FCCee Collider DEPOLARIZER DESIGN CONSIDERATIONS

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Acknowledgements:
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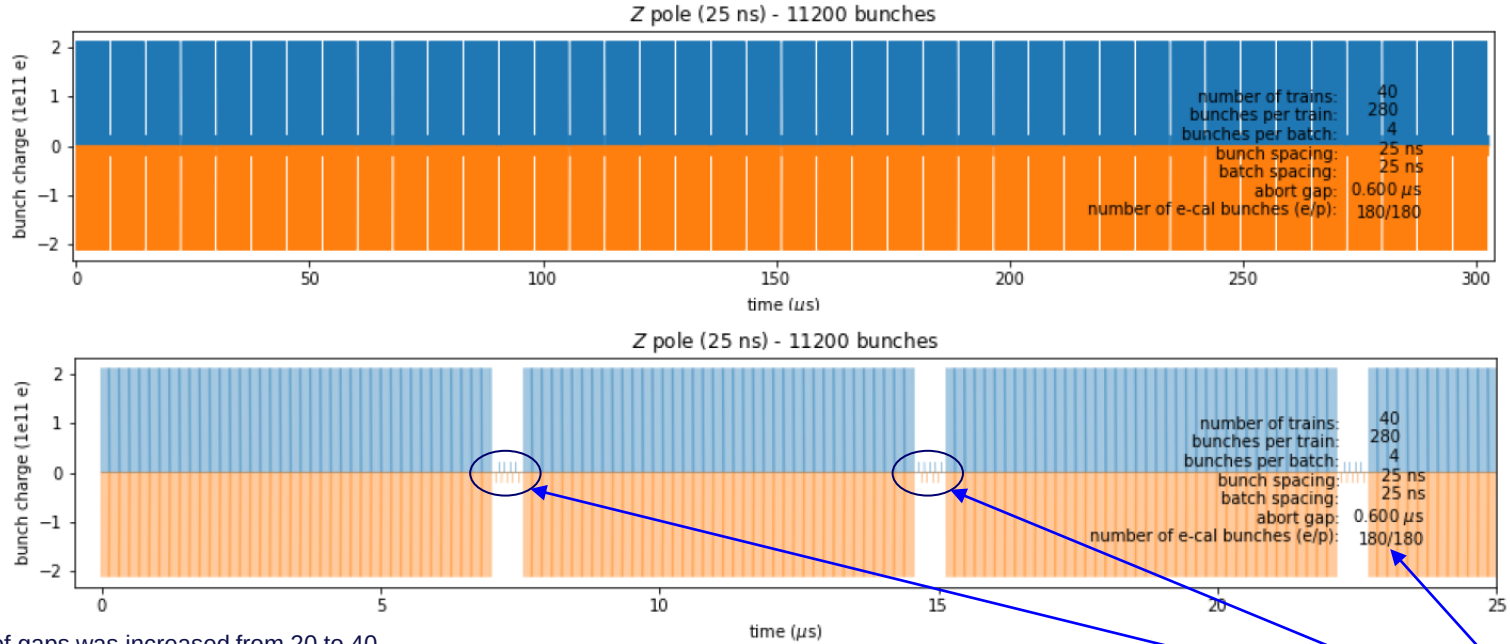
Epol WG

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 FCCee 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-mode: 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 to shake the beam to prevent polarization build-up

Filling pattern Z-pole – update of situation



Number of gaps was increased from 20 to 40
due to transient beam loading considerations in RF cavities
(I. Karpov)

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

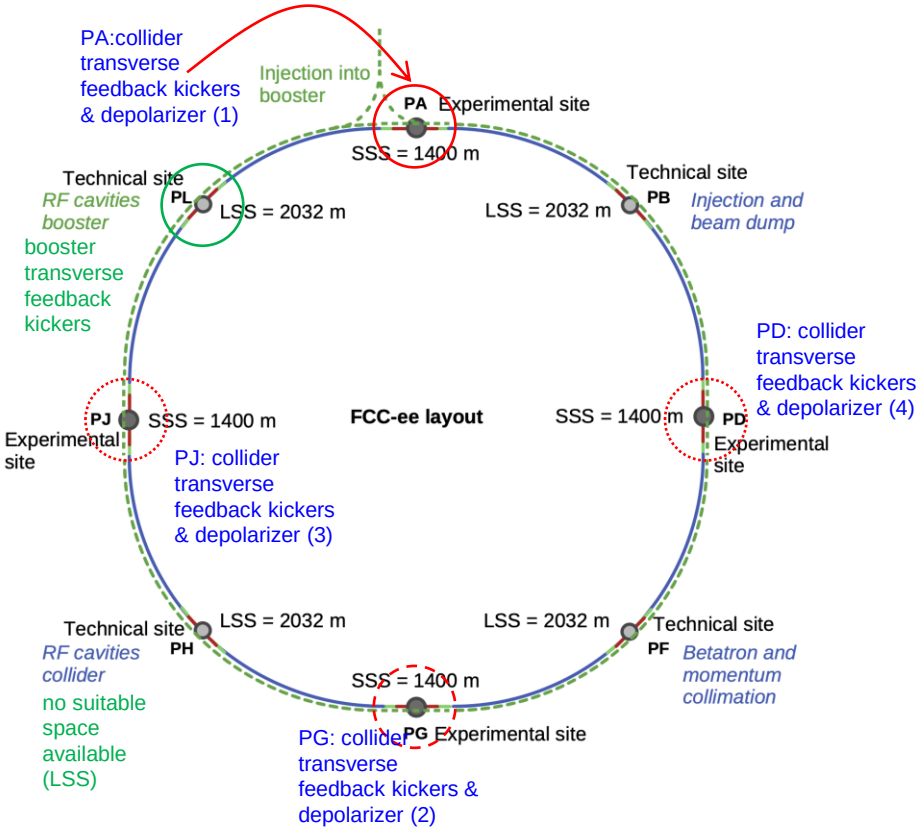
C. Carli et al. @FCC SAC 19.11.24

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, may require 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)

Considerations for placement in ring



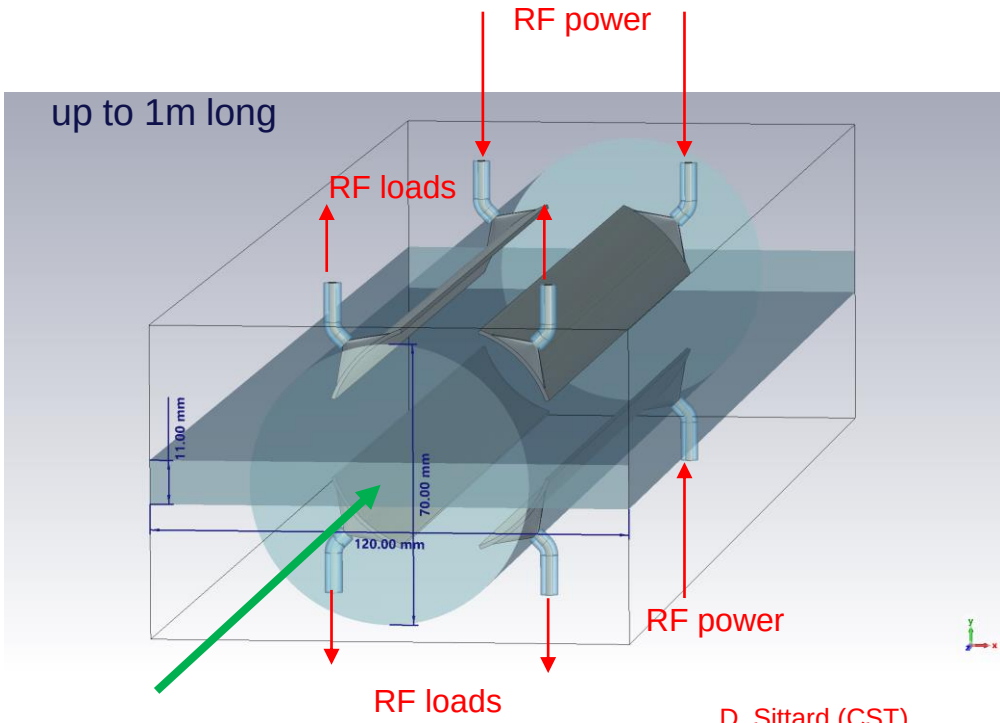
Update end of 2024:

- from the technical sites, locations 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 considered:
    - return arc
    - regular arc
  - implementation of any arc optics modification in four points preserves symmetry (4-fold)

Stripline kicker: arc compatible version (1st version)

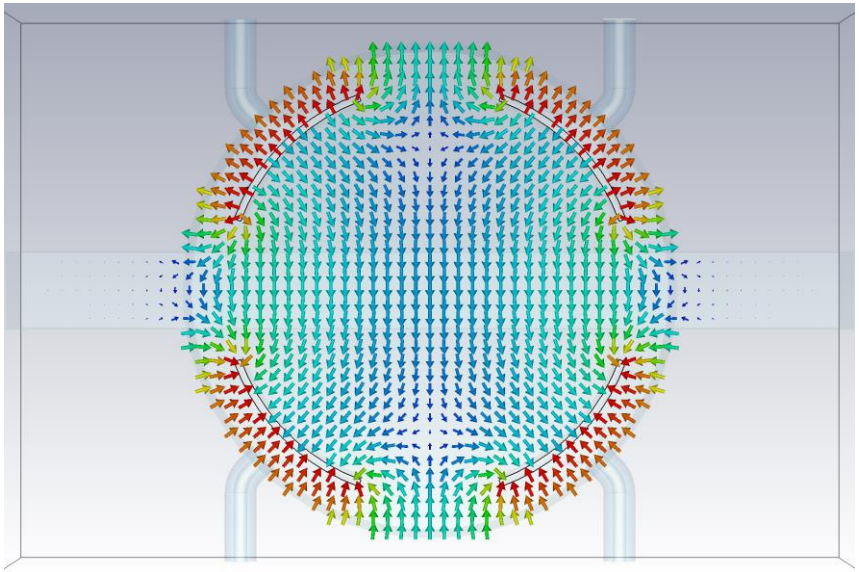
Characteristics (good for transverse feedback, but too low shunt impedance for depolarizer with arc compatible diameter)

- 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

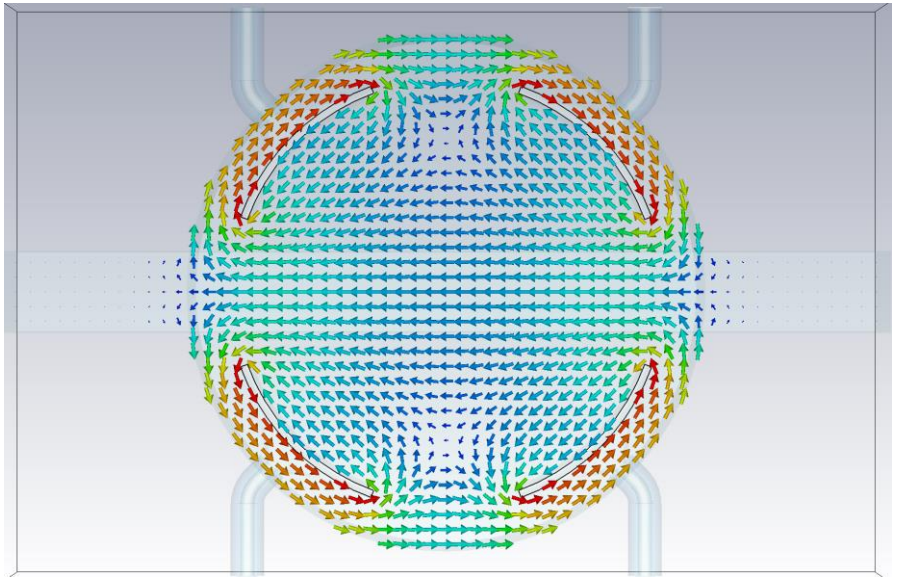


D. Sittard (CST)

Stripline kicker: field plots (70 mm chamber)



Electric field (vertical)



Magnetic field field (horizontal)

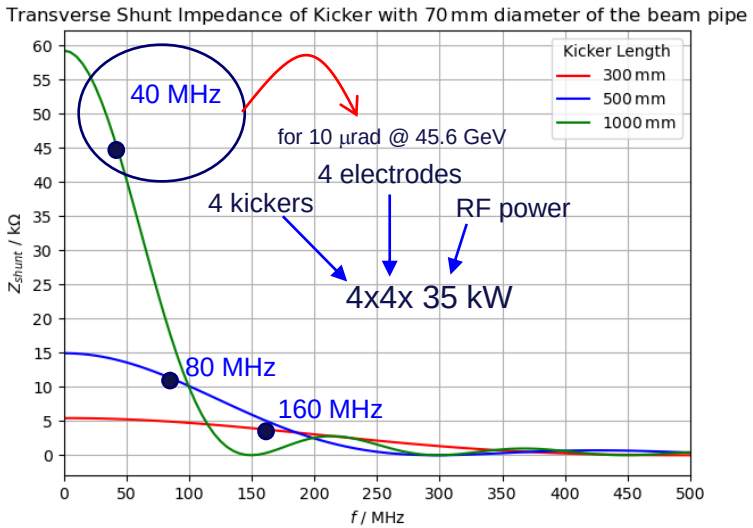
D. Sittard

- vertical kick evenly split between electric and magnetic fields

Shunt impedance kicker (four electrode version)

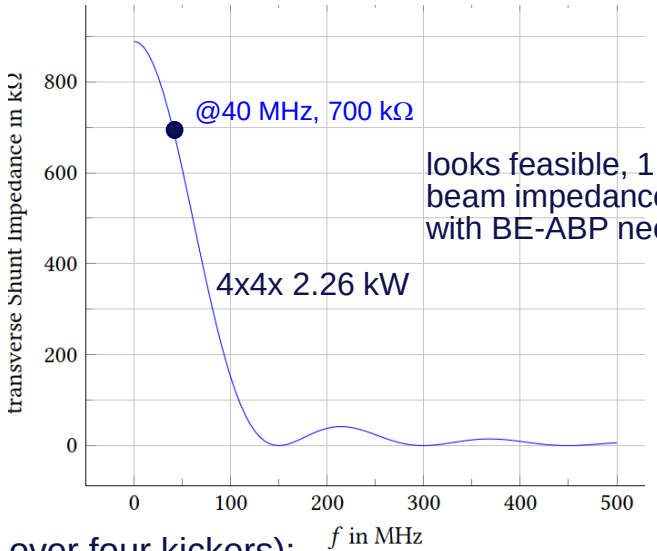
Adaptation of length to bandwidth also possible (using 1 m long kickers for 40 MHz +/- 20 MHz)

70 mm vacuum chamber diameter (directly arc compatible)



26 mm vacuum chamber (→ 18 mm between electrodes)

→ power need reduced by factor 15.6



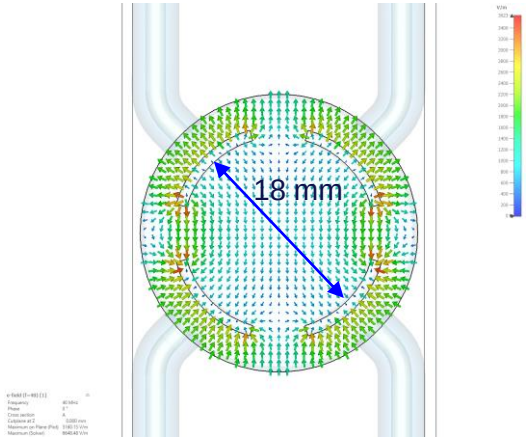
D. Sittard

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

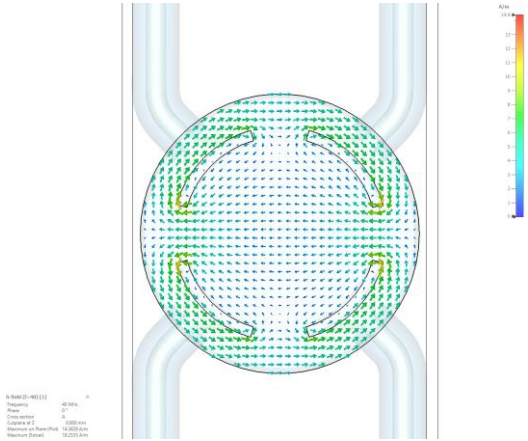
$$V_T = \sqrt{2PZ_s}$$

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

Stripline kicker: field plots (26 mm chamber)



Electric field (vertical)



Magnetic field field (horizontal)

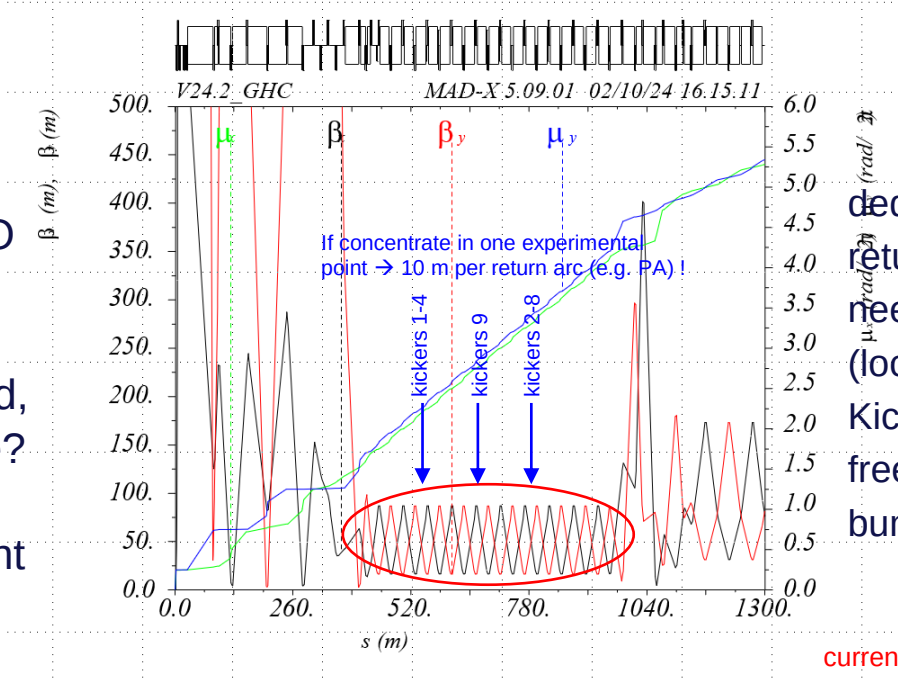
D. Sittard

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

Placement in return arcs or in arcs?

positron beam outgoing (clockwise) / right of IPs

- return arcs would be suitable location for transverse feedback kickers
- however, due to only two dipoles per FODO cell → less effect for depolarizer (I. Koop)
- arc much better suited, but is space available?
- plan to distribute depolarizers over eight locations anyway



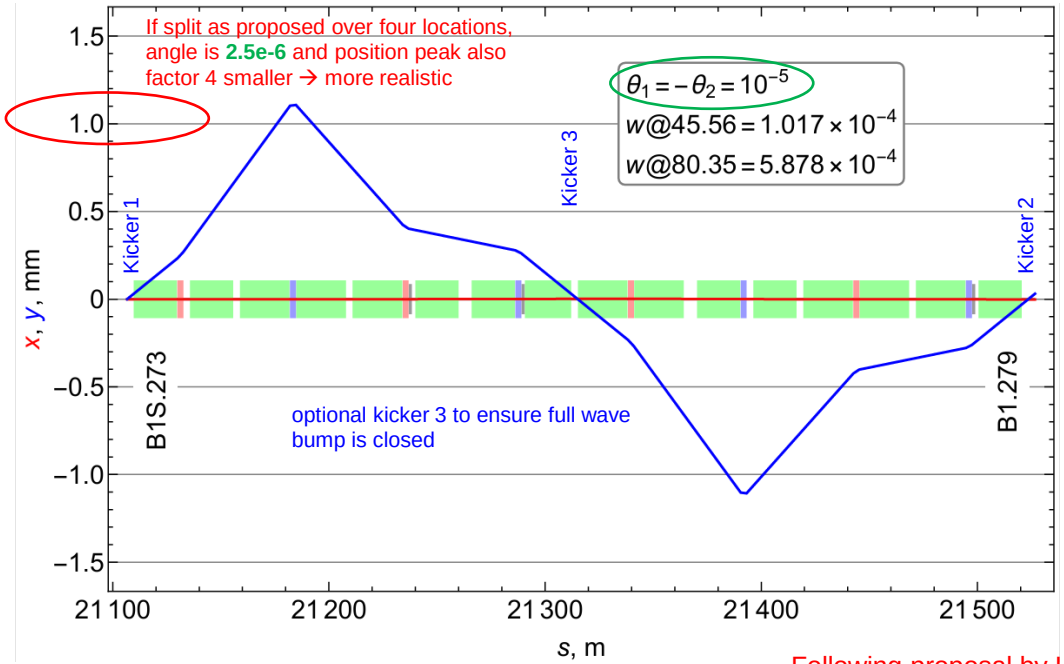
dedicated optics needed in return arc(s) adapted to the needs of the depolarizer kickers (local modulated bump)
Kicker #9 additional degree of freedom to adjust closing of bump (depolarizer function)

current optics plot: curtesy G. Roy

Placement in regular arcs re-visited

positron beam outgoing (clockwise) / right of IPs

- 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, at minimum two locations for implementing a closed bump with modulated amplitude can be provided by stripline kickers
  - 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)
  - four such systems per beam
  - 24 kickers in total for both beams combined, including the additional kicker to adjust closure
    - for 16 main kickers: 144 kW RF power
    - power needed for adjustment kickers is smaller

Next crucial steps – my view

- confirmation needed on available space in arcs or for modified return arc optics suitable for depolarizer
- feasibility of small diameter vacuum chamber kicker needs confirmation
  - beam impedance, needed tapers, synchrotron radiation
- follow-up on machine protection considerations
- optimization of electrode design, possible consideration of advantages of higher line impedance kicker

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
- monitoring of positions at appropriate distance from kickers in phase
- global monitoring of beam position required turn-by-turn, independent of pick-ups used for TFB
- interlocks need to be derived from this 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)

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
- 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)

Transverse Feedback Kickers

Requirements

- bunch-by-bunch operation calls for +/- 20 MHz minimum for 25 ns bunch spacing
- high gain required, not necessarily high kick strength
- low noise electronics
- prefered to provide feedback kicks in a band at a multiple of the bunch repetition frequency, nx40 MHz or nx50 MHz depending on bunch spacing
  - lowest betatron frequency is very low in frequency (~660 Hz)
- possibilities to distribute kicker system over several collider points considered before but seems at present not required, but needs independent confirmation
- fast damping rates required for low order modes only
- have a set of kickers available at different phase advances is an advantage (if fractional tune options close to 0.5 or integer, it is a must)
- highest beta function for given aperture, low dispersion for associated set of pick-ups
- additional synergy to be explored for applications as in LHC (AC-dipole for optics measurements …)

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

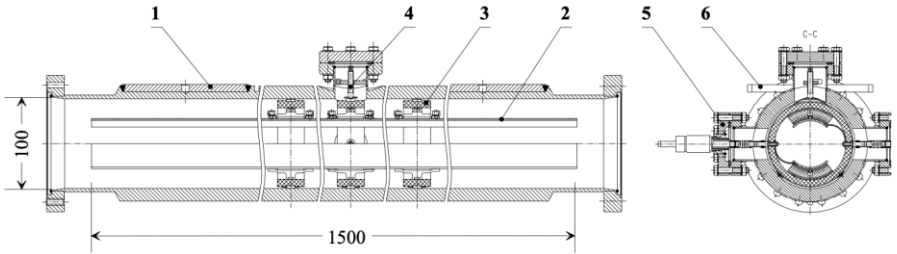


Table 1: Beam Parameters and Requirements

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}	

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