# Review of top-up injection schemes for electron storage rings

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# Contents

- Brief history of top-up injection
- Conventional injection scheme
- Demand in the future accelerators
- New(er) schemes
- Overview
- Kicker and septum R&D
- Improvements on injector
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- 2000's: Further developments mainly in KEKB [3] and PEP colliders [4]
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  - Maximum photon flux always
  - Constant synchrotron radiation heat load to accelerator
    - Stable electron beam → Stable photon beam


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Top-up operation has increased the accelerator performance significantly!

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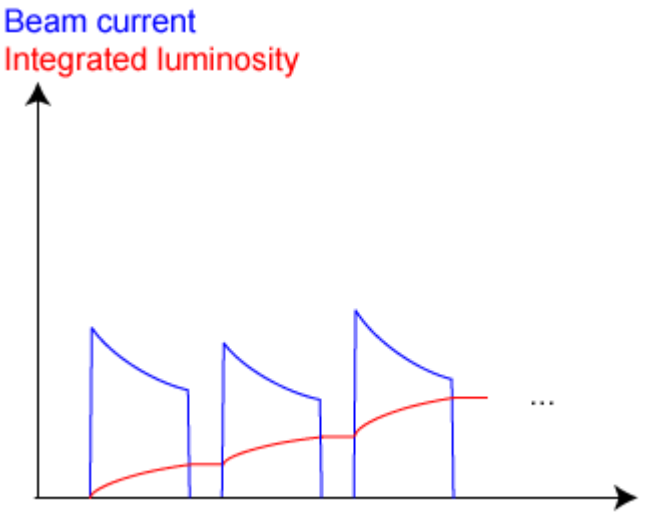


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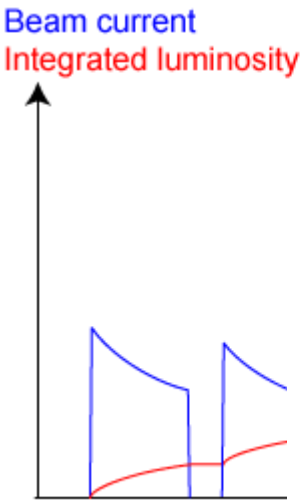


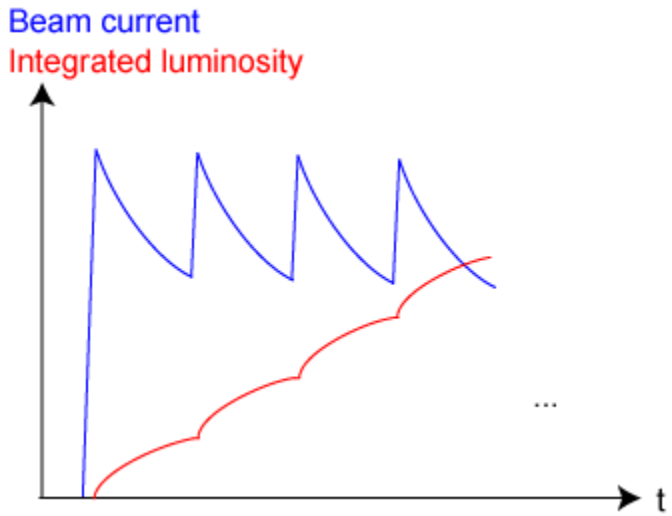


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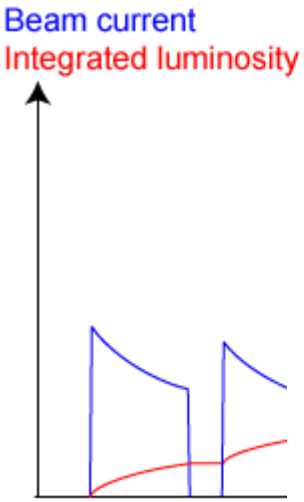


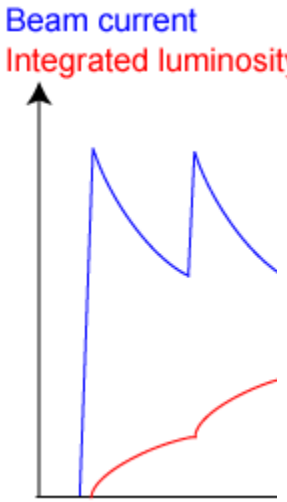


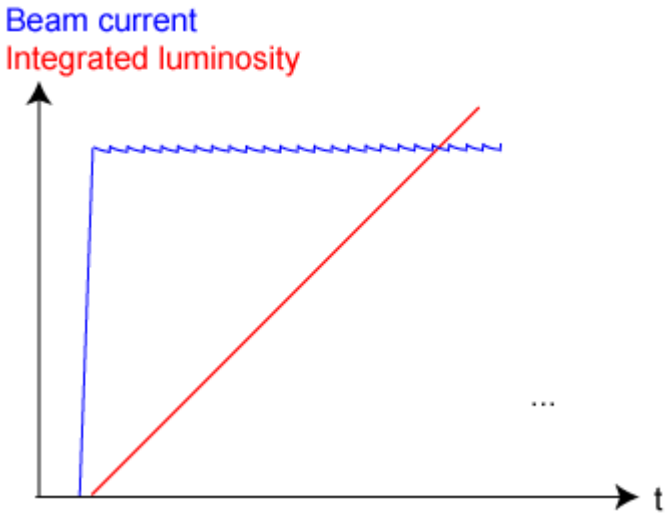


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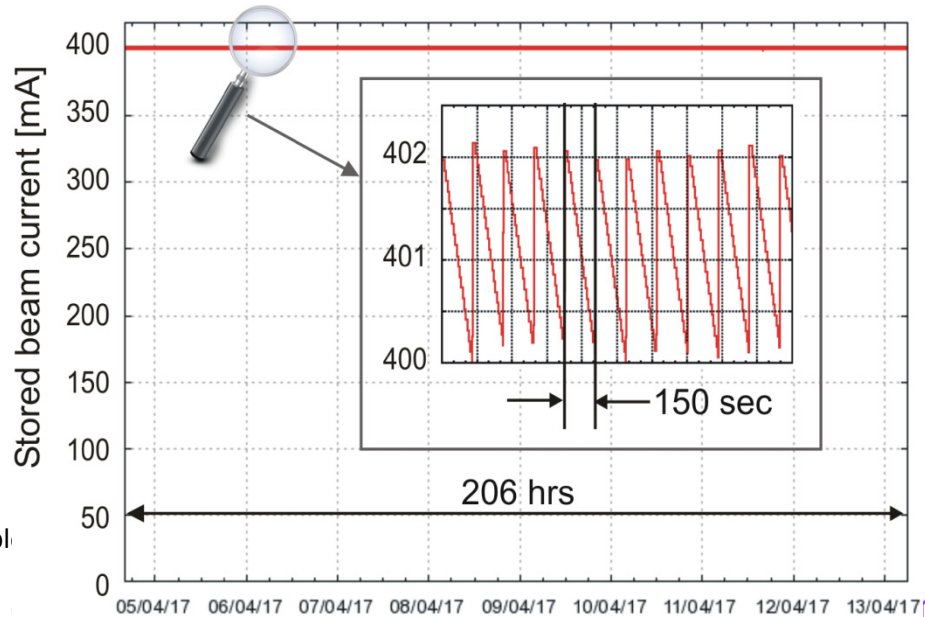


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  - Used for the first realizations of top-up operation mode
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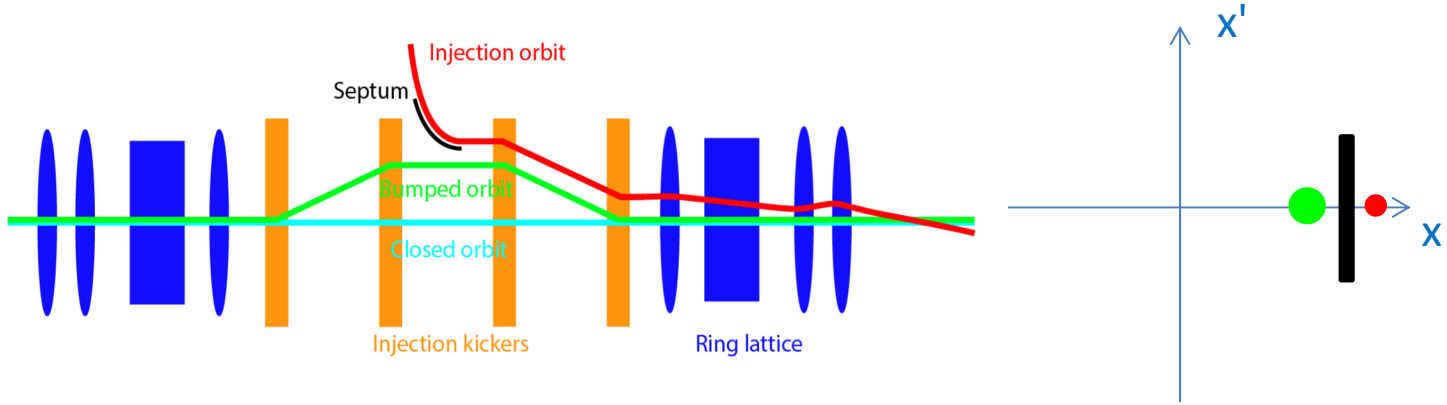
  - Injection beam separated from the stored beam at the time of injection



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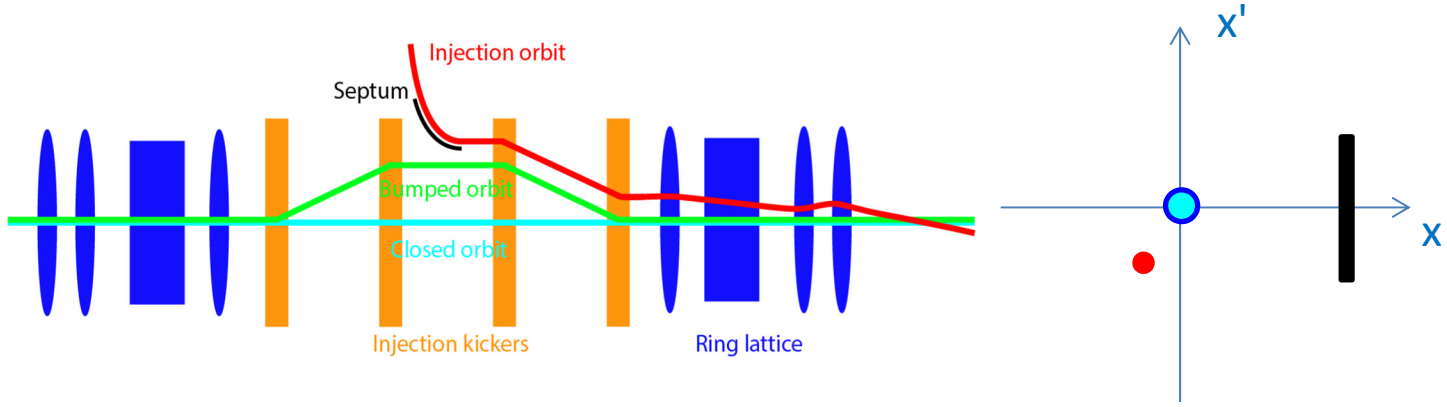

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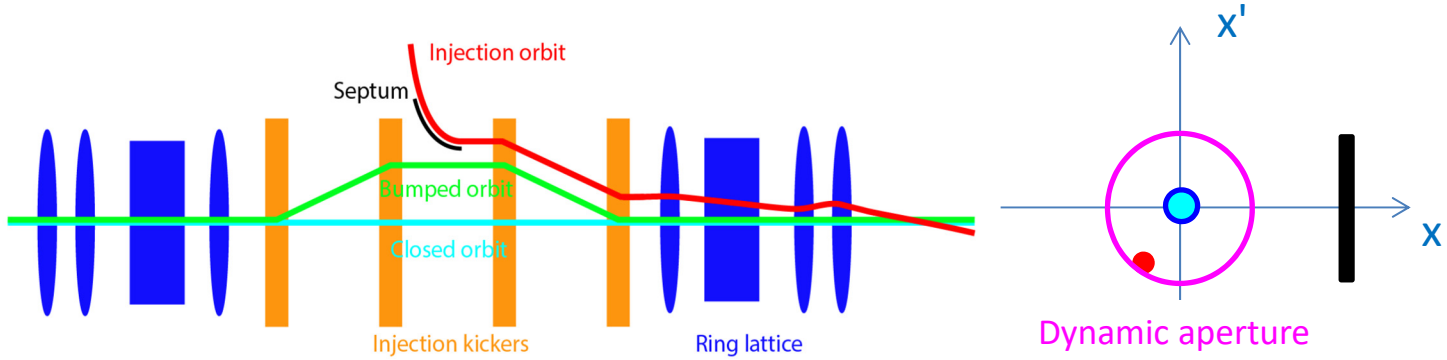

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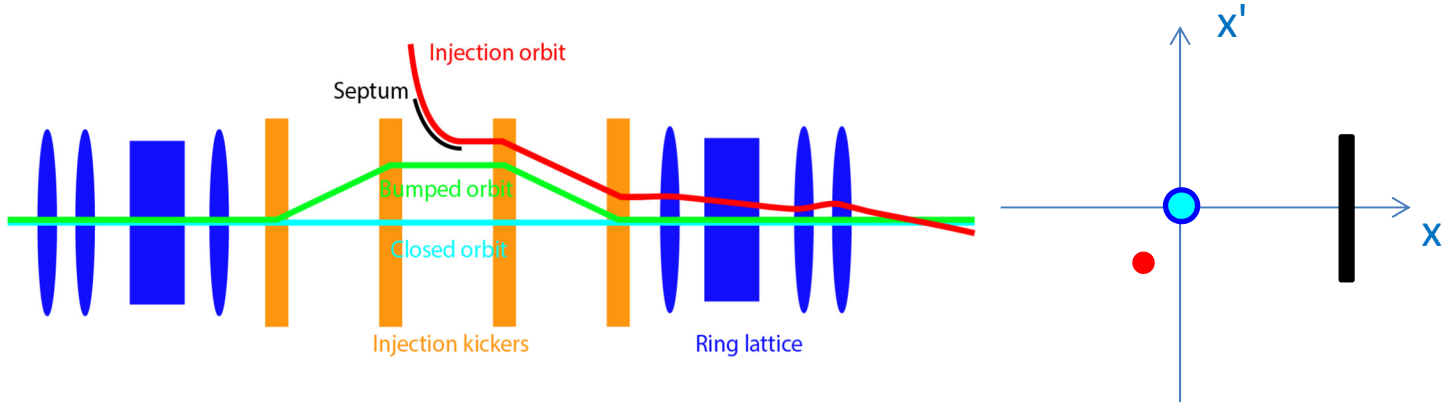

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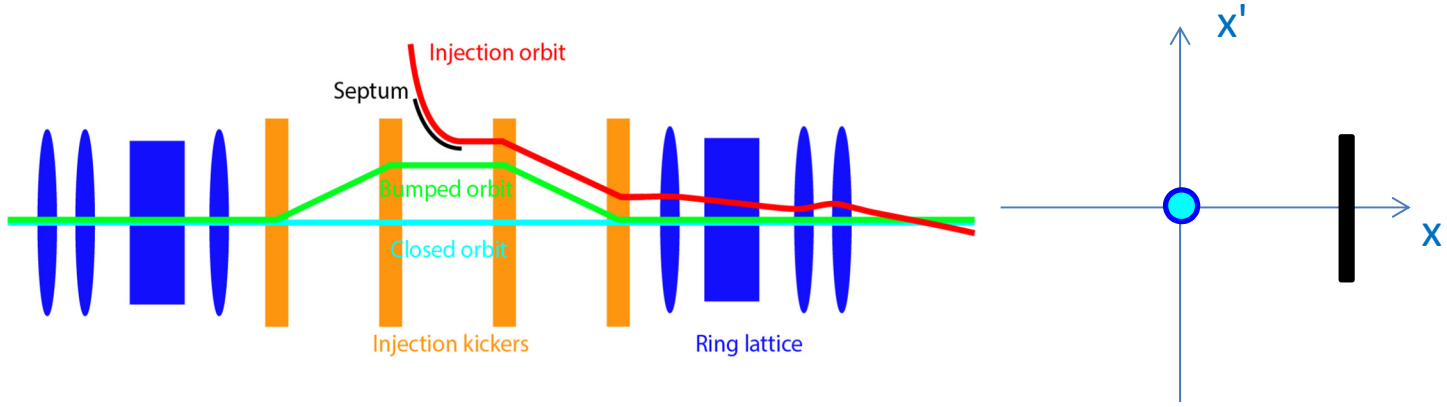

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# Demand in the future accelerator

- Limitation and side effect in Conventional injection
  - Dynamic aperture to accept the injection beam is essential
  - The orbit bump, in practice, may not be fully closed, and then the stored beam is disturbed
- Future machine aiming at *high performance*
  - In general, the higher performance, the smaller dynamic aperture will be
    - Light source based on multi-bend achromat
    - Collider with very small $\beta^*$

    ➡ Strong sextupoles for chromaticty correction
- New injection schemes aiming at
  - Less dynamic aperture required
  - Ultimately, no disturbance to the stored beam
  - 100% injection efficiency is preferable if not essential

# Contents

# Synchrotron phase space injection (1)

- Modified conventional injection scheme
  - Developed at the LEP [7, 8]
- Layout and beam in phase space
  - Septum + Kicker bump, as in the conventional injection
  - Ring optics includes a finite dispersion function at the septum
  - *Off-energy injection beam* is placed onto the corresponding off-energy orbit → Synchrotron oscillation instead of betatron oscillation

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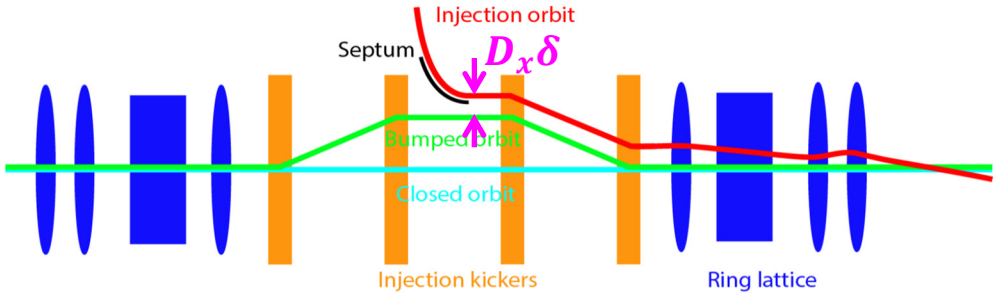


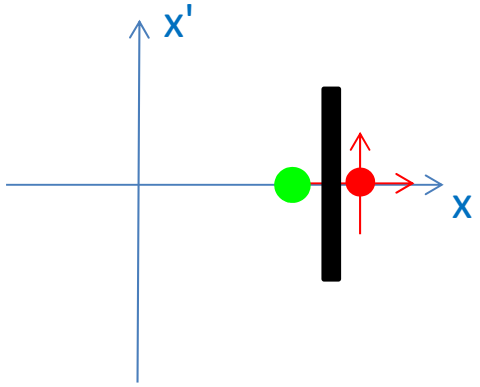

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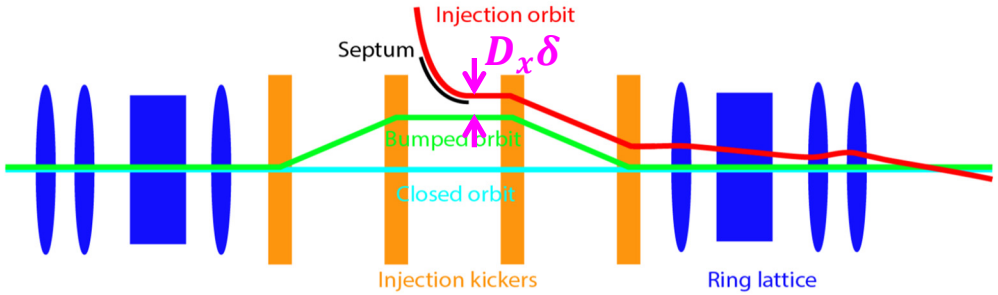


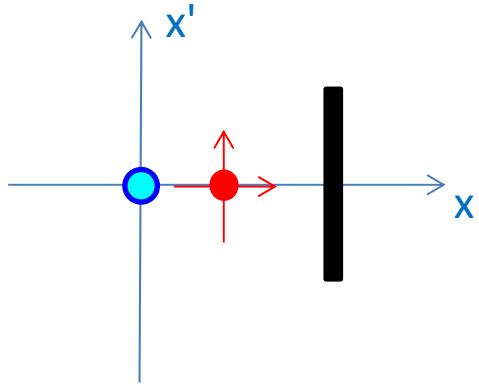

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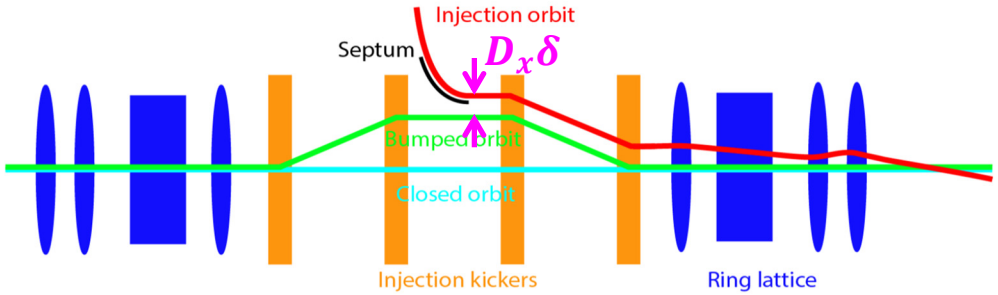


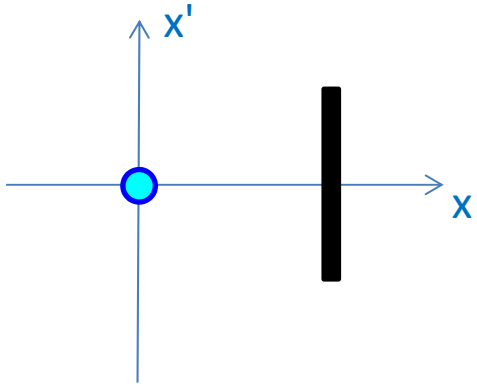

# Synchrotron phase space injection (2)

- Synchrotron phase space injection at LEP
  - Higher injection efficiency than the conventional injection scheme
  - With physics optics ($\beta$*=5 cm), accumulation was possible only with synchrotron phase space injection
  - The higher injection efficiency resulted in a mitigation of adverse radiation dose to the detector.

  Noted that dispersion is zero at IP.

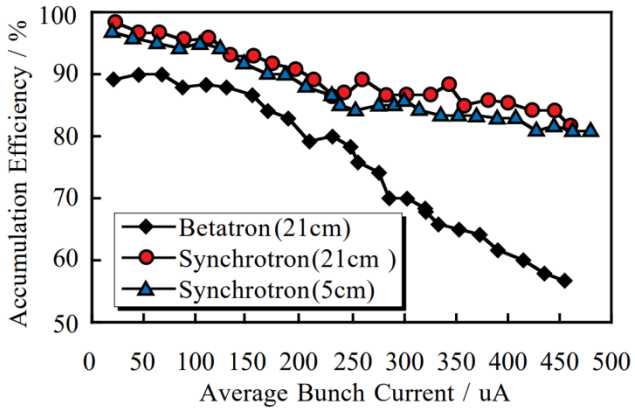


Figure 6: Accumulation Efficiency vs. Accumulated Bunch Current for Betatron and Synchrotron Injection. Note the Suppressed Zero Scale.

Figure from [8]

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  - Injection with off-energy injection beam is also possible, similarly to Synchrotron phase space inj. [11]
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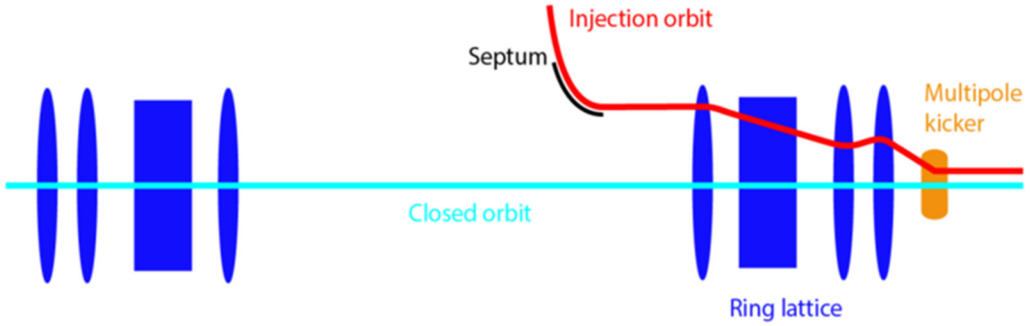


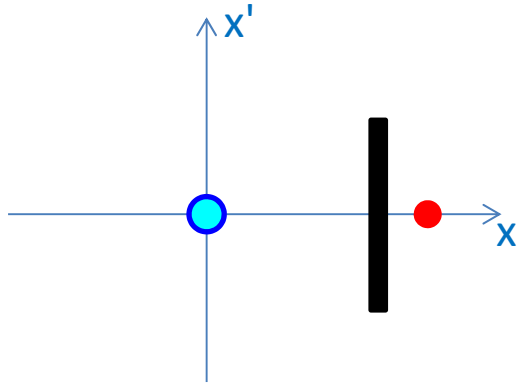



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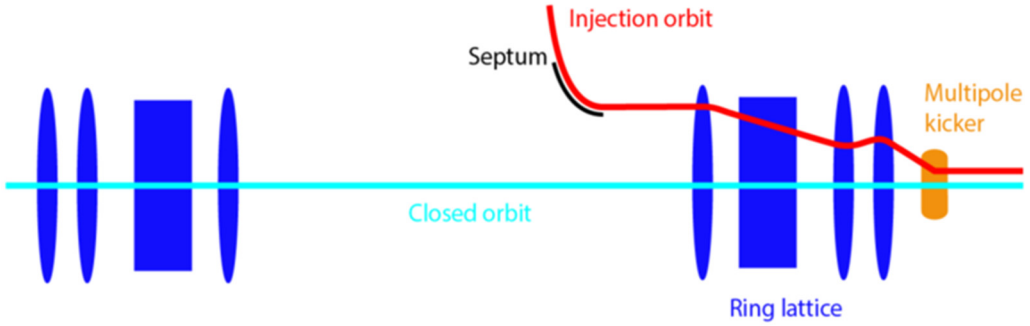


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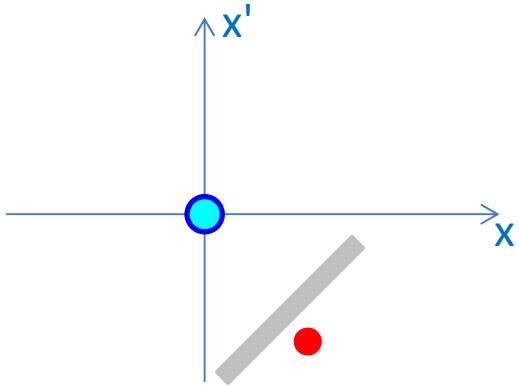

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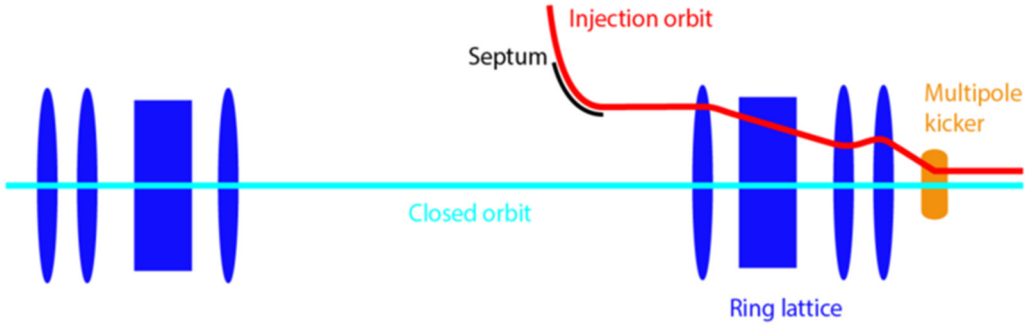


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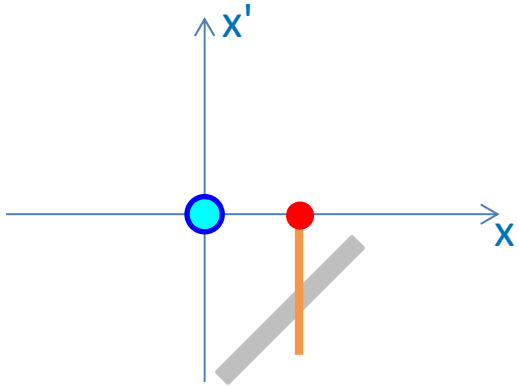

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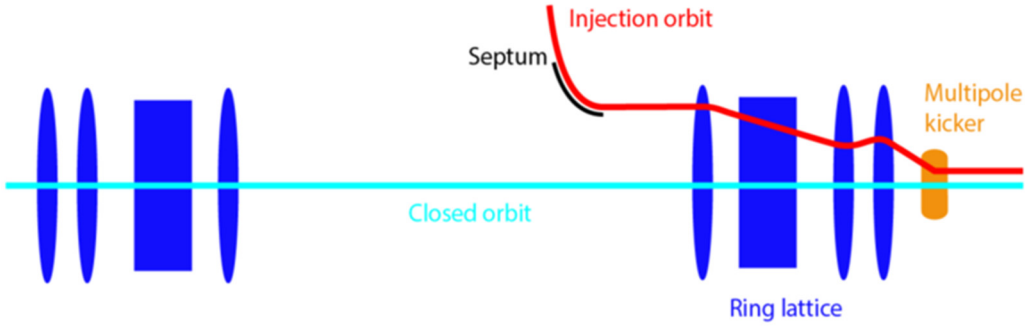


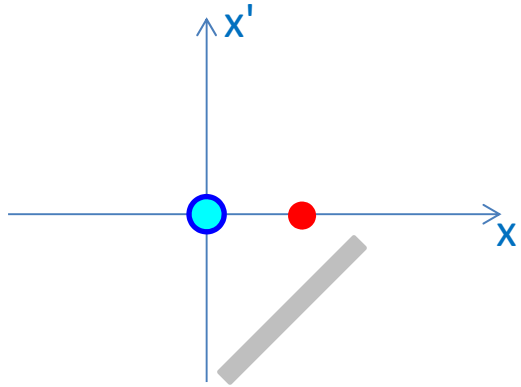



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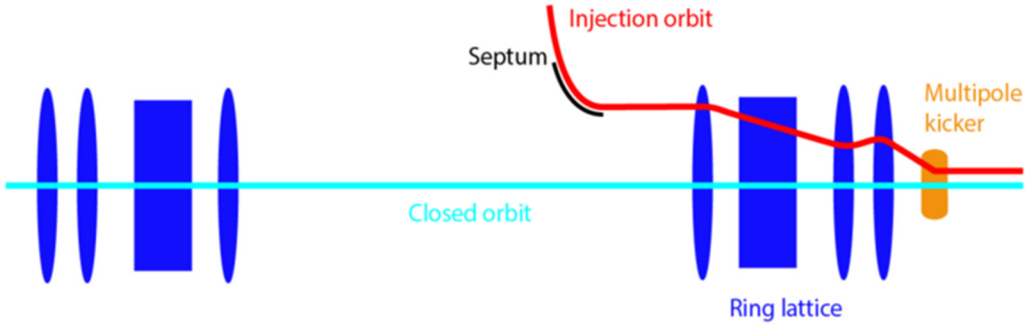


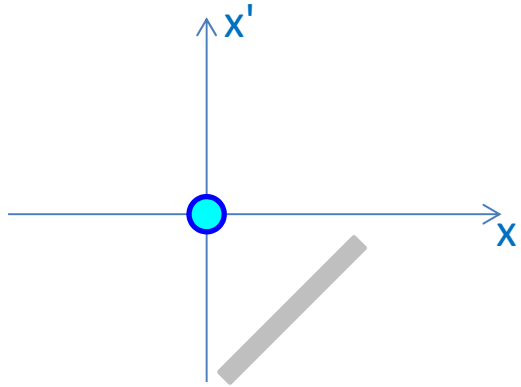



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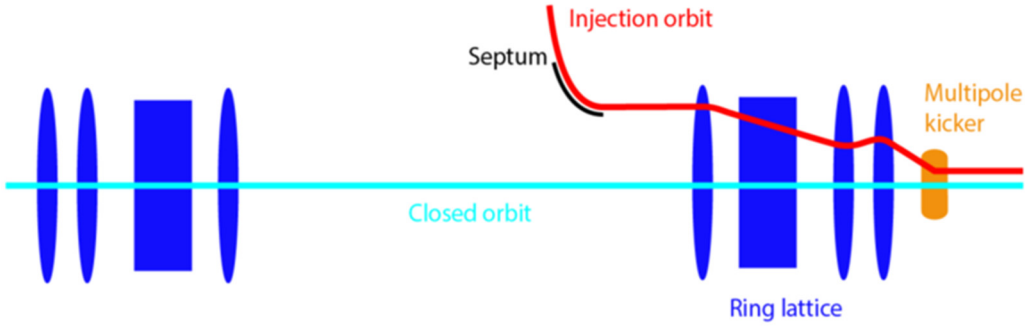


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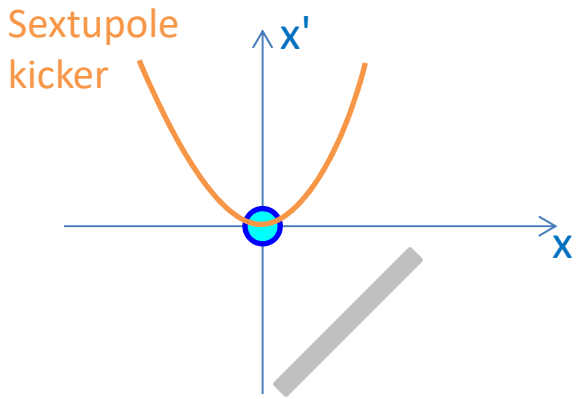


# Multipole kicker injection (2)

- Multipole kicker injection (MKI) at KEK PF [12] R. Takai et al., DIPAC'11
  - Using pulse sextupole magnet
  - Used for the user operation at KEK PF since 2011 [12]

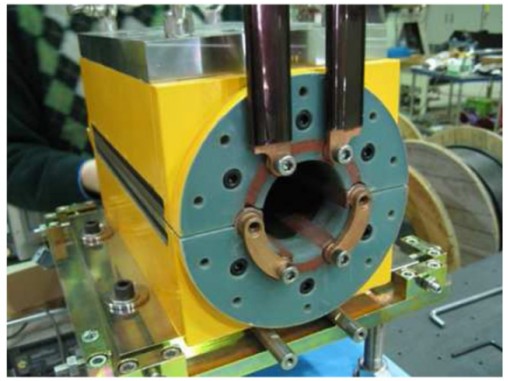


FIG. 13. (Color) Front view of the PSM. The glass epoxy board (green) and the epoxy resin (brown) are used for insulation.

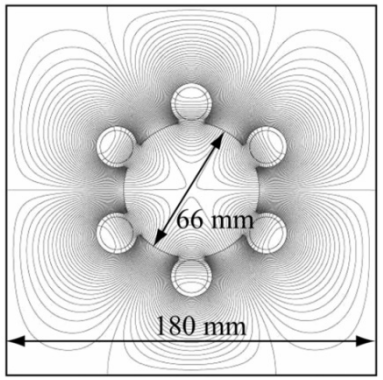



FIG. 12. Cross-sectional view and two-dimensional magnetic field distribution of the PSM. The bore diameter is 66 mm. The coil is a one-turn copper bar with a diameter of 15 mm.

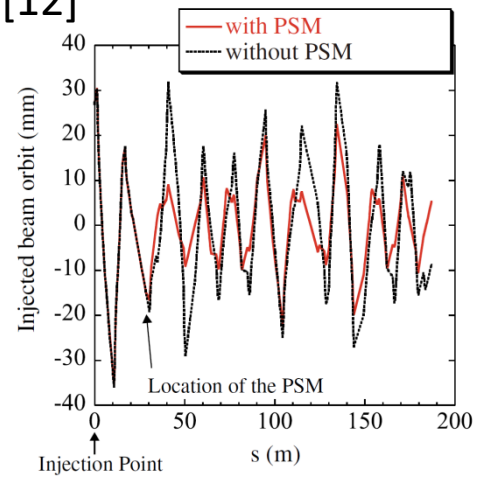



FIG. 8. (Color) Horizontal orbit of the injected beam at the PF ring with (red) and without (black) a PSM. The orbit displays the first circulation of the beam.

Figures from [10]

# Multipole kicker injection (3)

- Disturbance to the stored beam measured at KEK PF (and PF-AR)

Kicker bump

Sextupole kicker

Quadrupole kicker

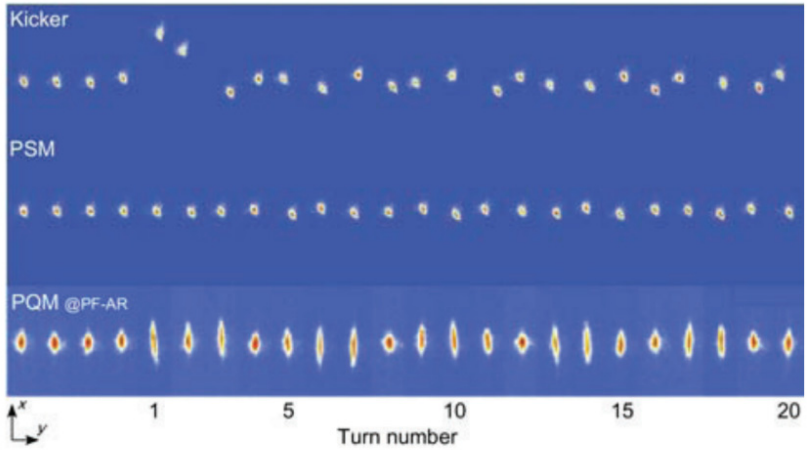


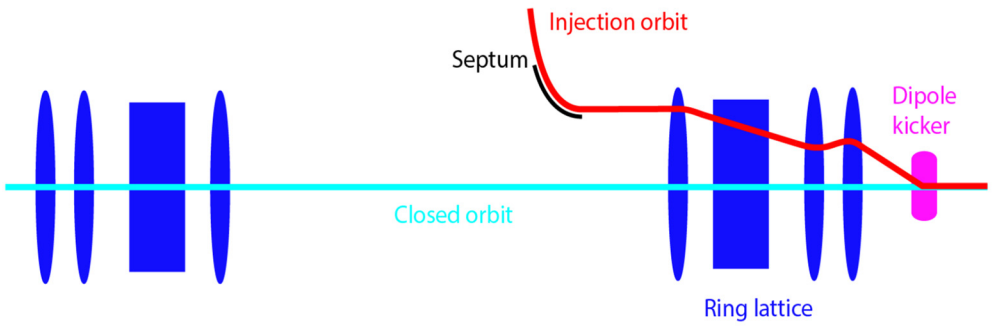

Figure 4: Turn-by-turn stored beam profiles in the kicker, PSM, and PQM injections measured by using a fast-gated camera.

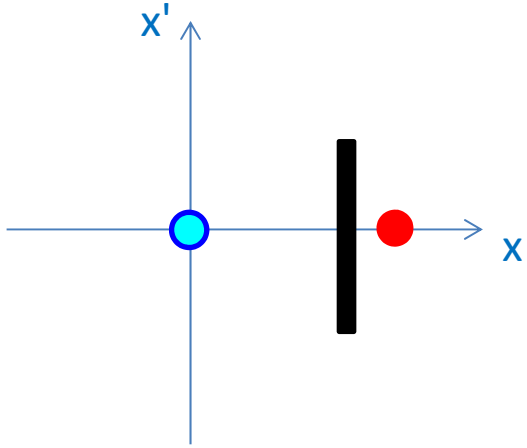
Figure from [12]

# Swap-out injection (1)

- Swap-out injection
  - Proposed for APS upgrade [13, 14]
- Layout and beams in phase space
  - Septum + Short pulse kicker (Bunch-by-bunch injection) or Kicker with flat-top (Bunch train)
  - Required dynamic aperture is fully minimized

[13] M. Borland, NIM-A (2000).
[14] L. Emery and M. Borland, PAC'03.



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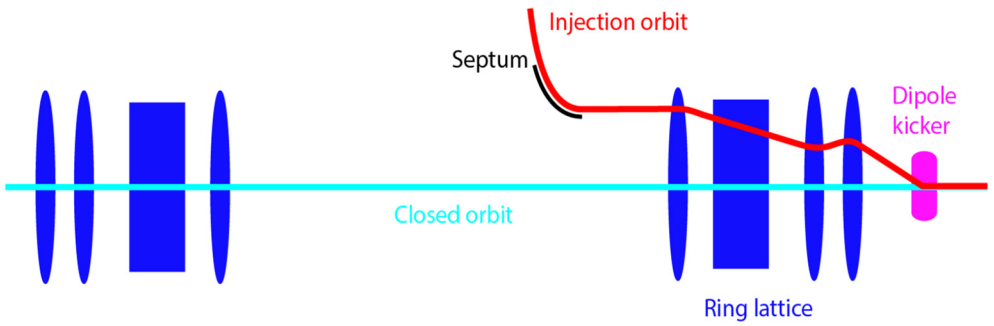


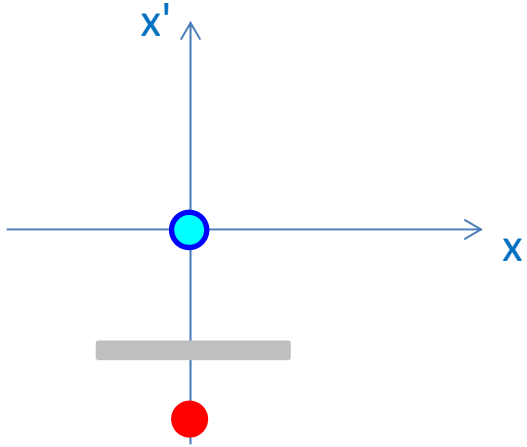

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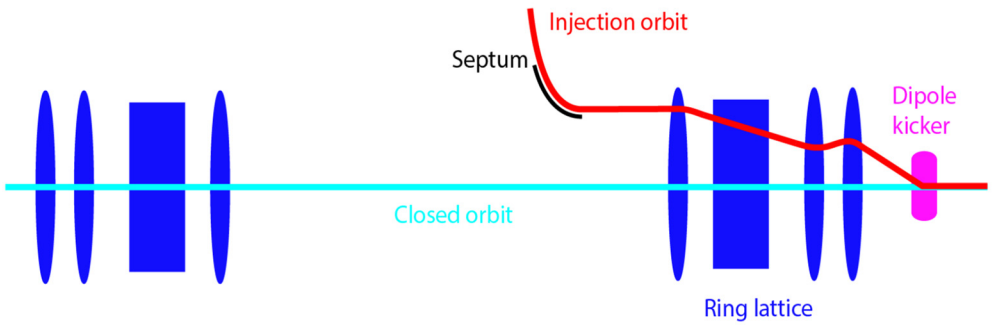
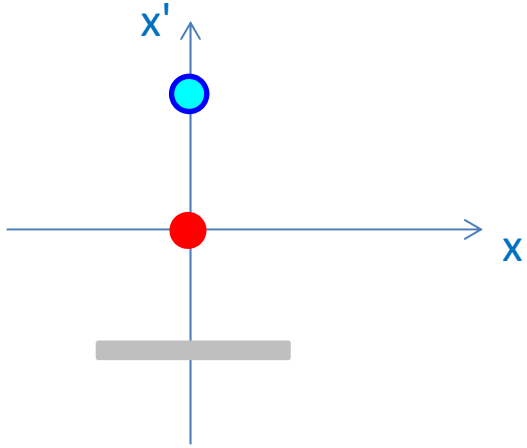
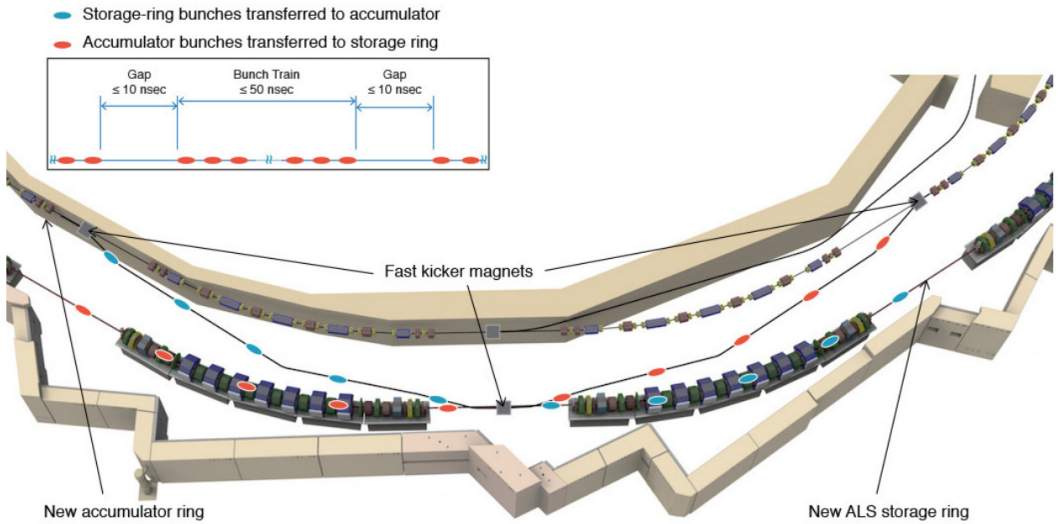


# Swap-out injection (2)

- Plan at ALS upgrade, bunch train swapping-out

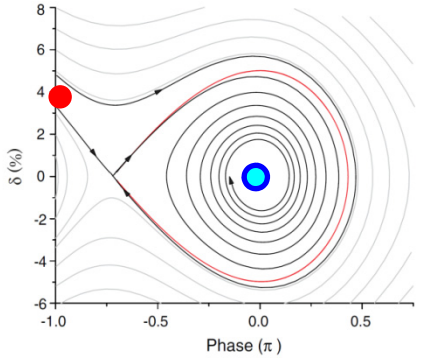


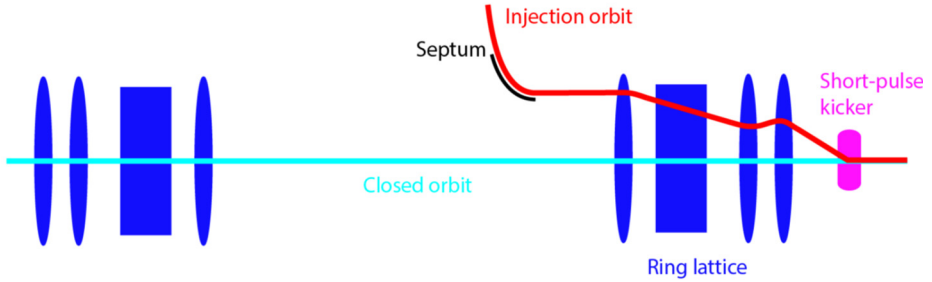

← Accumulator ring to prepare full charge injection bunches

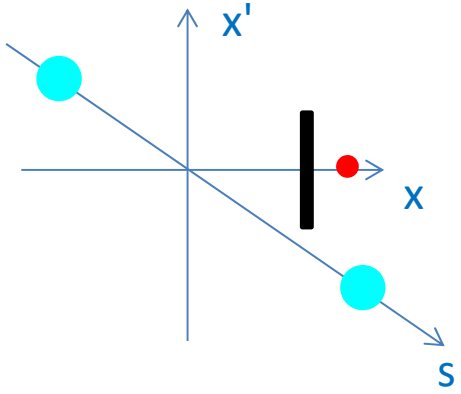
Figure from
[15] S. Henderson, IPAC 15.

# Longitudinal injection (1)

- Longitudinal injection
  - Proposed for future light sources [16]
- Layout and beams in phase space
  - Septum + Short pulse kicker
  - Injection beam energy and timing are shifted
  - Dynamic aperture requirement is relaxed




[15] M. Aiba et al., PR ST-AB (2015)

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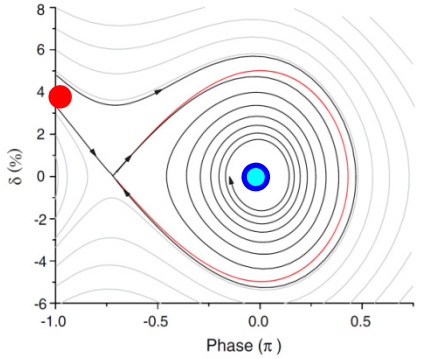


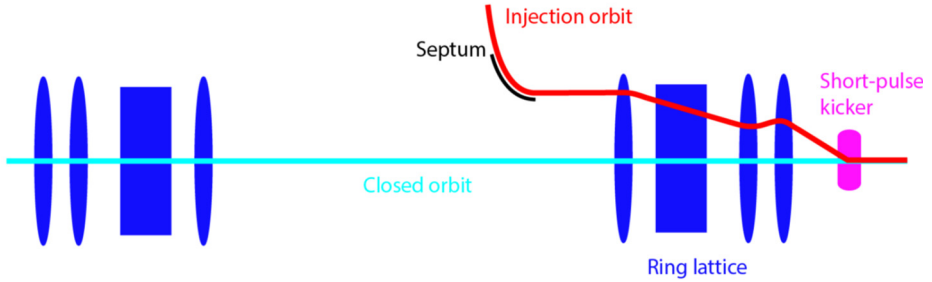


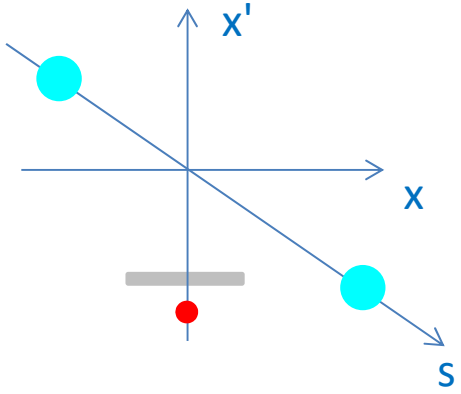


[15] M. Aiba et al., PR ST-AB (2015)

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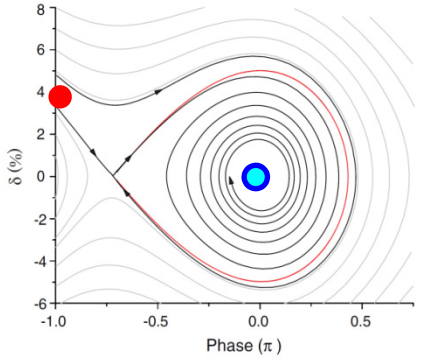


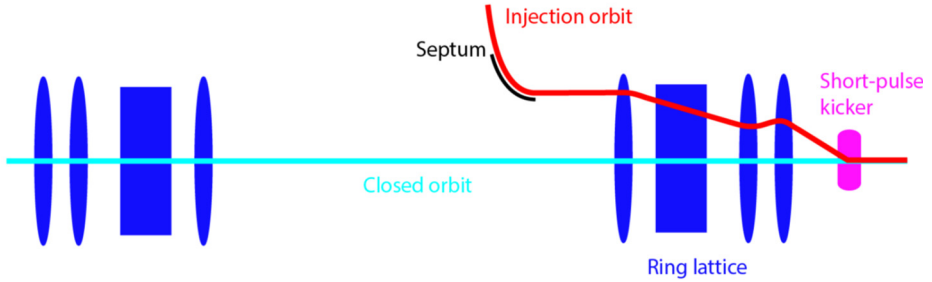


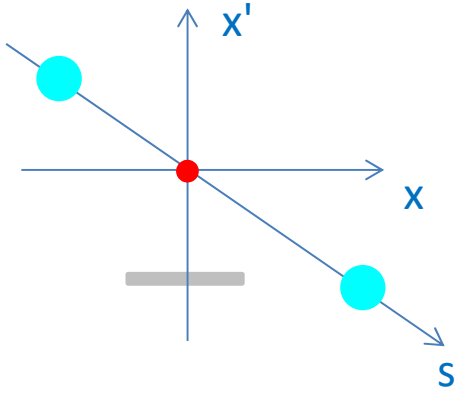


[15] M. Aiba et al., PR ST-AB (2015)

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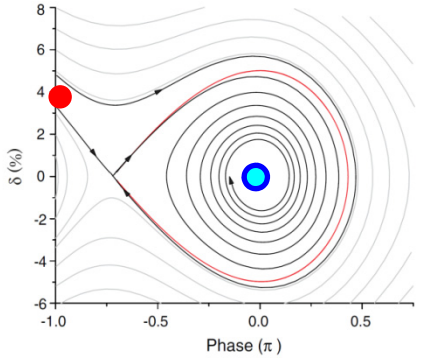
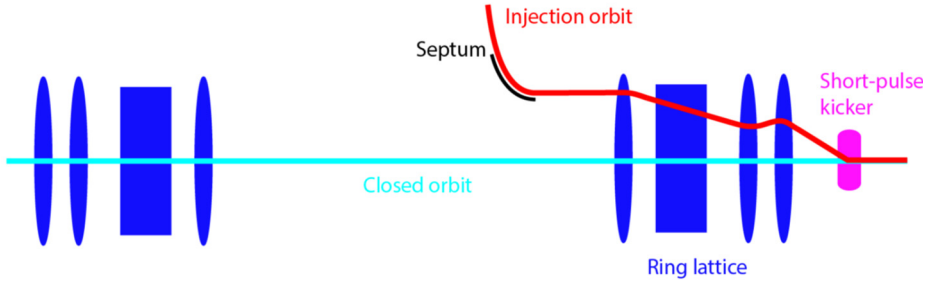
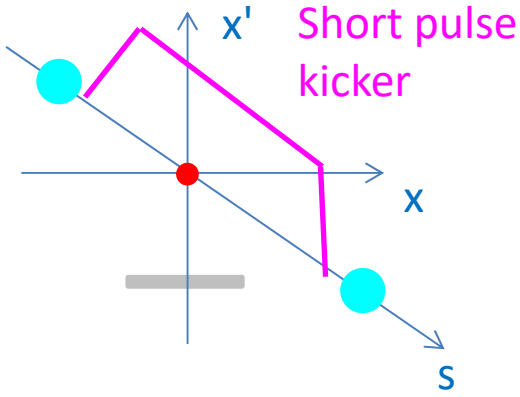


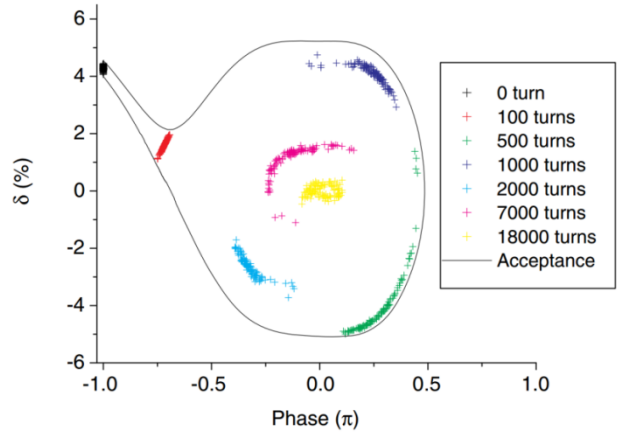



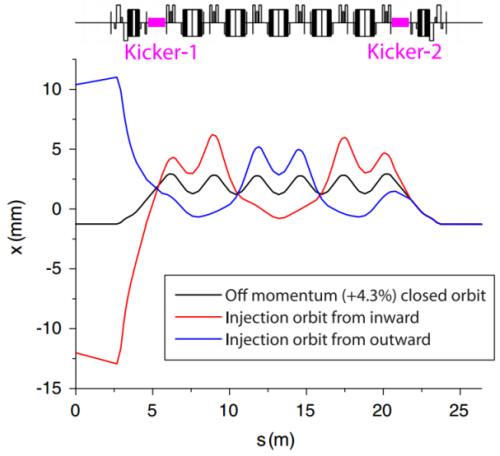




[15] M. Aiba et al., PR ST-AB (2015)

# Longitudinal injection (2)

- Simulation with MAX-IV lattice (100 MHz RF) [16]
  - Linac injector provides  small longitudinal emittance
  - 100 % injection efficiency achieved



# Longitudinal injection (3)

- Longitudinal injection with bunch merging [17, 18]
  - Fundamental and 2nd harmonic cavities are used
  - Large longitudinal emittance can be accepted

[17] B. C. Jiang et al., NIM-A, (2016).
[18] G. Xu et al., IPAC 16.

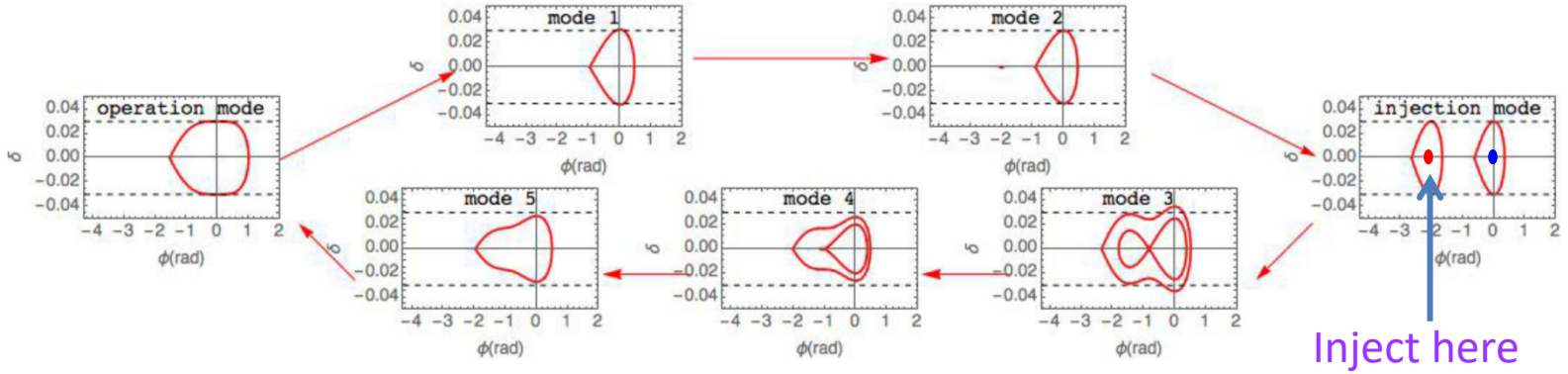



Figure from [18]

# Longitudinal injection (4)

- Longitudinal injection with 3 RF systems [19]
  - 3rd harmonic cavity is widely used for bunch lengthening
  - One more RF system to further prolong the bunch and RF bucket (1+2+3)

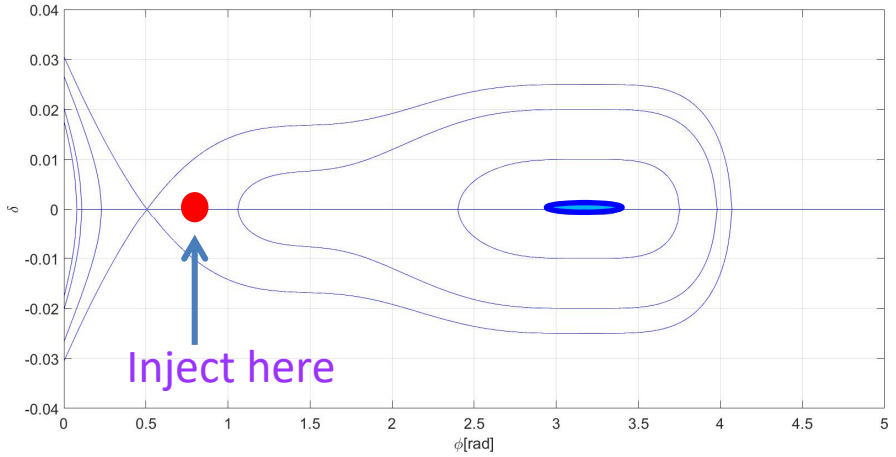


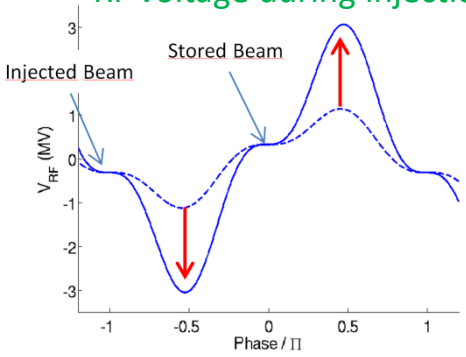

Figure from [19] G. Xu, TWIIS (2017)

# Longitudinal injection (5)

- Longitudinal injection with “Longitudinal nonlinear kicker”, for SOLEIL upgrade [20]
  - RF voltages and phases of fundamental and 3rd harmonic cavities are varied during injection
  - Synchrotron oscillation of injection beam is quickly damped while the stored beam while the stored beam is unaffected
  - Possibly combined with off-energy MKI to avoid short pulse kicker

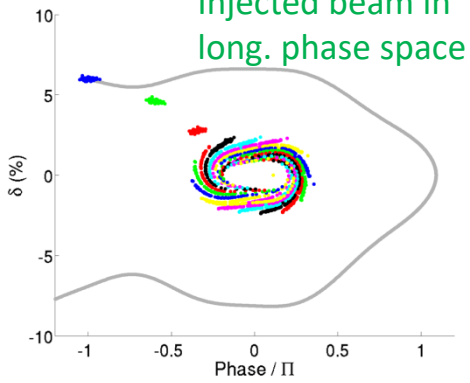
[20] M.-A. Tordeux, TWIIS (2017).

RF voltage during injection




Increase of the main & 3rd harmonic RF voltage during injection process (200 µs)

Injected beam in long. phase space




Injection of the Booster beam
$\varepsilon_x = \varepsilon_z$ = 15 nm.rad, $\sigma_s$ = 35 ps

Figures courtesy of M.-A. Tordeux

Analogy with transverse resonance injection:

Quad + Multipole
to control trajectory in
transverse phase space

⇕

Fundamental +3rd harmonic
RF cavities to control
trajectory in long. phase space

# Contents

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# Separation and kicker type

- Separation
  - At the time of injection, the injection beam must be separated from the stored beam ↔ Liouville's theorem
  - The injection beam is later merged to the stored beam ↔ Synchrotron radiation damping
- Kickers
  - Various types of kicker are available
    - Kicker bump, multipole kicker, short pulse kicker, etc.

Separation planes × Kicker types
→ a number of injection schemes

# Overview of injection schemes (1)

# Overview of injection schemes (1)

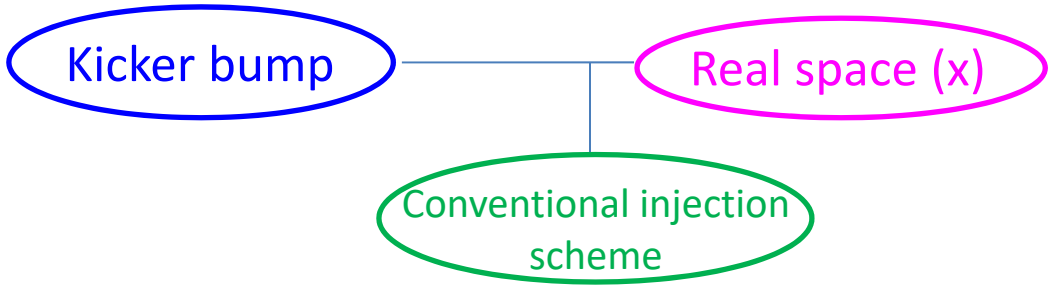
Kicker bump

# Overview of injection schemes (1)

Kicker bump

Real space (x)

# Overview of injection schemes (1)



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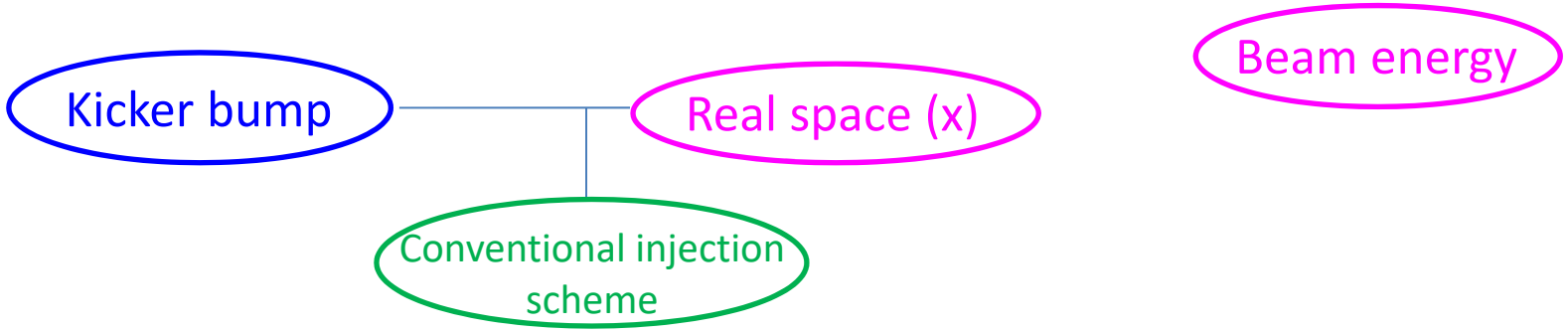

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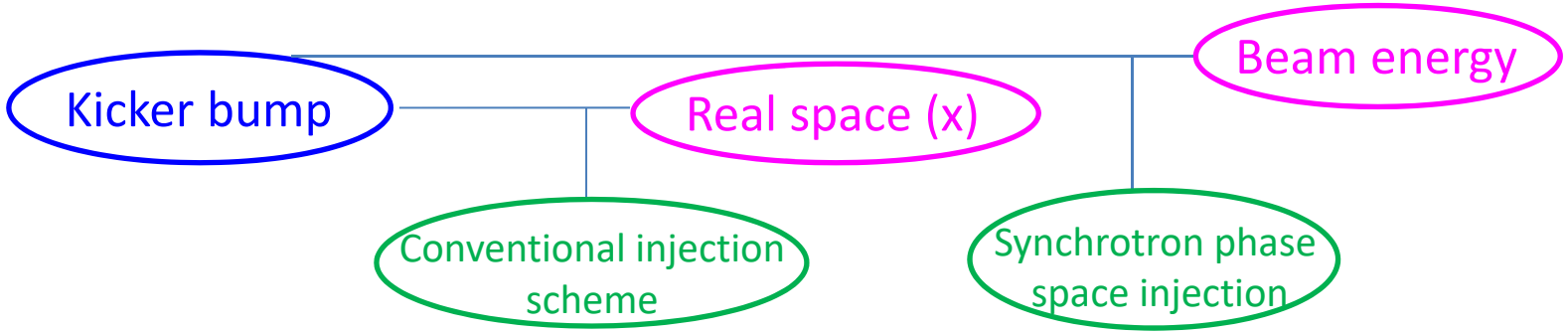

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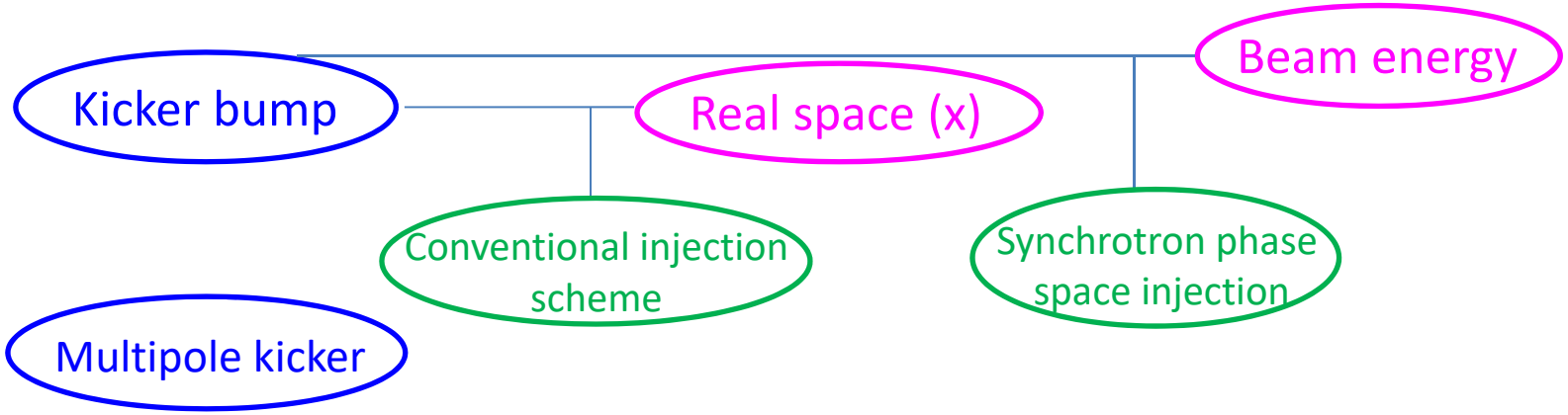

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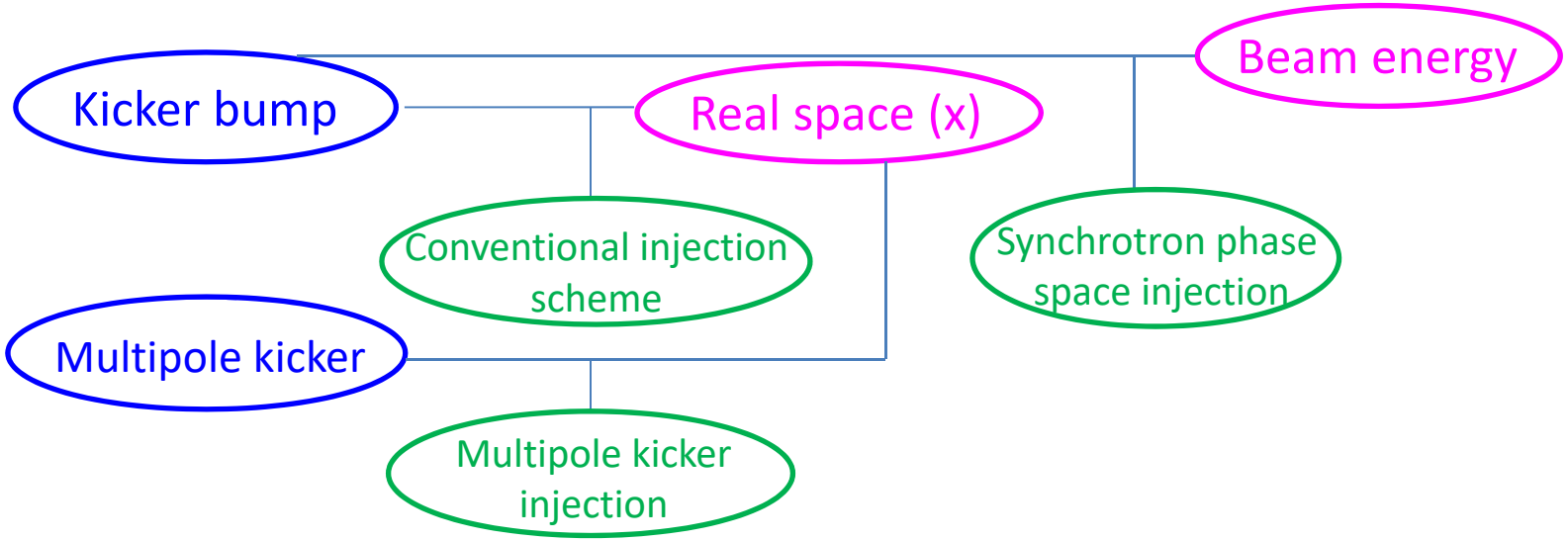

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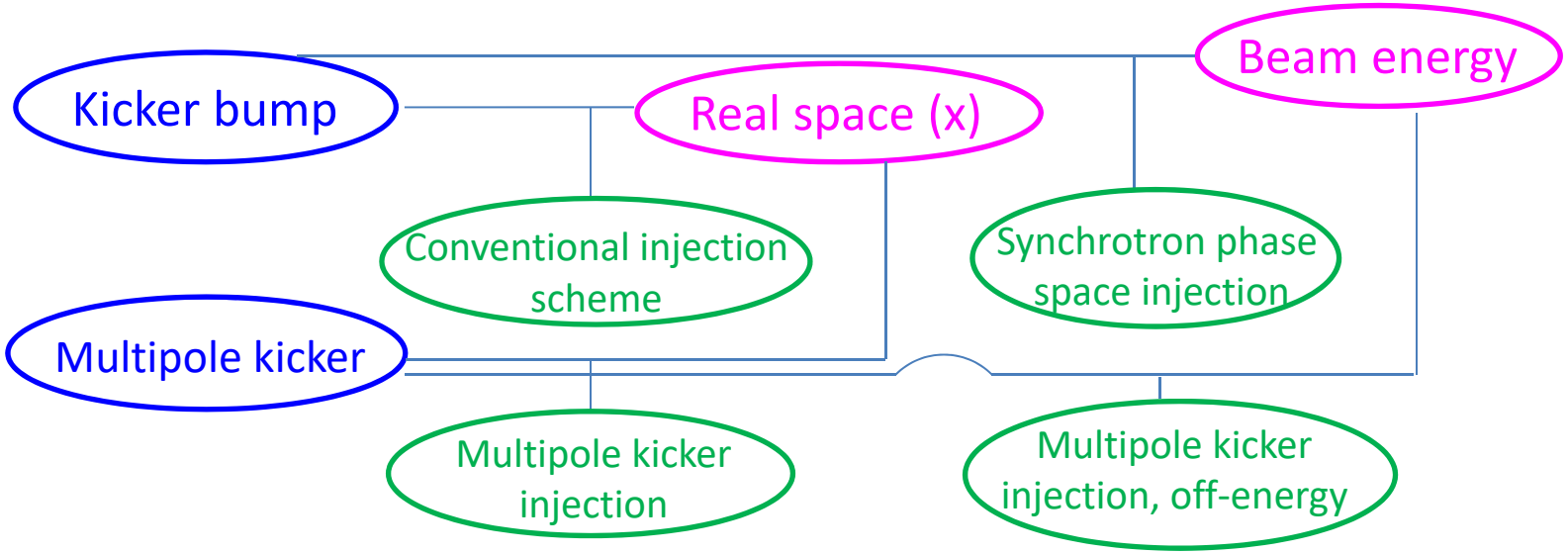

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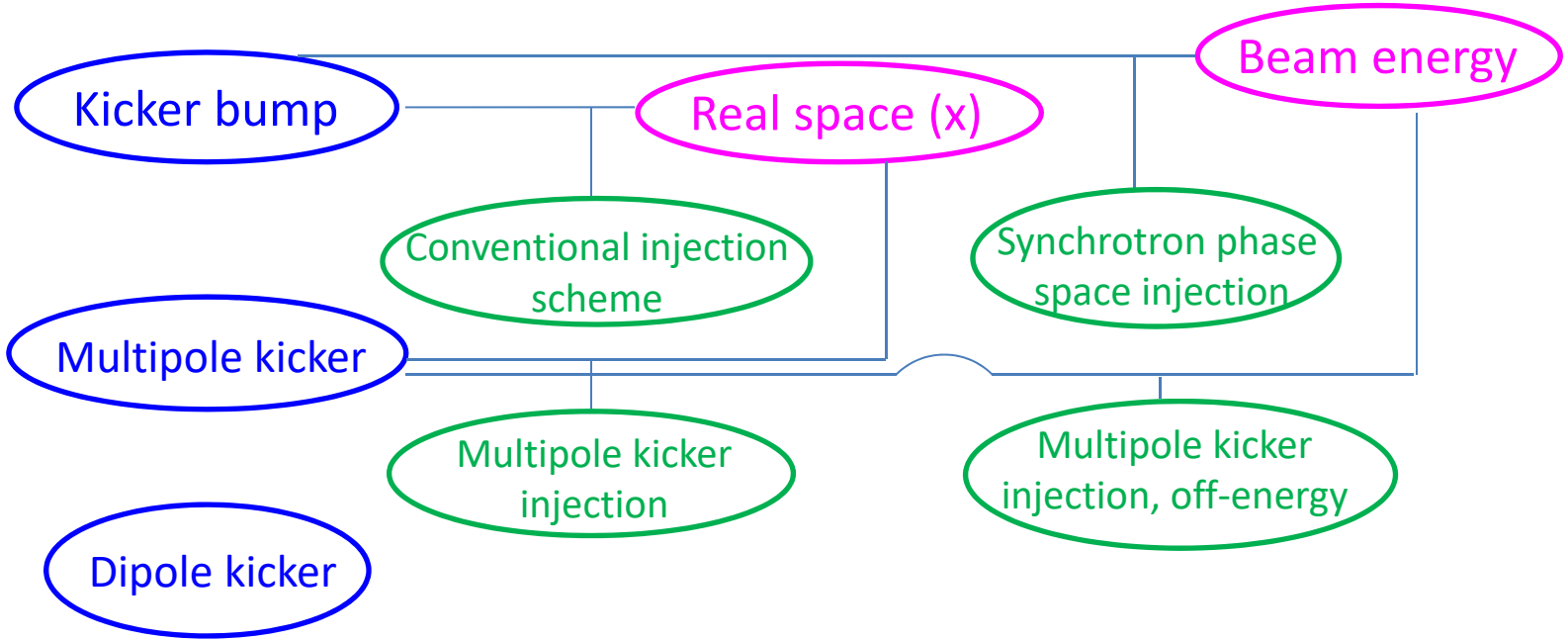

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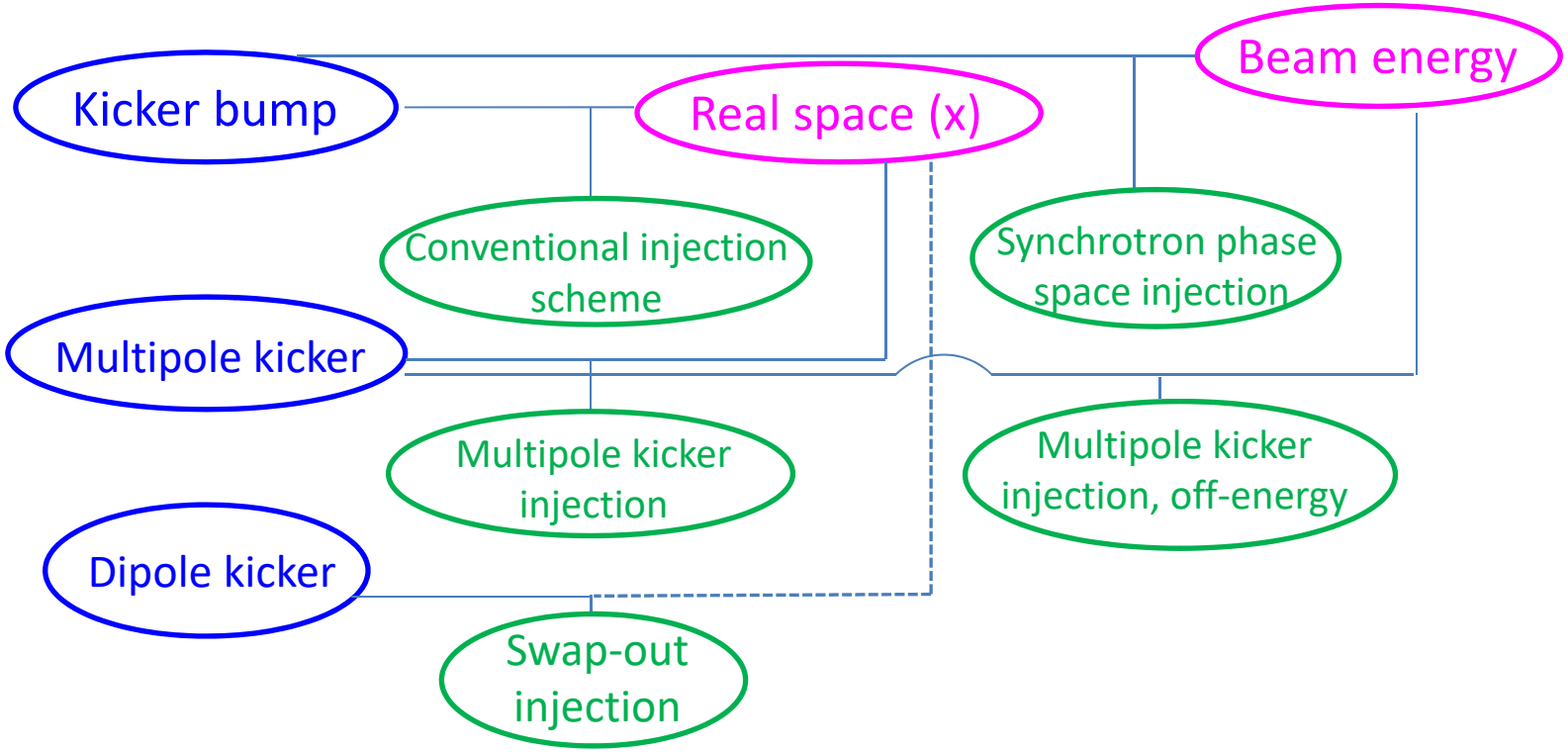

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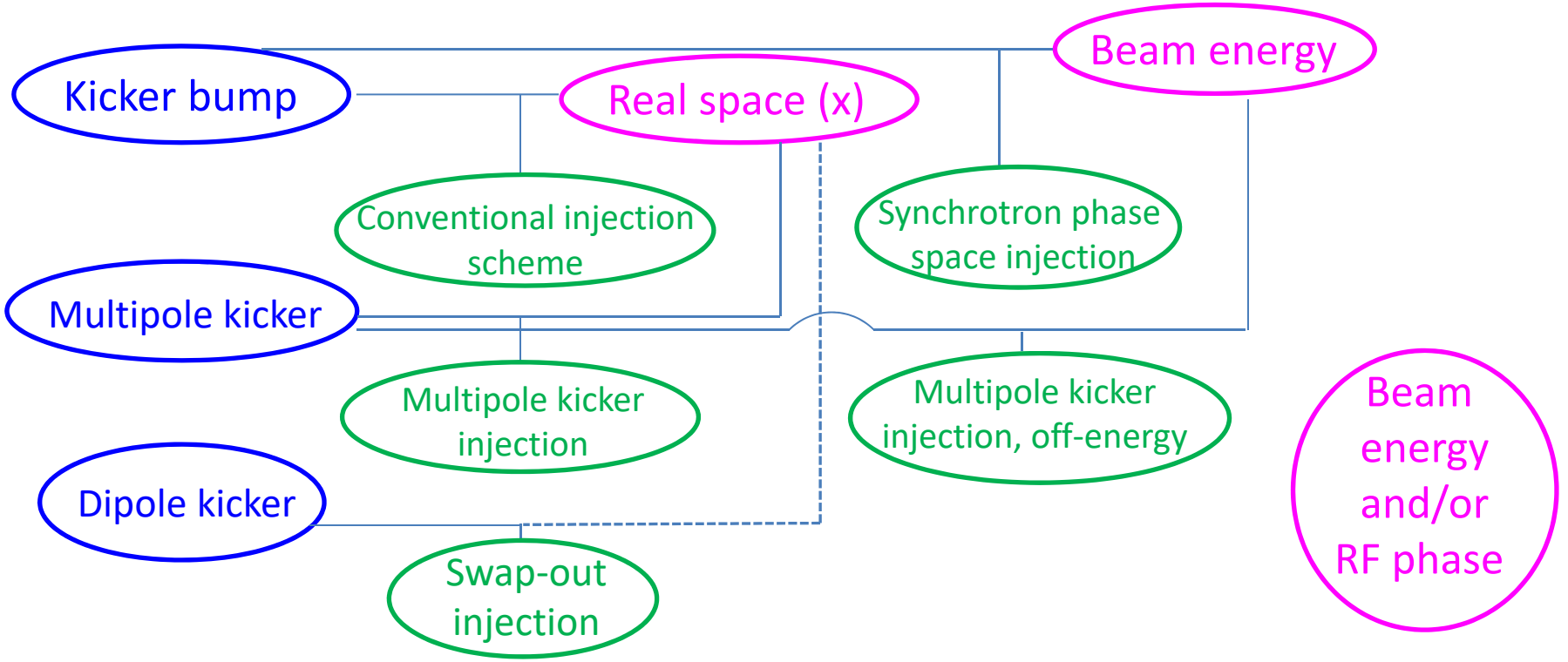

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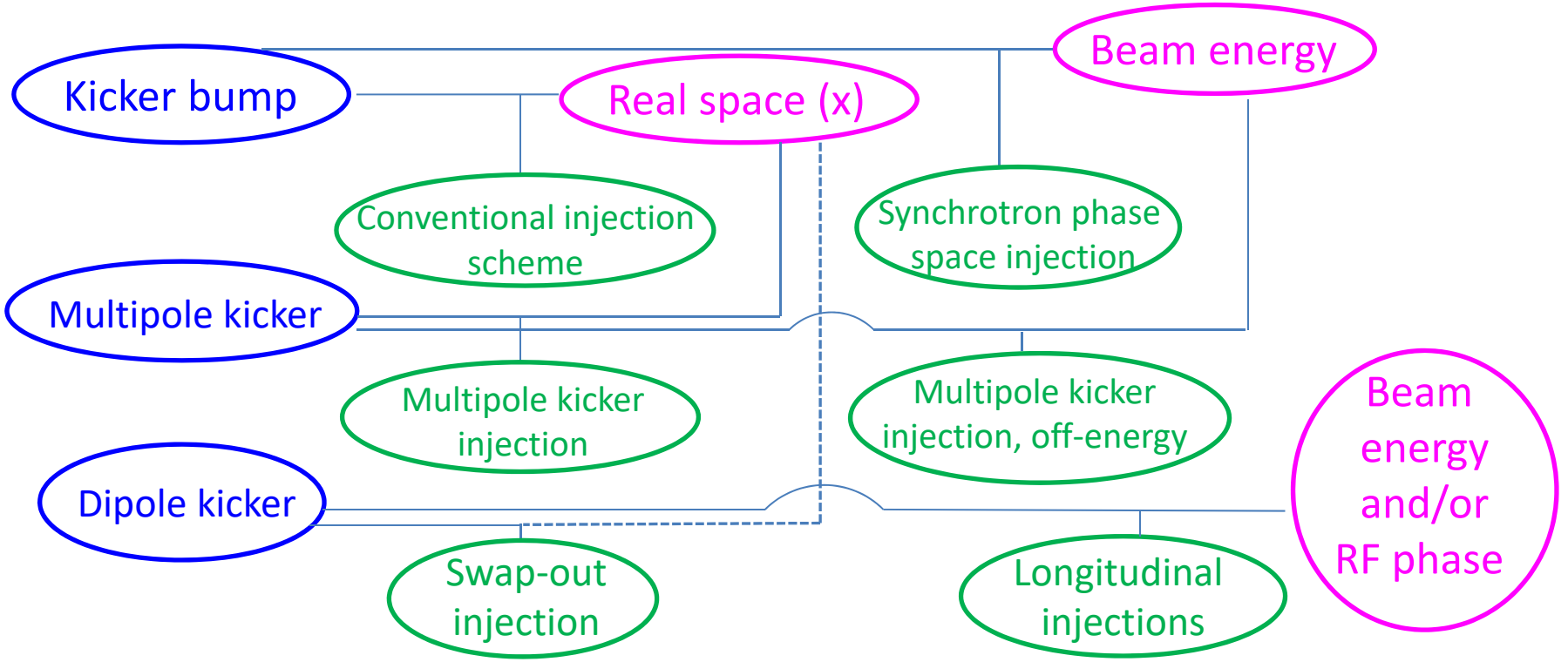

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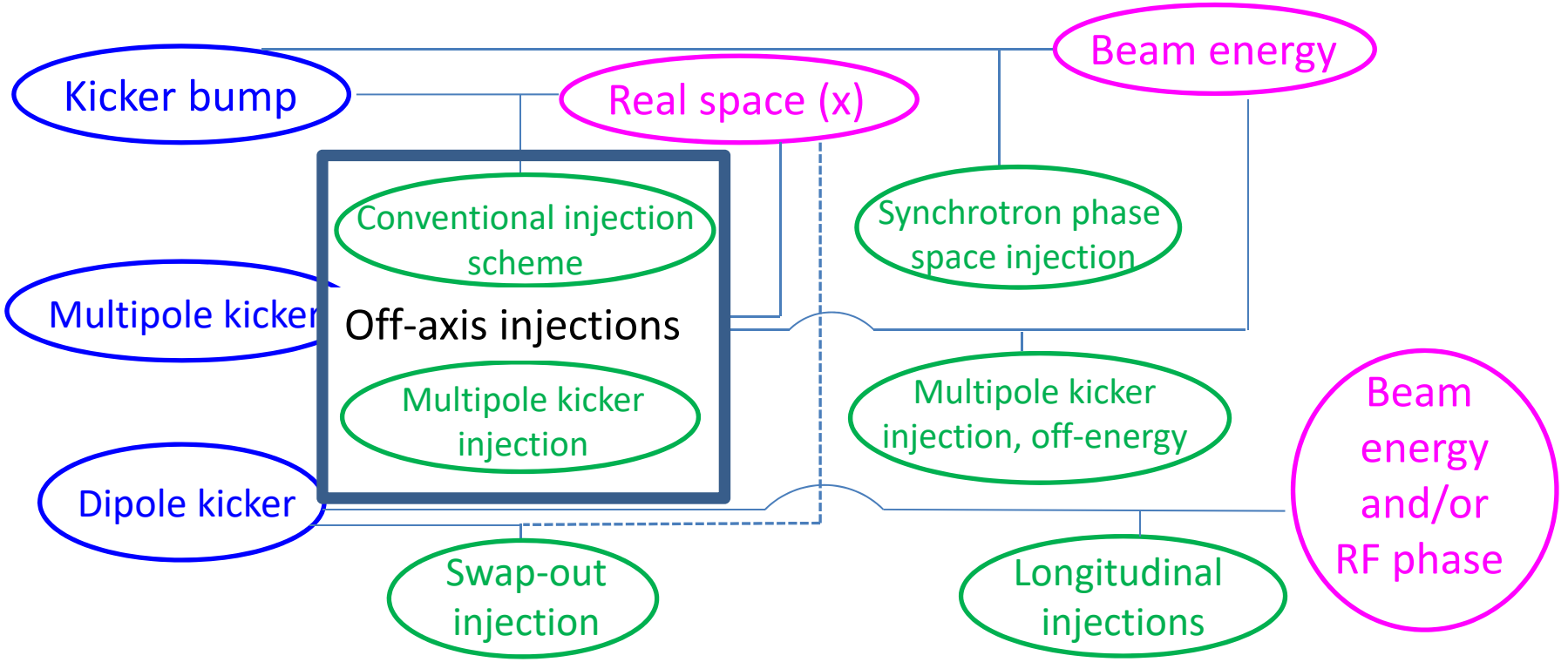

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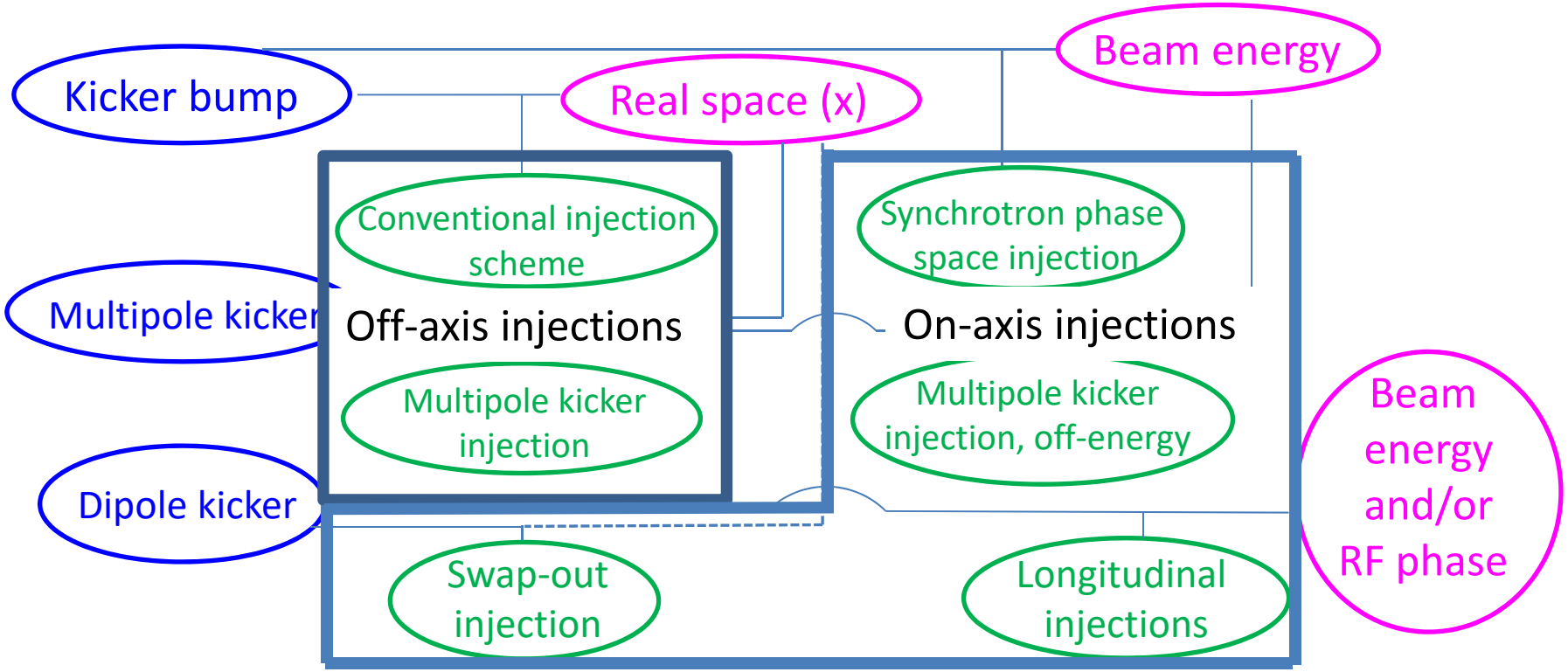

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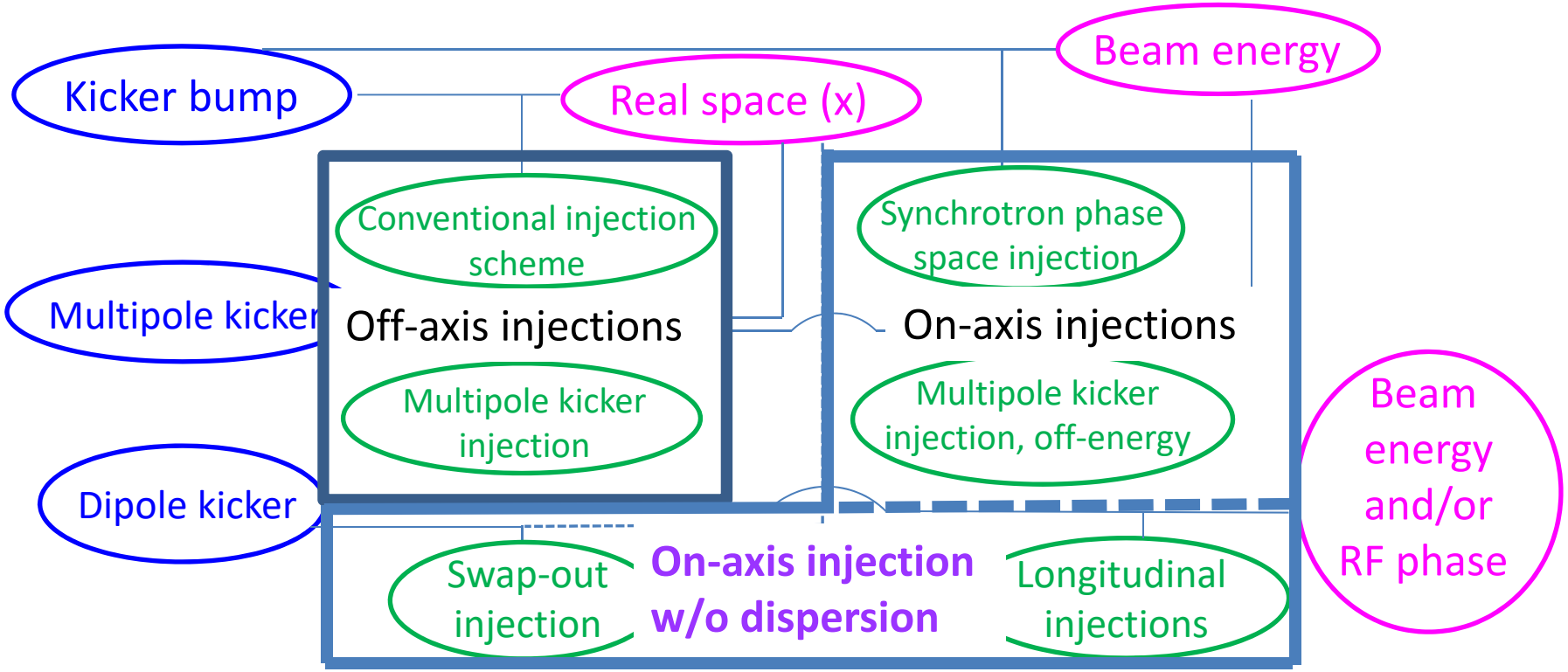

# Overview of injection schemes (2)

- Overview in a table…

| Injection scheme | Separation | Kicker type | Dispersion requirement |
|---|---|---|---|
| Conventional injection | Transverse | Kicker bump | None (Zero at septum) |
| Synch. phase space inj. | Beam energy | Kicker bump | Finite at Septum |
| Multipole kicker inj. | Transverse | Multipole/Nonlinear kicker | None |
| MKI, off-energy | Beam energy | Multipole/Nonlienar kicker | Finite at kicker |
| Swap-out injection, | Transverse | Short/Long pulse (dipole) kicker | None |
| Long. inj. | Beam energy and RF phase | Short pulse kicker | None |
| Long. inj., 2 rf | RF phase | Short pulse kicker | None |
| Long. inj., 3 rf | RF phase | Short pulse kicker | None |
| Long. inj., long. NLK | Beam energy and RF phase | Multipole/Short-pulse kicker | None |

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# Short pulse kicker

- Short pulse kicker development at KEK ATF [21]

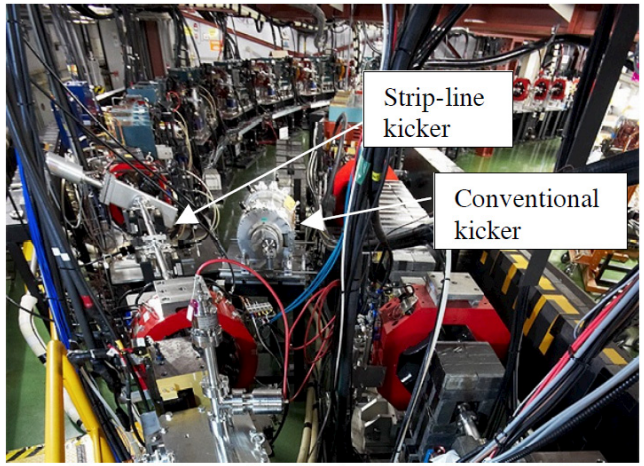


Figure 1 Two units of strip-line kickers in ATF

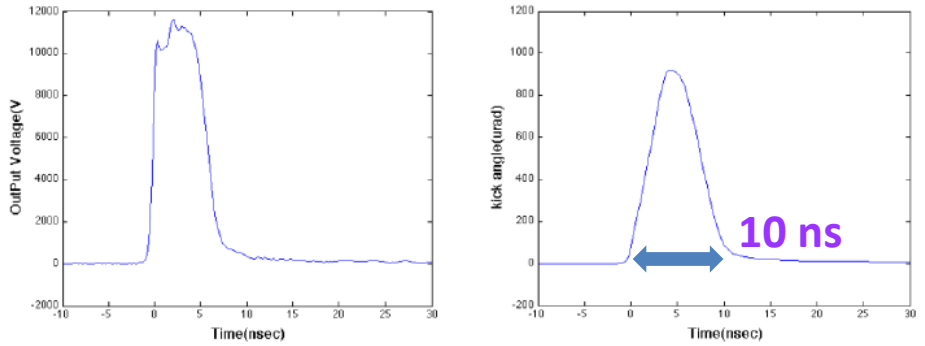


Figure 3: Pulse waveform of the pulser(left) and the estimated kick field(right)

Figures from [21] T. Naito et al., IPAC'10

# Nonlinear kicker

- Nonlinear kicker to improve MKI. Development at BESSY-II [22] and MAX-IV/SOLEIL [23]
  - Kicker consists of 8 coils
  - Wider zero/small field region around the axis
  - Zero/small gradient for injection beam

[21] T. Atkinson et al., IPAC'11
[22] S. C. Leemann and L. O. Dalin, PAC'13

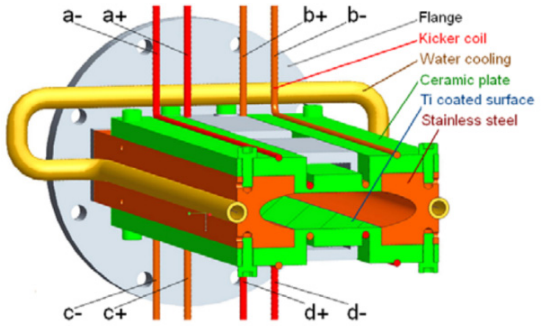
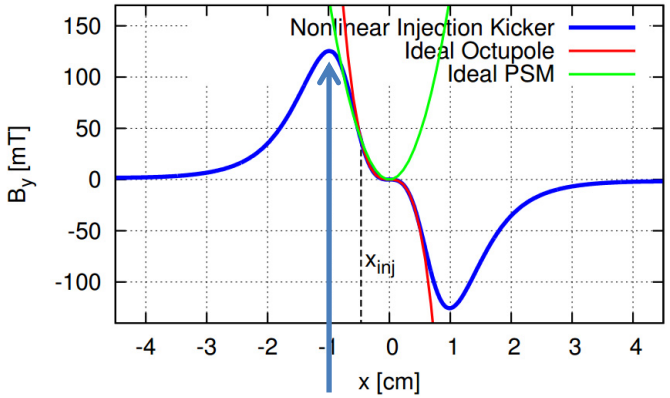



Figure 3: Sectional view of kicker magnet structure, second magnet design.

Figure from [22]




Ideally, inject here

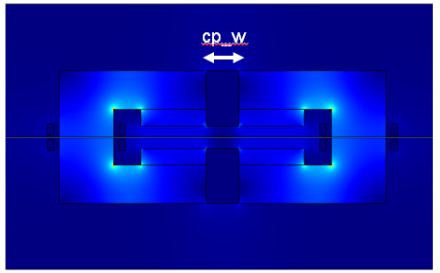
Figure from [23]

# New idea for MKI kicker

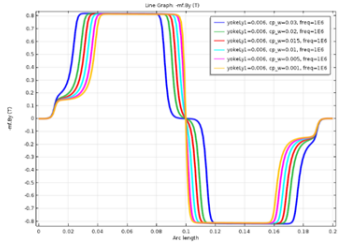
## POSSIBLE OTHER APPLICATION

- The injection straight section features the same vertical b-function as ID straights
- We need to top-up with closed gap, i.e. through a 6mm vertical aperture

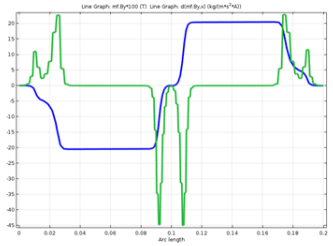
➢ Use this principle to design a low gap in-vacuum non-linear kicker/bladeless septum




- Width of copper plates determines:
- Central gradient
- Distance to achieve maximum field



- 2 c-shape kickers separated by copper plates:
- Zero dipole on axis, small quadrupole
- Injected beam sees almost no gradient (interesting in case of large injected emittance)
- Low gap: very high field achievable



- Additional coil can be used to cancel the remaining gradient

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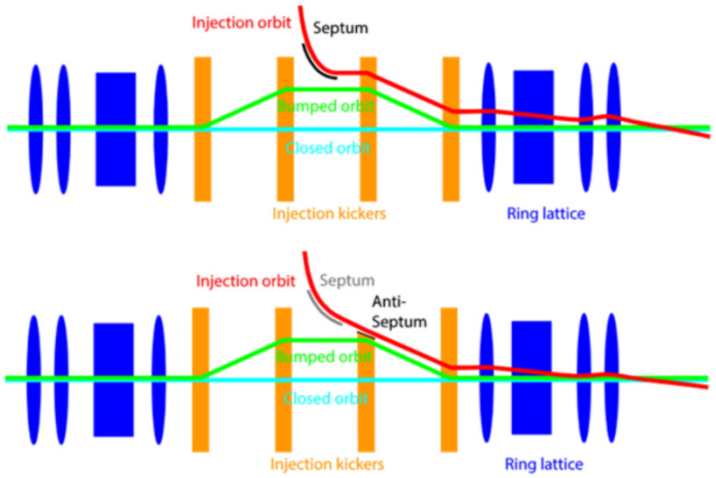
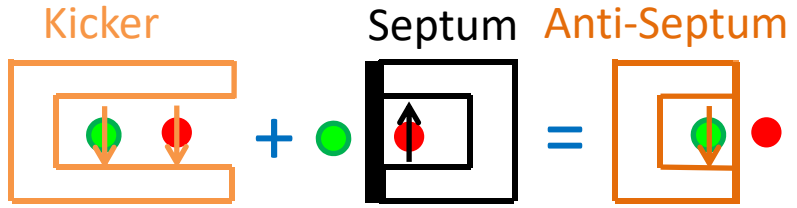
The European Synchrotron | ESRF

[24] S. White, TWIIS, 2017

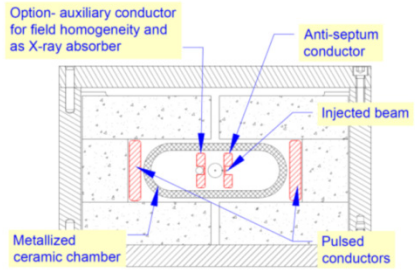
# Anti-septum

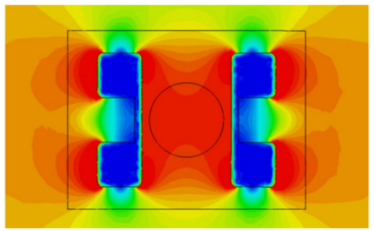
- "Anti-septum" [25]
  - Typical eddy current septum thickness of about 3 mm can be reduce to 1 mm or less since stray field is excited at the other side
  - Dynamic aperture requirement of the conventional injection scheme is relaxed




Anti-septum with a masking conductor



[25] C. Gogh and M. Aiba, IPAC'17

# Contents

- Brief history of top-up injection
- Conventional injection scheme
- Demand in the future accelerators
- New(er) schemes
- Overview
- Kicker and septum R&D
- Improvements on injector
- Summary
- References

# Emittance exchange

- Simulation of emittance exchange in BESSY-II booster [26]
  - $\varepsilon_x \gg \varepsilon_y \rightarrow \varepsilon_x \ll \varepsilon_y$ using a pulse skew quadrupole

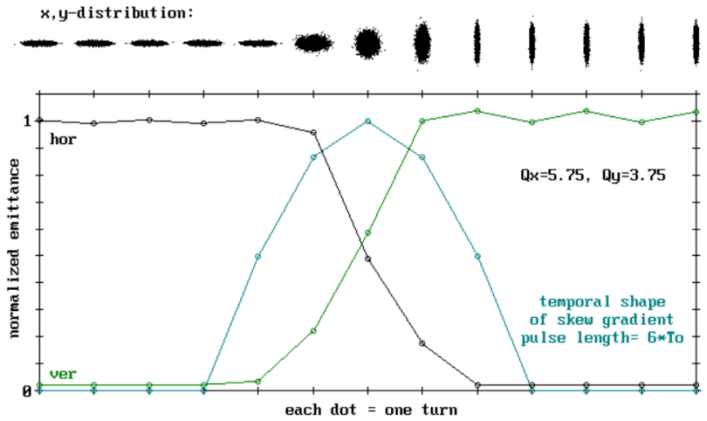



Figure 4: Impact of a skew quadrupole π-pulse on the emittance in the synchrotron.

Figure from
[26] P. Kuske and F. Kramer, IPAC'16

# Full energy linac injector

- Linac injector is capable of providing small emittance injection beam
- Light source + FEL at the same cite, a few examples
  - PSI: SLS + SwissFEL (Unfortunately separated by the river…)
  - RIKEN: SPring-8 + SACLA (New transport line is built)
  - Lund: MAX IV + Short pulse facility (Used as injector by design)

# Contents

# Summary

- Top-up operation has vastly increased the performance of lepton colliders and light sources
- Future accelerators, however, may need advanced injection schemes
  - Relaxing aperture requirement
  - Eliminating disturbance to the stored beam
  - Achieving 100% injection efficiency
- Dynamic aperture requirement qualitatively

  Swap-out injection < On-axis injections < Conventional injection
- Kicker and septum developments to support new injection schemes have been performed/underway
- Possible improvements on injector are being explored

# Contents

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