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Top-up injection scheme into the collider

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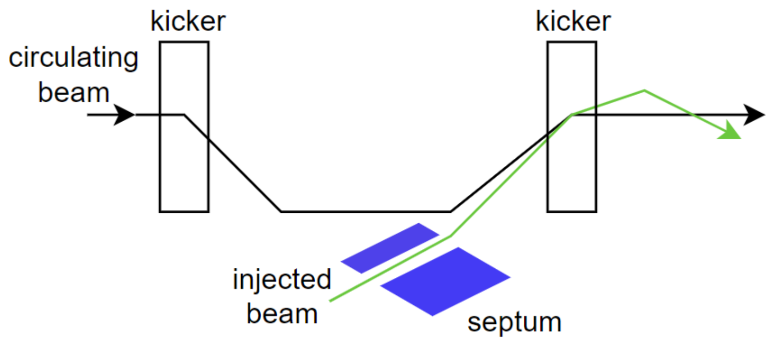
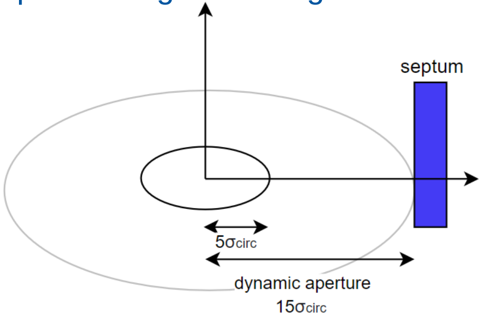
Context and outline

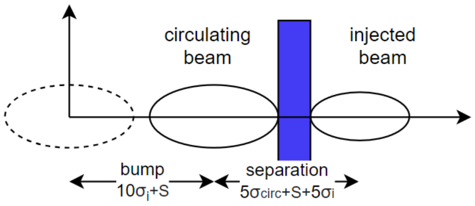
- The FCC lepton collider aims at maintaining record-high luminosities
  - Beam lifetime and high bunch charge require continuous top-up injection
- Introduction to top-up injection conventional concept
  - On-axis Vs Off-axis
  - Experience from LEP
- Baseline scheme
  - Hardware and concept selection
  - Z-mode design
  - Possible optimisation
  - Other modes concepts
- Machine protection concerns
- MKI scenario
- Conclusion

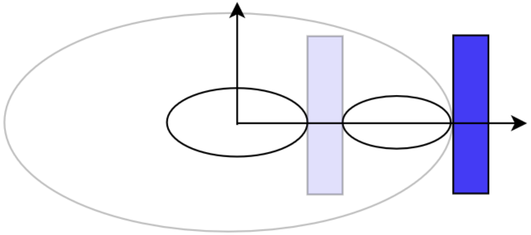
Introduction to top-up injection: conventional concept

- Dipole kickers magnets create a closed bump to bring the stored beam trajectory close to the injection system (see G. Favia and J. Borburgh on Thu)
- Two kickers are placed with 180° phase advance between them (π-orbit-bump)
- The bump is constant for up to a single turn while off before and after
- Beam separation at the injection septum
  - Off-axis means the separation exists in the transverse space -> betatron oscillations and damping
  - On-axis means the separation exists in momentum at a dispersive region -> longitudinal oscillations and damping





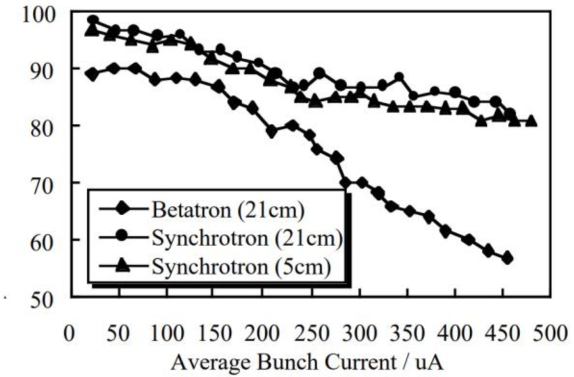




[1] P. Hunchak, 2021 FCCIS WP2 Workshop ,link

Introduction to top-up injection: history of LEP

- LEP was design for both on-axis and off-axis top-up injection
  - Operation started with off-axis injection until the first tests in 1994
  - Following commissioning and comparison, on-axis injection became the nominal injection scheme
- Advantages of the on-axis
  - Faster damping since the injected beam undergoes longitudinal oscitations
  - Flat trajectories in the achromatic experimental straight sections reduced radiation doses to experiments
  - Overall, less affected by injection errors and provided better injection efficiency at higher bunch current



[1] Collier, Paul. "Synchrotron phase space injection into LEP." Proceedings Particle Accelerator Conference. Vol. 1. IEEE, 1995.

Baseline scheme: selection

- Injection Septum technology
  - Electrostatic septum
    - Minimal blade thickness of ~100 µm
    - A potential availability risk was identified due to photo-electron induced sparking, as observed in the SPS when accelerating positrons [2]
    - An ongoing R&D program in ABT aims at characterizing the sparking probability in the presence of synchrotron radiation
  - Magnetic septum
    - Thicker blade of 1 mm to a few mm is needed
    - Several technology available
  - New baseline concept uses a **thin magnetic septum of 2.8 mm** blade thickness (see J. Borburgh on Thu)

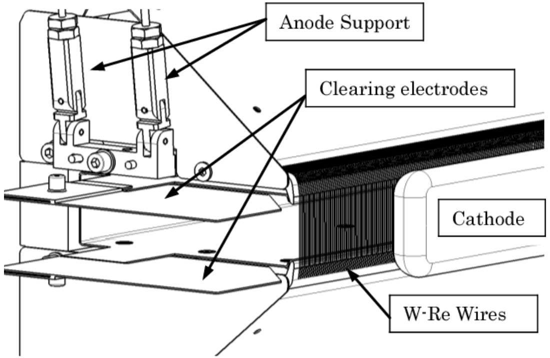


Fig. 1. ZS electrostatic septum used for SPS slow extraction

- Baseline injection scheme
  - Every scheme was reviewed in 2018 [3] and conventional as well as multipole kicker injection schemes were considered suitable
  - Off-axis injection scheme
    - Experience from LEP is directly applicable : lower radiation to experiments with on-axis scheme
    - Modelling of SR power deposition around experimental area showed that betatron injection with gap of ~10σ is not feasible [1]
  - On-axis injection scheme
    - Septum gap between injected and circulating beams opened by dispersion and momentum offset
    - Requires sufficient dynamic aperture and flexible optics to obtain a large dispersion at the injection point
  - The baseline scheme uses **on-axis injection**

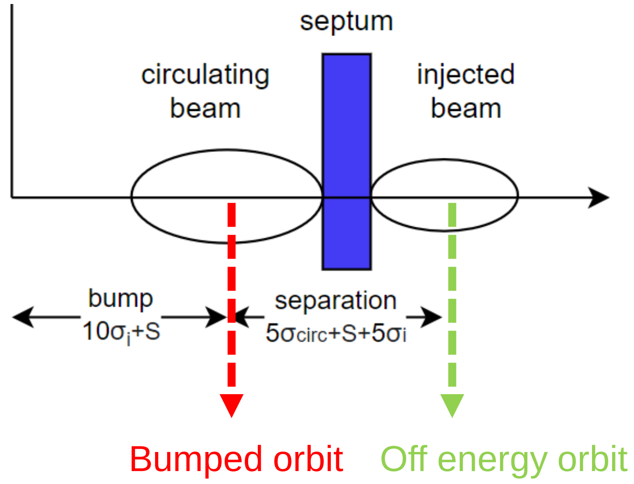
[1] K. Andre, SR power deposition from injected beam, 161st FCC-ee Optics Design Meeting,
[2] Dubois, R ; Weisse, E ; Keizer, R L, First comments on the interaction of synchrotron light with the electrostatic septa of the SPS, SPS-ABT-Tech-Note-88-05
[3] Aiba, Masamitsu, et al. “Top-up injection schemes for future circular lepton collider.” Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 880 (2018): 98-106.

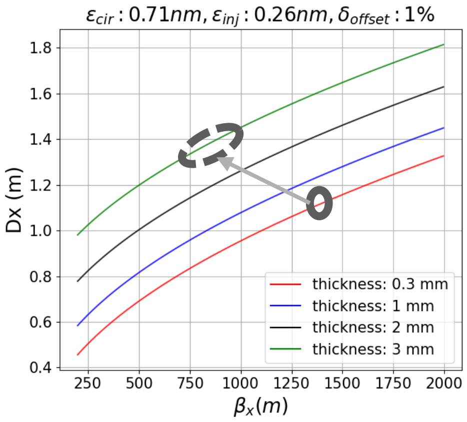
Baseline scheme: Z-mode requirements

- Ring dynamic aperture limits the injected beam < ± 1 %
- Requirements:

$$\left|D_x \delta_{offset}\right| = 5\sigma_{cir} + S + 5\sigma_{inj}$$

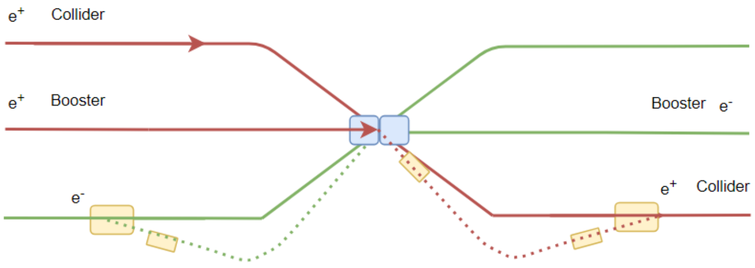
  – $\delta_{cir,BS} = 0.109\%$ [3]
  $\epsilon_{cir} = 0.71nm$ [3], $\epsilon_{inj} = 0.26\, nm$ [4]
  – $\sigma_{cir} = \sqrt{\epsilon_{cir}\beta_x + (D_x\delta_{cir})^2}$,
  $\sigma_{inj} = \sqrt{\epsilon_{inj}\beta_x}$ (considers achromatic injected beam)
- Simplified analytical constraint on the optics
  – $D_x = \frac{(S+5\sqrt{\epsilon_{inj}\beta_x})\delta_{offset}+5\sqrt{\epsilon_{cir}\beta_x\left(\delta_{offset}^2-25\delta_{cir}^2\right)+(S+5\sqrt{\epsilon_{inj}\beta_x})^2\delta_{cir}^2}}{\left(\delta_{offst}^2-25\delta_{cir}^2\right)}$
- First optics constraints
  – $D_x = 1.4$ m and $\beta_x = 1000$ m for 2.8 mm blade thickness

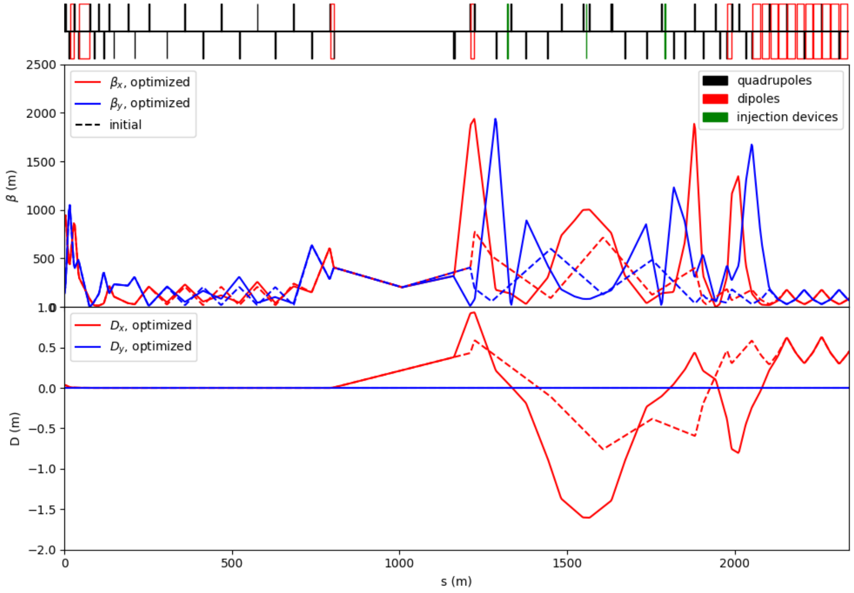




Baseline scheme: Z-mode optics design and matching

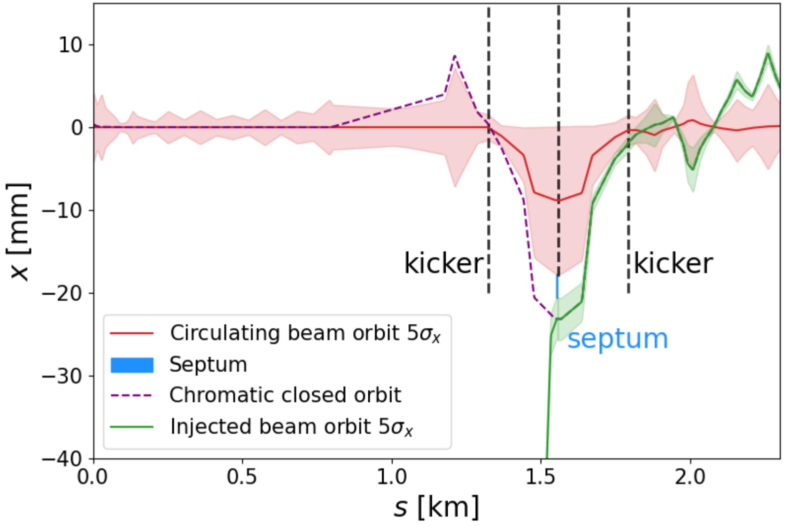
- Optics constraints at the injection point
  - $D_x = 1.4$ m and $\beta_x = 1000$ m
  - Makes use of the dispersion created by the separation dipoles at the center of the straight section
- Optics matching to the ring lattice
  - Twiss parameters are matched on both sides of the straight section
  - Phase advance across the straight section matched
  - No matching of the W function
- Large D_x and β_x
  - Reducing the requirement on energy offset
- π mode bump
- Effects in ring dynamics
  - No significant effect observed in late 2023 on GHC lattice (MR59)
  - Systematic validation of the injection optics is required

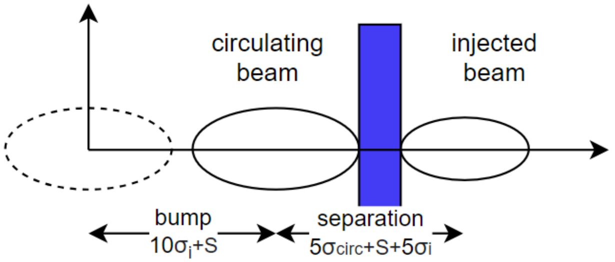




Baseline scheme: Z-mode envelopes and aperture

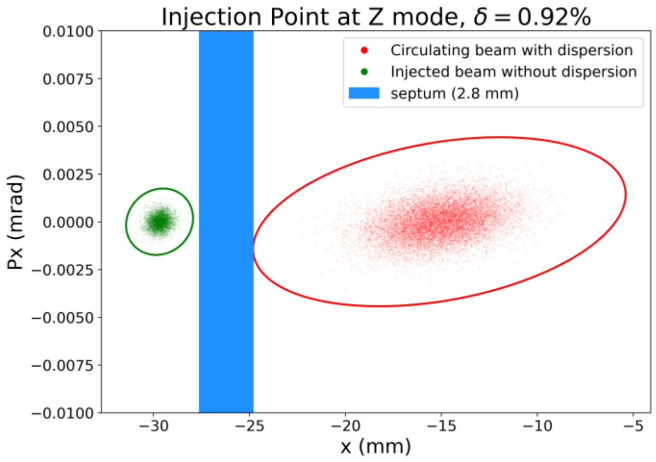
- Circulating beam bumped close to the injection septum
  - Bump amplitude of 10σ + septum thickness
  - Fast bump lasting only 1 turn
- Parameters
  - Kicker strength: 36 μrad
  - Rise and fall time depend on filling scheme
    rise & fall time 1.1 μs
    flat-top time: 304 μs for full turn filling
- Strong requirements on kickers field flatness is challenging to maintain over 304 μs (see G. Favia on Thu)
- Large envelopes due to dispersion
  - Need to ensure the aperture is sufficient with and without the injection bump

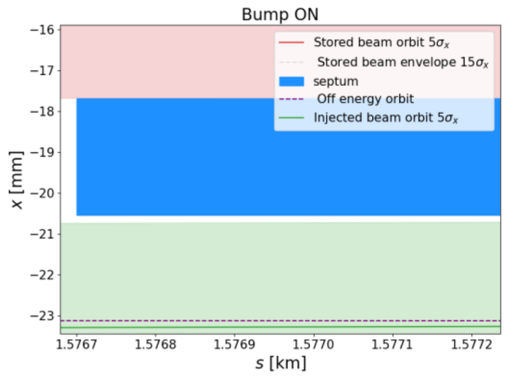




Baseline scheme: Z-mode envelopes at the injection point

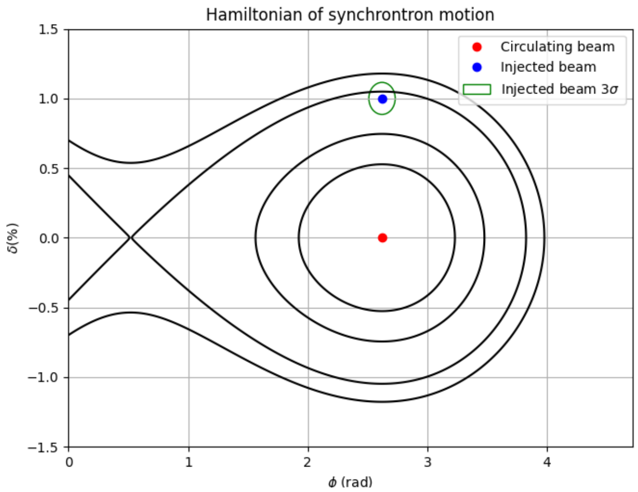
- Real space geometry of the envelopes at the septum
  - Deflection angle of the circulating beam is 0.1 mrad
  - Stray field impact for the circulating beam ~1 µrad
  - Maximum gap between septum and injected beam 5σ envelope is ~0.2mm
  - No need for wedged septum -> septum has fixed thickness across entire length
- Halo interception by the septum
  - Septum clashes with part of the circulating beam during the injection turn
  - Halo absorption upstream of the septum needs to be considered and halo population precisely quantified in the presence of beam-beam



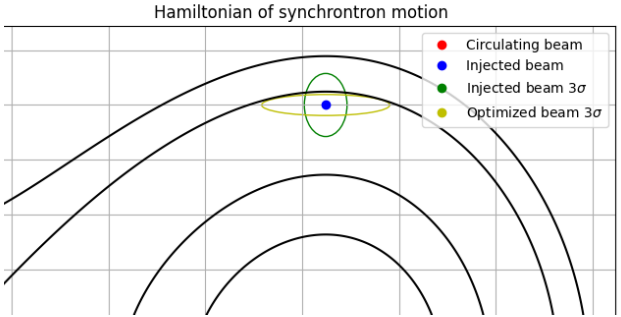


Baseline scheme: Z-mode longitudinal phase space

- Longitudinal parameter
  - RF acceptance in collider: 1.06% [1]
  - Energy offset of beam extracted from booster : 1%
  - Energy spread of beam extracted from booster : 0.038 %
  - Bunch length of beam extracted from booster : 2.43 mm



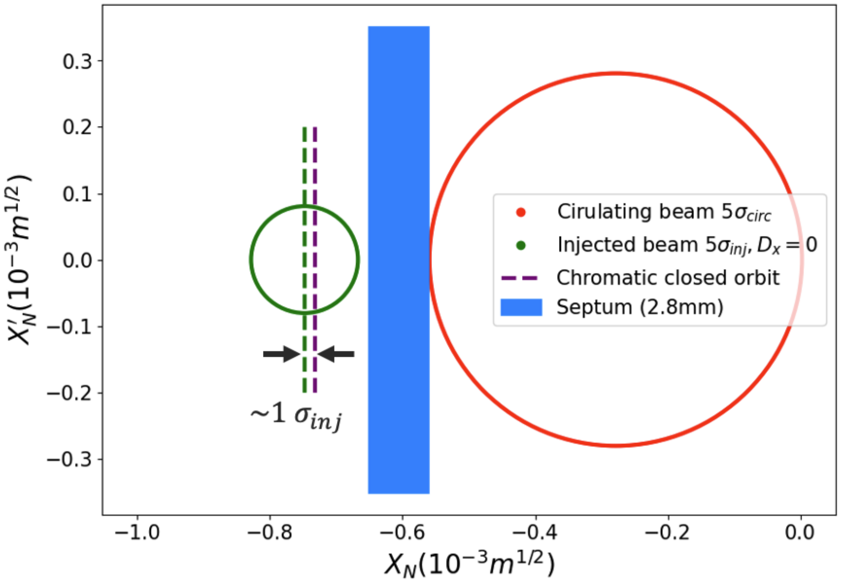
- Goal of ≥ 3 σ_z injected beam capture
  - Increase collider ring RF acceptance
  - Decrease energy offset of injected beam → ≤0.95%
  - Accept lower injection efficiency



[1] K. Oide, Collider GHC lattice,

Baseline scheme: optimisation with hybrid on-off axis injection scheme

- Limitations to the energy offset of the injected beam
  - RF acceptance
  - Dynamic aperture
- Small betatron offset of a few sigma remains acceptable [1]
- Hybrid optimization reduces momentum offset at the expense of
  - $D_s\delta < 5\sigma_{cir} + S + 5\ \sigma_{inj}$
    -> Offset = $5\sigma_{cir} + S + 5\ \sigma_{inj}$ - $D_s\delta$
- Betatron oscillation damping is slower than longitudinal
  - Z-mode longitudinal damping time is ~0.3 s
  - Z-mode considering injections every ~3 s



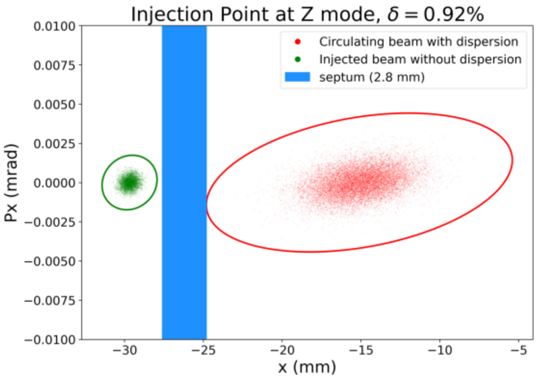
- Taking the orbit with an energy offset of 1% as an example

  Distance between injected beam and off energy orbit

  ~ 1.5 mm ≡ ~1 σ_{inj}

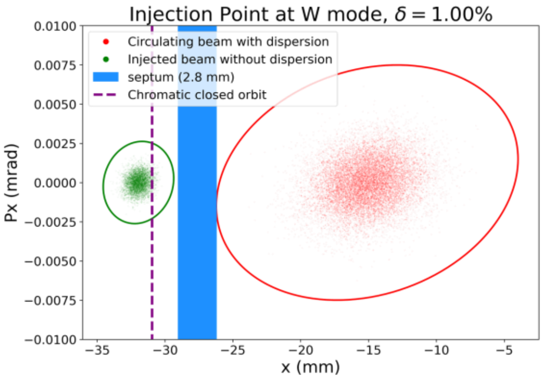
[1] K. Andre, SR power deposition from injected beam, 161st FCC-ee Optics Design Meeting,

Baseline scheme: first estimates at other modes



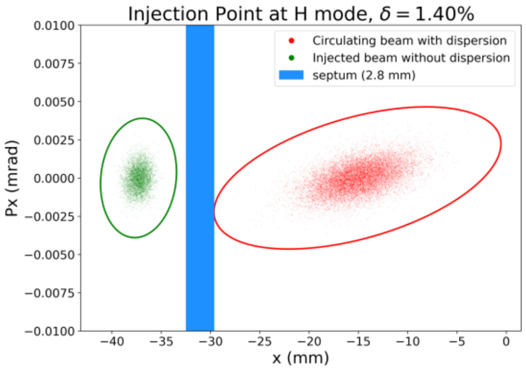
On axis injection

- $\delta = 0.92\%$
- RF acceptance:1.06%
- $\epsilon_{cir} = 0.7$ nm
- $\epsilon_{inj} = 0.12$ nm



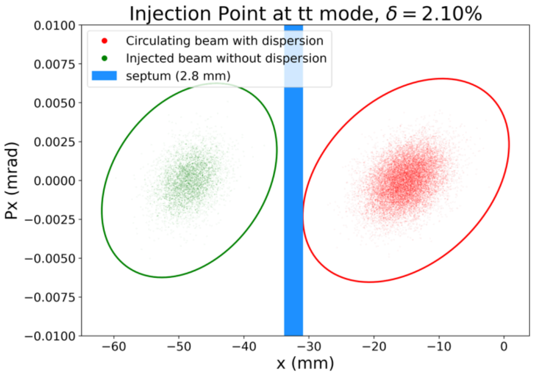
Hybrid On-off axis injection

- $\delta = 1\%$
- RF acceptance: 3.32 %
- $\epsilon_{cir} = 2.16$ nm
- $\epsilon_{inj} = 0.27$ nm
- Offset of 1 mm or ~ 0.5σ



On axis injection

- $\delta = 1.40\%$
- RF acceptance: 2.06%
- $\epsilon_{cir} = 0.63$ nm
- $\epsilon_{inj} = 0.6$ nm



On axis injection

- $\delta = 2.1\%$
- RF acceptance: 3.06%
- $\epsilon_{cir} = 1.51$ nm
- $\epsilon_{inj} = 1.4$ nm

Baseline scheme: first estimates at other modes

FCC-ee collider parameter [1]

Beam energy GeV	45.6	80	120	182.5
Horizontal emittance [nm]	0.7	2.16	0.66	1.51
RF acceptance [%]	1.06	3.32	2.06	3.06
Energy acceptance (DA) [%]	$\pm$1.0	$\pm$1.0	$\pm$1.9	-2.8/+2.5
Energy Spread (BS) σ_δ [%]	0.11	0.105	0.176	0.184
Septa blade thickness (mm)	2.8			

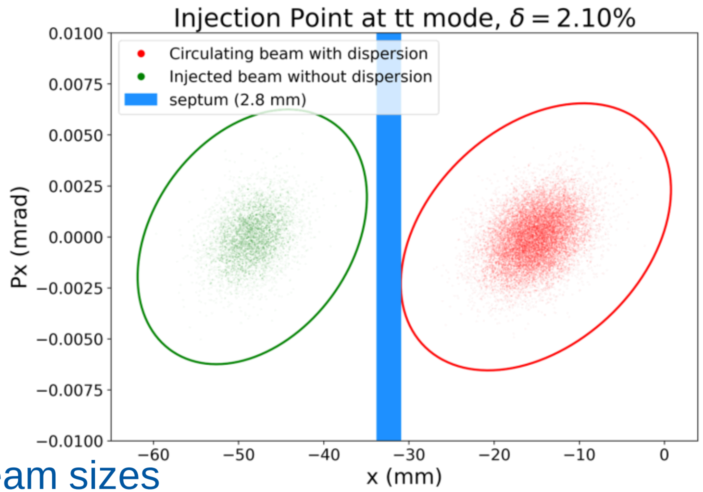
FCC-ee booster parameter

Beam energy GeV	45.6	80	120	182.5
Horizontal emittance [nm]	0.12	0.27	0.6	1.4
Energy spread [10^{-3}]	0.38	0.67	1.01	1.53
Extraction bunch length [mm]	2.43	2.56	2.26	1.98

[1] K. Oide, Collider GHC lattice,
[2]Booster lattice, GitLab

Baseline scheme: first estimates at other modes

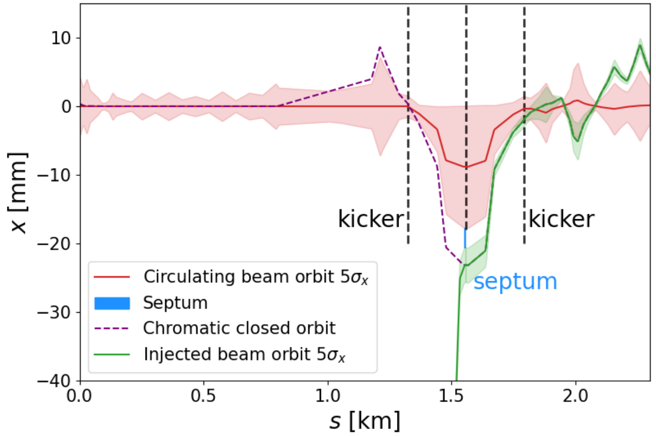
- Status
  - Injected beam dispersion is mismatched causing betatron beating of the injected beam
  - Baseline scheme developed for the Z-mode requires adapted parameters at other modes
  - Higer-energy optics rematched to the Z injection lattice

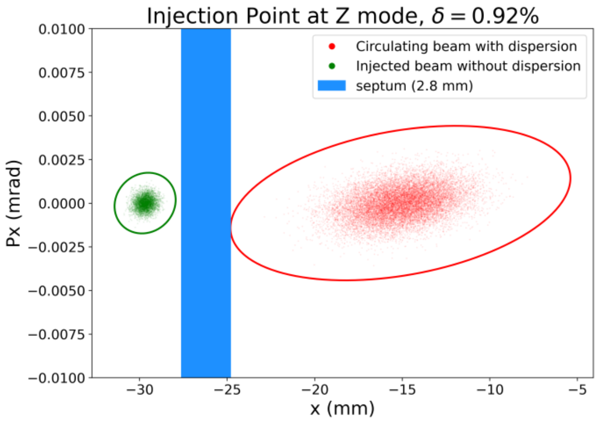


- Challenges
  - Longitudinal beam parameters matching is not possible at large momentum offsets close to the acceptance limit
  - Top-mode large emittance presently requires very large beam sizes
  - Possible hardware changes between modes
- Next steps
  - Tracking of injected beam to estimate injection efficiency and validation at every mode
  - Considering requirements on the booster vertical emittance
  - Presently using the booster horizontal equilibrium which may not be easily reachable for the Z-mode -> need to consider the effect of larger horizontal emittance

Machine protection consideration

- Present status from discussion in 2023 between several groups of CERN [1] identified several critical failure cases and possible mitigation methods
- Collider injection bump
  - Circulating beam is bumped for 1 turn
  - Failure of the ring kicker causes >10 sigma oscillation around the ring
  - Simple model by A. Abramov (BE-ABP, CERN) shows that such oscillation is too large for the collimation system
  - Reviewing the possibility to split each kicker in 2 independent systems to limit the maximum oscillation to ~5 sigma
- Other systems are slow (septa, dipoles, quadrupoles)
  - Failure could be mitigated by a fast dump trigger system (with reaction within 1 turn or less)
  - Feasibility of a system with reaction time ≤ 1 turn remains to be studied
- Circulating beam scraping on the injection septum needs to be considered
- Comprehensive and systematic review on injection, extraction and beam transfer failure cases is needed

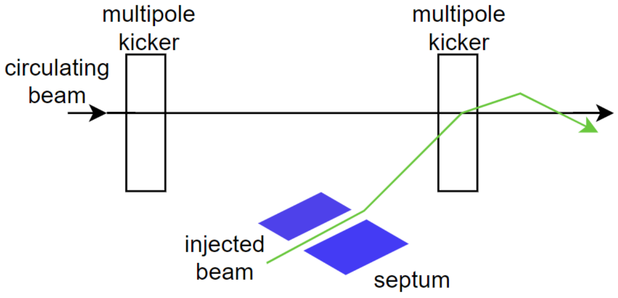




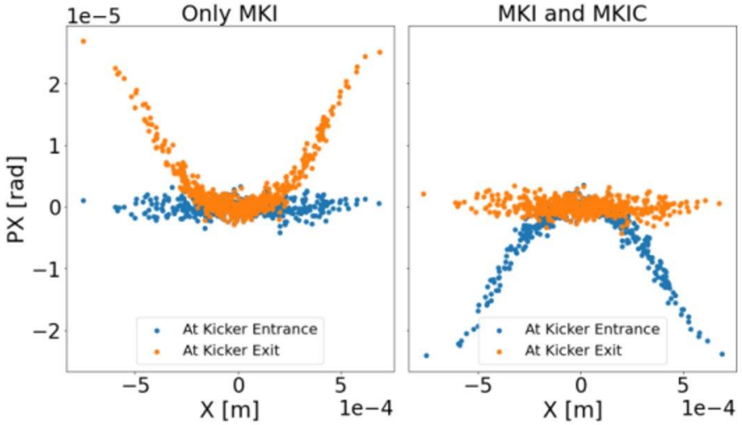
[1] A. Abramov, Y. Dutheil, M. Hofer, A. Lechner, C. Wiesner, S. Yue, FCCee beam transfer meetings special machine protection, indico

MKI injection scheme: back-up injection concept

- Fast kicker magnet producing a non-linear field as close as possible from a step function
- The effect of the highly non-linear field on the stored beam is countered by an identical magnet 180º phase advance upstream
- Effort until 2023 by University of Saskatchewan-Canadian Light Source (P. Hunchak and M. Boland) with support of CERN
- Potential advantages
  - Larger gap at the injection septum
  - Lower optics constraints at the injection point
  - Smaller circulating beam oscillations in case of injection failure
  - Can be simulated with minimal changes to the injection straight section layout



Stored beam at MKI [1]



[1] P. Hunchak, Beam-tracking simulations and error studies, FCC-ee injection #13, 2022

Conclusion

- Baseline top-tup injection scheme uses **on-axis injection**
  - Limits or removes oscillations of the injected beam in experimental straight sections
  - Primarily developed at the Z-mode, generalisation to other modes is ongoing
- Ring requirements
  - **Dynamic aperture is critical** for top-up injection
  - Collimation and collimation scheme behaviour has not been considered yet
- Challenges and assumptions to be studied
  - Injected beam size is reduced by using zero dispersion -> dispersion mismatch causes betatron beating of injected beam
  - Z-mode **longitudinal damping time ~0.3 s is not negligible** compared to the repetition time of ~3 s and may limit or prevent using any betatron offset or beating
  - Using linear optical functions determined around the reference momentum
  - Machine protection concerns may be critical to the baseline scheme
  - Full ring transfer presents hardware challenging
- Next steps towards the FSR
  - Injection scheme tracking with synchrotron radiation and possibly beam-beam
  - Agree on a realistic minimal injection efficiency for the injector chain requirement (possibly 80% after a commissioning period)
  - **Review of the injection scheme to be scheduled in the fall at CERN**