TRANSVERSE FEEDBACK SYSTEM FOR FCC-EE

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Acknowledgements:
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Epol WG

FCCee collider and booster transverse feedback systems

Key requirements

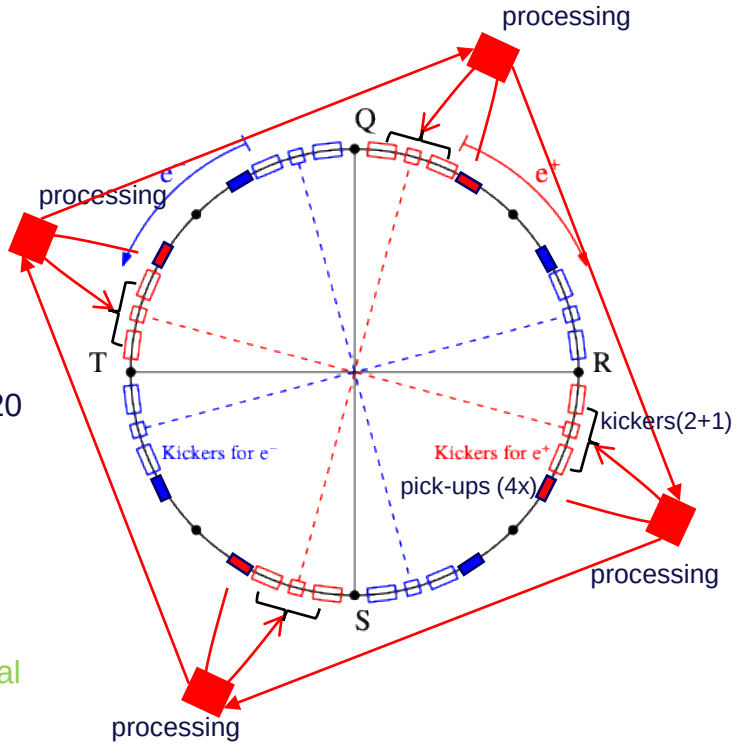
- need bunch-by-bunch operation at 25 ns bunch spacing → defines bandwidth
- can operate at multiple of bunch repetition frequency (short bunches) → no need to work in "base-band" as in LHC → helps as it reduces *relative* bandwidth
- sets of RF matched strip-lines with carefully chosen length as kickers seem obvious choice
- Booster:
  - request to also operate to damp a significant transverse injection error → defines maximum kick requirements
    - needs estimate of injection errors, filamentation time, … to define system
  - moderate damping times only for instabilities (not beyond experience from LHC)
  - single location in ring sufficient, but also resonant depolarizer function if polarized beams are injected
- Collider:
  - need to damp very fast transverse instabilities → four turns risetime, high gain system
    - favors distributed system with multiple pick-ups and kickers
    - possibility of synergy with exciter for resonant depolarization (as in LEP)

Recapitulation

- FCC-ee requires a coupled bunch transverse feedback system
- fast rise times of the instability of 4 turns caused by the resistive wall impedance are predicted for the lowest order coupled bunch modes, see M. Miglorati (FCC week 2025)
- requires shortest possible latency (1-2 turns), short latency ensures transverse FB disentabled from orbit FB
  - use several pick-ups for “spacial sampling”, see D. Teytelman (FCC week 2024)
  - notch filter for closed orbit supression
  - distributed kicker system for possibly feeding back low frequency mode with less than 1 turn delay, see A. Drago (FCC week 2018)
- lowest betatron frequency can be as low as 500 Hz for a tune fractional tune of 0.15
  - the feedback system should cover all unstable modes, i. e. frequencies up to half the bunch repetition frequency → 20 MHz bandwidth for baseline 25 ns bunch spacing
  - when introducing shorter bunch spacings (5 ns) at least a few feedback kickers are needed to cover frequencies up to 100 MHz, the mixed scheme proposed for electron cloud mitigation needs further scrutiny on how the bunches oscillate, and simulations with realistic feedback

Distributed feedback system

- distrubuted system with four-fold symmetry
- kickers and pick-ups installed at on out-going beam at start of arc
- points “Q,R,S,T” can be either experimental points or technical points
- three kickers per point and beam (12 per beam, 24 total)
  - two strong kickers (also main depolarizer bump kickers)
  - one shorter kicker (polarizer bump correction)
    - can have a higher frequency reach (100 MHz)
- four pick-ups per point and beam (16 per beam, 32 total)
  - spacial sampling, i.e. betatron phase advance between pick-ups 60-120 degrees, covering one period of betatron oscillation
  - pick-ups down stream of kickers (immediate monitoring of system malfunction)
- low latency data links connecting the four processing nodes per beam
  - simulations needed to determine what processing will provide additional damping to the low order coupled bunch modes using these links

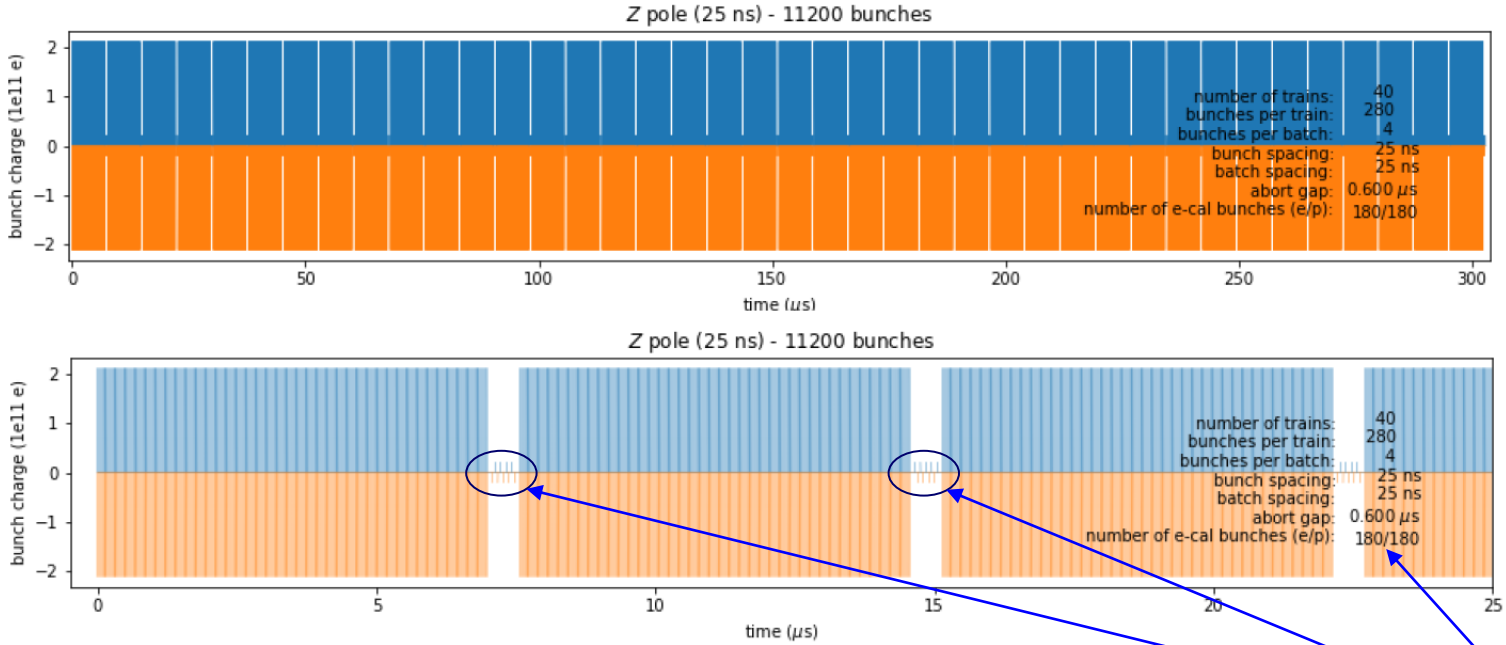


Depolarizer kickers and transverse feedback

Possible synergies with transverse feedback kickers

- due to similar requirements for bandwidth synergy between the needed kickers for the transverse feedback and the depolarizer have been explored
- long, *O*(m), stripline kickers operating at a multiple of the bunch repetition frequency offer good RF power efficiency and sufficient bandwidth
- differences in requirements between transverse feedback and depolarizer kickers are
  - depolarizer kicker only needed for vertical kicks, transverse feedback also for horizontal plane kicks
  - implementation of depolarizer excitation as a modulated local orbit bump requires one or several sets of pairs of kickers with bending magnets in between
    - no perturbation on experimental points permitted, recommended to have a tuning possibility with a third kicker per set of kickers
  - kick strength required for depolarizer is high (10 μrad) and adequate protection is needed to prevent acting on Physics bunches (loss of synchronisation with gaps)

Filling pattern Z-pole – update of 2024



H. Bartosik, FCC week 2024
(new alternate filling schemes with short trains of 5 ns spaced bunches need study)

Collider filling pattern for whole ring and zoom

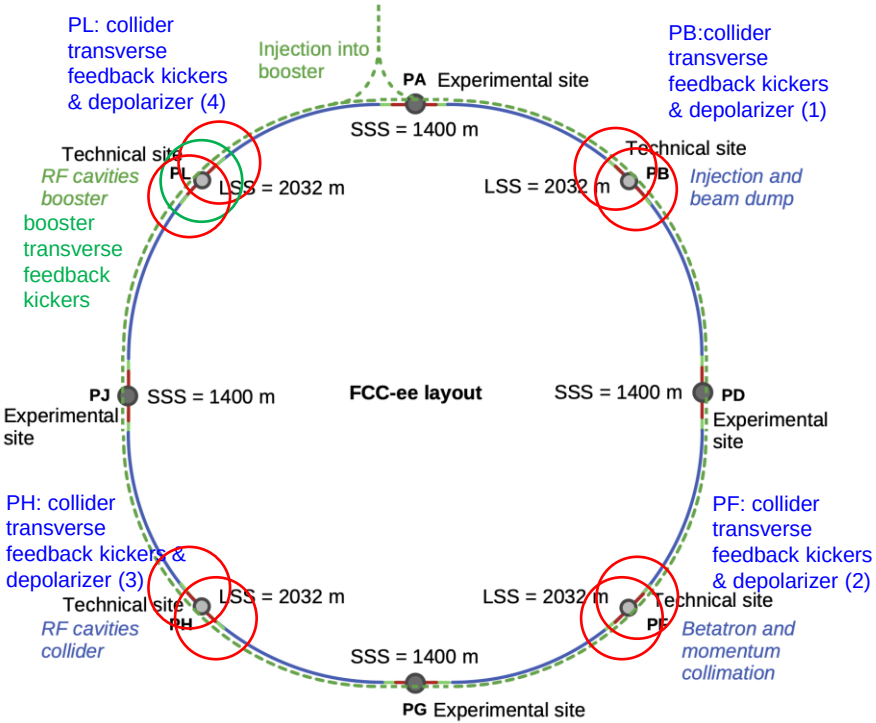
e-cal bunches of at least one gap are affected by injection bump risetime, so effectively 175 (one beam), 176 (the other beam) useful bunches at maximum

FCCee collider needs depolarizer kicker

Basic functional requirements (for operation at Z and WW energies)

- For resonant depolarization powerful transverse electromagnetic kickers are needed in FCC-ee that provide vertical kicks with fields that can be modulated to target witness bunches placed in gaps between the trains of bunches used for Physics
  - Z-pole: number of gaps between bunch trains recently increased from 20 to 40
    - option 1: leaving one gap reserved for injection bump risetime
      - 175 bunches of one type and 176 bunches of the other type in 39 gaps
    - option 2: leaving four gaps reserved for injection bump risetime
      - 162 bunches of each type can be fitted in the 36 gaps available
    - witness bunches have a spacing of 100 ns with bunches from the other beam in the matching gaps being shifted by 50 ns in order not to collide in the experiments
    - the 100 ns spacing is needed to be able to target them individually with the suggested depolarizer kicker (due to its bandwidth limitation)
  - for Physics bunches the same type of kicker system can be used to continuously or on demand shake the beam to prevent polarization build-up

Considerations for placement in ring



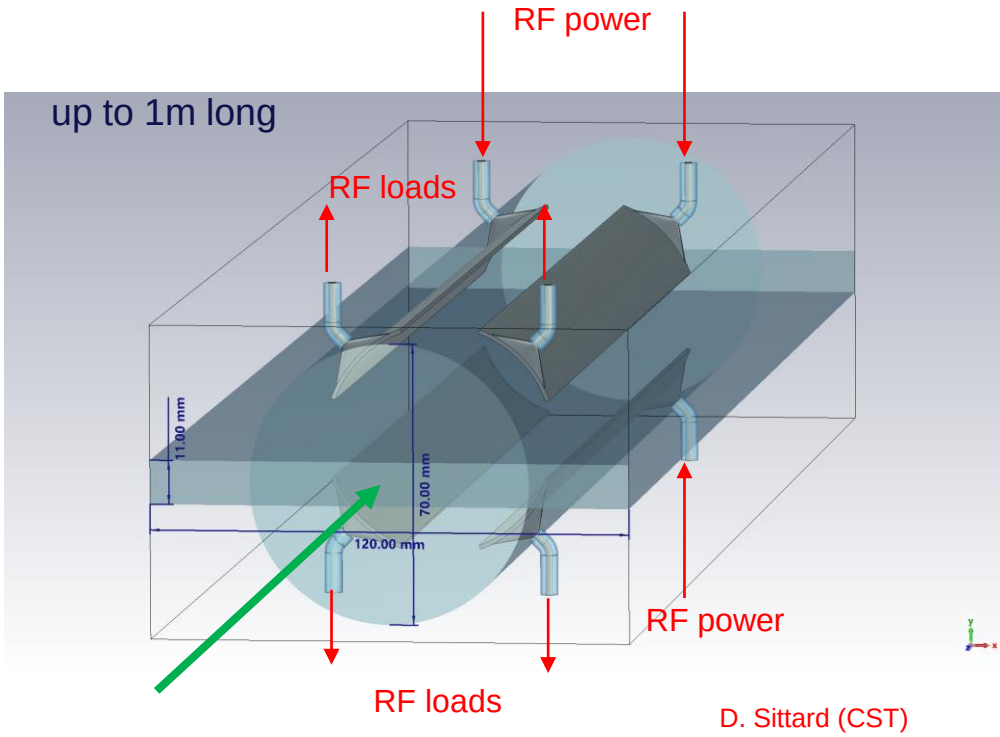
Update 2025:

- from the technical sites the straight sections where RF is located, offer advantages but space is an issue (in collider), and so are the large diameter beam pipes between cavities
  - PL: booster RF → space available (?)
  - PH: collider RF → many collider cavities, hardly any space left in tunnel
- experimental sites (PA, PG, PD, PJ)
  - spaces to be considered:
    - return arc (optics not really suited)
    - regular arc, out-going beam
- technical sites (PB, PF, PH, PL) now preferred
    - regular arc, out-going beam

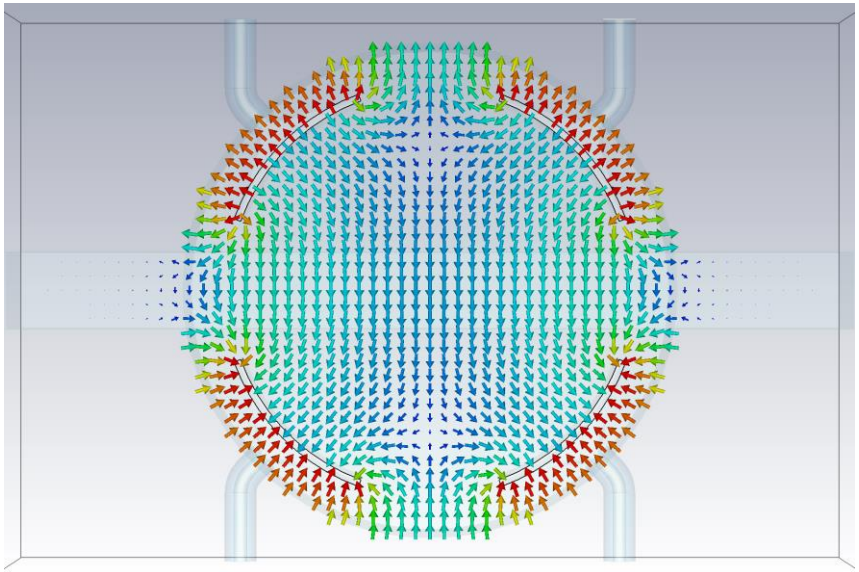
Stripline kicker: arc compatible version (1st version)

Characteristics (good for transverse feedback, but too low shunt impedance for depolarizer with arc compatible diameter)

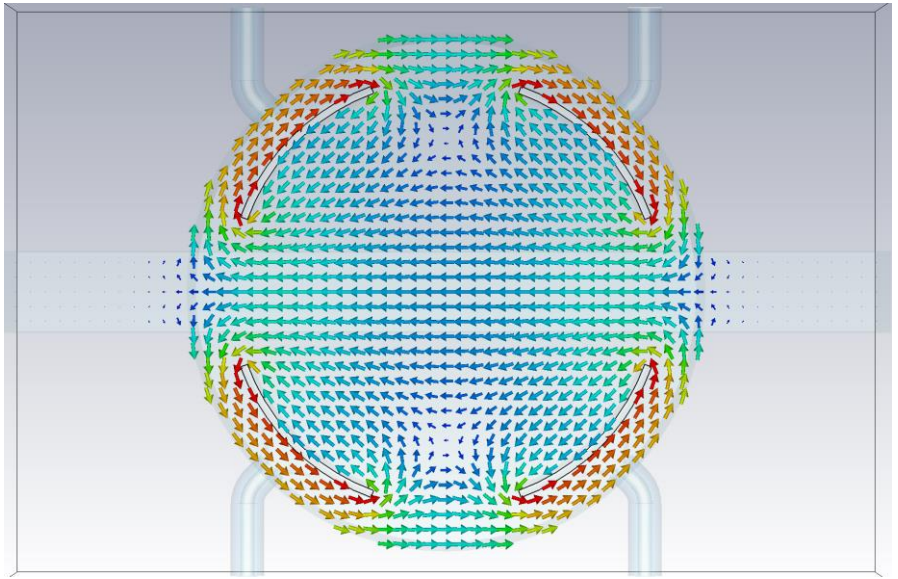
- four electrodes arranged at 45 degrees
- leaves horizontal plane free for synchrotron radiation absorbers similar as for BPM designs
- compatible with vacuum chamber diameters of 60-70 mm foreseen for arcs (initial proposal)
- small diameter also desirable for increased shunt impedance, but matching to 50 Ohm must be considered for both differential mode and common mode
- universal design that can be powered to provide vertical or horizontal kicks, even simultaneously, power can be directed to plane that needs high level kicks
- device is a backward coupler, powered at beam downstream ports and terminated at upstream ports
- action on beam provided in equal parts from magnetic and electric fields
- length can be adjusted to match actual needs for bandwidth
- total kick strength provided by set of kickers, placed at the appropriate phase advance / optics as needed



Stripline kicker: field plots (70 mm chamber)



Electric field (vertical)



Magnetic field field (horizontal)

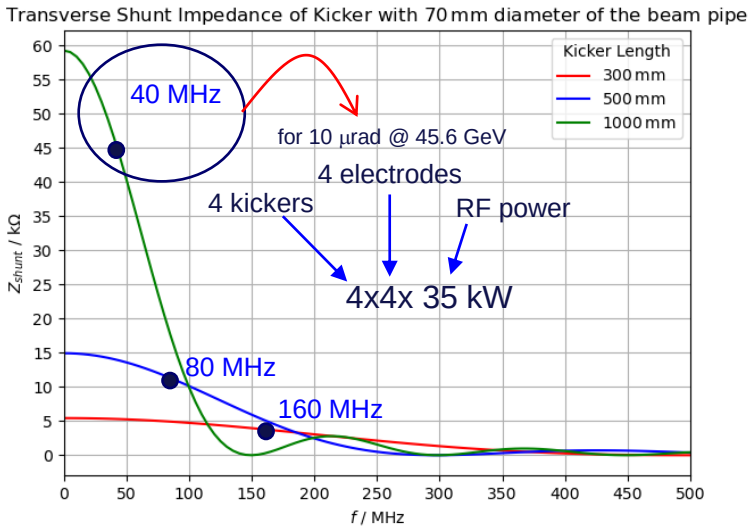
D. Sittard

- vertical kick evenly split between electric and magnetic fields
- optimization is planned to start this year (beam impedance, details of the design compatible with short bunch length …)

Shunt impedance kicker (four electrode version)

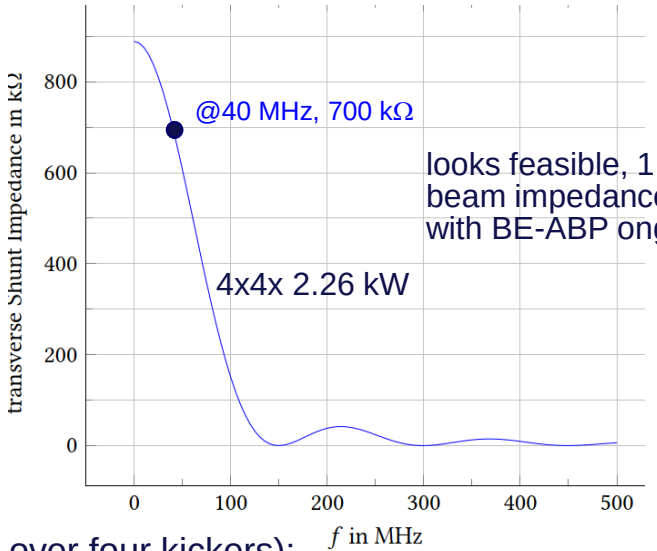
Adaptation of length to bandwidth also possible (using 1 m long kickers for 40 MHz +/- 20 MHz)

70 mm vacuum chamber diameter (directly arc compatible)



26 mm vacuum chamber (→ 18 mm between electrodes)

→ power need reduced by factor 15.6



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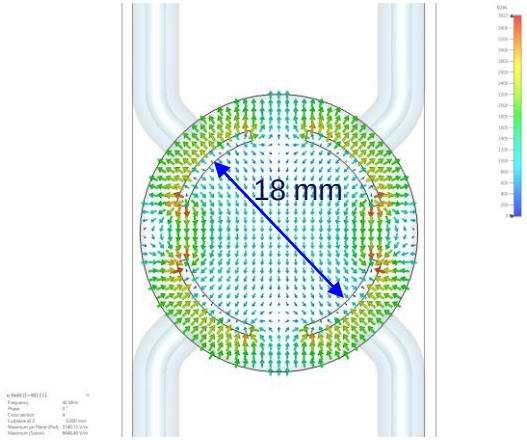
integrated transverse kick 450 kV needed (split voltage over four kickers):

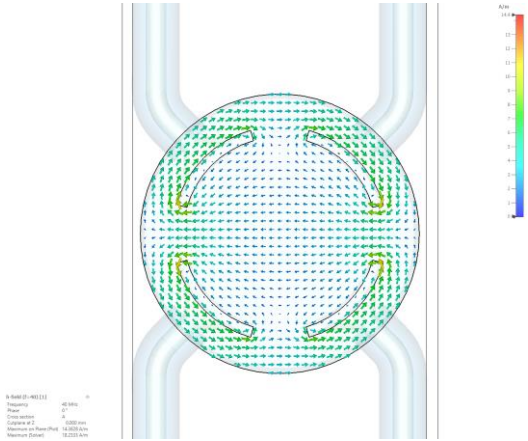
$$V_T = \sqrt{2PZ_s}$$

- total length *per beam* for kickers ~10 m (+ overhead tapers)
- 3 m per location per beam (if split over four points per beam)

Stripline kicker: field plots (26 mm chamber)



Electric field (vertical)



Magnetic field field (horizontal)

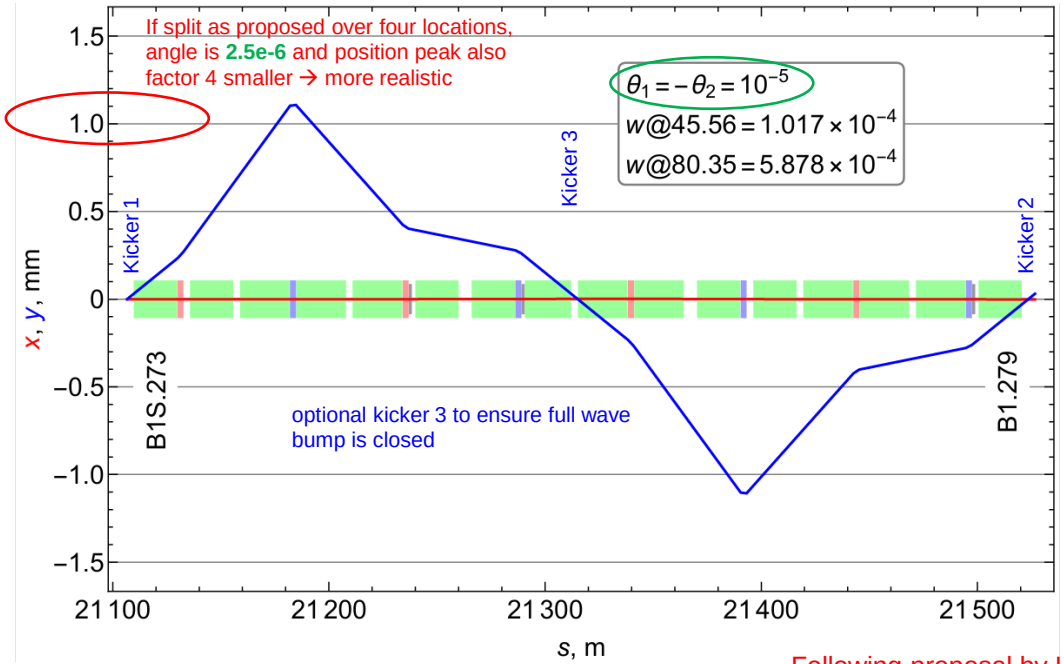
D. Sittard

- vertical kick evenly split between electric and magnetic fields
- 18 mm diameter stay clear aperture

Placement in regular arc under study

positron beam outgoing (clockwise) / right of Ips, see also K. Oide FCC week 2025

- split system over eight locations, left and right of experimental points
- chose kickers of lengths of 1 m, 26 mm chamber
- → at least 8 kickers per beam for four full wave bumps per beam
- + the optional third kicker to ensure bump closure (another 4 kickers per beam)
- 24 kickers in total



Following proposal by I. Koop

https://indico.cern.ch/event/1471324/contributions/6220925/attachments/2963259/5212471/Koop-depolarizer%20review.pdf

Kick voltage and kick angle summary

- 10 μrad at 45 GeV → 450 keV/c transverse momentum kick needed for the depolariser function, several kickers needed to implement this modulated closed bump
- stripline kickers offer a viable solution
- split over four locations per beam
  - use sets of 1 m long kickers (RF matched to 50 Ω) with four electrodes for each location to create local modulated bump (2x4x2.26 kW = 18 kW RF power per bump)
  - four such systems per beam
  - 24 kickers in total for both beams combined
    - for 16 main kickers: 144 kW RF power
    - for 8 adjustment kickers: 36 kW RF power
    - bandwidth for adjustment kicker can be higher

Kicker lengths and powers (table is for one of four locations)

Location	Function	Length	Power
left of IP e^-	open bump	1.0 m	9.04 kW
left of IP e^-	correction	0.75 m	4.5 kW
left of IP e^-	close bump	1.0 m	9.04 kW
right of IP e^+	open bump	1.0 m	9.04 kW
right of IP e^+	correction	0.75 m	4.5 kW
right of IP e^+	close bump	1.0 m	9.04 kW

Next crucial steps – my view

- optimization of kickers with respect to having high power efficiency (shunt impedance) in operating band and acceptable beam impedance overall
  - optimization of electrode design, possible consideration of advantages of higher line impedance kicker
- simulations, of multi-particle type, with more realistic feedback model and machine impedance to check damping of coupled bunch modes
- converging on exact installation location, space needed with tapers
- follow-up on machine protection considerations

Thank you for your attention.

Spare

Machine Protection considerations (03.10.24)

What can go wrong?

- excitations not correctly synchronized
- excitation amplitudes not correct leading to not closed depolarizing bumps
- any of the other excitations that will certainly be used (AC dipole mode etc.) need to be protected against failures
- very strong kicks possible comparable or even larger than at LHC injection

Mitigation

- protection with BLMs of limited or of no use due to small beam size, absence of significant halo
- monitoring of positions at appropriate distance from kickers at specific phase advance
- global monitoring of beam position required turn-by-turn, independent of pick-ups used for TFB
- interlocks need to be derived from this monitoring
  - use also down strip TFB pick-ups for monitoring
- beam stoppers?

- machine protection task force working group requested examination of failure scenarios and mitigations
- from MP point of view not clear if entangling TFB and depolarizer system into one system is the optimum due to the different kick strength required for both systems and the possible failure scenario
  - possibility to have common kickers, with combination of signals before kicker (pulsed system for de-polarizer, cw system for feedback function)

LHC ADT kicker (LHC transverse feedback)

- high impedance tetrode amplifiers
- kicks with electric field only
- 6 m effective length split over 4 kickers twice as strong as depolarizer kicker system (2 μrad at 450 GeV/c)
- full amplitude not as bunch selective as needed for FCCee
- due to resonances not (readily?) suitable for short electron bunches

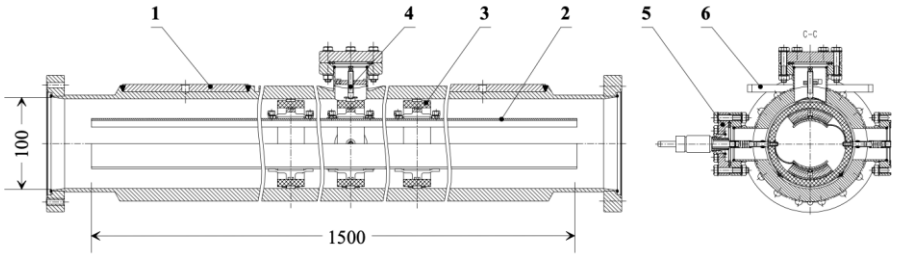


Table 1: Beam Parameters and Requirements

Injection beam momentum	450	GeV/c
Static injection errors ($\beta = 183$ m)	2	mm
ripple ($\beta = 183$ m)	2	mm
resistive wall growth time	14	ms
decoherence time	68	ms
tolerable emittance growth	2.5	%
overall damping time	4.7	ms (53 turns)
standard bunch spacing	25	ns
minimum gap between batches	995	ns
lowest betatron frequency	> 2	kHz
highest frequency to damp	20	MHz
Electro-static kickers	base band	
aperture of kickers	52	mm
number of kickers per plane and beam	4	
length of kicker plates	1.5	m
nominal voltage up to 1 MHz	± 7.5	kV
kick per turn at 450 GeV/c up to 1 MHz	2	μrad
rise-time 10-90%, $\Delta V = \pm 7.5$ kV	350	ns
rise-time 1-99%, $\Delta V = \pm 7.5$ kV	720	ns
frequency range for gain	0.001–20	MHz
noise dominated by pick-up signal quantisation	10 bit/2 σ_{beam}	

W. Hofle et al. PAC 2001