Injection:
Electron (and positron) beams

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Introduction

- Electron and positron rings
  - Colliders (e^+, e^-)
  - Light sources (e^-)
  - Synchrotrons (e.g. Booster rings of above applications)
  - Industrial machines, etc.
- Top-up injection
  - Keeps beam current essentially constant
  - Keeps maximum luminosity production / photon beam flux in colliders / light sources
- Non top-up injection
  - Non top-up injection may be performed simply with septa and dipole kickers (Single turn “fast” injection)

The main scope of the lecture is Top-up injection

Non top-up injection is trivial for electron beams (at least on paper)

Top-up injection at SLS

- Outline
  - The beam current is kept in a range of 400-402 mA during the operation
  - 500 MHz RF system is equipped
    - 390 RF buckets out of 480 (Circumference =288 m) are filled
  - Booster cycle is 3 Hz, and top-up injection is bunch by bunch
  - Filling pattern feedback is applied to realise a flat charge distribution
- A movie is shown in the lecture

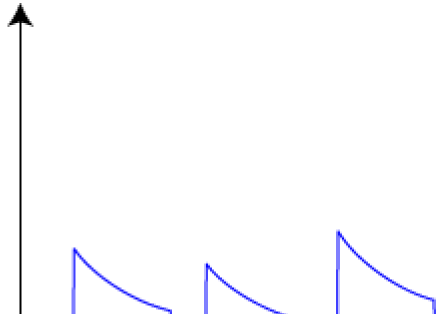
Brief history of top-up injection (1)

- 1980’s: First top-up injections in colliders [1]
  - With physics detectors off
  - Integrated luminosity gain due to shorter injection time
- 1990’s: Further developments mainly in KEKB and PEP colliders [2]
  - With physics detectors on
  - Almost constant beam currents, maximising integrated luminosity
- 1990: First top-up injection in the light source SORTEC [3]
- 2000- : Most light sources employ top-up injection [4]

Top-up injection has been standard
for colliders and light sources

Brief history of top-up injection (2)

- Beam current & Luminosity in colliders
  - No top up (Right top)
  - Top up with detectors off (Left bottom)
  - Top up with detectors on (Right bottom)



(b) Continuous injection mode (Feb. 2005-).

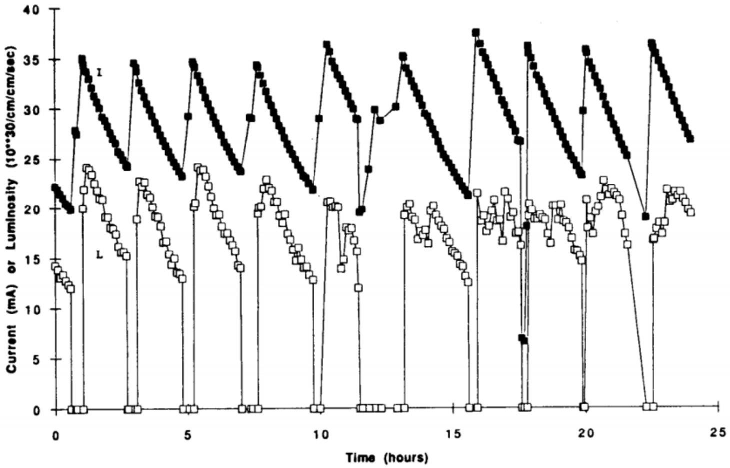


Figure 7 PEP beam current and luminosity for 24 hours (May 1985).

Figure taken from [1]

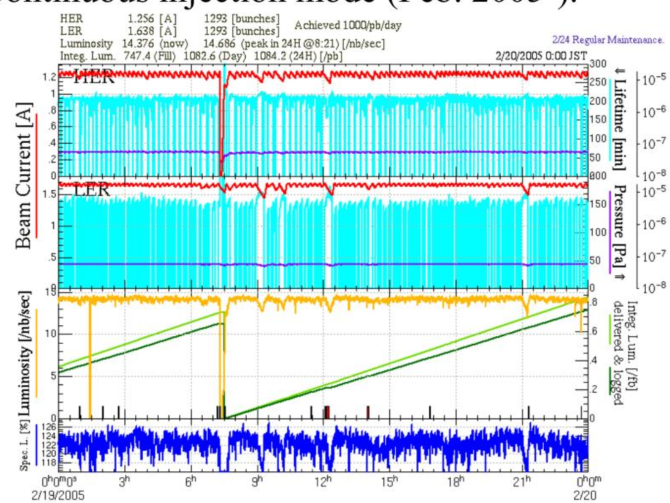
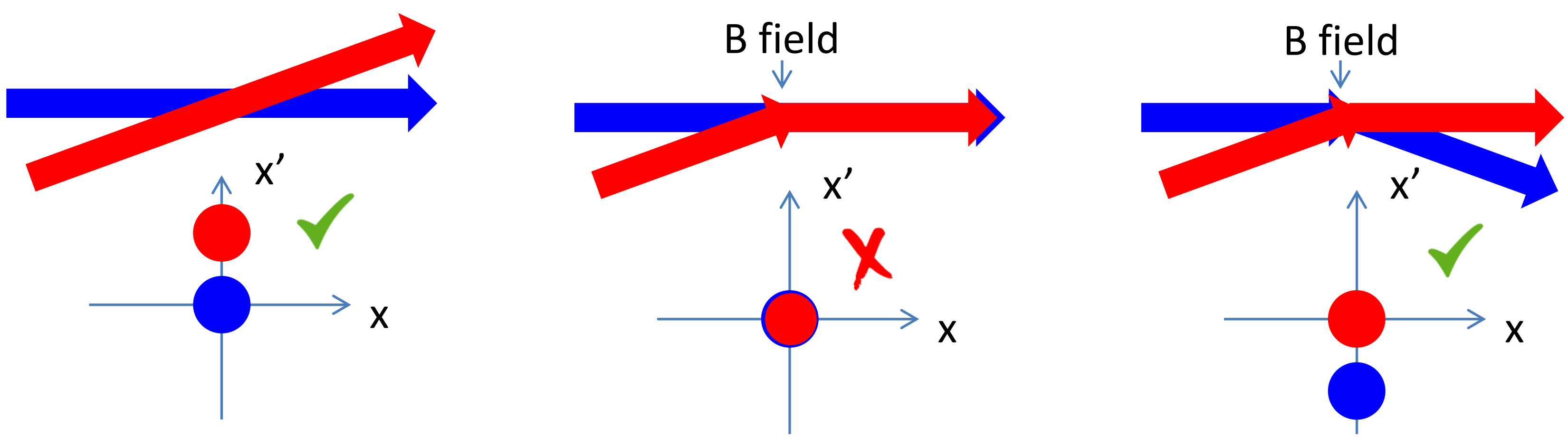


Figure 1: Typical KEKB operation in one day.

Figure taken from [5]

Physics behind top-up injection (1)

- Liouville's theorem (for accelerator physics)
  - Under the influence of conservative forces the density of the particles in phase space stays constant [6]
  - This is true for charged particles moving in magnetic field
  - For beam injection into rings, injection beam particles cannot overlap *in phase space* with the stored beam particles at the time of injection

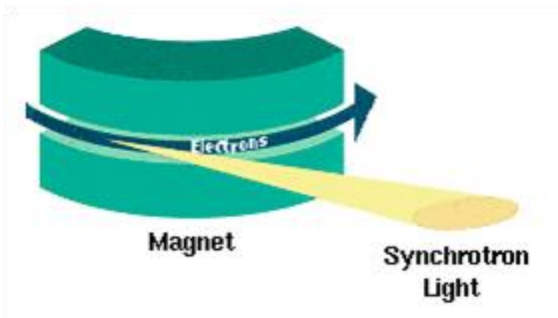


Top-up injection cannot continue as the entire phase space will be filled with particles!?

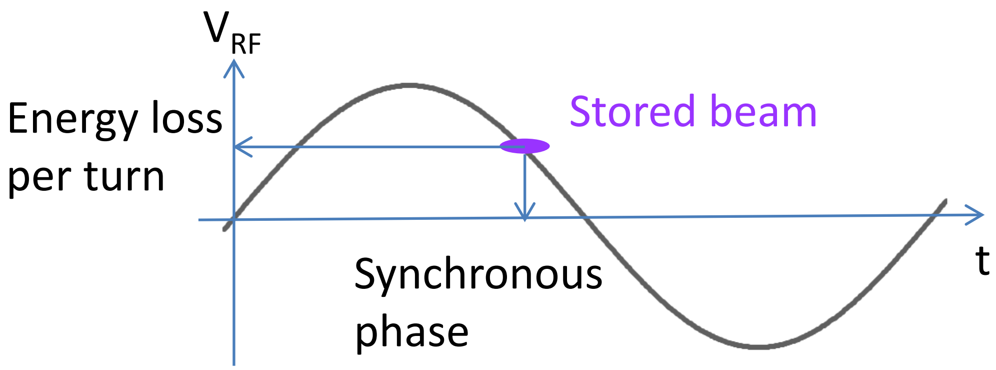
Physics behind top-up injection (2)

- Synchrotron radiation (SR) damping [6]
  - Photon emission when charged particle is *accelerated*
    - Bending field gives a transverse acceleration
    - Emission due to longitudinal acceleration is normally marginal
  - Particle energy loss $\propto \gamma^4/\rho$ (with transverse acceleration)
    - With γ and ρ being Lorentz factor and curvature radius
    - Can be significant for $e^{+/-}$ while marginal for hadrons
    - Makes system non-conservative
  - Energy loss is recovered by RF turn by turn

SR [Figure taken from Wikipedia]



Energy recovery by RF

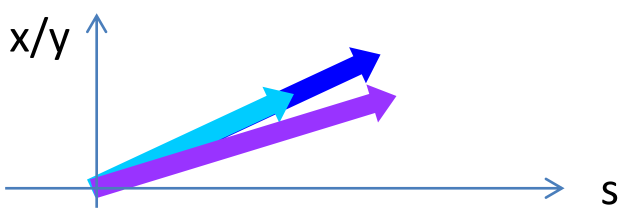


Physics behind top-up injection (3)

- Radiation damping in transverse plane (Betatron oscillation)
  - Longitudinal and transverse momenta loss due to SR while only longitudinal acceleration with RF
- Radiation damping in longitudinal plane (Synchrotron oscillation)
  - Energy loss due to SR is proportional to $(1+\delta)^3$, where δ is the fractional energy deviation ($\Delta E/E$)

SR damping, transverse

Initial Energy loss Energy recovered

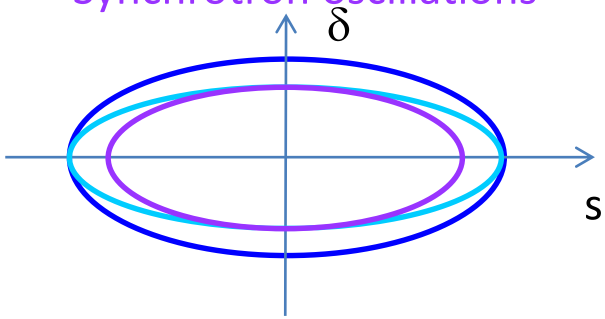


(Arrow = Particle momentum)

SR damping, longitudinal

Initial Energy loss+recovery

Synchrotron oscillations

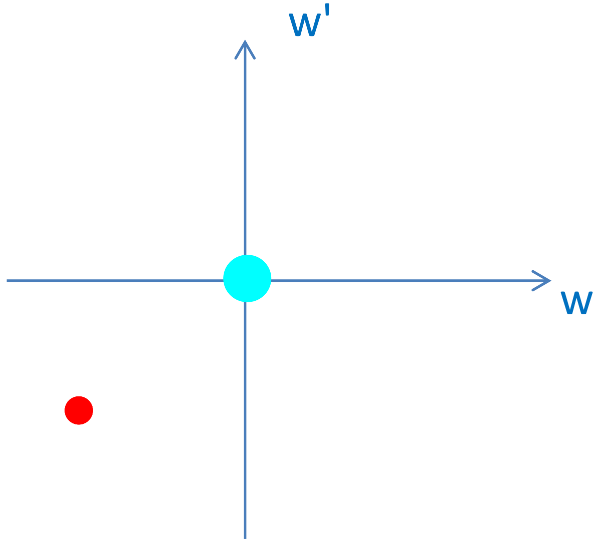


(Area of ellipse = Longitudinal emittance)

Note: Emittance will not be zero because the synchrotron radiation excites betatron and synchrotron oscillation at the same time. Equilibrium emittances are determined such that the damping and excitations cancel each other.

Physics behind top-up injection (4)

- Injection process (to be repeated!)



Thanks to SR damping, top-up injection can continue unlimitedly!

Note: For non top-up injection, the initial injection errors, namely mismatch and centroid offset, are to be "forgotten" in $e^{+/-}$ machines, while they have to be minimised in hadron machines.

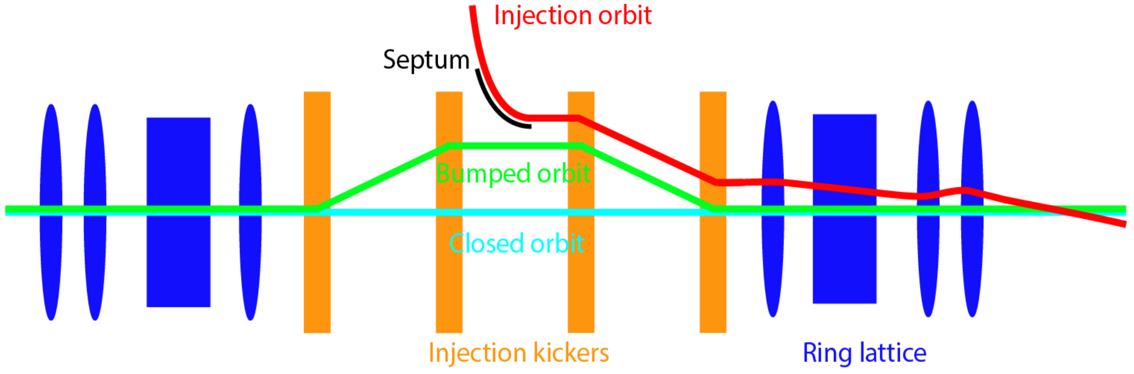
Top-up injection schemes

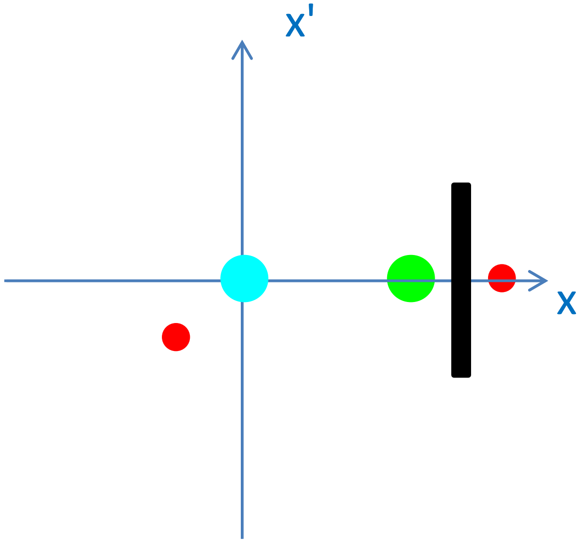
	Separation	Kicker	Disturbance to stored beam
Conventional injection	Transverse or Longitudinal	Orbit bumper (Dipole kickers)	Dipolar oscillation
Multipole kicker injection	Transverse or Longitudinal	Multipole kicker	Multipolar oscillation
Swap-out injection	"Transverse"	Dipole kicker	Dipolar and multipolar oscillations
Resonance injection	Transverse	Multipole magnets	Multipolar oscillation
Longitudinal injection	Longitudinal	Dipole kicker	None

Separation planes × Kicker magnets
→ Various injection schemes

Conventional injection (1)

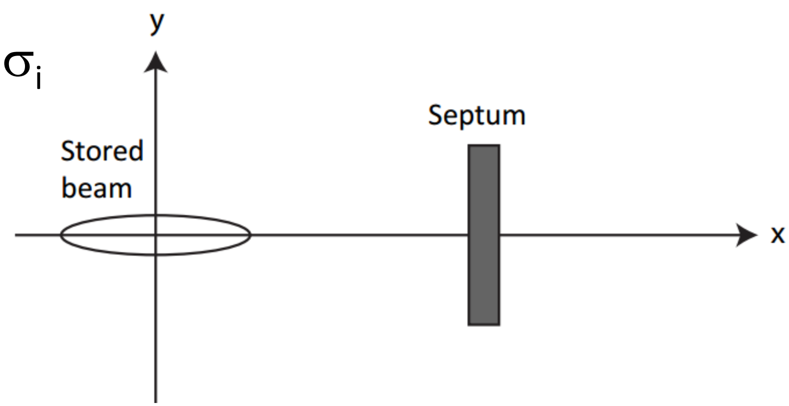
- Motivation: First realisations of top-up injection
- Injection scheme
  - Hardware: Septum + Kicker bump (a series of kickers)
  - Separation: Transverse plane

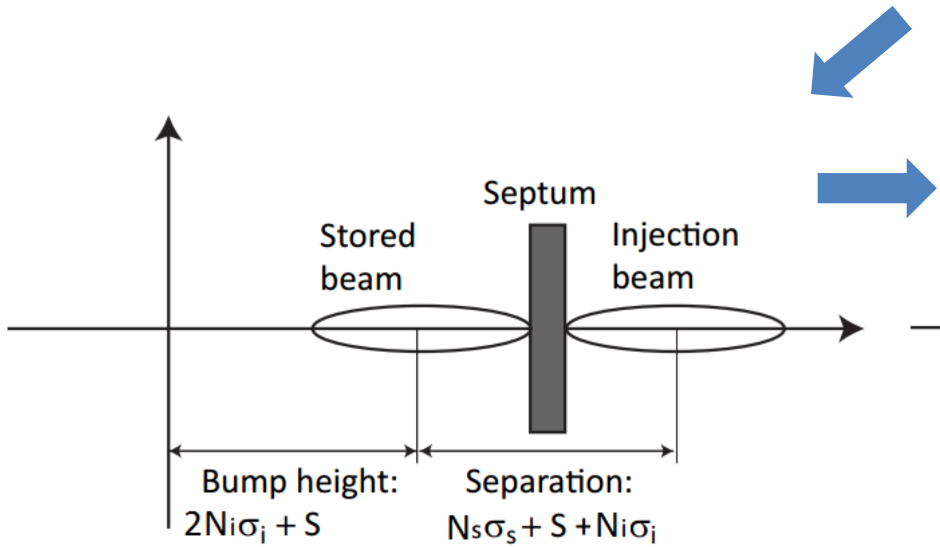


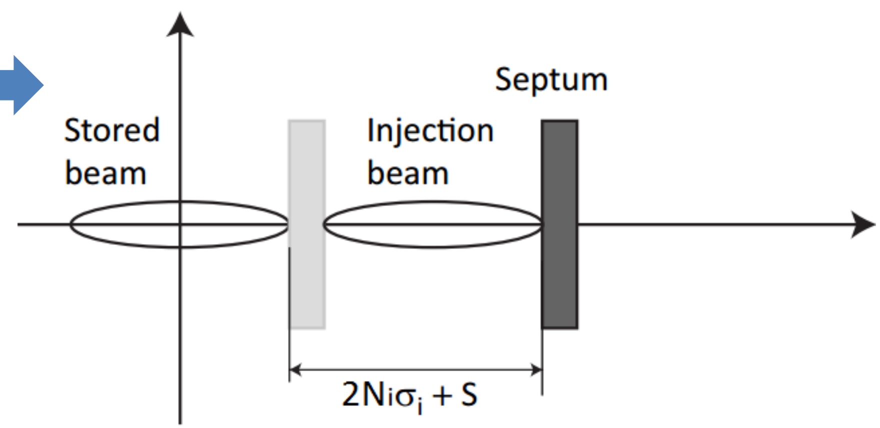


Conventional injection (2)

- Parameters to be considered
  - Stored and injection beam sizes: σ_s, σ_i
  - Septum thickness: S
  - Clearances in units of beam size: N_s, N_i



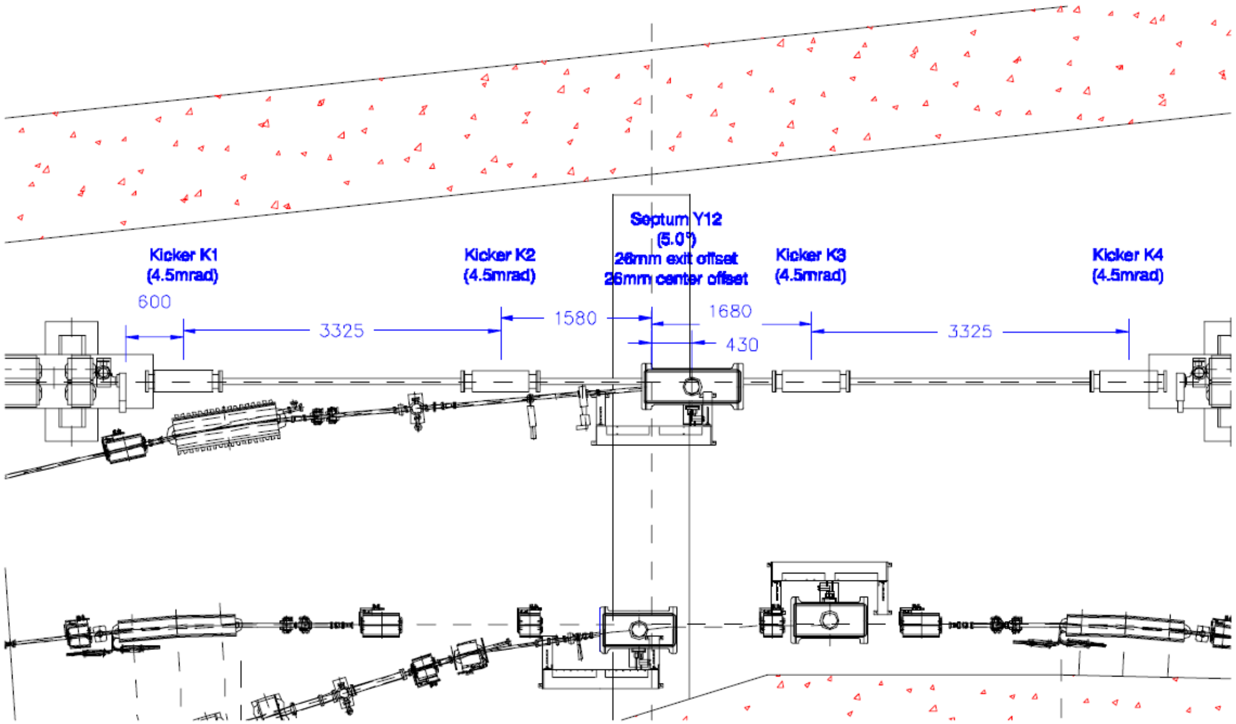




Minimum bump height is found from these parameters

Conventional injection (3)

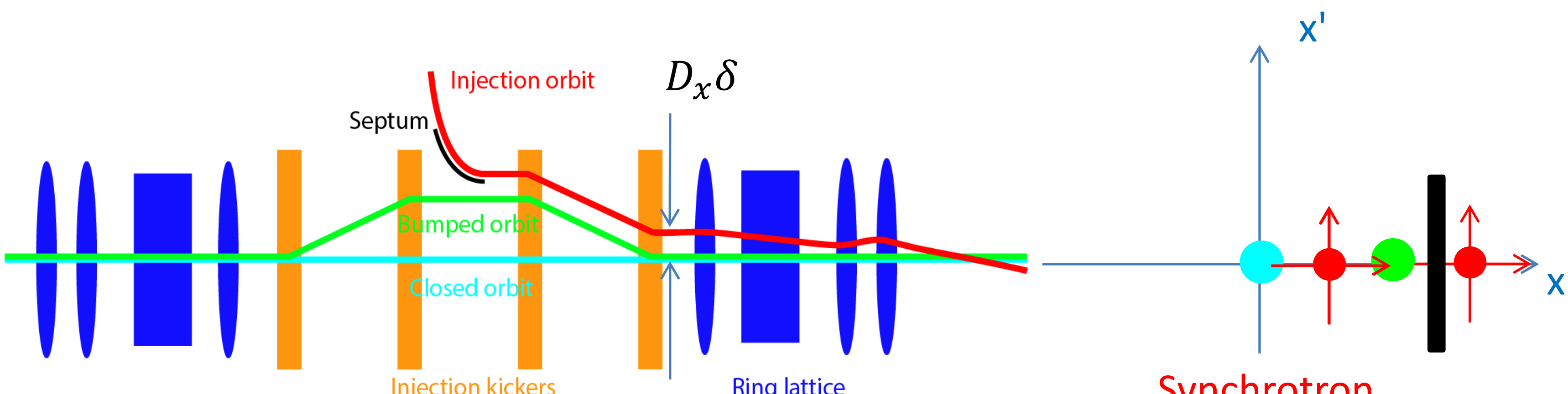
- Example – Swiss Light Source



Straight section ~ 10 m
Circumference = 288 m
Revolution period ~ 1 μs
Beam energy = 2.4 GeV
Kicker bump: 6 μs half sine
Septum: 70 μs full sine

Conventional injection (4)

- Synchrotron phase space injection [7] with off-energy injection beam
  - Motivation: Higher injection efficiency. Less background for physics detector are expected in collider
- Injection scheme
  - Hardware: Septum + Kicker bump
  - Separation: Longitudinal plane (Energy offset)
  - Spatial separation at the septum is still necessary and achieved through finite dispersion function: Separation $= D_x\delta$
  - By adjusting the injection beam energy and orbit to match with the above separation, the injection beam can be situated onto the off-energy closed orbit



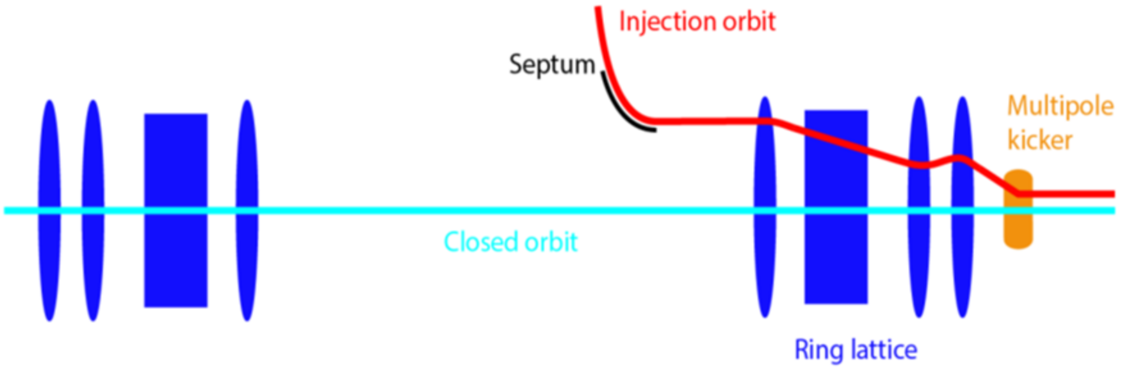
Synchrotron oscillation

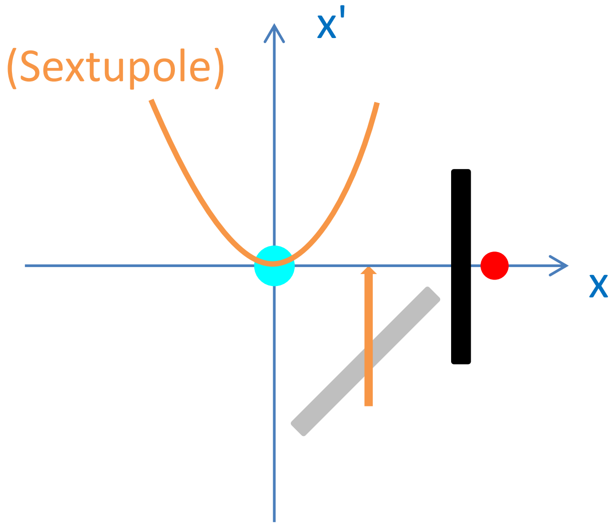
Conventional injection (5)

- Discussion
  - Orbit bump
    - 3- or 4-kickers within a straight section
      → Medium energy rings; a long enough straight section may be available and the beam is still soft to kick
    - 2 (or more)-kickers over a longer section including quadrupoles
      → High energy rings; the beam is hard to kick – Orbit bump is enhanced by the quadrupoles (Bump height = $\theta_{kicker}\sqrt{\beta_{kicker}\beta_{septum}}\sin\mu_{k,s}$)
      → Low energy (small) rings; a long straight section may not be available
  - Disturbance to the stored beam
    - When the orbit bump is not fully closed, the stored beam is displaced from the closed orbit
      - The bump closure may be deteriorated with stray field from septum, errors in quadrupole fields, different kicker field profile in time, etc.
    - "Bad design" including sextupoles (and higher multipoles) within the orbit bump makes it difficult to close the bump

Multipole kicker injection (1) [8]

- Motivation: Mitigation of beam disturbance using no dipole kicker
- Injection scheme
  - Hardware: Septum + Multipole kicker (Quad or higher multipole)
  - Separation: Transverse plane





Multipole kicker (By=0 at x=0) does not kick the stored beam centroid

Multipole kicker injection (2)

- Example – KEK PF

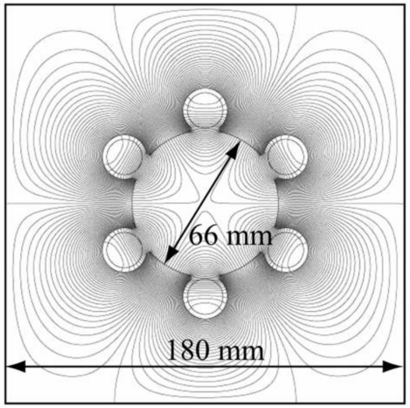


FIG. 12. Cross-sectional view and two-dimensional magnetic field distribution of the PSM. The bore diameter is 66 mm. The coil is a one-turn copper bar with a diameter of 15 mm.

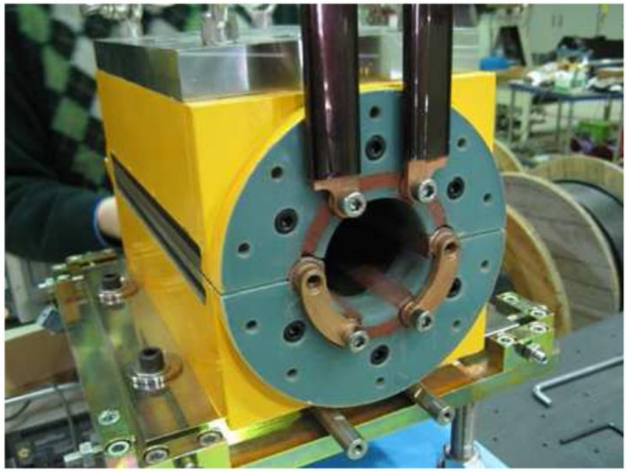


FIG. 13. (Color) Front view of the PSM. The glass epoxy board (green) and the epoxy resin (brown) are used for insulation.

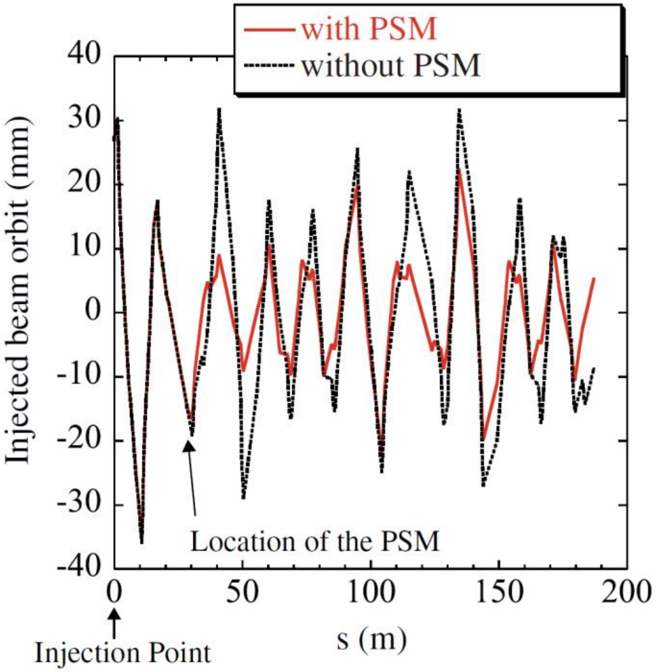
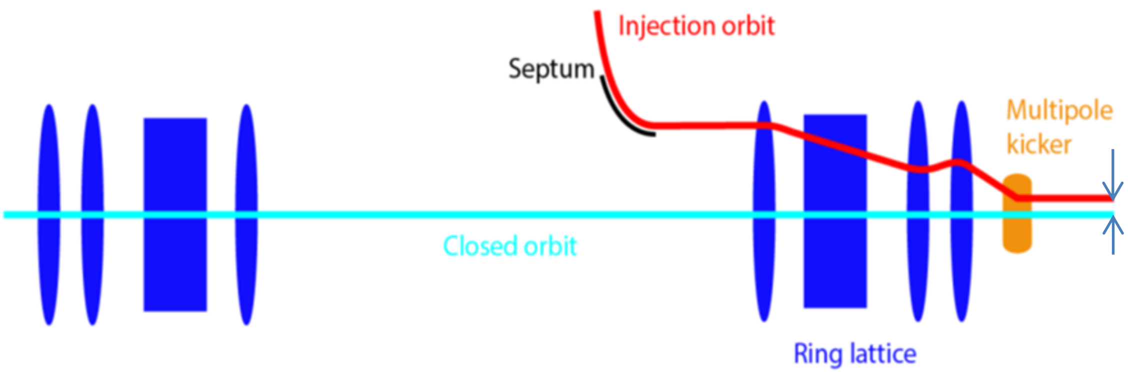


FIG. 8. (Color) Horizontal orbit of the injected beam at the PF ring with (red) and without (black) a PSM. The orbit displays the first circulation of the beam.

Figures taken from [8]

Multipole kicker injection (3)

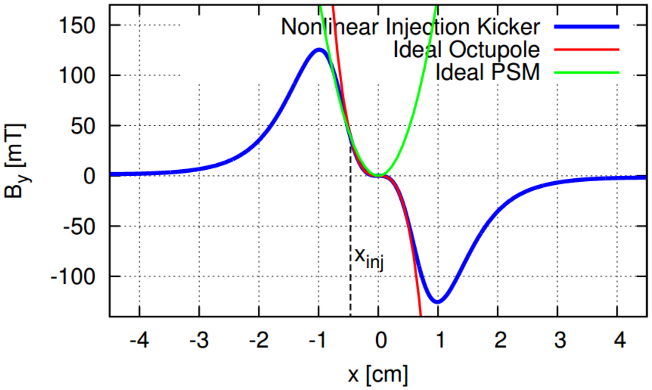
- Injection with off-energy injection beam [9]
  - Motivation: Combining the advantages of Synchrotron phase space injection and Multipole kicker injection
- Injection scheme
  - Hardware: Septum + Multipole kicker
  - Separation: Longitudinal plane (Energy offset)
  - Off-energy beam can be injected transversely on-axis similarly to Synchrotron-phase-space injection



$x = D_x \delta$
(and $x' = D_x{}' \delta$)

Multipole kicker injection (4)

- Discussion
  - Multipole kicker
    - Not only dipole kick, which is necessary for injection, but also (de)focusing due to feed-down quadrupole component
    - Nonlinear kicker [10][11] may avoid the adverse focusing if the beam is injection at the peak



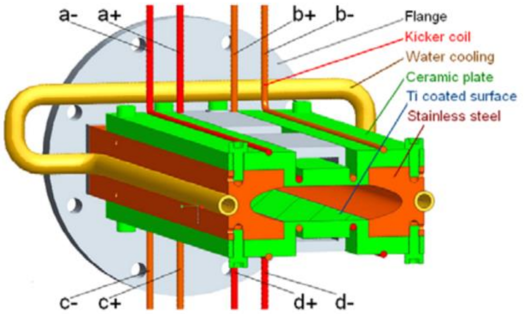


Figure 3: Sectional view of kicker magnet structure, second magnet design.

Figure taken from[12]   Figure taken from [11]

  - Disturbance to the stored beam
    - Dipole kick to the stored beam if the kicker is (largely) misaligned. Beam-base alignment is doable with reasonable effort.
    - Temporary emittance increase when the separation must be small due to a limited machine aperture (This is normally marginal)

Conventional and multipole kicker injections at KEK PF

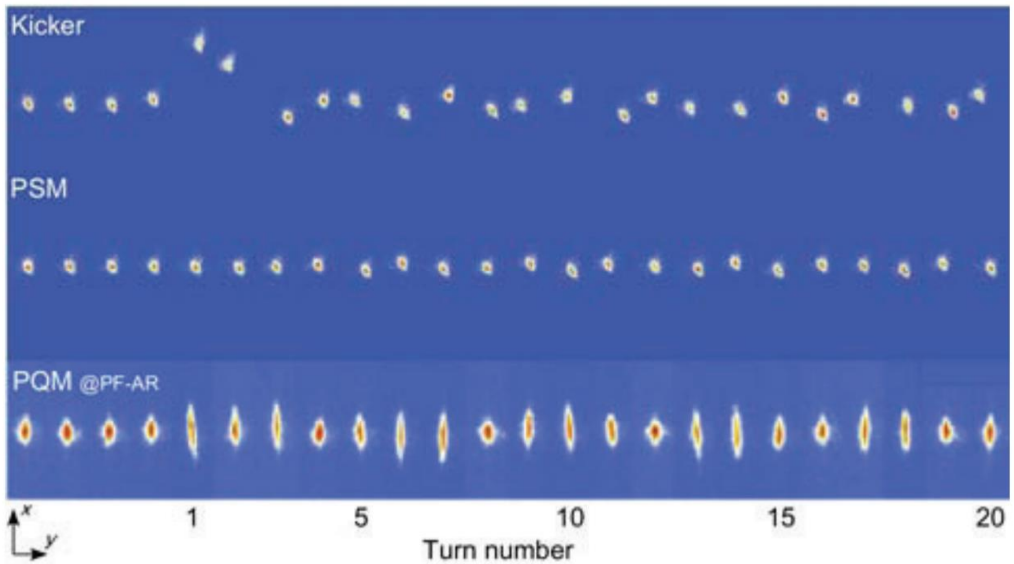


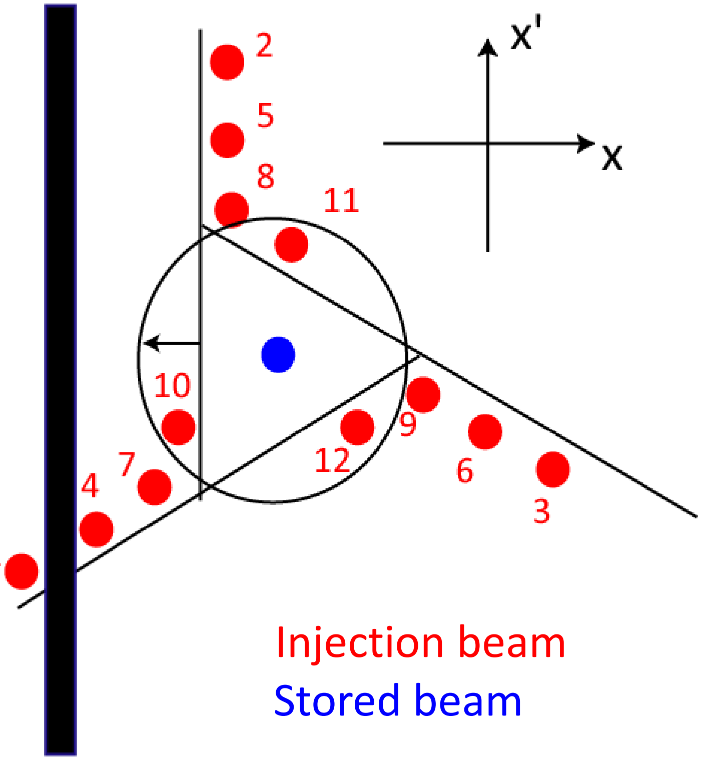
Figure 4: Turn-by-turn stored beam profiles in the kicker, PSM, and PQM injections measured by using a fast-gated camera.

Figure taken from [13]

Disturbance to the beam gets smaller with higher multipole kicker. Nevertheless, the disturbance in the conventional injection scheme can be mitigated in principle.

Resonance injection (1)

- Motivation: Injection into small ring; Revolution period << Kicker decay time
- Injection scheme
  - Hardware: Septum + Multipole kicker
  - Separation: Transverse plane
  - Betatron tune is set to be close to a resonance



Resonance condition MQx~N
(M and N are integer)
Kicker to excite resonance = 2M pole
(Sextupole kicker for M=3)

Resonance injection (2)

- Example - SR-Ring [10]
  - Using half integer resonance (M=2)
  - Circumference = 3.14 m
  - Resonance exciter (kicker) decays over 100 turns

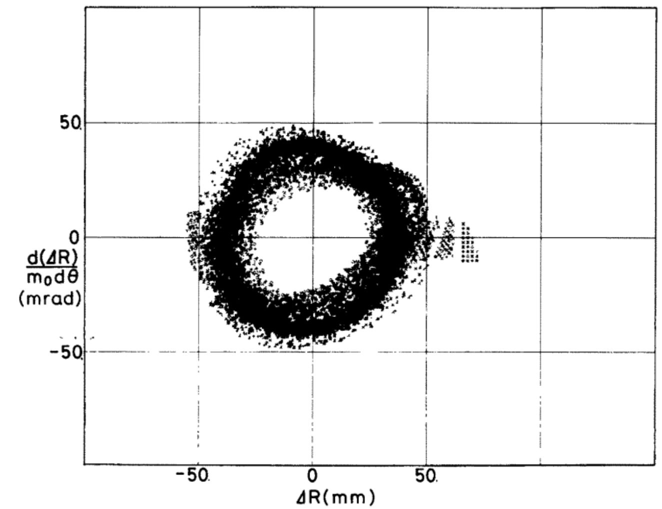


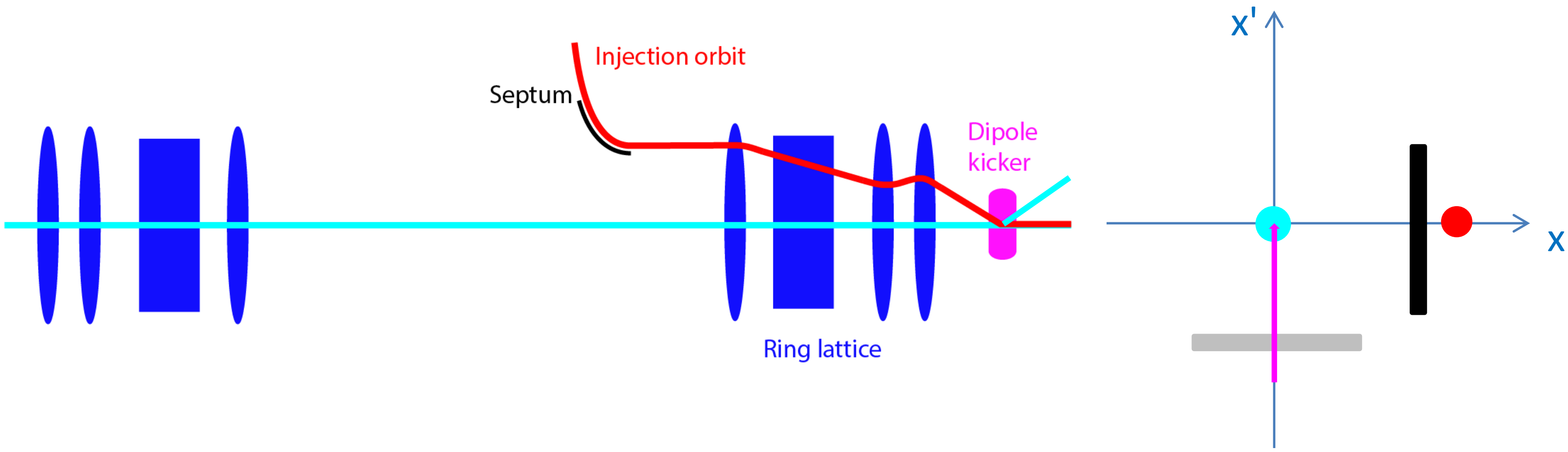
Fig. 7. Phase plot of radial motion showing the capture process with the same condition as in fig. 4 but with the perturbator linearly damping by 1% of full excitation per turn of a particle and with rf field of 60 kV and 2nd harmonic mode.

Figure taken from [10]

- Discussion
  - Injection efficiency is not good normally but there may not be any better choice for small ring…
  - Low efficiency may be accepted since small rings are for low energy beams
  - Stored beam is disturbed when the phase space topology is changed but the disturbance may be marginal

Swap-out injection (1) [14]

- Motivation: Enable an injection into very small aperture rings
- Injection scheme
  - Hardware: Septum + Dipole kicker
  - Separation: Transverse plane (Beam angle)
  - Replace bunch(es) by full-charge bunch(es)

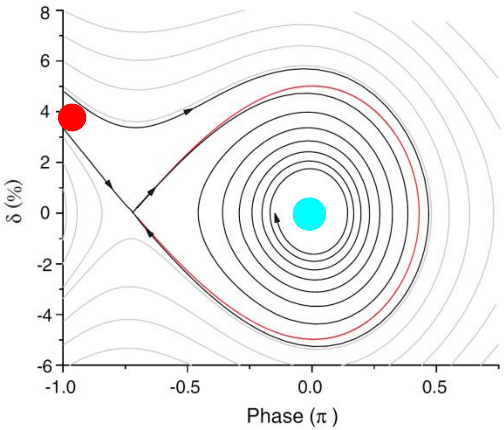


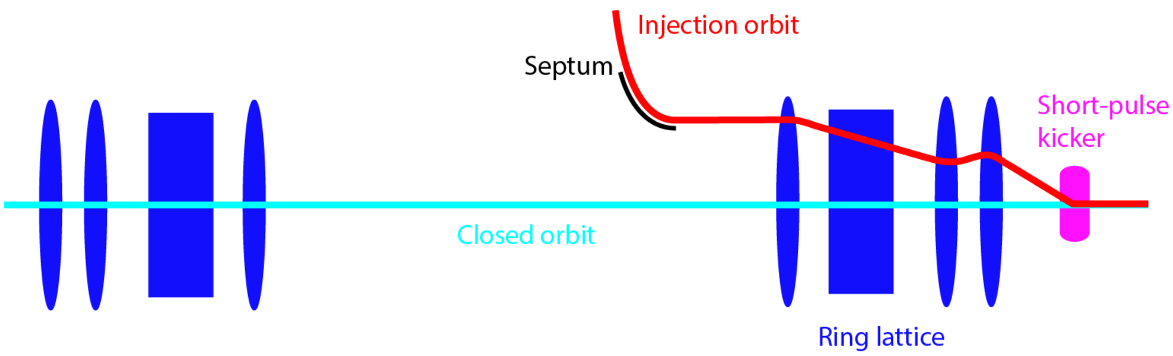
Swap-out injection (2)

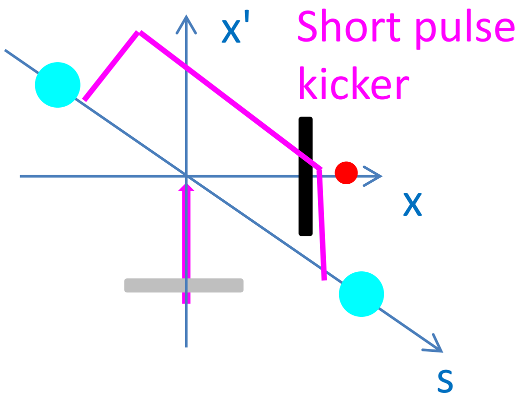
- No example yet, but planned for future light sources (e.g. ALS and APS upgrade)
- Discussion
  - Short pulse kicker (for bunch-by-bunch replacement) or long-flat-top kicker (for bunch train replacement) is required
  - Full charge injector or accumulator ring, where injection bunches are prepared, is required
  - No beam disturbance when the injection beam is fully matched and centred

Longitudinal injection (1) [15]

- Motivation: No beam disturbance at all and higher injection efficiency into small aperture ring
- Injection scheme
  - Hardware: Septum + Short pulse kicker
  - Separation: Longitudinal plane (Energy and time offset)

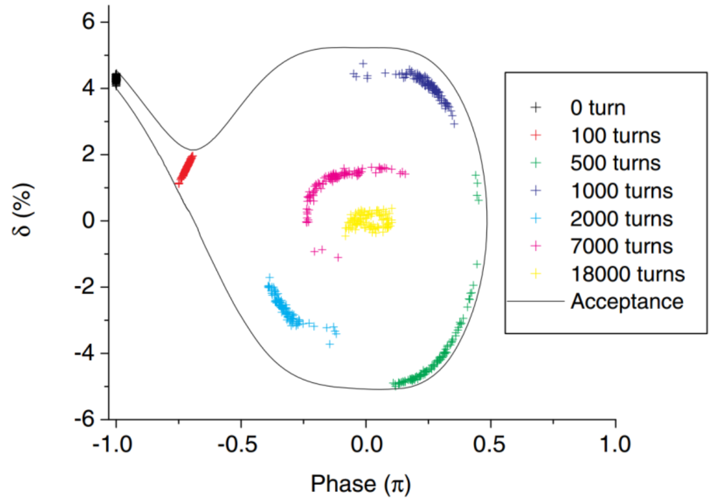


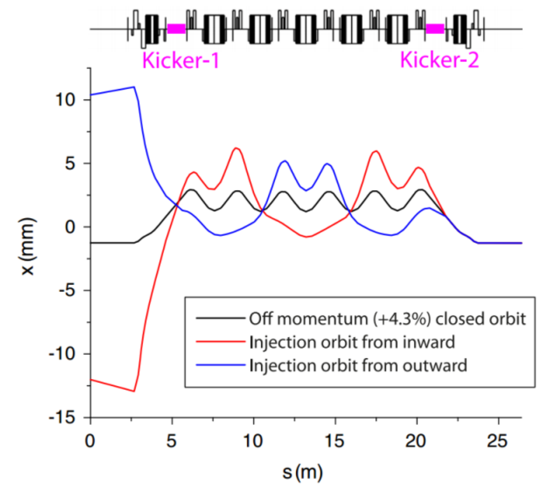




Longitudinal injection (2)

- No example yet but simulation result for MAX IV is promising [14]:





- Discussion
  - Short pulse kicker
    - Difficult when the bunch spacing is of the order of 1 ns
  - Injection beam
    - Small energy spread and short bunch length are required (Can be generated with a linac though)

Summary

- Top-up injection has become standard for lepton colliders and light sources
- A variety of injection schemes with different types of kickers and separation planes are available
- Optimum scheme may depend on
  - Ring circumference
  - Beam energy
  - Ring aperture
  - Beam time structure
  - Etc.

Reference

[1] J. T. Seeman, “Injection Issues of Electron-Positron Storage Rings”, Proc. of B FACTORIES: The State of the Art in Accelerators, Detectors and Physics, SLAC-400, pp.233-241 (1998)

[2] U. Wienands, “Lepton Collider Operation with Constant Currents”, Proc. of PAC’05, pp.149-153

[3] S. Nakamura, et al. Proc. of EPAC’90, p.472 (1990)

[4] H. Ohkuma, “Top-up Operation in Light Sources”, Proc. of EPAC’08, pp.36-40 (2008)

[5] M. Satoh, “Simultaneous Top-up Injection for Three Different Rings in KEK Injector Linac, Proc. of IPAC’10, pp.4287-4289 (2010)

[6] H. Wiedemann, “Particle Accelerator Physics I – Basic Principles and Linear Beam Dynamics”, Springer, ISBN 3-540-64672-X

[7] P. Collier, “Synchrotron Phase Space Injection into LEP”, Proc. of PAC’95, pp.551-553 (1995)

[8] H. Takaki et al., “Beam Injection with a Pulsed Sextupole Magnet in an Electron Storage Ring”, Phys. Rev. ST Accel. Beams, 13, 020705 (2010)

[9] A. Saa Hernandez, “Longitudinal Top-up Injection for Small Aperture Storage Rings”, Presentation at Workshop on Low Emittance Lattice, Rome, Italy (2014)

[10] T. Takayama, “Resonance Injection Method for the Compact Superconducting SR-Ring”, Nucl. Instrum. And Methods B, 24/25, pp.420-424 (1987)

[11] T. Atkinson, M. Dirsat, O. Dressler and P. Kuske, “Development of a Non-linear Kicker System to Facilitate a New Injection Scheme for the BESSY II Storage Ring”, Proc. of IPAC2011, pp.3394-3396 (2011)

[12] S. C. Leemann and L. O. Dalin, “Progress on Pulsed Muktipole Injection for the MAX IV Storage Rings”, Proc. of PAC2013, pp.1052-1054 (2013)

[13] R. Takai et al., “Beam Profile Measurement during Top-up Injection with a Pulsed Sextupole Magnet,” Proc. of DIPAC’11, pp.305-307 (2011)

[14] L. Emery and M. Borland, “Possible Long-Term Improvements to the Advanced Photon Source”, Proc. of PAC’03, pp.256-258 (2003)

[15] M. Aiba et al., “Longitudinal Injection Scheme Using Short Pulse Kicker for Small Aperture Electron Storage Rings”, Phys. Rev. ST Accel. Beams, 18, 020701 (2015)