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Top-up injection baseline scenario

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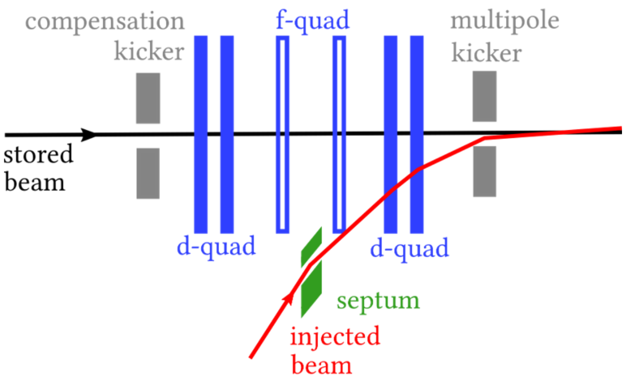
Context

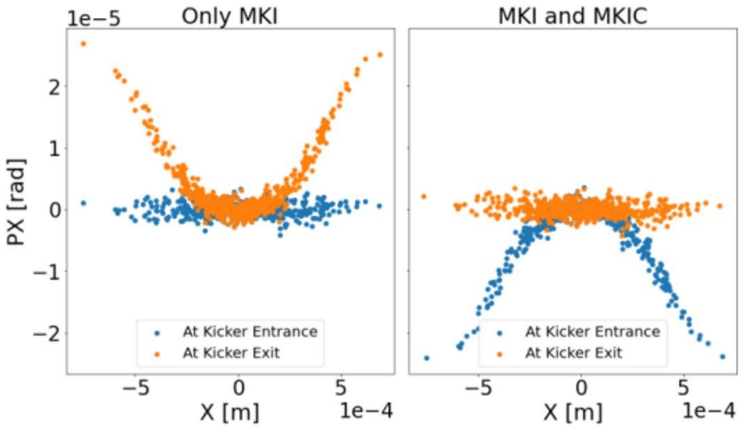
- The FCC lepton collider aims at maintaining record-high luminosities
- The beam lifetime as well as the need to maintain the charge of colliding bunches requires a continuous top-up injection scheme
  - Every scheme was reviewed in 2018 [1] and conventional as well as multipole kicker injections scheme were considered suitable
  - Activities to date aimed at progressing on the technical implementation of those schemes
- The full energy booster in the same tunnel will accelerate up to 10% of the maximum collider intensity to fill and refill every bucket
- With a limited number of straight sections the combined integration of both geometries and optics is critical
- Several schemes are being explored and the path towards the current baseline is presented here

Top-up scheme explored : Multipole Kicker Injection (MKI)

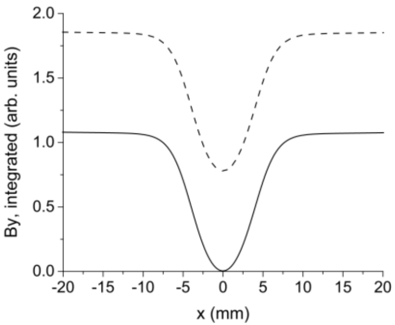
- Fast kicker magnet producing a non-linear field as close as possible from a step function
- The effect of the highly non-linear field on the stored beam is countered by an identical magnet 180º phase advance upstream

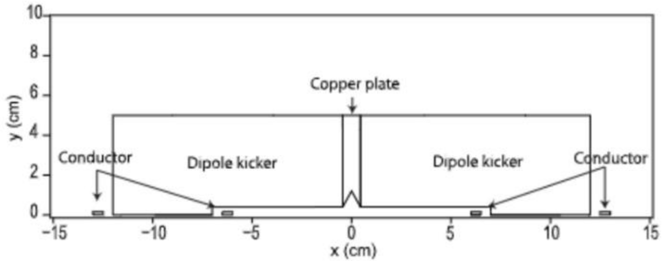


Stored beam at MKI



MKI kicker possible design [1]

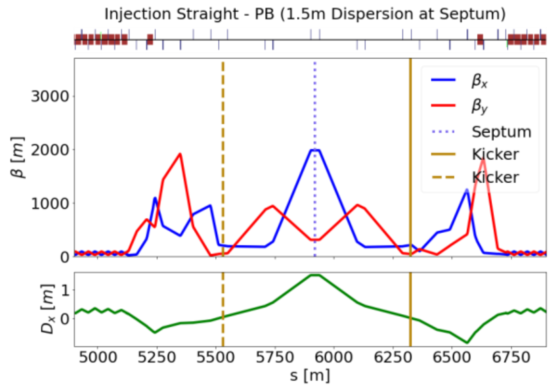


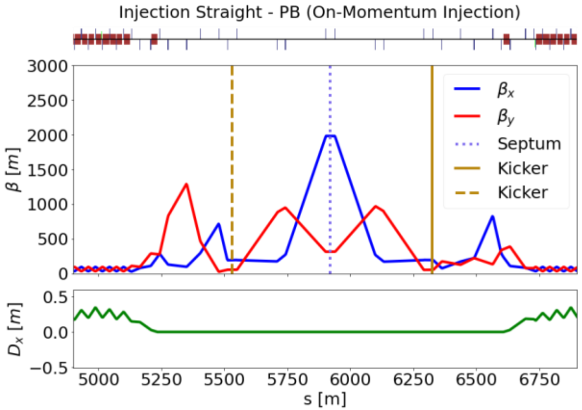


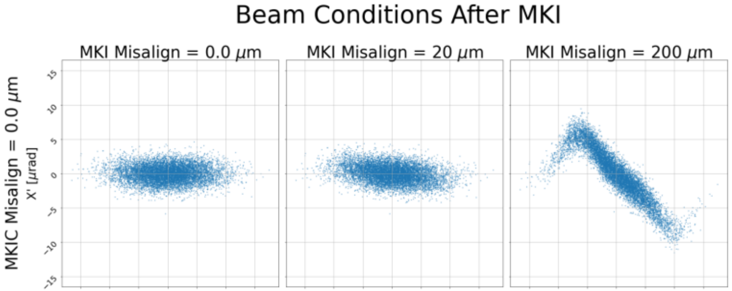
Top-up scheme explored : Multipole Kicker Injection (MKI)

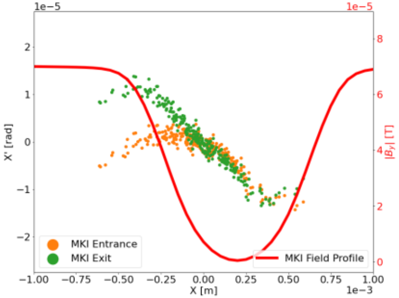
- Effort driven by University of Saskatchewan-Canadian Light Source (P. Hunchak and M. Boland) with support of CERN
- Implementation of the scheme and optics design using both on and off-axis and multiturn tracking

- This scheme is considered for several light source
- However, it imposes strong constraints in the position of the beam at the MKIs and requires R&D to confirm the achievable field





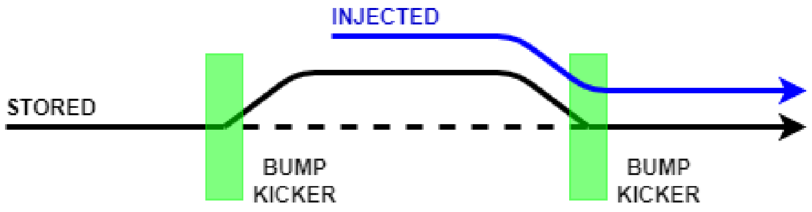


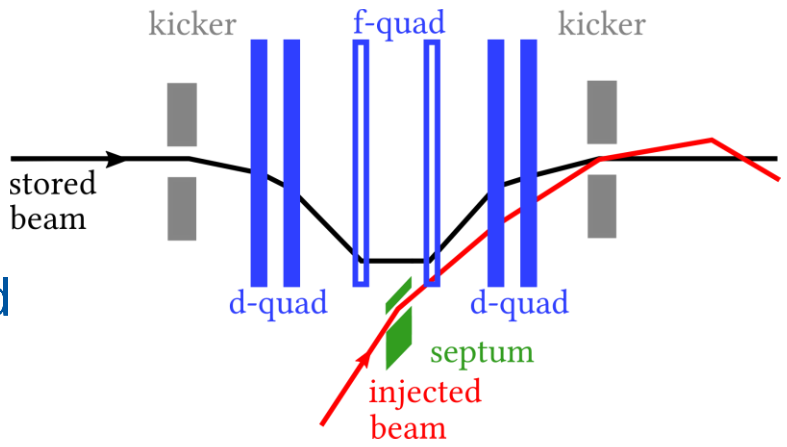


Top-up scheme baseline : conventional bump injection

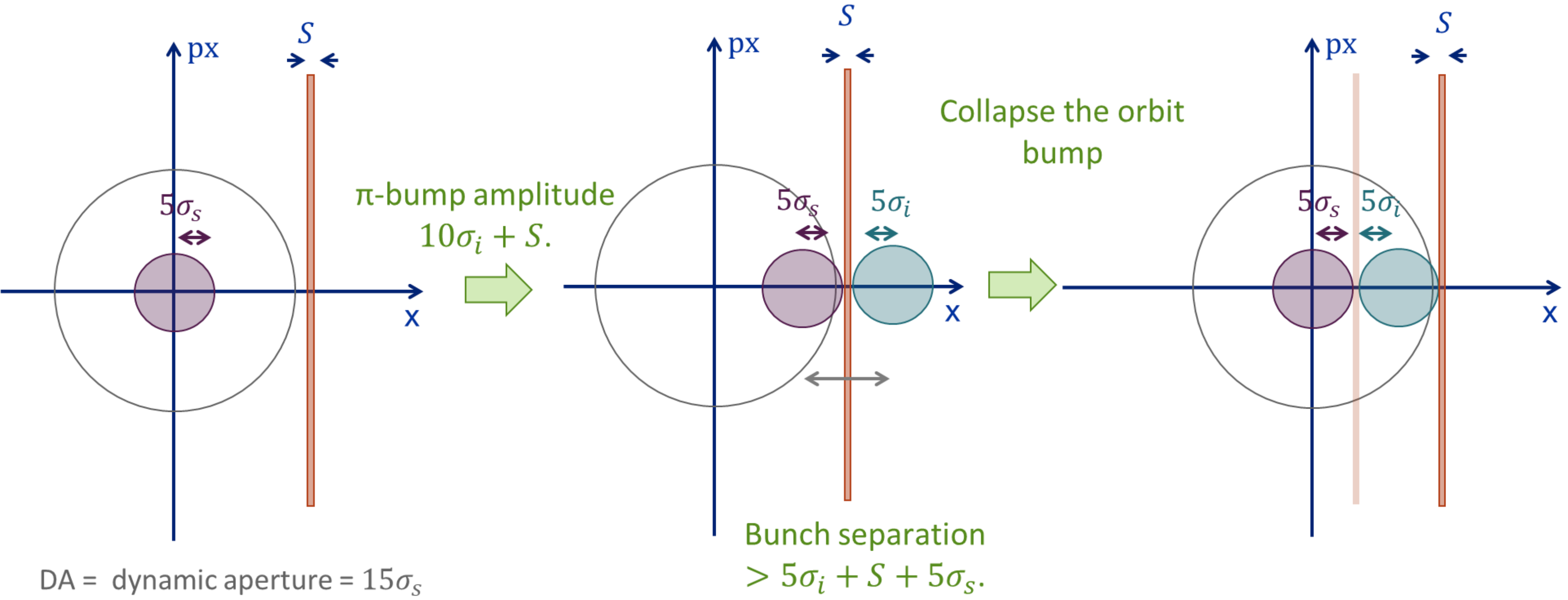
- Dipole kickers magnets create a closed bump to bring the stored beam trajectory close to the injection system
- Two kickers are placed with 180° phase advance between them (π-orbit-bump)
- The bump is constant for a single turn while off before and after

- Two possible version with on-momentum off-axis or off-momentum on-axis injected beam



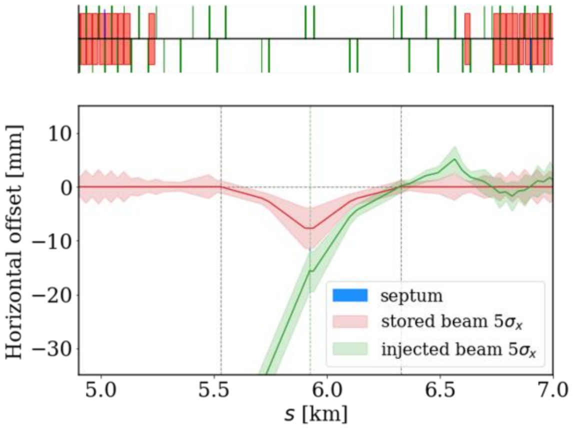


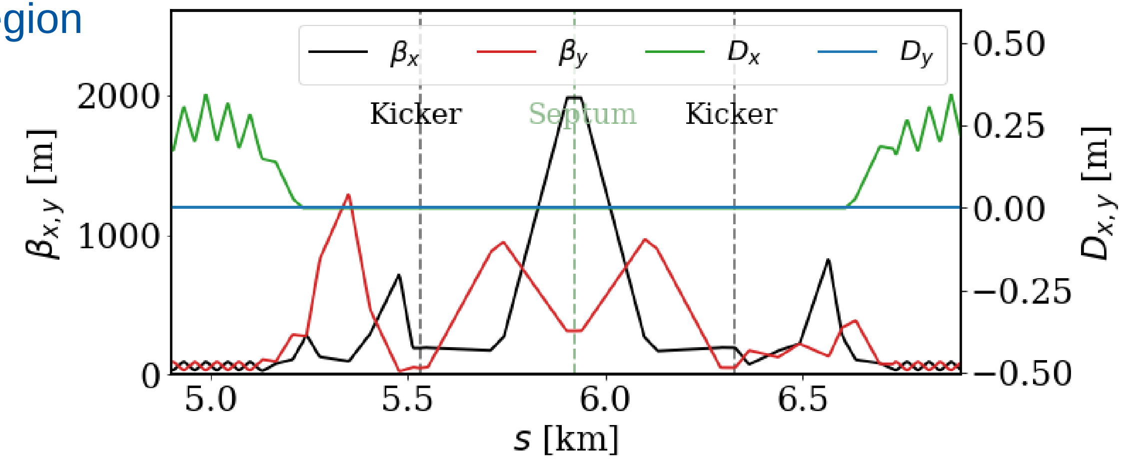
Top-up scheme baseline : conventional bump injection



Top-up scheme baseline : conventional bump injection off-axis

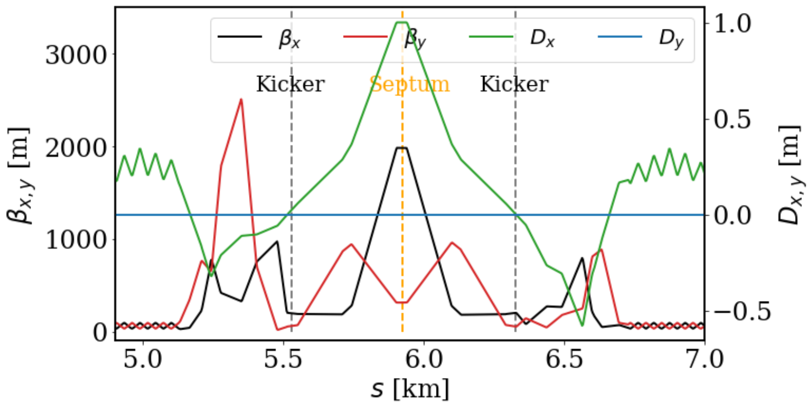
- Injection off-axis
  - Injected beam is separated in the transverse horizontal plane from the closed orbit
- Injected beam trajectory
  - Large horizontal transverse oscillation during damping which may perturb experiments
- Multiturn tracking of the injected beam [3]
  - Geant 4 model of the interaction region
  - Synchrotron radiation power at the IP mask due to the injected beam offset
  - Only a scheme 4σ(ring) + 3σ (injected) seems possible

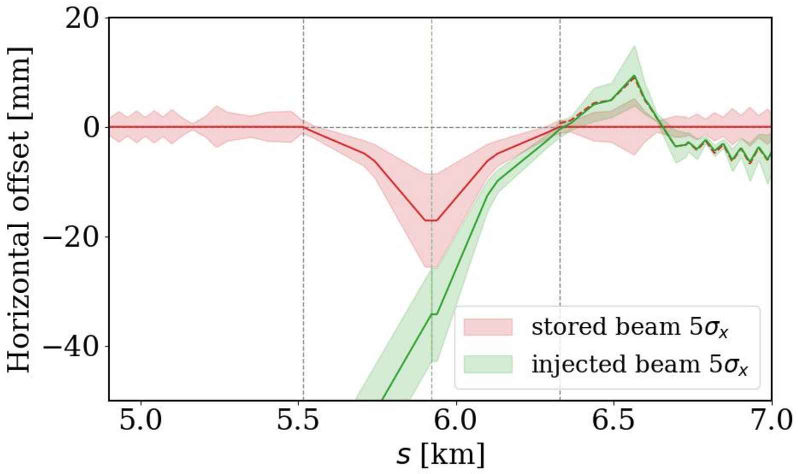




Top-up scheme baseline : conventional bump injection on-axis

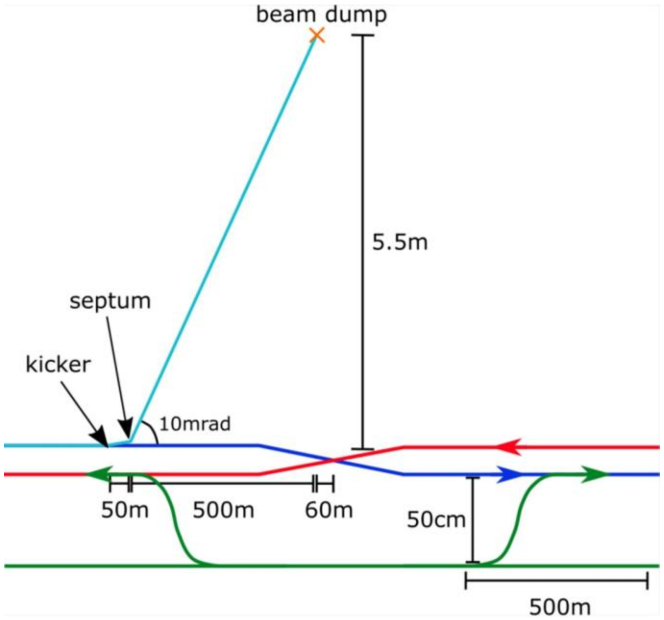
- Injection on-axis
  - Beam is injected off-energy, on the chromatic closed orbit
- Scheme
  - Dispersion and momentum offset provide the required distance between the circulating and injected beams
    - Dispersion of 1 m
    - Momentum offset -1.9%
- Larger orbit bump needed as beam size increased by dispersion
- Places strong requirements on the dynamics aperture





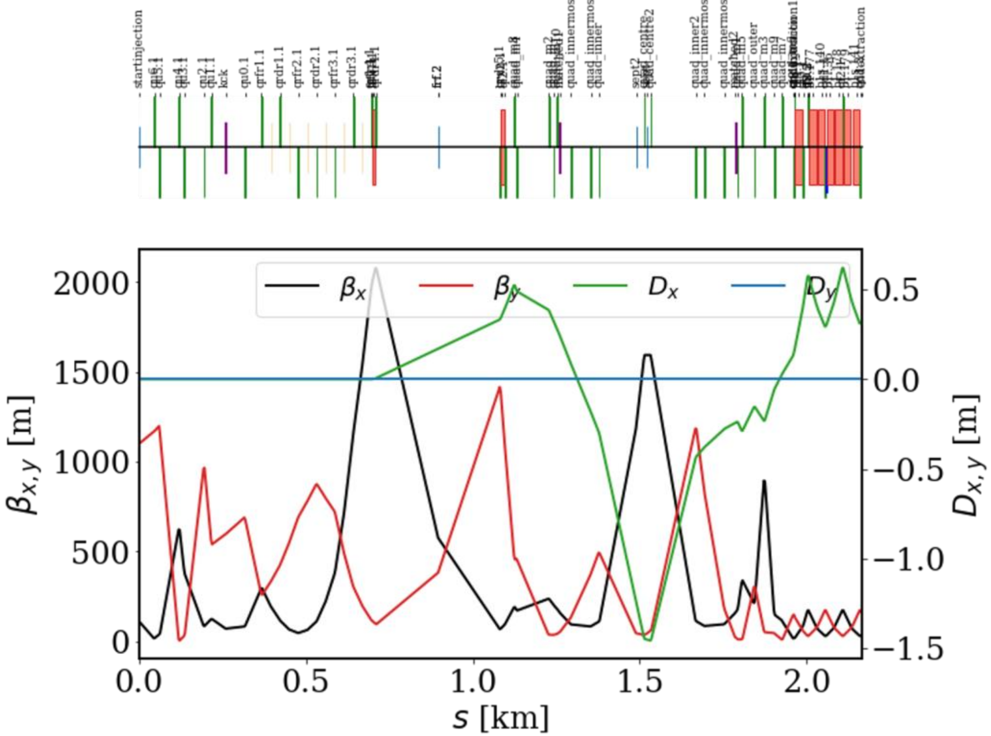
Injection optics and combined integration

Geometrical baseline scenario for injection and extraction layout.
Position of the booster ring and relative planes between rings is indicative only.



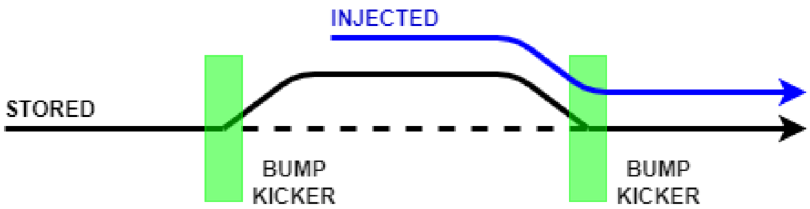
First combined injection extraction optics, with dispersion.

extraction
Injection



Hardware choices : Orbit bump kickers

- Stripline technology
- Beam and integration specifications
    - 36 urad deflection
    - Several meters of available space
    - 1 us rise time and 1 us fall time
    - 304 us flat-top
    - Repetition rate <0.1Hz



- Maximum hardware specifications (tt)
    - Integrated electric field : 3.3 MV
    - Integrated magnetic field : 10.9 mTm
- Established technology but impedance effects needs to be considered during the design

Hardware choices : Thin injection septum

- Electrostatic technology
- Beam and integration specifications
  - 100 urad deflection
  - 300 um maximum effective width
- Maximum hardware specifications (tt)
  - Integrated electric field 17.4 MV
  - 6 m total length and 2.9 MV/m

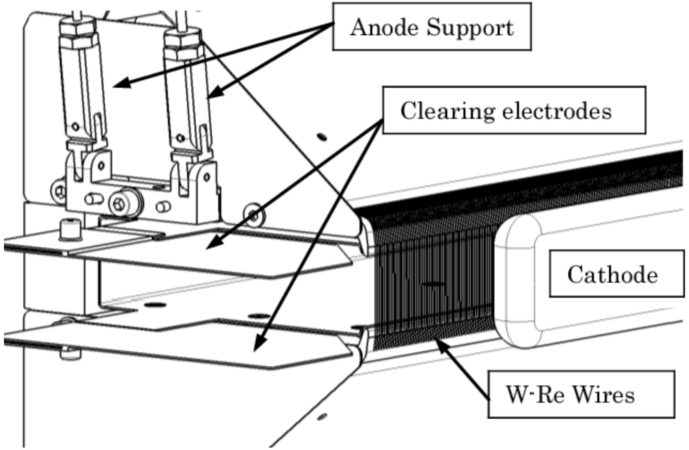


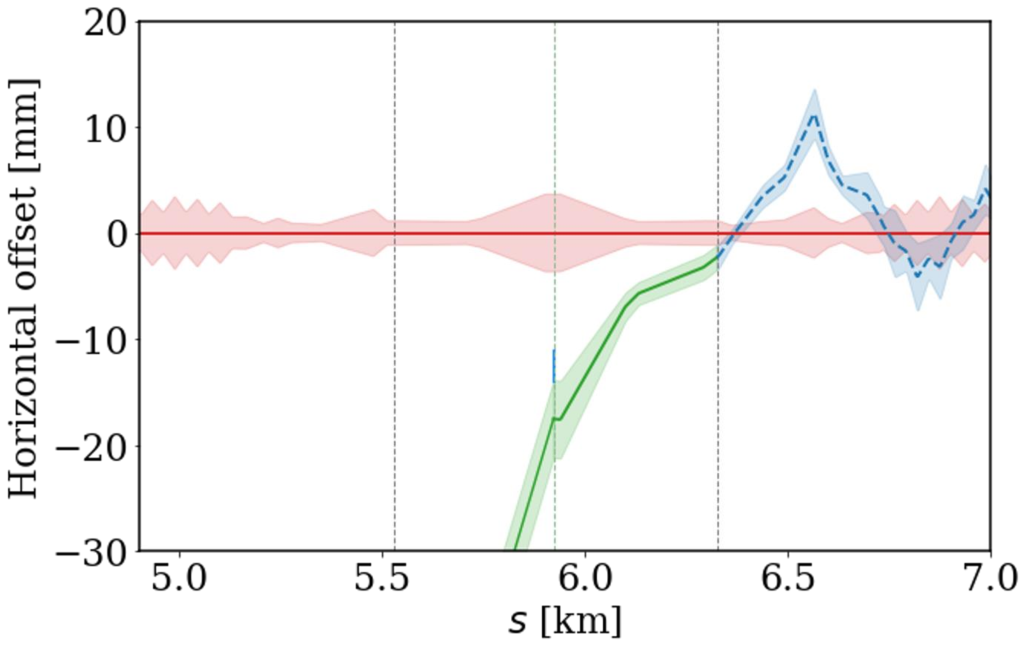
Fig. 1. ZS electrostatic septum used for SPS slow extraction

- R&D is needed to understand the breakdown probability as a function of voltage in presence of synchrotron radiation
  - Ongoing collaboration between CERN and University of Tartu (Estonia)
  - Hardware test planned at CERN using existing electric septum equipment

Operational considerations : Failure scenario

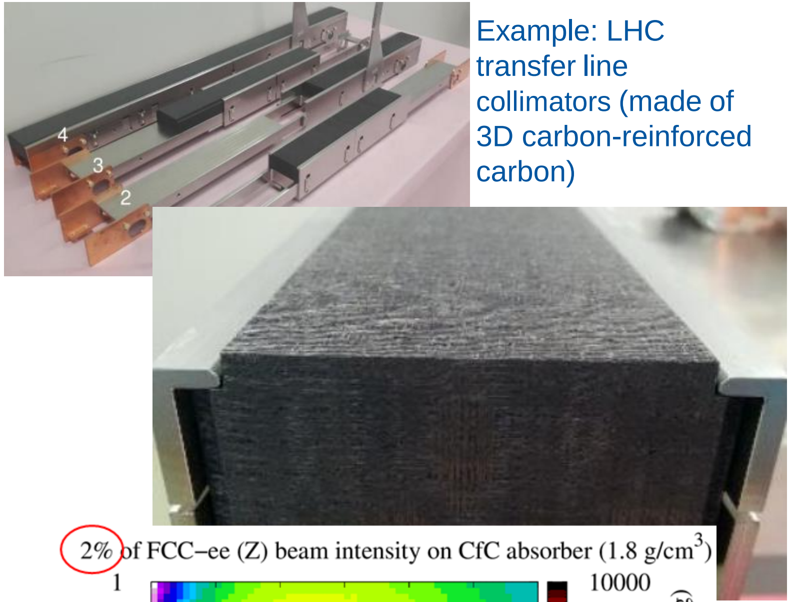
- Maximum injected beam energy is around 2 MJ
- Injection failures considerations
  - Kicker systems may spuriously kick the circulating beam
  - Injection septa may spark and miss the injected beam
- Systematic failure study of the different component of the injection system
- Local and global protection to ensure

Example of missing injection kick

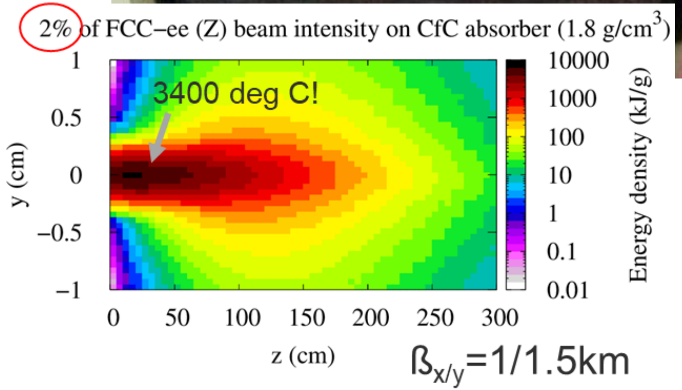


Operational considerations : Material challenges for injection protection

- Injection protection devices are essential for avoiding damage to the machine in case of injection failures
- Destructive potential of FCC-ee beams:
  - The stored beam energy in FCC-ee is much lower than in the LHC, but the beam brightness is much higher
  - There is no solid material, which can sustain the impact of a full FCC-ee injection train (=10% of beam intensity) on a single spot*
  - Even 2% of the beam intensity is expected to exceed the material limit of the most robust absorbers like graphite or carbon-reinforced carbon presently used in high-energy colliders
- A credible injection projection concept needs to be developed under consideration of the absorber robustness



Example: LHC transfer line collimators (made of 3D carbon-reinforced carbon)



*Even with β-functions as high as 1000 m

Conclusion

- A baseline scenario for top-up injection has been identified
  - Largely relies on demonstrated technologies
  - Ongoing R&D on electrostatic septa breakdown probability in the presence of synchrotron radiation
  - On-axis is a favored due to lower beam excursion and a more localized dump of the synchrotron radiation around IPs
  - Like for the LEP, the final design should allow switching between on- and off-axis injection
- The MKI is still under studies and the current injection region optics does not exclude it
- Next steps
  - Costing of hardware elements and ancillary systems
  - Review of the combined optics and merging with the main collider optics repository
  - Integration of beam transfer from the booster and extraction to the dumps for both rings
  - Realistic failure scenario and mitigation strategies which may constrain further the injection scheme

Thank you

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References

[1] 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.

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

[3] K. Andre, 161st FCC-ee Optics Meeting, link