

Longitudinal off-energy Injection

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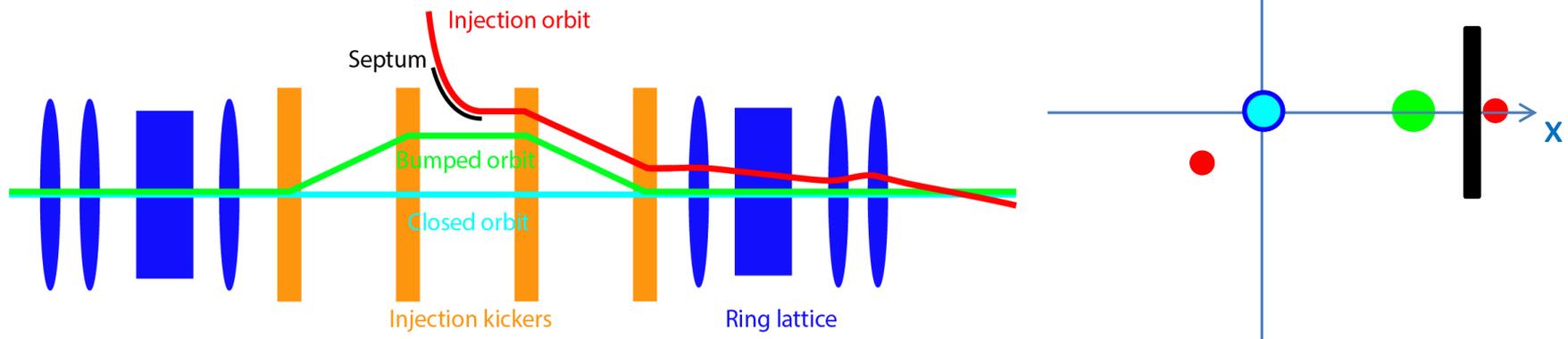
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Introduction

- 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
 - Kicker bump introduces adverse beam disturbances although it is transparent to circulating bunches in principle... → Transparent to the circulating bunches, ideally without kicker bump

Conventional Scheme

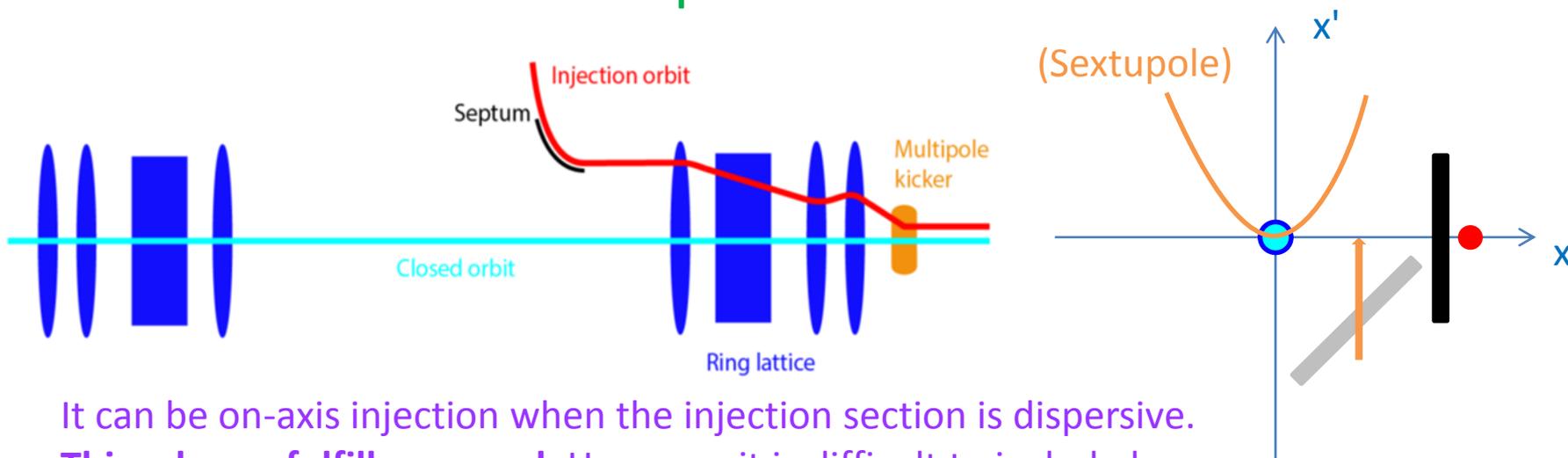
- Septum + Injection chicane (pulsed)
 - Off-axis injection*
 - Transparent to circulating bunches (in principle)
 - With kicker bump



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

Multipole kicker injection*

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

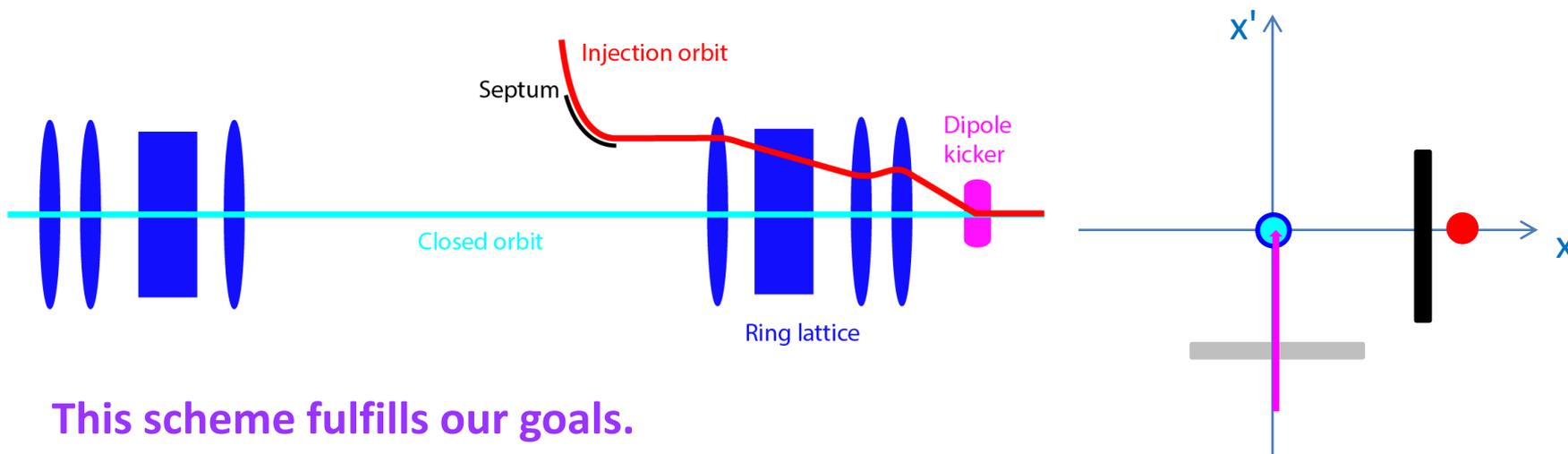


It can be on-axis injection when the injection section is dispersive. **This scheme fulfills our goal.** However, it is difficult to include large dispersion in small emittance (light source) lattice...

* 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 kicker bump



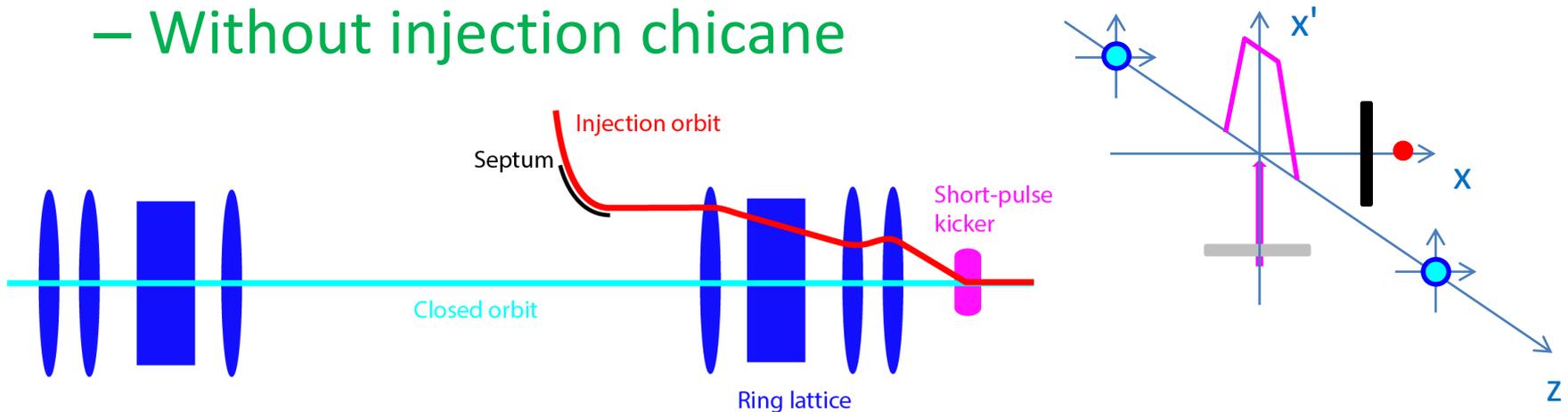
This scheme fulfills our goals.

It is noted that full bunch injector or accumulator is required.

* 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:

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

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

z : Longitudinal position

c : Speed of light

α : Momentum compaction

δ : Relative momentum deviation, $\frac{dP}{P} \sim \frac{dE}{E}$

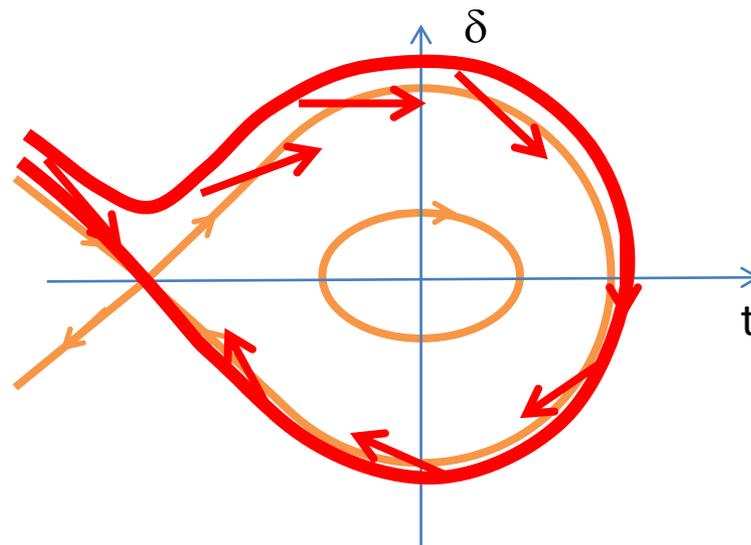
e : Electron charge

V : RF voltage

U_0 : Radiation loss per turn for the nominal energy

E_0 : Nominal beam energy

T_0 : Revolution period

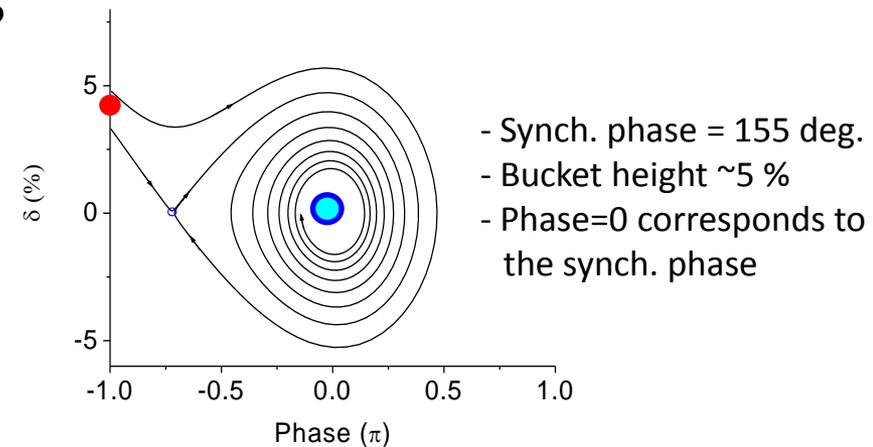


RF bucket is modified
by the energy dependent terms

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

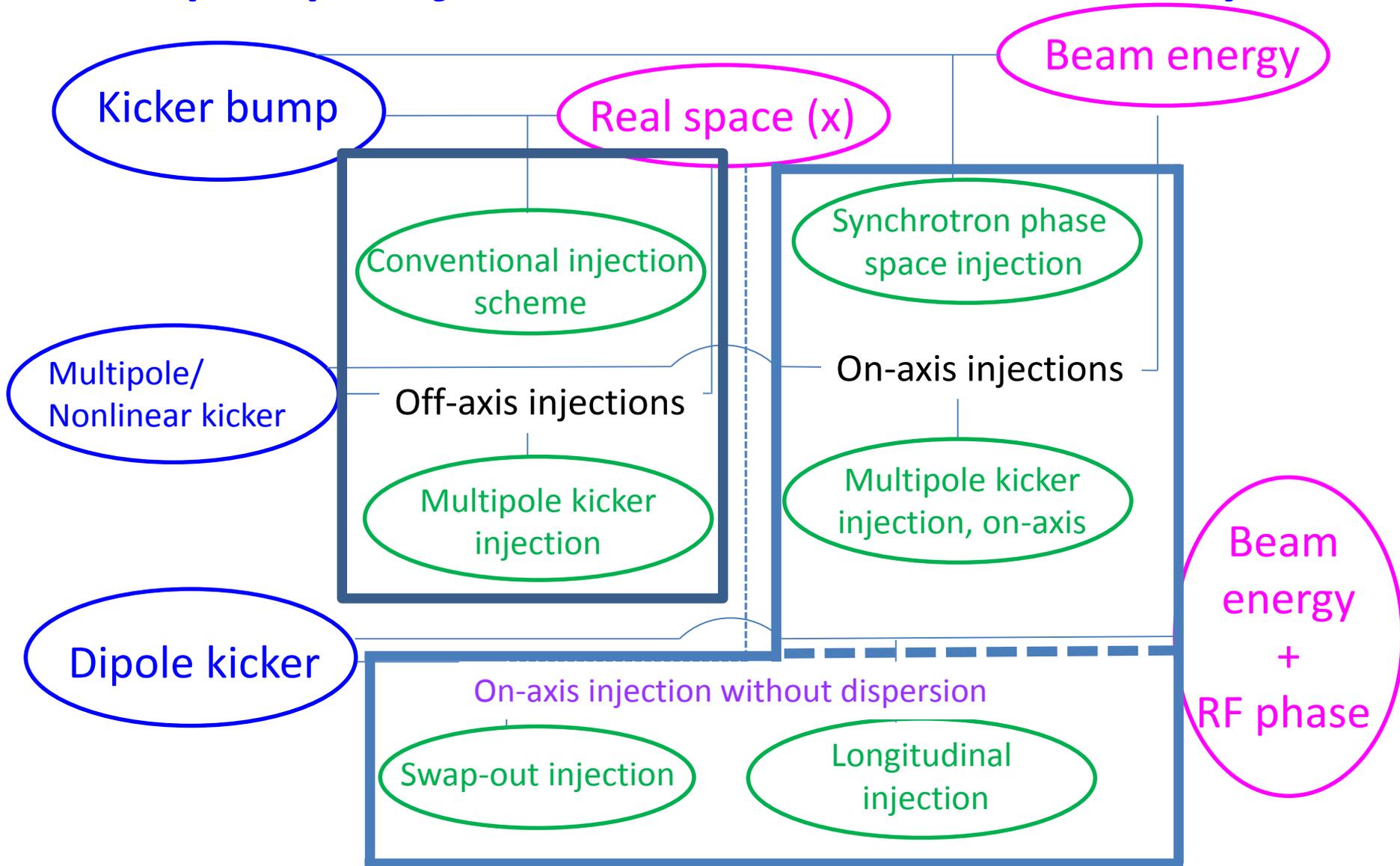


It allows an injection between two circulating bunches at the expense of slightly higher injection energy!
 (Need to match the injection orbit to the off-momentum closed-orbit)

* Low energy part of proton accelerator

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

Top-up injection scheme “family”



Simulation (1)

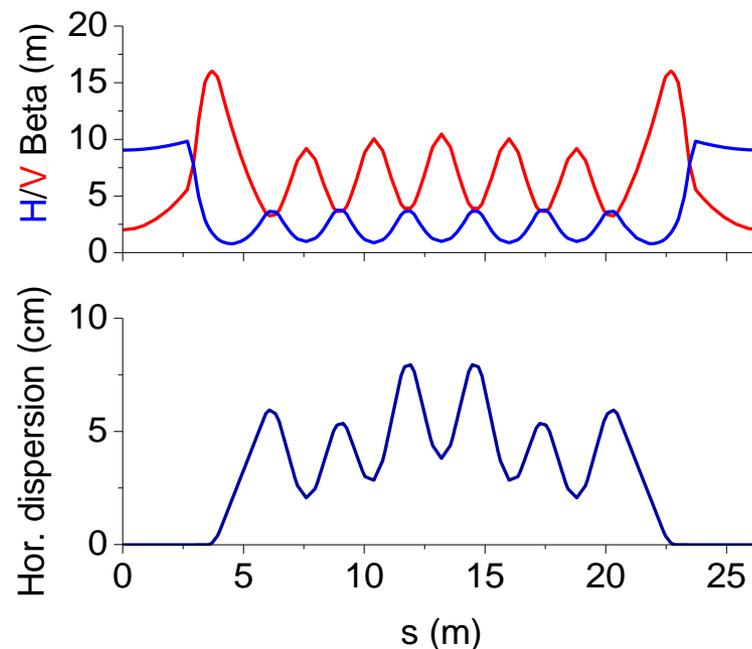
- Application to MAX-IV 3 GeV lattice^{*/**}

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 $\pm 5\%$ bucket height

7BA lattice functions



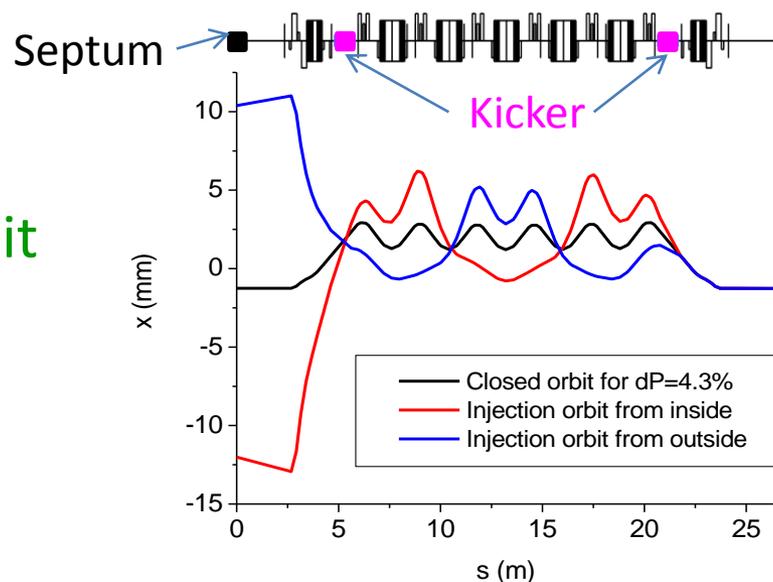
* Lattice file, courtesy of S. C. Leemann

** Multipole kicker injection is baseline scheme

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.

Injector

- Longitudinal injection requires injection beams with rather short bunch and small energy spread...
- There is “new trend” in science labs, which fulfils the injector requirement: Light source + FEL
 - PSI: SLS + SwissFEL
 - DESY: PETTRA + European X-FEL
 - Elettra: Elettra + Fermi
 - RIKEN: SPRing-8 + SACLA (New injection line is built)
 - Lund: MAX IV + Short pulse facility (Used as injector by design)
 - And more!

Short pulse kicker

- Rough cost estimation (F. Marcellini)
 - 100k Euro for MAX IV application simulated
 - 20k per pulse generator (4 needed)
 - 20k for stripline and vacuum components
- Developments of short pulse kicker
 - Not specifically for longitudinal injection but for other applications
 - Continuously on-going; picked up activities:
 - T. Naito et al., NIM-A, 571,p.599 (2007)
 - D. Alesini et al., PRSTAB, 111002 (2010)
 - Nakamura et. al., Proc. PASJ (2014)

Summary

- Longitudinal injection scheme:
 - “Golf-club” acceptance allows us to inject a bunch between two circulating bunches
 - Fully transparent top-up injection scheme
 - Requirements, namely off-energy acceptance together with RF bucket height, are essential for light sources for decent beam lifetime (not for injection)
 - Robust against machine imperfections; On-axis injection
 - Short pulse kicker developments are on-going, not only for this scheme but in general for injections and other applications