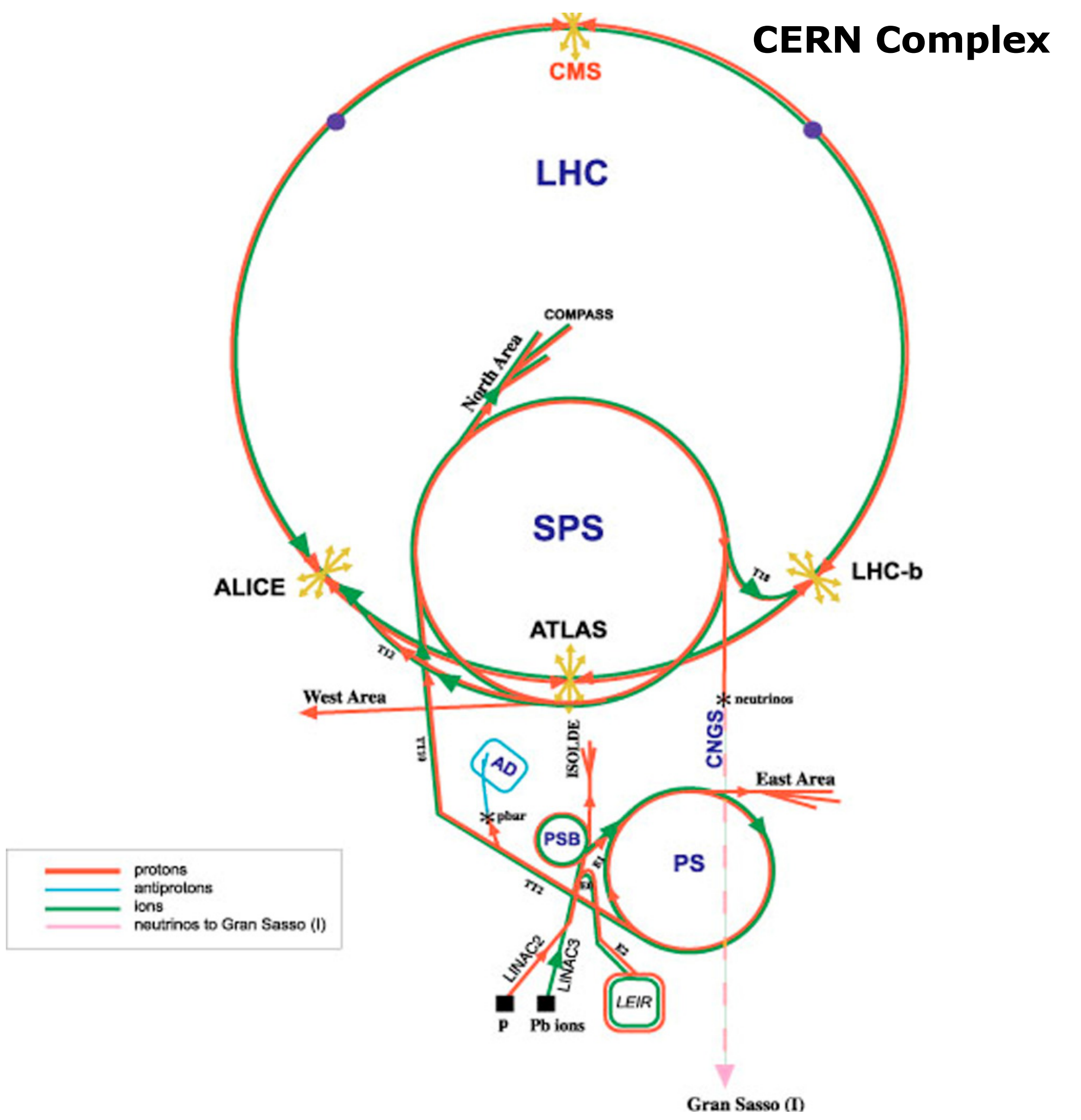
Injection, extraction and transfer

- An accelerator has limited dynamic range.
- Chain of stages needed to reach high energy
- Periodic re-filling of storage rings, like LHC
- External experiments, like CNGS



Transfer (in, out, and between machines) is important!

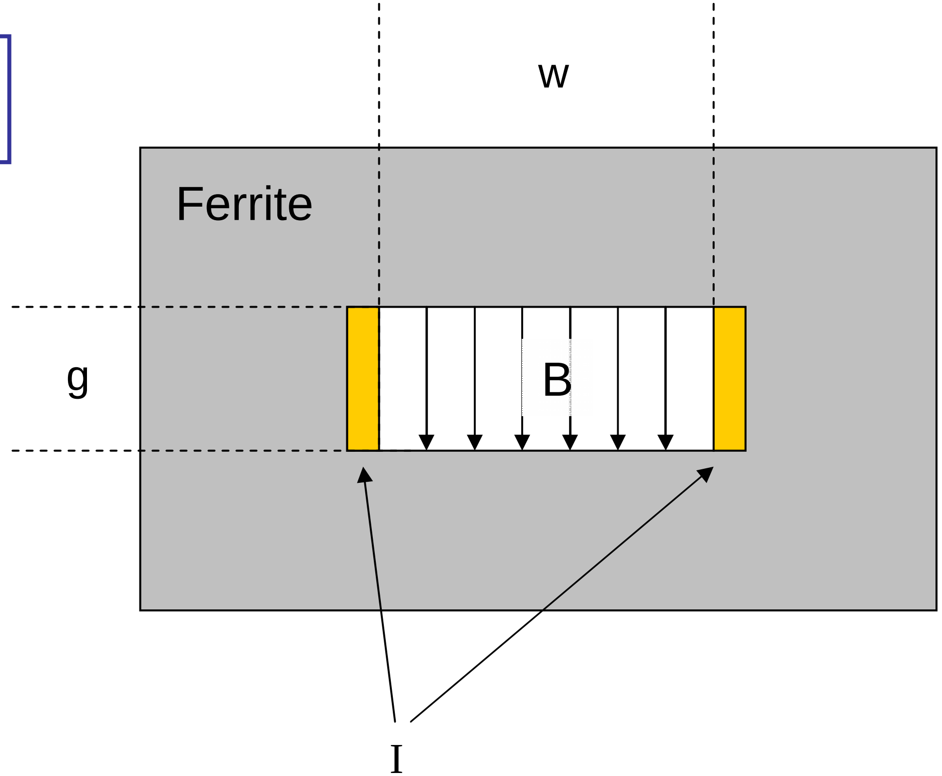
LHC:	Large Hadron Collider
SPS:	Super Proton Synchrotron
AD:	Antiproton Decelerator
ISOLDE:	Isotope Separator Online Device
PSB:	Proton Synchrotron Booster
PS:	Proton Synchrotron
LINAC:	LINear Accelerator
LEIR:	Low Energy Ring
CNGS:	CERN Neutrino to Gran Sasso

Injection and Extraction

- Kickers and septa
- Normalised phase space
- Injection
  - Single-turn hadron injection
  - Injection errors, filamentation and blow-up
  - Multi-turn hadron injection
  - Charge-exchange H- injection
  - Lepton injection
- Extraction
  - Single-turn (fast) extraction
  - Non-resonant multi-turn extraction
  - Resonant multi-turn (slow) extraction

Kicker

Pulsed magnet with very fast rise time (100ns – few μs)



$B = \mu_0 I / g$

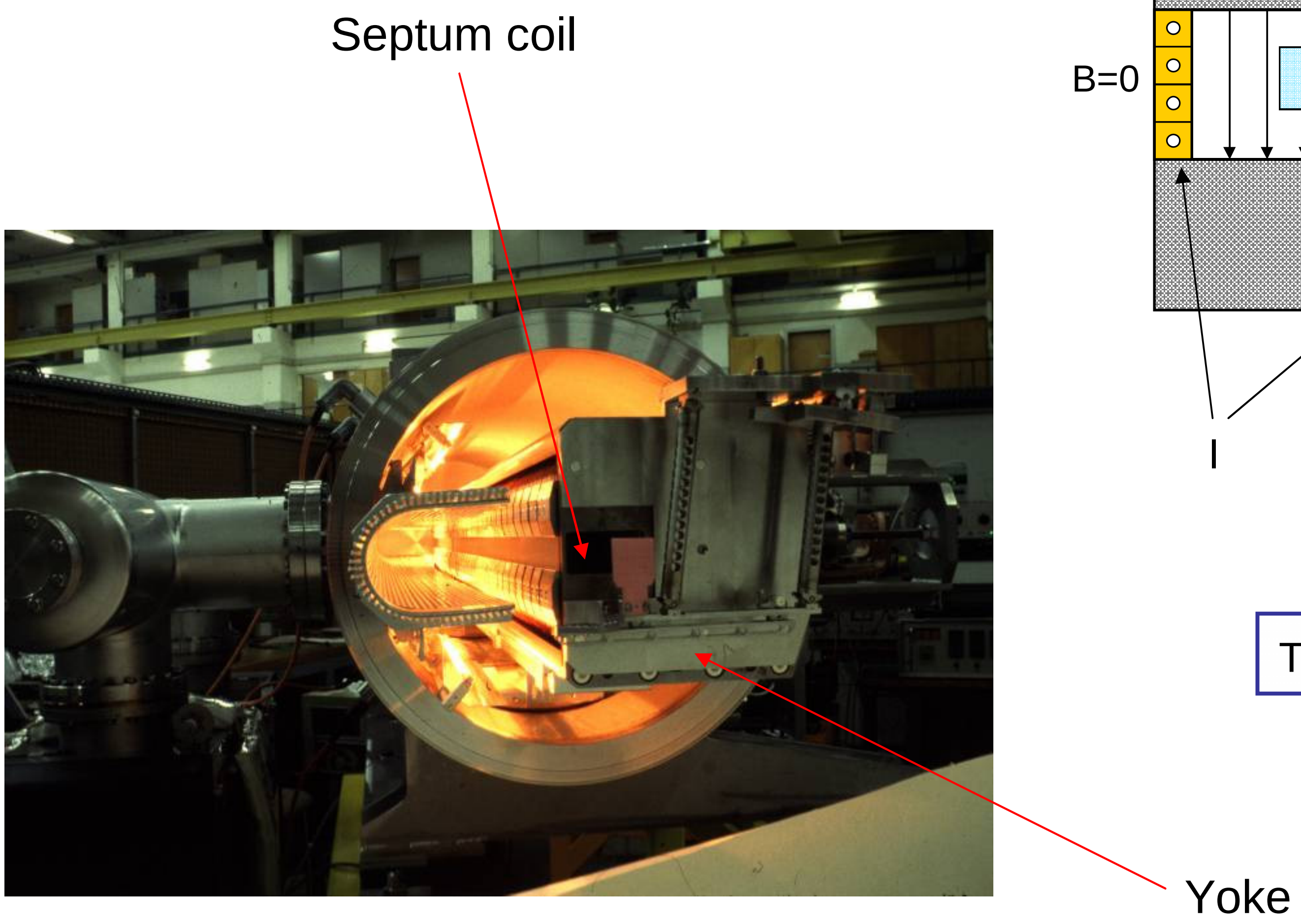
$L = \mu_0 w l / g$ (magnet length l)

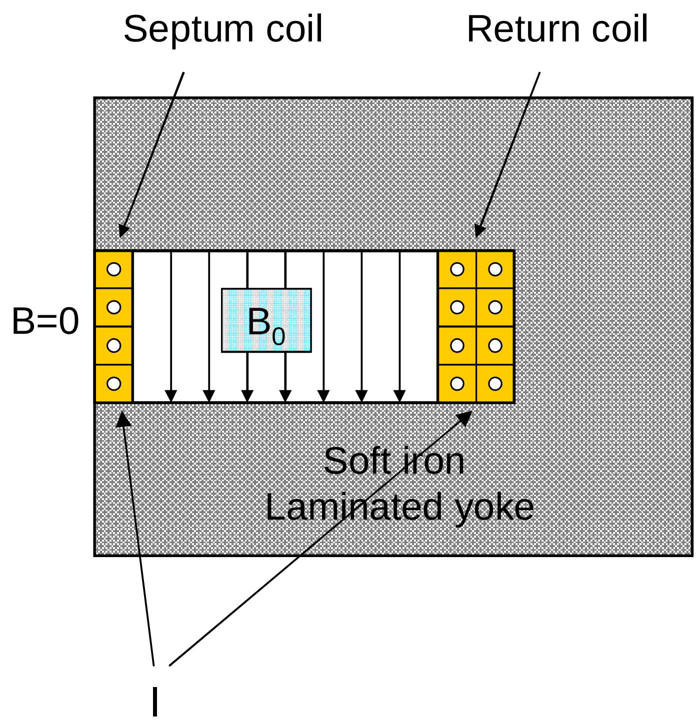
$dI/dt = V/L$

Typically 3kA in 1μs rise time

Magnetic septum

Pulsed or DC magnet with thin (2-20mm) septum between zero field and high field region

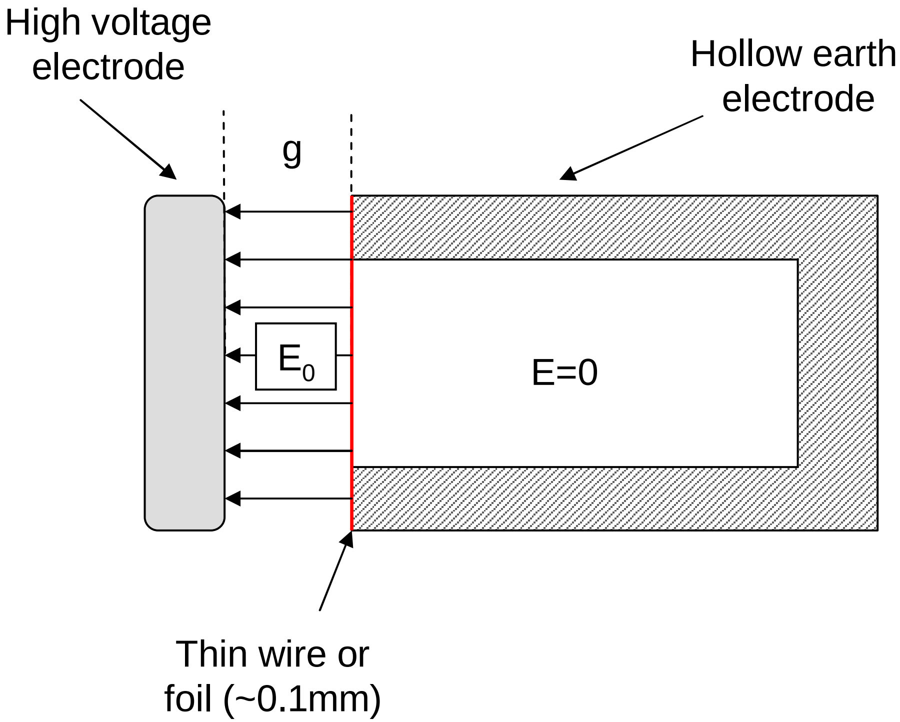




Typically I 5-25kA

Electrostatic septum

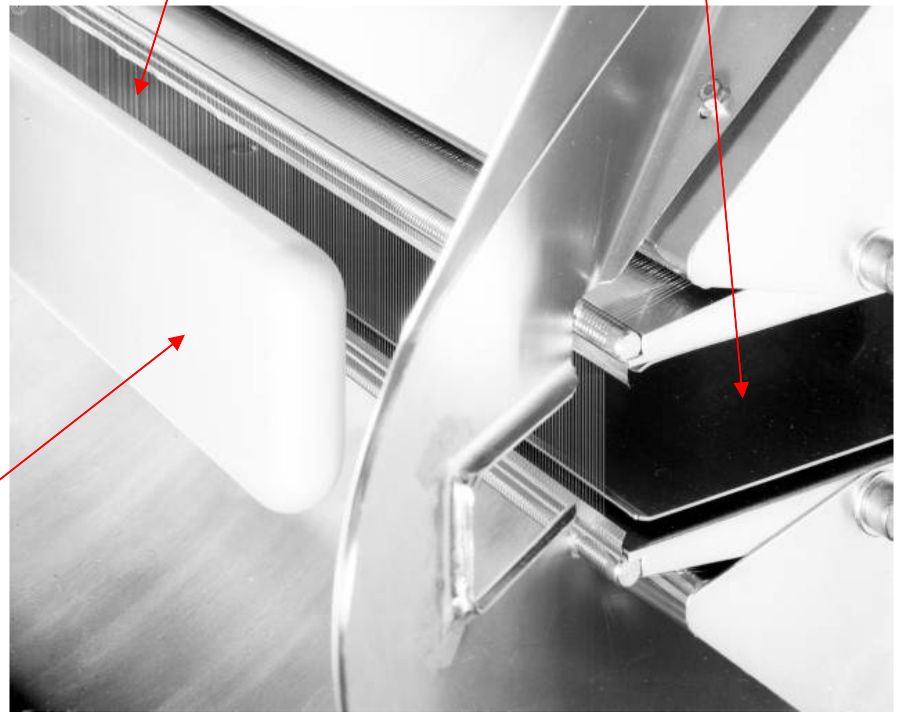
DC electrostatic device with very thin (~0.1mm) septum between zero field and high field region



$E = V / g$

Typically $V = 200kV$

$E = 100kV/cm$



Normalised phase space

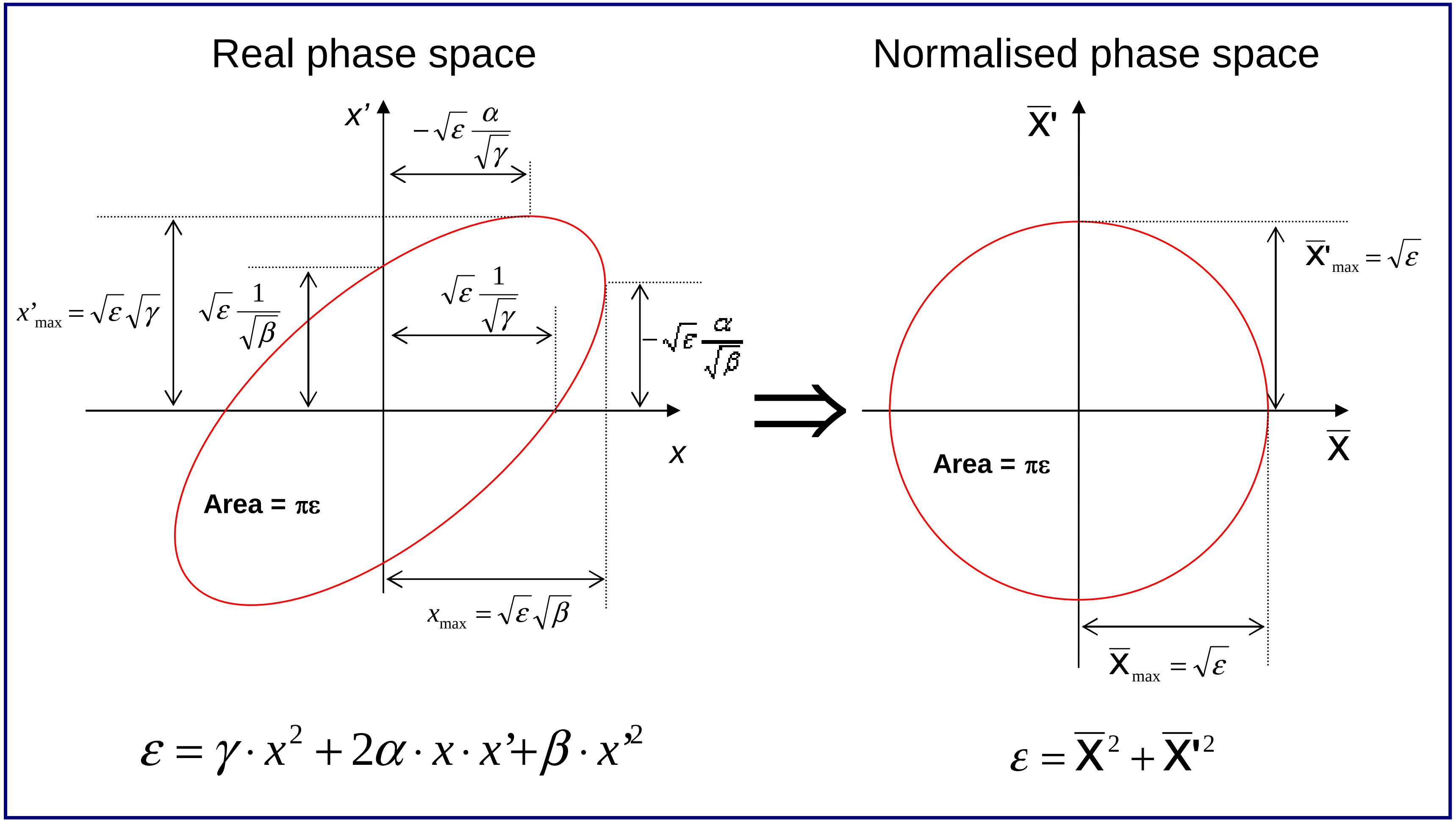
- Transform real transverse coordinates *x*, *x'* by

$$\begin{bmatrix} \overline{X} \\ \overline{X}' \end{bmatrix} = \mathbf{N} \cdot \begin{bmatrix} x \\ x' \end{bmatrix} = \sqrt{\frac{1}{\beta_S}} \cdot \begin{bmatrix} 1 & 0 \\ \alpha_S & \beta_S \end{bmatrix} \cdot \begin{bmatrix} x \\ x' \end{bmatrix}$$

$$\overline{X} = \sqrt{\frac{1}{\beta_S}} \cdot x$$

$$\overline{X}' = \sqrt{\frac{1}{\beta_S}} \cdot \alpha_S x + \sqrt{\beta_S}\, x'$$

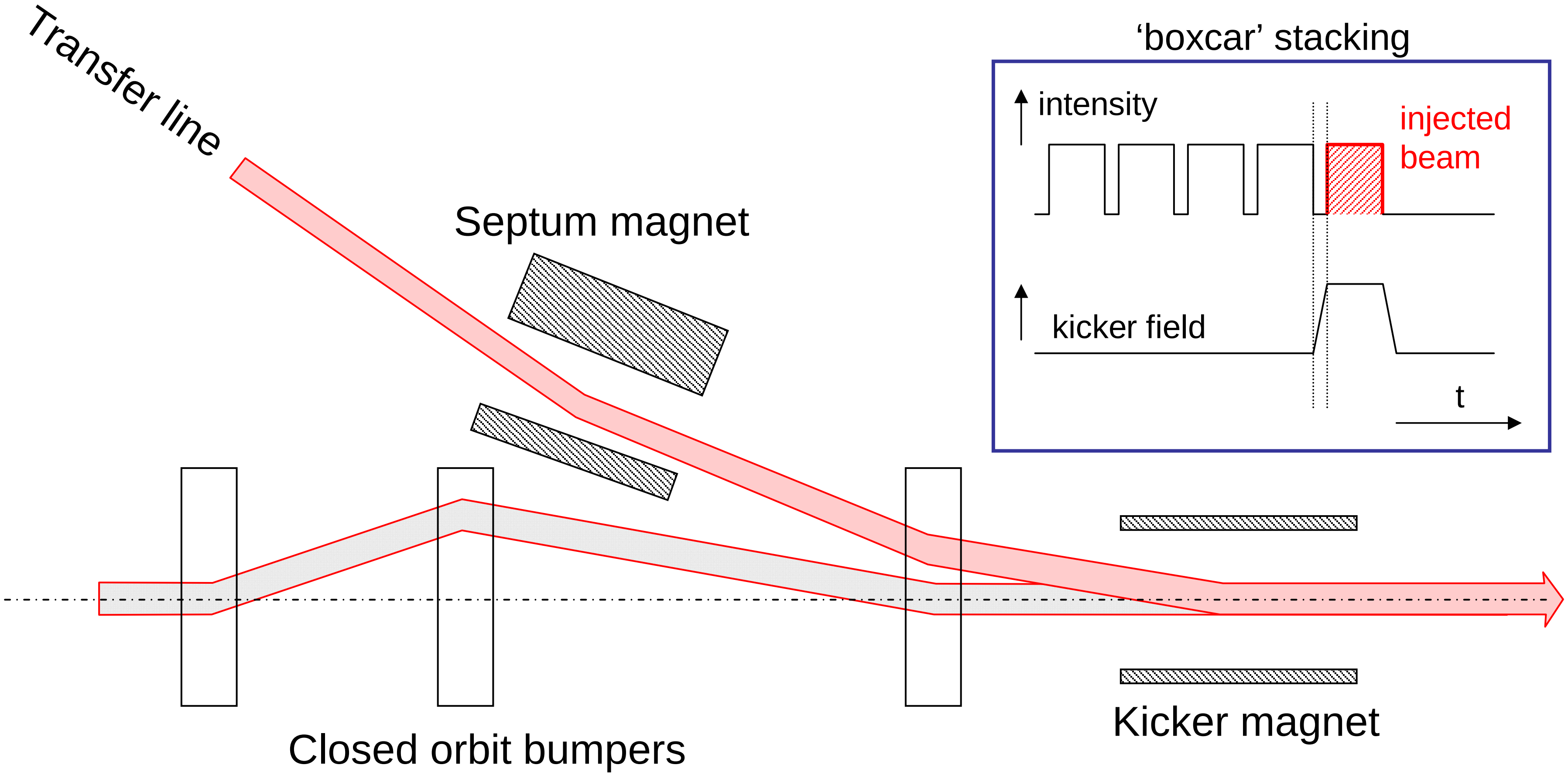
Normalised phase space



Injection

- Inject one or more bunches into a synchrotron, in one or more turns
- Elements involved:
  - Transfer line
  - Bumper magnet
  - Septum magnet
  - Fast kicker magnet
  - Synchrotron (receiving machine)

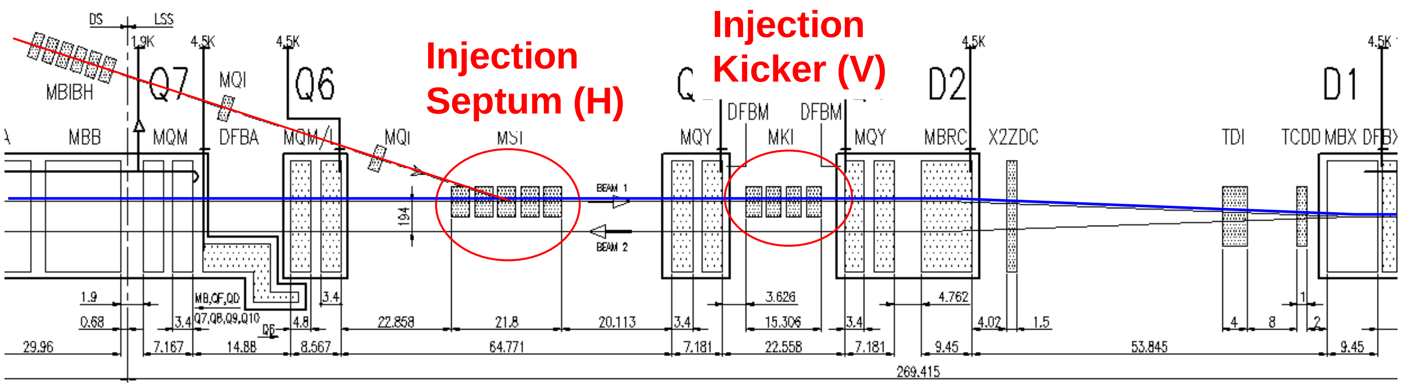
Single-turn injection

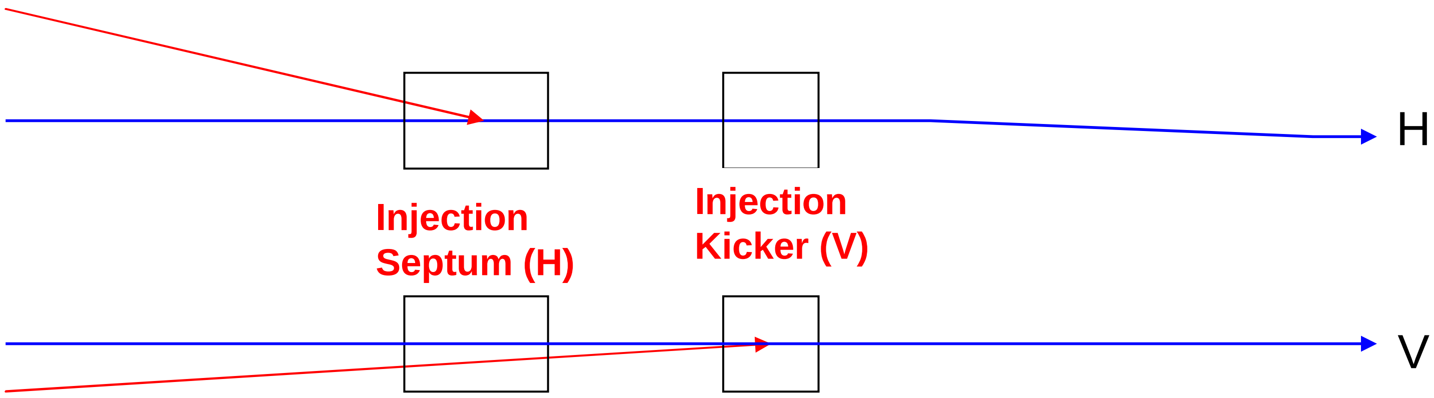


- Septum deflects the beam onto the closed orbit at the centre of the kicker
- Kicker compensates for the remaining angle

Single-turn injection

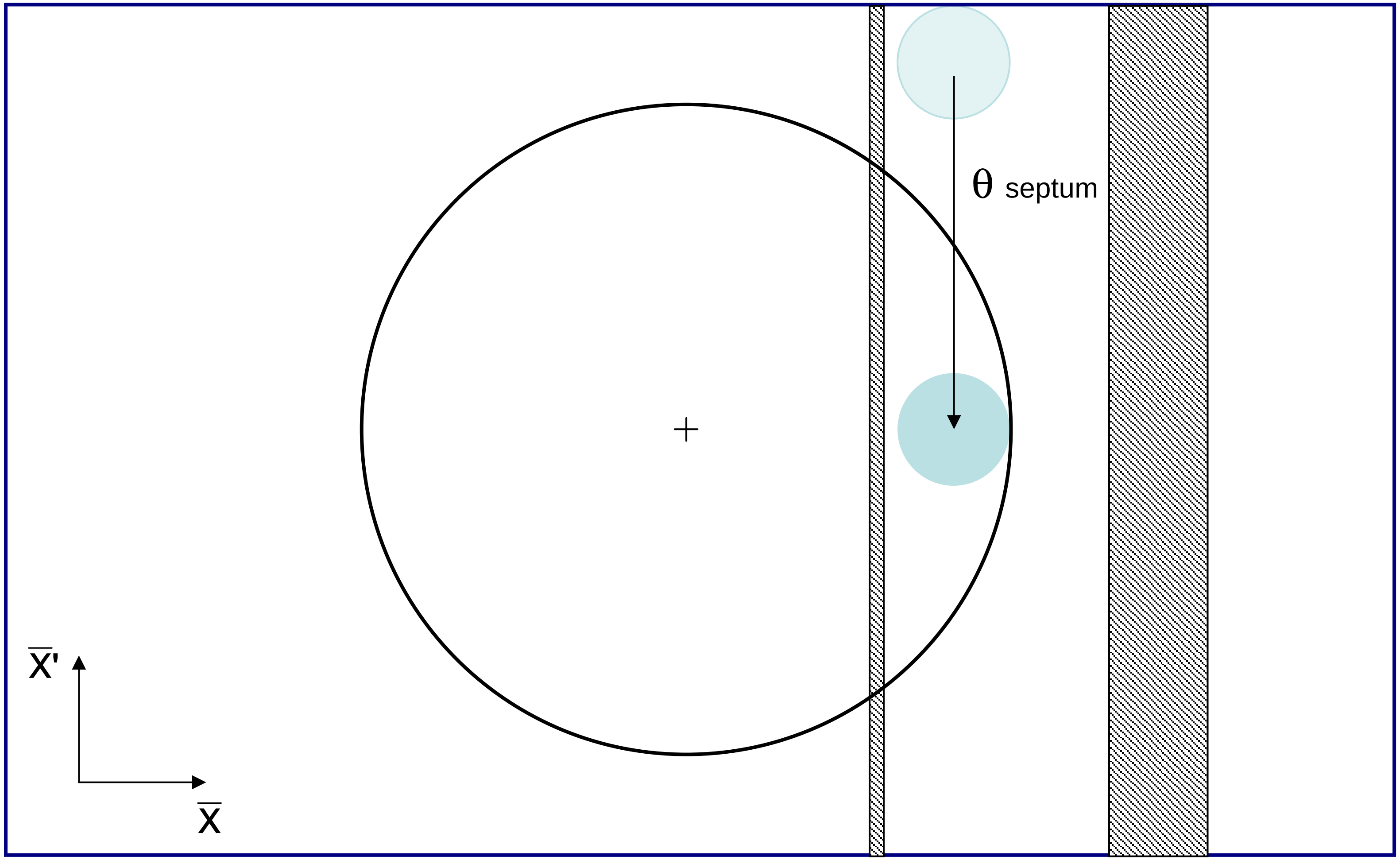
Example system – injection into the LHC at 450 GeV/c





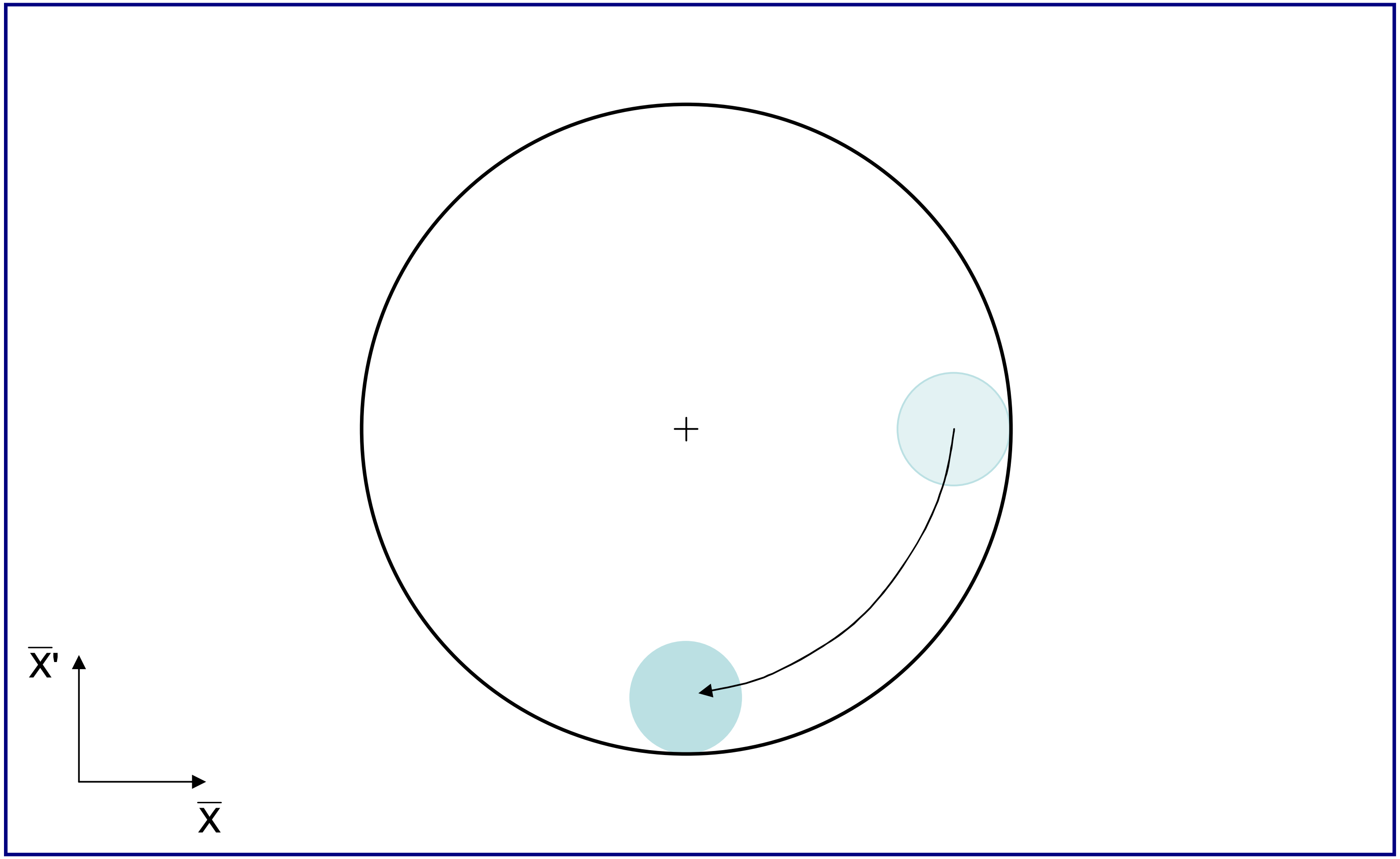
Single-turn injection – normalised phase space

Large deflection by septum



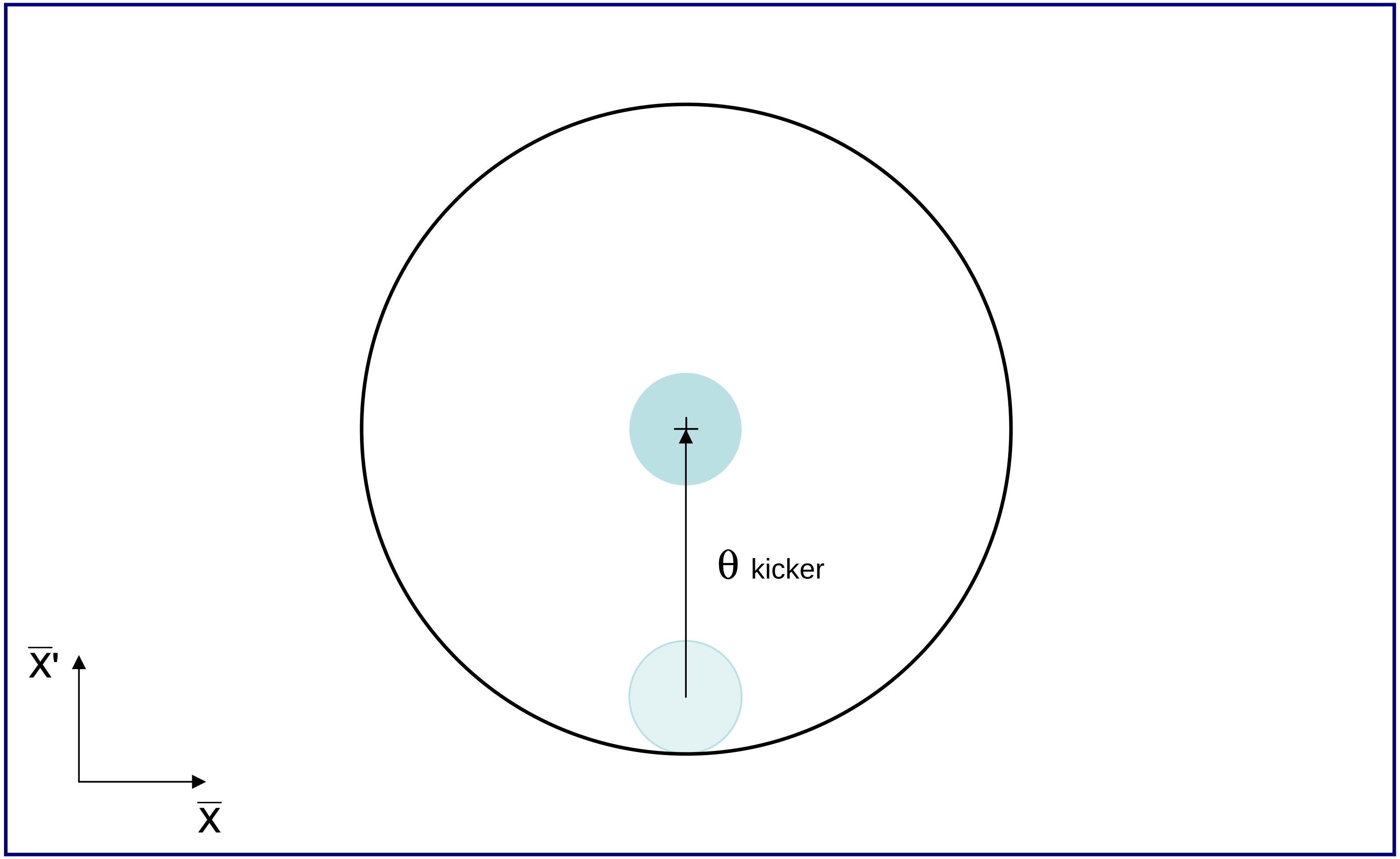
Single-turn injection

π/2 phase advance to kicker location

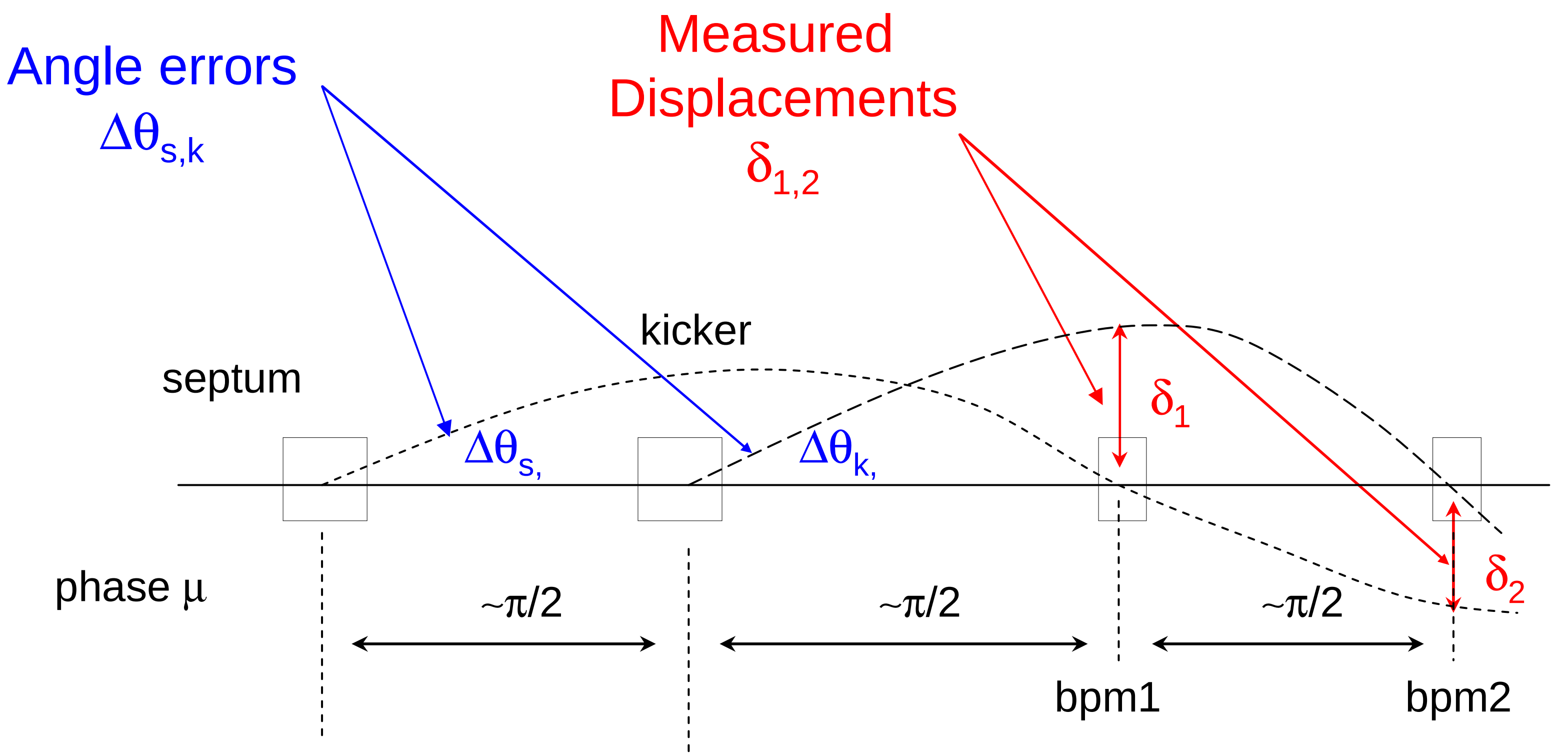


Single-turn injection

Kicker deflection places beam on central orbit



Injection errors



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

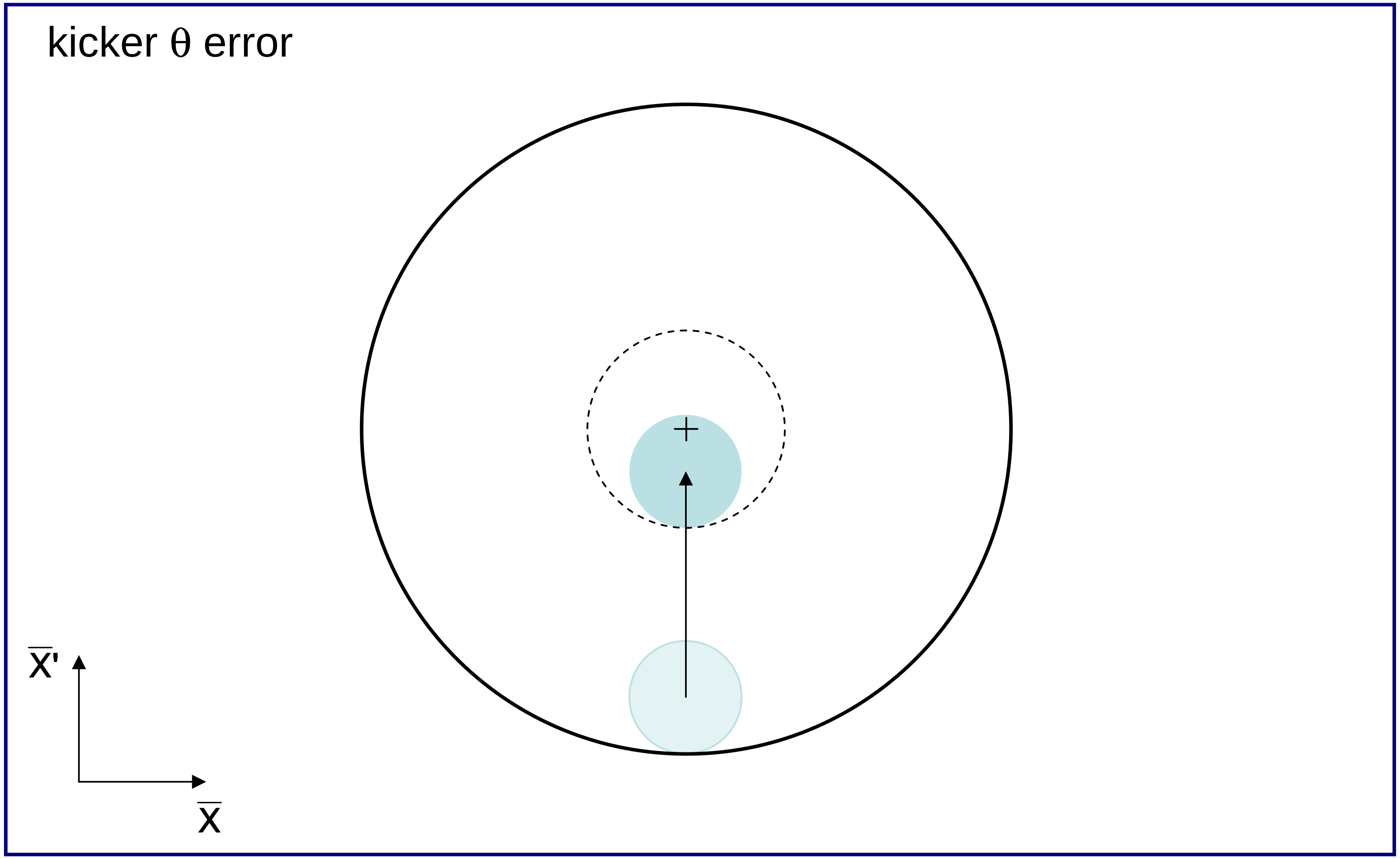
$$\approx \Delta\theta_k \sqrt{(\beta_k\beta_1)}$$

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

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

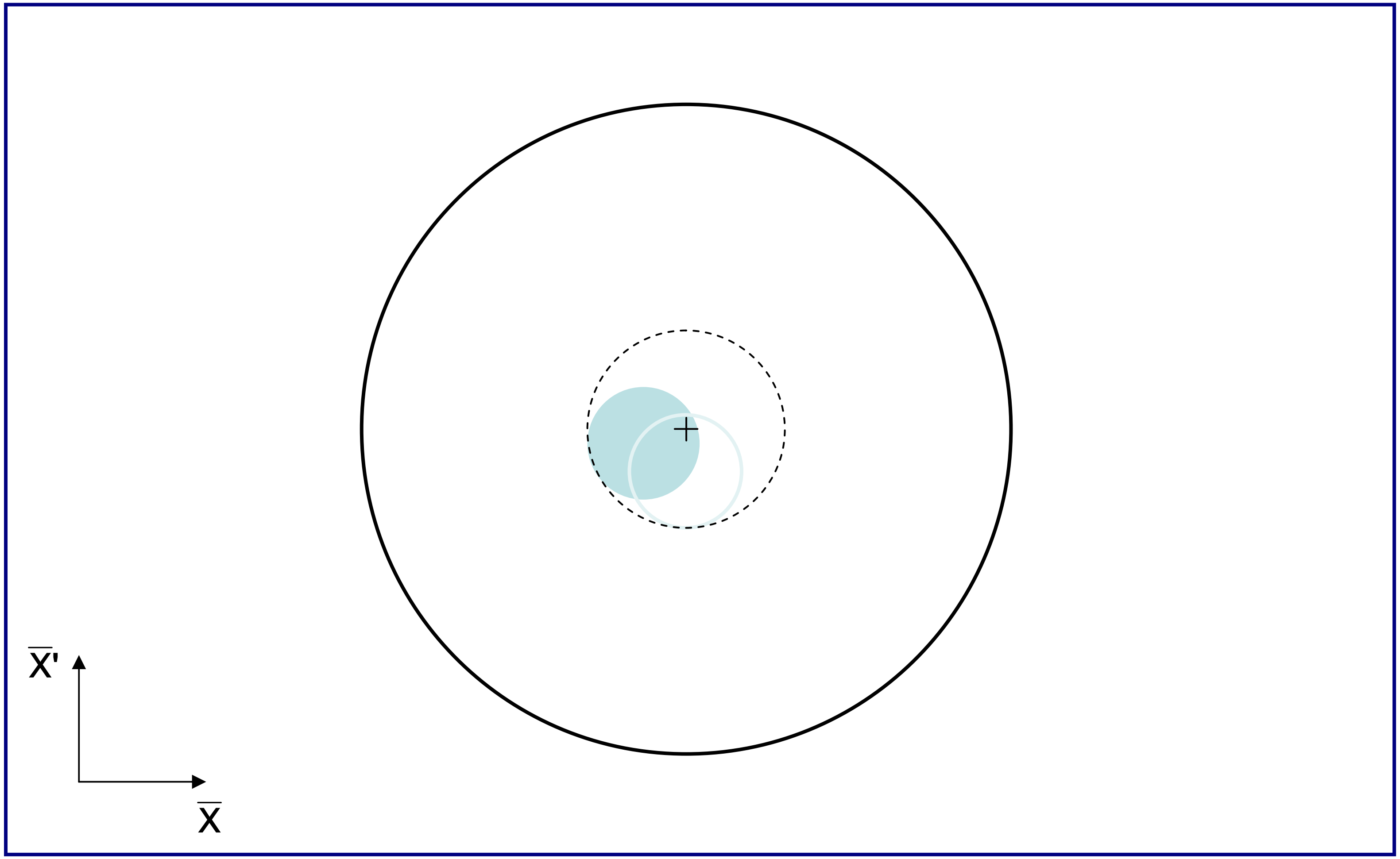
Injection oscillations

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



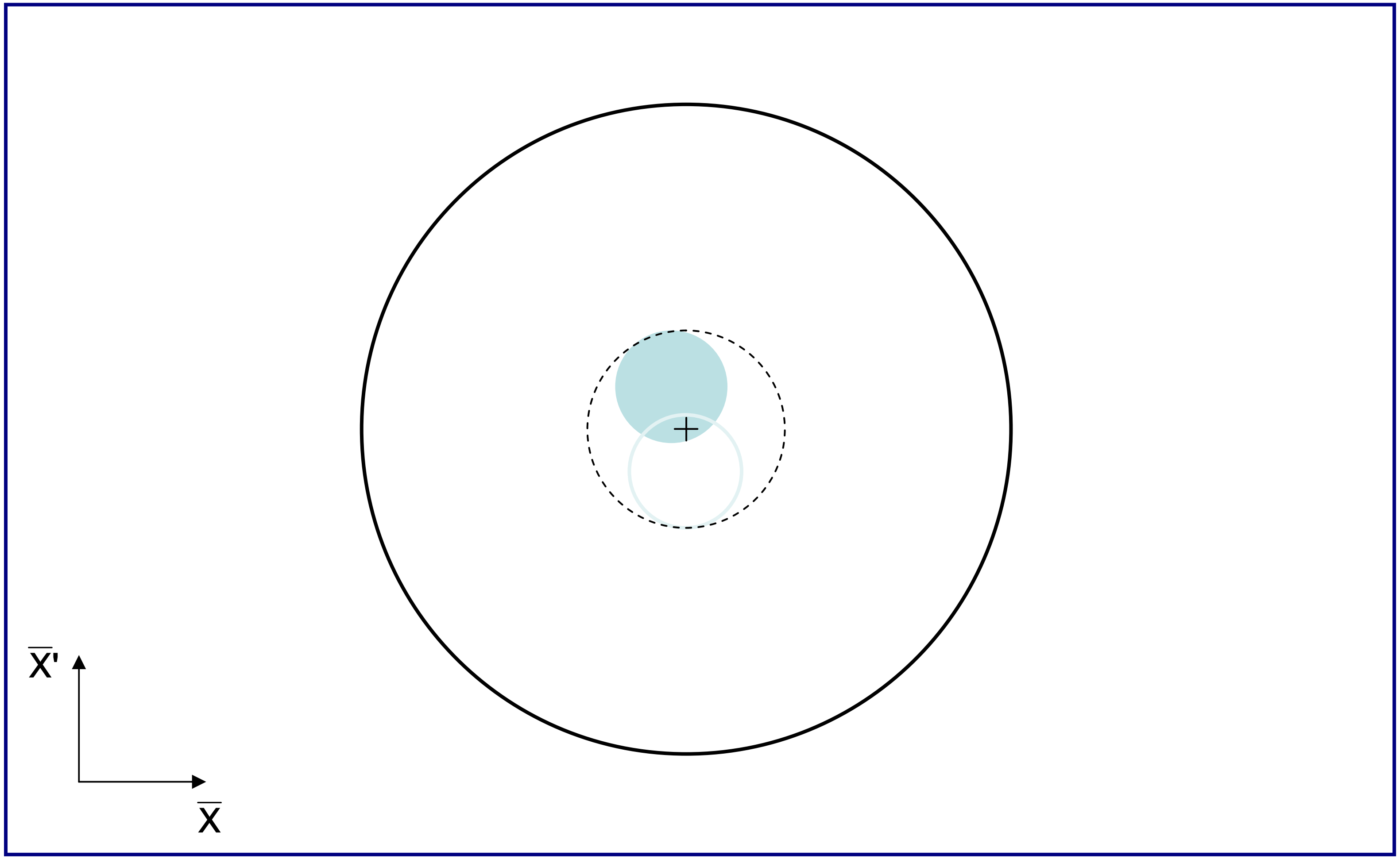
Injection oscillations

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



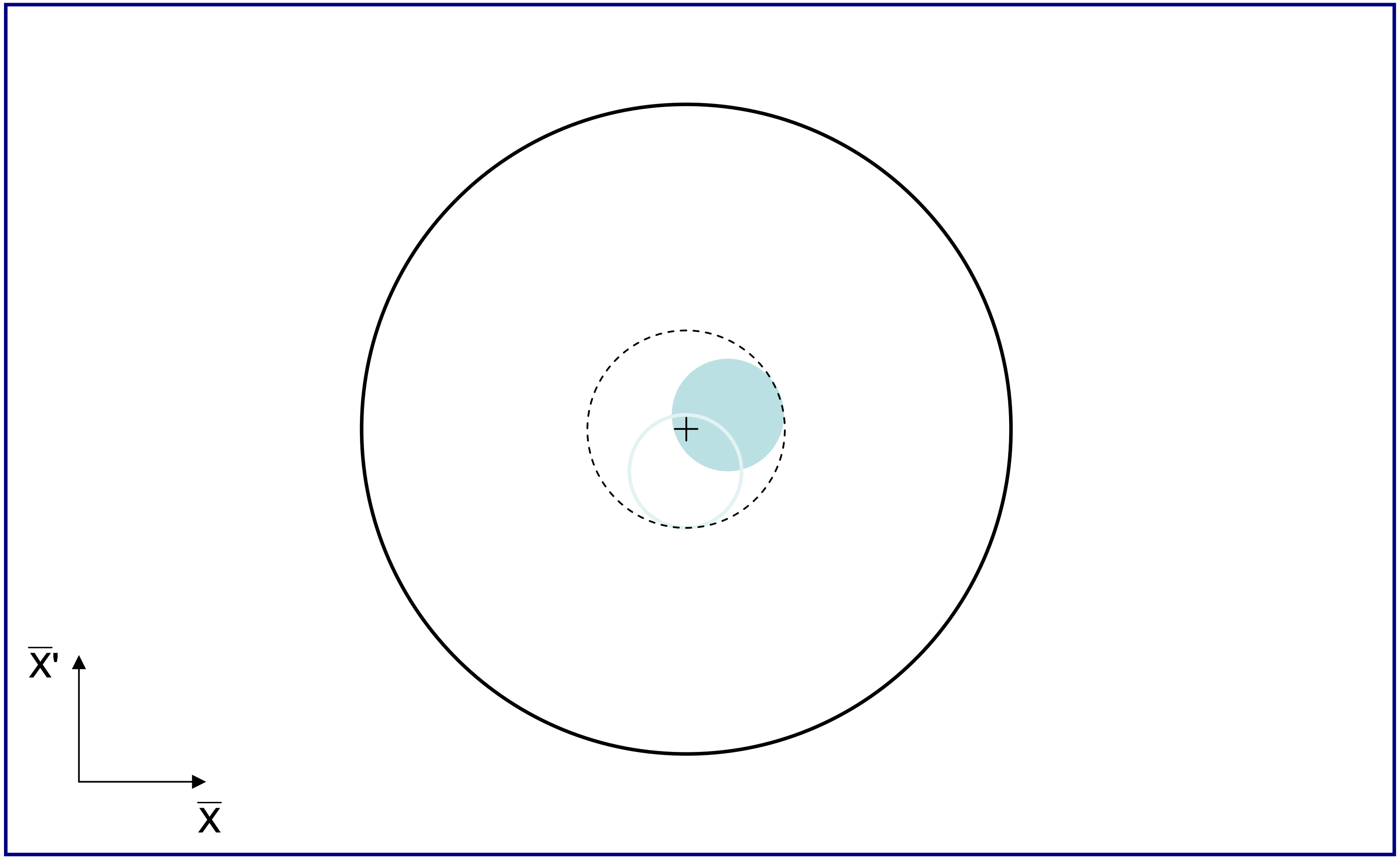
Injection oscillations

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



Injection oscillations

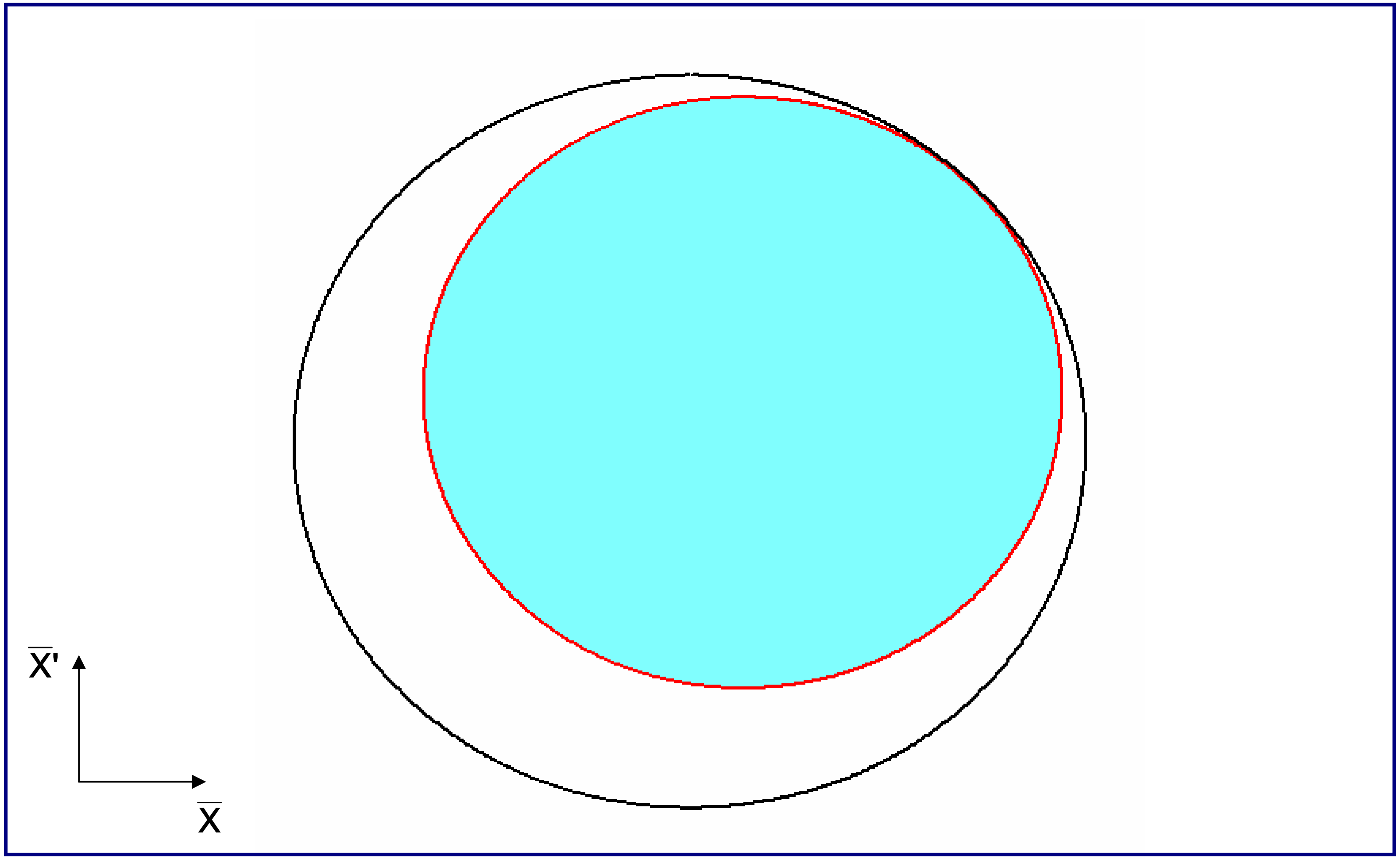
For imperfect injection the beam oscillates around the central orbit. 4



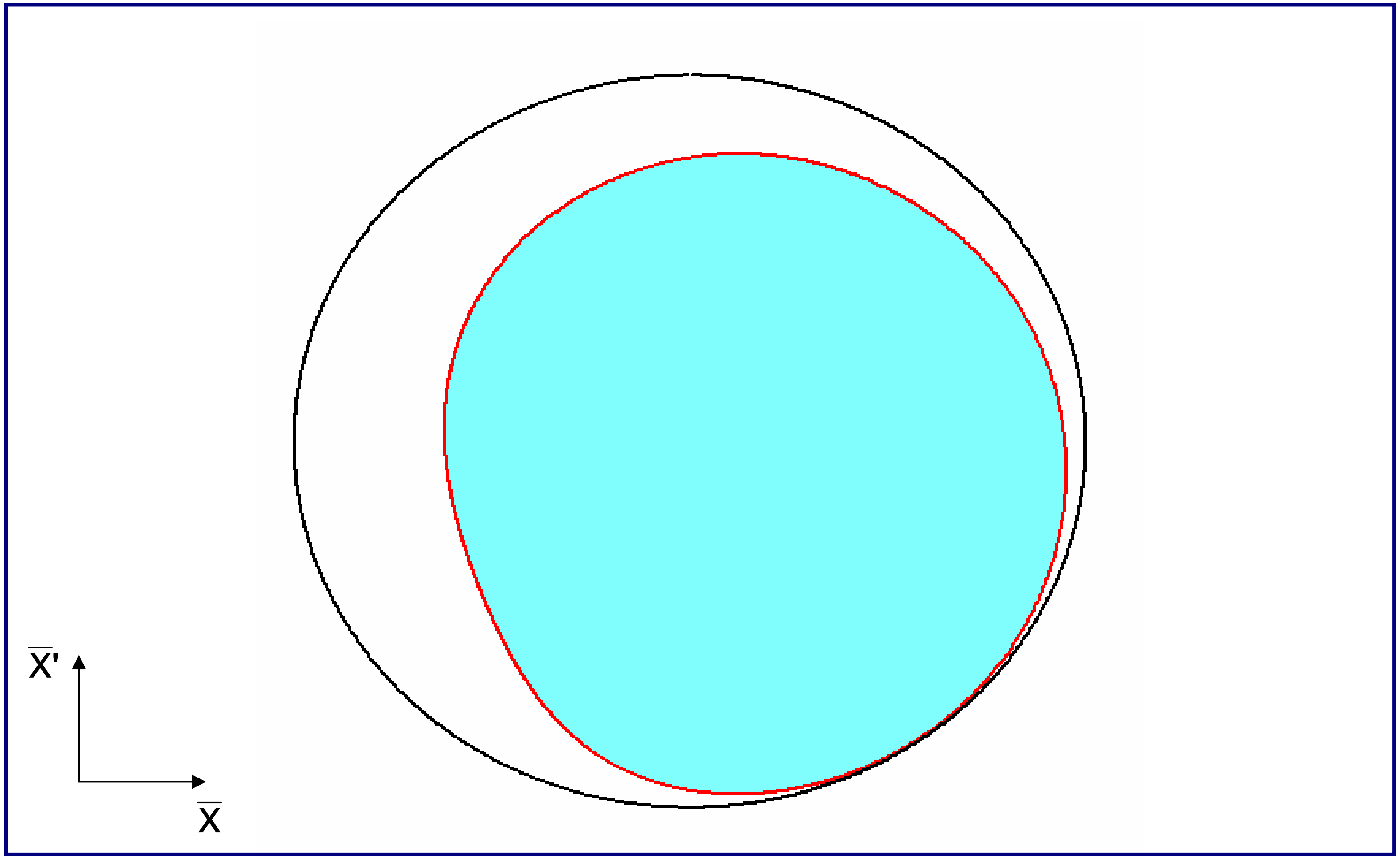
Filamentation

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

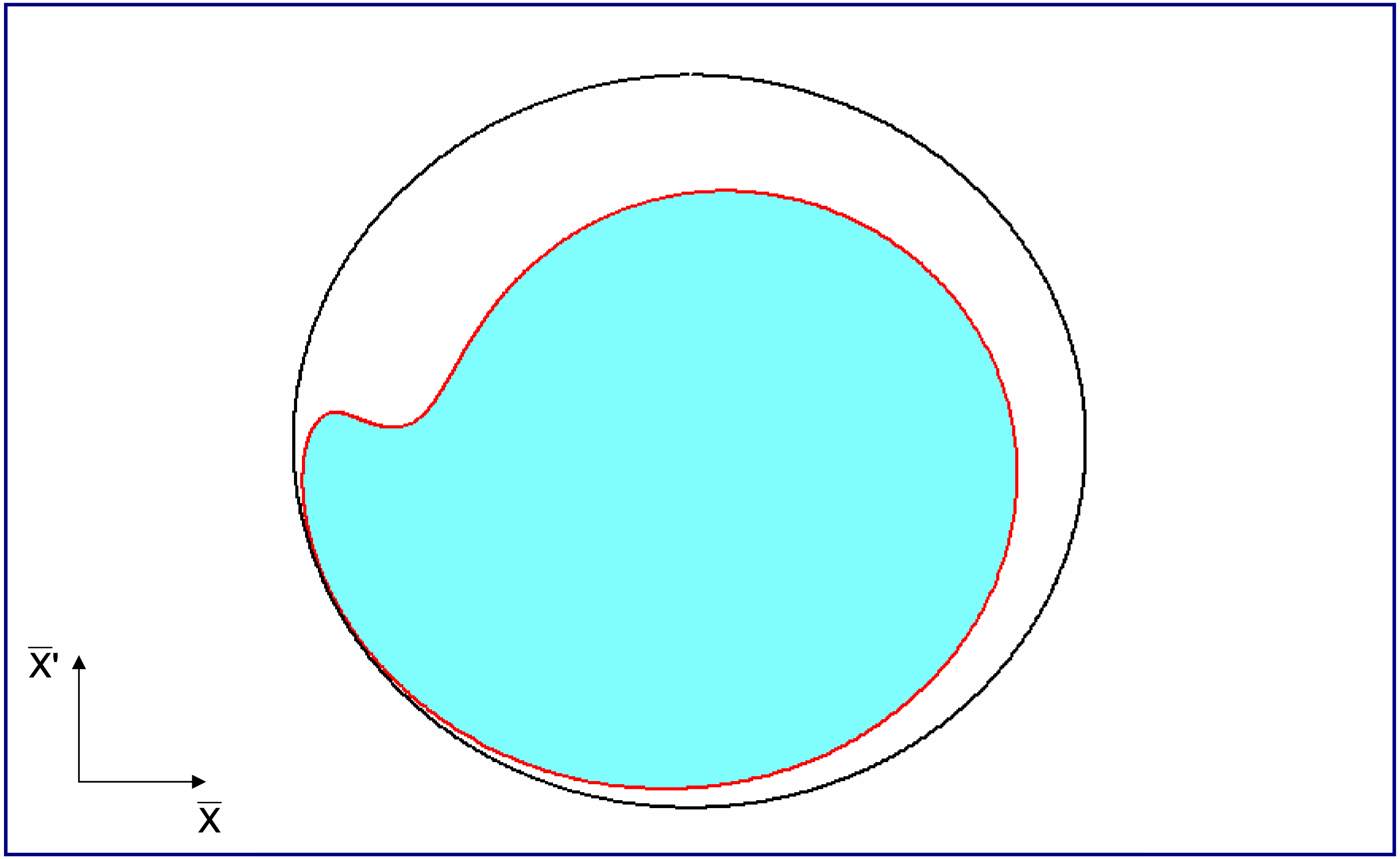
Filamentation



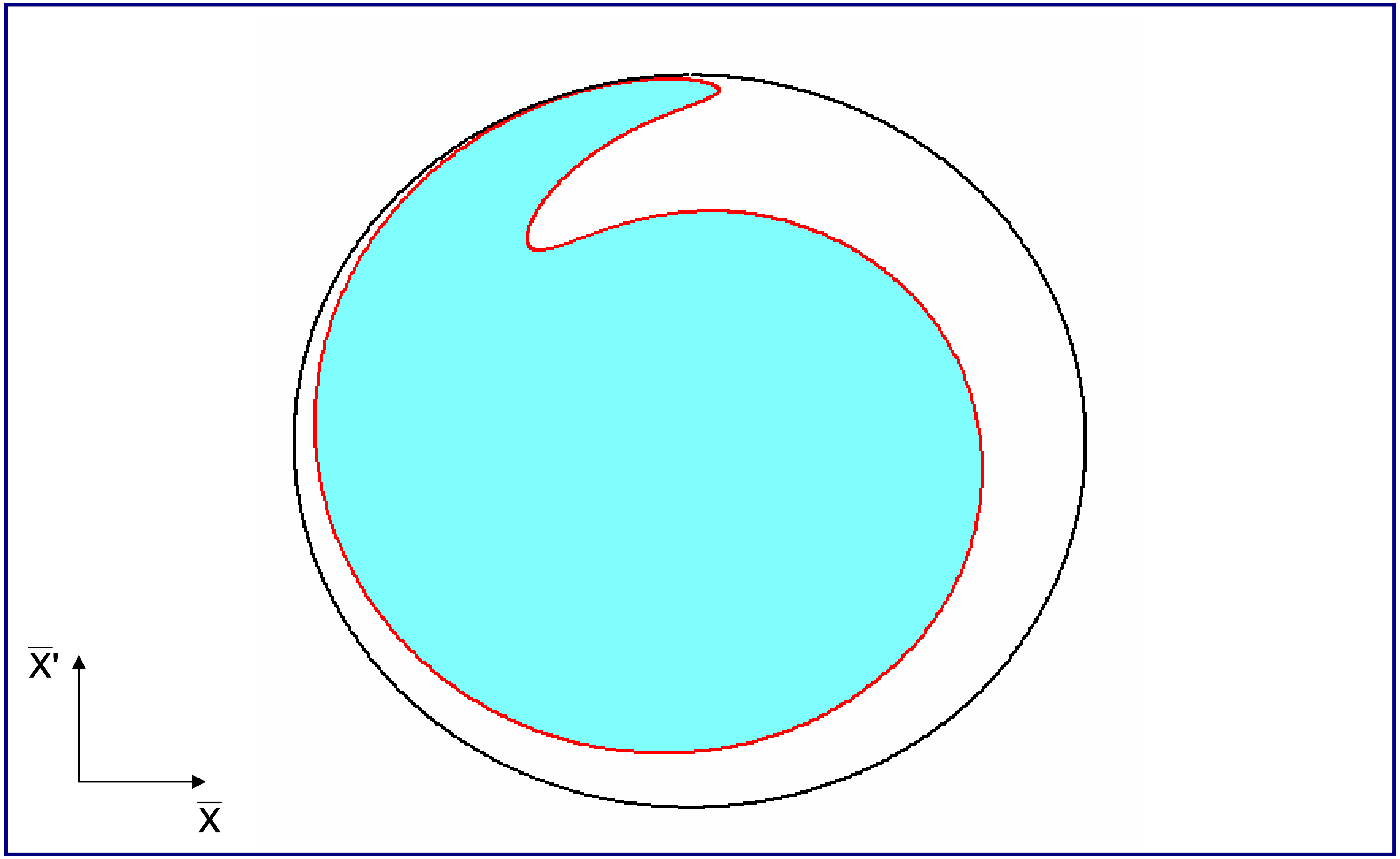
Filamentation



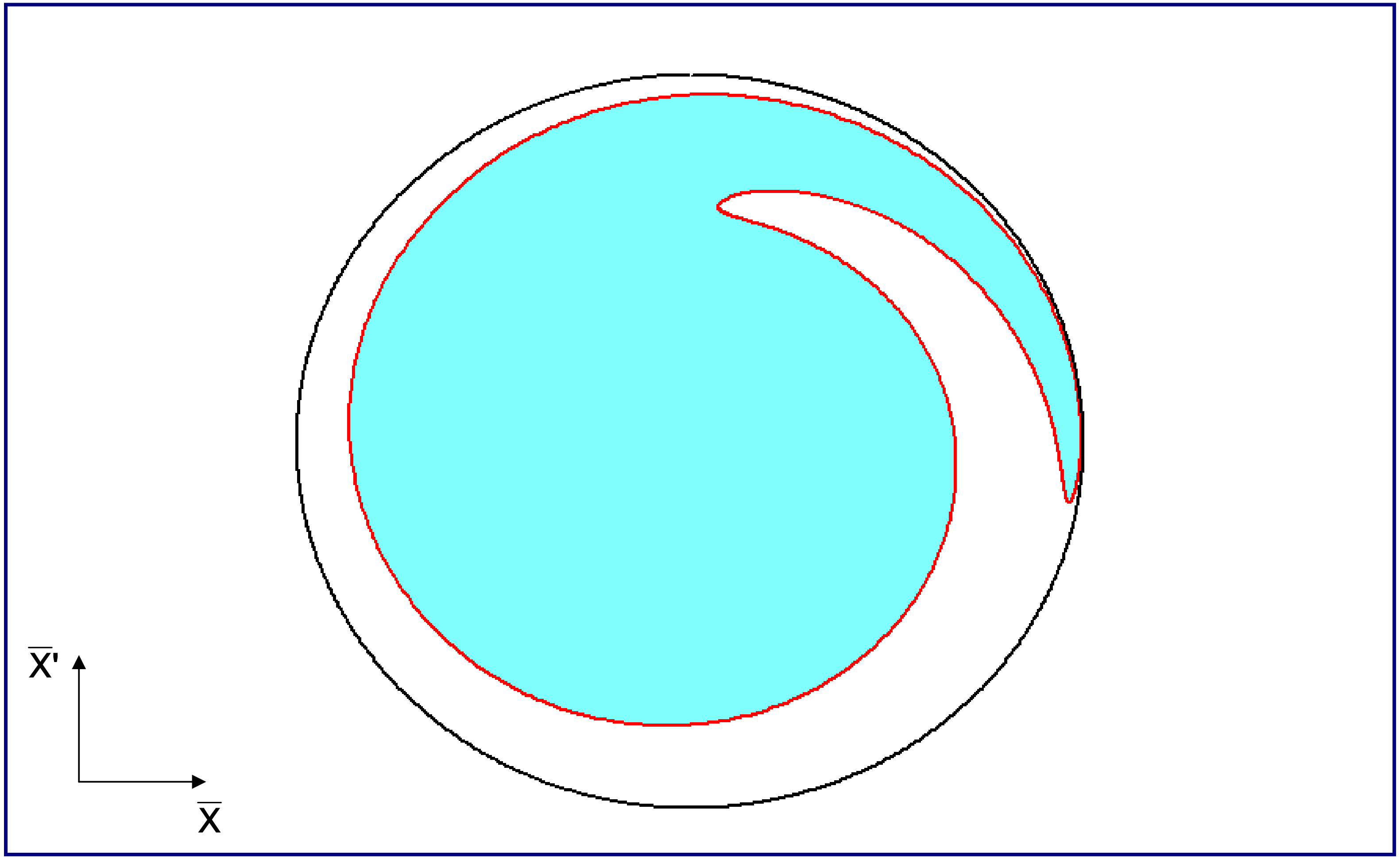
Filamentation



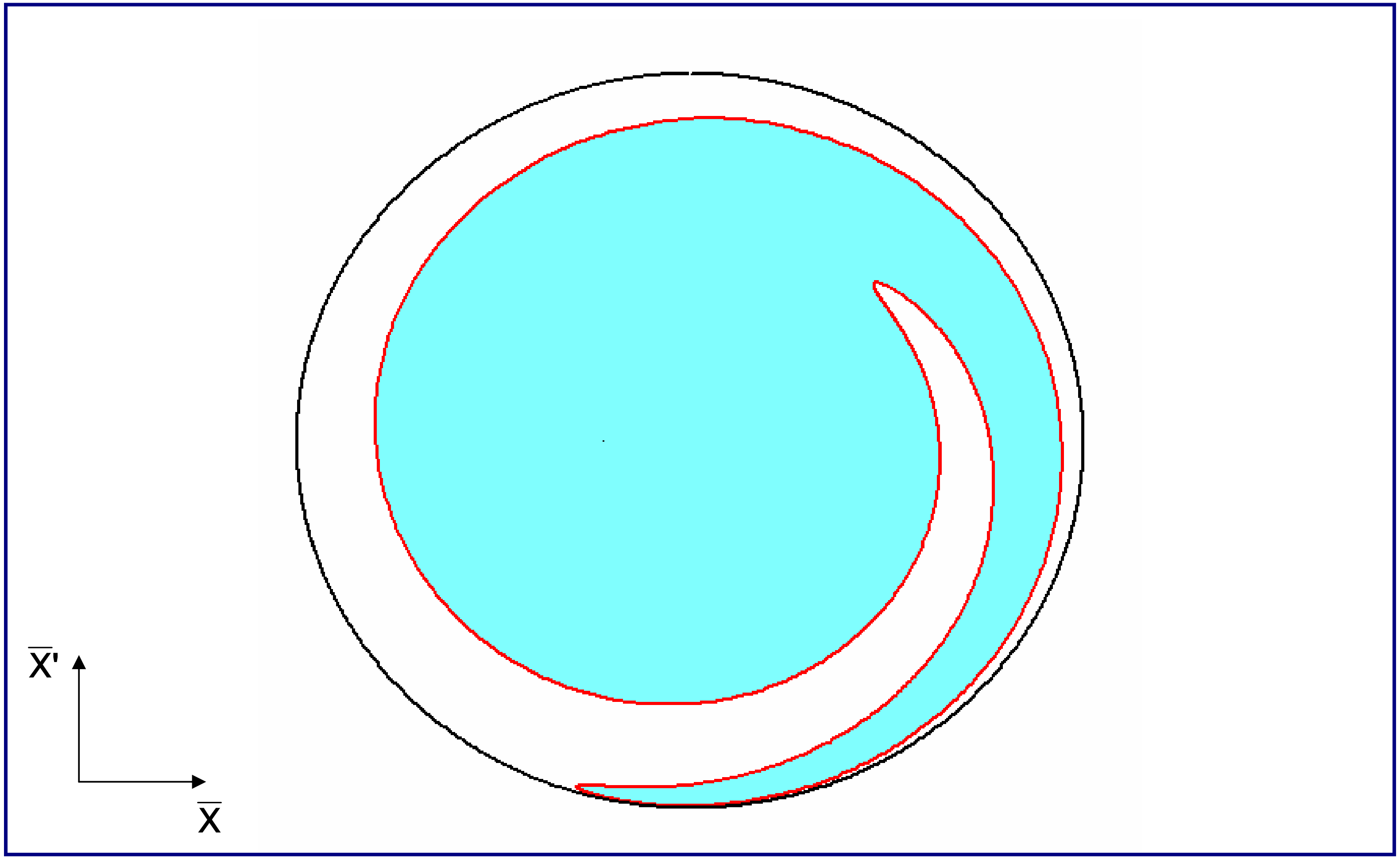
Filamentation



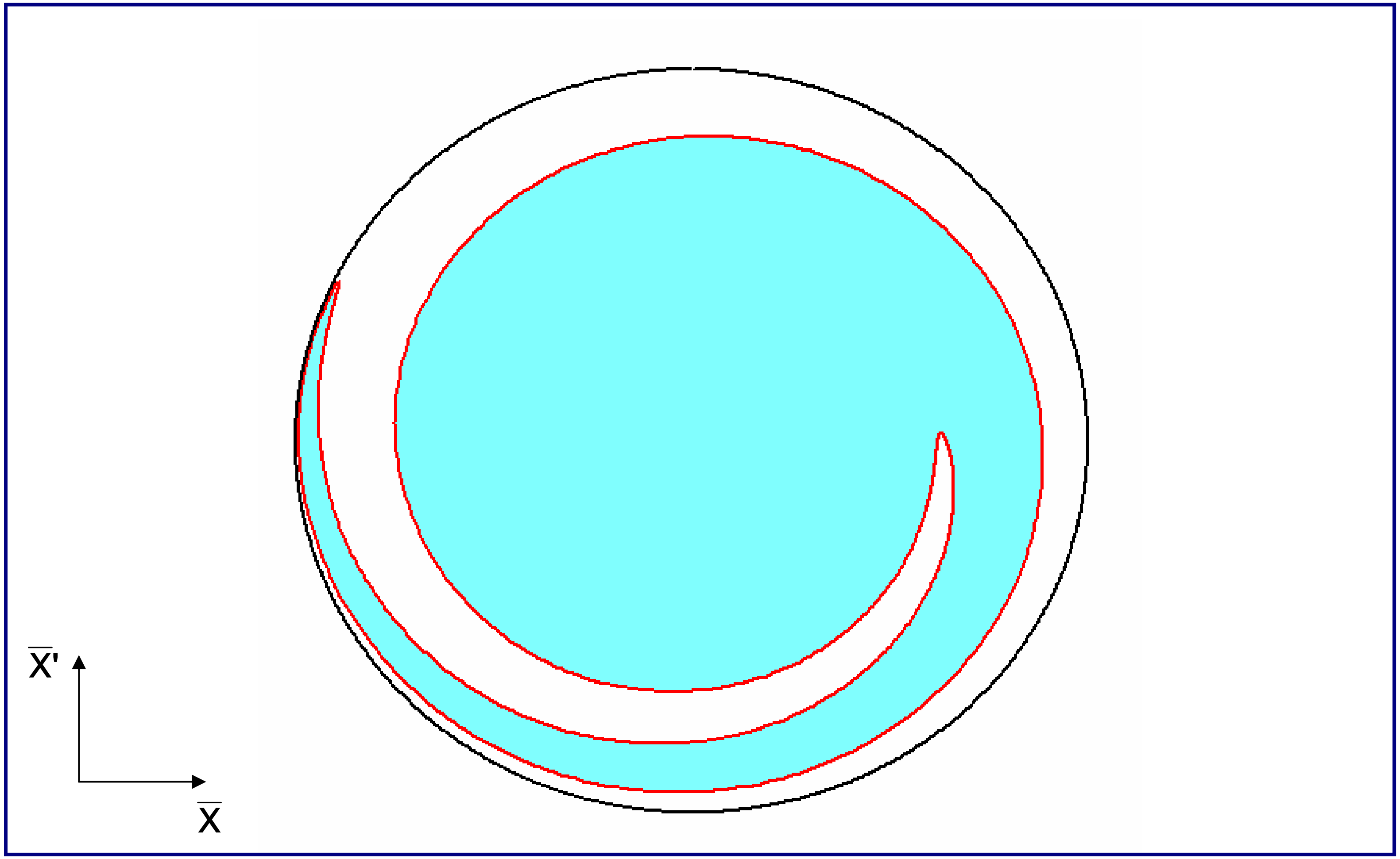
Filamentation



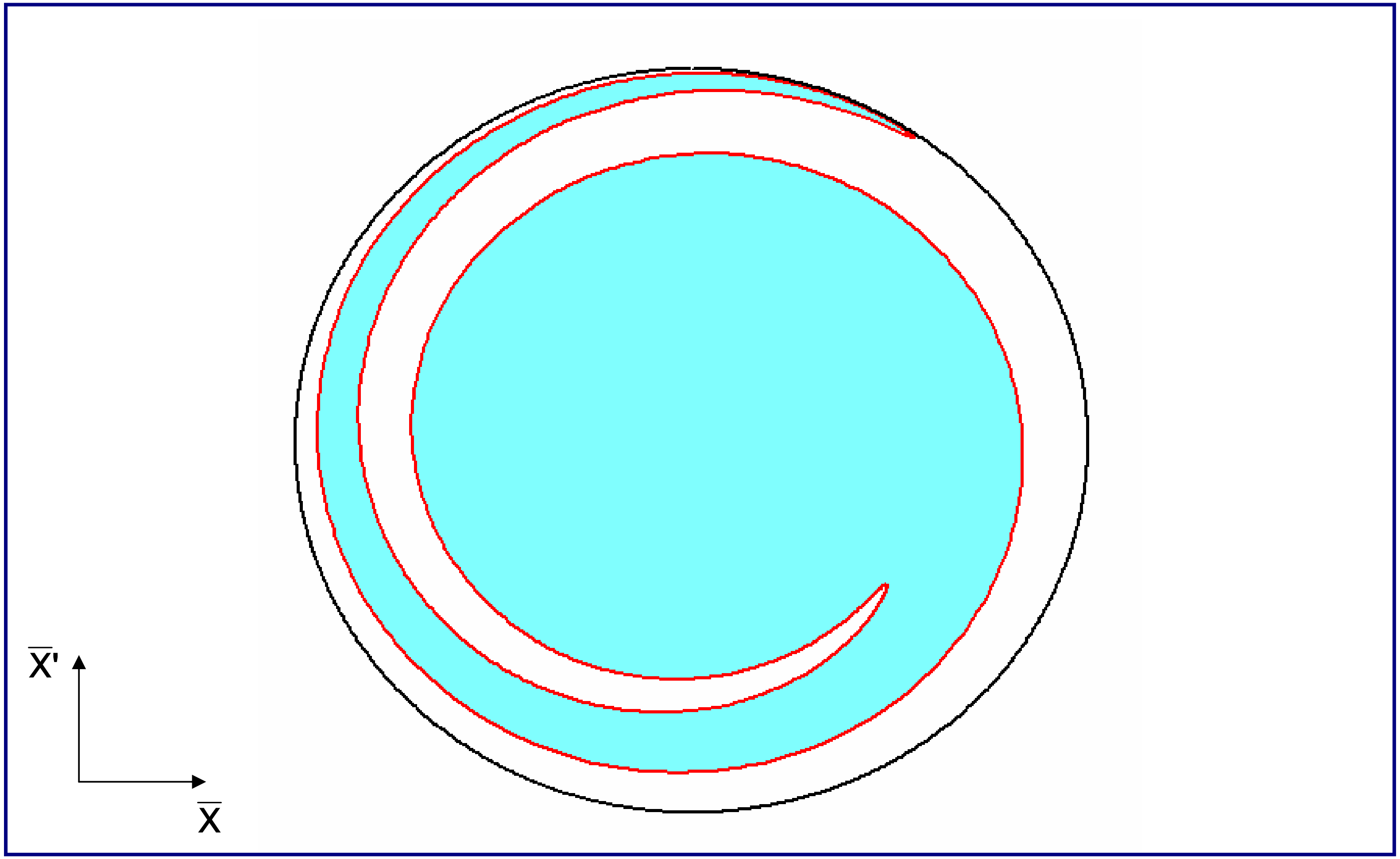
Filamentation



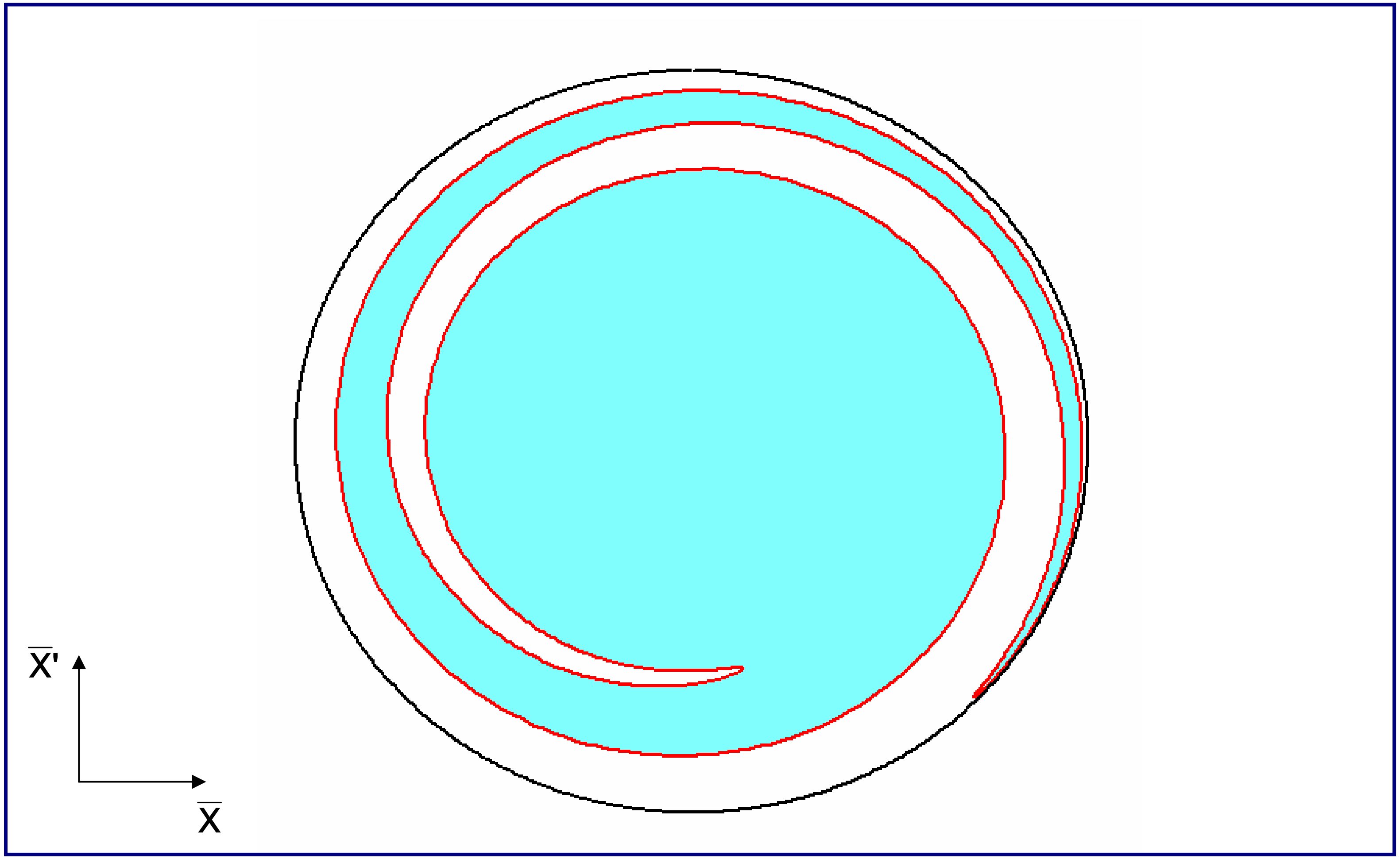
Filamentation



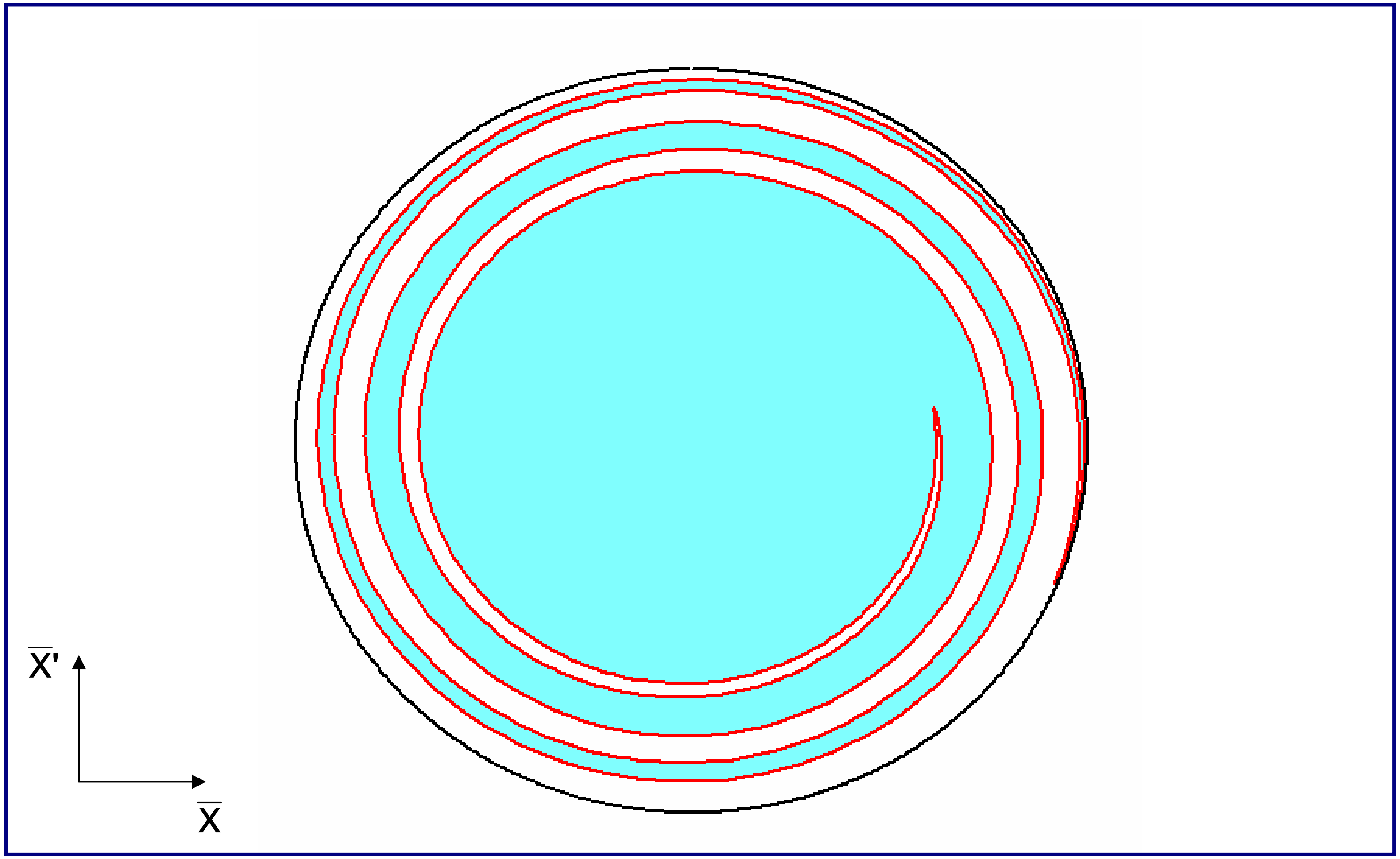
Filamentation



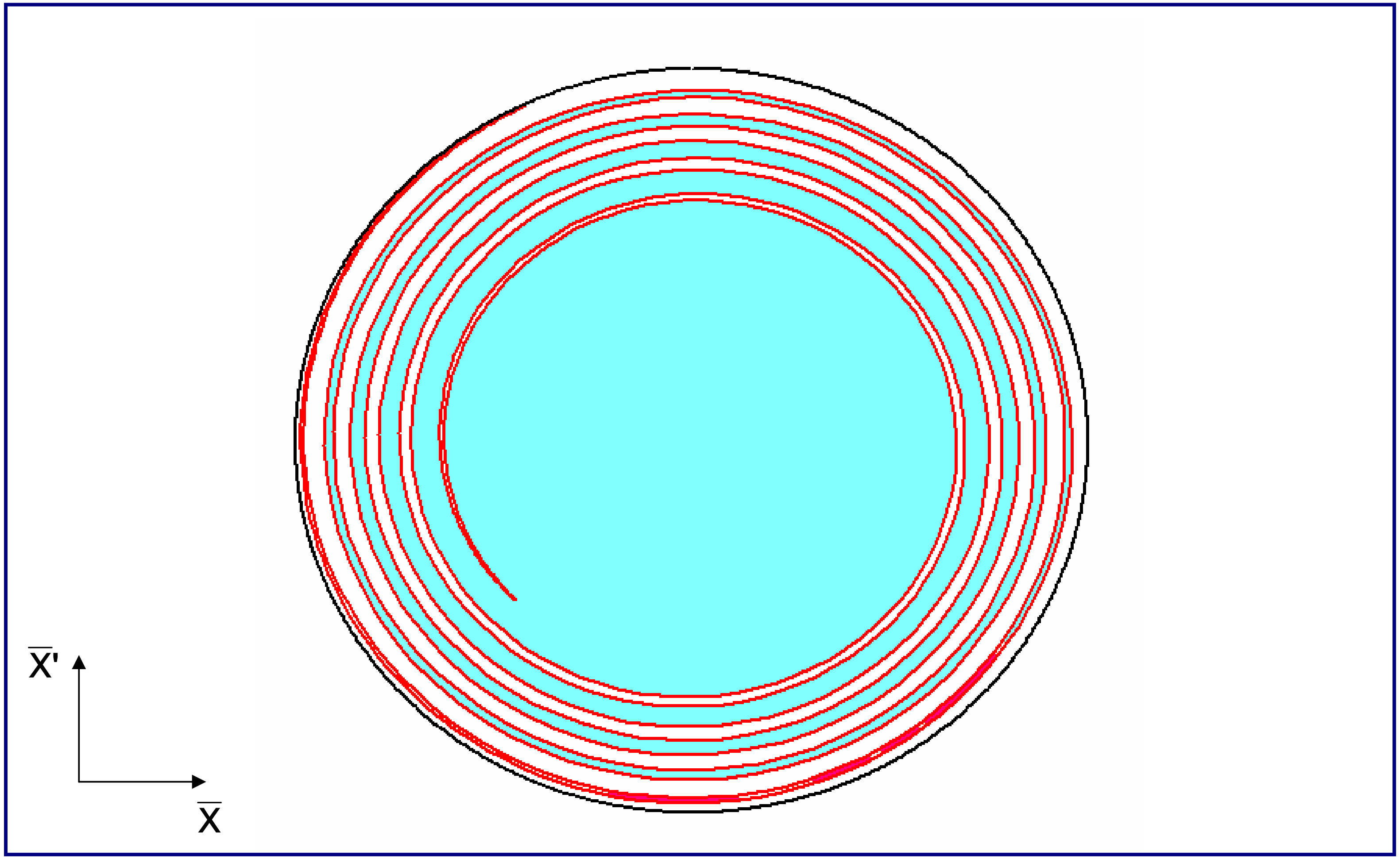
Filamentation



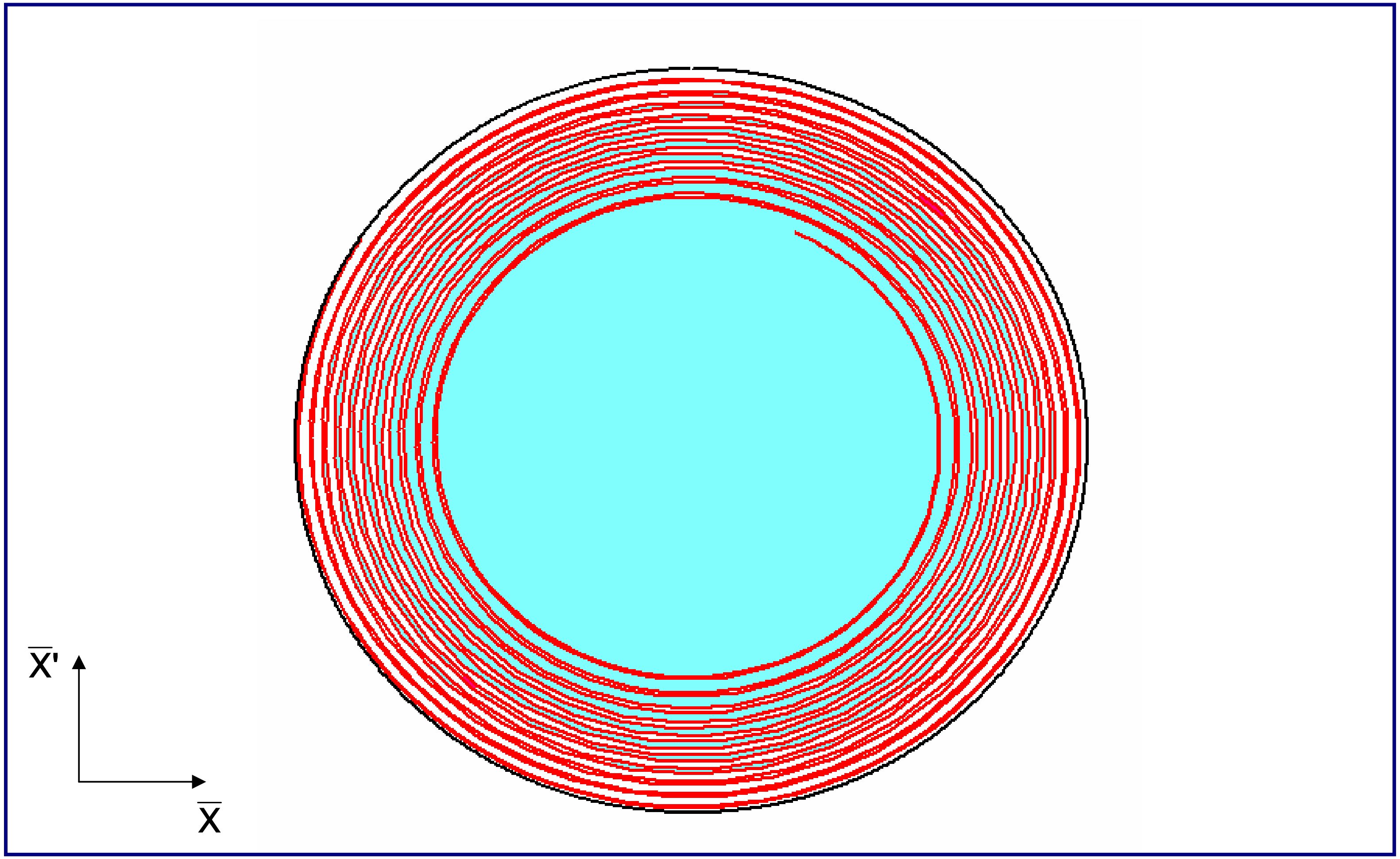
Filamentation



Filamentation

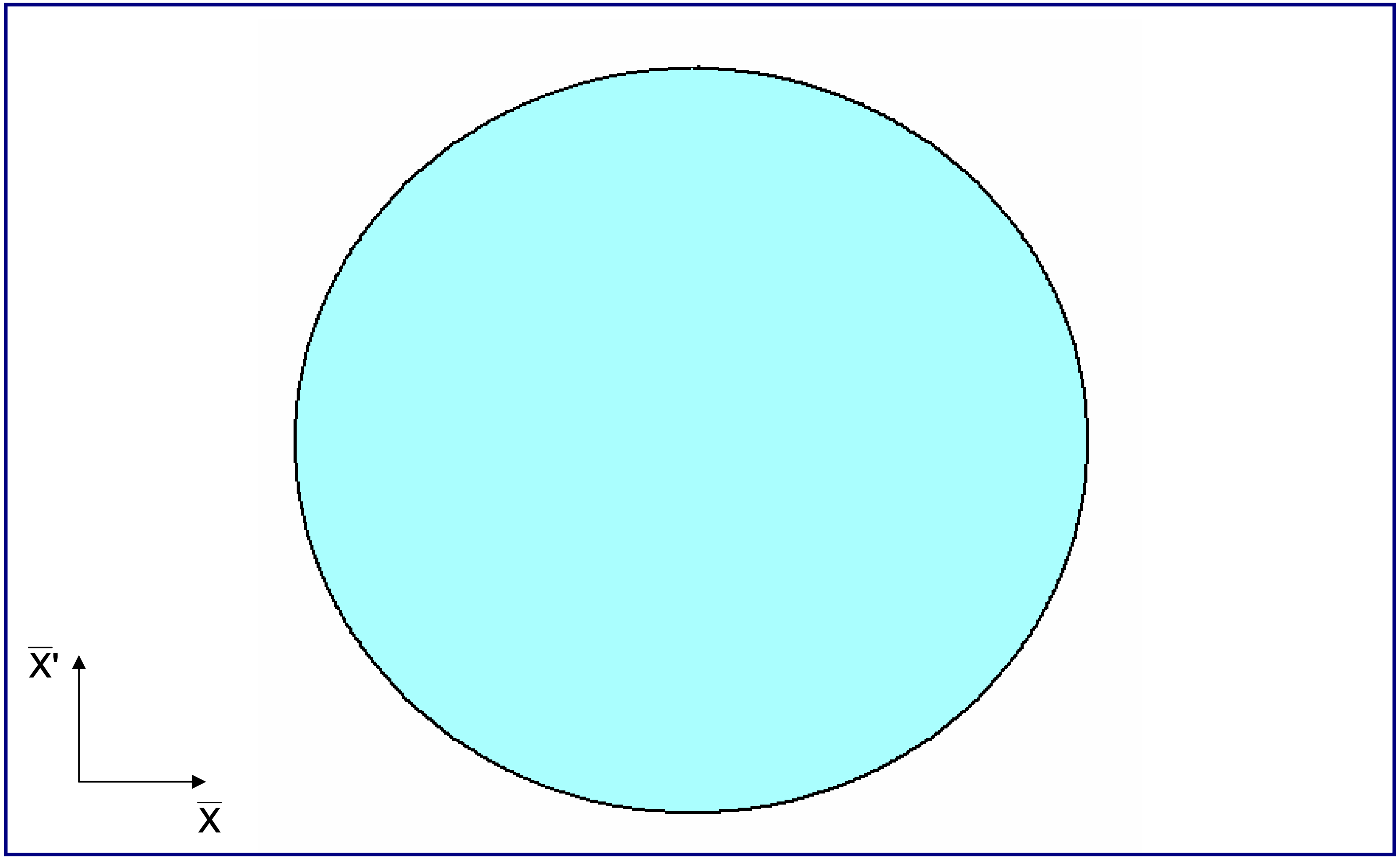


Filamentation



Filamentation

Eventually phase space is effectively filled $\Rightarrow$ emittance increase

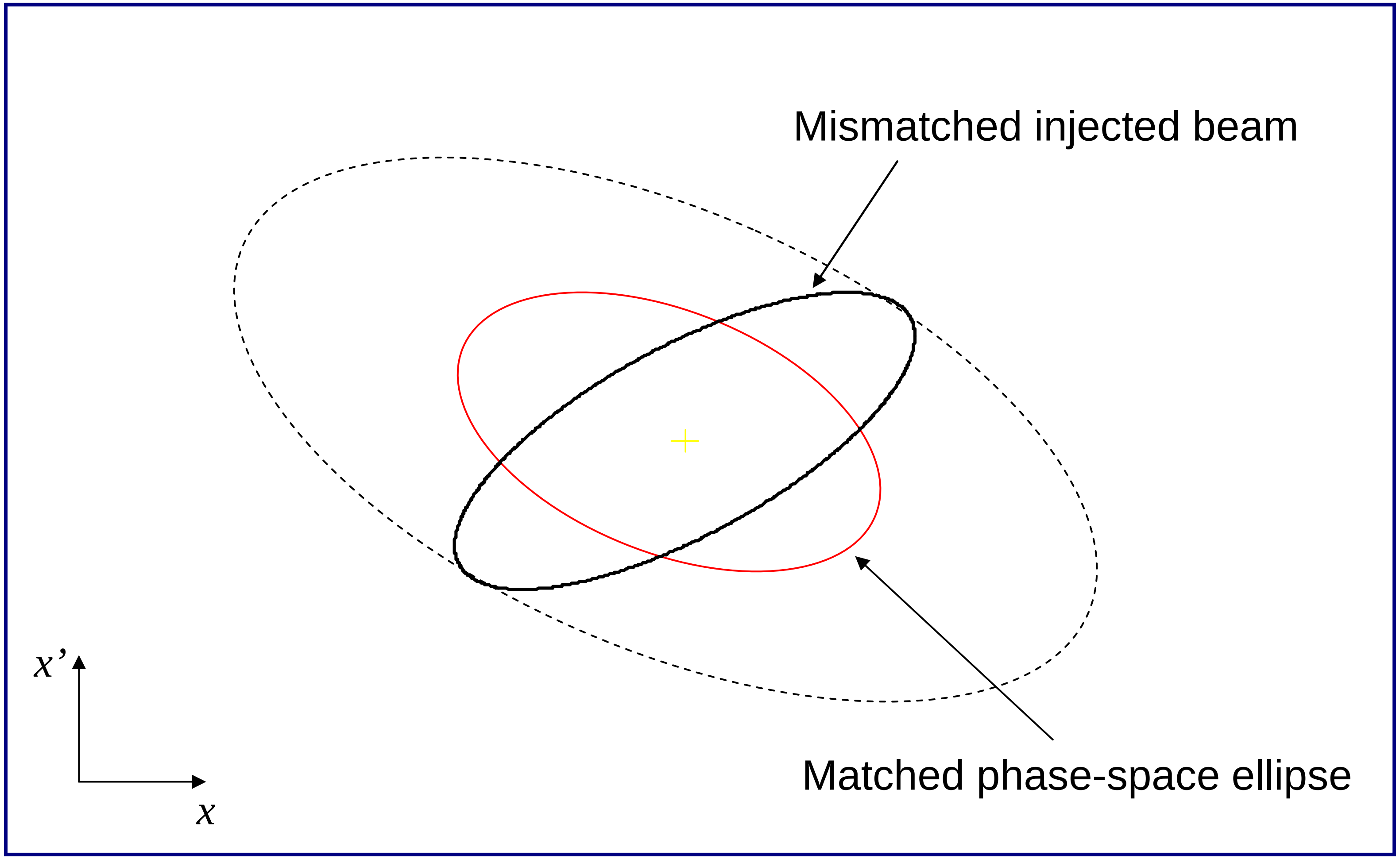


Emittance blow-up

- Any residual transverse oscillation will lead to an emittance blow-up through filamentation
- Transverse damper systems used to damp injection oscillations
  - Bunch position pick-up linked to a kicker
- Possible that injection trajectory is well corrected, but there is still an emittance blow-up
  - Optical mismatch

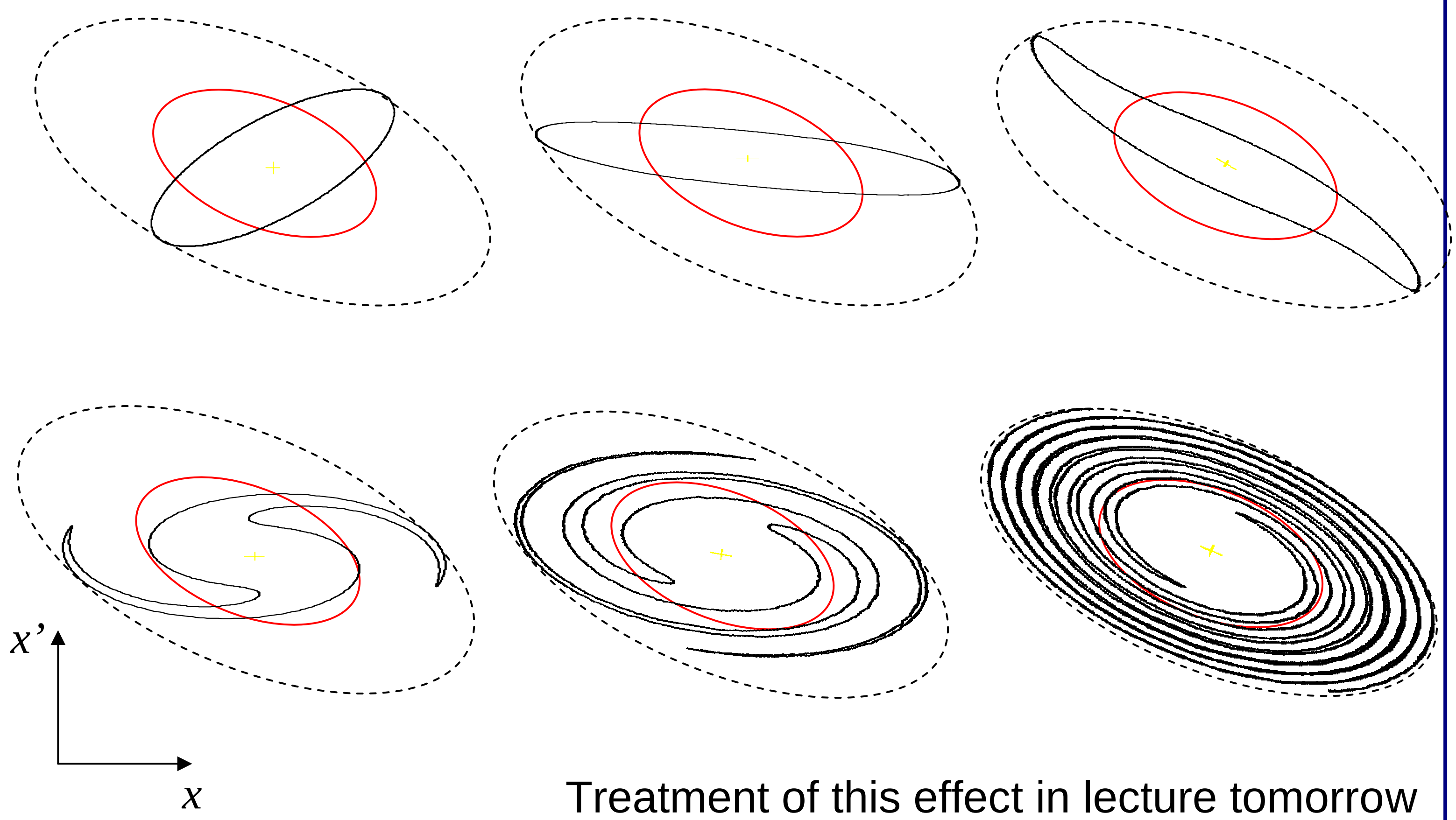
Optical Mismatch at Injection

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

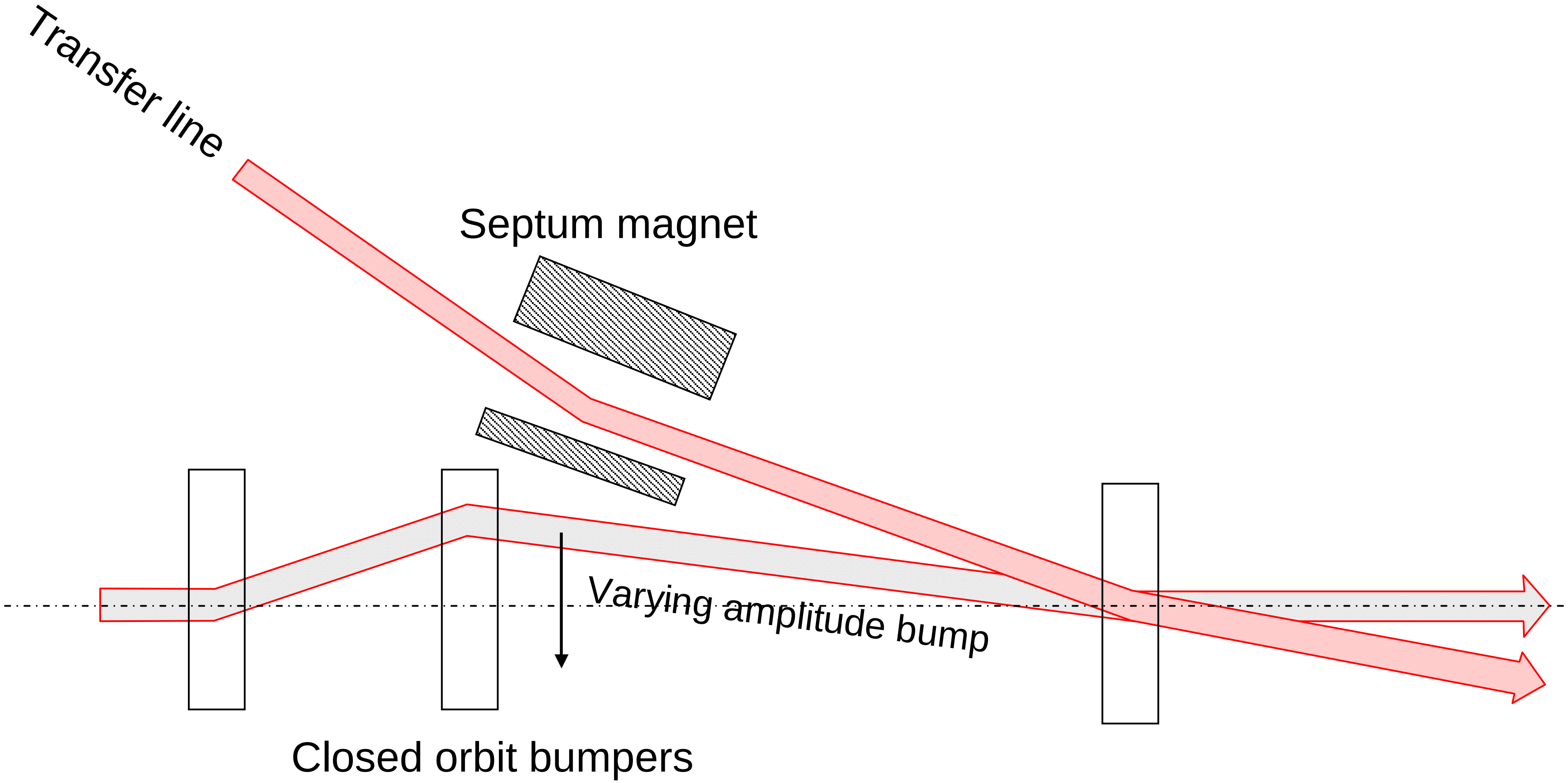


Treatment of this effect in lecture tomorrow

Multi-turn injection

- For hadrons the beam density at injection is either limited by space charge effects or by the injector (heavy ions...)
- We cannot increase charge density, so we fill the horizontal phase space to increase injected intensity.
  - Acceptance of receiving machine larger than delivered beam emittance
- Elements used
  - Septum
  - Fast beam bumpers, made out of 3 or 4 dipoles, to create a local beam bump

Multi-turn injection for hadrons

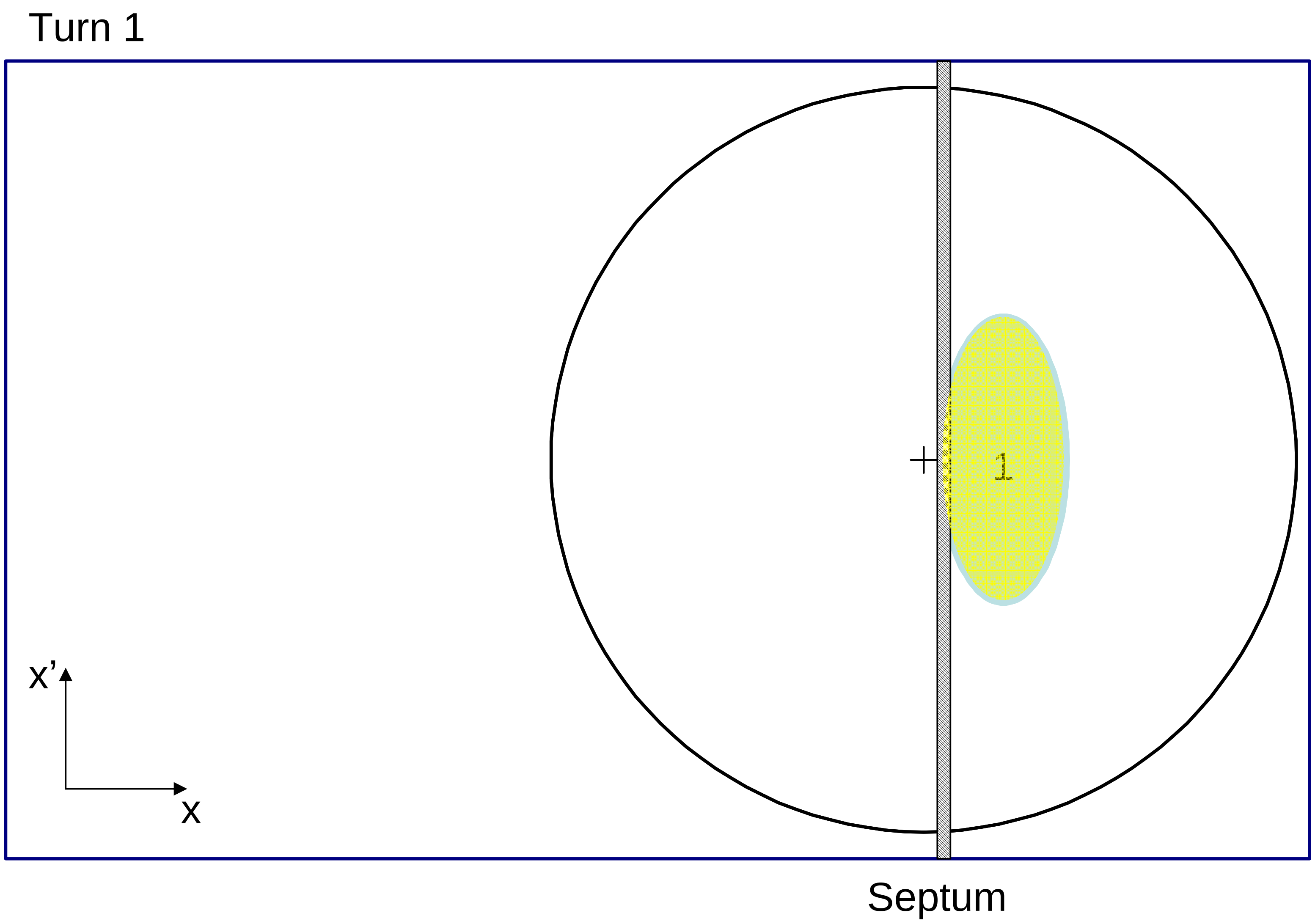


- Bump amplitude varies with time
- Inject a new bunch at each turn
- Phase-space painting

Multi-turn injection for hadrons

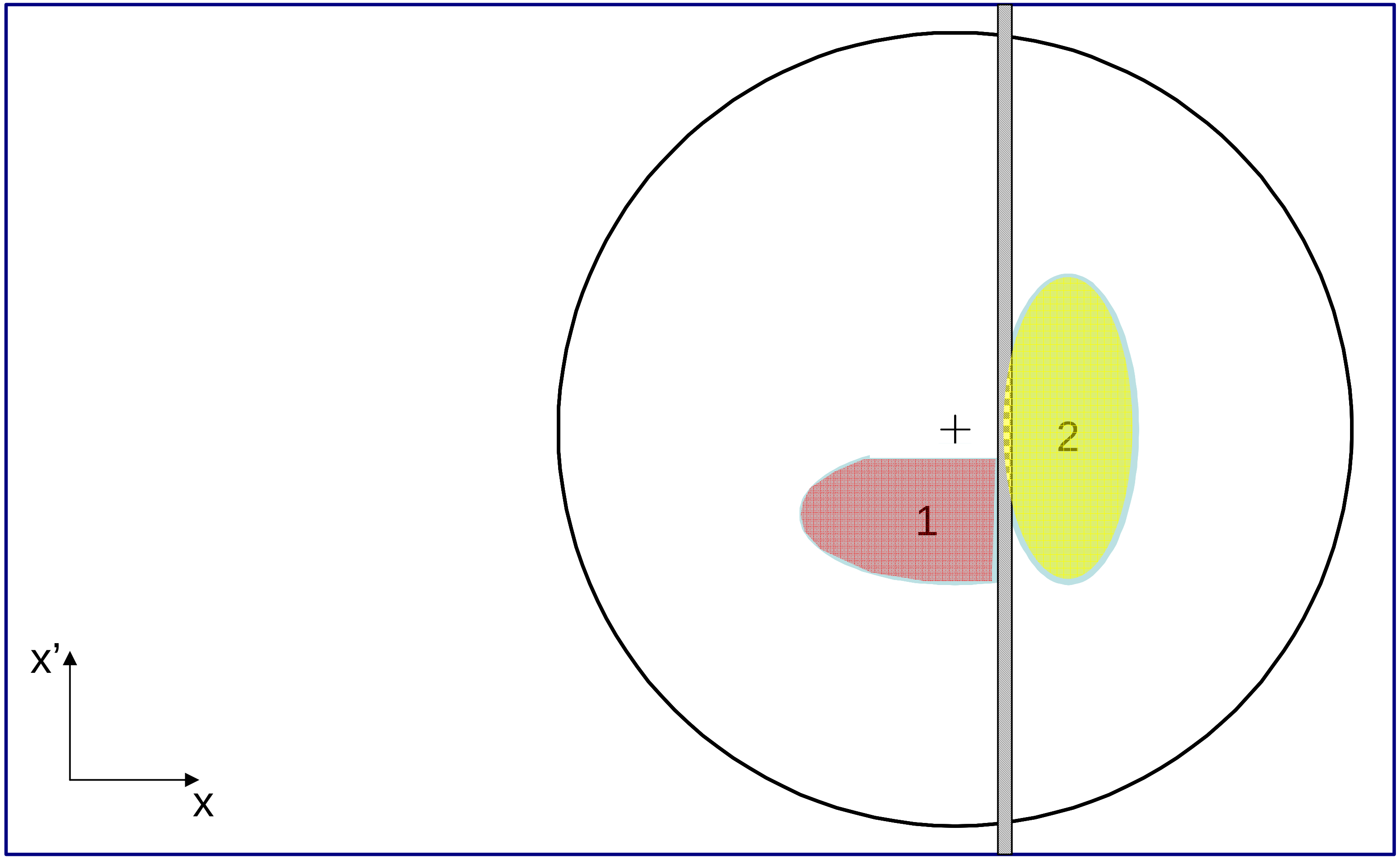
- Example: fractional tune $Q_h = 0.25$
  - Beam rotates $\pi/2$ per turn in phase space
- On each turn
  - Inject a new batch
  - Reduce the bump amplitude

Multi-turn injection for hadrons

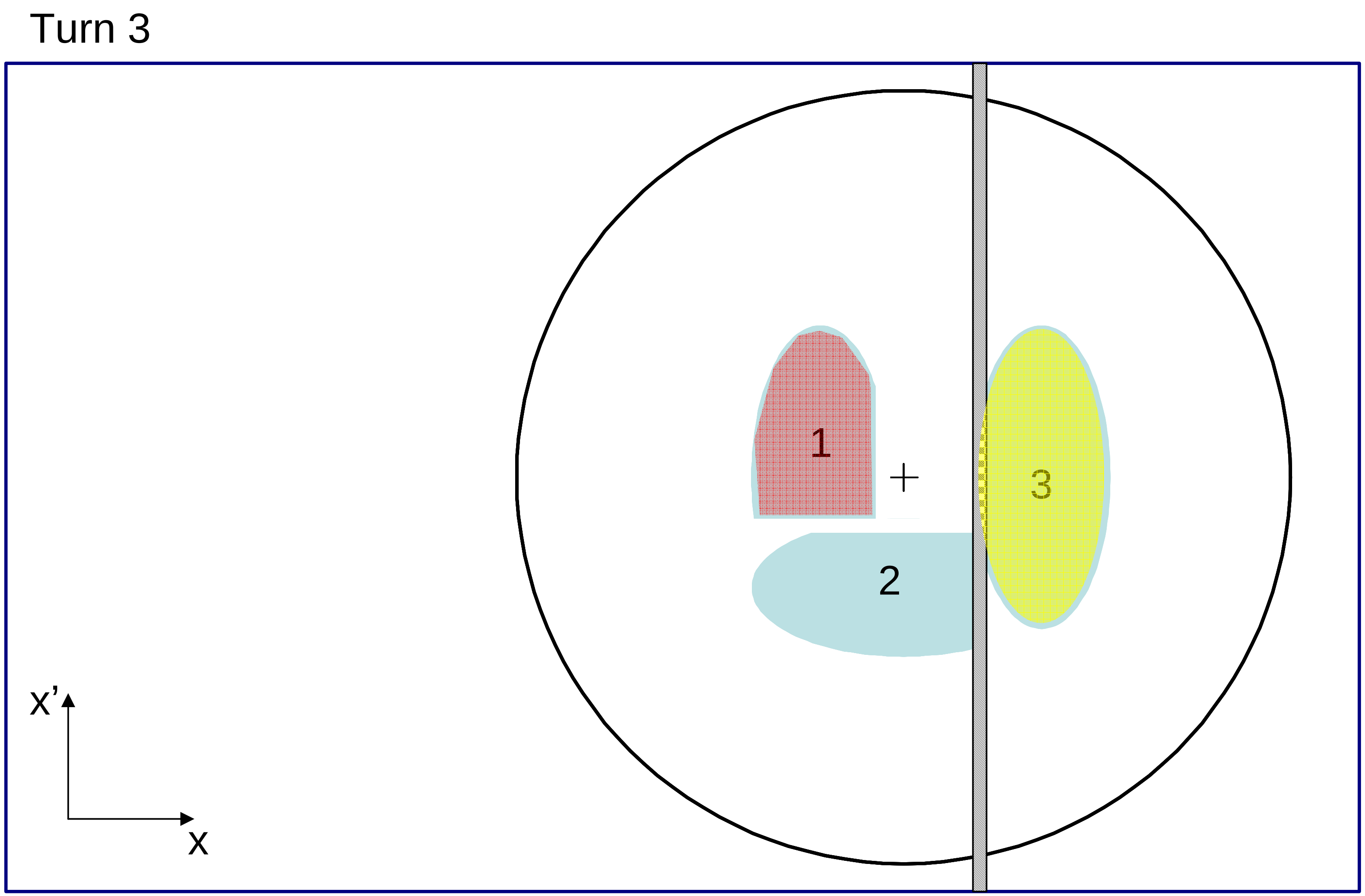


Multi-turn injection for hadrons

Turn 2

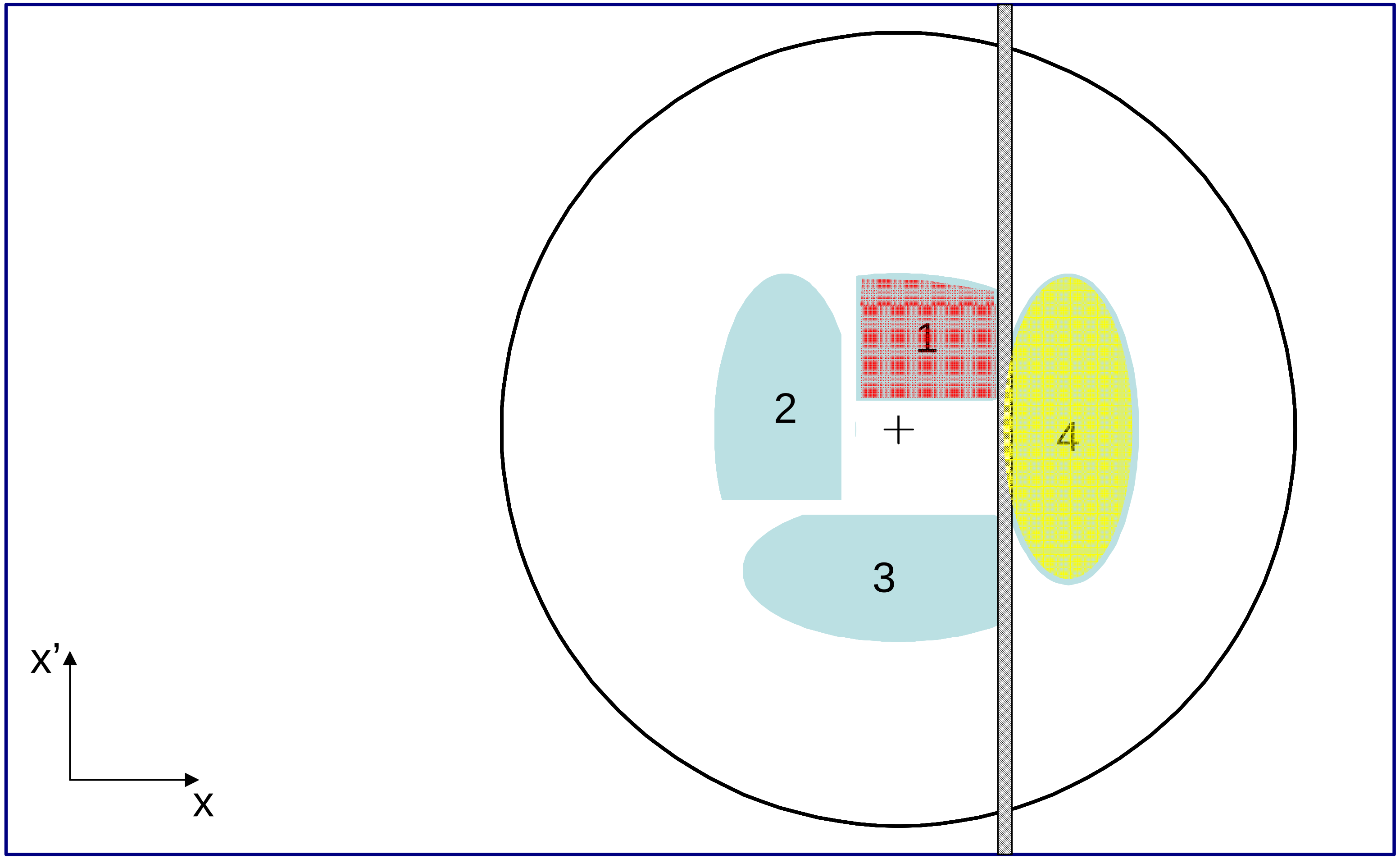


Multi-turn injection for hadrons



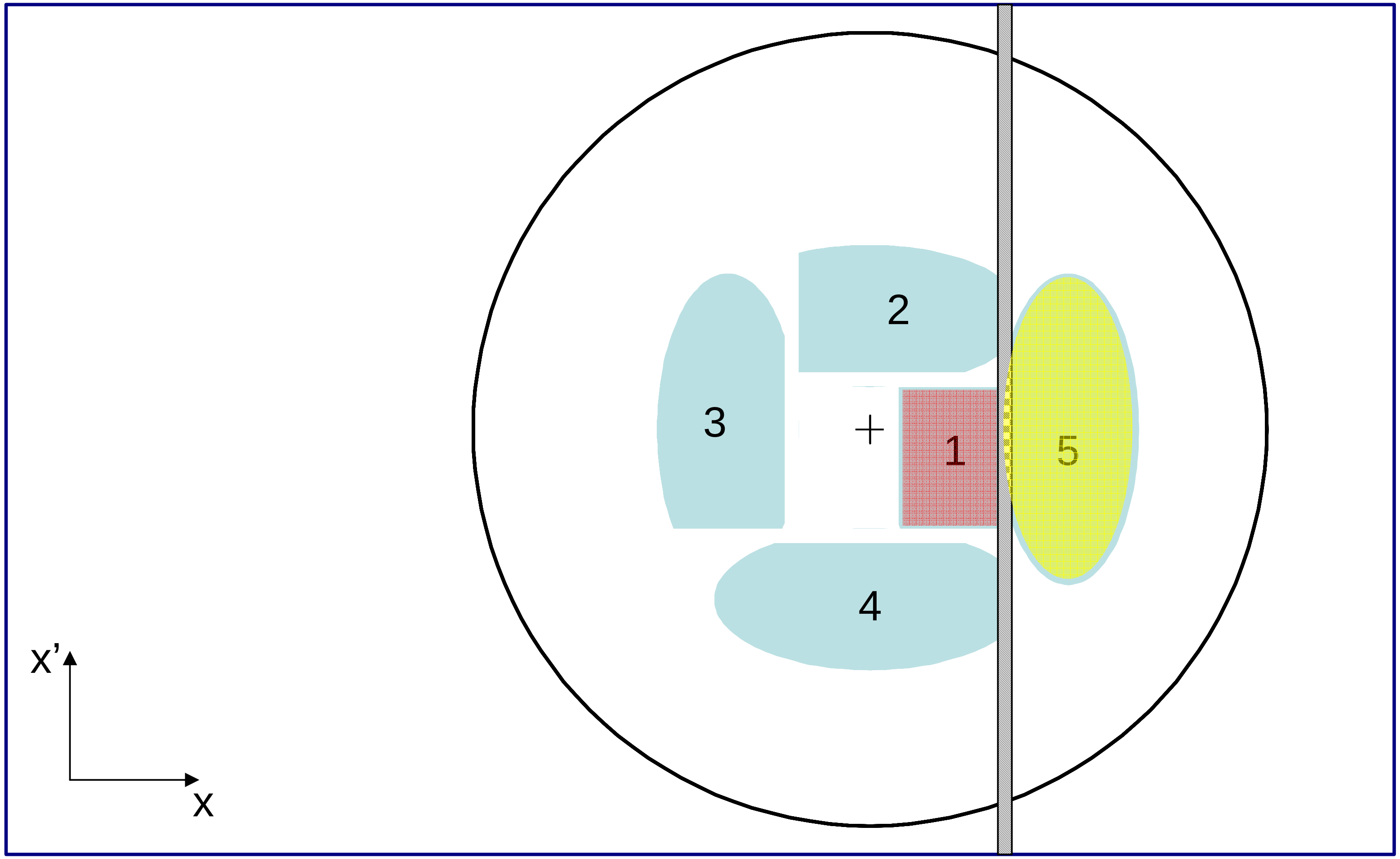
Multi-turn injection for hadrons

Turn 4

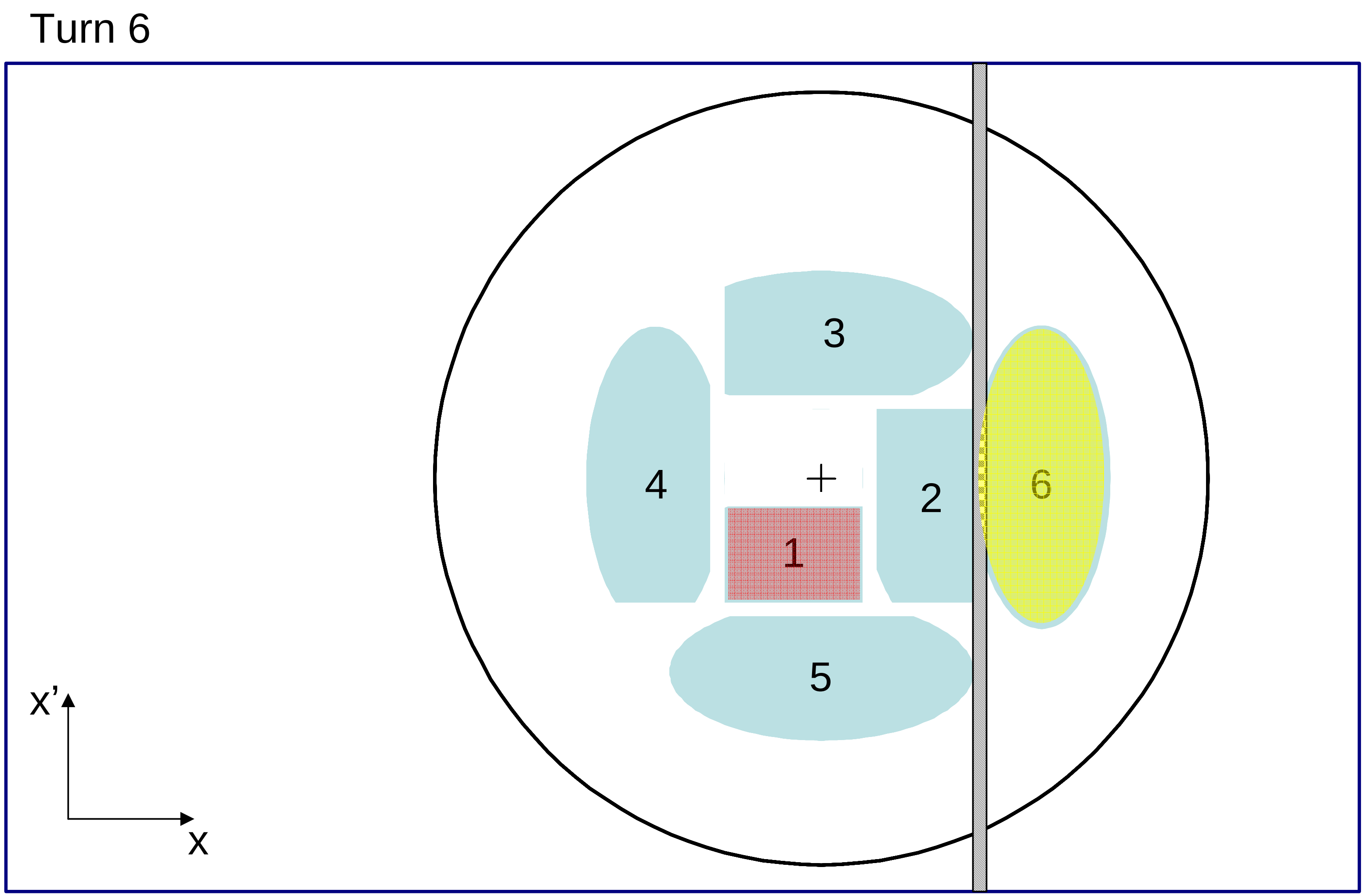


Multi-turn injection for hadrons

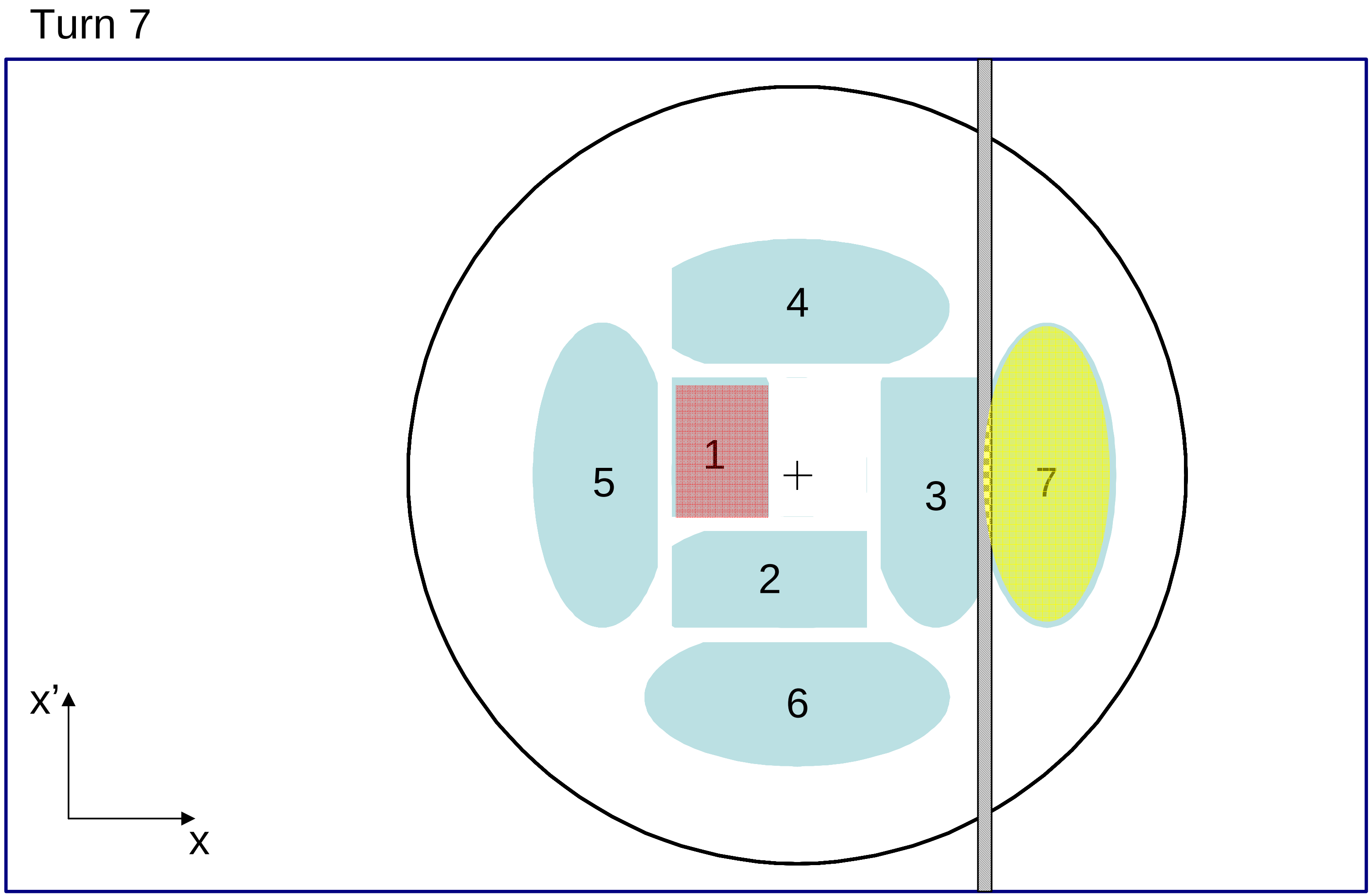
Turn 5



Multi-turn injection for hadrons

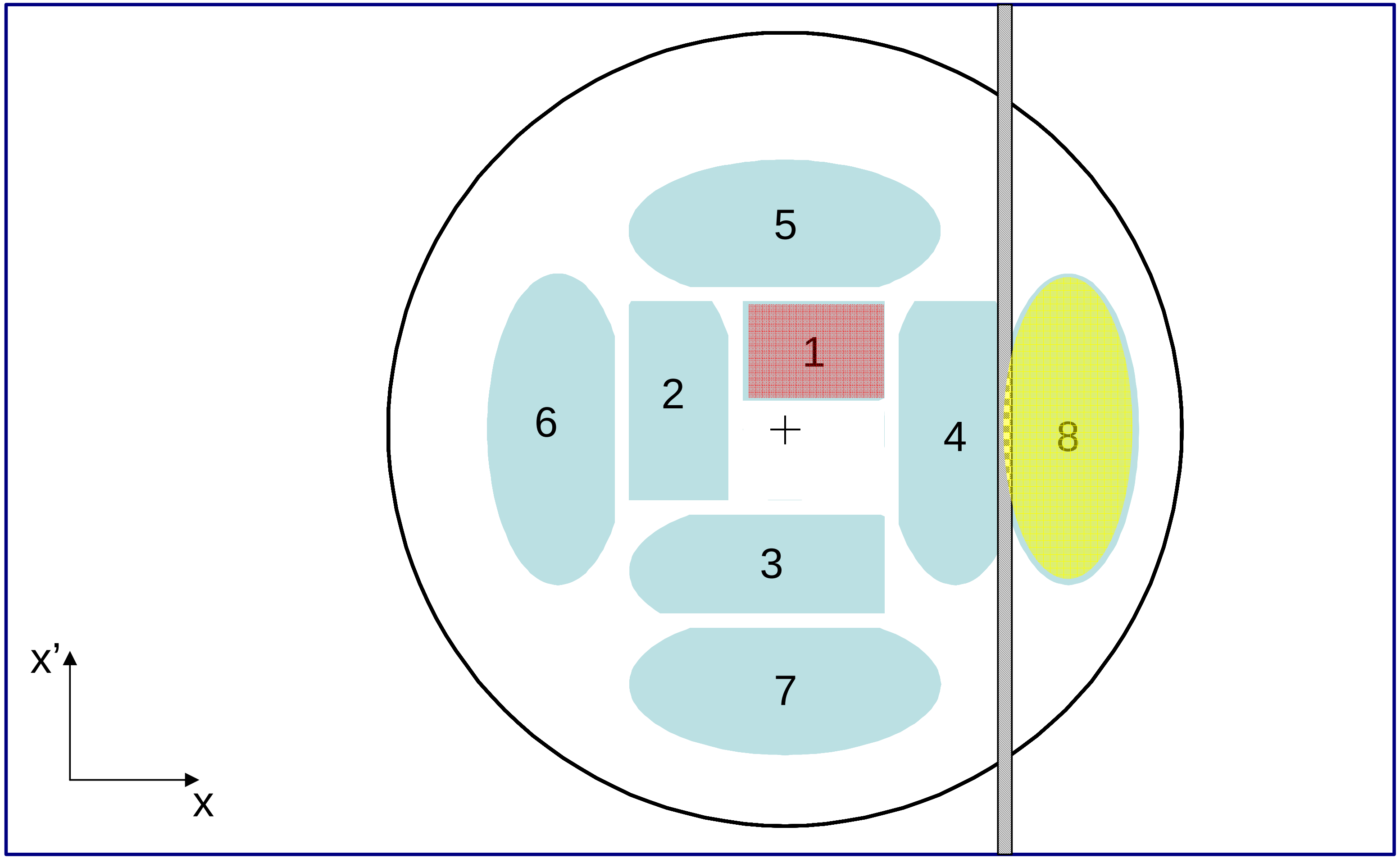


Multi-turn injection for hadrons



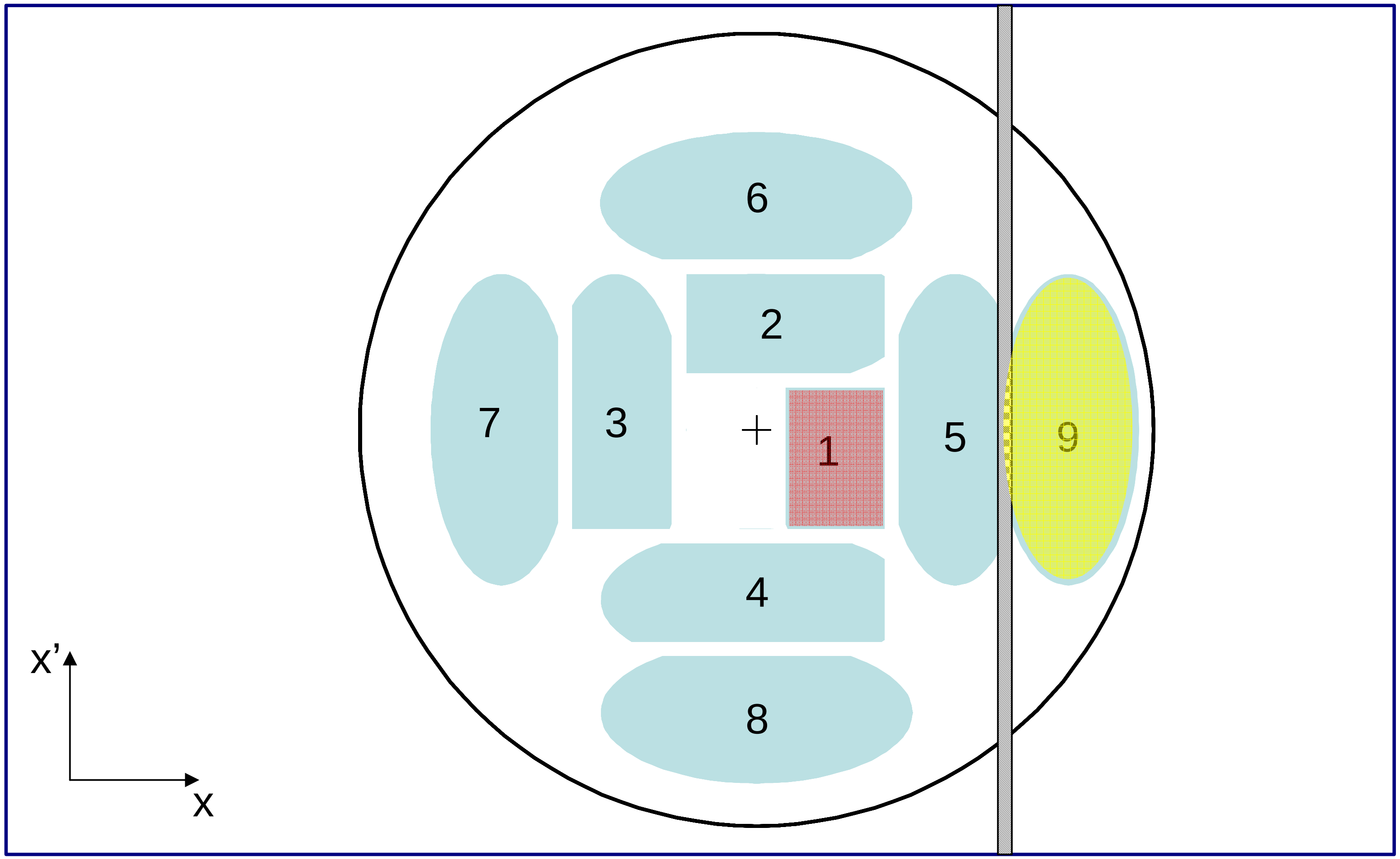
Multi-turn injection for hadrons

Turn 8



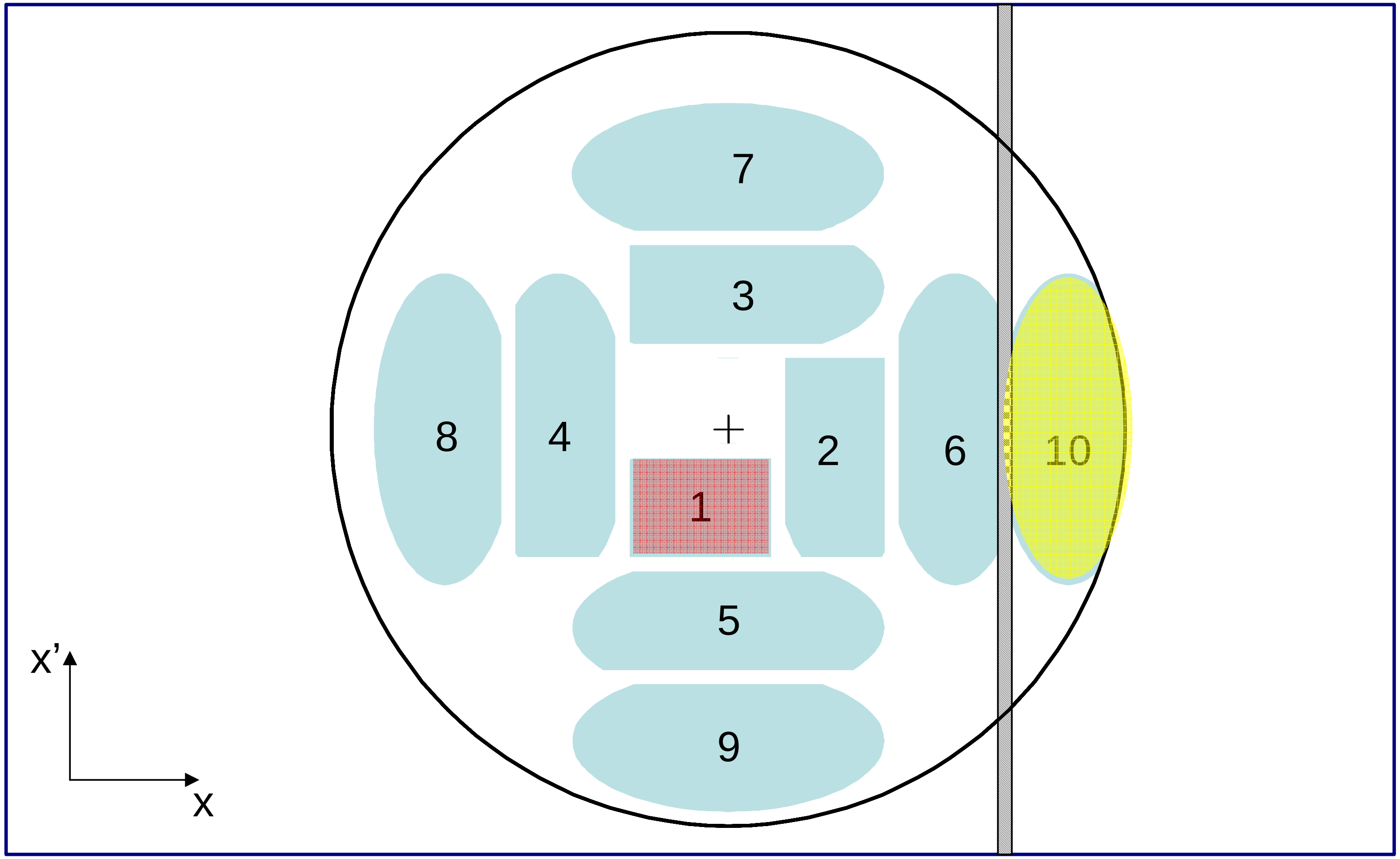
Multi-turn injection for hadrons

Turn 9



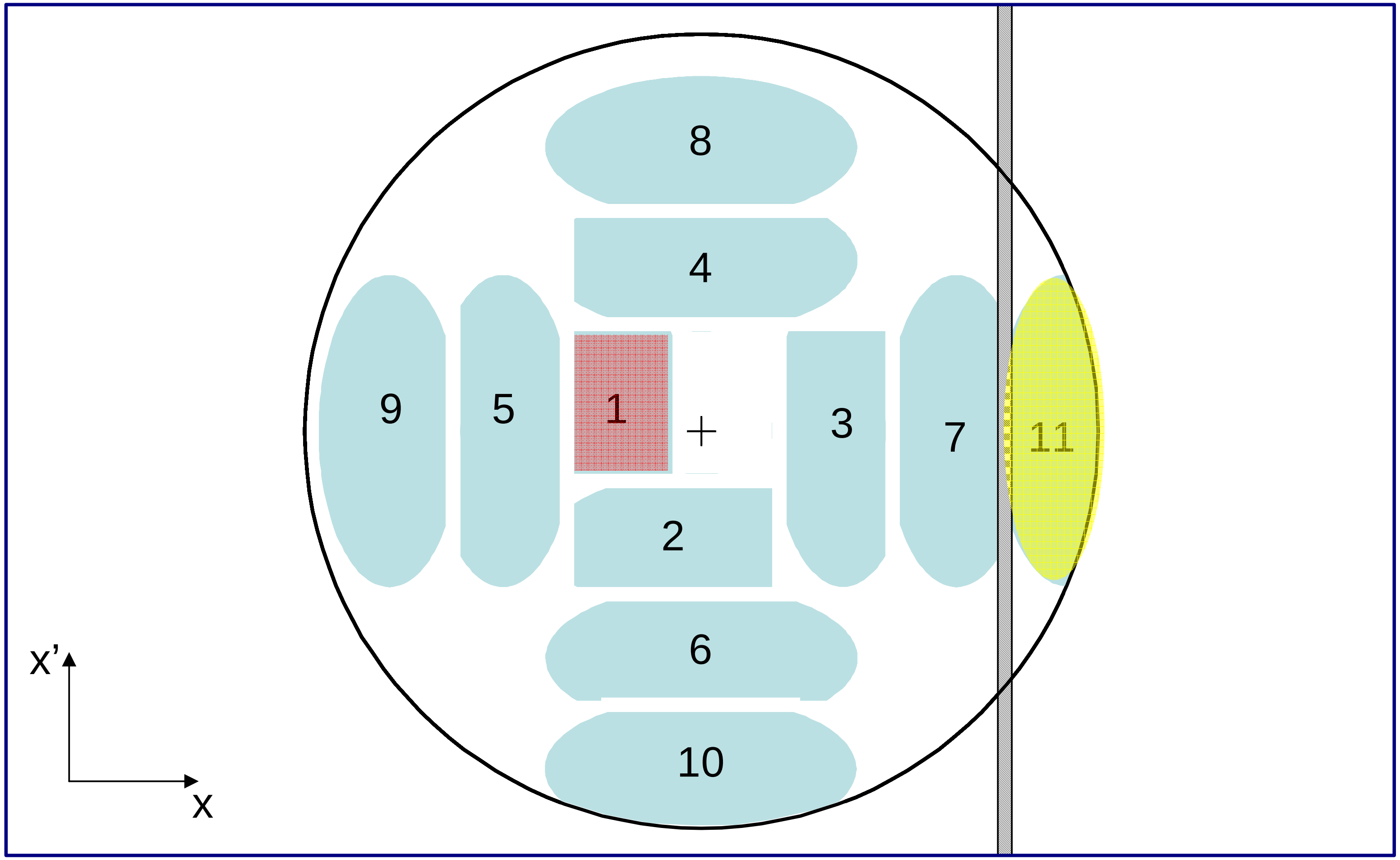
Multi-turn injection for hadrons

Turn 10

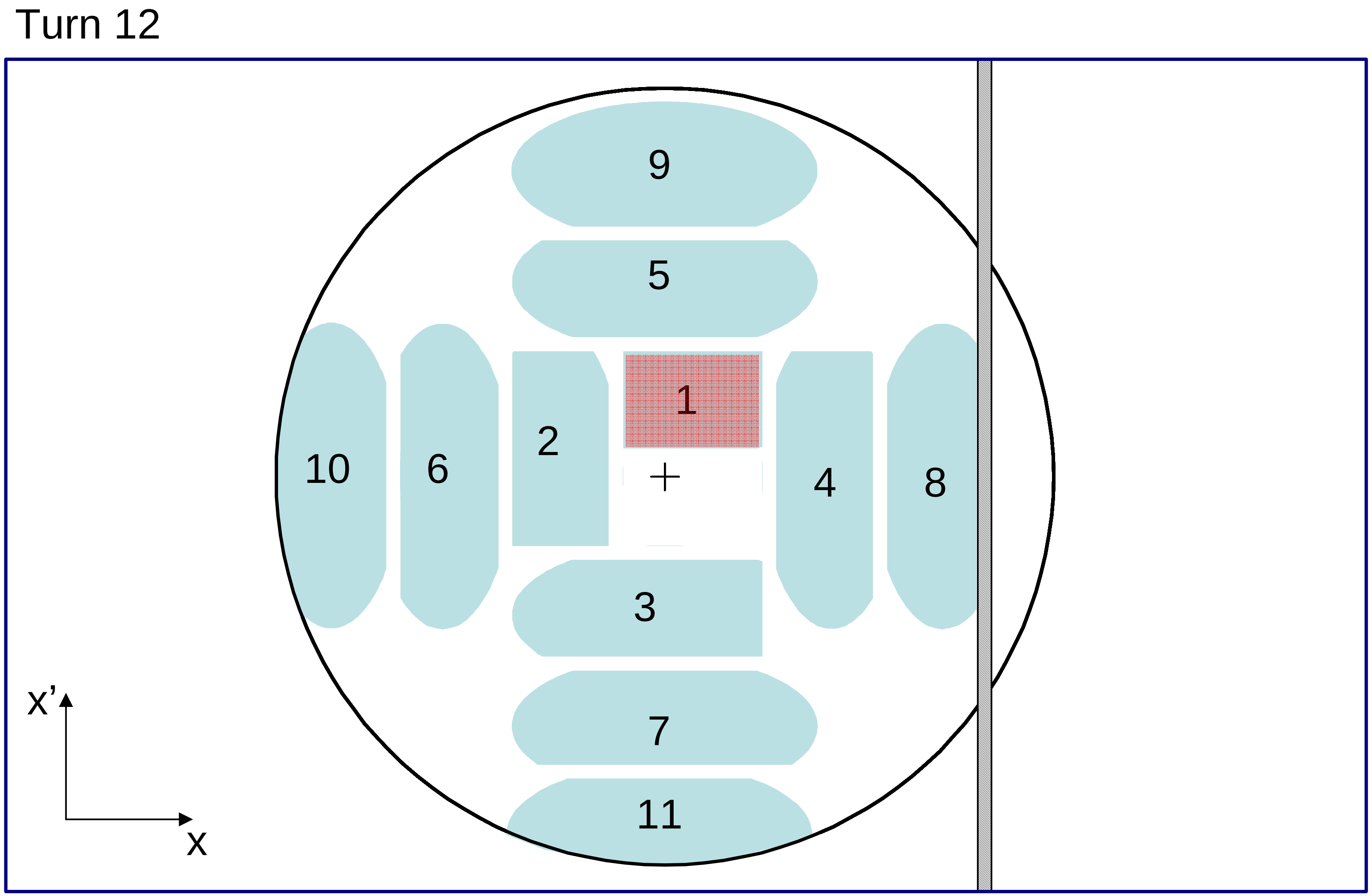


Multi-turn injection for hadrons

Turn 11

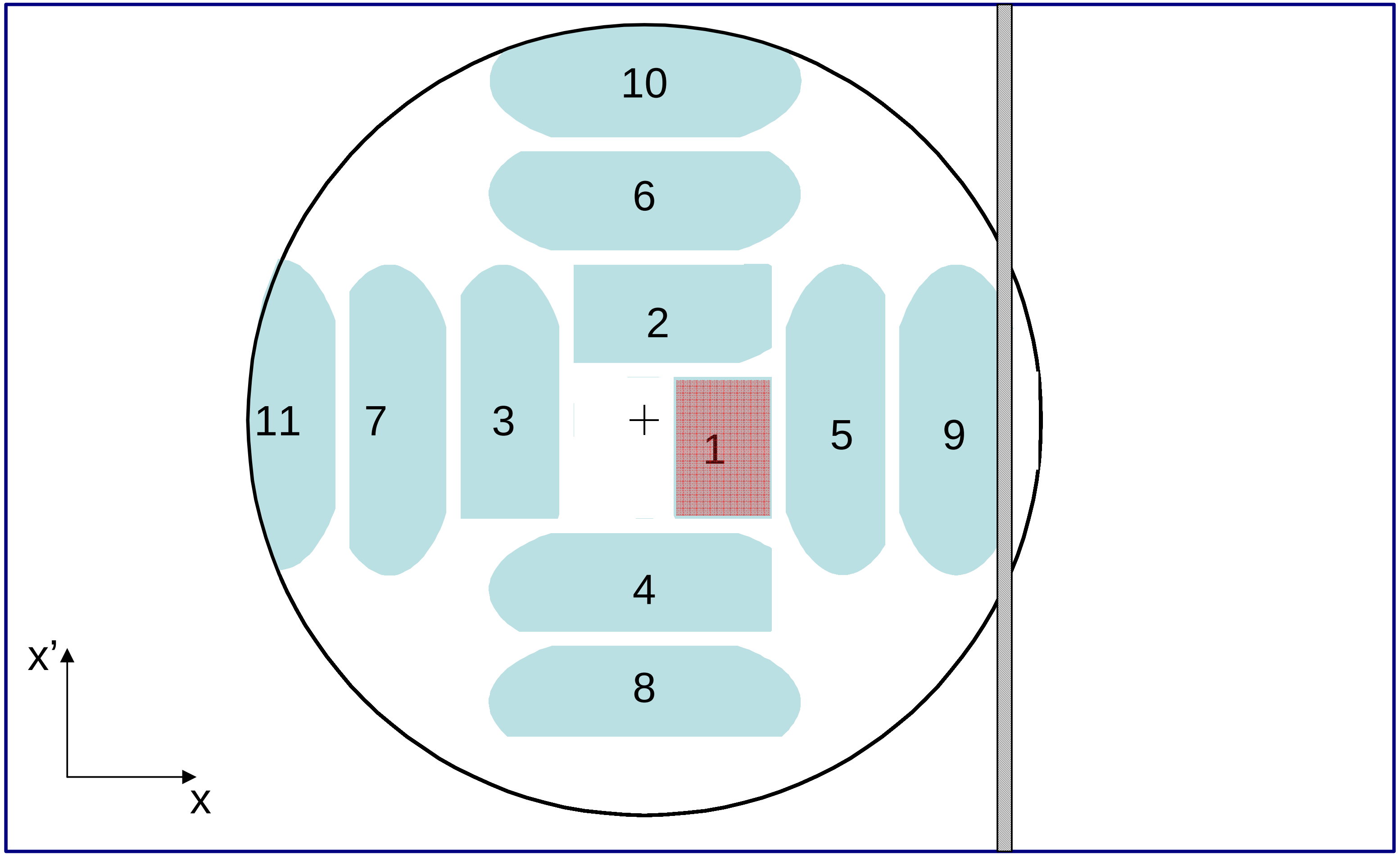


Multi-turn injection for hadrons



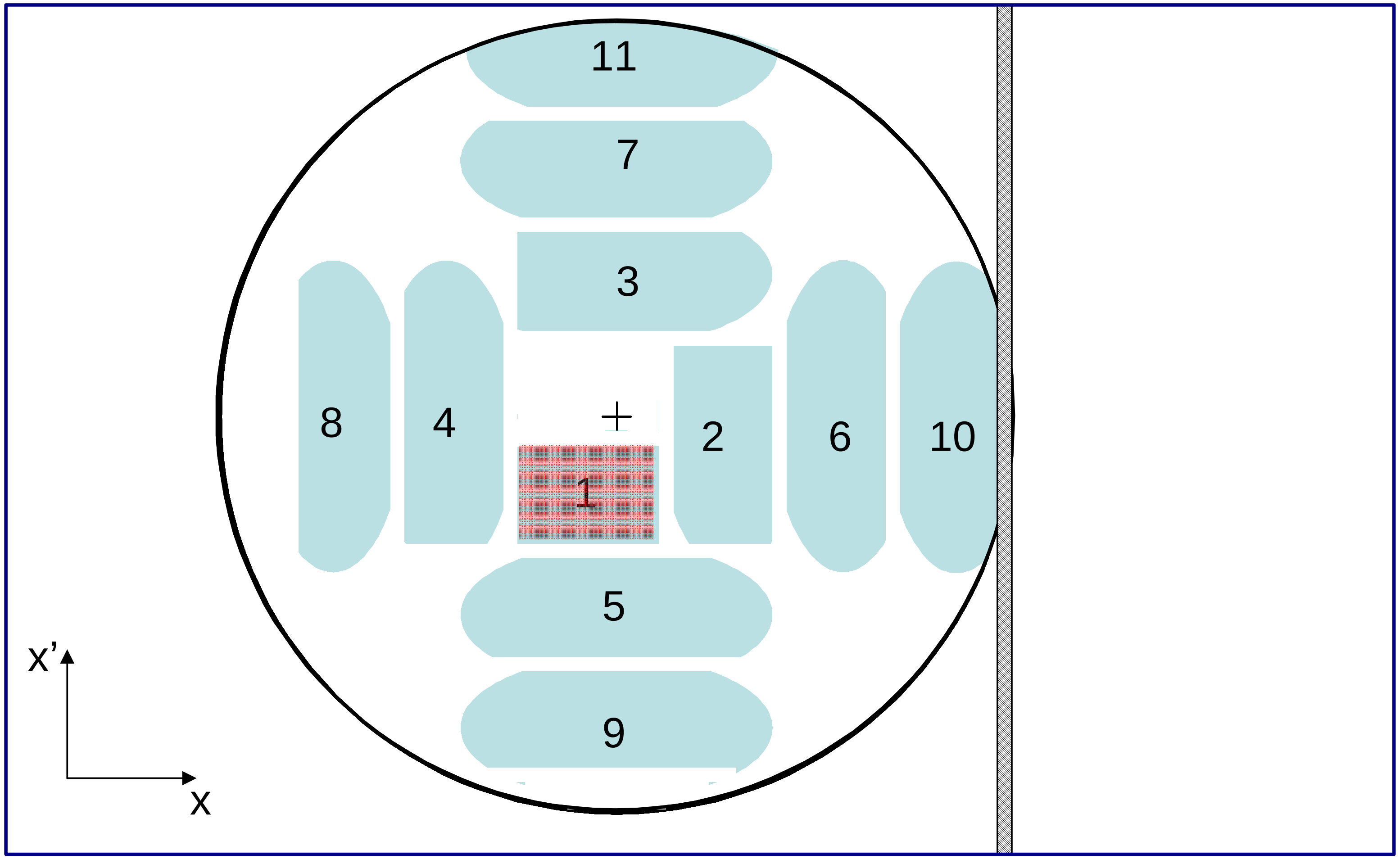
Multi-turn injection for hadrons

Turn 13

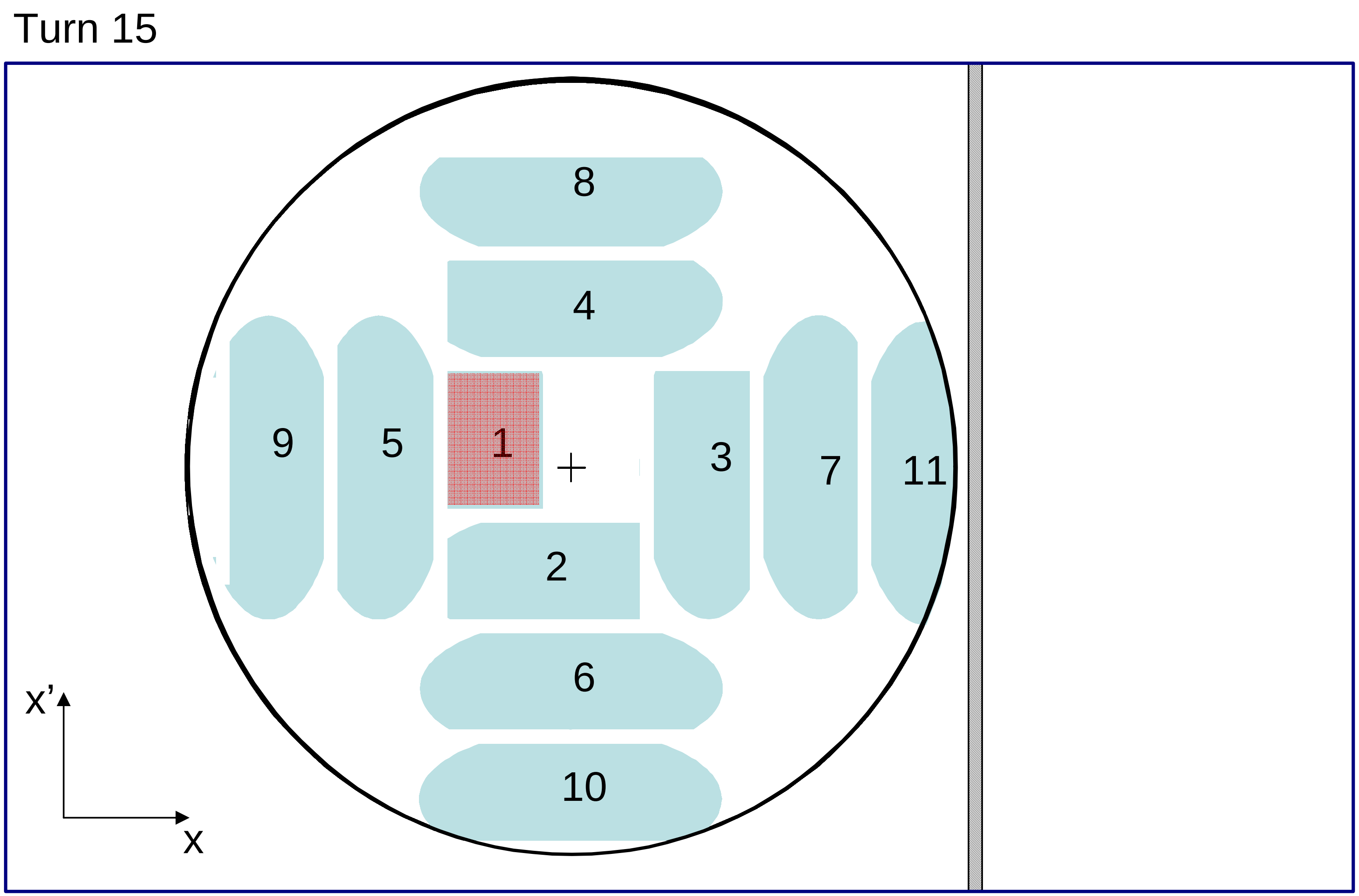


Multi-turn injection for hadrons

Turn 14



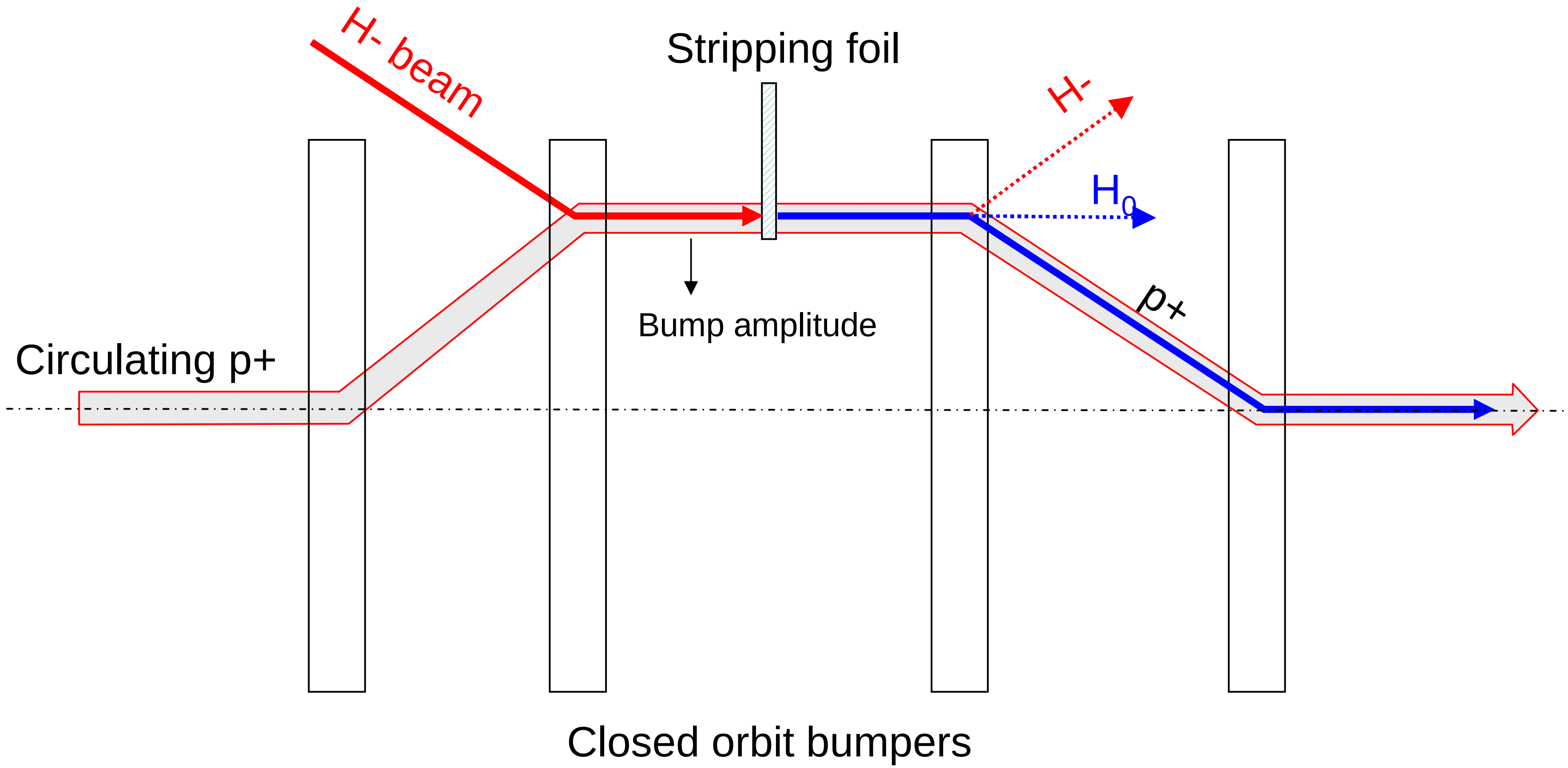
Multi-turn injection for hadrons



Multi-turn injection for hadrons

- Requirements:
  - To control the tune Q_h accurately
  - To control the bump accurately
  - A very thin septum
- In order to:
  - Minimise losses
  - Fill the horizontal phase space most efficiently
  - Reduce phase space dilution

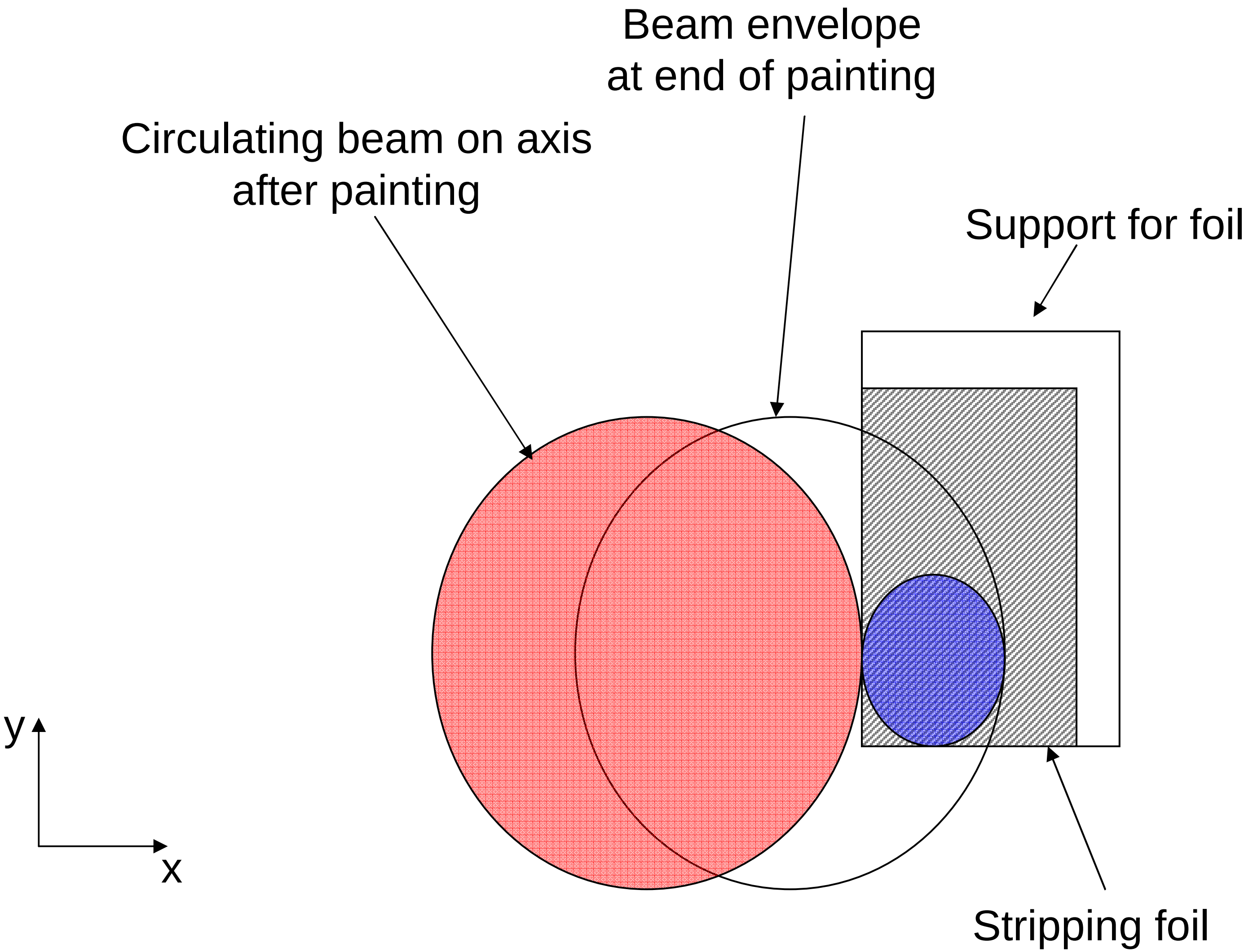
Charge exchange H- injection



Charge exchange H- injection

- Possible to "beat" Liouville's theorem, which says that emittance is conserved….
- Paint uniform transverse phase space density by modifying the beam bump and steering injected beam
- Foil thickness calculated to double-strip most ions (99%)
  - 50 MeV - 50 μg.cm-2
  - 800 MeV - 200 μg.cm-2 (~1μm of C)
- Carbon or Aluminium foils can be used – very fragile!
- Bump reduced during injection to paint phase space, and to zero after injection, to avoid excessive foil heating and unnecessary beam blow up

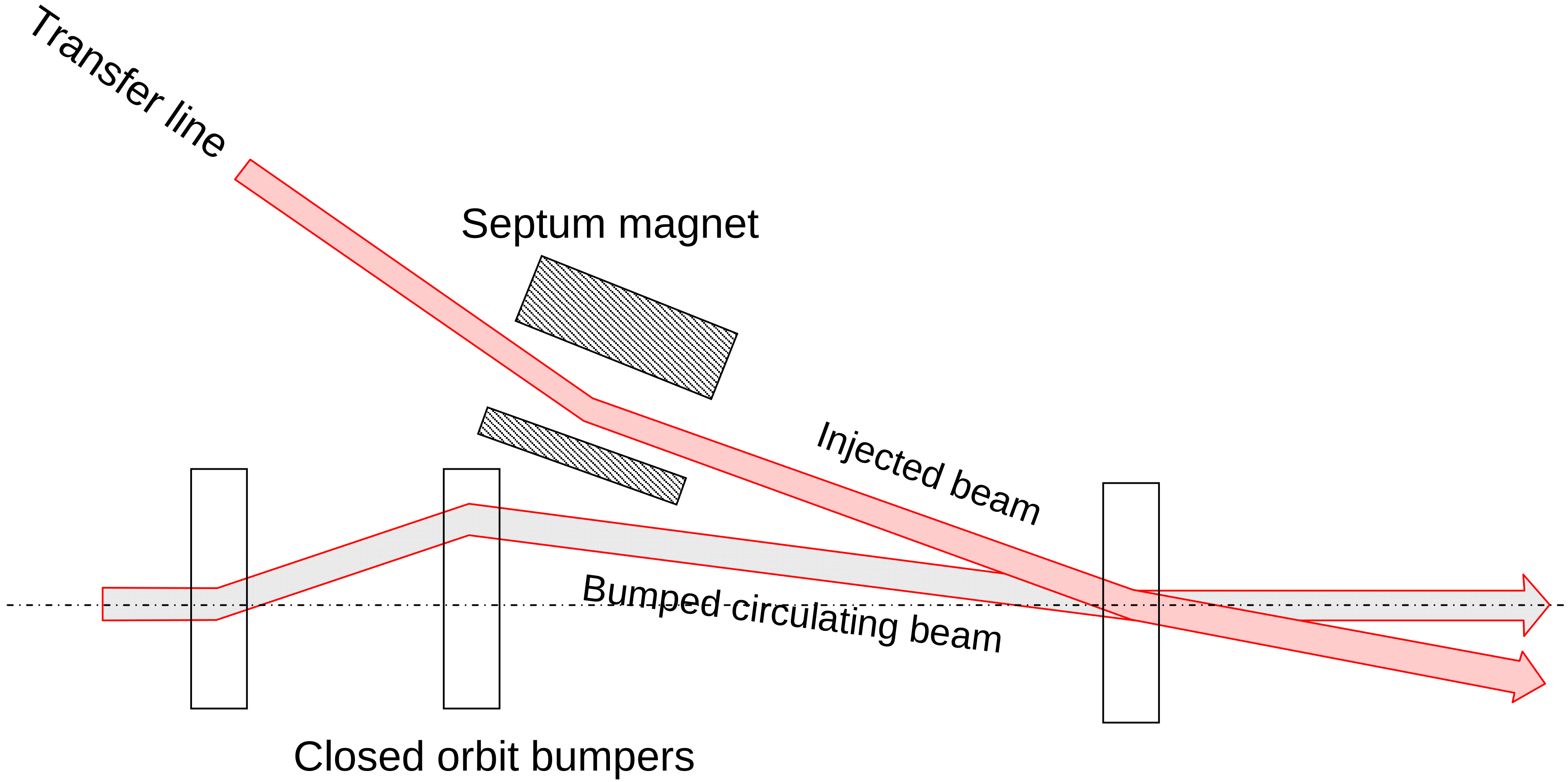
Charge exchange H- injection



Lepton injection

- Single-turn injection can be used as for hadrons; however, *lepton motion is damped* (different with respect to proton or ion injection).
- Can use transverse or longitudinal damping:
  - Transverse - Betatron accumulation
  - Longitudinal - Synchrotron accumulation

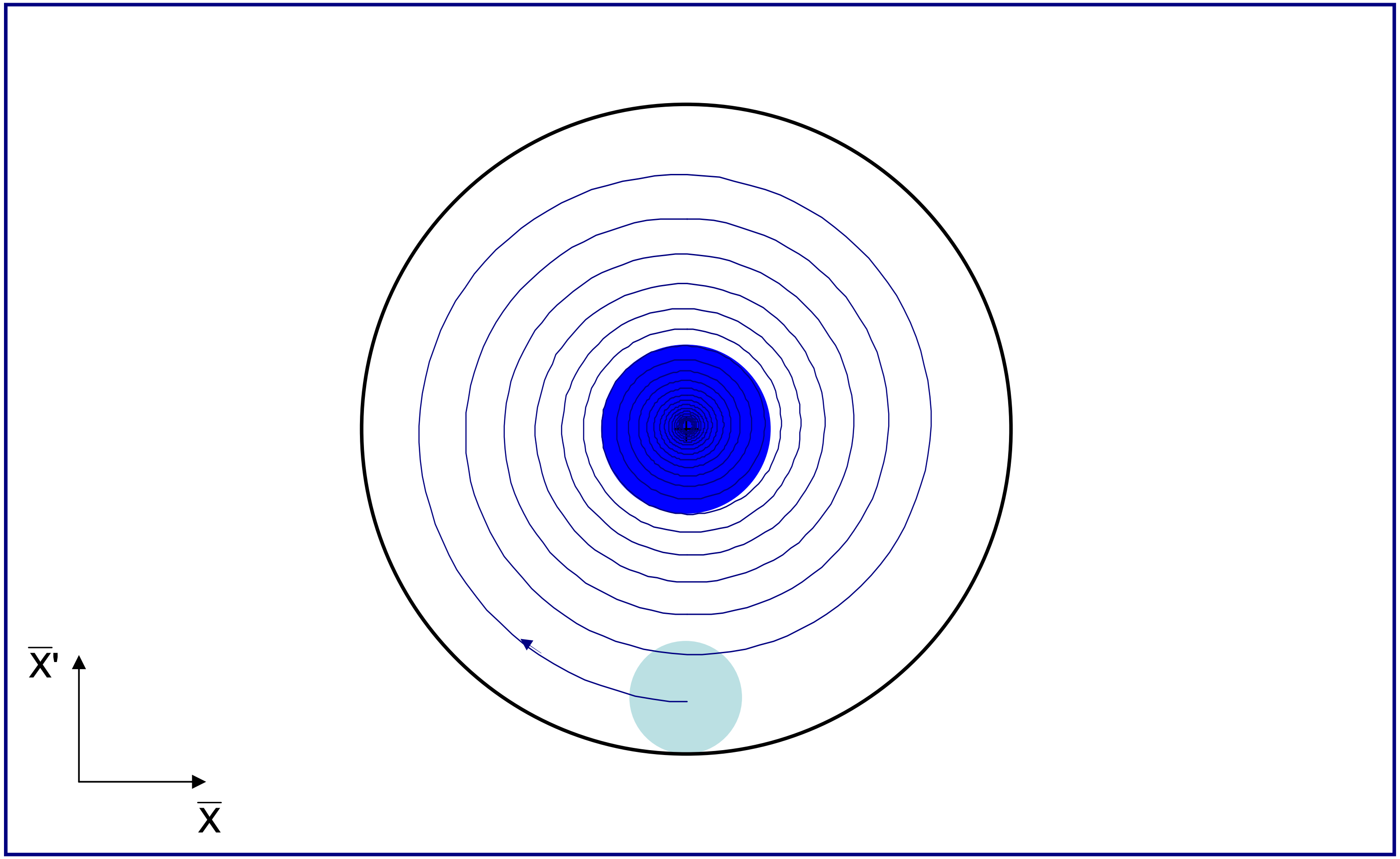
Betatron lepton injection



- Beam injected with an angle with respect to the closed orbit
- Injected beam performs damped betatron oscillations about the closed orbit

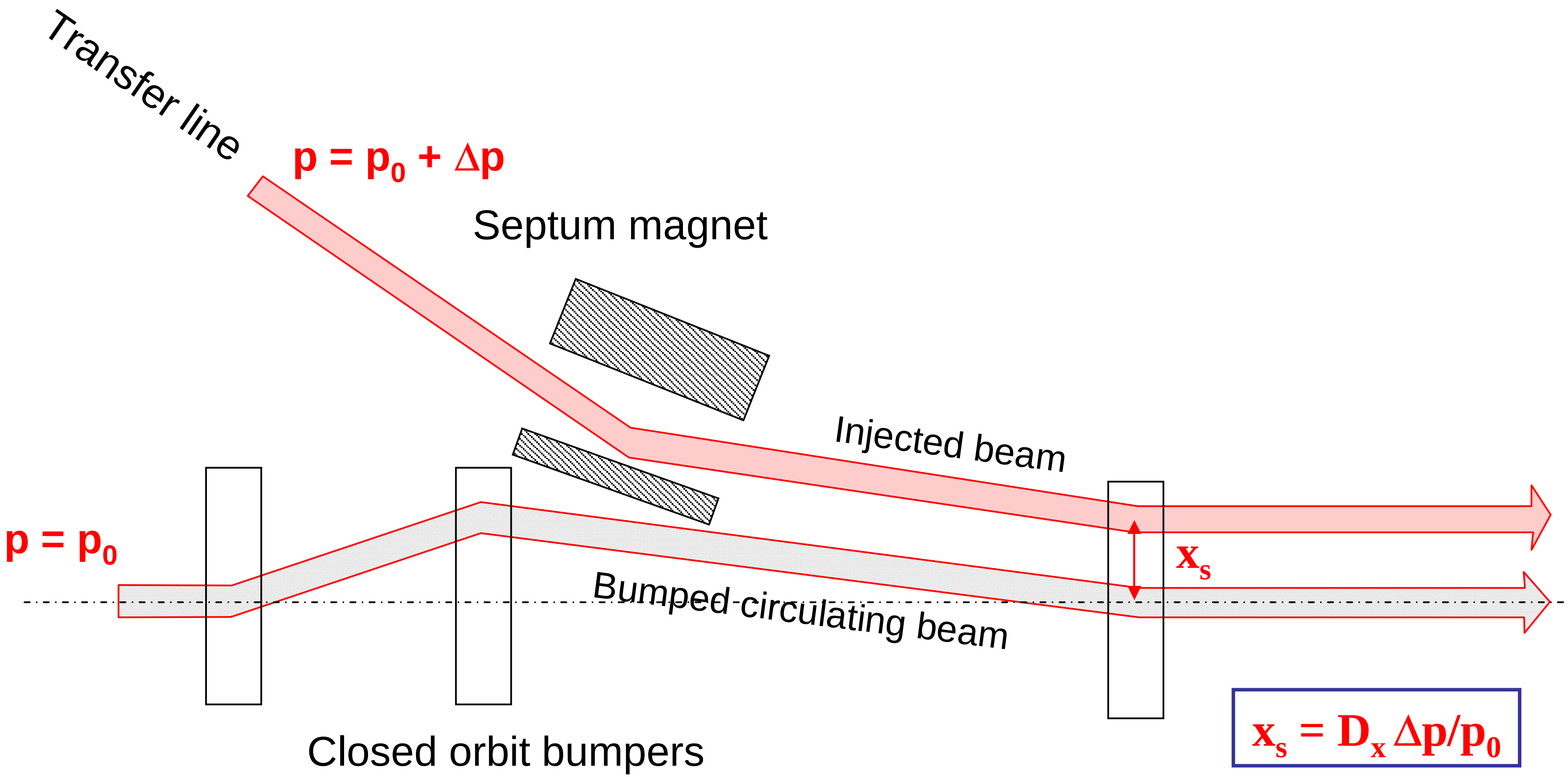
Betatron lepton injection

Injected bunch performs damped betatron oscillations



In LEP at 20 GeV, the damping time was about 6'000 turns (0.6 seconds)

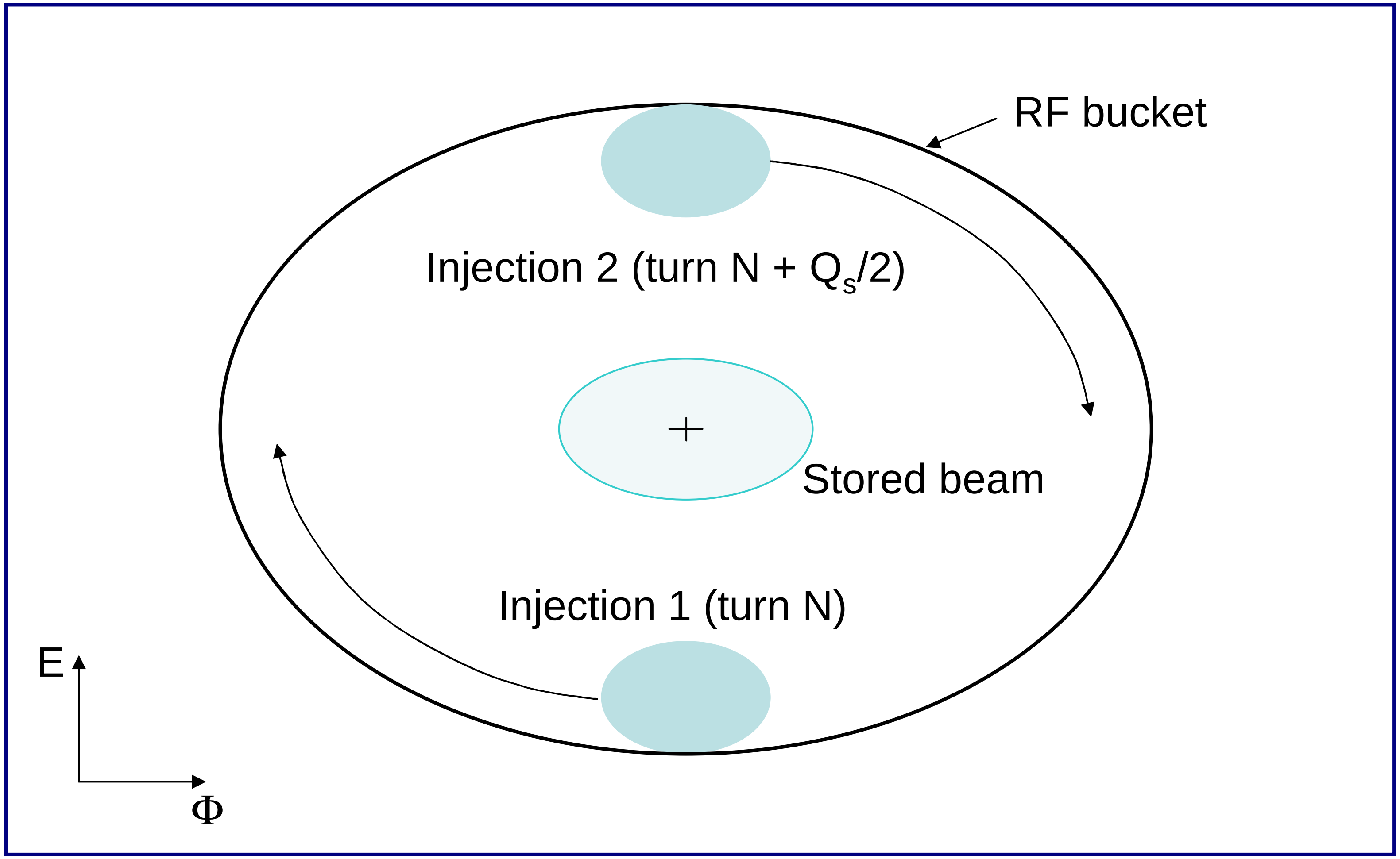
Synchrotron lepton injection



- Beam injected parallel to circulating beam, onto dispersion orbit of a particle having the same momentum offset $\Delta p/p$.
- Injected beam makes damped *synchrotron oscillations* at Q_s but does not perform betatron oscillations.

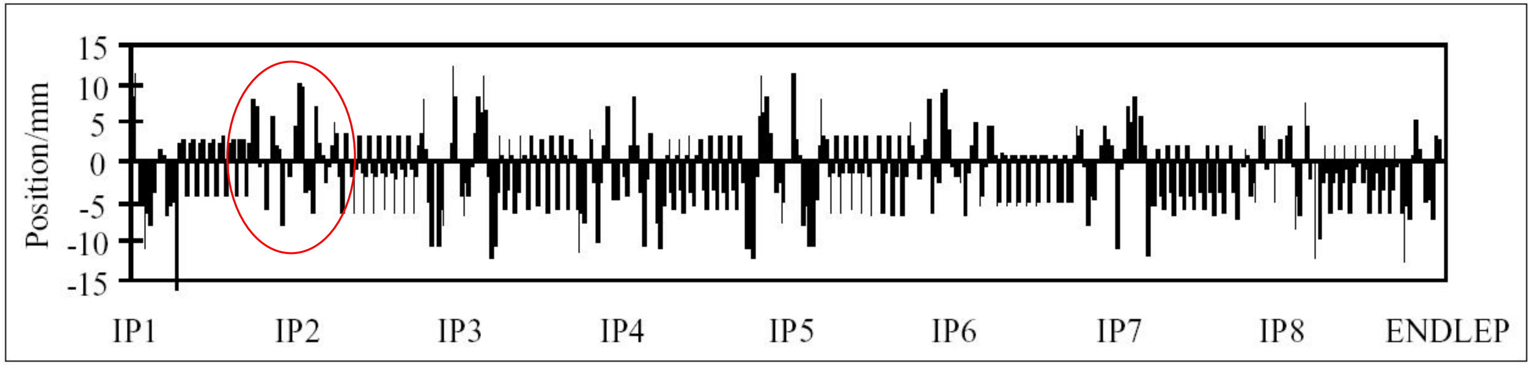
Synchrotron lepton injection

Double batch injection possible….

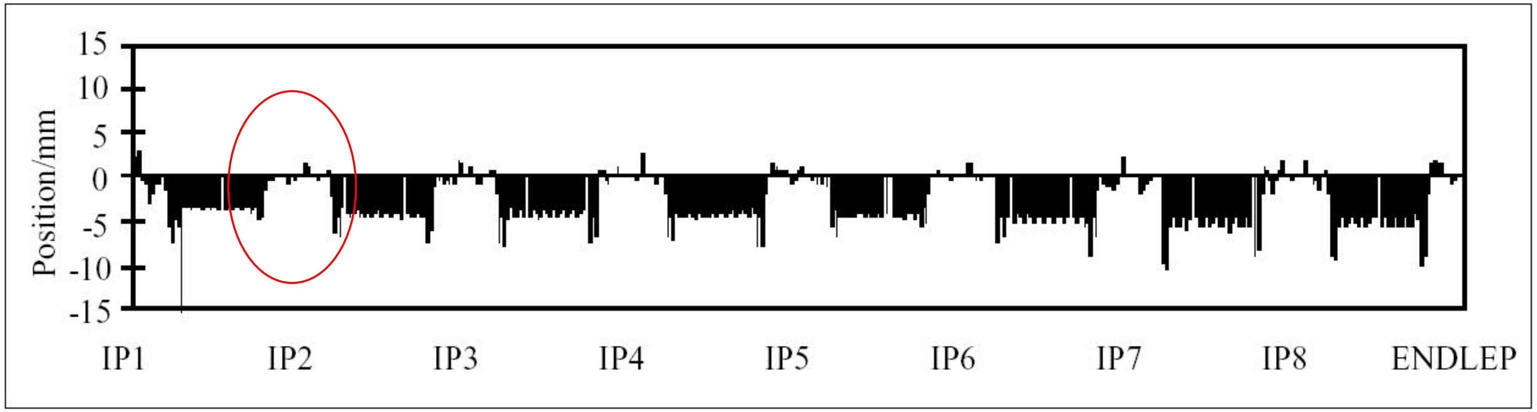


Longitudinal damping time in LEP was ~ 3’000 turns (2 x faster than transverse)

Synchrotron lepton injection in LEP



Optimized Horizontal First Turn Trajectory for Betatron Injection of Positrons into LEP.



Optimized Horizontal First Turn Trajectory for Synchrotron Injection of Positrons with ΔP/P at -0.6%

Small orbit with Synchrotron Injection in zero dispersion straight sections gave improved background for LEP experiments

P.Collier

Injection - summary

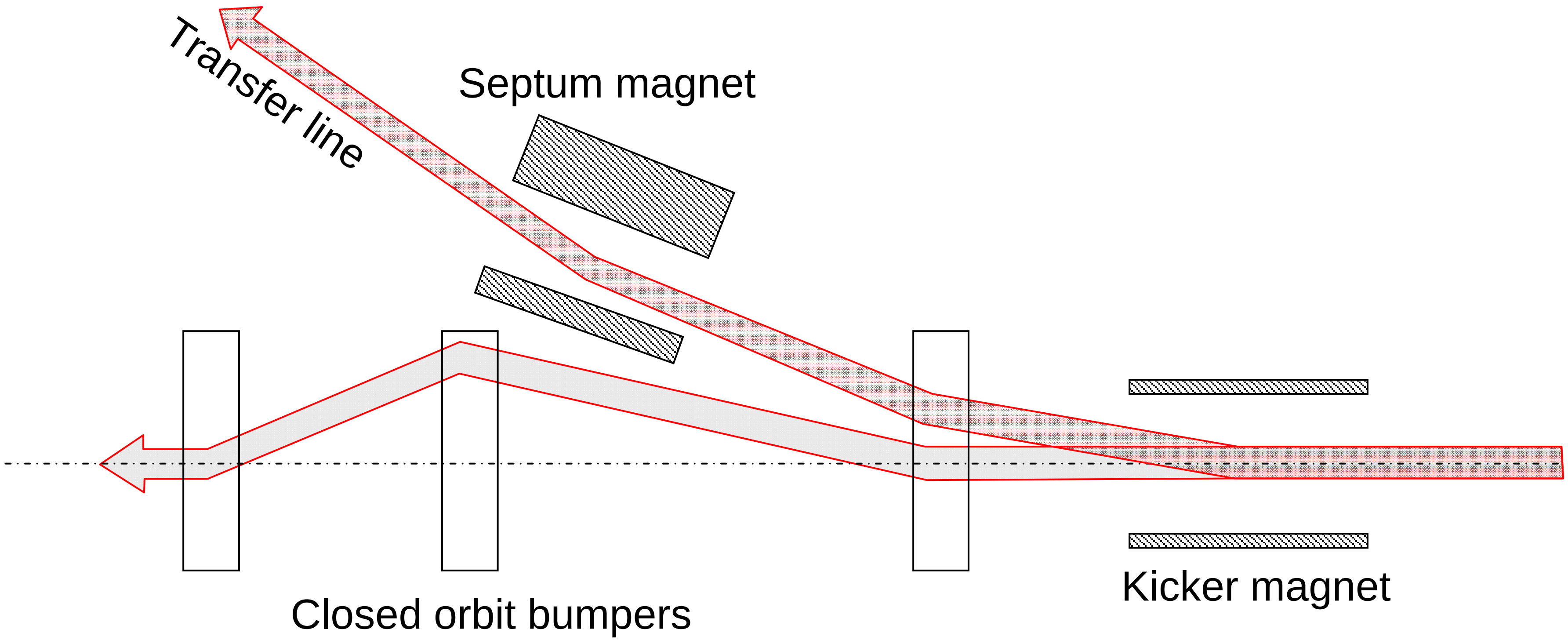
- Kickers, septa and bumpers elements used
- Single-turn injection for Boxcar stacking: transfer between machines in accelerator chain
- Angle / position errors $\Rightarrow$ injection oscillations
- Uncorrected oscillations $\Rightarrow$ filamentation $\Rightarrow$ emittance increase
- Multi-turn injection for hadrons: phase space painting
- H- injection allows injection into same phase space area
- Lepton injection: take advantage of damping

Extraction

- To reduce kicker and septum strength, beam moved near to septum by closed orbit bump

- Fast extraction: ≤1 turn
  - Whole beam kicked into septum gap and extracted.
- Non-resonant multi-turn extraction: few turns
  - Beam kicked to septum; part of beam ‘shaved’ off each turn.
- Resonant multi-turn extraction: many thousands of turns
  - Non-linear fields excite resonances which drive the beam slowly across the septum.
- Resonant low—loss multi-turn extraction: few turns
  - Non-linear fields used to trap ‘bunchlets’ in stable island. Beam then kicked across septum and extracted in a few turns

Fast single turn extraction

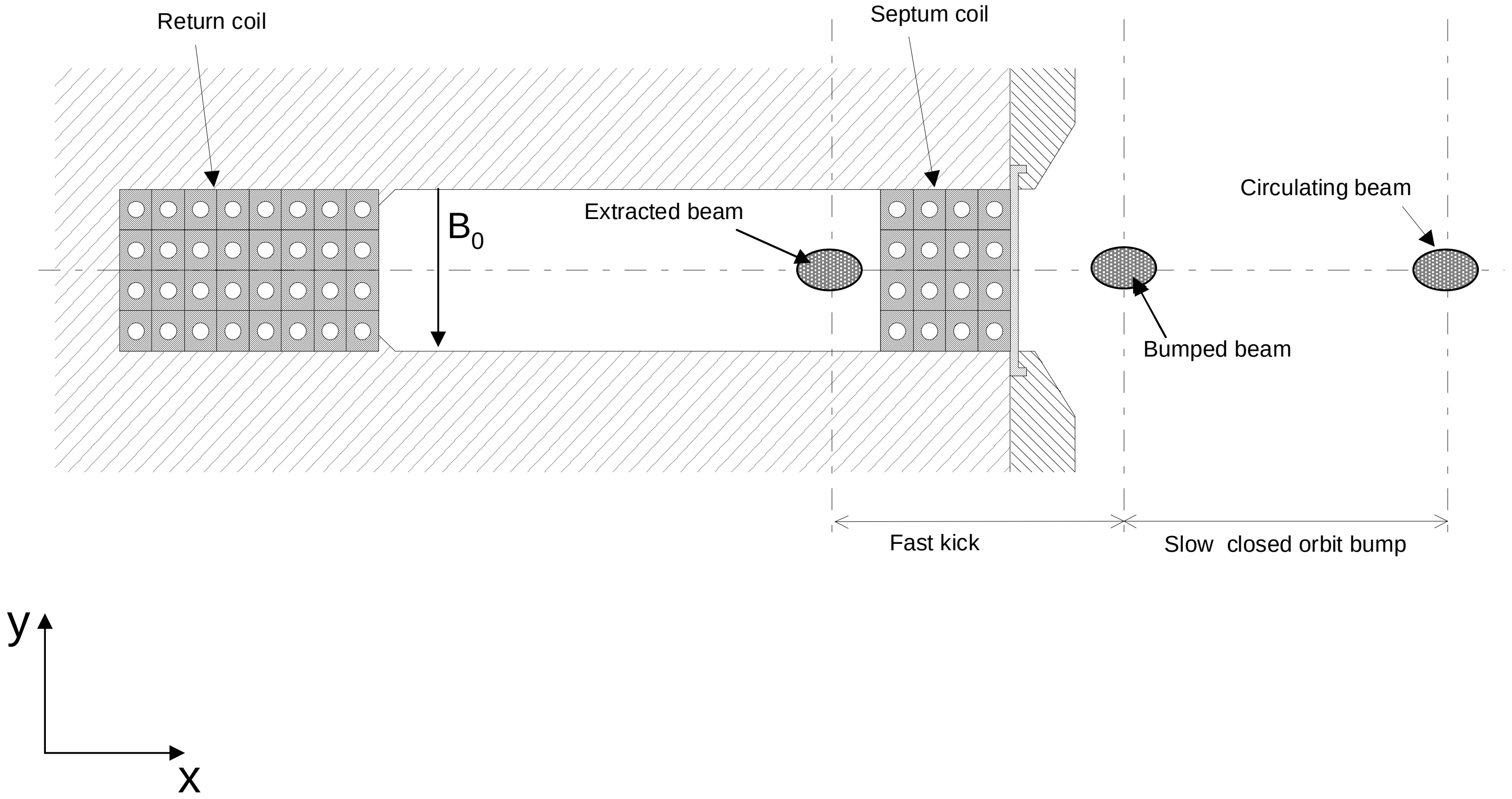


- Kicker deflects the entire beam into the septum in a single turn
- Septum deflects the beam entire into the transfer line
- Most efficient (lowest deflection angles required) for $\pi/2$ phase advance between kicker and septum

Fast single turn extraction

- For transfer of beams between accelerators in an injector chain.
- For neutrino production.
  - If septa used only for this purpose, they can be pulsed - few 10 ms.
- Septum deflection may be in the other plane to the kicker deflection.
- At high energies many kicker and septum modules may be required

Fast single turn extraction

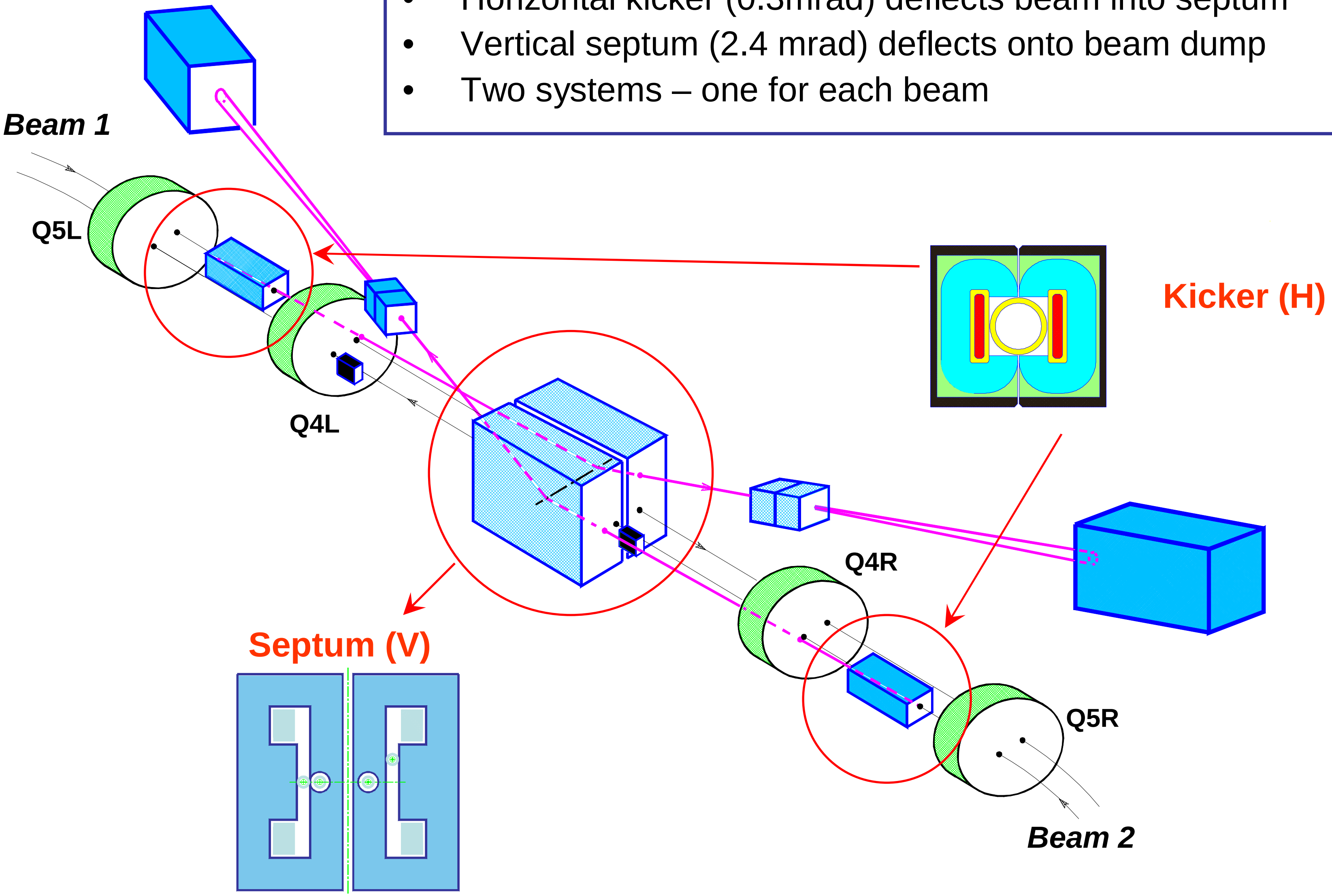


- View at the septum entrance. Here the clearances are the smallest.
- For high energies / intensities, machine protection becomes an issue.

Fast single turn extraction

Example system - fast extraction from LHC at 7TeV/c (for beam dump)

- Horizontal kicker (0.3mrad) deflects beam into septum
- Vertical septum (2.4 mrad) deflects onto beam dump
- Two systems – one for each beam

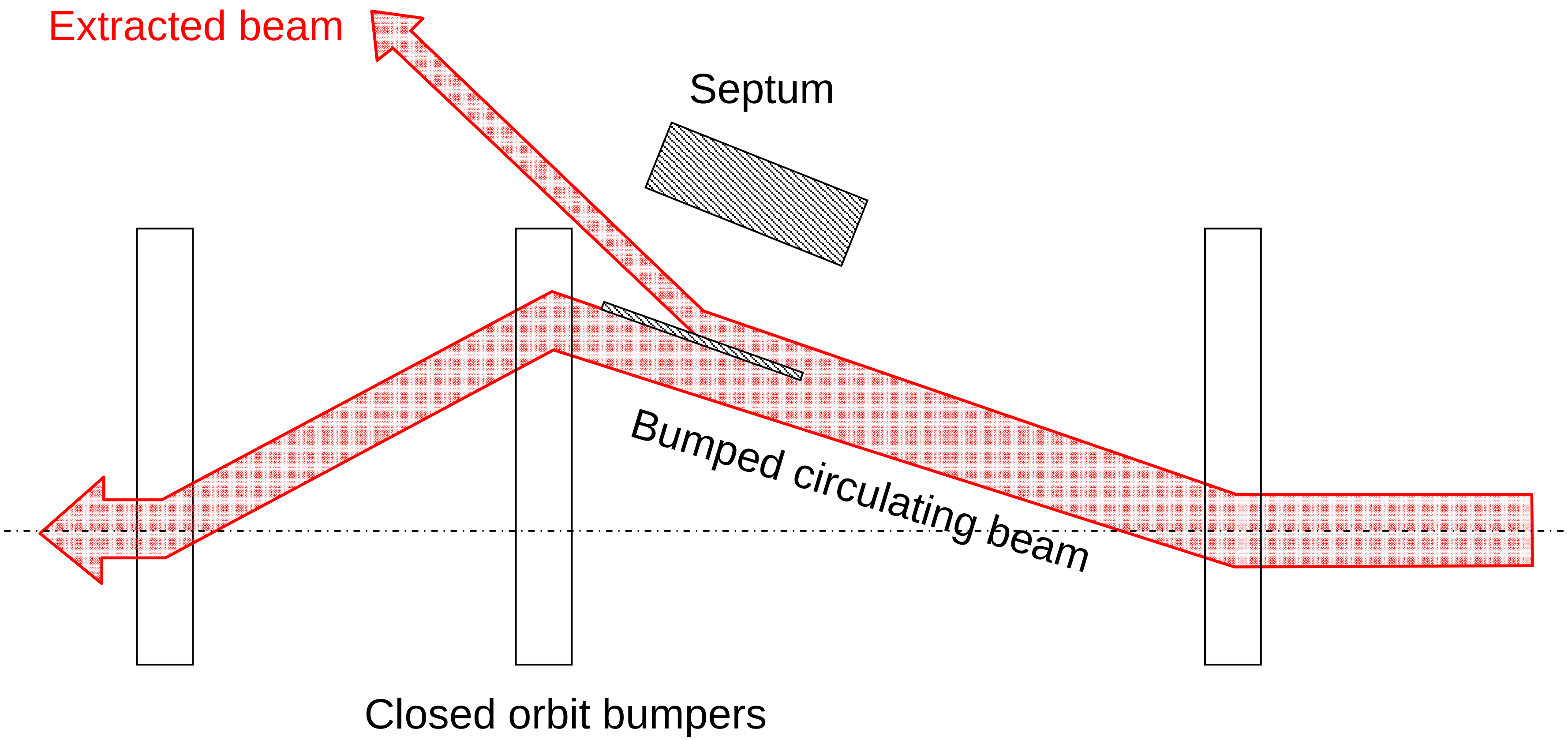


Multi-turn extraction

- Some filling schemes require a beam to be injected in several turns to a larger machine…
- And, Fixed Target physics experiments often need a continuous flux of particles…

- Multi-turn extraction…
  - Non-Resonant multi-turn ejection (few turns) for filling e.g. PS to SPS at CERN for high intensity proton beams (>2.5 10^{13} protons)
  - Resonant extraction (ms to hours) for experiments

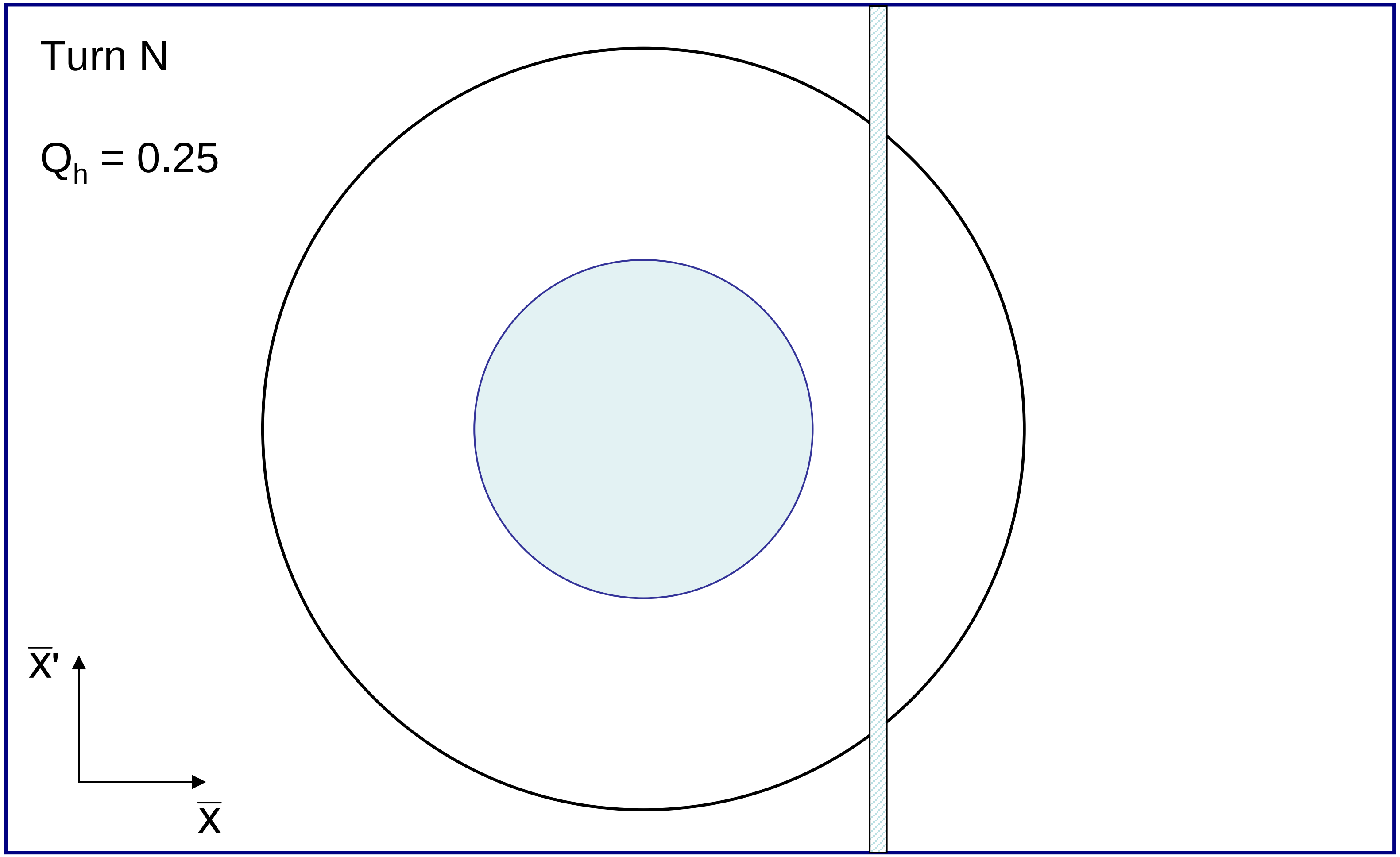
Non-resonant multi-turn extraction



- Fast bumper deflects the whole beam onto the septum
- Beam extracted in a few turns, with the machine tune rotating the beam
- Intrinsically high-loss process – thin septum essential

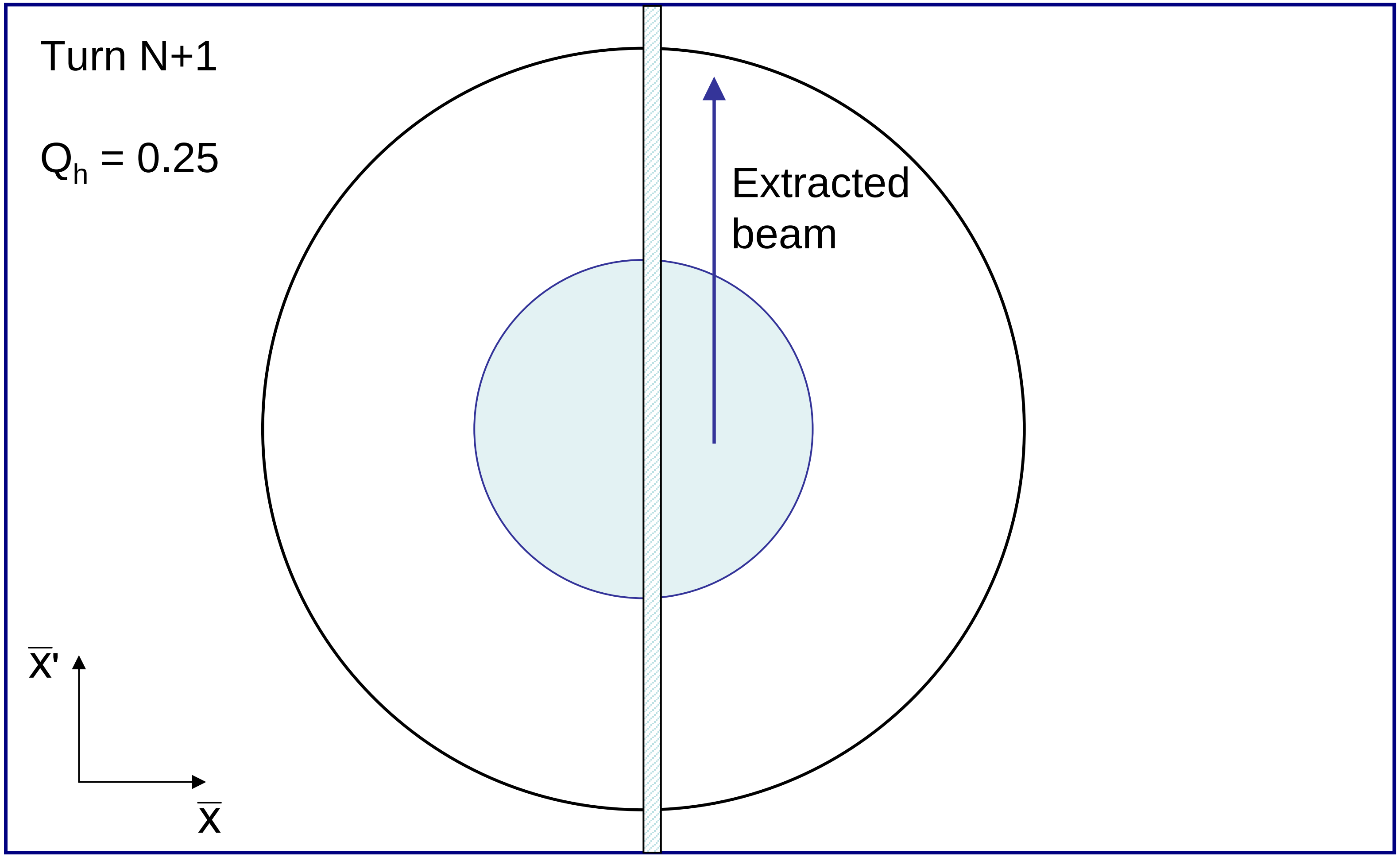
Non-resonant multi-turn extraction

Just before extraction….



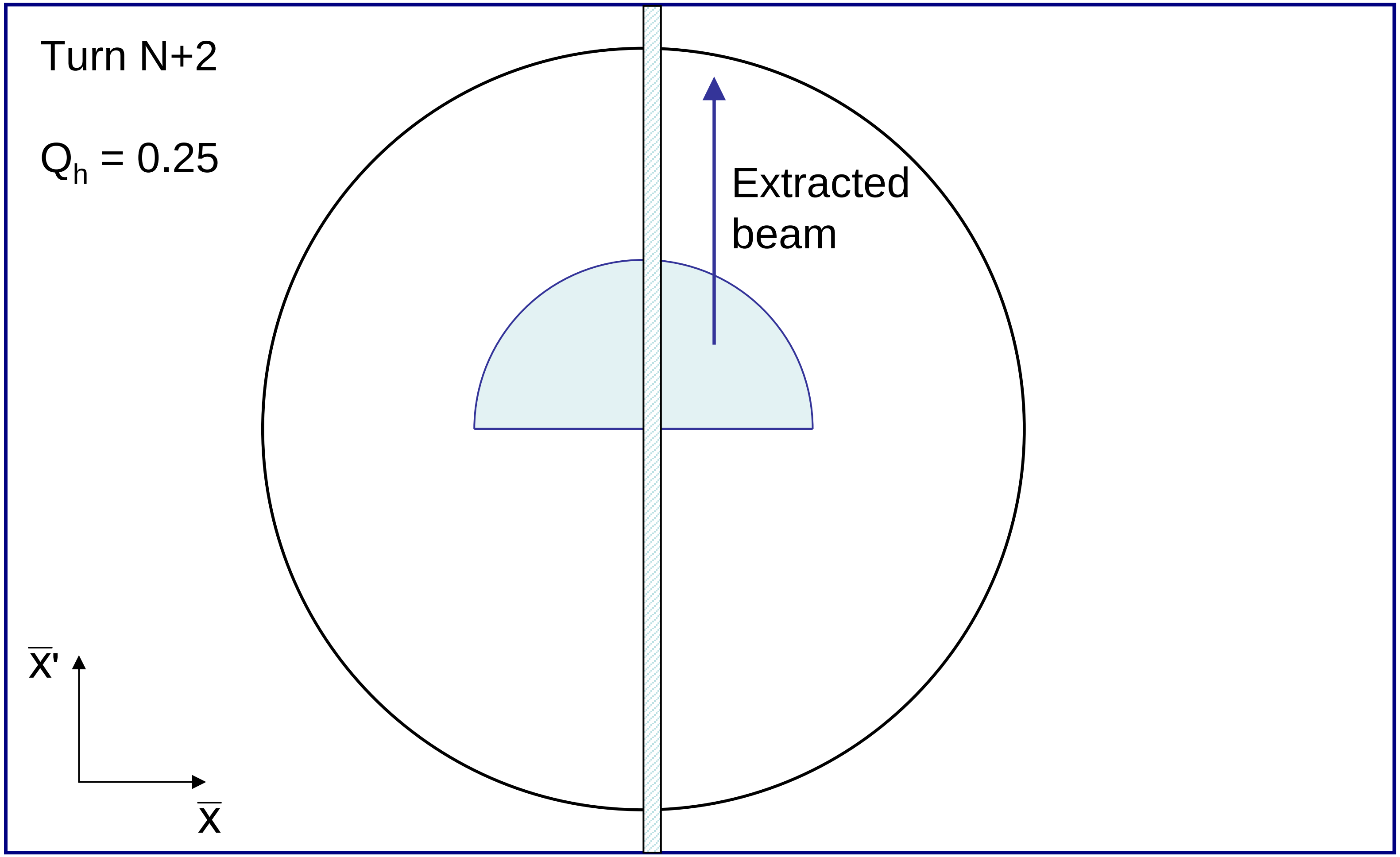
Non-resonant multi-turn extraction

Fast closed orbit bump moves part of the beam across the septum



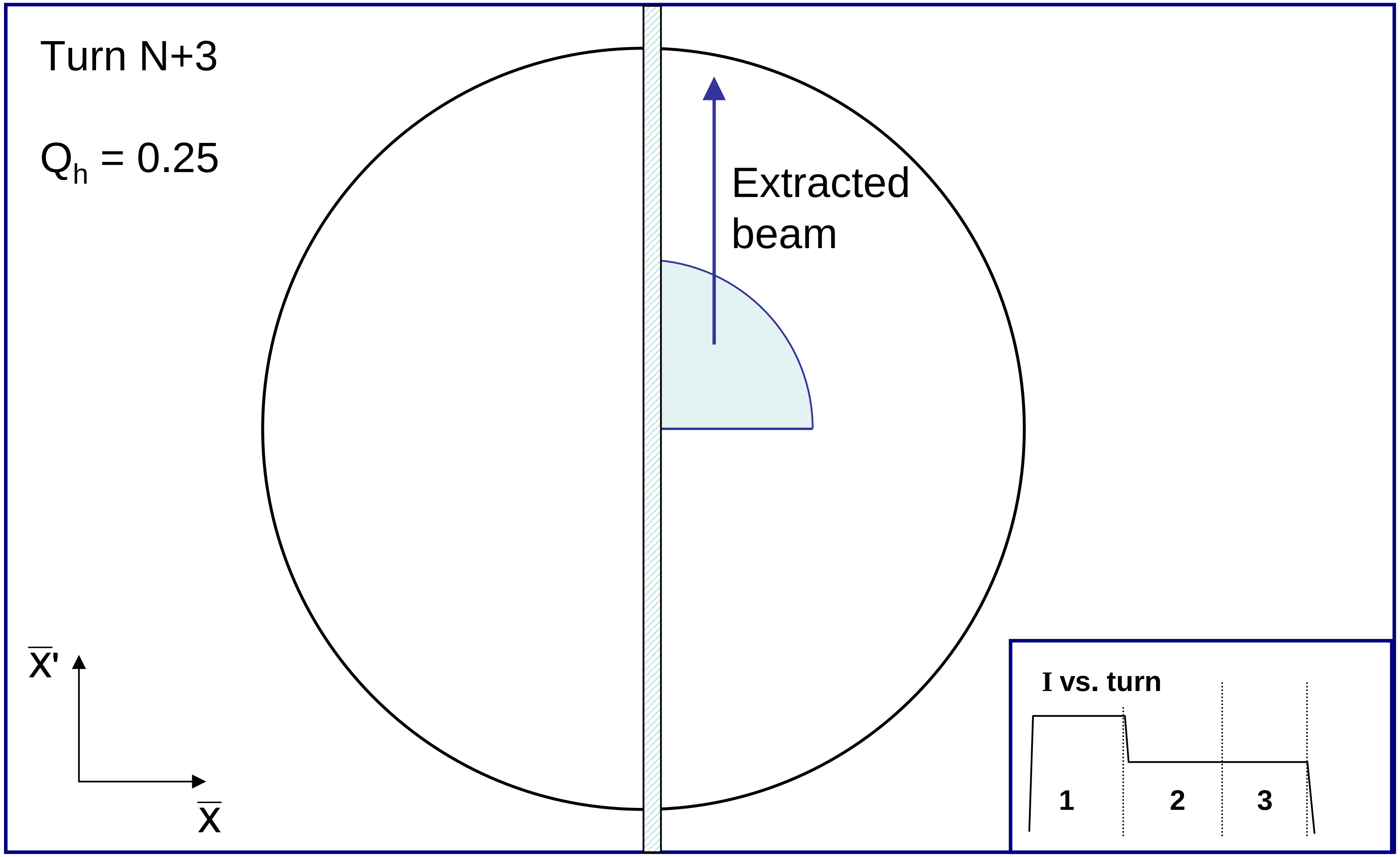
Non-resonant multi-turn extraction

The beam rotates across the septum….



Non-resonant multi-turn extraction

…and the last part is extracted on the final turn.

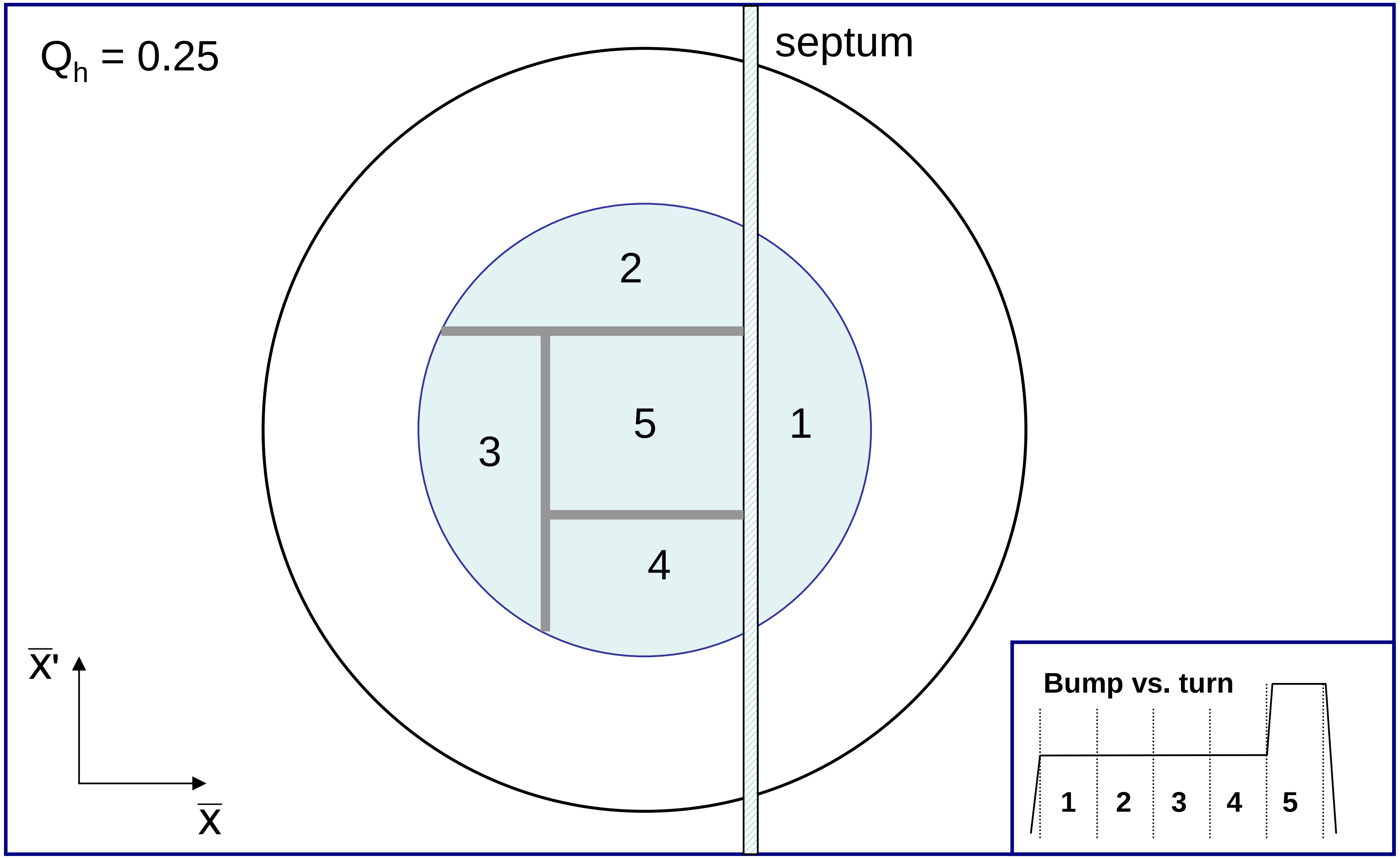


Non-resonant multi-turn extraction

- Example system: CERN PS to SPS Fixed-Target ‘continuous transfer’.
  - Accelerate beam in PS to 14 GeV/c
  - Empty PS machine (2.1 μs long) in 5 turns into SPS
  - Do it again
  - Fill SPS machine (23 μs long)
  - Quasi-continuous beam in SPS (2 x 1 μs gaps)
  - Total intensity per PS extraction $\approx 3 \times 10^{13}$ p+
  - Total intensity in SPS $\approx 5 \times 10^{13}$ p+

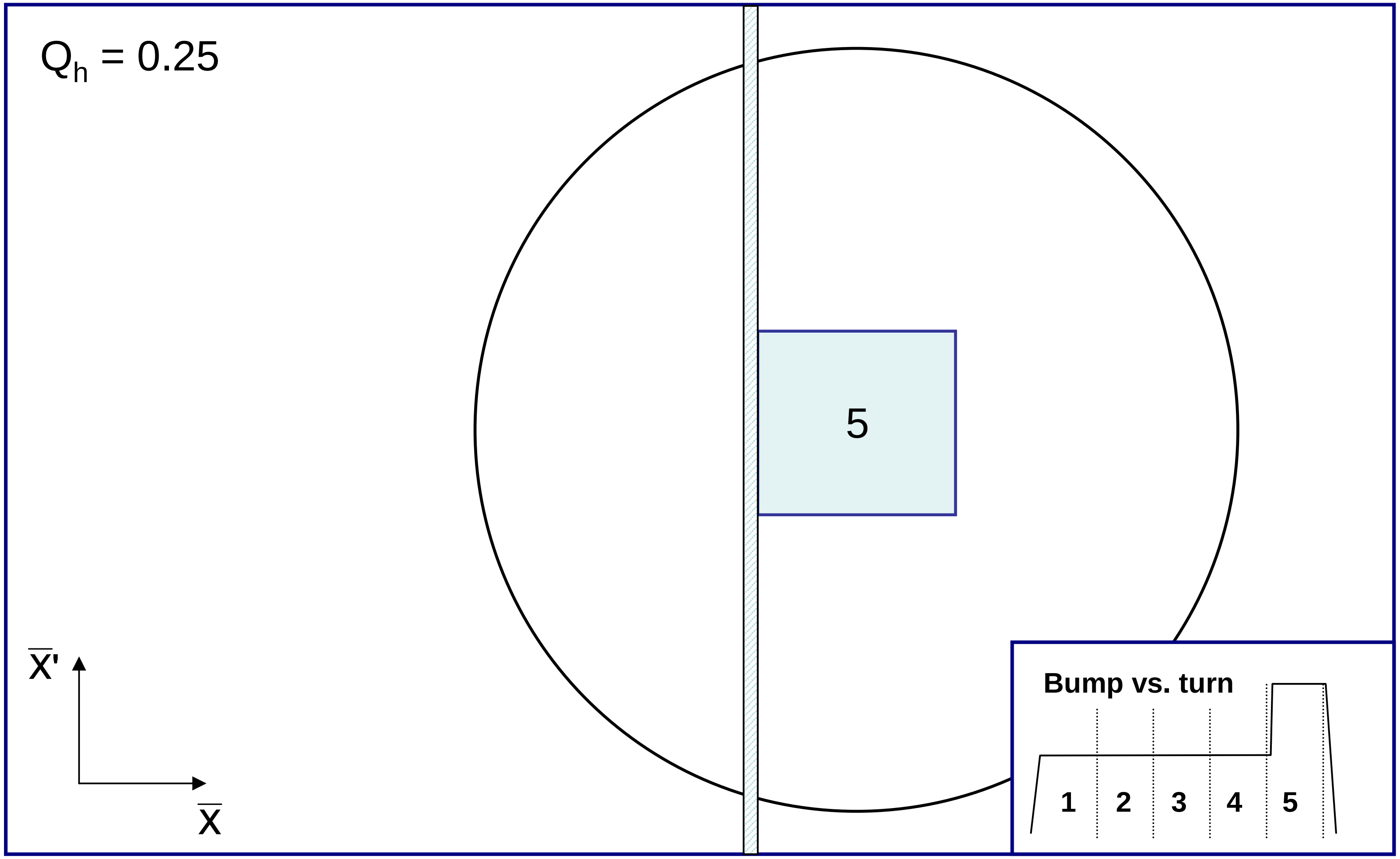
Non-resonant multi-turn extraction

CERN PS to SPS: 5-turn continuous transfer



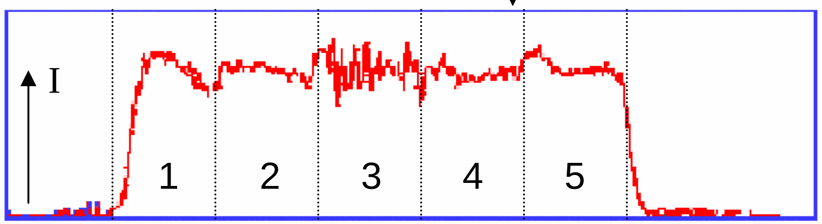
Non-resonant multi-turn extraction

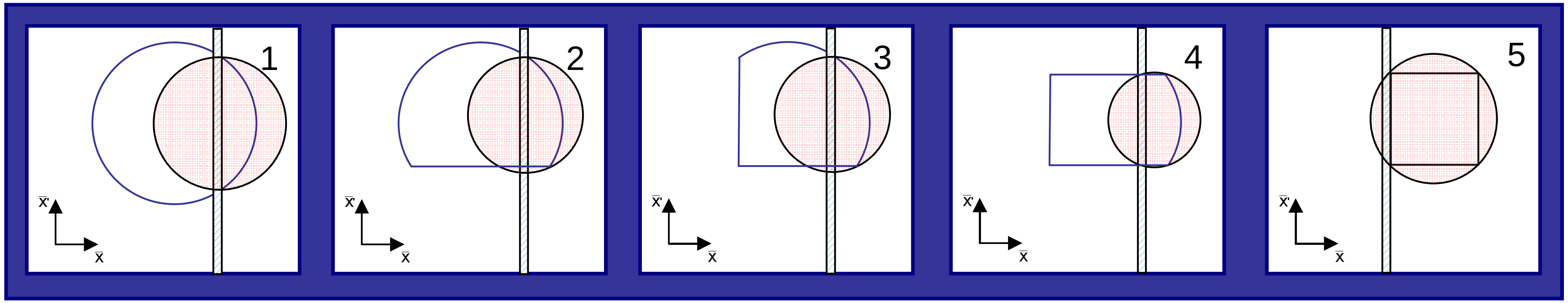
CERN PS to SPS: 5-turn continuous transfer – 5th turn



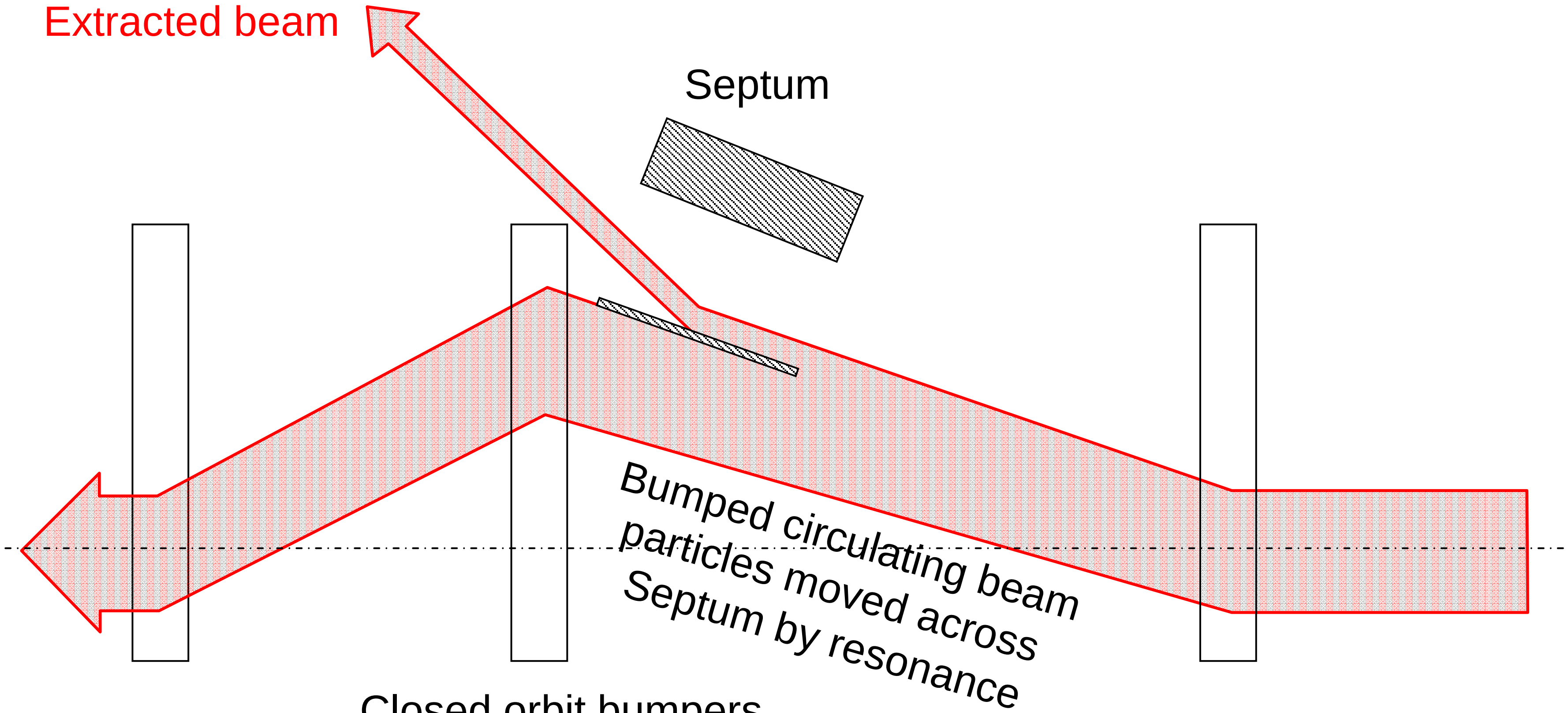
Non-resonant multi-turn extraction

- CERN PS to SPS: 5-turn continuous transfer
  - Losses impose thin (ES) septum… second septum needed
  - Still about 15 % of beam lost in PS-SPS CT
  - Difficult to get equal intensities per turn
  - Different trajectories for each turn
  - Different emittances for each turn





Resonant multi-turn extraction

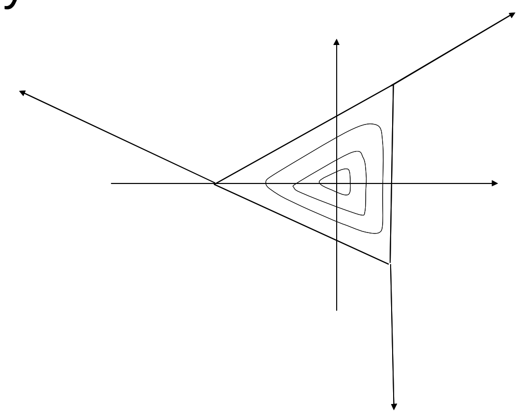


- Slow bumpers move the beam near the septum
- Horizontal tune adjusted closed to n^{th} order betatron resonance
- Multipole magnets excited to define stable area in phase space, size depends on $\Delta Q = Q - Q_r$

Resonant multi-turn extraction

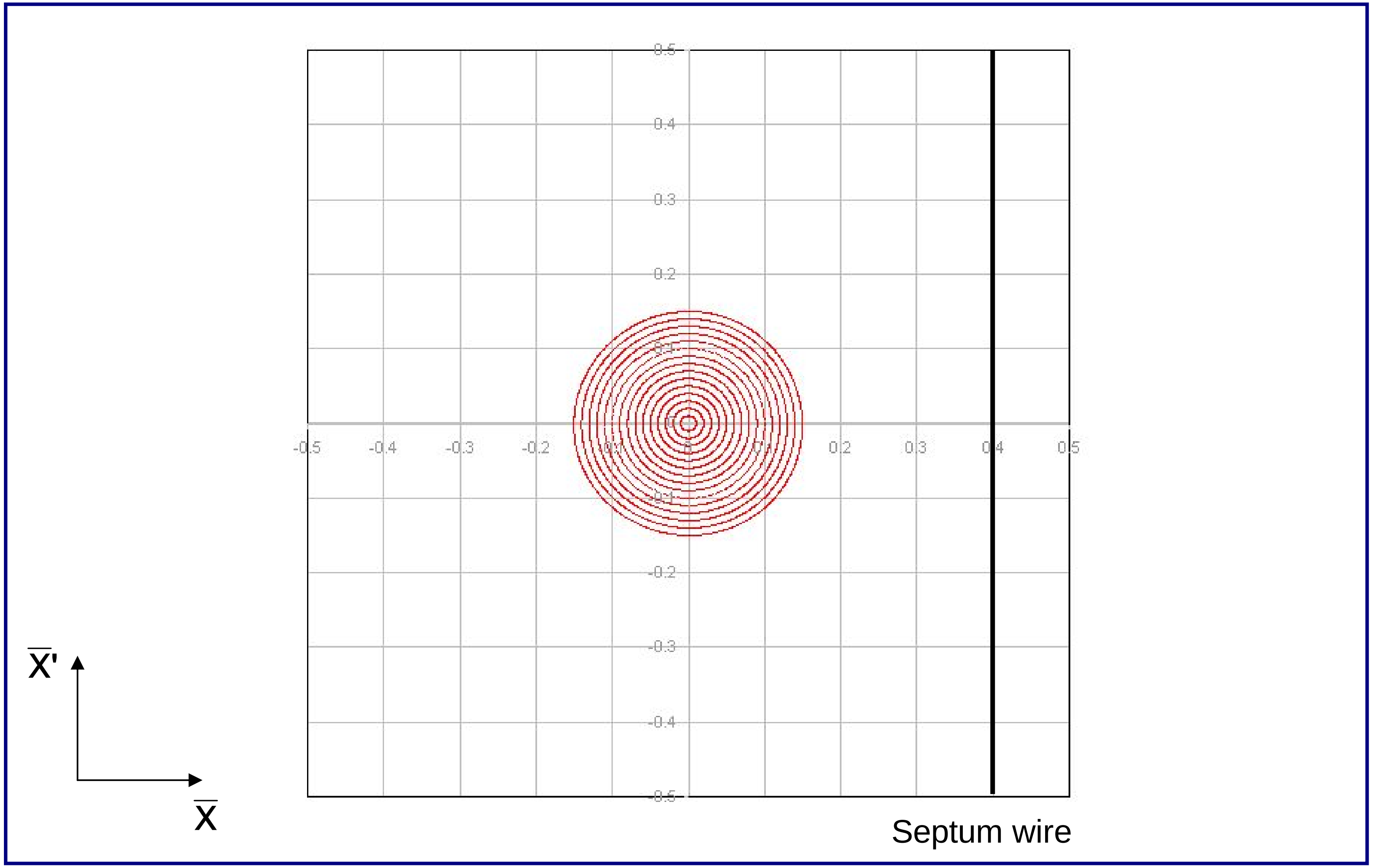
- 3^{rd} order resonances – Lecture from O.B.
  - Sextupole fields distort the circular normalised phase space particle trajectories.
  - Stable area defined, delimited by unstable Fixed Points.

$$R_{fp}^{1/2} \propto \Delta Q \cdot \frac{1}{k_2}$$



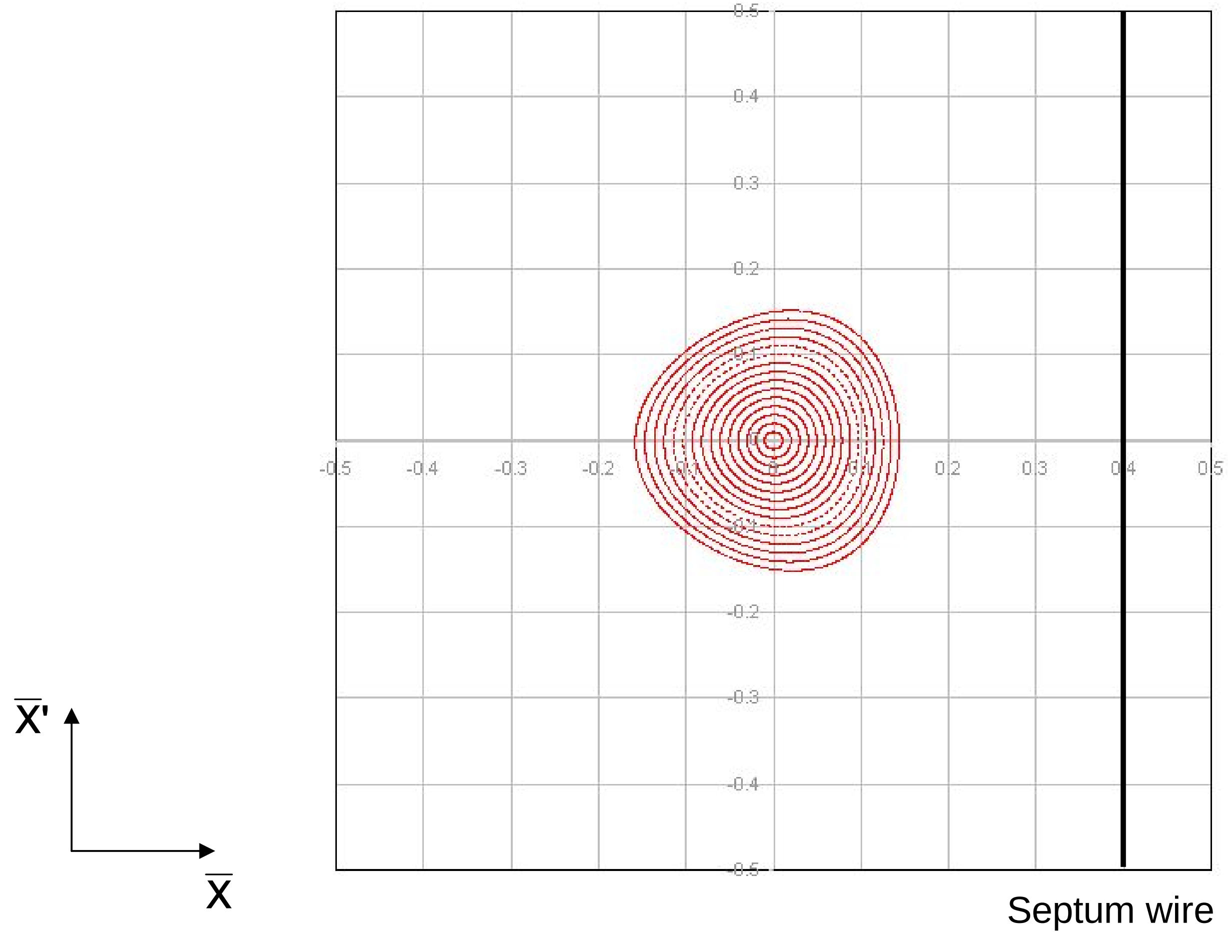
  - Sextupoles families arranged to produce suitable phase space orientation of the stable triangle at thin electrostatic septum
  - Stable area can be reduced by increasing the sextupole strength, or (easier) by approaching Q_h to the resonant 1/3 integer tune
  - Reducing ΔQ with main machine quadrupoles can be augmented with a ‘servo’ quadrupole, which can modulate ΔQ in a servo loop, acting on a measurement of the spill intensity

Third-order resonant extraction



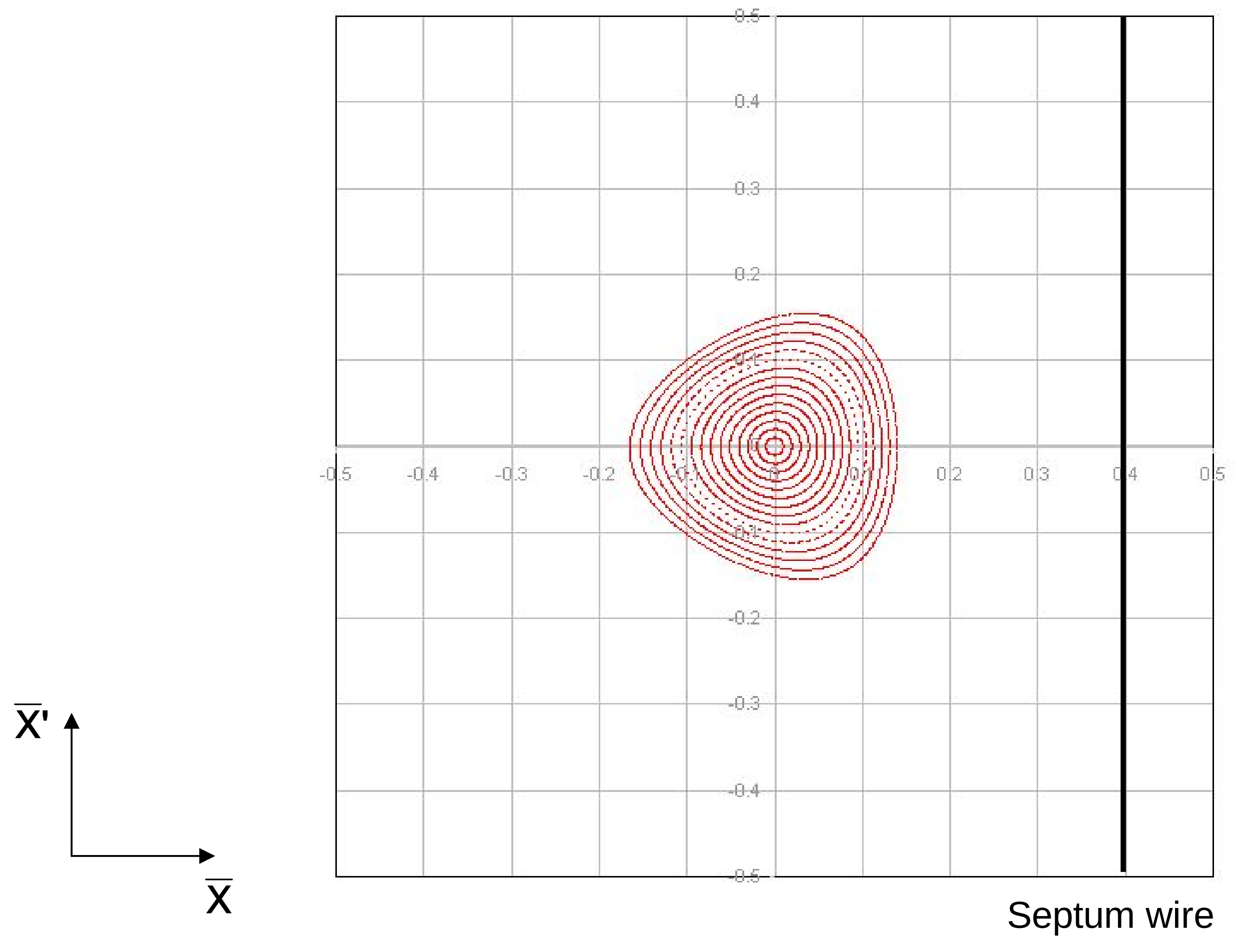
- Particles distributed on emittance contours
- ΔQ large – no phase space distortion

Third-order resonant extraction

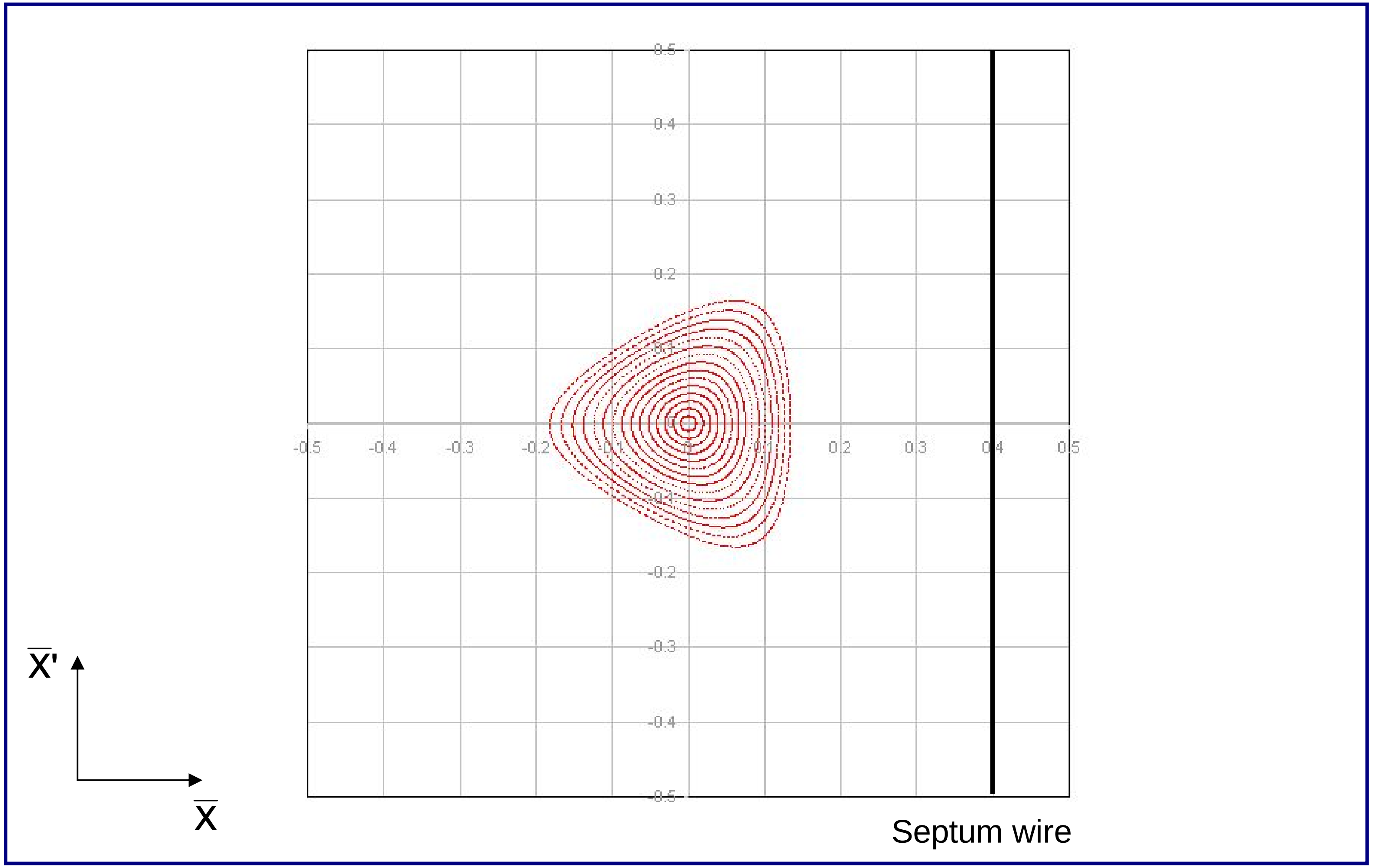


• Dedicated sextupole magnets produce a triangular stable area in phase space
• ΔQ decreasing – phase space distortion for largest amplitudes

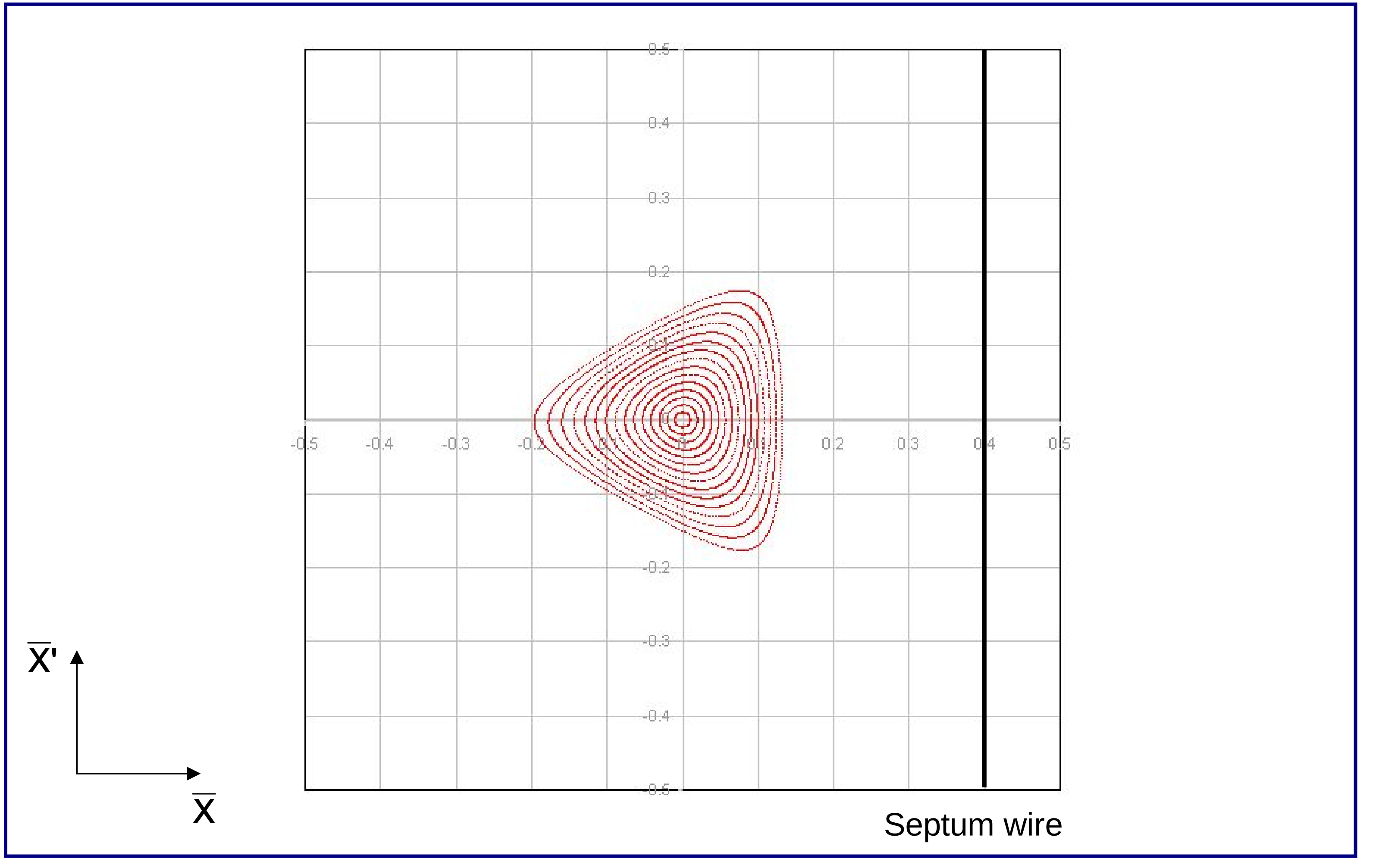
Third-order resonant extraction



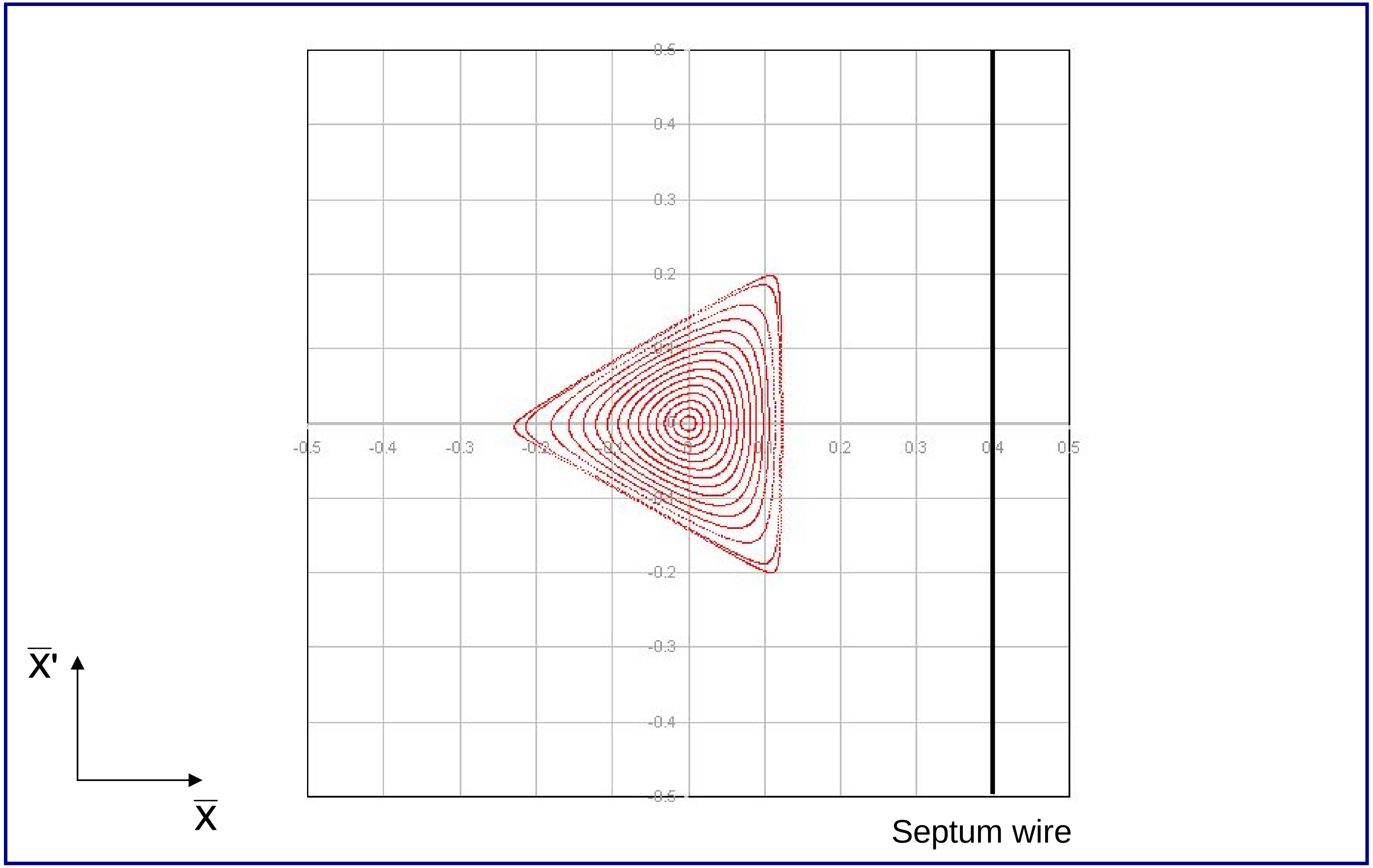
Third-order resonant extraction



Third-order resonant extraction

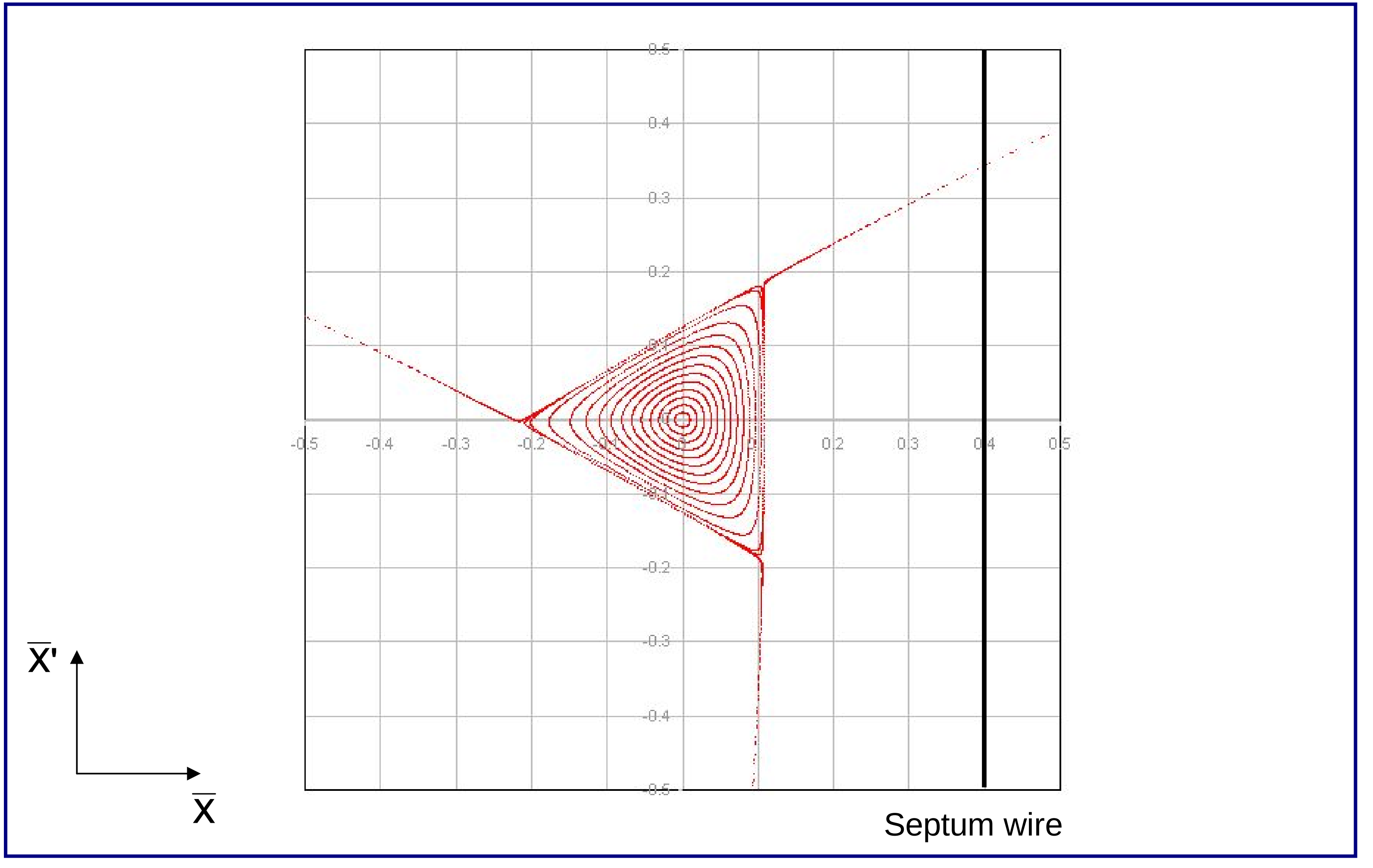


Third-order resonant extraction



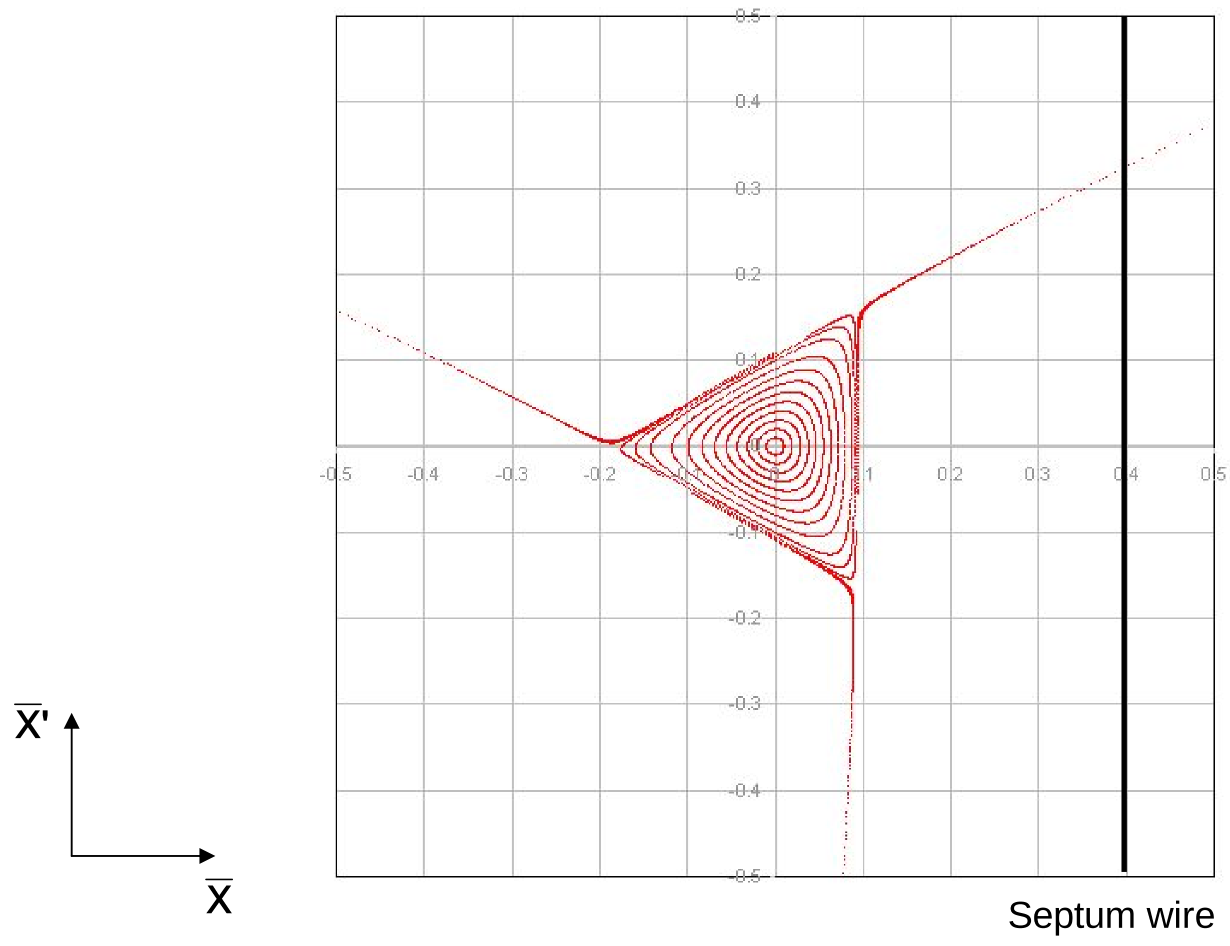
- ΔQ small enough that largest amplitude particles are close to the separatrices
- Fixed points locations discernable at extremities of phase space triangle

Third-order resonant extraction



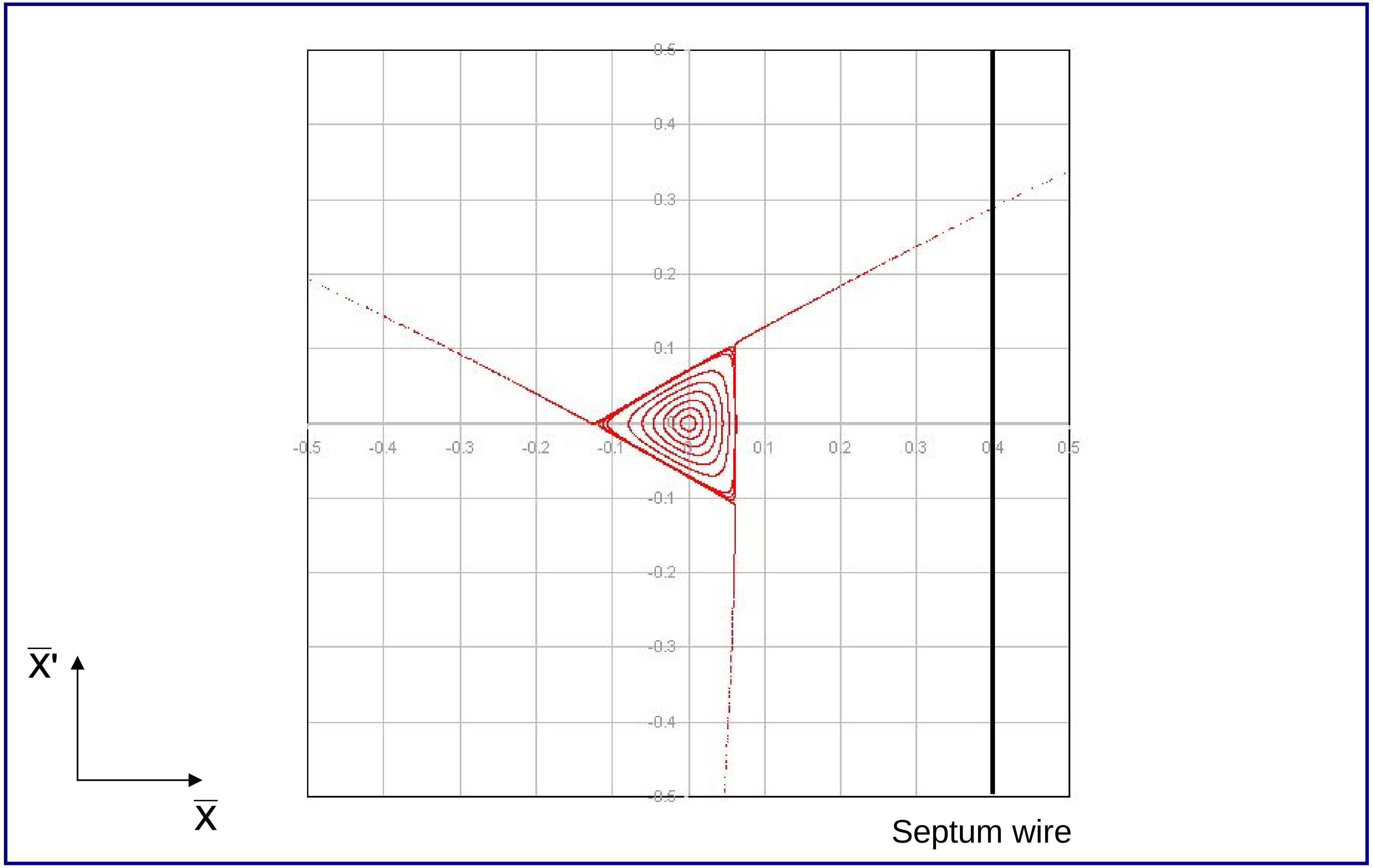
- ΔQ now small enough that largest amplitude particles are unstable
- Unstable particles follow separatrix branches as they increase in amplitude

Third-order resonant extraction



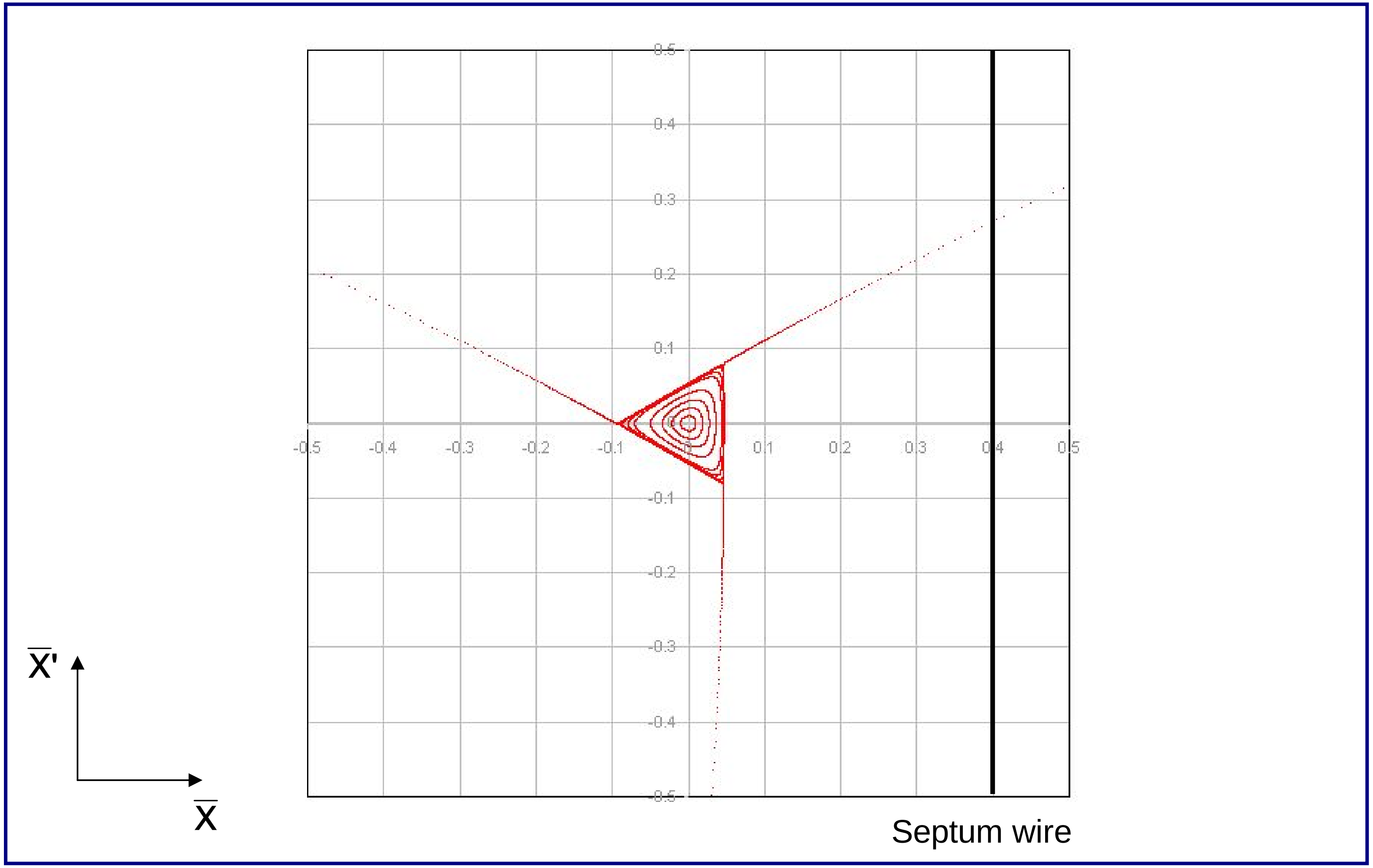
• Stable phase area shrinks as ΔQ gets smaller

Third-order resonant extraction



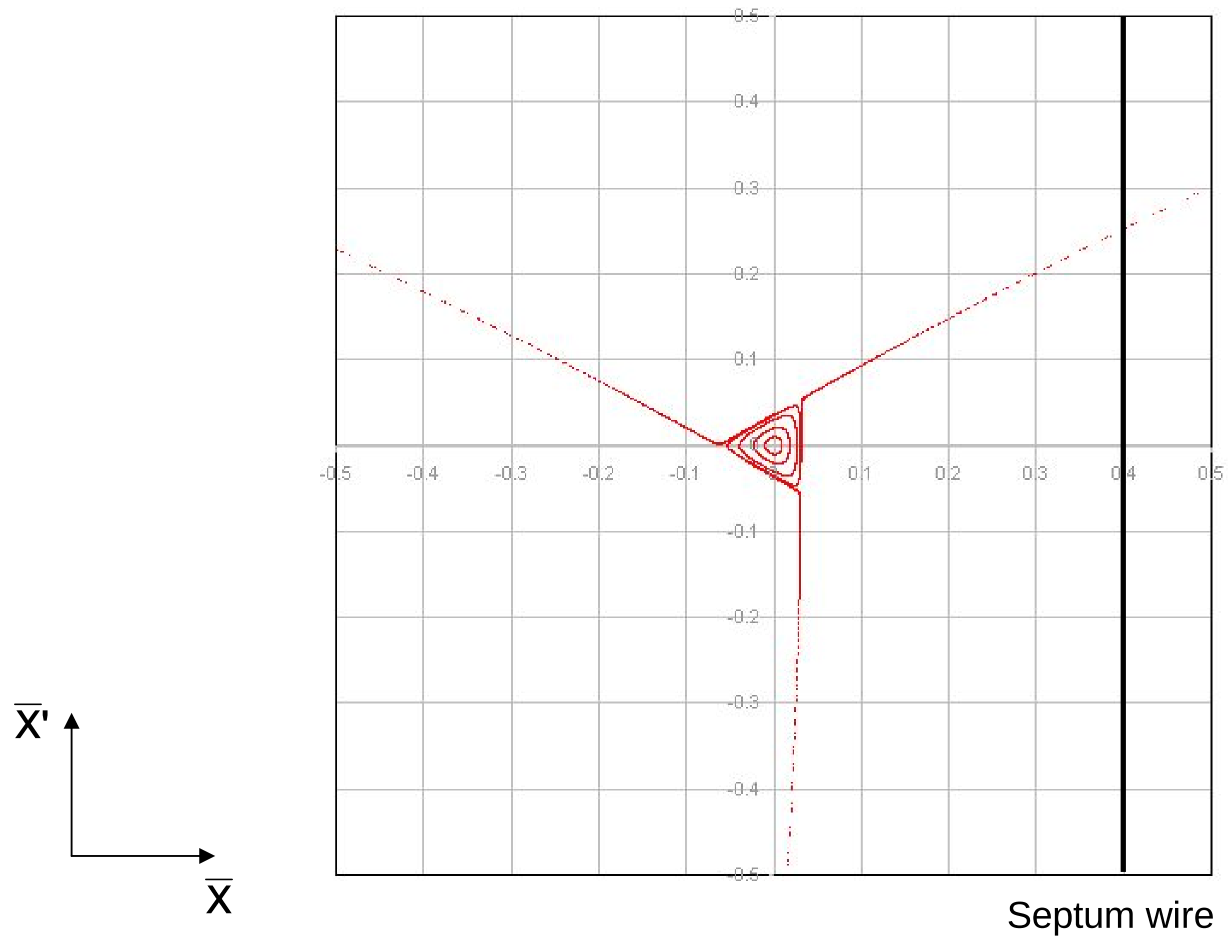
- Separatrix position in phase space shifts as the stable area shrinks

Third-order resonant extraction

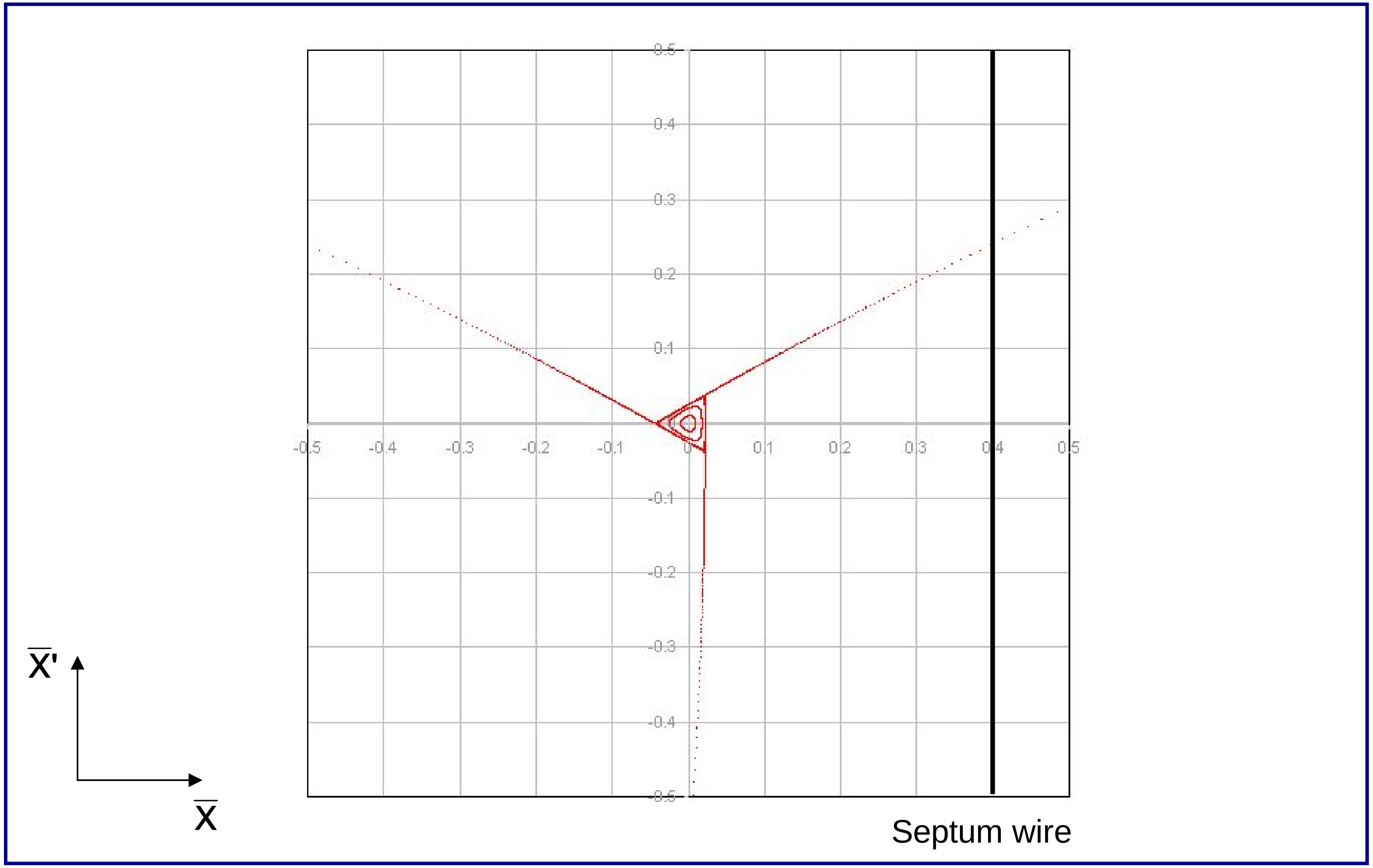


• As the stable area shrinks, the beam intensity drops since particles are being continuously extracted

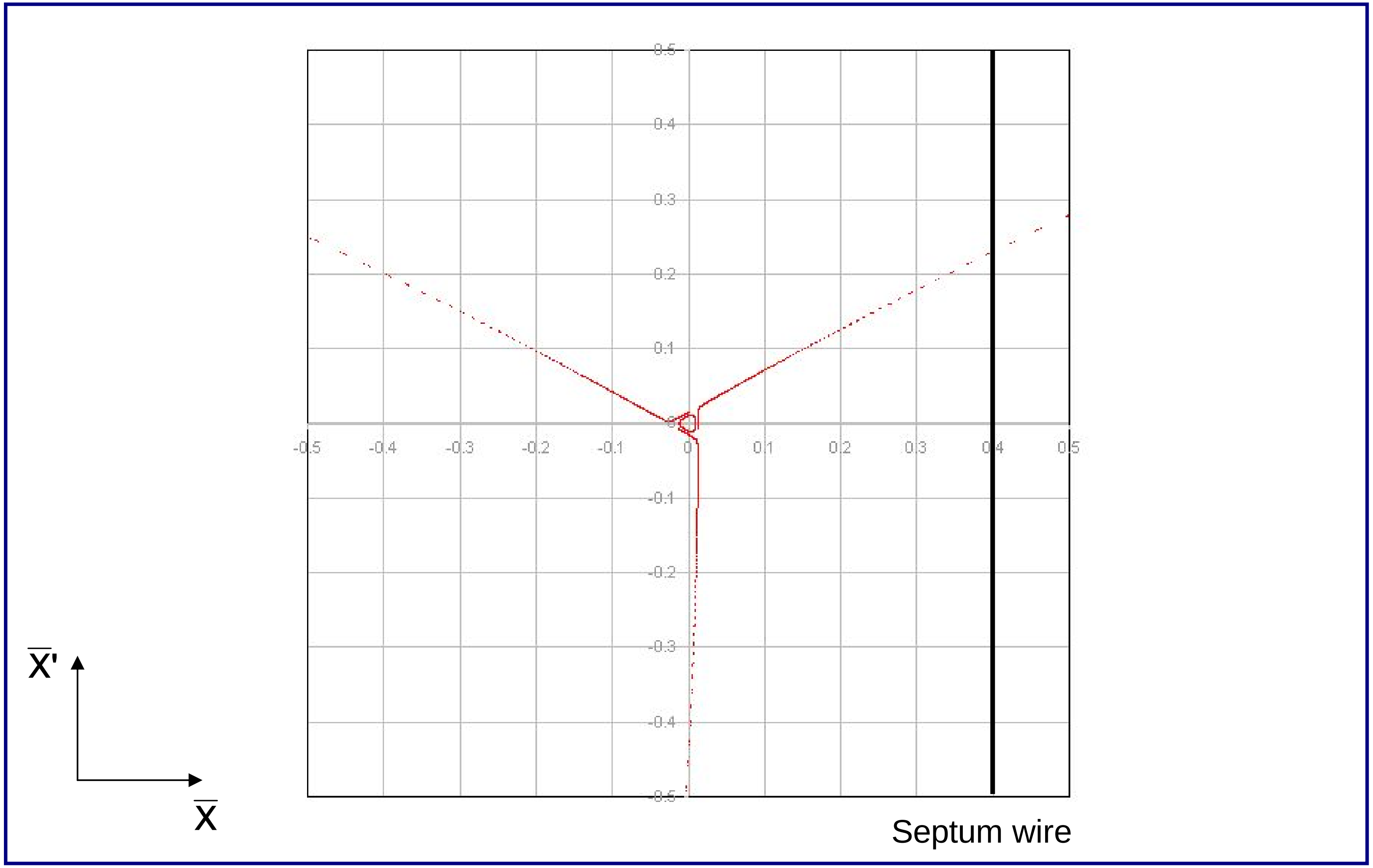
Third-order resonant extraction



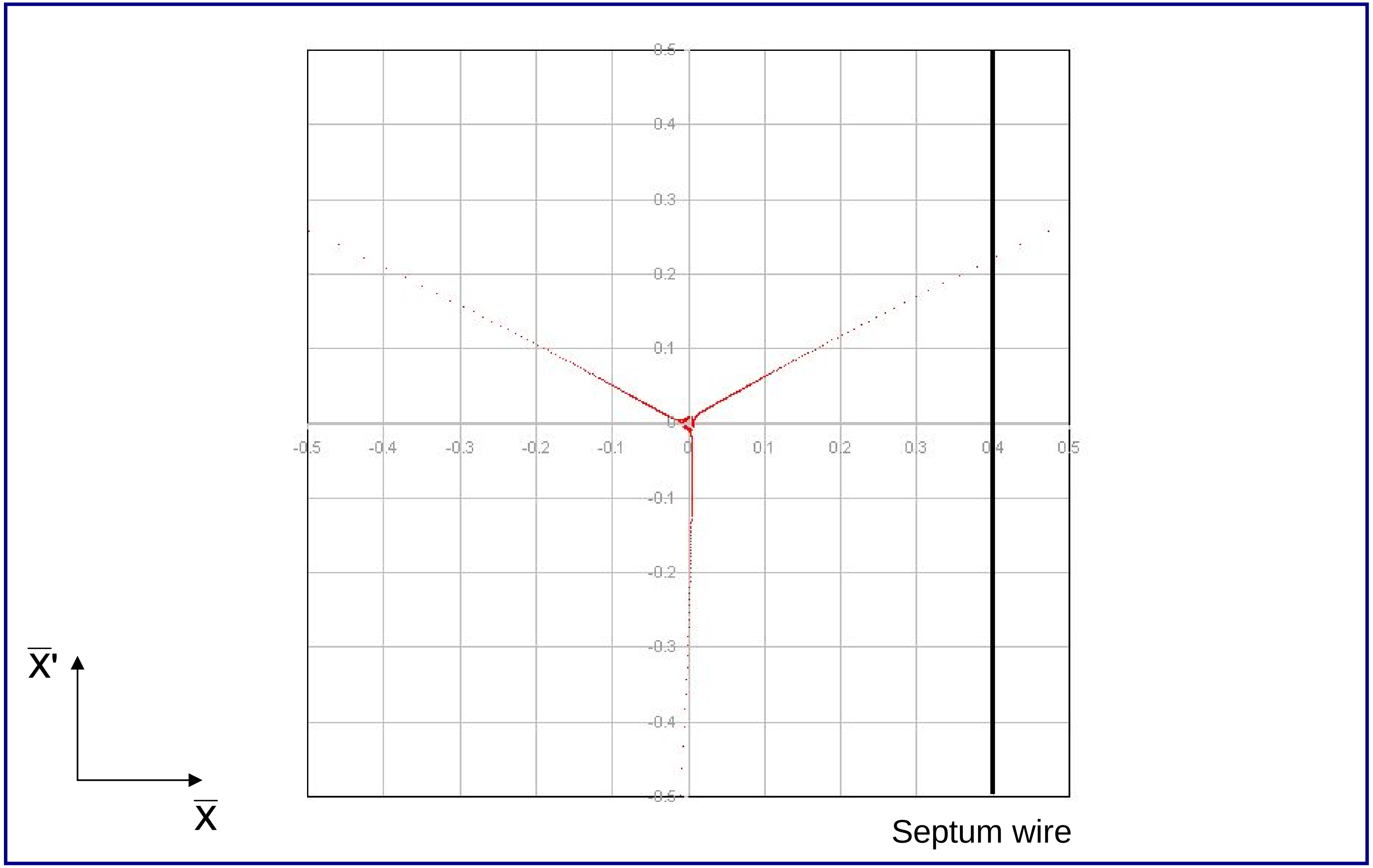
Third-order resonant extraction



Third-order resonant extraction



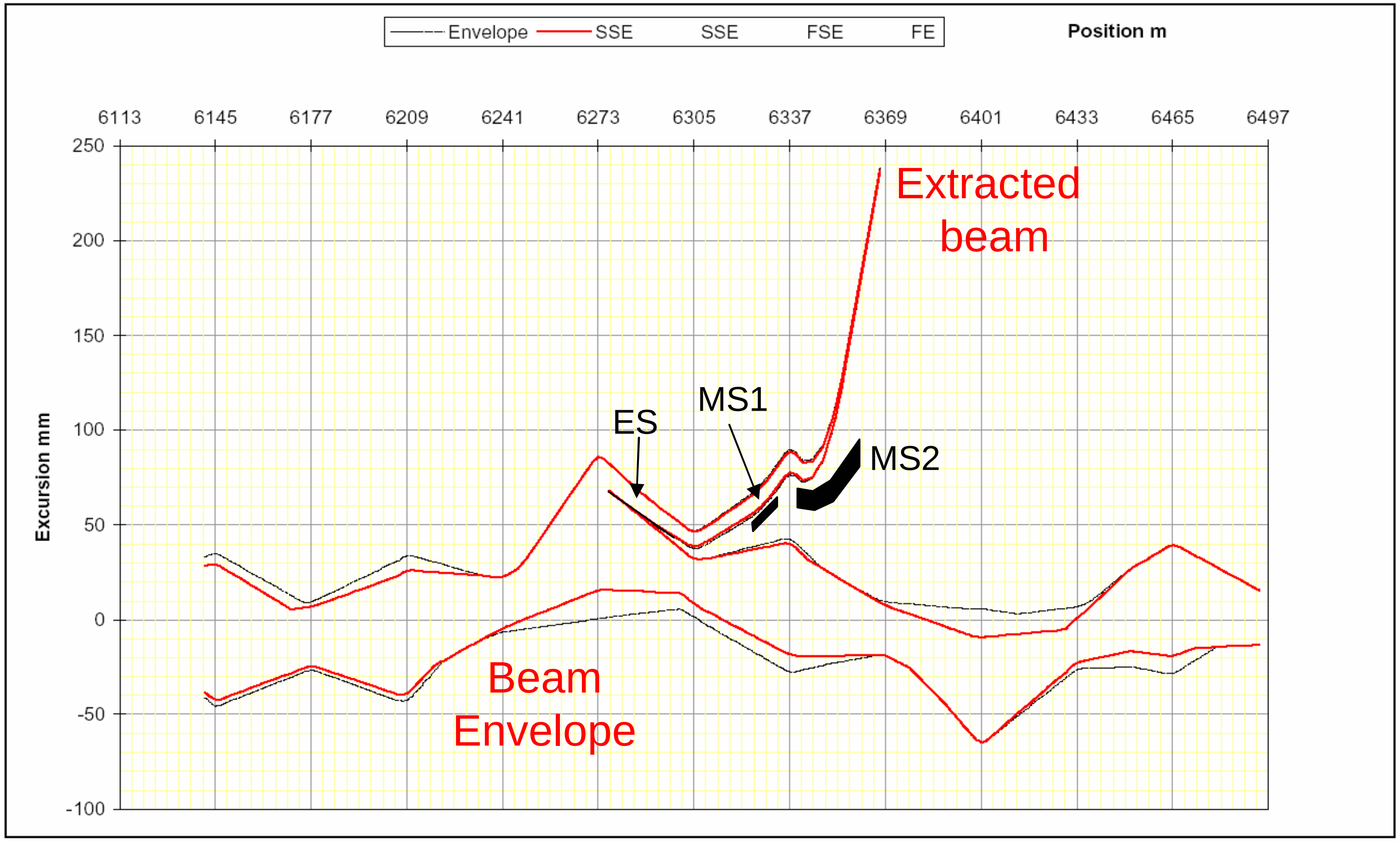
Third-order resonant extraction



• As ΔQ approaches zero, the particles with very small amplitude are extracted.

Third-order resonant extraction

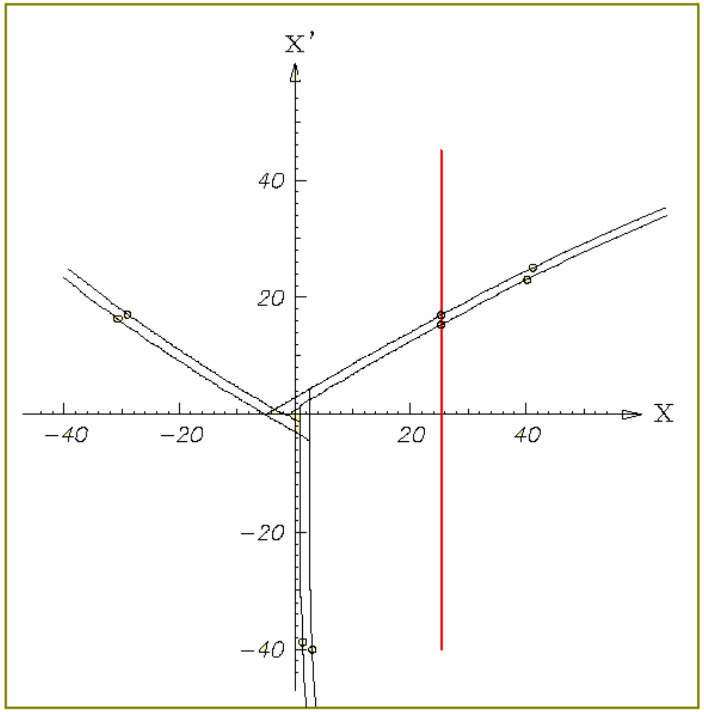
System example – SPS slow extraction at 450 GeV/c.
~3 x 10^{13} p+ extracted in a 2 second long spill (100,000 turns)



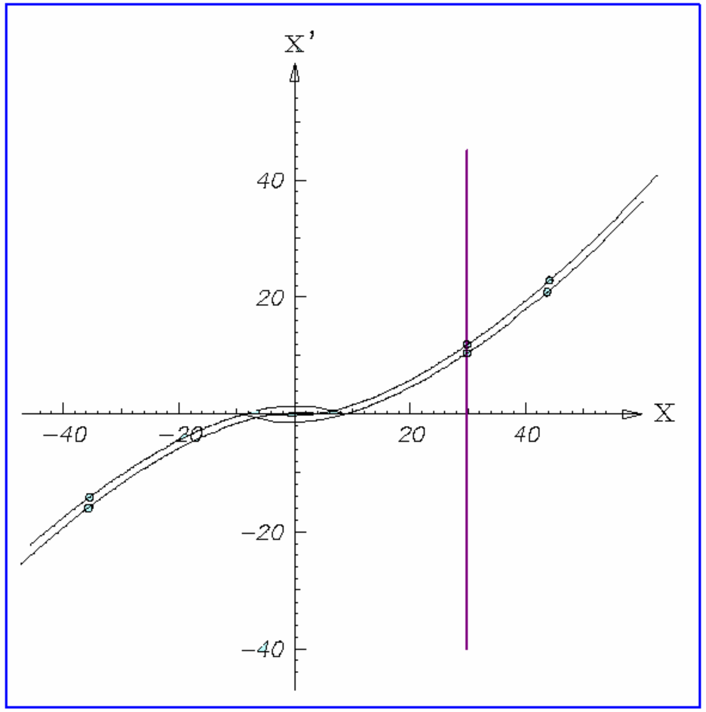
Second-order resonant extraction

- 2^{nd} and 4^{th} order resonances – Lecture from O.B.
  - Octupole fields distort the regular phase space particle trajectories.
  - Stable area defined, delimited by two unstable Fixed Points.
  - Beam tune brought across a 2^{nd} order resonance ($Q \rightarrow 0.5$)
  - Particle amplitudes quickly grow and beam is extracted in a few hundred turns.

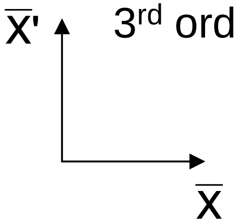
Second-order resonant extraction



3^{rd} order resonant extraction



2^{nd} order resonant extraction

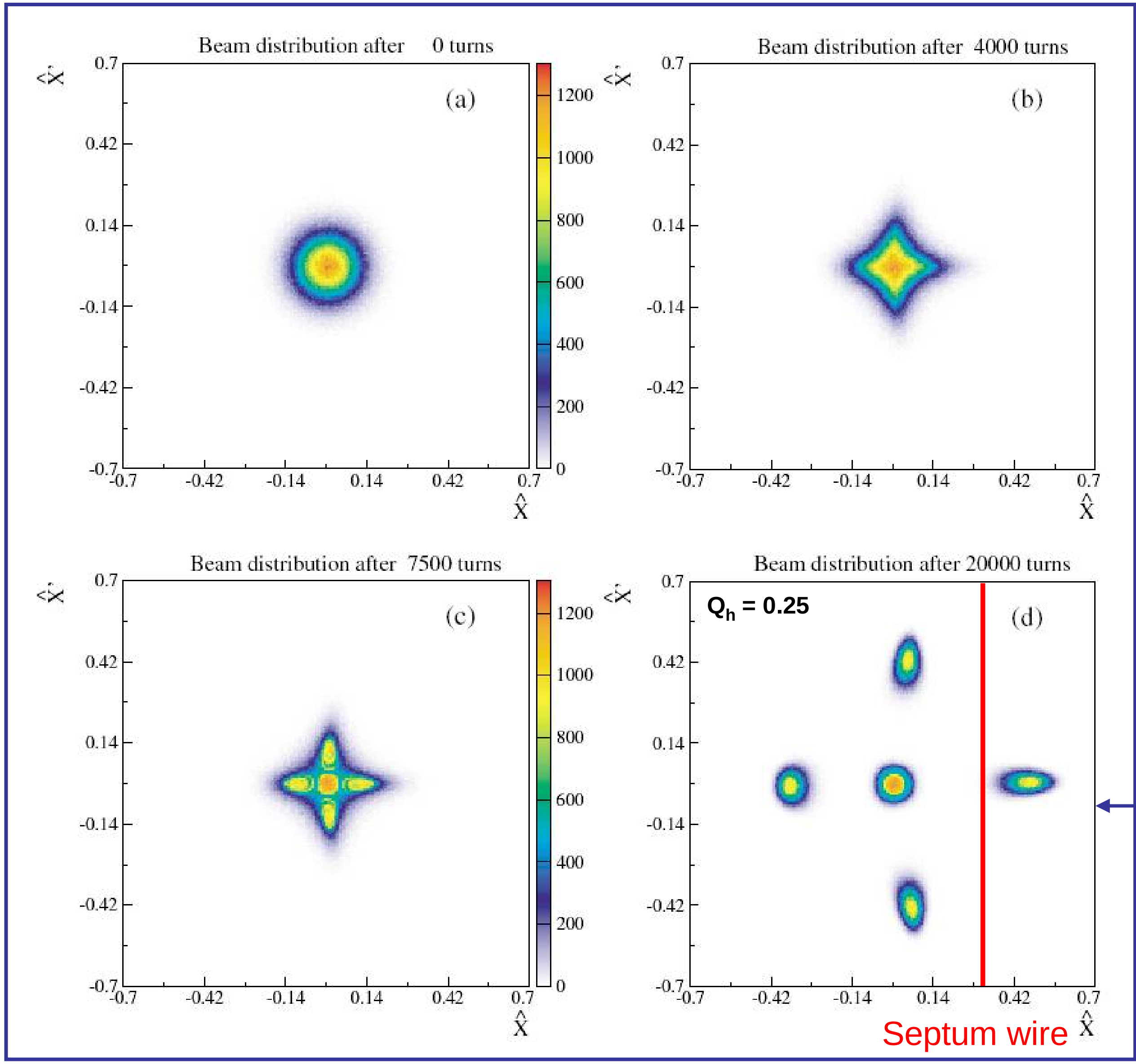


- Amplitude growth much faster than 3^{rd} order resonance – much shorter spill
- Used where intense pulses are required on target – e.g. neutrino production

Resonant low-loss multi-turn extraction

- Adiabatic capture of beam in stable islands
  - Use non-linear fields (sextupoles and octupoles) to create islands of stability in phase space
  - A slow (adiabatic) tune variation to cross a resonance and to drive particles into the islands (capture)
  - Variation of field strengths to separate the islands in phase space

Resonant low-loss multi-turn extraction

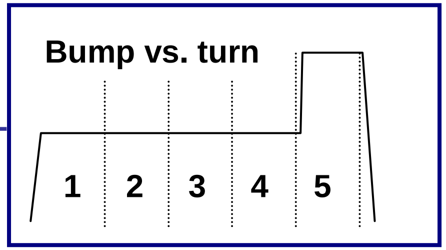


a. Unperturbed beam

b. Increasing non-linear fields

c. Beam captured in stable islands

d. Islands separated and beam bumped across septum – extracted in 5 turns



Resonant low-loss multi-turn extraction

- Several big advantages
  - Losses reduced virtually to zero (no particles at the septum)
  - Phase space matching improved with respect to existing non-resonant multi-turn extraction - all ‘beamlets’ have same emittance and optical parameters

- Being implemented in CERN PS – SPS
  - High intensity beam for neutrino experiment in SPS / Gran Sasso would produce too many losses with present CT
  - Only possibility to increase extracted beam intensity

Extraction - summary

- Kickers, septa and bumpers elements used.
- Single-turn fast extraction for Boxcar stacking (transfer between machines in accelerator chain), beam abort
- Non-resonant multi-turn extraction: slice beam into equal parts for transfer between machine over a few turns.
- Resonant multi-turn extraction: create stable area in phase space $\Rightarrow$ slowly drive particles into resonance $\Rightarrow$ long spill over many thousand turns.
- Resonant low-loss multi-turn extraction: create stable islands in phase space: slice off over a few turns.