CERN

FCCee booster
Injection and extraction concepts

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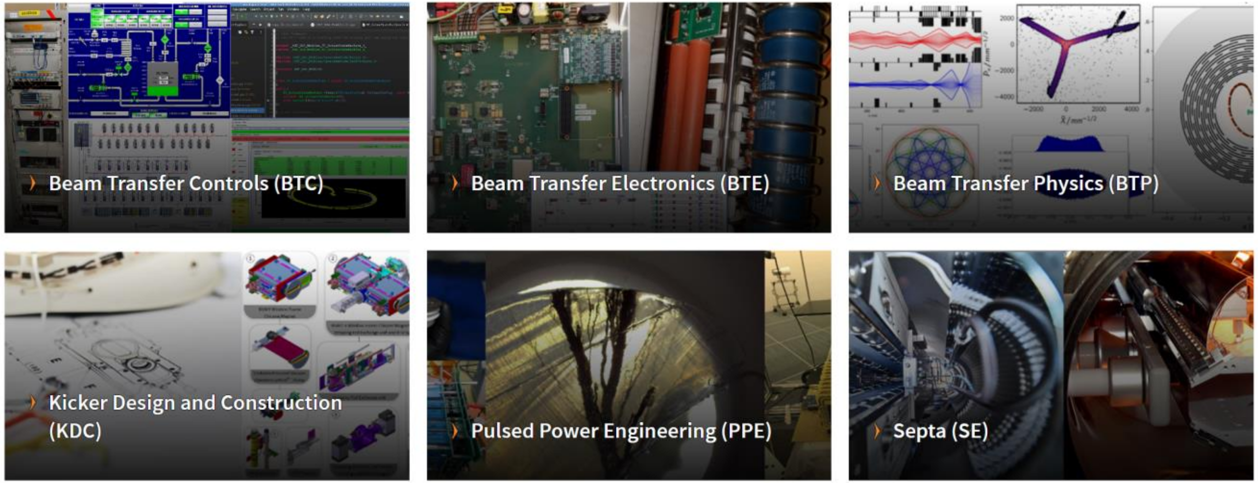
CERN ABT group and FCC

- The ABT group is in charge of the design, development, construction, installation, exploitation and maintenance of injection and extraction related equipment and beam-transfer systems
- Core FCC team of 15 experts
  - Representation of all expertise of the group from beam dynamics concept to hardware fabrication and control system
  - Regular meeting to review progress and follow the evolution of the various parameters

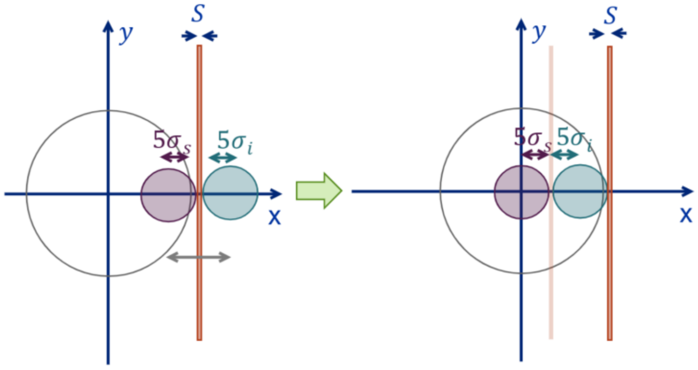


Outline

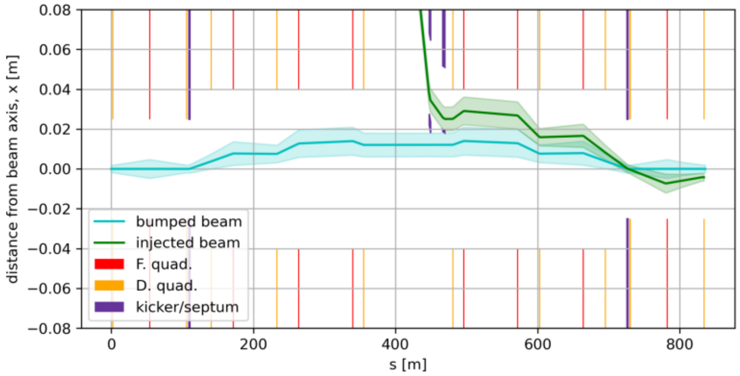
- Injection
  - Conventional off-axis scheme review
  - Review of possibilities
  - Layout and injection placement
  - Dedicated straight and in-arc concept
  - Fast injection CCW in-arc with optics and apertures
  - Hardware system
- Extraction
  - Layout and location
  - Hardware systems
  - Optics and aperture
- Update on collider top-up injection
- Conclusion

Injection: Conventional off-axis scheme review

- Conventional off-axis injection in horizontal
  - Established by E. Howling and R. Ramjiawan in 2022 [1]
  - Off-axis injection takes advantage of SR damping
  - Baseline scenario of the midterm review
- Flexible scheme
  - Uses one-turn closed bump in the horizontal plane
  - Initial concept used stripline kickers but reviewed to ferrite kickers due to power consumption
- Cons
  - Most fitted for top-up injection or when the kicker cannot rise and fall between bunches
  - Limited integration possibility with 200Hz injection as damping time ~10s



[1]



[1]

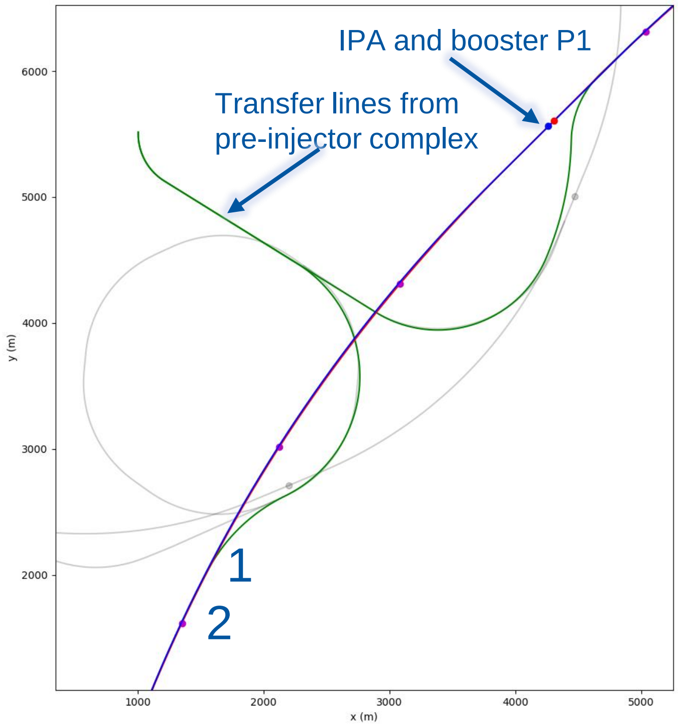
[1] E. Howling, Design Studies Towards the FCC-ee Booster Ring Injection and Extraction, 2022, cds
[2] R. Ramjiawan, FCC-ee e^+e^- Injection and Booster rRng, eeFact22, doi:10.18429

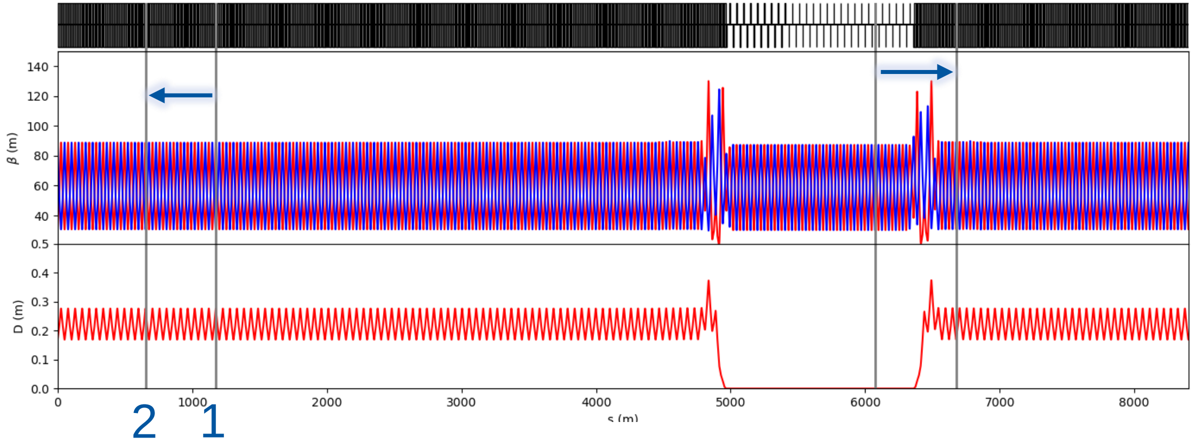
Injection: review of possibilities

- 2 possible beam structure
  - 16 GeV trains coming from the SPS (up to ~30 µs)
  - 20 GeV, 2 bunches coming from the HE linac
- Present discussion focuses on the HE linac beam parameters
  - 20 GeV beam
  - RMS normalized emittance of 10 µm
  - Bunch length ~1 mm
  - 2 bunches separated by 15 ns, and bunches every 15 ns in the booster ring
- Conventional bumped orbit injection
  - Not favorable due to the very long damping time and very frequent injections
- New proposal for fast injection scheme
  - Uses fast rise time and short flat-top stripline kicker
  - Hardware, layout and integration constraint to achieve a short rise&fall time kicker

Injection: placement and location

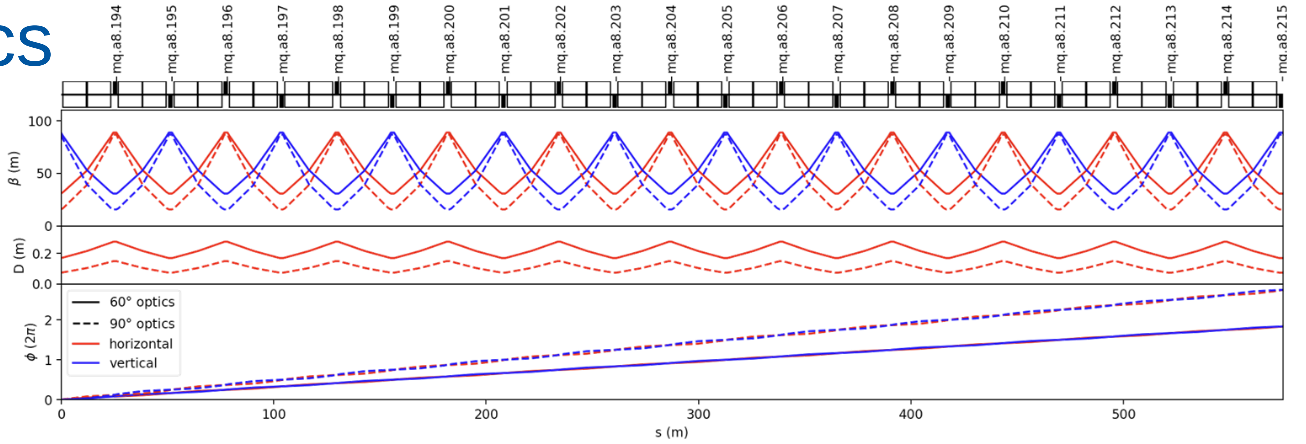
- Follows Wolfgang sitting of transferlines [1]
- Injection location moved downstream to the closest alcove (every 1.6km)
- CCW injection of positron in the arc towards P8
  - Present concept focuses on the CCW injection
- CW injection of electrons at the start of the arc towards P2





[1] W. Bartmann, Siting and transfer lines, FCCweek2023

Injection: arc optics



- 2 different optics
  - 60° for Z and W
  - 90° for H and tt

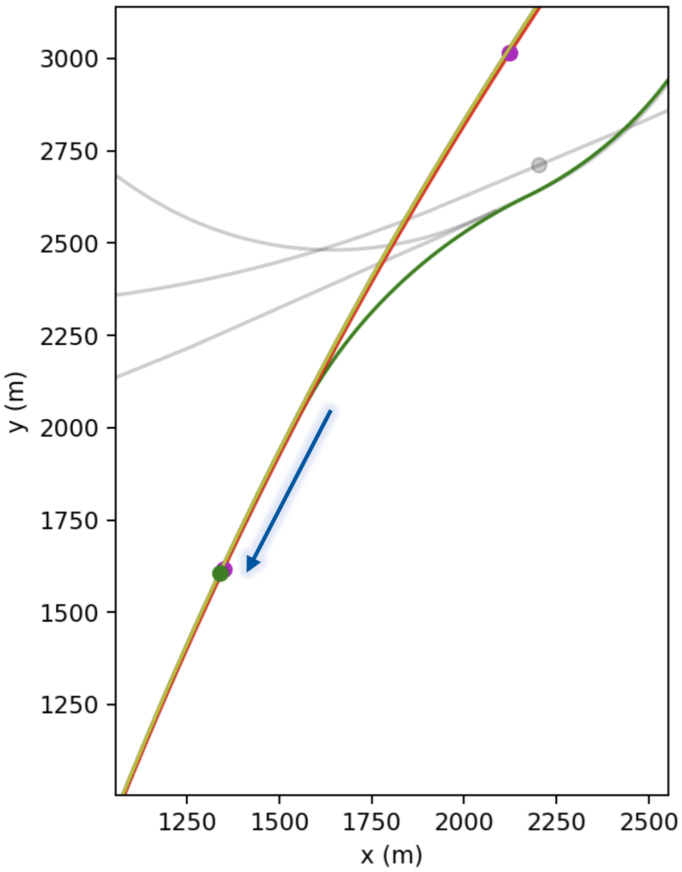
- 2 solution for injection design
  1. Use a dedicated straight section
     - Optics requires handling of the dispersion, cancelled or not
     - Trajectory requires stronger dipoles and causes transverse offset of the booster *wrt* to the collider
  2. Use the existing arc
     - Possible effects from the strong synchrotron radiation
     - Limited optics possibilities and unavoidable dispersion
     - Possibility to restore the reference optics after injection

Injection: dedicated straight

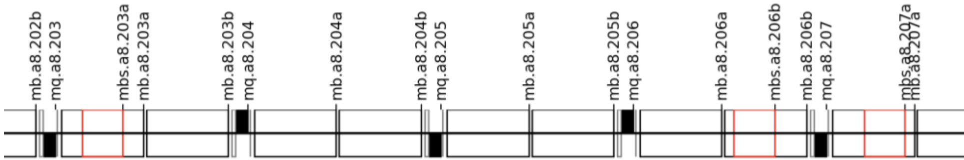
- Concept
  - With stronger dipoles on each side to open a gap, >100m
  - With additional quadrupoles to match Twiss parameters
- Pros
  - Without dipoles the introduction of injection element is simpler and apertures larger
  - May provide locally slightly lower radiation levels due to the straight booster
  - Possibly simpler optics adjustment between 60° and 90° lattices
- Cons
  - Larger dipole fields to maintain the same trajectory
  - Horizontal offset *wrt* to the collider

Injection: in-arc concept CCW

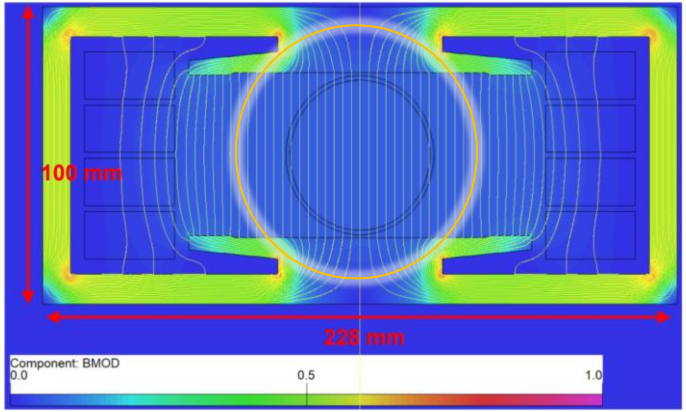
- Focus of this talk
- In-arc concept
  - Layout is modified to free space for the introduction of septa and kicker systems
  - Kicker system is sufficiently fast to rise and fall between bunches (<15 ns)
  - Minimal changes to the layout and optics
  - Vertical injection investigate here
- In-arc placement
  - Injection point chosen downstream of the transfer line merging with the collider tunnel, at the first alcove
  - An alcove is needed to house the pulsed power system near the magnet
- Pros
  - Minimizes the changes to the arc lattice and may restore the nominal optics after injection
- Cons
  - High radiation levels due to the booster SR
  - Constrained layout and apertures due to the presence of dipoles
  - Requires special dipole design



Injection: in-arc layout CCW



- Layout
  - Injection from the right to the left
  - Septum in position 206
    Kicker in position 203
- New dipole type
  - Magnet with half length and same angle as nominal (~1 mrad)
  - Larger vertical aperture (50 mm -> 70 mm)
- Extraction channel for quadrupole in 207
- Kicker position
  - Dipole 203a
  - Short dipole placed in the center of the long one -> no change of the trajectory
- Septa positions
  - Dipoles 206b & 207a
  - Short dipoles symmetric placement around quadrupole 207 -> no change of the trajectory



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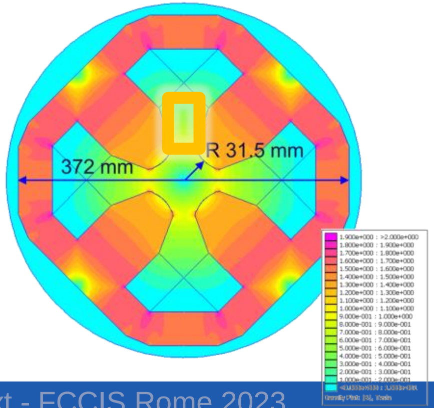
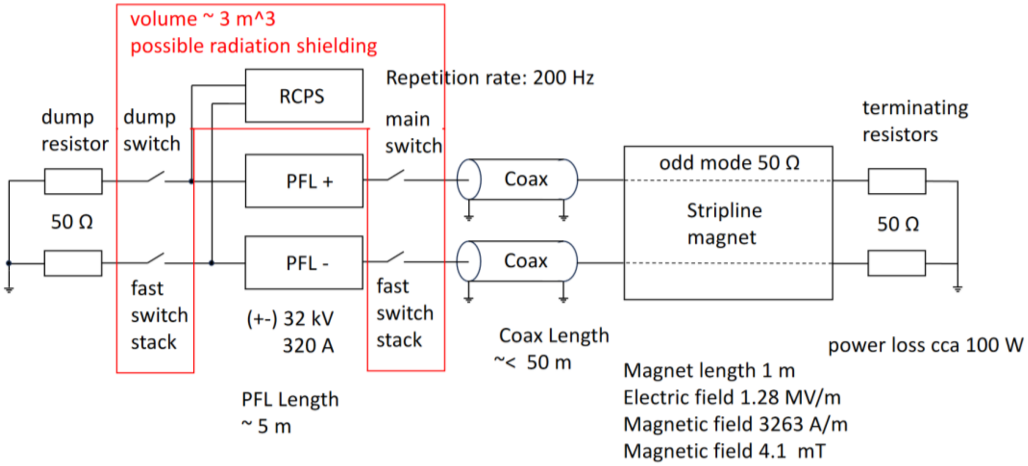


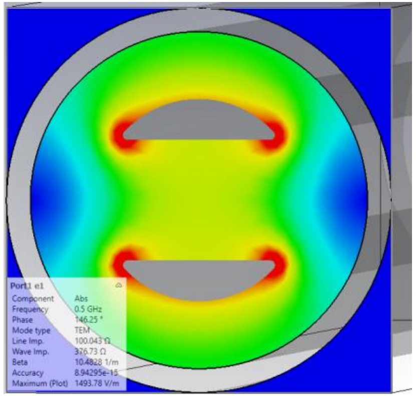
[1] C.J. Erikson et. Al, Status of the FCC-ee booster and collider magnet developments, FCCweek 2023

Injection: kicker hardware system

Courtesy P. Martinek

- Specifications
  - Provide up to 100 μrad deflection at 20 GeV
  - Fast rise and fall time <15 ns
- Proposed system
  - Pulse forming line for energy storage
  - High voltage power supply for fast recharge between injections
- Constraints
  - Generator has to be placed close to the magnet
  - Switches are sensitive to radiation





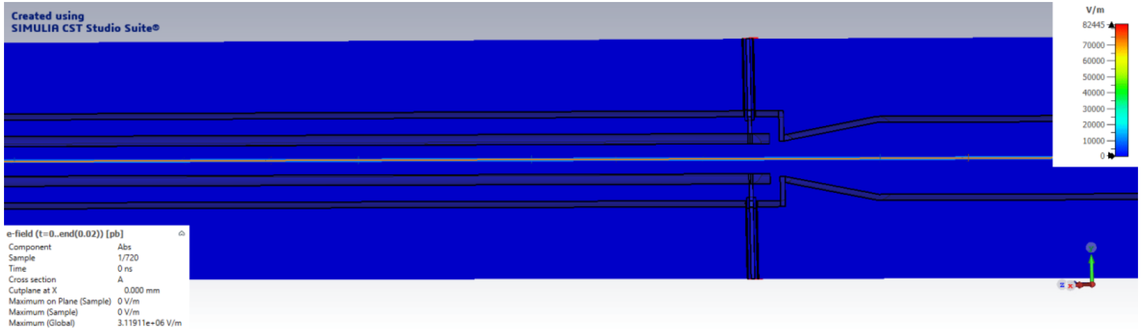
Half-moon electrodes

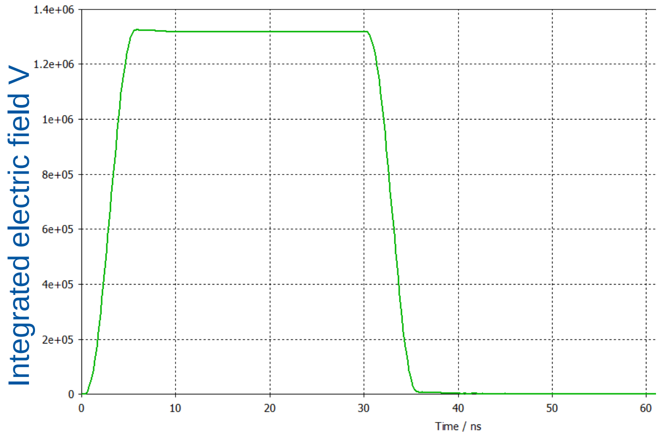
Injection: stripline kicker simulation

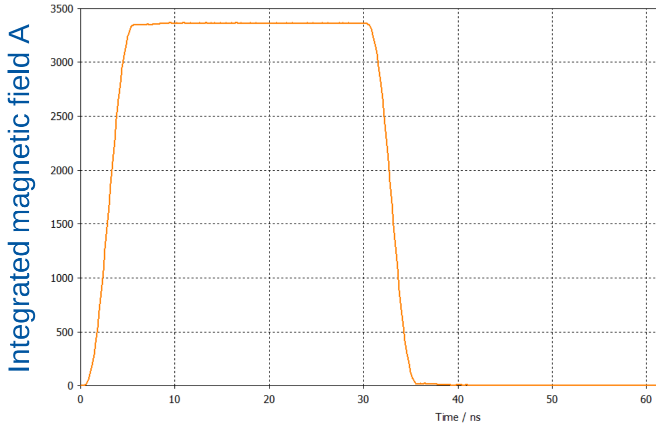
Courtesy P. Martinek

- From the graphs of the integrated magnetic and electric field, it is possible to verify the performance of the design

- It is also possible to determine the rise and fall times of the entire magnet. Parasitic parameters of the pulse generator and cables are not included in the rise and fall time on the graph. The real value of the rise time will be greater.



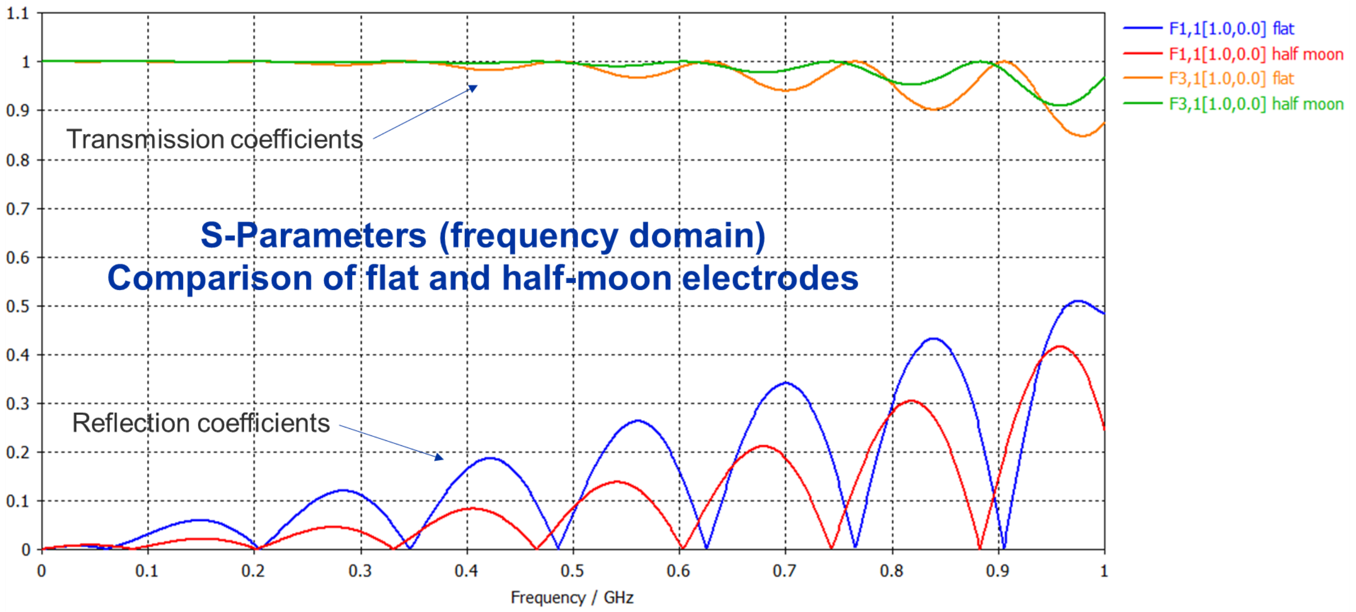




Injection: stripline kicker simulation

Courtesy P. Martinek

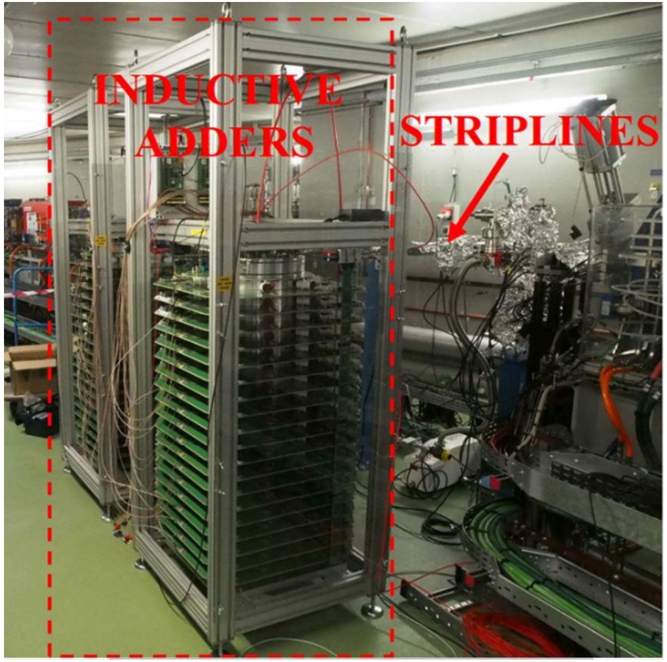
- simulation of the electric field in the time domain in the kicker magnet booster injection



Injection: stripline kicker experience at CERN

Courtesy M. Barnes

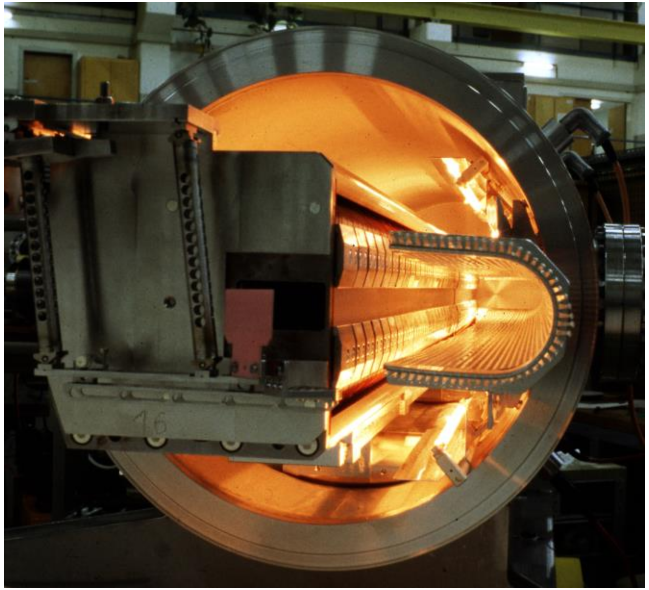
- No stripline kickers presently used at CERN
  - 4 sets of striplines were (historically) installed in CTF3 with 5 ns rise time
- Pulsed power technology is used for every system



[1] C. Belver Aguilar, Development of Stripline Kickers, cds
[2] I. Rodriguez Garcia, Calculation methodology and fabrication procedures for particle accelerators strip-line kickers, cds

Injection: Septum hardware system

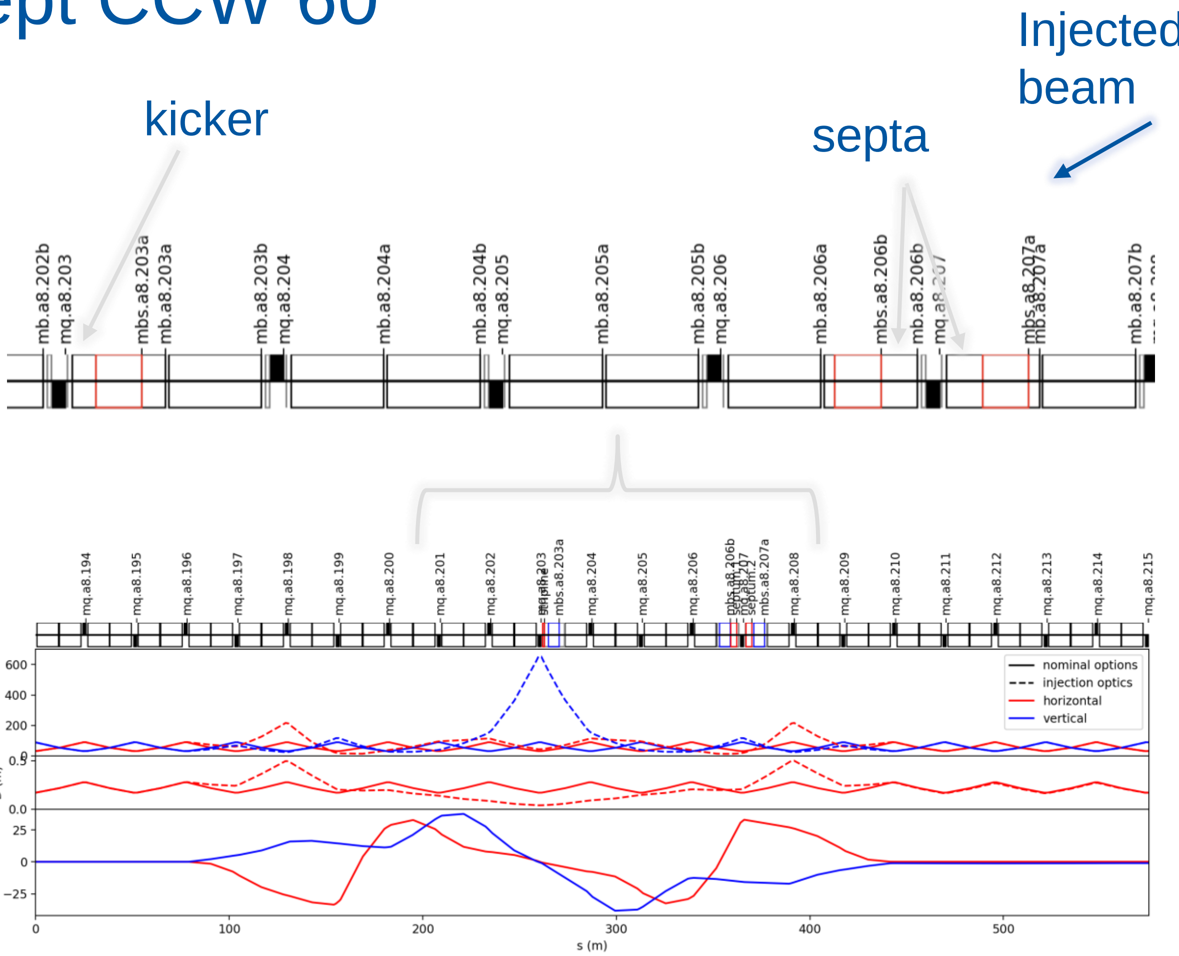
- Specifications
  - 10 mm blade thickness
  - Injection at 200Hz for up to ~30s, followed by ~30s without beam
  - Field of 0.1T
- Operation
  - Motorised but fixed once setup
  - DC operation during injection



PS extraction septum for up to 26 GeV protons (courtesy J. Borburgh, SY-ABT-SE)

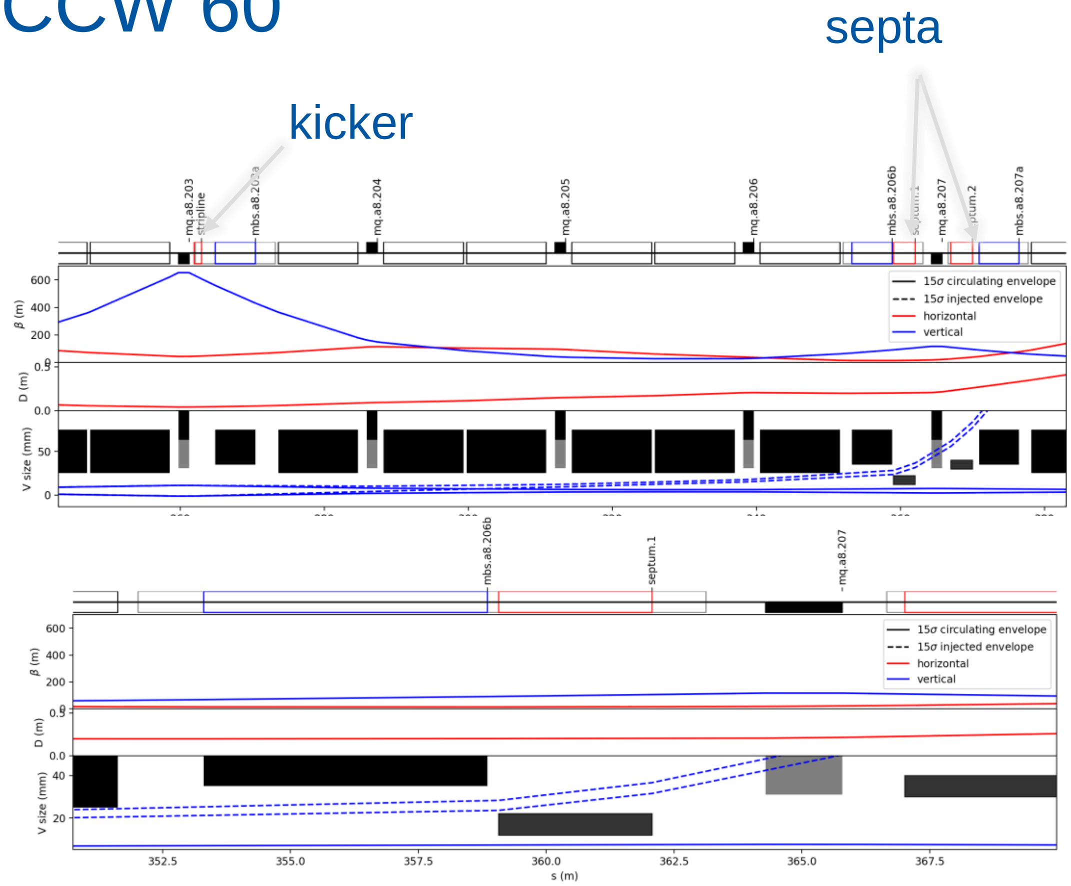
Injection: in-arc concept CCW 60°

- Symmetric quadrupole powering with 8 independent supplies
- Exact matching of twiss parameters and phase advance
- Vertical injection
- New dipole type with same angle and half length from nominal
  - 3 dipoles replaced by shorter version with slightly larger vertical aperture
  - Very small mismatch due to the asymmetric dipole changes



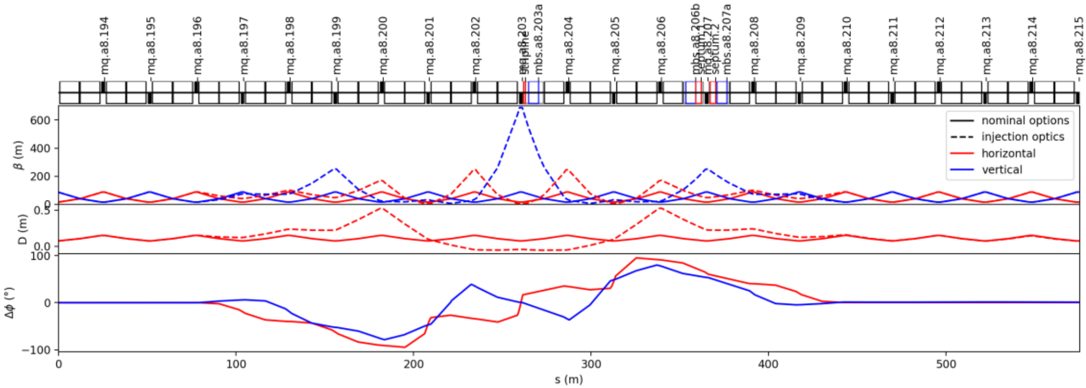
Injection: in-arc concept CCW 60°

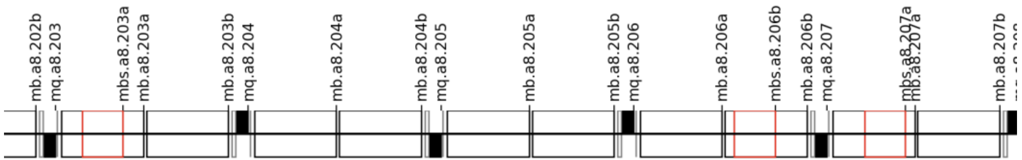
- Settings
  - Kicker angle of 90 urad
  - Septum angles of 4.5 mrad each
- Envelopes and apertures
  - Circulating beam closed orbit bumped by 5 mm
  - Septum blade located 12 mm from the circulating beam
  - Concept preserve large apertures for injected and circulating beams



Injection: in-arc concept CCW 90°

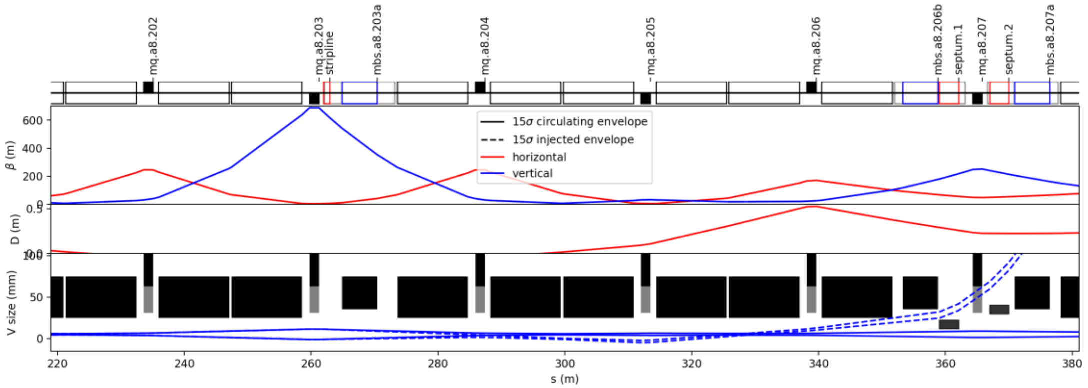
- Symmetric quadrupole powering with 8 independent supplies
- Exact matching of twiss parameters and phase advance
- Vertical injection
- Same elements at the same locations as for 60° optics
  - Different optics settings but similar scheme

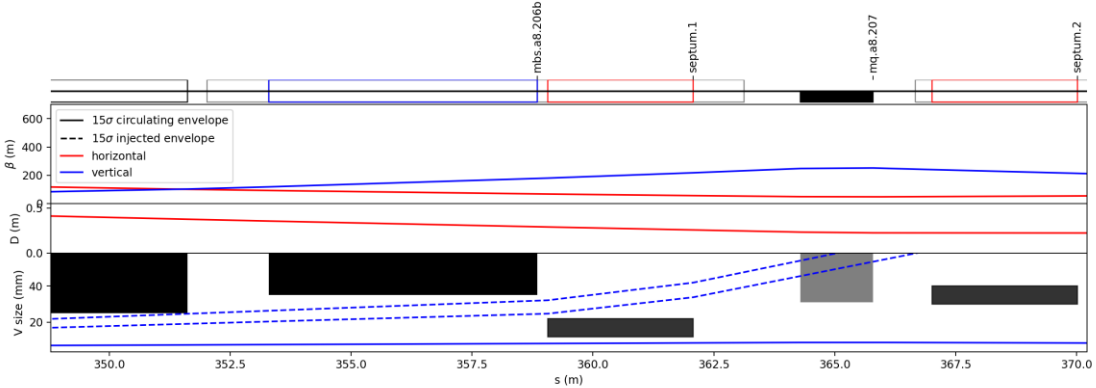




Injection: in-arc concept CCW 90°

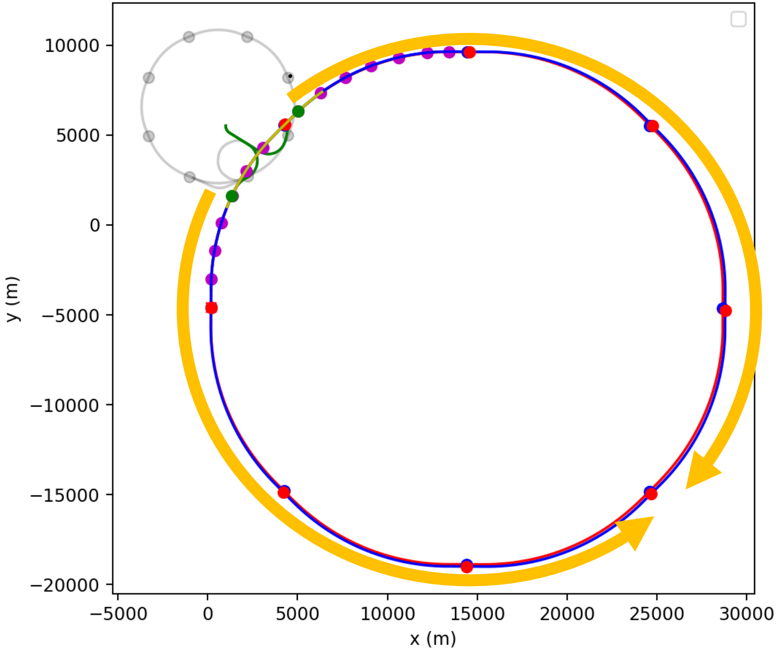
- Settings
  - Kicker angle of -90 μrad
  - Septum angles of 4.5 mrad each
- Envelopes and apertures
  - Circulating beam closed orbit bumped by 5 mm
  - Concept preserve large apertures for injected and circulating beams





Injection: non-local concept

- Further concept with injection and septum where the transfer lines reaches the collider tunnel
- Single kicker in one of the straight sections
  - Electrons and positrons oscillate
- Pros
  - Only one kicker system, located in a straight section
  - More flexible placement of the kicker and its generator
  - Lower radiation level
- Cons
  - Requires large aperture along the whole ring



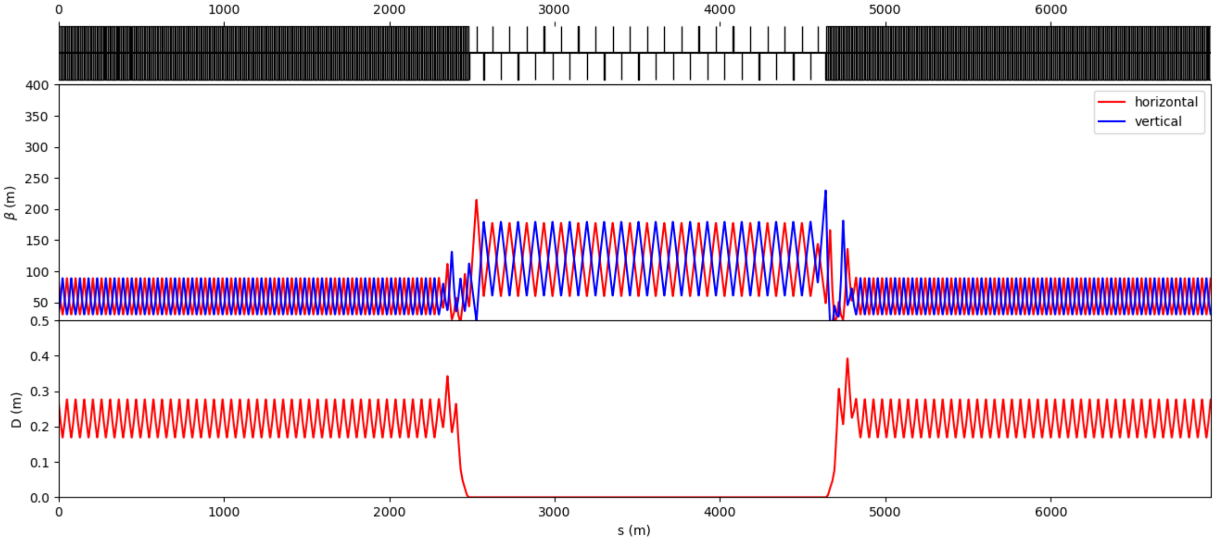
Injection: conclusion

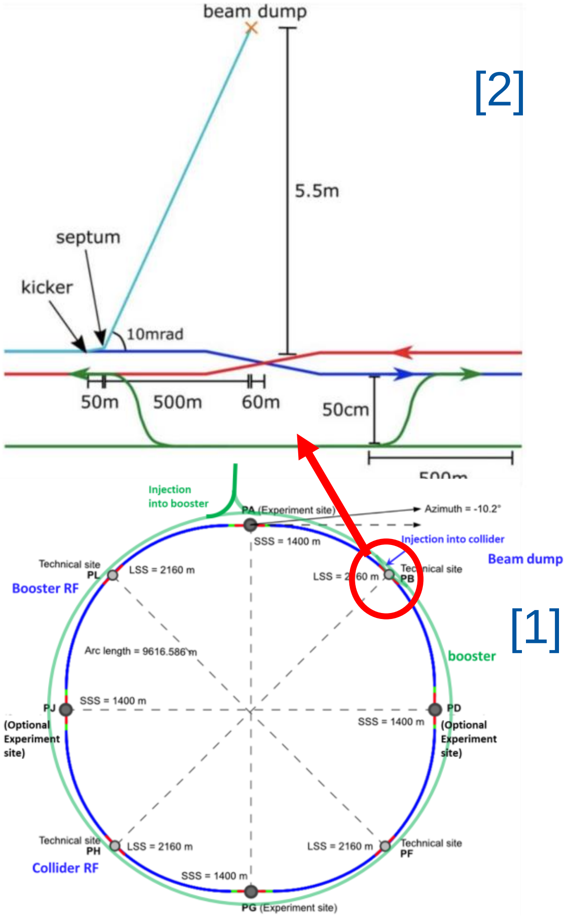
- The off-axis injection concept is no longer favored
- The baseline scheme uses fast injection of bunch pairs coming from the linac
- In-arc injection concept
  - Present design seems feasible
  - Completion of the scheme is pending discussion with magnet experts and lattice design
- Hardware system
  - Septa systems do not seem to present any specific challenges
  - Stripline kicker hardware is conceptually simple but may benefit from prototyping
  - 200 Hz operation seems feasible but hardware and controls could be prototyped
- Controls
  - 200 Hz operation may require to consider fast interlocking
- Challenges and next step
  - Finalise a baseline scheme (in-arc dedicated straight, in-arc local, non-local)
  - Review of the optics and injection elements impedance with the ring design team
  - Review harwared placement and potential radiation effect, in particular on HV cables

Extraction: placement and location

Courtesy S. Yue

- Booster extraction point located at the straight section of P2 (IPB) both for electron and positron
- Also containing collider injection and extraction
- Beam will be injected to collider ring via on axis injection

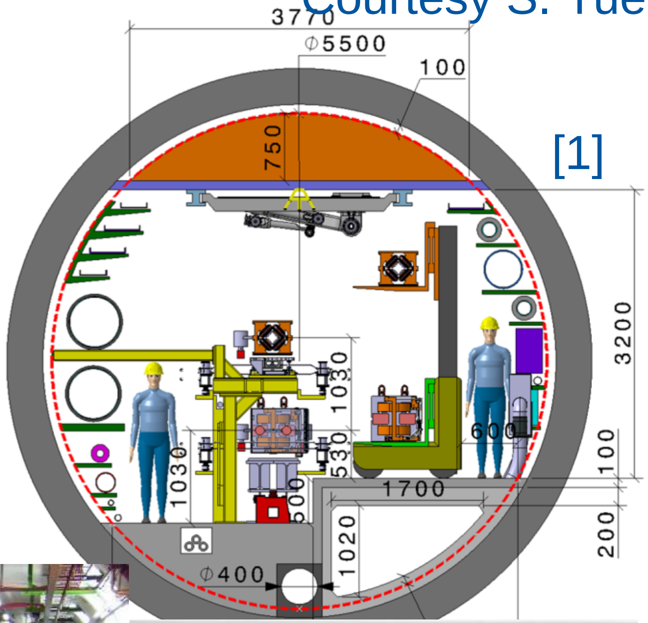




Extraction: hardware system

Courtesy S. Yue

- Ferrite kicker
  - Deflection angle: 0.143 mrad,
  - Rise & fall time: 1 μs, flattop: 304 μs, repetition rate ~ 0.1Hz
  - Length of 2 m
  - 2 modules on each side, 4 in total
- Septa
  - Deflection angle: 2 mrad
  - Thickness of 10 mm
  - Length of 2 m
  - 8 modules in total



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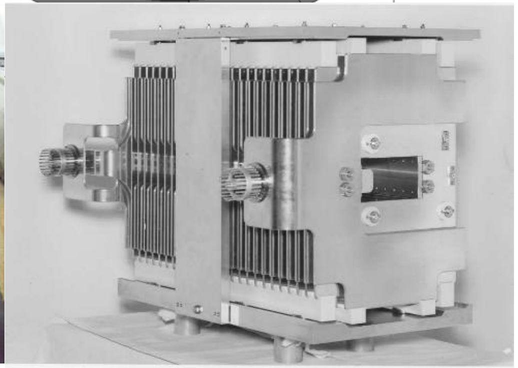
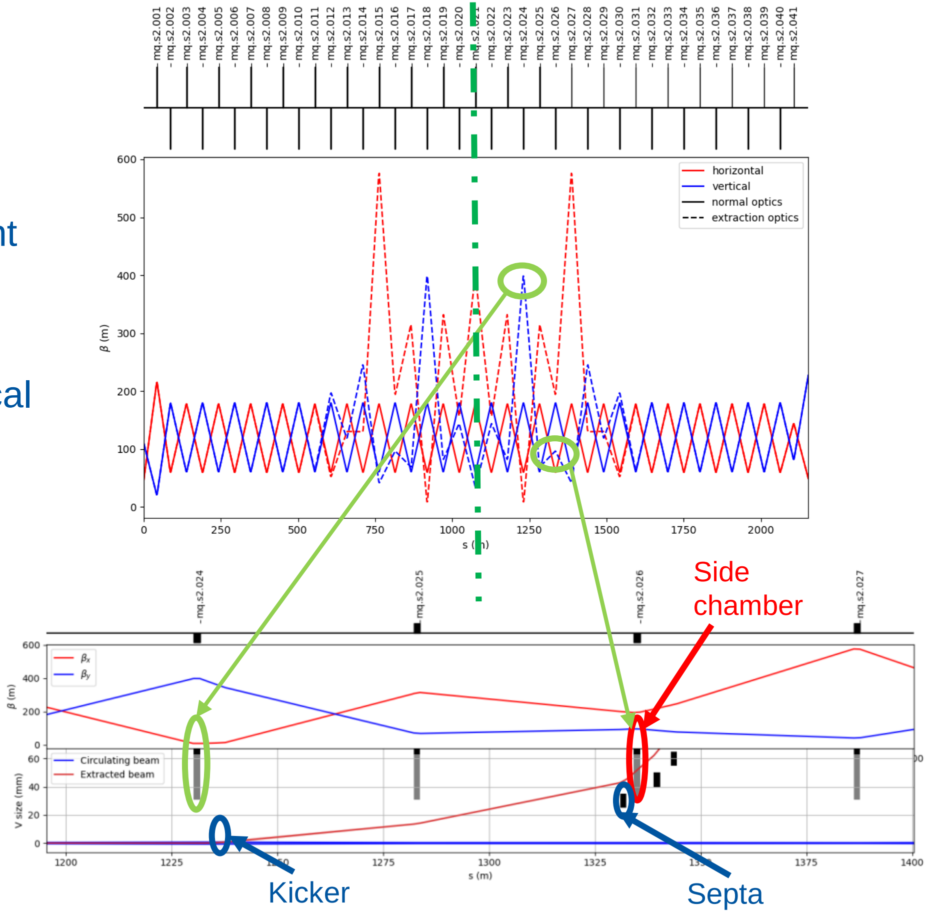


[2]

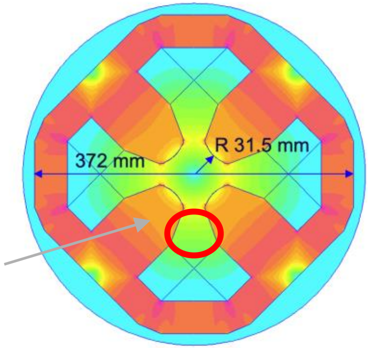
Extraction: optics and beam envelope for Z mode

Courtesy S. Yue

- Vertical extraction scheme
- Considering a vertical emittance of 100x the design one (0.53 pm×100)
- Concept
  - Symmetric quadrupole powering with 8 independent supplies
  - Vertical extraction: distance between booster and collider ring is 1030 mm
  - Beam offset 43mm: can be extracted through vertical focusing quadrupole
  - Smallest distance between septa and circulating beam: 25 mm



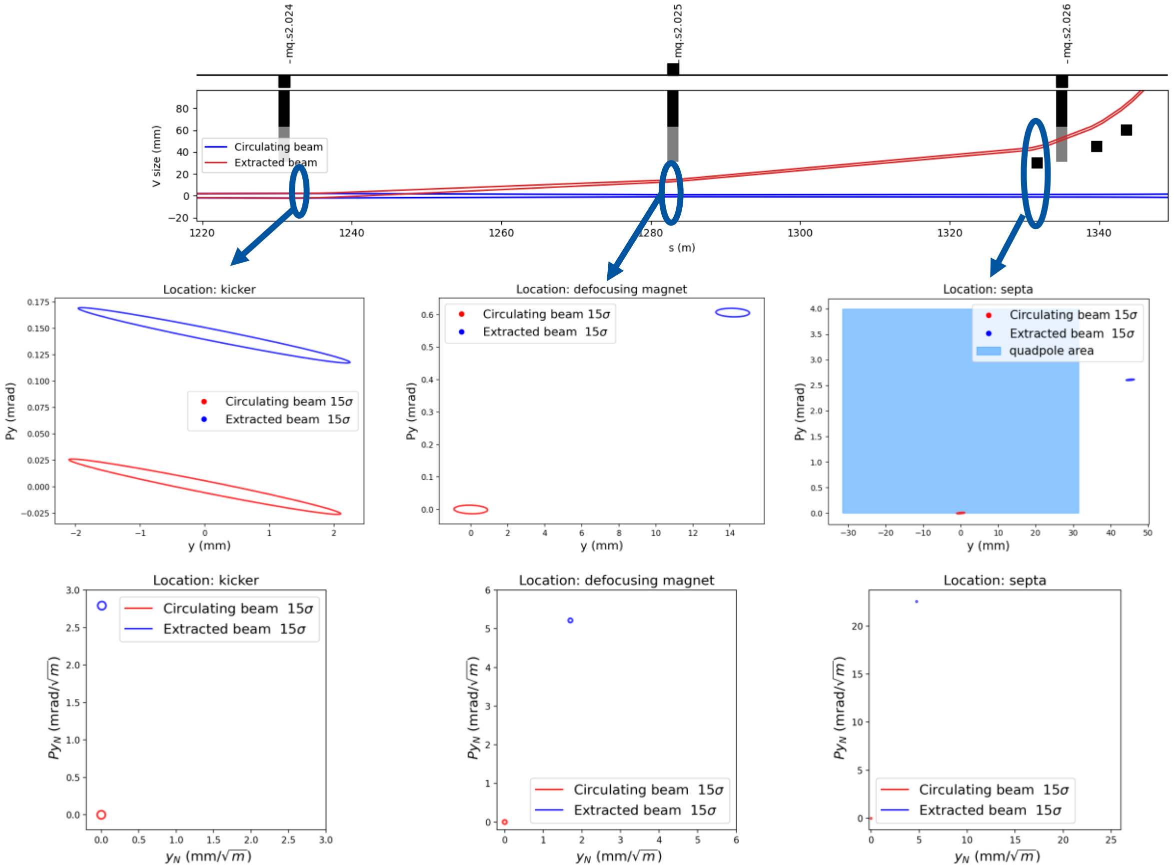
Vacuum chamber for extracted beam



Extraction: phase space

Courtesy S. Yue

- Phase space at
  1. Kicker
  2. Septa
  3. Defocusing quadrupole
- Vertical emittance:
  - ϵ_y= 0.53 pm×100
- Sufficient space for extraction with a 10 mm septum

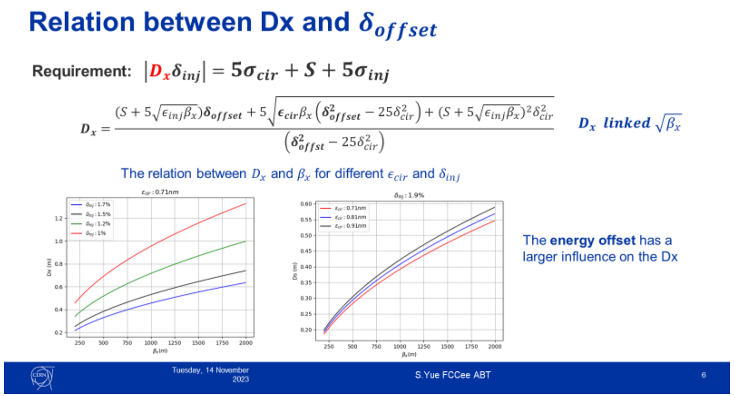


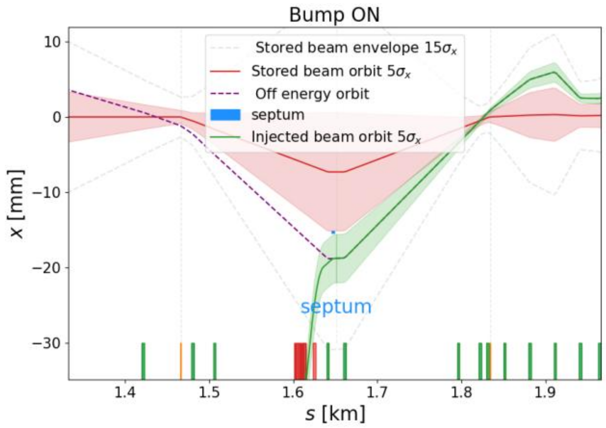
ExtractionS: conclusion

- Extraction to collider
  - Fast extraction with kicker and septum
  - Large available apertures due to the very small beam size
  - Machine protection
    - The present maximum intensity (10% of the maximum collider intensity) cannot be safely intercepted in case of injection failure due to the small beam size
    - May require to be split in several extraction, separated by a short duration
  - Further optimisation of the scheme may see a reduction of the required kick angle
  - Review of the optics with the latest version of the booster lattice
- Extraction to dump
  - A dump system to safely extract the beam from the booster is necessary
  - Requires to follow the energy of the booster beam
  - Need fast reaction and complete discarding of the circulating beam
  - Active and passible protection elements may require to place the system at another straight section
  - Similar magnet hardware to extraction of collider can be used

Update on collider injection scheme

- Baseline is on-axis injection with 1.1% energy offset
- Presented the FCCee beam transfer meeting by S. Yue (SY-ABT) here
- MR and new branch on the collider optics repo
  - M. Hofer first result on the influence of injection region optics seem
- Next steps
  - Adding extraction (dump) optics to the PB straight
  - Optimisation framework for adding some off-axis (limits established by K. Andre here due to SR power deposition around IRs by the as a function of the injected beamlet transverse offset)
  - Review of SR losses and effect on the thin electrostatic septum
  - Review of the injection scheme and its failure cases with SY-STI





Conclusion

- Injection
  - Reviewed from the mid-term concept to a fast injection scheme
  - Hardware system concept may be adapted for SPS trains (~30 µs)
  - High levels of radiation need careful consideration
- Extraction
  - Fast extraction in PB straight to the collider
  - Fast extraction on PB or PF to the booster dump
- Hardware systems
  - 200 Hz operation at injection is challenging, for control and pulsed power systems
  - Realistic radiation and SR environment have to be considered for the placement of elements but also for controls and pulsed power systems
  - Making use of established technologies, developments are required but no show-stoppers have been identified
  - Radiation is a big concern for equipment
  - The use of hot-spares should be considered against multi-days intervention times
- Machine protection
  - Main concern for extraction system and transfer to the collider ring
  - Machine protection consideration need to be included at the concept stage with lattice design, injection systems and STI experts together
  - Split extraction from the booster, for instance 10x30 µs trains, should be possible but requires developements
- Next steps
  - Review of the optics and adapt, the concepts showed here use 2022 booster optics
  - Review the impedance of beam transfer elements

Thank you