CERN

FUTURE
CIRCULAR
COLLIDER

Top-up injection scheme in the collider

S. Yue & Y. Dutheil, on behalf of SY-ABT
CERN, Geneva, Switzerland

Outline

- Top-up injection conventional concept
- Baseline scheme
- Particle tracking
- Collider dump system
- Conclusion

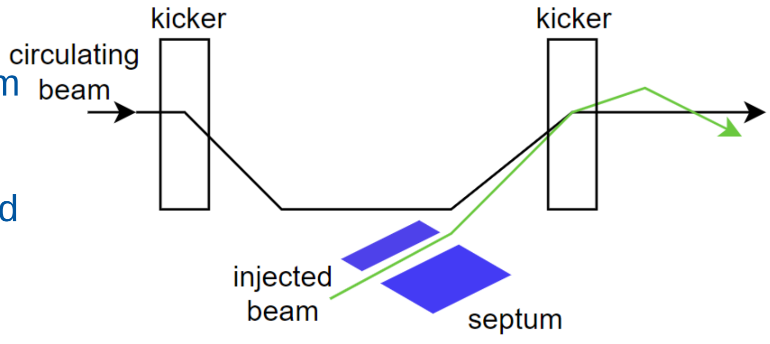
Introduction to top-up injection: conventional concept

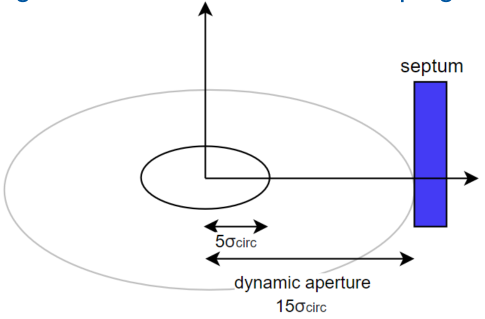
- Dipole kickers magnets create a closed bump to bring the stored beam trajectory close to the injection system

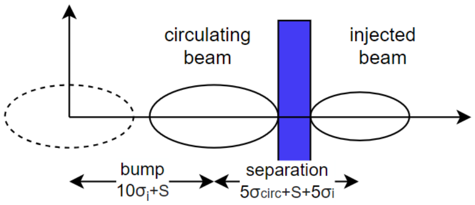
- Two kickers are placed with 180° phase advance between them (π-orbit-bump)

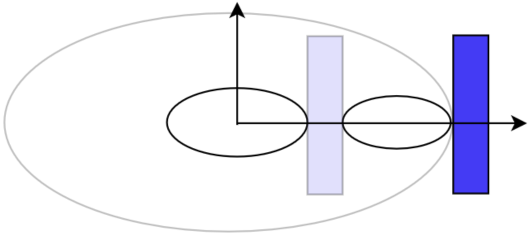
- The bump is constant for up to a single turn while off before and after

- 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



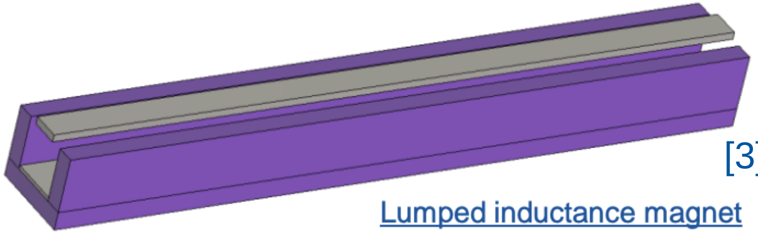






[1] P. Hunchak, 2021 FCCIS WP2 Workshop ,link

Baseline scheme:



- Injection technology
  - **Magnetic septum with a 2.8 mm blade thickness**
    - Several technology available
  - **Lumped inductance kicker**
    - 1.1 μs with rise and fall within the abort gap between trains
    - **Change to 600 ns abort gap with this technology is being investigated**

- Baseline injection scheme
  - Every scheme were reviewed in 2018 [2] and conventional as well as multipole kicker injection schemes were considered suitable
  - 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 conventional injection**

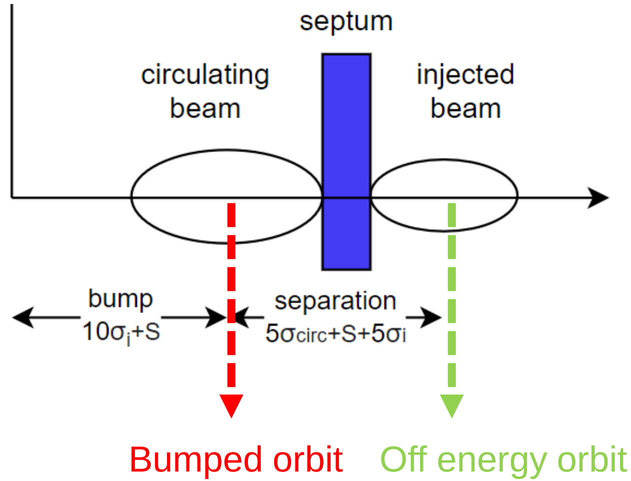
[1 Dubois, R ; Weisse, E ; Keizer, R L, First comments on the interaction of synchrotron light with the electrostatic septa of the SPS, SPS-ABT-Tech-Note-88-05
[2] Aiba, Masamitsu, et al. "Top-up injection schemes for future circular lepton collider." Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 880 (2018): 98-106.
[3] G. Favia, ABT: Hardware design for beam transfer equipment and related challenges, SY FCC general workshop

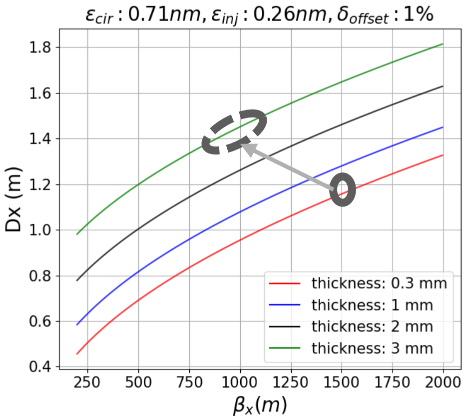
Baseline scheme: Z-mode requirements

- Ring dynamic aperture limits the injected beam < $\pm 1\ \%$
- Requirements:

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

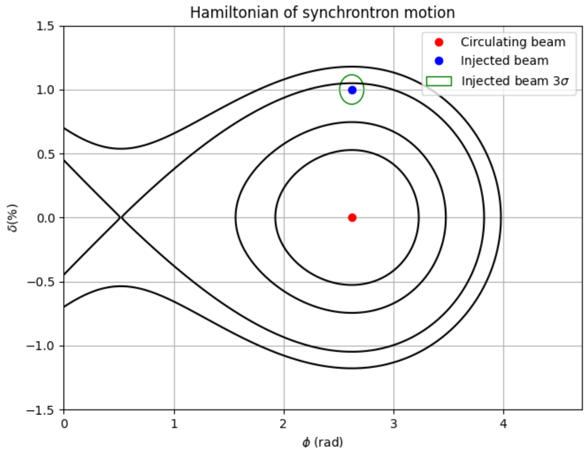
  - $\delta_{cir,BS} = 0.109\%$[3]
    $\epsilon_{cir} = 0.71nm$[3], $\epsilon_{inj} = 0.26\ nm$[4]
  - $\sigma_{cir} = \sqrt{\epsilon_{cir}\beta_x + (D_x\delta_{cir})^2}$,
    $\sigma_{inj} = \sqrt{\epsilon_{inj}\beta_x + \cancel{(D_x\delta_{inj})^2}}$ (considers mis-matched dispersion)
- Simplified analytical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





Baseline scheme: Z-mode longitudinal phase space

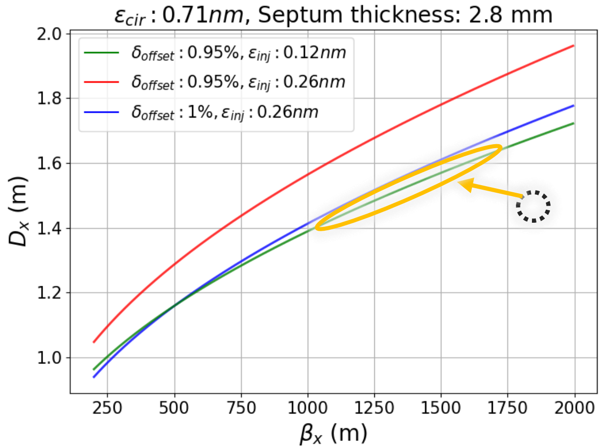
- Longitudinal parameter
  - RF acceptance in collider: 1.06% [1]
  - Energy offset of beam extracted from booster : 1%
  - Energy spread of beam extracted from booster : 0.038 %



- Goal of ≥ 3 σ_z injected beam capture
  - Decrease energy offset of injected beam → ≤0.95%

$$\delta_{offset}: 1\% \rightarrow 0.95\%,\ |D_x|: 1.4\ m \rightarrow 1.6\ m,\ \beta_x = 1000\ m$$

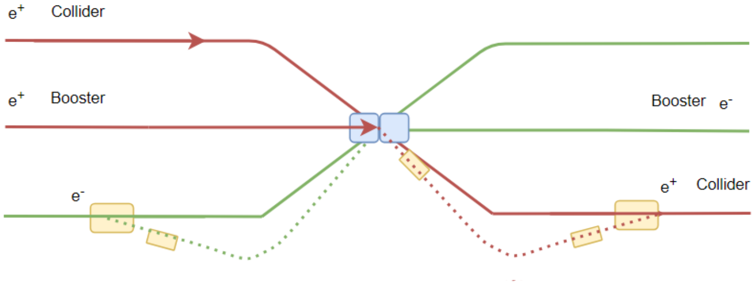
- Oide's Solution[2]: $|D_x| = 1.5\ m$, $\beta_x = 1800\ m$
  - Great progress, but need a smaller β_x !
  - $\beta_x \sim 1300m\ (\epsilon_{inj} = 0.12\ nm)$

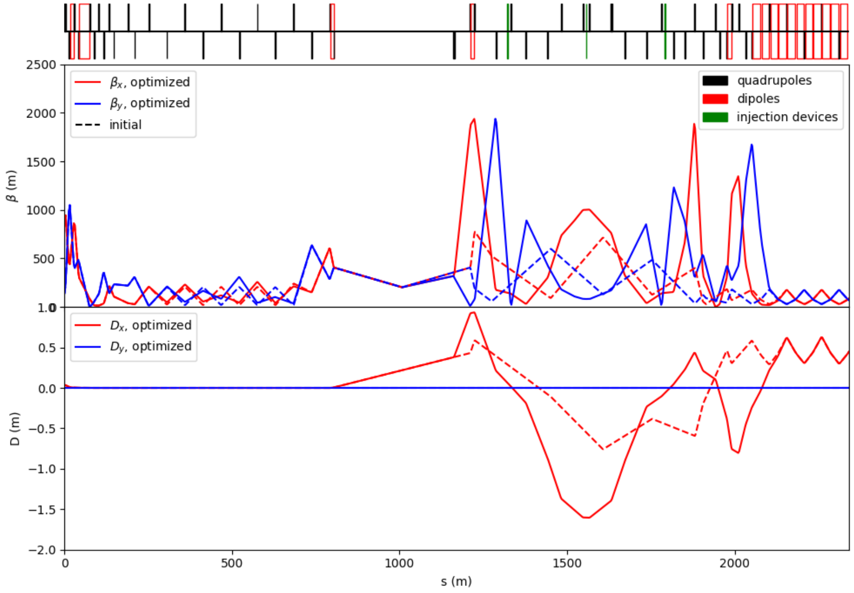


[1]K. Oide, Collider GHC lattice
[2]K. Oide, Optics with finite chromaticities + several changes, FCC optics meeting

Baseline scheme: Z-mode optics design and matching

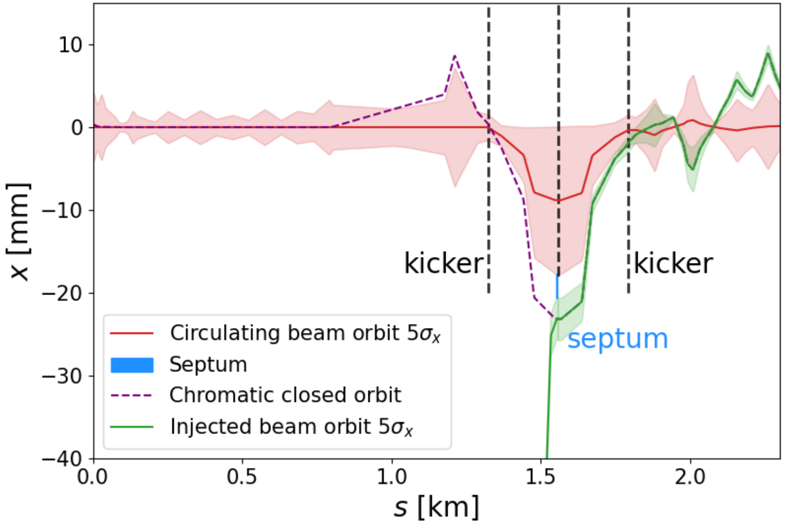
- Optics constraints at the injection point
  - $D_x = 1.6$ m and $\beta_x = 1000$ m
  - Makes use of the dispersion created by the separation dipoles at the center of the straight section
- Optics matching to the ring lattice
  - Twiss parameters are matched on both sides of the straight section
  - Phase advance across the straight section matched
  - No matching of the W function
- Large D_x
  - Reducing the requirement on energy offset
- π mode bump created by 2 bumpers

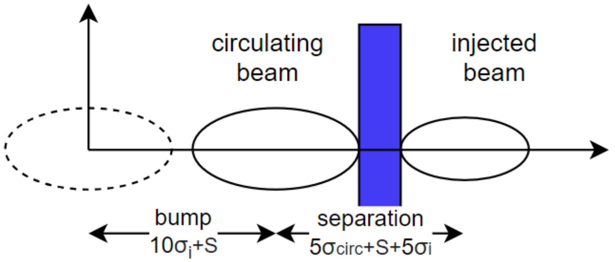




Baseline scheme: Z-mode envelopes and aperture

- 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 & fall time 1.1 µs
    flat-top time: 304 µs for full turn filling
  - Septum strength: 0.1 mrad
  - Blade thickness: 2.8 mm
- Large envelopes due to dispersion
  - Need to ensure the aperture is sufficient with and without the injection bump

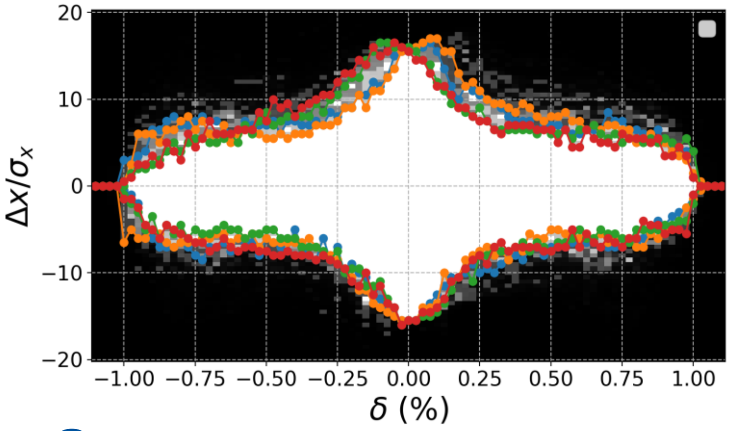




Dynamic aperture (DA): Z mode

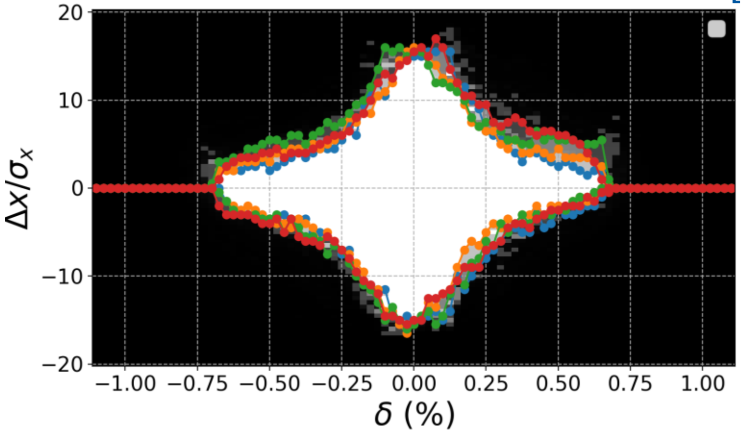
- Initial concept aims at on-axis injection with 1% energy offset
  - On axis injection injects on the chromatic closed orbit an minimizes the injected beam offset around the experiments -> favored scheme
  - Off-axis scheme injects besides the circulating beam, with a betatron offset
- Not possible due to the significant reduction of DA with the present injection optics

DA without injection optics



DA with injection optics

[1]

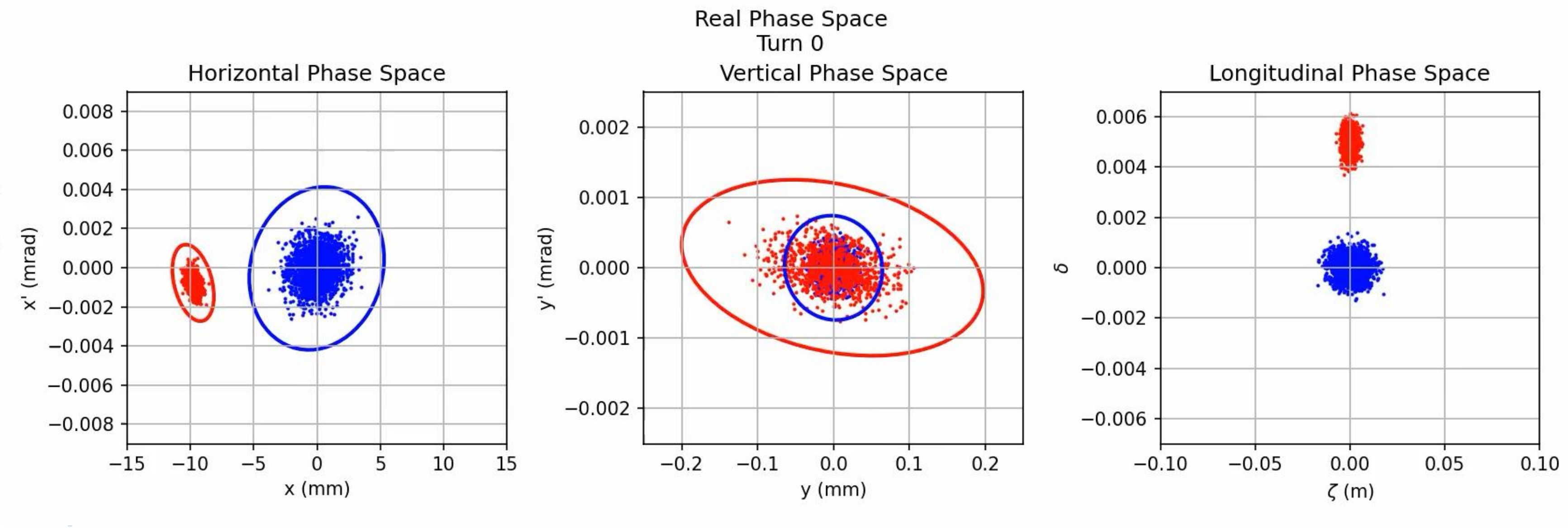


- Status
  - Ongoing discussions with K. Oide for the injection optics design
  - Baseline scheme switched to hybrid on-off axis with lower injection energy offset

[1] K. Andre, DA studies with Xsuite, FCC optics meeting

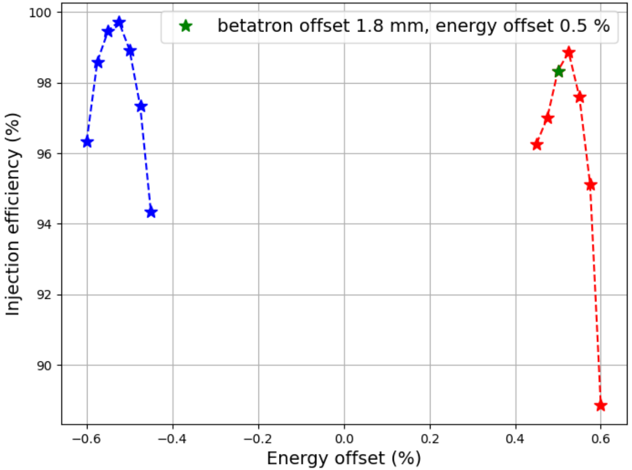
Baseline scheme

- Due to limited momentum acceptance of the lattice with injection optics, feasibility of hybrid on-off axis injection was studied.
- On the hybrid injection scheme, injected beam has an energy offset as well as a horizontal offset with respect to off-energy orbit: $\boldsymbol{\Delta} x_{offset} = 5\sigma_{cir} + S + 5\sigma_{inj} - |D_x\delta|$

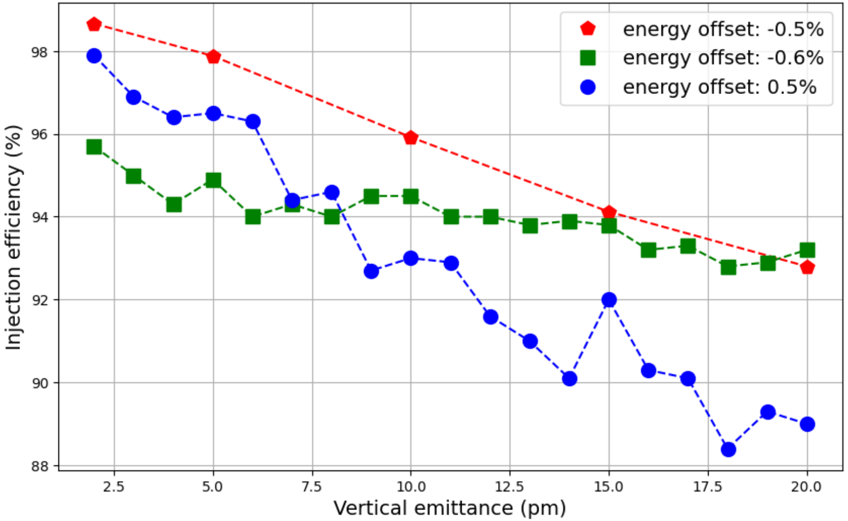


Baseline scheme : injection efficiency simulations

- Present tracking ignores errors and collective effects (beam-beam, impedance, …)
  - **The operational injection efficiency goal of 80% is used to size the injector complex** [1]
- Scanning of the injection efficiency versus various parameters



Energy offset scan



Vertical emittance scan

[1] H. Bartosik, meeting series FCCee injectors parameters

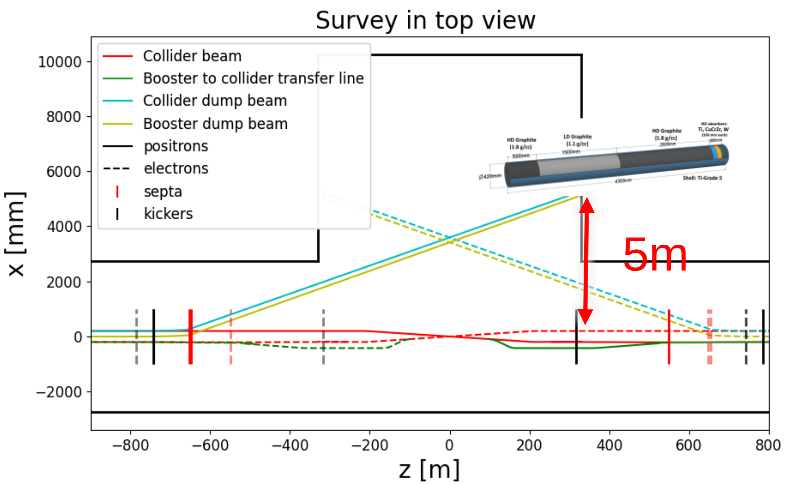
Collider dump design: Z mode

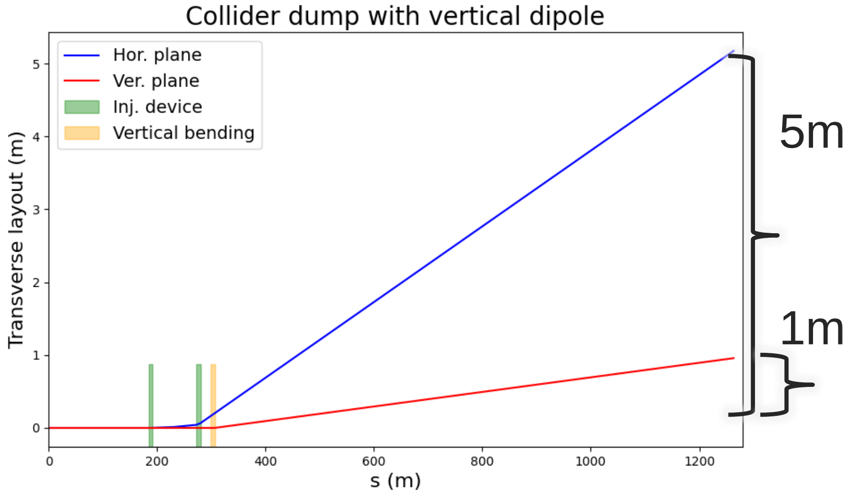
- Layout:
  - Transfer line length: 1200 m
  - 5.2 m horizontal offset
    - Additional shielding between dump and beam line is under studied
  - Fixed beam energy for dump

- Vertical bending magnet:
  - Increase beam vertical size using ver. dispersion
  - 1 m elevation

- Possible to have one common dump for collider and booster beams [1]
  - specifications are being reviewed with SY-STI

- Injection device:
  - Kicker: 0.3 mard, rise time: 1.1 us
  - Septum: 4.5 mrad
  - Similar design with booster dump

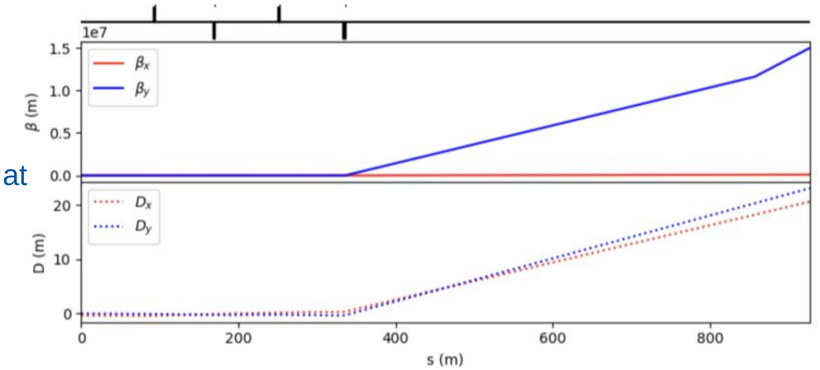


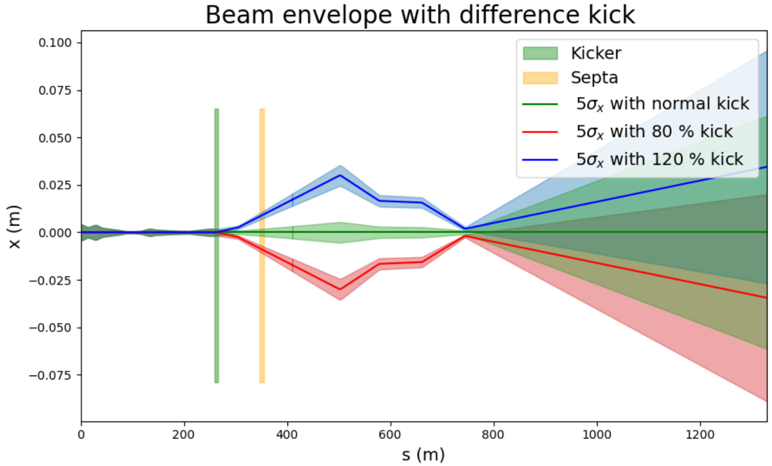


[1] A. Lechner, STI: Radiation-related challenges and shielding design ,SY FCC general workshop

Collider dump: optics design

- Optics design:
  - 4 quads in the transfer line are used for optics optimization
  - Leveraging horizontal and vertical dispersion to increase the beam size at the dump
  - To reduce energy density → need a round beam
  - Reduce the influence of kicker ripple → phase advance close to π
- Large beam size at the dump
  - $1\ \sigma_x: 11.7\ mm,\ \beta_x = 103\ km,\ D_x = 20\ m,\ \epsilon_x = 0.71\ nm$
  - $1\ \sigma_y: 10.5\ mm,\ \beta_y = 15000\ km,\ D_y = 20\ m,\ \epsilon_y = 1.9\ pm$
  - Beam size and overall scheme was discussed with STI
  - Beam remains within $\pm$100mm on the dump
- Allows large kicker pulse ripple ($\pm 20\%$) and the loss of one module
  - The quadrupoles of the line haven't been specified, and use a passive form instead.
- Failure cases and mitigation methods remain to be studied in detail





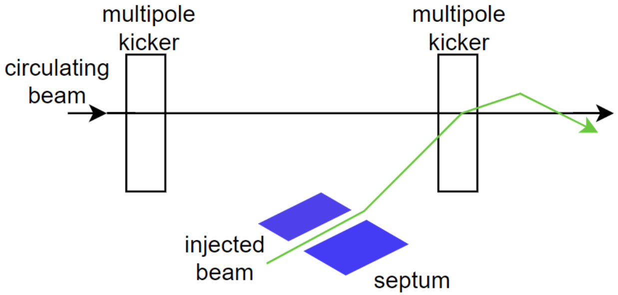
Conclusion

- Baseline top-tup injection scheme for the FSR
  - Current injection lattice reduces the DA, and thus the hybrid injection is used
  - Hardware system
    - Thin magnetic septum and lumped inductance kicker
    - Kicker rise/fall time decrease from 1100 ns to 600 ns is being investigated
  - Modelled efficiency >95%, but no error or collective effects are considered
  - W mode is more challenging due to the larger beam size -> requires increased betatron injection offset
- Top-up injection prospects
  - Discussions to re-vitalize a top-up injection WG (MKI, collective effects, errors, SR, injection/machine protection, …)
  - on-axis is needed for operation, primarily to minimize effect on experiments
  - 80% injection efficiency is used for the sizing of the injector complex
- Collider dump
  - Vertical dispersion is used to increase beam size (common dump at the height of the booster)
  - Optics optimization to maximize beam size and minimize the influence of kicker ripple

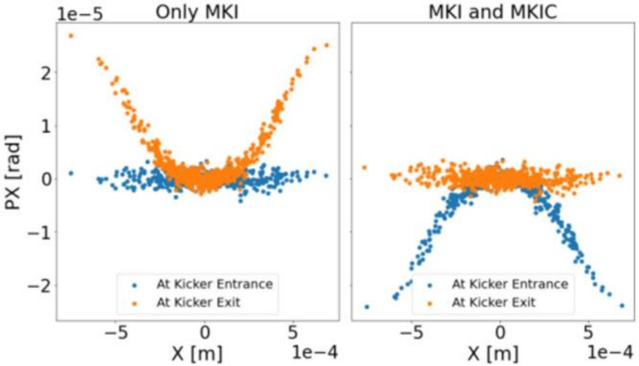
Back-up: Alternative scheme: injection concept

- MKI injection scheme
  - 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
  - Potential advantages
    - Larger gap at the injection septum
    - Lower optics constraints at the injection point
    - Smaller circulating beam oscillations in case of injection failure

- 4 bumpers instead of 2
  - No strong constraint for π mode orbit bump



Stored beam at MKI [1]



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