FCC-ee e^+e^- injection and Booster ring

Rebecca Ramjiawan[1]

M. Barnes[1], W. Bartmann[1], J. Borburgh[1], A. Chance[2], B. Dalena[2], Y. Dutheil[1], M. Hofer[1], P. Hunchak[3]

[1]CERN, [2] CEA Paris-Saclay, [3] University of Saskatchewan

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Outline

Injection into the Collider ring

- Conventional bump injection vs. Multipole Kicker Injection (MKI)
- On-axis and off-axis injection
- Kicker and septa technology considerations

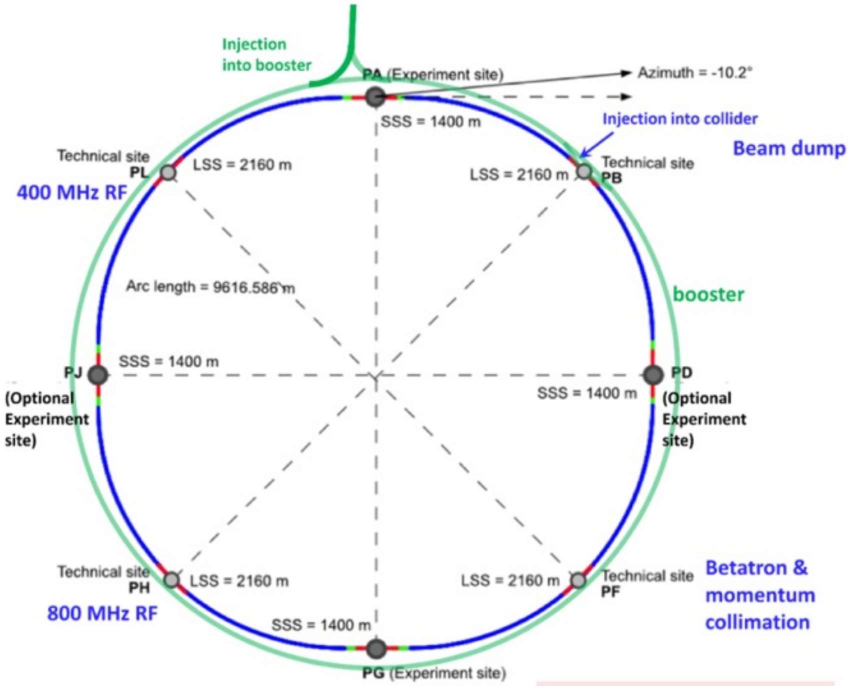
FCC-ee Booster ring

- Status of the booster ring design
- Booster ring Dynamic Aperture studies
- Booster ring equilibrium emittance

FCC-ee

- The Future Circular electron-positron Collider (FCC-ee) is a proposed 91.17 km future machine which would operate in four modes spanning 45.6-182.5 GeV.
- The beam lifetime is limited by synchrotron radiation and Bhabha scattering and to achieve a high integrated luminosity the beam will require continuous top-up injection.
- Top-up injection planned via a full-energy booster in the same tunnel as the collider ring - either stacked with or adjacent to the collider ring.

[1]



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4IP lattice

[2]

Parameter	Unit	Z	$t\bar{t}$
Beam energy	[GeV]	45.6	182.5
Beam lifetime	[min.]	19	9
Beam current	[mA]	1280	5
Magnetic rigidity	[Tm]	152.1	608.7
Emittance (x/y)	[nm/pm]	0.71/1.42	1.49/2.98
Energy spread	[%]	0.132	0.221

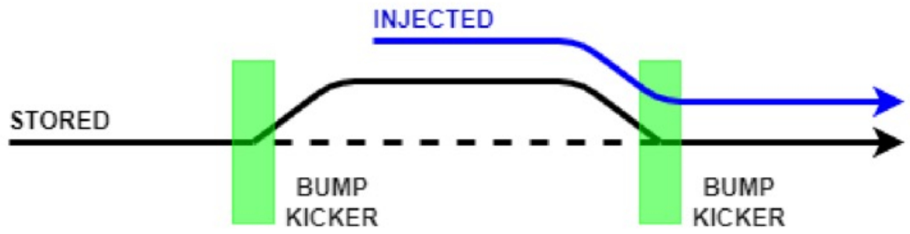
Top-up injection strategies

Injection methods

Several injection methods were considered [3] and two were selected as viable options.

Conventional bump injection

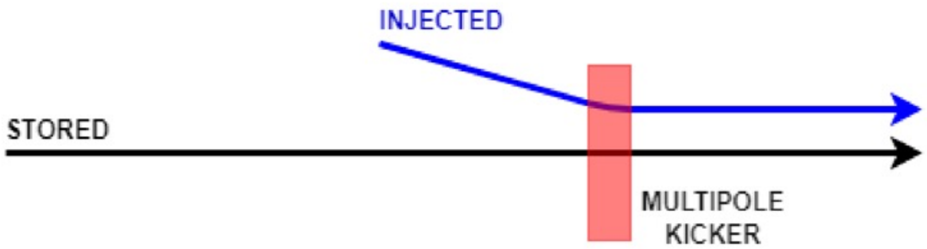
- A dynamic orbit bump (dipole kickers) brings the beam close to the septum for **one** revolution.
- Two kickers are placed with 180° phase advance between them (π-orbit-bump).



[4]

Multipole kicker injection

- Kicker has minimal on-axis field (for the stored beam).
- Kicker has significant off-axis field (for the injected beam).
- Ideal multipole kicker field is a step-function.



[4]

Off-axis vs. on-axis injection

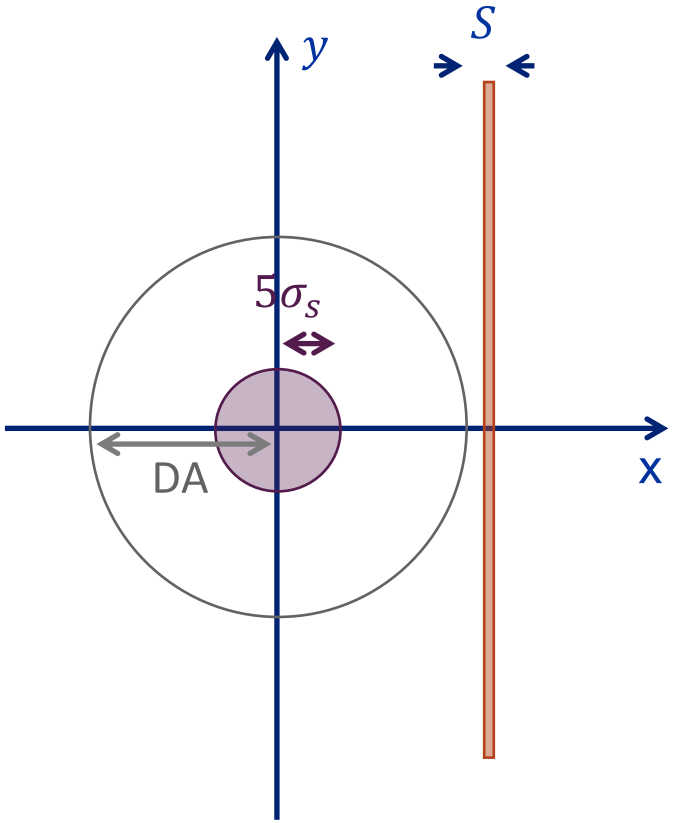
Liouville's theorem: Under conservative forces, the density of the particles in phase-space stays constant [5] ∴ you cannot inject into this phase-space.

Instead, injected beams are separated either transversely or in momentum, and merge via ***synchrotron radiation damping***.

- **Off-axis:** injected with a **transverse** offset.
- **On-axis:** injected with **momentum** offset onto off-momentum closed orbit. This requires there to be dispersion at the septum to separate the beams by energy.

Conventional bump injection configuration

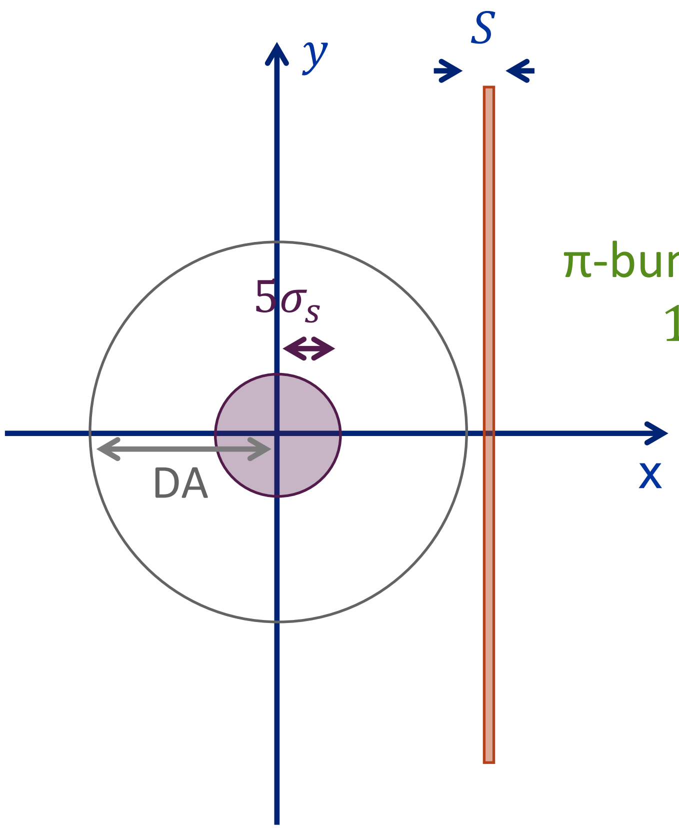
Stored beam, before orbit bump.
Septum outside of DA.



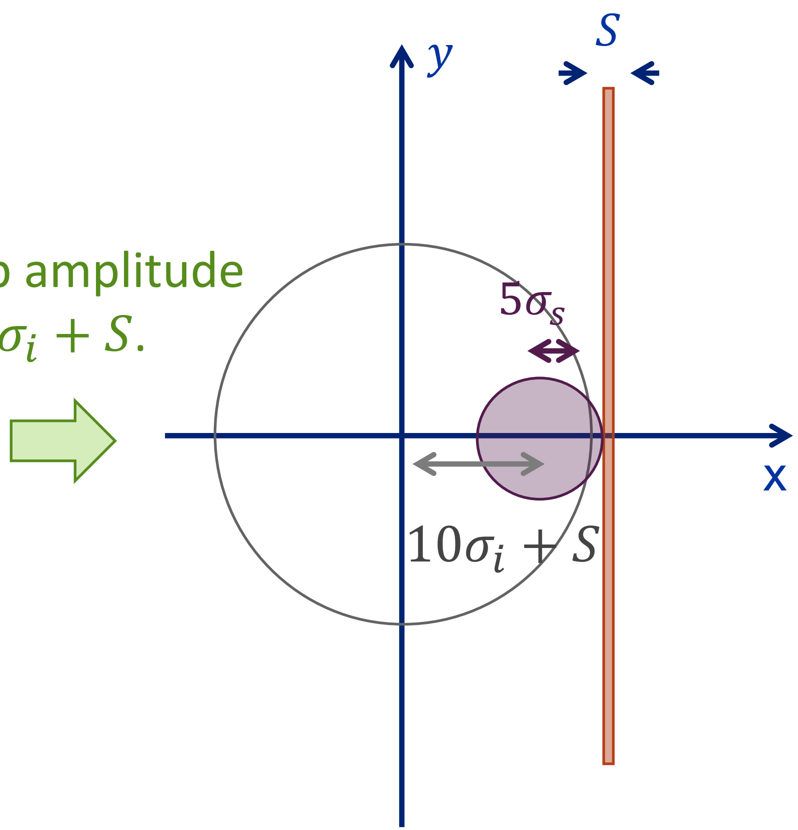
DA = dynamic aperture = $15\sigma_s$

Conventional bump injection configuration

Orbit bump brings stored beam close to septum for one revolution.



π-bump amplitude $10\sigma_i + S$.

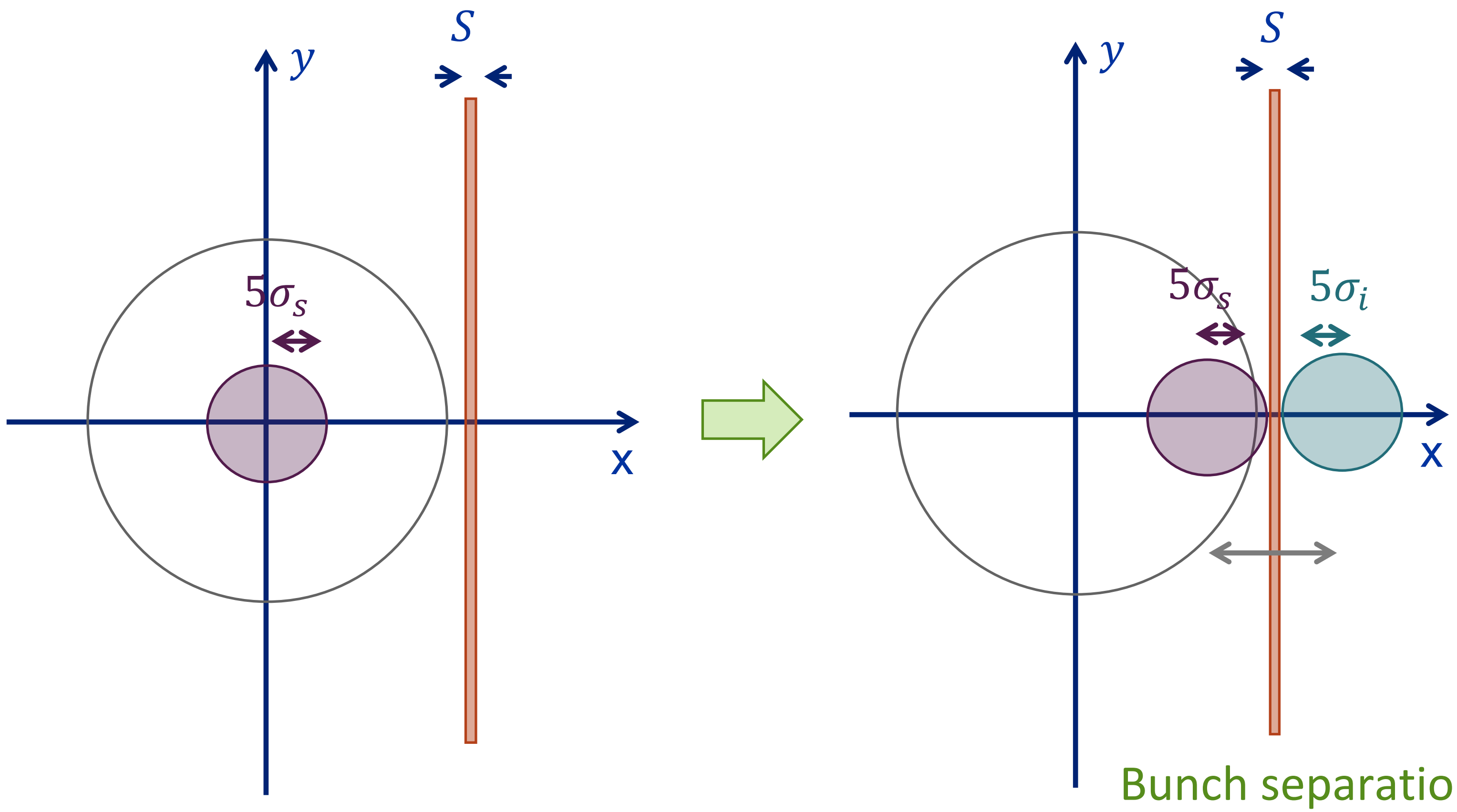


DA = dynamic aperture = $15\sigma_s$

Bump amplitude

Conventional bump injection configuration

The injected beam envelope is separated from the stored beam by the septum width.



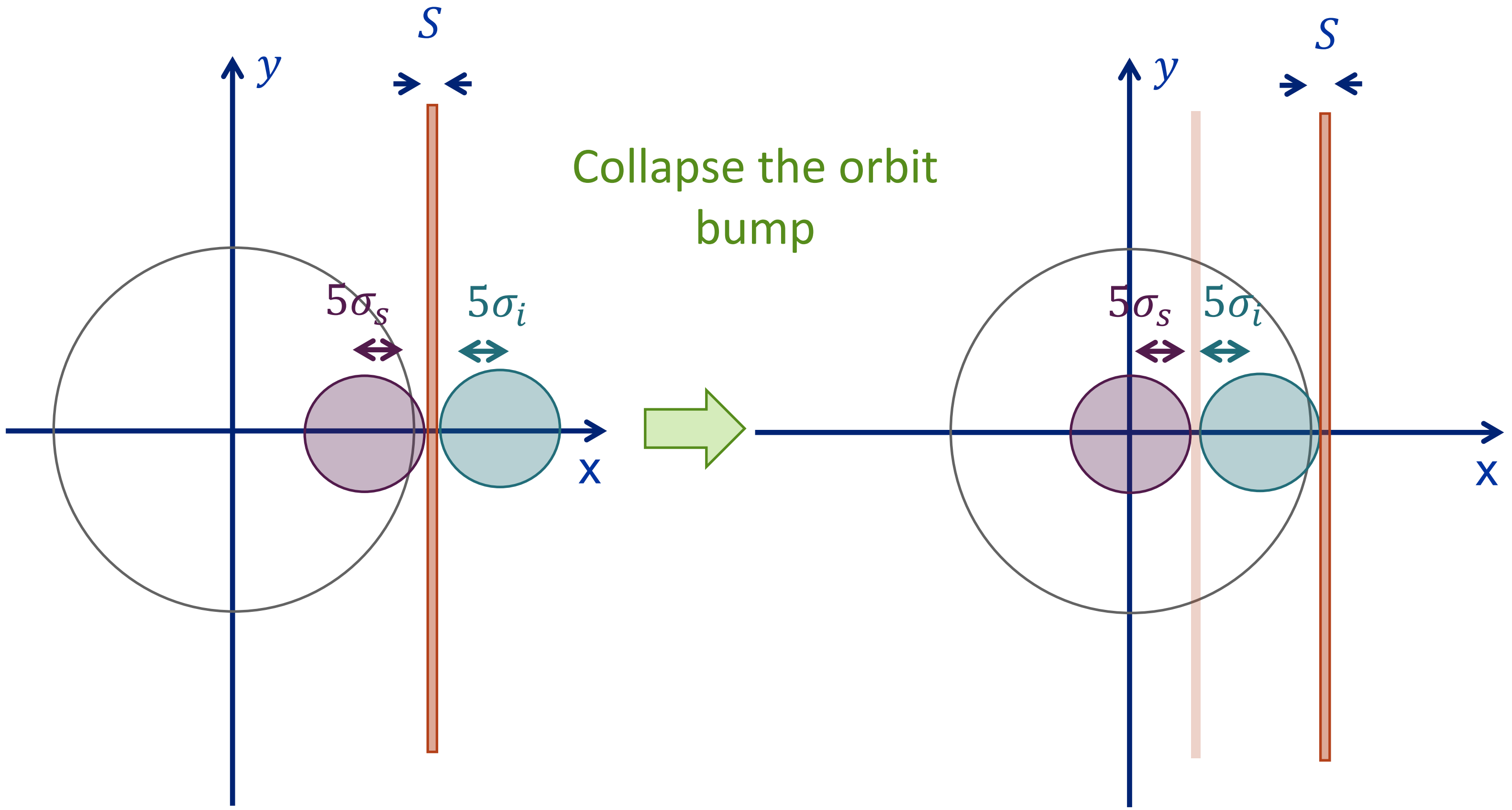
Bunch separation
$> 5\sigma_i + S + 5\sigma_s$.

Conventional bump injection configuration

Once the orbit bump is collapsed the beam envelopes are still separated by the septum blade width.

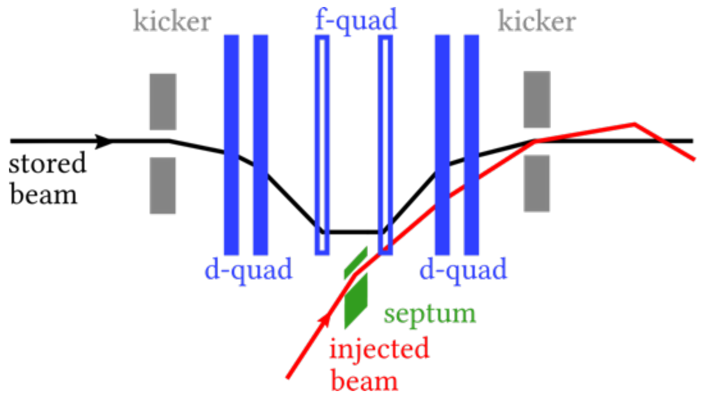
This width corresponds to the region of the injected beam lying **outside the DA**.

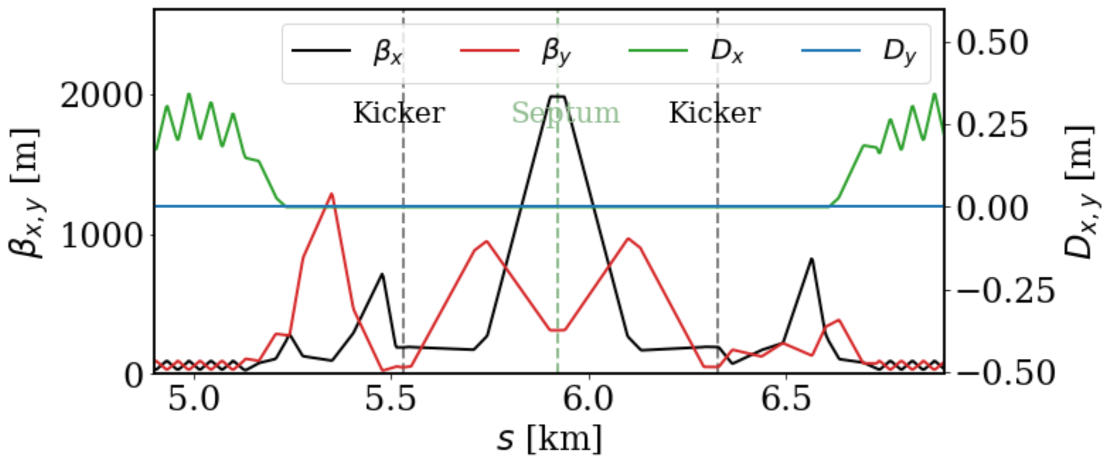
Therefore, this injection scheme requires a thin septum such as an **electrostatic wire septum**.



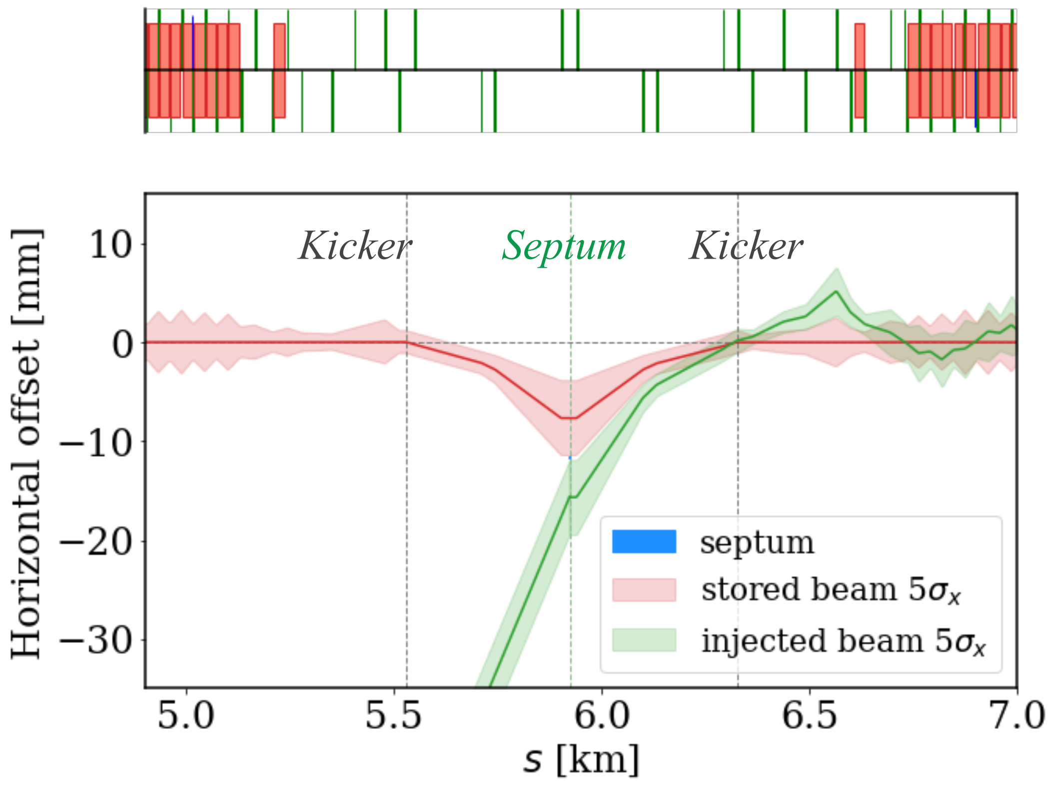
Conventional injection (off-axis)

- Assuming 200 μm septum-width. Desirable to have large β_x at septum.
- Bump amplitude: 7.6 mm
- Beam-beam offset at septum: 15.7 mm
- Kicker deflection angle: 12.5 μrad





Injection region optics.



Electrostatic septum

Electrostatic septum with tensioned wires separating the high-field and field-free regions (e.g the CERN SPS ZS septum [6]).

Blade widths of order 100s of microns are possible.

R&D planned at CERN to look into the effect of X-rays on electrostatic septa sparking rates as a function of electric field.

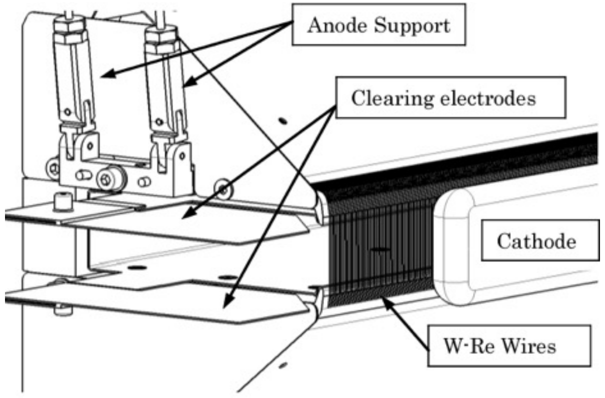
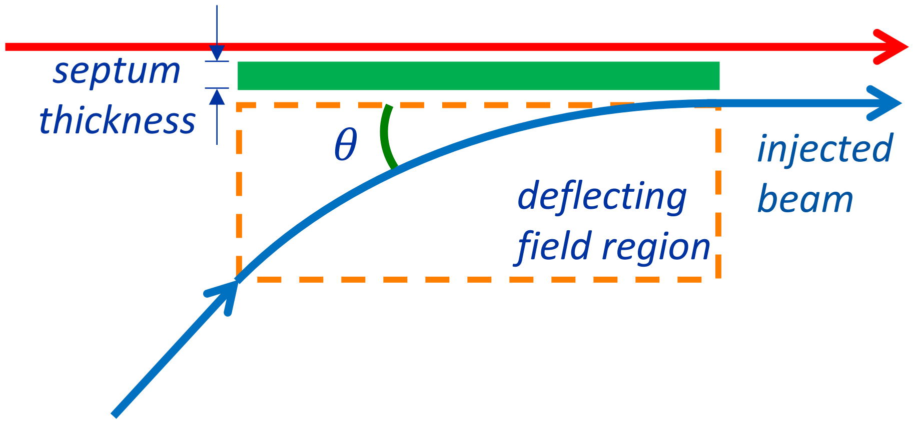


Fig. 1. ZS electrostatic septum used for SPS slow extraction

[6]



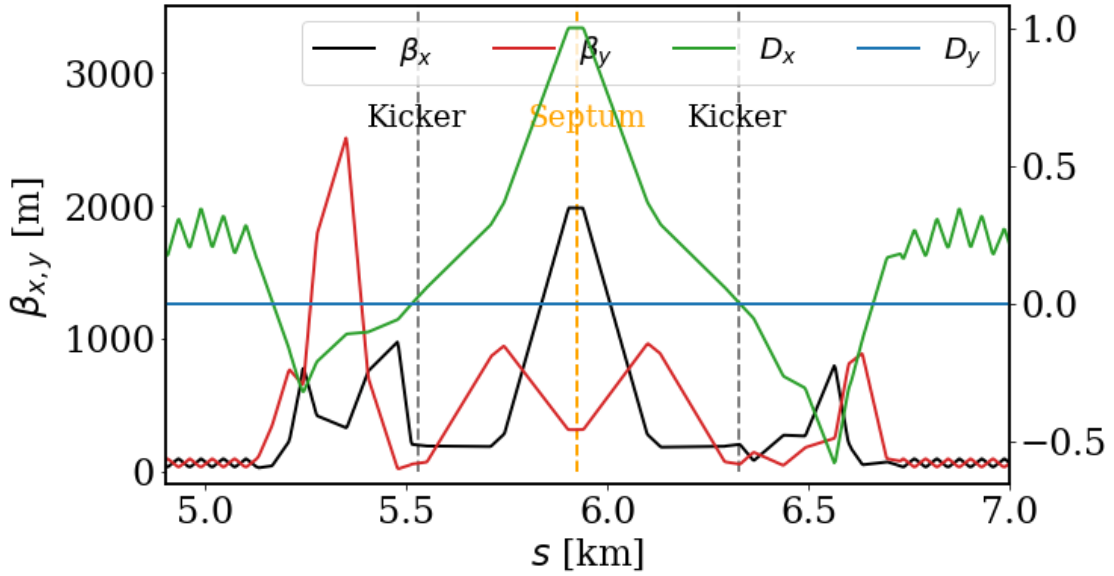
Preliminary - still under study

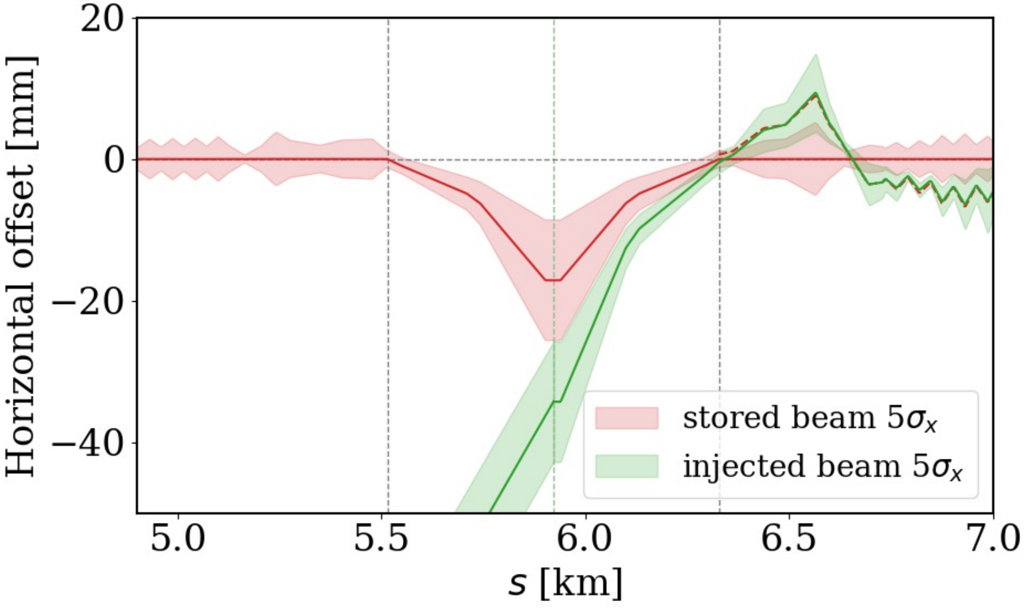
Septum

Parameter	Value
Deflection angle	65 μrad
Int. field ($\overline{\varepsilon t}$)	11.2 MV
Electric field	1.87 MV/m
Potential difference	37.4 kV
Septum thickness	200 μm
Gap width	20 mm
Length	2×3 m

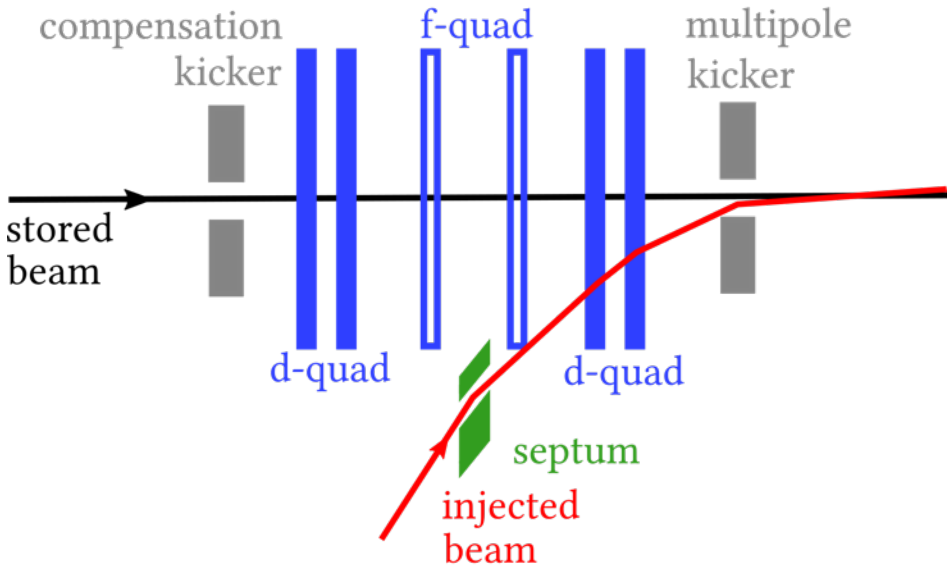
Conventional injection (on-axis)

- Injecting onto the **off-momentum closed orbit**.
- A larger orbit bump is needed because the beam size is increased by dispersion.
- Separation between injected and stored beams of $|D_x\delta|$ ⇢ **momentum offset** of -1.9%.
- Kicker deflection: 27 µrad. Septum deflection: > 65 µrad.



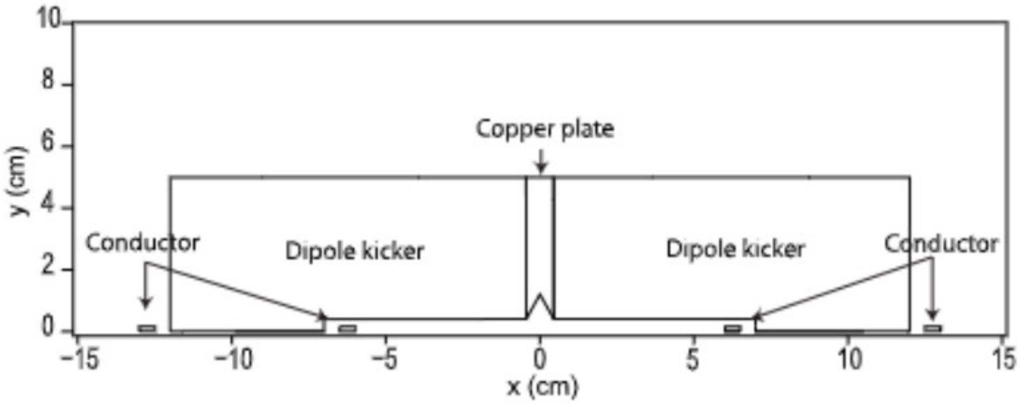


Multipole kicker injection (MKI)



- Ideally zero field for the stored beam and constant field for the injected beam (R&D needed).
- Compensation kicker to correct for perturbation to the stored beam distribution.
- Can use magnetic septum with blade width 3 mm.

MKI kicker proposal, two C-shaped dipoles powered similarly



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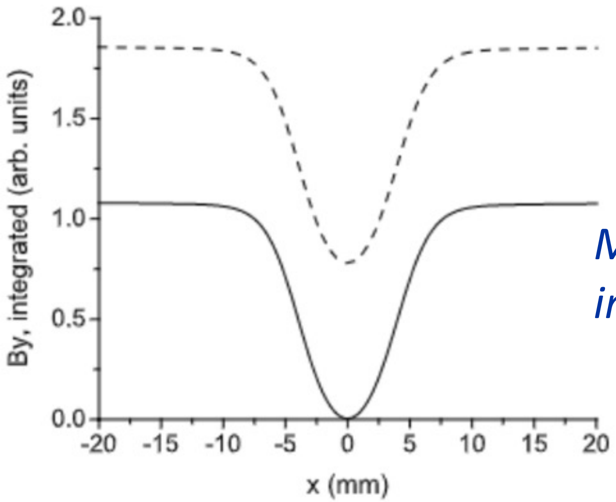

MKI kicker integrated field

[3]

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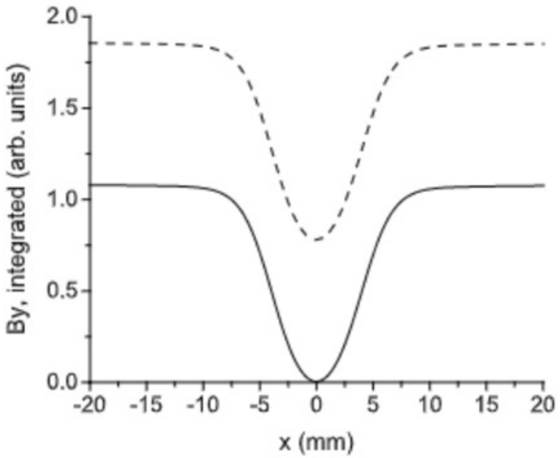
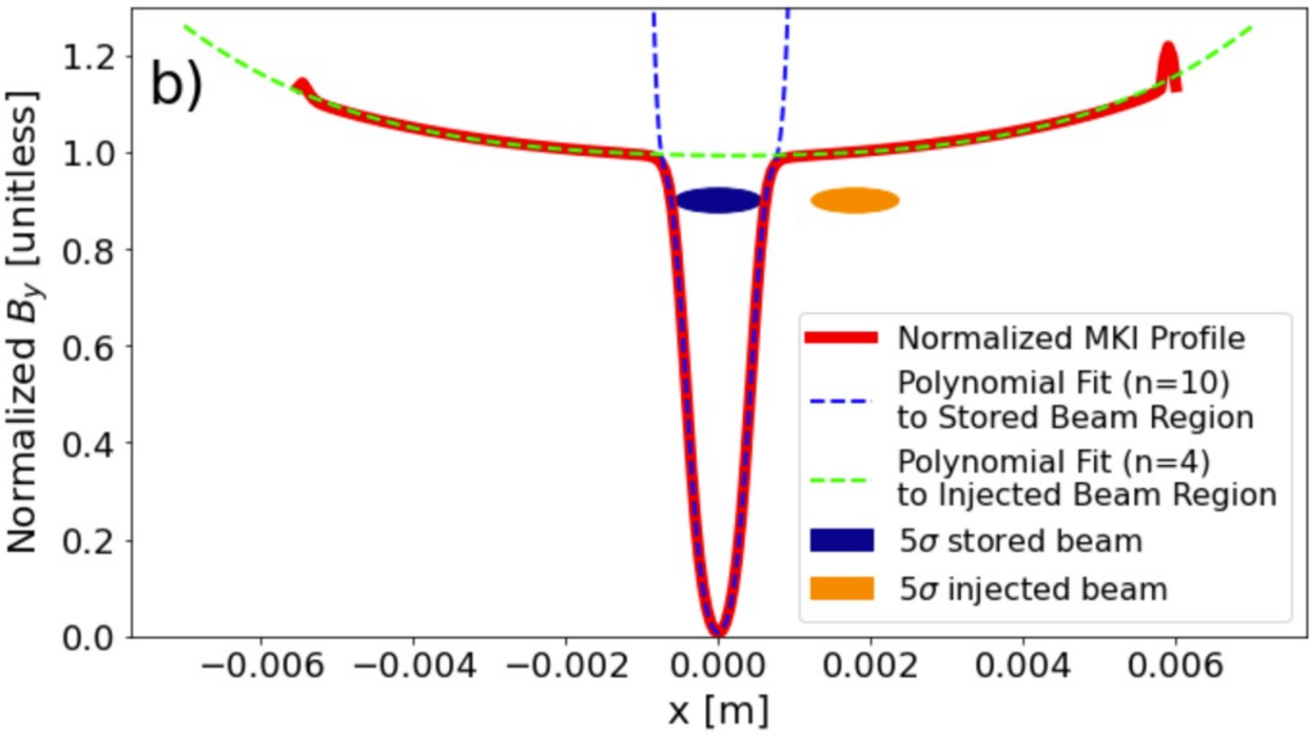
Multipole kicker tracking studies

- Kicker field modelled using separate polynomials for the two regions.
- If the septum field varies more than a few percent then the injected beam would be within the low-field region of the multipole kicker.



MKI kicker integrated field

[3]



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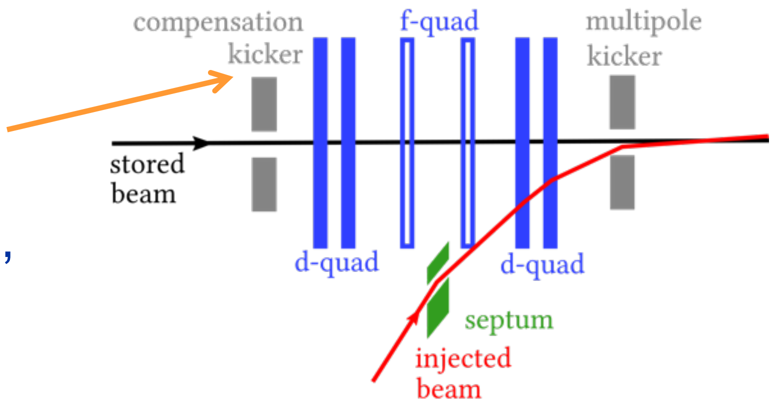
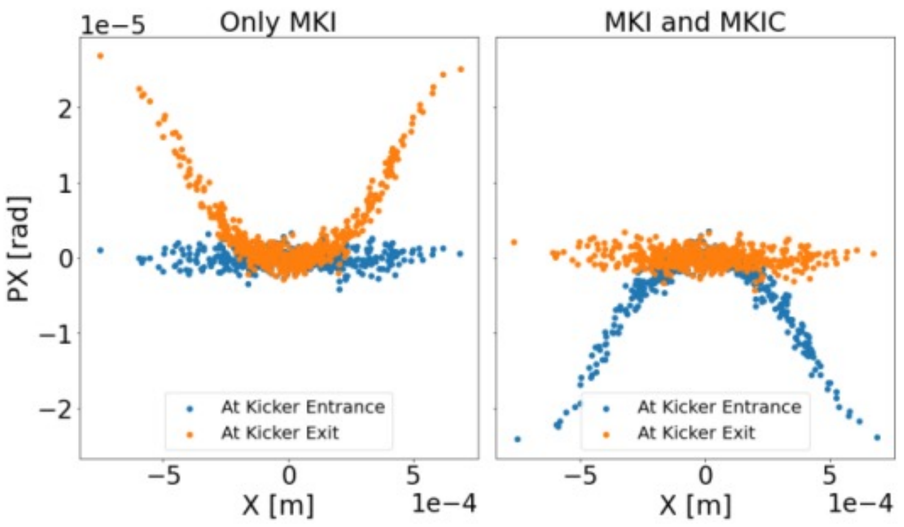
Compensation multipole kicker

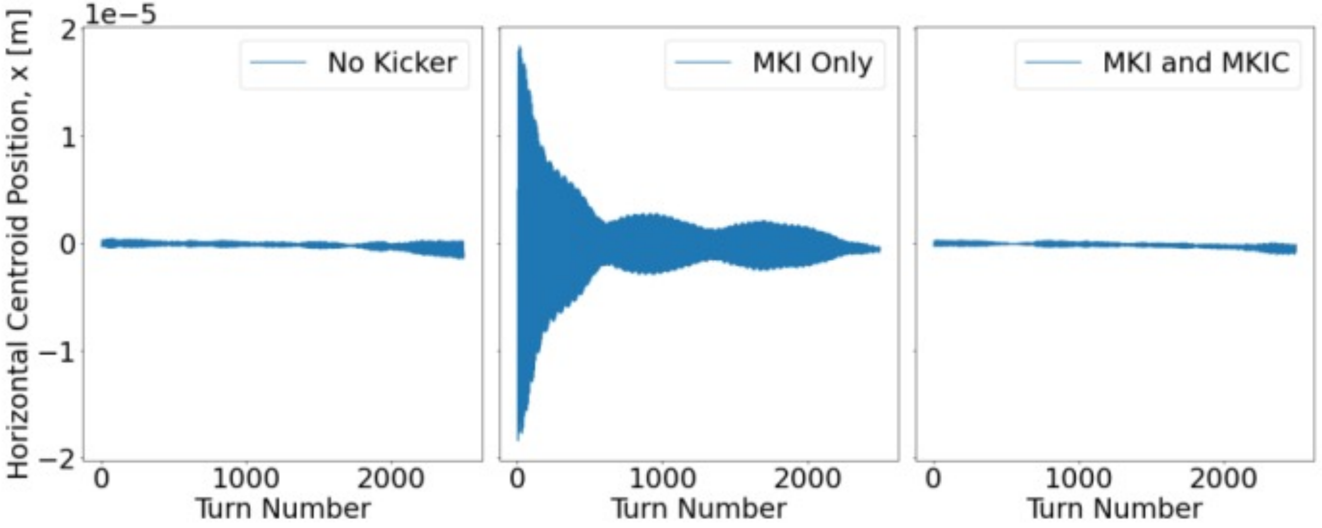
- Without the compensation kicker there would be an increase in σ_x which would result in factor of 5 decrease in luminosity.
- 180° phase advance from MKIC to MKI allows for '-I transformation' which counters effect on stored beam.



Stored beam at MKI



Stored beam offset at IP



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Multipole kicker injection (off-axis)

- Separation of beams at septum

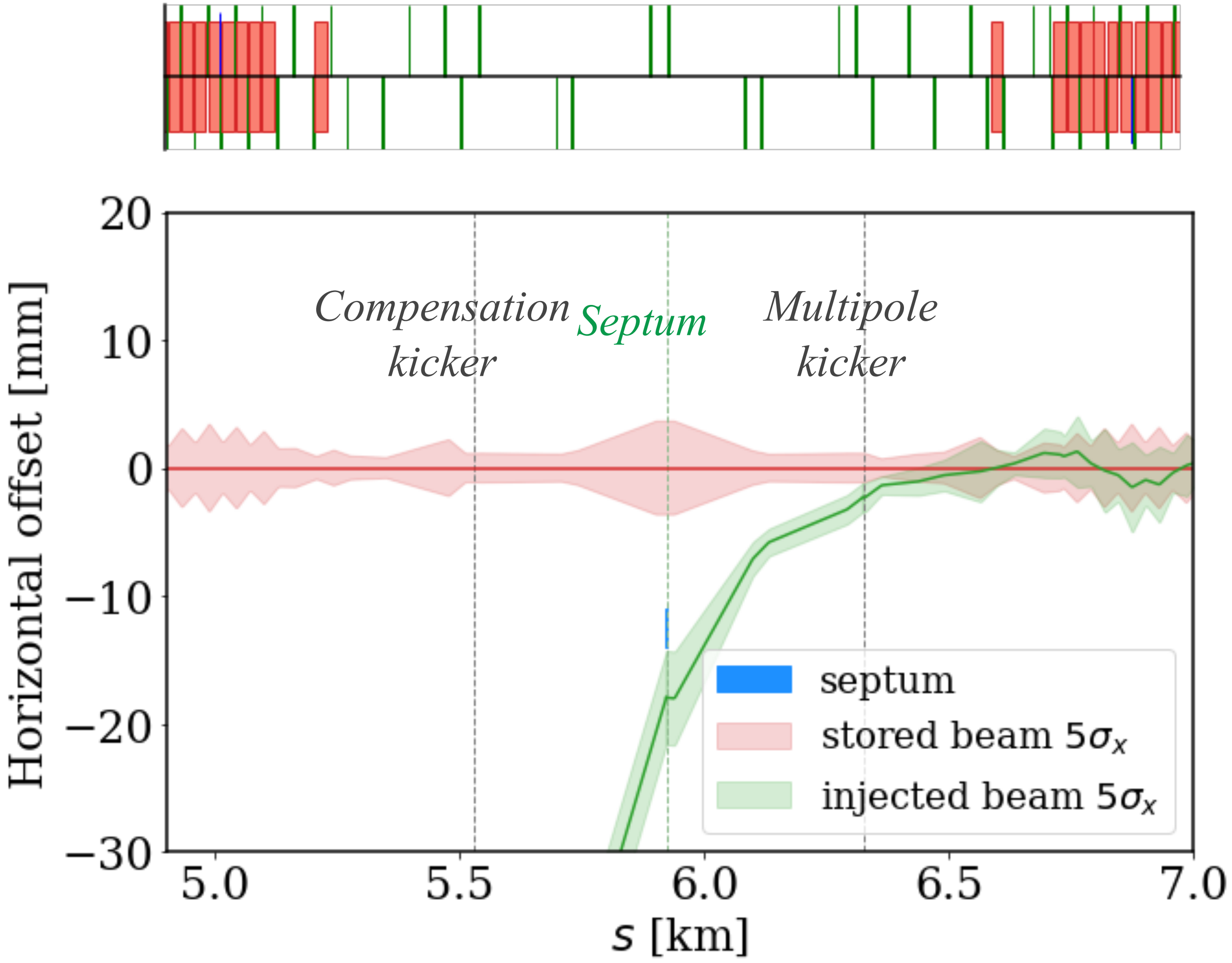
  $$> 5\sigma_s + 10\sigma_s + S + 5\sigma_i,$$

  to account for betatron oscillations of injected beam.

- Beams separated at kicker causing betatron oscillations.

- **Kicker deflection:** 29 µrad

- **Septum deflection:** >65 µrad



Conclusions

- We consider four strategies for top-up injection: conventional and multipole kicker injection, with both off-axis and on-axis injection.
- **On-axis injection** means less background to experiments and, at LEP, meant better injection efficiency. However, there is a smaller dynamic aperture off-momentum (Z, W modes).
- **Conventional bump injection** could use existing kicker technology, although would require R&D to see whether an electrostatic septum could withstand the synchrotron radiation.
- **Multipole kicker injection** would cause less disturbance to the stored beam, perturbing the beam distribution rather than the trajectory. However, this requires good alignment between kicker and beam and the kicker field would not be a perfect step function (MKI kicker R&D required).

Converging to a single strategy over the next 12-18 months, comparing using metrics such as luminosity, experiment background, machine protection, feasibility/availability/reliability, cost,…

Further studies

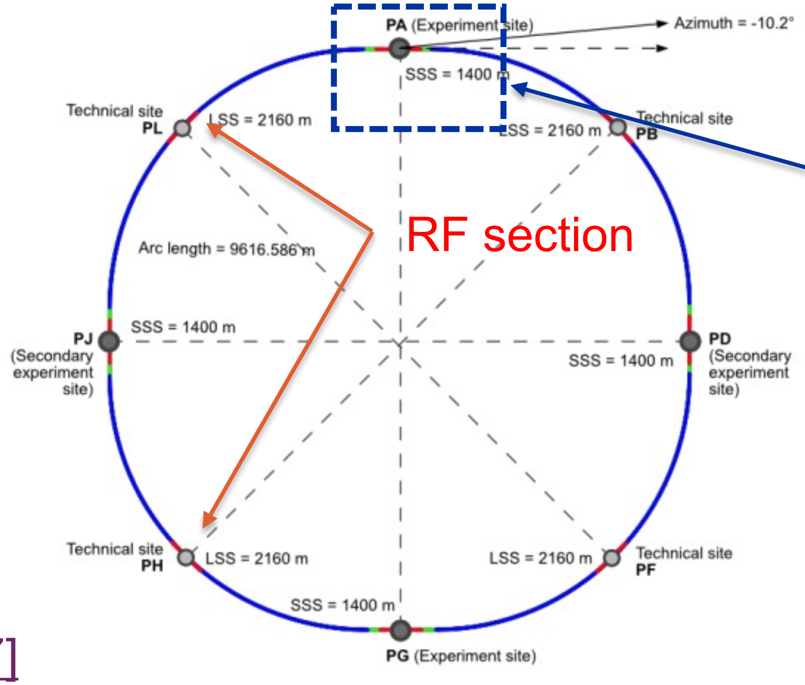
- Injection with misalignments and corrections. Estimation of injection efficiency.
- Beam-beam effects and estimation of the background to experiments.
- Update studies for 4IP lattice. Consider configurations of electron/positron injection.
- Machine protection studies for injection failure scenarios.
- Injection optics will need designing for the W-, H- and $t\bar{t}$-operations and also for on-axis MKI injection.
- R&D into the effect of X-rays on electrostatic septa sparking rates as a function of voltage.

Booster ring

B. Dalena, A. Chance

FCC-ee Booster layout

- Injection into the Booster either from a pre-booster ring (e.g. the SPS) or a 20 GeV linac.
- The bypass of the booster at the detectors is still an open question.
- Still to be decided if booster and collider are to be stacked or adjacent.
- Injection and extraction could be placed at PB.



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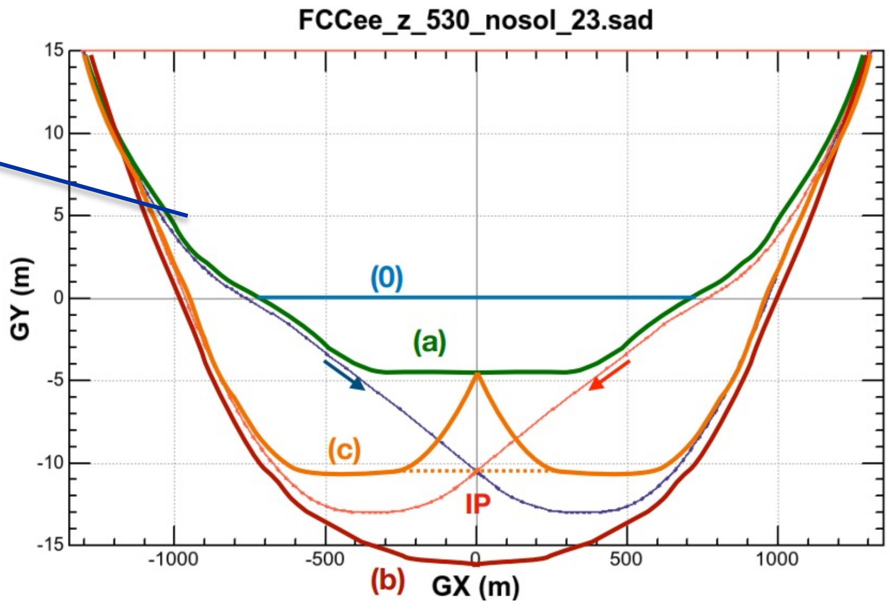
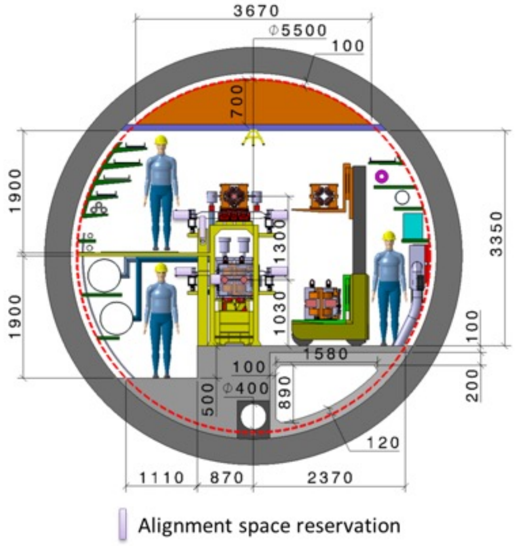


Booster bypass options



Stacked booster-collider configuration

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Booster ring equilibrium emittance

- Booster emittance at extraction should be less than the collider emittance.
- 60°/60° Optics for Z and W modes (the horizontal/vertical phase advance per FODO cell).
- 90°/90° Optics for H and $t\bar{t}$ modes.

	Equilibrium emittance [nm rad]		
Beam Energy [GeV]	60°/60°	90°/90°	Collider (new)
45.6 (Z)	0.235	0.078	0.71
80 (W)	0.729	0.242	2.16
120 (H)	4.229	0.545	0.64
175 ($t\bar{t}$)	3.540	1.172	1.49

[7]

60°/60° and 90°/90° optics

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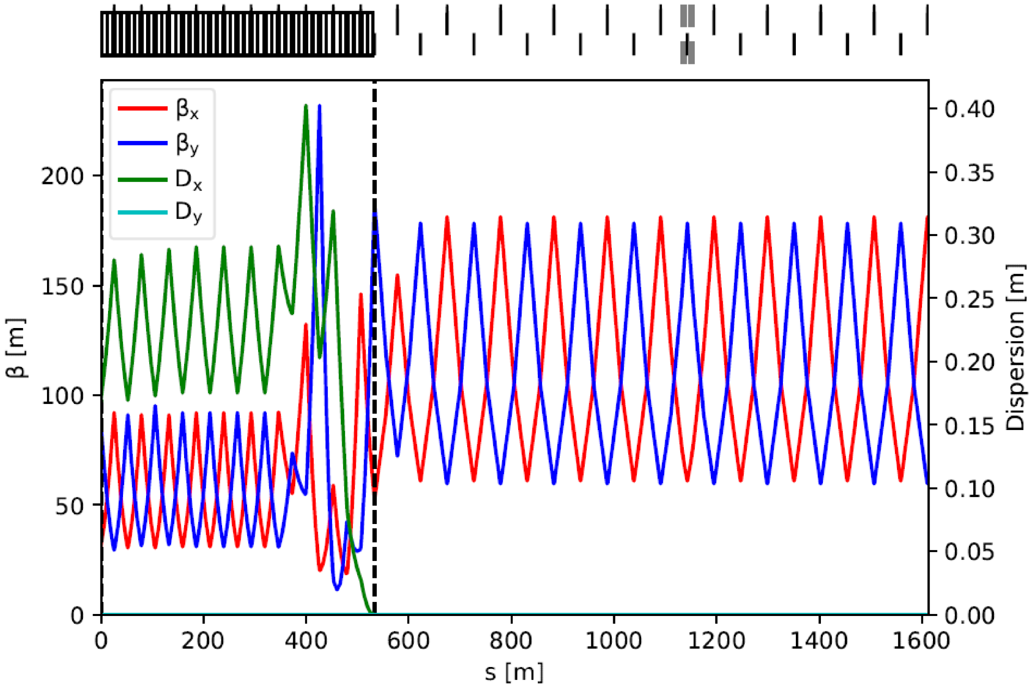
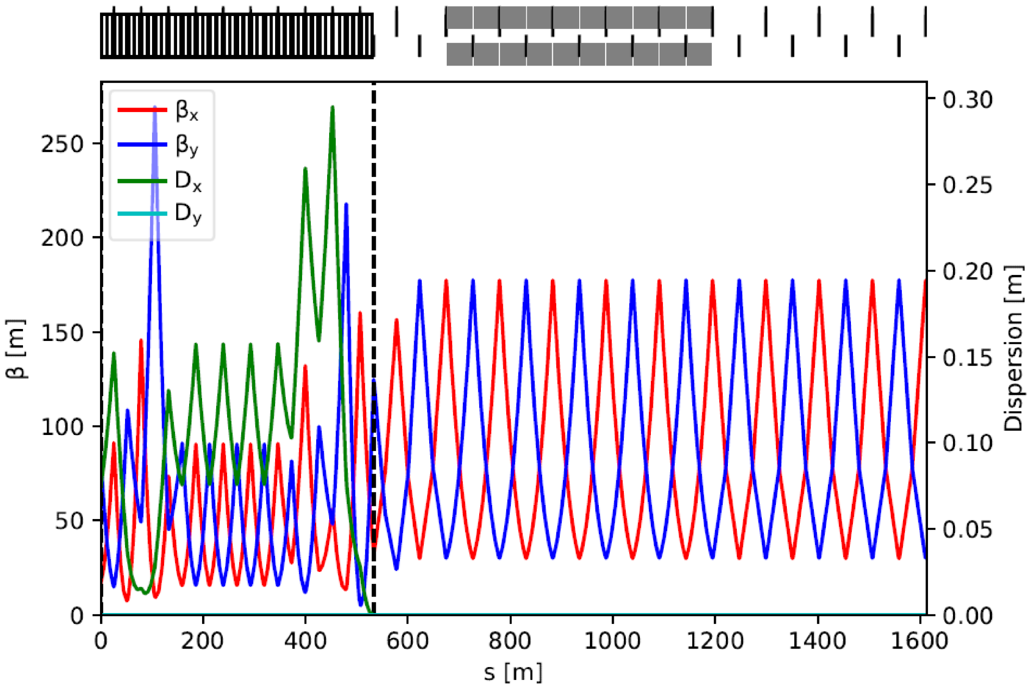
60°/60° Optics for Z and W modes.



90°/90° Optics for H and $t\bar{t}$-modes.



[7]

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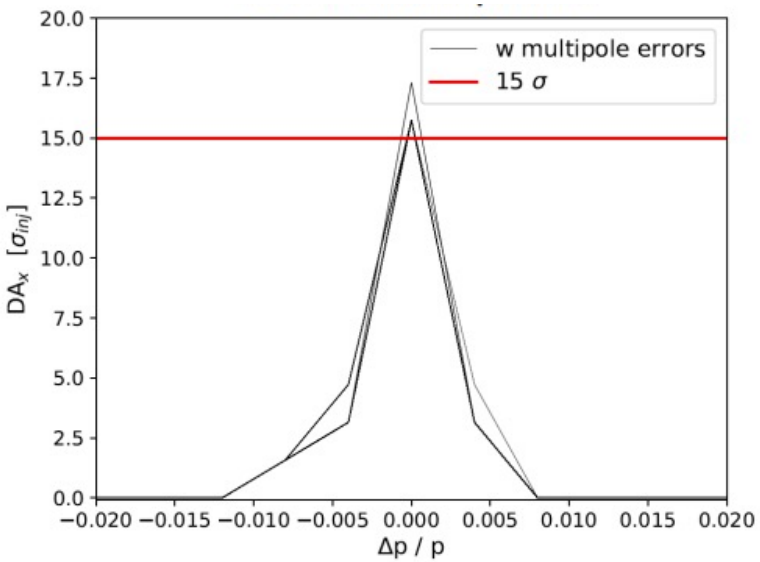
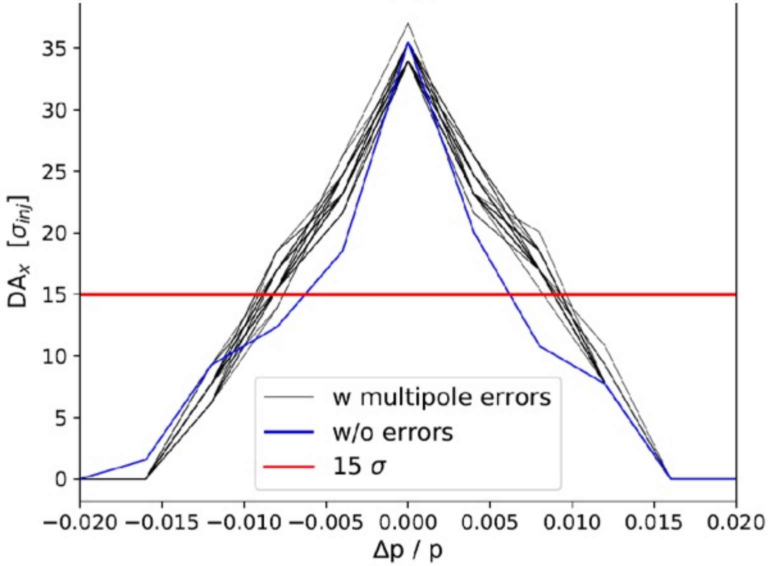
Booster ring dynamic aperture studies

- Static dipole field errors are considered but not yet the dynamic field effect.
- Using MAD-X Thin-Lens Tracking. 60 seeds shown.
- Dynamic aperture calculated over 4500 turns.
- Dynamic aperture for the 90°/90° optics is ~ 15σ (due to longitudinal motion). This would require a thin septum for injection, similar to the collider.

90°/90° optics



60°/60° optics



[8]

Emittance evolution

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- Synchrotron integral I_2 is too small to reach the collider parameters within 1.2 s.
- Target damping time ⇢ **0.1 s** (to fulfill cycle time).

Solutions considered:

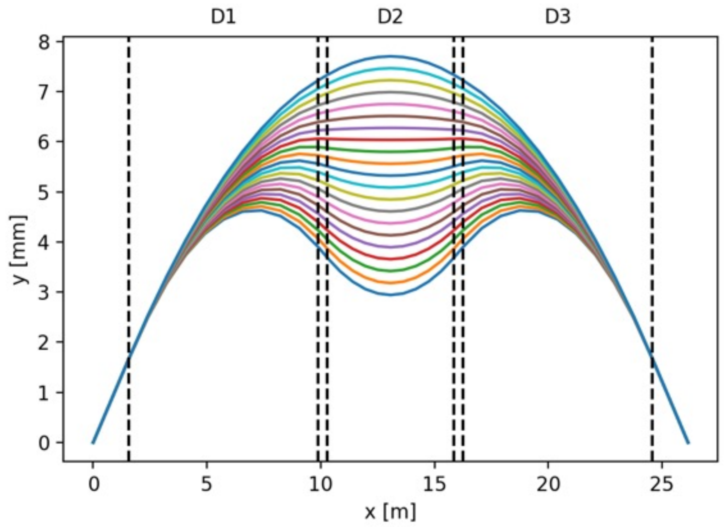
Damping wigglers - reduce damping time but increase equilibrium emittance.

Add 2 seconds once at extraction energy - no change to the optics design but increase Booster cycle-time.

2 dipoles with two different curvatures - damping time can be reduced using the ratio between the two different fields, the downside is different reference orbits [8].

[7]

Pole length	0.095 m
Pole separation	0.020 m
Gap	0.050 m
Number of poles	79
Wiggler length	9.065 m
Magnetic field	1.45 T
Energy loss per turn	126 MeV
Hor. damping time	104 ms
Hor. emittance (60°optics)	300 pm rad



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Conclusion

- Booster has exactly the same circumference as the collider with several options for bypass at the IP.
- 60°/60° optics for Z and W modes and 90°/90° optics for H and $t\bar{t}$ modes provides lower emittance for booster than collider.
- Sufficient dynamic aperture for 60°/60° optics - dynamic field effects to be added.

Further work

- Optimisation to improve the off-momentum DA for the 90°/90° optics.
- Define the tolerances and correctors for the linear imperfections.
- Establish method to reduce damping time.
- Finalise and integrate the injection and extraction region designs.

References

[1] Agapov, I., et al. “Future Circular Lepton Collider FCC-ee: Overview and Status.”

[2] K. Oide, 4 August 2022, https://indico.cern.ch/event/1178975/contributions/4952198/attachments/2488857/4274942/params_220804.pdf

[3] Aiba, Masamitsu, et al. “Top-up injection schemes for future circular lepton collider.” *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 880 (2018): 98-106.

[4] P. Hunchak, 2021 FCCIS WP2 Workshop , https://indico.cern.ch/event/1085318/contributions/4591346/subcontributions/356612/attachments/2360057/4028485/FCCee_Top-up_Injection_07-12-2021.pdf

[5] H. Wiedemann, Particle Accelerator Physics I—Basic Principles and Linear Beam Dynamics (1993).

[6] https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7764034&tag=1

[7] B. Dalena, https://agenda.infn.it/event/28874/contributions/169171/

[8] A. Chance, https://indico.cern.ch/event/1064327/contributions/4893280/attachments/2452216/4202177/2022_05_31_heb_status_FCCweek.pdf

Thank you for your attention