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Top-up injection schemes

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FCCee Week, Rome
14.04.2016

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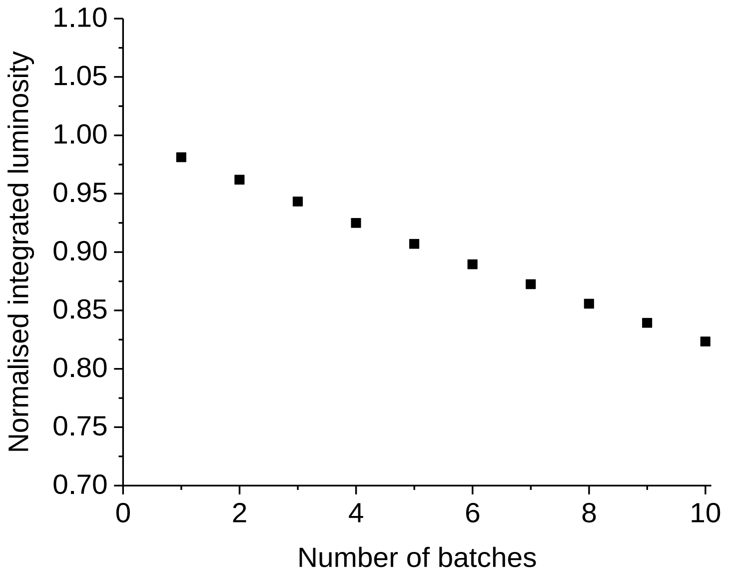
Introduction

- 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



(or Booster cycles to top-up all the bunches)

- 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!

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Boundary condition/Criterion

- Straight section = 1.5 km
- Booster emittance ~ Collider emittance

(This presentation is dedicated to the tt mode with ε= 1.3 nm that is most difficult case)

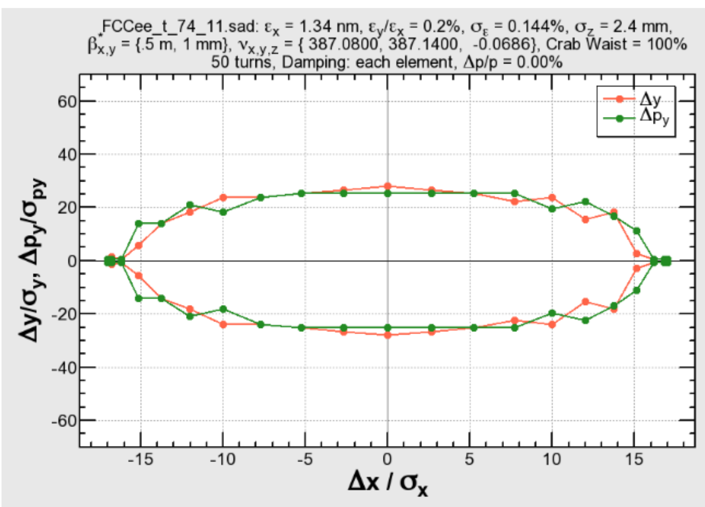
- Septum thickness = 5 mm (~3 mm + mechanical tolerance)

or 200 μm with a wire septum (20~30 μm wire + mechanical tolerance)

- Clearance = 5σ (4σ + 1σ tolerance)
- Assume dynamic aperture available ~15σ / ~5σ (on energy / 2% off energy)

Dynamic aperture in X-V plane

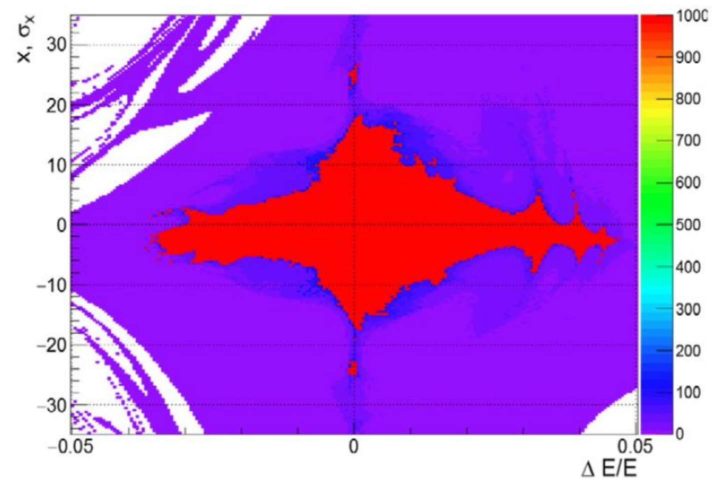
Courtesy of K. Oide



Dynamic aperture in X-dP/P plane

M. Benedikt et al., arXiv, “Status and Challenges for FCC-ee”

Figure 5 by P. Piminov and A. Bogomyagkov



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Top-up injection schemes

- Several top-up schemes

Conventional scheme, on/off energy	
~~Swap-out injection~~	~~See backup slide~~
~~Longitudinal injection~~	~~See backup slide~~
Multipole kicker, on/off energy	
~~Kickerless injection~~	~~See backup slide~~

On-energy injection
→ Separation in transverse phase space

Off-energy injection
→ Separation in longitudinal phase space

Down-select from the previous study, CERN-ACC-2015-065

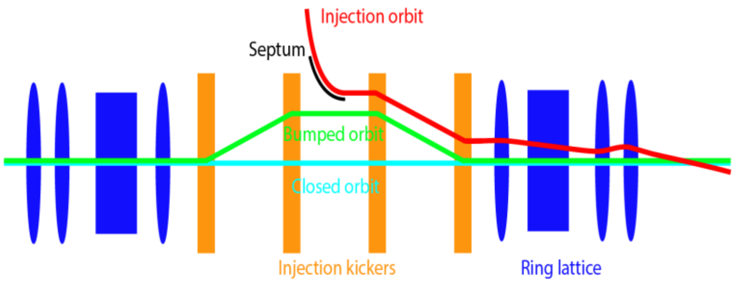
Down-select due to Boundary condition (not enough momentum aperture), and the scheme is applicable only for H and tt modes

Further investigation for the remaining schemes

Conventional scheme (1)

- Injection with orbit bump + septum
- Injection point
  - Light sources (Large aperture)
    - >30σ → 3~5 mm septum is fine
  - FCCee (Limited aperture)
    - Maximum ~10σ

    → Impossible with 5 mm septum (next slide)



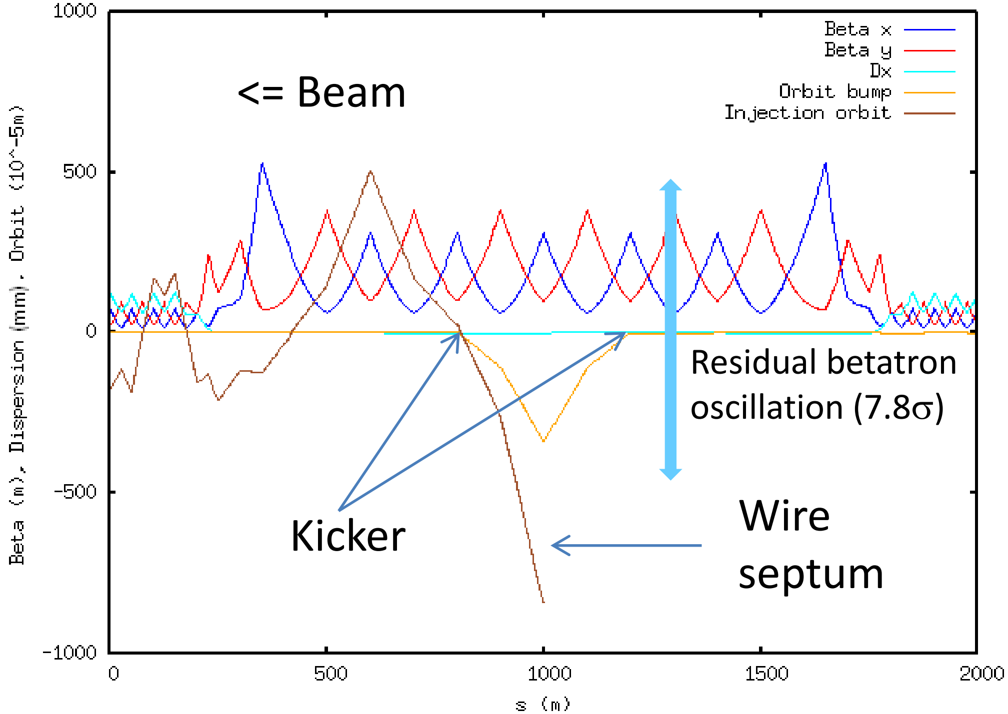
- Off-energy injection beam →Synchrotron phase space injection* with finite dispersion at septum

*P. Collier, Proc. of PAC 1995, p.551

Conventional scheme (2)

σ_s: Stored beam size
σ_i: Injection beam size
S: Septum thickness

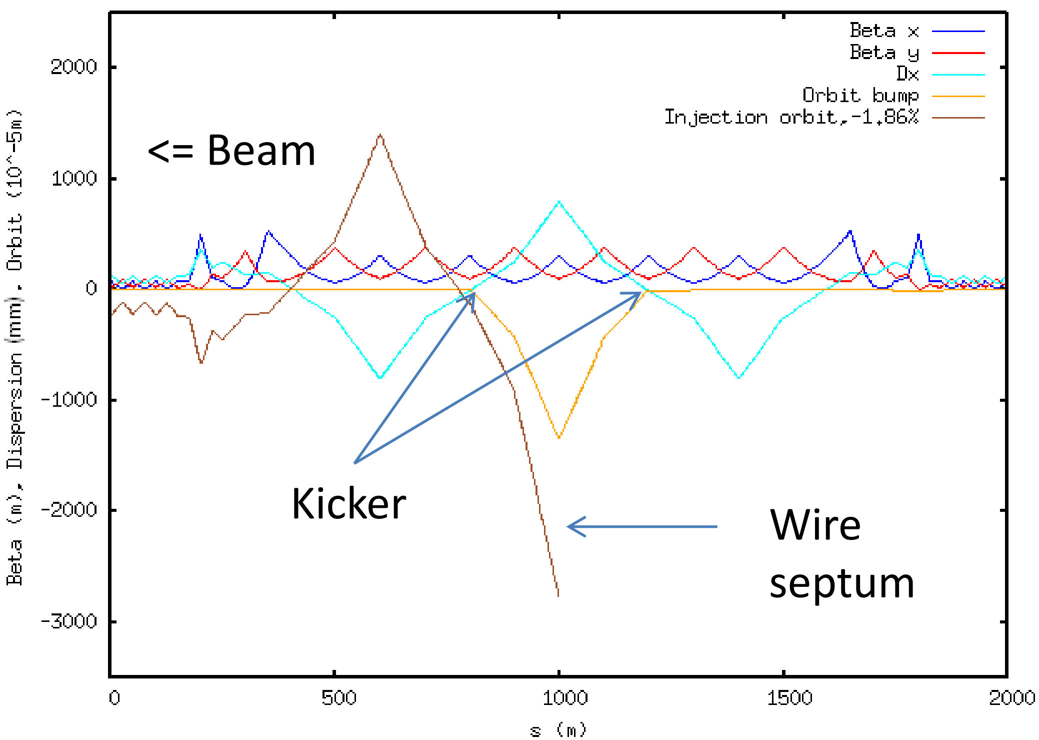
- On-energy, off-axis case
  - Separation required at septum= $5\sigma_s + S + 5\sigma_i$
    - σ_i optimum ~$0.5\sigma_s$
    - Larger beta function preferred to reduce the septum thickness in terms of beam sigma
    - S = 5 mm, however, corresponds to ~$4.4\sigma_s$ even for 1 km beta function (ε = 1.3 nm)
    - Wire septum is essential to keep the injection point <10σ
  - Bump height required = $10\sigma_i + S + \alpha$
    - Additional bump height to keep septum away from the residual betatron oscillation



- 200 m long cells
- Beta at septum/kicker = 312 m
- Phase advance = 90 deg/cell
- With dispersion suppressor
- Bump kicker strength = 11+α μrad (0.2+α m, ~0.03 T @ 175 GeV)
- Wire septum essential

Conventional scheme (3)

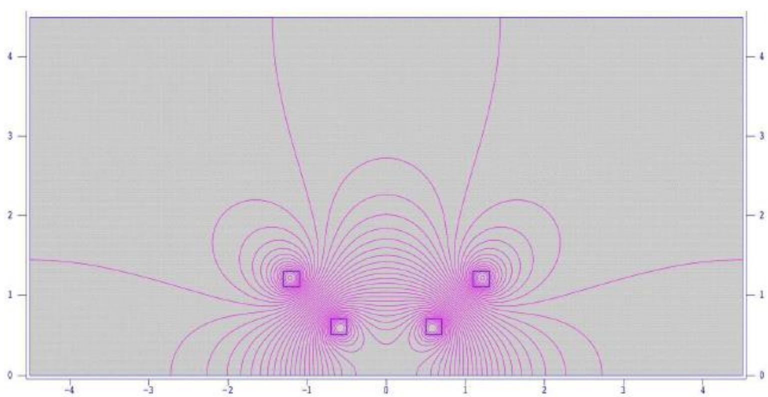
- Off-energy, on-axis case
  - Separation required at septum, $5\sigma_s + S + 5\sigma_i < Dx\ \delta_i$
    - Requirements for dispersion and energy offset (δ_i) are determined as well
    - σ_i optimum = σ_s (Very limited aperture for the off-energy beam)
    - $\sigma_{s/i}$ are increased due to the energy spread (0.19/0.14%) of the stored/injection beam
  - Bump height required = $10\sigma_i + S$

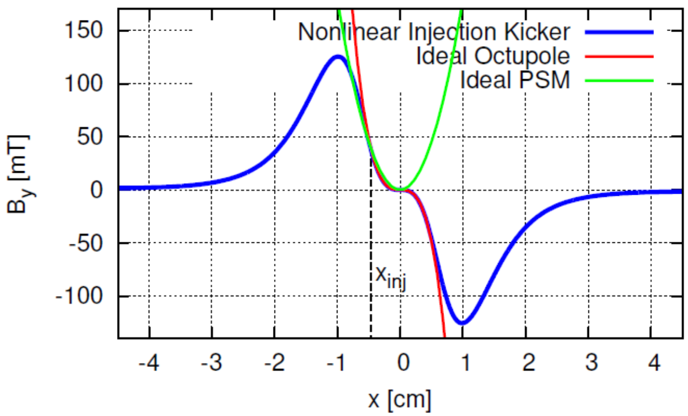


- 200 m long cells
- Beta at septum/kicker = 312 m
- Phase advance = 90 deg/cell
- Dispersion at septum = 0.8 m (Difficult to increase Dx…)
- Bump kicker strength = 44 μrad (0.8 m, ~0.03 T @ 175 GeV)
- δ_i=-2.46% to meet $5\sigma_s + S + 5\sigma_i < Dx\ \delta_i$ with 5 mm septum
- δ_i=-1.86% to meet $5\sigma_s + S + 5\sigma_i < Dx\ \delta_i$ with a wire septum (200 μm)
- Wire septum essential

Multipole kicker injection (1)

- Injection with multipole kicker + septum *
- Injection point
  - Light sources (Large aperture)
    - >30σ → Marginal kick for the store beam
  - FCCee (Limited aperture)
    - Maximum ~10σ → Some impact on the stored beam
- Nonlinear kicker**
  - Pros: Approximately dipole kick for the injected beam → Marginal mismatch from kicker
  - Cons: ~1.5 times less peak field → ~1.5 times more kick for the stored beam





- Off-energy injection beam → On-axis injection with finite dispersion at kicker

* H. Takaki et al., PR ST-AB, 13, 020705 (2010)
** T. Atkinson et al., IPAC'11
Figures from S. Leemann et al., L. O. Dallin, PAC'03

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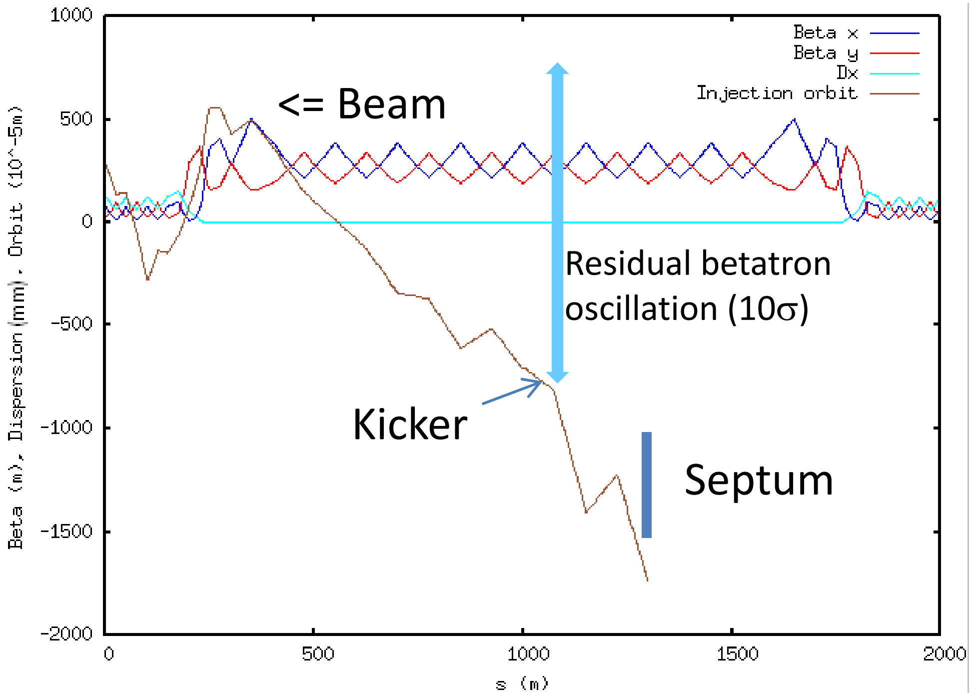
Multipole kicker injection (2)

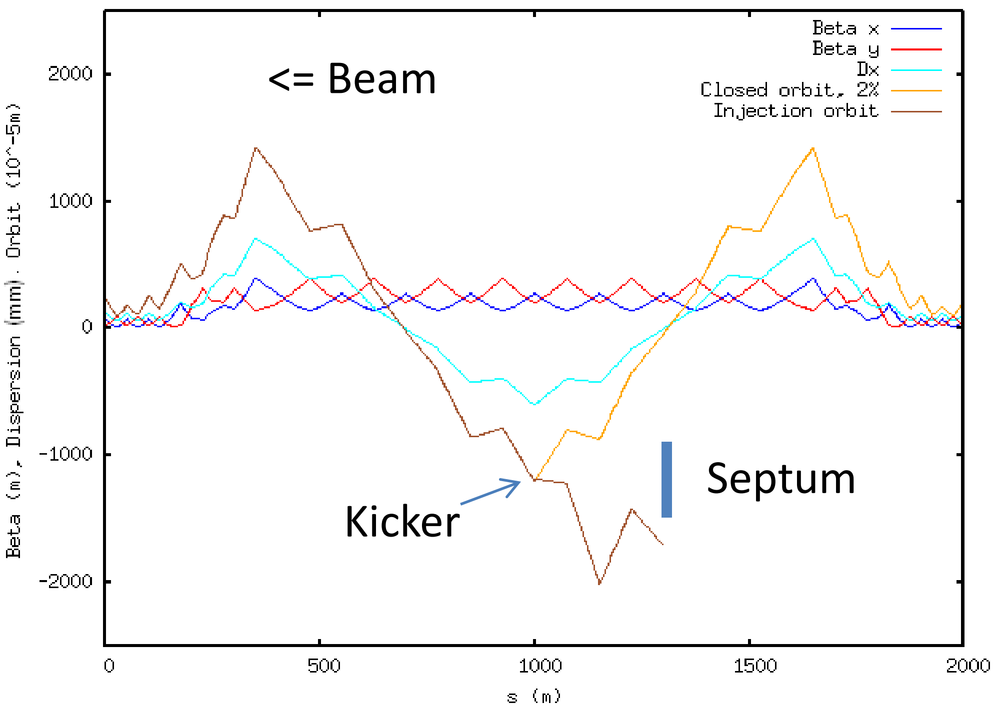
- On-energy, off-axis case
  - Separation required at septum= $15\sigma_s + S + 5\sigma_i$
    - The stored beam particles at $5\sigma_s$ are significantly kicked for 10σ injection point
    - Therefore, $15\sigma_s$ is to accept as much particles as in the dynamic aperture
    - At the same time, the injection point is at $10\sigma_s$, and thus $\sim 15\sigma_s$ is required anyway to accept the residual betatron oscillation of the injection beam
    - σ_i optimum ~ $0.5\sigma_s$



- 150 m long cells
- Beta at septum/kicker = 385 m
- Phase advance = 30 deg/cell
- With dispersion suppressor
- Sext. kicker strength = 1.7 m^{-2} (Nonlinear kicker: 2 m, 0.012 T peak)
- Emittance increase ~15% with 5 mm septum
- Emittance increase ~6% with a wire septum (200 μm)

Multipole kicker injection (3)

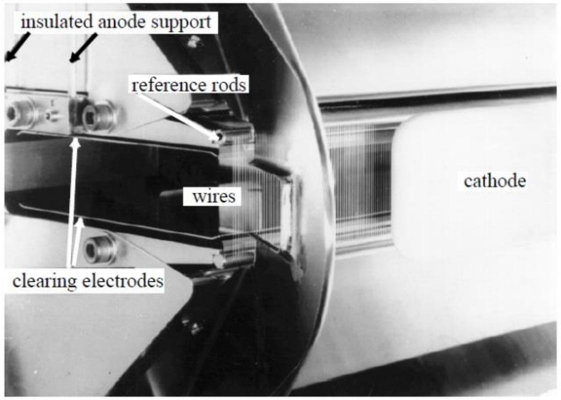
- Off-energy, on-axis case
  - Separation required at septum= $15\sigma_s + S + 5\sigma_i$
    - The stored beam particles at $5\sigma_s$ are significantly kicked
    - Therefore, $15\sigma_s$ is to accept as much particles as in the dynamic aperture
    - σ_i optimum ~σ_s (Very limited aperture for the off-energy beam)

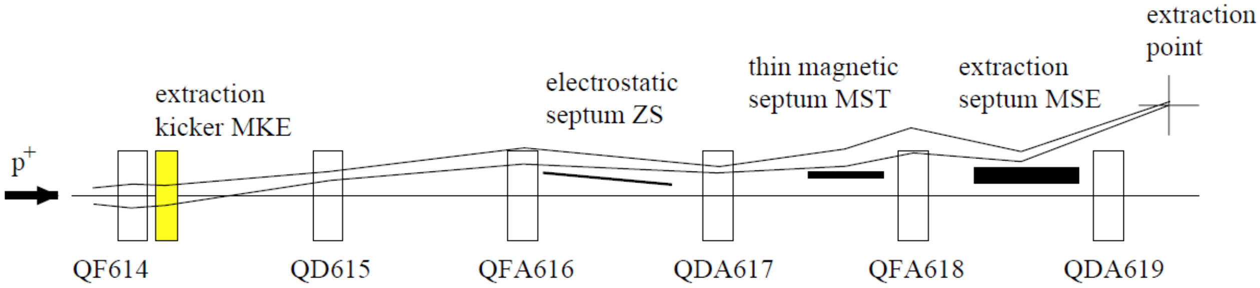


- 150 m long cells
- Beta at septum/kicker = 277 m
- Phase advance = 45 deg/cell
- Dispersion at kicker = 0.6 m
- δ_i= +2%
- Sext. kicker strength = 0.88 m^{-2} (Nonlinear kicker: 3 m, 0.012 T at peak)
- Emittance increase ~30% with 5mm septum
- Emittance increase ~20% with a wire septum (200 μm)

Wire septum (1)

- Thin septum available, e.g. SPS ZS septum*
  - 25 um wires
  - Field 100 kV/cm
  - 3 m * 5 units
  - Used for 450 GeV p-beam extraction





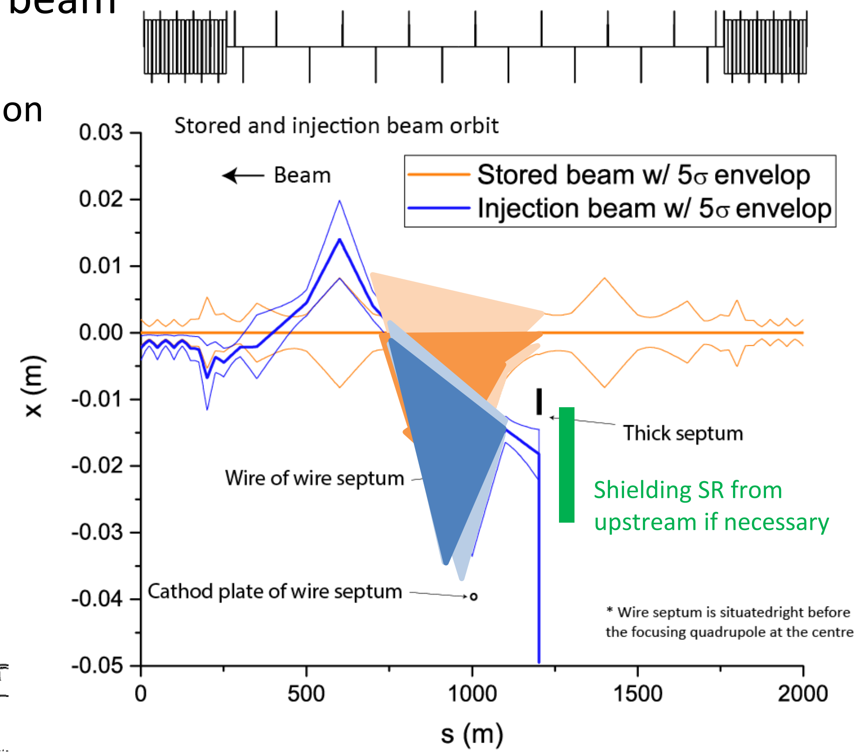
* Figures taken from B. Goddard and P Knaus, Proc. of EPAC 2000, p.2255

Wire septum (2)

- Specification for 175 GeV electron/positron beam
  - Amplification factor, $\sqrt{\beta_{WS}\beta_{thick\_septum}}$ ~300
  - ~12 MV integrated voltage for ~20 mm separation
    - for example <40 kV/cm, 3 m unit
- Synchrotron radiation
  - 90 degree cells in conventional injection scheme avoids the SR from the store beam ☺
  - SR mainly from the injection beam
  - SR characteristics (Conventional injection, off-energy)
    - Critical/Mean photon energy = 1.3/0.4 MeV
    - SR energy of ~2 mJ into WS gap per 1% top-up (~230 keV/particle)
- SPS/LEP experience*

Accelerator	Equipment	Beam mode	HV polarity	Field kV/cm	Spark rate h^{-1}
SPS	ZS	none	negative	145	1
SPS	**ZS**	**p, e+,e-**	**negative**	**100**	**10**
LEP	ZX	none	positive	50	0.2
LEP	ZX	none	negative	50	0.4
LEP	**ZX**	**e+,e-**	**positive**	**15**	**0.01**
LEP	ZX	e+,e-	negative	15	4
LEP	ZL	none	bipolar	50	0.2
LEP	**ZL**	**e+,e-**	**bipolar**	**30**	**0.0004**
LEP	ZL	e+,e-	negative	30	4

Table 2: Spark rates for the HV equipment in the SPS and LEP accelerators for combinations of proton (p) and e+,e- beams, and applied HV polarity. Normal operating conditions are in bold.



← ZX and ZL are separators, where the stored beam is going through

It seems encouraging to employ WS for FCCee injection

* N. Garrel, B. Goddard, W. Kalbreier and R. Keizer, CERN SL/95-18 (BT)

Experience from PF-AR, KEK*

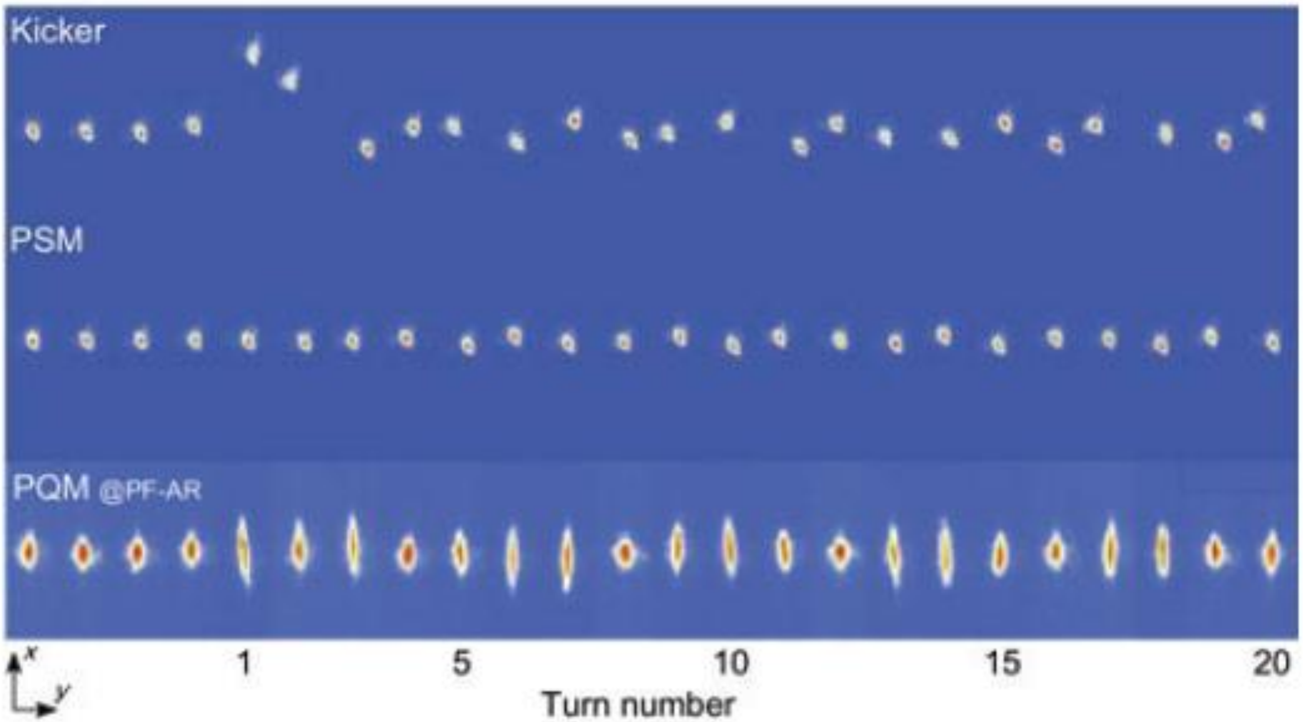


Figure 4: Turn-by-turn stored beam profiles in the kicker, PSM, and PQM injections measured by using a fast-gated camera.

*R. Takai et al., Proc. of DIPAC 2011, p.305

Open issues

- Beam-beam effects
  - Residual betatron/synchrotron oscillation of the injection beam is problematic though the injection beam charge is a few %?
  - Preferably off-energy (on-axis) injection?

    Higher inj. efficiency and less background at LEP.
  - A few % charge difference between e- and e+ colliding over one booster cycle. Acceptable?
  - Beam disturbance in Conventional injection needs to be evaluated.
  - How much emittance growth in Multipole kicker injection is acceptable?
- Filling scheme
  - Number of batches/bunches per booster cycle?
  - Timing: Ratio of Booster length to Collider length should be NB/NC with integer numbers?
  - Filling pattern feedback?

Summary

- Conventional scheme and Multipole injection are further investigated for the tt mode
  - Both schemes (and both on- and off-energy) may be feasible
  - Possible optics presented
  - Very thin septum (Wire septum)
    - Essential for the conventional scheme (on- and off-energy)
      - However, much relaxed specification w.r.t. SPS ZS septum
    - Preferable for Multipole injection scheme (on- and off-energy)
  - Injection is easier for the operation modes other than tt
- Detailed study of beam-beam effects is necessary to decide the suitable injection scheme

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Summary table

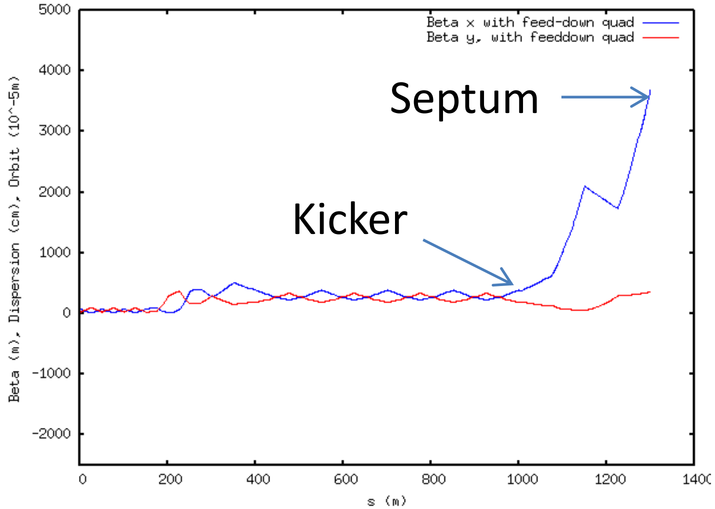
	Conventional	Multipole kicker
Residual oscillation (Injection beam)	Betatron / Synchrotron (On energy / Off energy)	Betatron / Synchrotron (On energy / Off energy)
Disturbance (Stored beam)	Betatron oscillation (in practice)	Emittance growth (intrinsic)
Wire septum	Essential	Mitigate emittance growth
Kicker specification	Feasible	Feasible
Separation, stored beam to septum	~15σ (5σ at the time of injection)	15σ

Backup slides

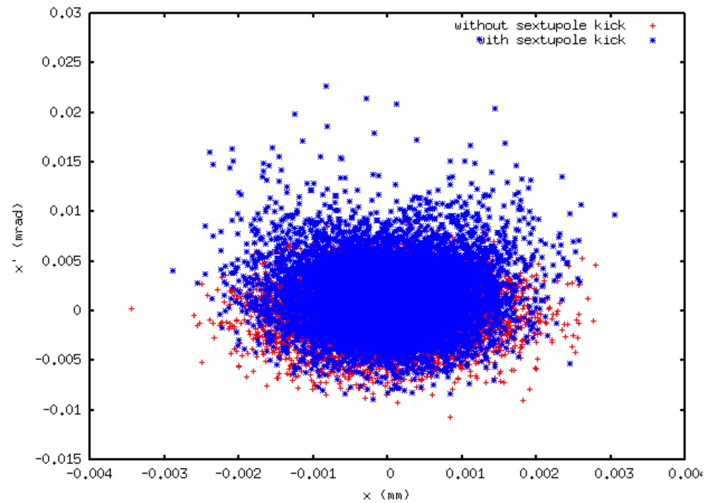
Influence of multipole kicker

- Mismatch
  - Injection beam is not only kicked by the multipole kicker but also de/focused due to feed-down quad component
  - Nonlinear kicker is essential for the lattice presented since the beam size becomes too big at the septum when normal sextupole kicker is employed
- Emittance growth
  - Since the injection point is rather close to the stored beam, the multipole kicker increases the stored beam emittance at the moment of top-up injection
  - Using a nonlinear kicker is assumed for the evaluation of the emittance growth, i.e. K2L is increased 1.5 times for the computation

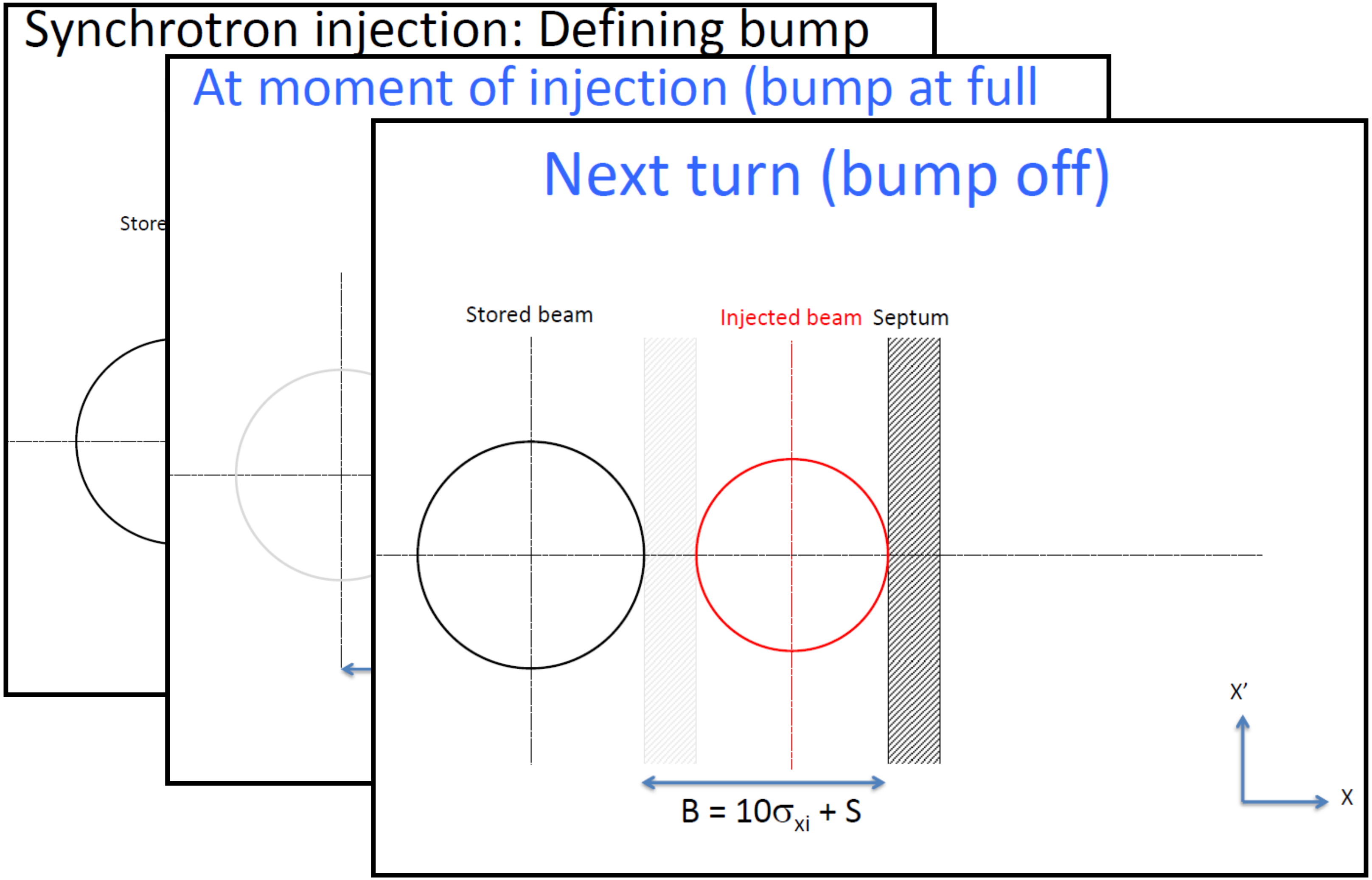
Beta function with feed-down quad (on-energy injection)



Particle distribution with and without sextupole kick at septum (off-energy inj.)



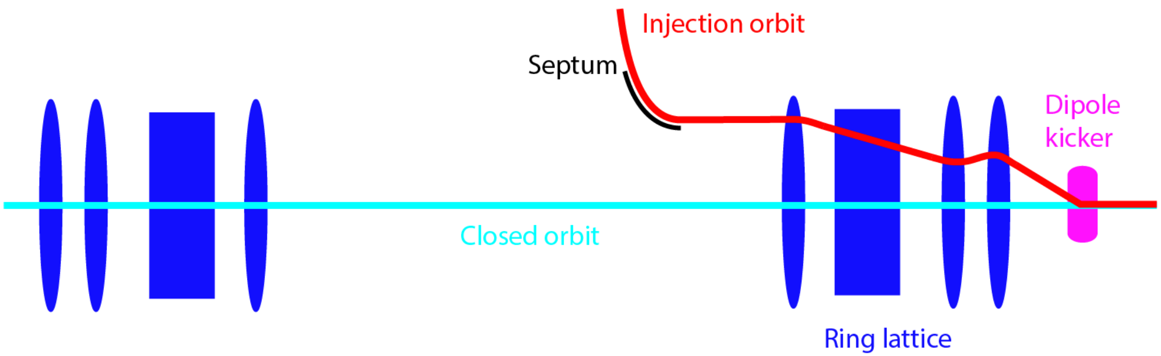
Required separation
Slides from B. Goddard

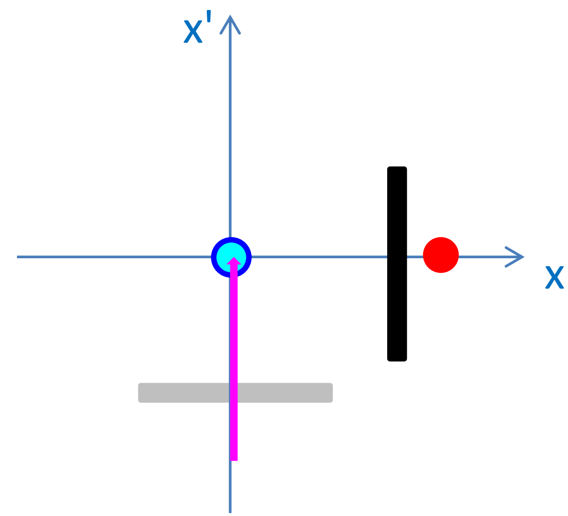


The requirement is basically the same for on-energy injection

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



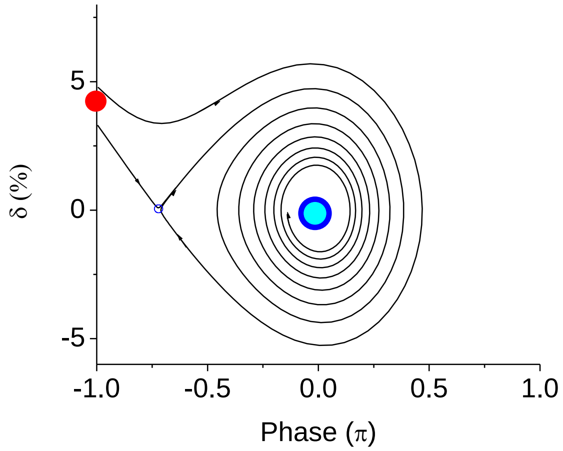


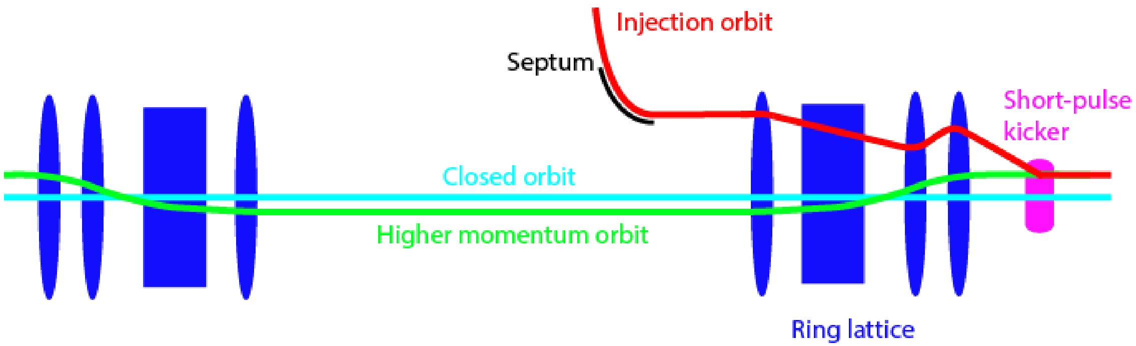
For FCCee, Booster may not provide an injection batch with full bunch charges…

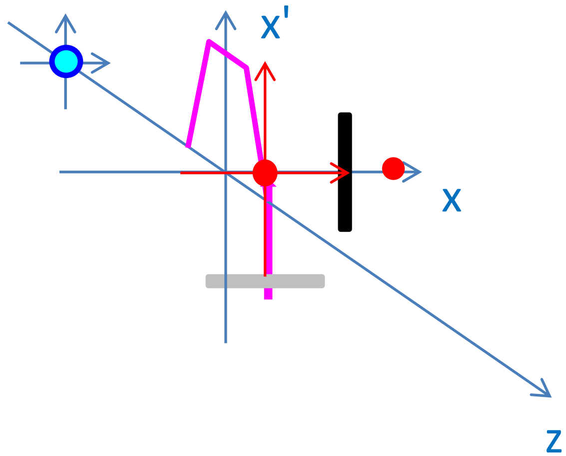
* L. Emery and M. Borland, Proc. PAC 2003, pp.256-258 (2003)

Longitudinal injection* - principle

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







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

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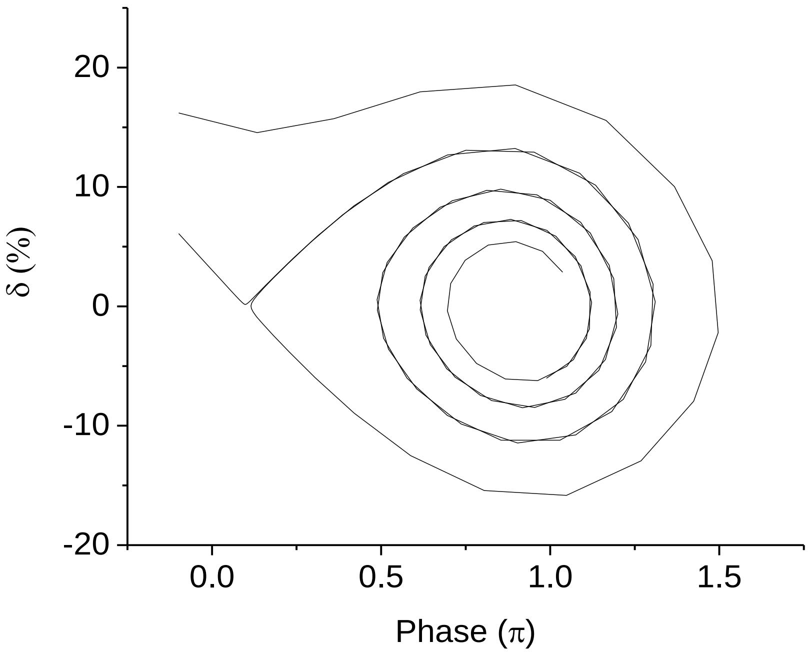
Longitudinal injection for FCC

Longitudinal 1-D tracking
with H mode parameters

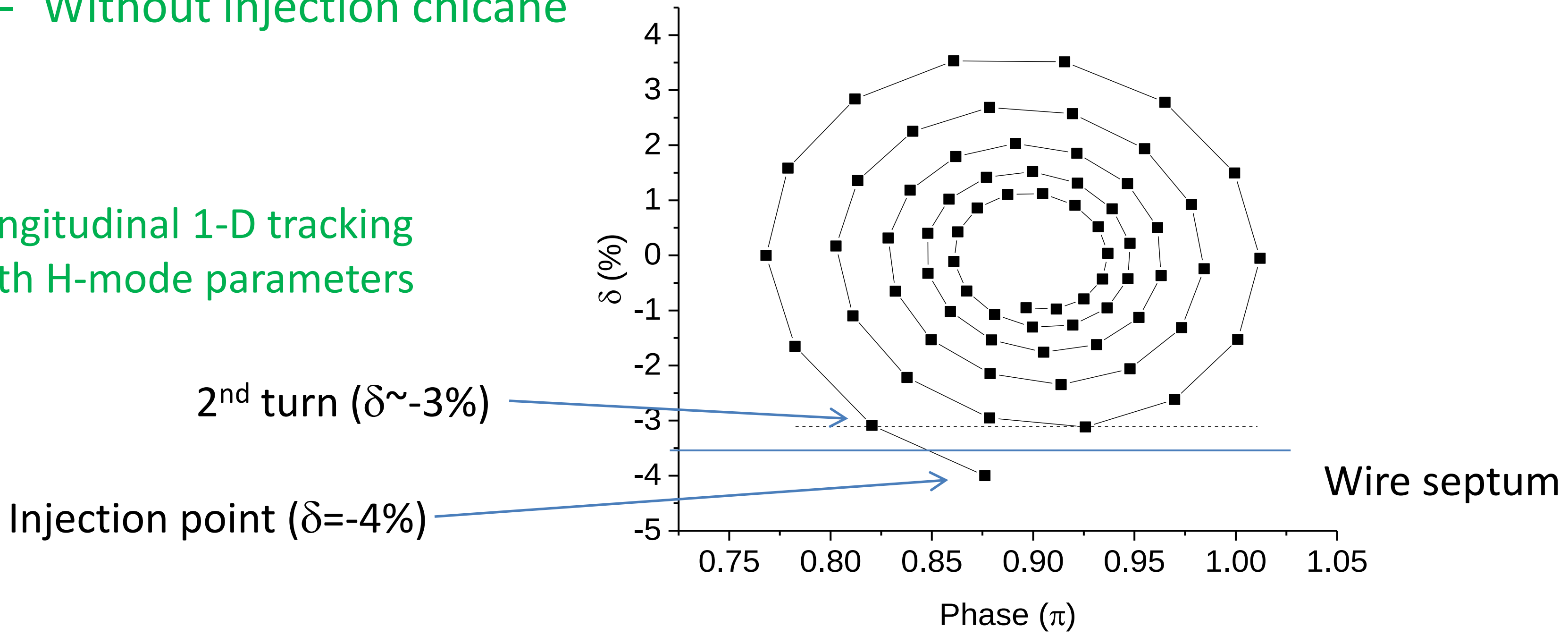


- Longitudinal phase space may not be suitable (too large bucket height)
- Short pulse kicker may be too challenging…
  - Fast decaying tail (~1 ns for 400 MHz RF)
  - Repetition (Bunch spacing corresponds to 4 MHz)

Kickerless injection

- 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



Not enough momentum aperture,
and the scheme is applicable only for H and tt modes...