Injection and extraction, single turn injection

USPAS

by

Mike Plum and Uli Wienands

Introduction

- What do we mean by injection?
  - Inject a particle beam into a circular accelerator or accumulator ring, at the right time, while
  - minimizing the beam loss and
  - placing the newly injected particles onto the correct trajectory
  - with the correct phase-space parameters
- What do we mean by extraction?
  - Extract the particles at the appropriate time, while
  - minimizing beam loss and
  - placing the extracted particles onto the correct trajectory
  - with the correct phase-space parameters

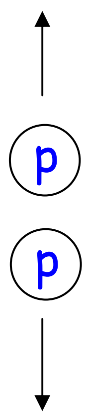
Introduction (cont.)

- Why do we care about injection and extraction?
  - If it is not done right, the accelerator facility won't work right
  - Injection and extraction can be the most complex parts of a ring (e.g. the injection area of the SNS has the most complex optics in the accelerator facility)
  - Once commissioning starts, issues concerning injection and extraction often come up due to unanticipated factors (e.g. PSR, SNS, …)
  - A good understanding of injection and extraction will lead to better design, fabrication, installation, and operation of your accelerator facility

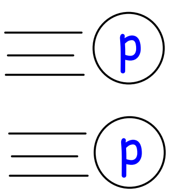
Basic difference between inj and extr.

- Beam energy at injection is often lower than at extraction
  - Space charge forces are higher because there is little cancellation of the magnetic and electric forces at low beam energy
  - Transverse oscillation amplitudes are smaller at high beam energies due to adiabatic damping (see section on normalized emittance)

Space charge cartoon



Two protons just sitting still will repel



Two protons traveling at the speed of light will neither repel or attract

Emittance vs. beam energy

The ellipse area, $\int dx'\,dx = \pi\varepsilon$

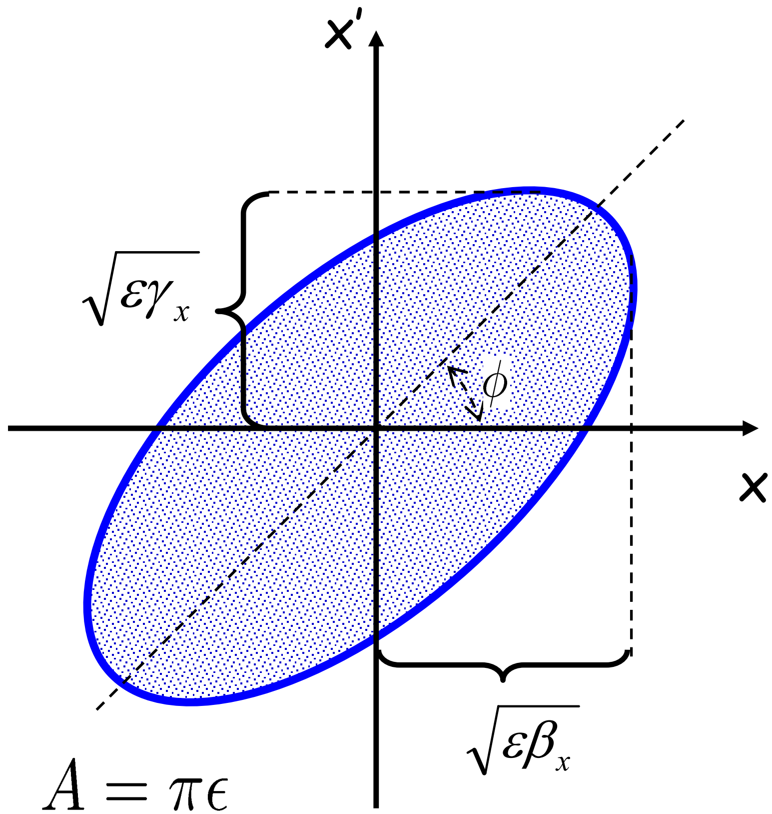
is not invariant when the particles are accelerated. But if we substitute transverse momentum, p_x, in place of x', it will be invariant

ε_n is the normalized emittance, and it is invariant when the beam is accelerated

$$\varepsilon_n = \beta\gamma\varepsilon$$

These β and γ are the relativistic parameters!

Beam Ellipse in Phase Space:



*

Emittance vs. beam energy (cont.)

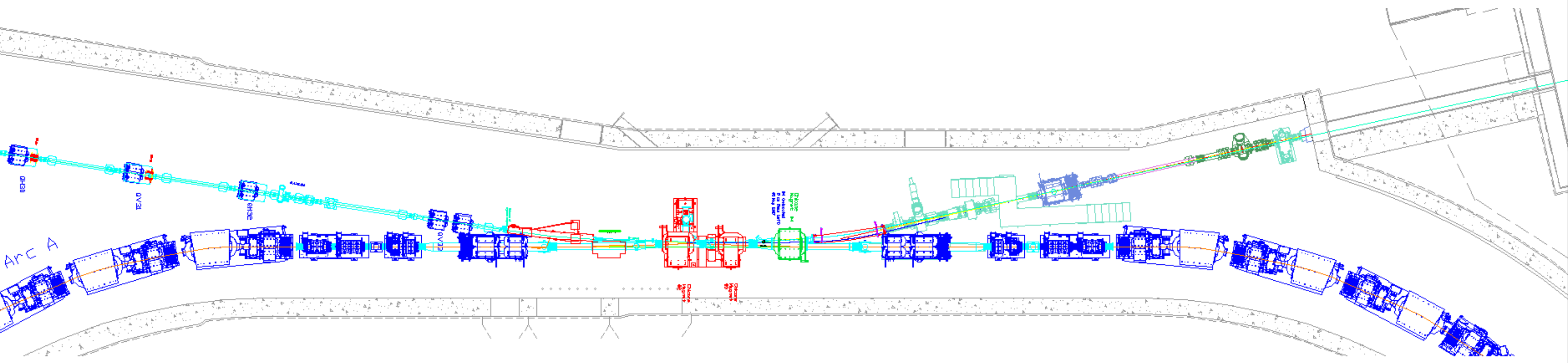
Beam size $\sigma_x = \sqrt{\varepsilon \beta_x} = \dfrac{\sqrt{\varepsilon_n \beta_x}}{\sqrt{\beta\gamma}}$ $\qquad \varepsilon_n = \beta\gamma\varepsilon$

The normalized emittance is constant, so as the beam is accelerated, the beam size gets smaller (for a given Twiss parameter β_x)

This is known as adiabatic damping

Injection system components

- Beam line transport up to the ring
- Beam transport to a dump for particles that are not properly injected
- RF cavities to paint beam longitudinally
- Septum magnet
- Magnets that merge incoming and circulating beams
- Bump magnets
- Stripper foils (charge exchange injection)
- Kicker magnet (single turn injection)



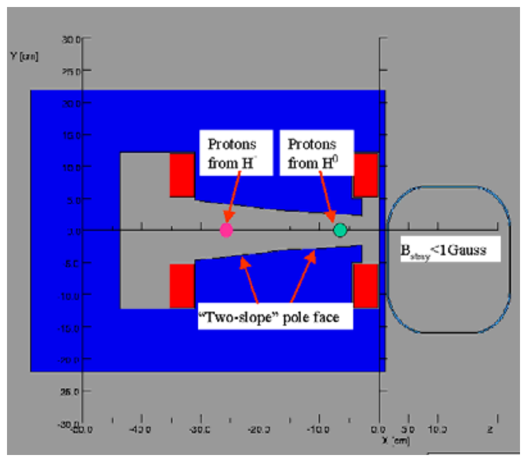
Example: SNS Ring injection area

Magnetic septum

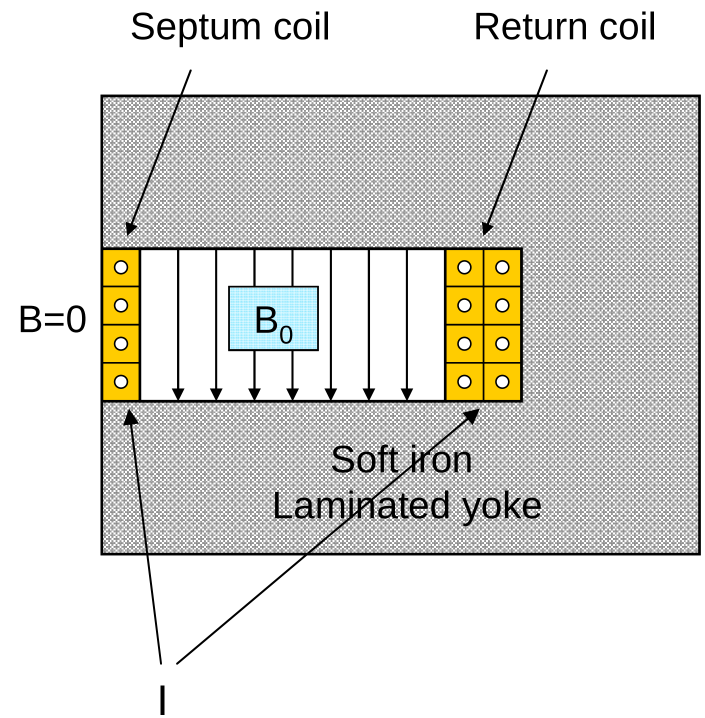
Example: SNS injection septum magnet

(Courtesy BNL)

Example: SNS injection dump gradient septum magnet



(Courtesy BNL)



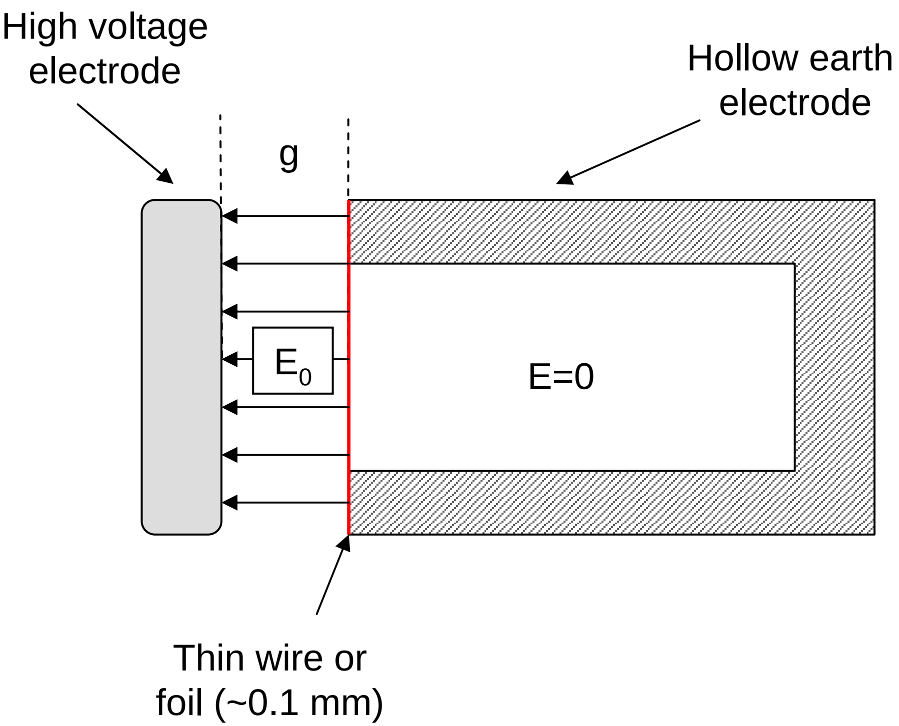
$B_o = \mu_0 I / g$

Typically I 5-25 kA

(Courtesy B. Goddard)

Electrostatic septum

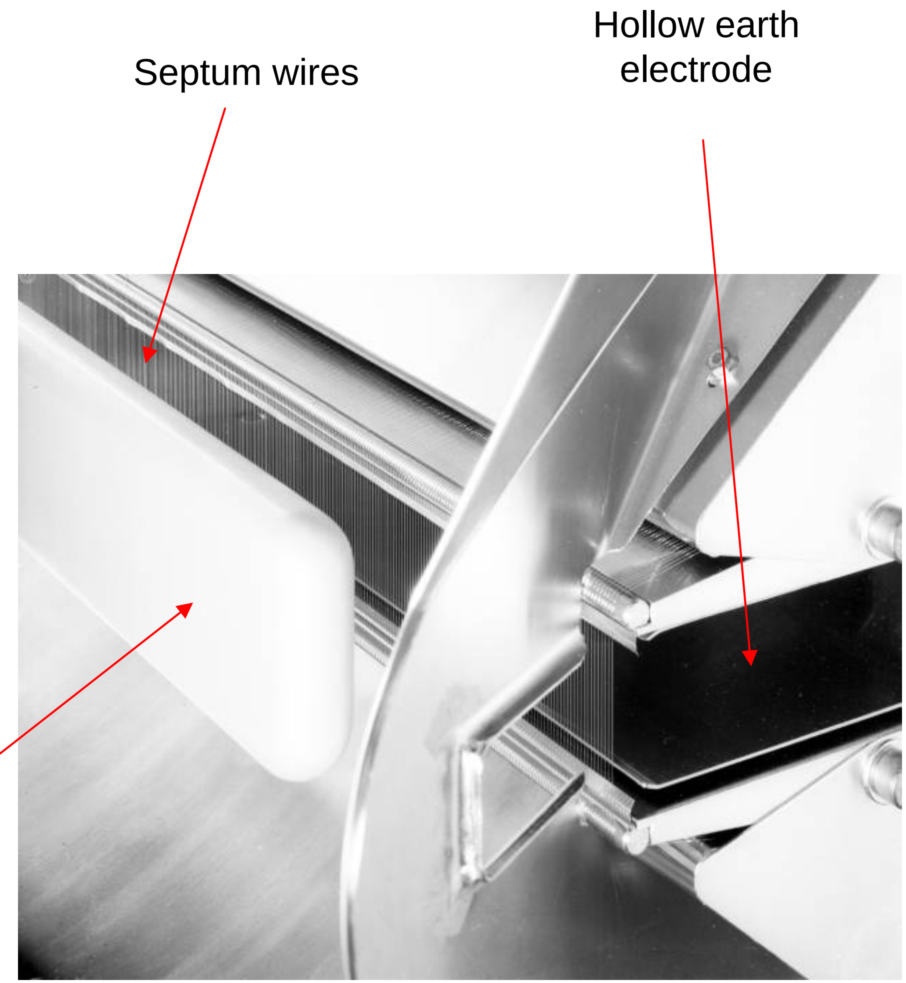
DC electrostatic device with very thin (~0.1mm) septum between zero field and high field region



$E = V / g$

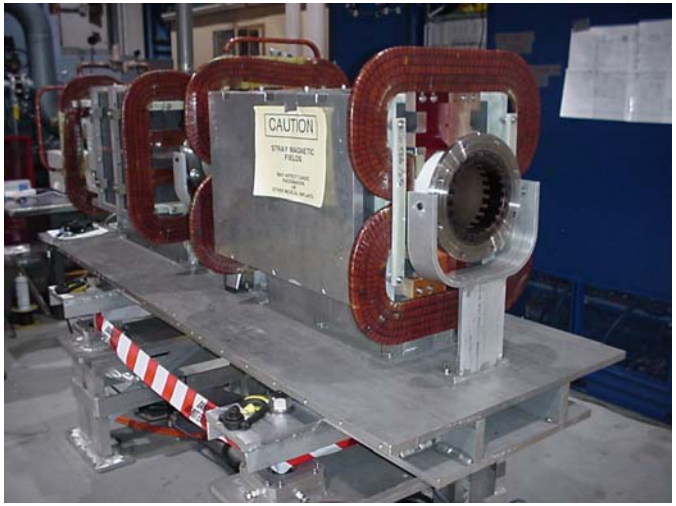
Typically V = 200 kV

E = 100 kV/cm



(Courtesy B. Goddard)

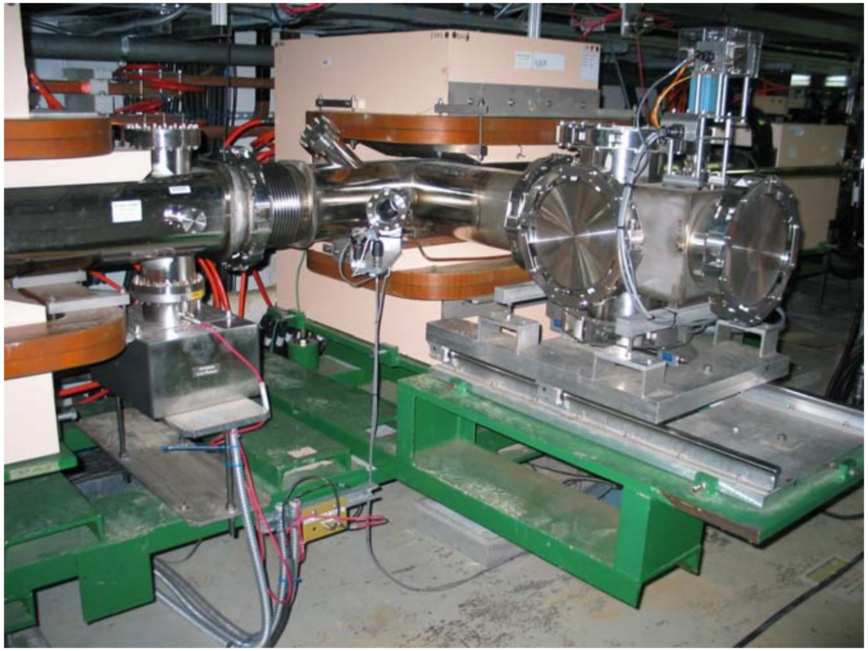
Injection bump magnets



Example: SNS injection bump magnets. Max rate of change is 1400 Amps in 250 usec. Ceramic vacuum chamber first coated with copper, then TiN.

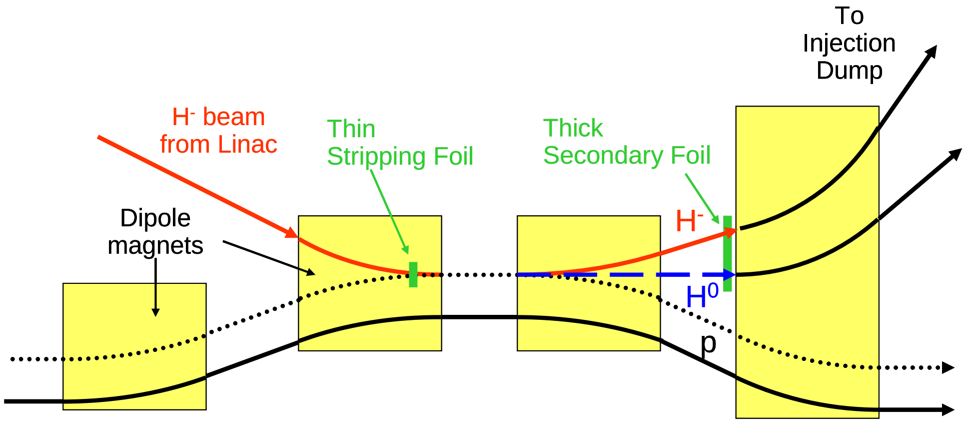
- Bump magnets, also known as kicker magnets, have magnetic fields that can be quickly changed to paint the beam into the ring acceptance
- This means that magnets must have low inductance ($\tau = L/R$)
- Also need pulsed power supplies
- Must be aware of eddy currents in metal vacuum chambers, which can distort the magnetic field and heat the vacuum chamber
- Ceramic beam pipes are often used, but then need to account for image currents

Injection chicane magnets



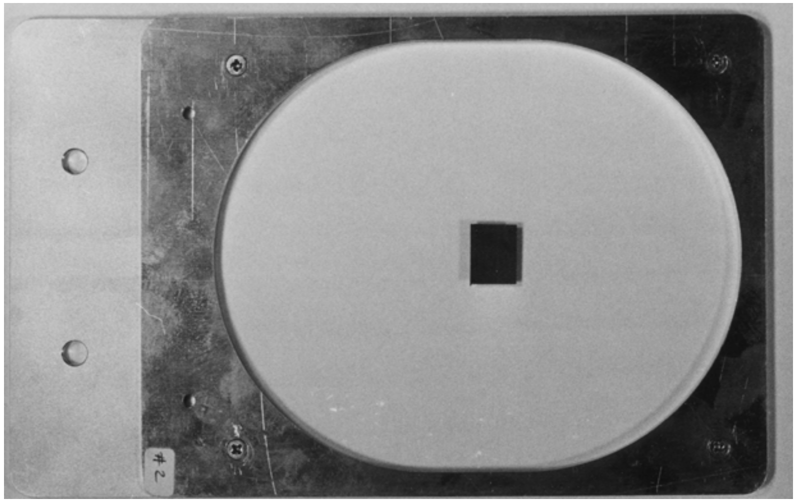
Example: SNS chicane magnet with the stripper foil changing mechanism

- Injection chicane magnets merge the injected and circulating beams.
- Sometimes use "C" magnets, with one open side, to fit "Y" shaped vacuum chambers



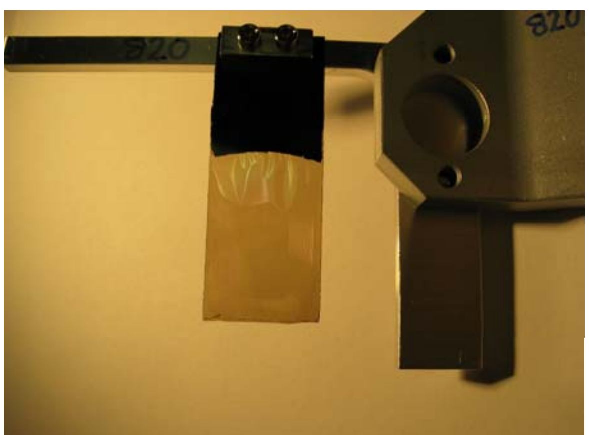
Example: SNS injection chicane

Stripper foils

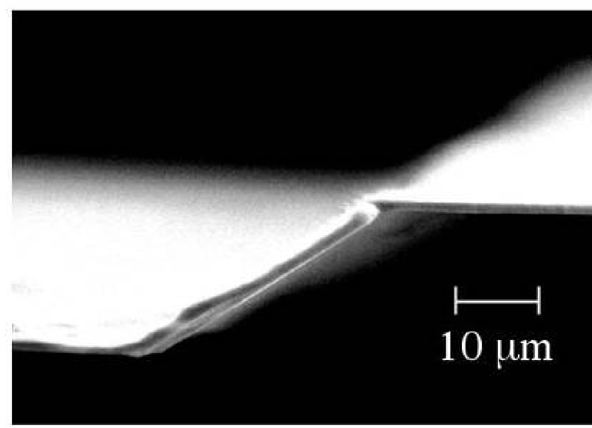


Old style PSR foil completely supported by carbon fibers

New style PSR foil



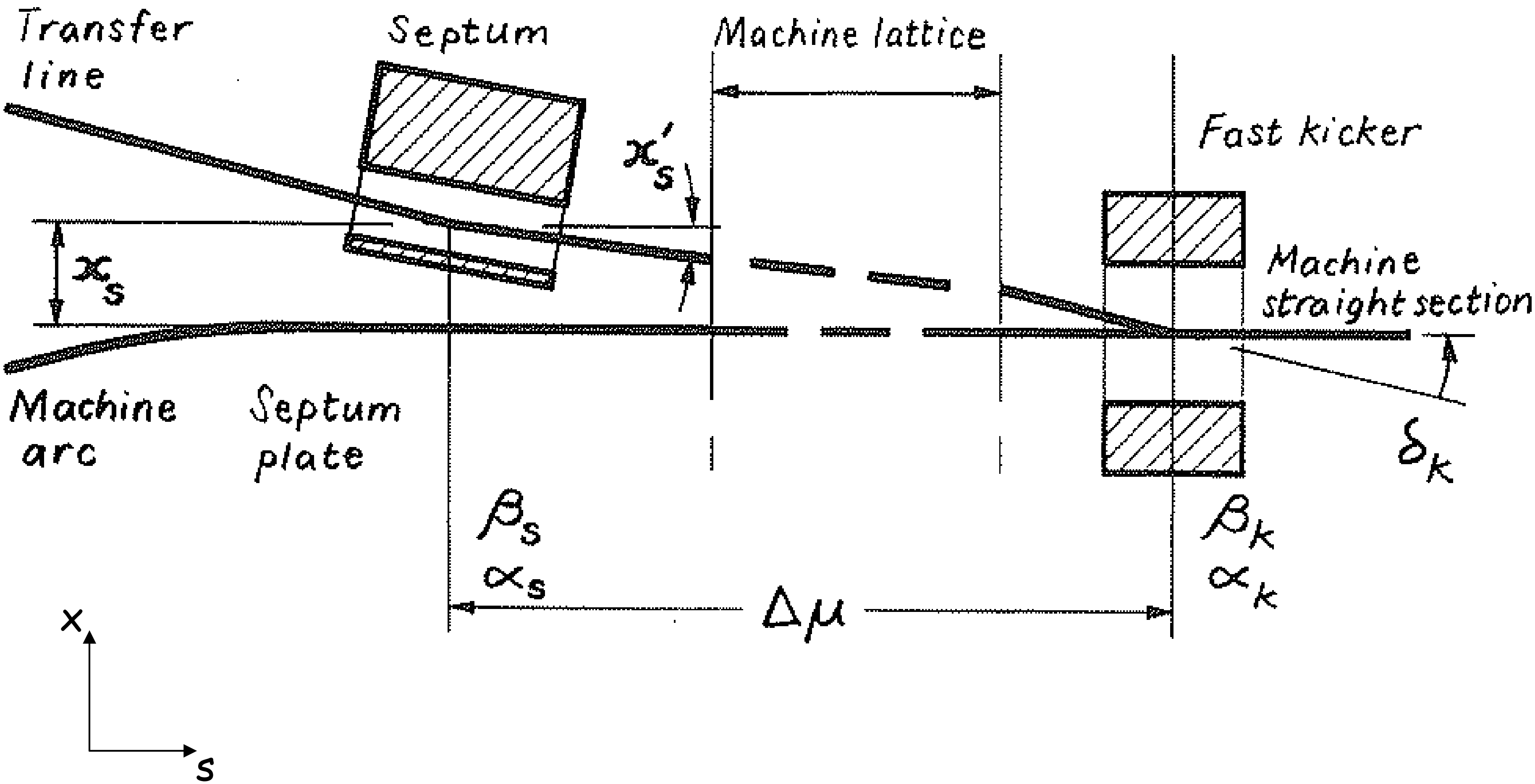
SNS diamond foil



Close up showing SNS diamond foil corrugation

Single turn injection

A maximum of one beam bunch is injected into each RF bucket



(Figure is from Bryant & Johnson, The Principles of Circular Accelerators and Storage Rings)

Hill's equations

- Equations of motion

$$x'' + K_x(s)x = 0$$
$$y'' + K_y(s)y = 0$$

where

$$x' \equiv dx/ds$$
$$y' \equiv dy/ds$$
$$K_x \equiv B'/(B\rho) + \rho^{-2}$$
$$K_y \equiv -B'/(B\rho)$$
$$B' \equiv \partial B_y/\partial x$$
$$B\rho = mv/q = \text{magnetic rigidity}$$

- Solution:

$$x(s) = A\sqrt{\beta(s)}\cos(\psi(s)+\phi)$$
$$x'(s) = -\frac{A}{\sqrt{\beta(s)}}\left[\alpha(s)\cos(\psi(s)+\phi)+\sin(\psi(s)+\phi)\right]$$
$$\alpha(s) \equiv -\beta'(s)/2$$

Beam position and angle at the septum

At the kicker, where $\beta(s) = \beta_k$ we desire $x(s) = 0$ and $x'(s) = -\delta_k$.

We will find the position and angle at the septum, $x(0)=x_s$ and $x'(0)=x'_s$

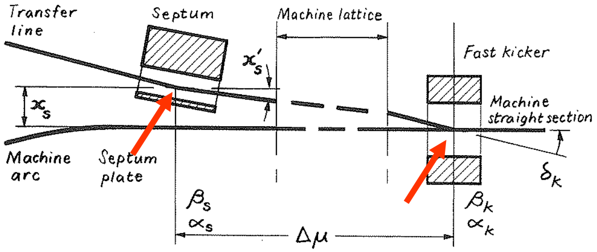
Let $\alpha(0) = \alpha_s$, and let the phase advance from the septum to the kicker be $\psi(s) = \mu$

$$x(s) = A\sqrt{\beta(s)}\cos(\psi(s)+\phi) = 0 \longrightarrow \mu + \phi = \pi/2$$

$$x'(s) = -\frac{A}{\sqrt{\beta(s)}}\left[\alpha(s)\cos(\psi(s)+\phi) + \sin(\psi(s)+\phi)\right] = -\delta_k \longrightarrow A = \delta_k\sqrt{\beta_k}$$

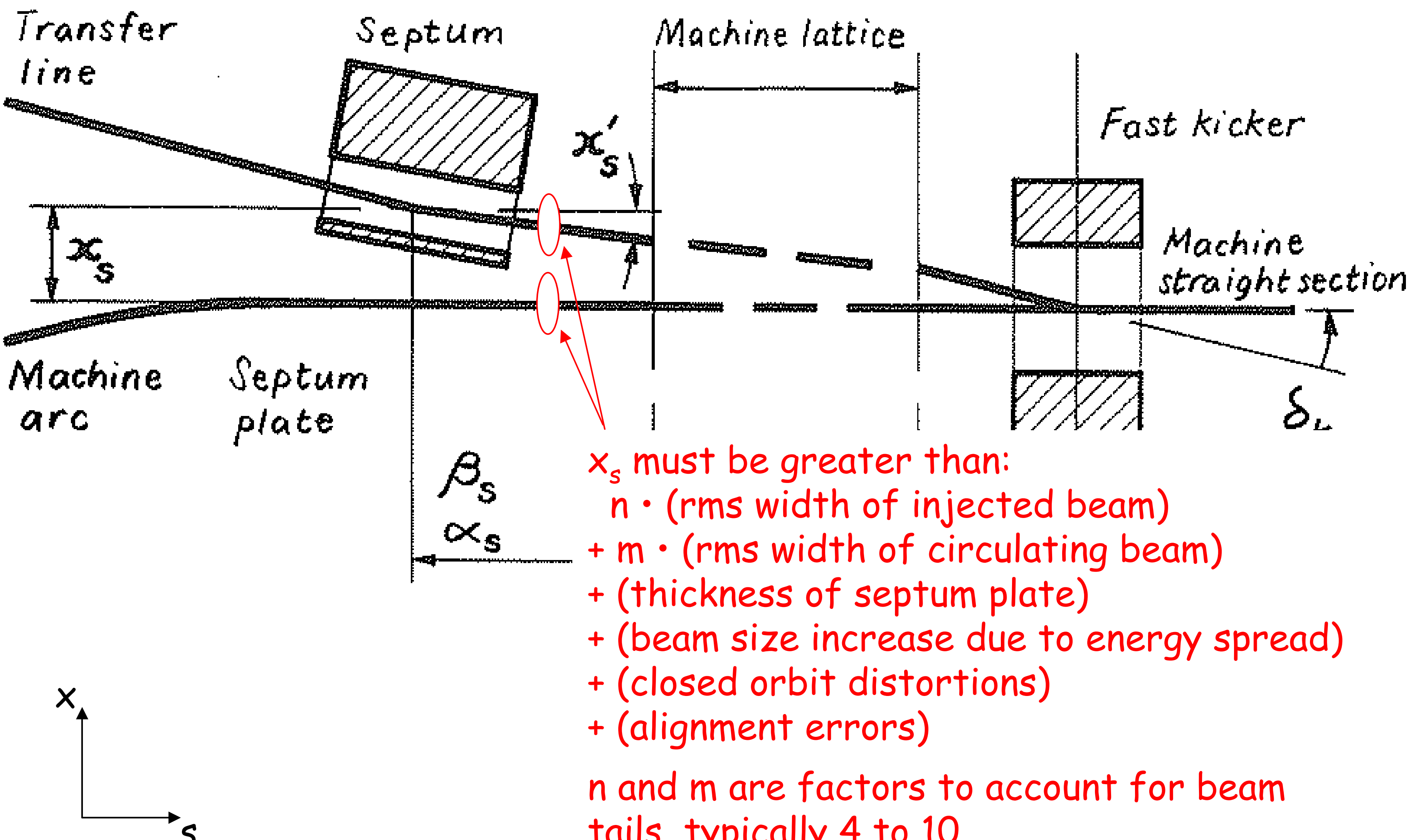
$$x_s = \delta_k\sqrt{\beta_k\beta_s}\sin\mu$$

$$x'_s = -\delta_k\sqrt{\frac{\beta_k}{\beta_s}}\left[\alpha_s\sin\mu + \cos\mu\right] = -\frac{x_s}{\beta_s}\left[\alpha_s + \cot\mu\right]$$



* (Beware that s is either a distance or designates the septum here)

Practical considerations



x_s must be greater than:
n • (rms width of injected beam)
+ m • (rms width of circulating beam)
+ (thickness of septum plate)
+ (beam size increase due to energy spread)
+ (closed orbit distortions)
+ (alignment errors)

n and m are factors to account for beam tails, typically 4 to 10

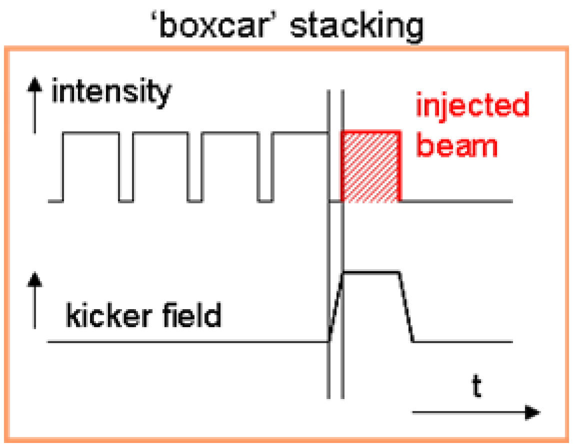
* Figure is from Bryant & Johnson, The Principles of Circular Accelerators and Storage Rings

Practical considerations - kicker

From solution on previous slide,

$x_s = \delta_k \sqrt{\beta_k \beta_s} \sin \mu$ therefore,

Kicker angle $\delta_k = \dfrac{x_s}{\sqrt{\beta_k \beta_s} \sin \mu}$



(Courtesy B. Goddard)

- To keep the cost of the kicker down we would like to reduce the kick angle δ as much as reasonably possible
  - Would like μ to be close to $\pi/2$
  - Would like large values of $\beta_{k.}$ (Note: large values of β_s would lead to large beam size, which would require larger separation of circulating and injected beam)
- The rise and fall time of the kicker must be fast enough that the field is practically zero when other beam bunches pass by the kicker (or for the case of just one bunch in the ring, when the head of the injected beam comes back around to the injection point)
- Typical rise and fall times are 50 to 150 ns. Typical voltage and currents are 40 to 80 kV and 2000 to 5000 A

Practical considerations - septum

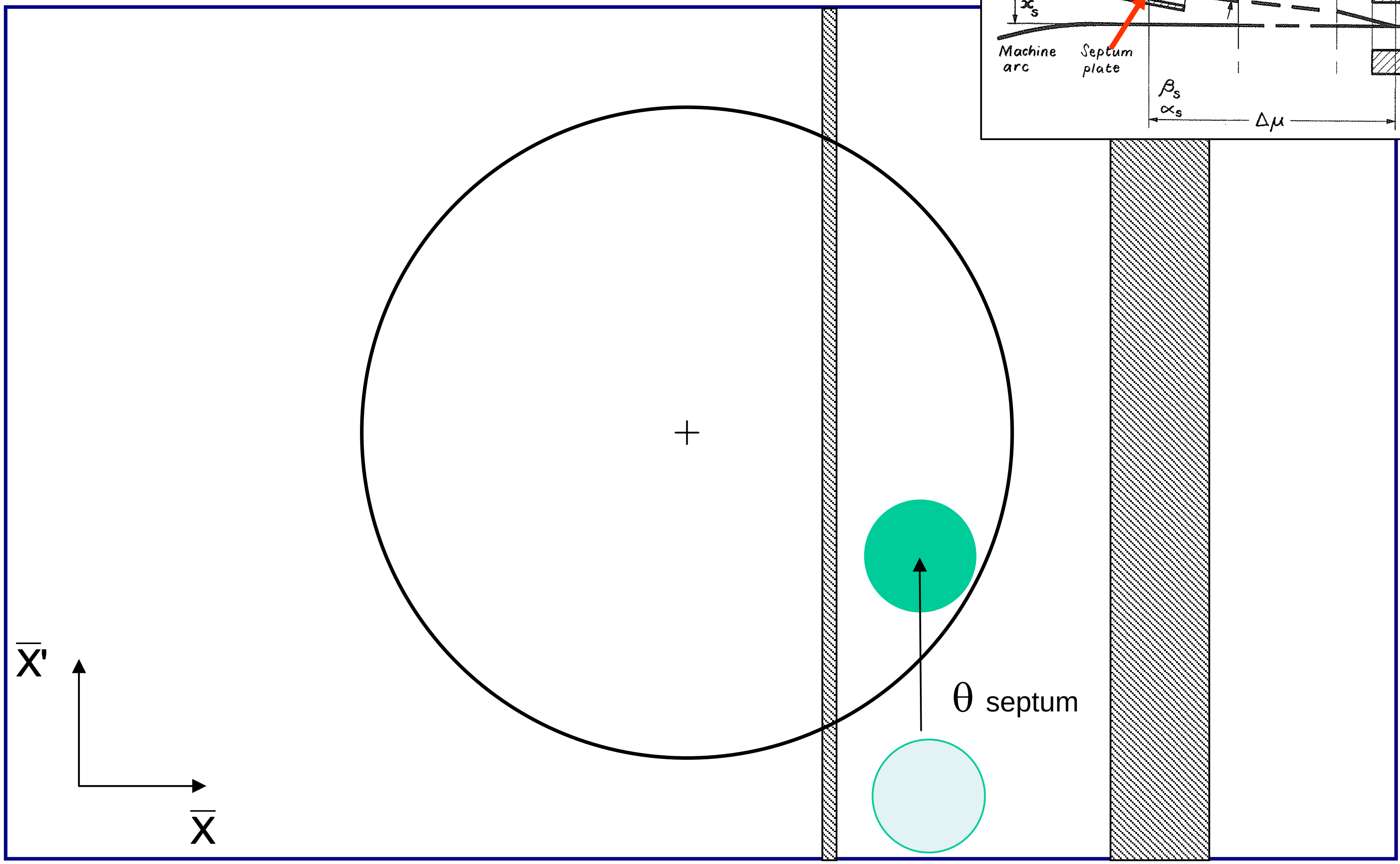
- Septum bend angle must be great enough that the incoming beam will clear the ring magnets upstream of the injection point
- The stray field of the septum must be small in the vicinity of the circulating beam
- Stray fields are of greater concerns at lower beam energies
- Electrostatic septa are weaker than their magnetic cousins, but the partition, or septum, can be made very thin
- Magnetic septum magnets are robust.
- Typical fields are up to about 1 to 1.5 T.

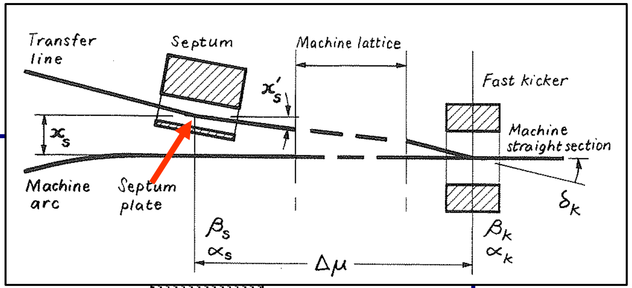
Practical considerations - other

- It is desirable that the Twiss parameters of the injected beam equal the Twiss parameters of the ring at the point of injection. Otherwise the effective emittance of the circulating beam will grow.
  - This is not necessarily the case for multi-turn injection

Single-turn injection - normalised phase space

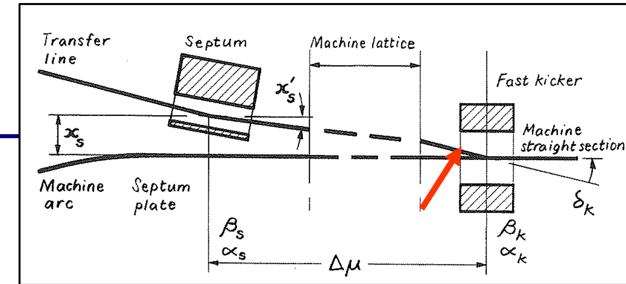
Large deflection by septum

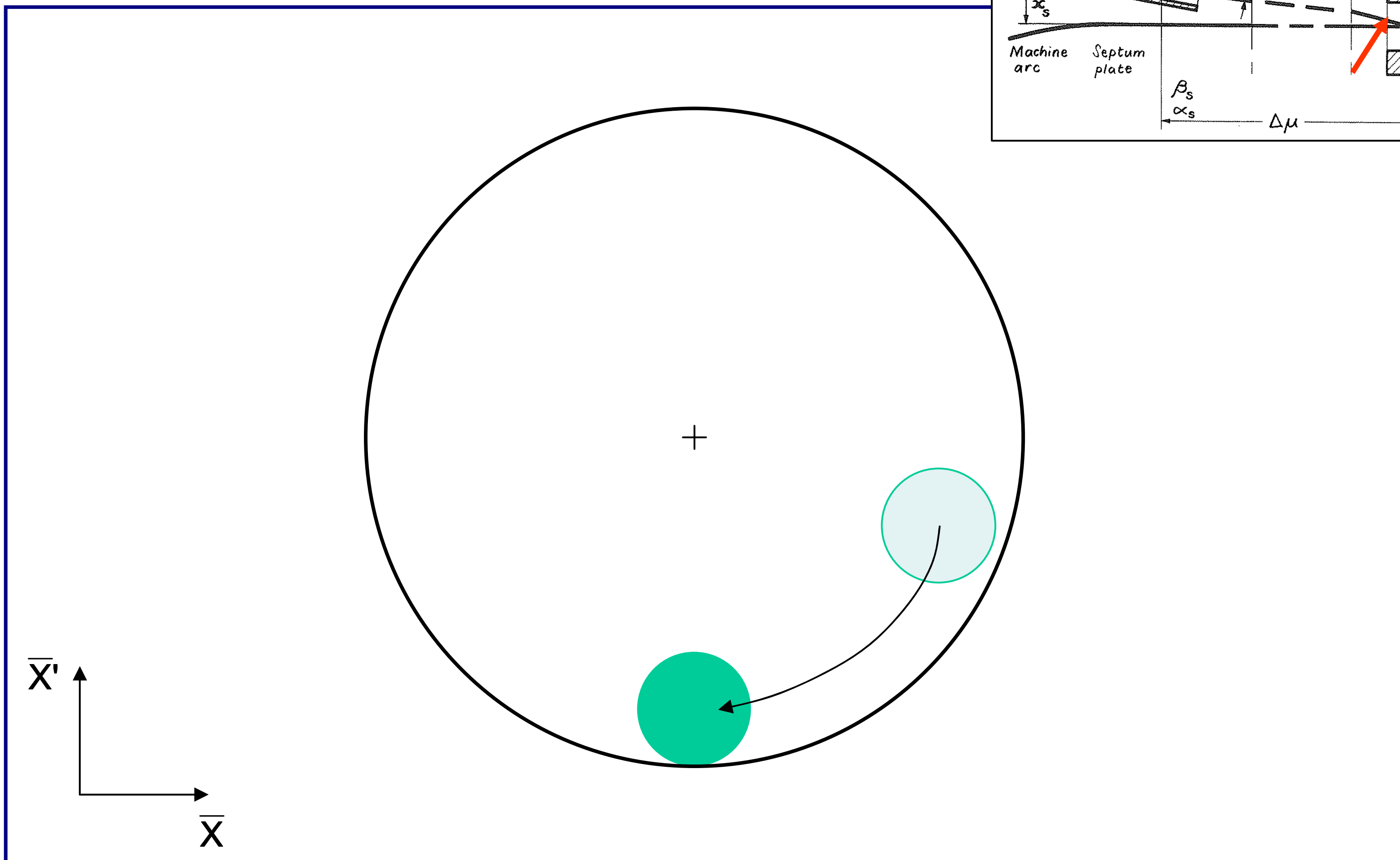




Single-turn injection

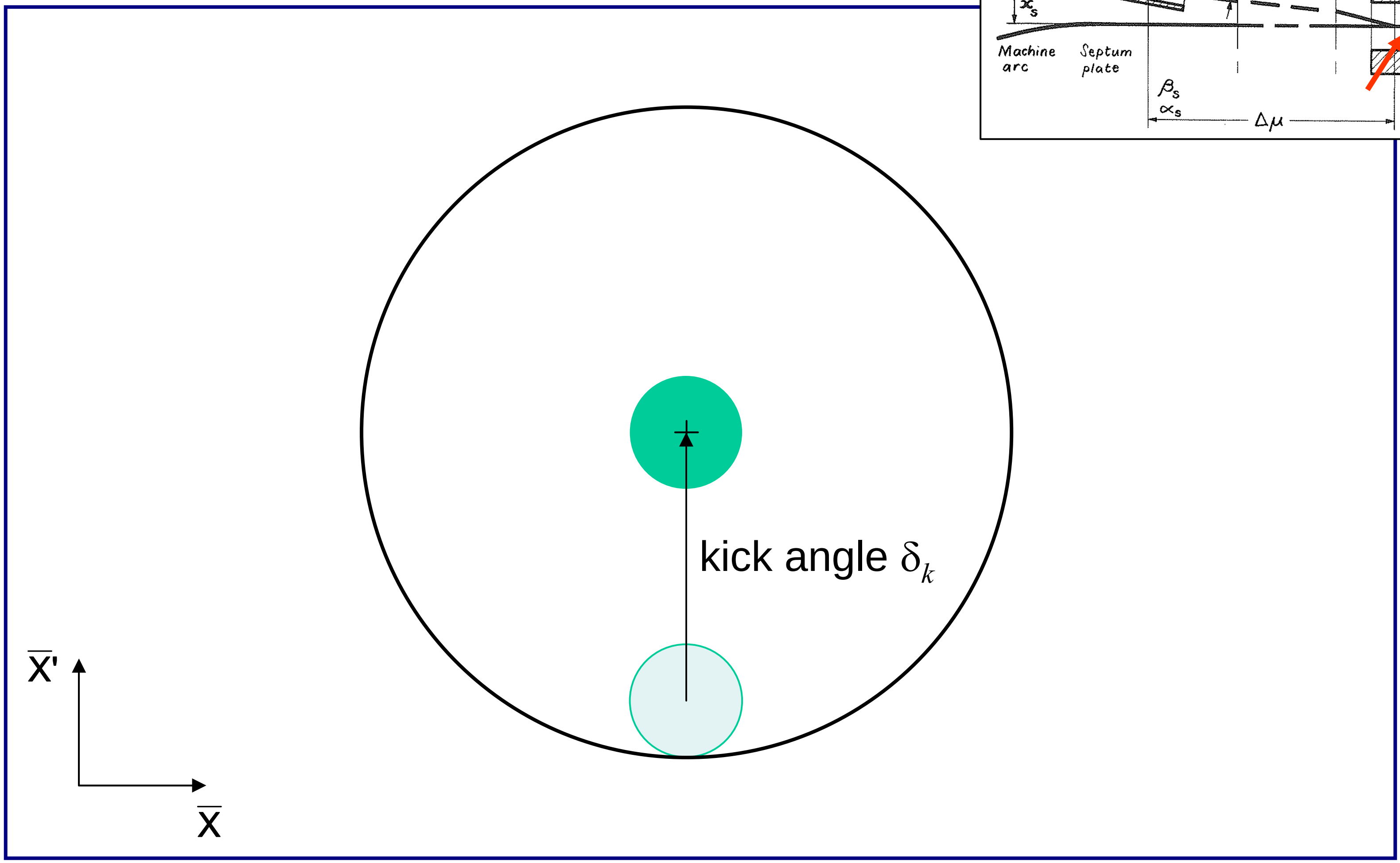
phase advance to kicker location

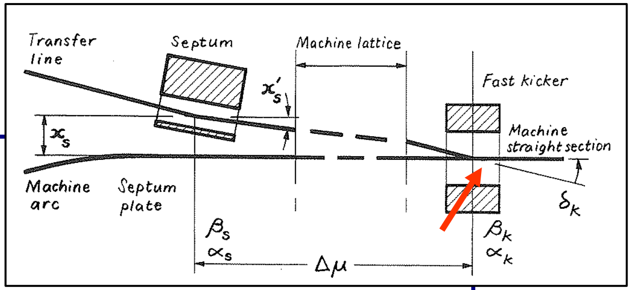




Single-turn injection

Kicker deflection places beam on central orbit

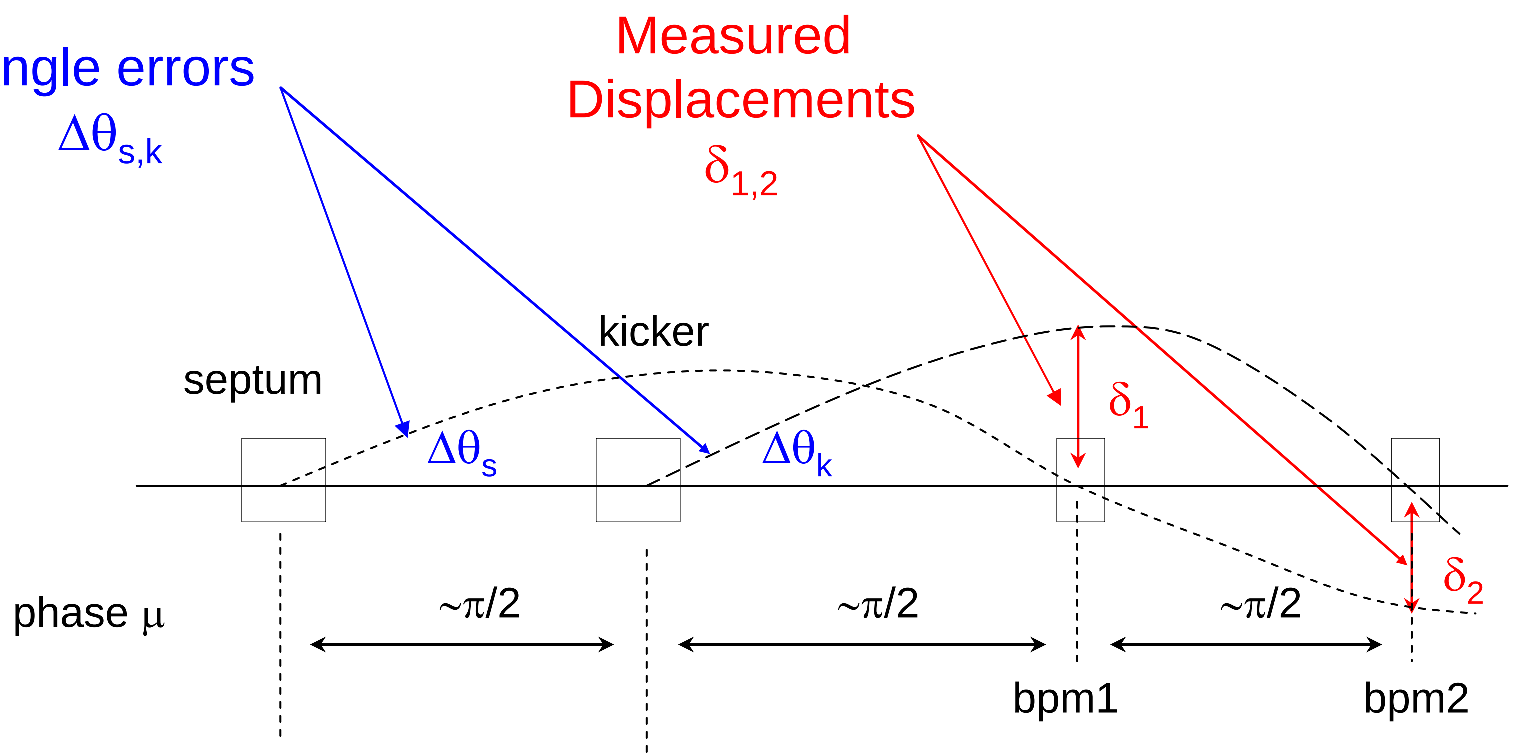




Injection errors

- Any residual transverse oscillation will lead to an emittance blow-up through filamentation
  - Error in septum angle
  - Error in ring kicker angle
  - Steering error
- Beam position monitors can be used to find the source of the error (see next slide)
- A "transverse damper" system can be used to damp these oscillations
- Possible that injection trajectory is well corrected, but there is still an emittance blow-up through optical mismatch

Injection errors



$$\delta_1 = \Delta\theta_s \sqrt{(\beta_s\beta_1)} \sin(\mu_1 - \mu_s) + \Delta\theta_k \sqrt{(\beta_k\beta_1)} \sin(\mu_1 - \mu_k)$$

$$\approx \Delta\theta_k \sqrt{(\beta_k\beta_1)}$$

$$\delta_2 = \Delta\theta_s \sqrt{(\beta_s\beta_2)} \sin(\mu_2 - \mu_s) + \Delta\theta_k \sqrt{(\beta_k\beta_2)} \sin(\mu_2 - \mu_k)$$

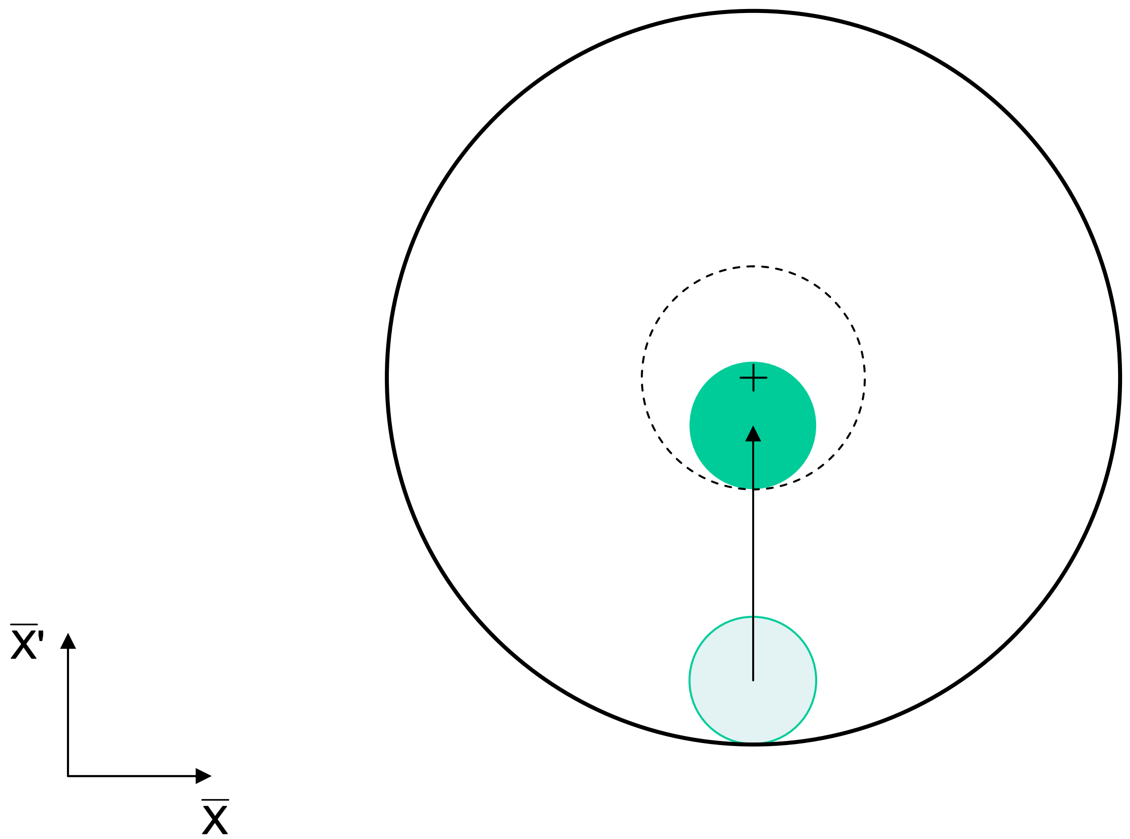
$$\approx -\Delta\theta_s \sqrt{(\beta_s\beta_2)}$$

*

Injection oscillations

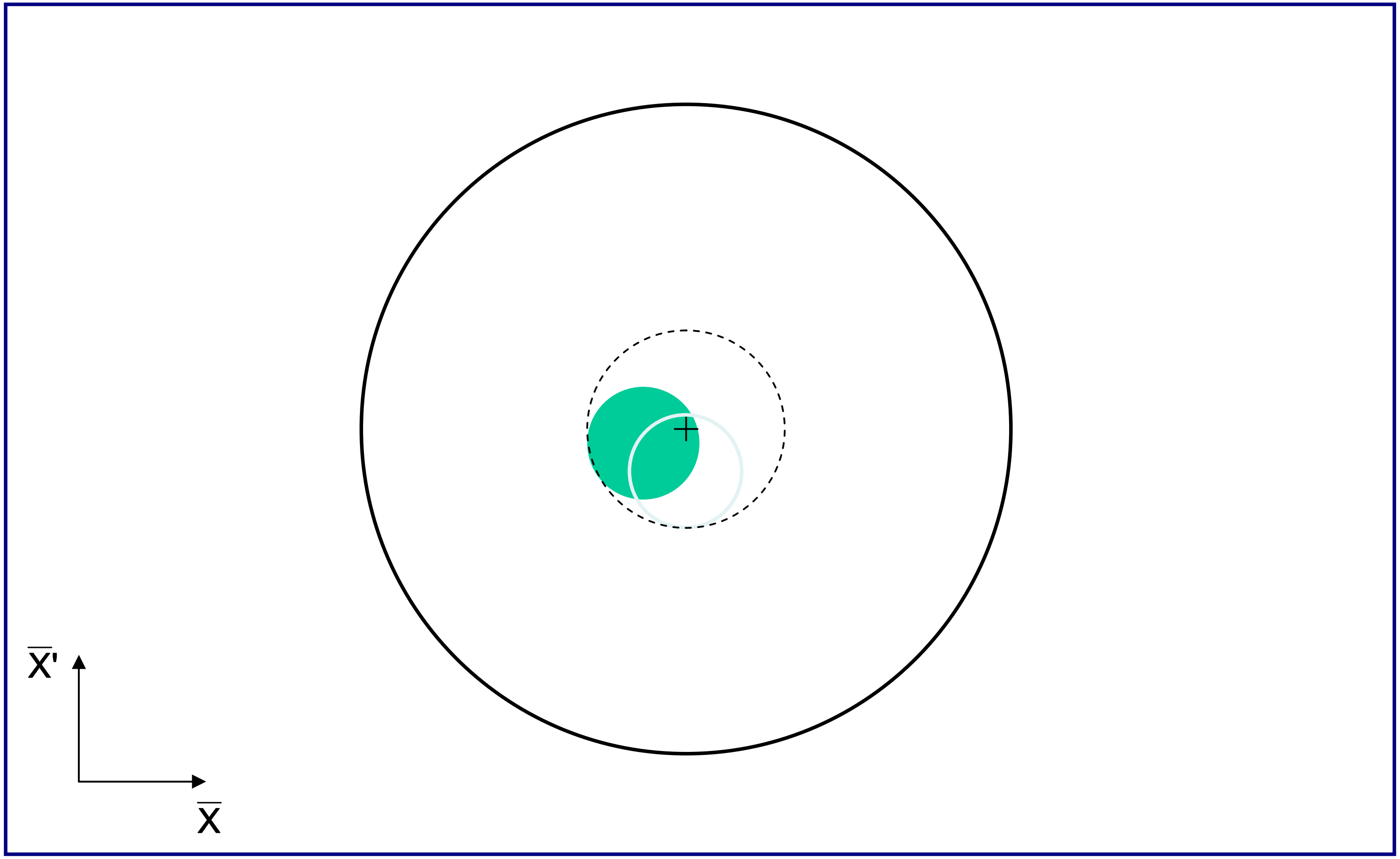
For imperfect injection the beam oscillates around the central orbit. 1

kicker θ error



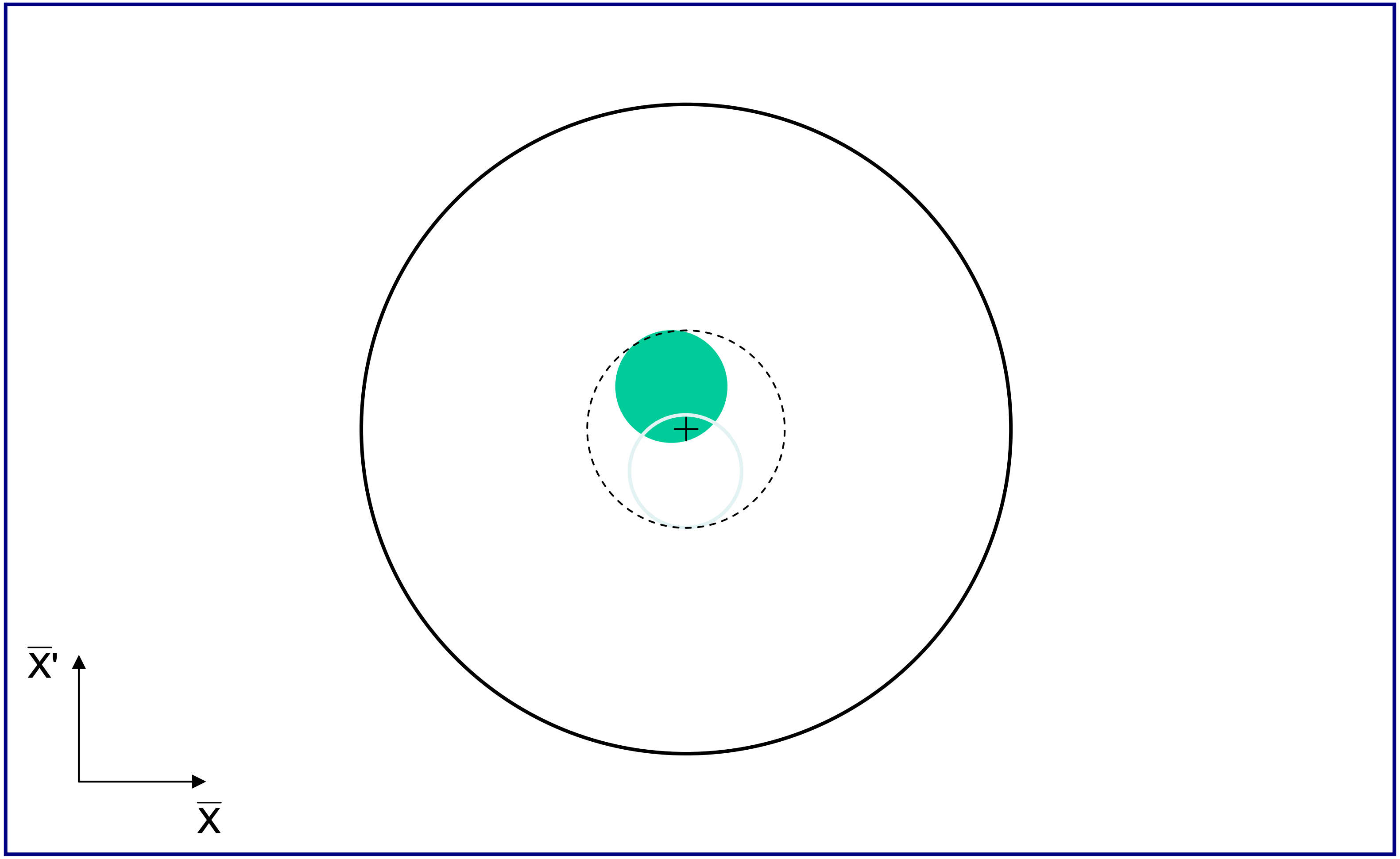
Injection oscillations

For imperfect injection the beam oscillates around the central orbit. 2



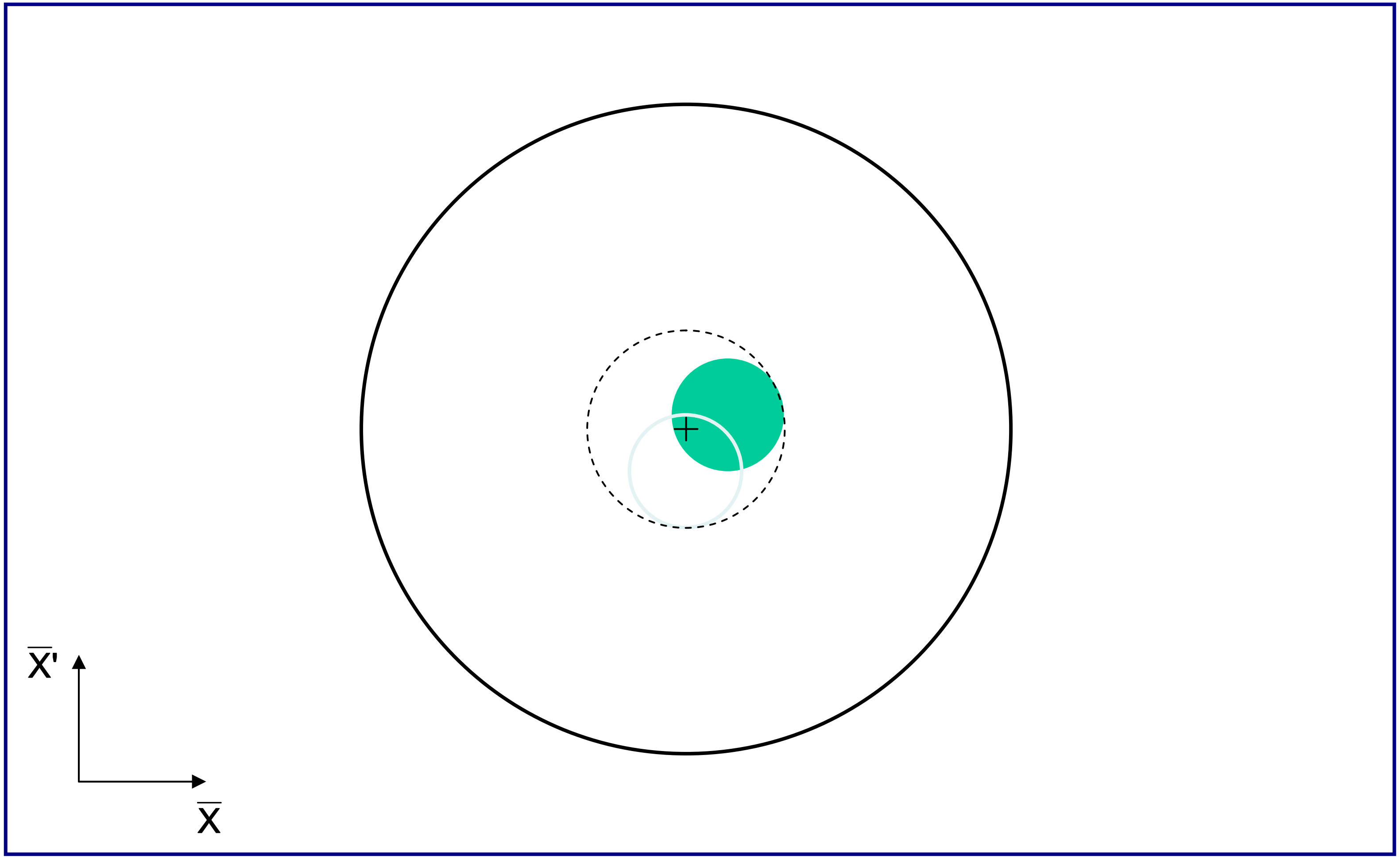
Injection oscillations

For imperfect injection the beam oscillates around the central orbit. 3



Injection oscillations

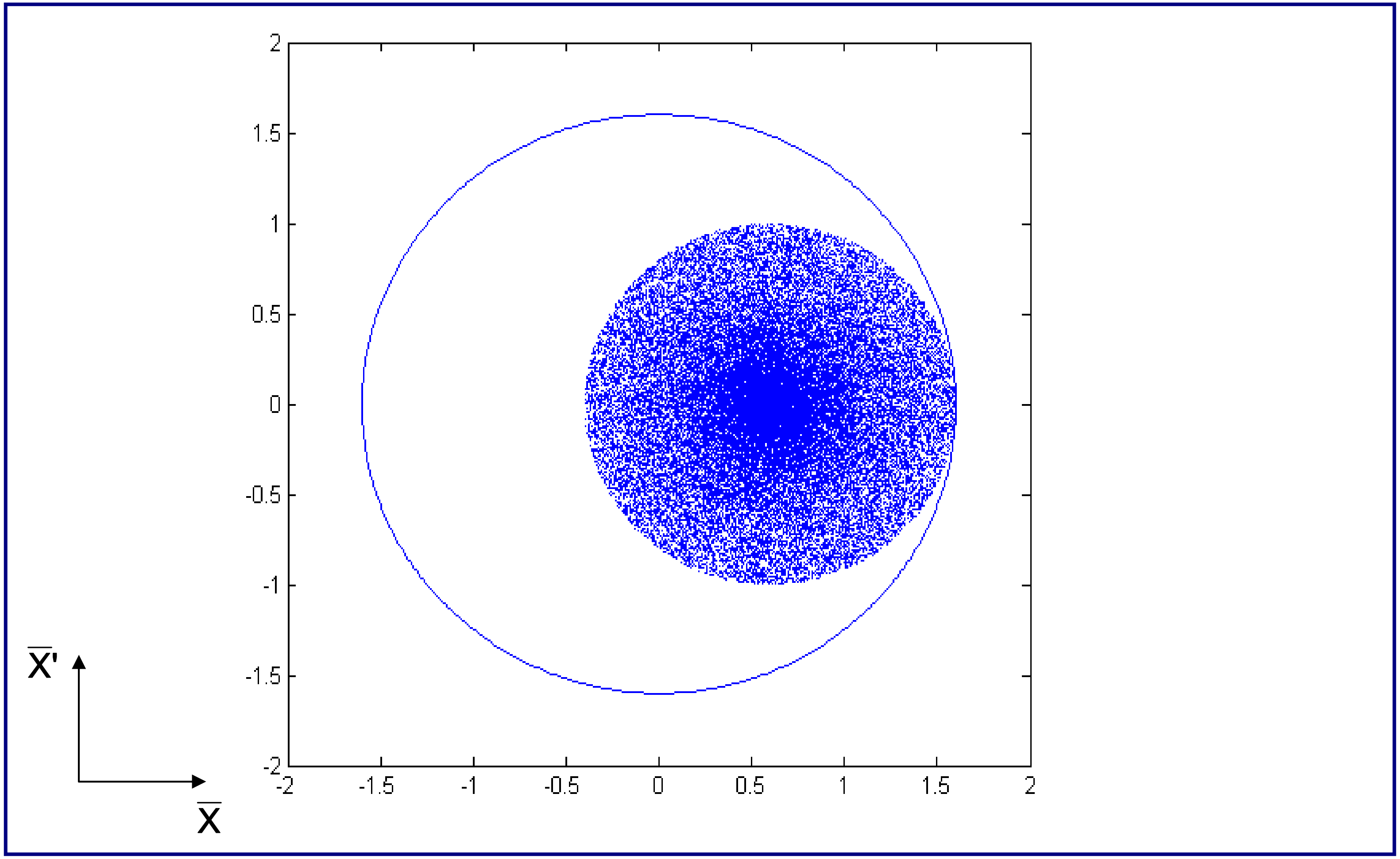
For imperfect injection the beam oscillates around the central orbit. 4



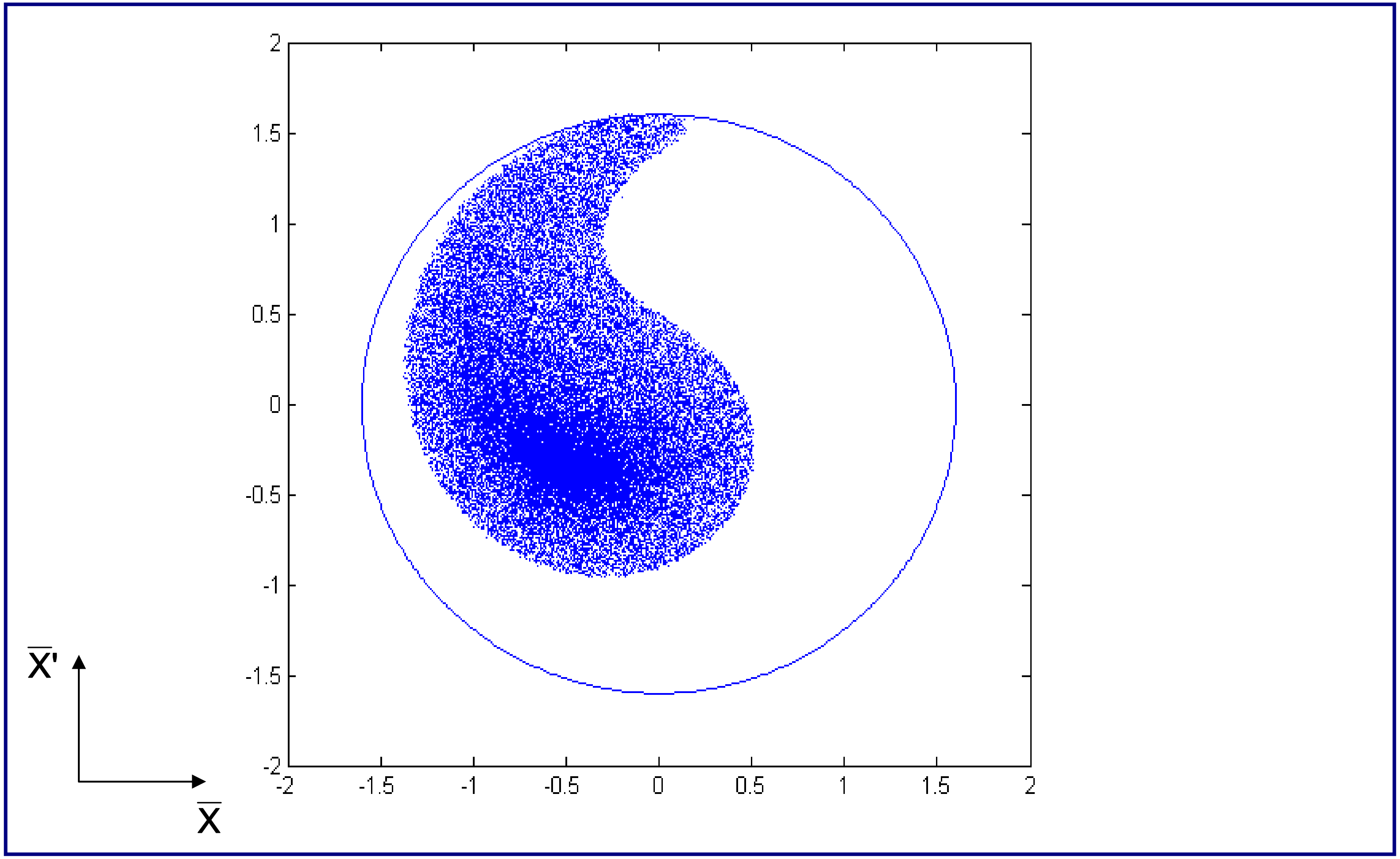
Filamentation

- Non-linear effects (e.g. magnetic field multipoles) cause amplitude dependent effects in particle motion.
- Over many turns, a phase-space oscillation is transformed into an emittance increase.

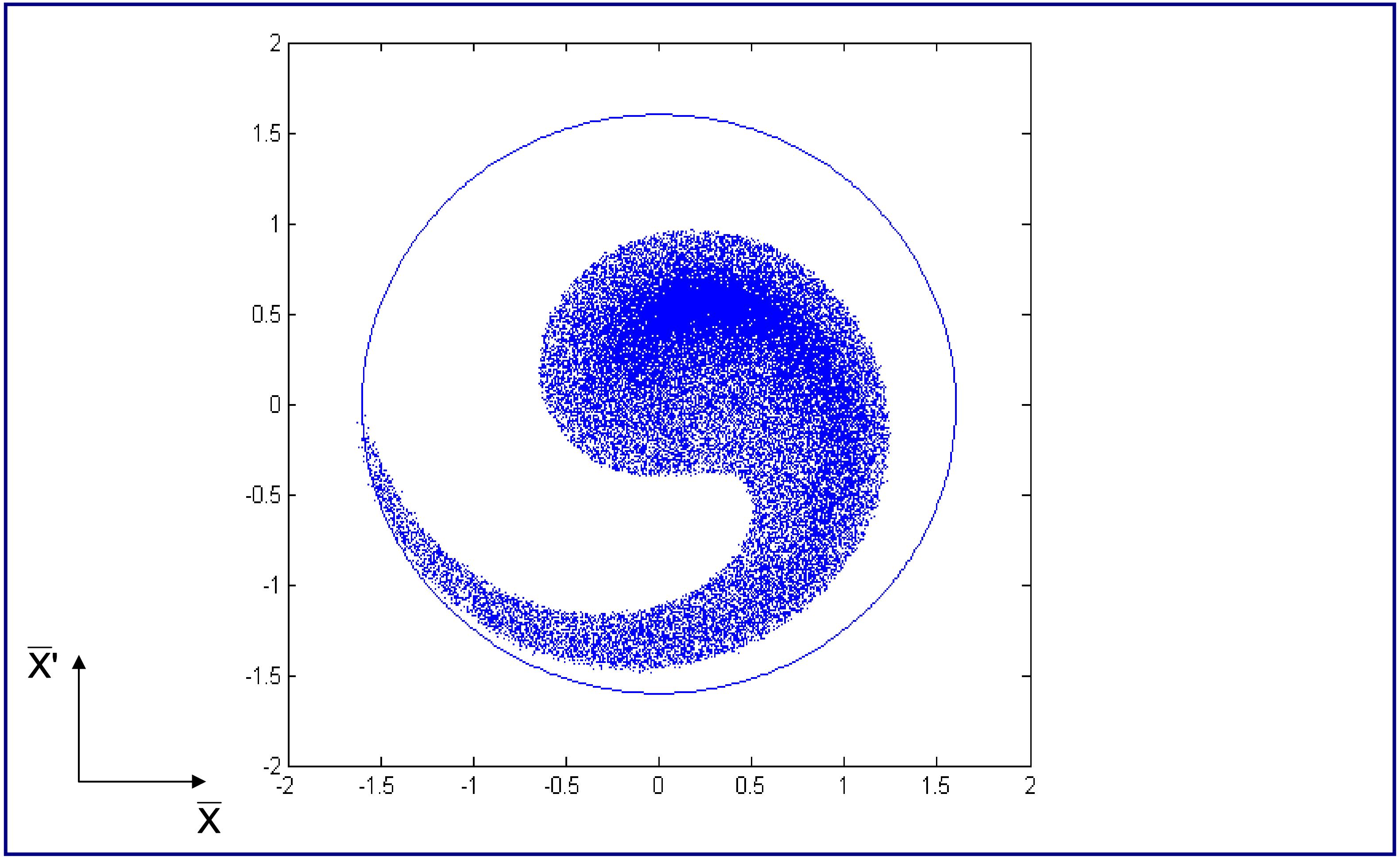
Filamentation



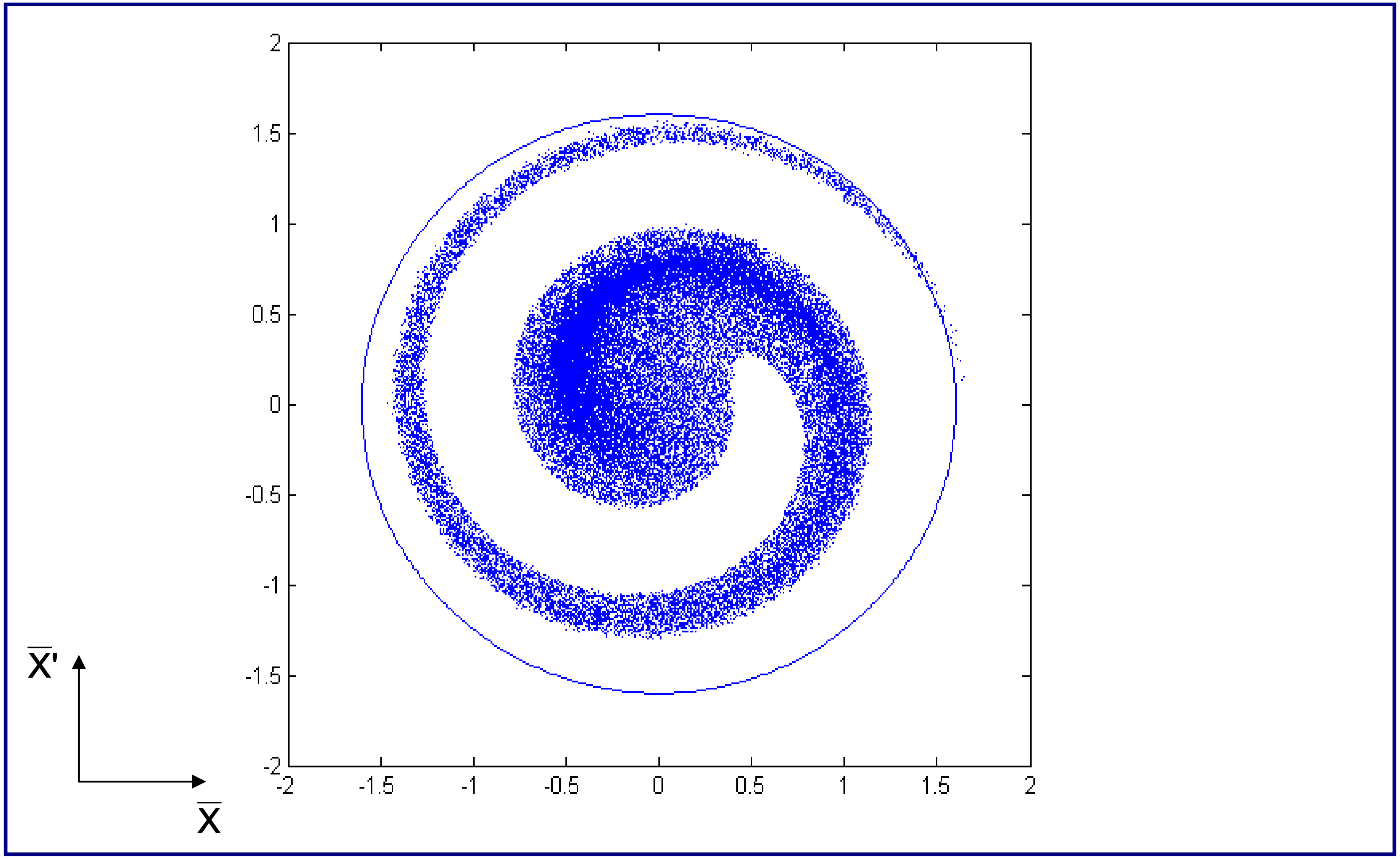
Filamentation



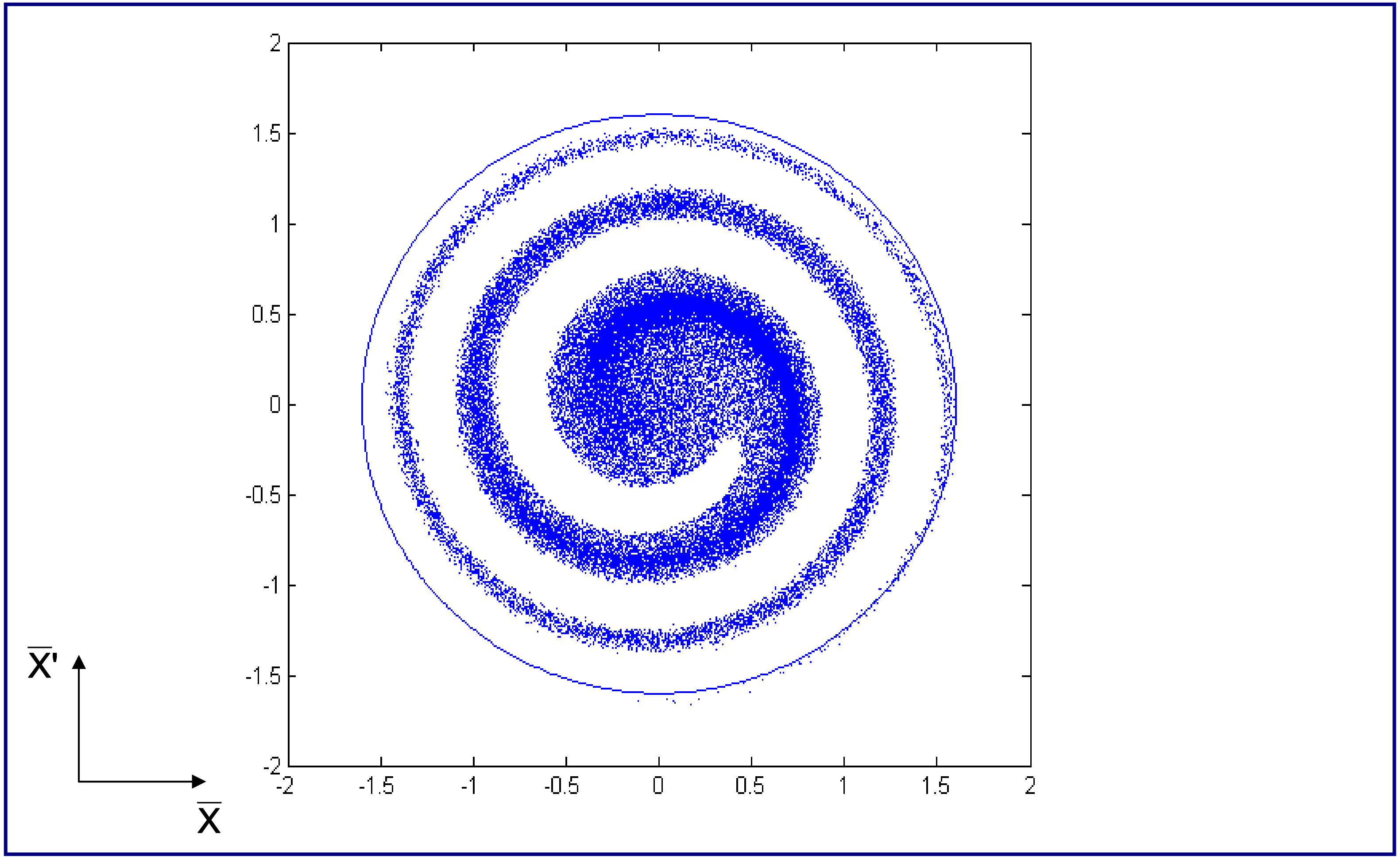
Filamentation



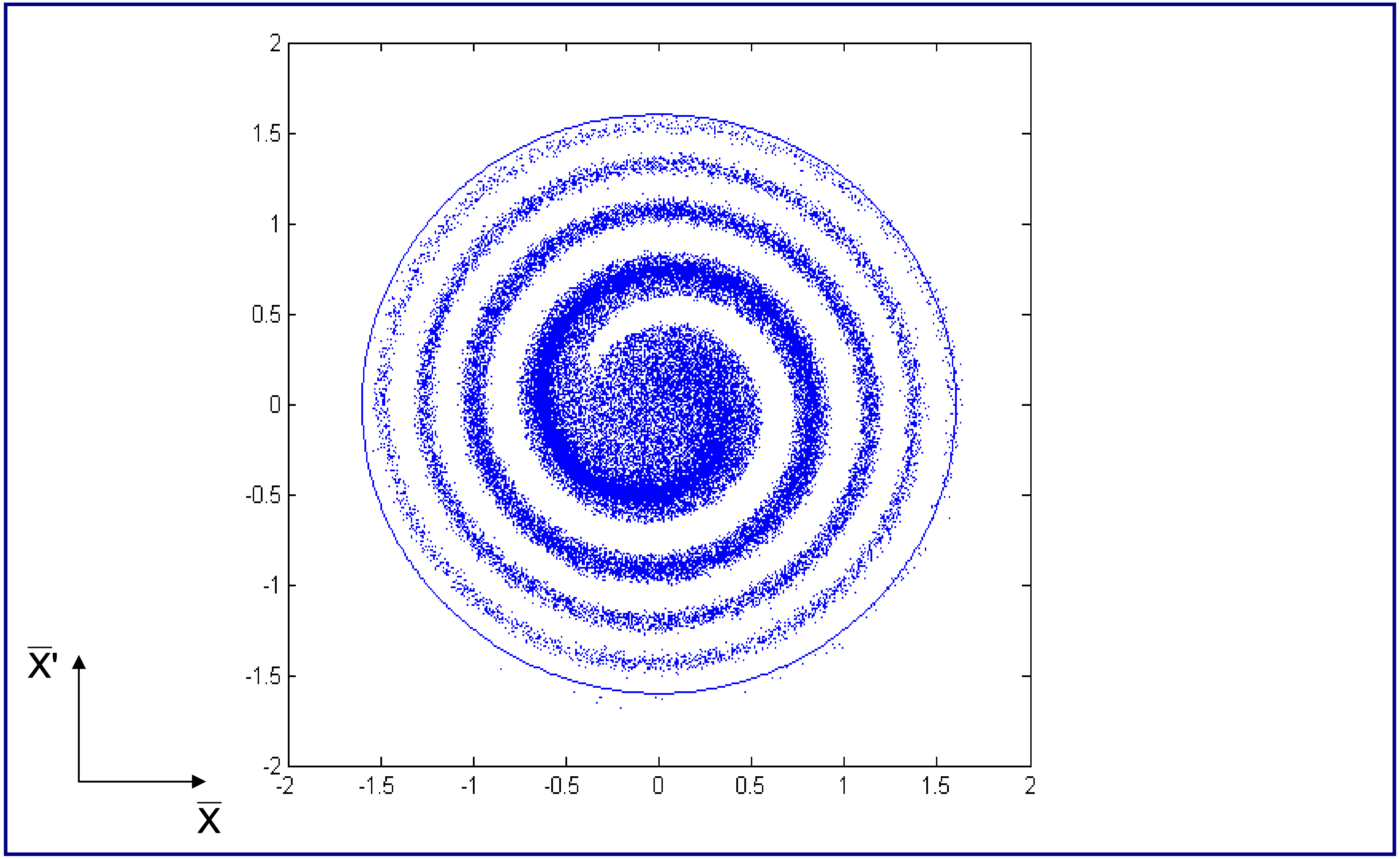
Filamentation



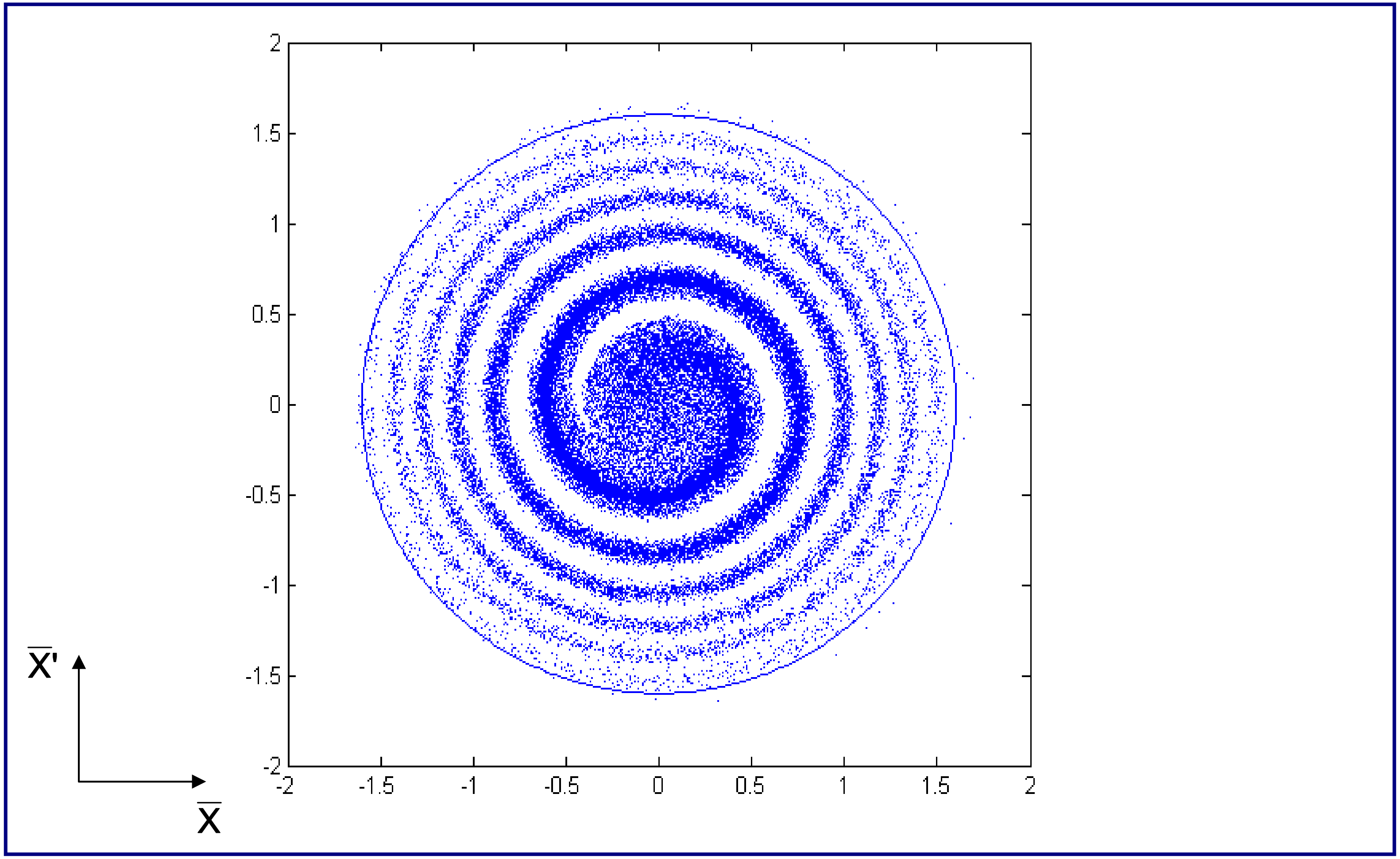
Filamentation



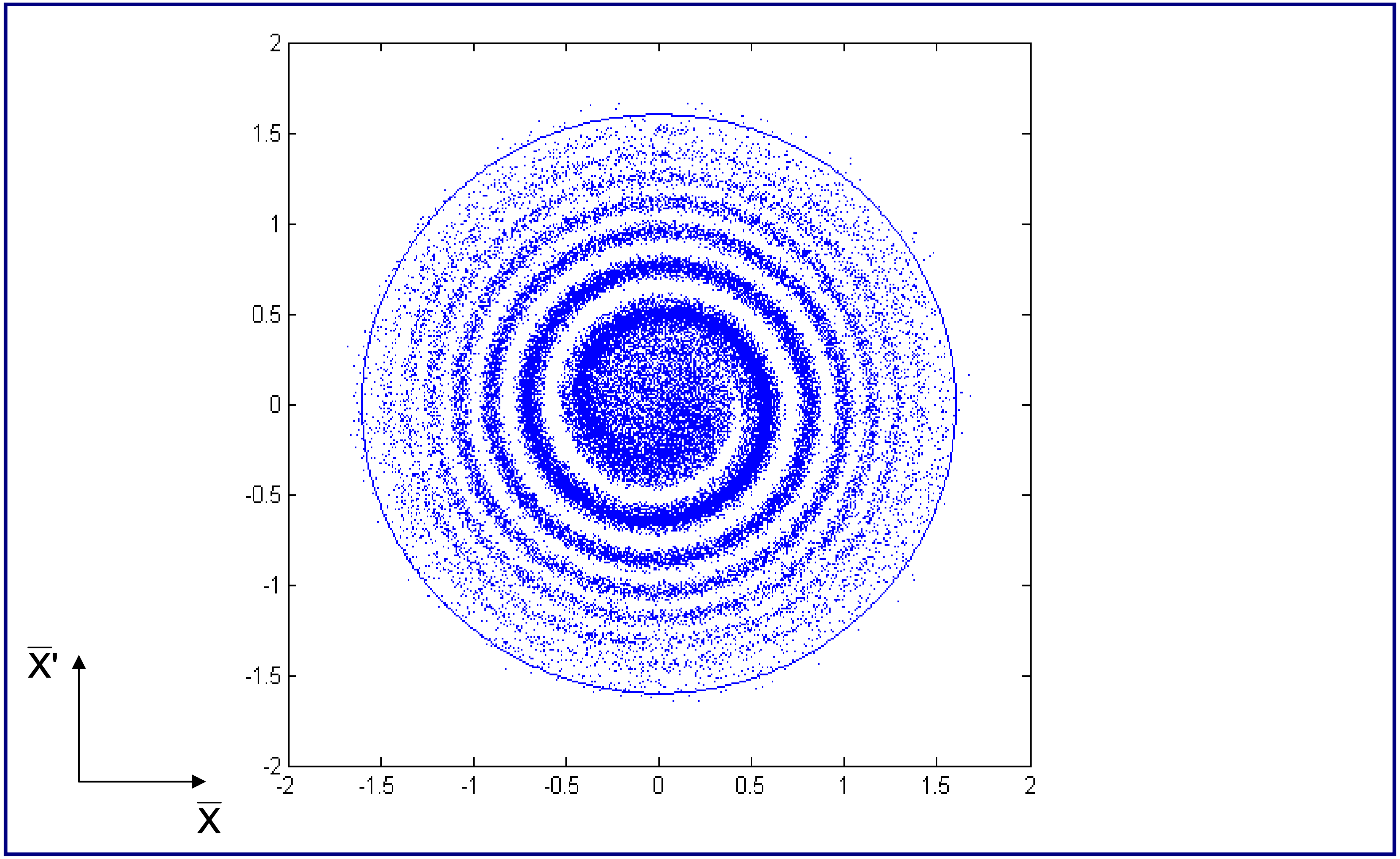
Filamentation



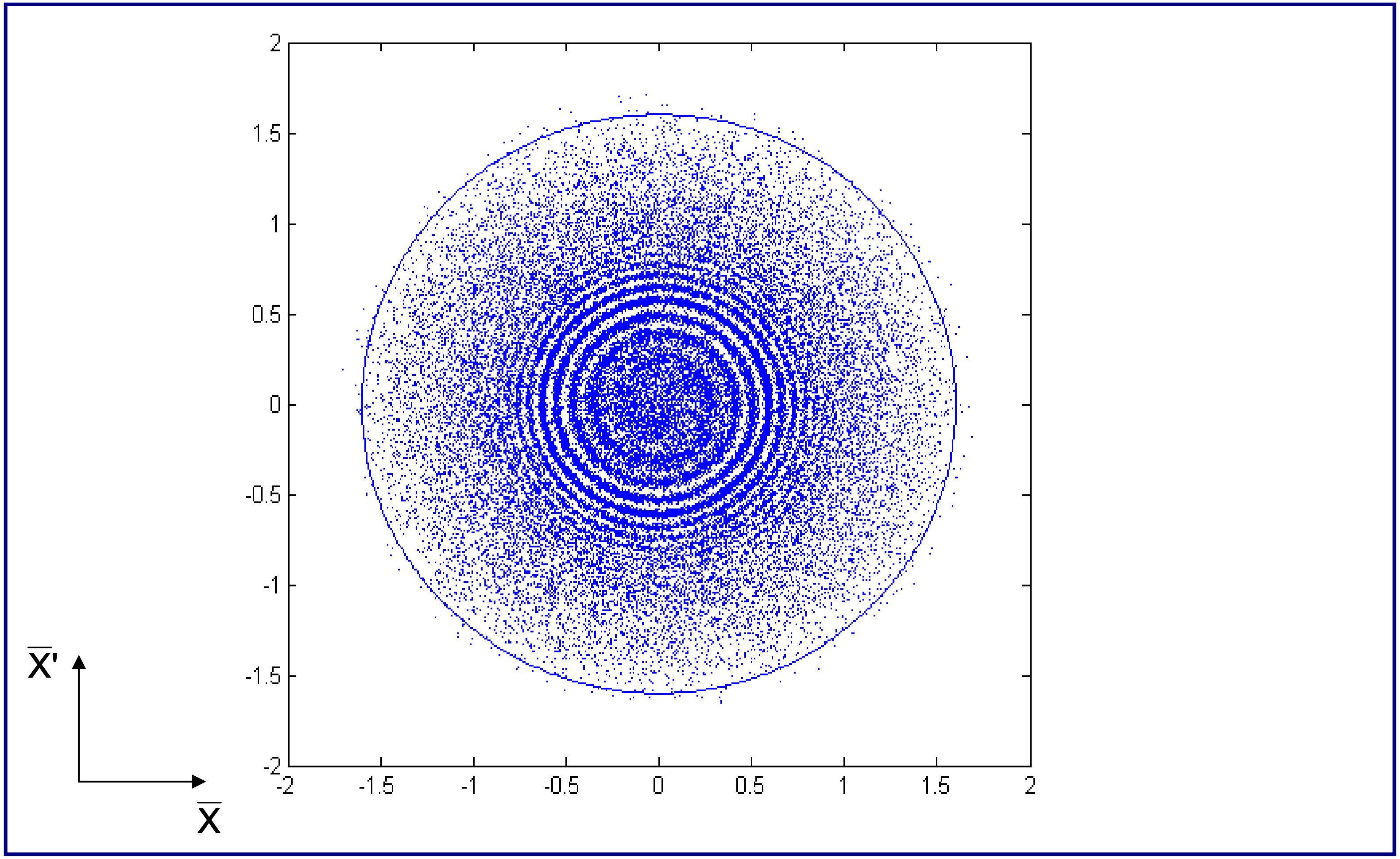
Filamentation



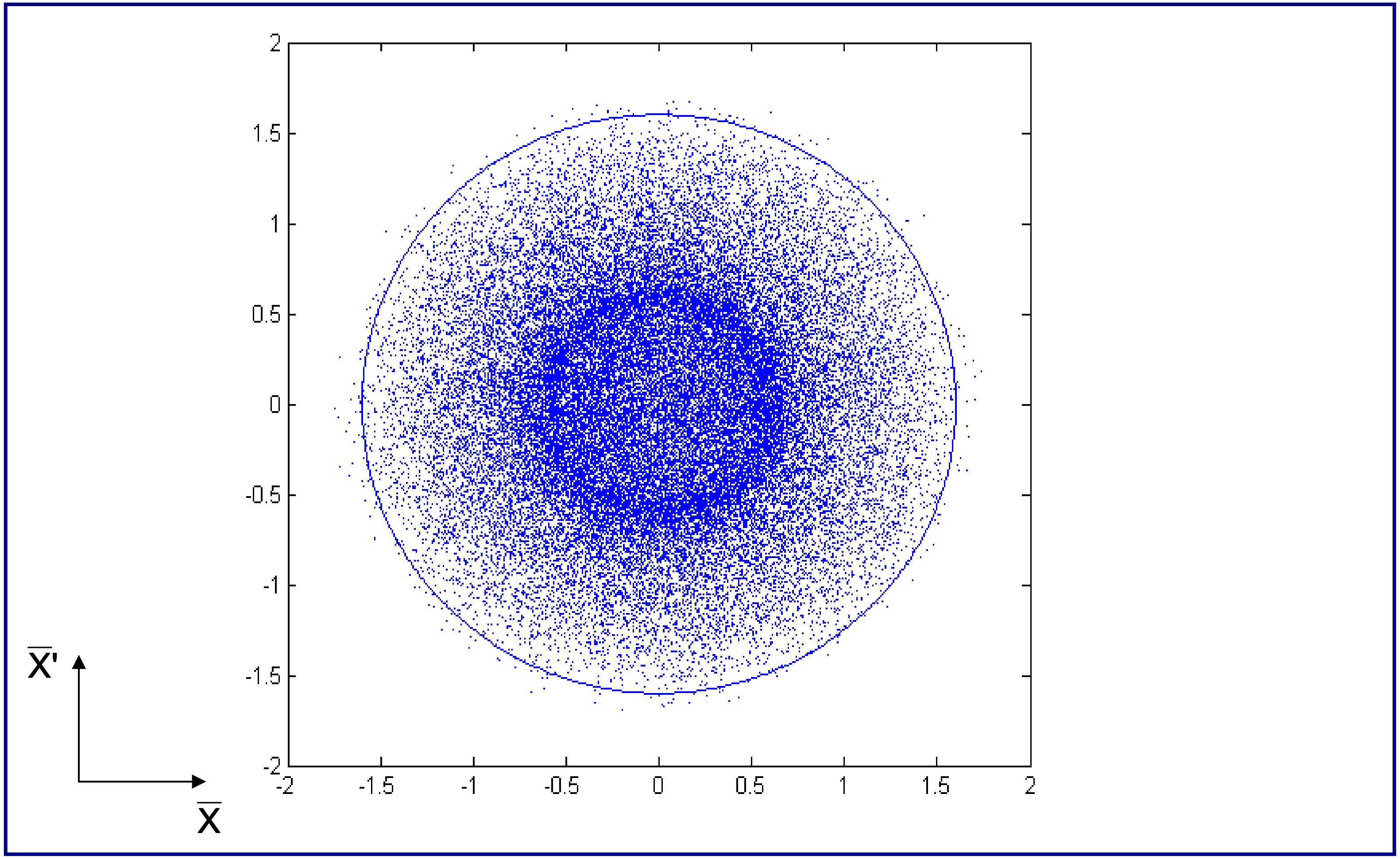
Filamentation



Filamentation

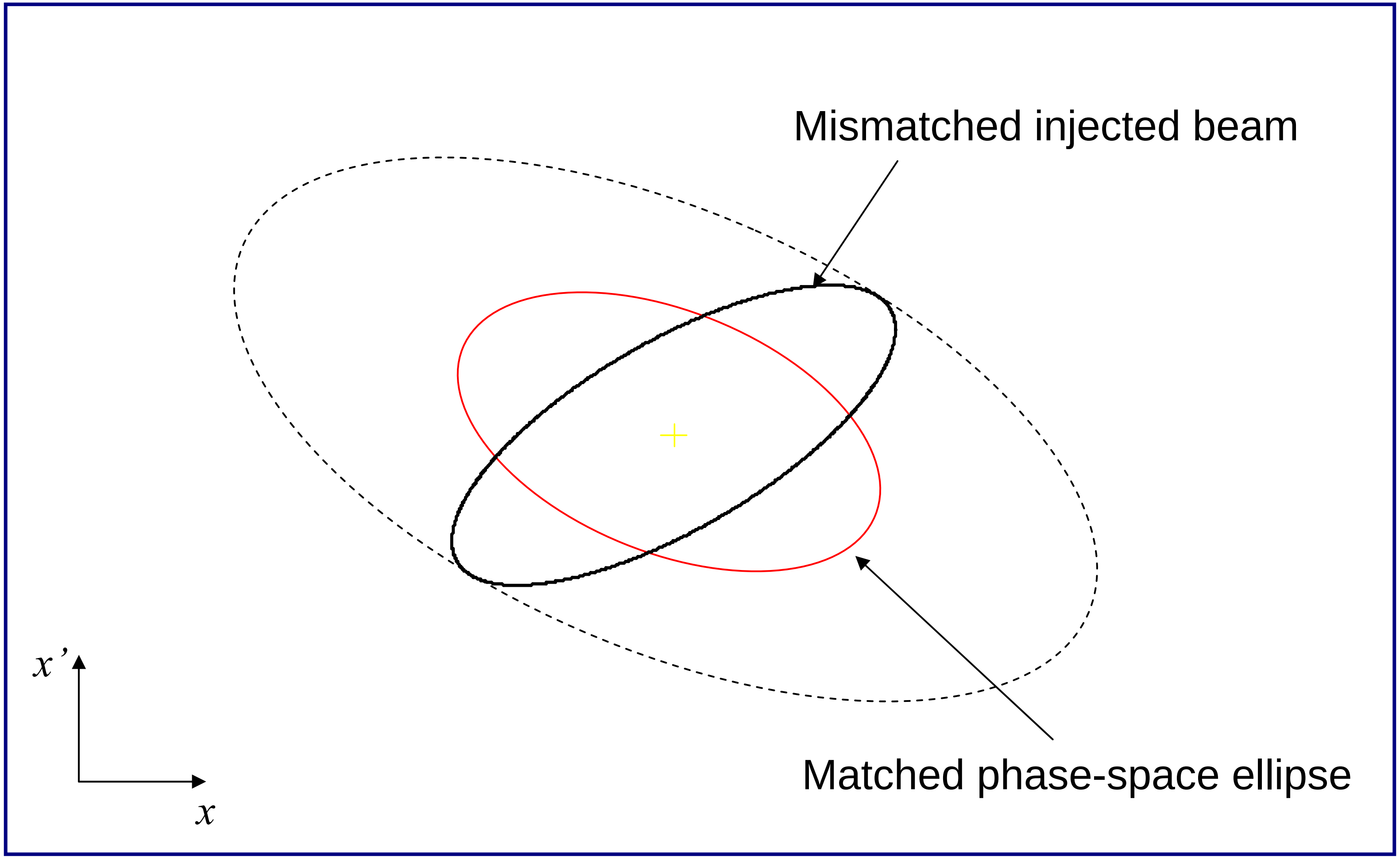


Filamentation



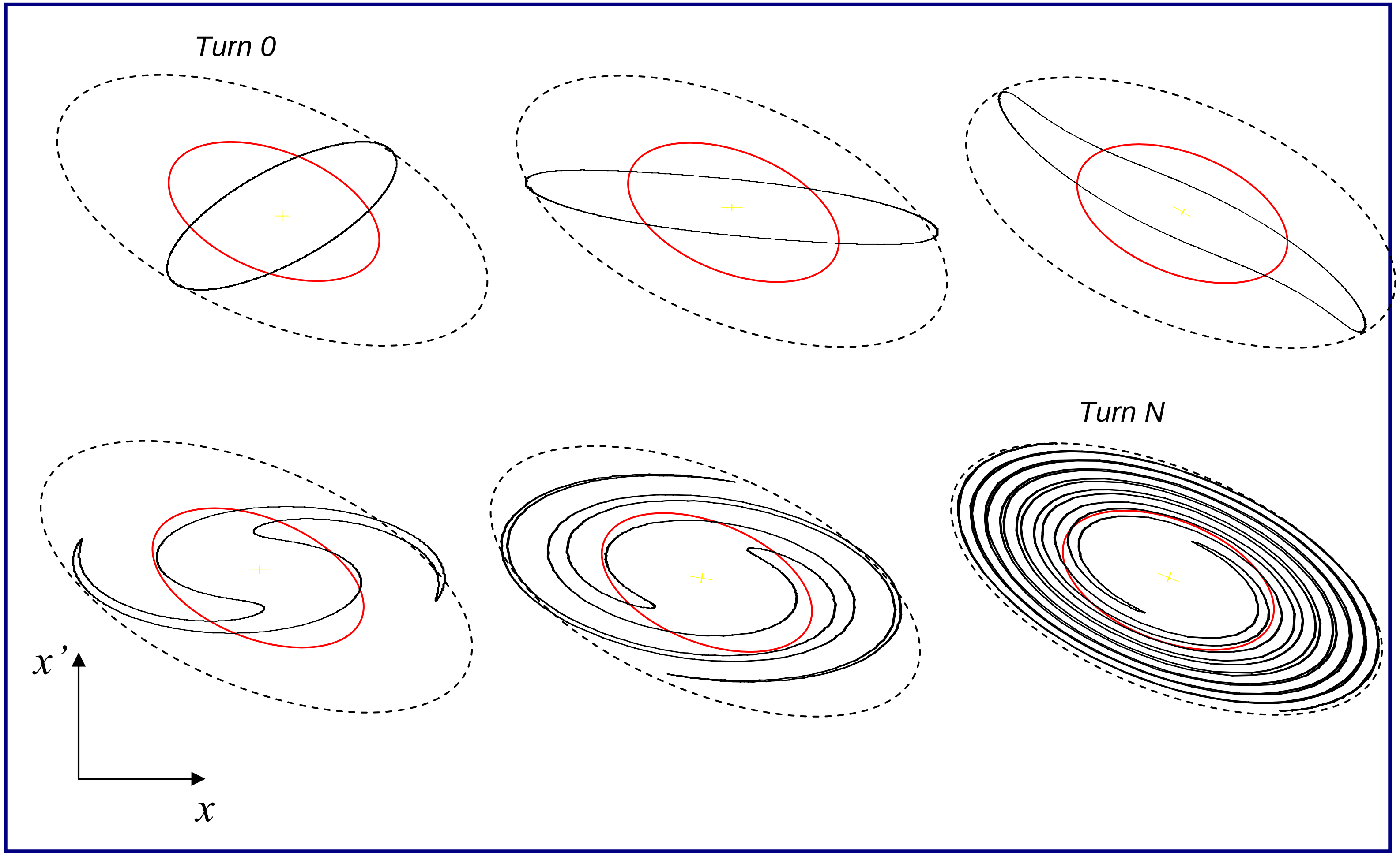
Optical Mismatch at Injection

Particles oscillate with conserved C-S invariant: $a = \gamma x^2 + 2\alpha xx' + \beta x'^2$



Optical Mismatch at Injection

Filamentation fills larger ellipse with same shape as matched ellipse



Recap

- Accelerator components involved in injection
- Single turn injection
  - Position and angle of incoming beam as a function of phase advance and kicker angle
  - Required separation of incoming and circulating beams
  - Optimum phase advance
- Injection errors
  - Injection oscillations
  - Filamentation
  - Mismatched injection

Acknowledgements

- Thanks to Brennan Goddard. Many of these slides were copied from his CAS course.

- backup slides