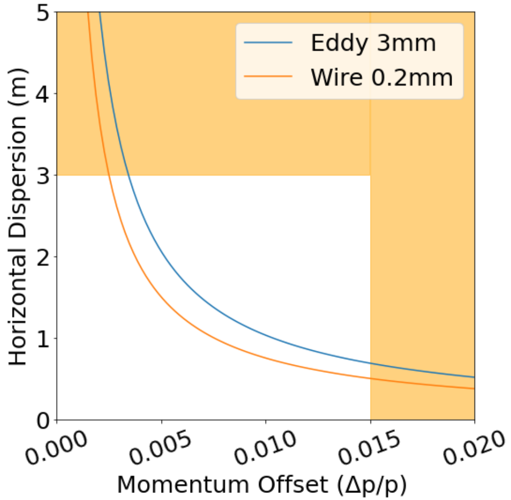
OPTICS COMPATIBLE WITH OFF-MOMENTUM INJECTION

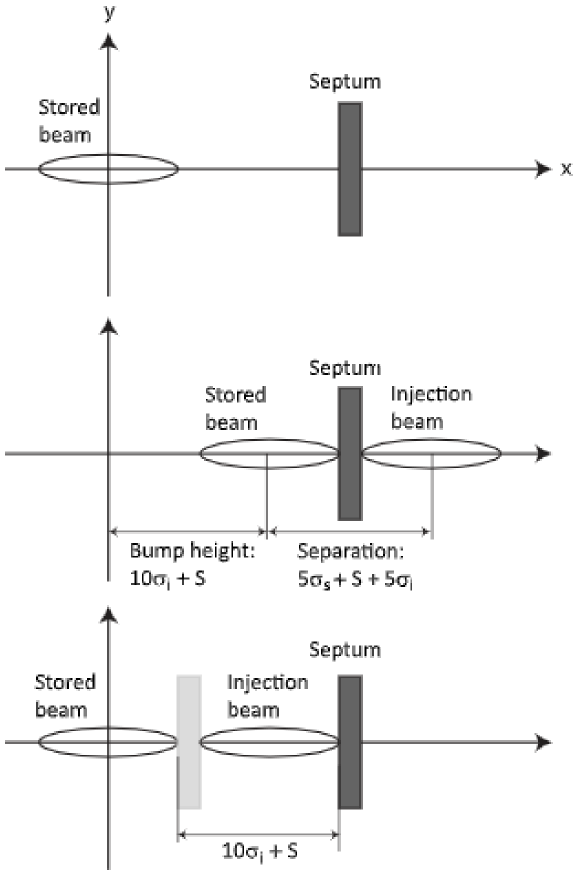
Matching Constraints

Optics need to be re-matched to have sufficient dispersion at the septum.
Then the off-momentum injected beam is placed on the dispersive orbit when the bump is closed.

Condition for Orbit Bump Off-momentum Injection

$$5\sigma_s + S + 5\sigma_i = |D_x \delta_p|$$





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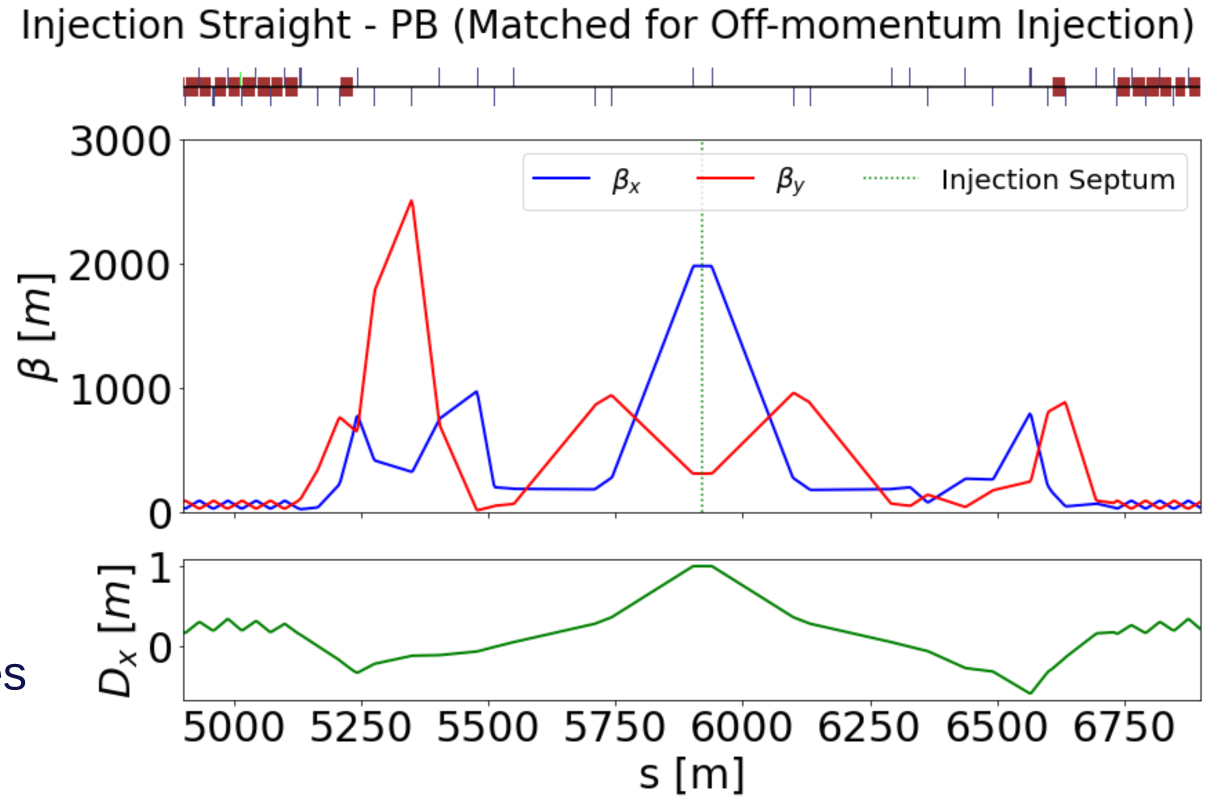
Key Matching Constraints

- Dispersion at septum = 1m
- Phase advance over straight is maintained

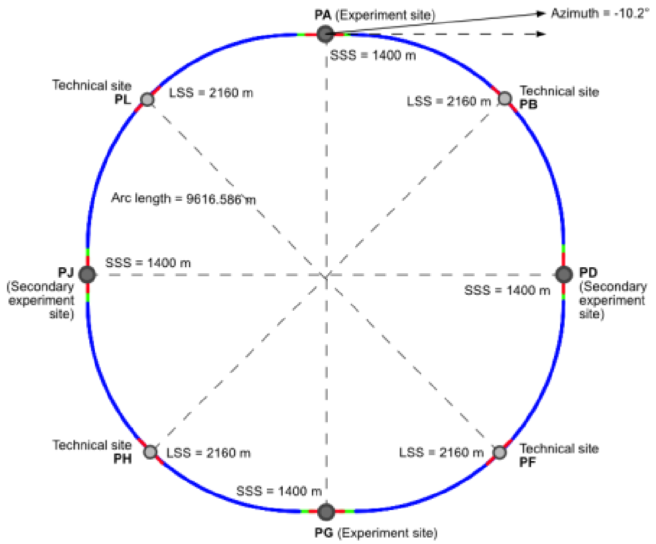
Off-momentum DA under investigation.

Then follow up with studies using misalignments.

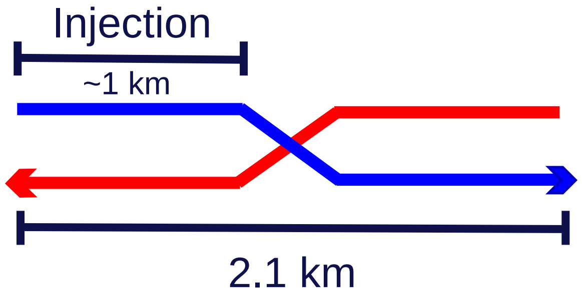


Outlook

- Studied top-up injection approaches for Z operation mode
- To be studied to determine injection efficiency:
  - Injection with misalignments and corrections
  - Other operation modes
  - Beam-beam effects
- Studies performed on old 2 IP lattice
  - New layout with longer straight sections
  - Complication arises in 4 IP
    - Beam crossing
    - Possibly combined with extraction



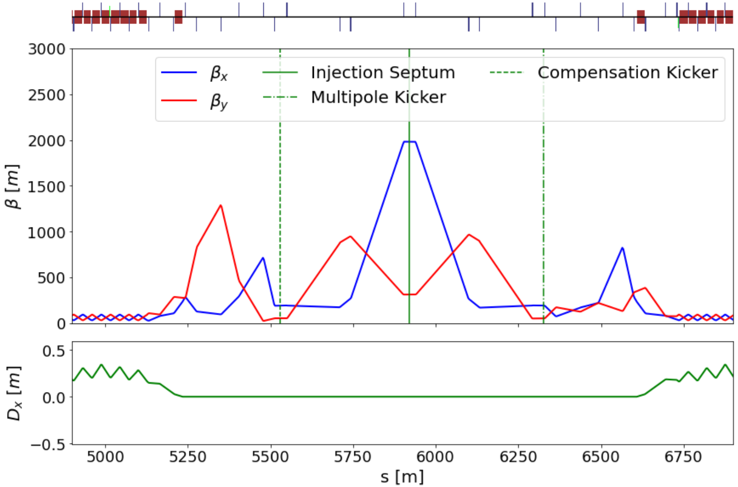
J. Gutleber - 144th FCC-ee Optics Design Meeting & 15th FCCIS WP2.2 Meeting



Thank you
for your attention

Gitlab Repository of Project Work:
https://gitlab.cern.ch/phunchak/fccee-injection-studies

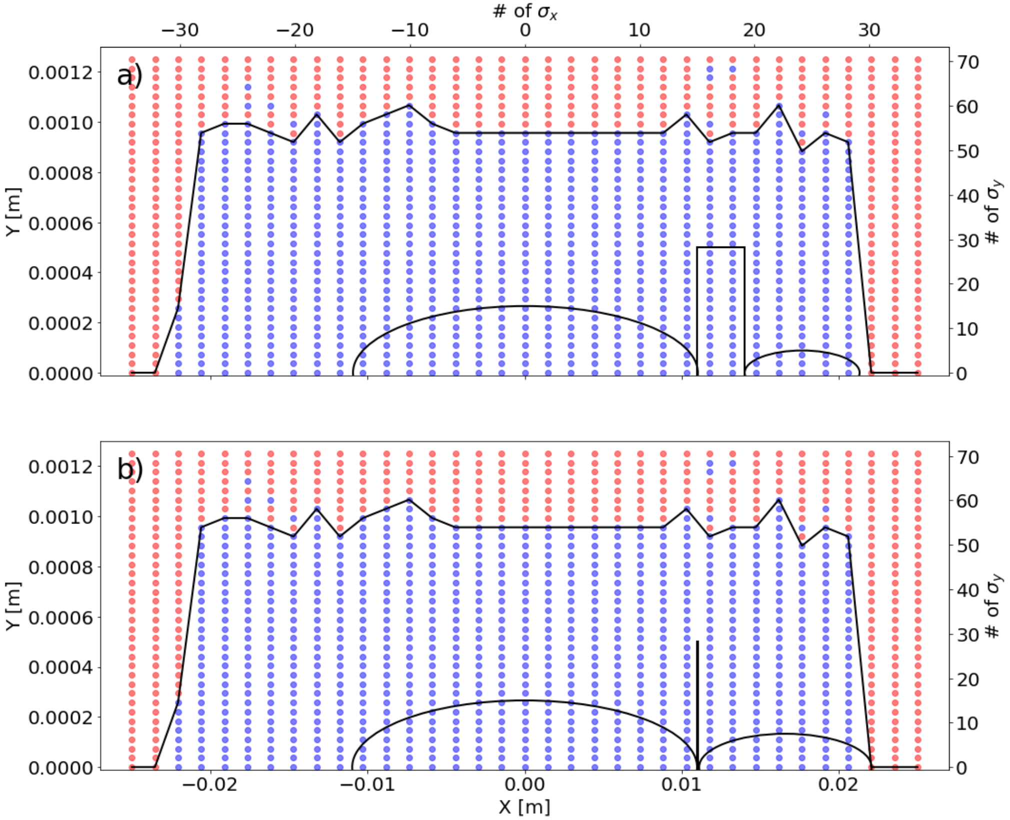
Placement of kickers



FCCee_z_216_nosol_1.seq

Element	Distance Downstream of IP at PA, $s[m]$	Horizontal Beta Function, $\beta_x[m]$	Horizontal Phase Function, $\mu_x[2\pi]$
Compensation Kicker	5530.0	191.22	17.18
Injection Septum	5922.74	1979.20	17.43
Multipole Injection Kicker	6325.0	193.02	17.68

Dynamic Aperture



Assume that injected emittance = stored emittance.

$$\varepsilon_x = 0.27\, nm \cdot rad$$
$$\varepsilon_y = 1.0\, pm \cdot rad$$

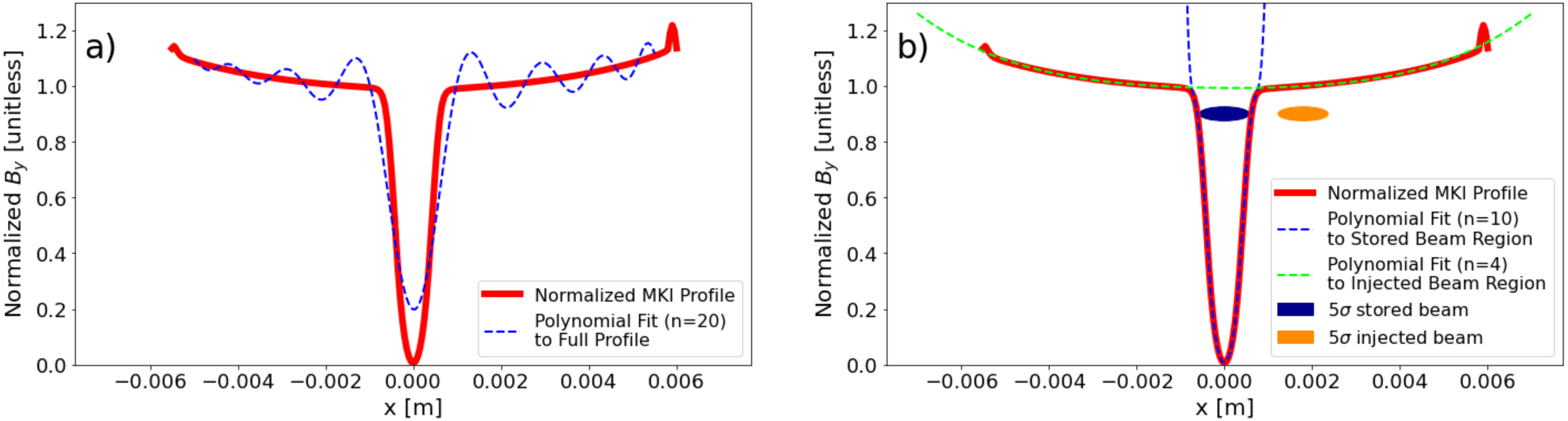
a) 3 mm eddy current septum
b) 0.1 mm electro-static wire septum

The thinner septum reduces dynamic aperture req. but not previously used.*
Our simulations show plenty of DA for either septum.

* M. Aiba "Top-up Injection Status and Next Steps" FCC Week 2021 https://indico.cern.ch/event/995850/contributions/4419415/attachments/2271652/3858072/FCC-ee_Injection_aiba.pdf

Modelling the Multipole Kicker

MKI has zero on-axis field to minimize disturbance of stored beam, large off-axis field to kick the injected beam.



MAD-X does not currently support arbitrary field elements.

- Maximum of 20th order polynomial not a good fit.
- Split into two fits, for interaction with stored/injected beam.