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The Physics of Particle Accelerators

an introduction

Basic Lecture material,

The Physics of Particle Accelerators, Klaus Wille **Chapters: 4.3-4.6**

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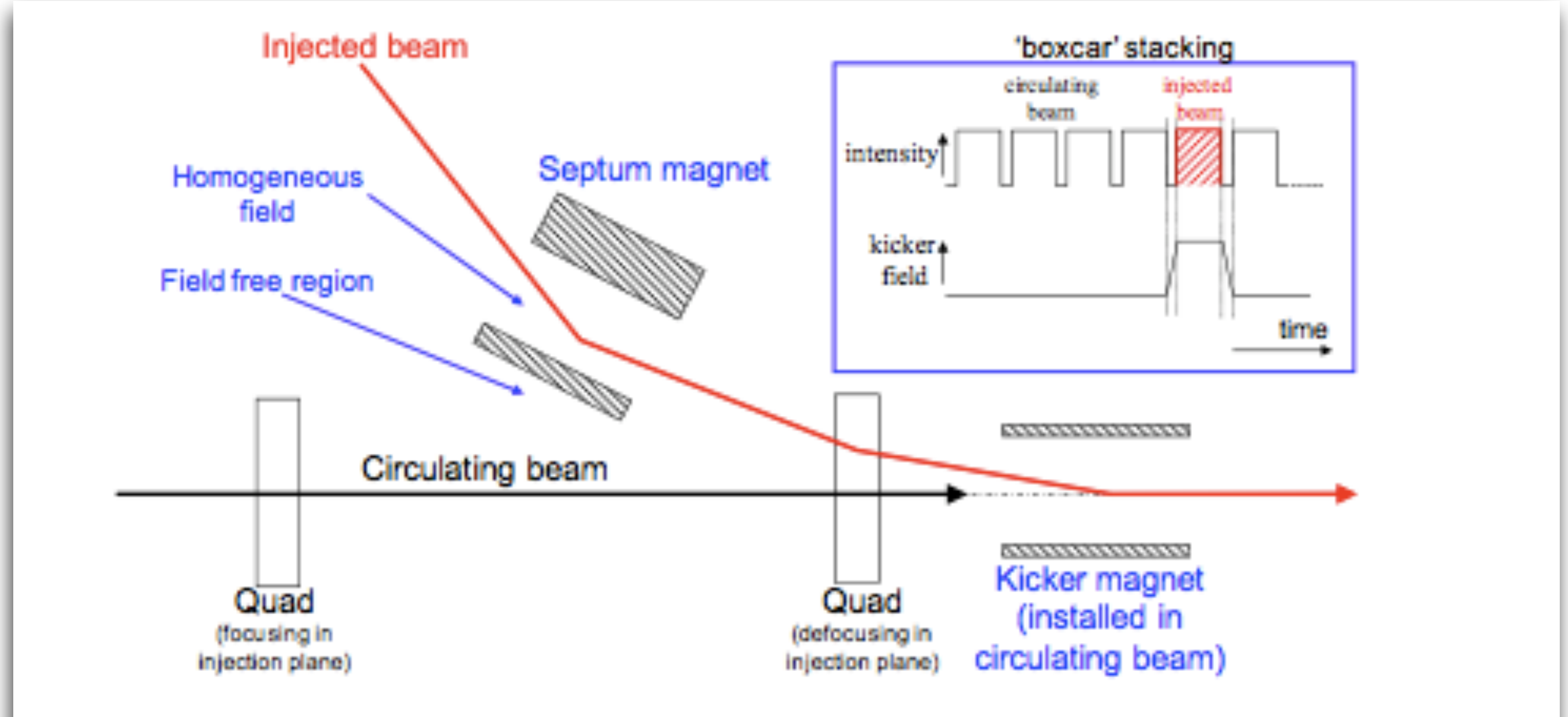
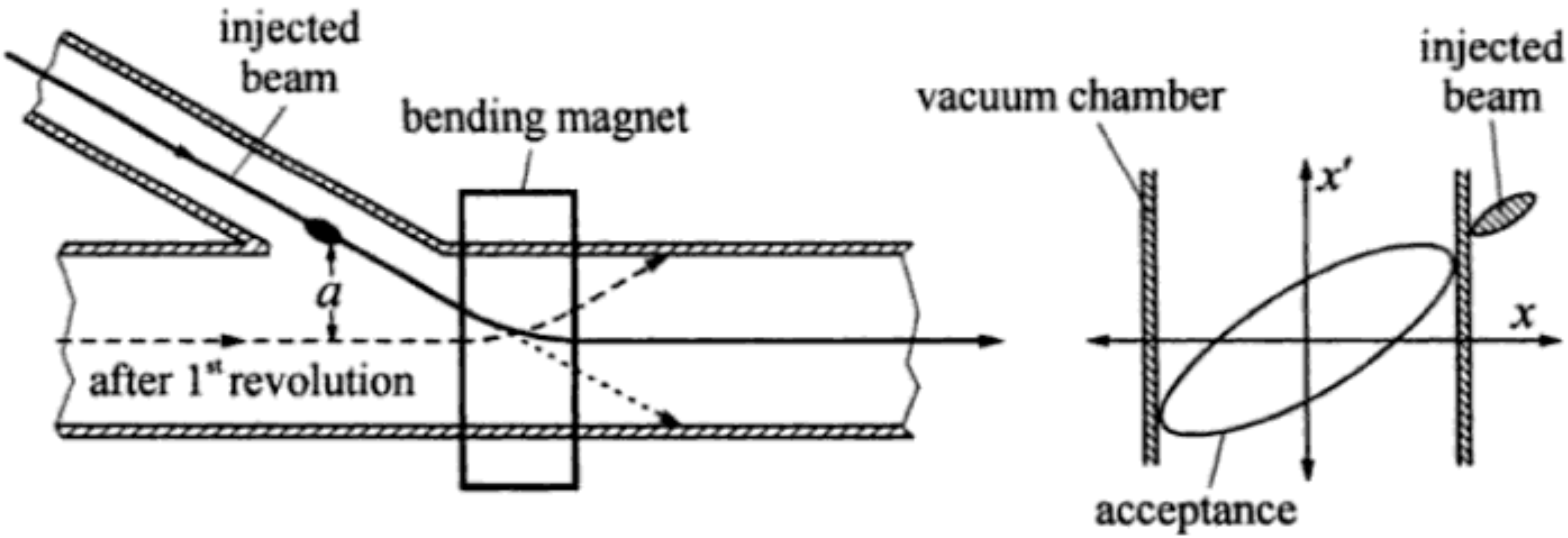


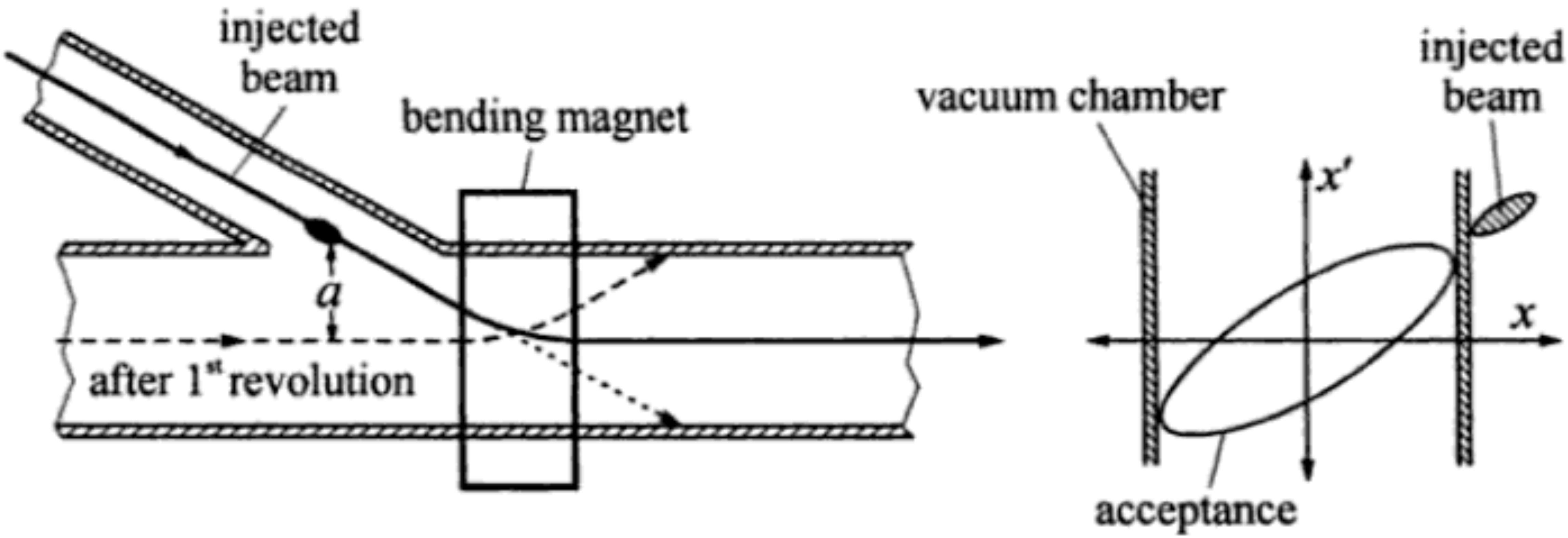
Fig. 1: Fast single-turn injection in one plane

- The fundamental problem of injection
- Injection of high proton and ion currents by 'stacking'
- Injection of proton beams using stripping foils
- Injection into electron storage ring

fundamental problem of injection



- Take a particle beam of well-defined energy from a pre-accelerator;
- Introduce it into a circular accelerator without any significant loss.
- External particle beam always lies outside of the acceptance of an accelerator.
- External beam separation from the orbit **a > d** !

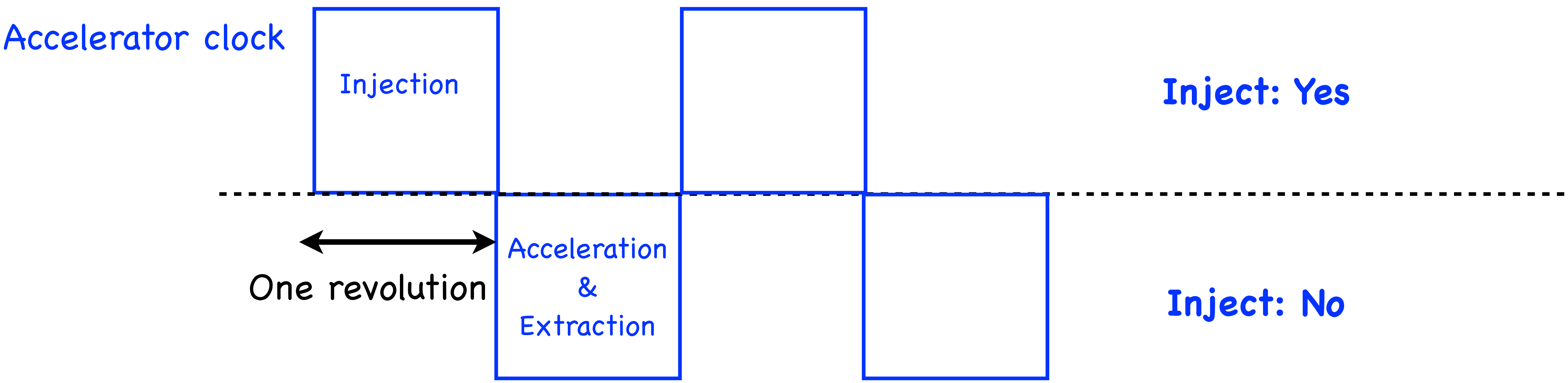


$$A_{\rm inj} \geq \frac{a^2}{\beta} > \frac{d^2}{\beta}$$

- **Step 1:** Injected beam would cross the orbit at a certain distance beyond the injection point and hit the vacuum chamber wall.
- **Step 2:** Install a dipole to deflect the beam onto the orbit.
- **Step 3:** After one revolution beam is deflected away from the orbit.
- **Step 4:** So... It is not possible to use static magnetic field. Kicker magnet?

fundamental problem of injection

- **Kicker magnet:**
  - should provide pulsed field;
  - field should build up less than one revolution and should disappear during the revolution following the injection;



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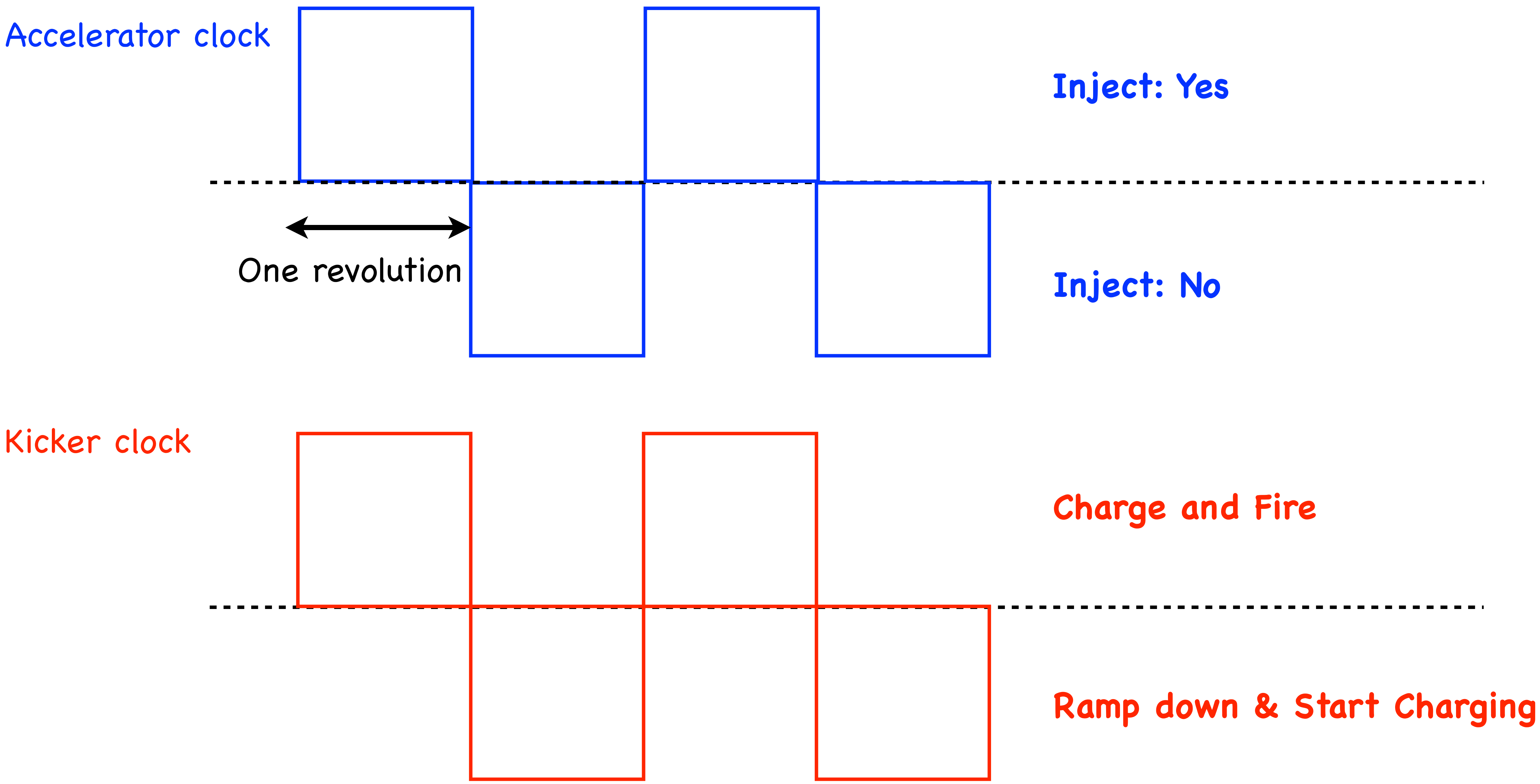

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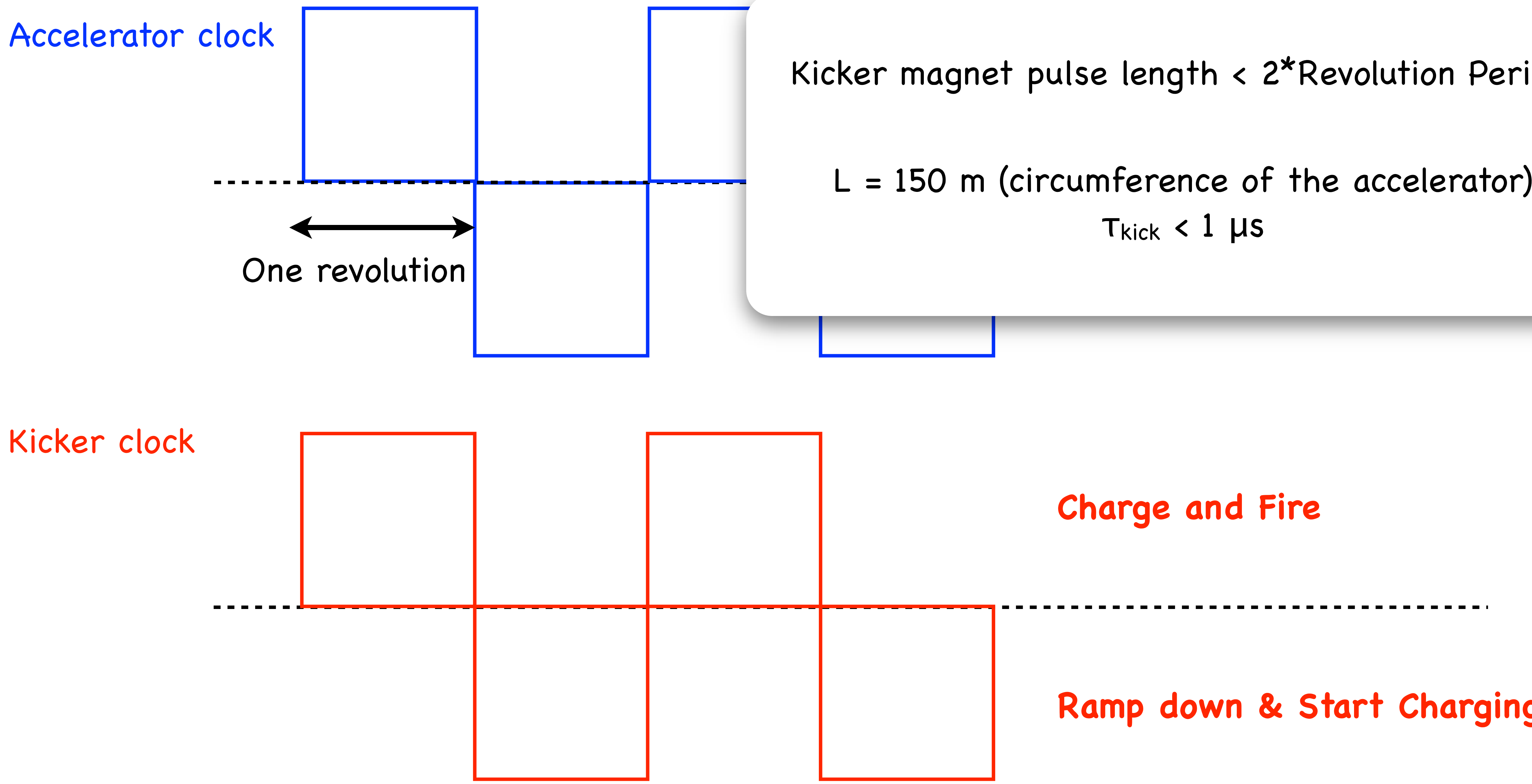
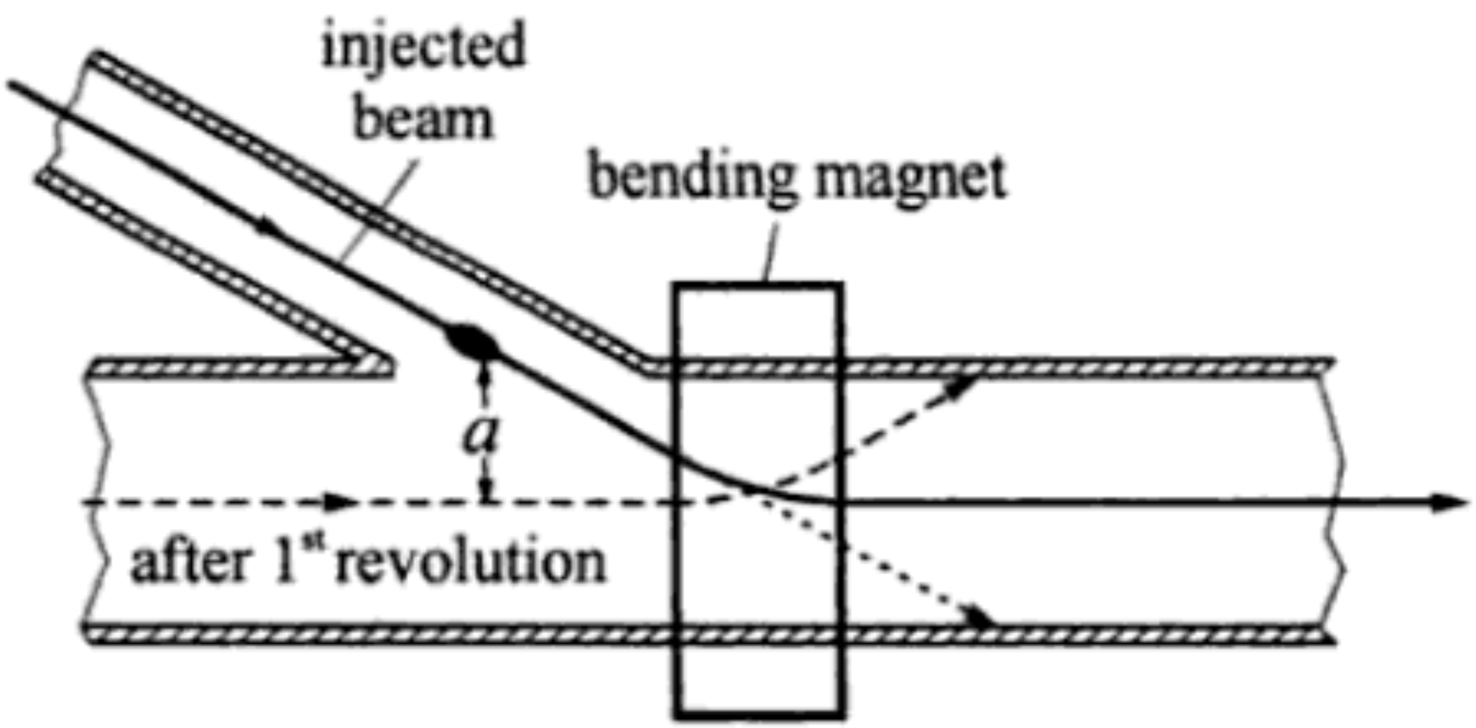


Kicker magnet pulse length < 2*Revolution Period

L = 150 m (circumference of the accelerator)

$\tau_{kick} < 1\ \mu s$

- To achieve high currents in storage rings, repeated injection needed...
- Can we use the same system????



fundamental problem of injection

- To achieve high currents in storage rings, repeated injection needed…
- Can we use the same system????

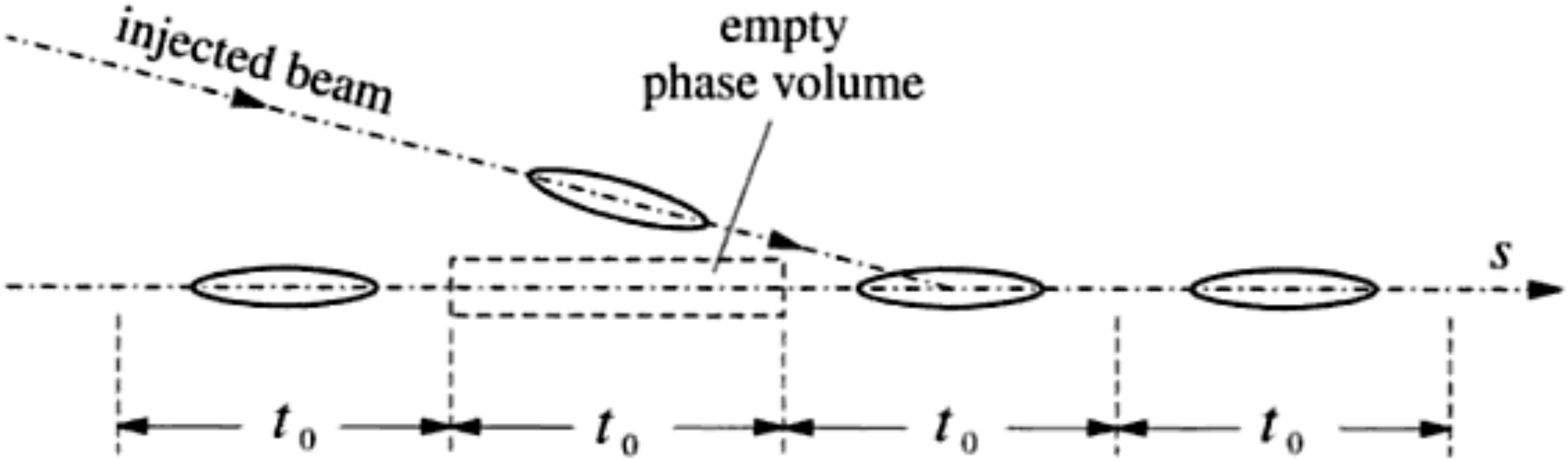
- NO…
- When the kicker is switched on for the second injection the particles traveling along the beam orbit will be deflected outwards and will be lost!

This is an example of a general problem in particle injection, when particles must be injected over several orbits or in several injection stages with arbitrary intervals. The injected beam takes up a finite volume in phase space, which consists of four transverse and two longitudinal dimensions. This phase volume may be expressed in the usual coordinates as follows:

$$\Delta V = \Delta x \cdot \Delta x' \cdot \Delta z \cdot \Delta z' \cdot \frac{\Delta p}{p} \cdot \Delta s \tag{4.3}$$

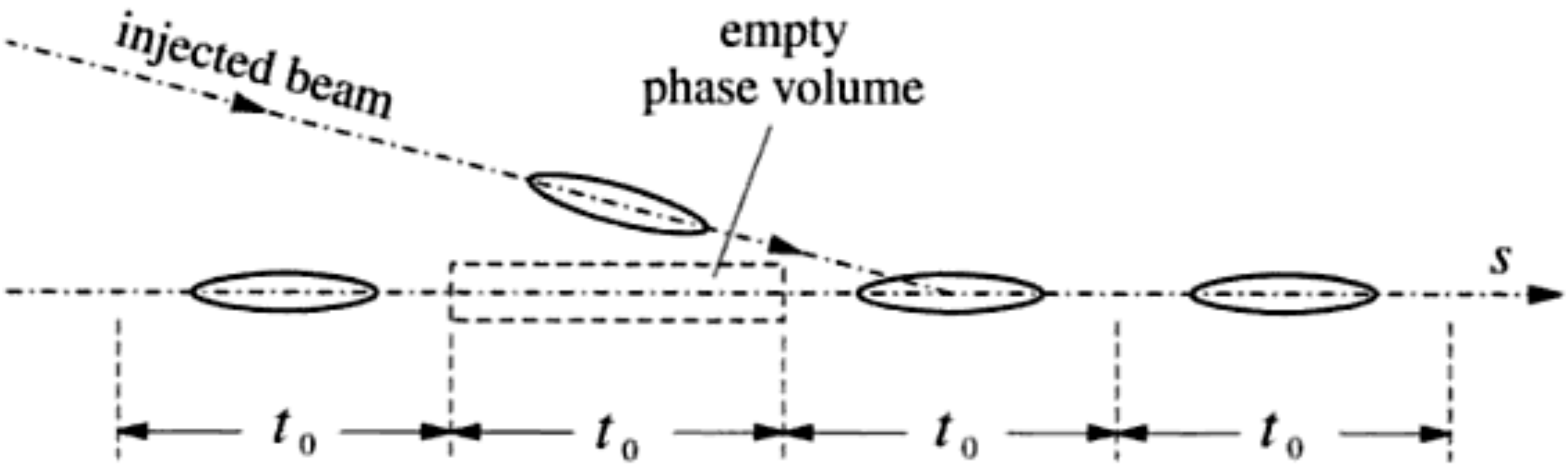
- 'Stacking' or 'slow injection/extraction',
- Most widely used for protons and heavy ions,
    - nearly no energy loss during the revolution via synchrotron radiation,
    - betatron oscillations induced during the injection continue undamped,
- Feasible when phase space occupied by beam $<$ phase space available by the accelerator,
- Phase space available by acc. is divided into adjacent but separate small volumes,
- Individual injected beams are stacked into the separate phase space volumes until they are filled.

Let's see two example...



Example 1: Injection with stacking in longitudinal phase space.

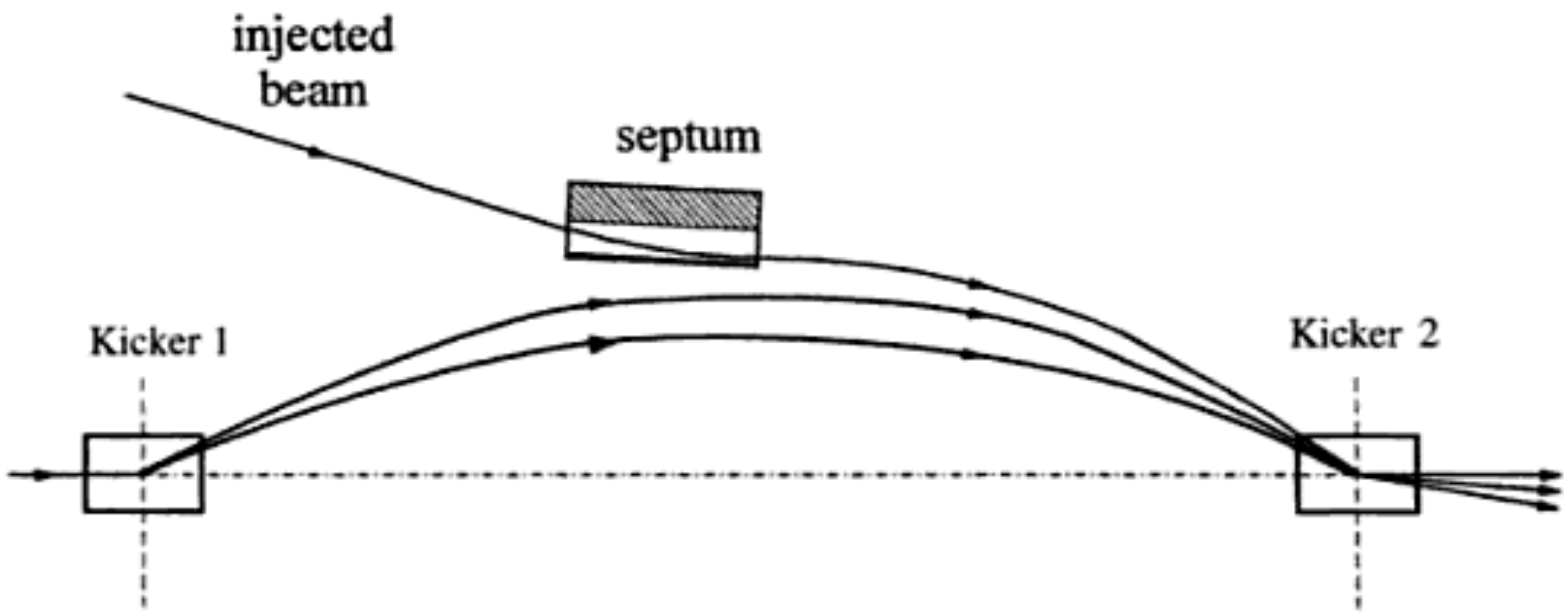
- Divide circular accelerator with length L into "n" sections.
- n empty spaces (sections) to be filled...
- Section length, $\Delta L = \tau_0 v$
- Length injected beam < ΔL @ First injection
- Shift injection timing by τ_0 fill next section @ Second injection
- Repeat the procedure "n" times until the available space is filled,
- Final beam current is "n" times larger than a single injection.



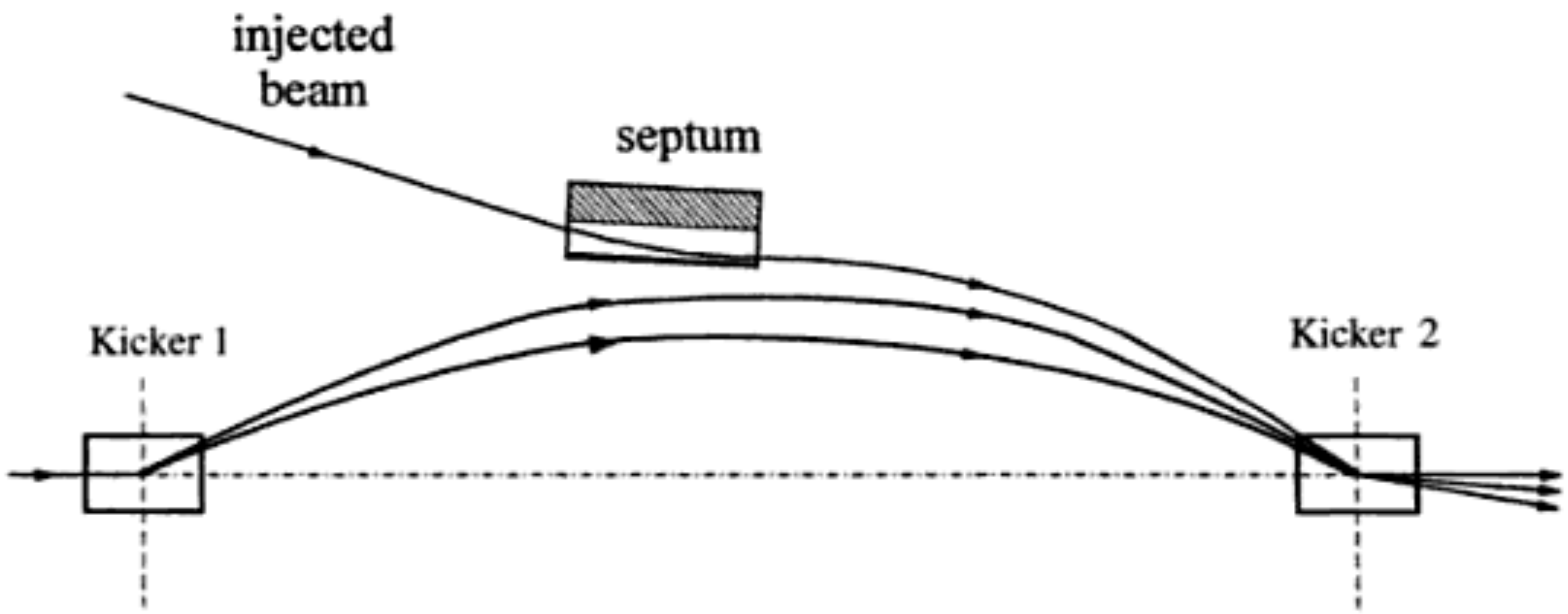
Example 1: Injection with stacking in longitudinal phase space.

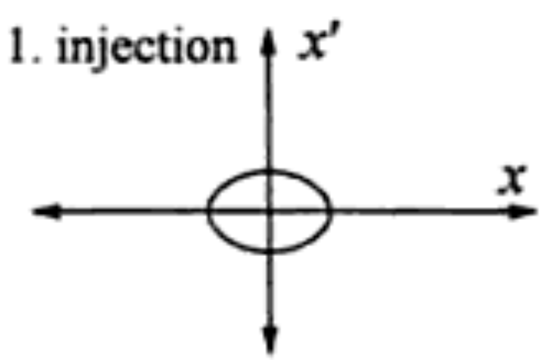
Difficulties

- Pulse length of the kicker magnet < τ_0
- Rising and falling edges should be << τ_0
- Kicker is not allowed to disturb a neighboring phase volume,
  - Easier for large accelerator, but a problem for small accelerators.

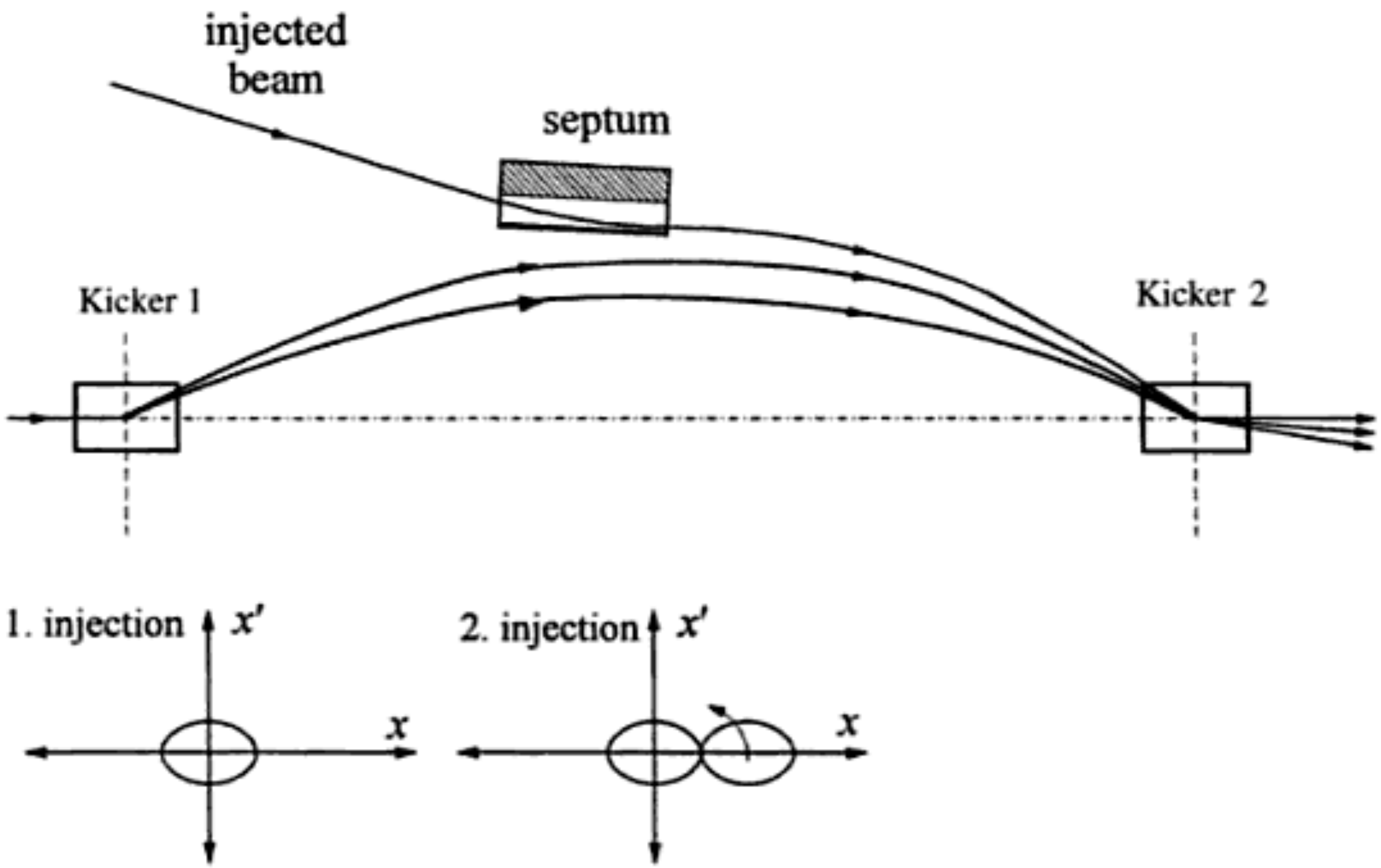


Instead of using the longitudinal phase space, stacking can also be performed in the transverse phase volume, as Fig. 4.7 shows. Here a local closed orbit bump is produced for a short time by means of two or three kicker magnets, using the procedure described in Section 3.18, and the strengths of the kickers are varied from one injection to another.

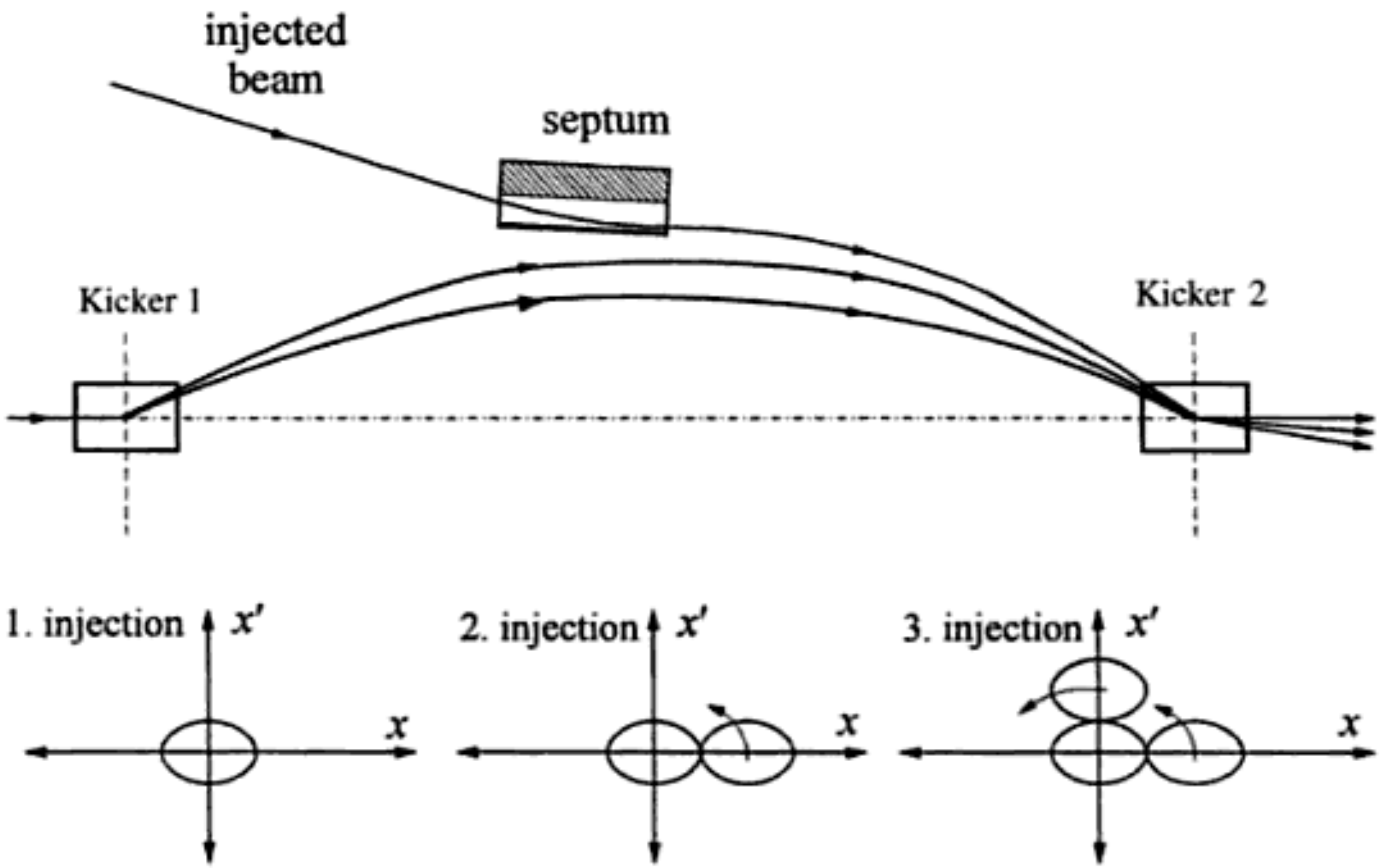




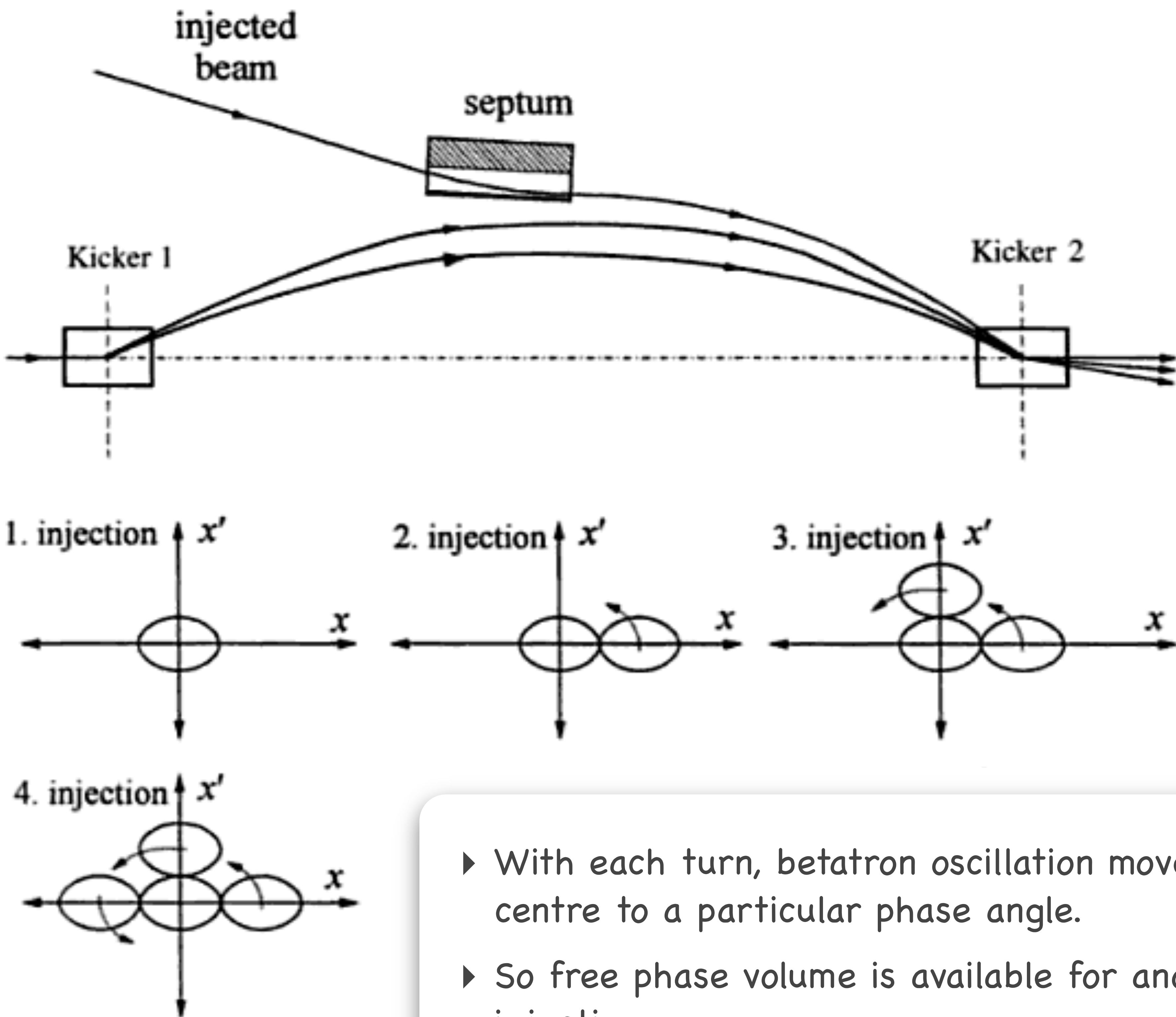
- Septum (a bending magnet) bends injected beam parallel to the orbit, within the acceptance ellipse of the accelerator.
- **First injection exactly into the orbit.**



- **Second injection,**
- Reduce kicker strength
- Orbit as close as possible to the septum without any loss.

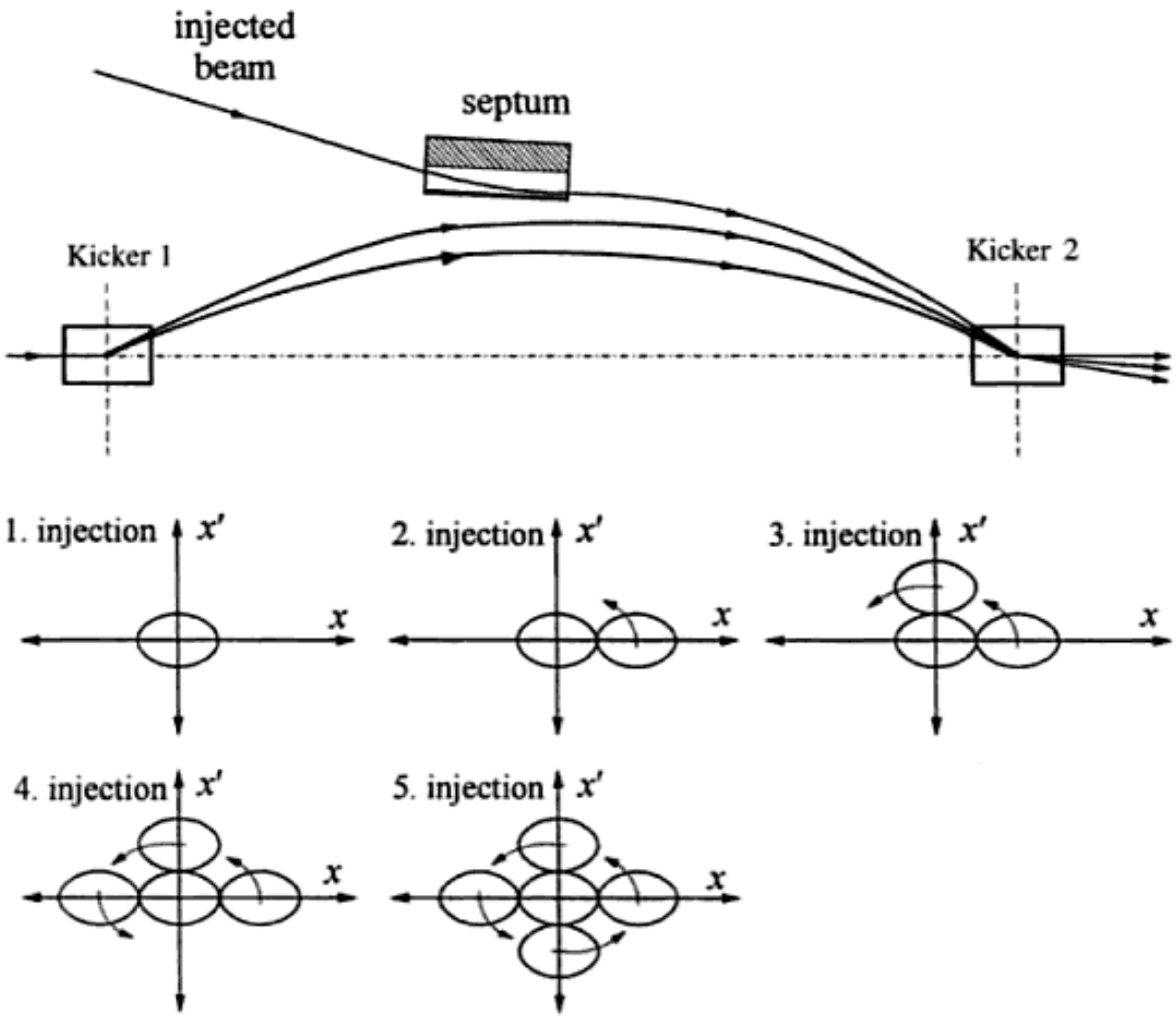


- Using the bump arrangement, repeat the injection,
- Depending on the working point Q.

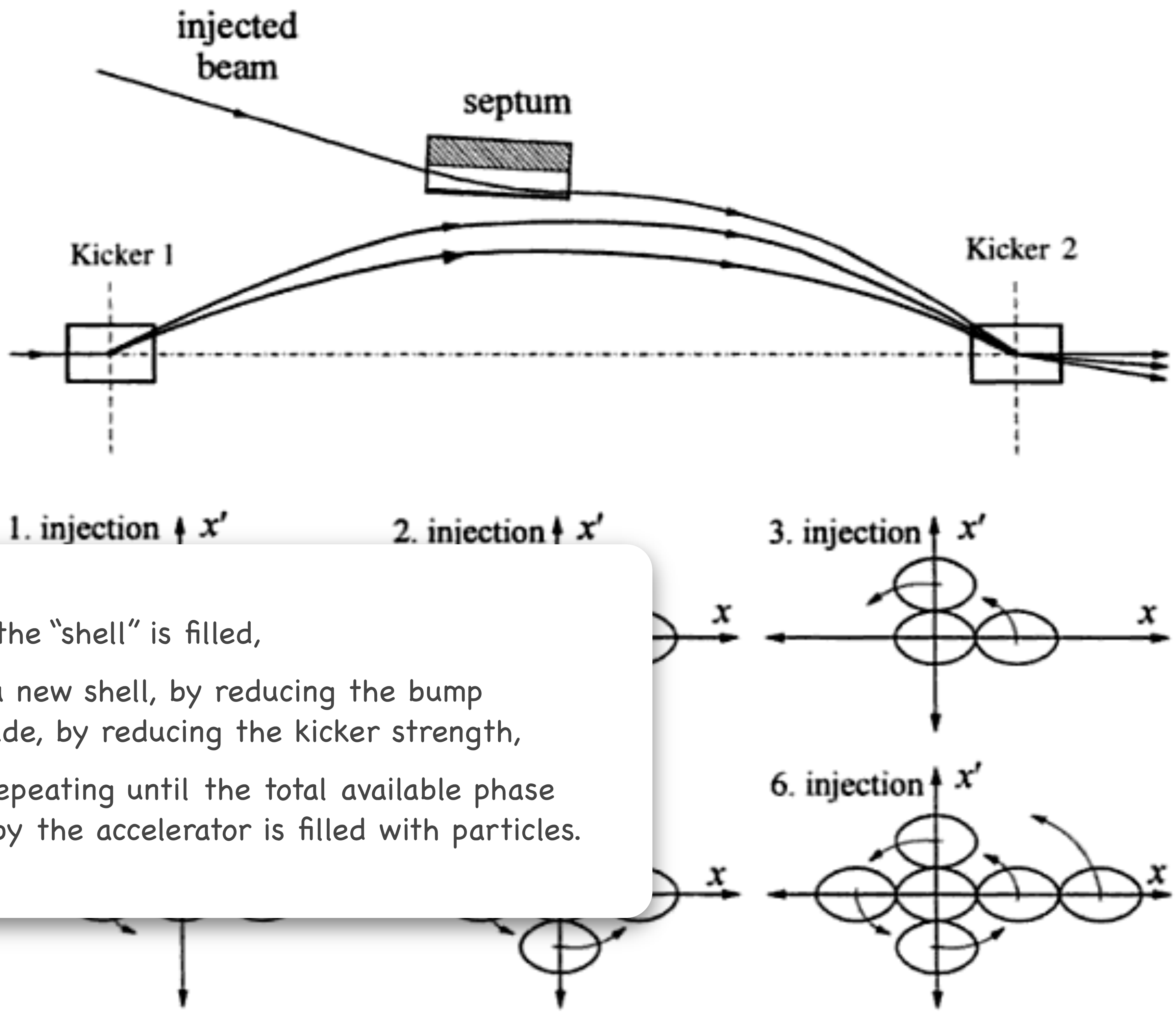


- With each turn, betatron oscillation moves the beam centre to a particular phase angle.
- So free phase volume is available for another injection.

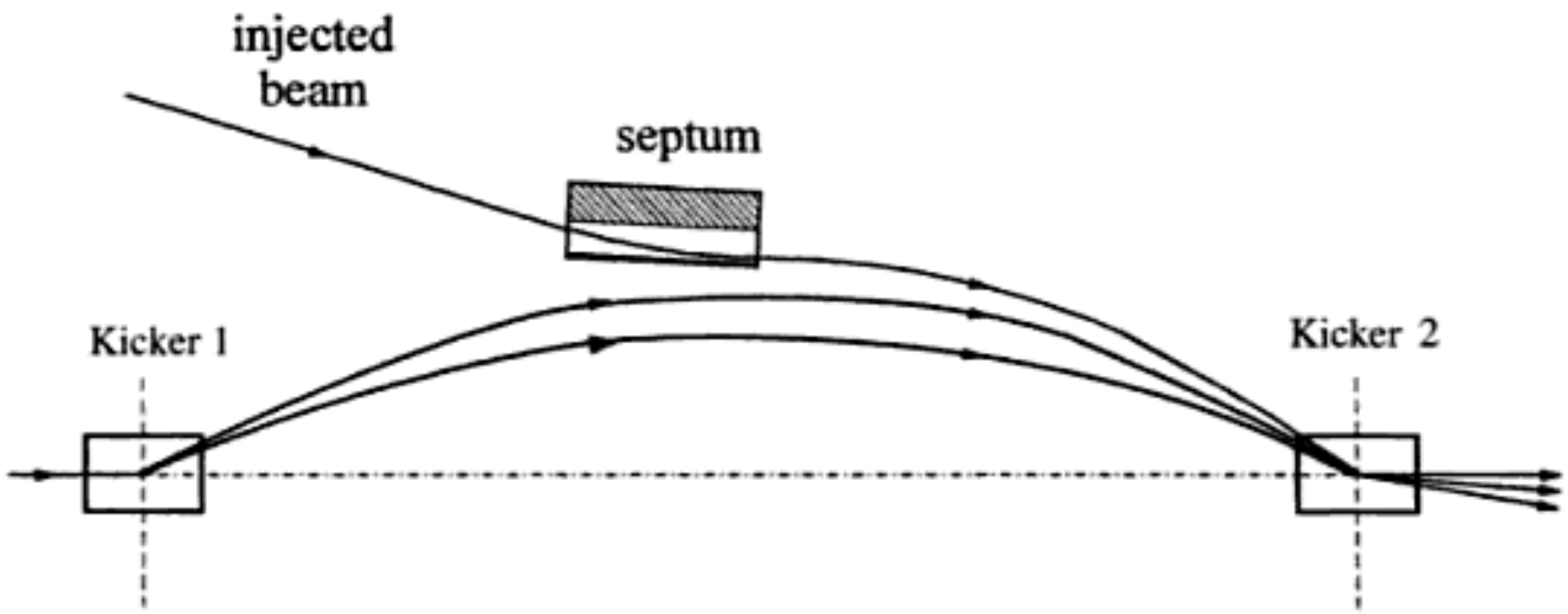
injection of high proton and ion currents by 'stacking'



injection of high proton and ion currents by 'stacking'

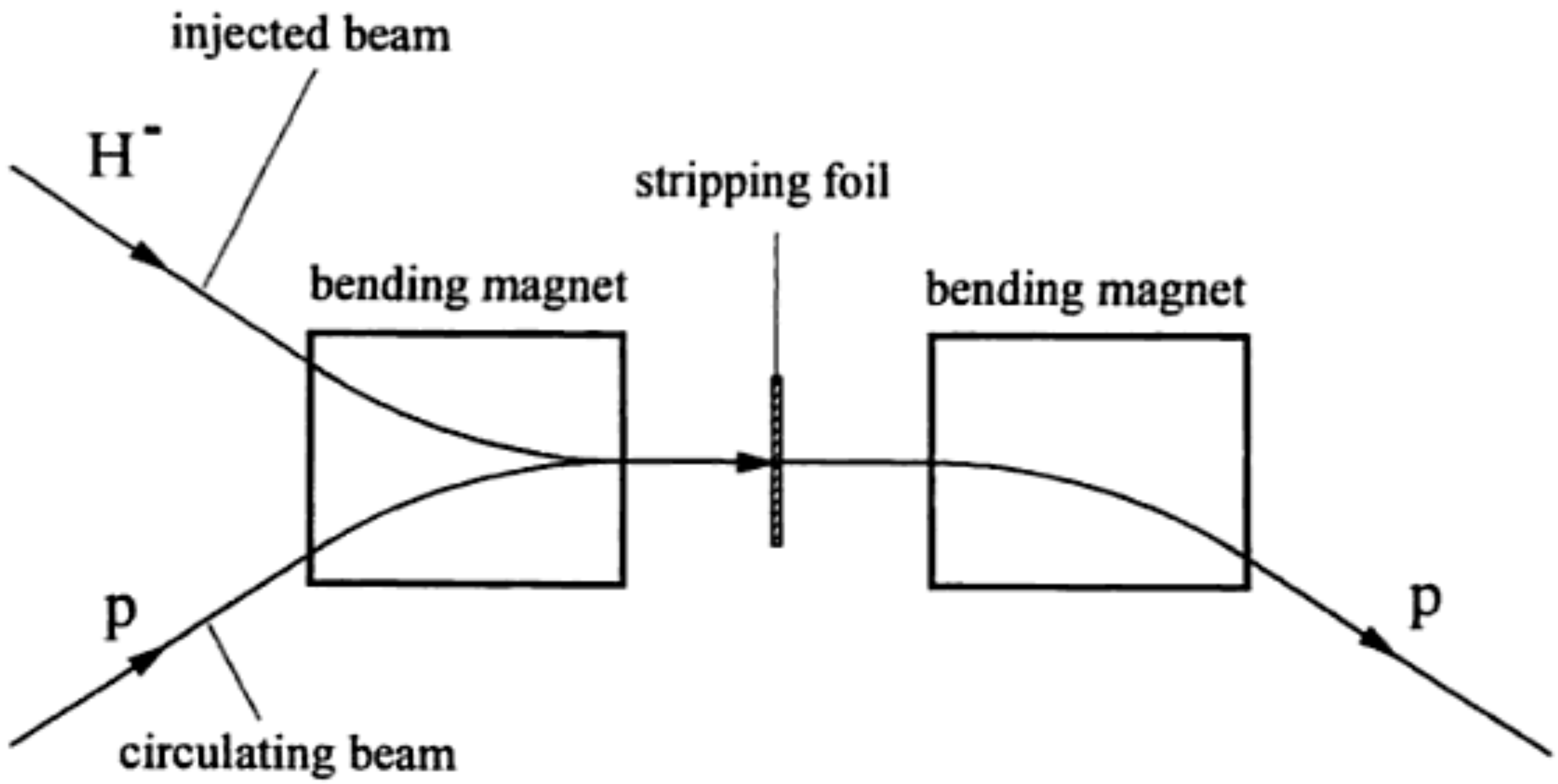


- When the "shell" is filled,
- Start a new shell, by reducing the bump amplitude, by reducing the kicker strength,
- Keep repeating until the total available phase space by the accelerator is filled with particles.

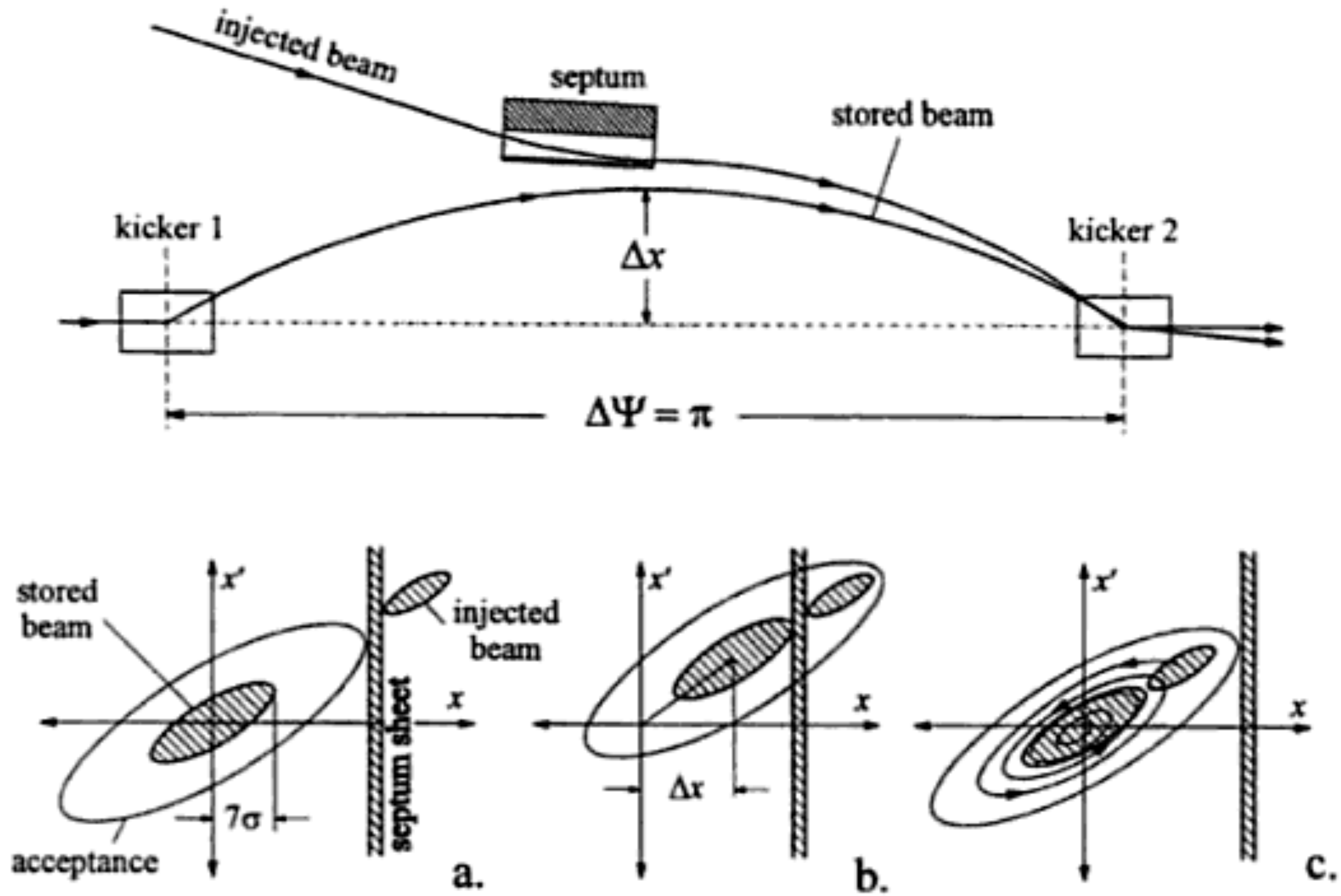


It should be noted that instead of using a variable-amplitude kicker bump, transverse stacking can also be performed by varying the particle energy, provided that the dispersion D at the injection point is sufficiently large. By varying their momenta, particles may be injected along different dispersive trajectories with a separation $x_{\mathrm{D}} = D\frac{\Delta p}{p}$ from the orbit. Apart from this the injection process proceeds exactly as in the case of the kicker bump.

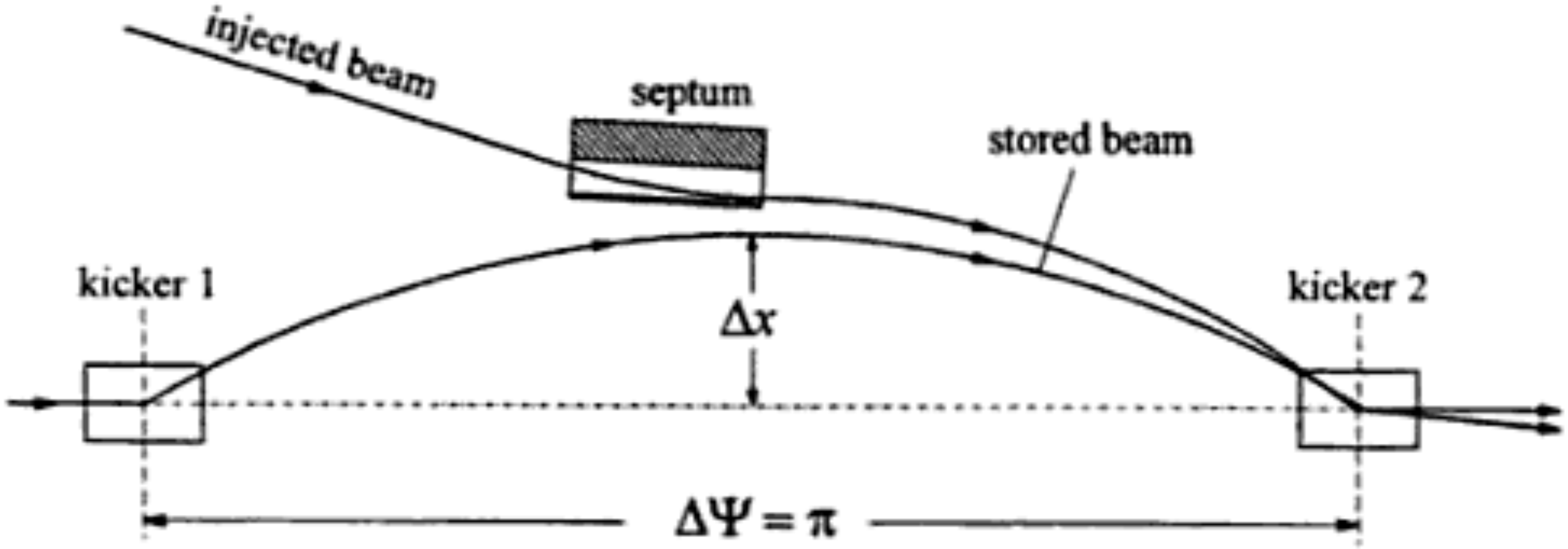
injection of proton beams using stripping foils

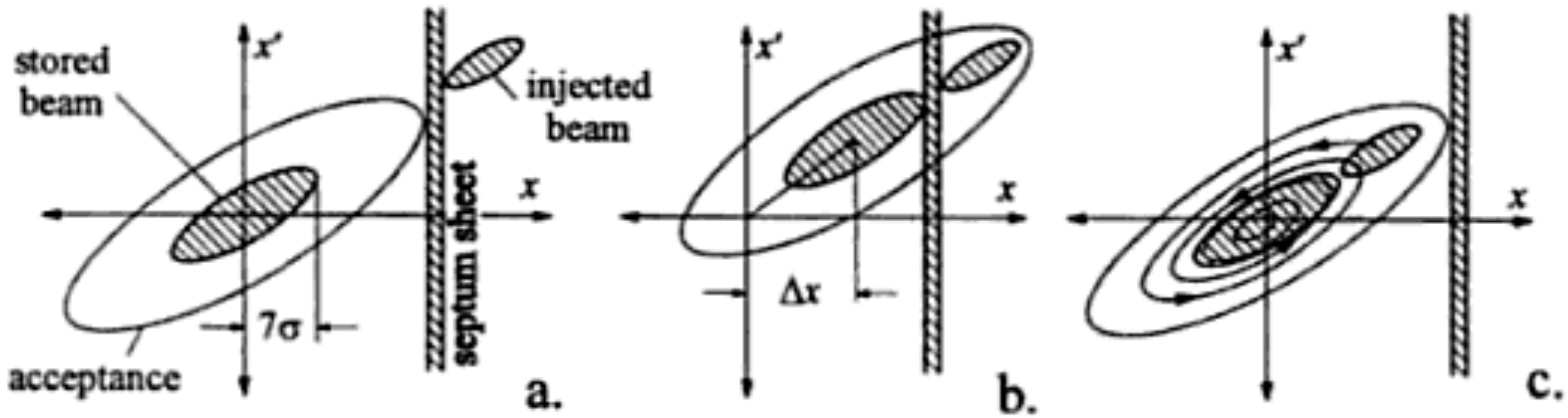


- Produce H^- ions enriched with electrons in an ion source,
- Bring them up to a high energy in a pre-accelerator,
- Use bending magnets to bend them onto the orbit,
- Provide encounter with a stripping foil -> protons are produced
- After a full revolution protons enter the bending magnet,
  - So do newly injected ions,
- Both are deflected in opposite directions due to their opposite charge,
- Injected and circulating beams automatically kept apart without any kickers...

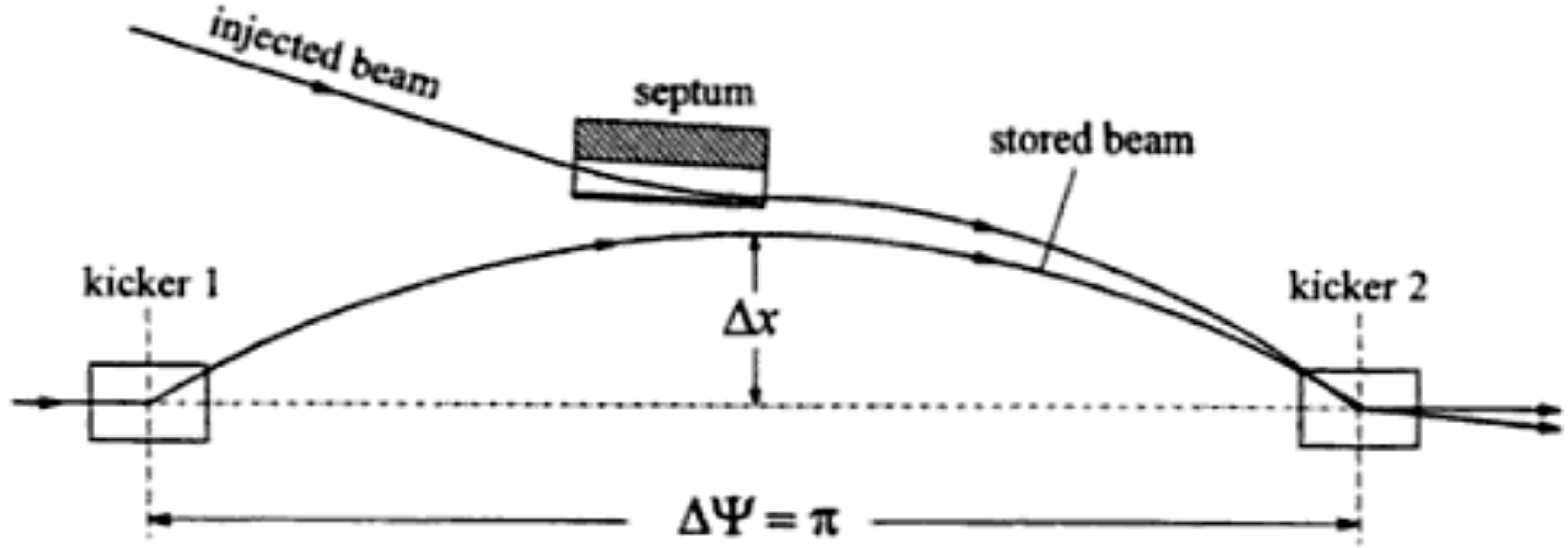


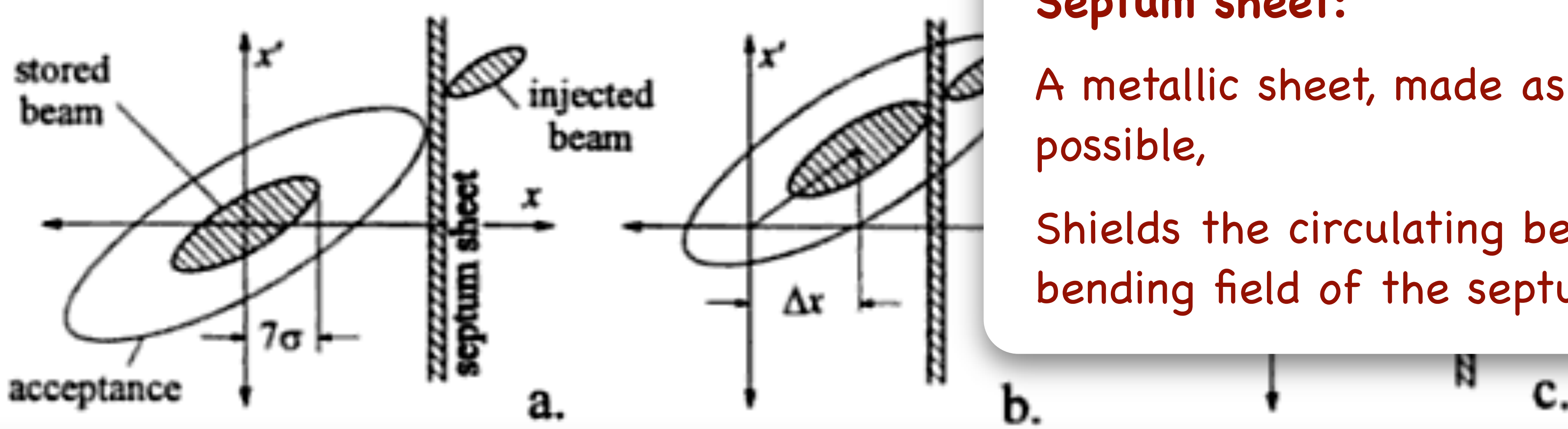
- **In electron storage rings,**
- Repeatedly inject particles into a given phase volume,
- without significant particle loss. **Why, how?**





- **In electron storage rings,**
- Electrons emit synchrotron radiation,
- Betatron oscillations die away due since the energy removed from the system.



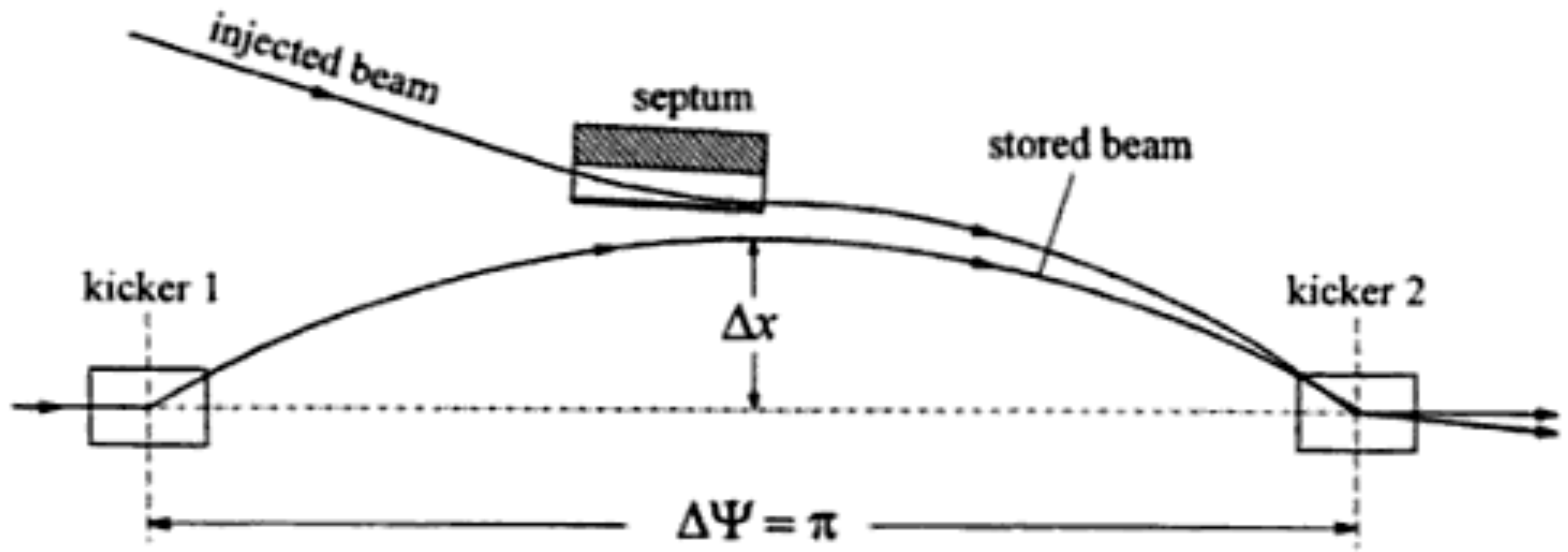


Septum sheet:

A metallic sheet, made as thin as possible,

Shields the circulating beam from the bending field of the septum magnet.

- **Recipe**
- Local orbit bump produced by fast kickers,
- Kicker pulse length about one period of revolution,
- Already stored, circulating beam about at least 7σ,
- An acceptance larger than the acceptance of stored beam, extending to the vacuum chamber (here septum sheet).



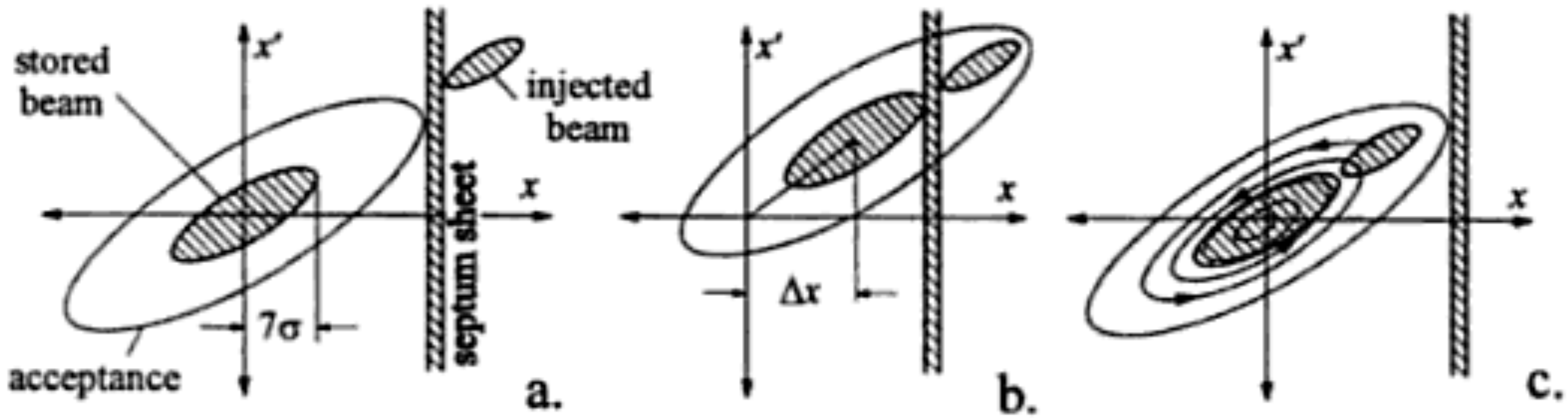
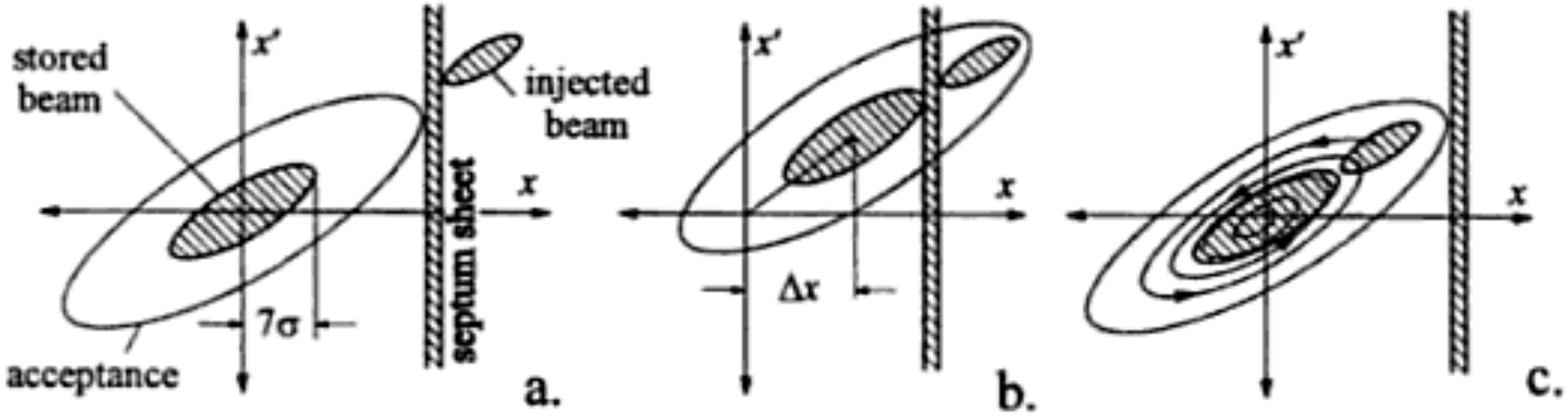


Fig. 4.9 Electron accumulation. The phase volume filled with the injected beam is freed up due to beam damping and becomes available again for the next injection. (a) is the phase diagram in the initial state before injection, (b) shows the state during injection, and (c) the state during the revolutions which follow.



The newly injected beam performs large betatron oscillations around the stored beam, but these oscillations are stable because they lie within the acceptance of the storage ring. As a result of the damping mentioned above, the amplitude of these oscillations decays away with time and the new particles move in a spiral inside the phase ellipse towards the orbit. After a few damping periods, lasting from 1 ms to a few tens of ms, the injected particles are incorporated into the stored beam, increasing its intensity. The phase volume occupied during the injection is now free again. This procedure may in principle be repeated as often as desired, yielding very high beam currents, until technical or physical limits are reached.

This injection technique circumvents the fundamental rule of injection stated above because energy is lost by radiation, and so Liouville's theorem no longer holds.

Questions?

Homework from last lecture?

Homework

Use MADX to design a simple extraction system for the following sequence:
Match kqf and kqd to obtain a periodic lattice with $\beta_x = 10, \beta_y = 39.6229, \alpha_x = 0, \alpha_y = 0$ at the start and end of the cell.

Assume a 5σ beam envelope for aperture calculations and a horizontal normalised emittance of 10^{-7}m.rad. Assume a septum thickness of 10mm and an outer quadrupole radius of 250mm. Match kick.k and sept.k to extract this beam.

```
Extraction_cell: sequence, L=10.00;
qf: quadrupole, L=0.1, K1:=kqf, at=0.05;
extkick:  hkicker, L=4.4, kick:=kick.k, at=2.5;
qd: quadrupole, L=0.1, K1:=kqd, at=4.95;
qd: quadrupole, L=0.1, K1:=kqd, at=5.05;
extsept:  hkicker, L=2.1, kick:=sept.k, at=8.65;
qf: quadrupole, L=0.1, K1:=kqf, at=9.95;
end.ext, at=10.00;
endsequence;
```

Assume the kicker is an electrostatic kicker, if the aperture is 25mm, and you are using 2.5GeV electrons, what is the voltage across the kicker?