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Longitudinal Top-up Injection for Small Aperture Storage Rings

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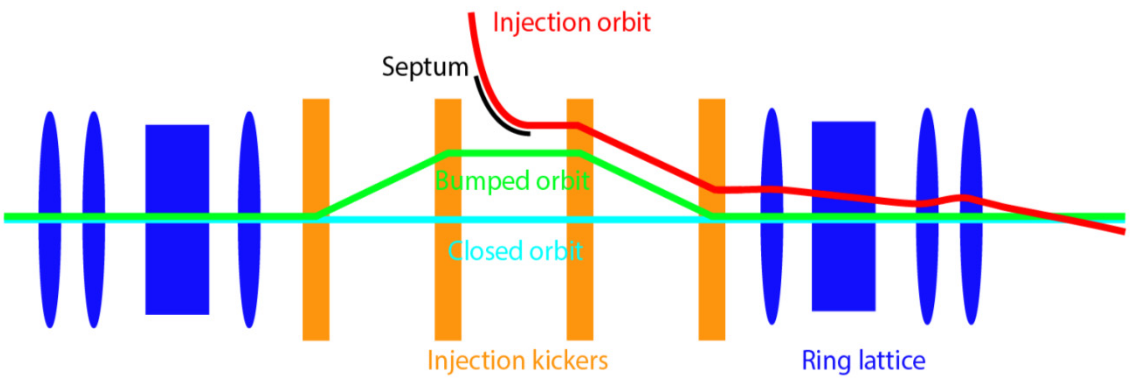
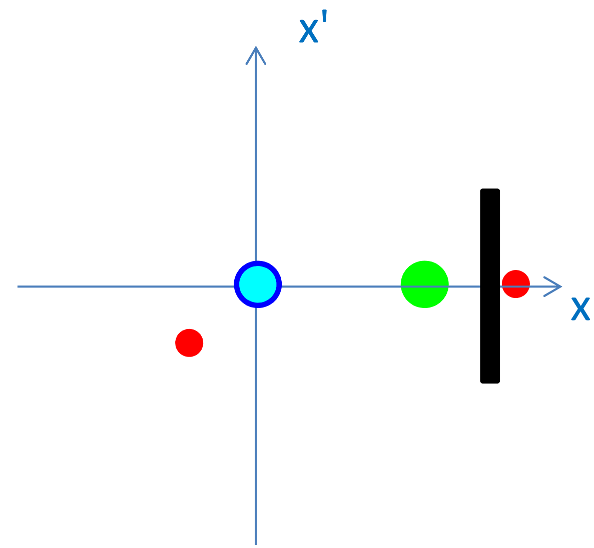
Introduction

- Lower and lower horizontal emittances (to be) achieved in 3rd generation light sources
  - Smaller physical/dynamic aperture available in corresponding low emittance storage rings (multi-bend achromat lattice) →Transversely on-axis
- Top-up injection for stable photon beam flux
  - Frequent injections to keep the e-beam current essentially constant →Top-up compatible (Transparent to circulating bunches)
  - Injection chicane introduces adverse beam disturbances although it is transparent to circulating bunches in principle… →Without injection chicane

Conventional Scheme

- Septum + Injection chicane (pulsed)
  - Off-axis injection*
  - Transparent to circulating bunches (in principle)
  - With injection chicane

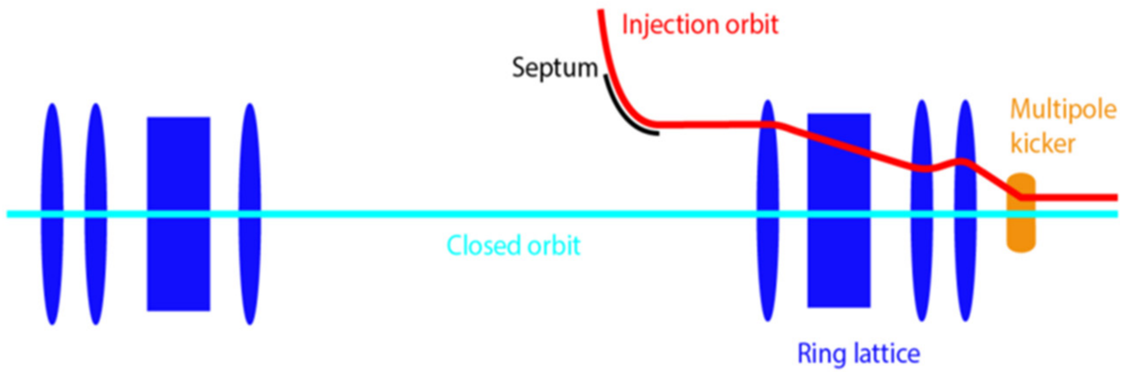


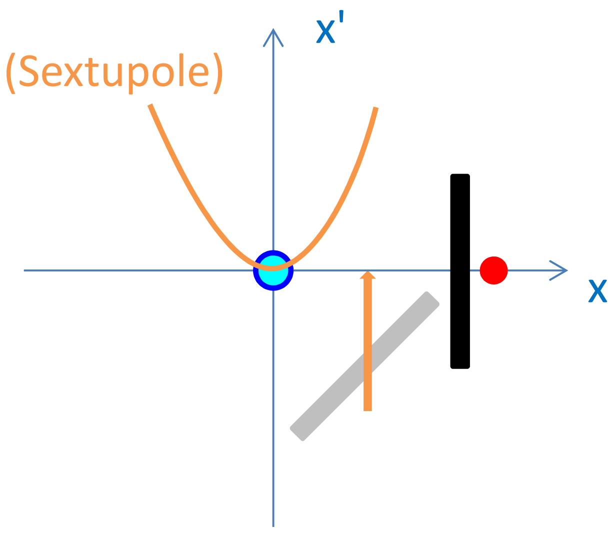


*Can be on-axis injection when the injection section is dispersive
(P. Collier, *Synchrotron phase space injection*, see backup slide)

Multipole kicker injection*

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

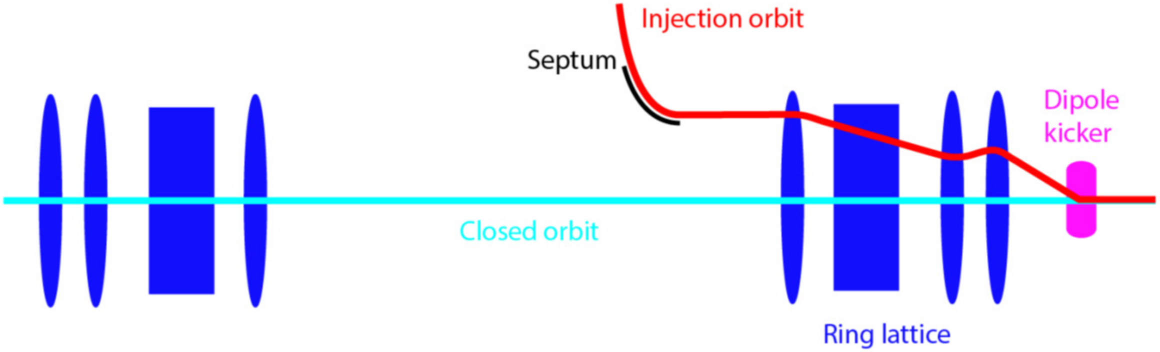


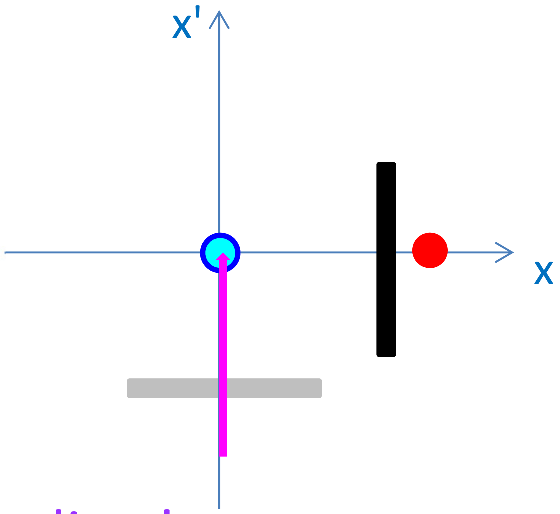


* H. Takaki et al., Phys. Rev. ST Accel. Beams, 13, 020705 (2010)

Swap 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



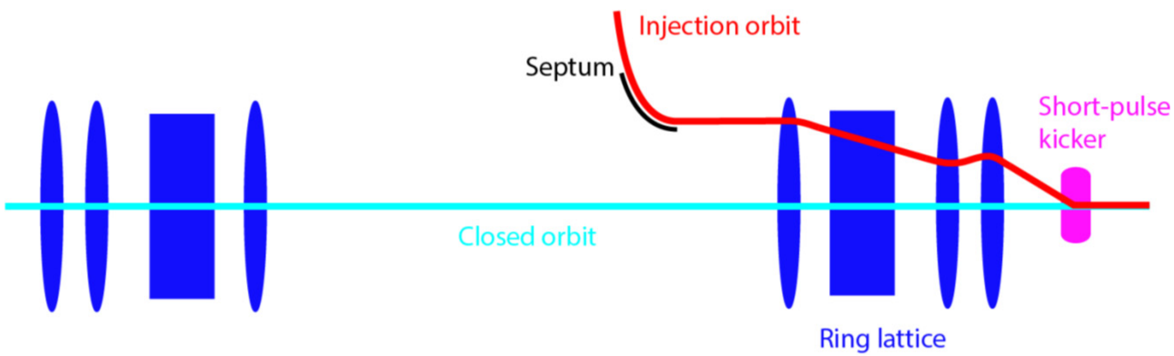


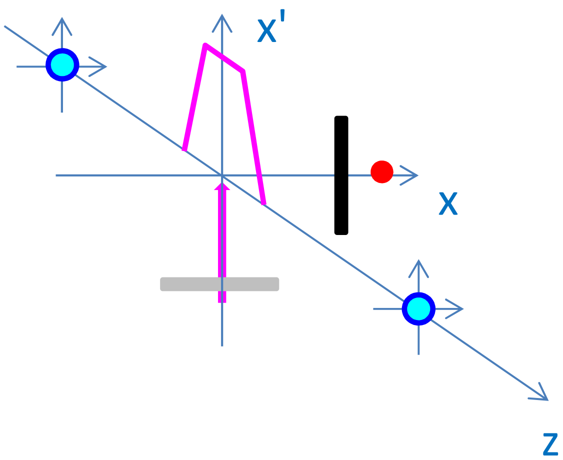
It fulfills our goals but may include some disadvantages…

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

Longitudinal Injection

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





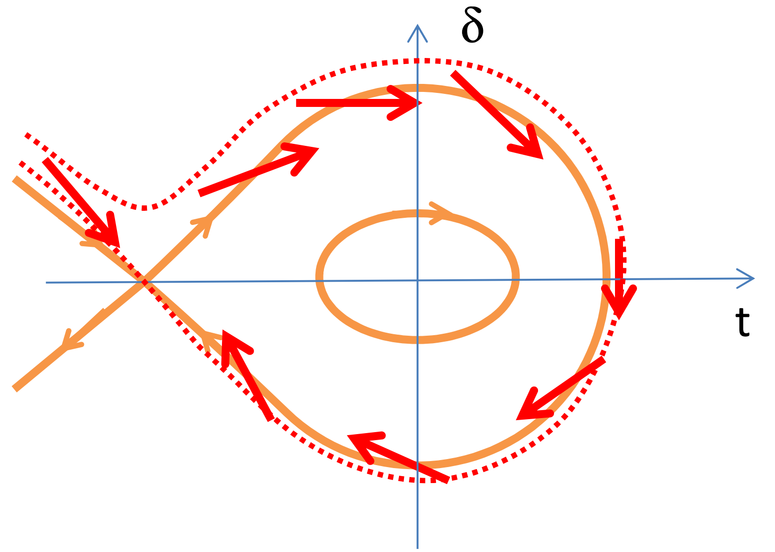
The injected bunch will be accepted?

Longitudinal Acceptance (1)

- Equations of motion & RF bucket:

$$\frac{dz}{dt} = -c\alpha\delta$$

$$\frac{d\delta}{dt} = \frac{eV - U_0(1+3\delta+3\delta^2+\delta^3)}{E_0 T_0}$$



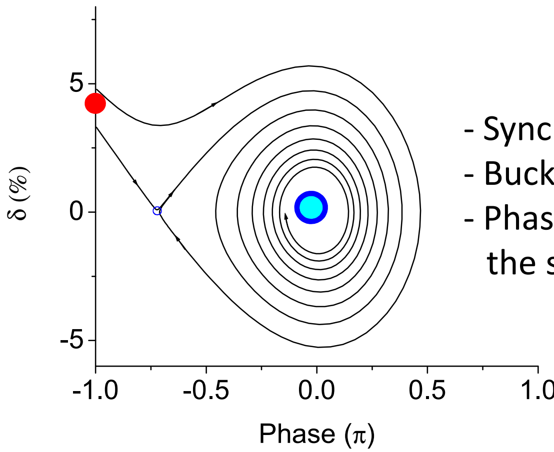
z : Longitudinal position
c : Speed of light
α : Momentum compaction
δ : Relative momentum deviation, $\frac{dP}{P} \sim \frac{dE}{E}$
e : Electron charge
V : RF voltage
U_0 : Radiation loss per turn for the nominal energy
E_0 : Nominal beam energy
T_0 : Revolution period

RF bucket is modified
by the energy dependent terms

Longitudinal Acceptance (2)

- "Golf-club" acceptance
  - Well known for the cases with acceleration*
  - Because of energy dependent radiation loss in electron storage rings

Long. acceptance plot with synchrotron radiation loss



- Synch. phase = 155 deg.
- Bucket height ~5 %
- Phase=0 corresponds to the synch. phase

It allows an injection between two circulating bunches at the expense of slightly higher injection energy!

(Need to match the injection orbit to the off-momentum closed-orbit)

* e.g., P. M. Lapostolle, Los Alamos National Laboratory, LA-11601-MS (1989)

Simulation (1)

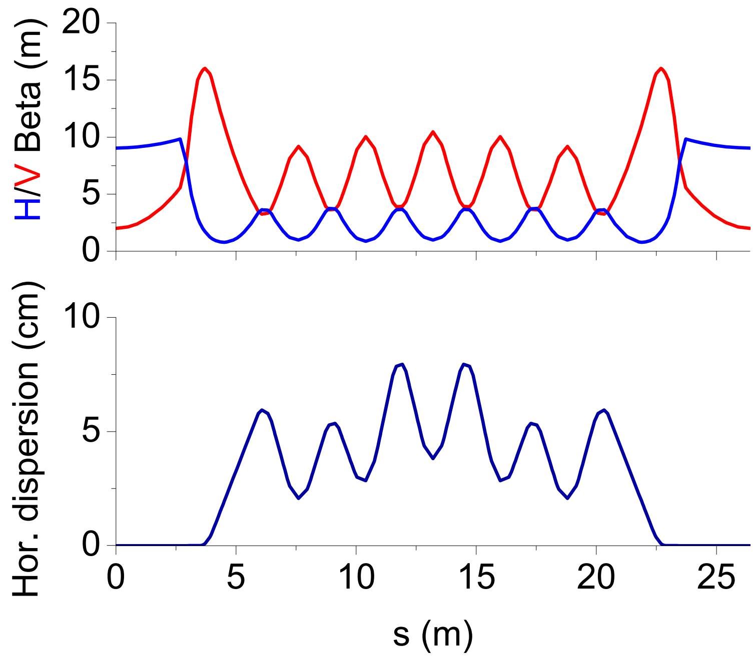
- Application to MAX-IV 3 GeV lattice*/**

Relevant parameters with 2 damping wigglers

Parameter	Value	Unit
Circumference	528	m
Beam energy	3.0	GeV
Momentum compaction	3.07×10^{-4}	-
Radiation loss per turn	0.58	MeV
Damping time Hor./Ver./Long.	12 / 18 / 12	ms
RF frequency	100	MHz
RF voltage (Fundamental/3HC)	1.42/0.423	MV
Hor. equilibrium emittance	0.25	nm
Betatron tune, Hor./Ver.	40.20 / 16.28	-

Parameters corresponding to ±5% bucket height

7BA lattice functions



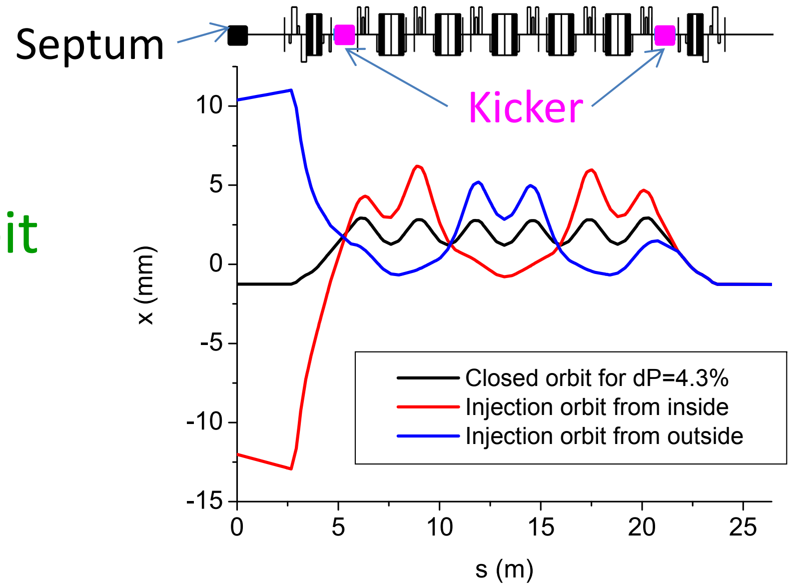
* Lattice file, courtesy of S. C. Leemann

** Multipole injection is planned

Simulation (2)

- On-axis injection (Fast injection)
  - Septum + 2 short pulse kickers, ~1.8 mrad each

Injection orbit matched to the off-momentum closed-orbit



Separation of ~10 mm with reasonable kick angle. Straight section may be available for one more beamline if the septum is situated at the end.

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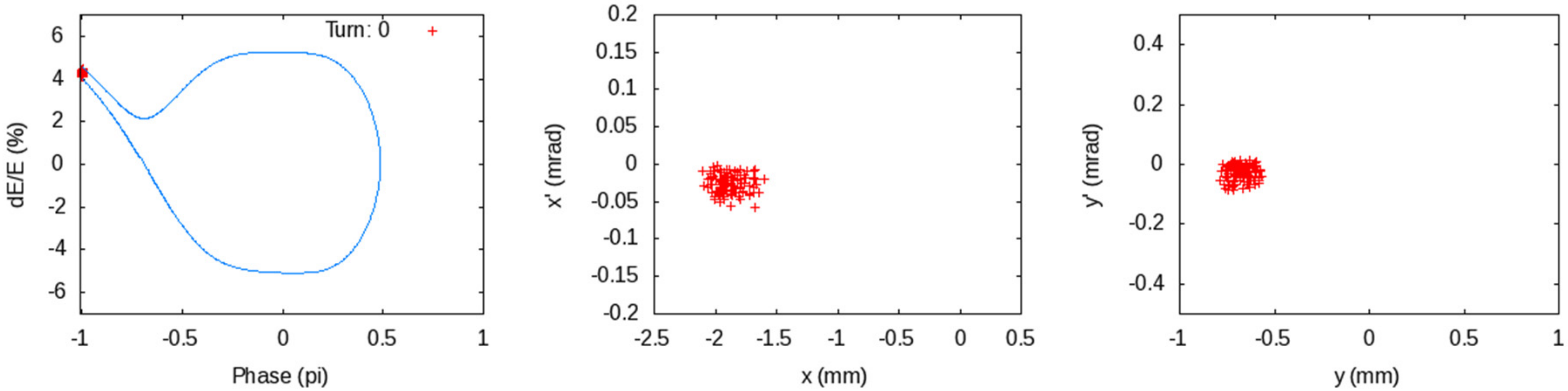
Simulation (3)

- Tracking (Elegant code*)



Errors: Beta-beat, rms, 3~6% (H/V) → Normal resonances
Sextupole ver. misalignment 50 mm rms
Quad roll error, 0.2 mrad rms → Linear coupling
Sextupole and Octupole roll error, 0.2 mrad rms → Skew resonances
+ Injection error, 0.5 mm at the middle of straight section (βx~9 m, βy~2 m)

Injection beam**: Normalised emittance 10 μm, Energy spread 0.1%, Bunch length 5 ps

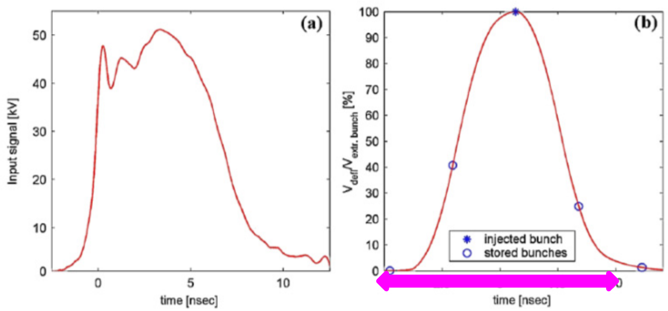
40 machines generated: 100% efficiency for 39 (95% for 1)

Robust against machine imperfections

*M. Borland, Advanced Photon Source LS-287 (2000)
**S. C. Leemann, Phys. Rev. ST Accel. Beams, 15, 050705 (2012)

Short pulse kicker (1)

- Short pulse kicker R&Ds
  - T. Naito et al., NIM-A, 571,p.599 (2007)
  - D. Alesini et al., PRSTAB, 111002 (2010)



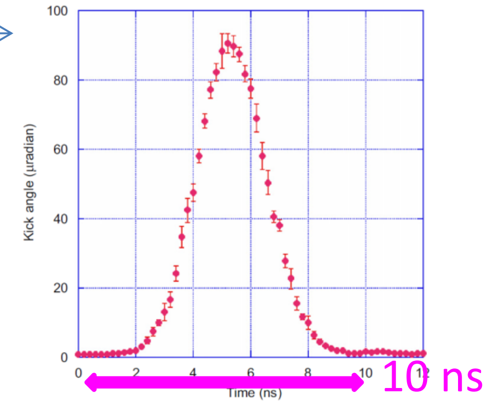
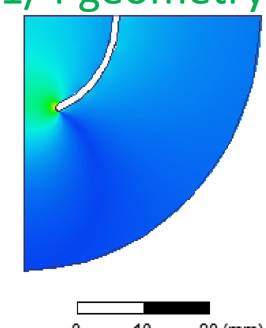


Fig. 9. Beam kick profile as a function of the kick pulse timing measured by the TBT-BPM. The kick angles were calculated from the betatron oscillation amplitude.

- Preliminary FEM field simulation
  - Pulser voltage 28 kV
  - Strip-line aperture ~27 mm diameter
  - Integrated kick angle ~1.8 mrad@3 GeV
  - Length ~1 m
  - Matched to 50 Ω

1/4 geometry



Kicker with pulse length of <10 ns (100 MHz) has been developed

Enough kick angle for MAX-IV example can be achieved

Short pulse kicker (2)

- Very short pulser (spec. from a company)

Output voltage	Rise time	Pulse width	Max repetition rate
2 kV	0.1-1 ns	0.2 - 3 ns	300 kHz
5 kV	0.1-1 ns	0.2 - 3 ns	200 kHz
10 kV	0.1-1 ns	0.2 - 3 ns	100 kHz
20 kV	0.1-1 ns	1 - 2 ns	10 kHz
50 kV	0.1-1 ns	1 - 2 ns	2 kHz
100 kV	0.1-1 ns	1 - 2 ns	1 kHz
200 kV	0.2-1 ns	1 - 2 ns	1 kHz

Very short pulser is commercially available
→ "Nano-second kicker" is feasible
→ Applicable to the rings with a common 500 MHz RF system

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Comparison

- Longitudinal injection and Swap injection fulfill our goals

  Pros and Cons

	Longitudinal injection	Bunch-by-bunch swap injection	Bunch train swap injection
On-axis injection	Yes (+dP)	Yes	
Transparent to circulating bunches	Yes	Pseudo	
Injection chicane	No	No	
Injector	Small long. emittance	Full bunch charge injector	Another ring required
Top-up dead-band	As in normal top-up	Wider dead-band	As in normal top-up
Kicker pulse length	~ bunch spacing	~ twice bunch spacing	Long flat-top (?)
Beam loss (radiation)	As in normal top-up	A few orders of magnitude higher	~twice

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Summary

- We investigated longitudinal injection scheme:
  - On-axis transversely and top-up compatible
  - “Golf-club” acceptance allows one to inject a bunch between two circulating bunches
  - Robust against machine imperfections
  - Required short pulse kicker is feasible

Thank you for your attention!

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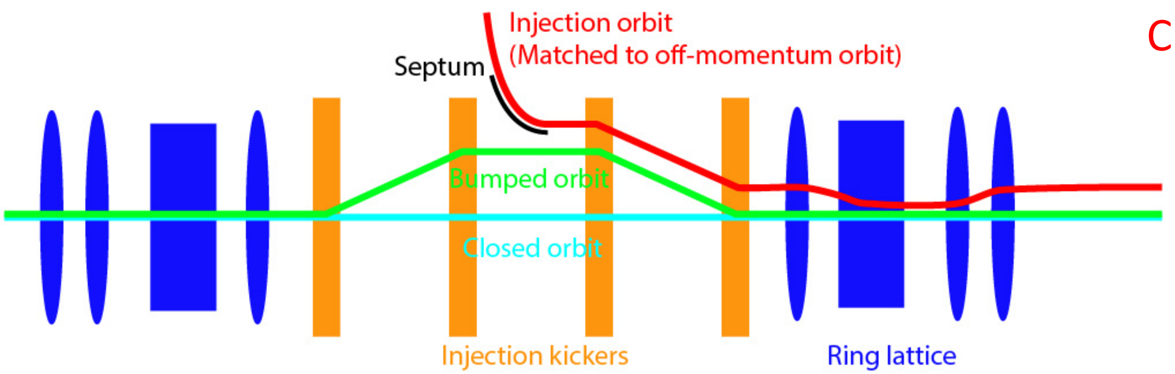
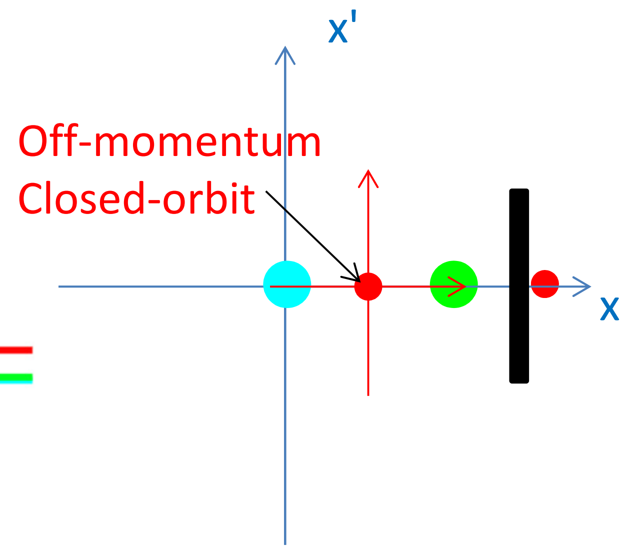
Backup slide

Synchrotron phase space injection*

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





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