Top-up injection

FCC week 2015

Masamitsu Aiba, Ángela Saá Hernández PSI

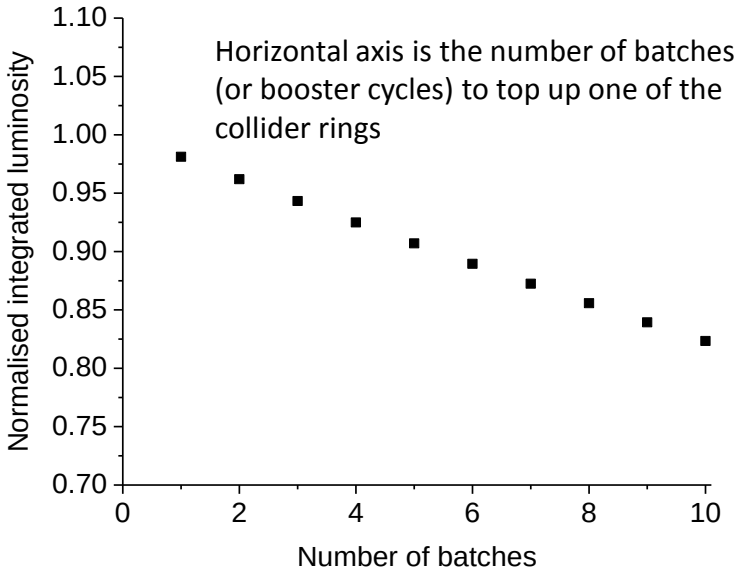
Frank Zimmermann, CERN

Introduction: Booster and top-up

- Top-up injection is essential because of very short luminosity life time
- Booster
  - Repetition <0.1 Hz
  - Top-up injection frequency <0.05 Hz (One booster filling two rings)
  - Emittance similar to the main ring emittance (Full energy booster)
  - Negligible collective effect for low charge in Booster
- Integrated luminosity vs Number of batches:
  - Higgs mode: Luminosity life time, tau=21 min
  - Assuming top-up injection at every 25 sec

- The number of batches of 2~4 would be optimum
  - Luminosity loss
  - Booster extraction kicker rise time / flat top
  - Collider ring injection kicker rise time / flat top
- Frequent top-up injection

  → Need robust injection scheme!



Introduction: Parameters

Operation mode	H	tt
Circumference [km]	100	
Bending radius [km]	11	
Beam energy [GeV]	120	175
Beam current [mA]	30	6.6
Bunches / beam	1360	98
Bunch population [10^{11}]	0.46	1.4
Transverse emittance:		
- Horizontal [nm]	0.94	2
- Vertical [pm]	1.9	2
Momentum compaction [10^{-5}]	0.5	0.5
Energy spread [%]		
- Synchrotron radiation	0.10	0.14
- Total (including BS)	0.14	0.19
Bunch length [mm]		
- Synchrotron radiation	0.81	1.16
- total	1.17	1.49
Energy loss / turn [GeV]	1.67	7.55
SR power / beam [MW]	50	50
Total RF voltage [GV]	5.5	11
RF frequency [MHz]	800	
Longitudinal damping time [turns]	72	23
Energy acceptance RF [%]	11.2	7.1
Synchrotron tune	0.096	0.10
Luminosity lifetime [min]	29	21

- This investigation is mainly for Higgs mode
- RF frequency of 400 MHz is assumed (instead of 800 MHz)

Taken from FCC-ACC-SPC-0003

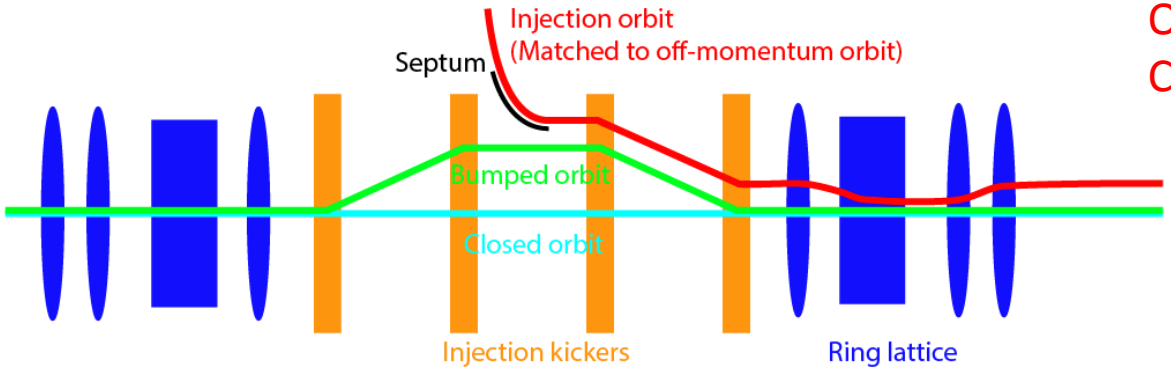
Top-up injection options

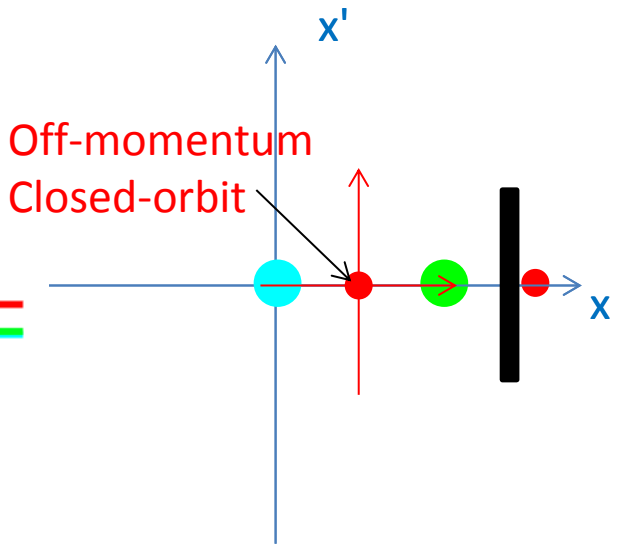
	On-axis	Off-energy	Off-phase
Conventional scheme	No	No	No
Synchrotron phase space injection	Yes	Yes	No
Swap-out injection	Yes	No	No
Longitudinal injection	Yes	Yes	Yes
Multipole kicker	No	No	No
Multipole kicker +	Yes	Yes	No
Kickerless injection	Yes	Yes	A little

- On-axis injection is preferable (assuming sufficient momentum acceptance…)
  - Possibly high injection efficiency
  - No betatron oscillation at IP

Synchrotron phase space injection* (1)

- Septum + Kicker bump
  - On-axis injection
  - Transparent to circulating bunches (in principle)
  - With injection chicane

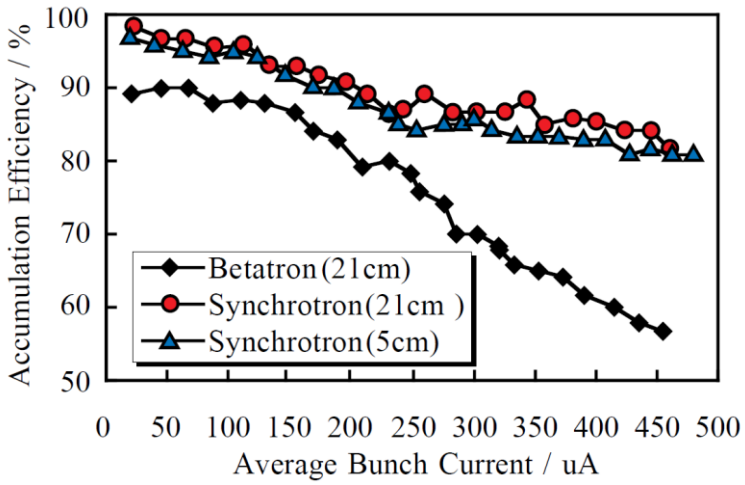




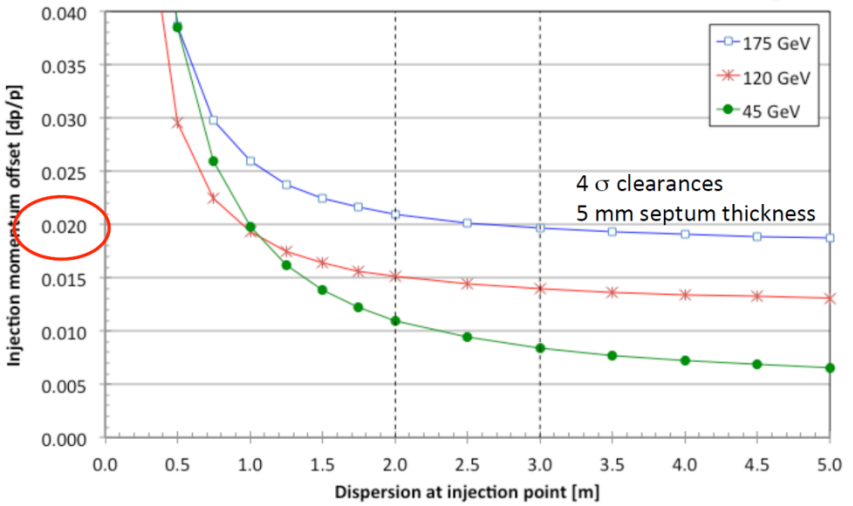
*P. Collier, Proc. of PAC 1995, pp.551-553 (1995)

Synchrotron phase space injection (2)

Injection efficiency at LEP
P. Collier, PAC 1995



C. Bracco, B. Goddard, 4th TLEP workshop, 2013

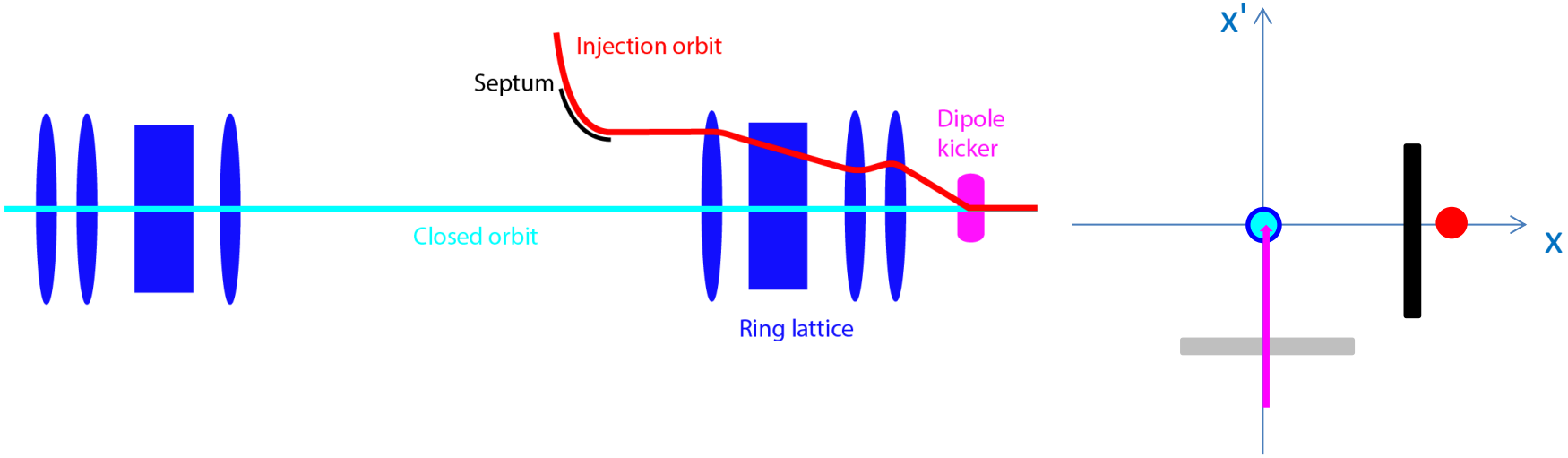


On-axis injection realised
better injection efficiencies
despite off-momentum injection beam!

Applicable to FCCee:
4σ clearance for 5 mm septum thickness
with δ=2%

Swap-out Injection*

- Bunch-by-bunch / The entire train at one time
- Septum + Short/Long-pulse dipole-kicker
  - On-axis injection
  - Pseudo-transparent to circulating bunches
  - Without injection chicane

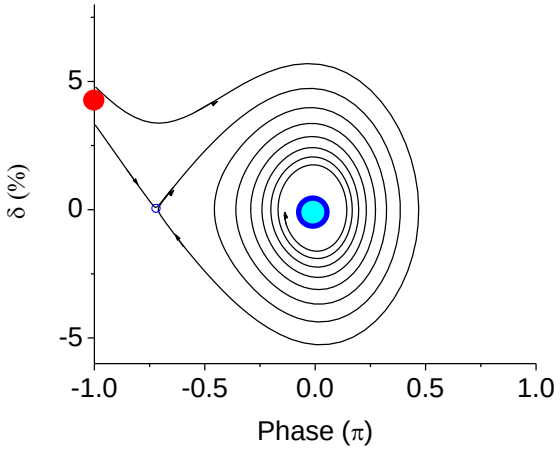


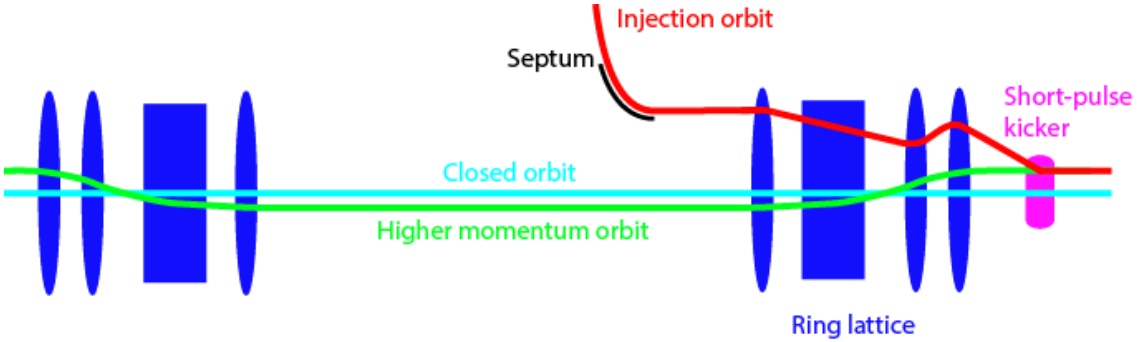
Booster may not provide an injection batch with full bunch charges…

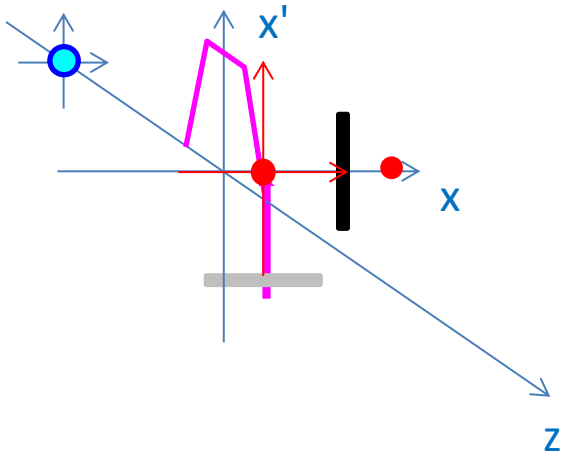
* L. Emery and M. Borland, Proc. PAC 2003, pp.256-258 (2003)

Longitudinal Injection* (1)

- Septum + Short-pulse dipole kicker
  - On-axis injection
  - Transparent to circulating bunches
  - Without injection chicane



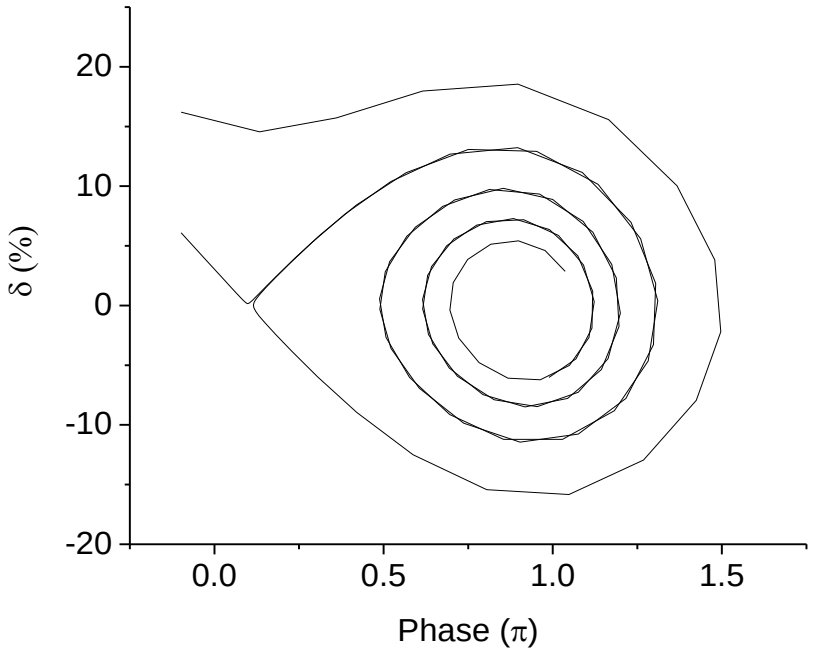




* M. Aiba et al., PRSTAB, 18, 020701 (2015)

Longitudinal Injection (2)

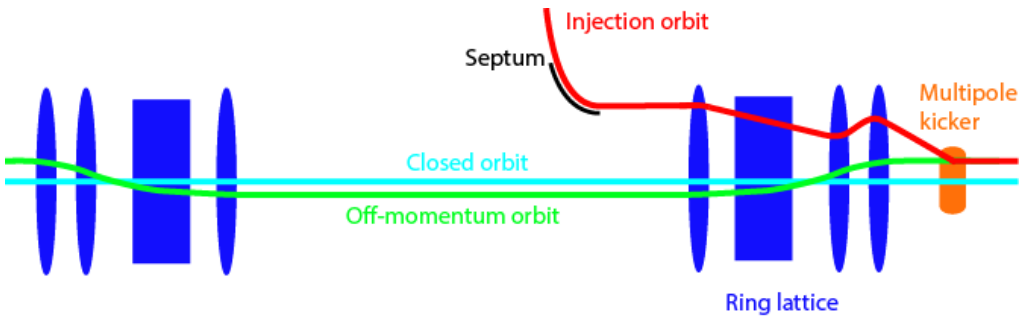
Longitudinal 1-D tracking
With H mode parameters

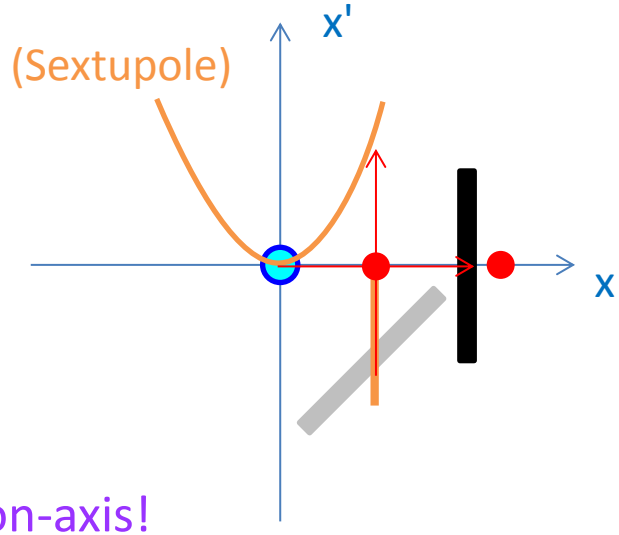


- Longitudinal phase space may not be suitable (too large bucket height)
- Short pulse kicker may be too challenging…
  - Fast decaying tail (~1 ns for 400 MHz RF)
  - Repetition (Bunch spacing corresponds to 4 MHz)

Multipole kicker injection +* (1)

- Septum + Multipole kicker
  - On-axis injection
  - Quasi-transparent to circulating bunches
  - Without injection chicane



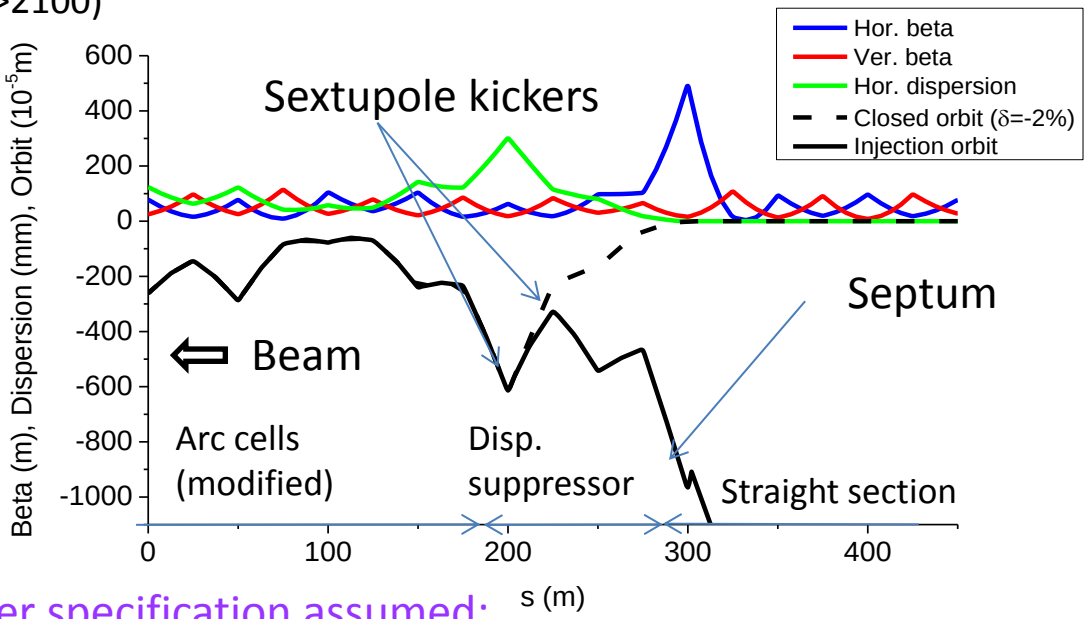


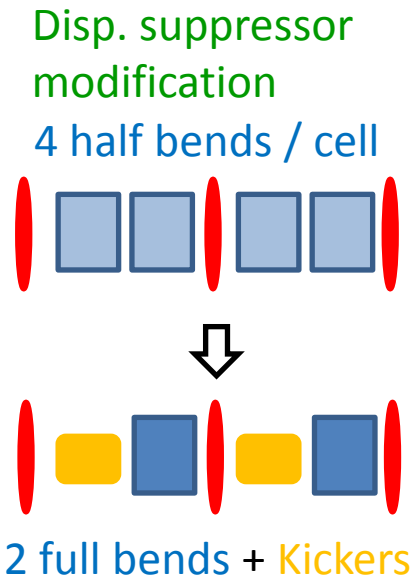
Off-momentum injection beam can be injected on-axis!

* A. Saa Hernandez, Low Emittance Ring workshop 2014

Multipole kicker injection + (2)

- Possible injection lattice and injection orbit
  - Original lattice consists of regular FODO cells (50 m) with classical dispersion suppressor (2 cells)
  - Half bends in the dispersion suppressor are integrated into single full bend to make a room for the sextupole kicker
  - Dispersion is enhanced to ~0.3 m at the multipole kicker location
  - The horizontal emittance increase is marginal (Lattice function modified over 20 dipoles out of >2100)





Kicker specification assumed:

Pole tip field = 0.09 T @ r = 30 mm @ 120 GeV

Corresponding to K2~0.5 m^{-3}

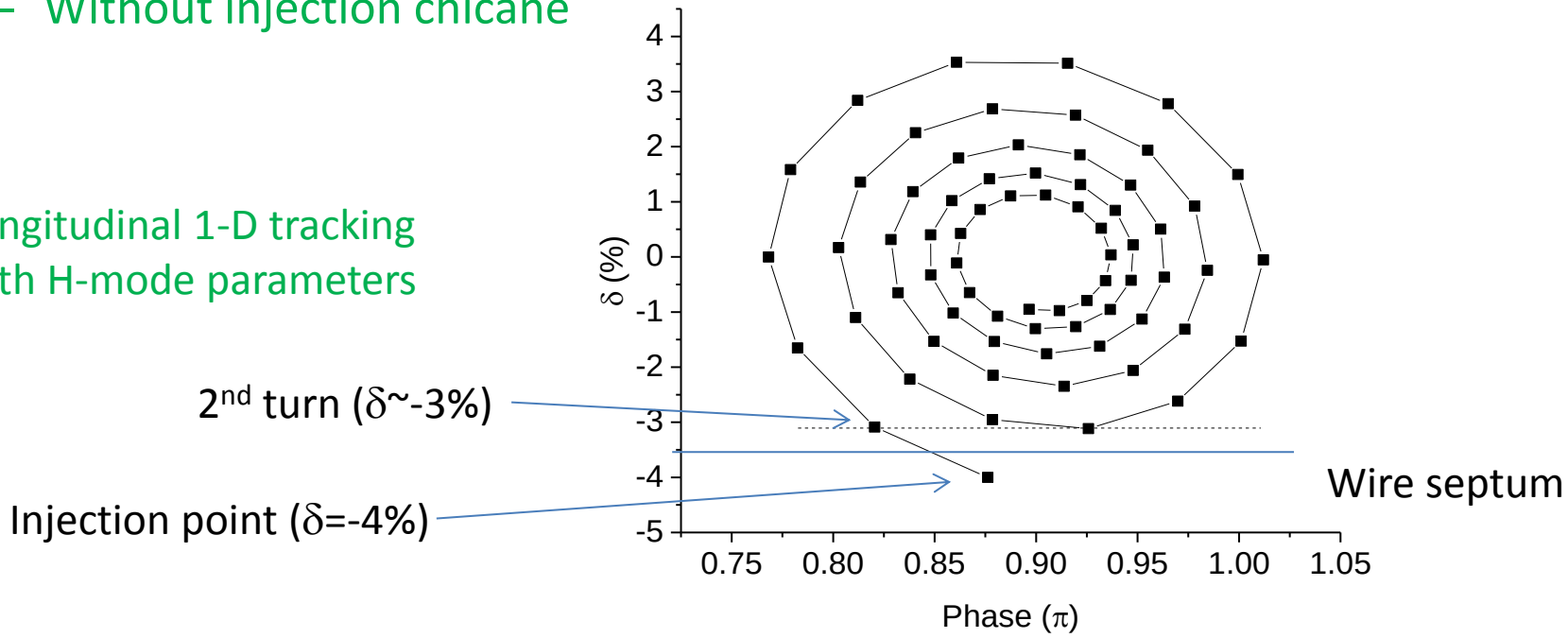
Length = 2*8 m (Using 2*10.5 m space -> Packing factor ~75 %)

(B mag. length = 10.5 m)

Kicker-less injection (1)

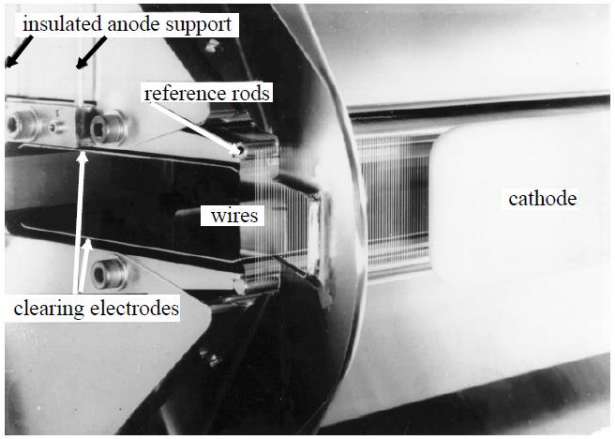
- Dream injection!!
- Septum only (like in cyclotrons)
  - On-axis injection
  - Transparent to circulating bunches
  - Without injection chicane

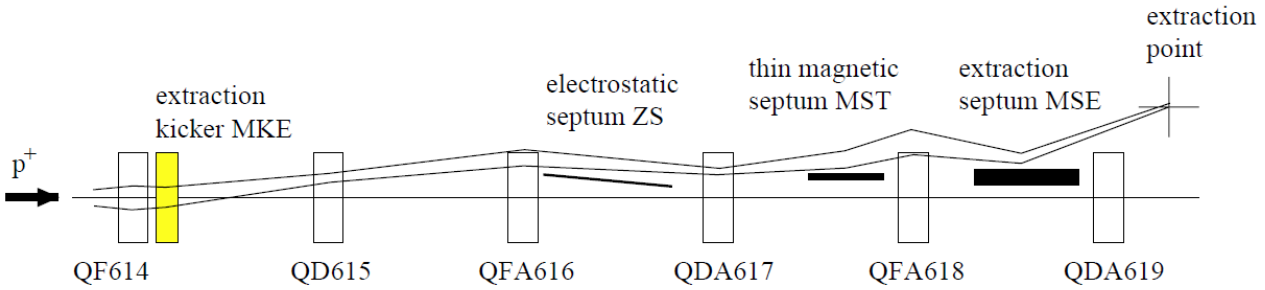
Longitudinal 1-D tracking
with H-mode parameters



Kicker-less injection (2)

- SPS ZS septum (Electrostatic wire septum)
  - 25 um wires
  - Field 10 MV/m
  - Used for 450 GeV p-beam extraction

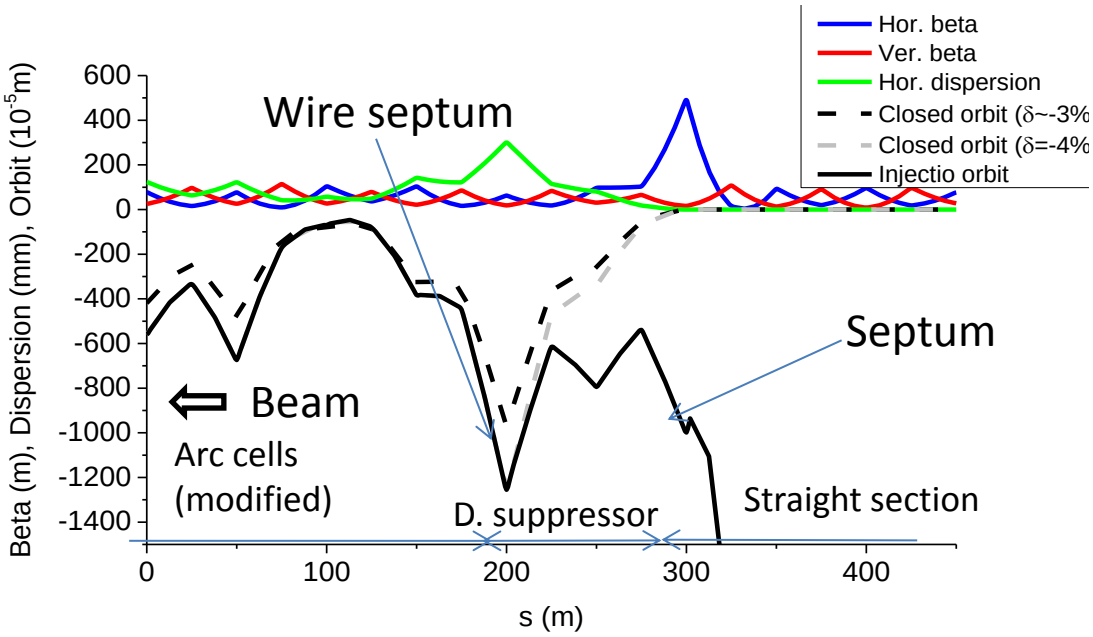




* Figures taken from B. Goddard and P Knaus, Proc. of EPAC'00, p.2255

Kicker-less injection (3)

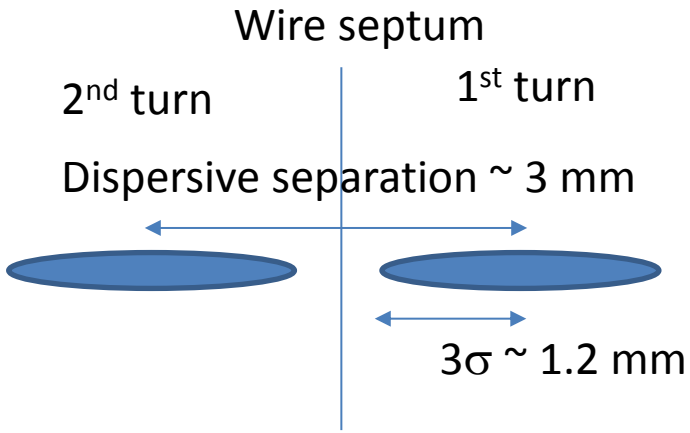
- Possible injection lattice and injection orbit
  - Same lattice to the multipole kicker injection



Wire septum specification assumed:
Kick angle 0.06 mrad
Corresponding voltage of 7.2 MV (ex. 3.6 MV/m, 2 m) @ 120 GeV

Kicker-less injection (4)

- H mode parameters
  - Energy 120 GeV
  - Hor. emittance 1 nm
  - Energy spread 0.1%
    (Negligible IBS for low charge)
- Lattice parameters
  - Hor. beta 60 m
  - Dispersion 0.3 m
- Injection condition
  - δ ~-4%
  - "Energy separation" between 1st and 2nd turn ~1%



$$\sigma = \sqrt{\varepsilon\beta + \eta^2\delta^2} \sim 0.39 \text{ mm}$$

Clearance >3σ with these parameters

Summary

- Top-up injection for FCCee (H) is investigated
- Three strong options:

Parameter table for Higgs mode	Syn. Injection[4,5]	Multipole+	Kicker-less
Kicker / Septum strength	Chicane, 0.4 mrad	Sext., K2L~8 m^{-2}	Wire septum, 0.06 mrad
Amplification factor (m/rad) $\sqrt{\beta_{septum}\beta_{kicker}}\sin\mu$	100	~120	~120
Dispersion at injection (m)	2.5	~0.3	~0.3
δ injected beam (%)	1.5	~2	~4
Blind-out due to kicker (%)[1]	3?	~0	0!
Compatibility with Z/W/tt[2]	Yes/Yes/Yes	Yes/Yes/Yes	No/No/Yes
Off-axis, on-momentum[3]	Yes	Yes	No

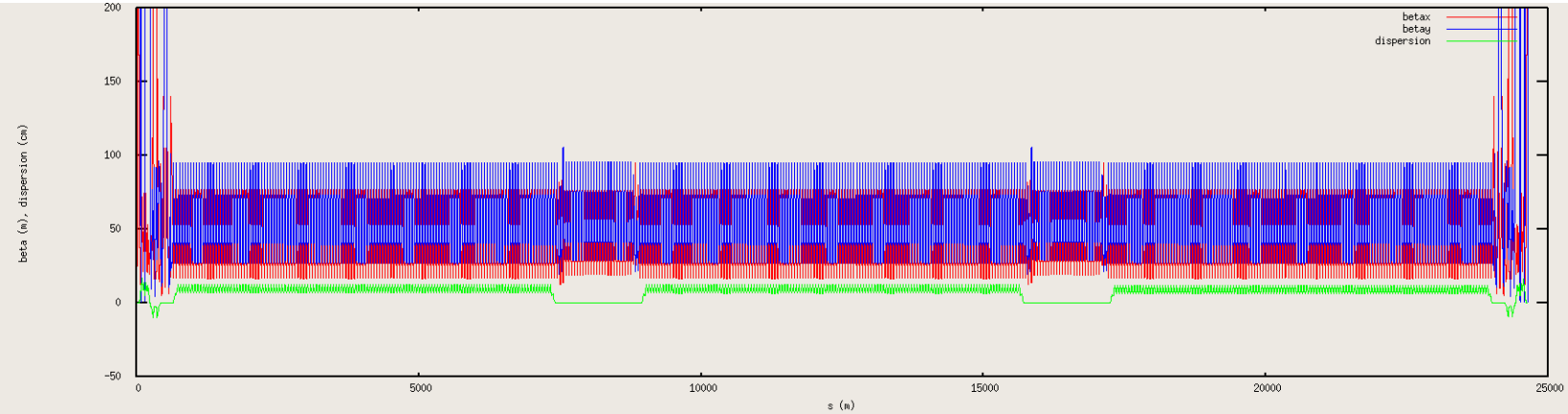
1) May need a gating for the data acquisition during injection period due to kicker disturbance
2) If the injection scheme is applicable to other operation modes than Higgs mode
3) The same injection devices can be used for off-axis, on-momentum injection
4) Parameters from C. Bracco and B. Goddard, 4th TLEP workshop (2013)
5) Synchrotron phase space injection might be much easier if wire septum is assumed??

Backup slides

Lattice

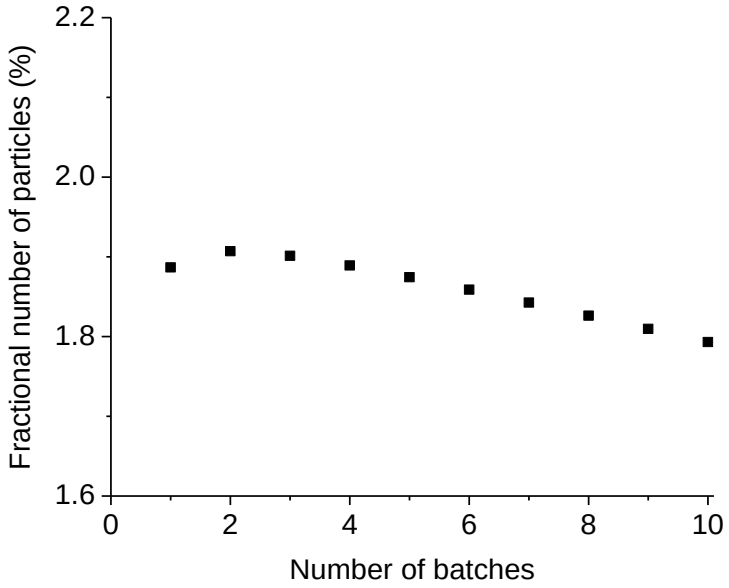
- Lattice from A. Bogomyagkov (BINP),
  - Presented at Advanced Optics Control workshop, CERN, Feb. 2015 (slides available on CERN indico)
  - Momentum acceptance (estimation from chromaticity) -3.1%/+1.9%, work in progress

Lattice, 1/4 ring



Booster intensity

- Booster intensity vs. Number of batches (H mode)



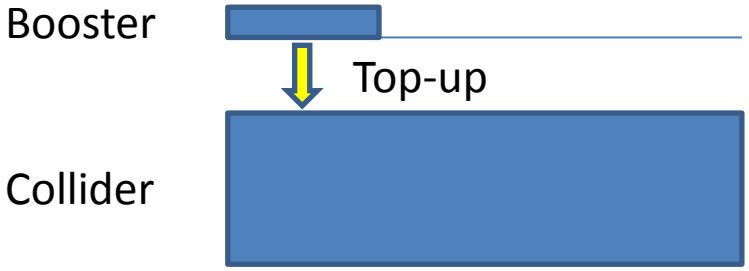
Vertical axis is the fractional number of particles with respect to the one in the collider ring.
Horizontal axis is the number of batches (or booster cycles) to top up one of the collider rings.

The total booster intensity is almost constant over the number of batches

Kicker flat top

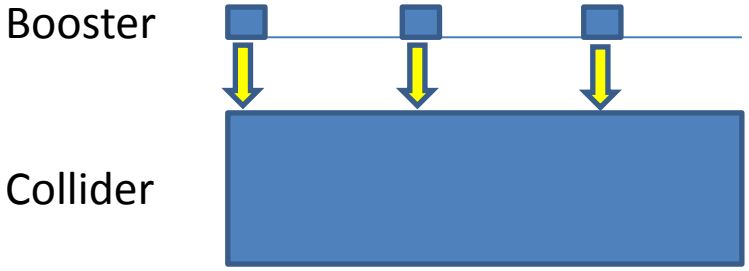
- Single transfer

Revolution period ~ 333 μs



Kicker flat top
= Revolution period / # Batches

- Multi transfer (multi batches / cycle)



Kicker flat top
= Revolution period / # Batches / # Transfer

Comfortable kicker flat top