Storage Ring Injection

S. Guiducci

LNF, 22 July 2016

Outline

- On axis injection
- Extraction
- Off axis injection for electrons or positrons

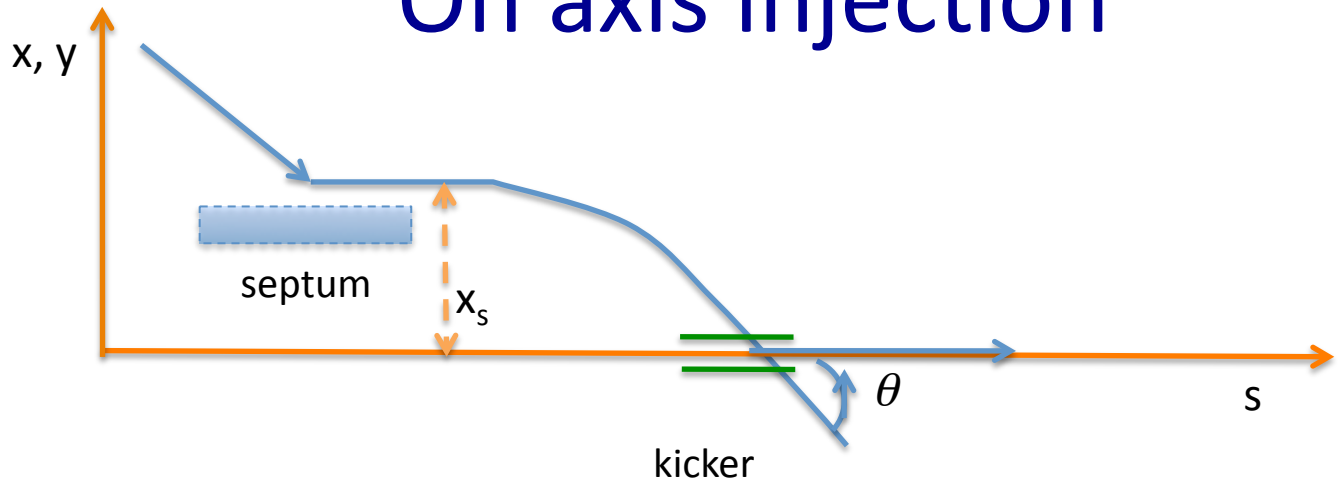
Injection

- Injection covers the final stage of transfer of beam from one accelerator to another, either from a linear to a circular machine or from one circular machine to another
- The design aims are to achieve the transfer with little beam loss and with a minimum dilution of the beam emittances

On axis injection

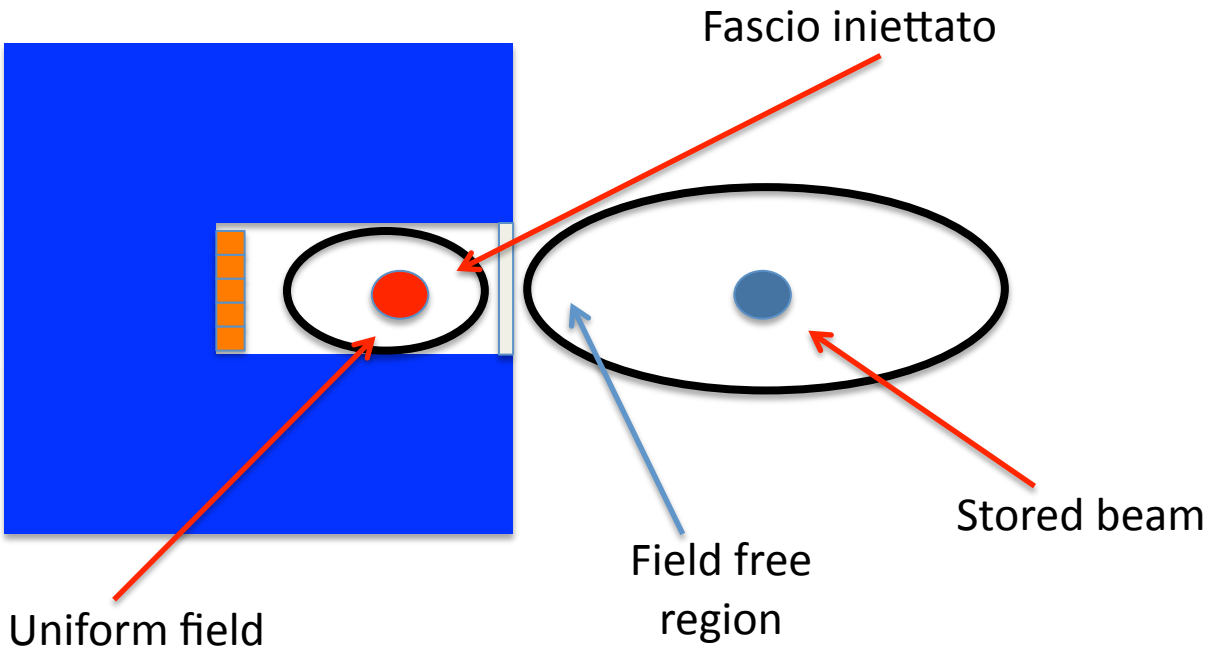
- Beam is injected onto the reference orbit via a septum magnet and a fast kicker element, with appropriate matching arranged in the transverse and longitudinal planes
- For efficient injection there should be no beam loss and very little emittance dilution, only that associated with transfer errors

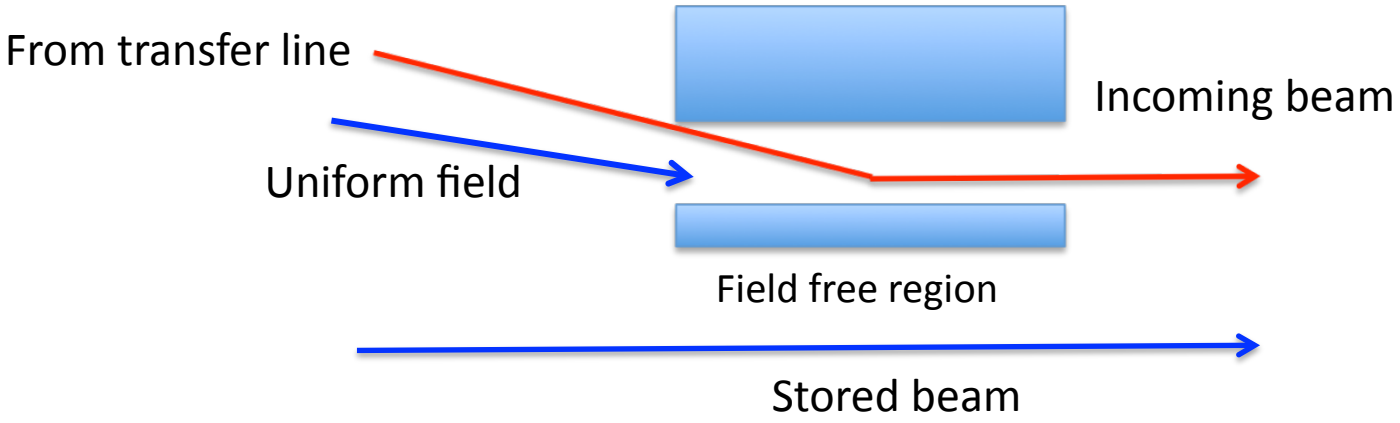
On axis injection



- The septum magnet gives a deviation to the incoming bunch without affecting the beam on the reference trajectory
- When the incoming beam trajectory crosses the axis a fast pulsed kicker deflects the beam and puts it on the reference trajectory
- When the bunch cross the kicker again after 1 turn the kicker is off

Septum magnet

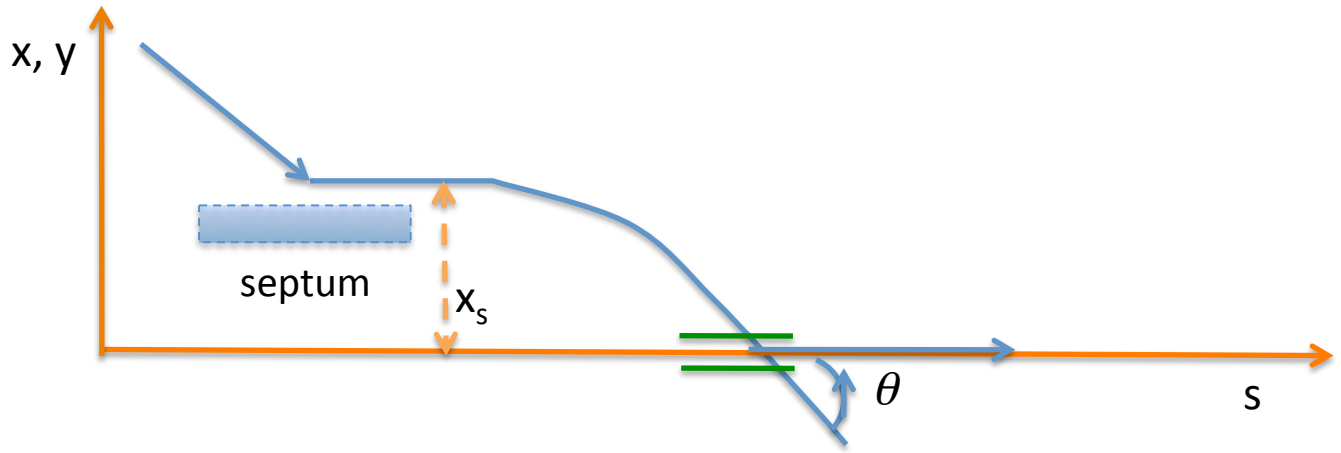




kicker

- Fast kicker magnets require to be switched off in times typically of 50 to 150 ns
- The kickers are powered from pulse-forming networks which are charged in the off-time of the machine cycle and rapidly discharged via thyratron switches when needed. The rise and fall times of the pulse are functions of the thyratron characteristics and the kicker design
- For very short pulse duration solid state devices are used
- Times of a few ns have been achieved in various tests (~ 5 ns at DAΦNE) and are required for future machines (damping rings for the International Linear Collider and very low emittance synchrotron light source storage rings)

On axis injection



In this example we assume $\alpha_x = 0$ and $D_x = D_{x'} = 0$ at the septum

Orbit at septum: **$x = x_s$, $x'_s = 0$**

The orbit at the kicker is:

$$x_k = x_s\sqrt{\beta_k/\beta_s}\cos\Delta\mu_{sk} \qquad x'_k = \frac{x_s}{\sqrt{\beta_s\beta_k}}\sin\Delta\mu_{sk}$$

With $\Delta\mu_{sk}$ the phase advance between septum and kicker. To have x=0 at the kicker a phase advance $\Delta\mu_{sk} = 90°$ is required (θ=kicker angle):

$$x_k = 0 \qquad x'_k = \theta = \frac{x_s}{\sqrt{\beta_s\beta_k}}$$

On axis injection

Successful on axis injection requires that:

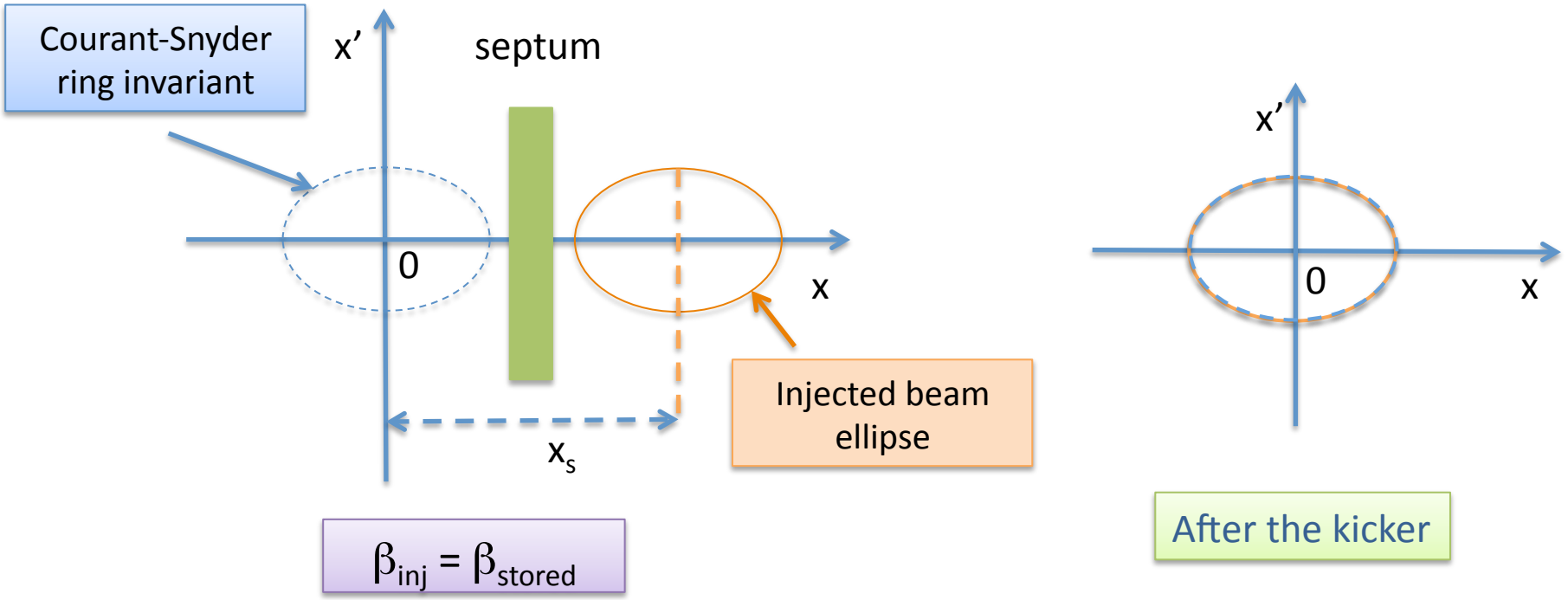
- the stray field of the septum unit is at an acceptable level
- the kicker field is reduced to zero in a time less than a fraction of the revolution period
- the RF system is capable of containing the transient beam loading introduced at the instant of injection

Beam matching in the transverse plane (x, x' or y, y')

At the septum exit the betatron and dispersion functions

$\alpha_x, \beta_x, \alpha_y, \beta_y, D_x, D'_x, D_y, D'_y$

must be identical to the ring lattice parameters at that point



At septum exit: injected beam is matched
→ emittance is preserved

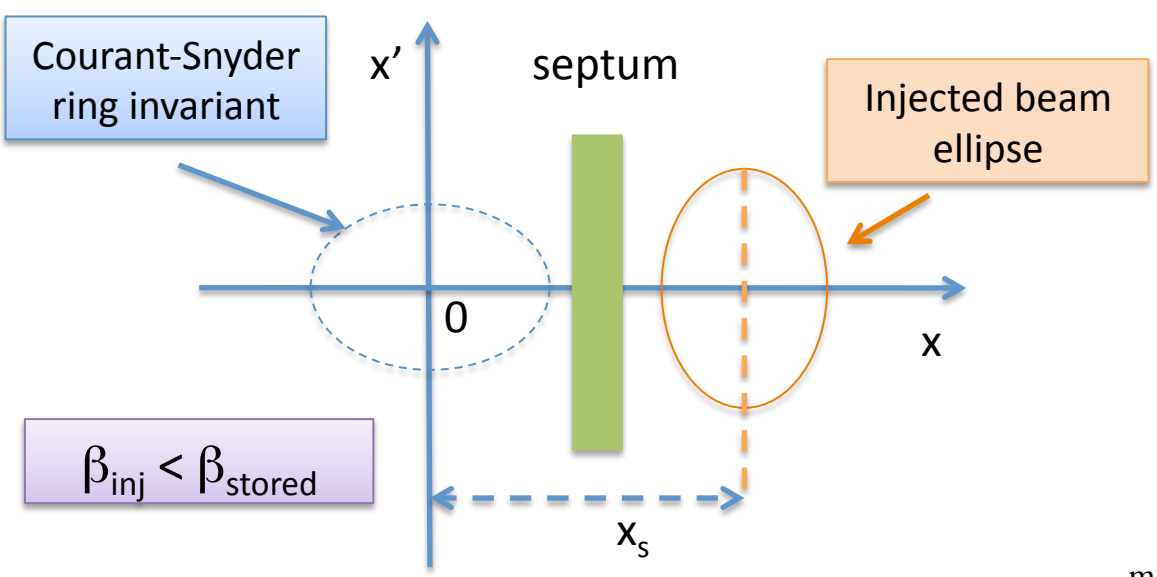
Beam matching in the transverse plane (x, x' or y, y')

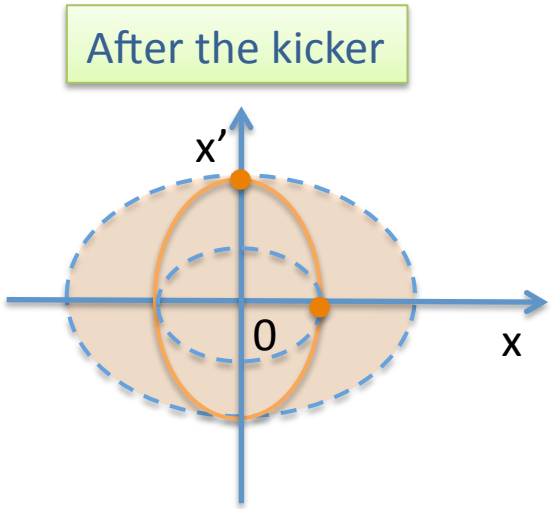
At the septum exit the betatron and dispersion functions

$\alpha_x, \beta_x, \alpha_y, \beta_y, D_x, D'_x, D_y, D'_y$

must be identical to the ring lattice parameters at that point

For simplicity we assume: $\alpha_x = 0$ and $\gamma_x = 1/\beta_x$





$$x_{inj}^{max} = \sqrt{\varepsilon_{inj}\beta_{inj}} \qquad x'^{max}_{inj} = \sqrt{\varepsilon_{inj}/\beta_{inj}}$$

At septum exit $\beta_{inj} < \beta_{stored}$
emittance increases as $\beta_{stored}/\beta_{inj}$

$$\varepsilon_{stored} = \left(x'^{max}_{inj}\right)^2 \beta_{stored} = \varepsilon_{inj}\beta_{stored}/\beta_{inj}$$

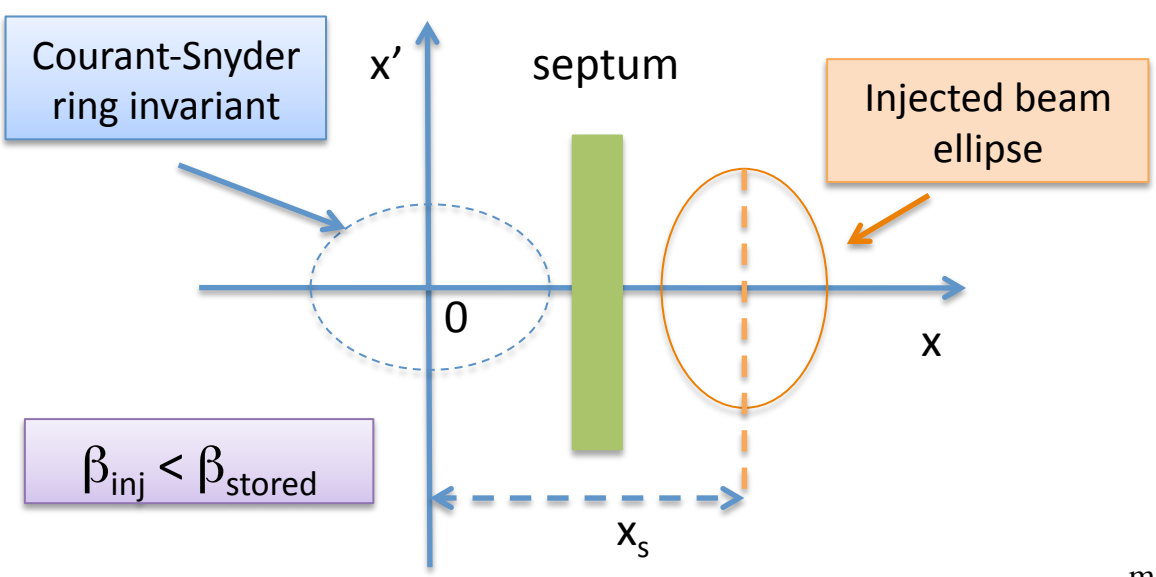
Beam matching in the transverse plane (x, x' or y, y')

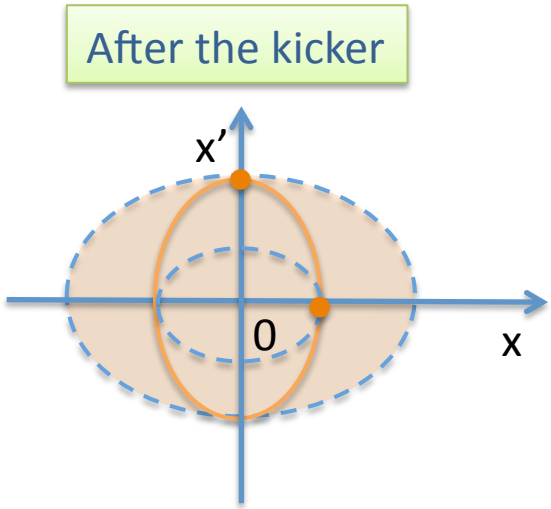
At the septum exit the betatron and dispersion functions

$\alpha_x, \beta_x, \alpha_y, \beta_y, D_x, D'_x, D_y, D'_y$

must be identical to the ring lattice parameters at that point

For simplicity we assume: $\alpha_x = 0$ and $\gamma_x = 1/\beta_x$





$$x_{inj}^{max} = \sqrt{\varepsilon_{inj}\beta_{inj}} \qquad x'^{max}_{inj} = \sqrt{\varepsilon_{inj}/\beta_{inj}}$$

$$\varepsilon_{stored} = \left(x'^{max}_{inj}\right)^2 \beta_{stored} = \varepsilon_{inj}\beta_{stored}/\beta_{inj}$$

$$\left(or \quad \varepsilon_{stored} = \left(x_{inj}^{max}\right)^2 / \beta_{stored} = \varepsilon_{inj}\beta_{inj}/\beta_{stored}\right)$$

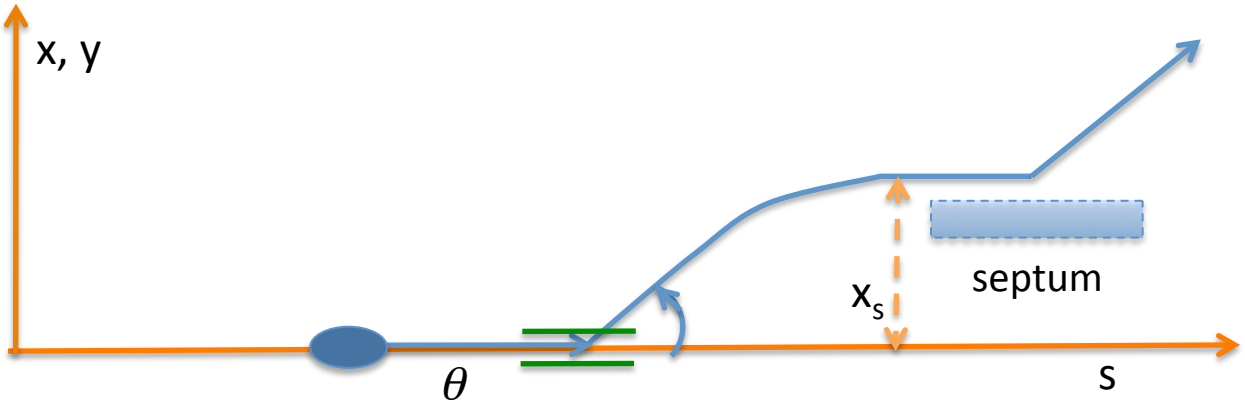
At septum exit $\beta_{inj} < \beta_{stored}$ emittance increases as:

$\beta_{stored}/\beta_{inj}$

(for $\beta_{inj} > \beta_{stored}$ emittance increases as:

$\beta_{inj} / \beta_{stored}$)

Extraction



Extraction is the inverse of the injection process

The kicker is turned on just before the bunch passage and deflects the beam out of the septum

The orbit after the kicker is: $x_k = 0$ $\quad x'_k = \theta$

The orbit at the septum is :

$$x_s = x'_k \sqrt{\beta_k \beta_s} \sin \Delta\mu_{ks} \qquad x'_s = x'_k \sqrt{\beta_k / \beta_s} \cos \Delta\mu_{ks}$$

With $\Delta\mu_{ks}$ the phase advance between kicker and septum

To have x'=0 at the septum a phase advance $\Delta\mu_{ks}$ = 90° is required:

$$x_s = \theta \sqrt{\beta_k \beta_s} \qquad x'_s = 0$$

Off axis injection

- To increase the current with respect to what is provided from the injector we want to inject the bunch on top of an already stored bunch
- In this case the kicker used to deflect the incoming bunch on the central trajectory deflects the already stored bunch out of the storage ring aperture
- To keep the stored bunch inside the aperture the kicker amplitude must be reduced
- The injected beam will be placed inside the ring aperture with a residual oscillation amplitude respect to the central orbit
- The residual oscillation amplitude will be reduced due to radiation damping and will become negligible in a few damping times
- This is the most common injection procedure for electrons and positrons

Off axis injection

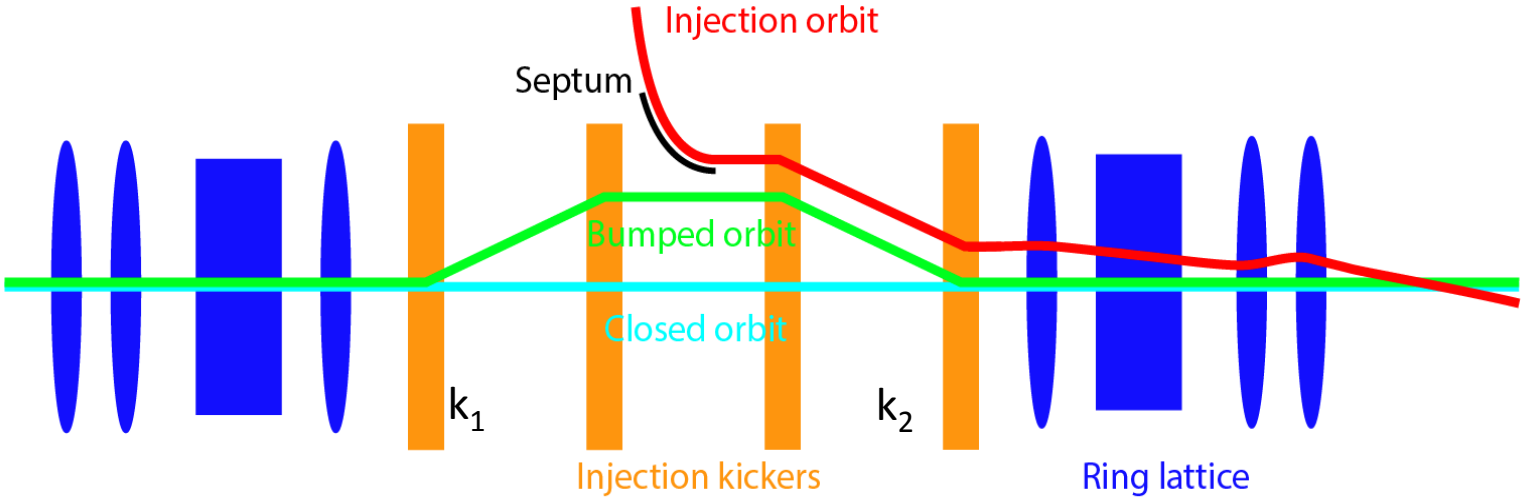
The stored bunch orbit is displaced towards the septum by means of 2 kickers with π phase advance difference in between

The first kicker k_1 deflects only the stored bunch

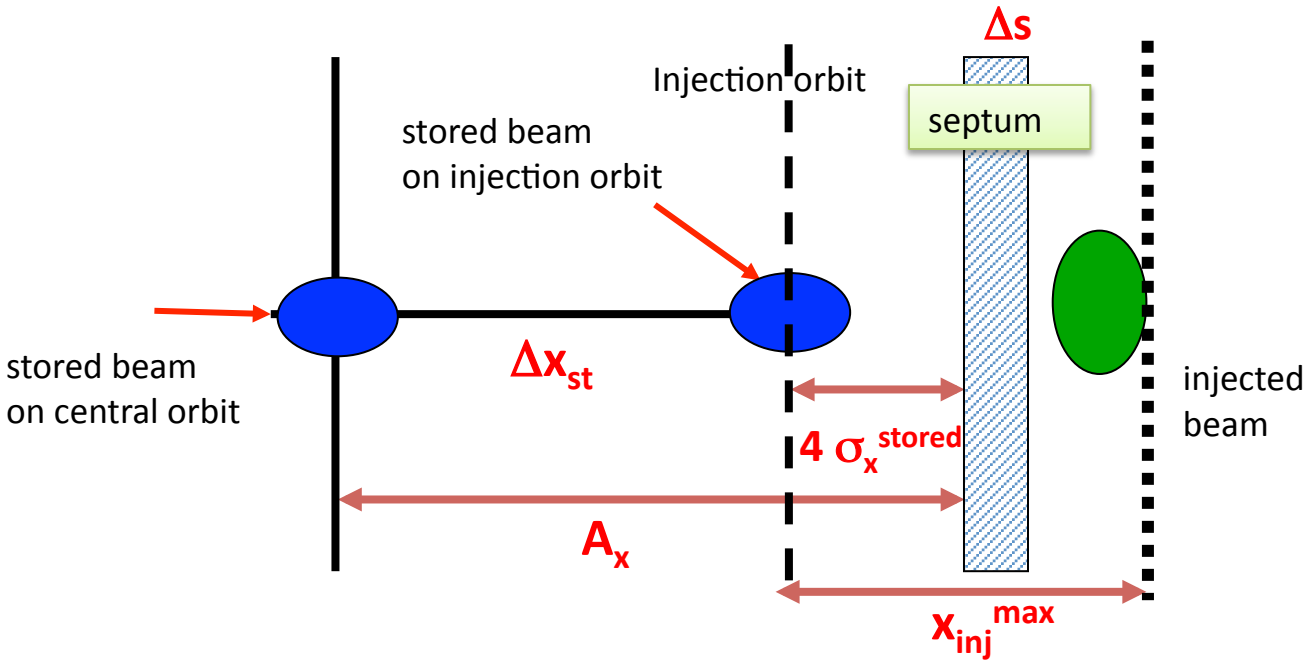
The second kicker k_2 kicks both the stored and the injected beam

The stored beam is put back on the central orbit

The injected beam is put inside the aperture with a residual oscillation orbit



Off axis injection

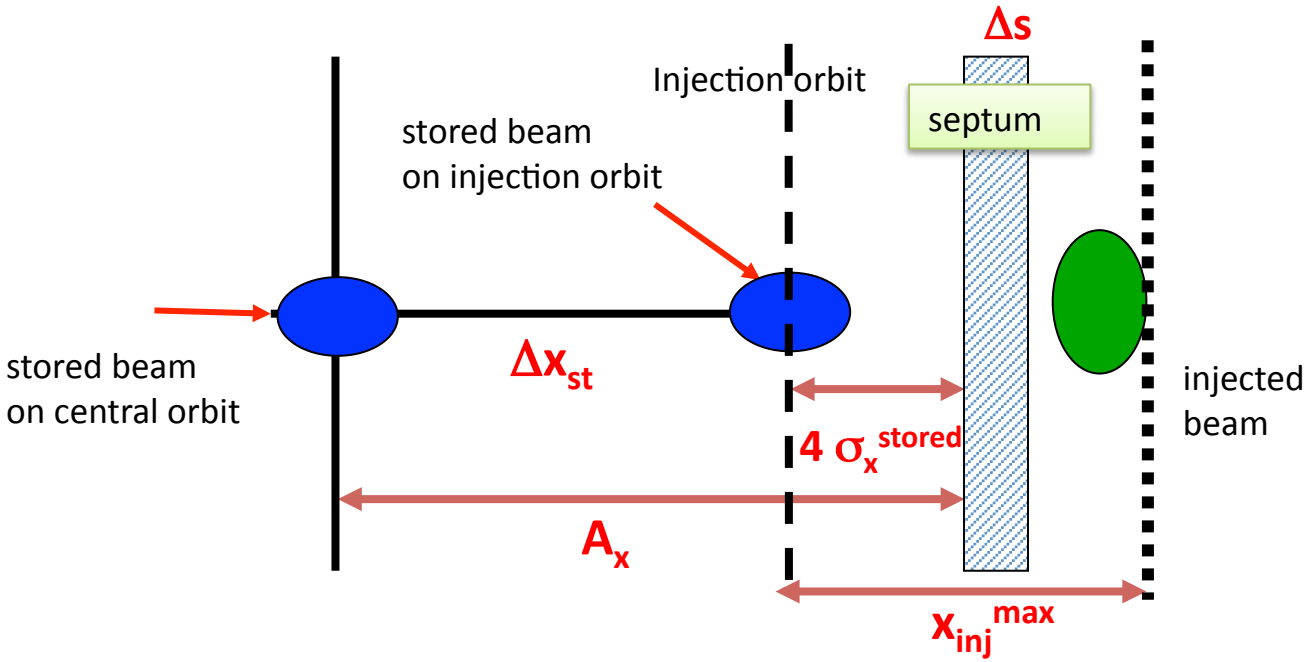


- **Minimal aperture needed at septum A_x:**

A_x has to be large enough to assure good beam lifetime for the stored beam

$A_x > x_{inj}^{max}$ for good injection efficiency

Off axis injection



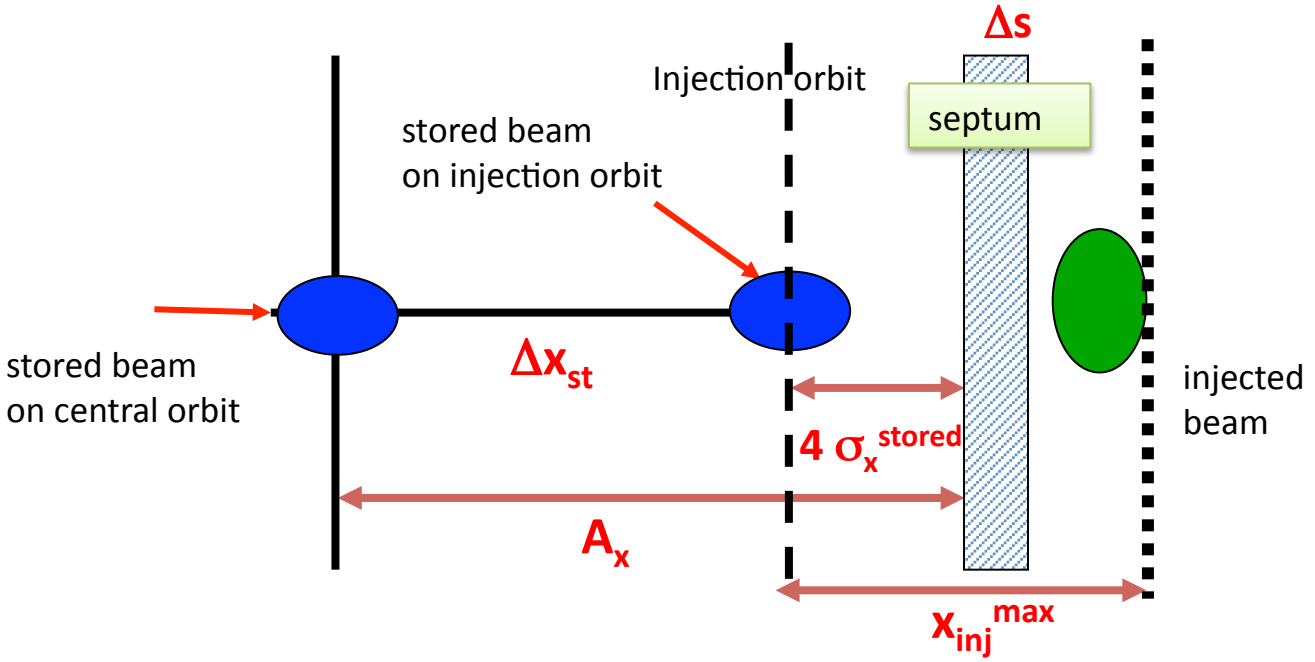
$$\Delta x_{st} \leq A_x - n\sigma_x^{stored} = A_x - 3\sqrt{\varepsilon_x^{stored}\,\beta_x^{stored}}$$

➢To keep losses on stored beam below 0.13% (probability for a gaussian distribution to be outside 3σ) we take n=3

$$\Delta x_{st} \geq \Delta s + 2k\sigma_x^{injected}$$

➢To injected 99% of the incoming beam we take k=2

Off axis injection



- **The angle of the injection kicker is:**

$$\theta = \Delta x_{st} \Big/ \sqrt{\beta_x^{kick} \beta_x^{stored}}$$

- **The maximum oscillation amplitude of the injected beam after the kicker is:**

$$x_{inj}^{\max} = \Delta s + 4\sigma_x^{inj} + 3\sigma_x^{stored}$$

- **And the corresponding phase space ellipse is:**

$$\varepsilon = \frac{x_{inj}^{\max\,2}}{\beta_{st}} = \frac{\left[\Delta s + 4(\sigma_x^{inj} + \sigma_x^{stored})\right]^2}{\beta_{st}}$$

Off axis injection issues

- Needed aperture
  - Optimum beta matching $\beta_{inj} < \beta_{stored}$
  - High value of beta stored at septum reduces the impact of the septum thickness
- Beam losses
  - Losses on the stored beam depend on the distance of the bumped orbit from the septum
  - Losses on injected beam depend on the distance from septum and on the maximum oscillation amplitude included in the ring aperture
  - Nonlinear elements in the ring and instabilities can produce losses of the injected beam
  - Losses due to errors and jitters: orbit, energy, matching, beam size

Off axis injection issues

- Kickers synchronization
  - It is very important that the orbit bump produced by the 2 kickers is very well closed to avoid oscillations of the stored beam: correct amplitude, good time synchronization and correct phase advance
- Injection saturation
  - When the particles lost in the injection pulse are equal to the particles in the incoming bunch the injection saturates and the current in the ring cannot be further increased

Multi-turn injection

- For protons or heavy ions, if the injected beam is longer than one revolution period, a multi-turn injection is used
- The orbit bump is reduced with time so that the early beam occupies the central region of the horizontal acceptance and the later beam the periphery of the acceptance
- At the end of injection the beam bump is reduced to zero
- Because of the finite thickness of the septum and the elliptical phase-space contours of the injected beam, there must result some emittance dilution
- If the injector emittance is ε_i and the number of injected turns is n the resulting emittance in the ring is:

$$\varepsilon_{st} > 1.5 n \varepsilon_i$$

MultiTurn Injection

In progress

~15 turns
~30 μs bump
~10 mrad kicks