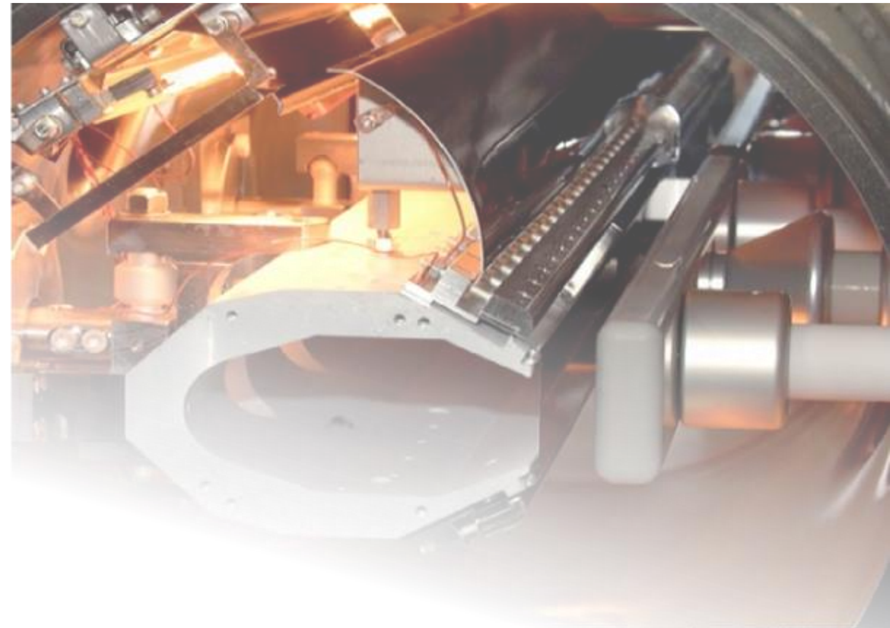
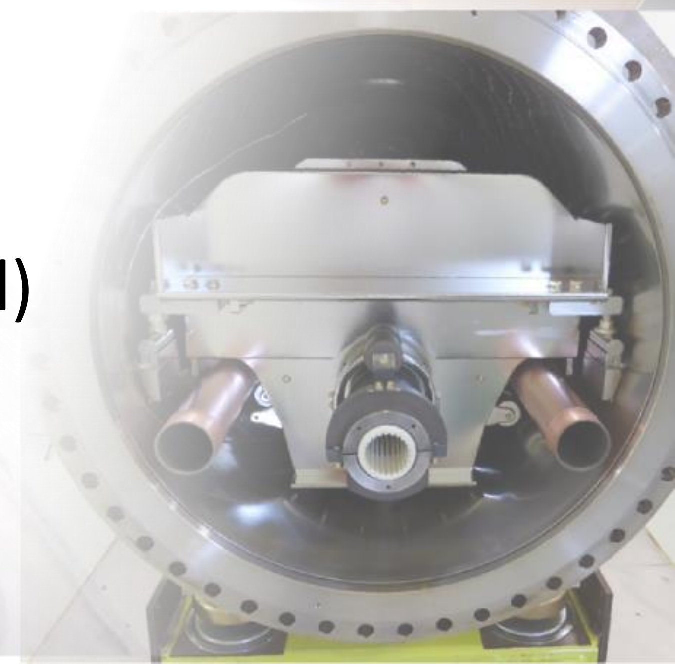
Injection and extraction

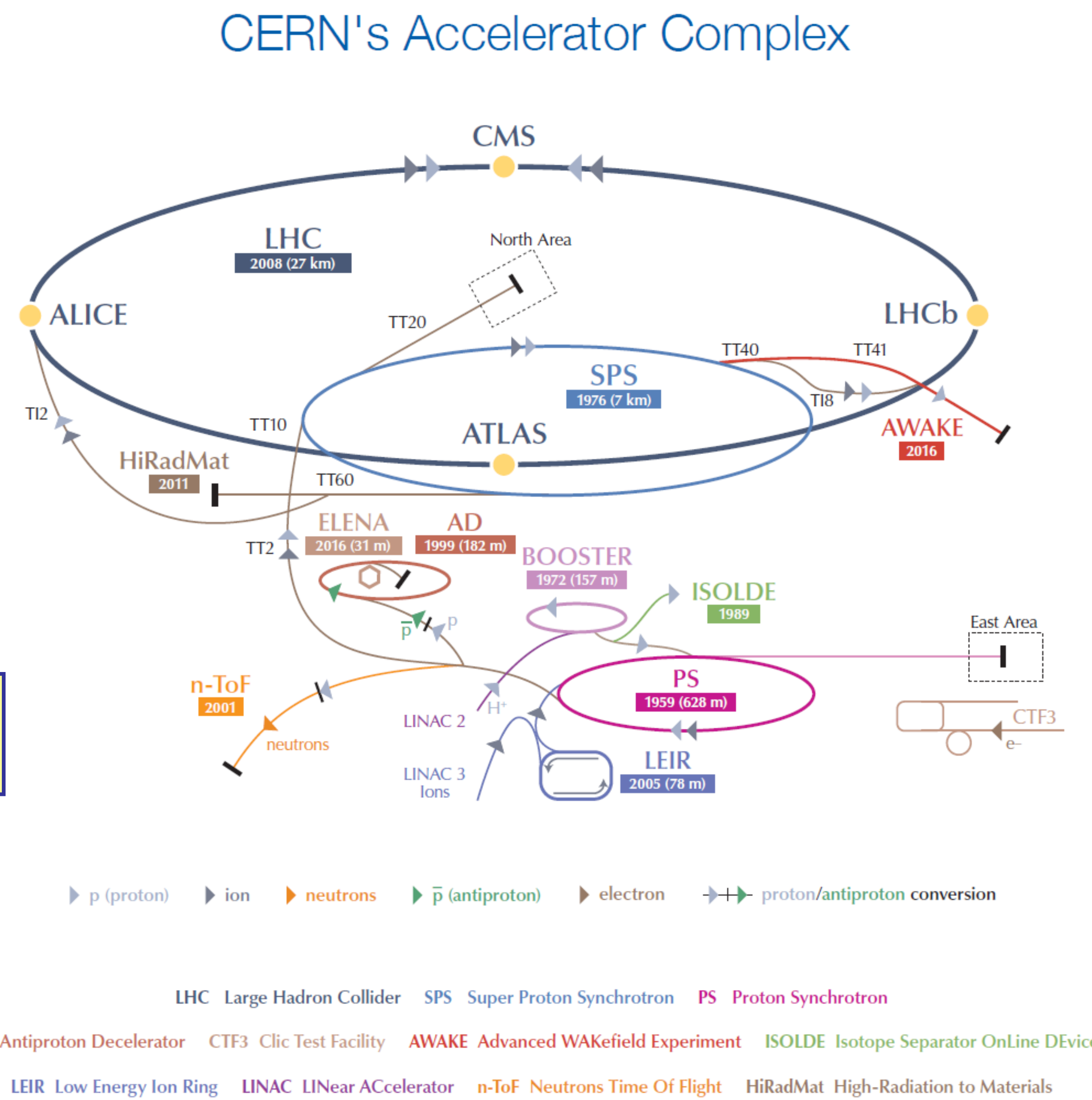


Wolfgang Bartmann
CERN
(based on lectures by Brennan Goddard)



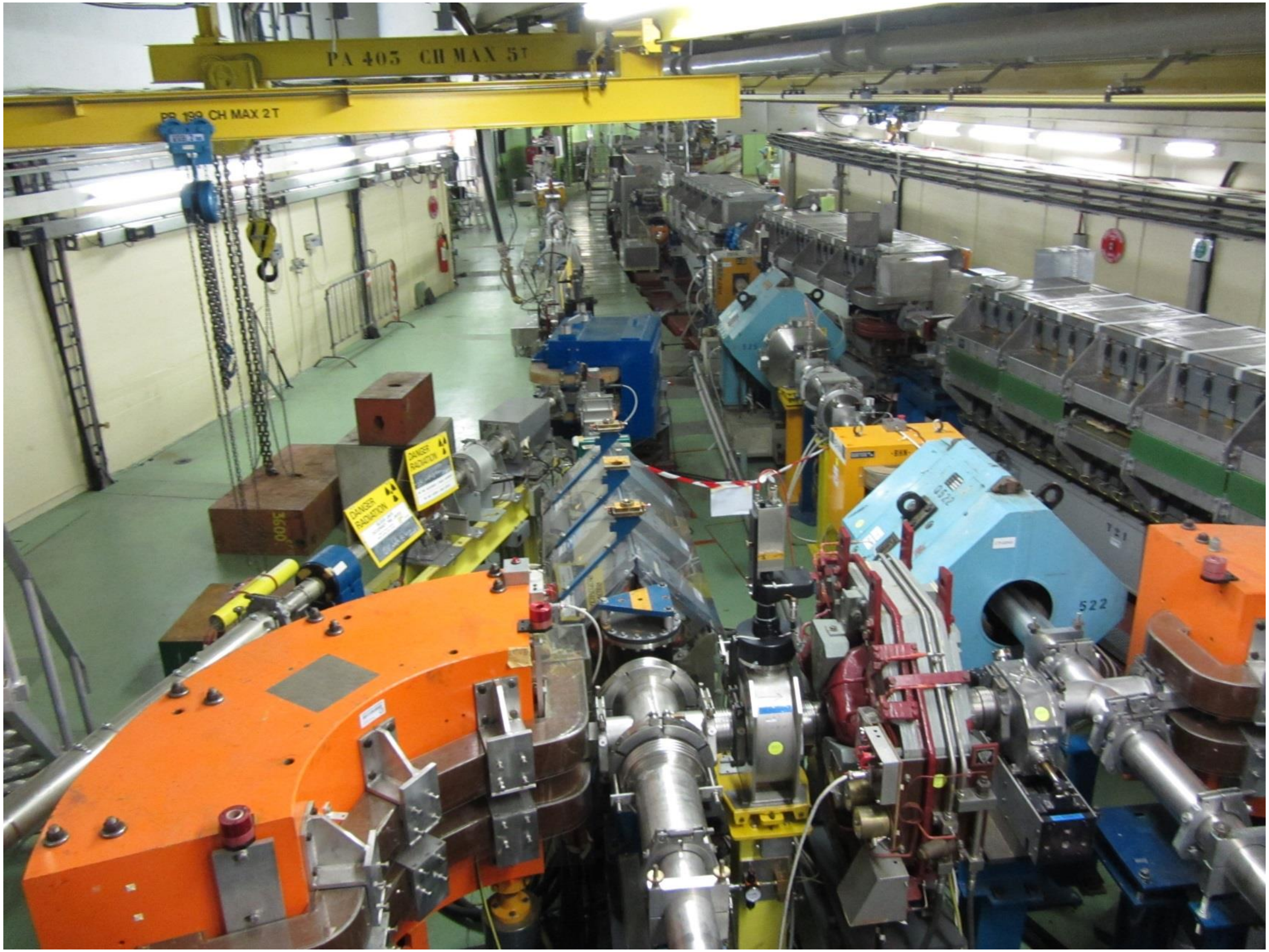
Injection, extraction and transfer

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



Beam transfer (into, out of, and between machines) is necessary.

Injection, extraction and transfer

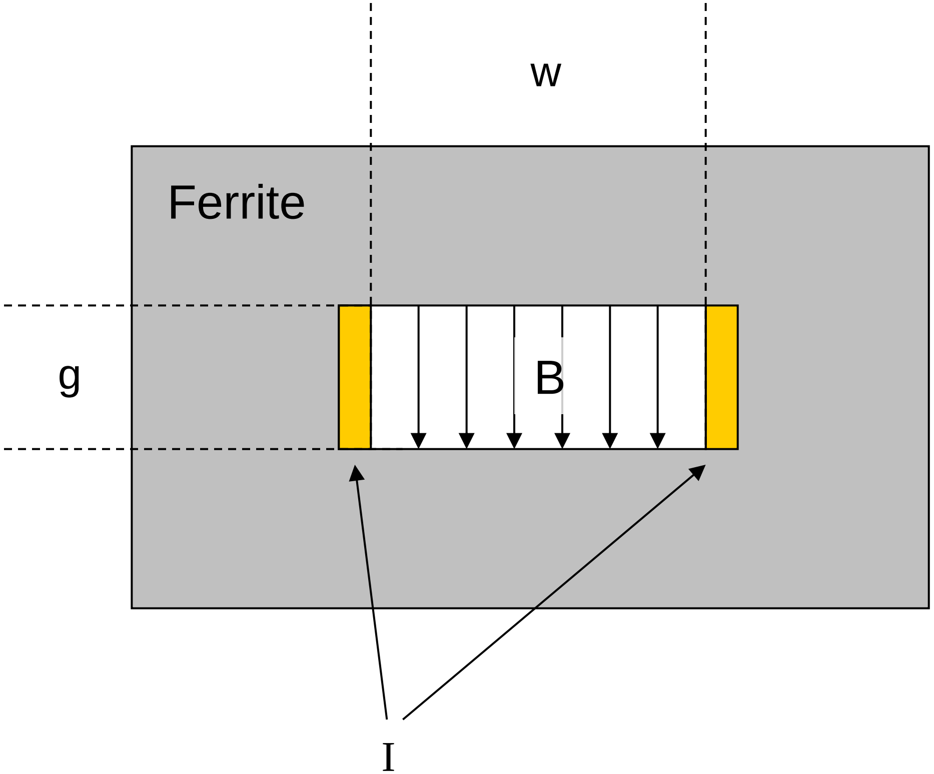


Injection, extraction and transfer

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

Kicker magnet

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



$B = \mu_0 I / g$

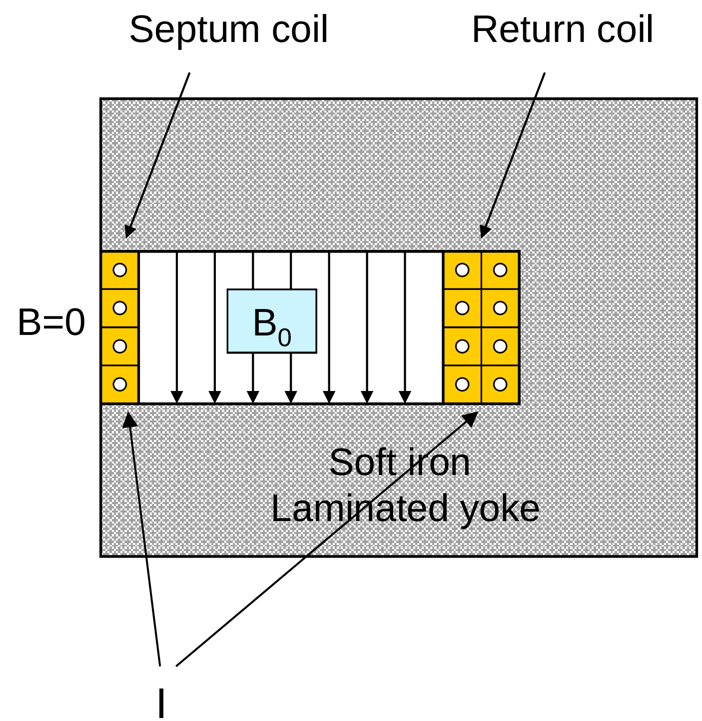
$L = \mu_0 w l / g$ (magnet length l)

$dI/dt = V/L$

Typically 3 kA in 1 μs rise time

Magnetic septum

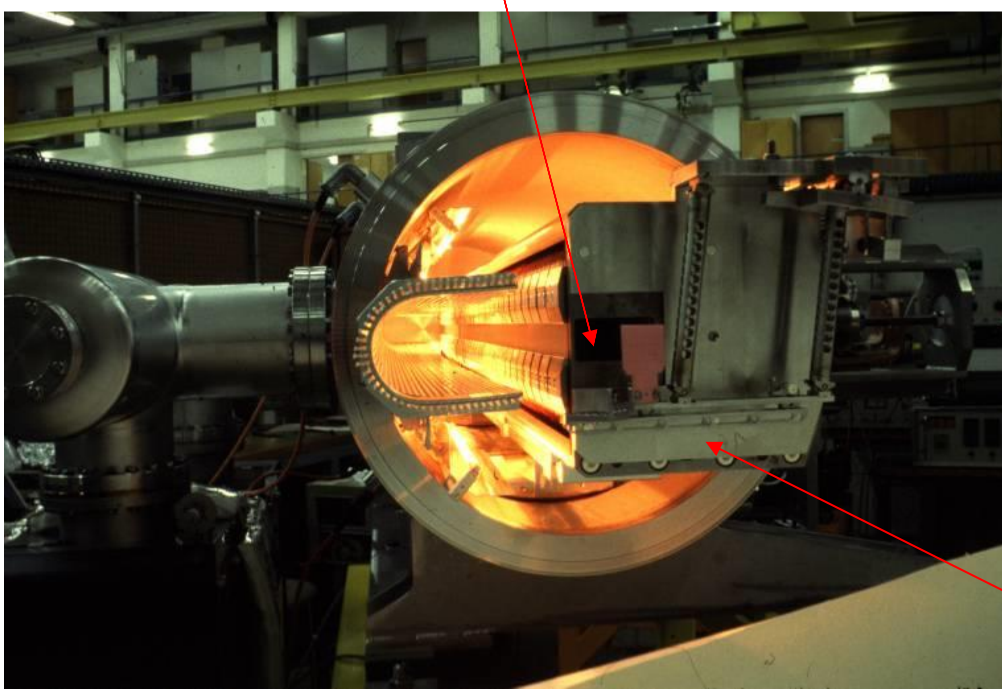
Pulsed or DC magnet with thin (2-20mm) septum between zero field and high field region



$B_o = \mu_0 I / g$

Typically I 5-25 kA

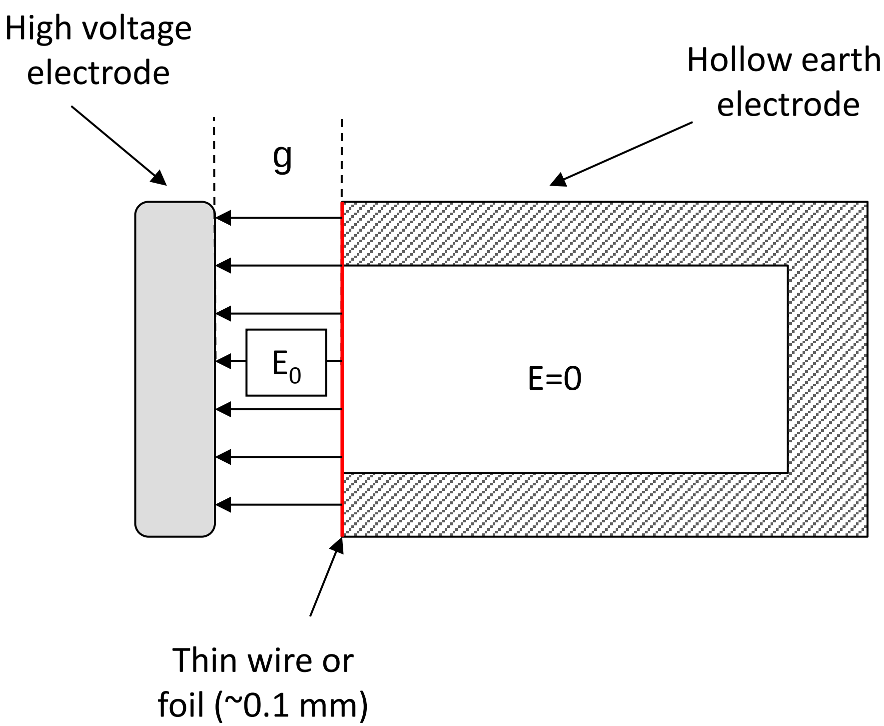
Septum coil



Yoke

Electrostatic septum

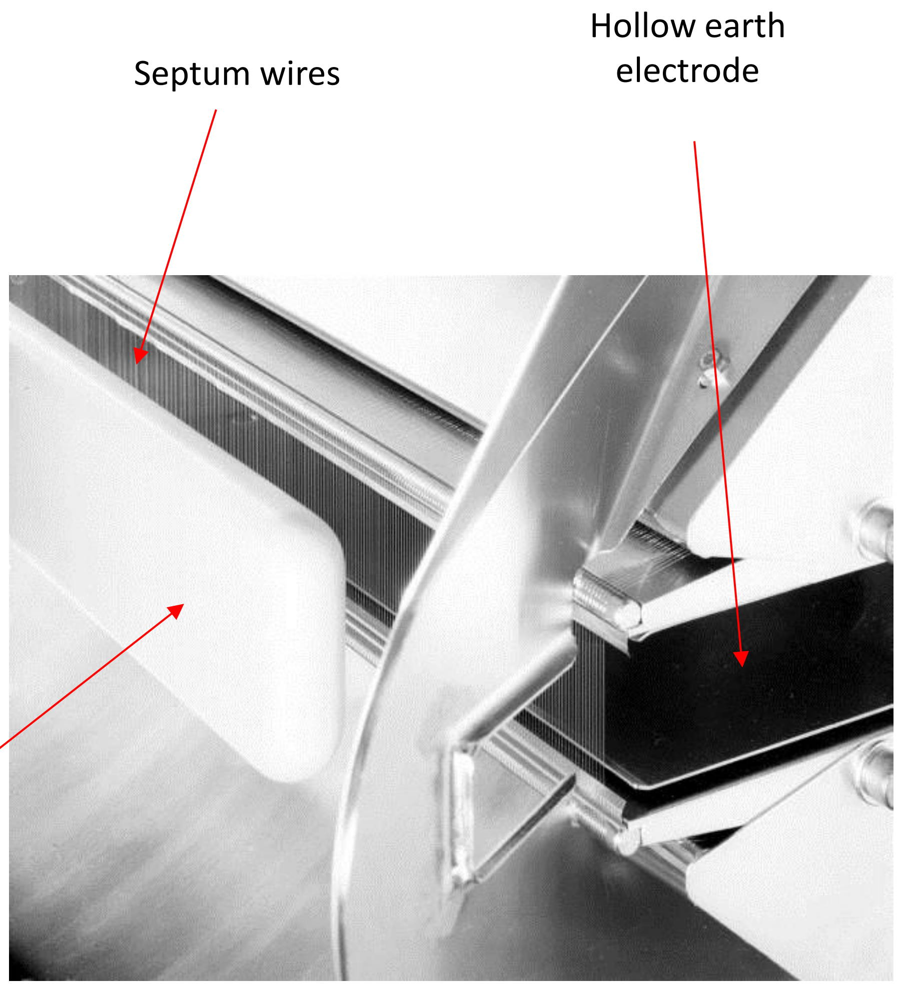
DC electrostatic device with very thin (~0.1mm) septum between zero field and high field region



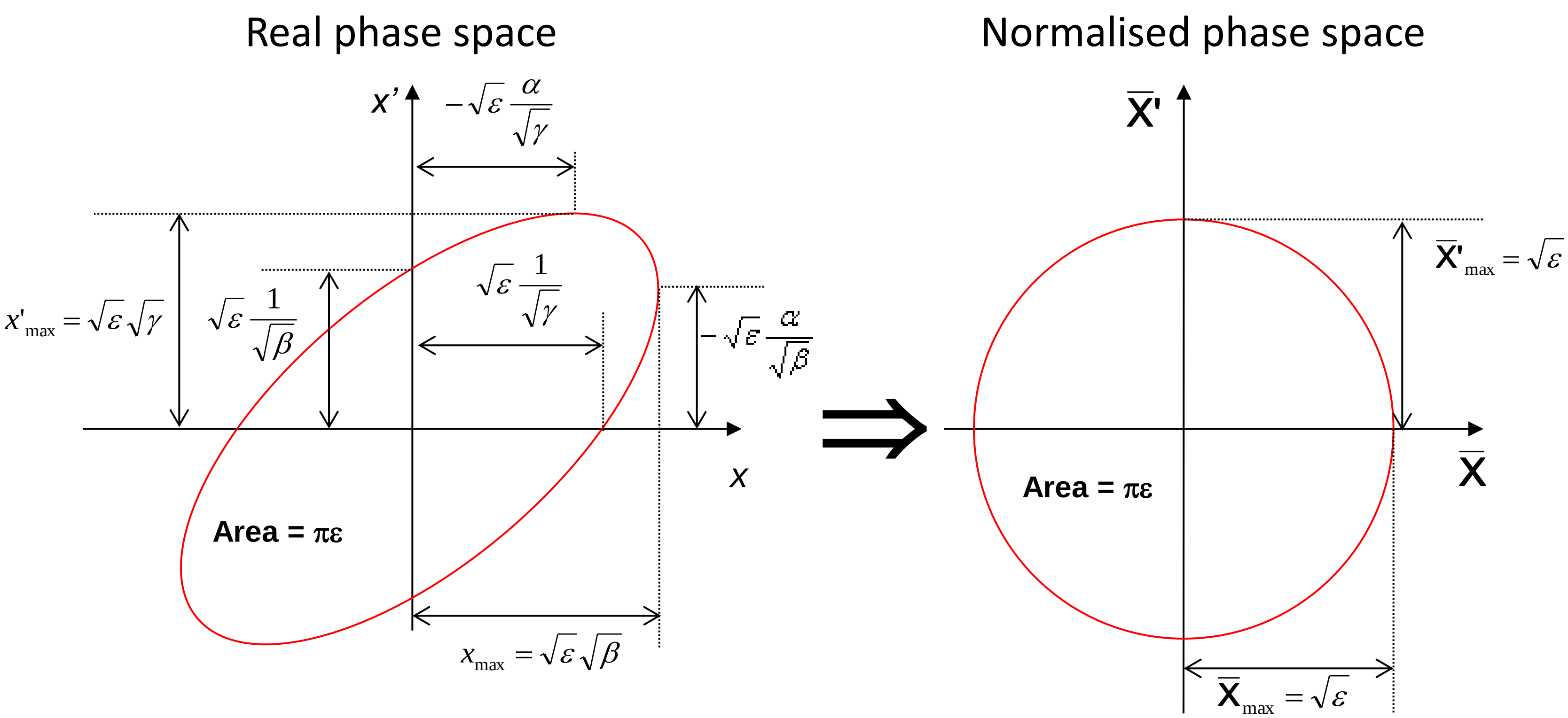
$E = V / g$

Typically V = 200 kV

E = 100 kV/cm



Normalised phase space



$$\varepsilon=\gamma\cdot x^2+2\alpha\cdot x\cdot x'+\beta\cdot x'^2$$

$$\varepsilon=\overline{X}^2+\overline{X}'^2$$

Normalised phase space

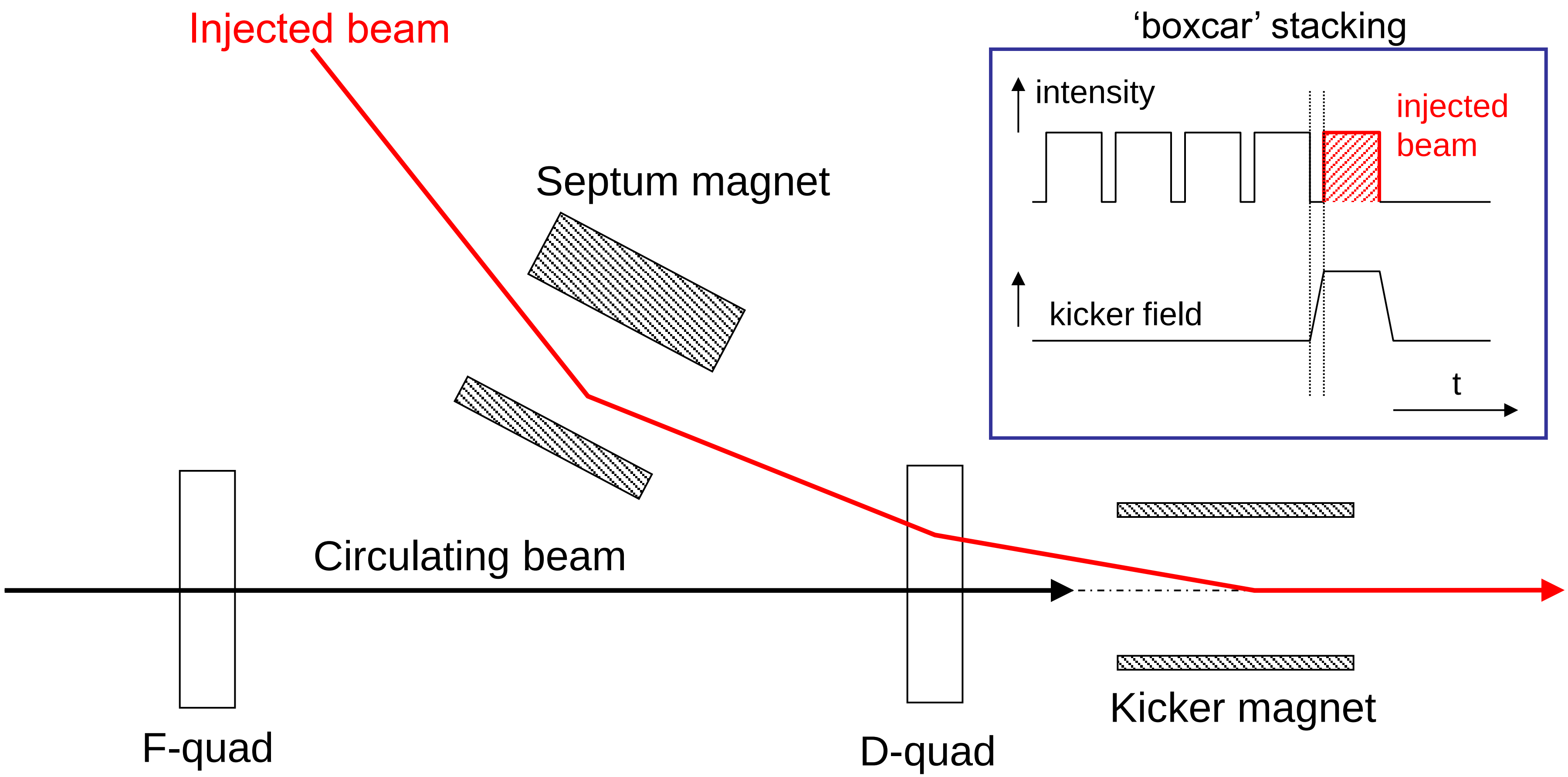
- Transform real transverse coordinates *x*, *x'* by

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

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

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

Single-turn injection – same plane

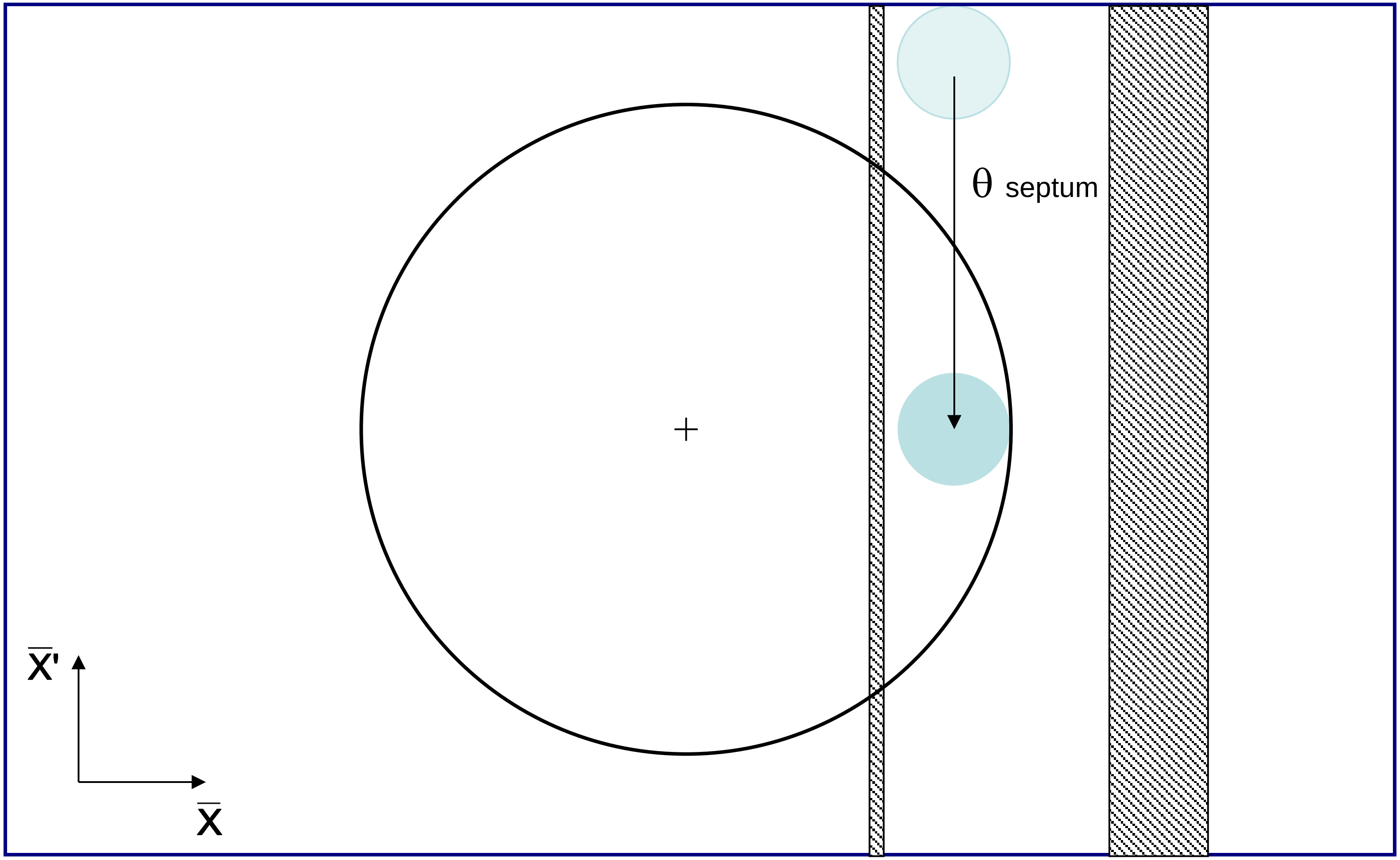


- Septum deflects the beam onto the closed orbit at the centre of the kicker
- Kicker compensates for the remaining angle
- Septum and kicker either side of D quad to minimise kicker strength

Single-turn injection

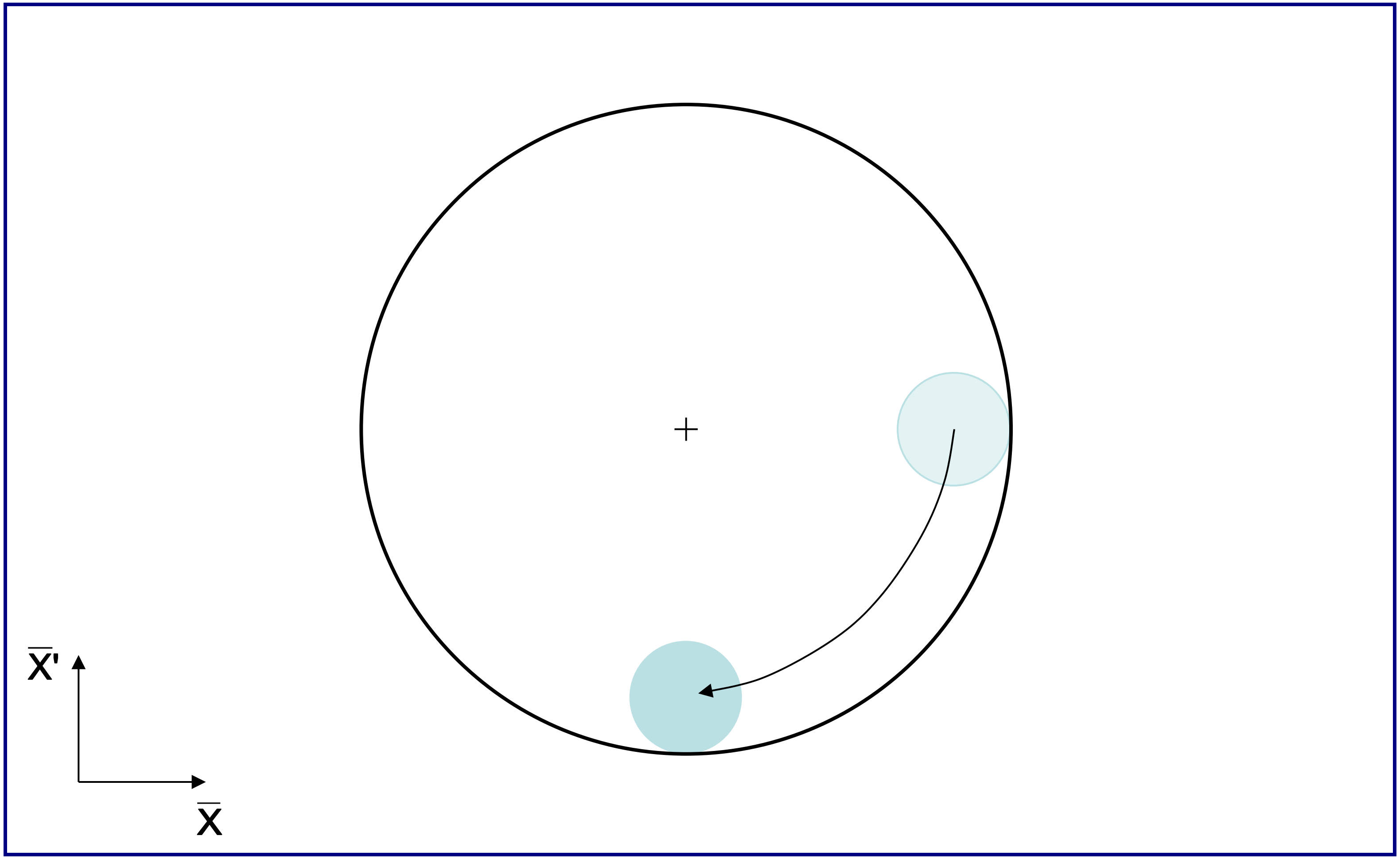
Normalised phase space at centre of idealised septum

Large deflection by septum



Single-turn injection

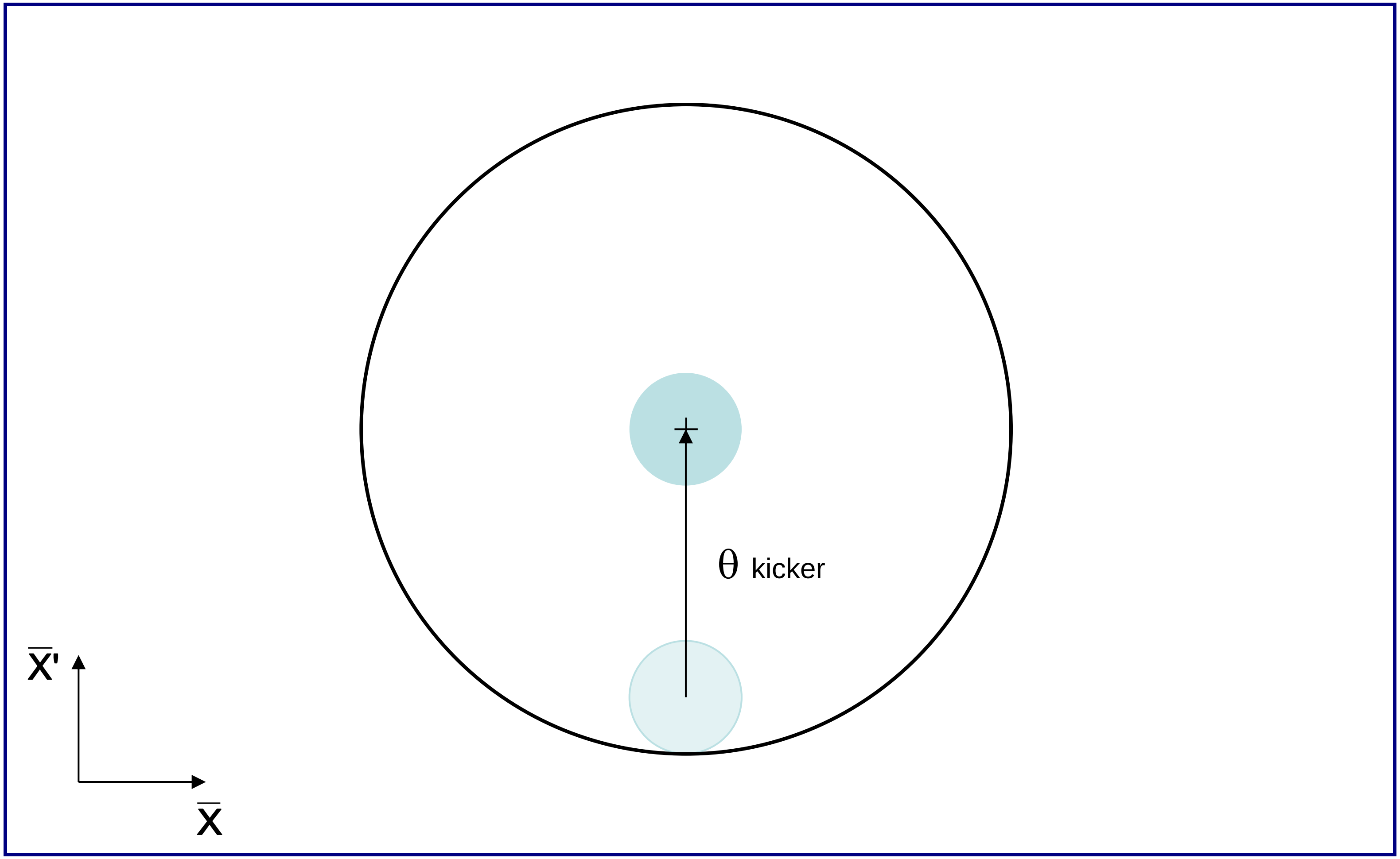
$\pi/2$ phase advance to kicker location



Single-turn injection

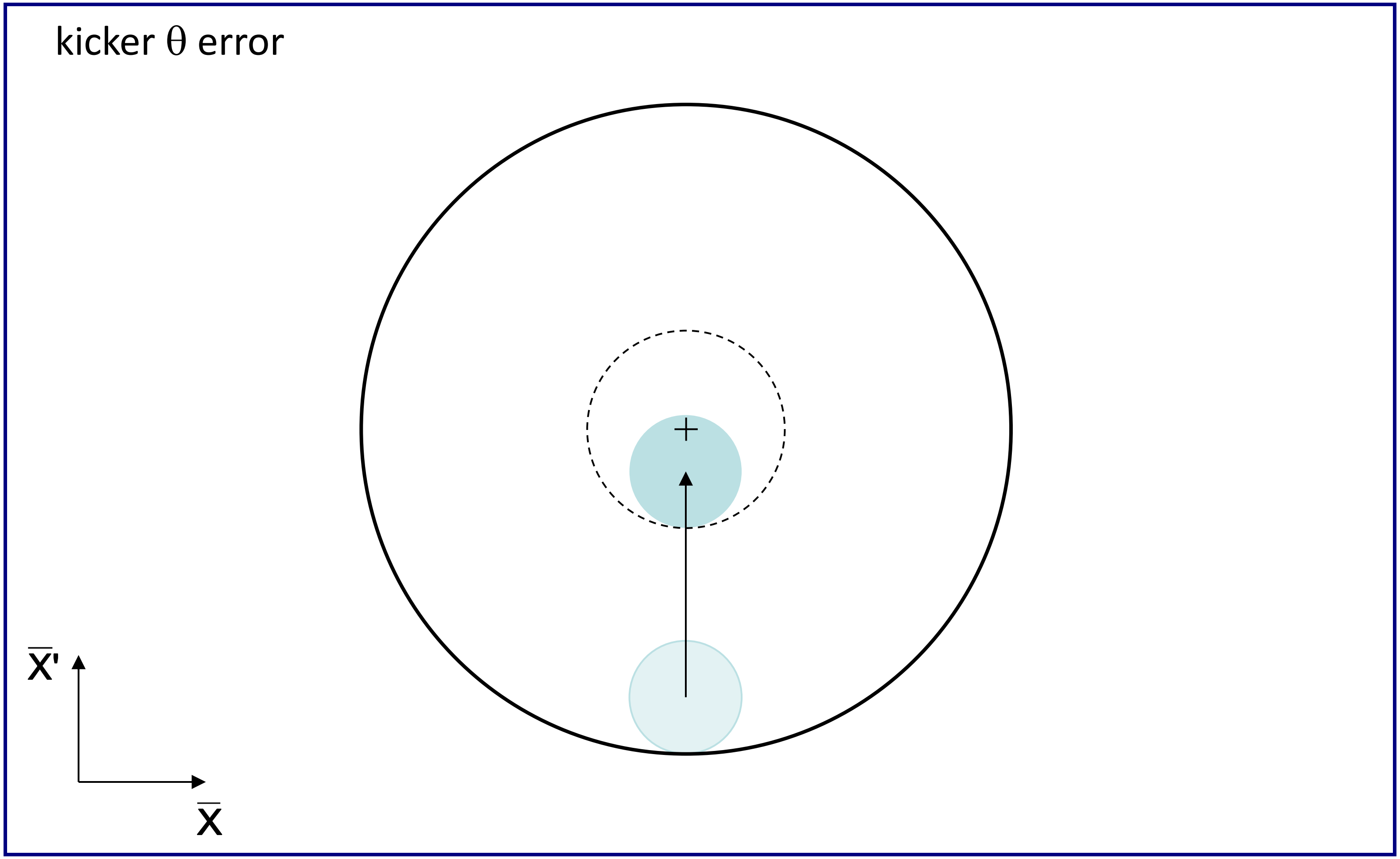
Normalised phase space at centre of idealised kicker

Kicker deflection places beam on central orbit



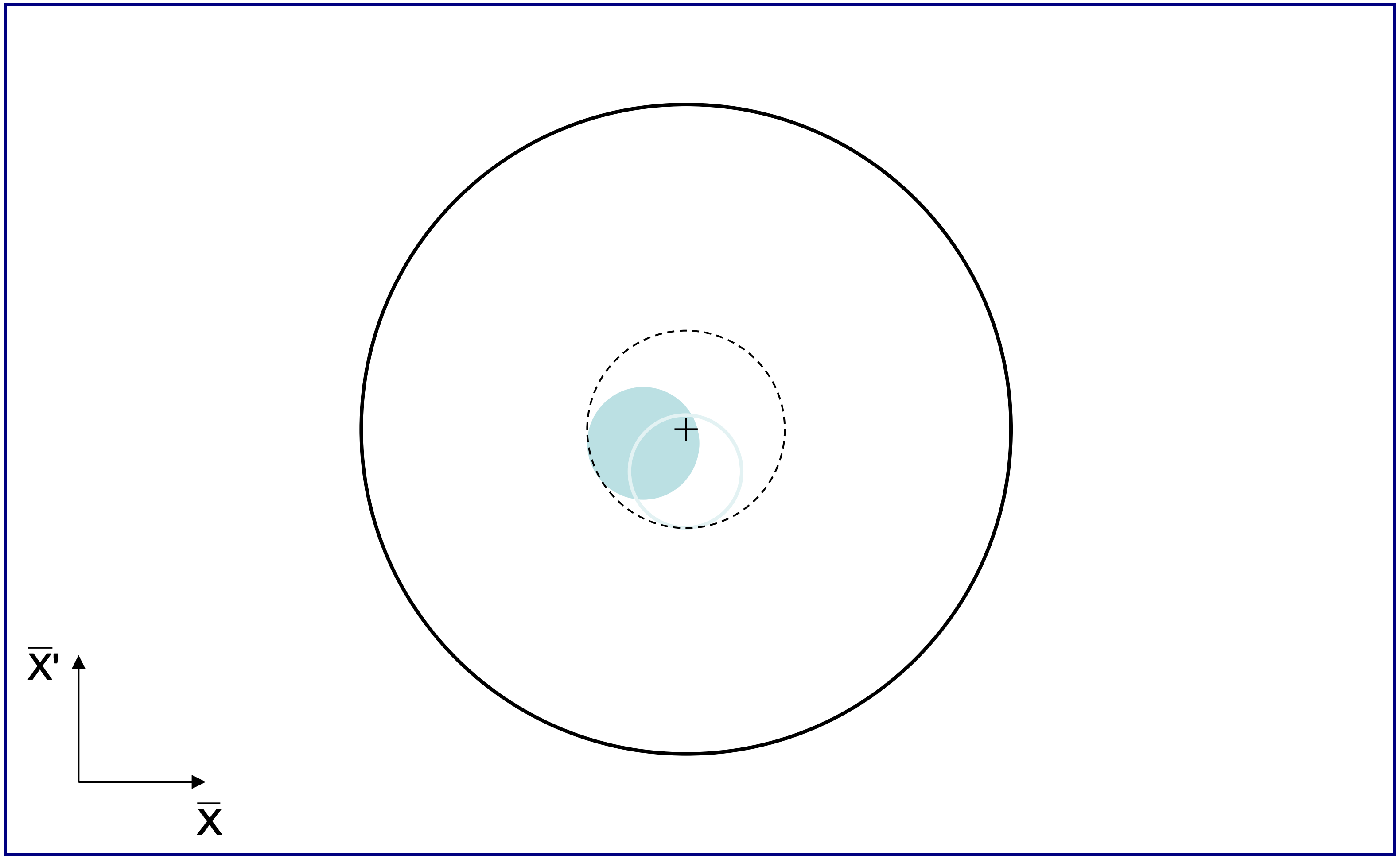
Injection oscillations

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



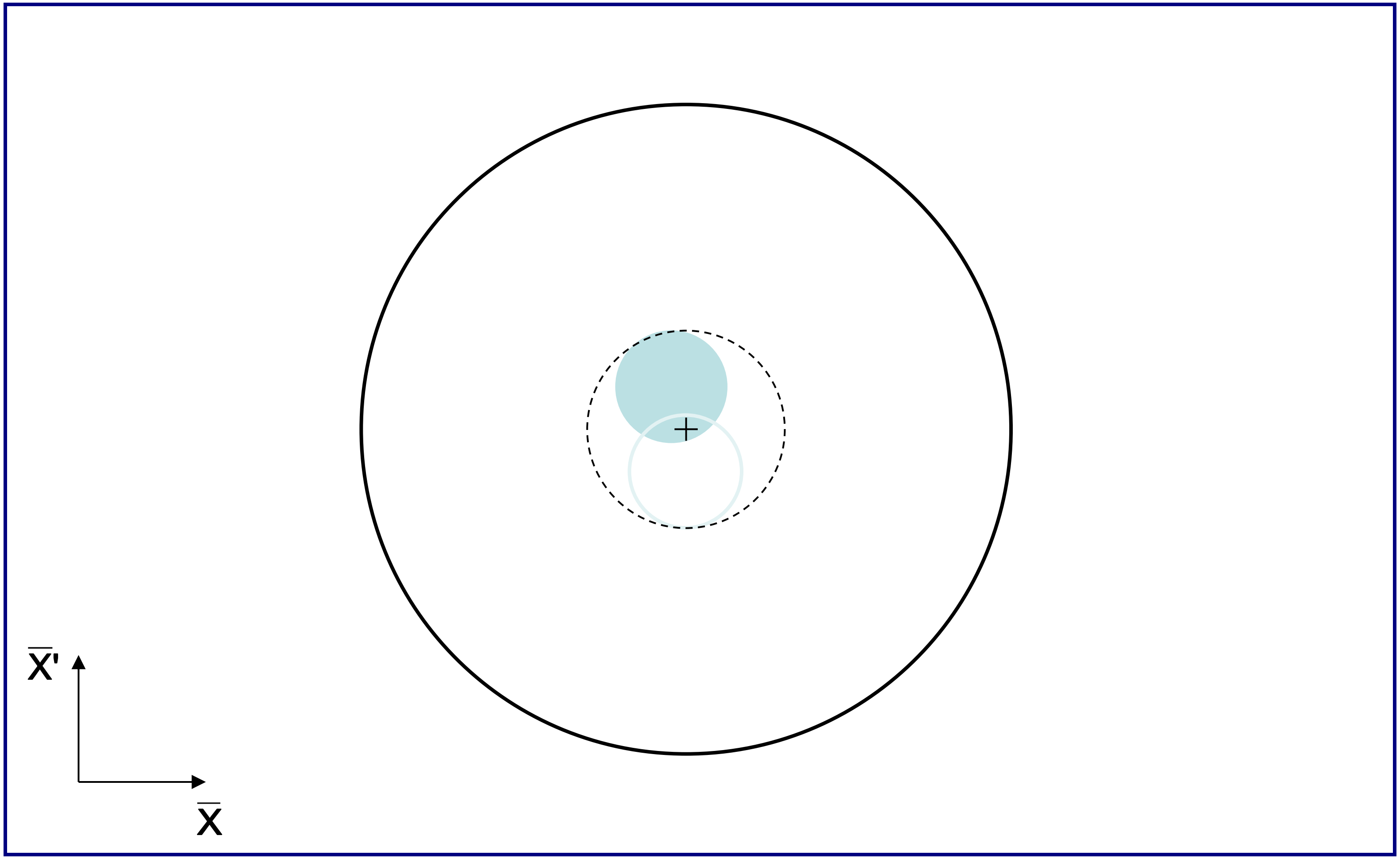
Injection oscillations

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



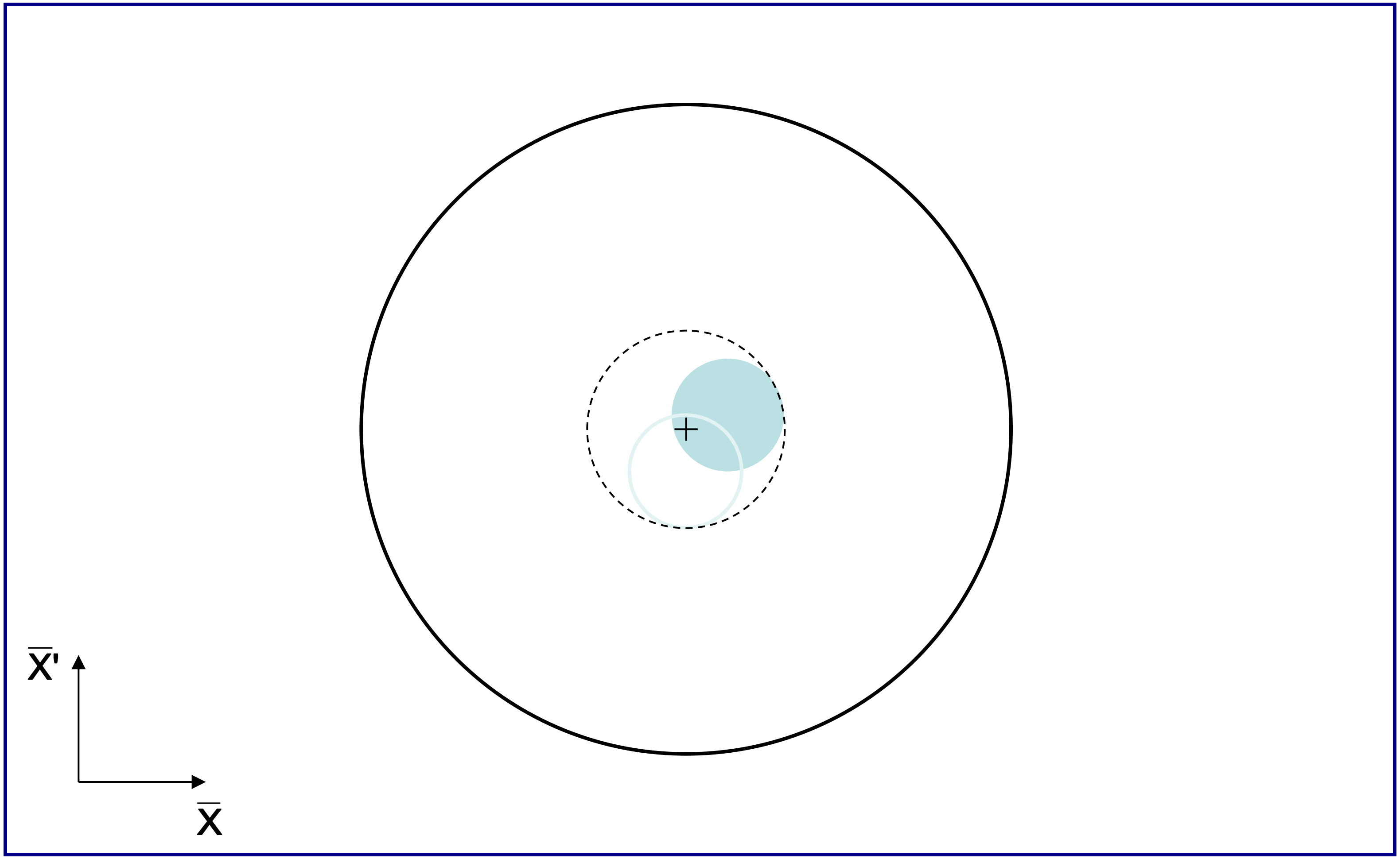
Injection oscillations

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



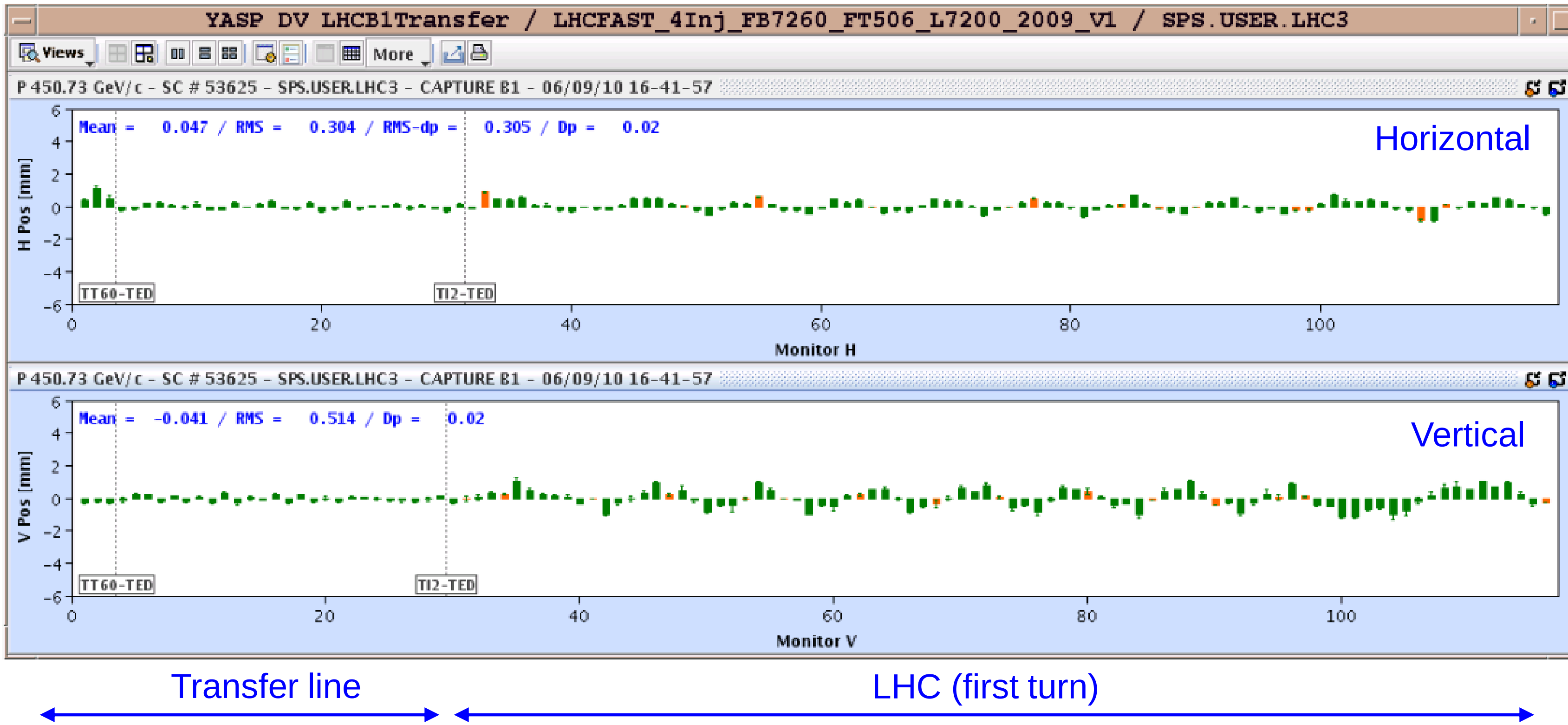
Injection oscillations

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

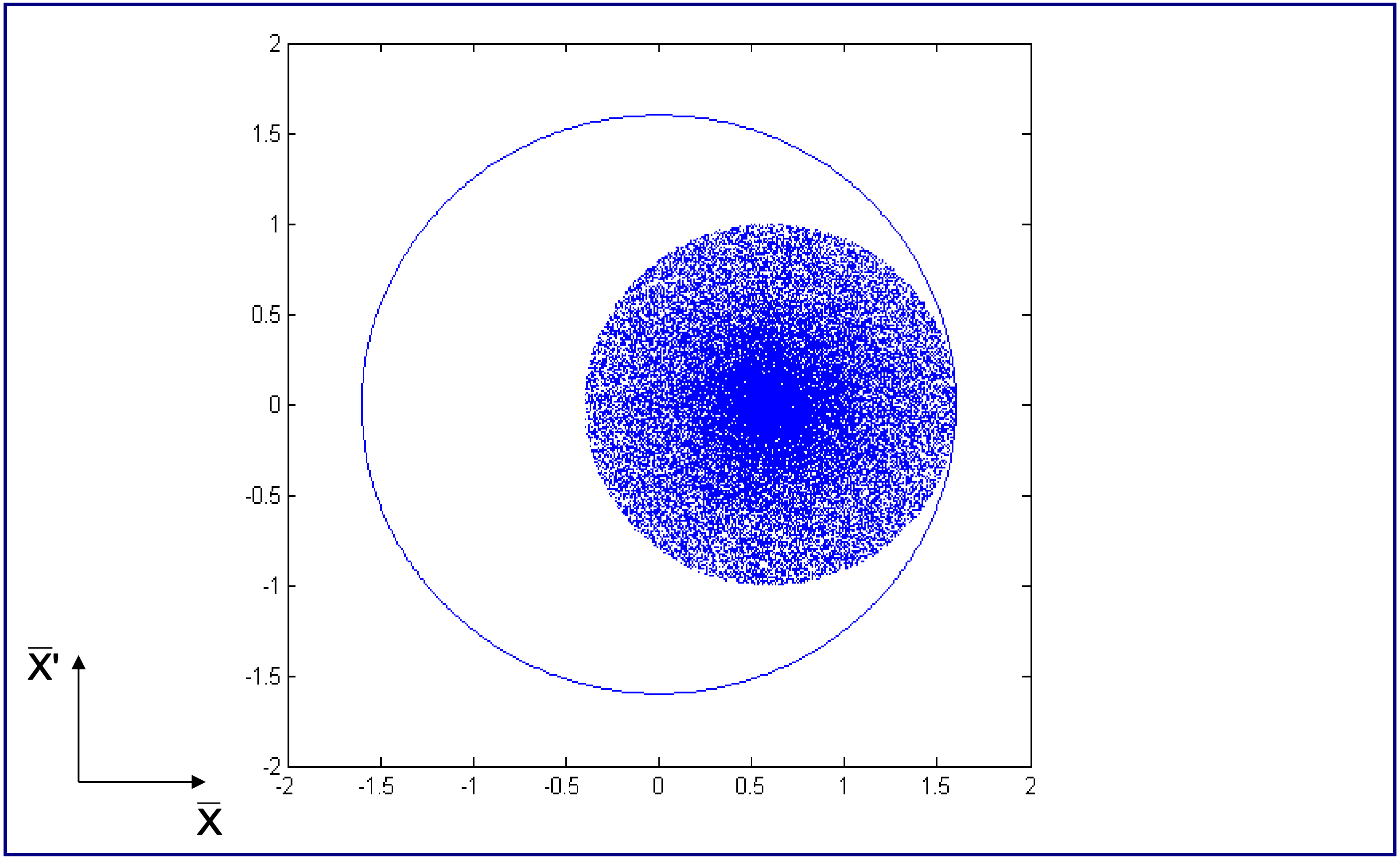


Injection oscillations

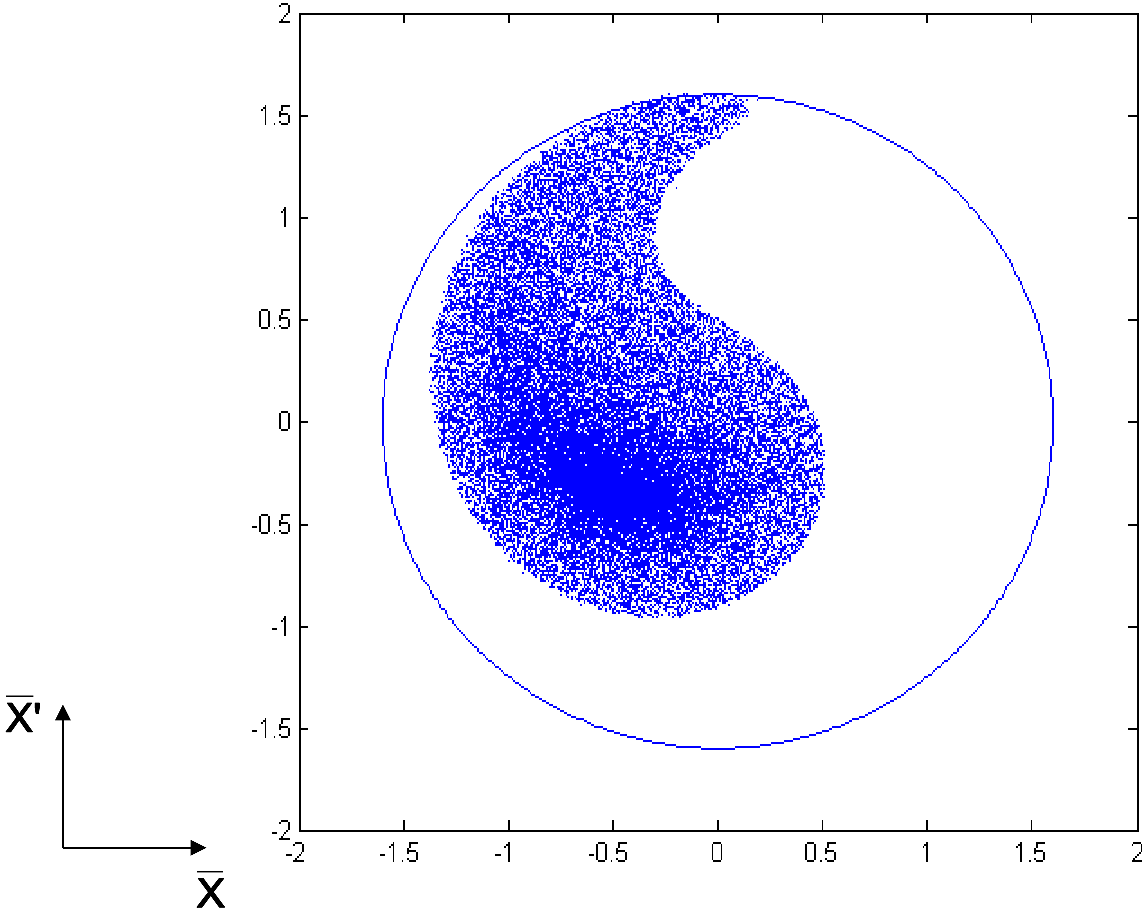
- Betatron oscillations with respect to the Closed Orbit



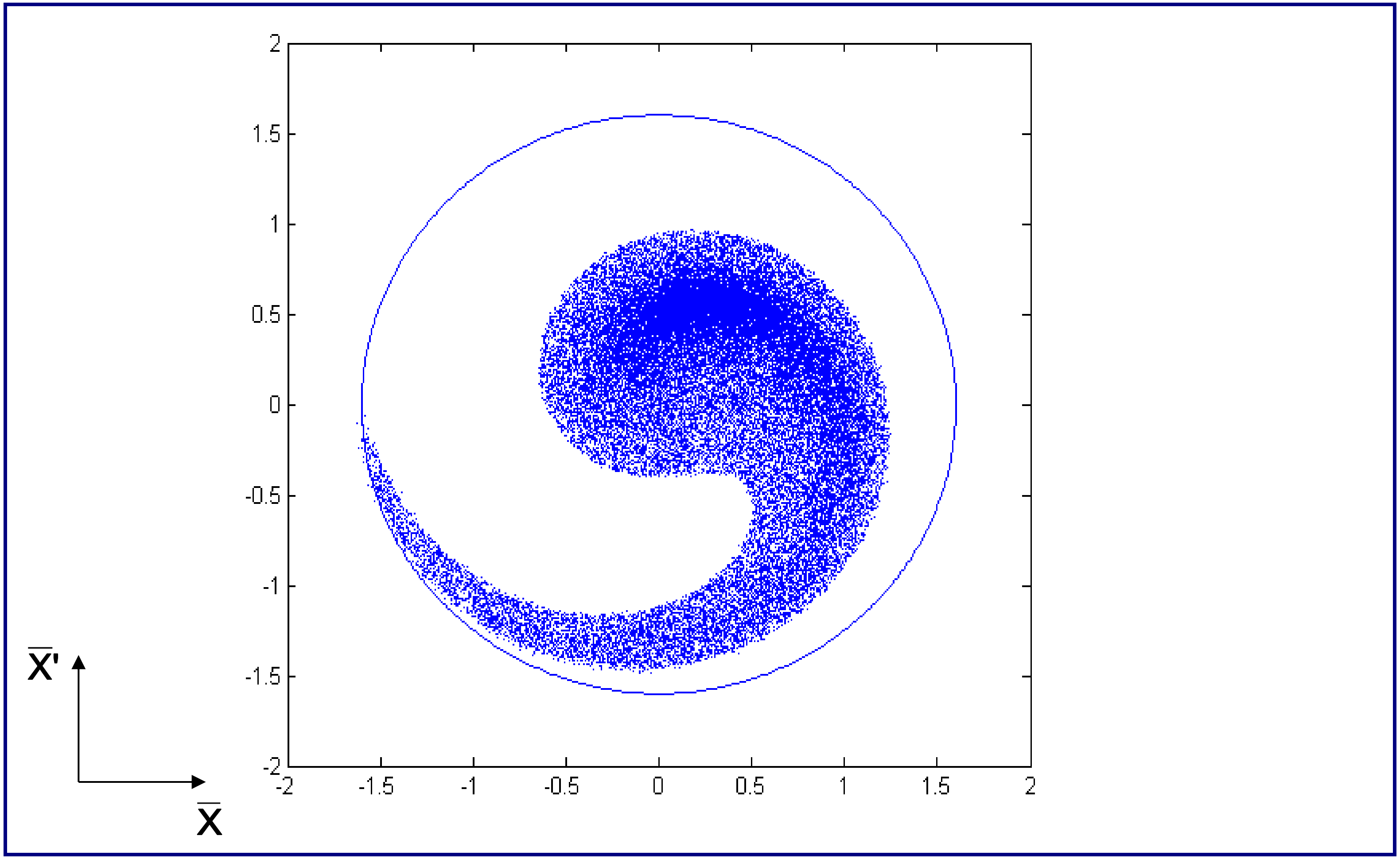
Filamentation



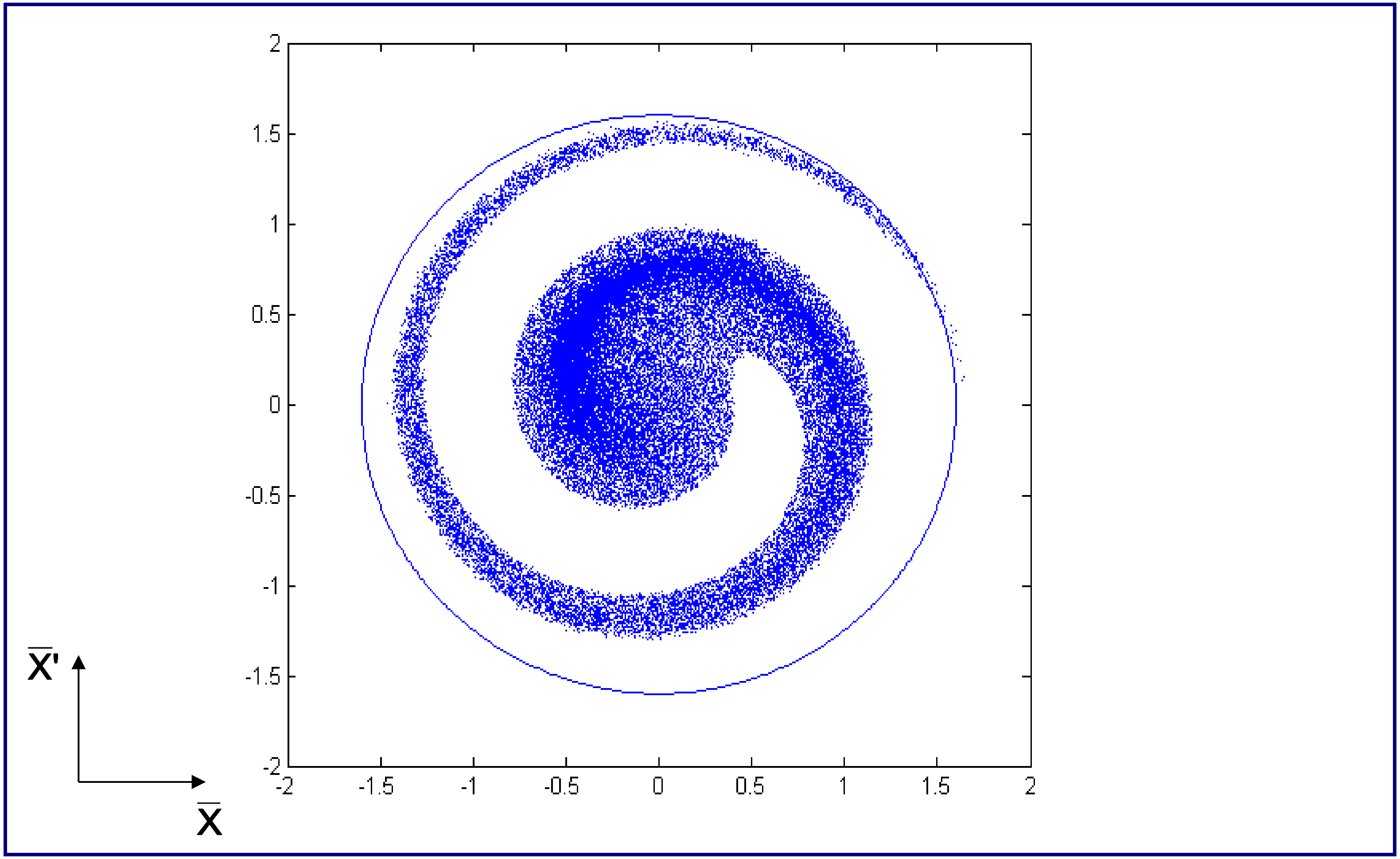
Filamentation



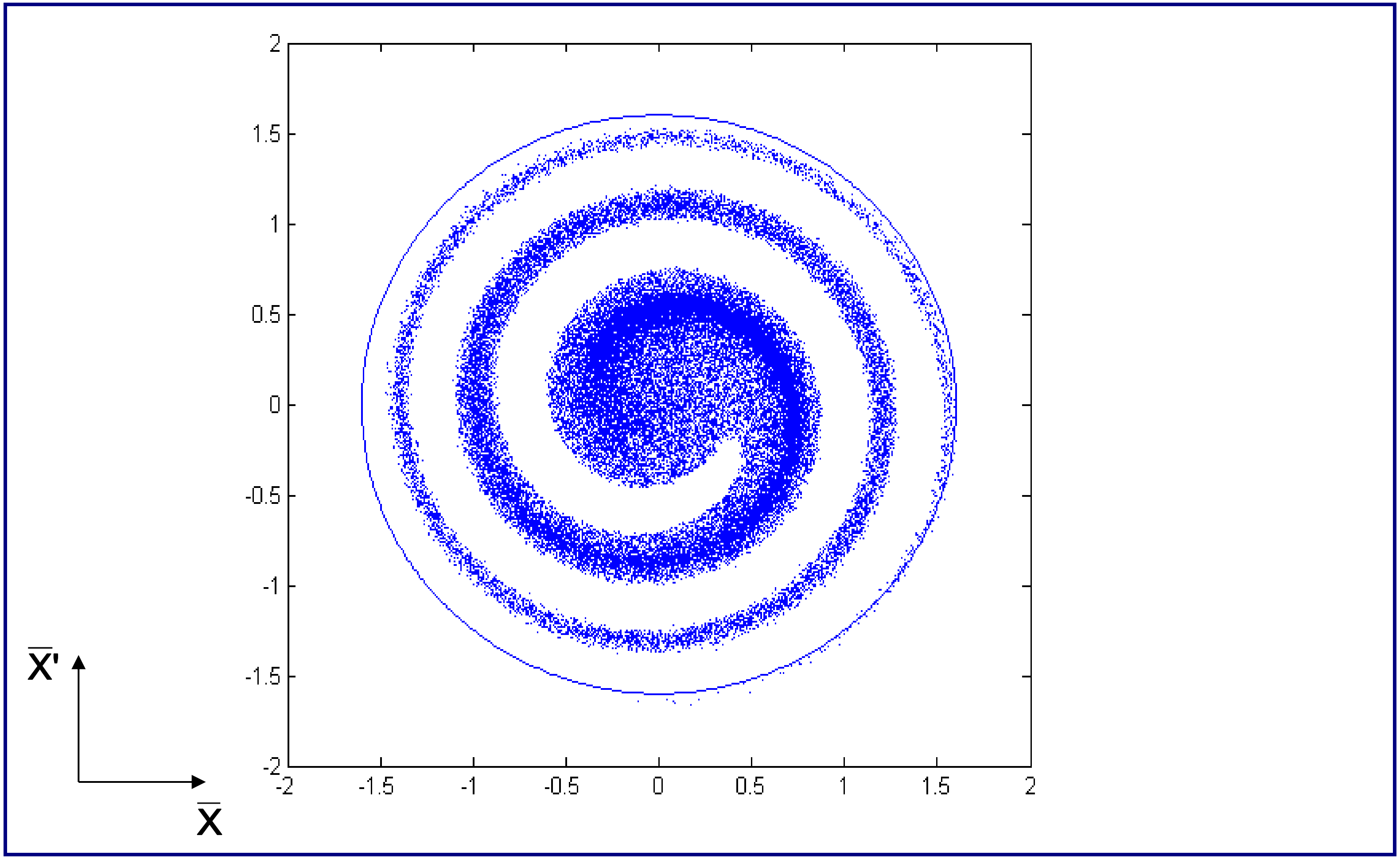
Filamentation



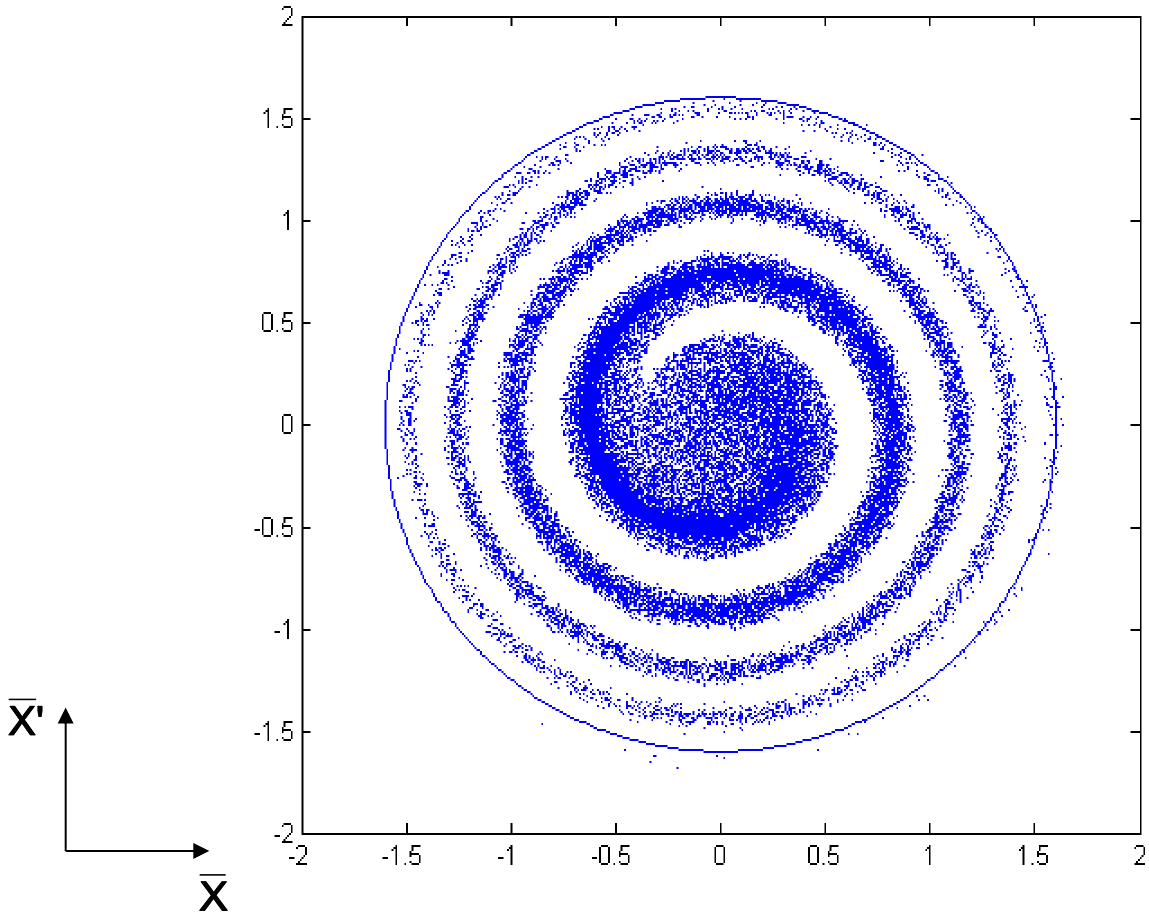
Filamentation



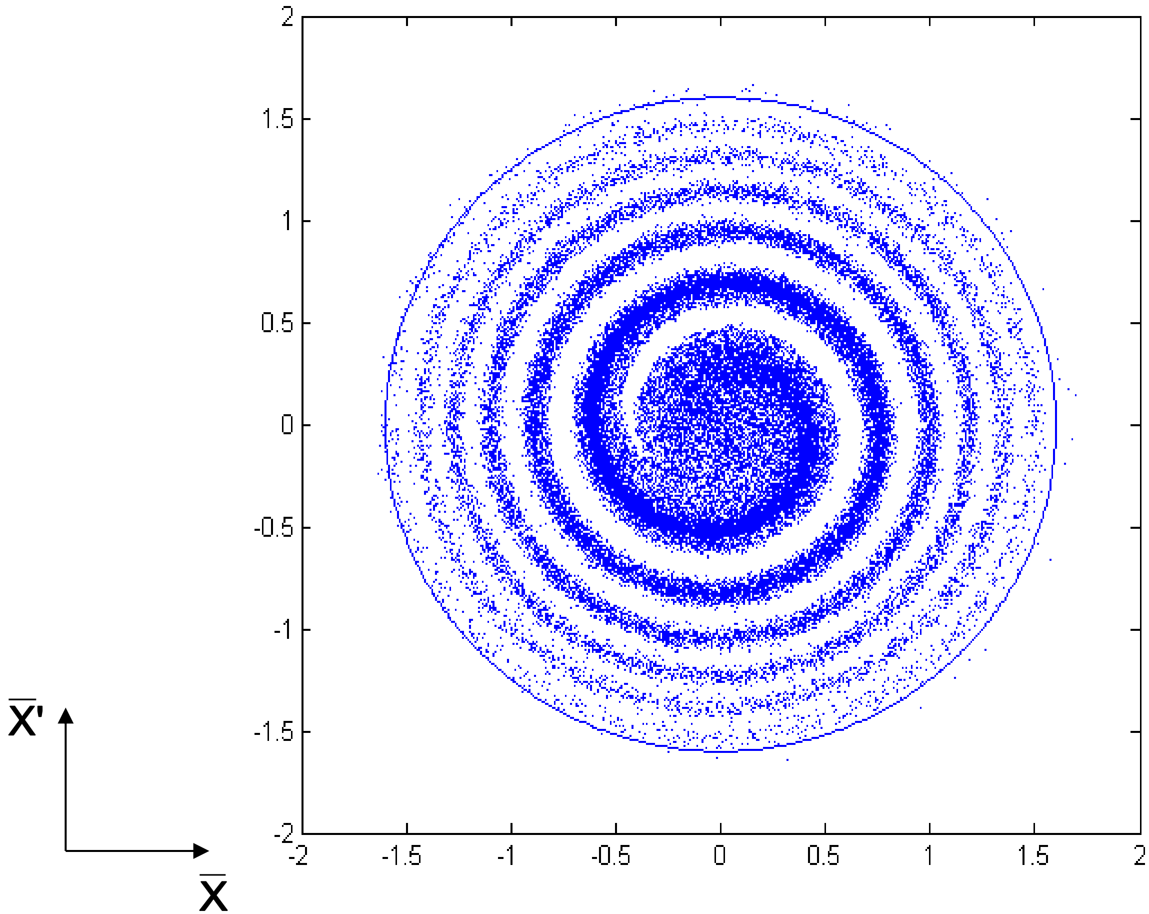
Filamentation



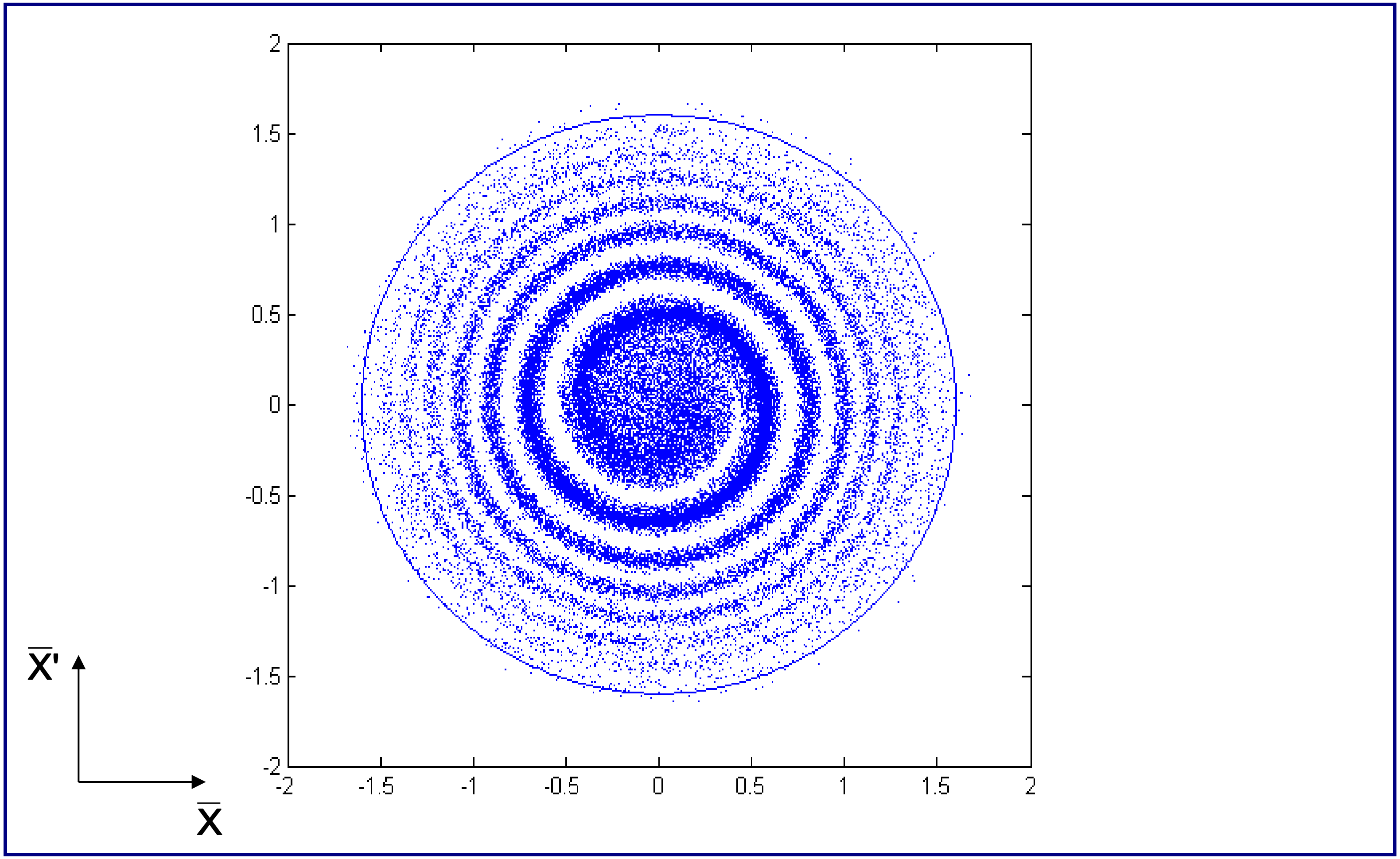
Filamentation



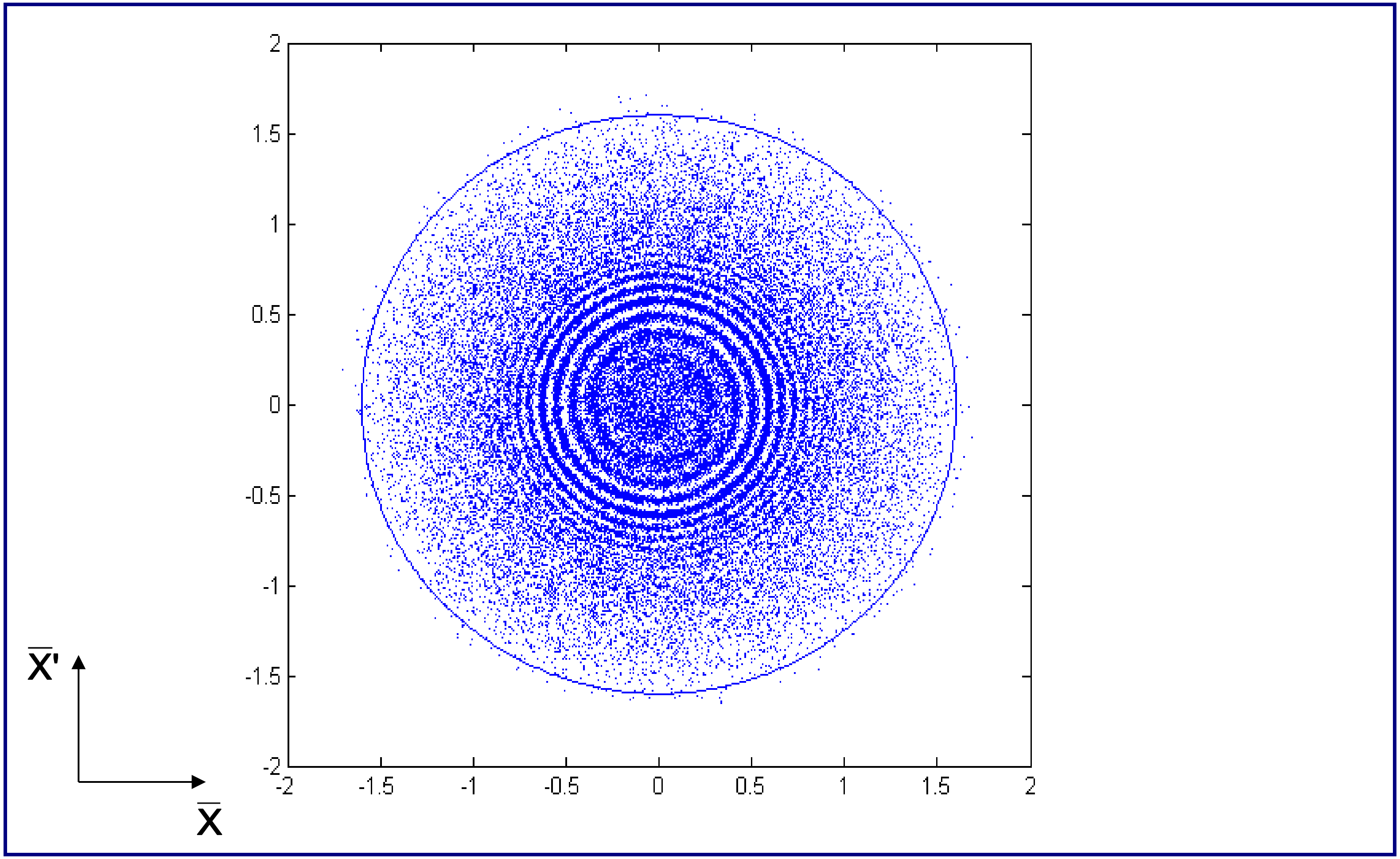
Filamentation



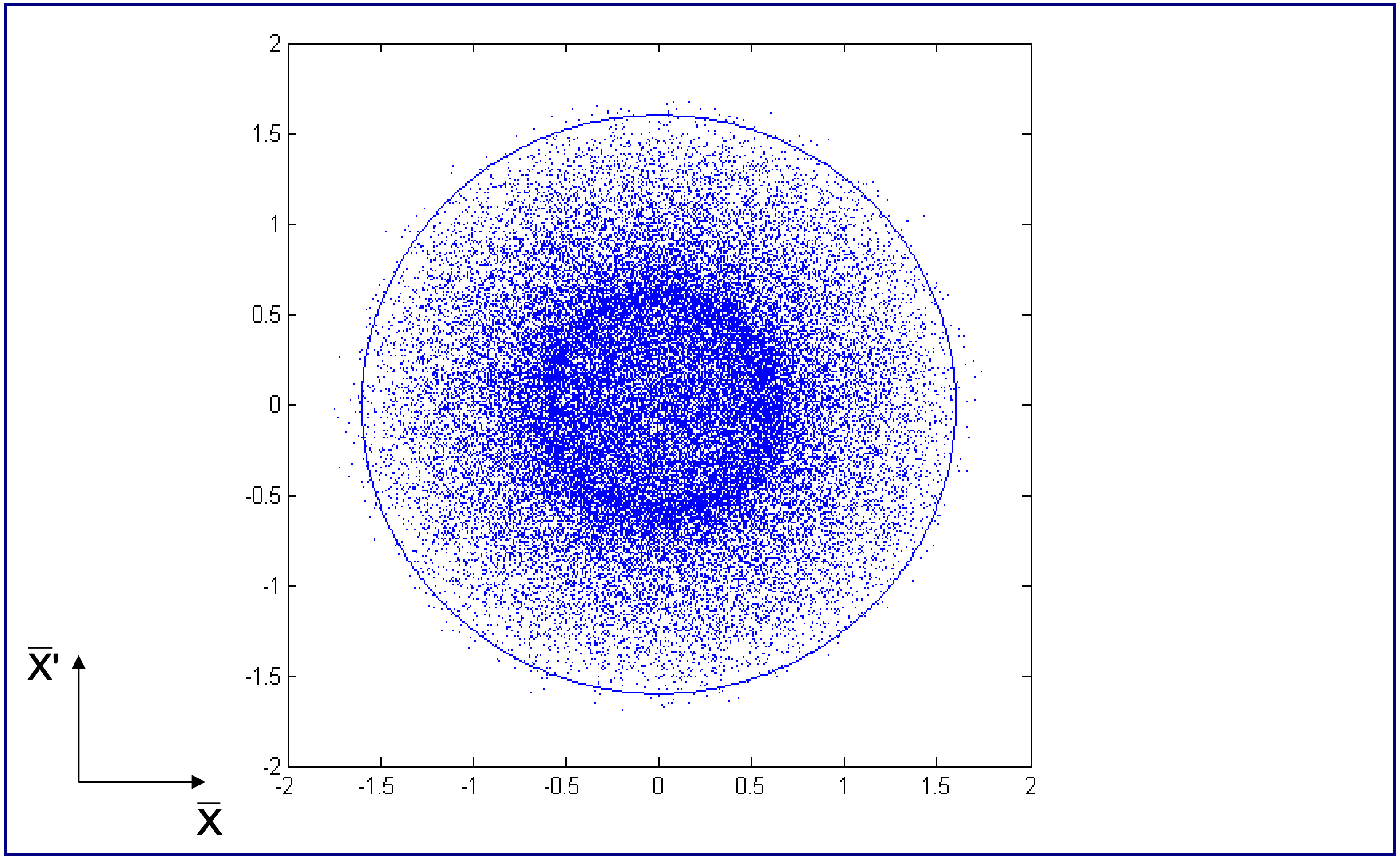
Filamentation



Filamentation



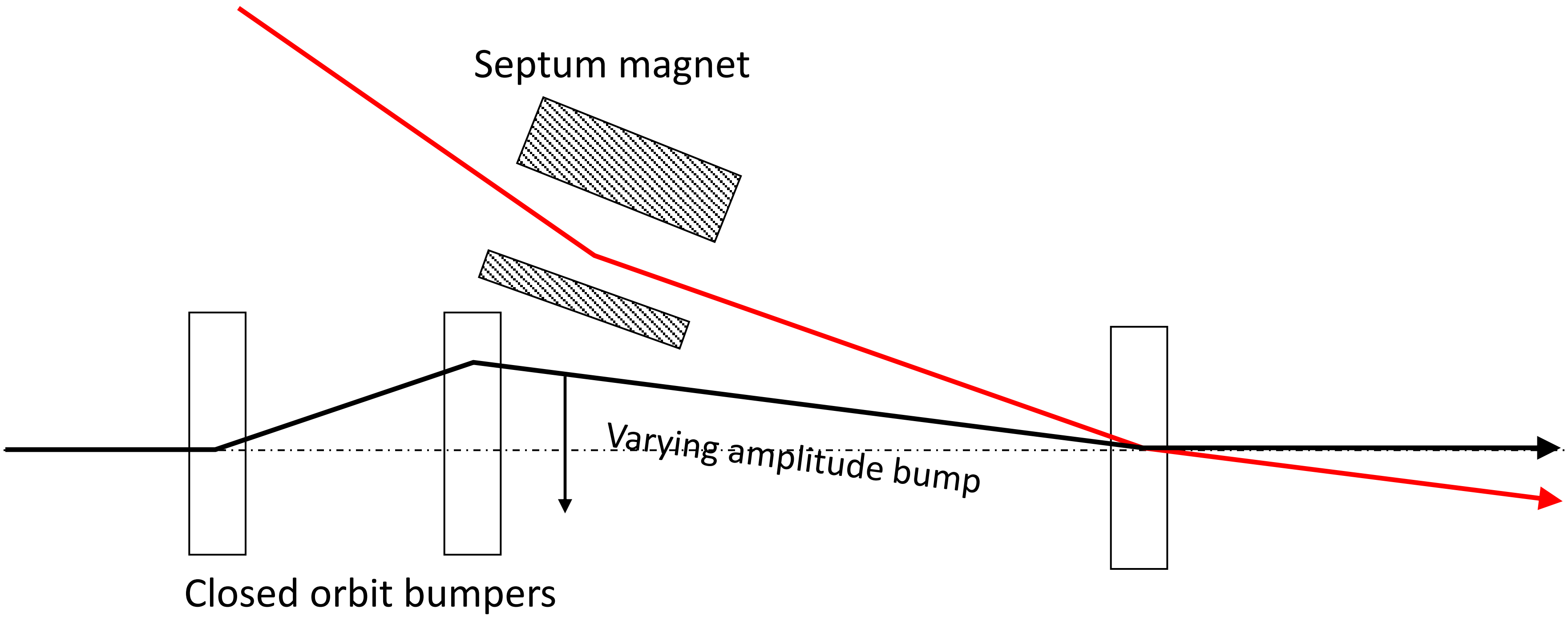
Filamentation



Multi-turn injection

- For hadrons the beam density at injection can be limited either by space charge effects or by the injector capacity
- If we cannot increase charge density, we can sometimes fill the horizontal phase space to increase overall injected intensity.
  - Condition that the acceptance of receiving machine is larger than the delivered beam emittance

Multi-turn injection for hadrons



- No kicker
- Bump amplitude decreases and inject a new bunch at each turn
- Phase-space "painting"

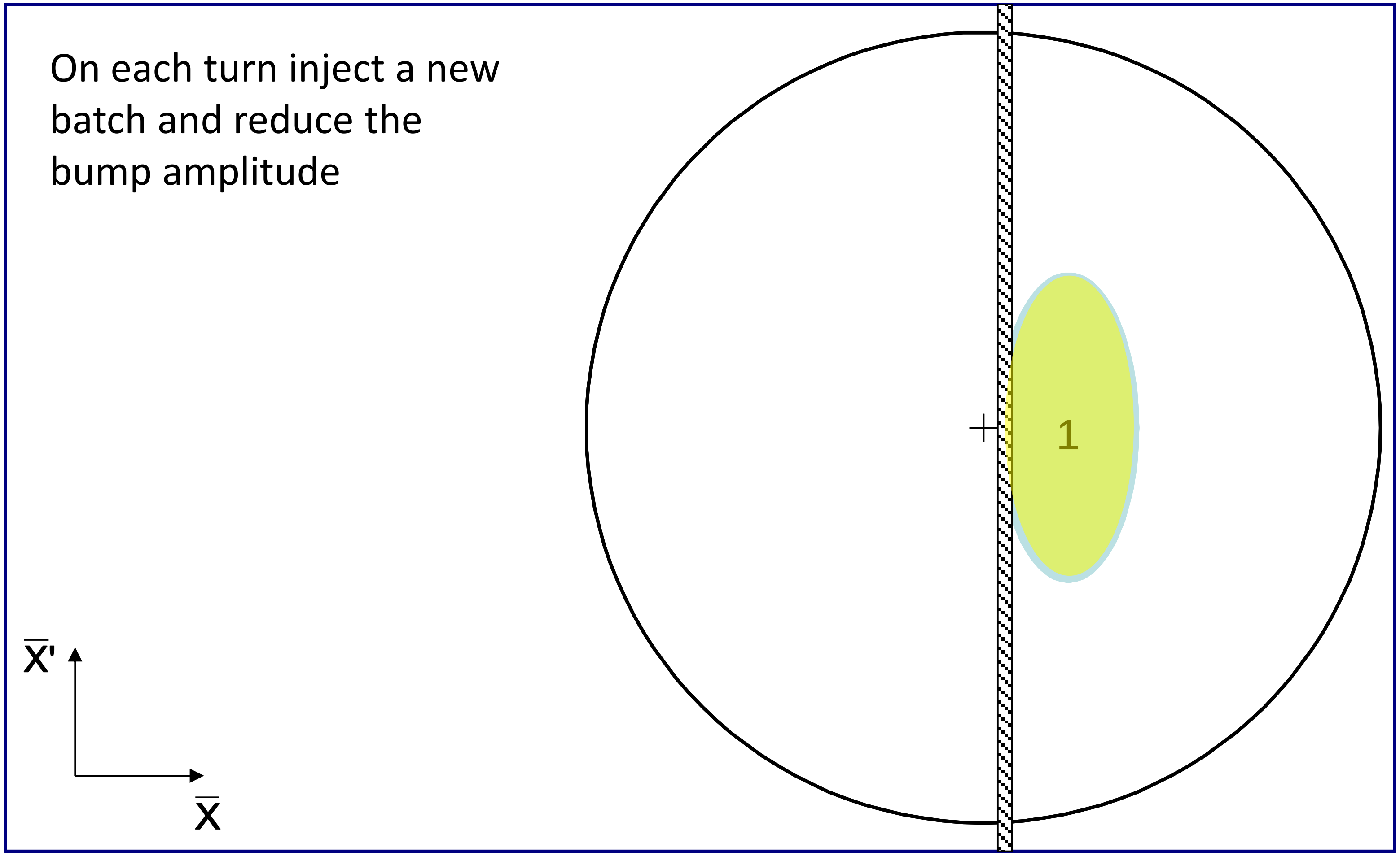
Multi-turn injection for hadrons

Example: CERN PSB injection, fractional tune Qh = 0.25

Beam rotates π/2 per turn in phase space

Turn 1

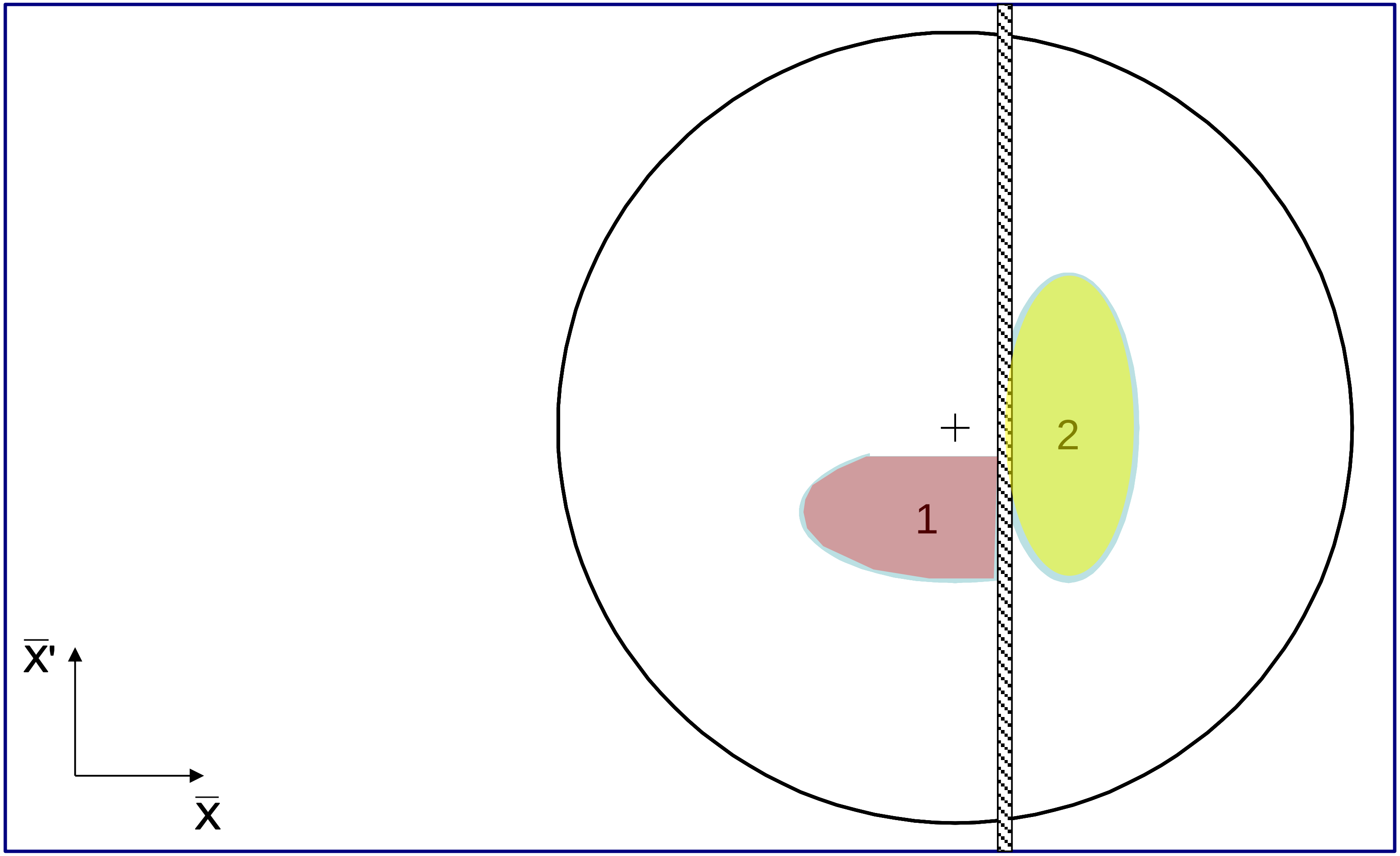
On each turn inject a new batch and reduce the bump amplitude



Septum

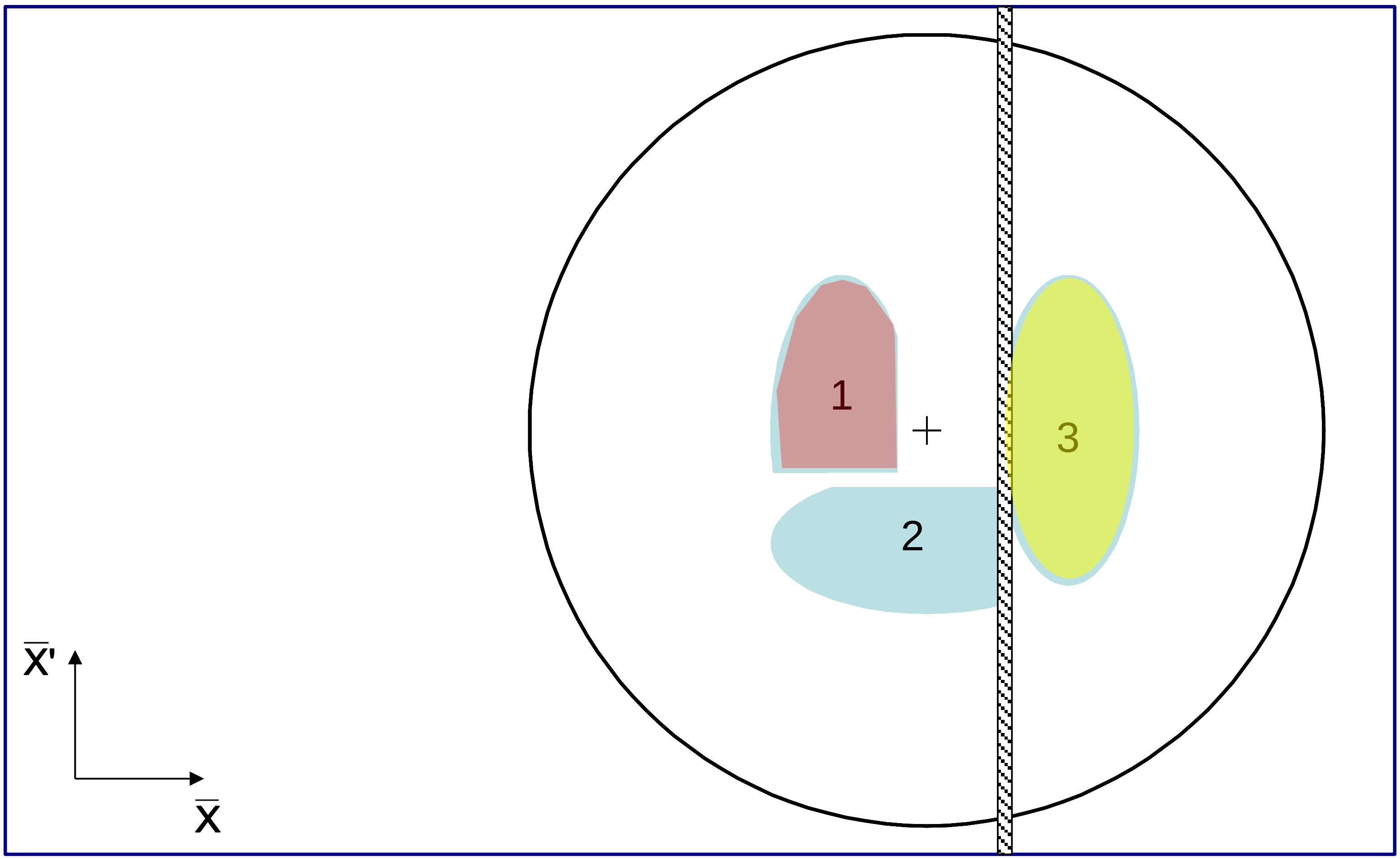
Multi-turn injection for hadrons

Turn 2



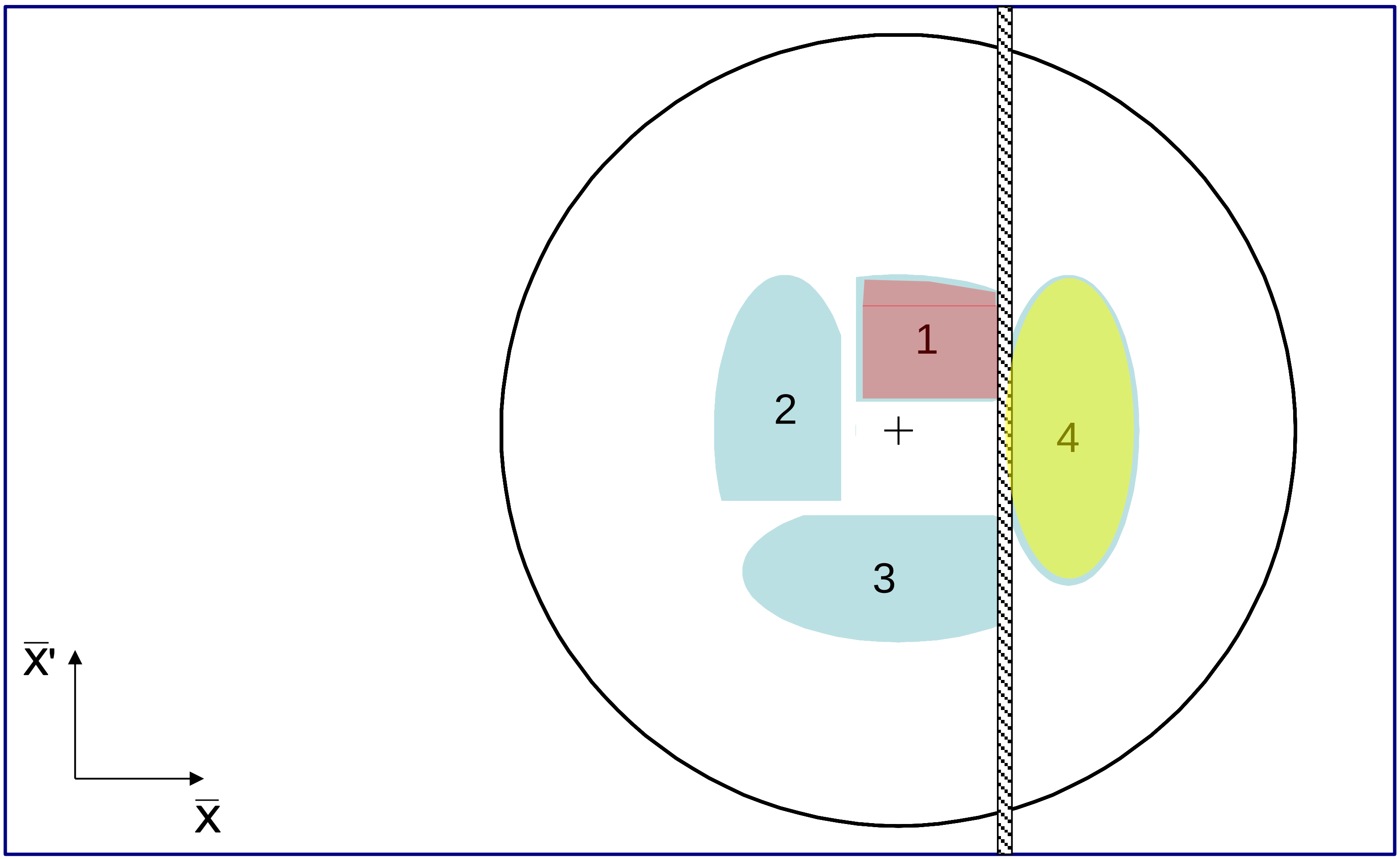
Multi-turn injection for hadrons

Turn 3



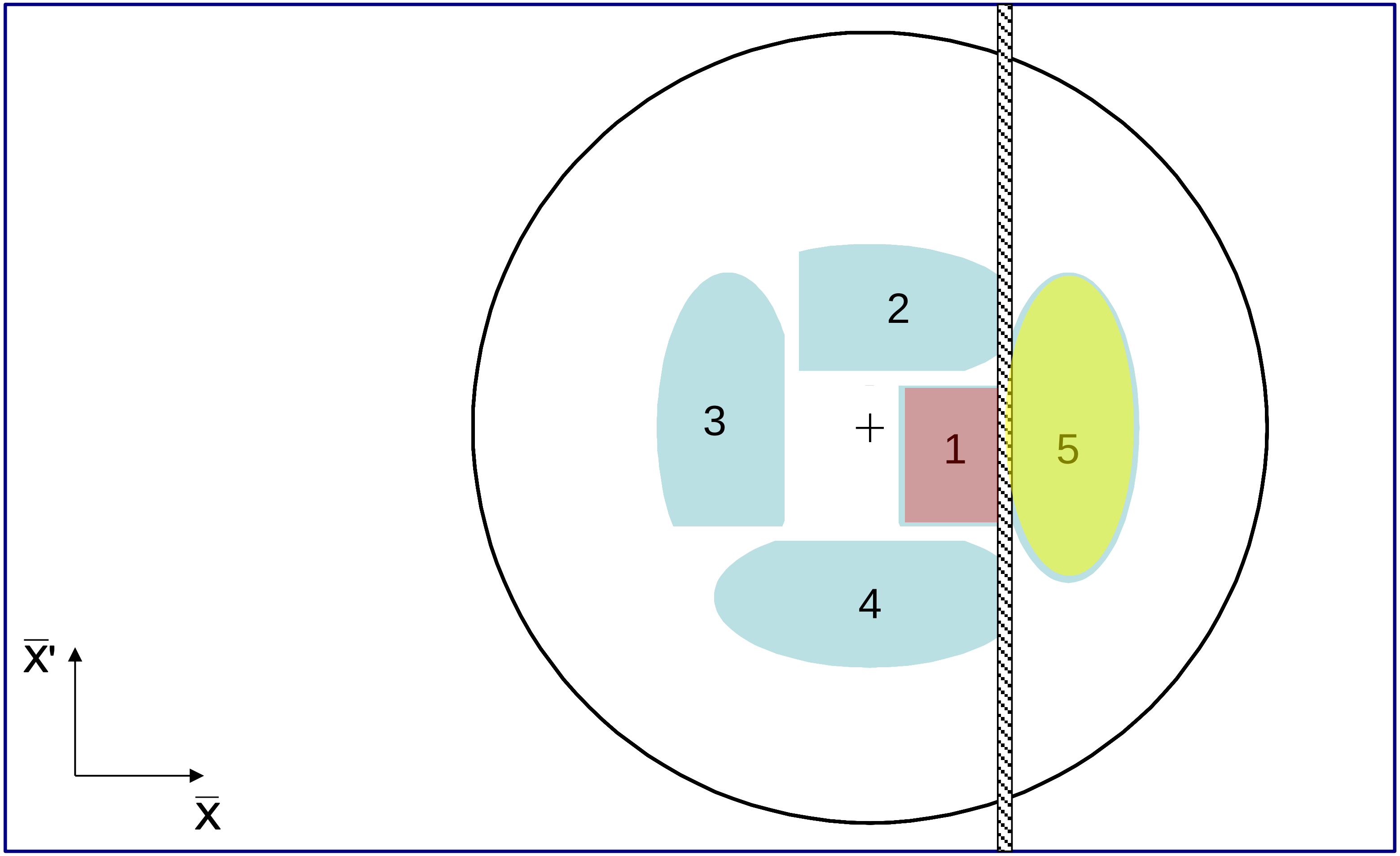
Multi-turn injection for hadrons

Turn 4



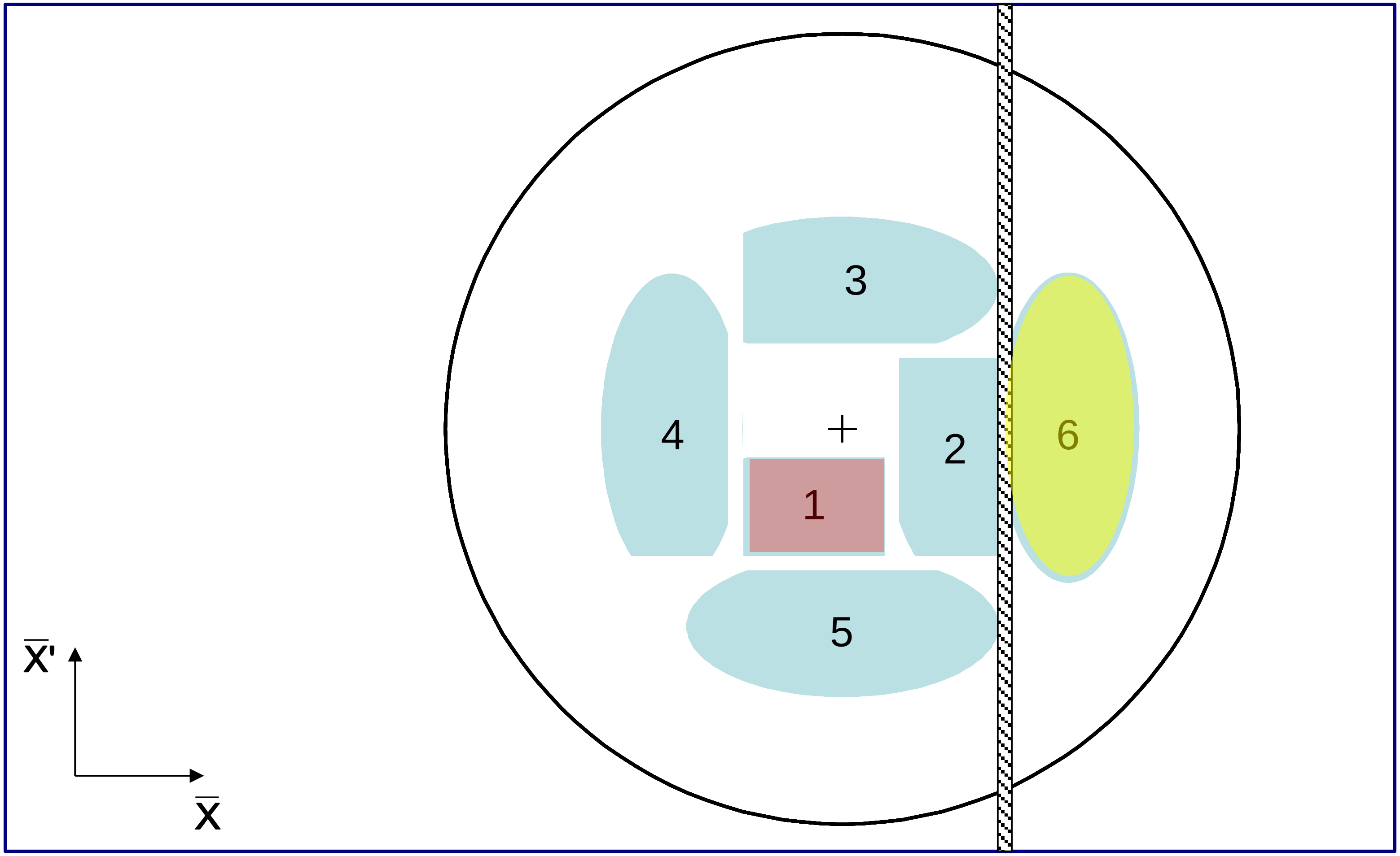
Multi-turn injection for hadrons

Turn 5



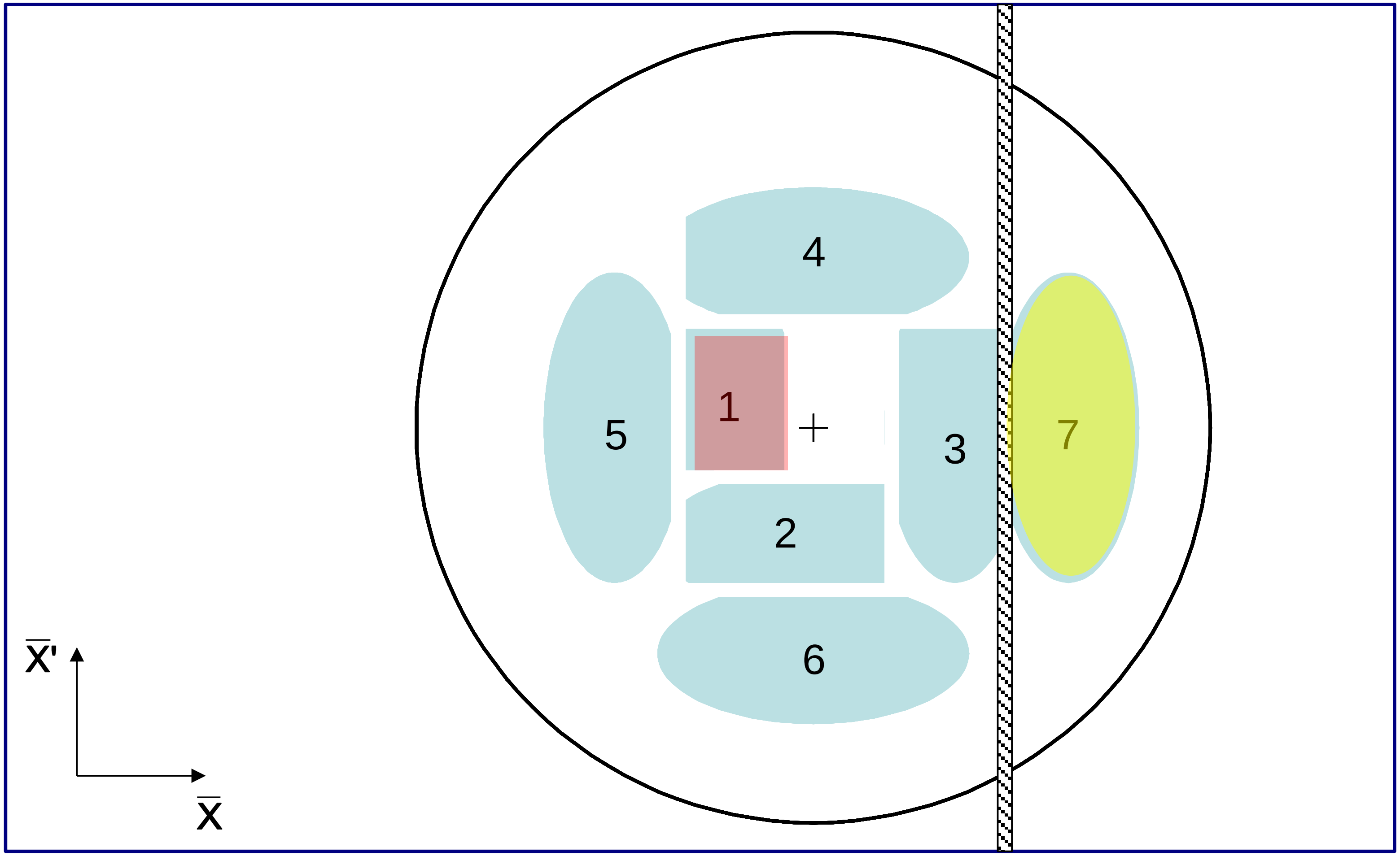
Multi-turn injection for hadrons

Turn 6



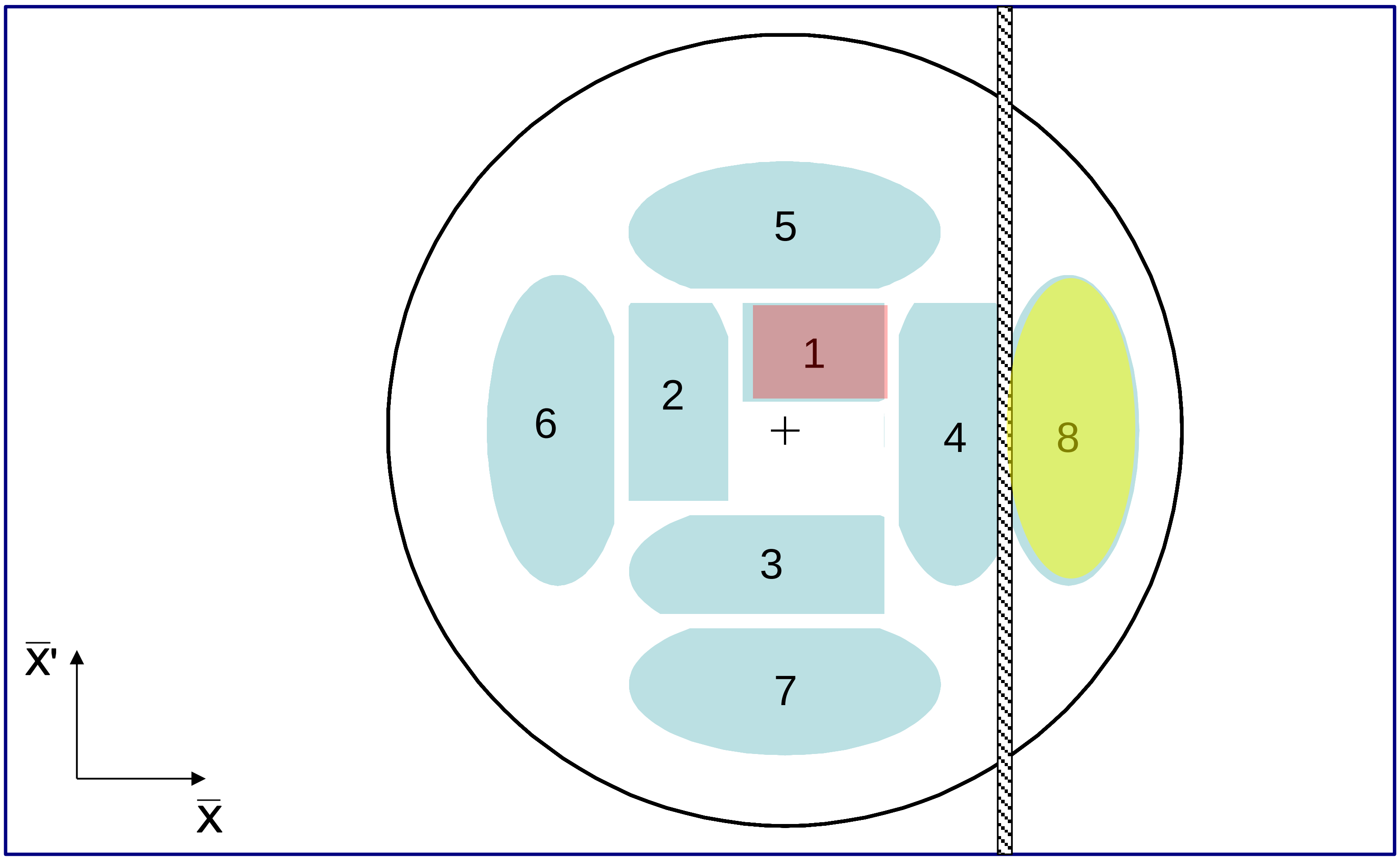
Multi-turn injection for hadrons

Turn 7



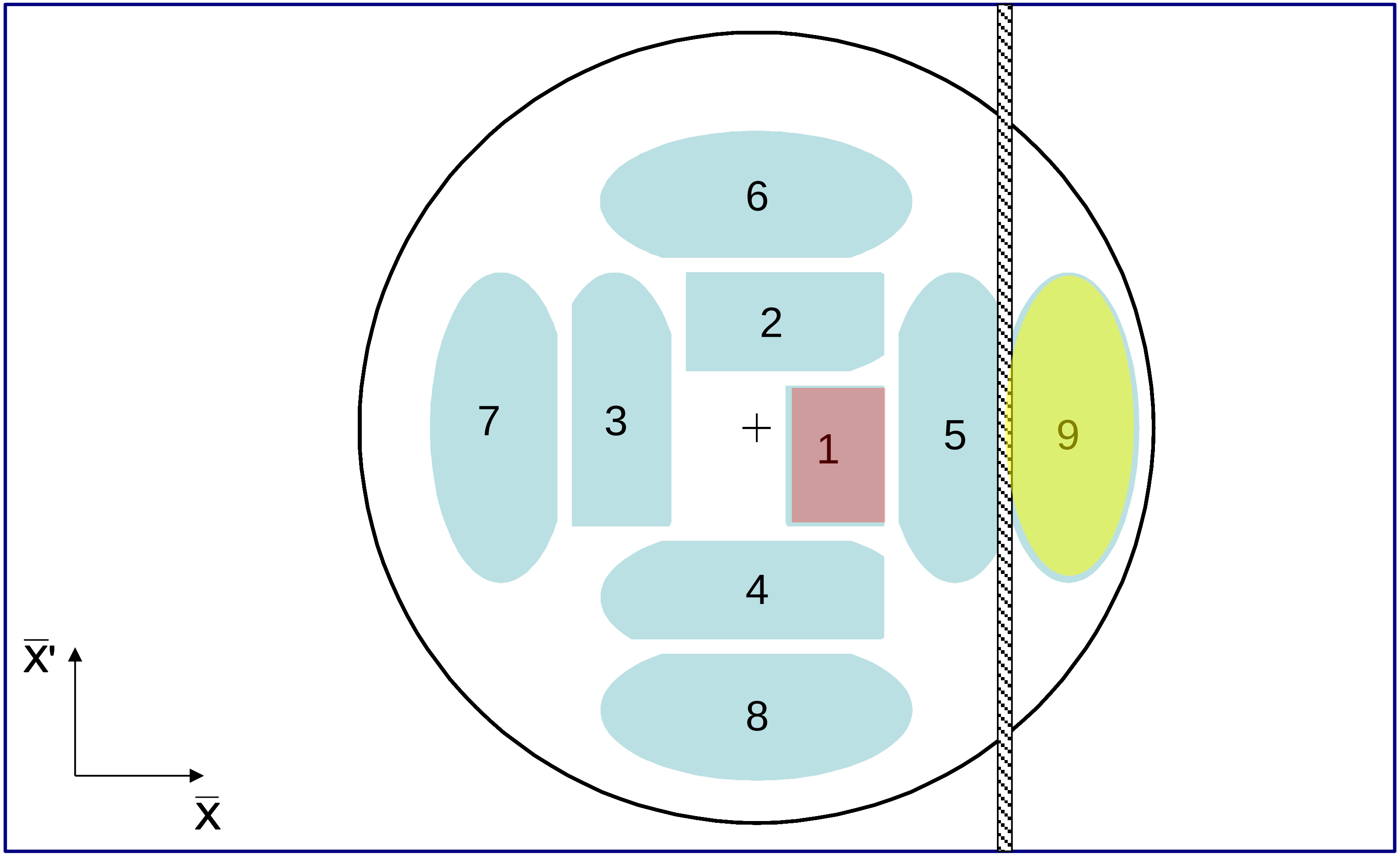
Multi-turn injection for hadrons

Turn 8

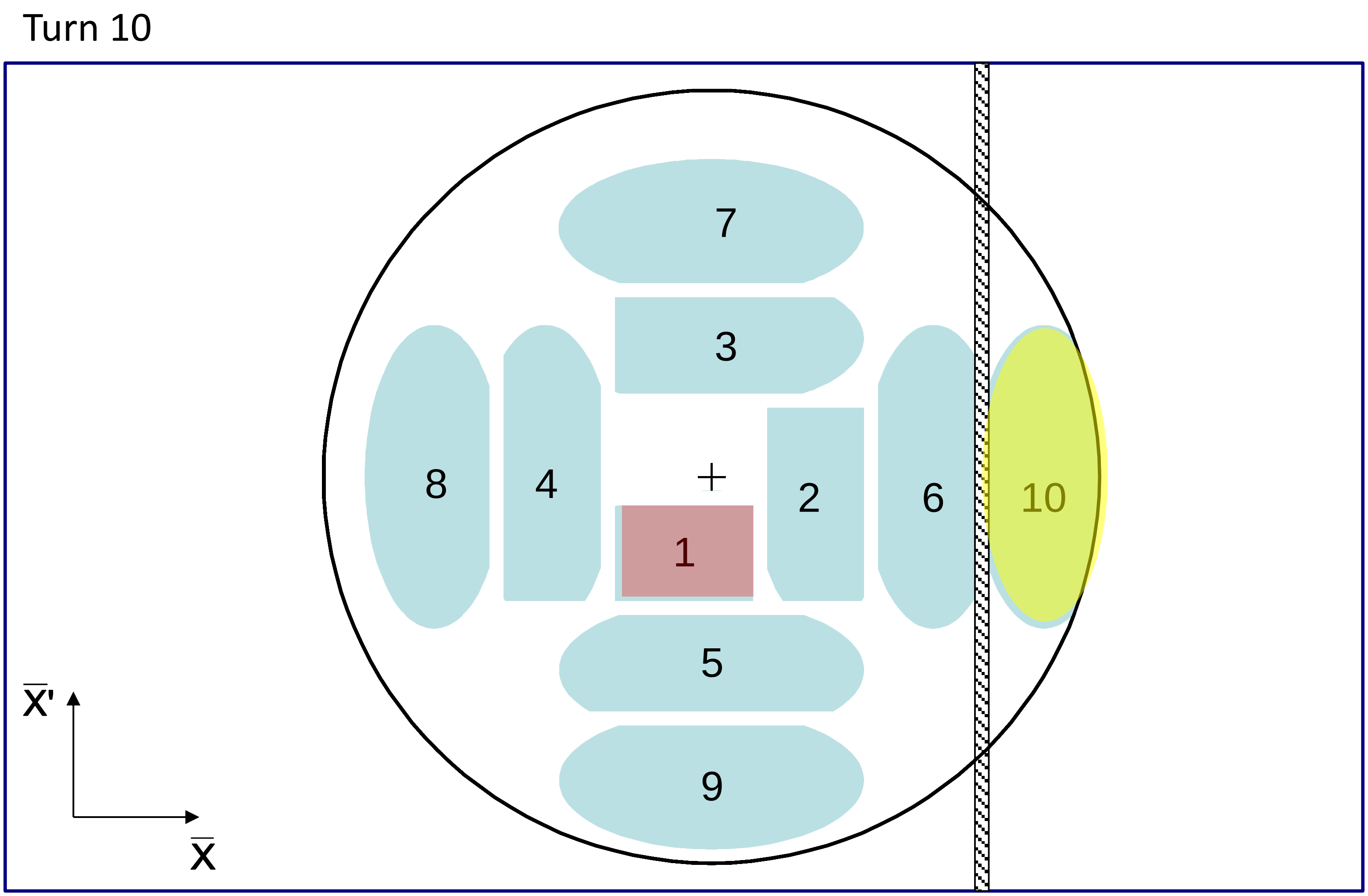


Multi-turn injection for hadrons

Turn 9

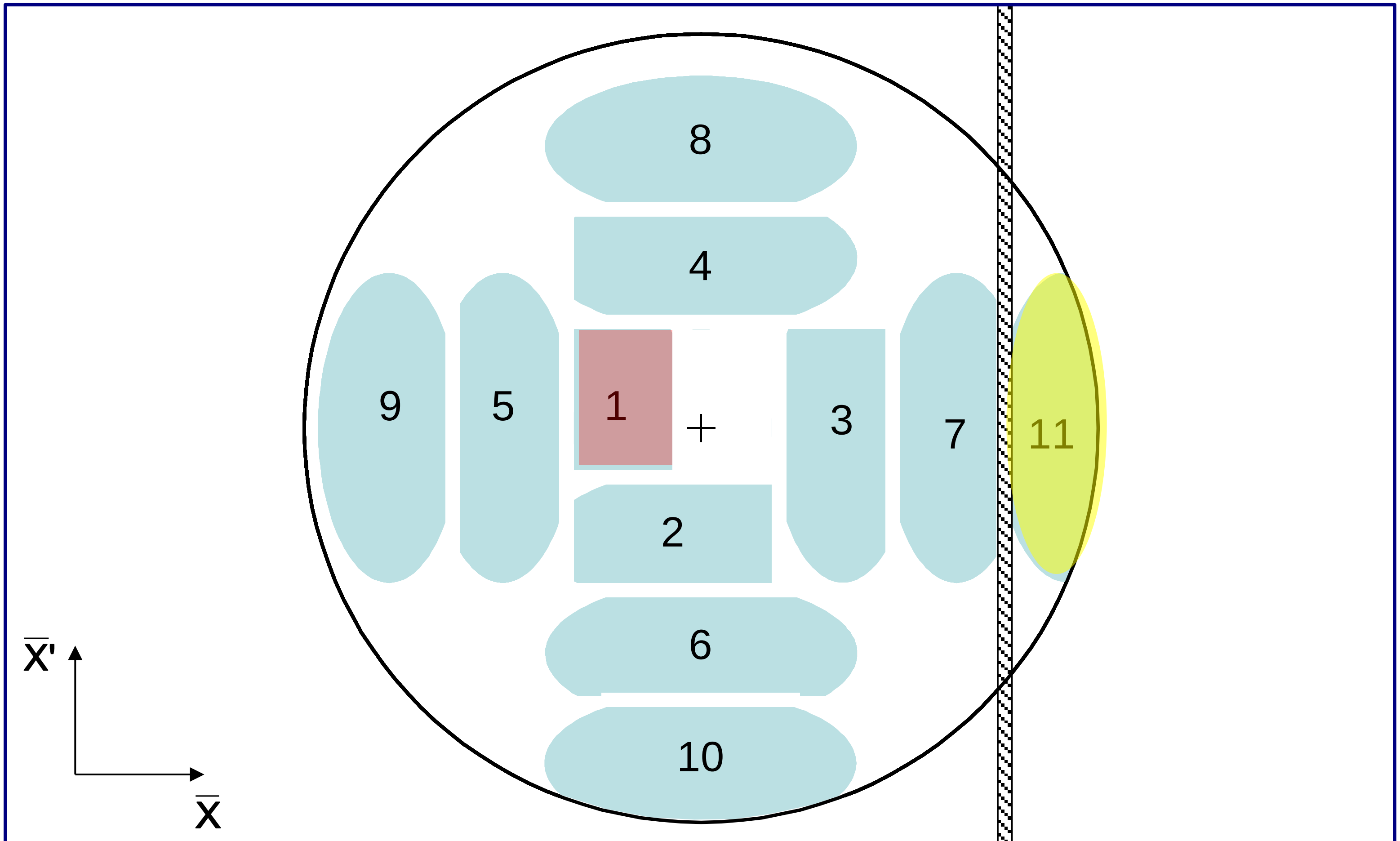


Multi-turn injection for hadrons



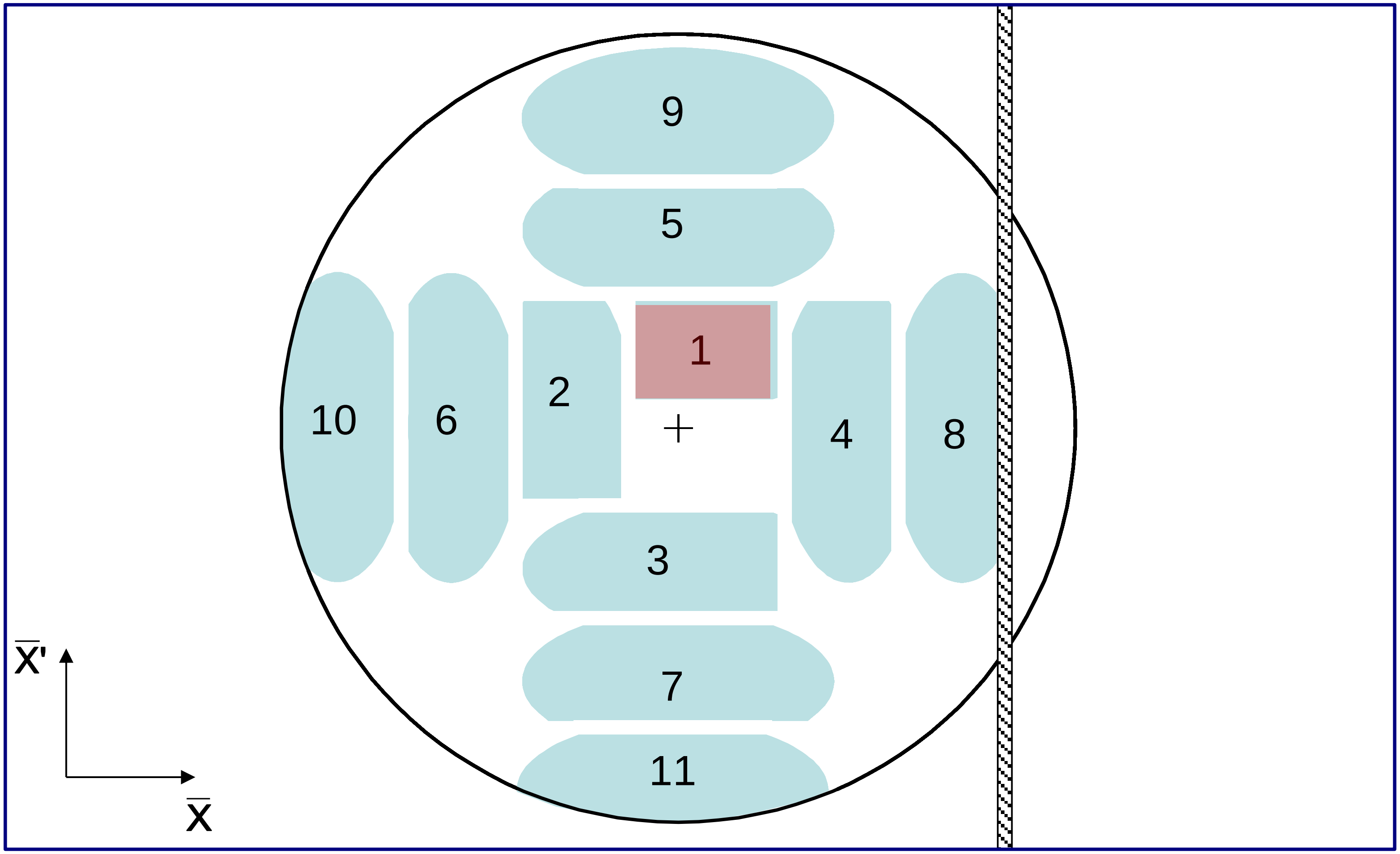
Multi-turn injection for hadrons

Turn 11



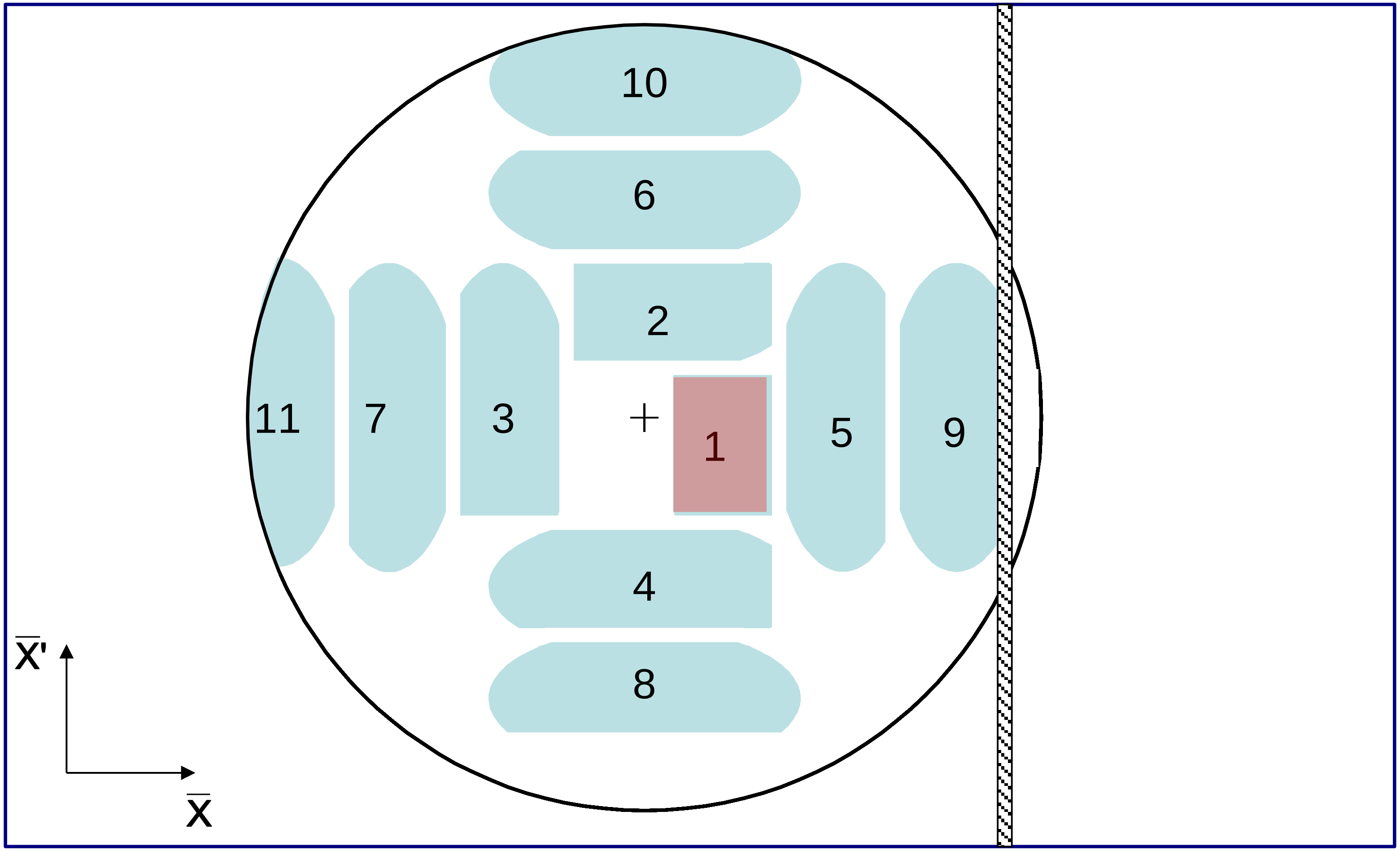
Multi-turn injection for hadrons

Turn 12



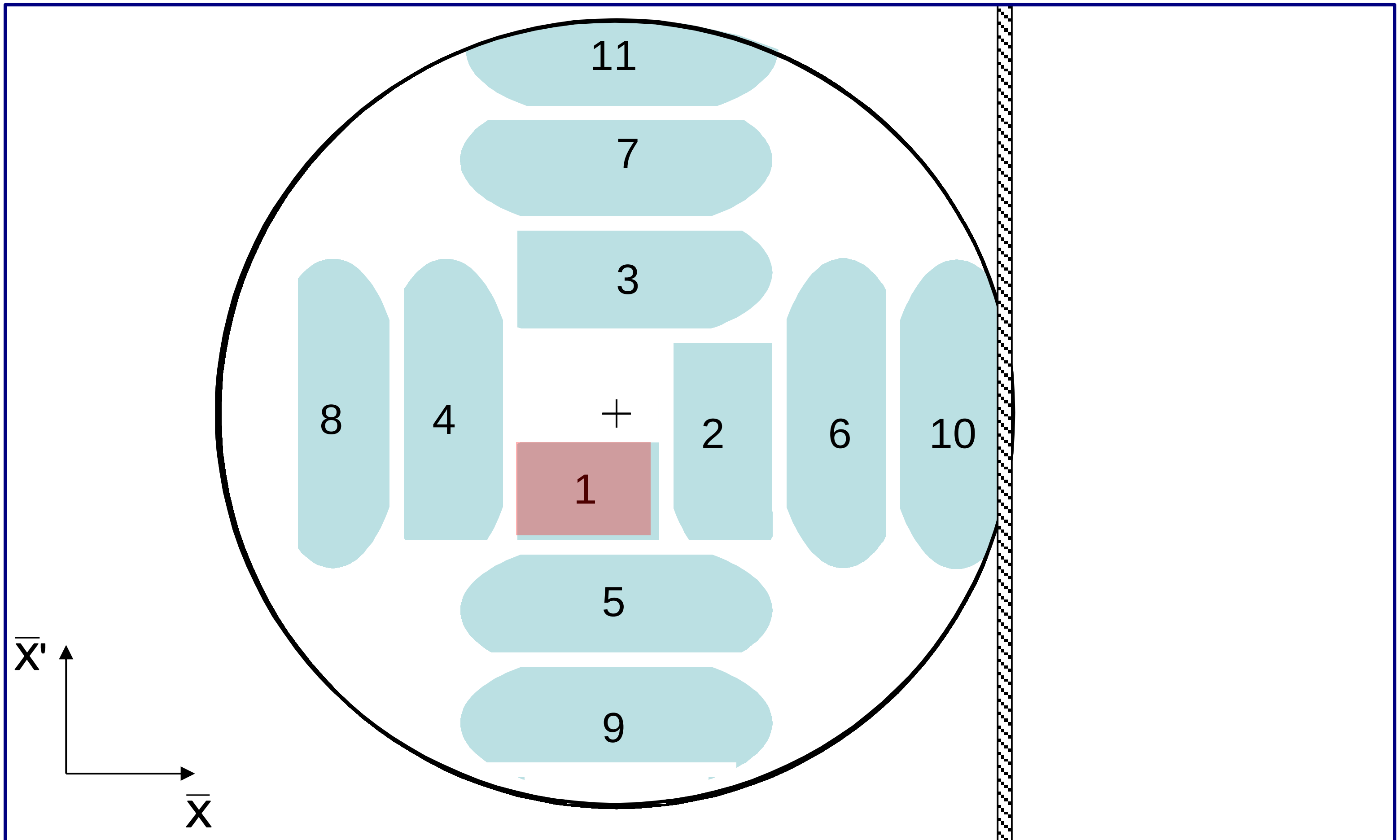
Multi-turn injection for hadrons

Turn 13



Multi-turn injection for hadrons

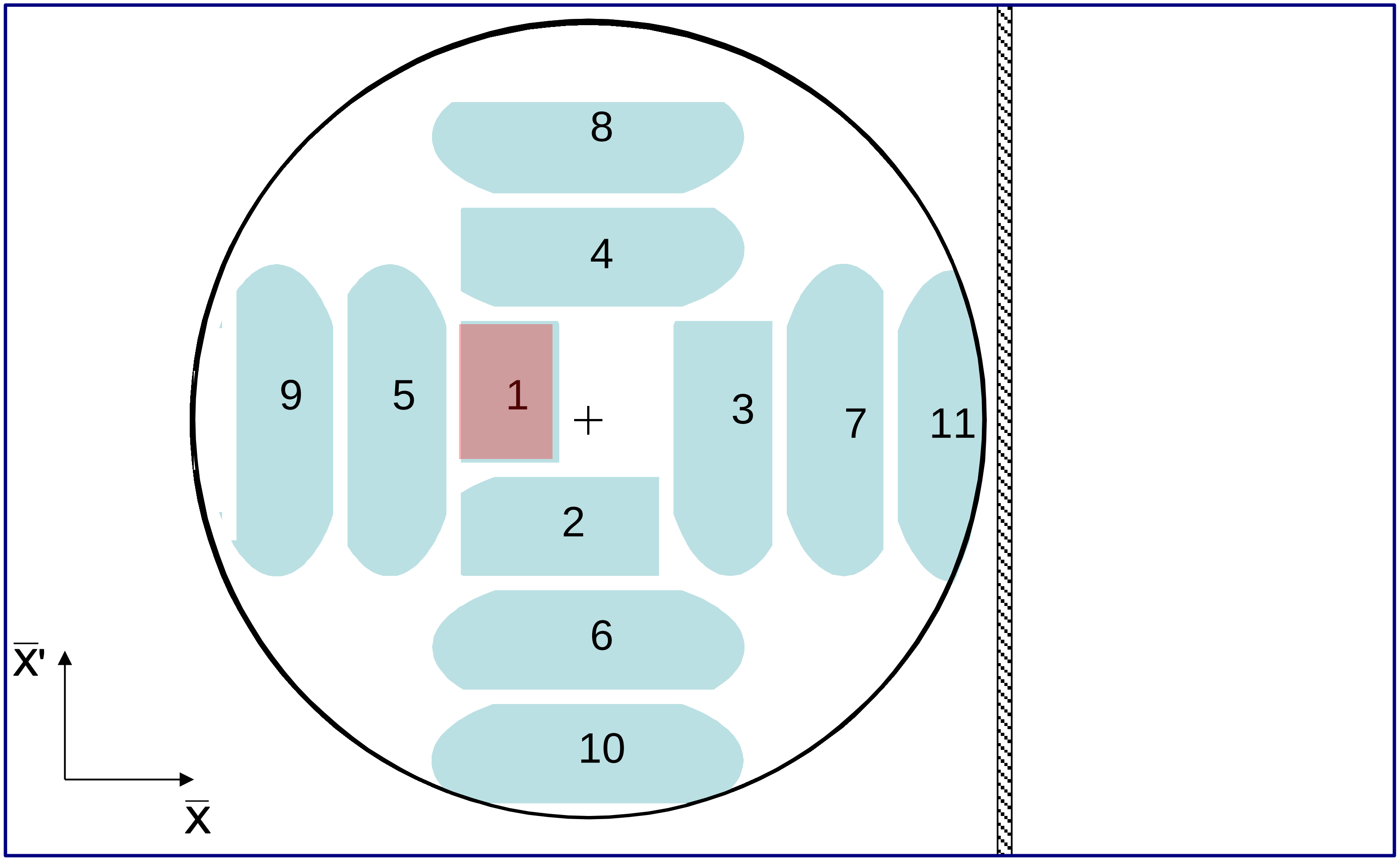
Turn 14



Multi-turn injection for hadrons

Phase space has been "painted"

Turn 15



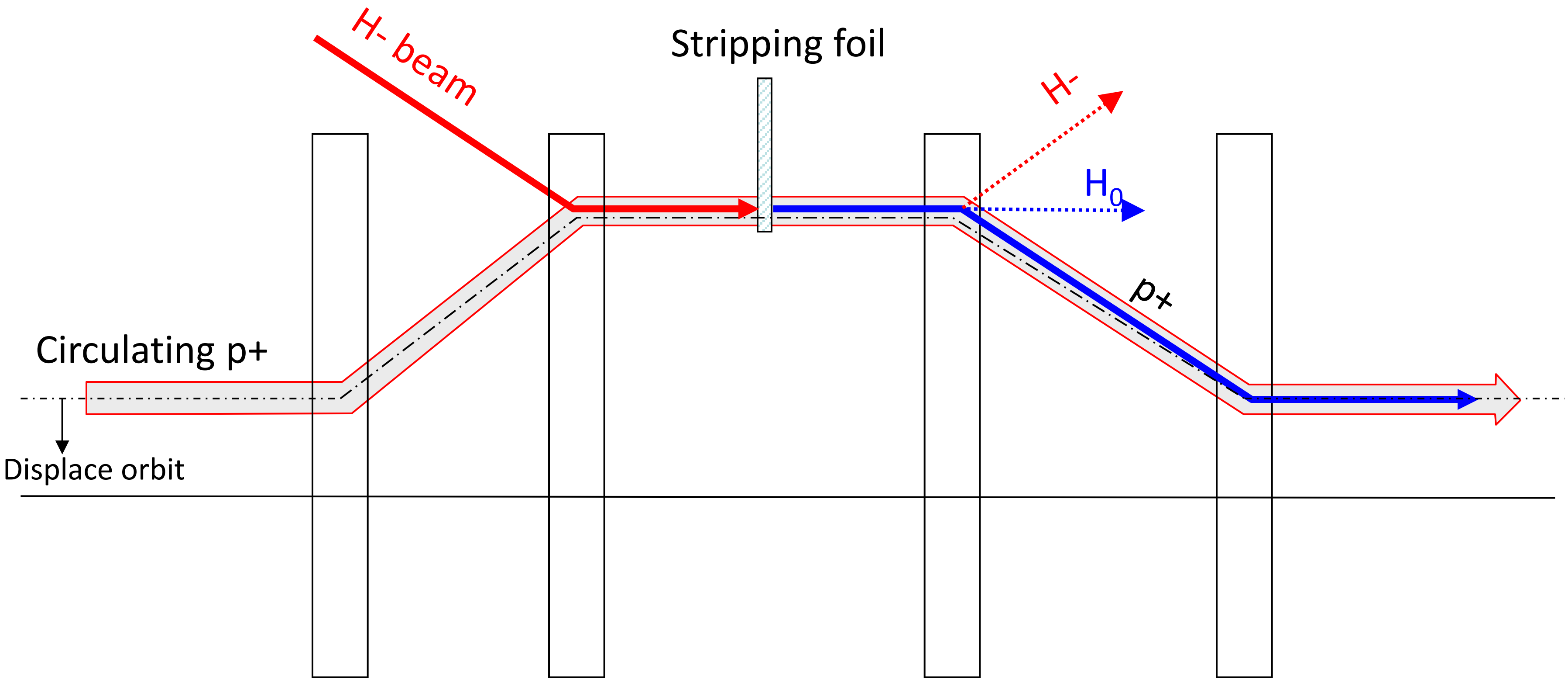
In reality filamentation occurs to produce a quasi-uniform beam

Charge exchange H- injection

- Multiturn injection is essential to accumulate high intensity
- Disadvantages inherent in using an injection septum
  - Width of several mm reduces aperture
  - Beam losses from circulating beam hitting septum
  - Limits number of injected turns to 10-20
- Charge-exchange injection provides elegant alternative
  - Possible to "cheat" Liouville's theorem, which says that emittance is conserved….
  - Convert H^- to p^+ using a thin stripping foil, allowing injection into the same phase space area

Charge exchange H- injection

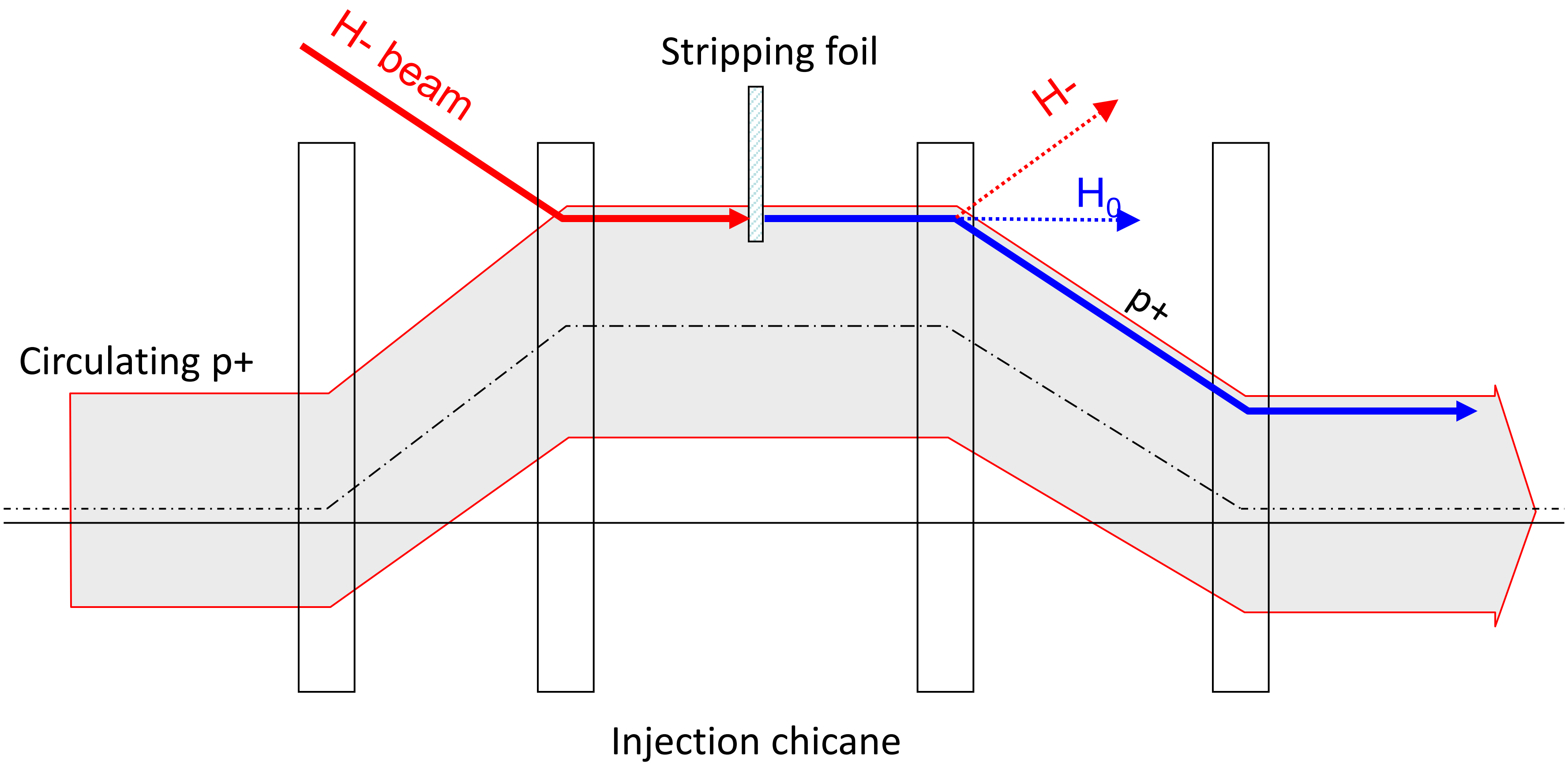
Start of injection process



Injection chicane dipoles

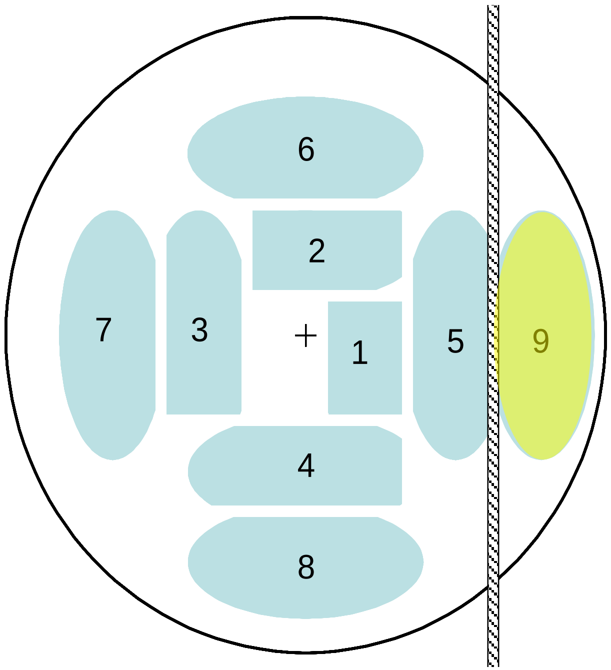
Charge exchange H- injection

End of injection process



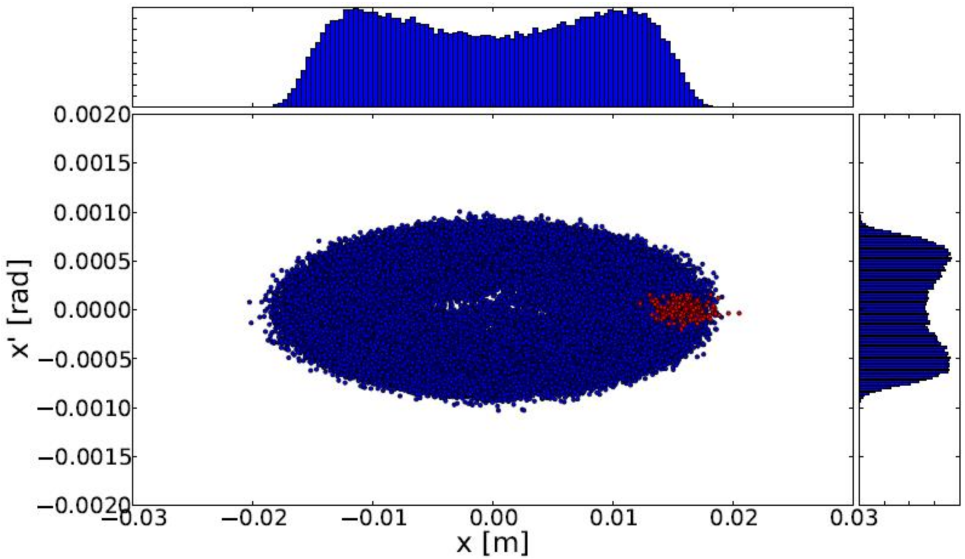
"Overinjection"

Multiturn injection of hadrons



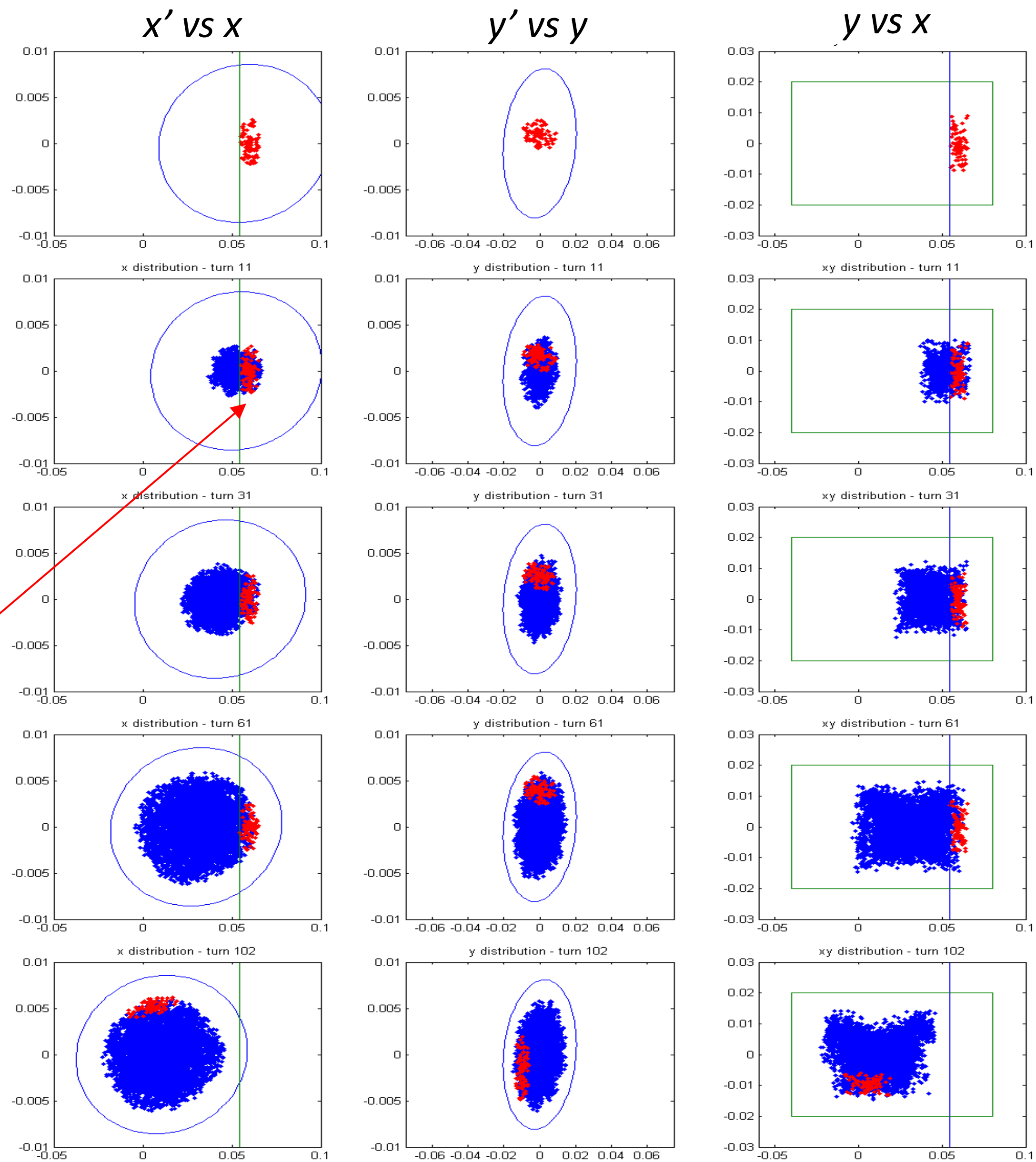
Septum → cannot inject on already occupied phase space area

Charge exchange injection



NO Septum needed → overinject on already occupied phase space area

H- injection - painting



Note injection into same phase space area as circulating beam

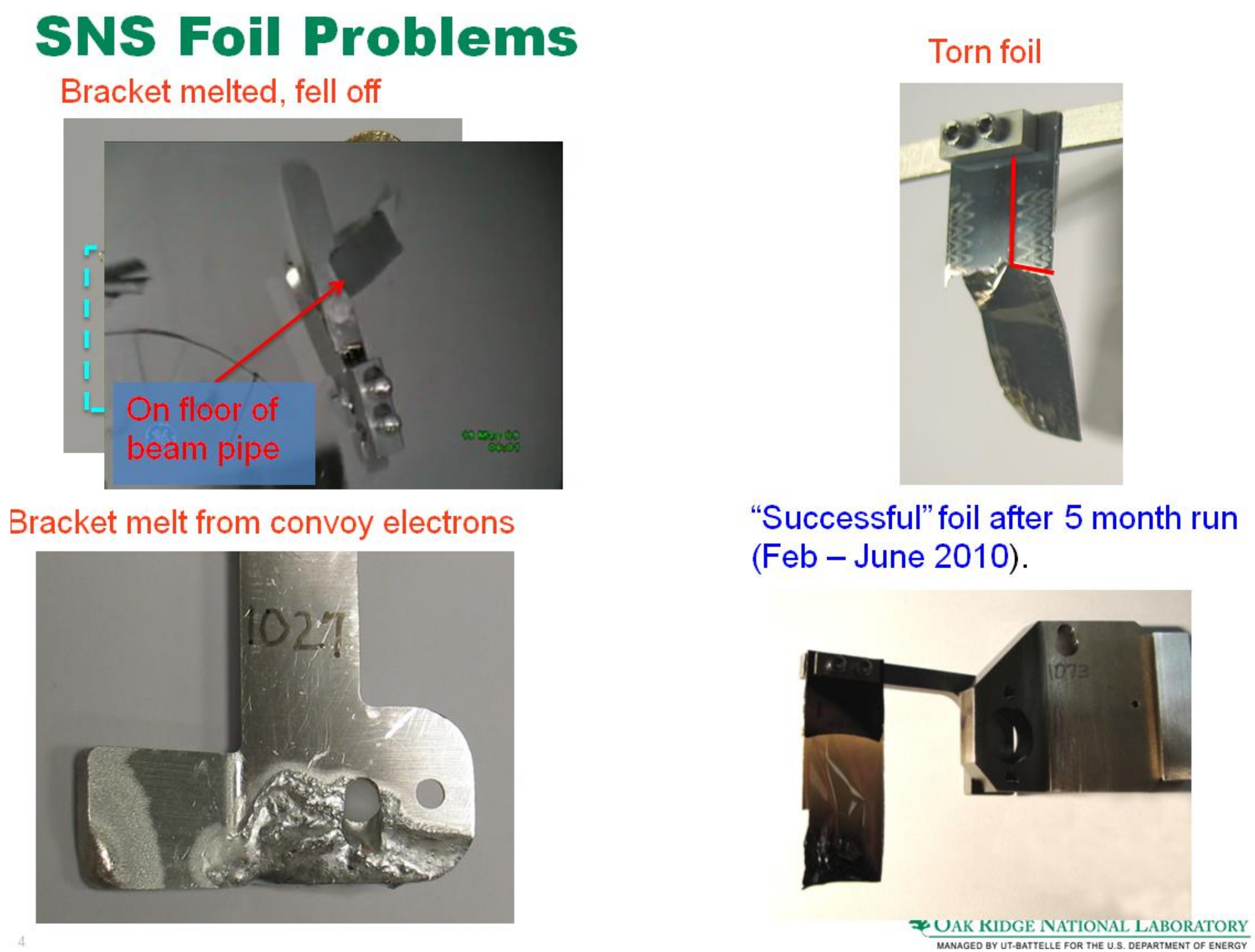
Time

~100 turns

Problems with foils

Foil damage

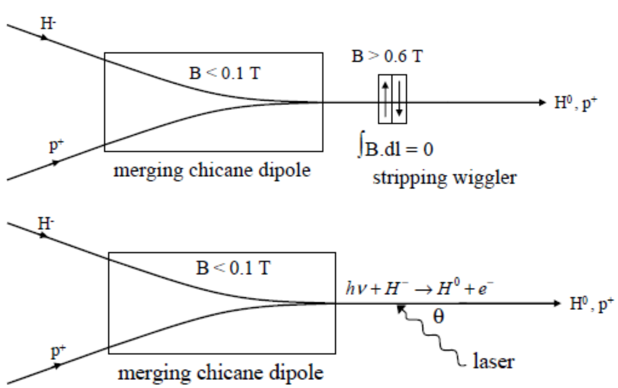
- Present machines on the high beam power frontier are approaching the limits of foils



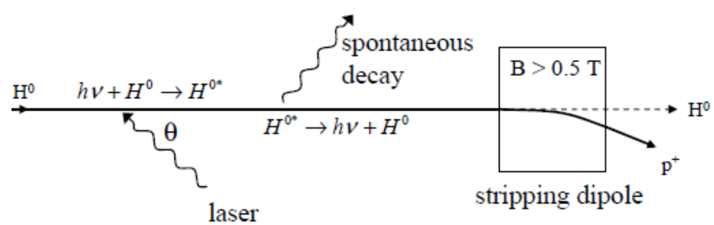
Sarah Cousineau, Laser stripping WS, Fermilab, 26-27 Sept-2013

Problems with foils

- Beam loss and radiation
  - Beam loss due to foil scattering (foil is highest loss point in SNS accelerator complex)
- Emittance growth due to foil scattering
  - Relevant for multi-purpose machines
- Laser stripping avoids a mechanical interaction with the beam

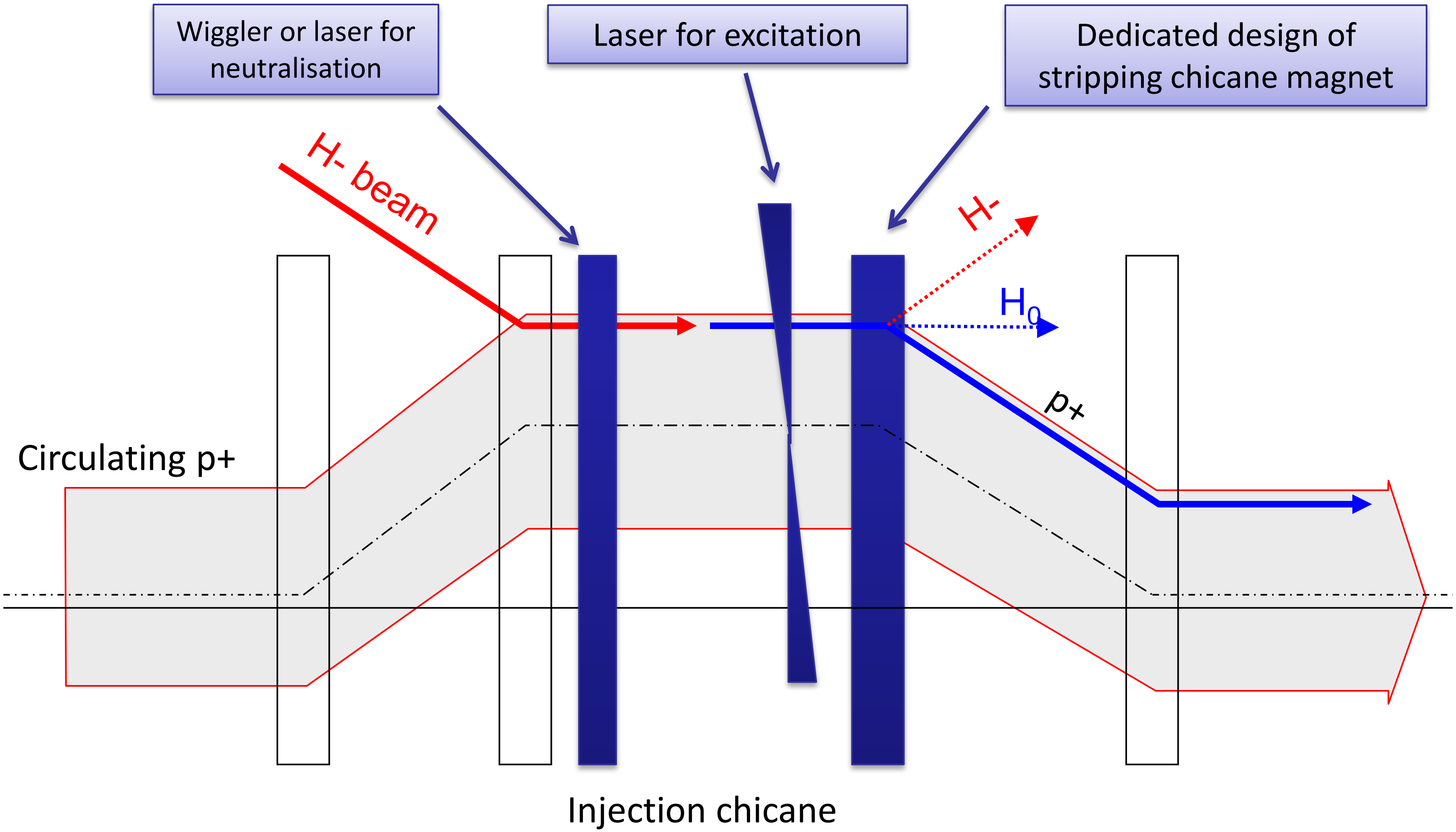


Neutralisation (H- → H0)



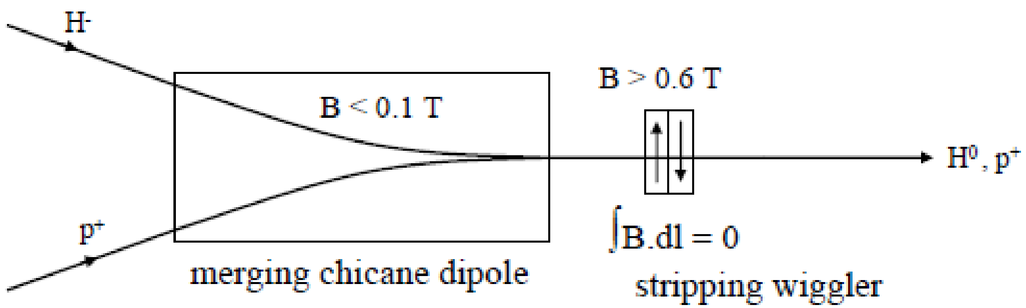
Stripping (H0 →p+)

H- injection with laser stripping

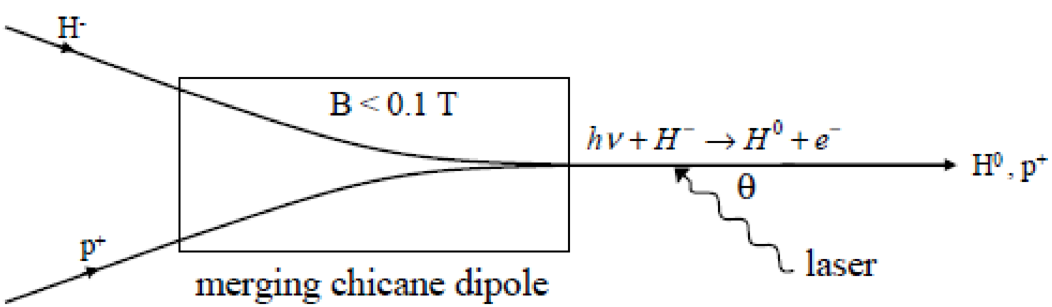


Laser stripping concept: H^- to H^0

- Either **Lorentz-stripping in a wiggler magnet**…



- or **Photo-dissociation**



Lorentz stripping

- H^- ion moving in magnetic field → Lorentz force tends to break it up
- Binding energy of extra electron 0.76 eV
- In ion rest-frame electric field E is the Lorentz-transform of the magnetic field B in the lab-frame

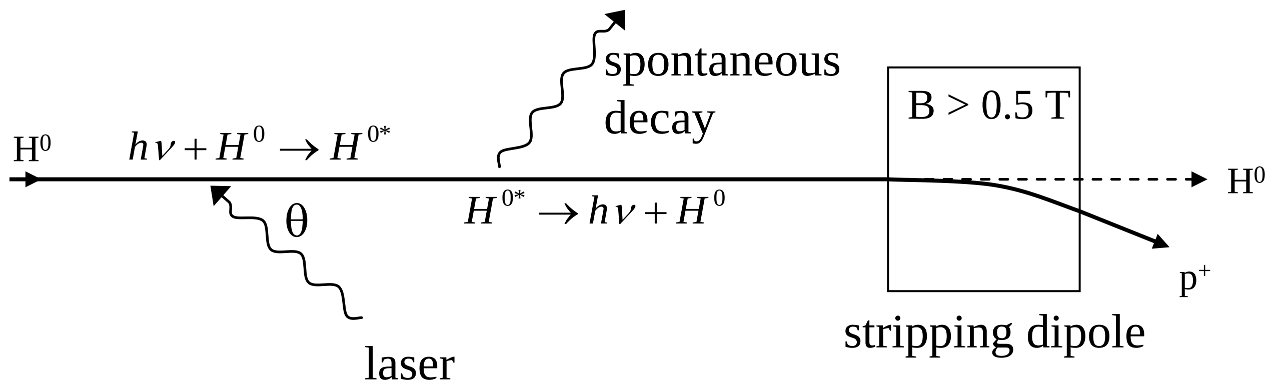
$$E[MV/cm] = 3.197 \cdot p\left[\frac{GeV}{c}\right] \cdot B[T]$$

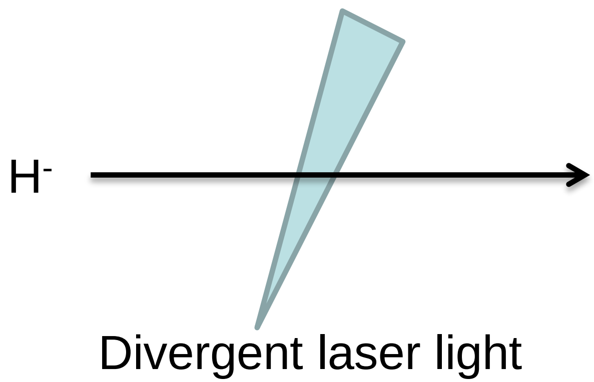
- The ion's lifetime can be parametrized as

$$\tau = \frac{A}{E} \cdot exp\left(\frac{C}{E}\right) \qquad A = 7.96e-14\ s \cdot \frac{MV}{cm}, C = 42.56\frac{MV}{cm}$$

H^0 --> p^+ stripping

divergent laser beam





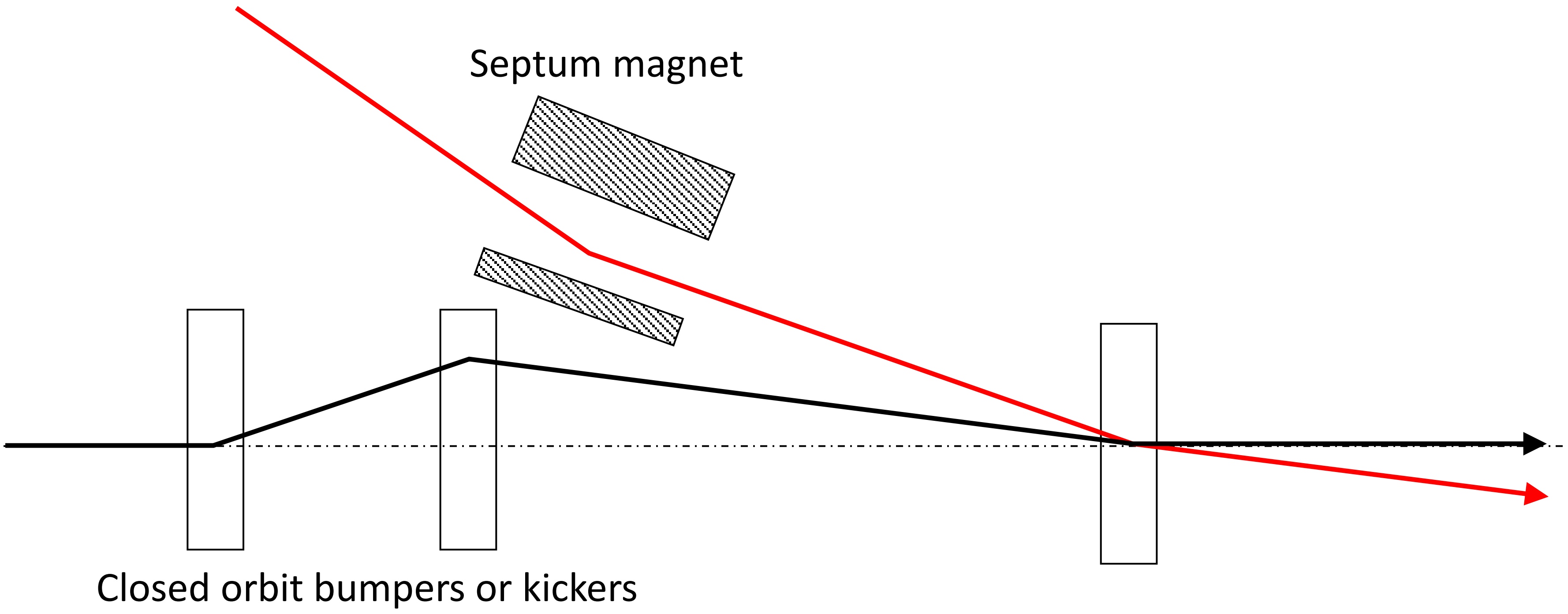
Scheme developed and tested at SNS (Danilov et al.):

- Resonant excitation of ground-state H^0 in field free region
- Stripping of excited electron in magnetic field
- Large spread of effective resonance frequencies →divergent beam

Lepton injection

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

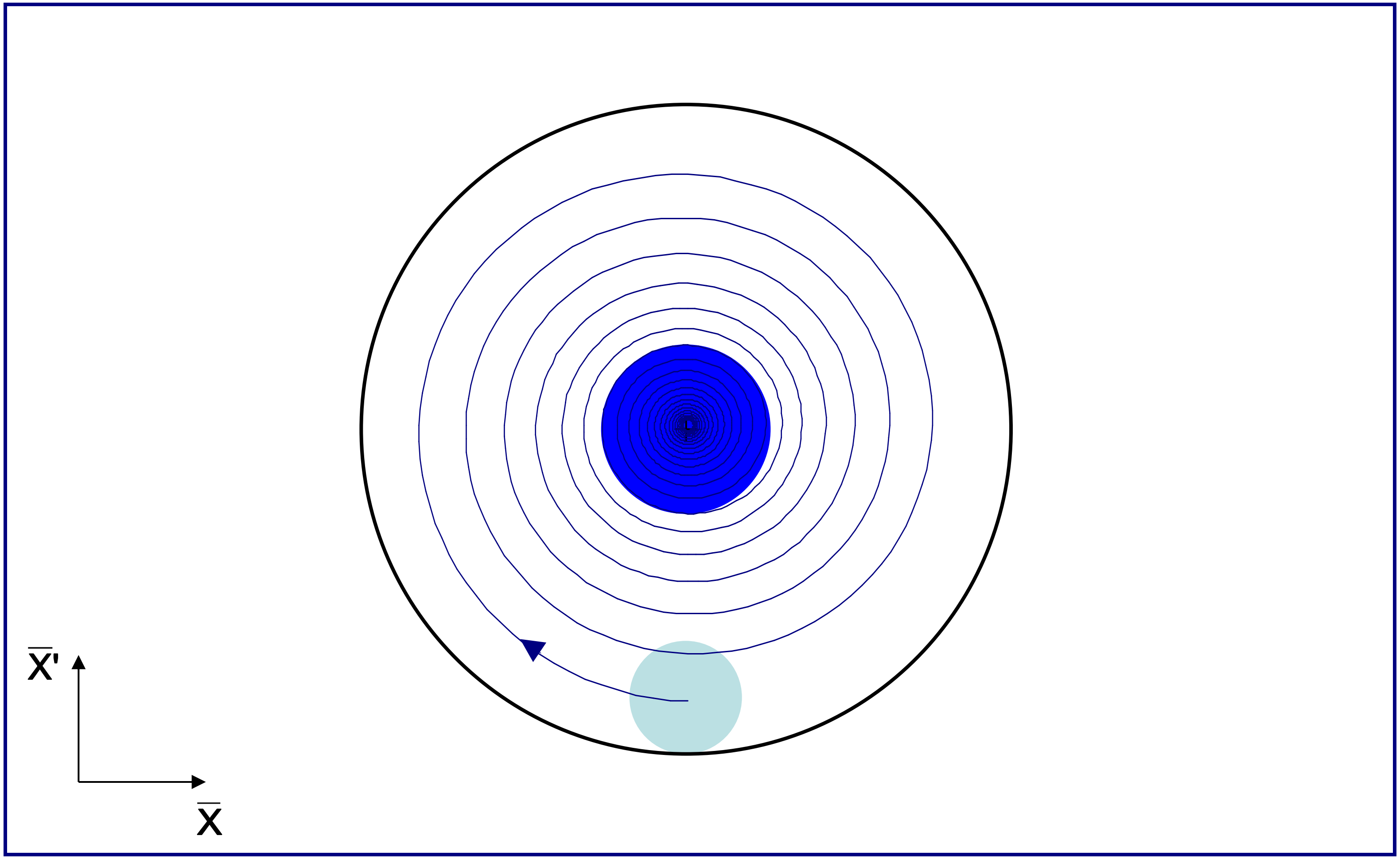
Betatron lepton injection



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

Betatron lepton injection

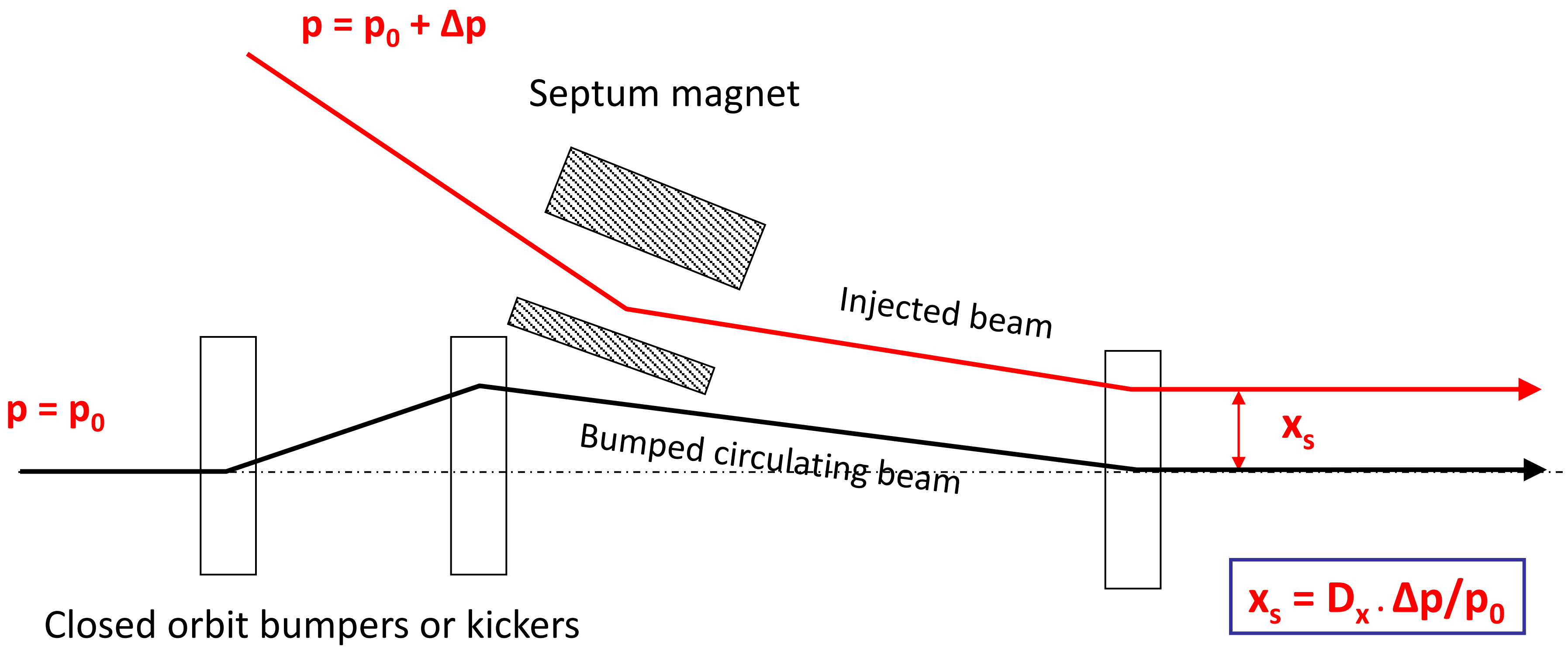
Injected bunch performs damped betatron oscillations



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

Synchrotron lepton injection

Inject an off-momentum beam

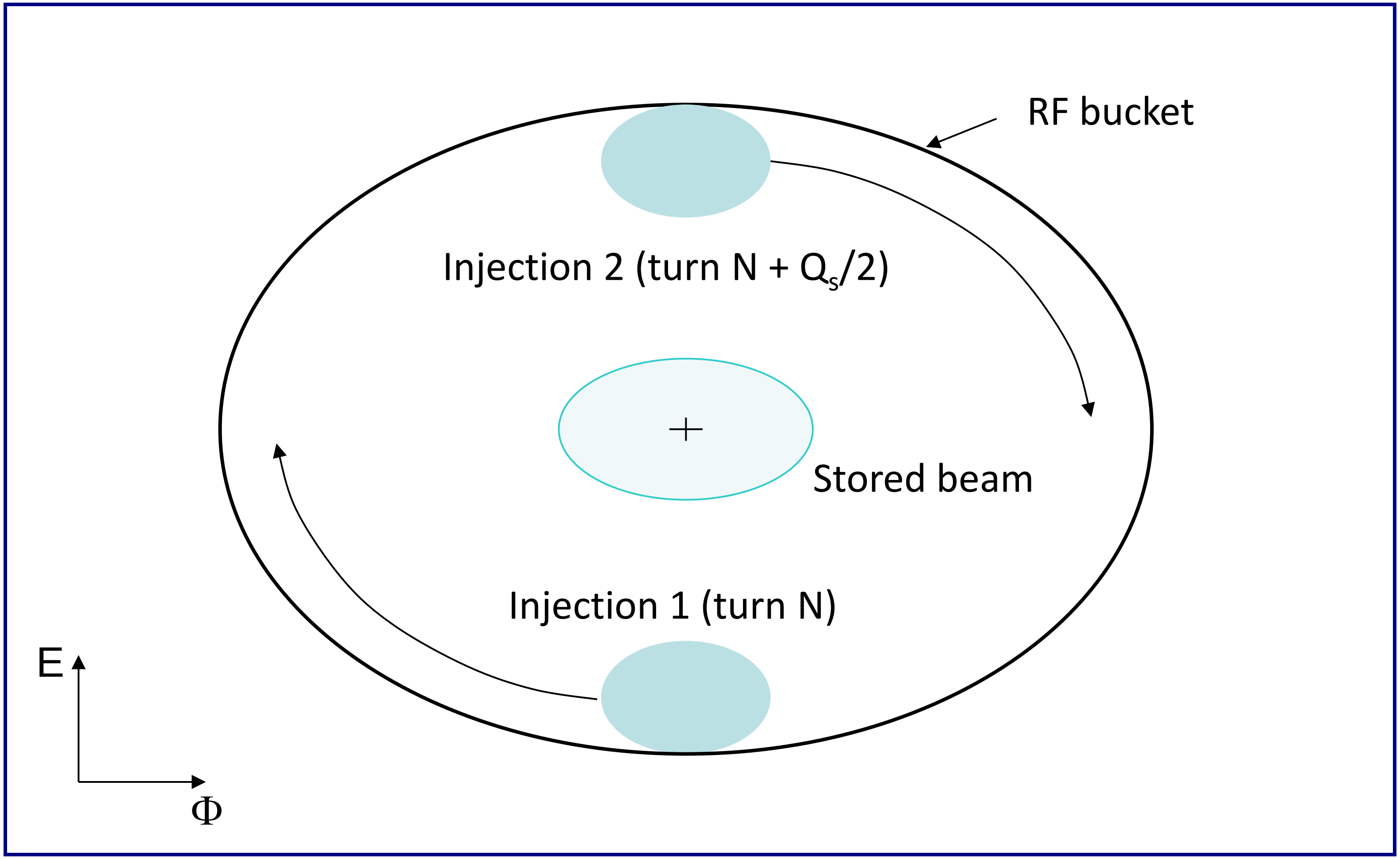


$x_s = D_x \cdot \Delta p / p_0$

- 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

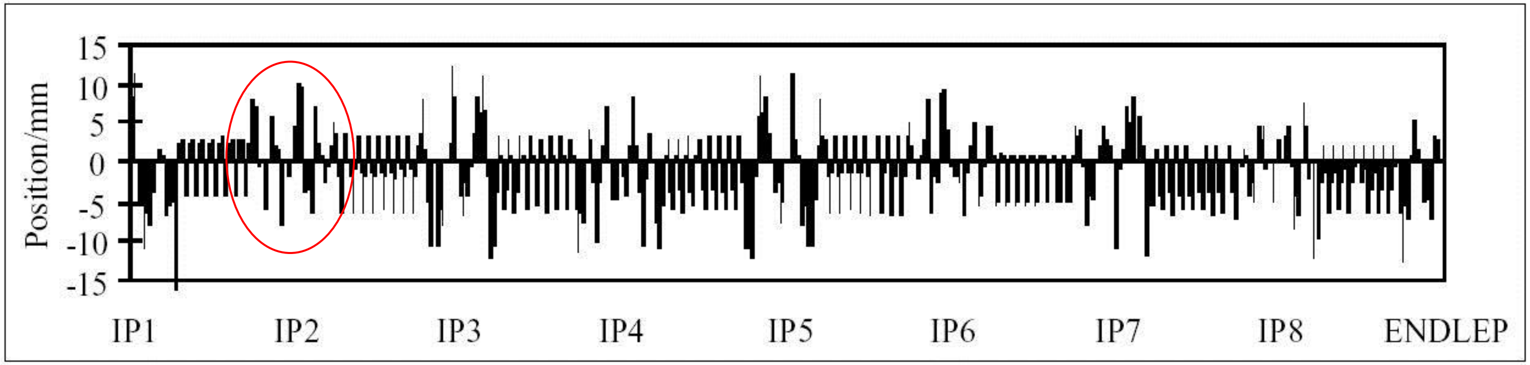
Synchrotron lepton injection

Double batch injection possible….

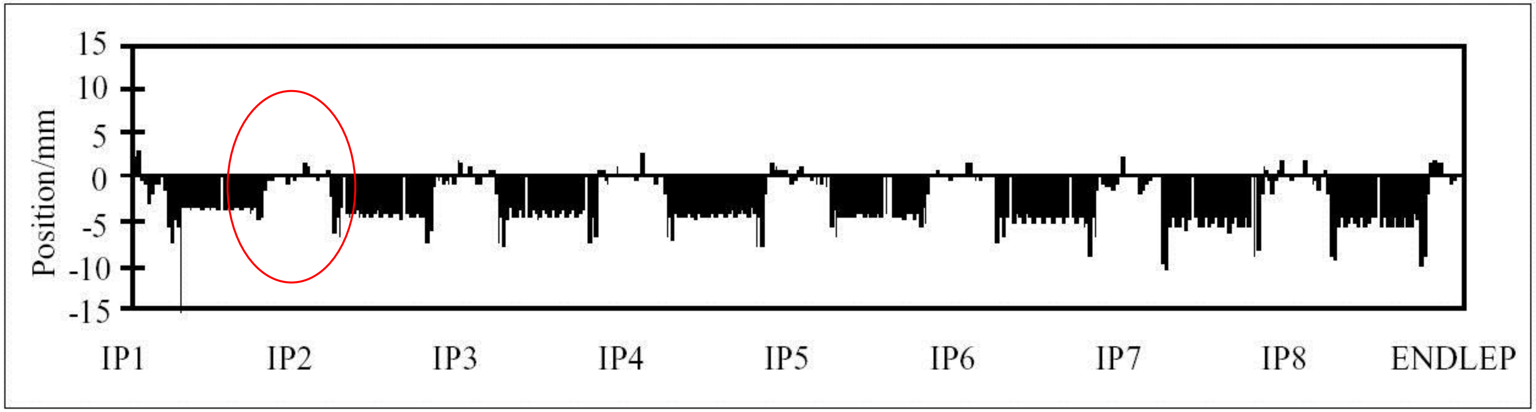


Longitudinal damping time in LEP was ~ 3’000 turns (2 x faster than transverse)

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 $\Delta P/P$ at -0.6%

Synchrotron Injection in LEP gave improved background for LEP experiments due to small orbit offsets in zero dispersion straight sections

Injection - summary

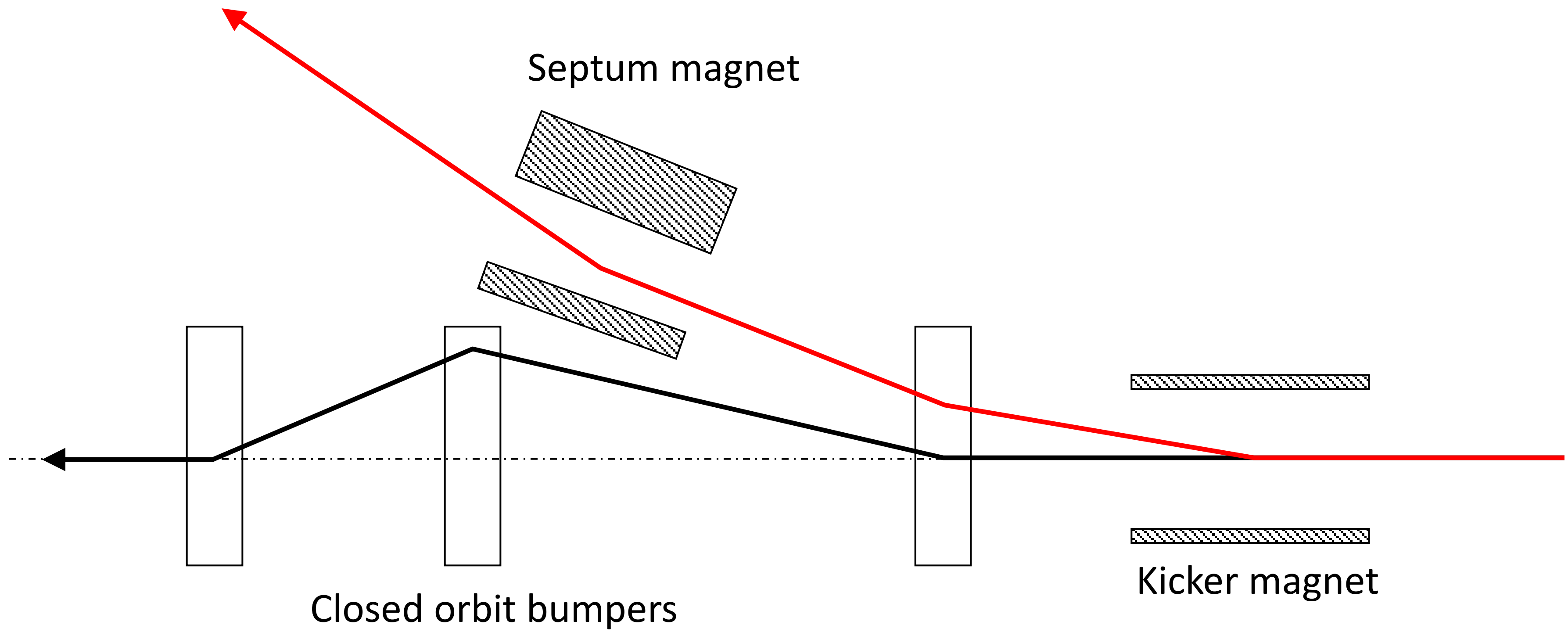
- Several different techniques
  - Single-turn injection for hadrons
    - Boxcar stacking: transfer between machines in accelerator chain
    - Angle / position errors ⇒ injection oscillations
    - Optics errors ⇒ betatron mismatch oscillations
    - Oscillations ⇒ filamentation ⇒ emittance increase
  - Multi-turn injection for hadrons
    - Phase space painting to increase intensity
    - H- injection allows injection into same phase space area
  - Lepton injection: take advantage of damping
    - Less concerned about injection precision and matching

Extraction

- Different extraction techniques exist, depending on requirements
  - Fast extraction: ≤1 turn
  - Non-resonant multi-turn extraction: few turns
  - Resonant multi-turn extraction: many thousands of turns
  - Resonant low-loss multi-turn extraction: few turns
- Usually higher energy than injection ⇒ stronger elements ($\int B.dl$)
  - At high energies many kicker and septum modules may be required
  - To reduce kicker and septum strength, beam can be moved near to septum by closed orbit bump

Fast single turn extraction

Whole beam kicked into septum gap and extracted.

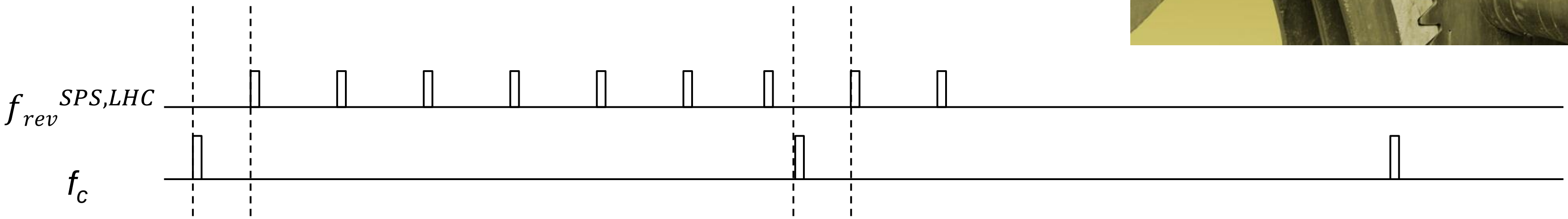


- Kicker deflects the entire beam into the septum in a single turn
- Septum deflects the beam entire into the transfer line
- Most efficient (lowest deflection angles required) for p/2 phase advance between kicker and septum

Synchronisation I

- Beam from PS has to be injected into right SPS bucket wrt to SPS revolution frequency
- Set frequency
  - Before beam is transferred, e.g. from SPS to LHC, the two machines must be synchronised on a common frequency f_c

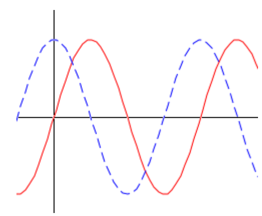
$$f_c = \frac{f_{rev}^{SPS}}{27} = \frac{f_{rev}^{LHC}}{7}$$

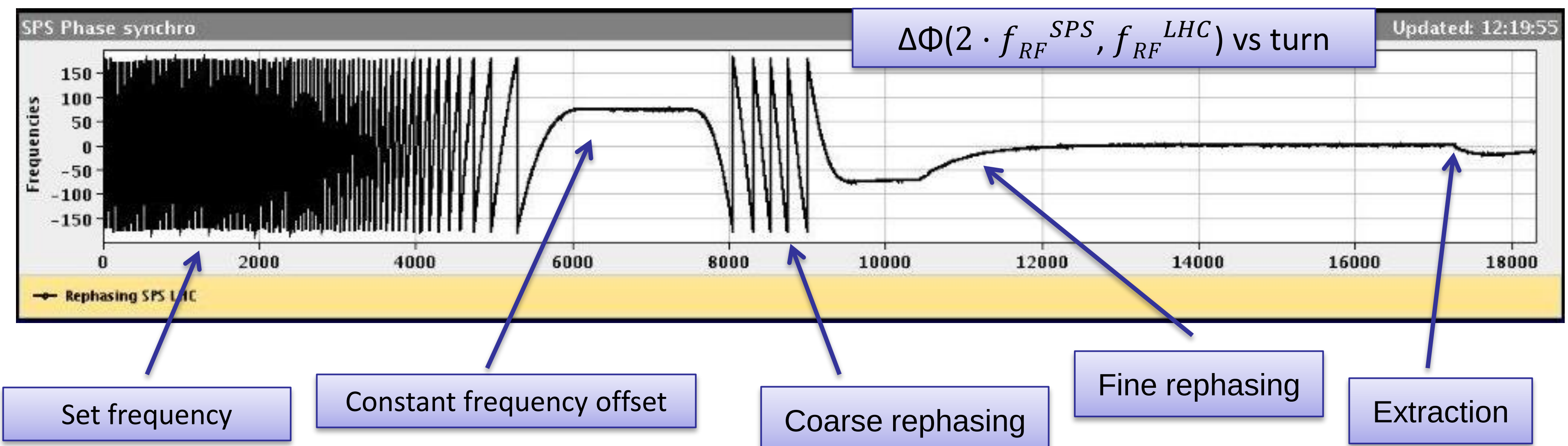


- Now the LHC can choose the bucket in which the first bunch will be injected
  → SPS must shift the beam to adapt to this position

Synchronisation II

- "Coarse" rephasing
  - Shift the beam in the SPS to reach wanted LHC bucket
  - To do so the particles will run for a short period on an average radius which is different from the central orbit ("radial steering")
  - Matching of common frequency f_c with SPS revolution frequency (TDC)
- "Fine" rephasing – phase matching
  - Correct the position within the bucket
  - Matching of $f_{RF}{}^{LHC}$ and $f_{RF}{}^{SPS}$ (phase lock loop)



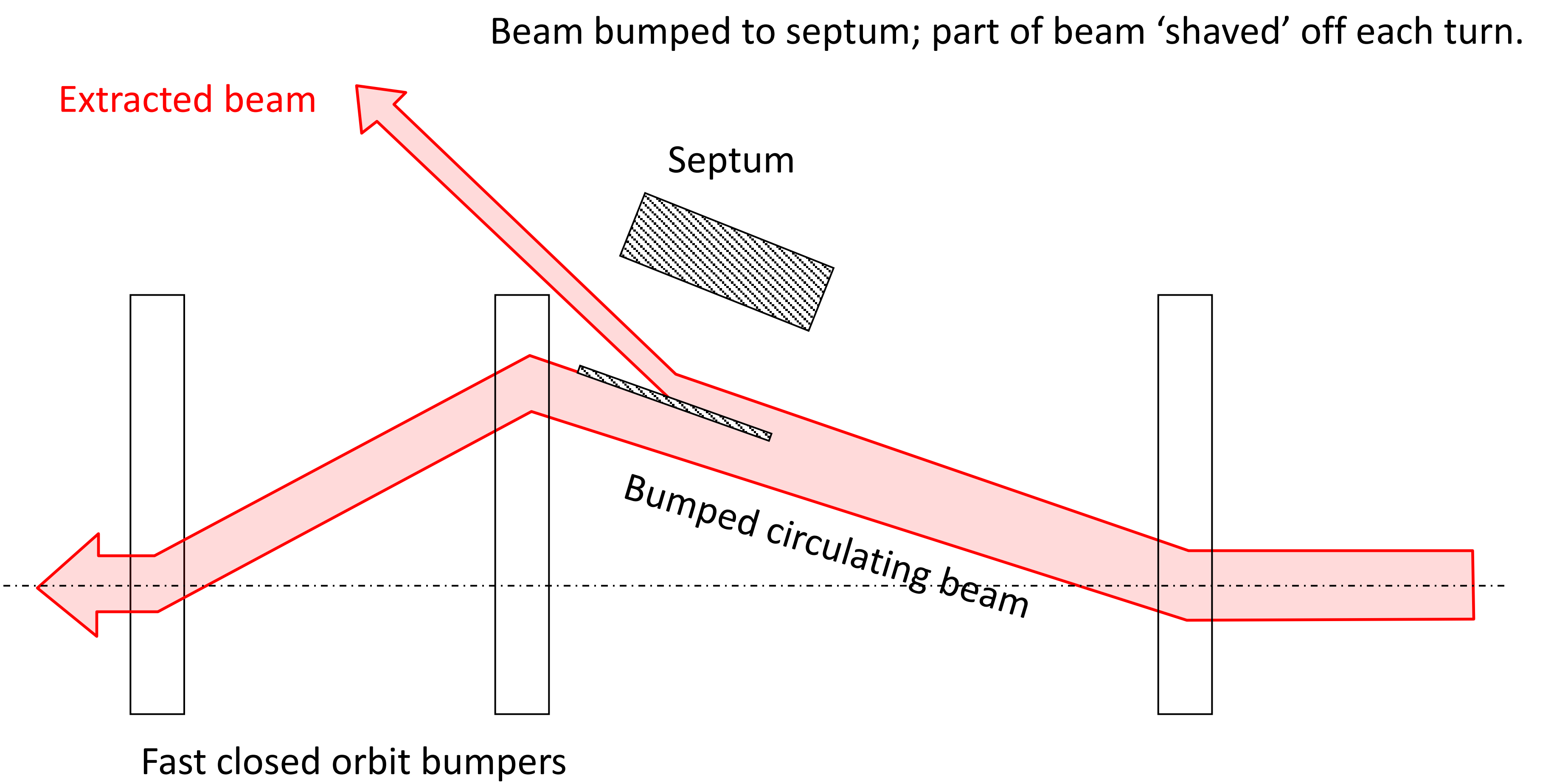


Multi-turn extraction

- Some filling schemes require a beam to be injected in several turns to a larger machine…
- And very commonly Fixed Target physics experiments and medical accelerators often need a quasi-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



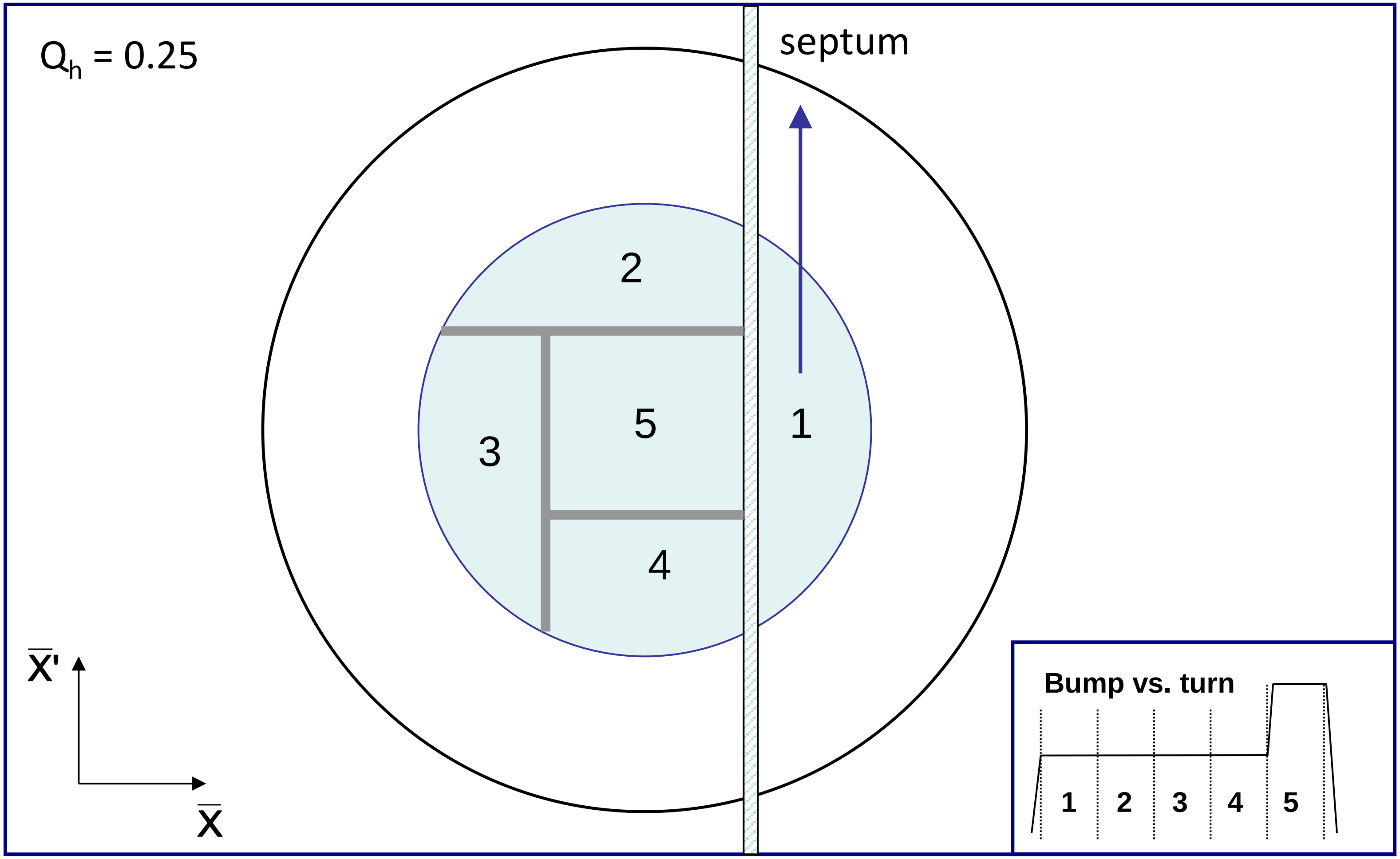
- Fast bumper deflects the whole beam onto the septum
- Beam extracted in a few turns, with the machine tune rotating the beam
- Intrinsically a high-loss process – thin septum essential

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 ≈ 3×10^{13} p+
  - Total intensity in SPS ≈ 5×10^{13} p+

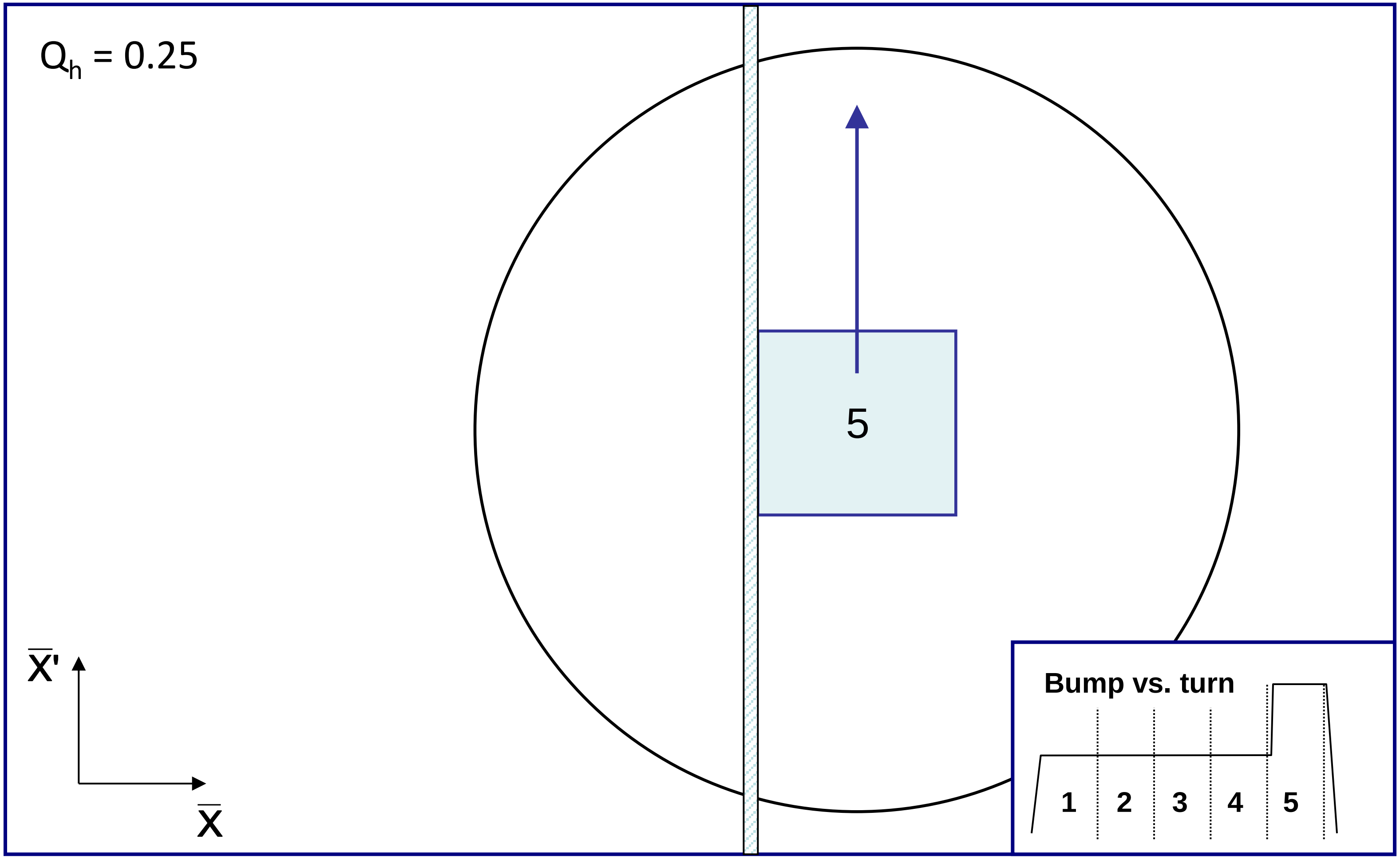
Non-resonant multi-turn extraction

CERN PS to SPS: 5-turn continuous transfer



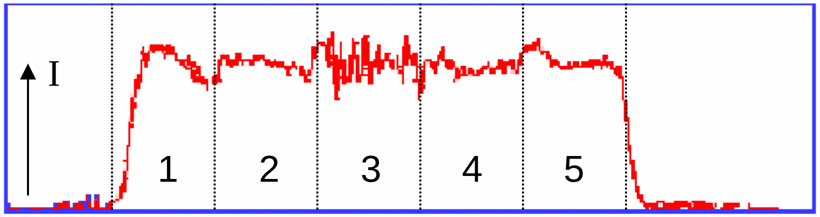
Non-resonant multi-turn extraction

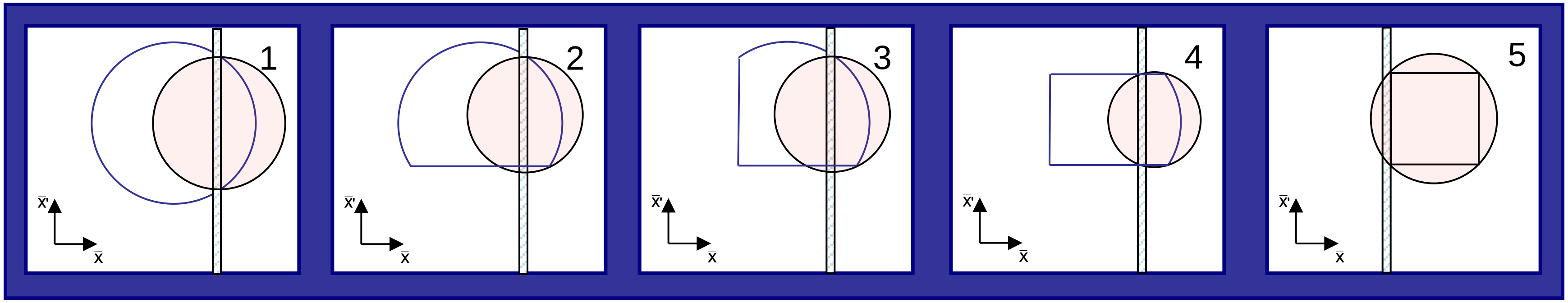
CERN PS to SPS: 5-turn continuous transfer – 5th turn



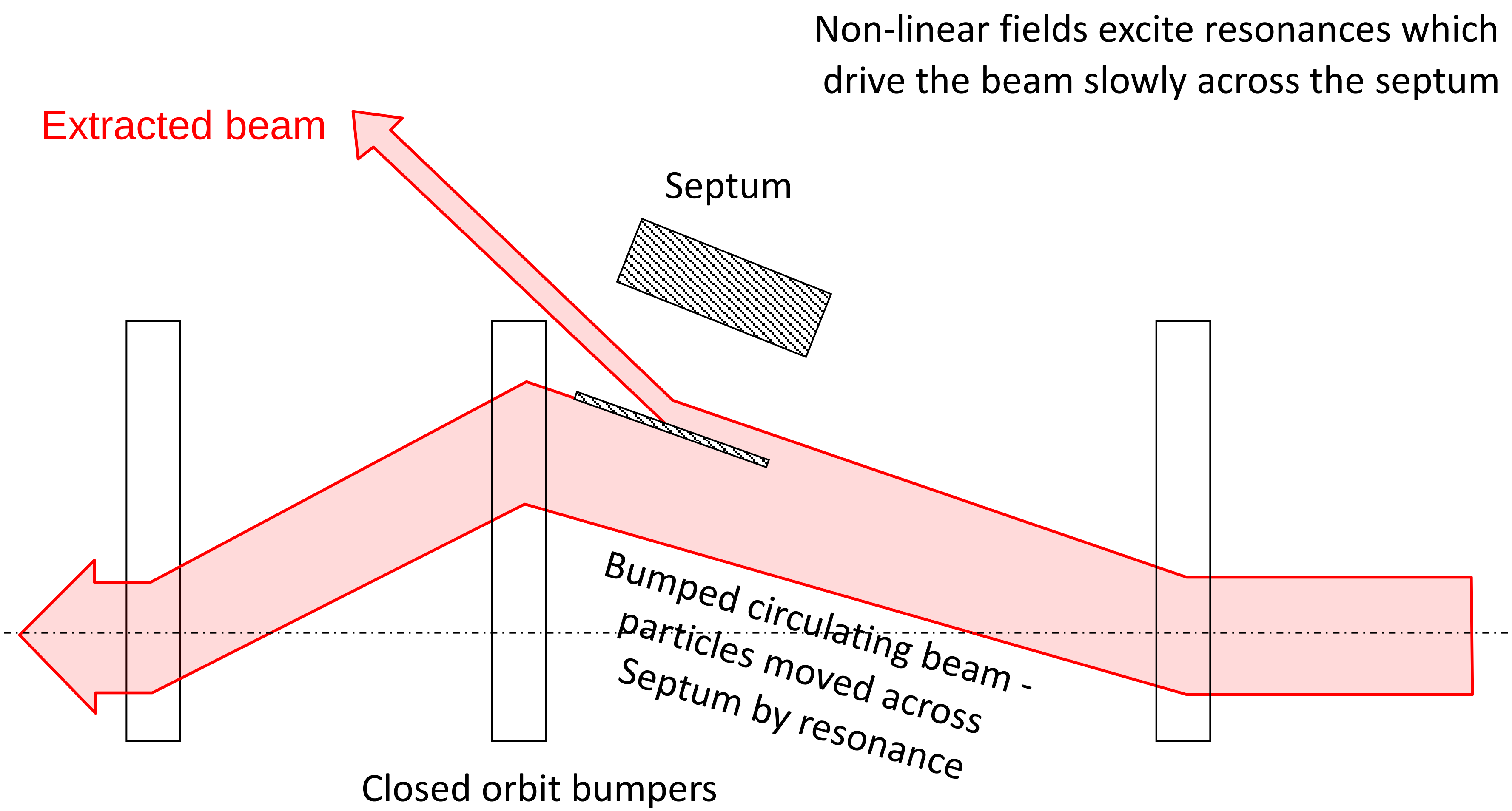
Non-resonant multi-turn extraction

- 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

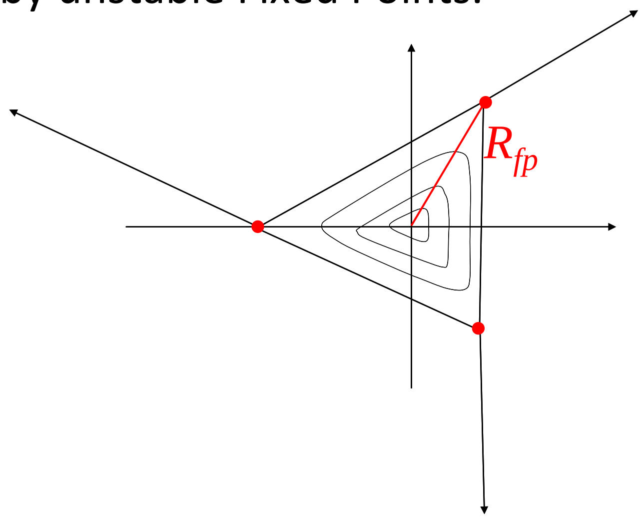


- Slow bumpers move the beam near the septum
- Tune adjusted close to n^{th} order betatron resonance
- Multipole magnets excited to define stable area in phase space, size depends on $\Delta Q = Q - Q_r$

Resonant multi-turn extraction

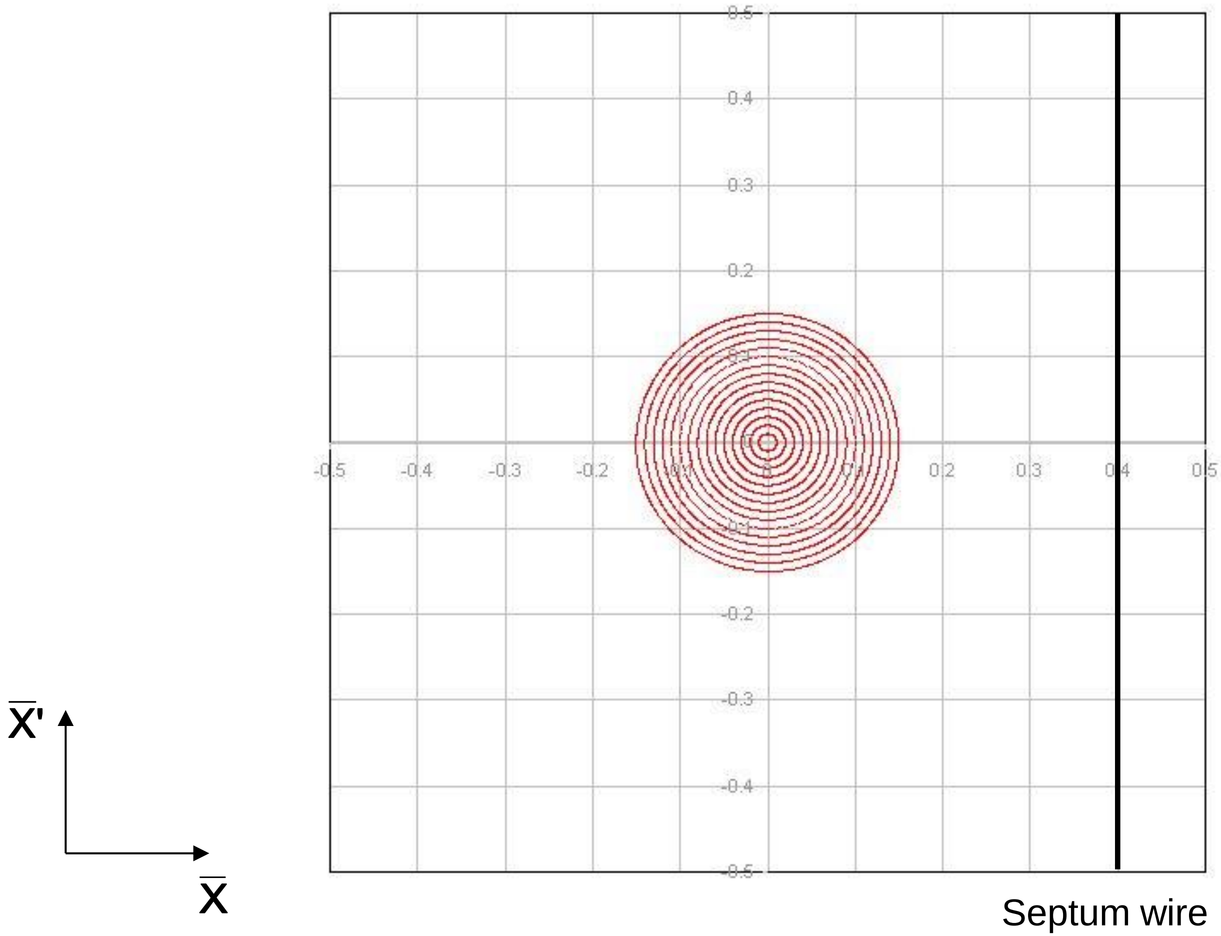
- 3^{rd} order resonances
  - Sextupole fields distort the circular normalised phase space particle trajectories.
  - Stable area defined, delimited by unstable Fixed Points.

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



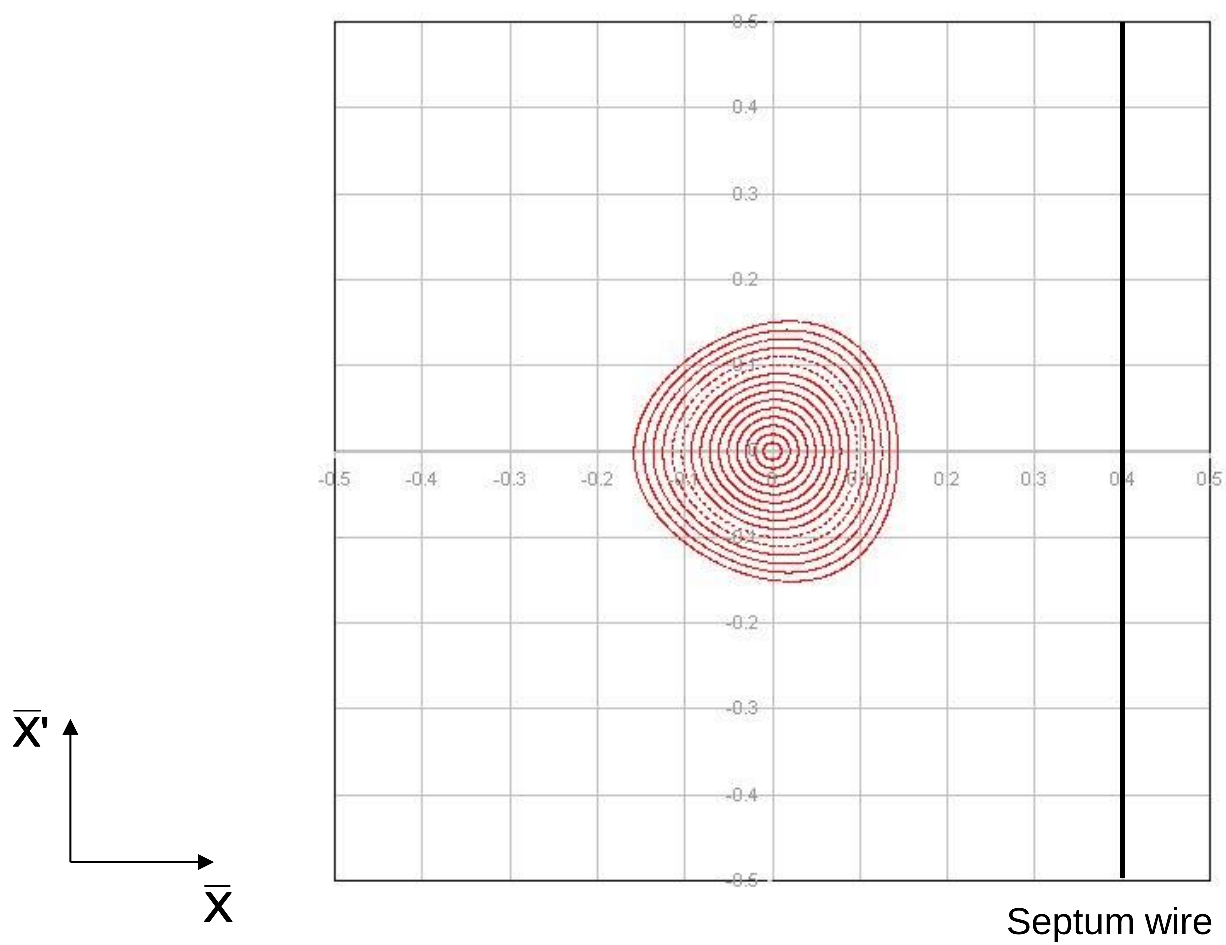
  - Sextupoles families arranged to produce suitable phase space orientation of the stable triangle at thin electrostatic septum
  - Stable area can be reduced by increasing the sextupole strength, or (easier) by approaching machine tune Q_h to resonant 1/3 integer tune
  - Reducing ΔQ with main machine 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



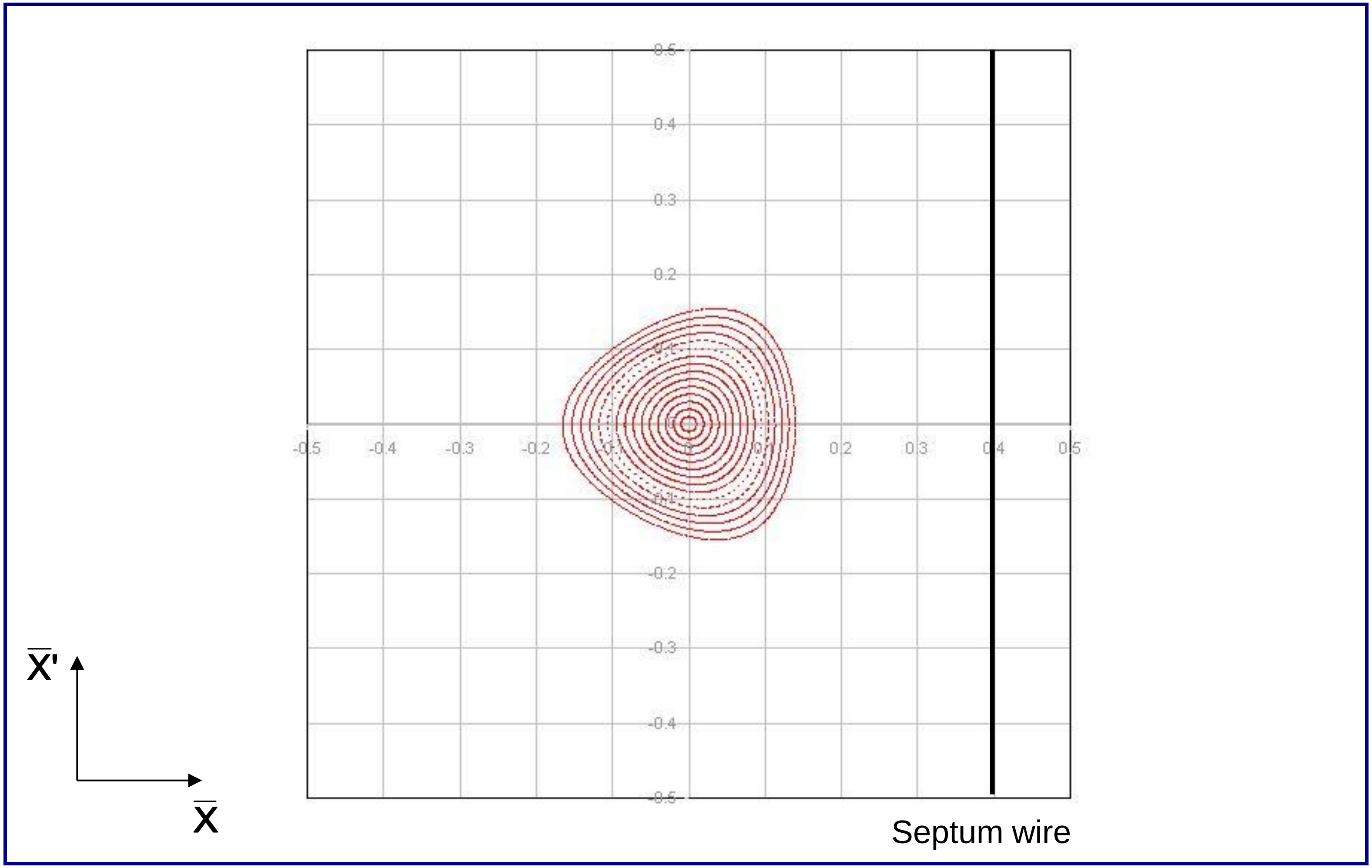
- Particles distributed on emittance contours
- ΔQ large – no phase space distortion

Third-order resonant extraction

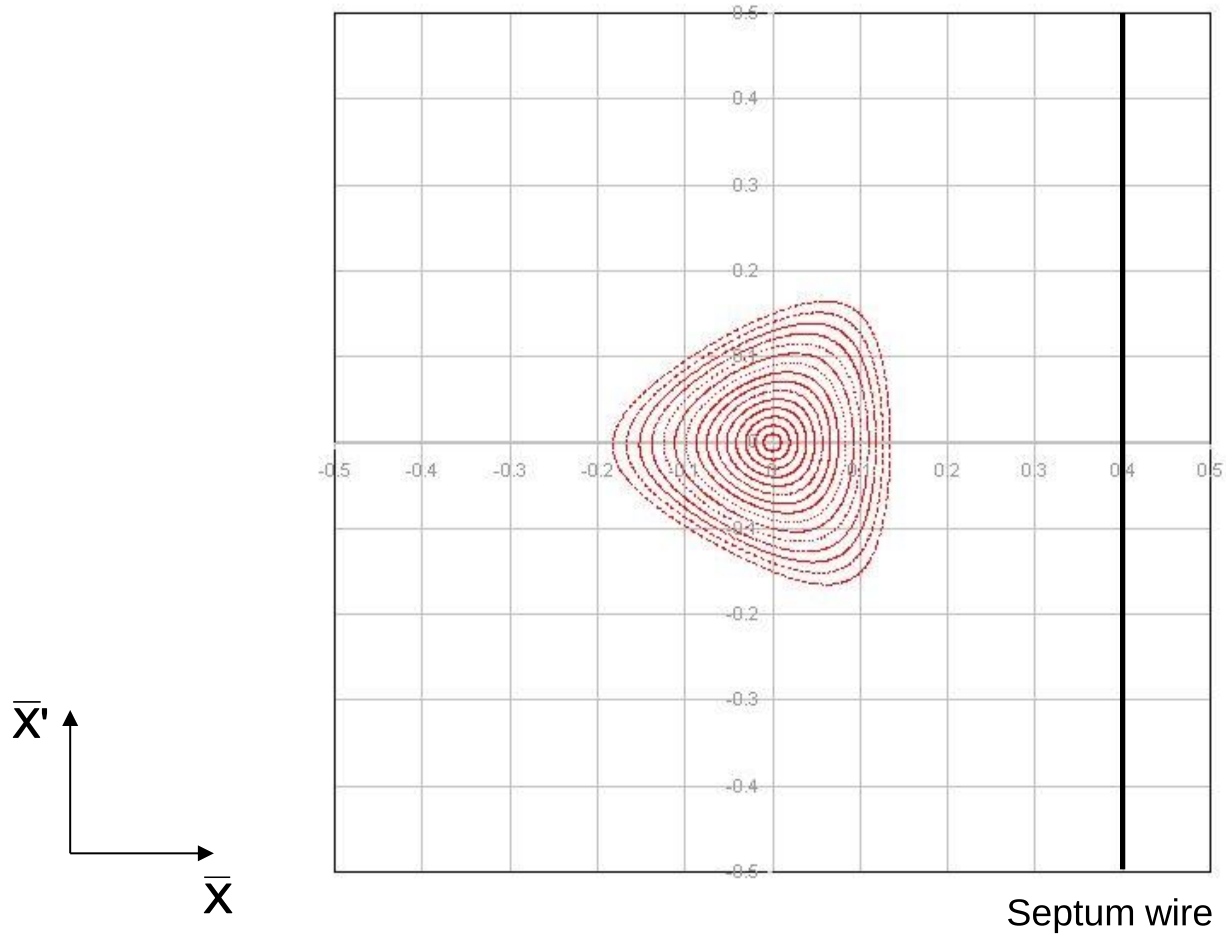


- Dedicated sextupole magnets produce a triangular stable area in phase space
- ΔQ decreasing – phase space distortion for largest amplitudes

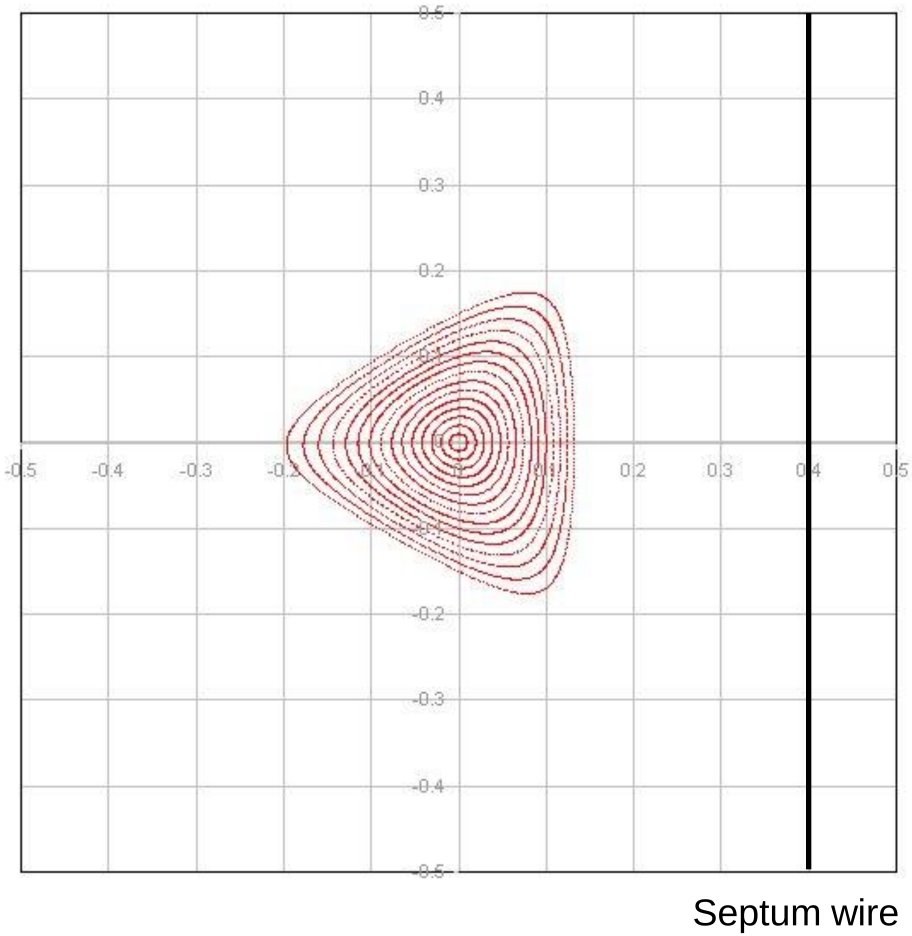
Third-order resonant extraction

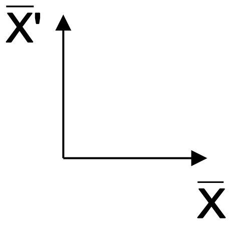


Third-order resonant extraction

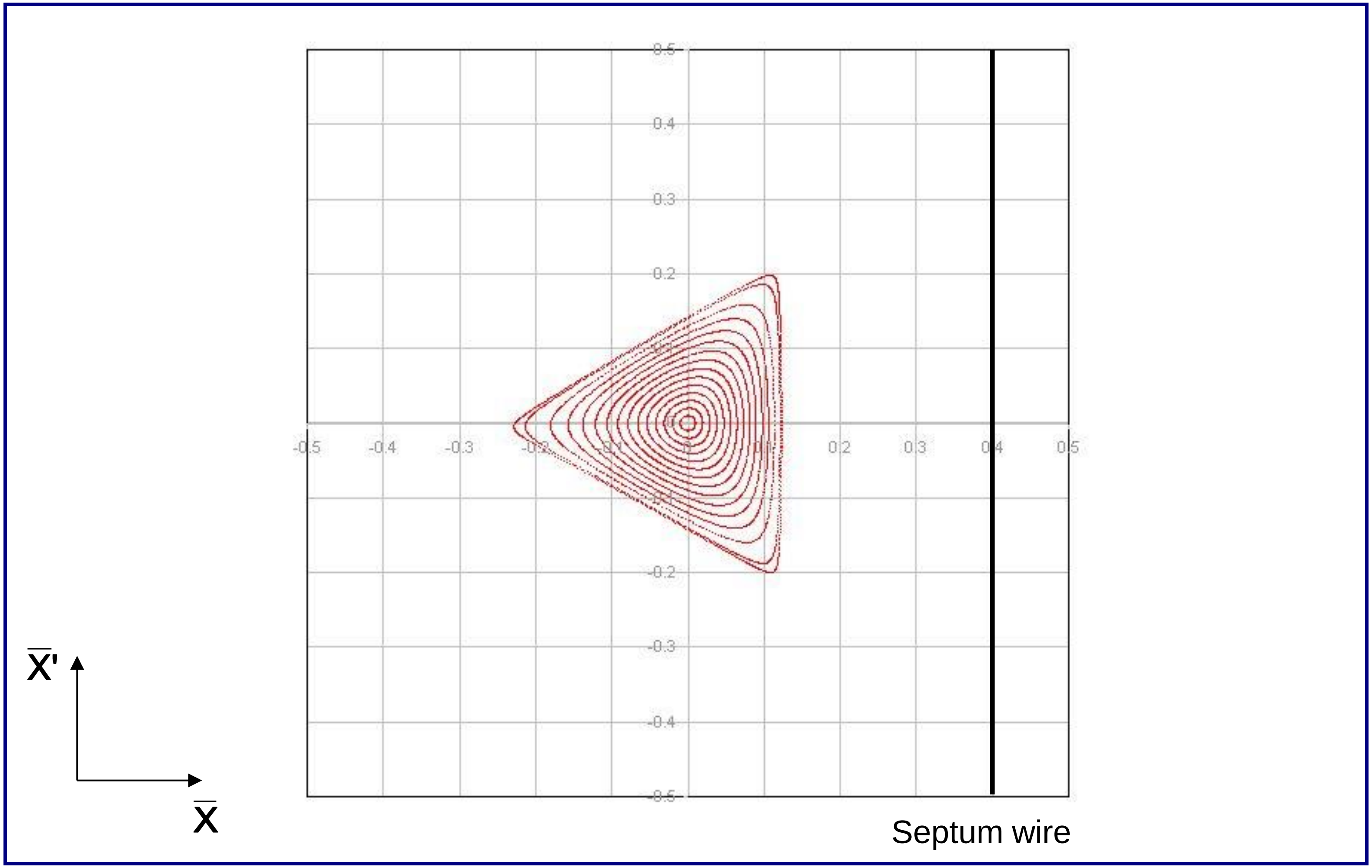


Third-order resonant extraction



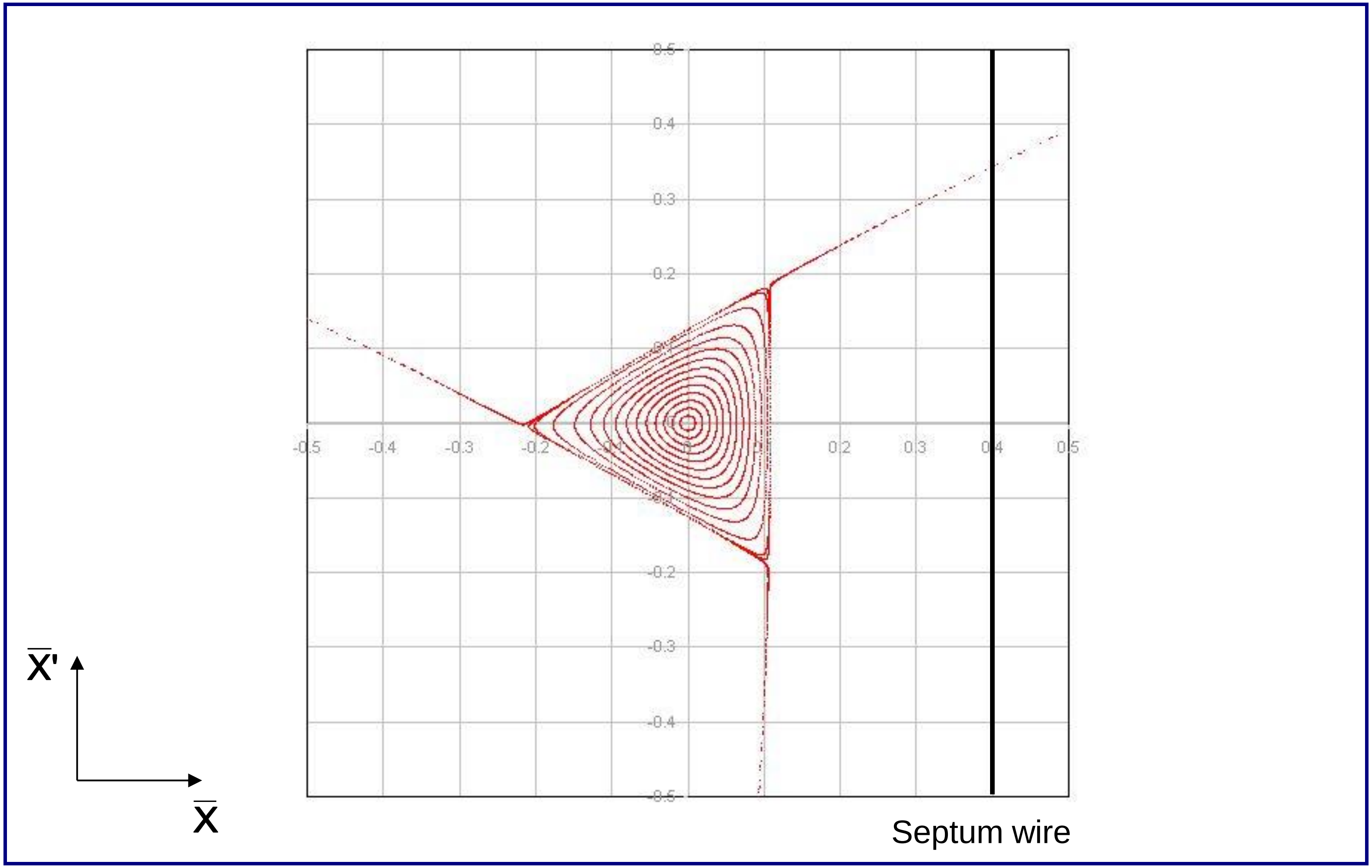


Third-order resonant extraction



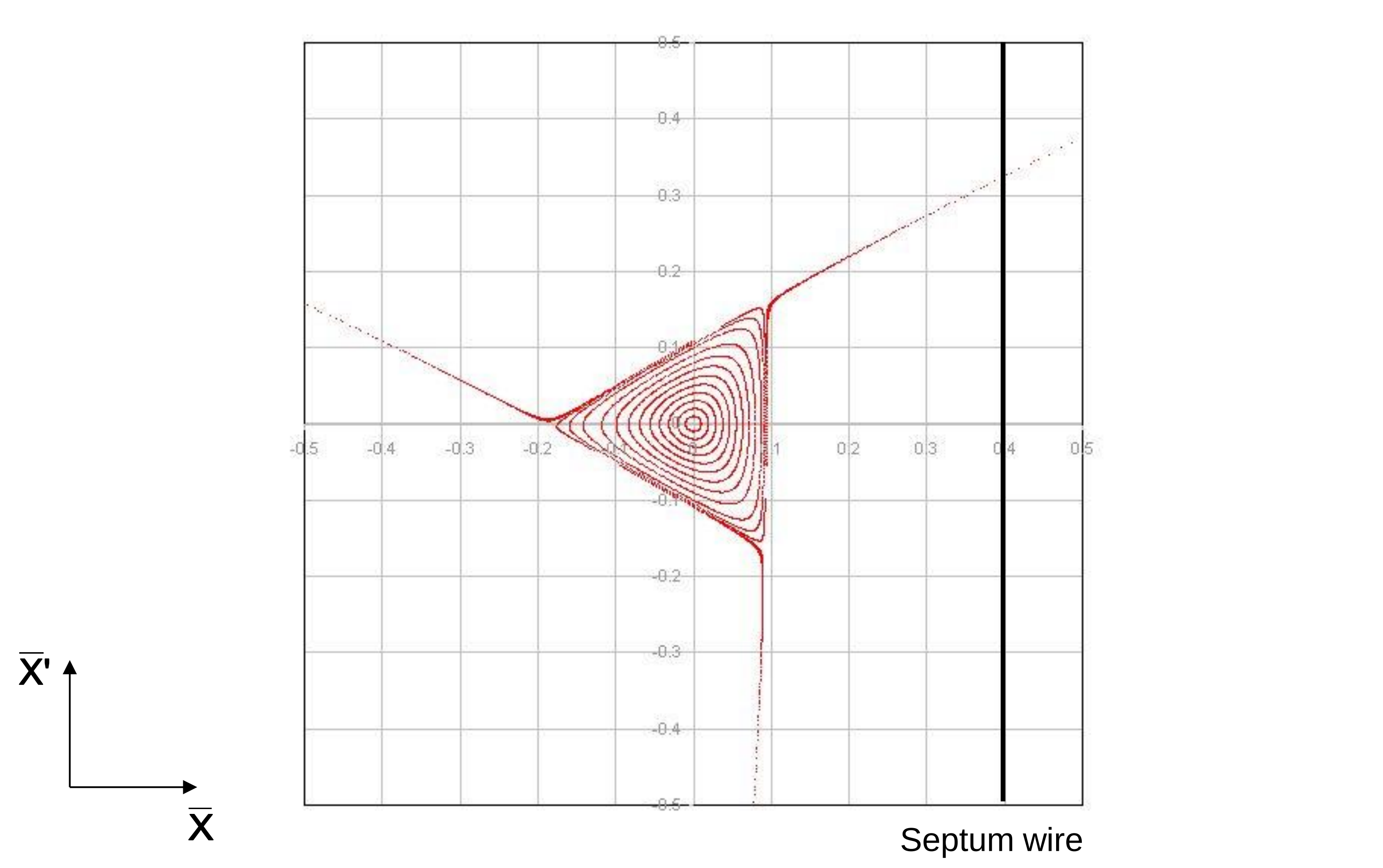
- DQ small enough that largest amplitude particles are close to the separatrices
- Fixed points locations discernable at extremities of phase space triangle

Third-order resonant extraction



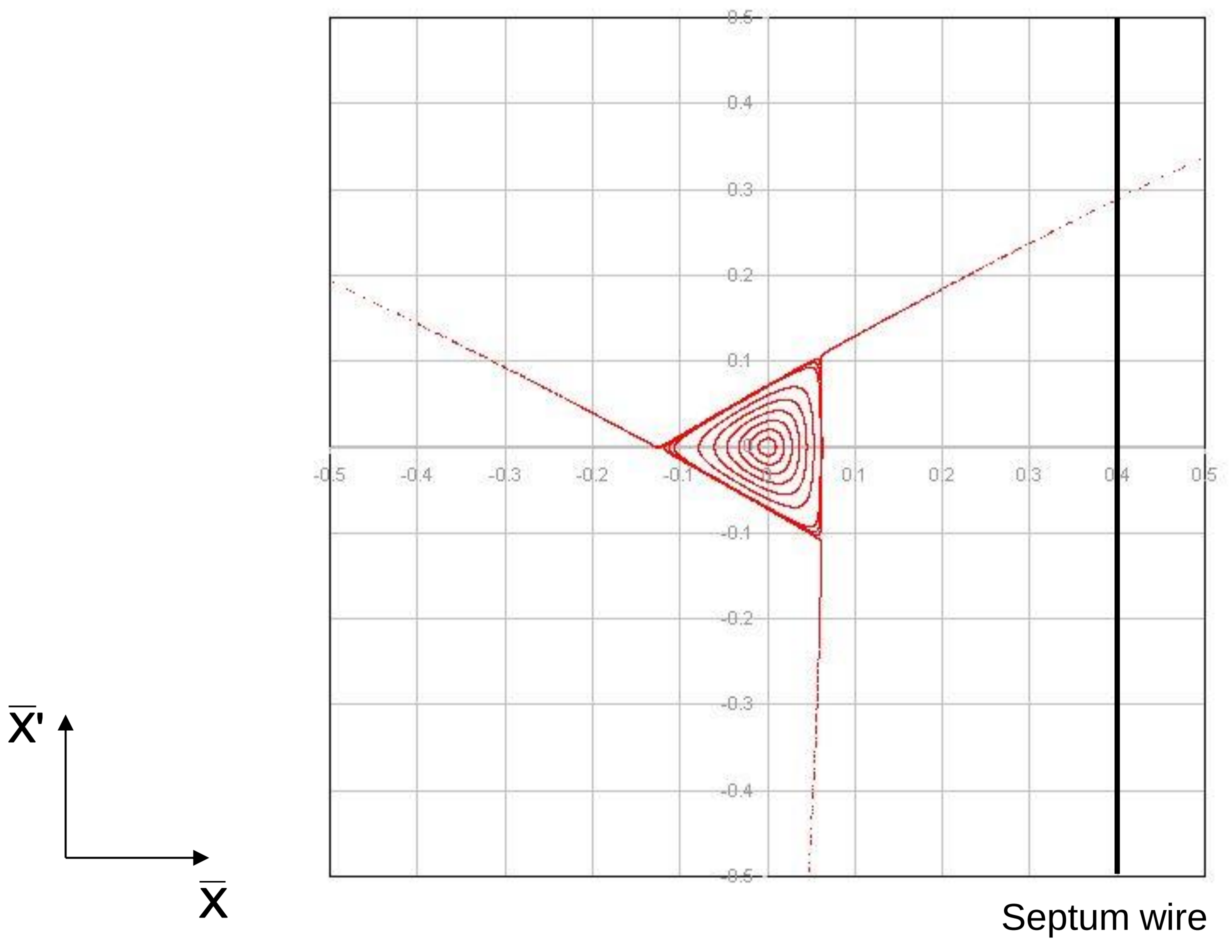
- ΔQ now small enough that largest amplitude particles are unstable
- Unstable particles follow separatrix branches as they increase in amplitude

Third-order resonant extraction



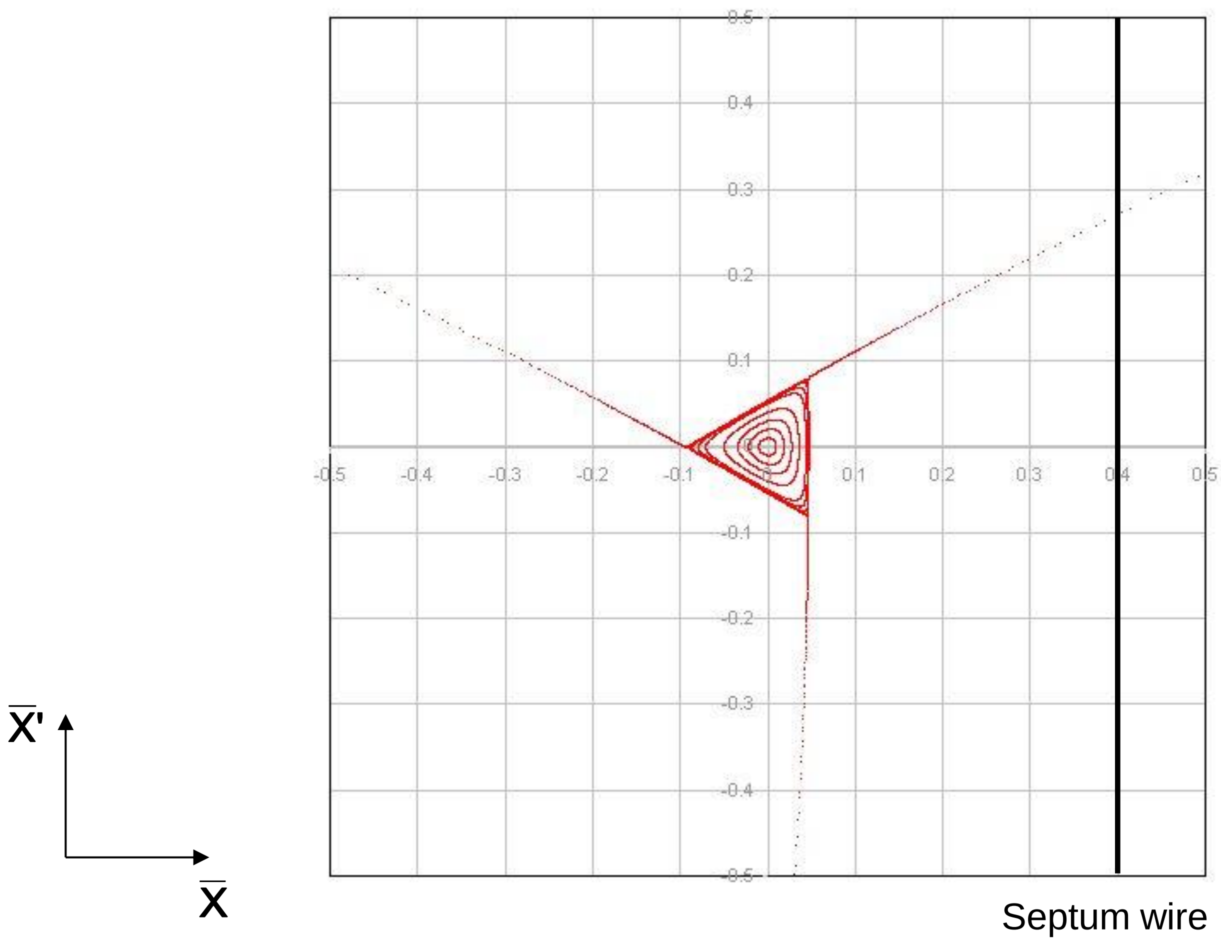
- Stable phase area shrinks as ΔQ gets smaller

Third-order resonant extraction



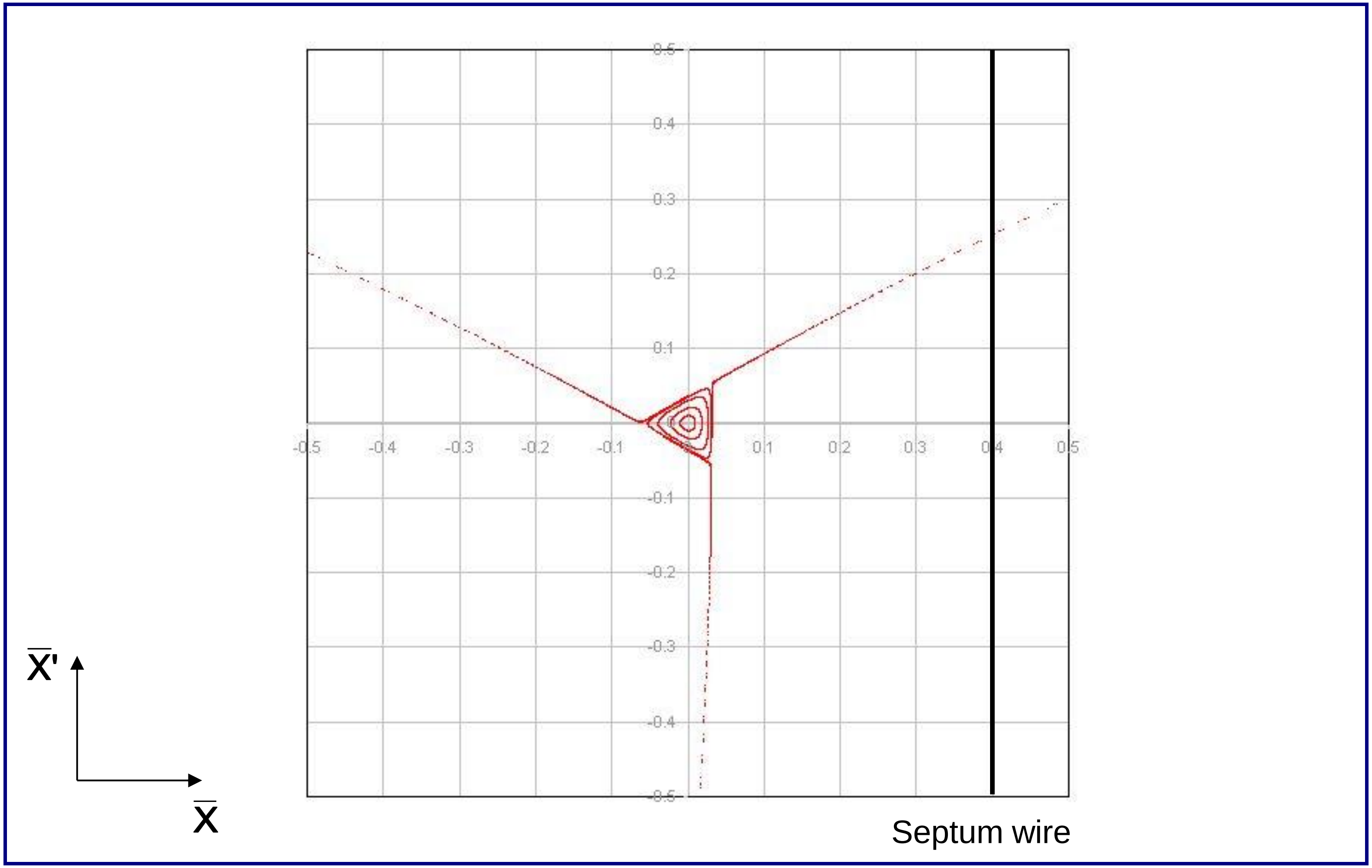
Separatrix position in phase space shifts as the stable area shrinks

Third-order resonant extraction

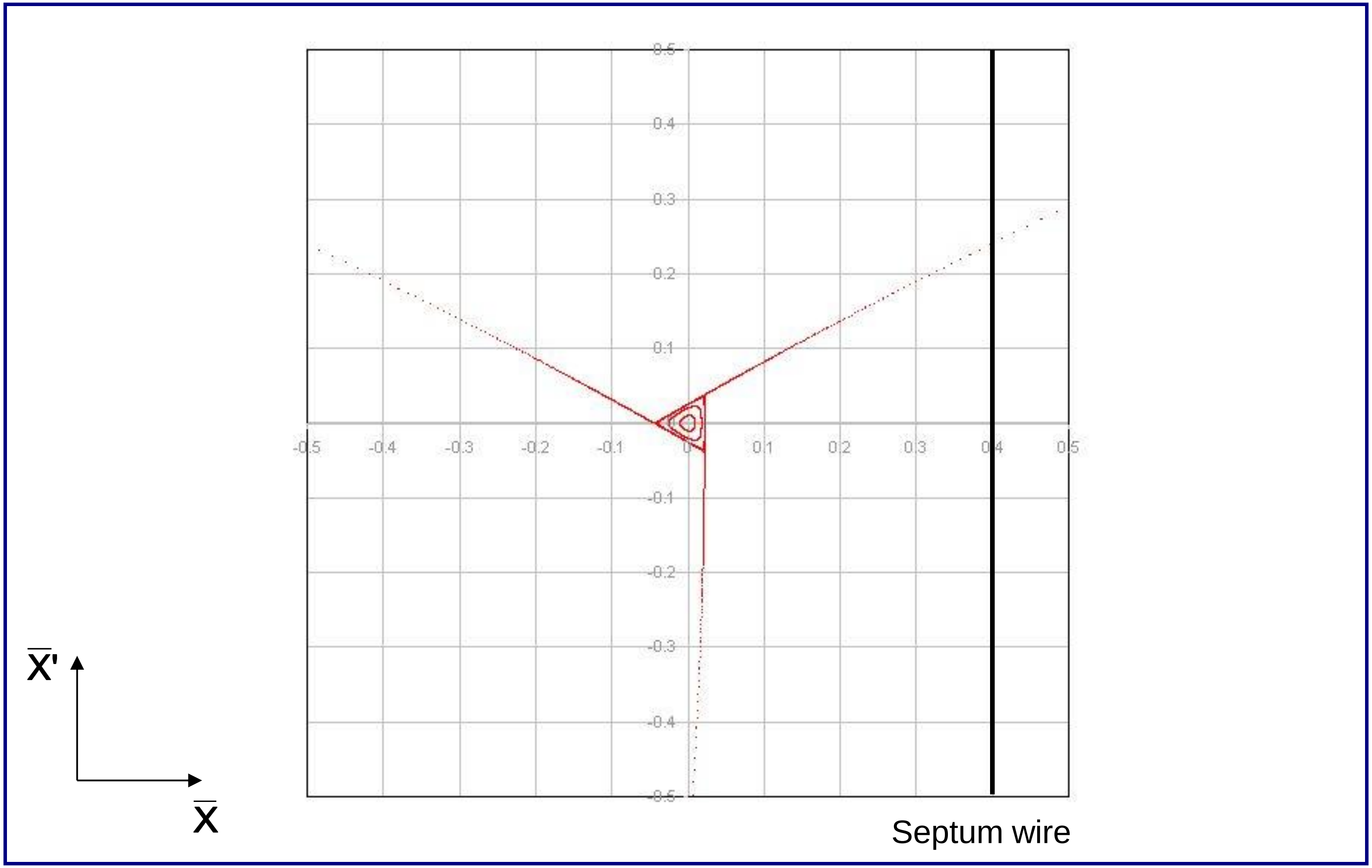


As the stable area shrinks, the beam intensity drops since particles are being continuously extracted

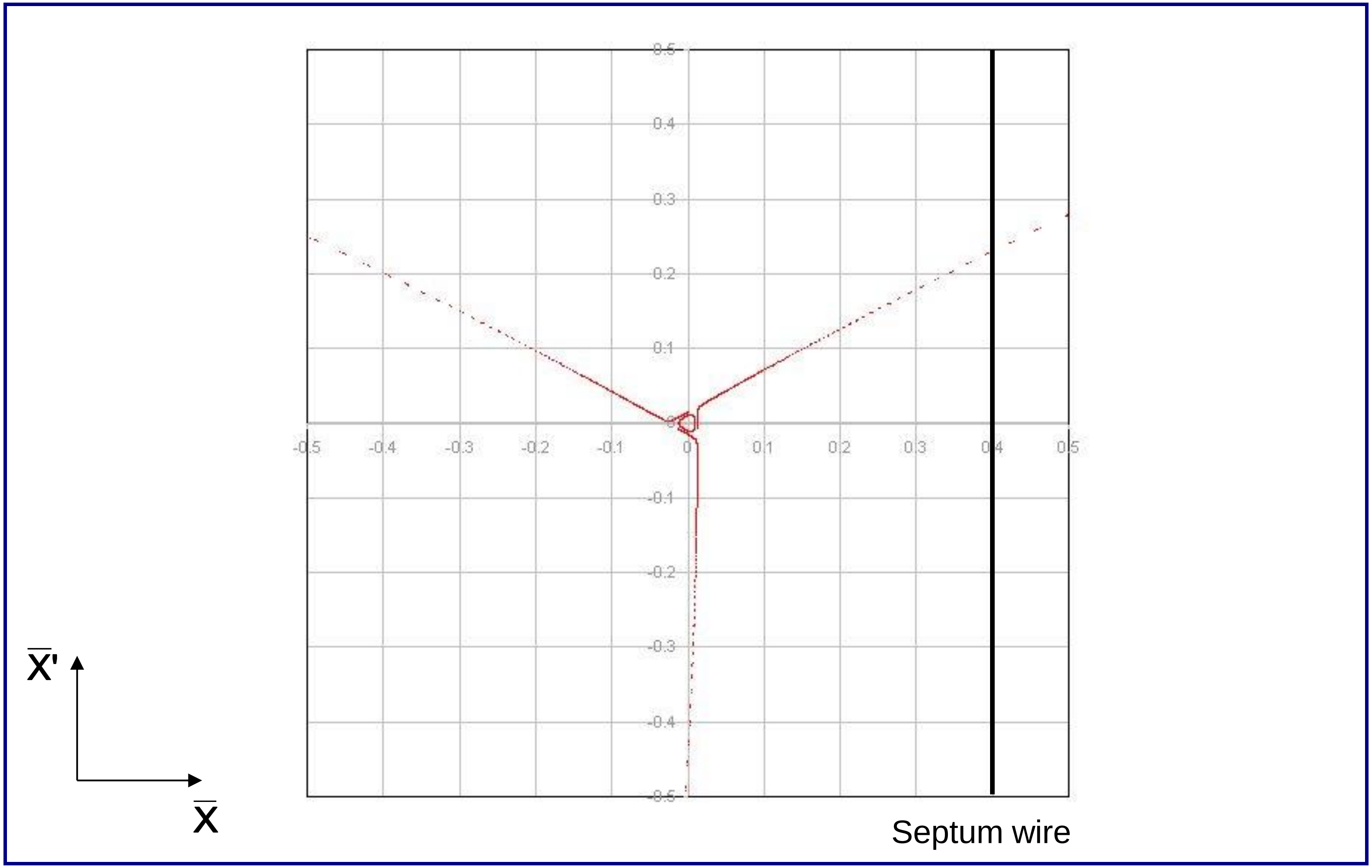
Third-order resonant extraction



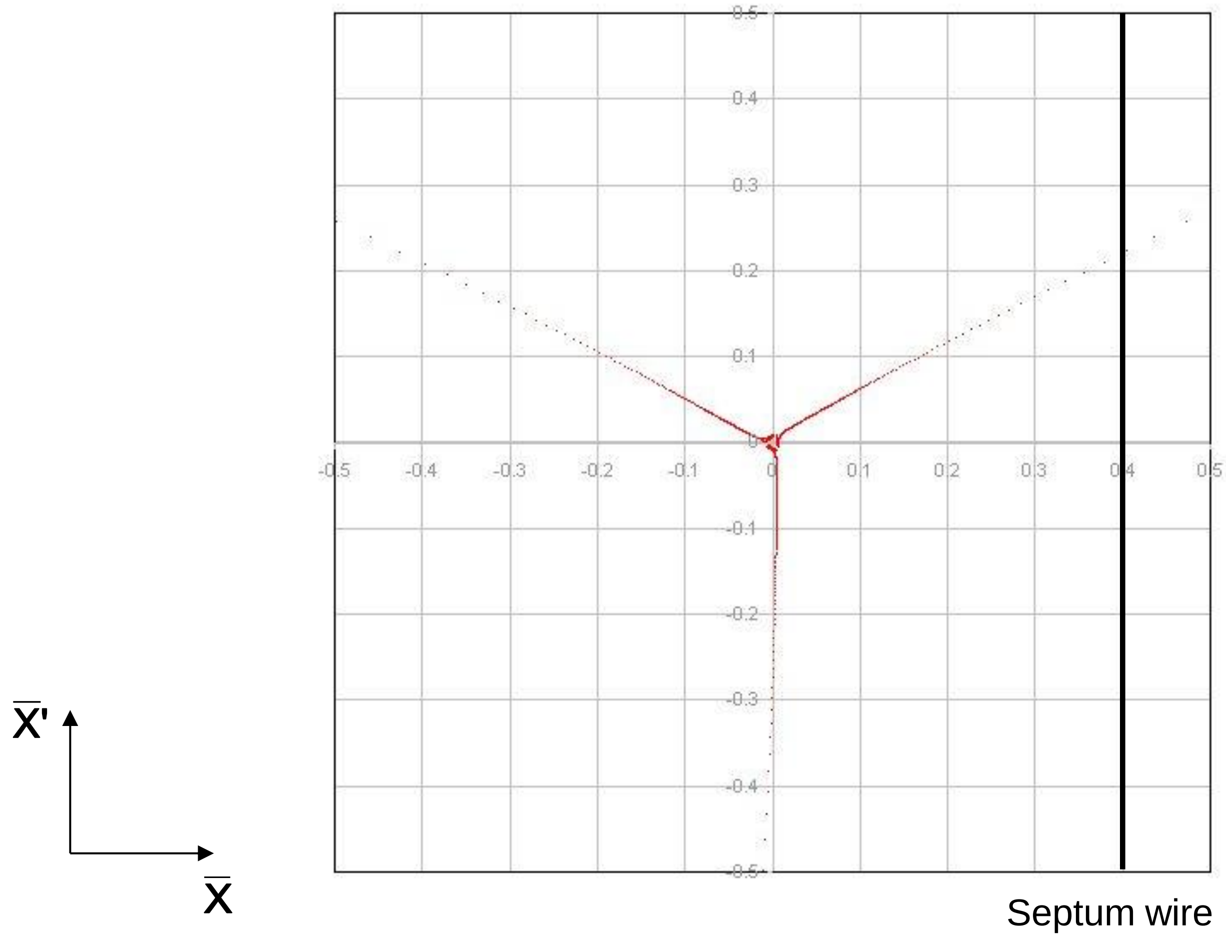
Third-order resonant extraction



Third-order resonant extraction



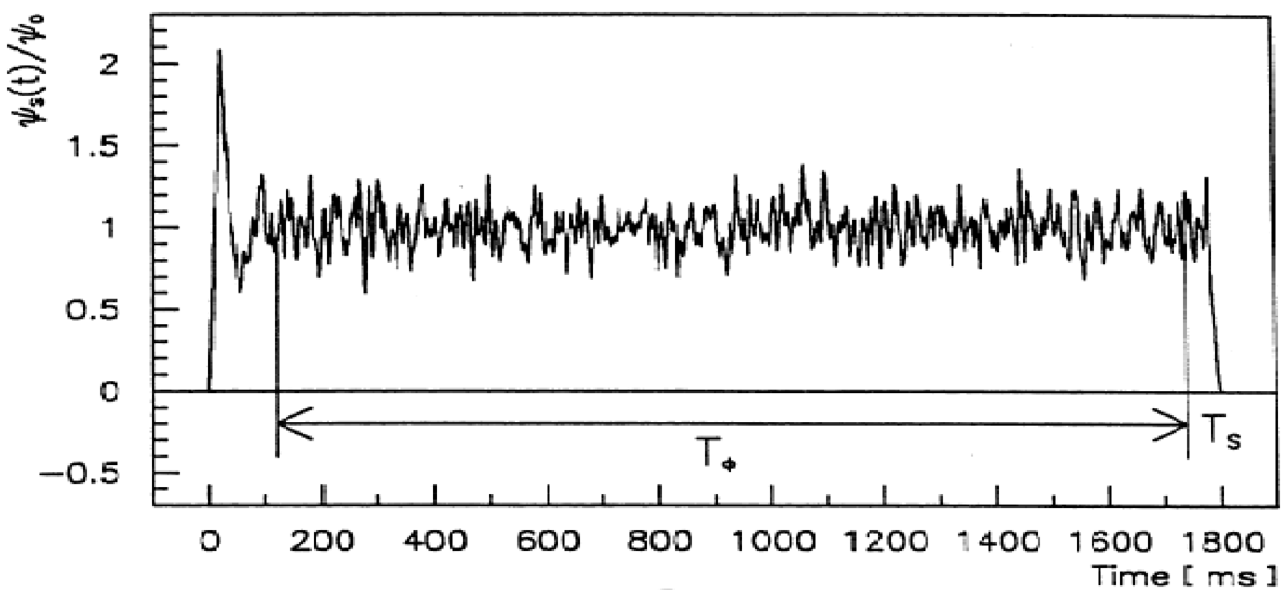
Third-order resonant extraction



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

Third-order resonant extraction

Example – SPS slow extraction at 450 GeV/c.
~3 x 10^{13} p+ extracted in a 2-4 second long spill (~200,000 turns)

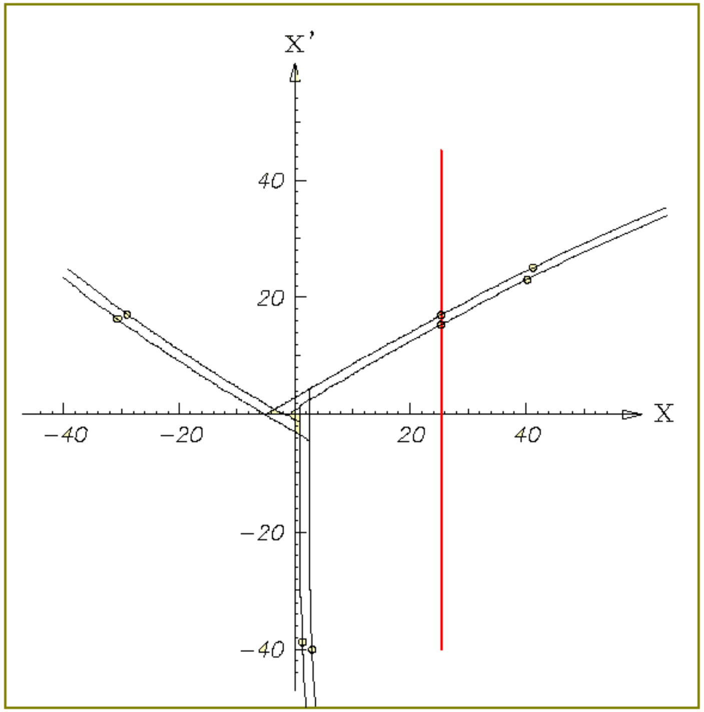


Intensity vs time:
~10^8 p+ extracted per turn

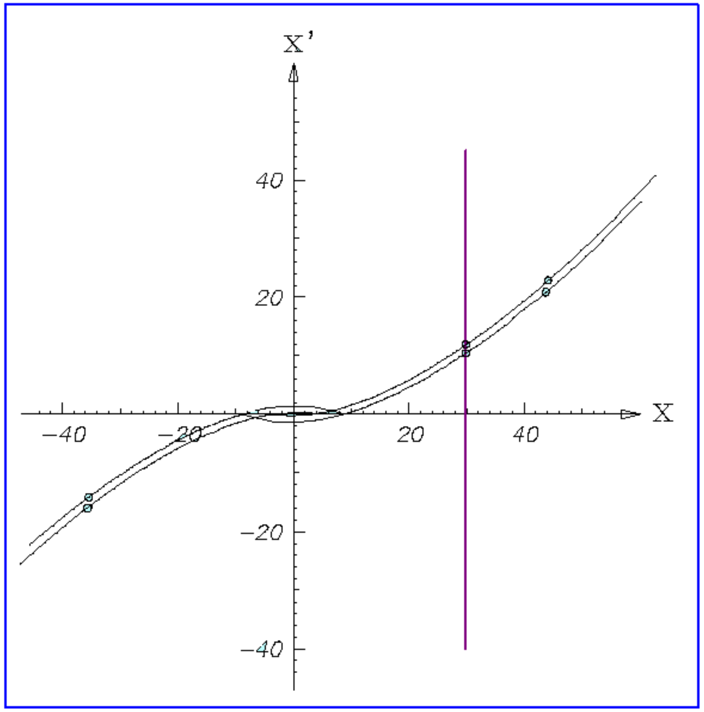
Second-order resonant extraction

- An extraction can also be made over a few hundred turns
- 2nd and 4th order resonances
  - Octupole fields distort the regular phase space particle trajectories
  - Stable area defined, delimited by two unstable Fixed Points
  - Beam tune brought across a 2nd order resonance ($Q \rightarrow 0.5$)
  - Particle amplitudes quickly grow and beam is extracted in a few hundred turns

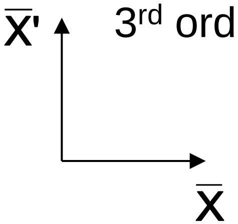
Resonant extraction separatrices



3rd order resonant extraction



2nd order resonant extraction



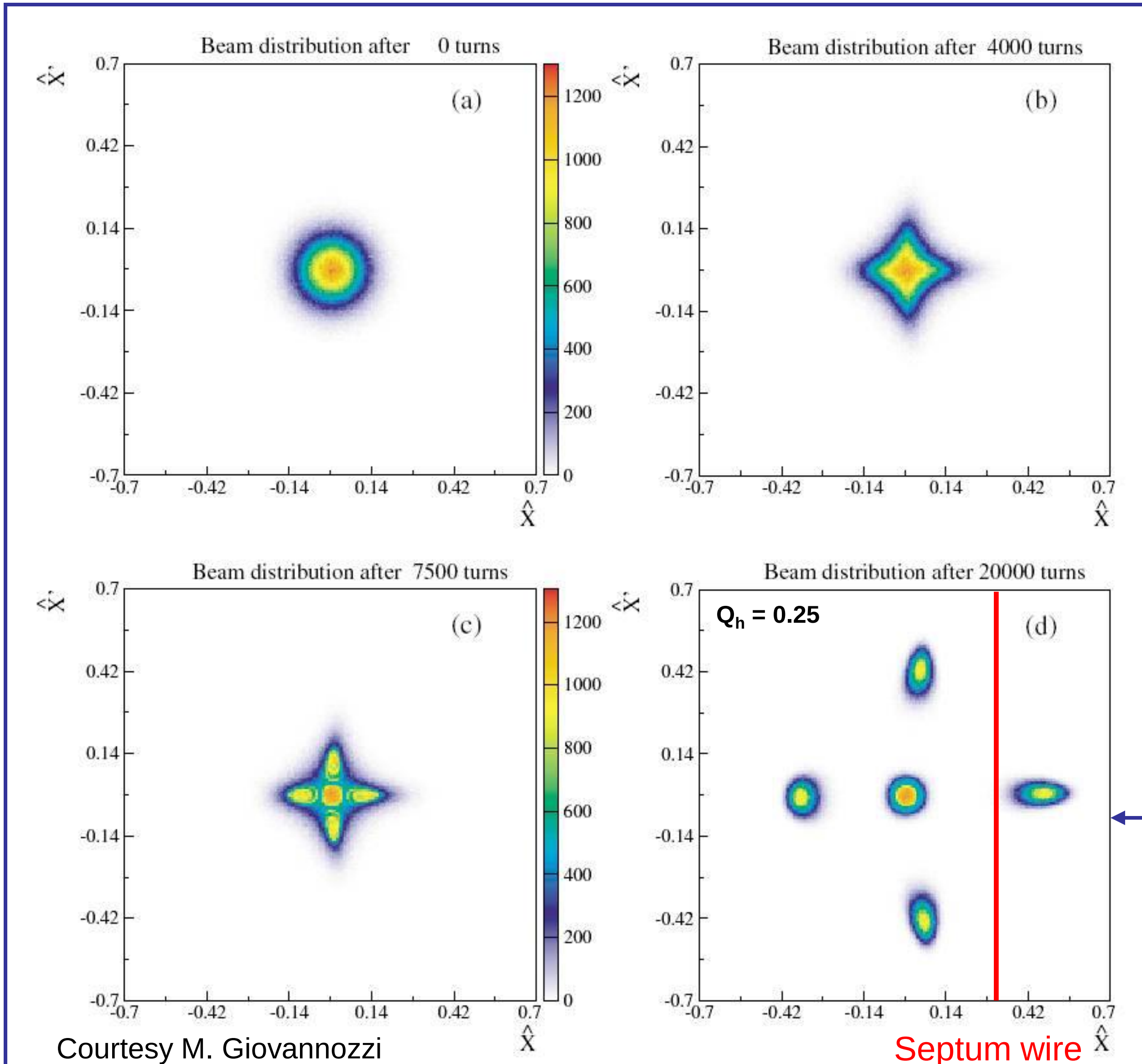
- Amplitude growth for 2nd order resonance much faster than 3rd – shorter spill
- Used where intense pulses are required on target – e.g. neutrino production

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

- 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

Resonant low-loss multi-turn extraction

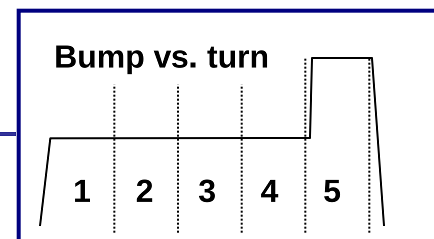


a. Unperturbed beam

b. Increasing non-linear fields

c. Beam captured in stable islands

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



Extraction - summary

- Several different techniques:
  - 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 ⇒ slowly drive particles into resonance ⇒ long spill over many thousand turns.
  - Resonant low-loss multi-turn extraction
    - create stable islands in phase space: slice off over a few turns.

Thank you for your attention