Injection: Hadron Beams

C. Bracco

Acknowledgements: T. Argyroupoulos, W. Bartmann,
H. Bartosik, C. Carli, V. Forte, M.A. Fraser B. Goddard,
A. Huschauer, V. Kain and F. Maria Velotti

Outline

- Introduction
- Single-turn injection
  - Principles and HW
  - Injection errors: mismatch, injection oscillations and emittance blowup
  - Aperture: protection devices and injection losses
  - Slip-stacking
- Multi-turn injection:
  - Phase space painting
  - Charge exchange H^- injection
  - Combined longitudinal and transverse injection
- Lessons learnt

Introduction

What do we mean by injection?

Place a particle beam into a circular accelerator or accumulator at the right time while:

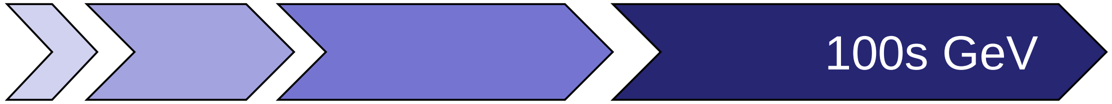
1. Placing the newly injected particles onto the correct trajectory with the correct phase-space parameters
2. Minimizing the beam losses

Injection is one of the most complex parts of a ring and if not properly designed can bring to:

- Machine damage
- Compromised beam quality ➔ reduced performance

Challenges

10s MeV



Space charge forces

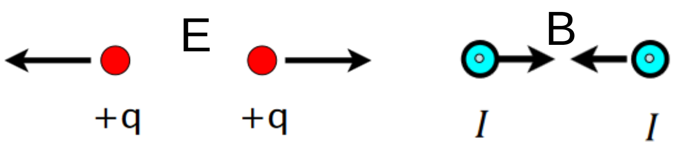
Machine protection related issues
(injection is fast!!)

Challenges

Space charge forces

"Self-forces" produced by the beam itself

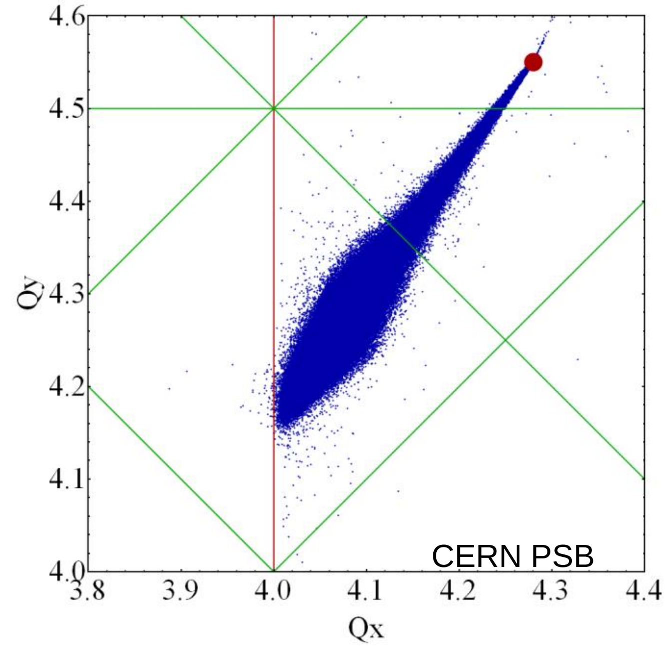
Machine protection related issues
(injection is fast!!)



Particles in an unbunched beam, with uniform density and circular cross-section will experience an incoherent tune shift:

$$\Delta Q_{x,y} \propto \frac{N}{\gamma^2 \beta \varepsilon_N} \quad [1]$$

This can lead to emittance blow up and losses. Effect is stronger at low energy and for high charge densities ➔ limit achievable brightness!

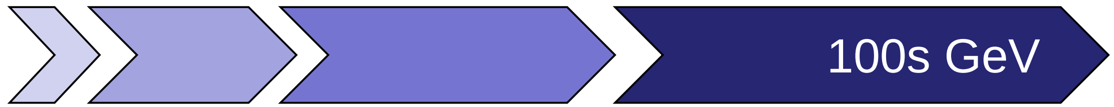


N= number of particles per unit length
γ and β = relativistic factors
ε_N = normalised emittance

M. Ferrario's Lecture

Challenges

10s MeV



Space charge forces

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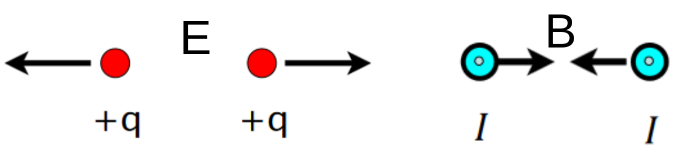

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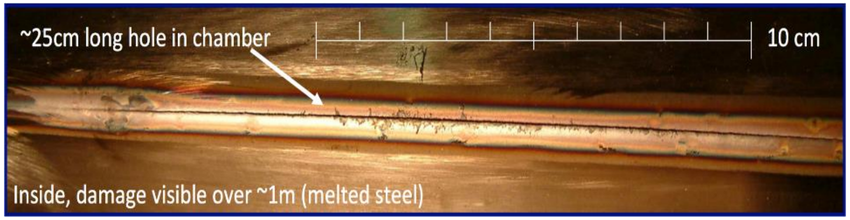
M. Ferrario's Lecture

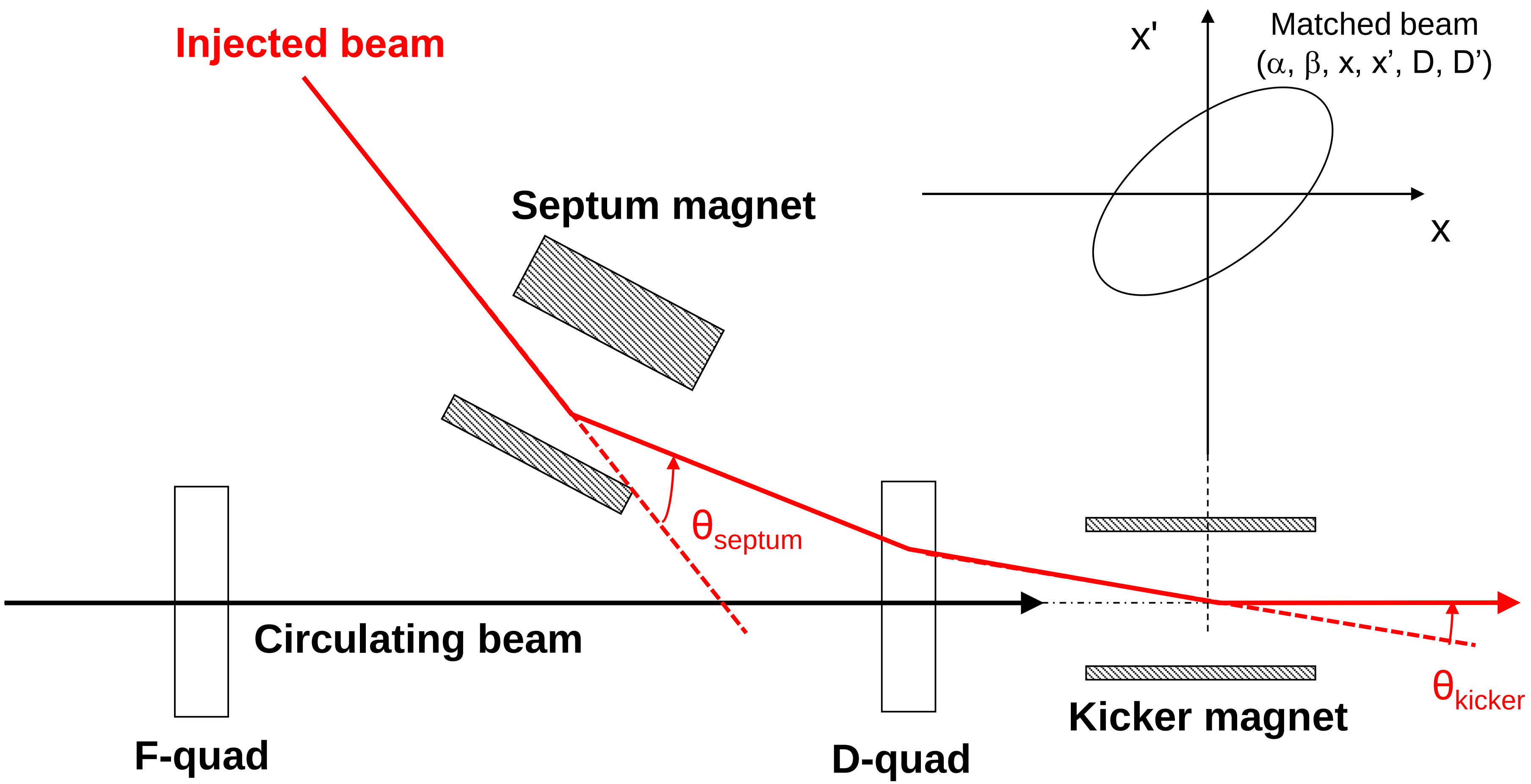
Machine protection related issues
(injection is fast!!)

High stored energy: up to 2.4 MJ* for each LHC injection (x2 for HL-LHC)
➔ ~ 0.5 kg of TNT!



*(288 bunches) x (1.15×10^{11} ppb) x (450 GeV)

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

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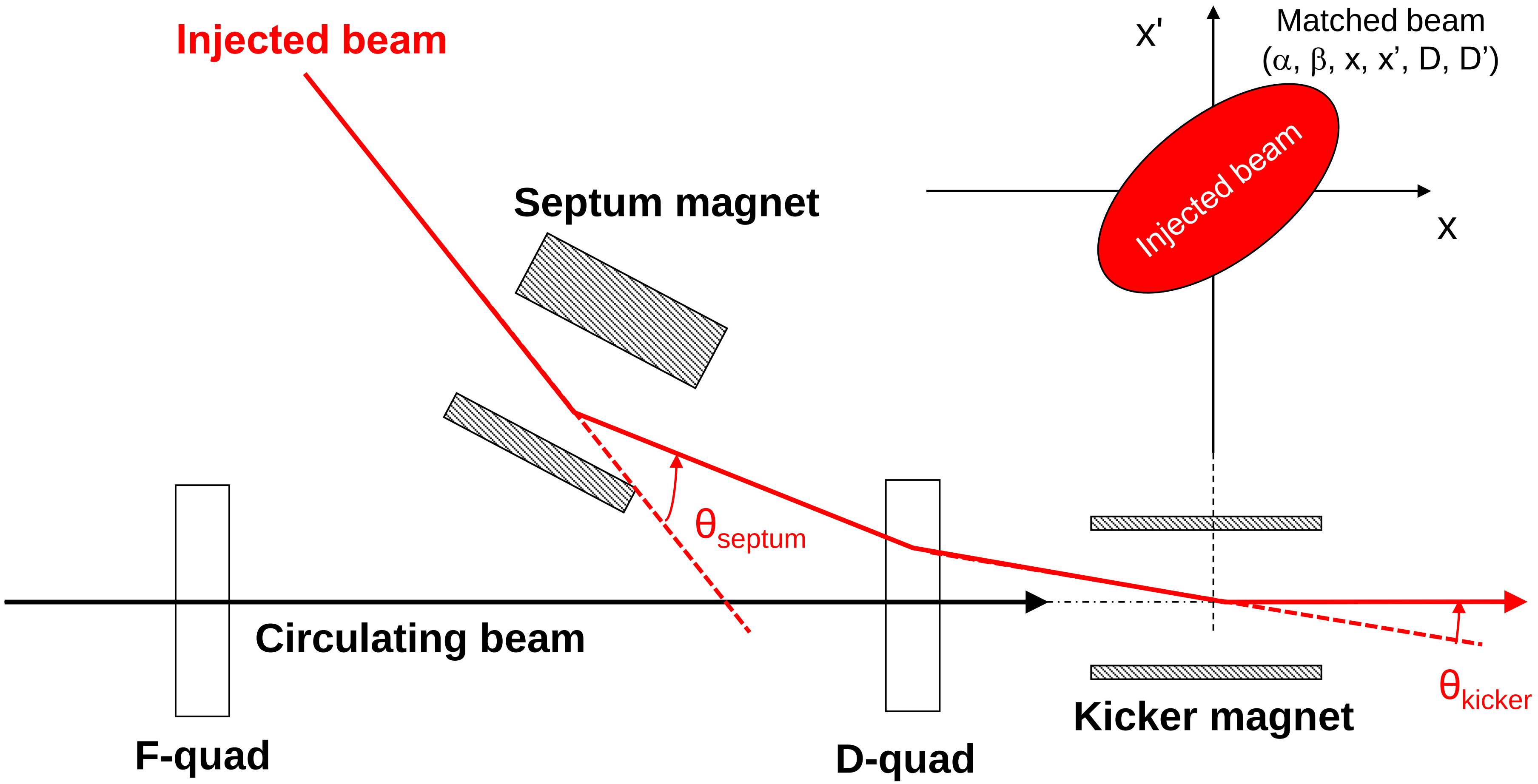

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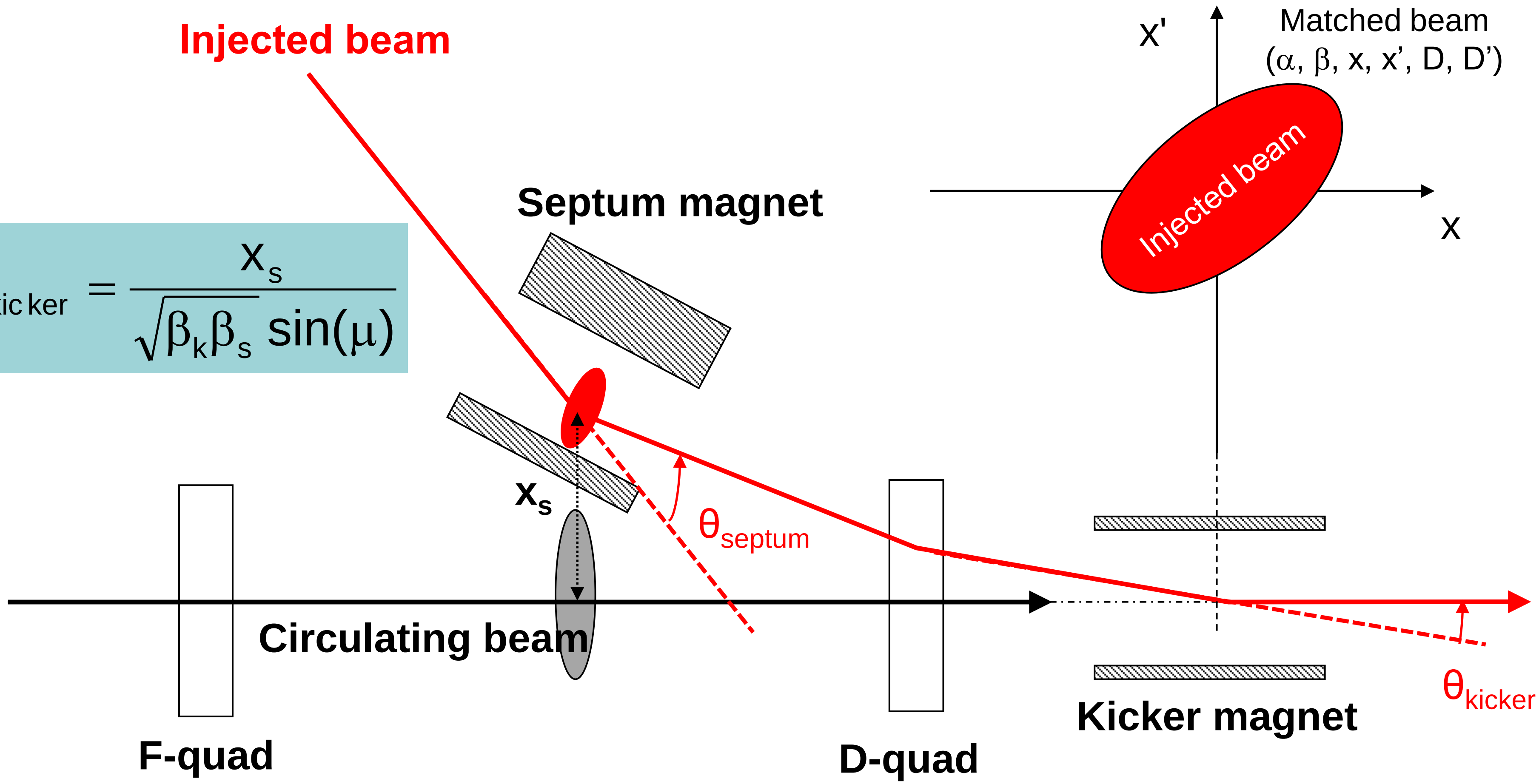
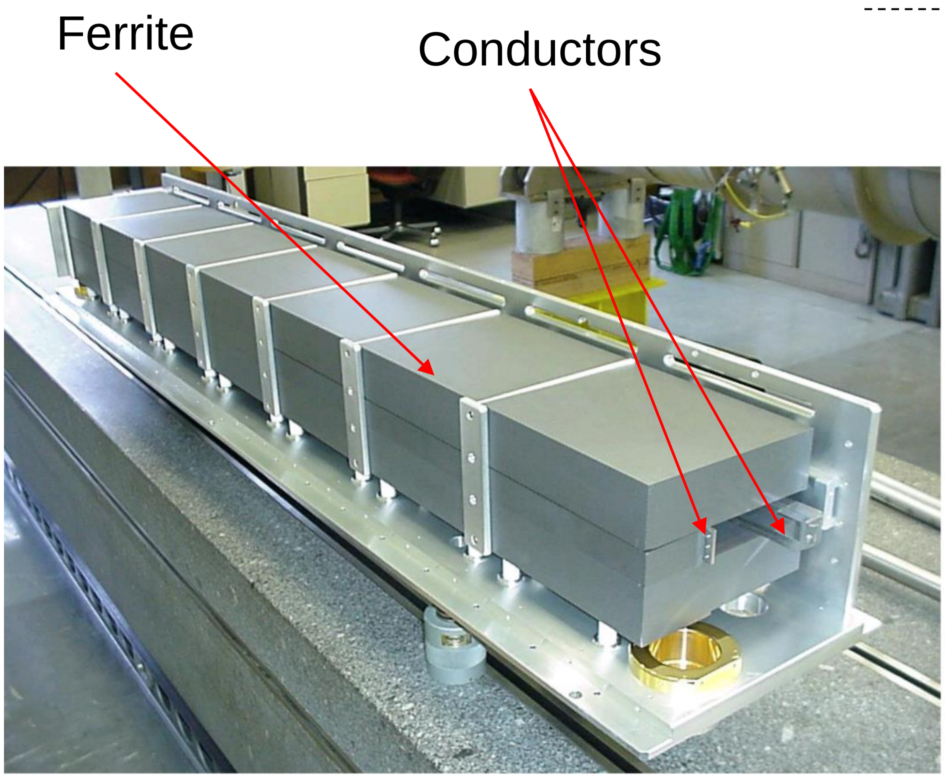


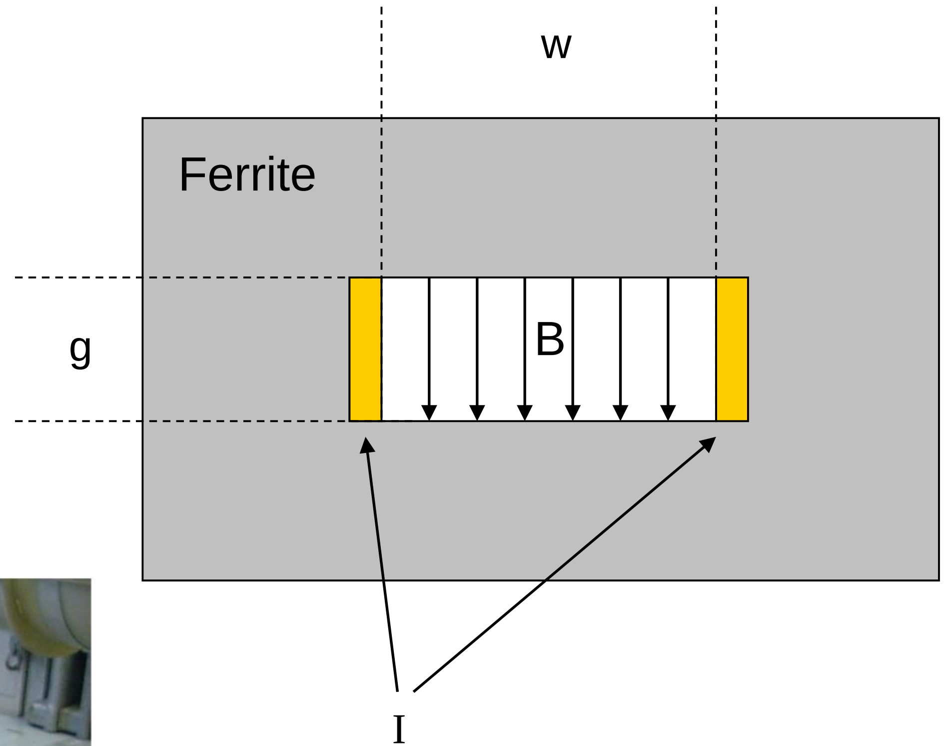
$$\theta_{kicker} = \frac{x_s}{\sqrt{\beta_k \beta_s} \sin(\mu)}$$

The position of the injected beam at the septum x_s has to be larger than:
injected beam envelope + circulating beam envelope + thickness of the septum blade + beam size increase due to energy spread + closed orbit distortion + alignment errors

Kicker magnet

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





$B = \mu_0 I / g$

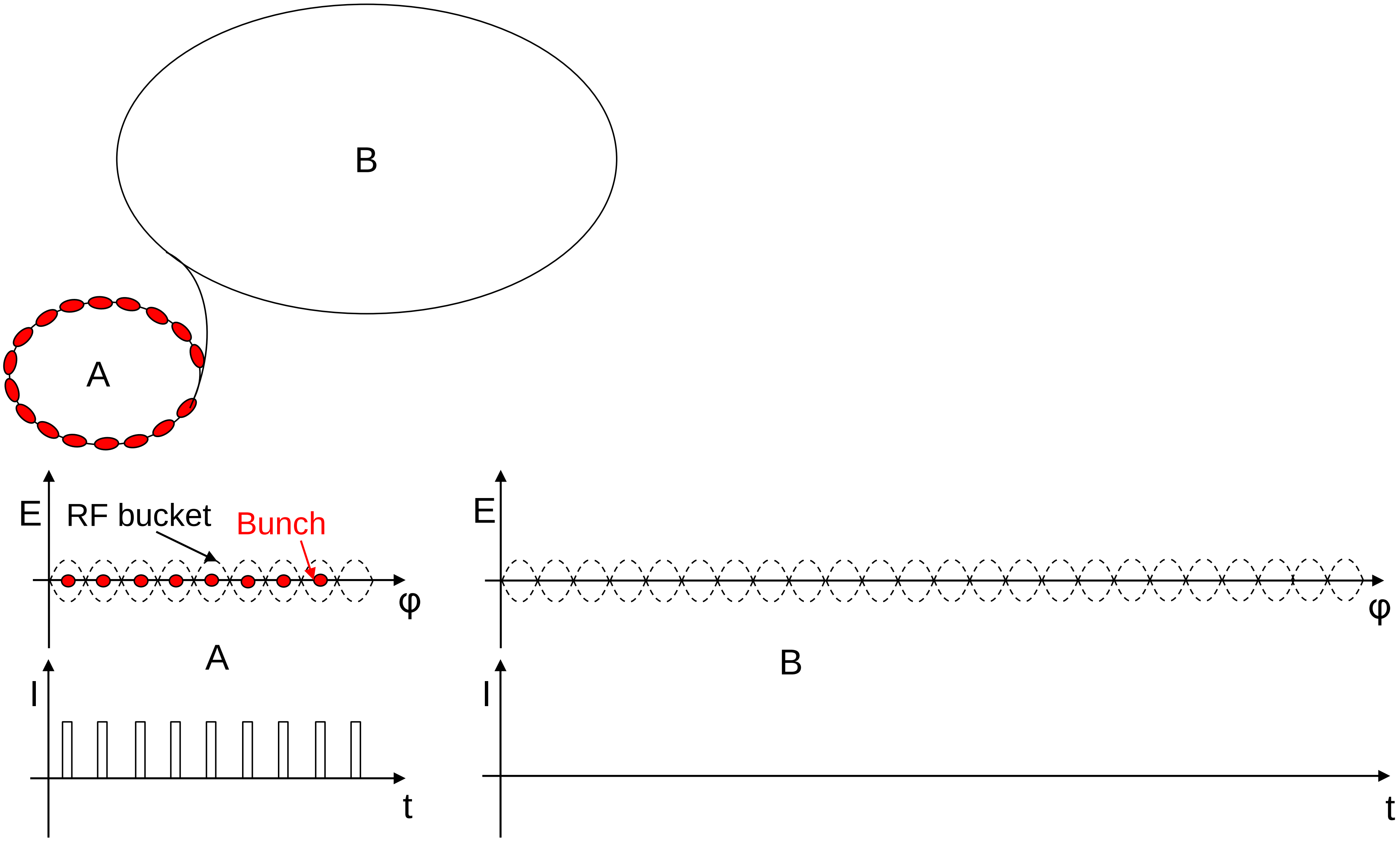
L [per unit length] $= \mu_0 w / g$

$dI/dt = V / L$

Typically 3 kA in 1 μs rise time

M. Barnes' Lecture

Filling factor



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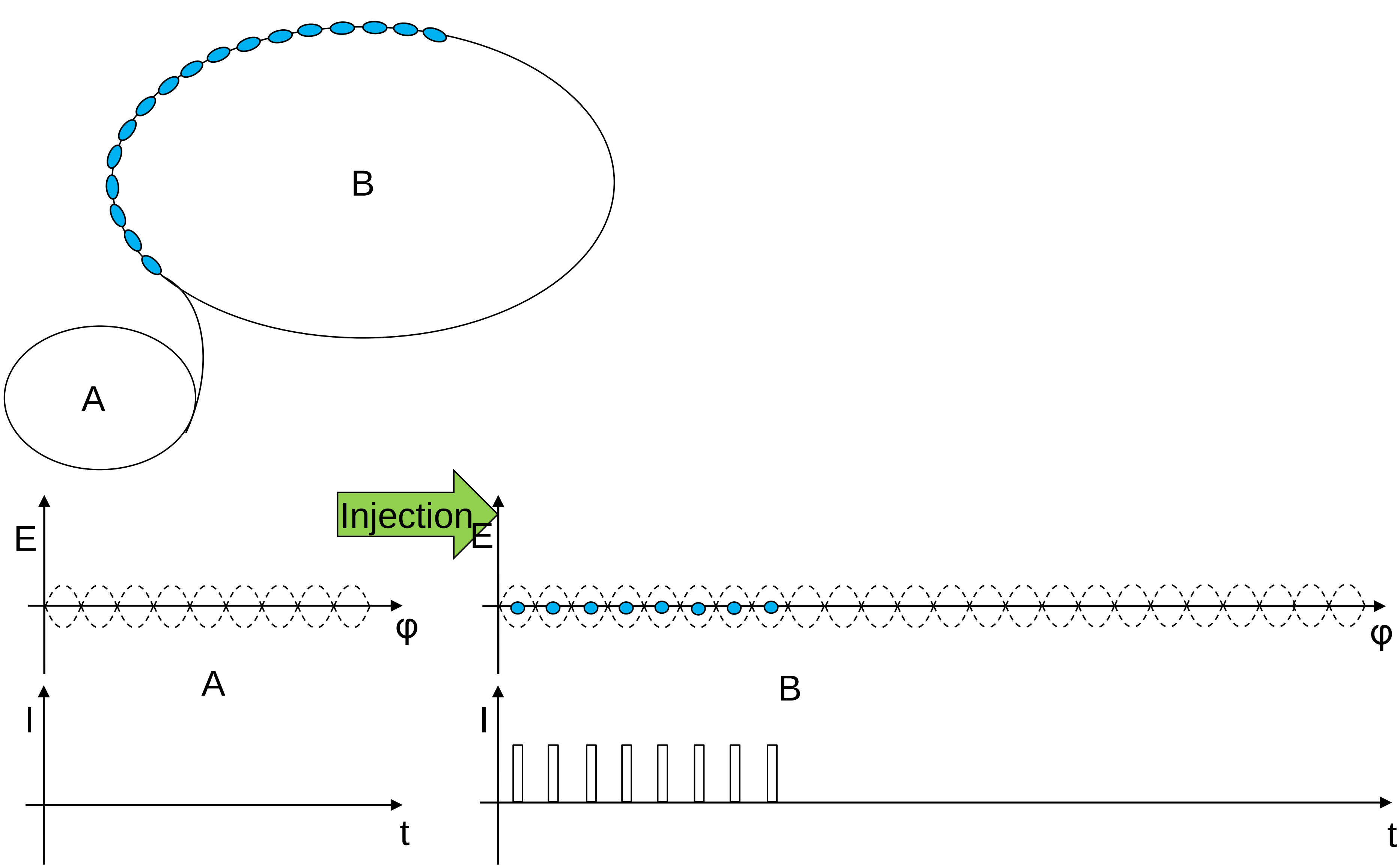

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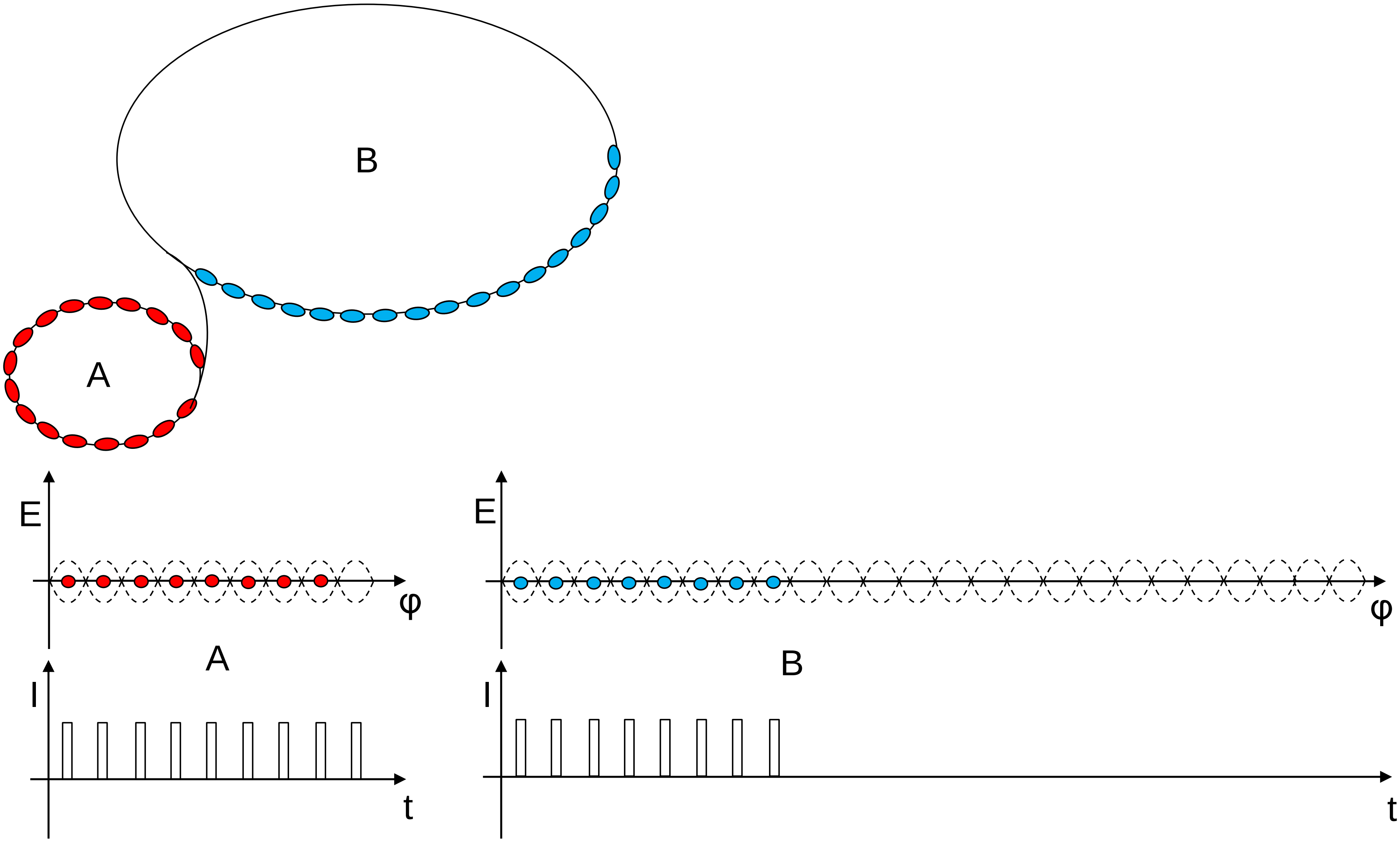

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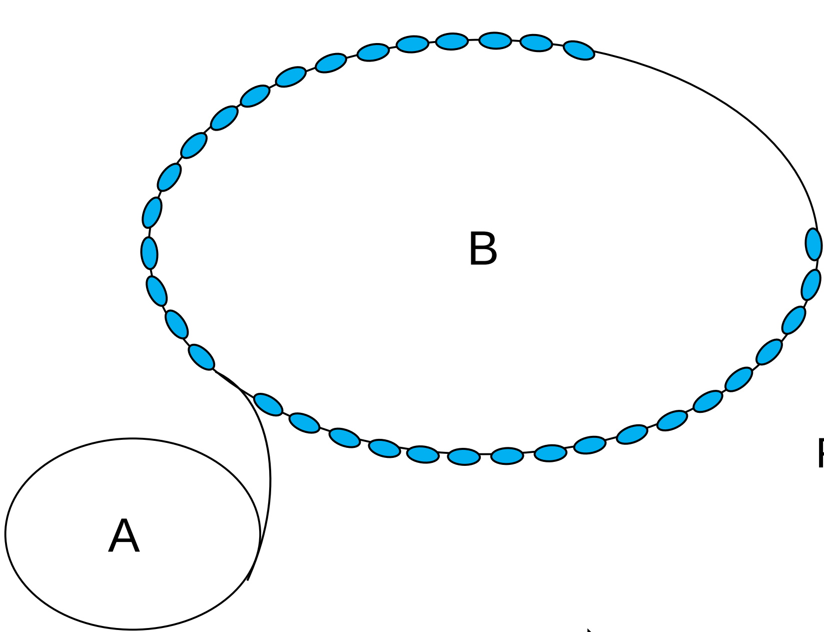
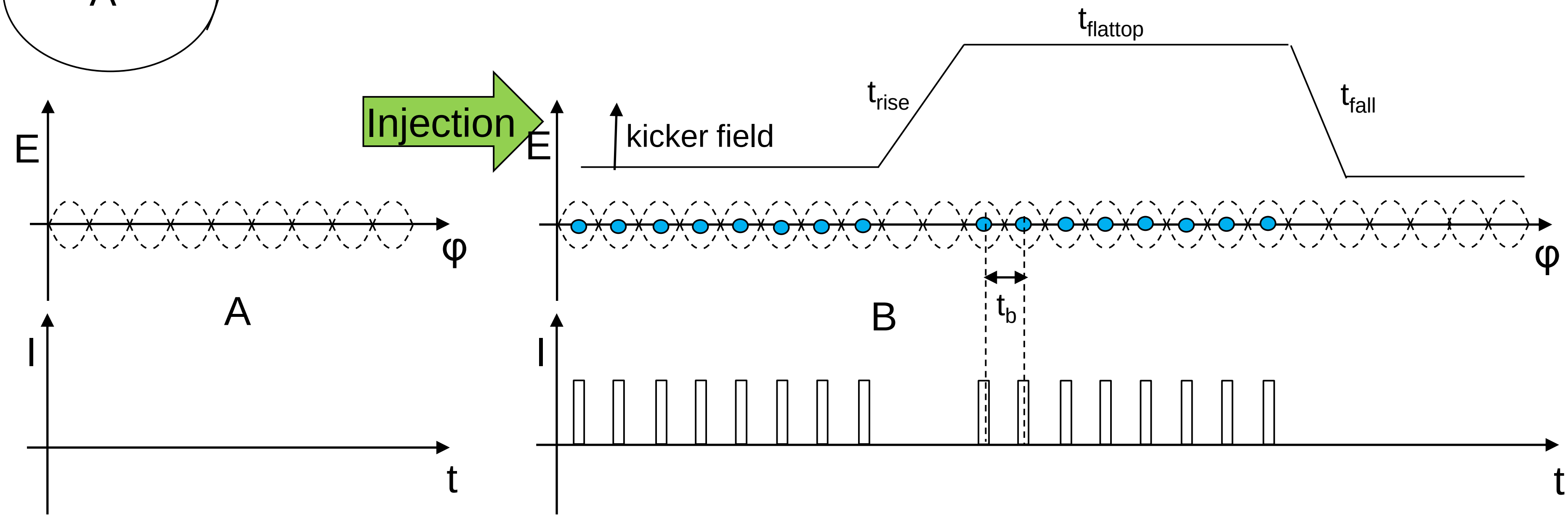


Ideal number of storable bunches: $n_b = \frac{L_B}{t_b}$

due to t_{rise} and t_{fall} the number of bunches which can be stored is:

$$\overline{n}_b = \frac{n t_{flattop} - \left[(n-1)t_{rise} + t_{fall}^{**}\right]}{t_b} \quad \text{where} \quad n \approx \frac{L_B}{L_A}$$

Filling factor [%]: $f = \frac{\overline{n}_b}{n_b}$ The lower t_{rise} the higher f

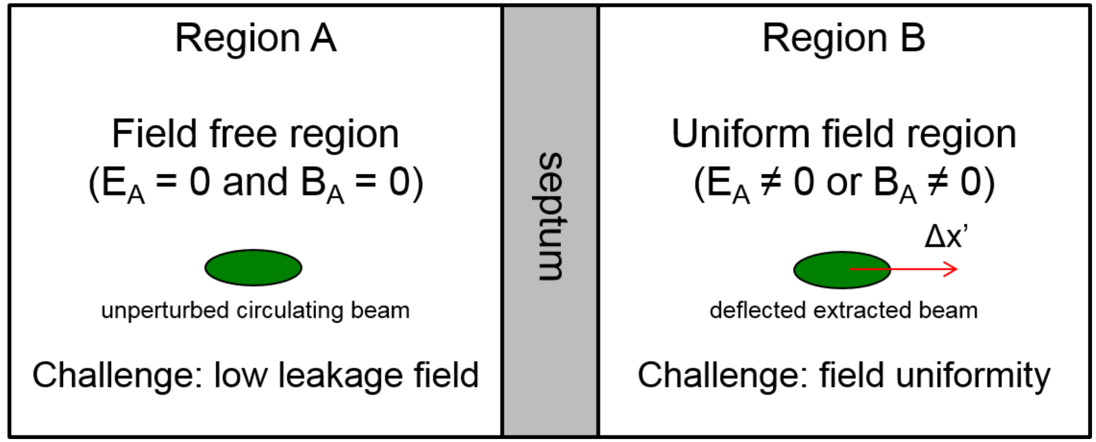


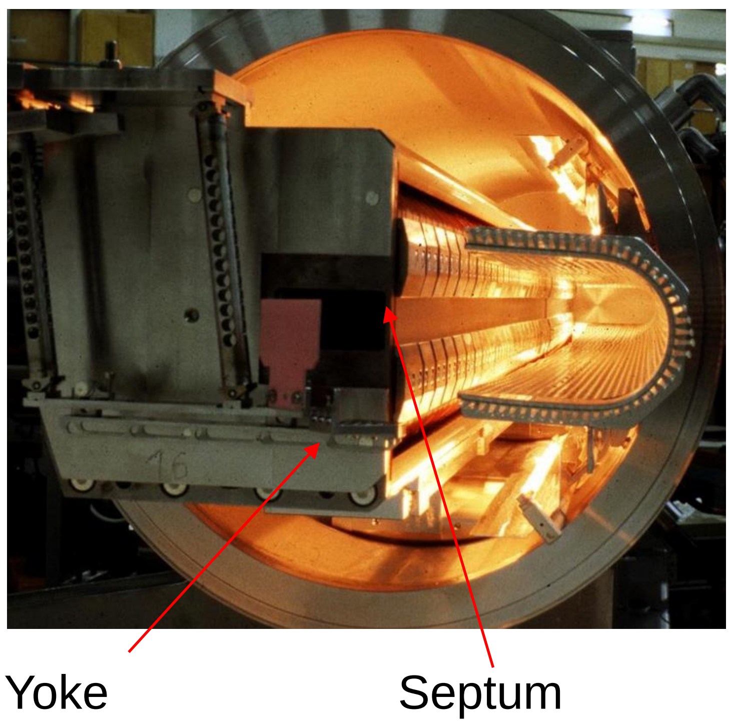
**In reality t_{fall} has to be replaced with $t_{abort} > t_{fall}$ which is the pulse time of the extraction kickers

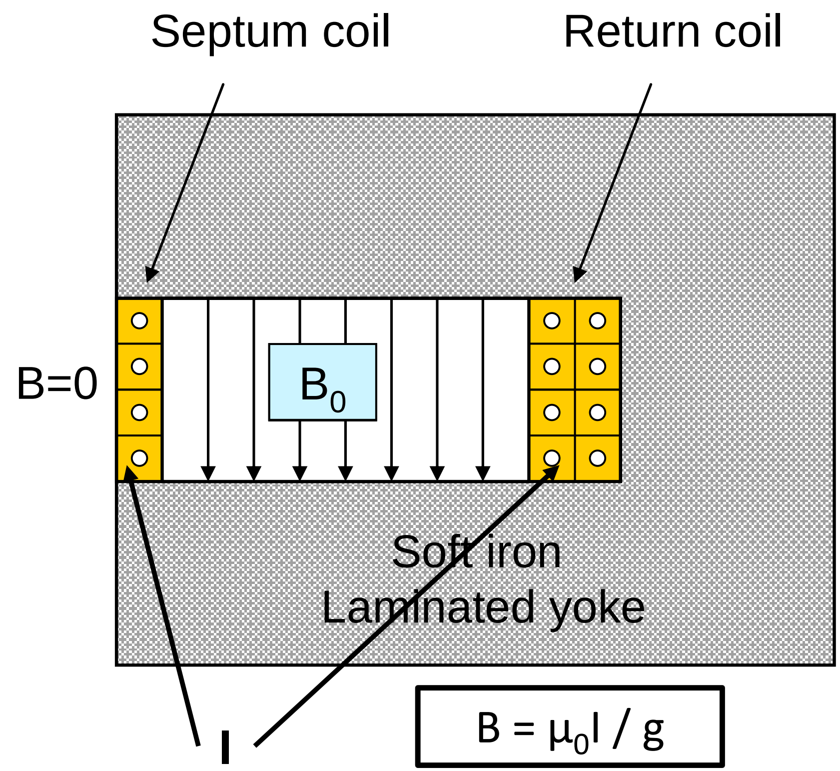
Magnetic septum

Pulsed or DC magnets with thin (2 -20 mm) septum between zero and high field region.
Typically ~x10 higher deflection compared to kickers. I ~5-25 kA

M. Paraliev's Lecture



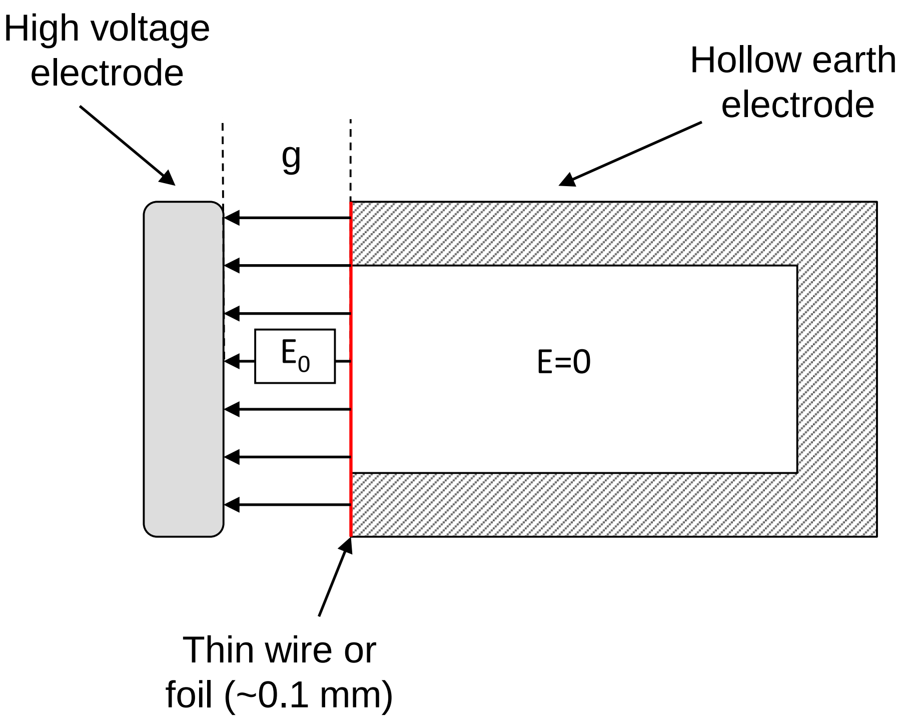




$$B = \mu_0 I / g$$

Electrostatic septum

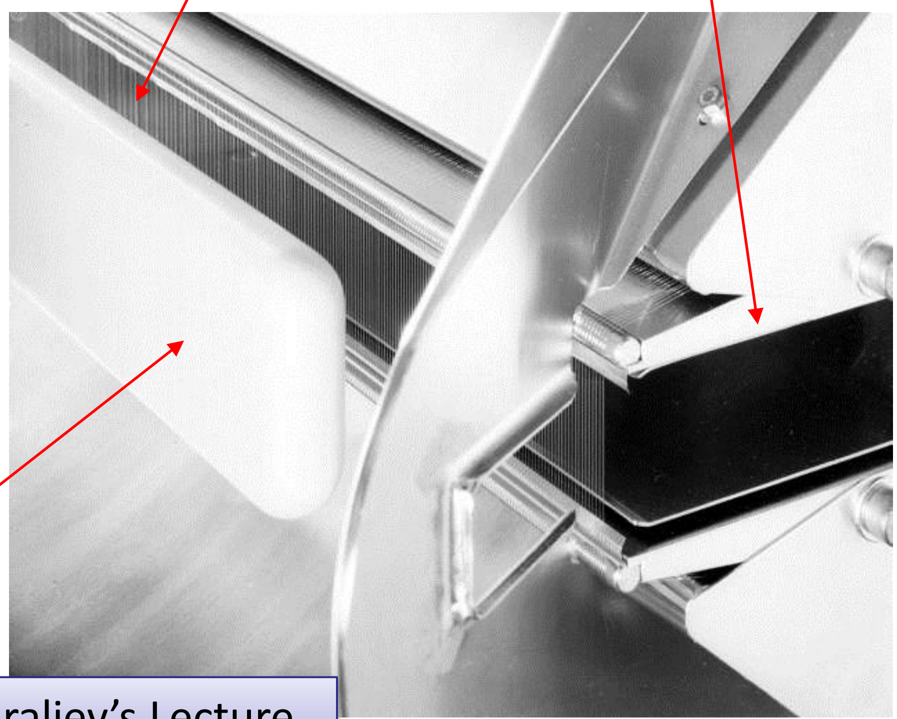
DC electrostatic device with very thin septum between zero field and high field region



$E = V / g$

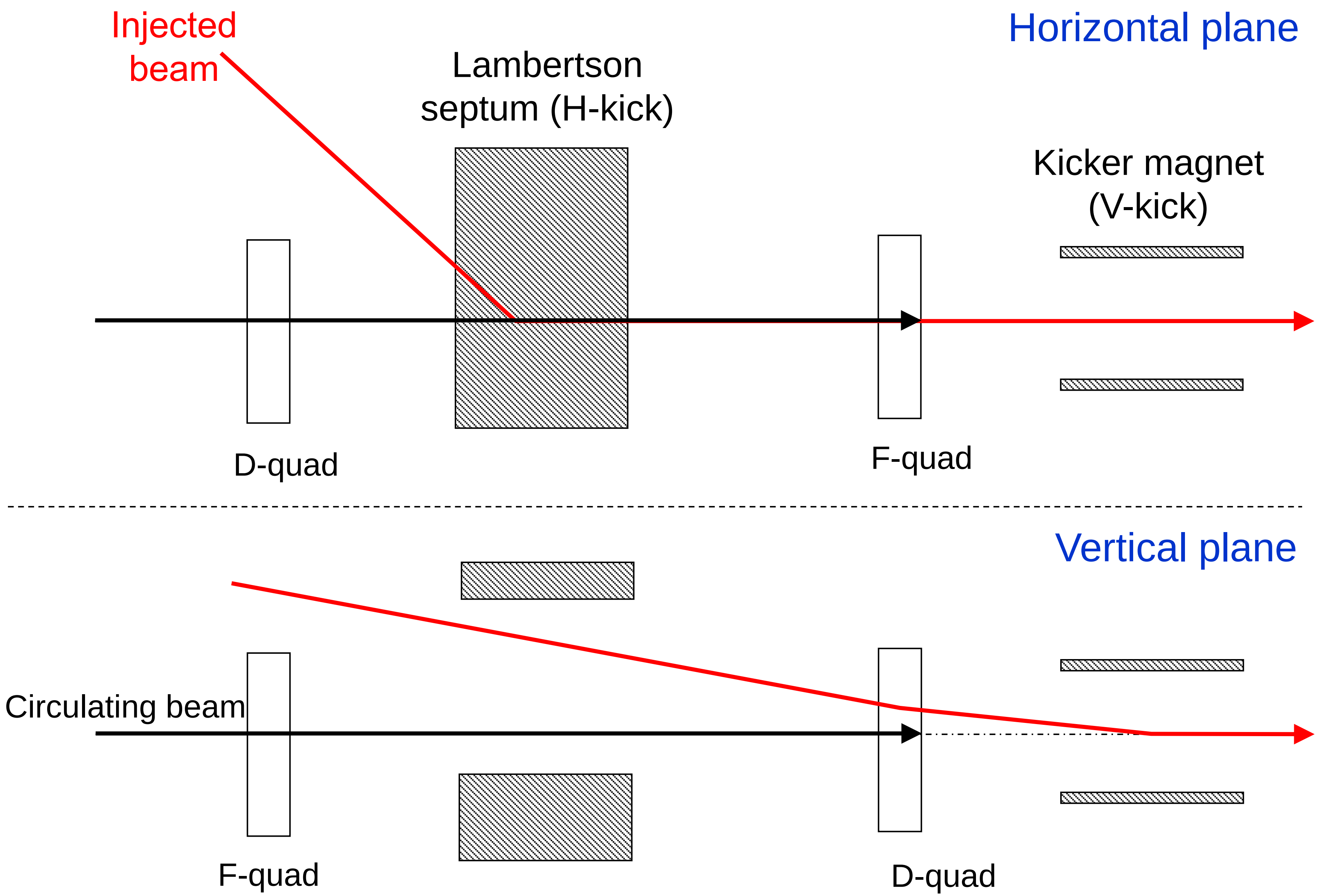
Typically $V = 200$ kV

$E = 100$ kV/cm



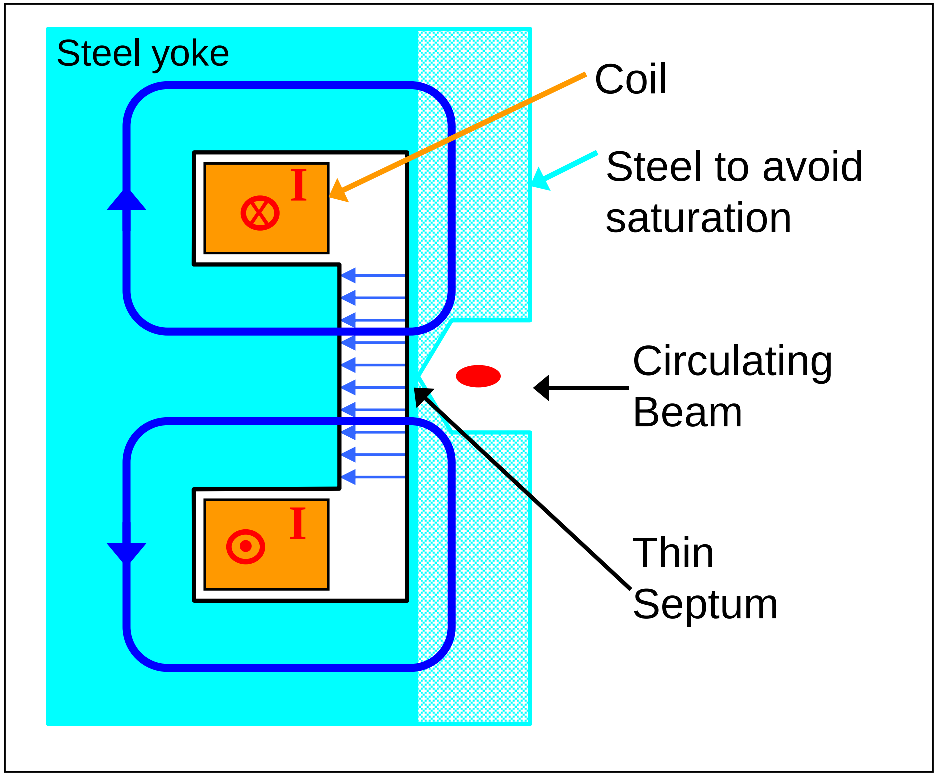
M. Paraliev's Lecture

Two planes injection



Lambertson septum

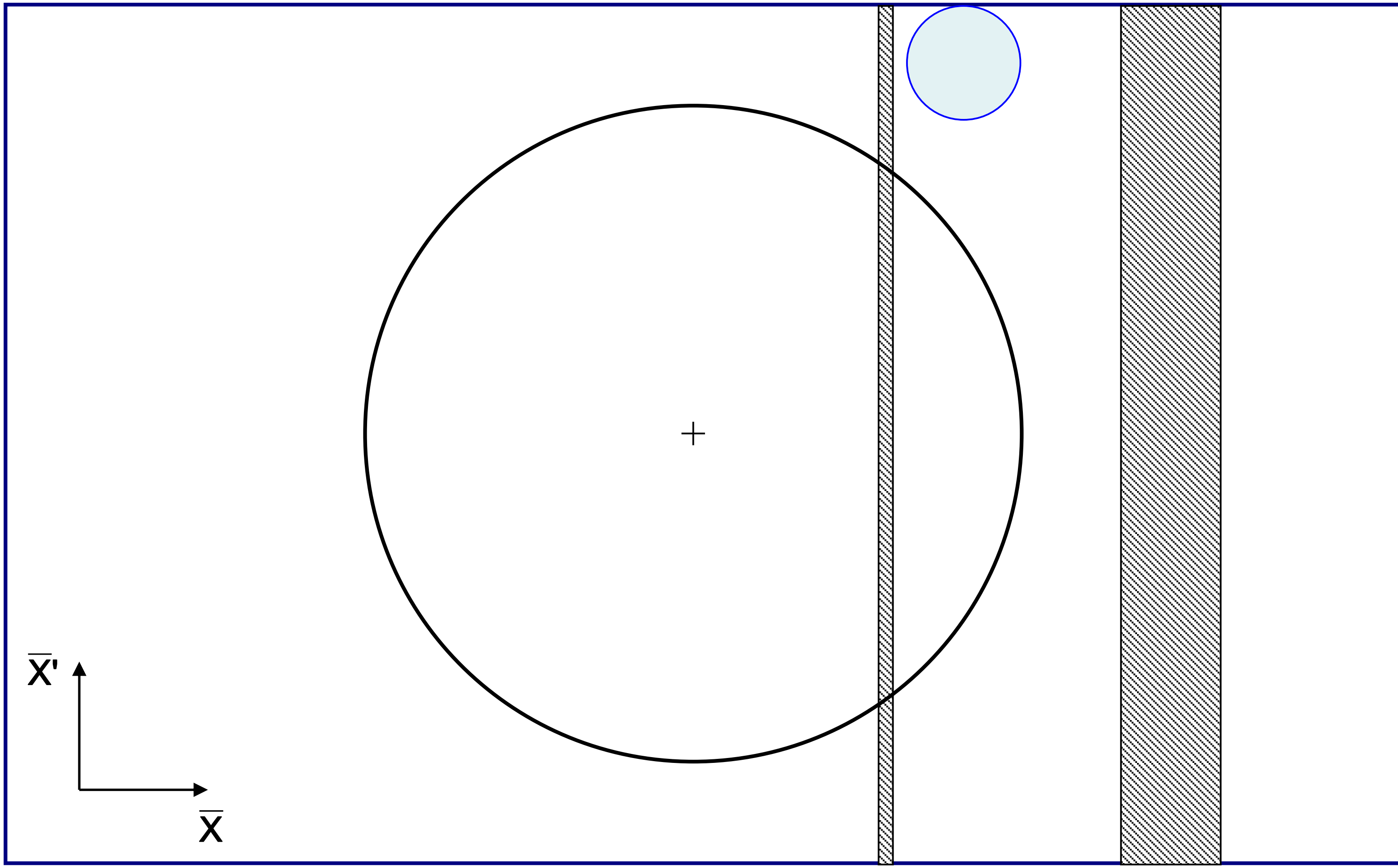
M. Paraliev's Lecture



- Magnetic field in gap orthogonal to previous example of septa:
  - Lambertson deflects beam orthogonal to kicker: dual plane injection/extraction
- Rugged design: conductors safely hidden away from the beam
- Thin steel yoke between aperture and circulating beam – however extra steel required to avoid saturation, magnetic shielding often added

Single-turn injection

Normalised phase space at centre of idealised septum



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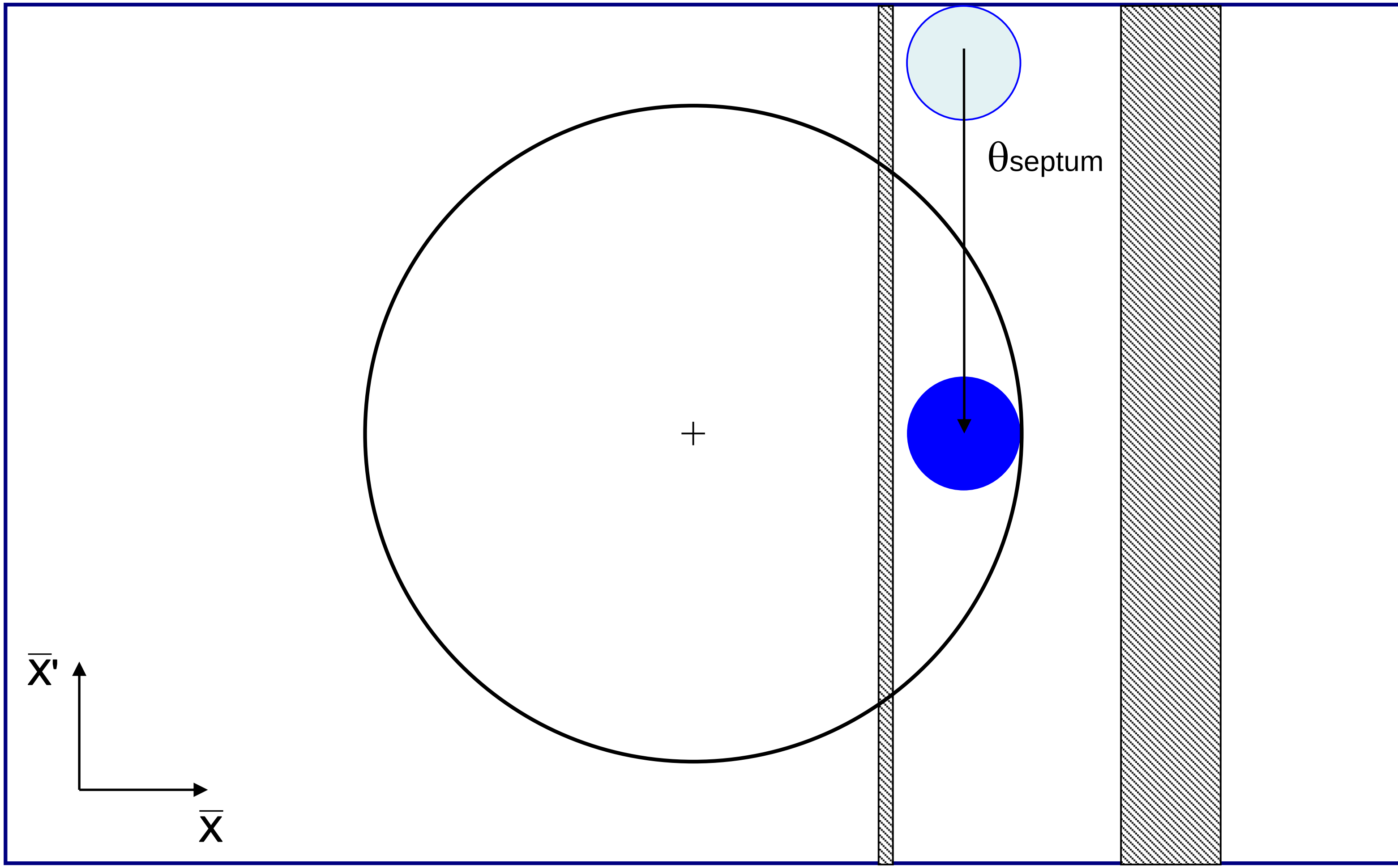

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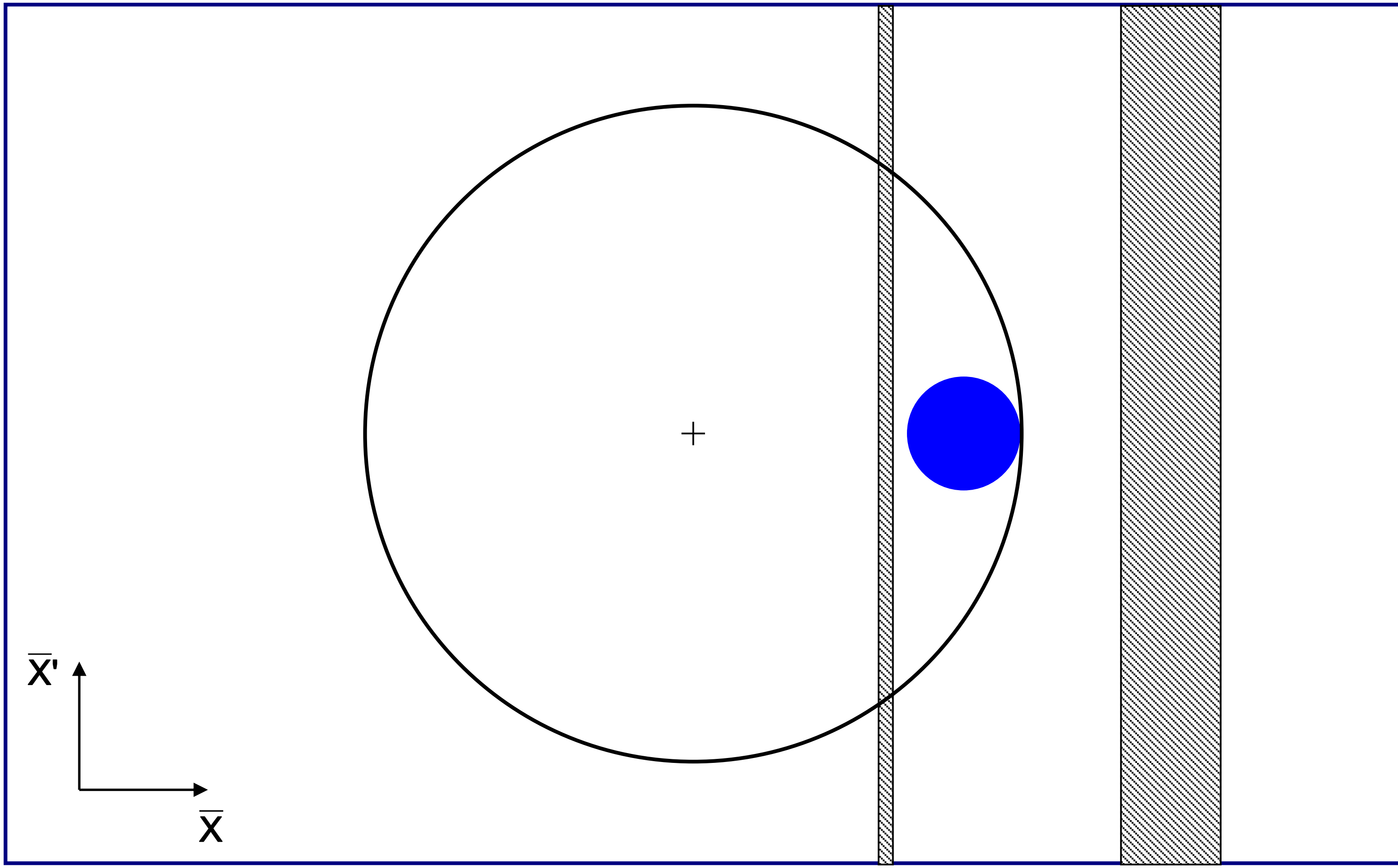
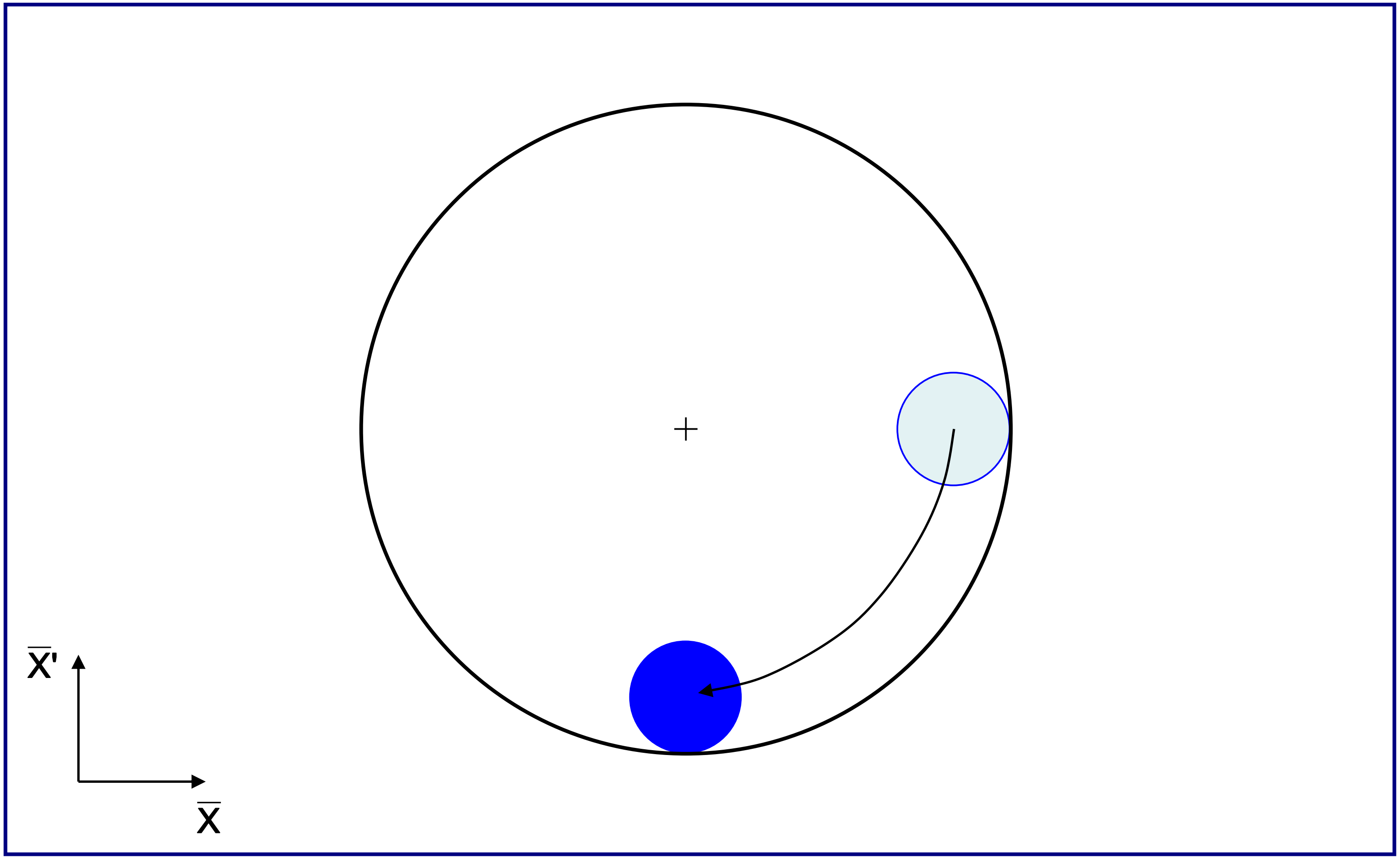


Single-turn injection

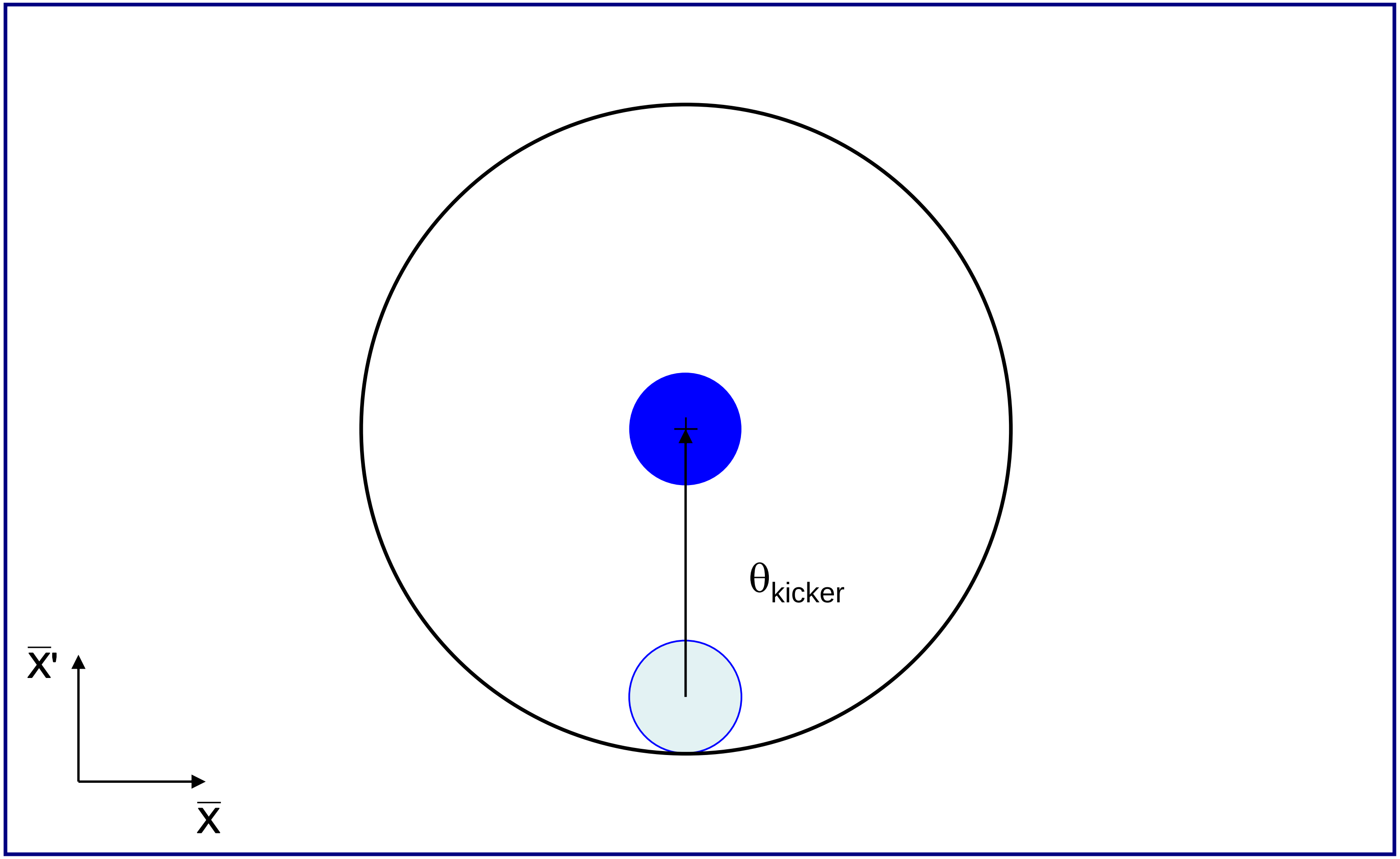
μ/2 phase advance to kicker location



Single-turn injection

Normalised phase space at centre of idealised kicker

Kicker deflection places beam on central orbit:



Injection errors

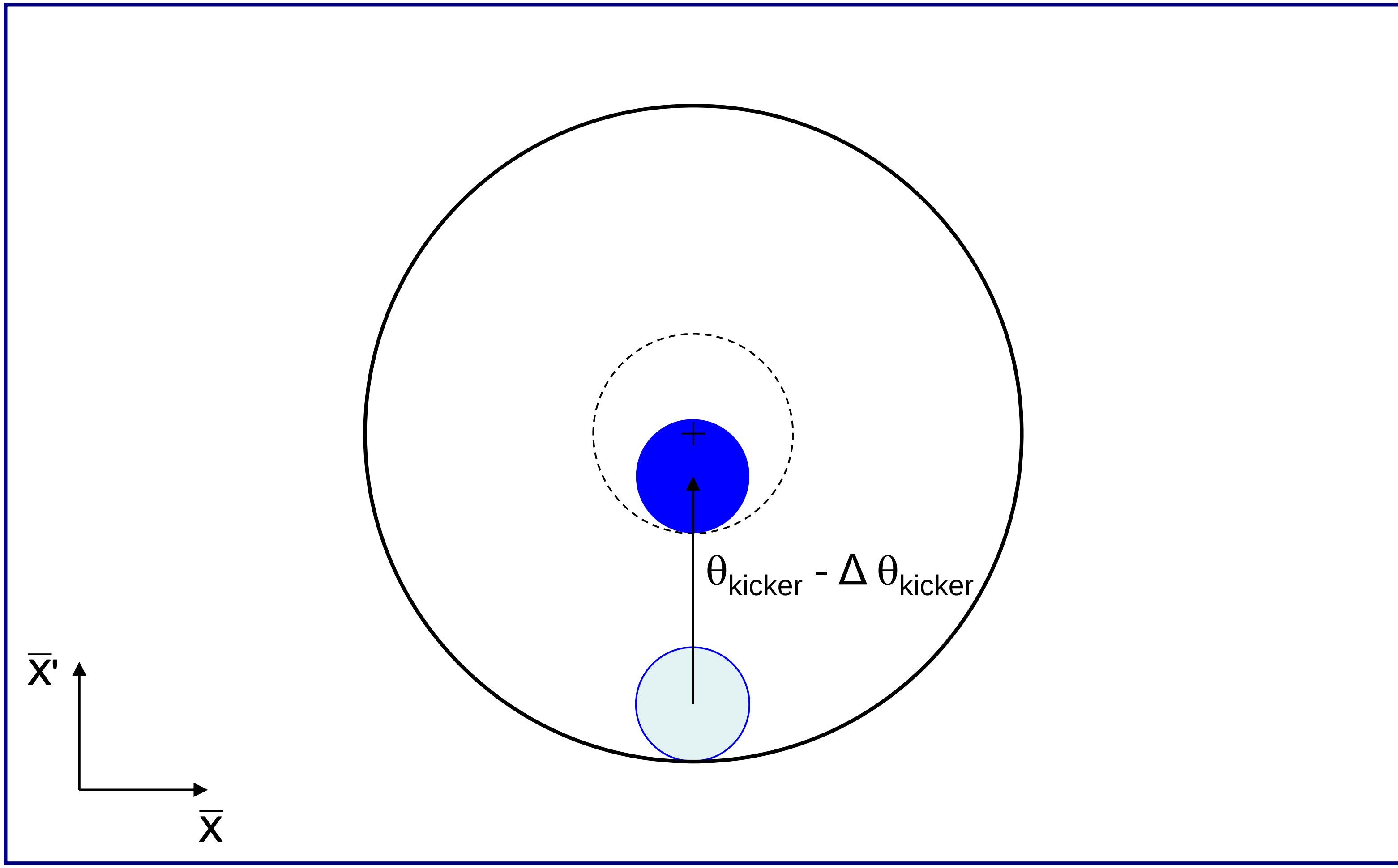
Transverse errors such as:

- Error in septum angle
- Error in ring kicker angle
- Steering error (including extraction kicker angle from previous accelerator)

Will lead to an emittance blow-up through filamentation due to the non-linear effects (e.g. higher-order field components) which introduce amplitude-dependent effects into particle motion.

Injection oscillations

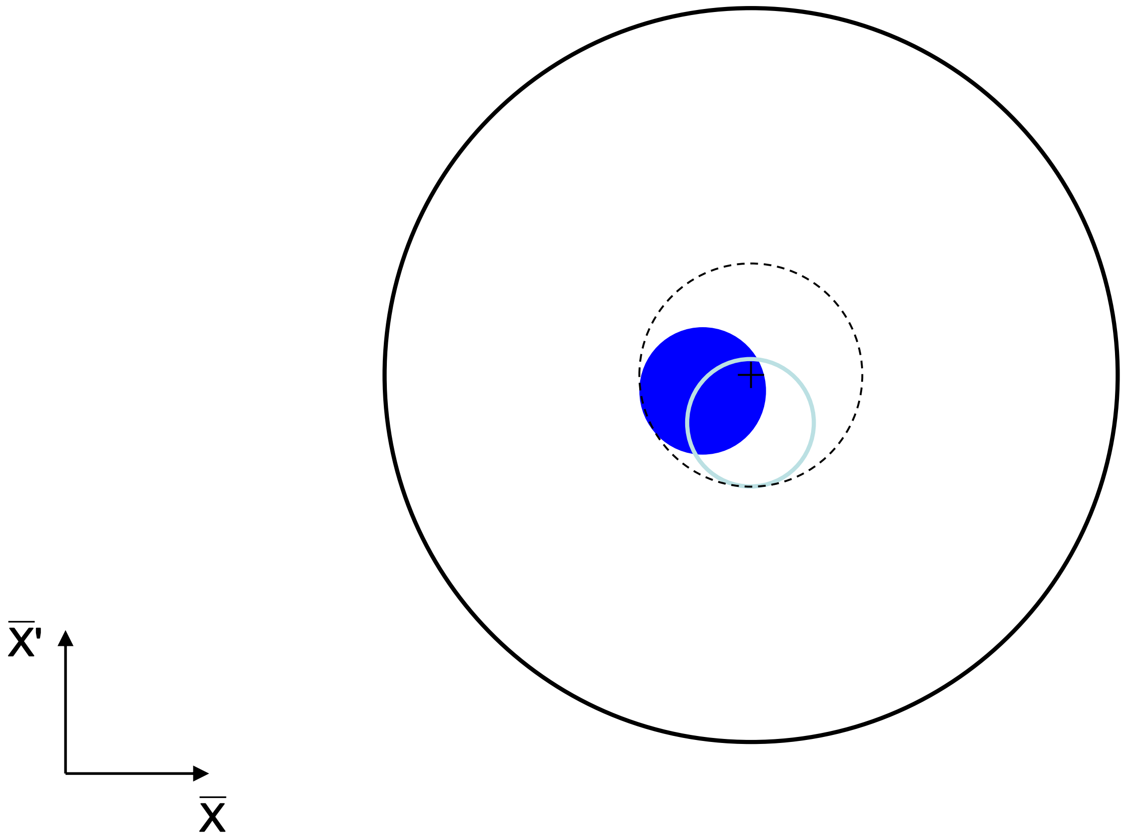
For imperfect injection the beam oscillates around the central orbit, e.g. kick error, Δ:



Injection oscillations

For imperfect injection the beam oscillates around the central orbit, e.g. kick error, Δ:

After 1 turn…



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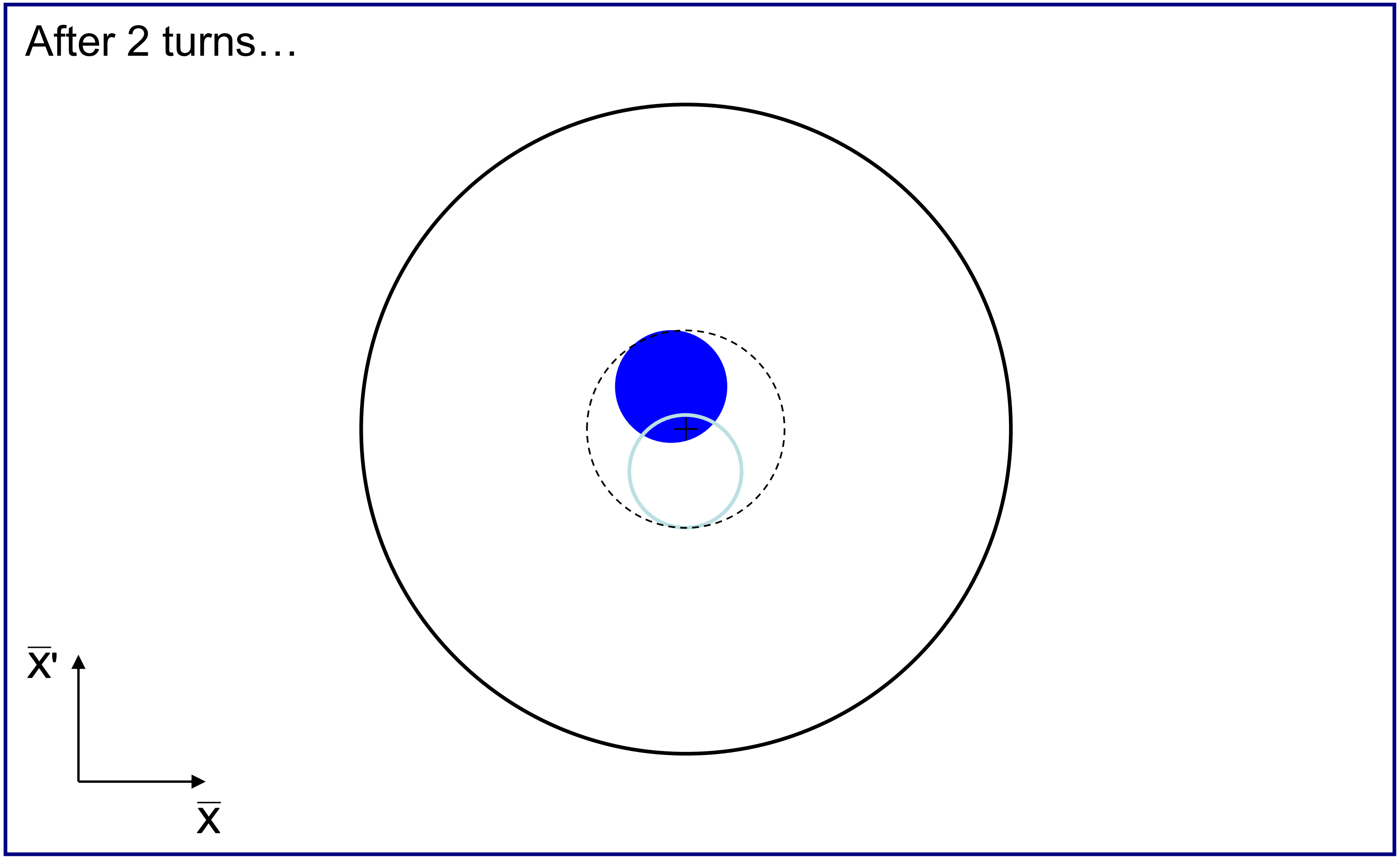
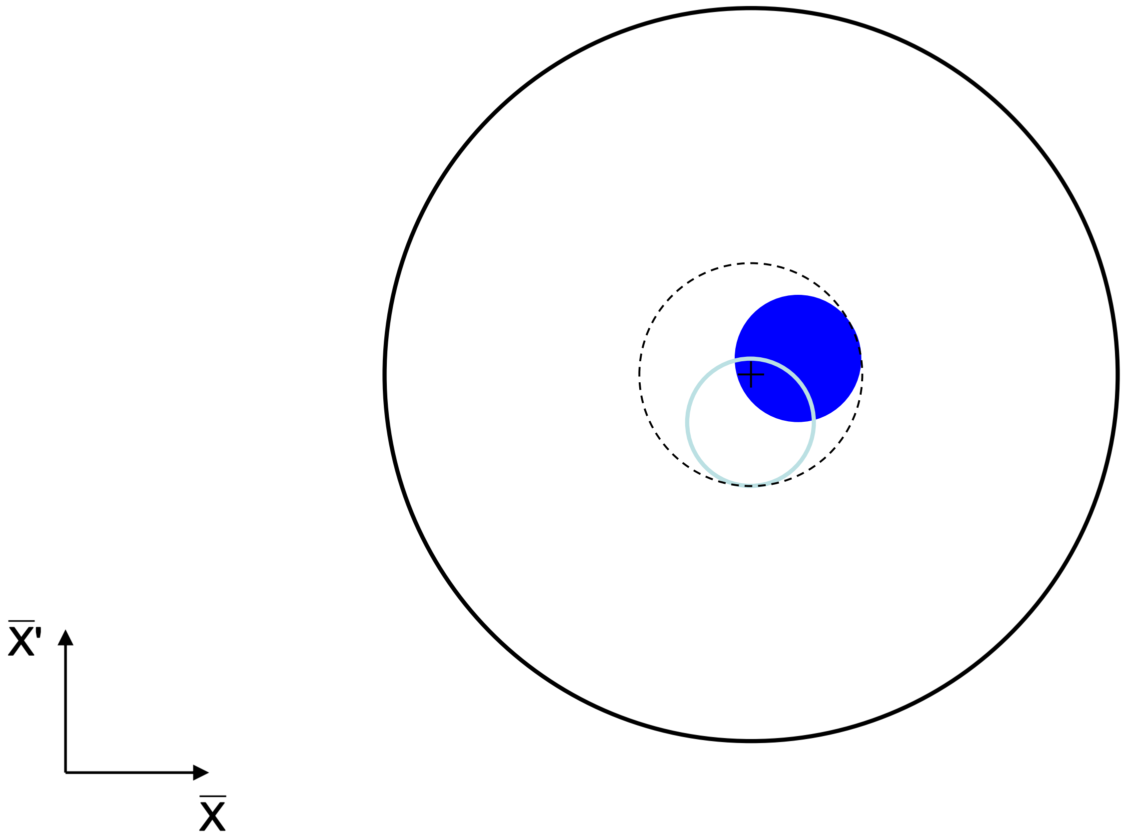


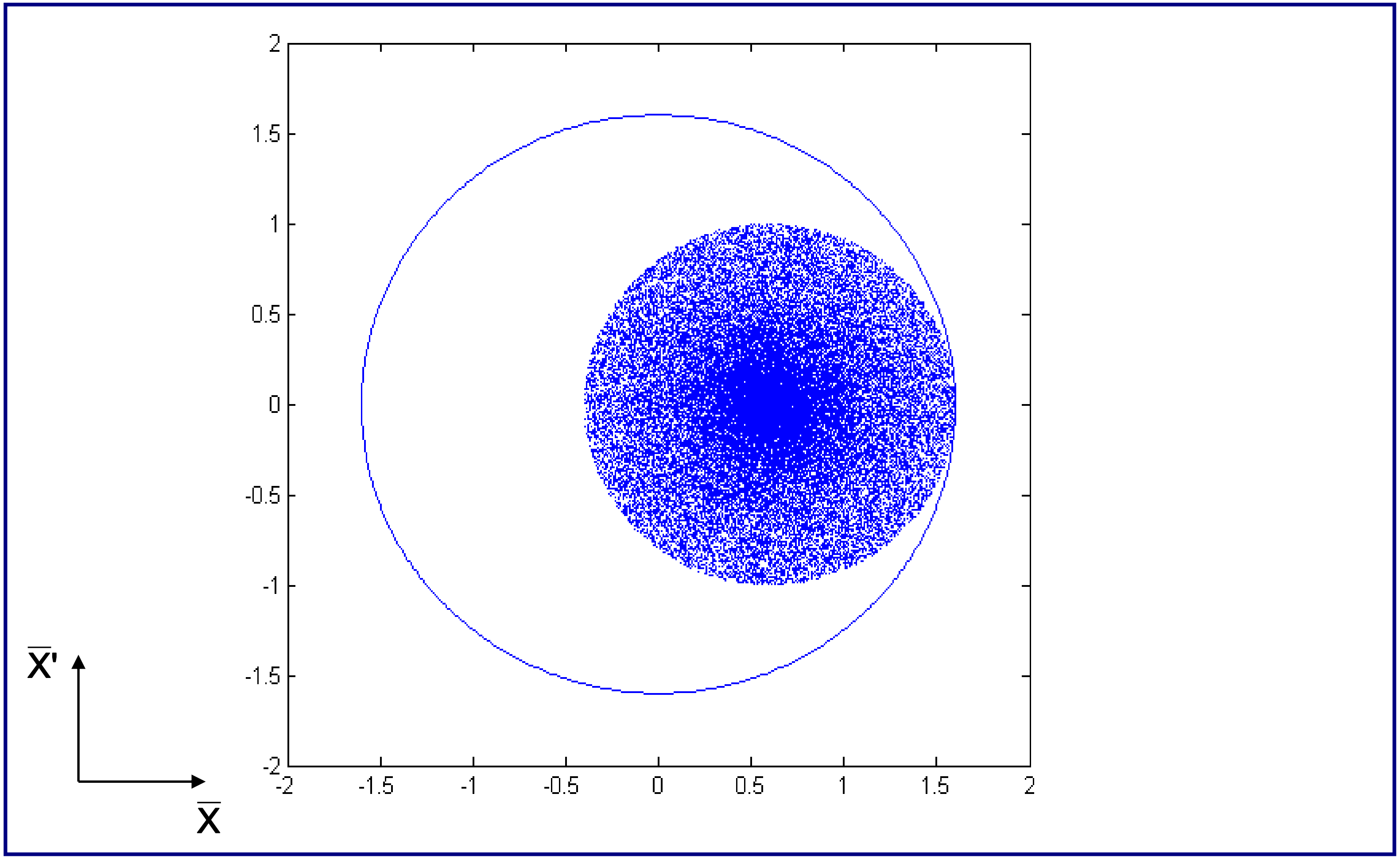
Injection oscillations

For imperfect injection the beam oscillates around the central orbit,
e.g. kick error, Δ:

After 3 turns etc…



Filamentation



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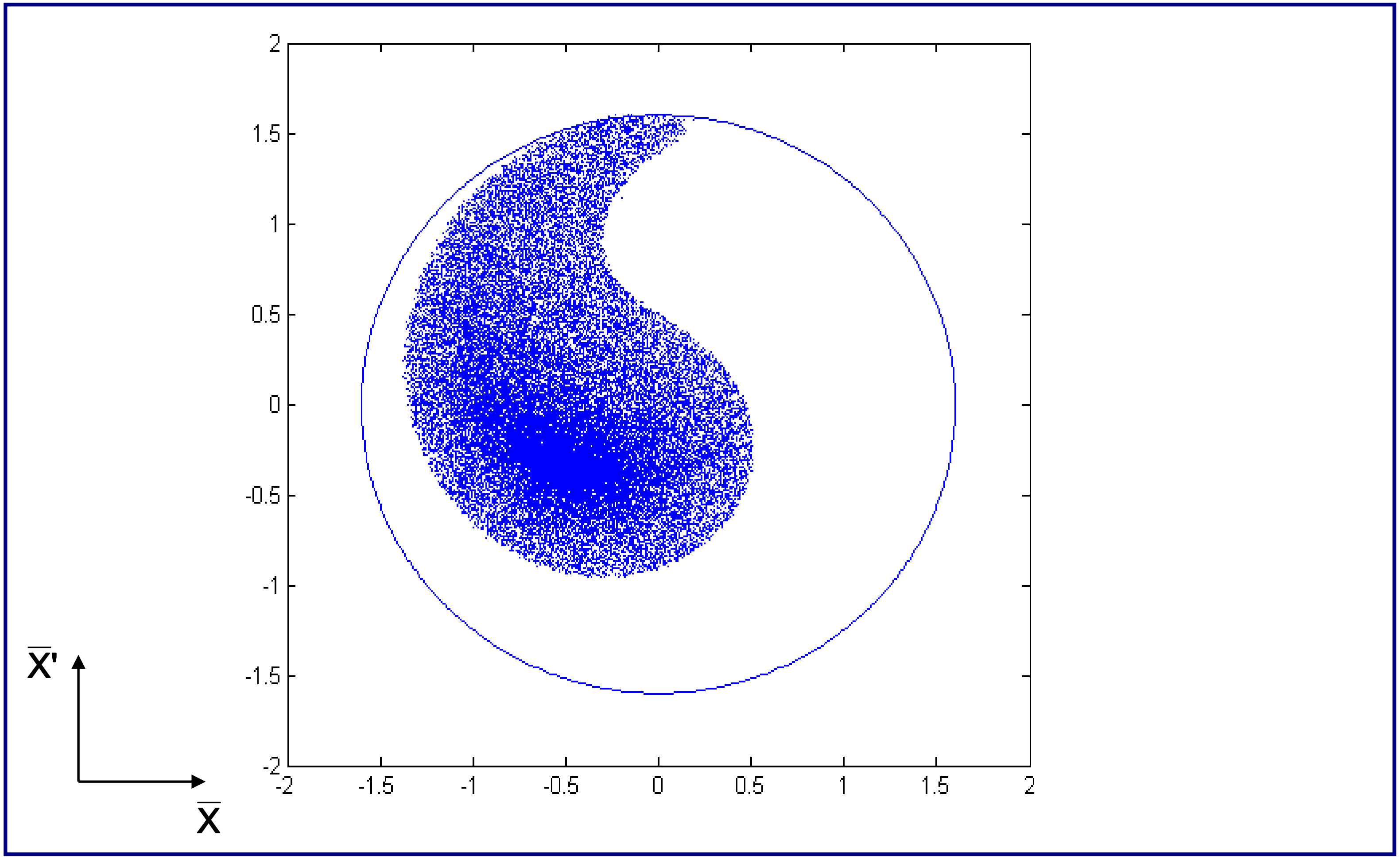

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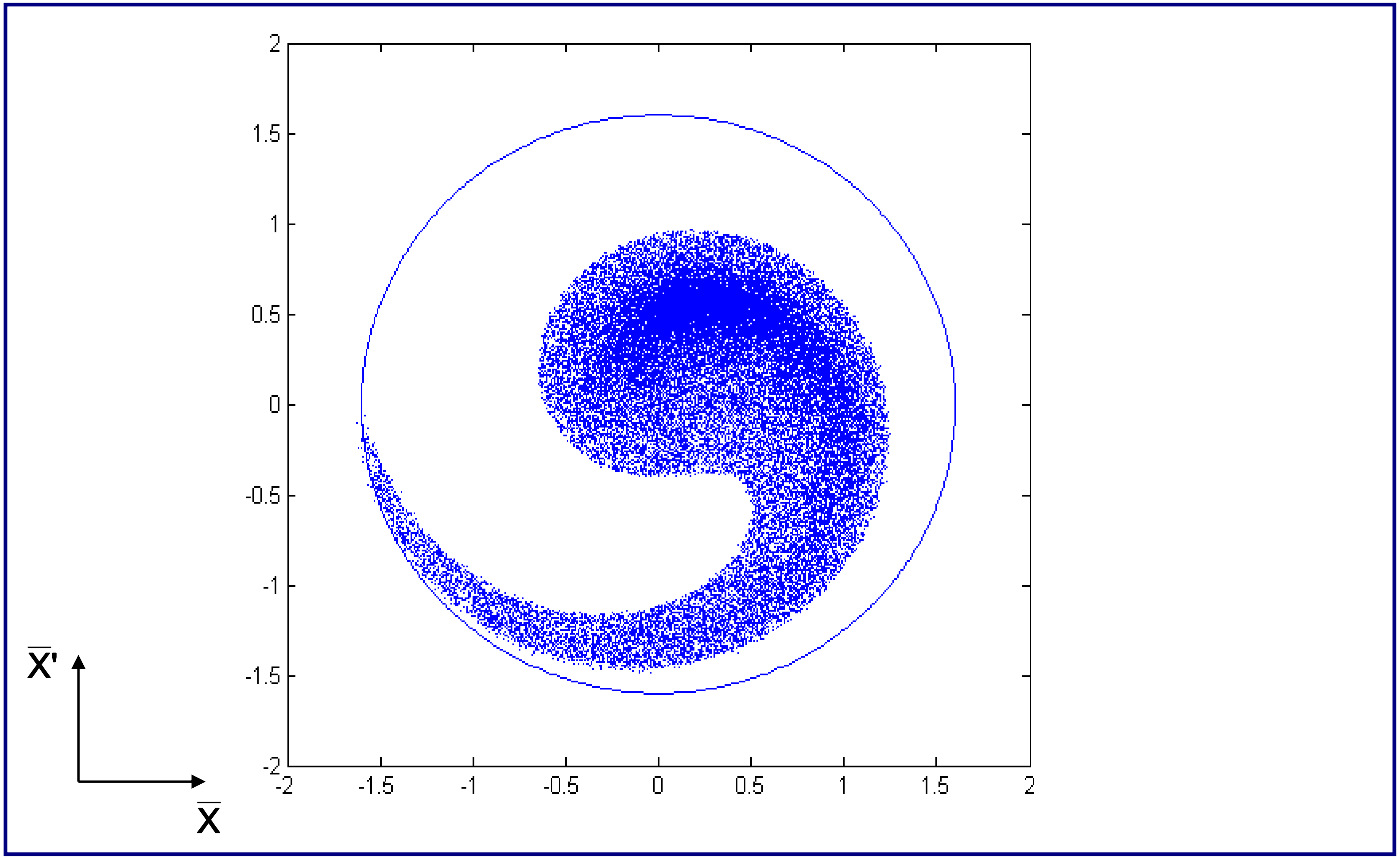

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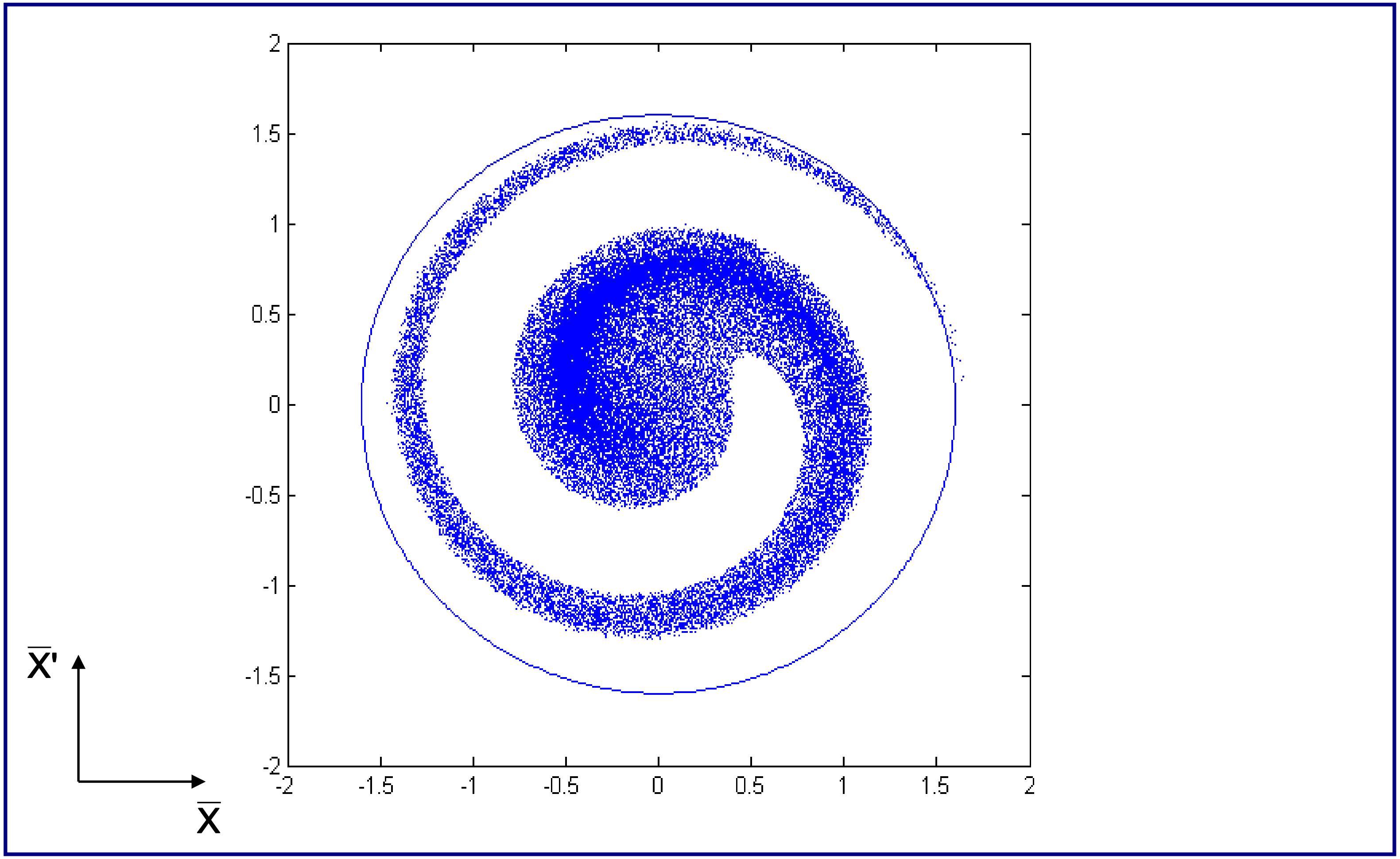

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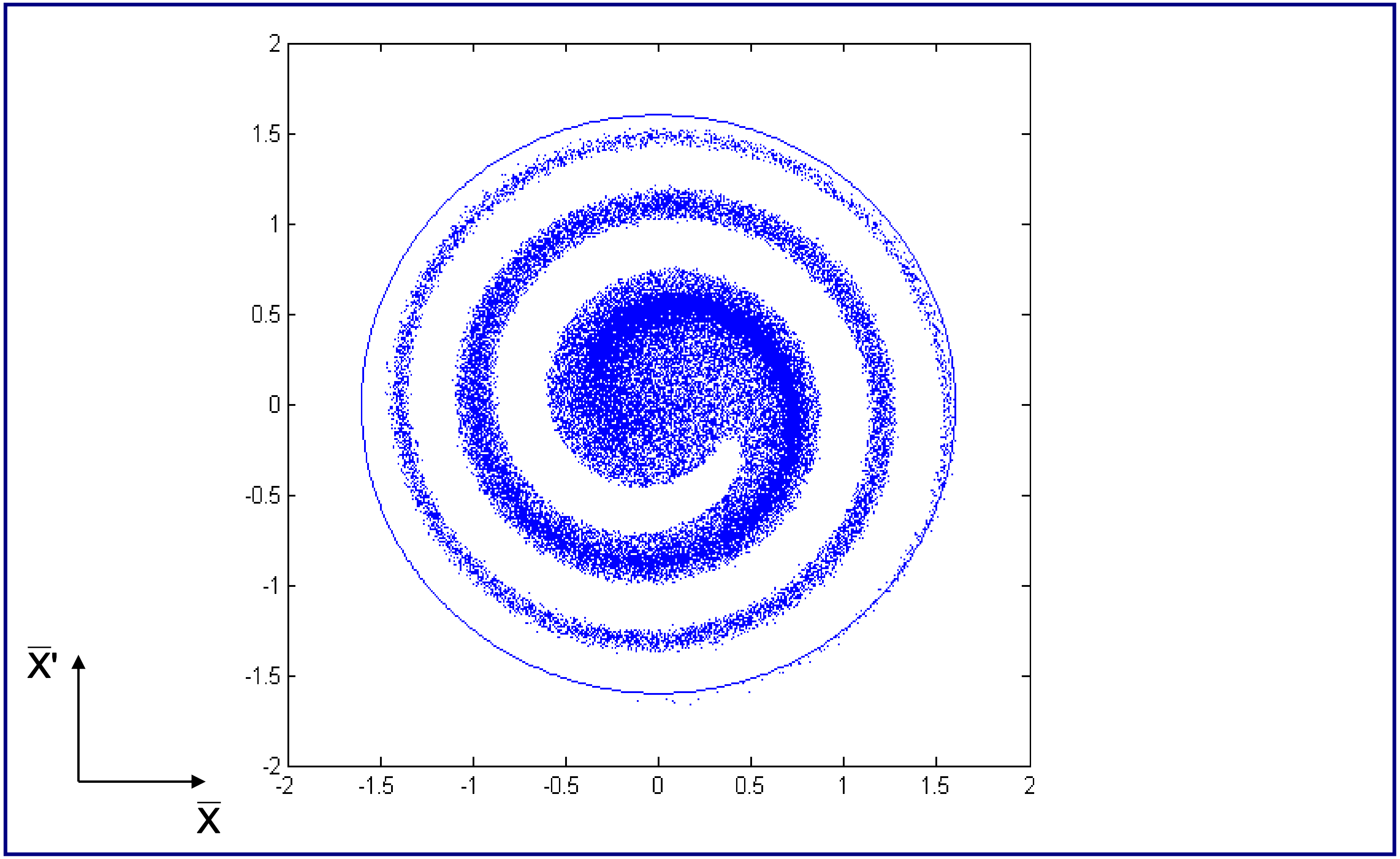

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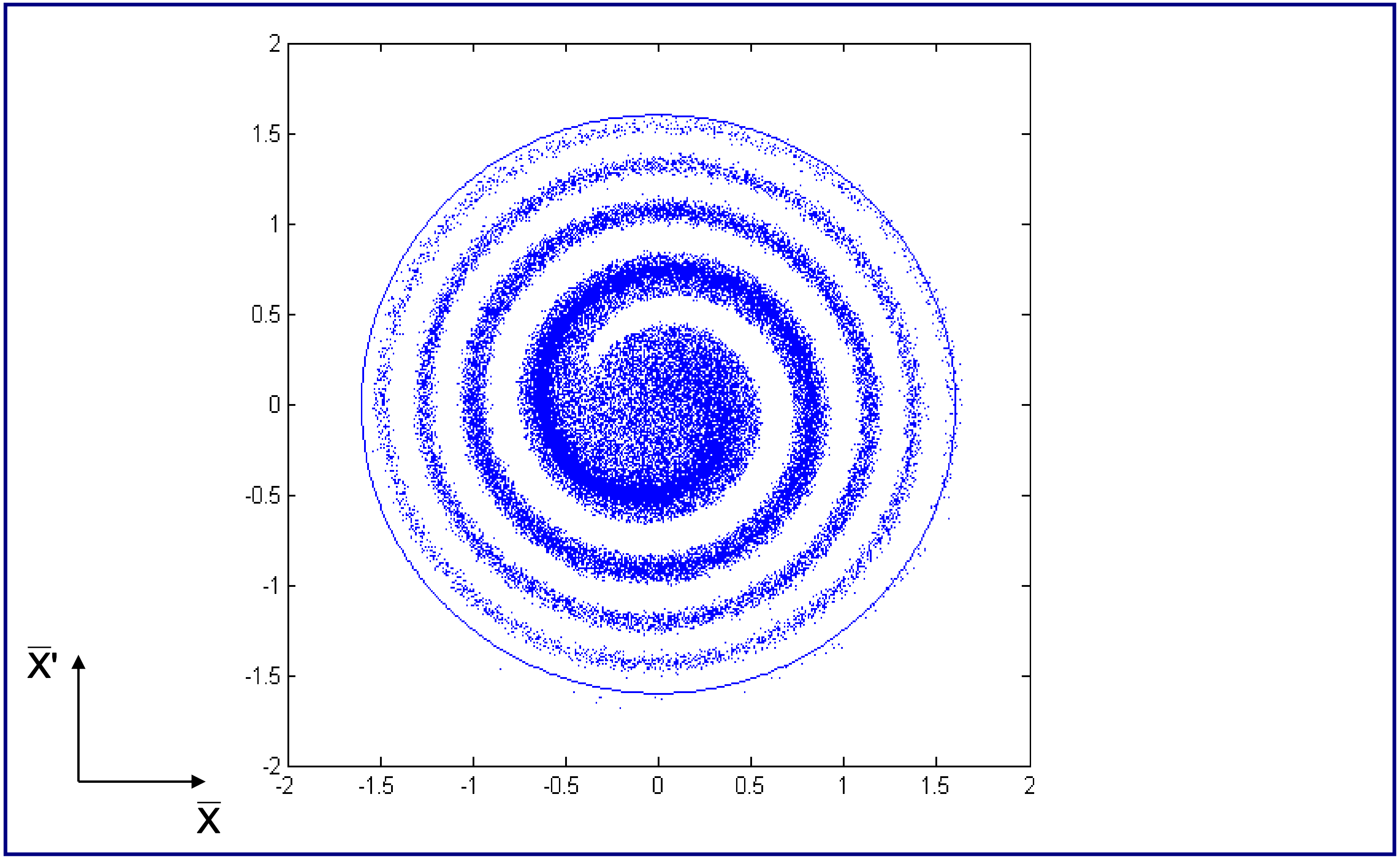

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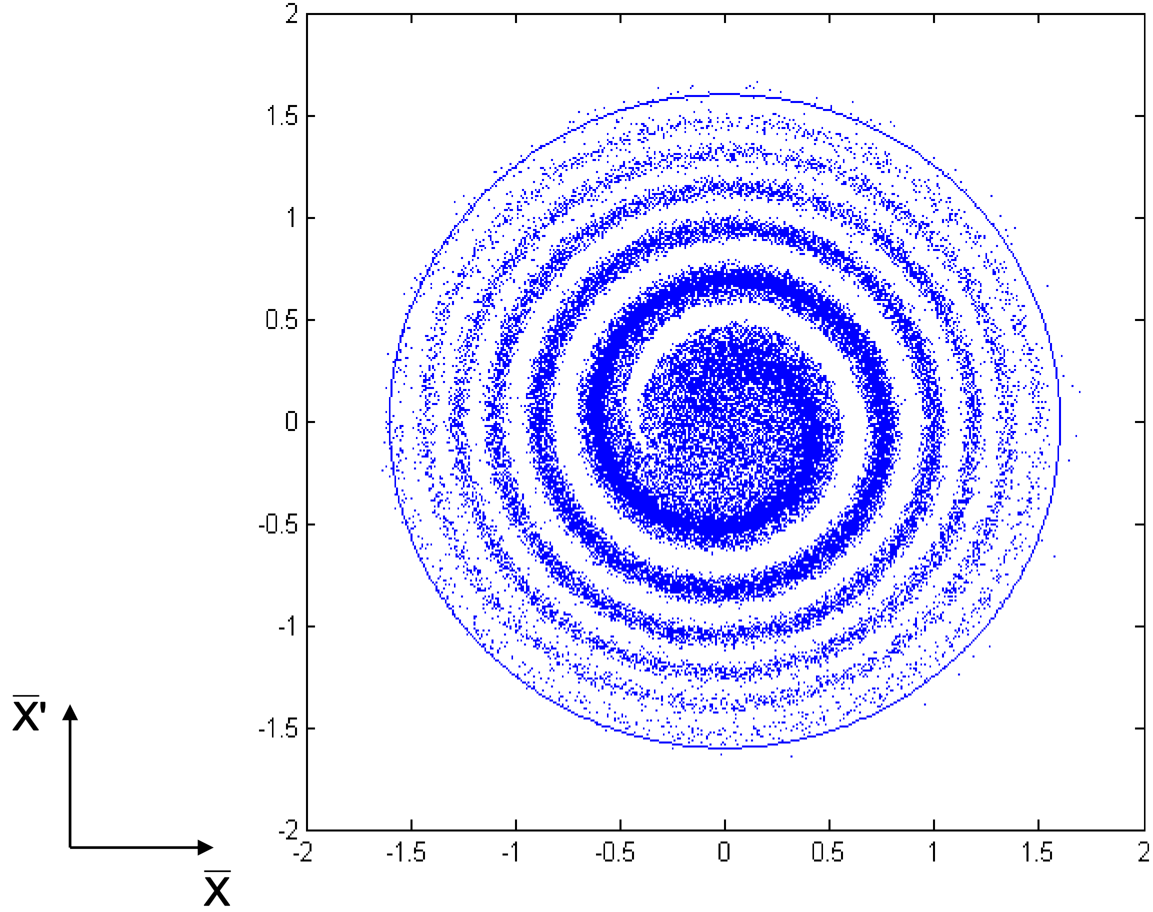

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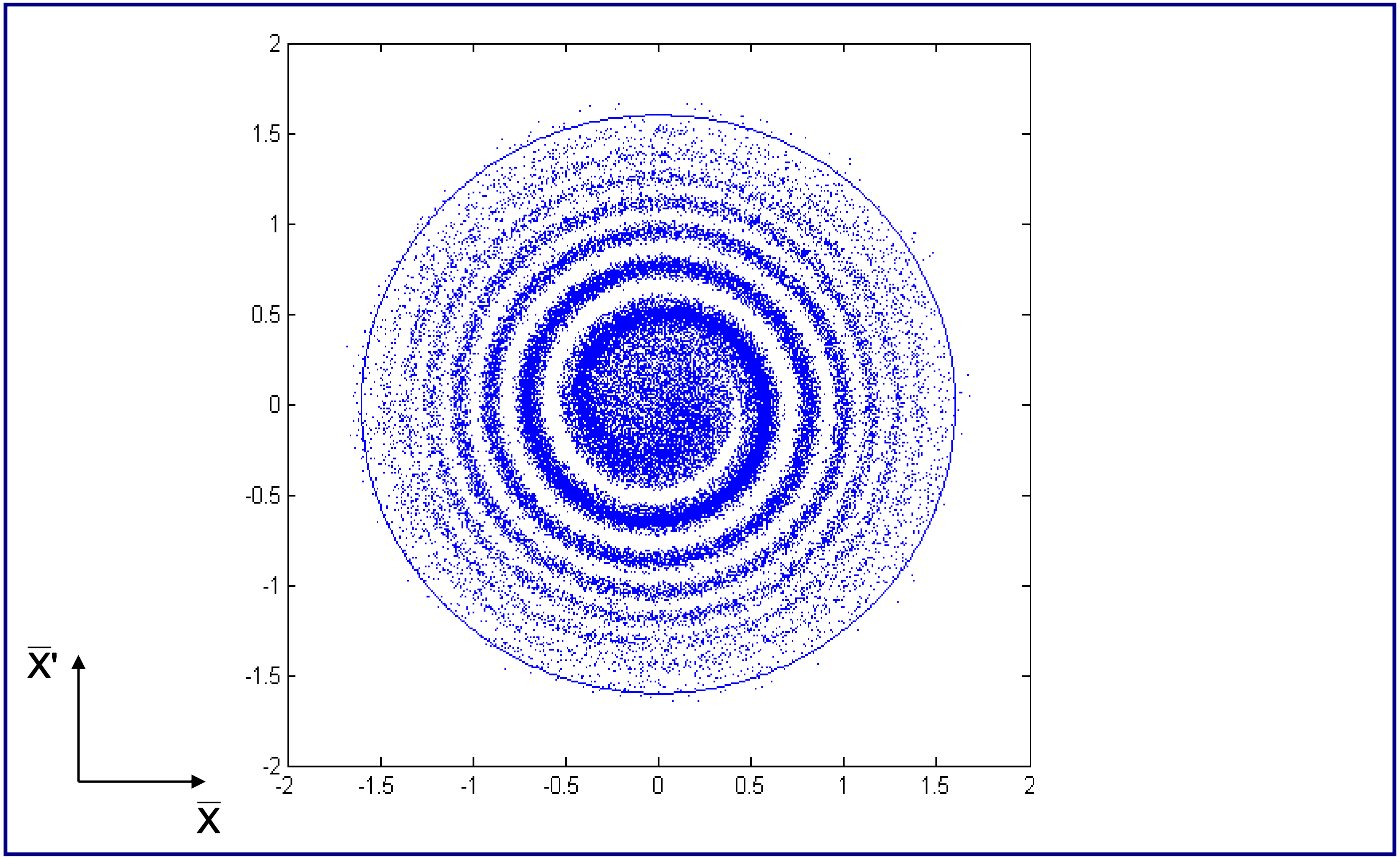

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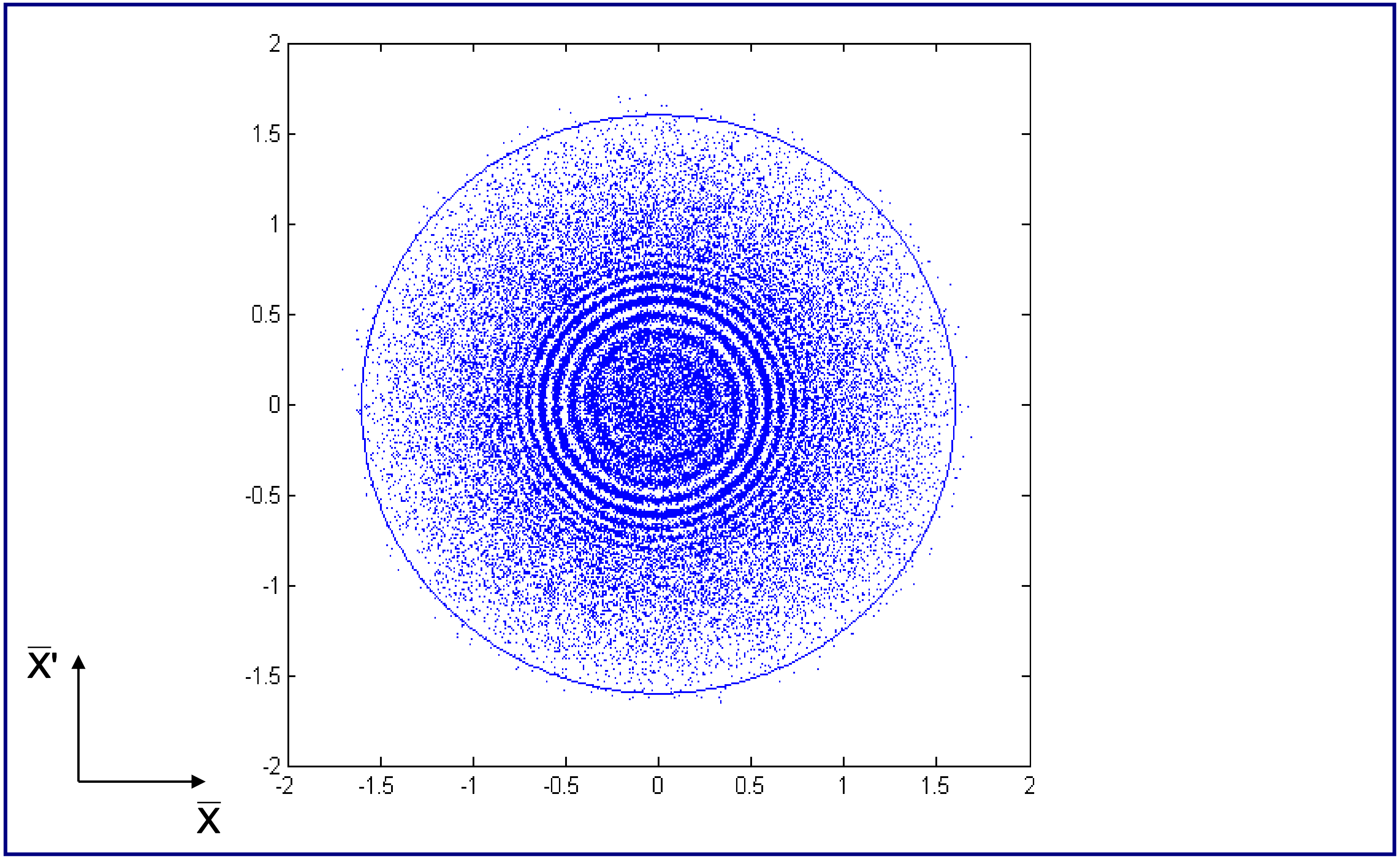

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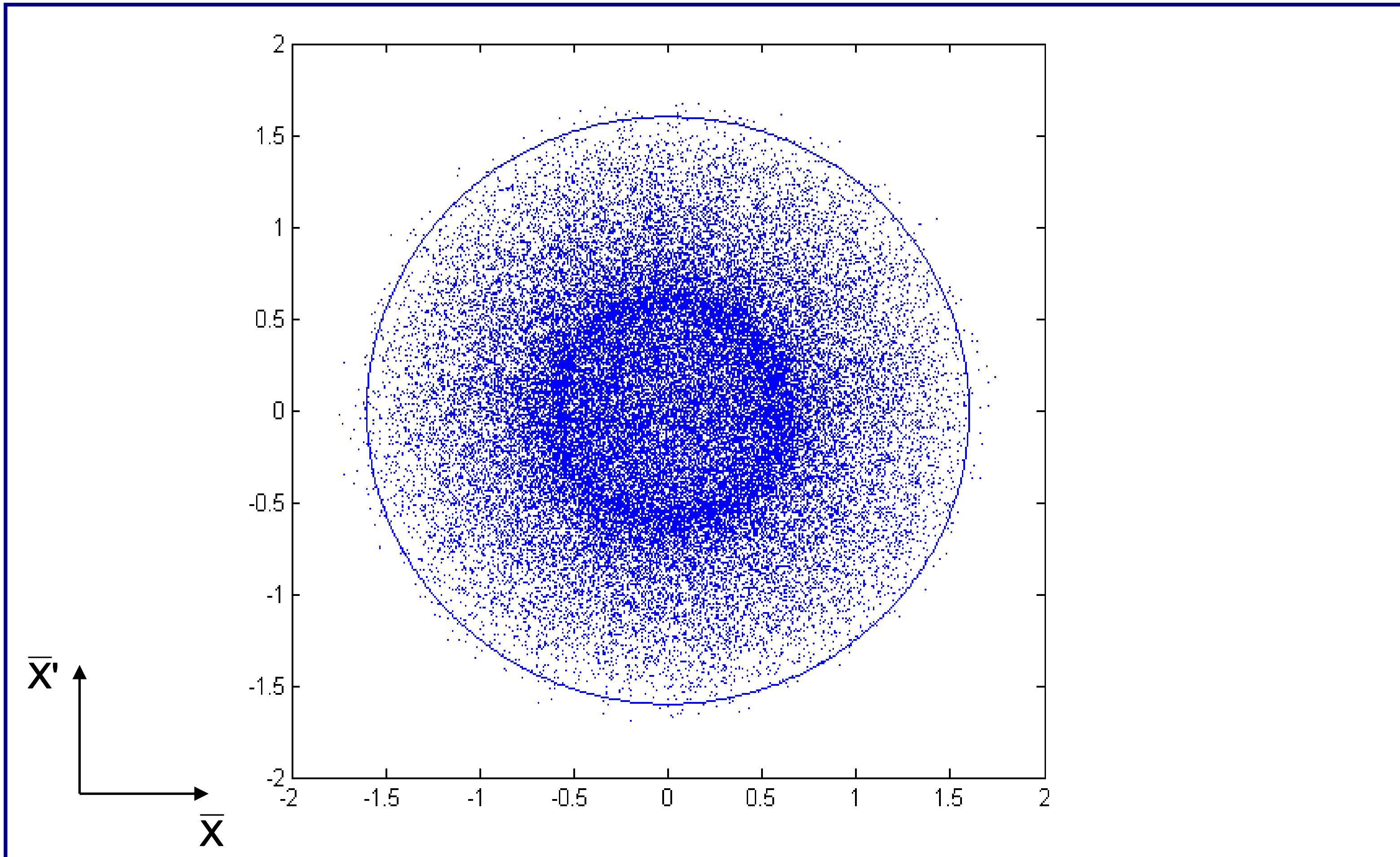
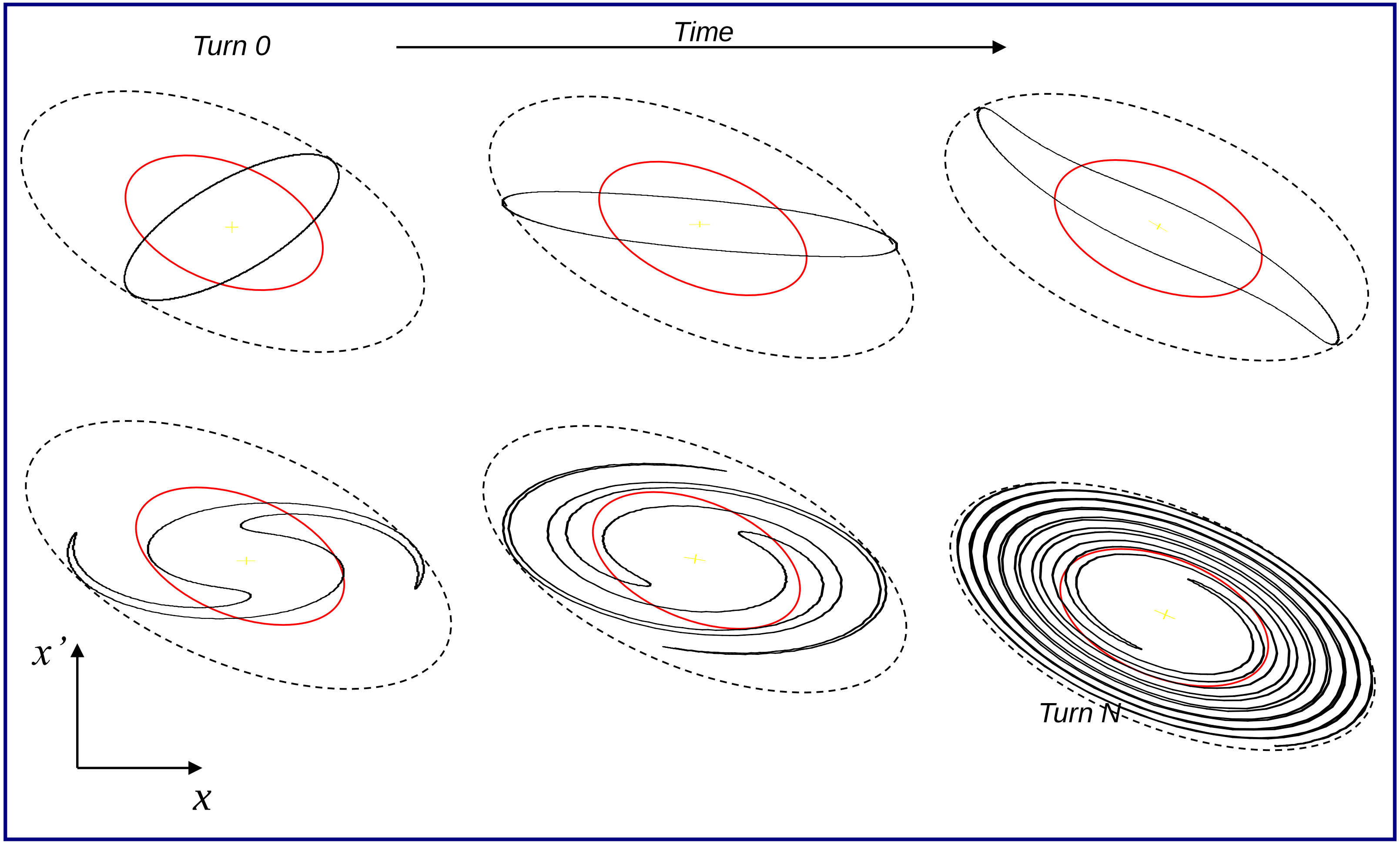


V. Kain's Lecture

Optical Mismatch at Injection

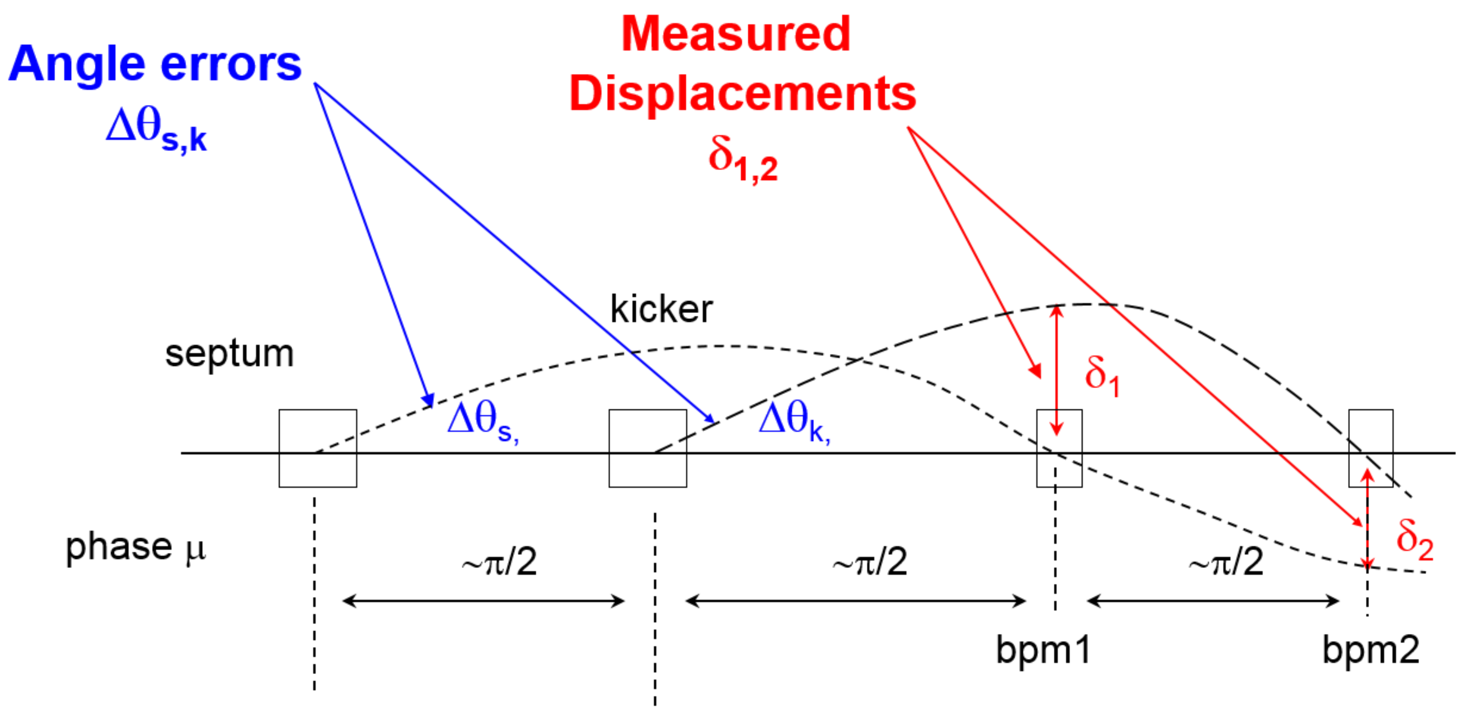
- Filamentation fills larger ellipse with same shape as matched ellipse



V. Kain's Lecture

Kicker and Septum errors

Beam position monitors can be used to find the source of the error

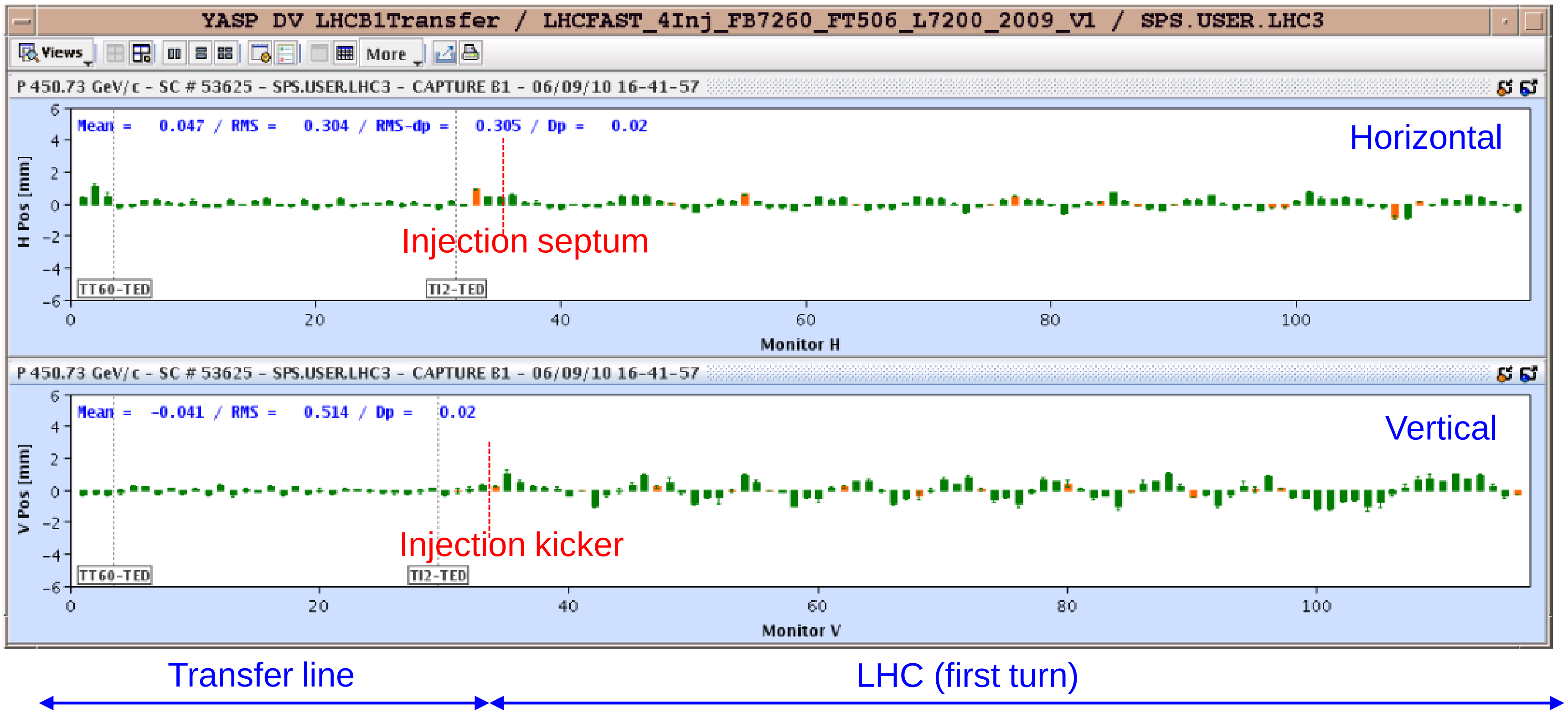


$$\delta_1 = \Delta\theta_s \sqrt{(\beta_s\beta_1)} \sin(\mu_1 - \mu_s) + \Delta\theta_k \sqrt{(\beta_k\beta_1)} \sin(\mu_1 - \mu_k) \approx \Delta\theta_k \sqrt{(\beta_k\beta_1)}$$

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

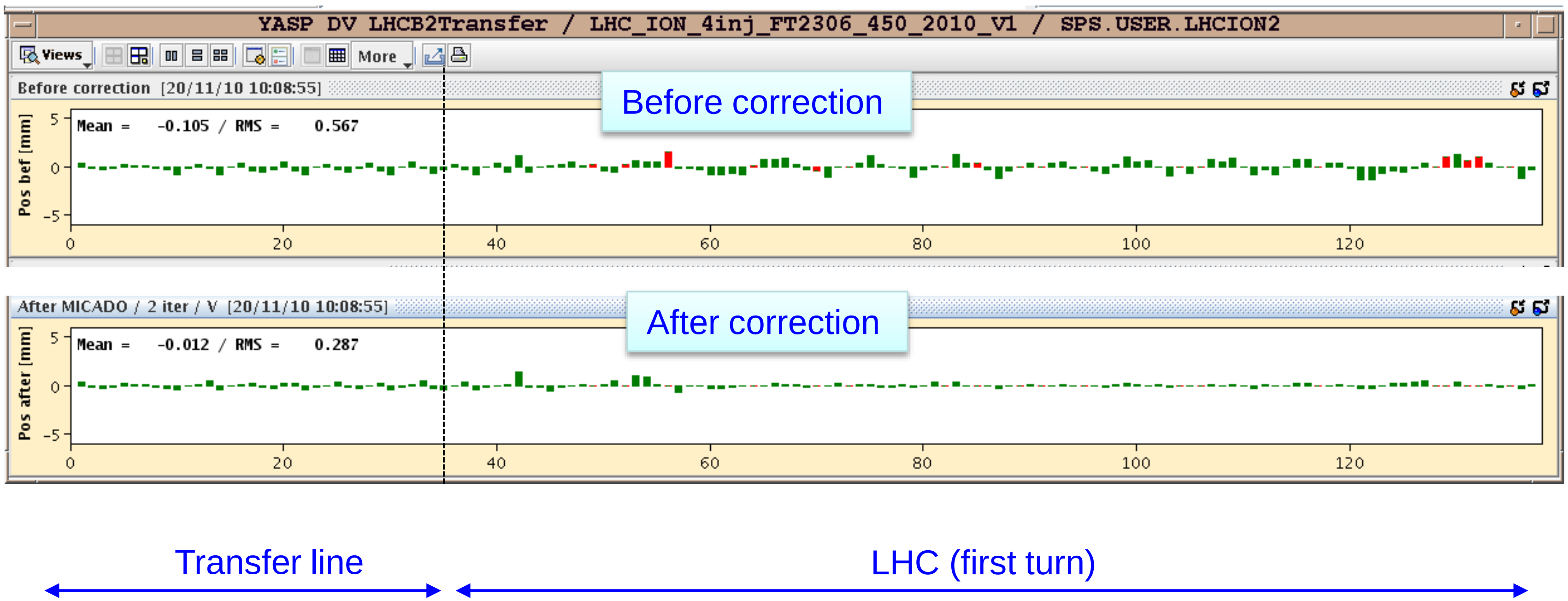
Injection oscillations

- Betatron oscillations with respect to the Closed Orbit:



Injection oscillation correction

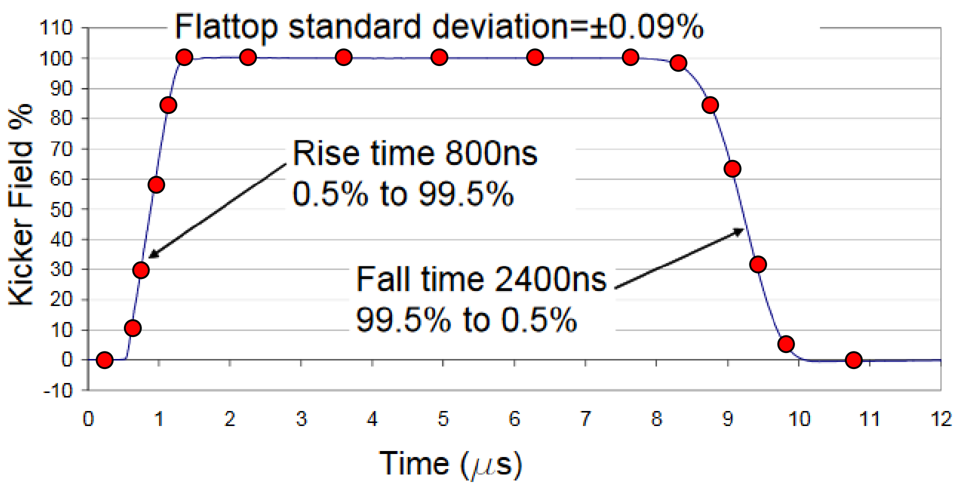
- Injection oscillations due to steering errors in the transfer line can be mitigated by a correct steering of the line (needed corrections calculated from BPM reading)

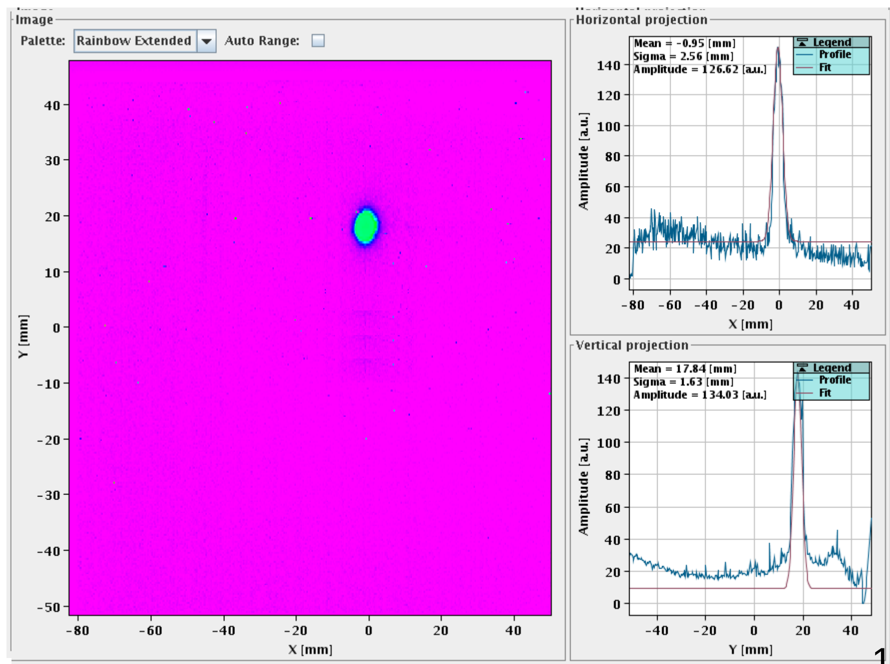


Injection kicker waveform

Ideal waveform

We can measure the kick seen by the beam by varying the delay of the kicker wrt the beam (1 bunch) and measuring the position of the beam on a downstream screen





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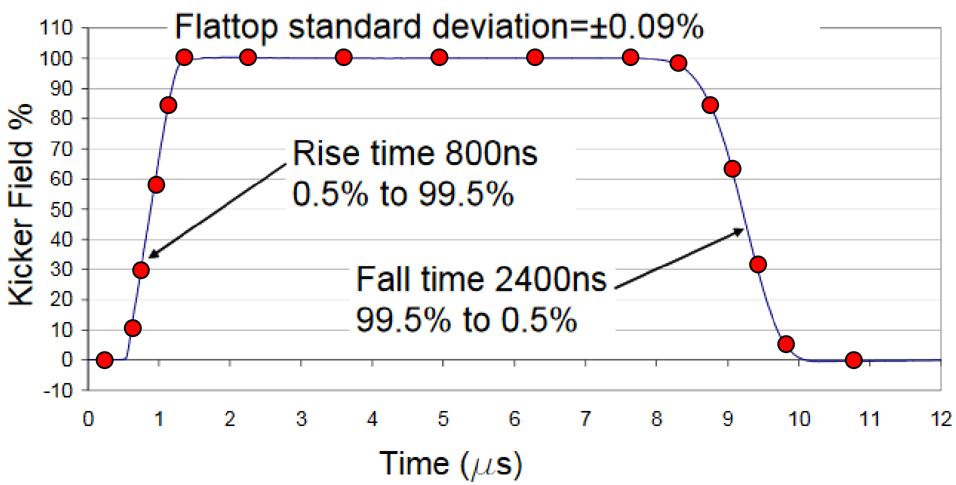

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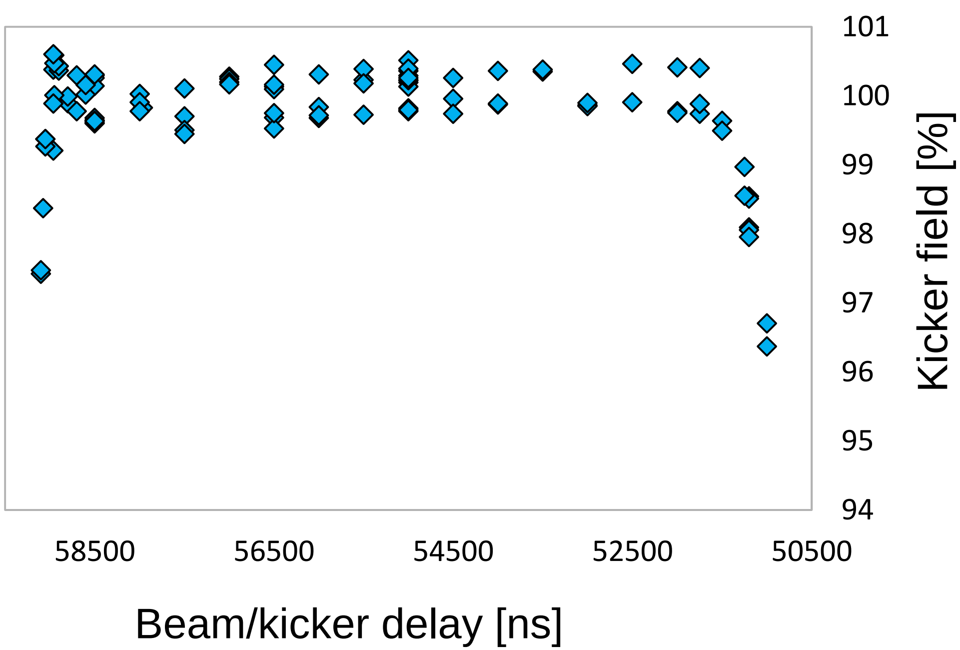

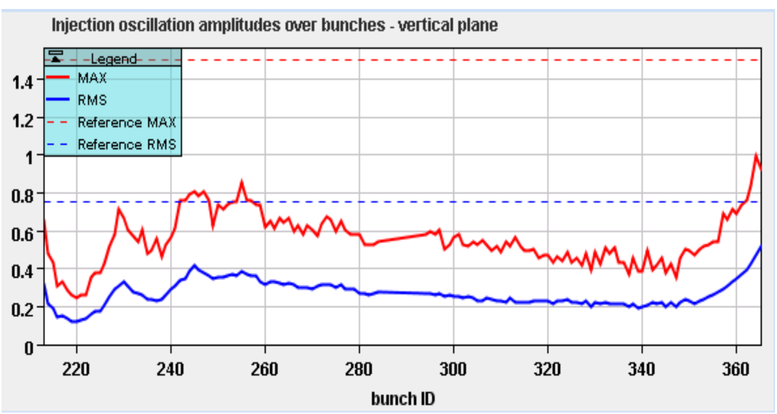

Multi-bunch injection: bunch-by-bunch position wrt closed orbit

Injection kicker waveform

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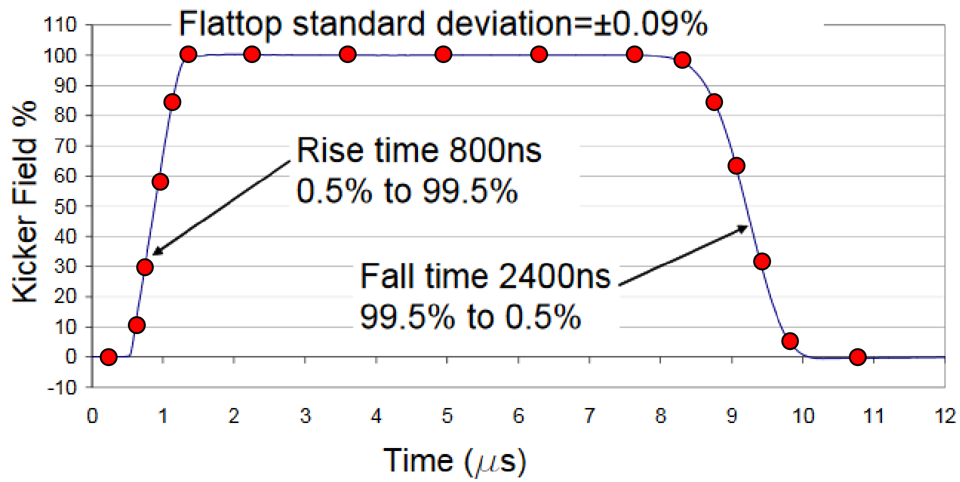

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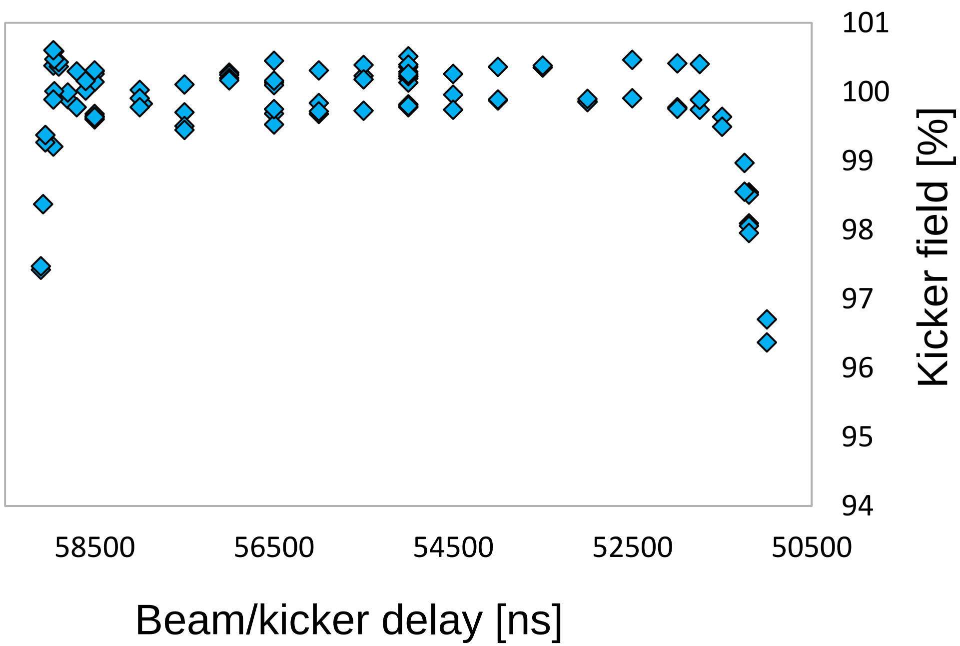
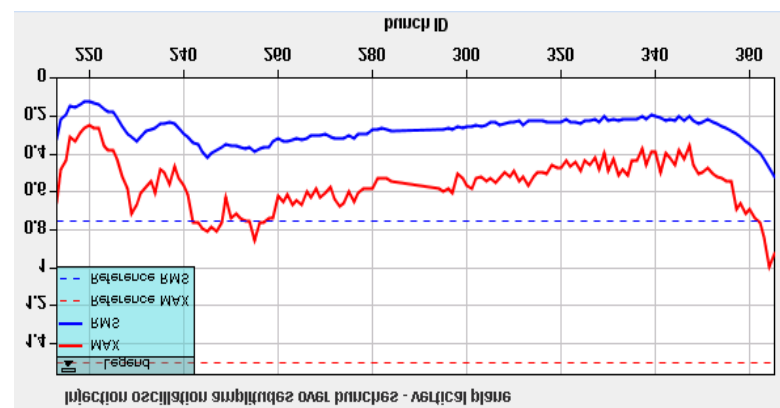
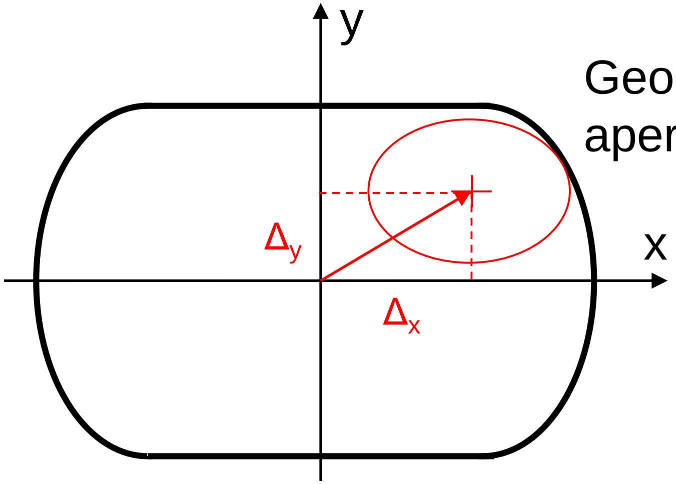




Multi-bunch injection: bunch-by-bunch position wrt closed orbit

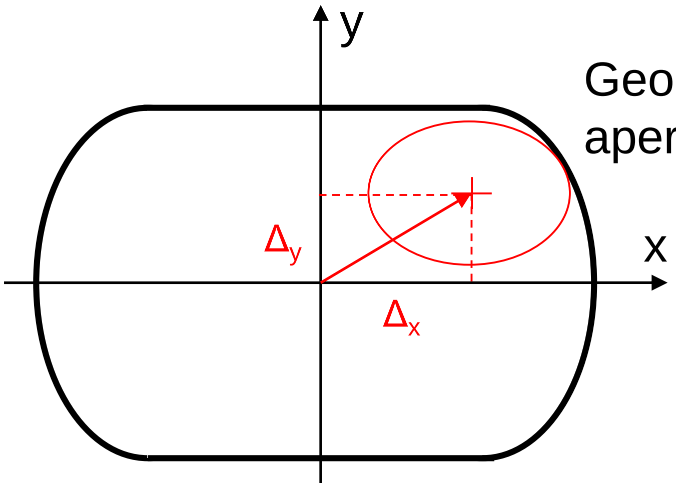
Aperture



Maximum beam displacement:

$$\Delta_{x,y}(s) = CO^{peak}_{x,y}\sqrt{\frac{\beta_{x,y}(s)}{\beta^{max}_{x,y}(s)}} + [\delta^{mech}_{x,y}(s) + \delta^{align}_{x,y}(s)] + k_\beta D_{x,y}(s)\delta_p + d^{sep}_{x,y}(s) + d^{inj}_{x,y}(s) + d^{axis}_{x,y}(s)$$

Aperture



Geometrical aperture $A^{geom}_{x,y}$

Orbit displacement due to crossing and separation
Injection oscillations
Magnet axis offset wrt ring axis

Maximum beam displacement:

$$\Delta_{x,y}(s) = CO^{peak}_{x,y}\sqrt{\frac{\beta_{x,y}(s)}{\beta^{max}_{x,y}(s)}} + [\delta^{mech}_{x,y}(s) + \delta^{align}_{x,y}(s)] + k_\beta D_{x,y}(s)\delta_p + d^{sep}_{x,y}(s) + d^{inj}_{x,y}(s) + d^{axis}_{x,y}(s)$$

Closed orbit

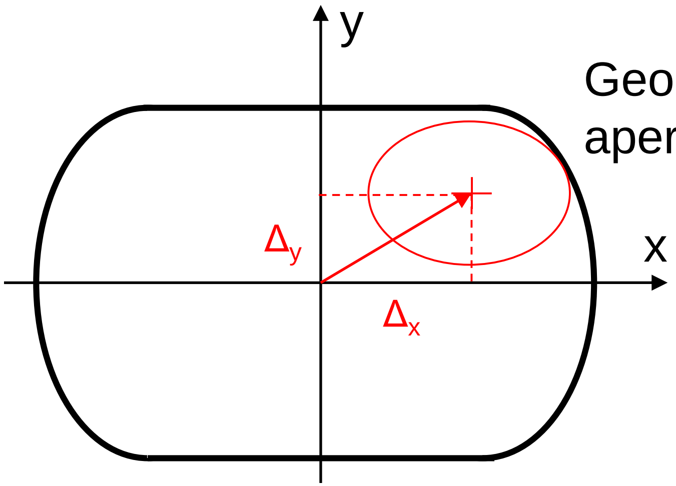
Mechanical and alignment tolerances

Dispersive term
δ_p = momentum offset + max. momentum spread
k_β = β-beating correction
Taking into account parasitic coupling:

$$D_{x,y}(s) = D^{linear}_{x,y}(s) + k_D\sqrt{\frac{\beta_{x,y}(s)}{\beta_{QF,x}}}D_{QF}$$

k_D = coupling coefficient
D_{QF} = peak linear dispersion

Aperture



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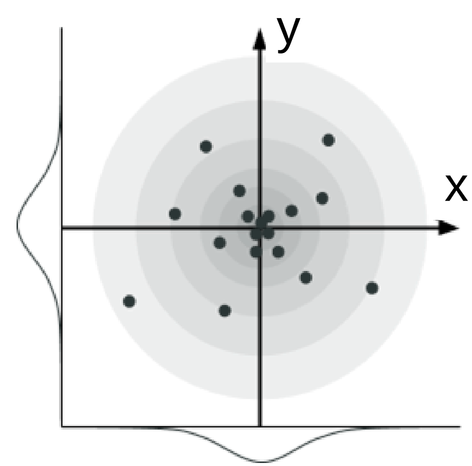
Betatron beam envelope (maximum oscillation amplitude of the beam particles):

$$\delta_{x,y}(s) = n_{x,y}\sigma_{\beta_{x,y}}(s)$$ where $$\sigma_{\beta_{x,y}}(s) = k_\beta\sqrt{\varepsilon_{x,y}\beta_{x,y}(s)}$$ betatron beam size

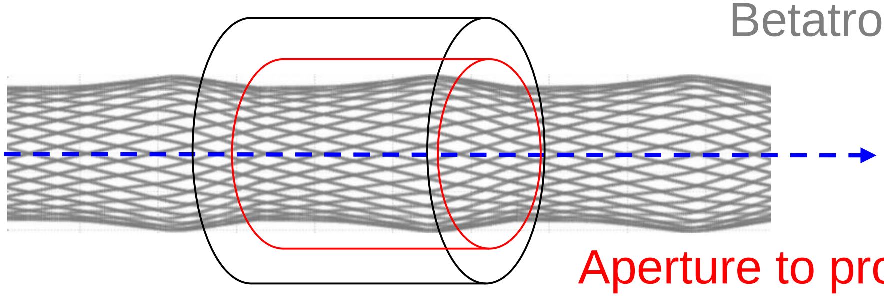
How many $n_{x,y}$ have to fit in the aperture? It depends on the stored beam energy and the aperture which has to be protected. The higher the stored energy the larger $n_{x,y}$ (special care for superconductive machines!)

Aperture



Stored energy: $E_{stored}(x,y) = n_{part}(x,y)E^{tot}_{part}$

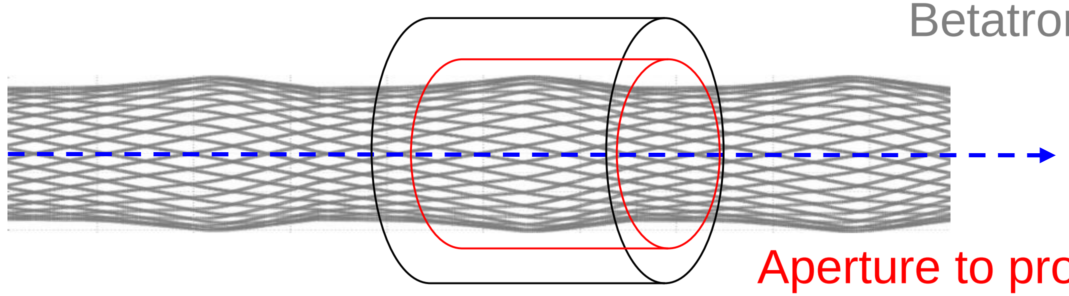
for a Gaussian (in general non uniform) distribution
E_{stored} varies with the amplitude



$$n_{x,y} \leq A^{prot}_{x,y}[\sigma_{\beta_{x,y}}] \leq \min_{s\in[0,L]}\left(\frac{A^{geom}_{x,y}(s) - \Delta_{x,y}(s)}{\sigma_{\beta_{x,y}}(s)}\right)$$

How can we einsure that this condition is fulfilled?

Protection Devices



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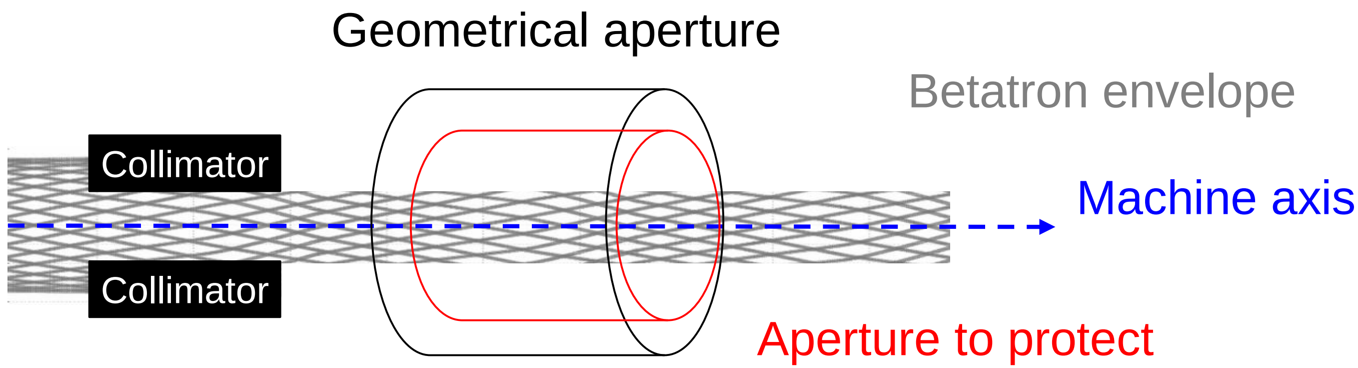

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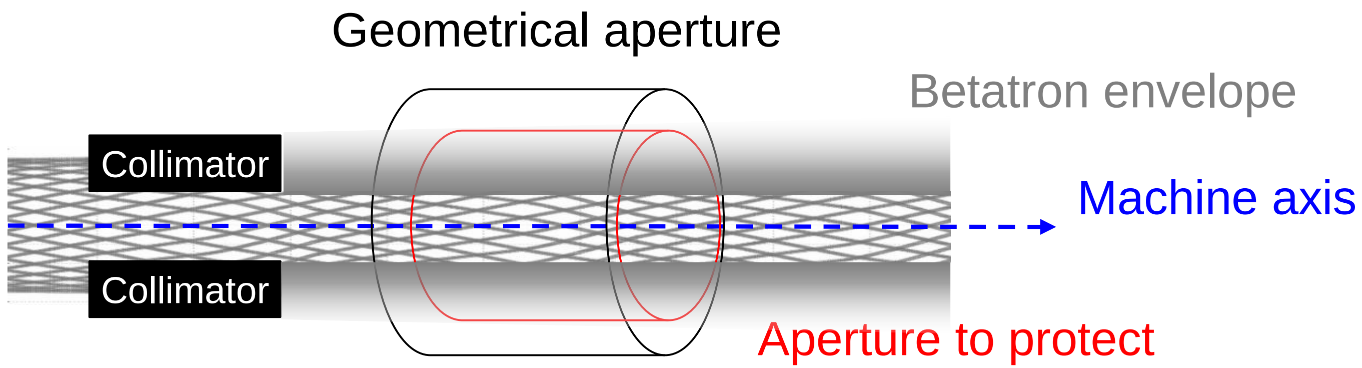
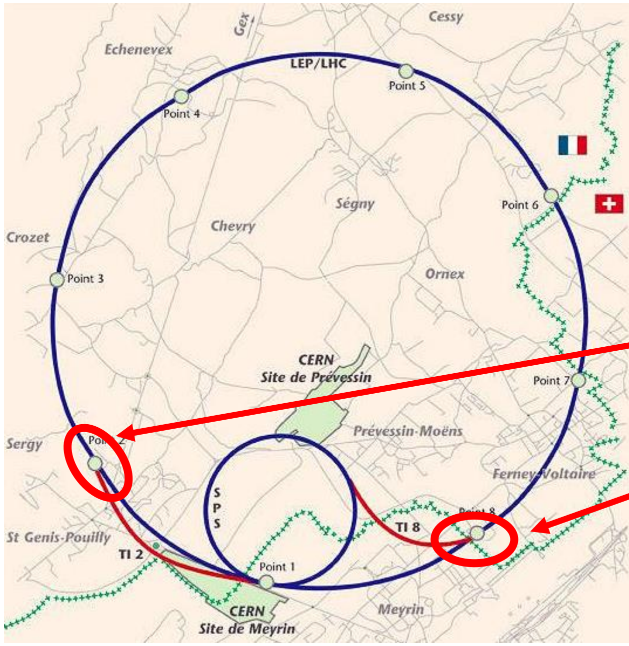
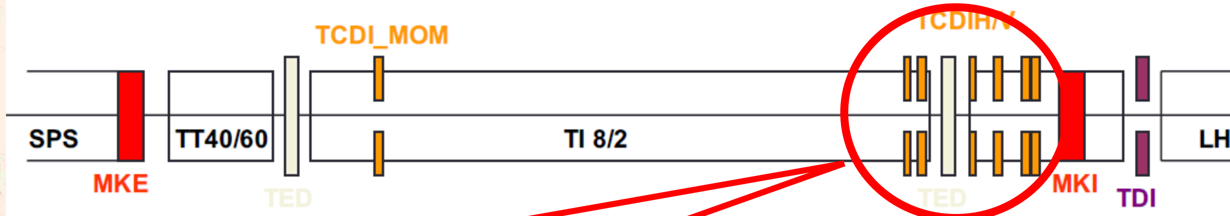


- Passive protection devices are designed to dilute and absorb beam energy safely
- They have to withstand direct beam impacts and reduce the energy deposition on the downstream elements due to secondary showers to below the damage limit
- Failures associated with beam transfer equipment are typically very fast and difficult to catch by active systems (e.g. interlocks, magnet current monitors etc.)

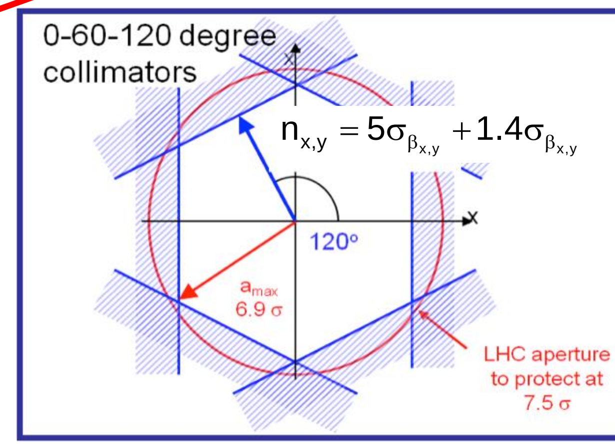
LHC transfer line collimators



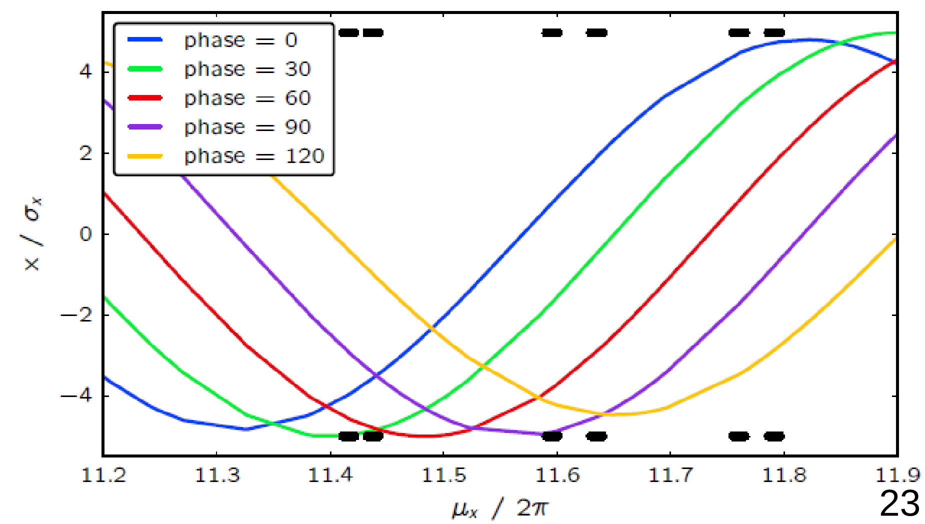


$$a_{max} = \frac{n_{x,y}}{\cos\left(\frac{\Delta\mu_{x,y}}{2}\right)}$$

$$n_{x,y} = n_{coll} + n_{error}$$

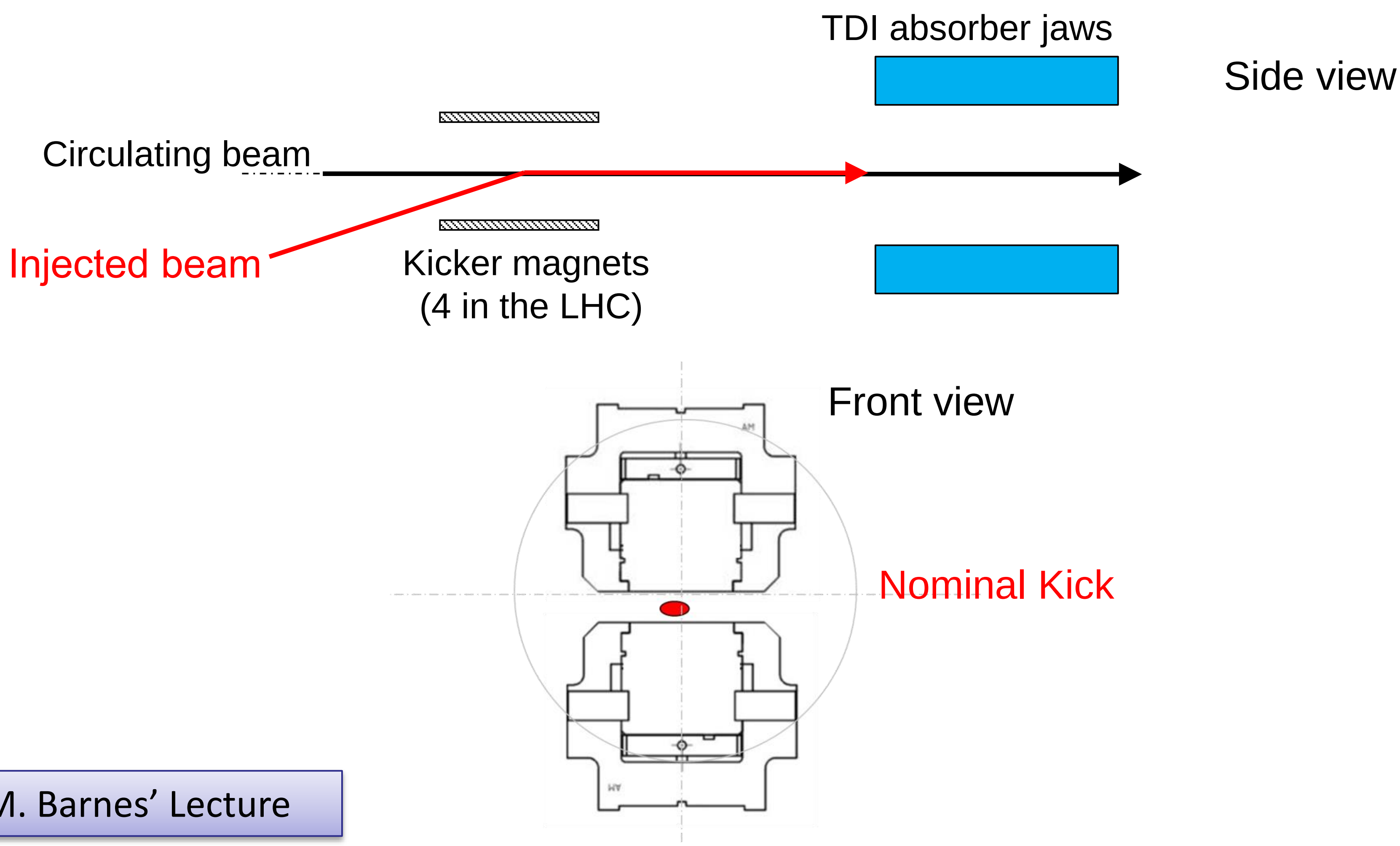


A system of 3 collimators (2 jaws each) per plane at 60° phase advance from each other is installed at the end of the SPS-to-LHC TLs [3]➔ optimized ratio: provided protection/number of collimators. Intercept large amplitude oscillations and attenuate escaping intensity below damage limit of LHC aperture ➔ collimator geometry (material and active length)



LHC injection protection

- LHC has a dedicated injection dump (TDI [3]) to protect against fast failures of the injection kicker



M. Barnes' Lecture

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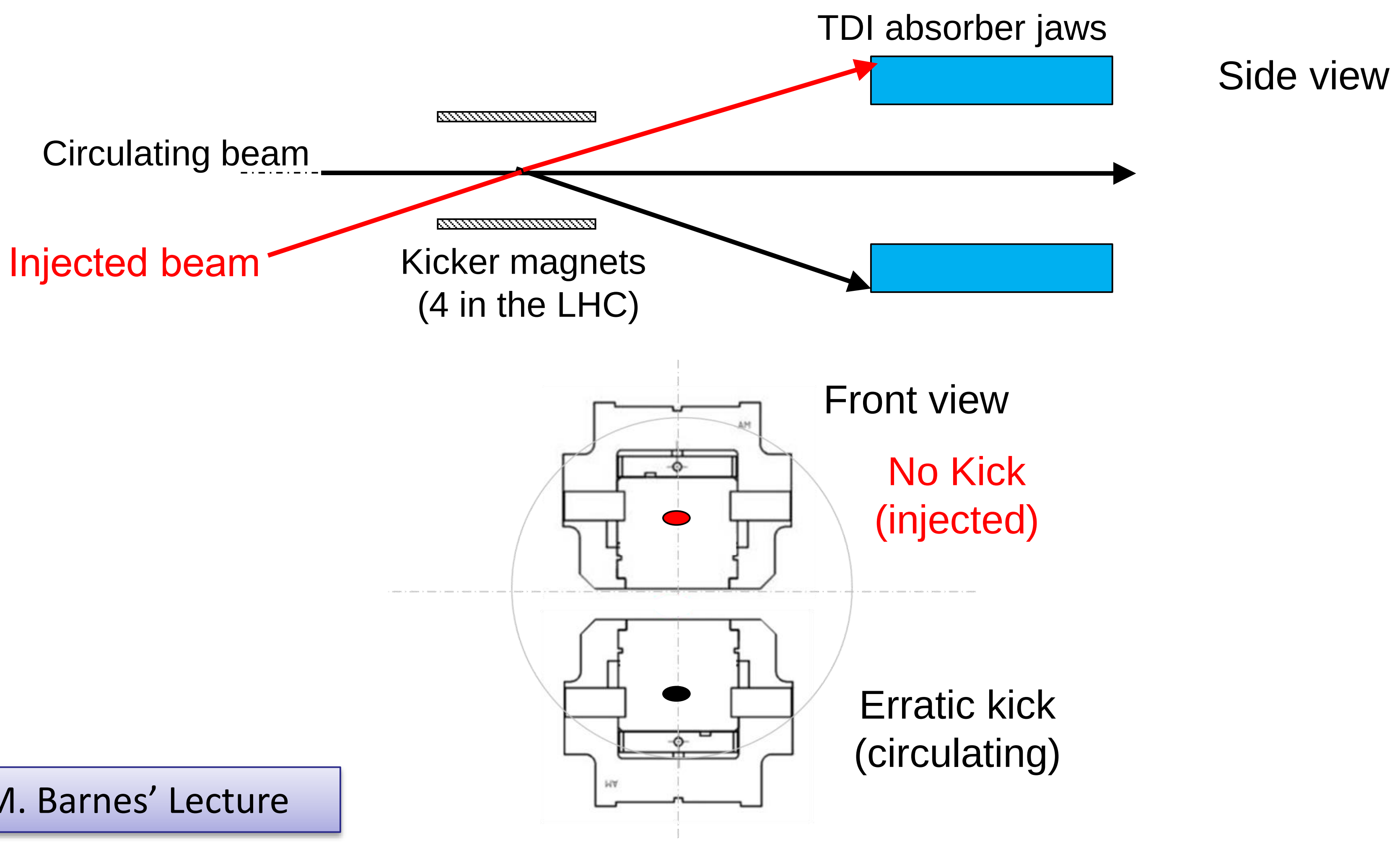

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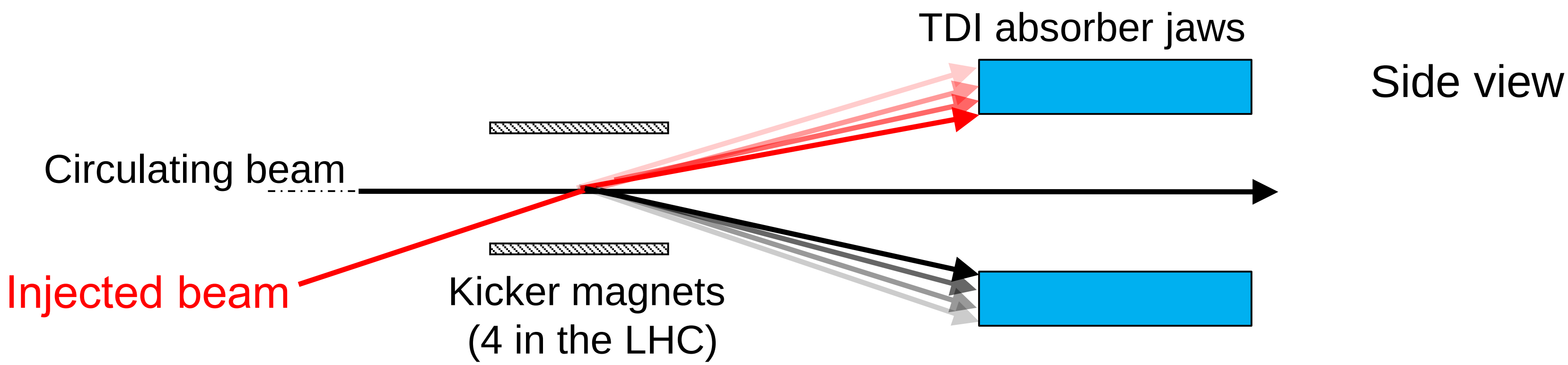

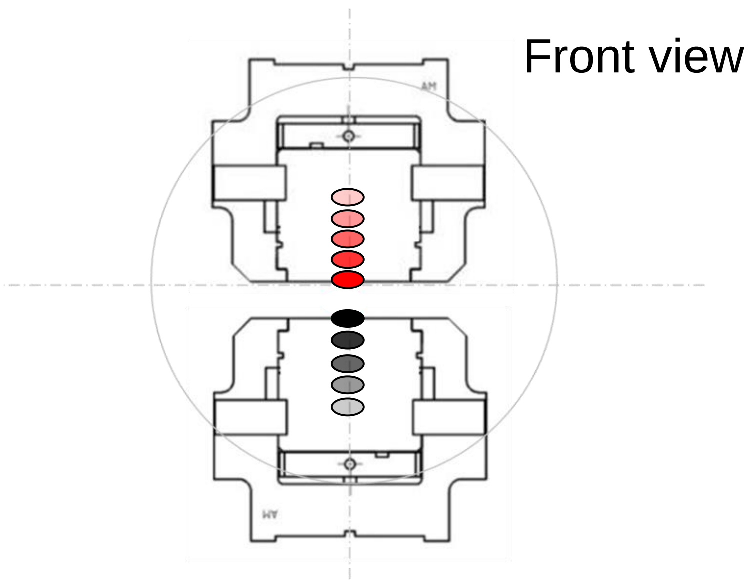

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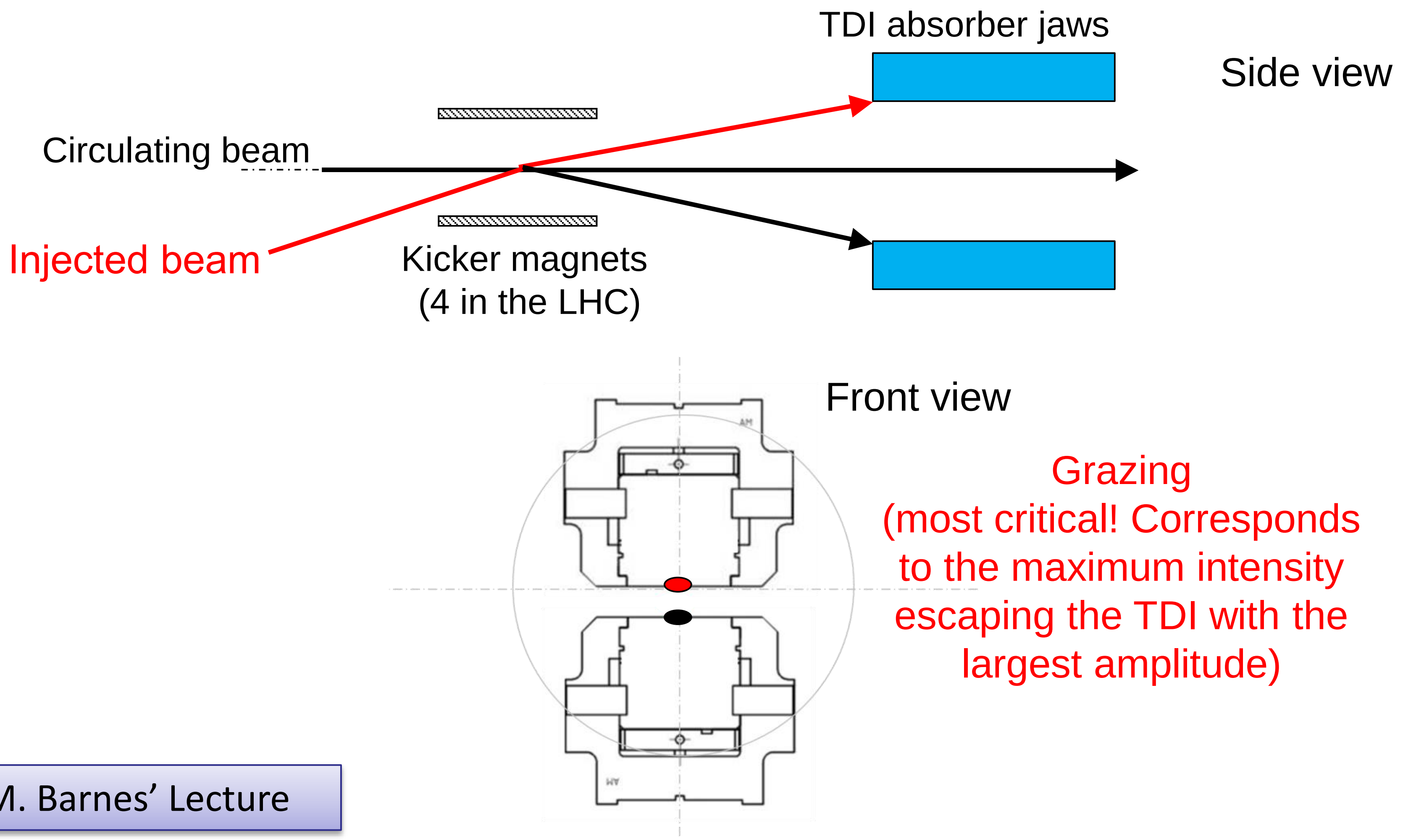

M. Barnes' Lecture

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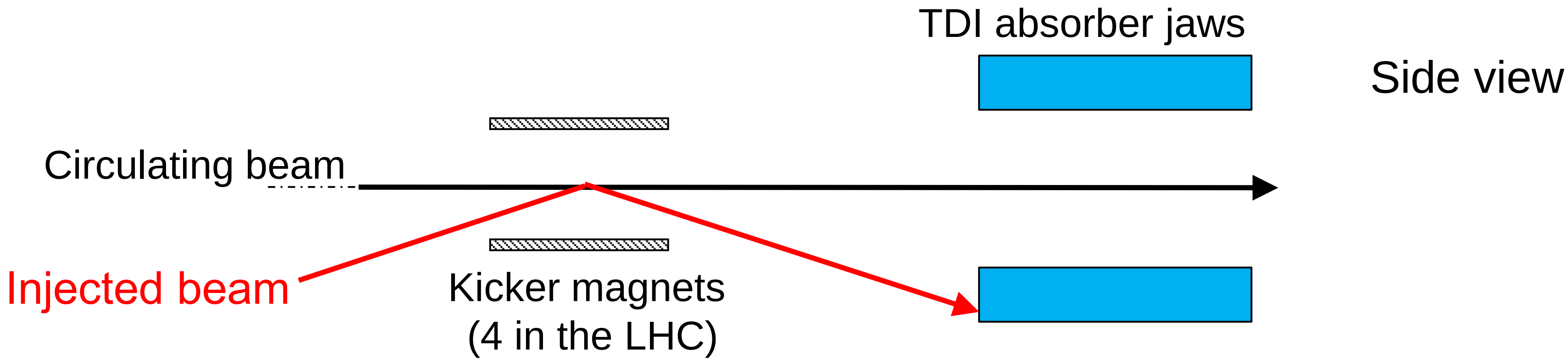
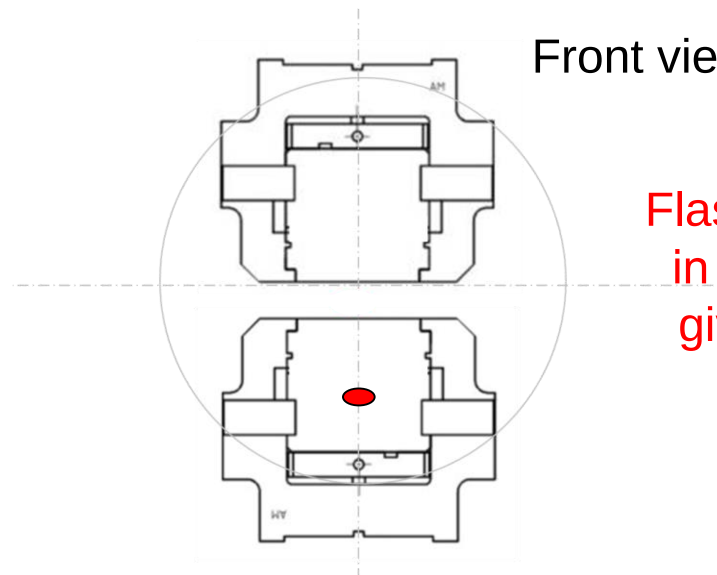


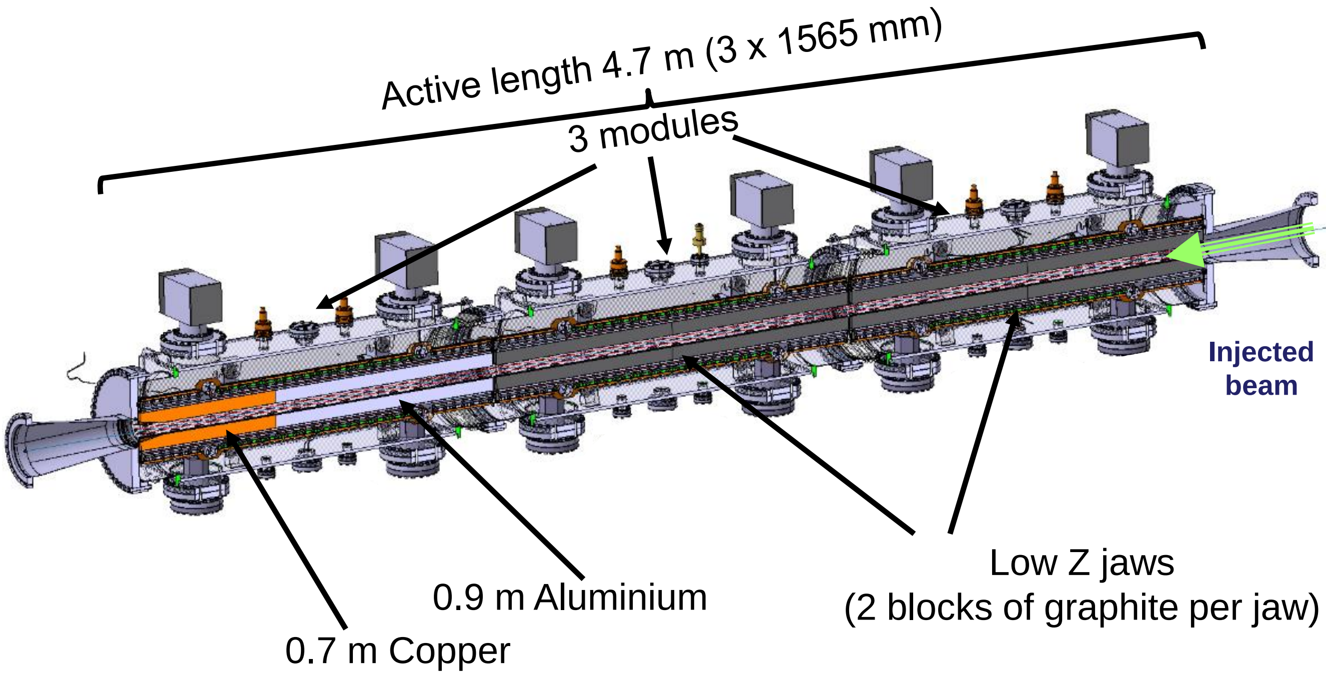


Flash-over (short-circuit) in kicker: "worst-case" gives twice deflection

M. Barnes' Lecture

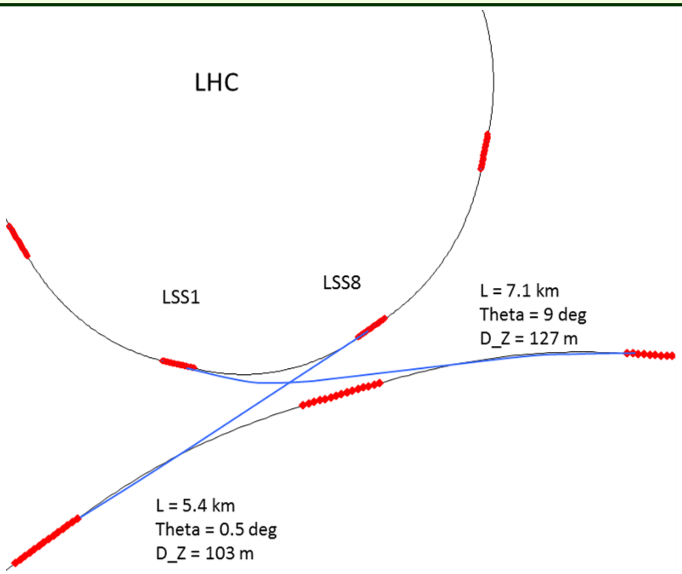
Injection protection collimators for HL-LHC

TDIS: 4.75 m active length, 2 low Z material modules + 1 high Z material module to absorb secondary showers



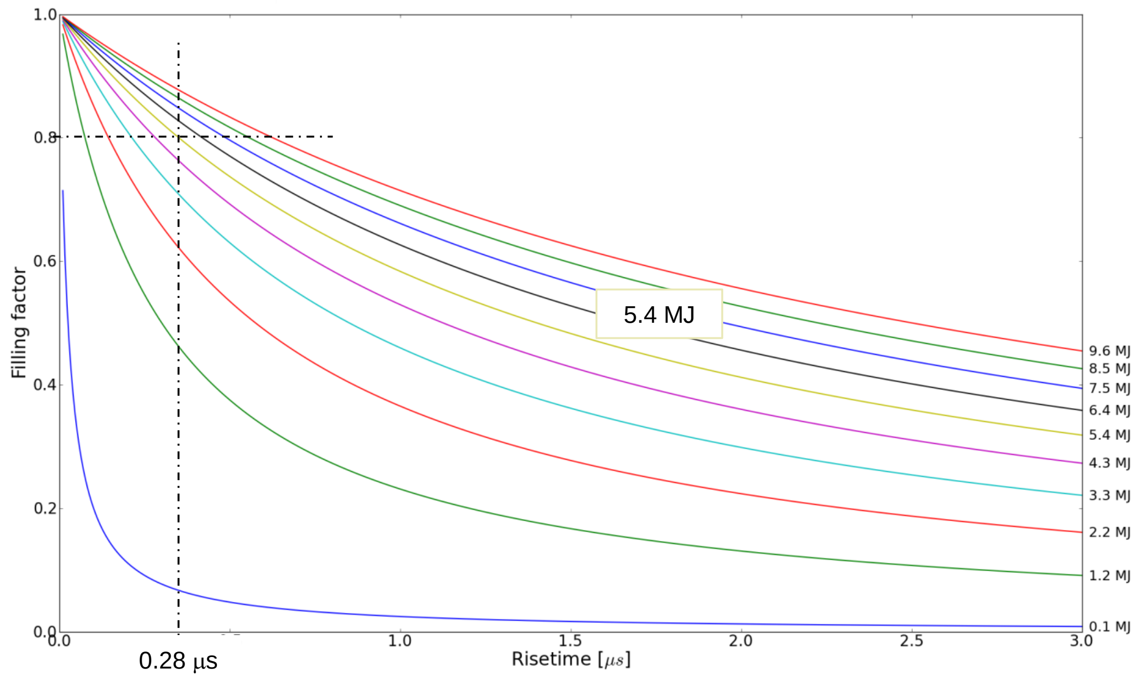
5 MJ stored energy per injection ➔ already at **the limit of what materials can deal (robustness and transmission)**.

Injection into FCC



Assumptions:
LHC used as injector for the FCC
Injection energy = 3.3 TeV (x7 HL-LHC)
Bunch population = 1.1E11 ppb
LHC can be filled with ~2800 bunches but, in order to limit the stored energy of the injected beam into the FCC to **5 MJ** one can **extract/inject 90 bunches at the time ➔ reduce kicker flattop! [6]**

t_{rise} injection kicker defined by the target filling factor assuming a target filling factor of 80% ➔ 0.28 μs



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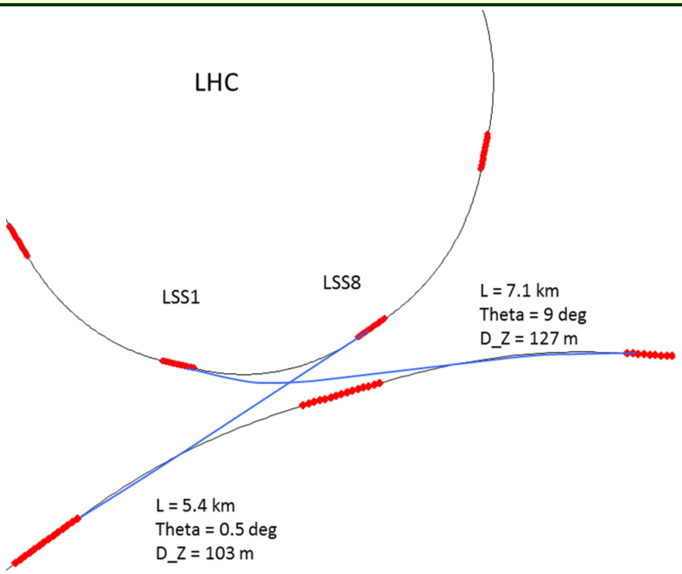

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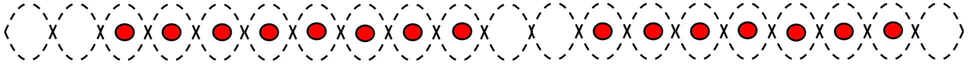
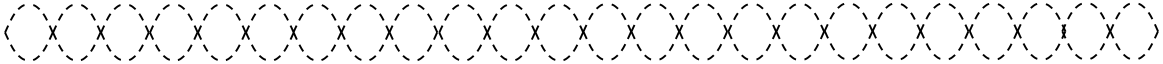
The LHC is emptied to fill FCC by pulsing the extraction/injection kickers at high frequency. Required kicker recharging time driven by synchronisation of two machines to common frequency:

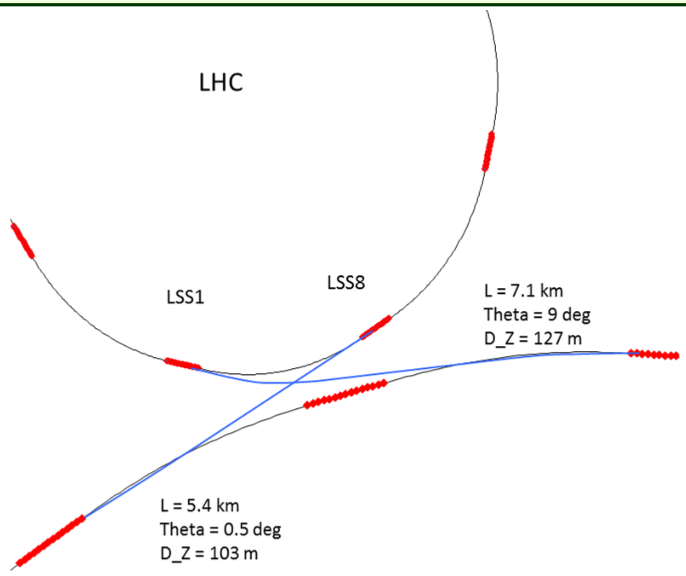


LHC



FCC

Injection into FCC



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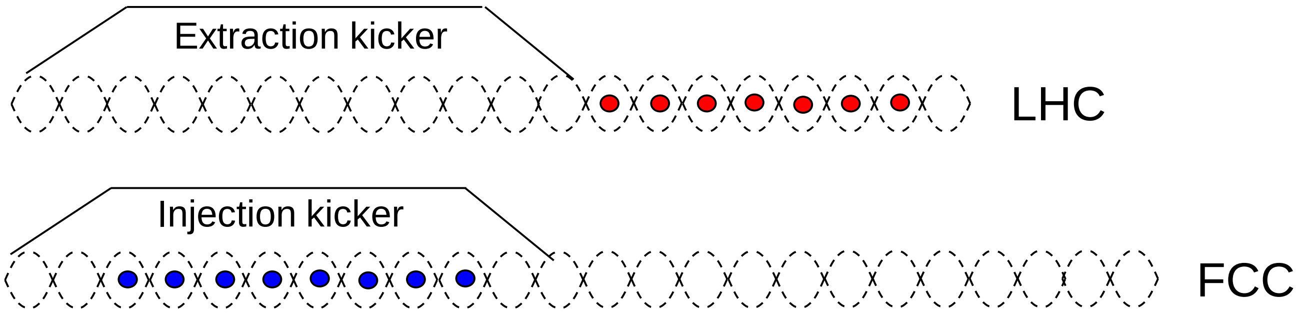
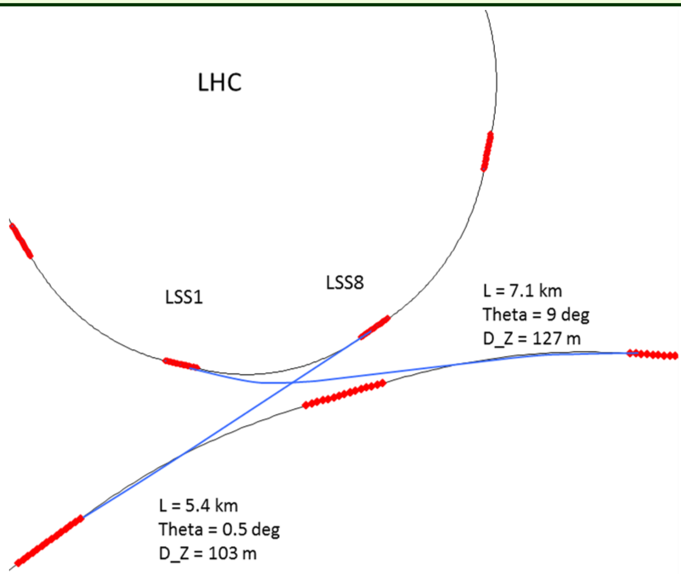


$$f_c = \frac{f_{rev}^{FCC}}{C_{LHC}}$$

Recharging at **115 Hz** (0.03 Hz for LHC injection kickers)

M. Barnes' Lecture

Injection into FCC



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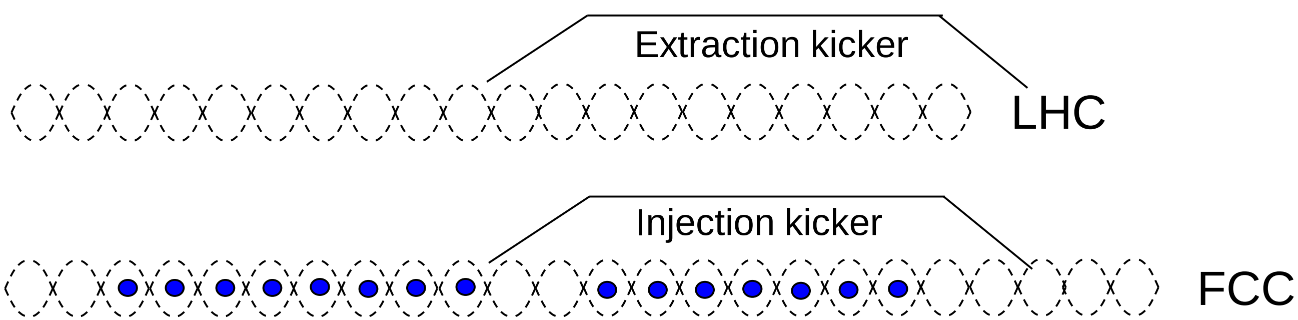

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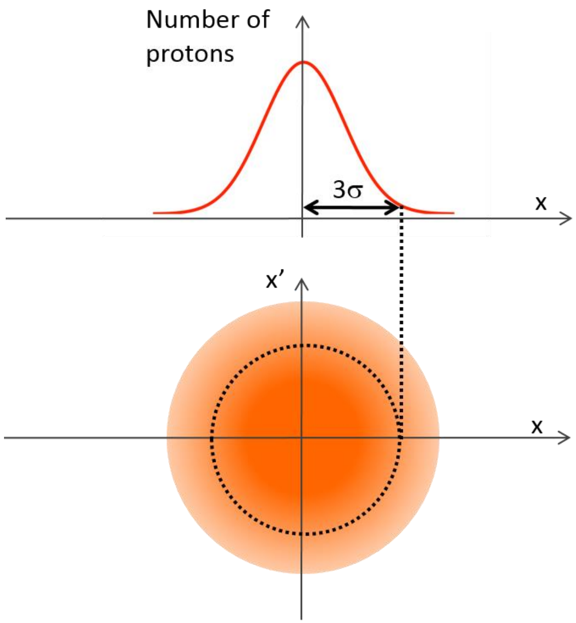
M. Barnes' Lecture

Injection Losses

Injection losses are caused by "some" beam intercepted by machine aperture restrictions (ideally protection elements). These losses have to be kept as low as possible to prevent damage and minimize activation.

Transverse losses [7]



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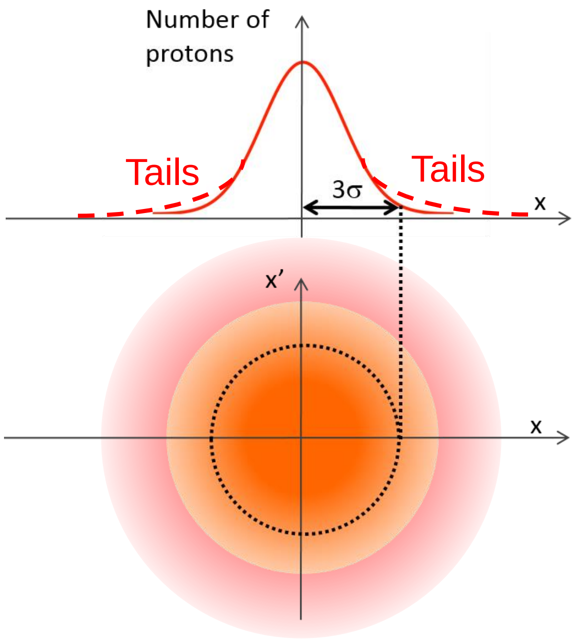

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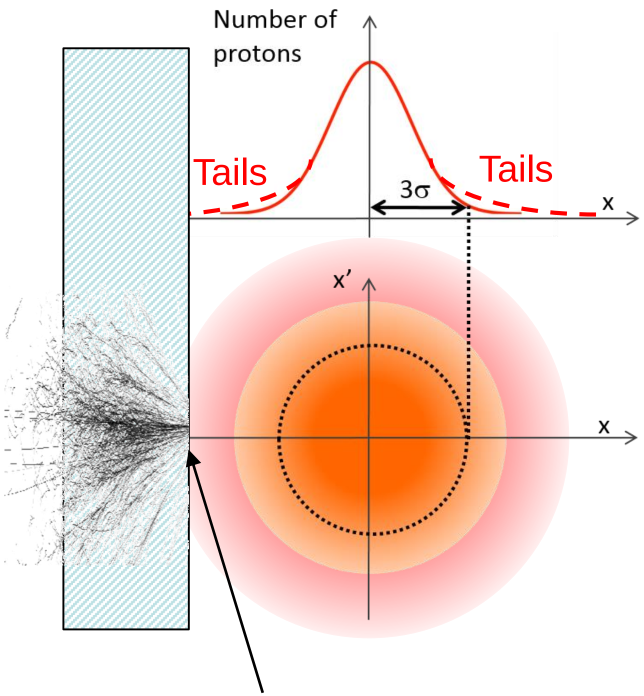

Losses ➔ secondary showers

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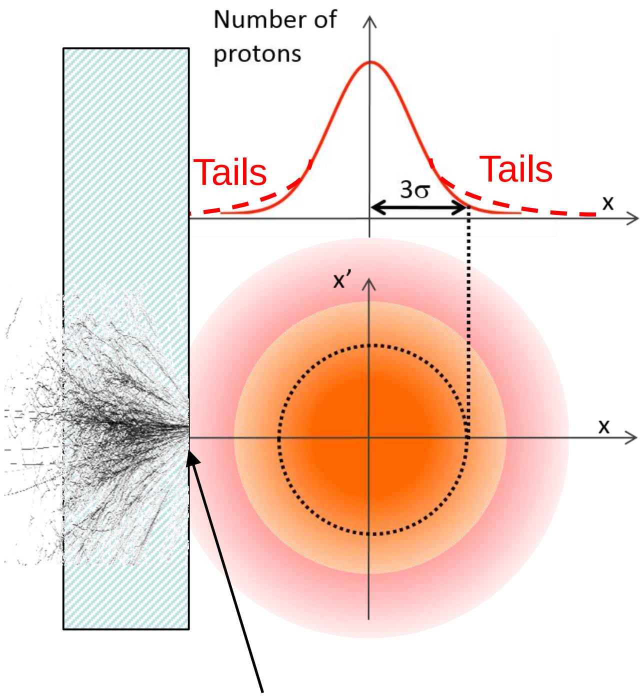
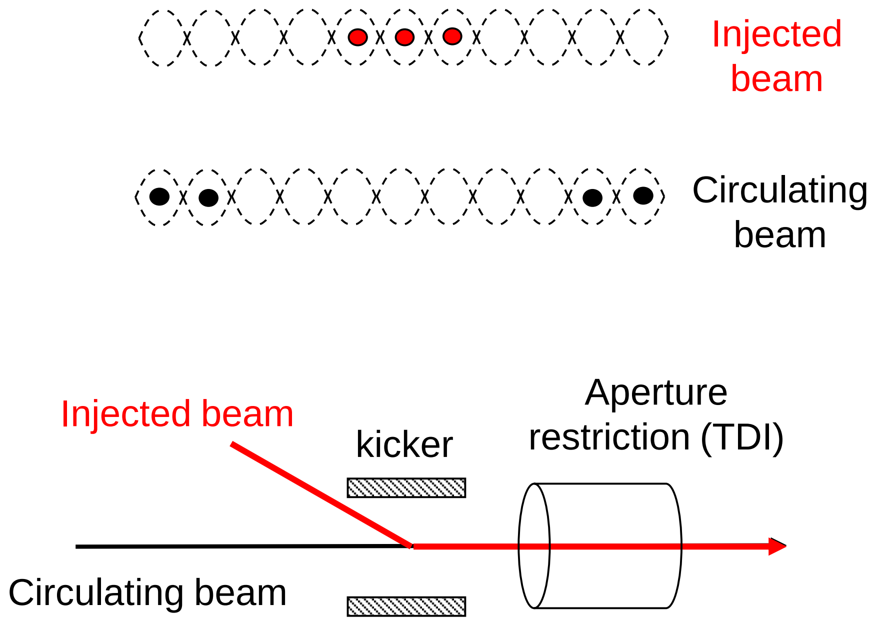


Losses ➔ secondary showers

Longitudinal losses [8]



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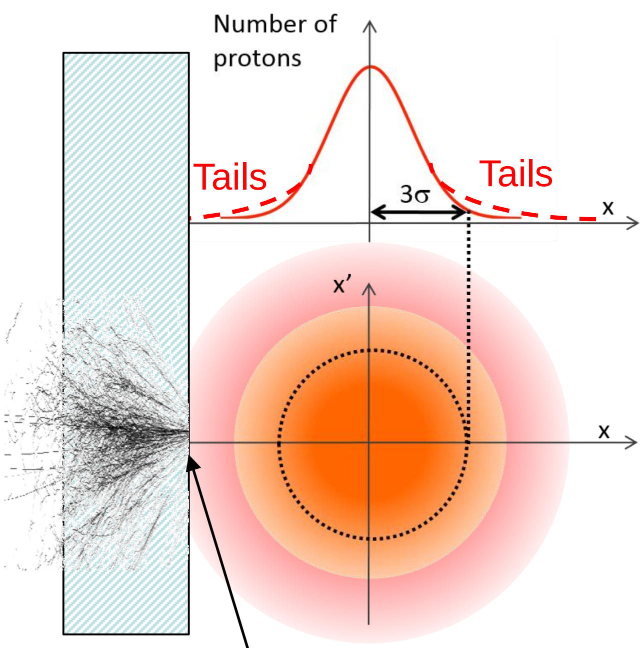

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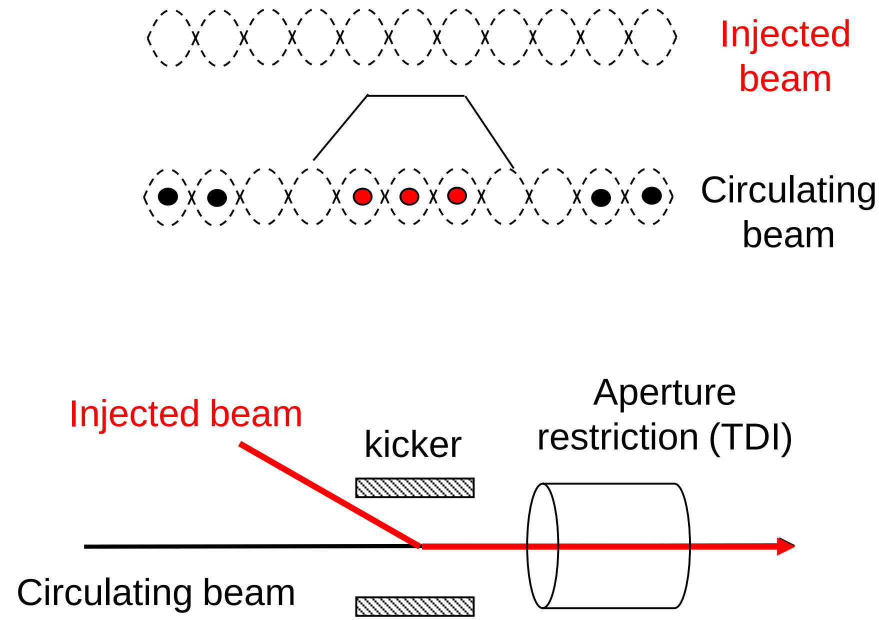

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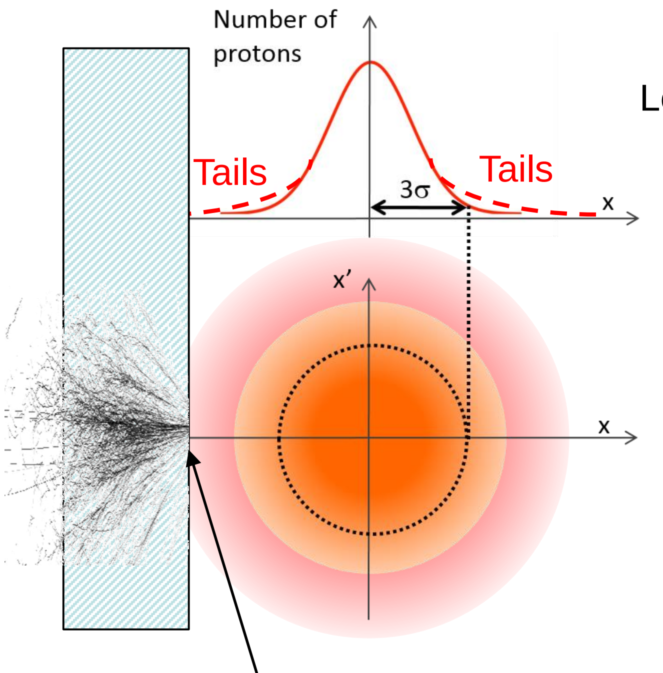
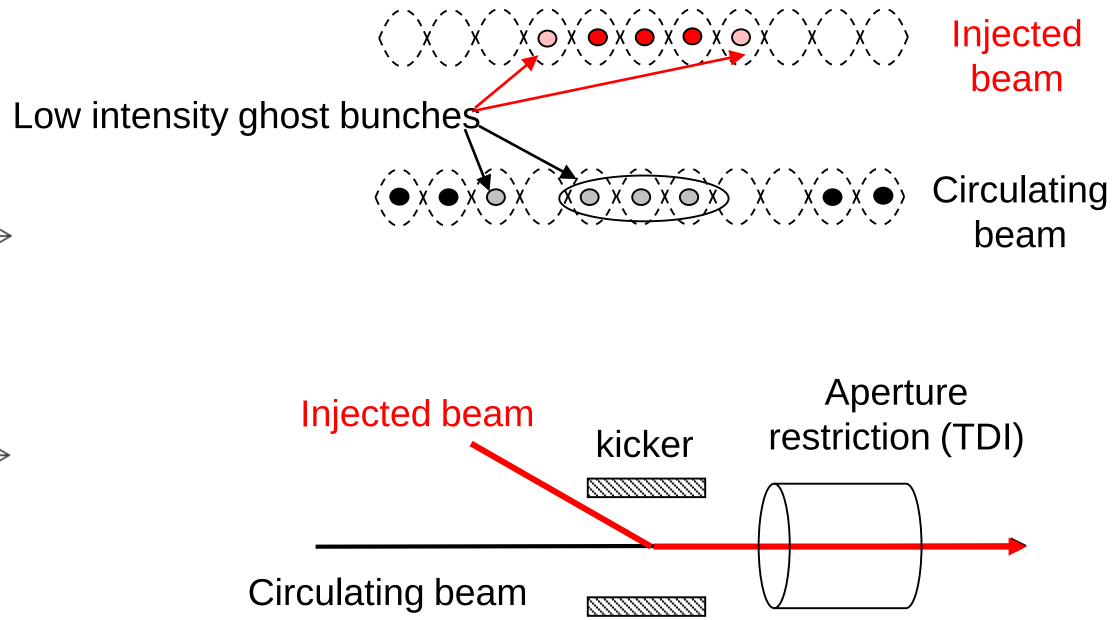


Losses → secondary showers

Longitudinal losses [8]



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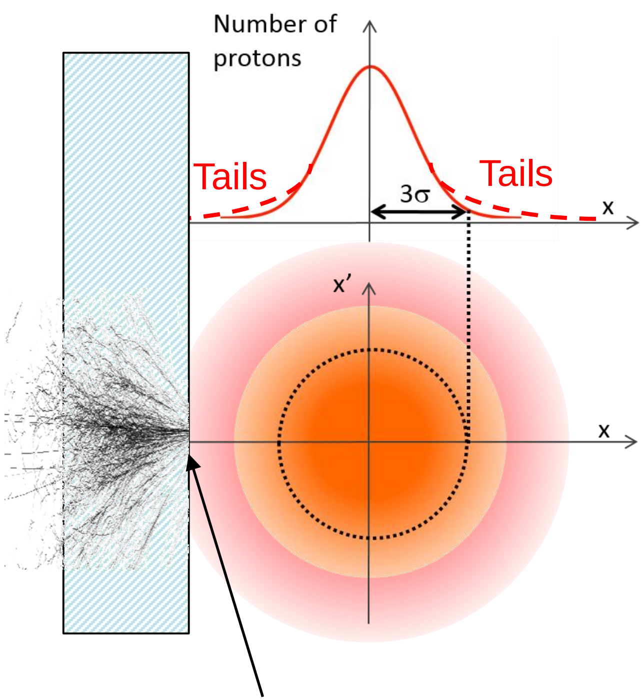

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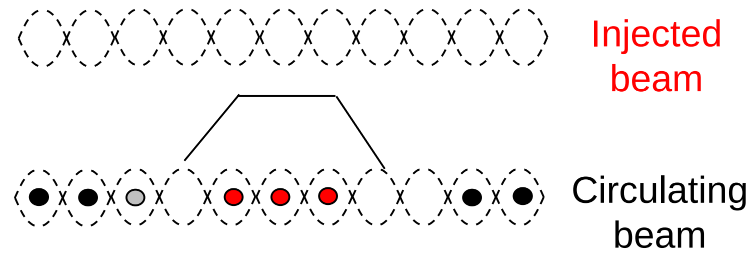

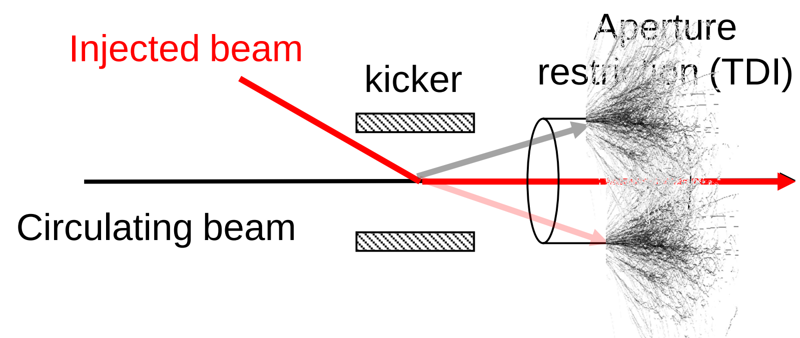

Ghost bunches are lost ➔ secondary showers

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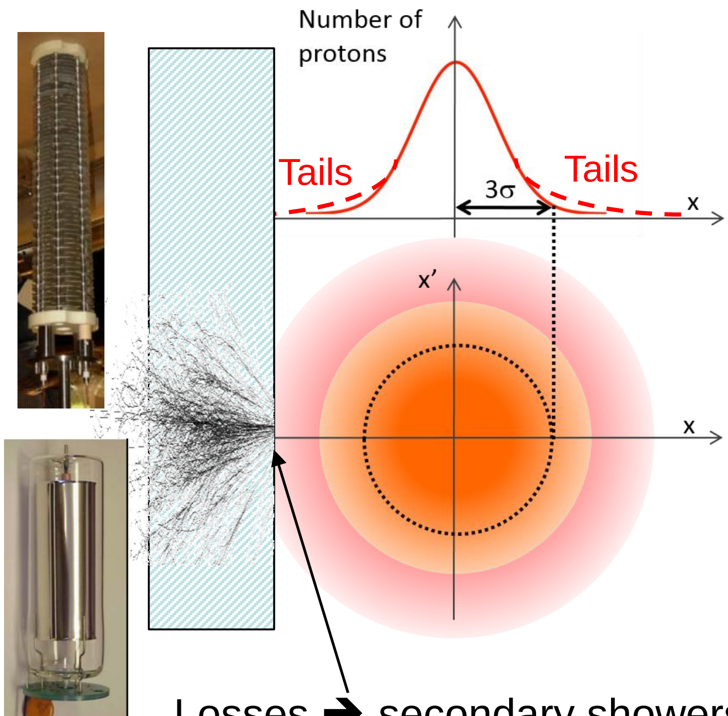
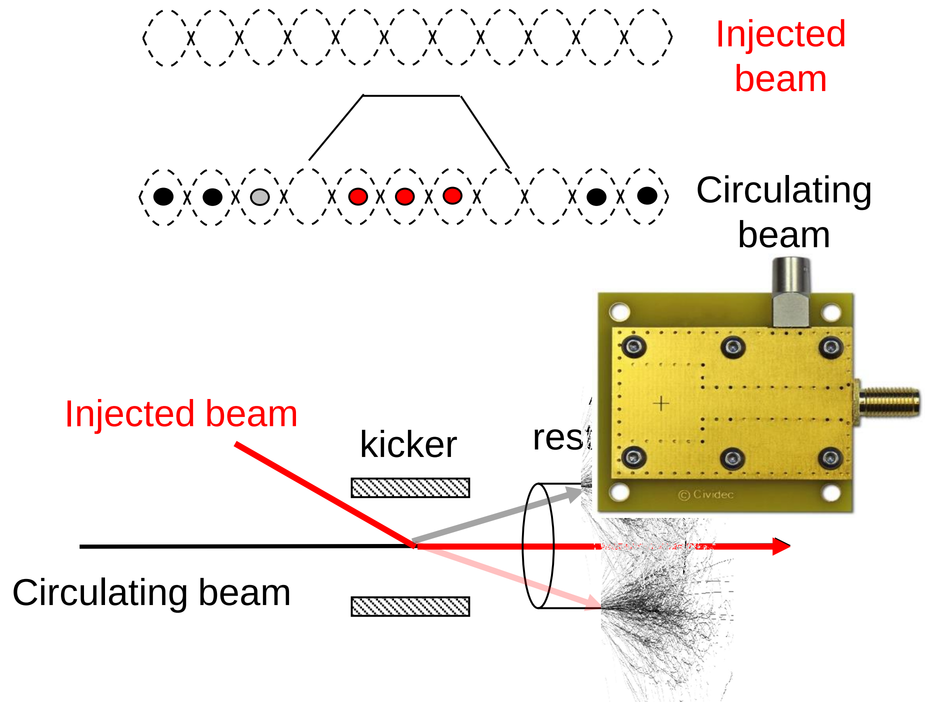


Losses → secondary showers
Conventional ionization chambers

Longitudinal losses [8]

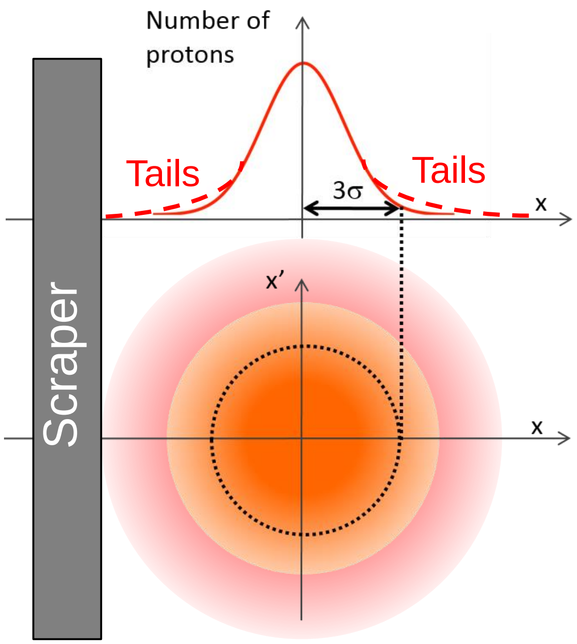


Ghost bunches are lost → secondary showers
Diamond beam loss monitors
(ns time resolutions)

Mitigations for losses

Optimize steering and RF settings!

Transverse beam scraping in pre-injector to remove tails before transfer and injection in next machine [9]



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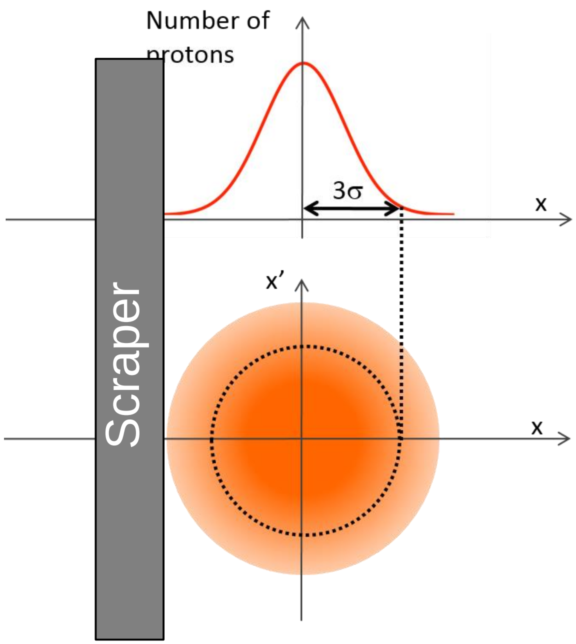

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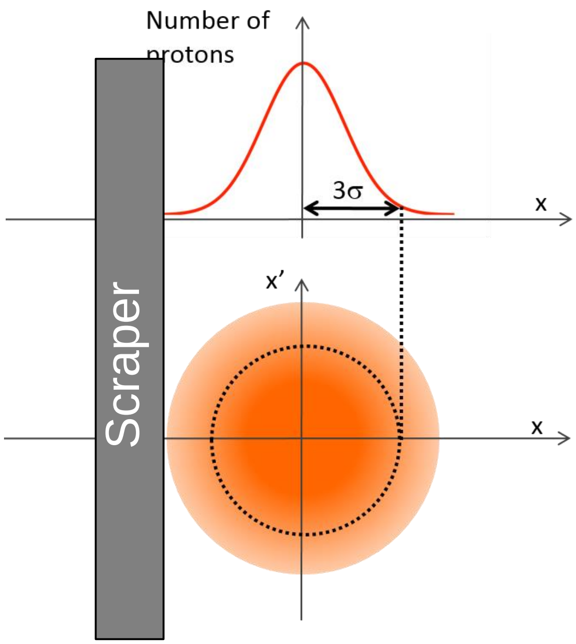
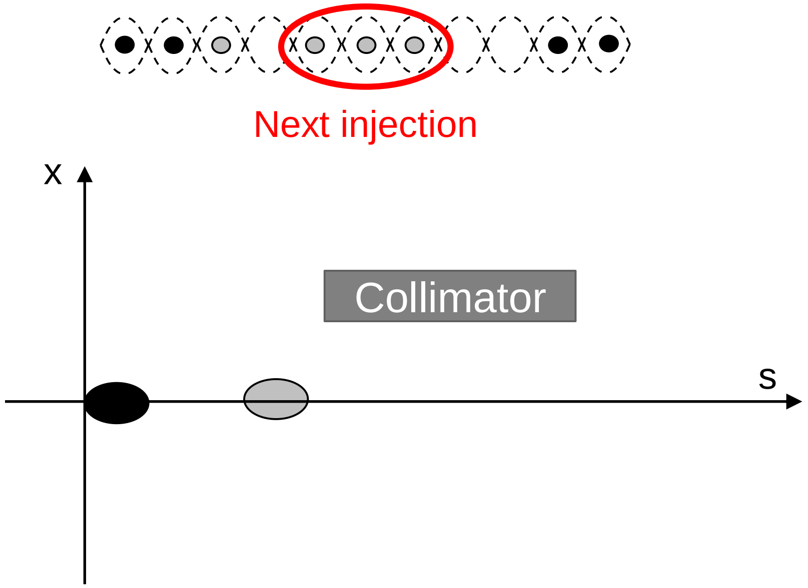


Injection cleaning: excite betatron oscillations (with transverse damper) of ghost bunches occupying the buckets where the beam has to be injected ➔ ghosts lost in cleaning insertions



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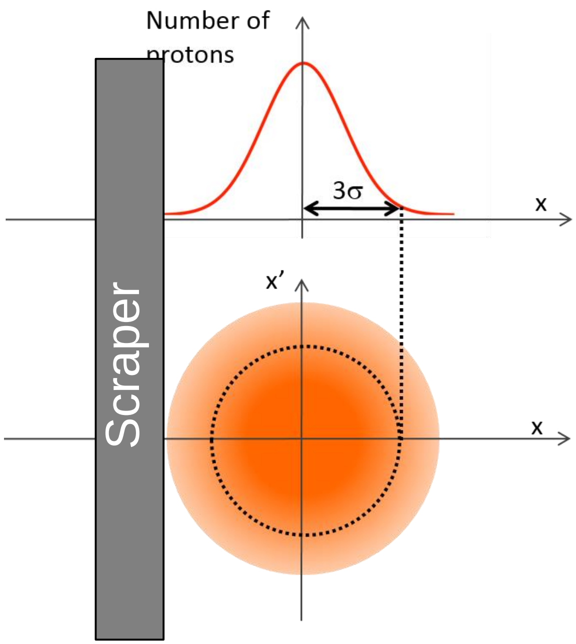

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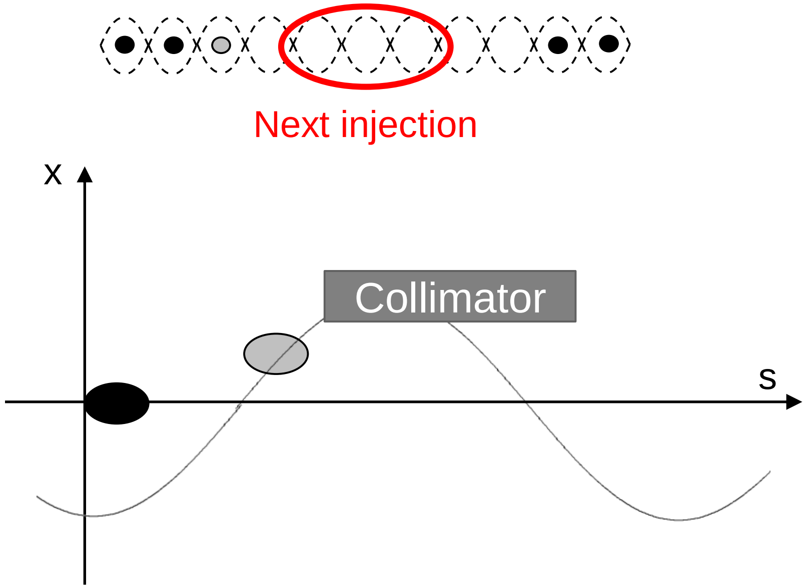
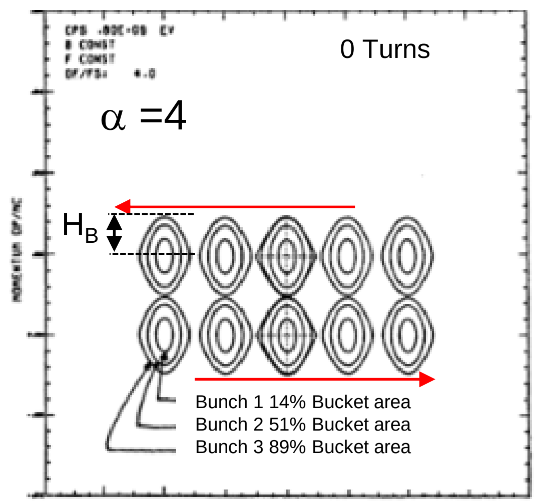
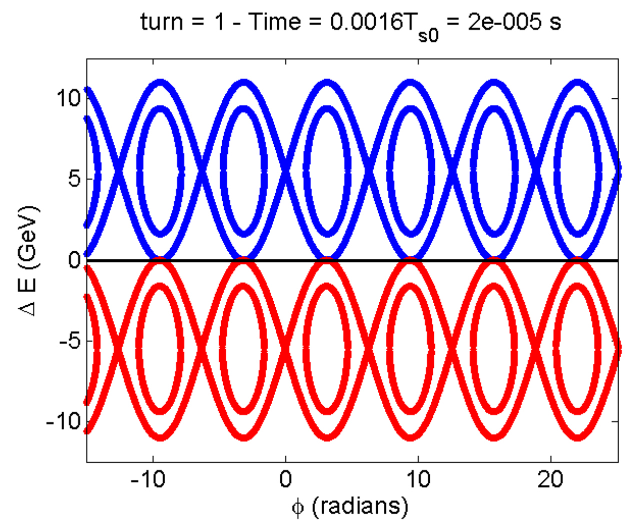


Slip stacking

- It is a configuration used to store (and accelerate) particle beams with different momenta in the same accelerator. Demonstrated for the first time at the CERN SPS to increase the production of anti-protons for p-pbar physics [10]
- The two beams (b_1 and b_2) are longitudinally focused by two RF cavities with a small frequency difference ($\Delta f = f_2 - f_1$)
- Each beam is synchronized to one RF cavity ($b_1 \rightarrow f_1$ and $b_2 \rightarrow f_2$) and perturbed by the other (f_1 ⚡ b_2 and f_2 ⚡ b_1)
  - Slip-stacking parameter $\alpha = \Delta f/f_s = 2\,\Delta E/H_B$ large perturbation when $\alpha \rightarrow 1$

Stationary buckets:
α >4 to keep buckets independent, still emittance growth [11]





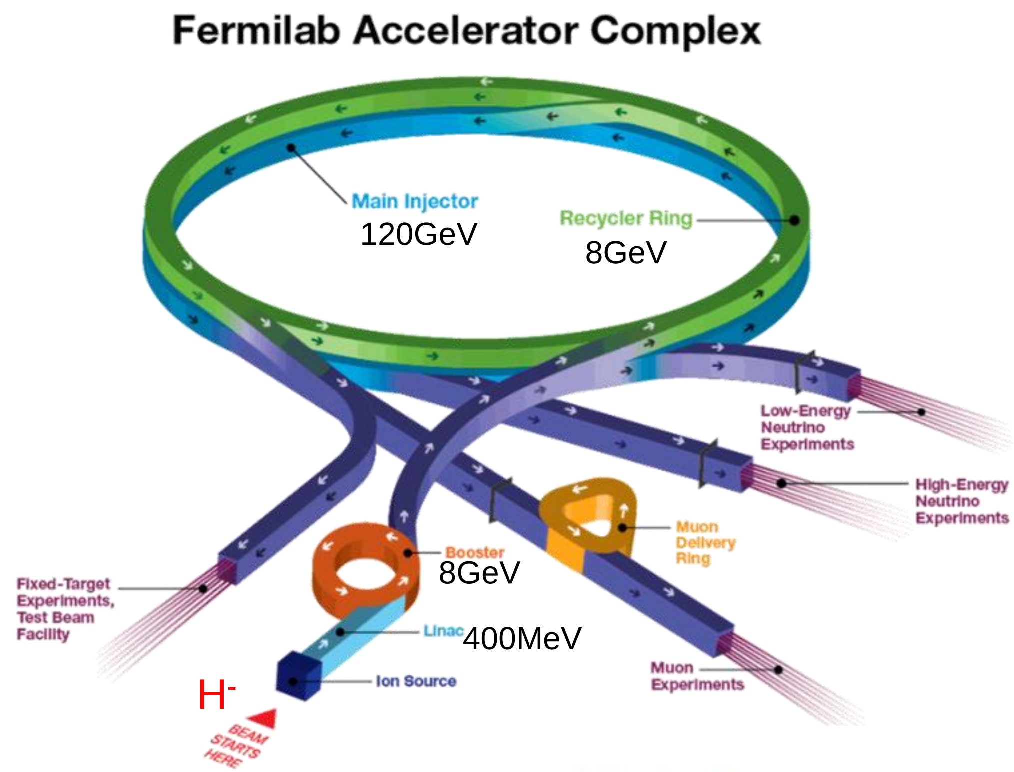
T. Argyropoulos

- The bunches rotate at different frequencies and will periodically coincide azimuthally producing high local line density. These bunches can be directly "used" or being combined in a large bucket with frequency $(f_2+f_1)/2$

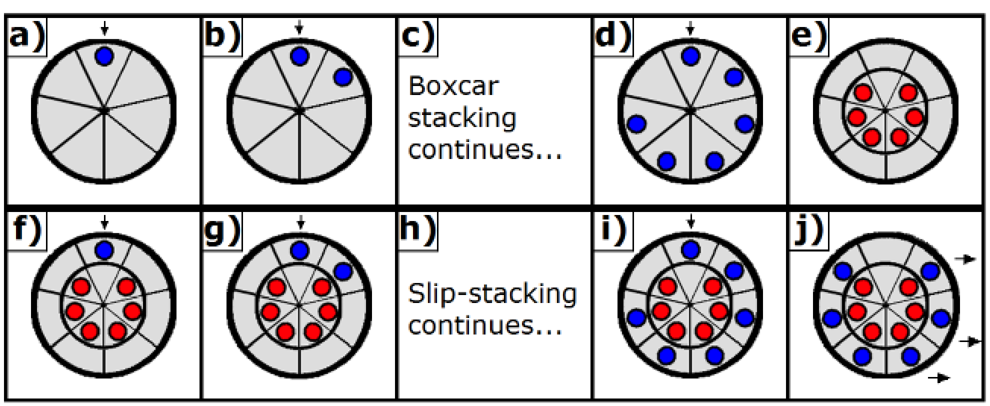
Slip-Stacking at Fermilab

Fermilab used slip-stacking initially for $\bar{p}$ production in the main injector, then in the Recycler to double the power of the proton beam. Aim: **increase the power** for target physics in particular **neutrino physics** (from 700 kW up to 1.2 MW and beyond)

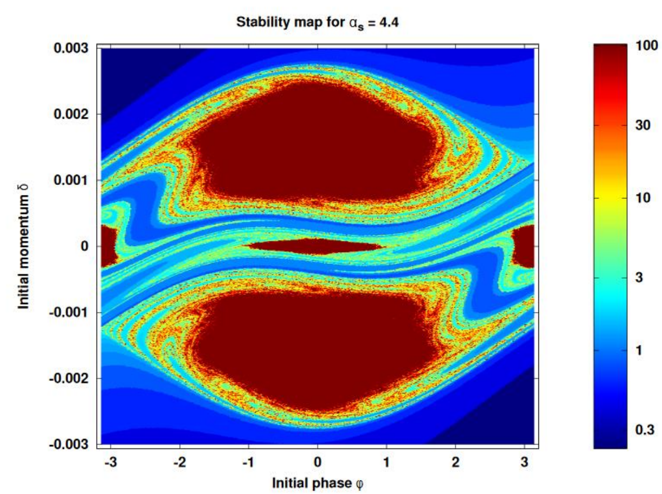
12 batches are accumulated in the recycler by overlapping azimuthally two beam with different momenta



[12]



e) F
f) 7
g) I
afte
inje
j) T
bea
freq



ıp
ext

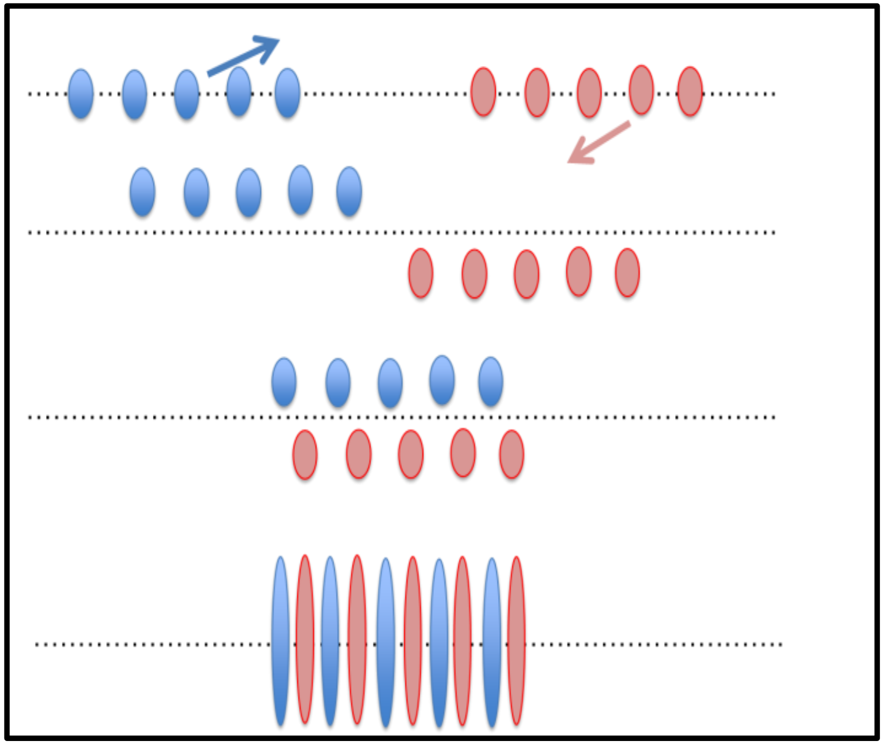
*Booster harmonic number and cycle rate

Slip-stacking at CERN

Momentum slip-stacking will be used in the SPS to increase the number of bunches for HL-LHC ion physics

T. Argyropoulos

- Two super-batches (24 bunches separated by 100 ns) injected into the SPS from the PS
- The two super-batches are captured by two pairs of 200 MHz cavities (independent control)
- RF frequency variation to accelerate the first batch and decelerate the second
- Let the batches slip
- Bring them back by decelerating the first and accelerating the second
- Once the bunches are interleaved they are recaptured at average RF frequency



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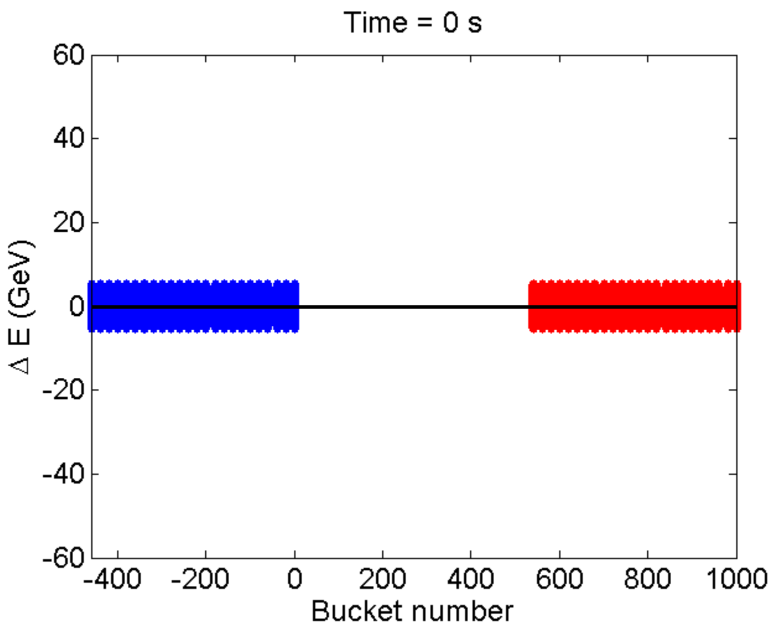

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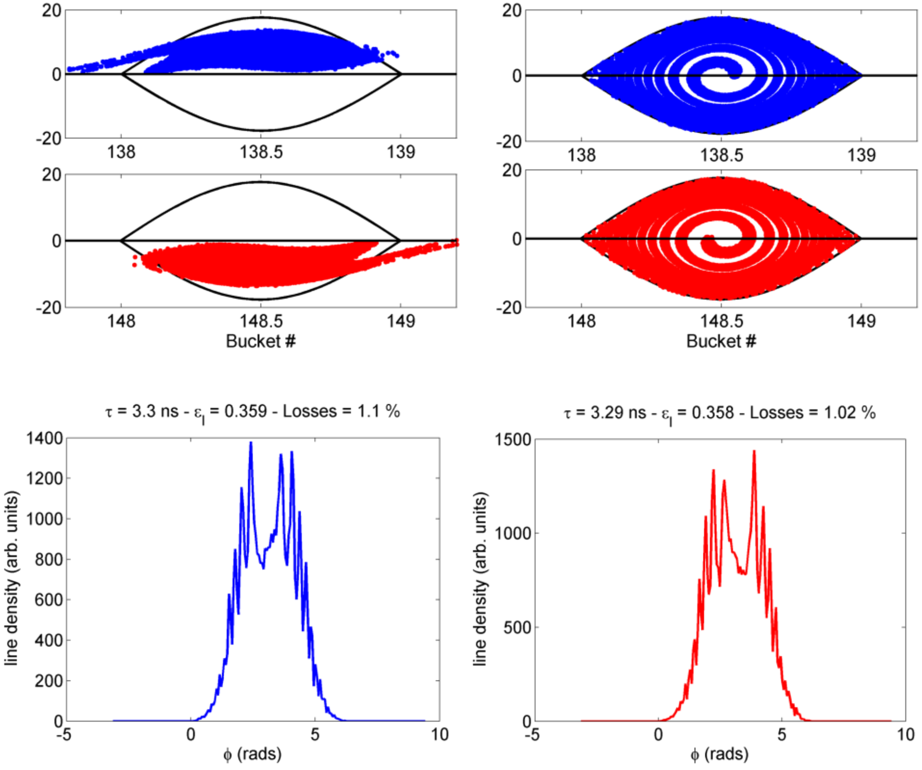
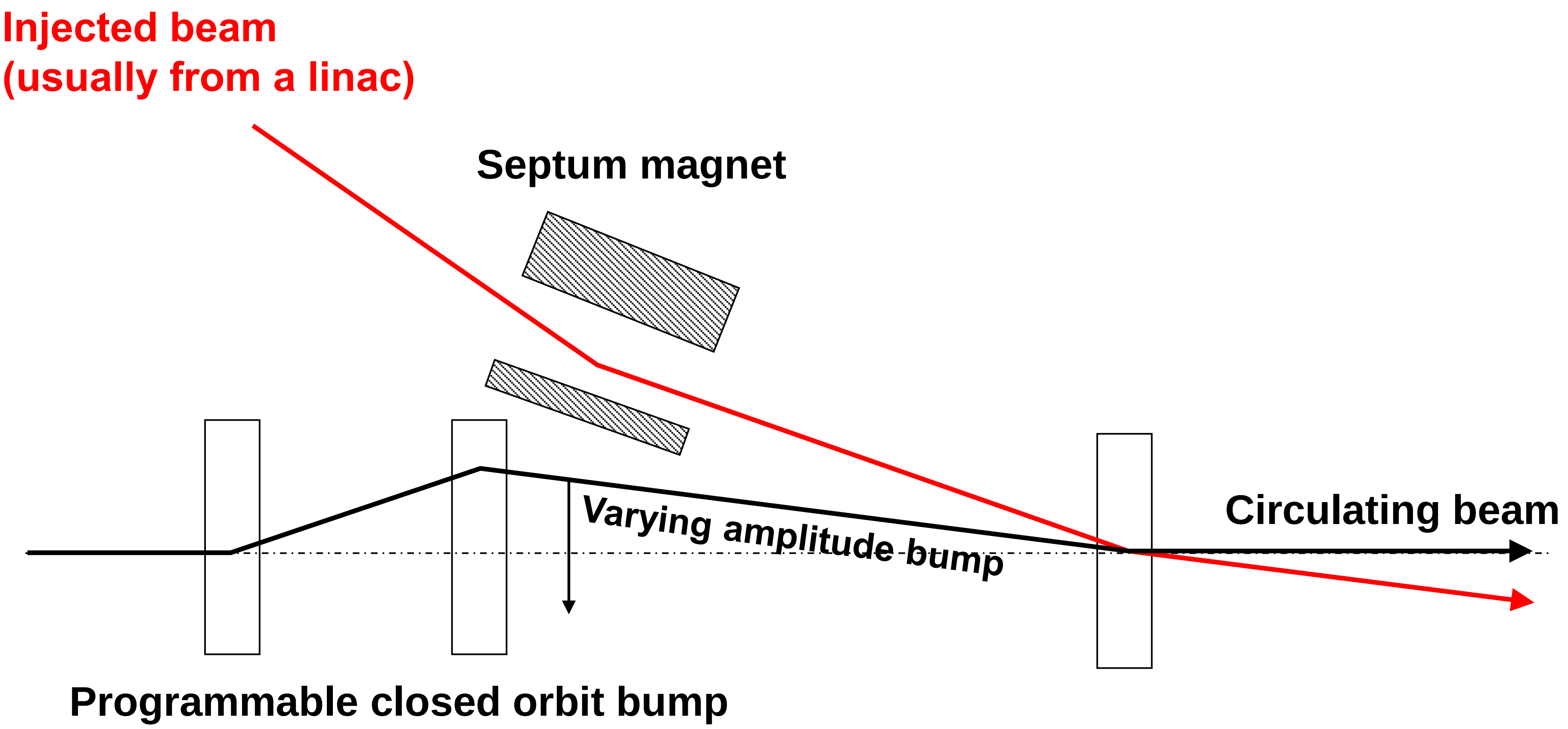


X3 emittance blowup after recapture

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.
  - If the acceptance of the receiving machine is larger than the delivered beam emittance we can accumulate intensity
- Proton and heavy-ion distributions are function of the details of the multi-turn process and of the space charge level achieved.

Multi-turn injection for hadrons

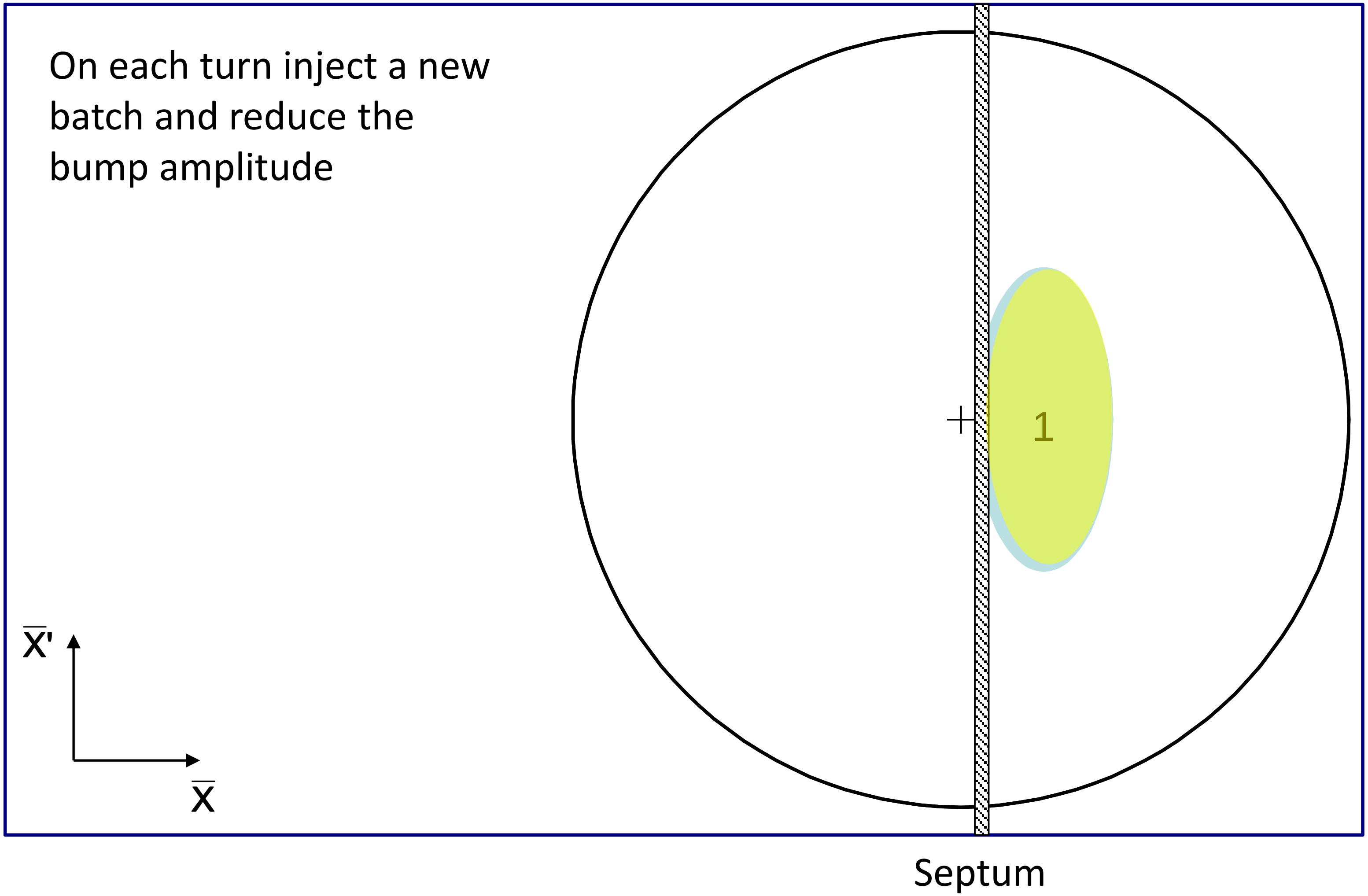


- No kicker but fast programmable bumpers
- Bump amplitude decreases and a new batch injected turn-by-turn
- Phase-space "painting"

Multi-turn injection for hadrons

Example: CERN PSB injection, high intensity beams, fractional tune $Q_h \approx 0.25$
Beam rotates π/2 per turn in phase space

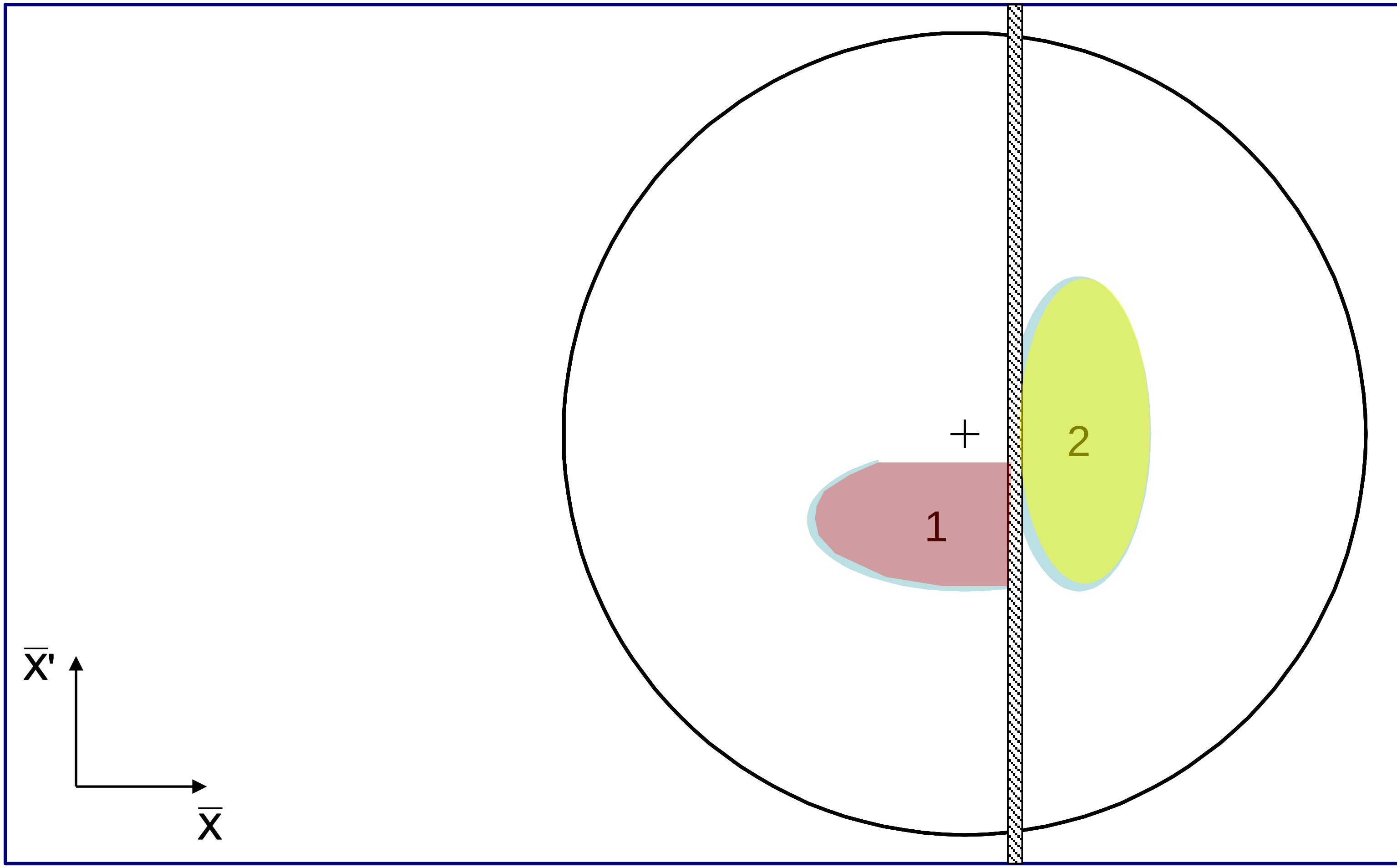
Turn 1



Multi-turn injection for hadrons

Example: CERN PSB injection, high intensity beams, fractional tune $Q_h \approx 0.25$
Beam rotates $\pi/2$ per turn in phase space

Turn 2

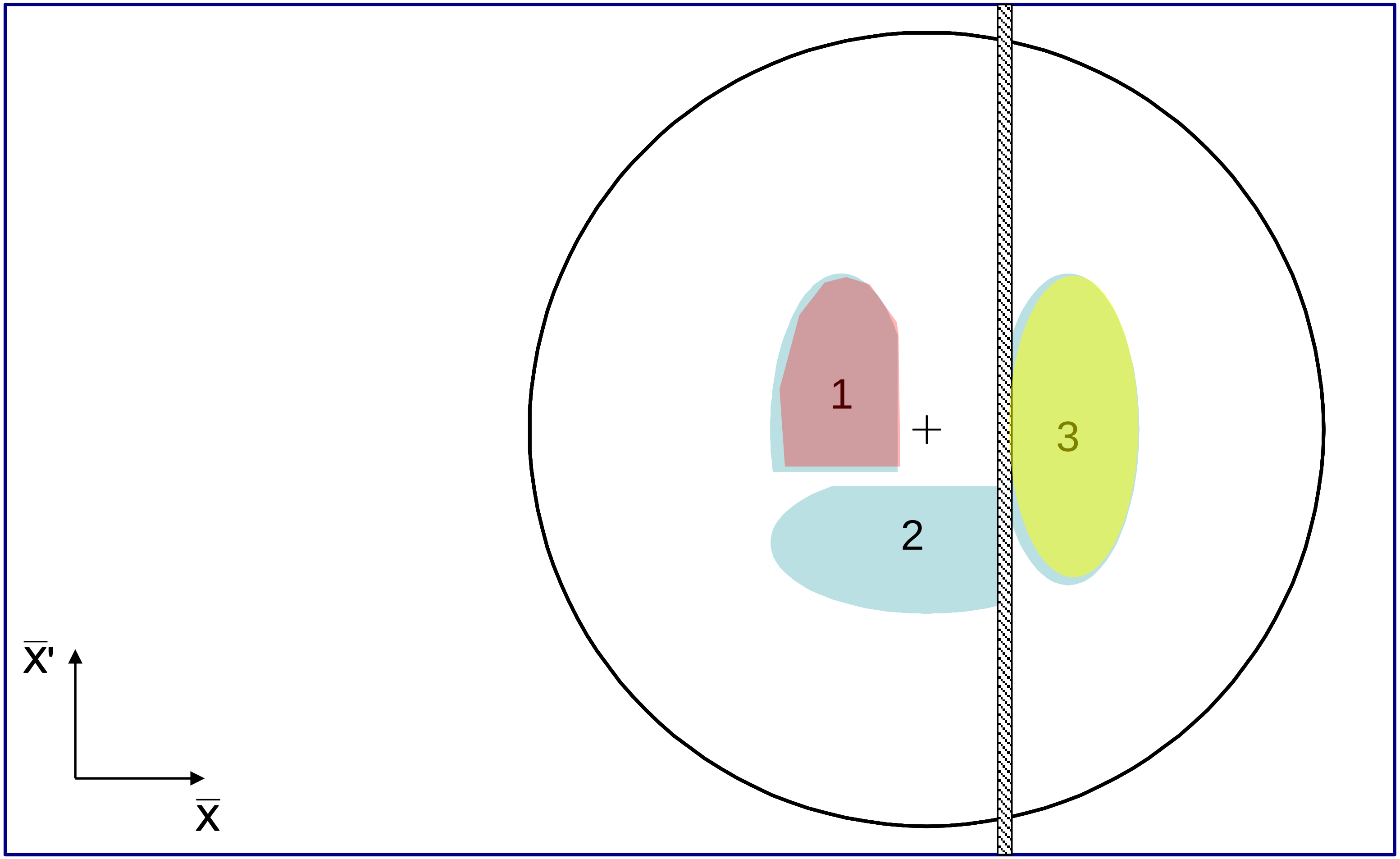


Septum

Multi-turn injection for hadrons

Example: CERN PSB injection, high intensity beams, fractional tune $Q_h \approx 0.25$
Beam rotates $\pi/2$ per turn in phase space

Turn 3

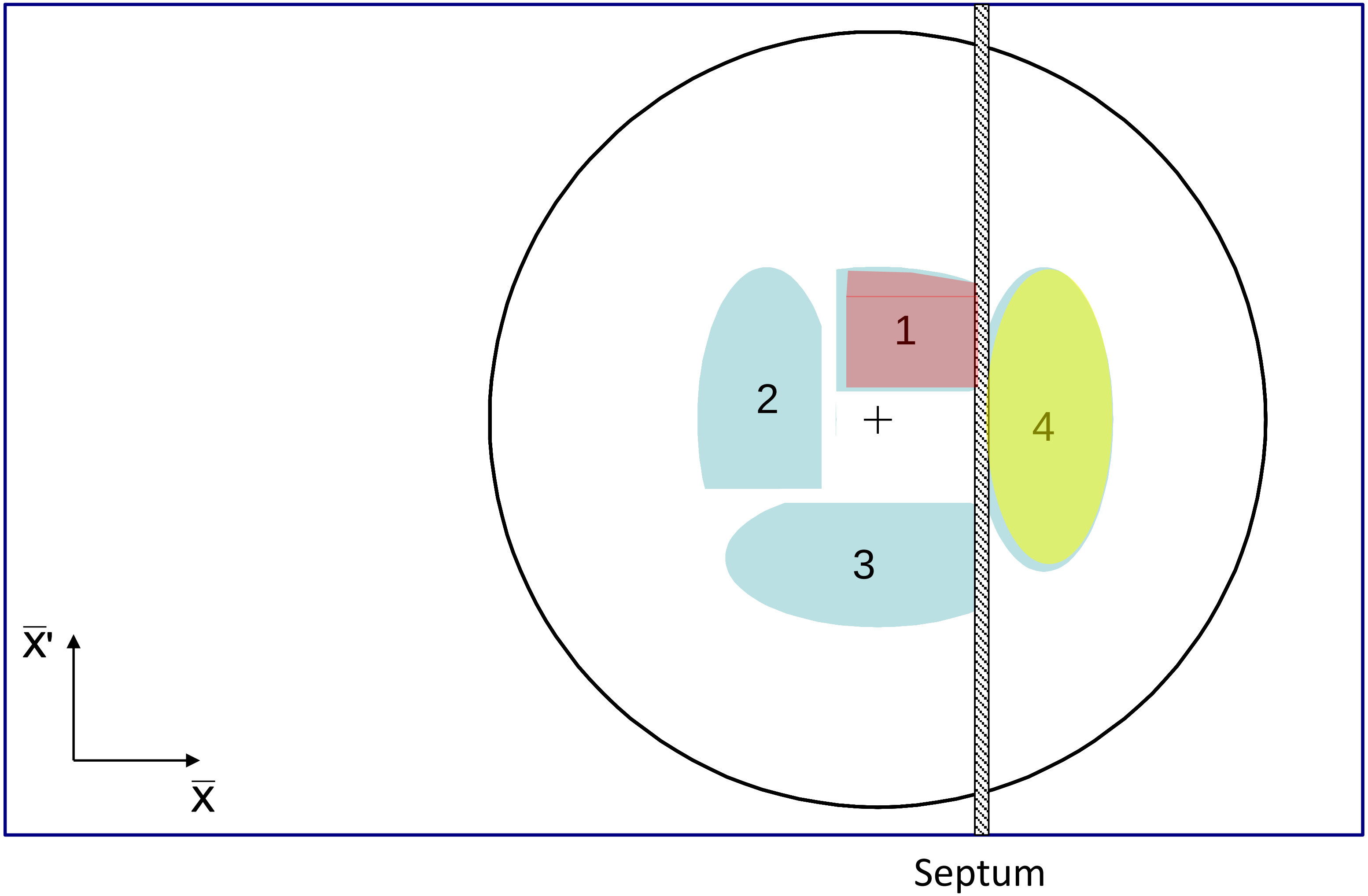


Septum

Multi-turn injection for hadrons

Example: CERN PSB injection, high intensity beams, fractional tune $Q_h \approx 0.25$
Beam rotates $\pi/2$ per turn in phase space

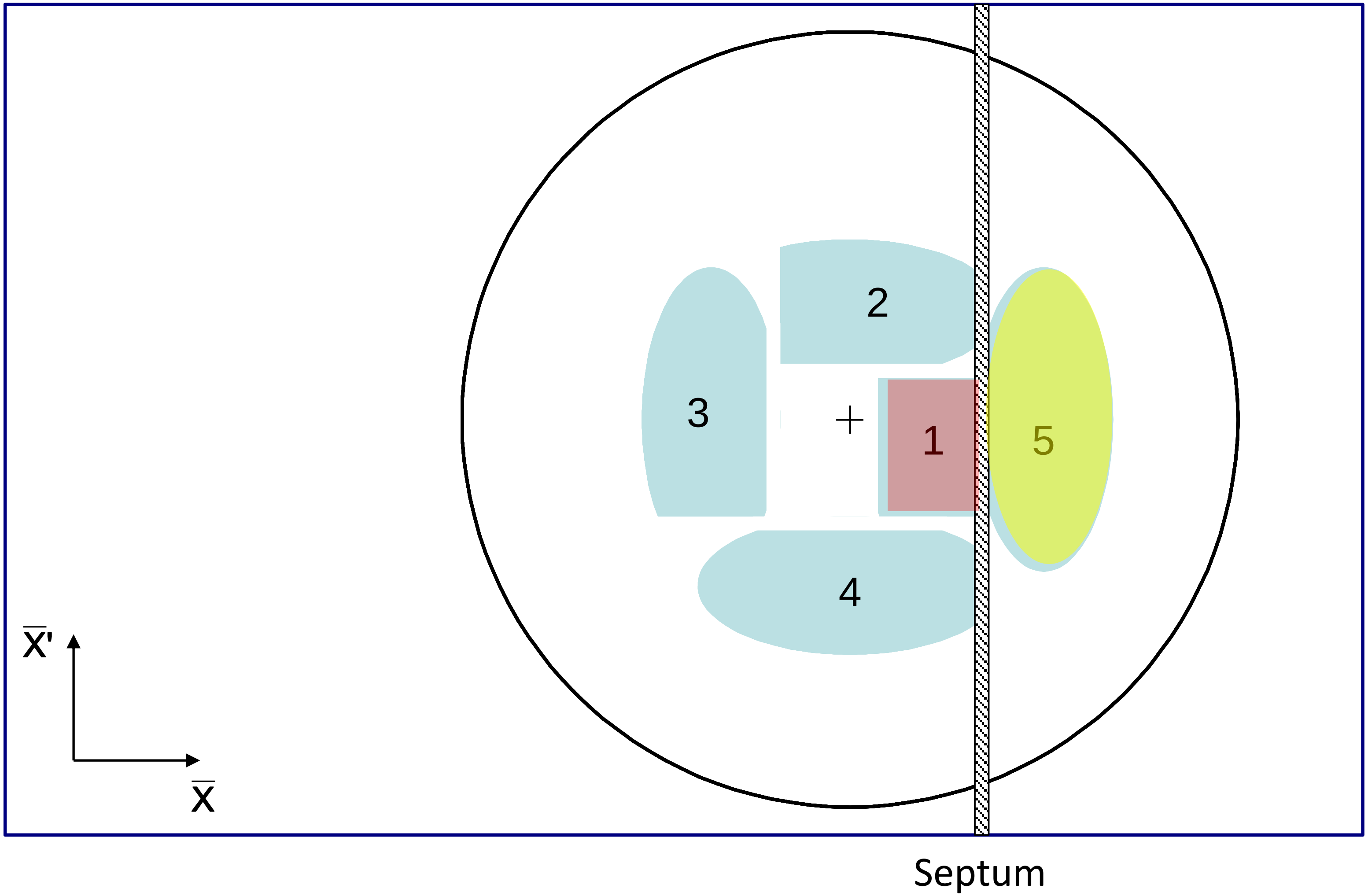
Turn 4



Multi-turn injection for hadrons

Example: CERN PSB injection, high intensity beams, fractional tune $Q_h \approx 0.25$
Beam rotates π/2 per turn in phase space

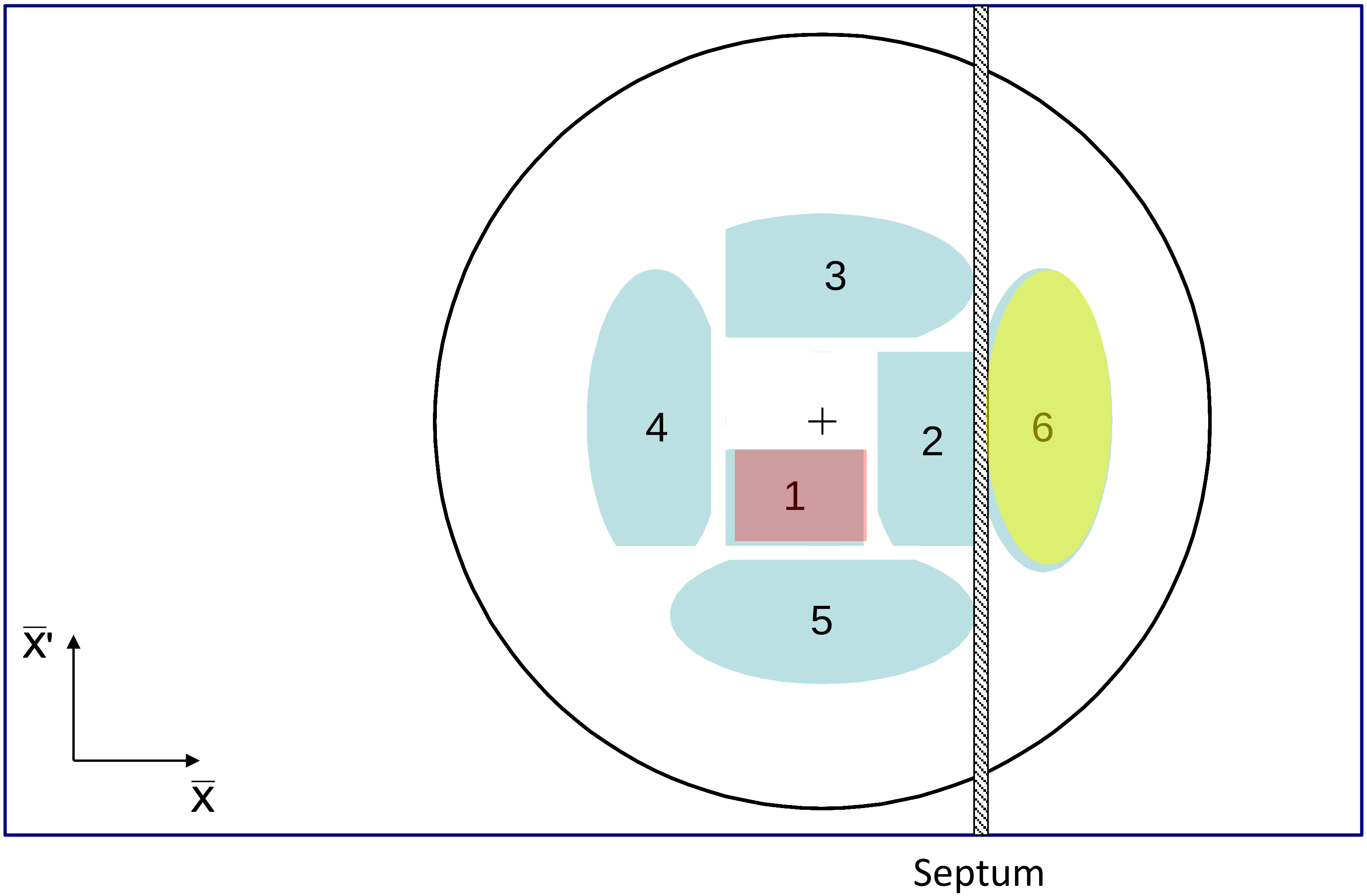
Turn 5



Multi-turn injection for hadrons

Example: CERN PSB injection, high intensity beams, fractional tune $Q_h \approx 0.25$
Beam rotates π/2 per turn in phase space

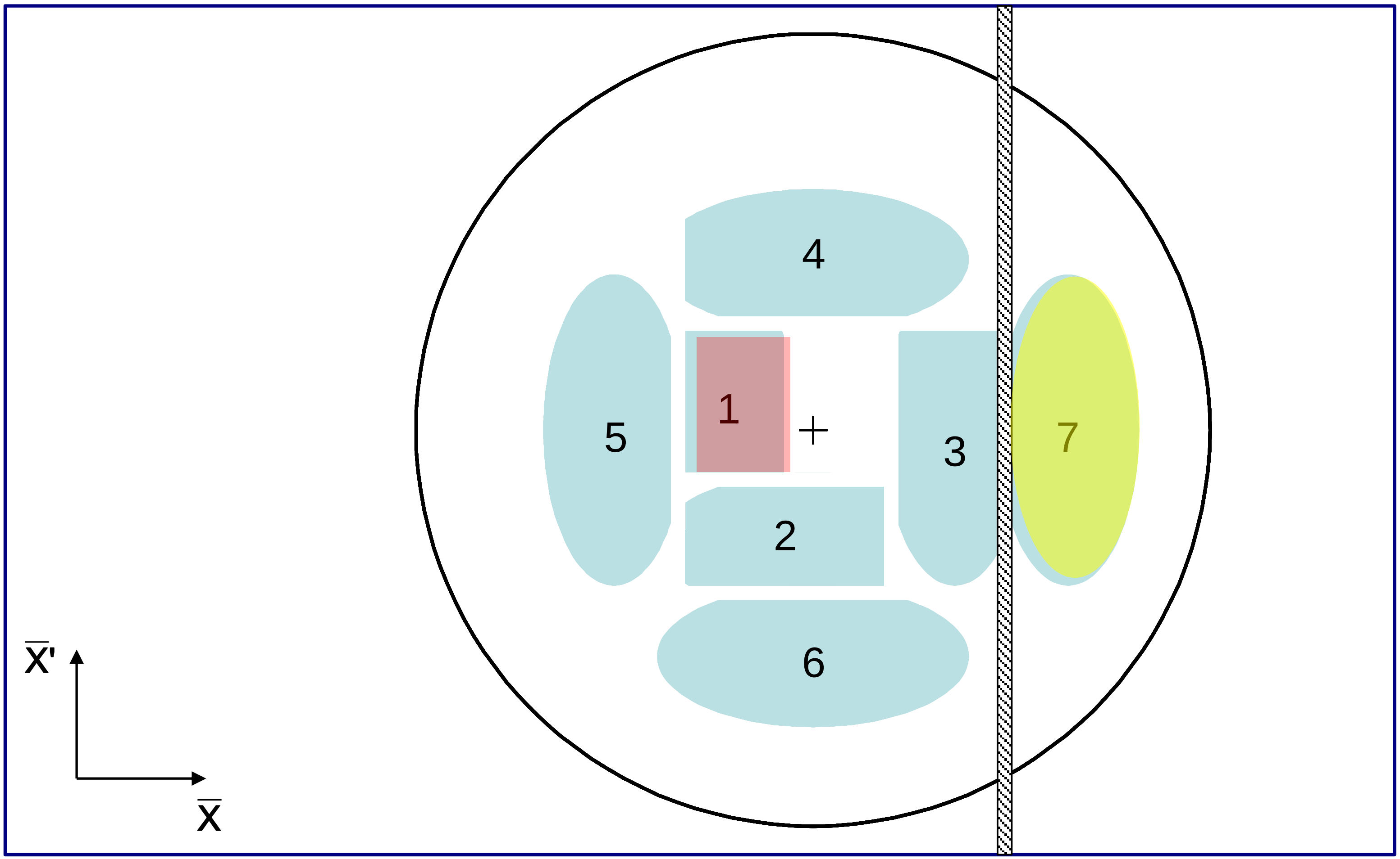
Turn 6



Multi-turn injection for hadrons

Example: CERN PSB injection, high intensity beams, fractional tune $Q_h \approx 0.25$
Beam rotates π/2 per turn in phase space

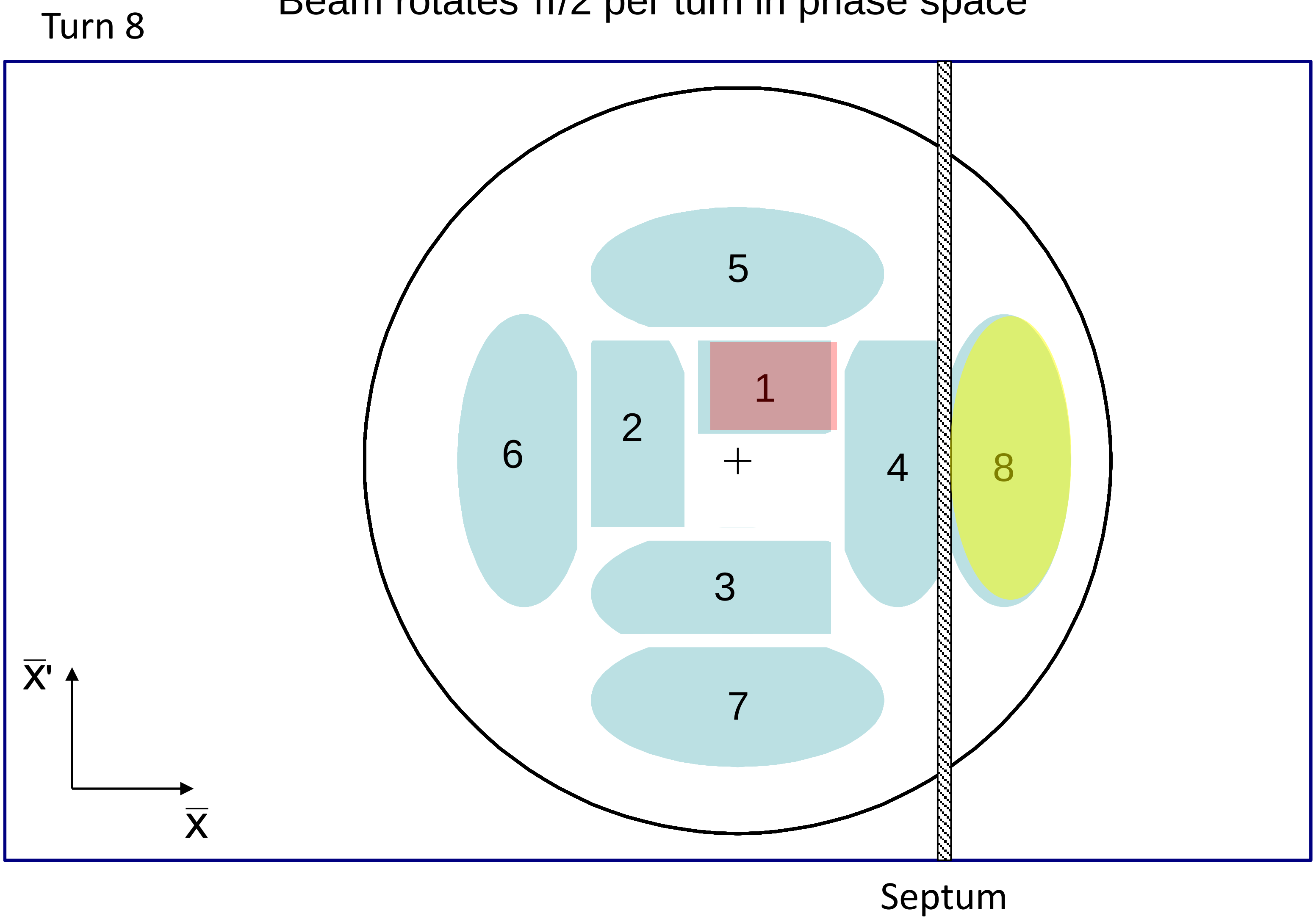
Turn 7



Septum

Multi-turn injection for hadrons

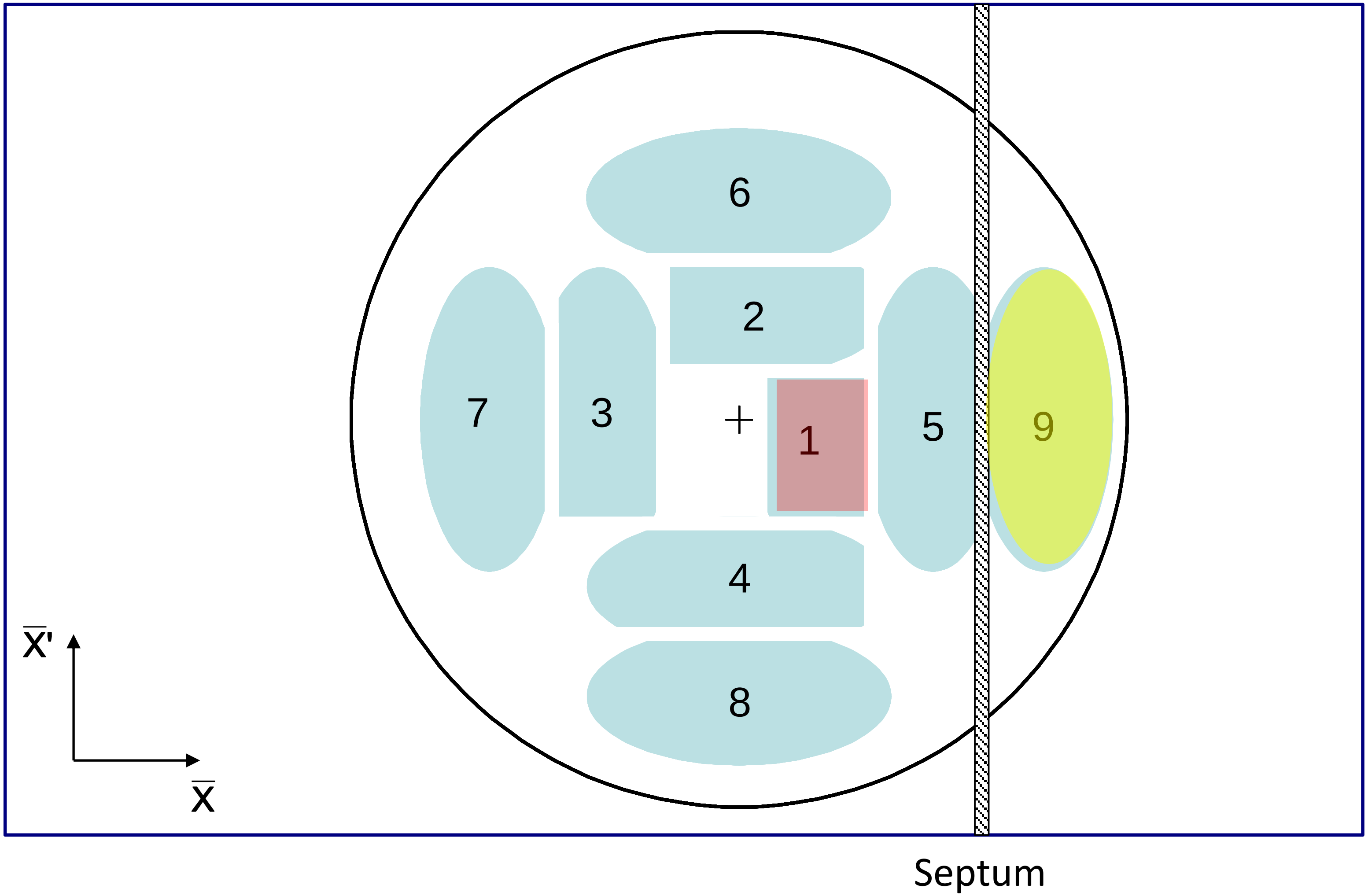
Example: CERN PSB injection, high intensity beams, fractional tune $Q_h \approx 0.25$
Beam rotates $\pi/2$ per turn in phase space



Multi-turn injection for hadrons

Example: CERN PSB injection, high intensity beams, fractional tune $Q_h \approx 0.25$
Beam rotates π/2 per turn in phase space

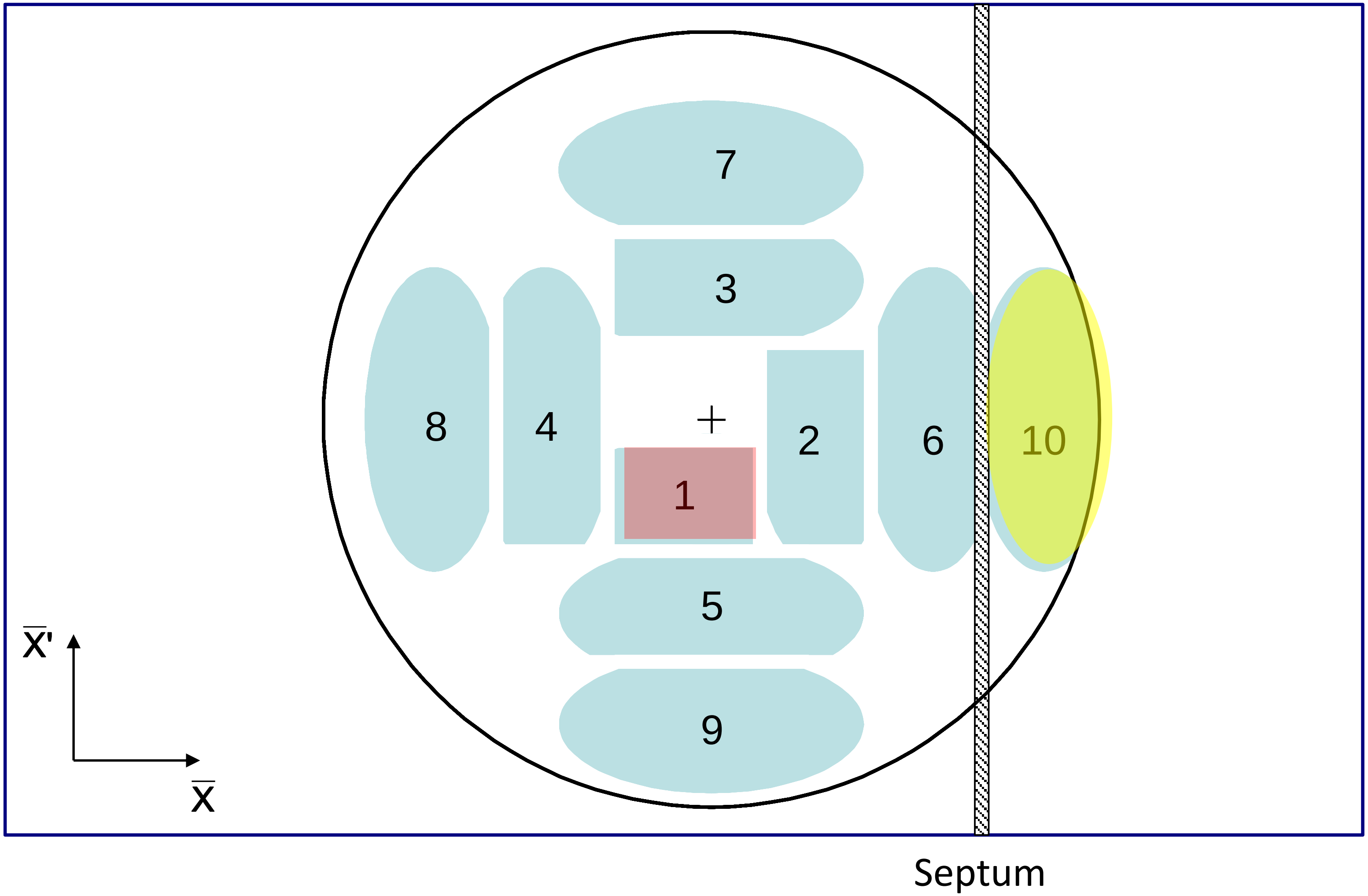
Turn 9



Multi-turn injection for hadrons

Example: CERN PSB injection, high intensity beams, fractional tune $Q_h \approx 0.25$
Beam rotates π/2 per turn in phase space

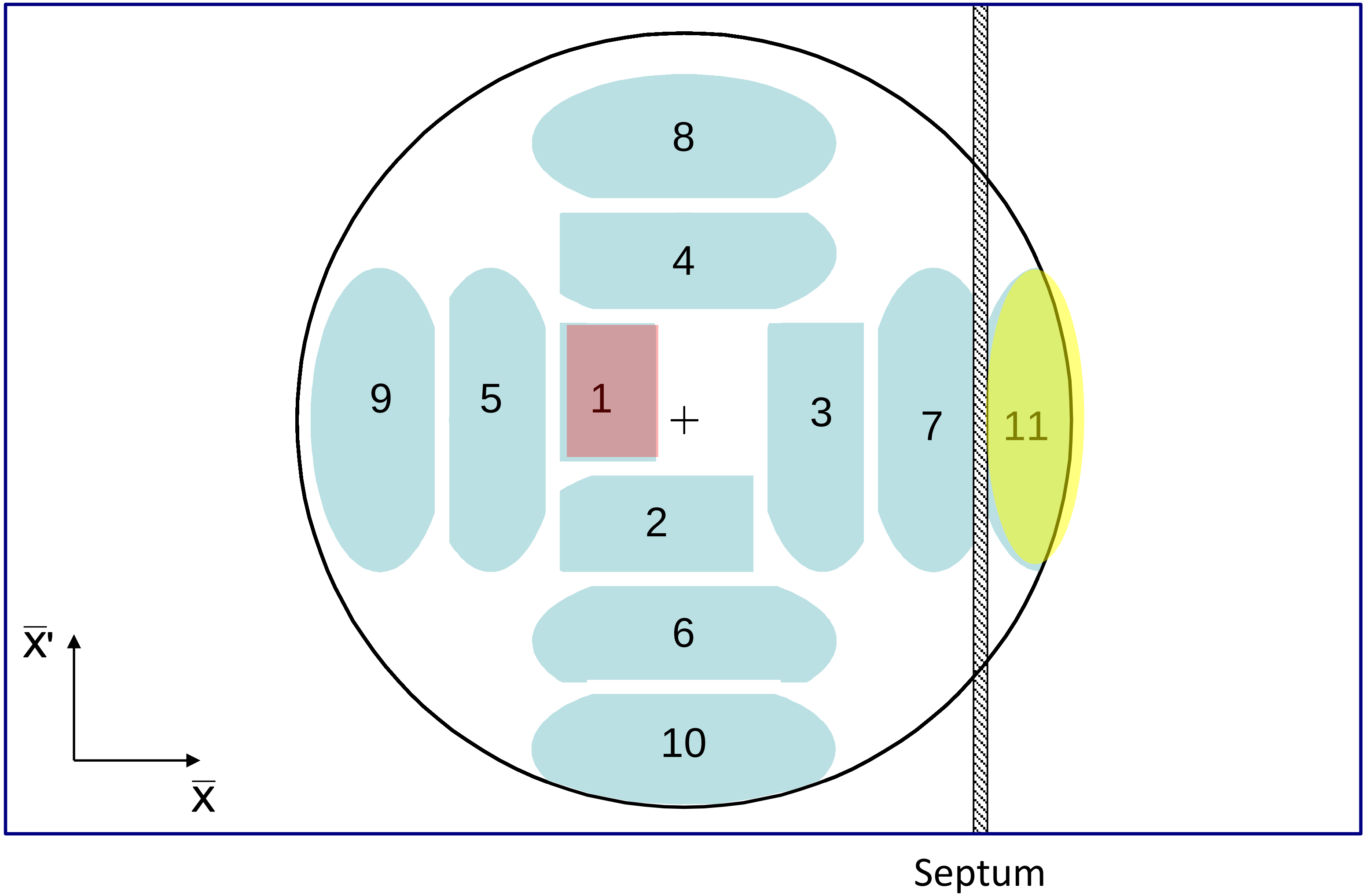
Turn 10



Multi-turn injection for hadrons

Example: CERN PSB injection, high intensity beams, fractional tune $Q_h \approx 0.25$
Beam rotates $\pi/2$ per turn in phase space

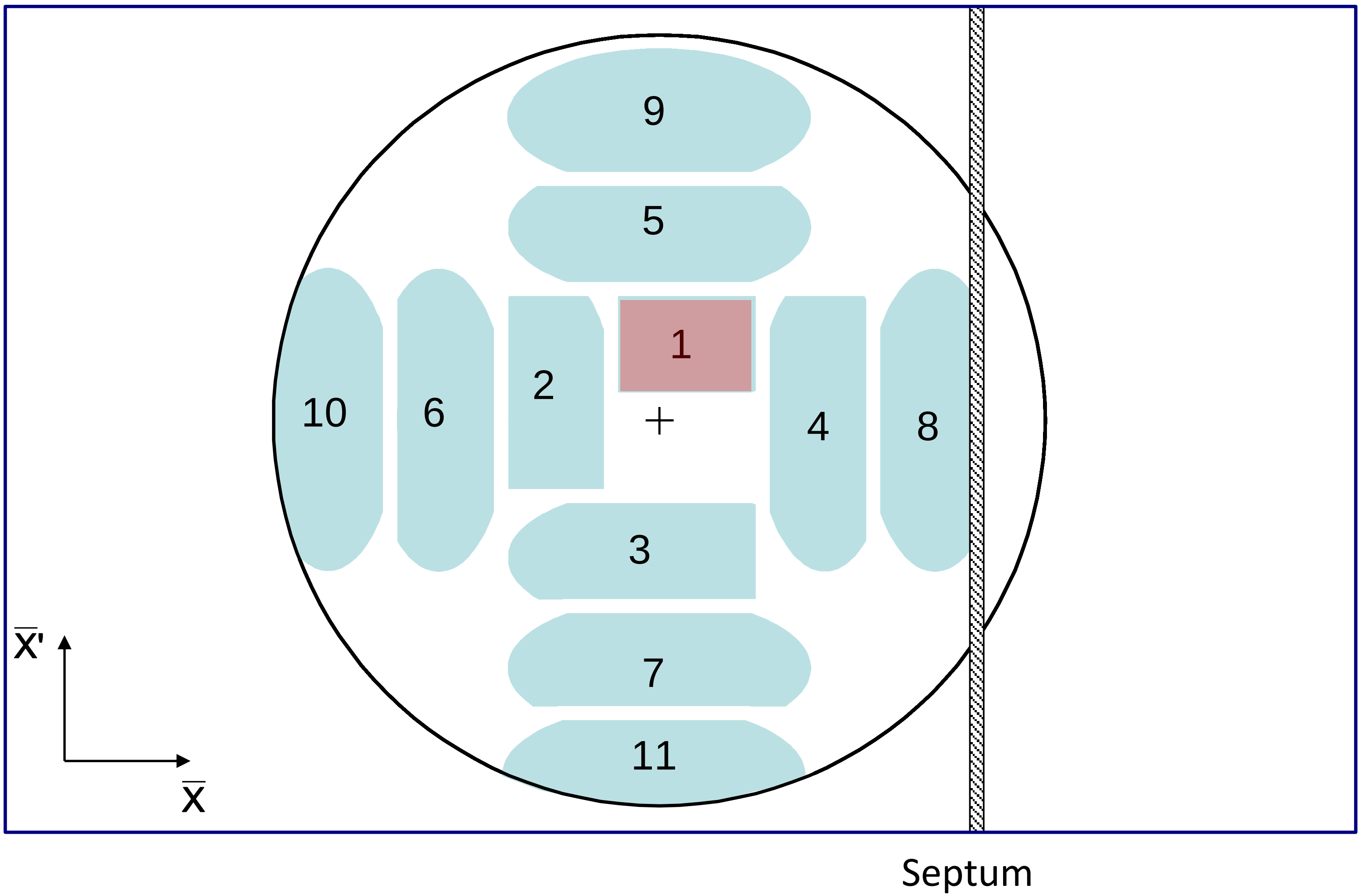
Turn 11



Multi-turn injection for hadrons

Example: CERN PSB injection, high intensity beams, fractional tune $Q_h \approx 0.25$
Beam rotates π/2 per turn in phase space

Turn 12



Multi-turn injection for hadrons

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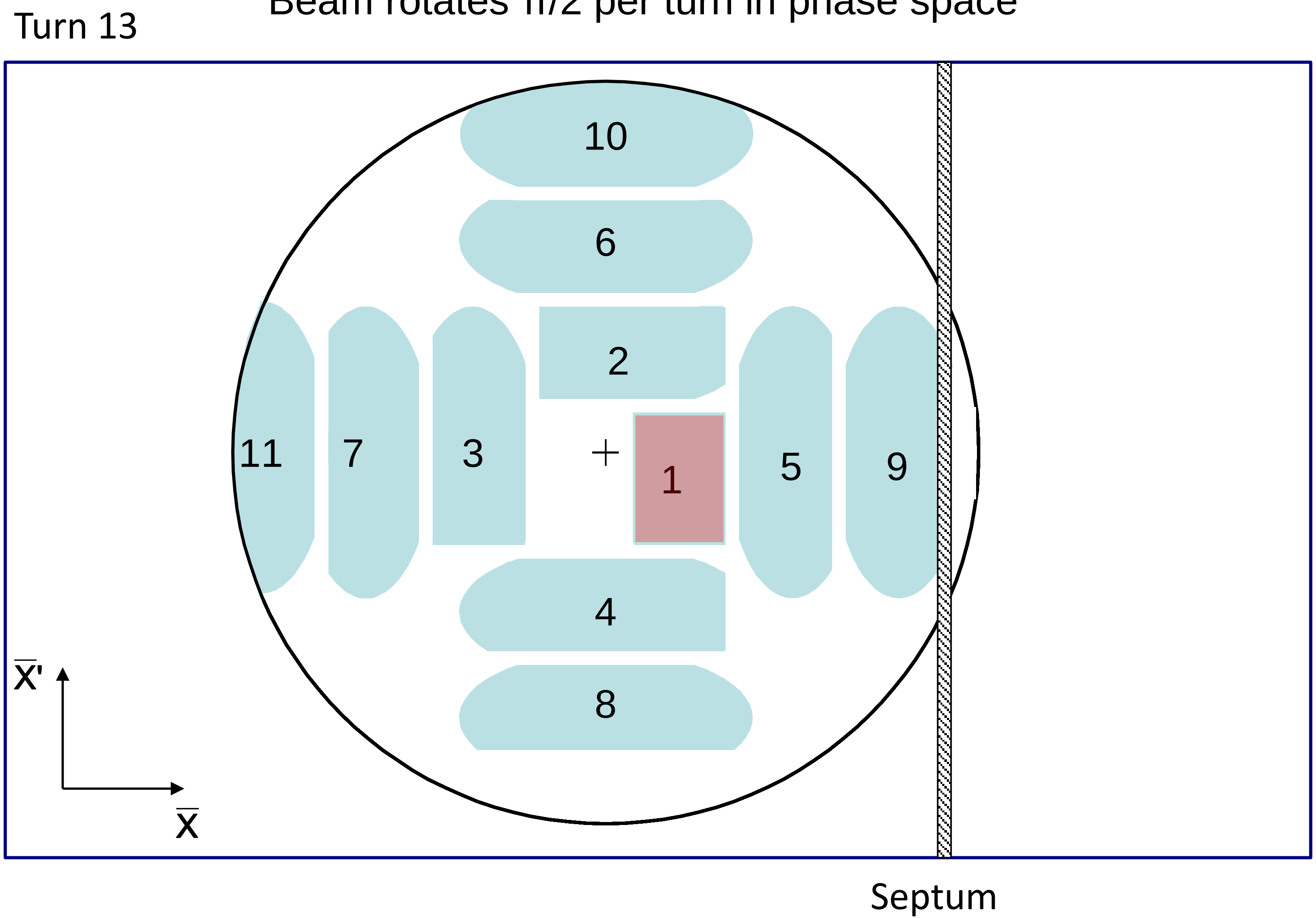
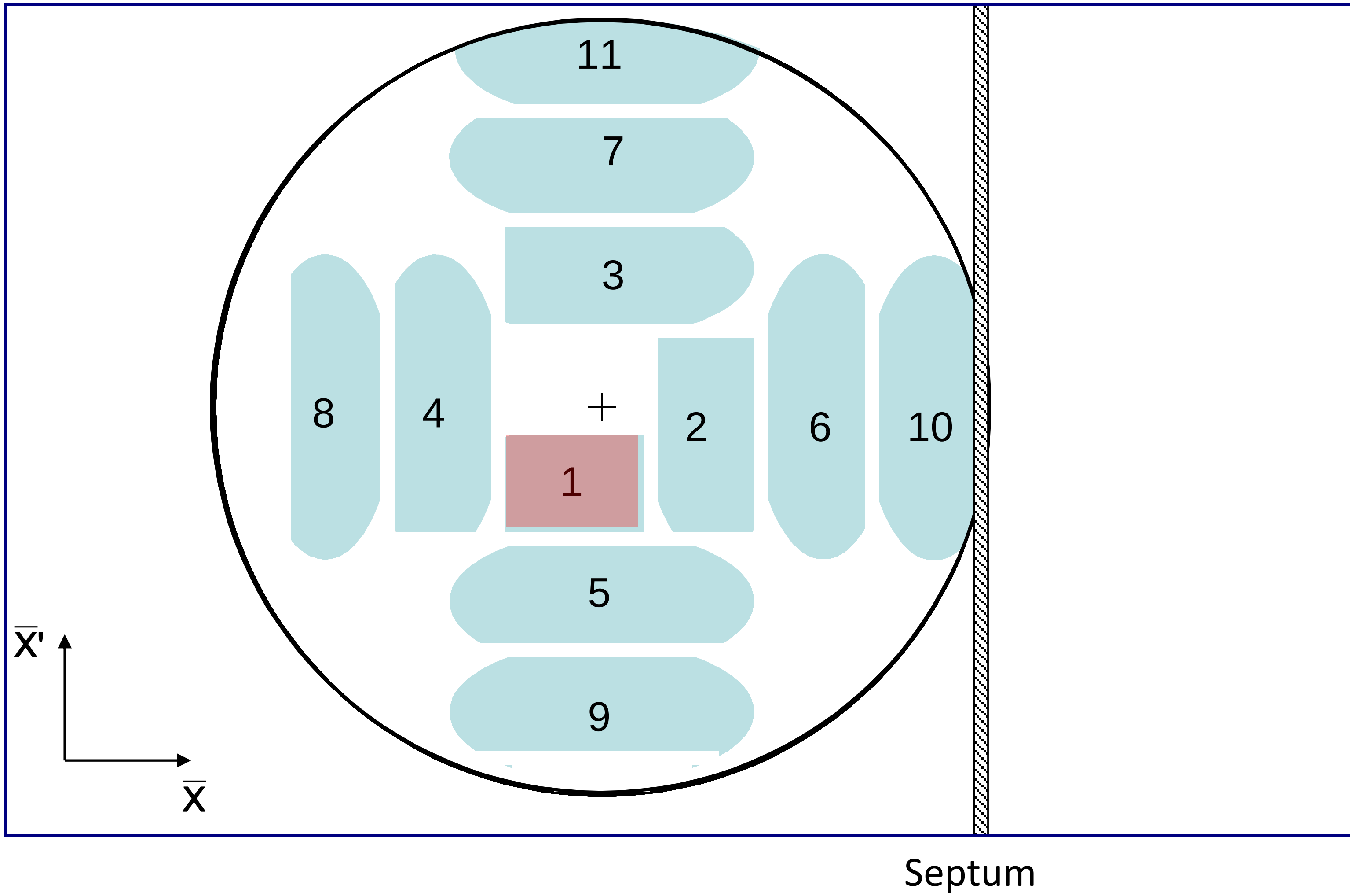
Beam rotates π/2 per turn in phase space



Multi-turn injection for hadrons

Example: CERN PSB injection, high intensity beams, fractional tune $Q_h \approx 0.25$
Beam rotates π/2 per turn in phase space

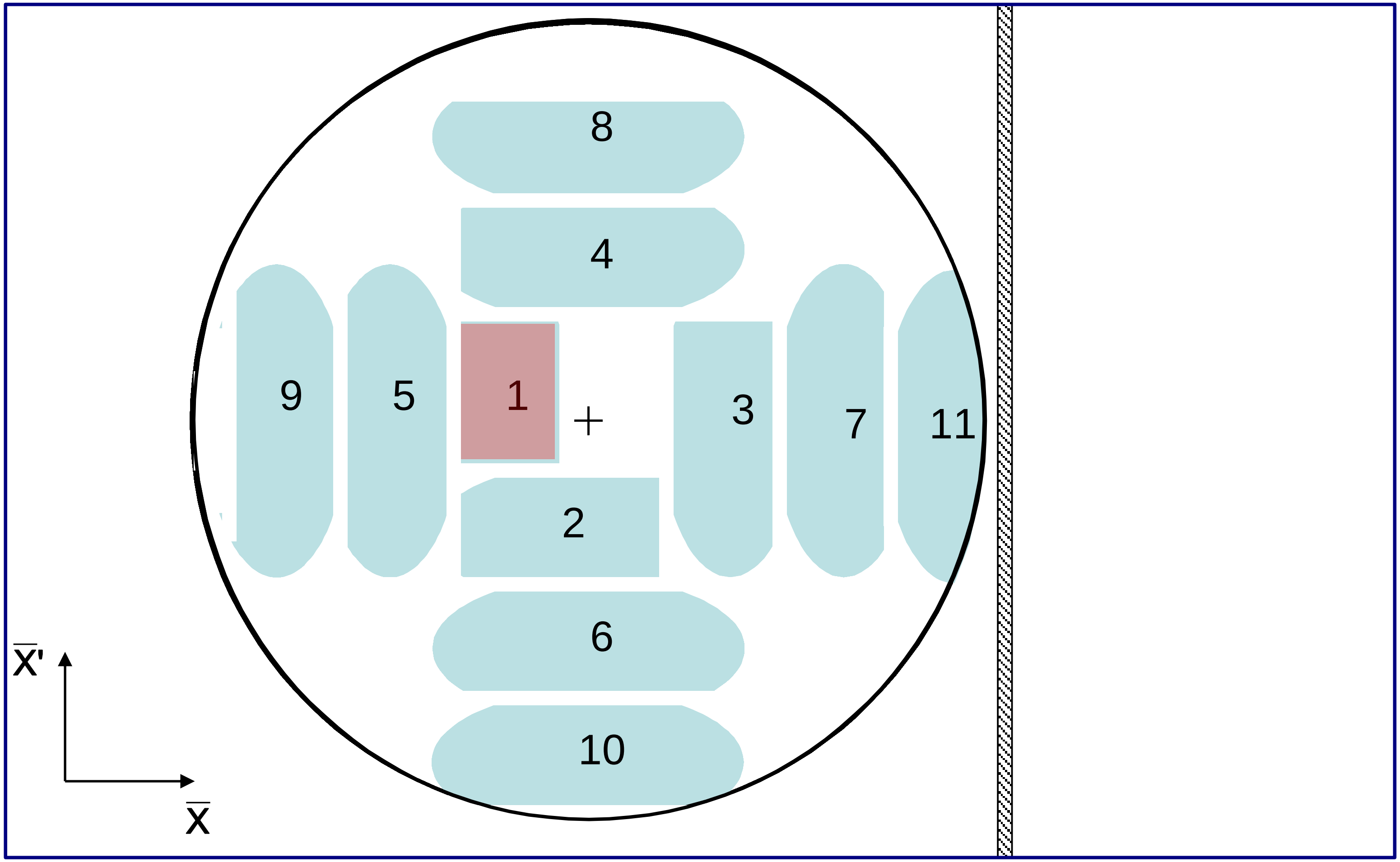
Turn 14



Multi-turn injection for hadrons

Phase space has been "**painted**"

Turn 15

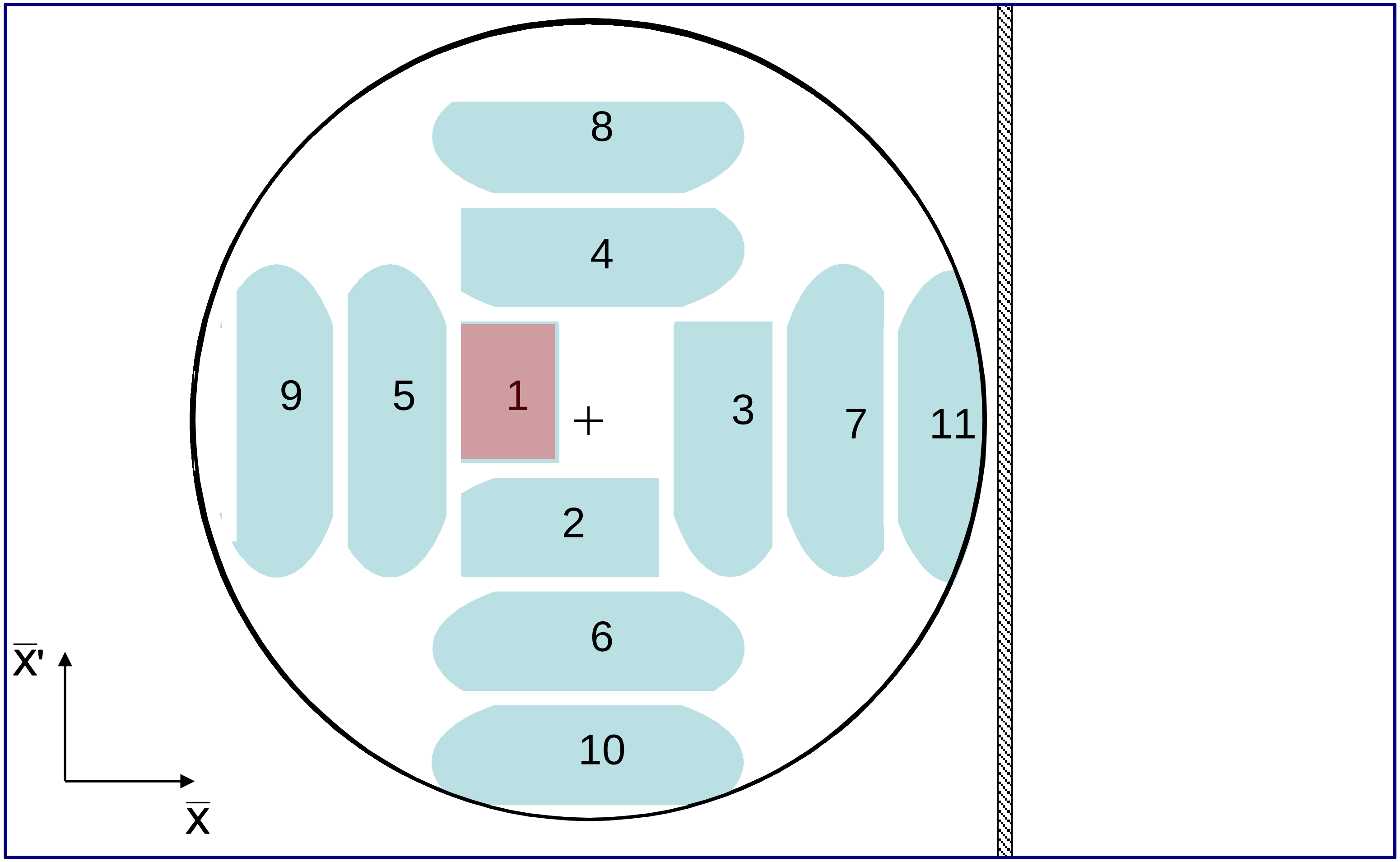


In reality, filamentation (often space-charge driven) occurs to produce a quasi-uniform beam

Multi-turn injection for hadrons

Phase space has been "**painted**"

Turn 15

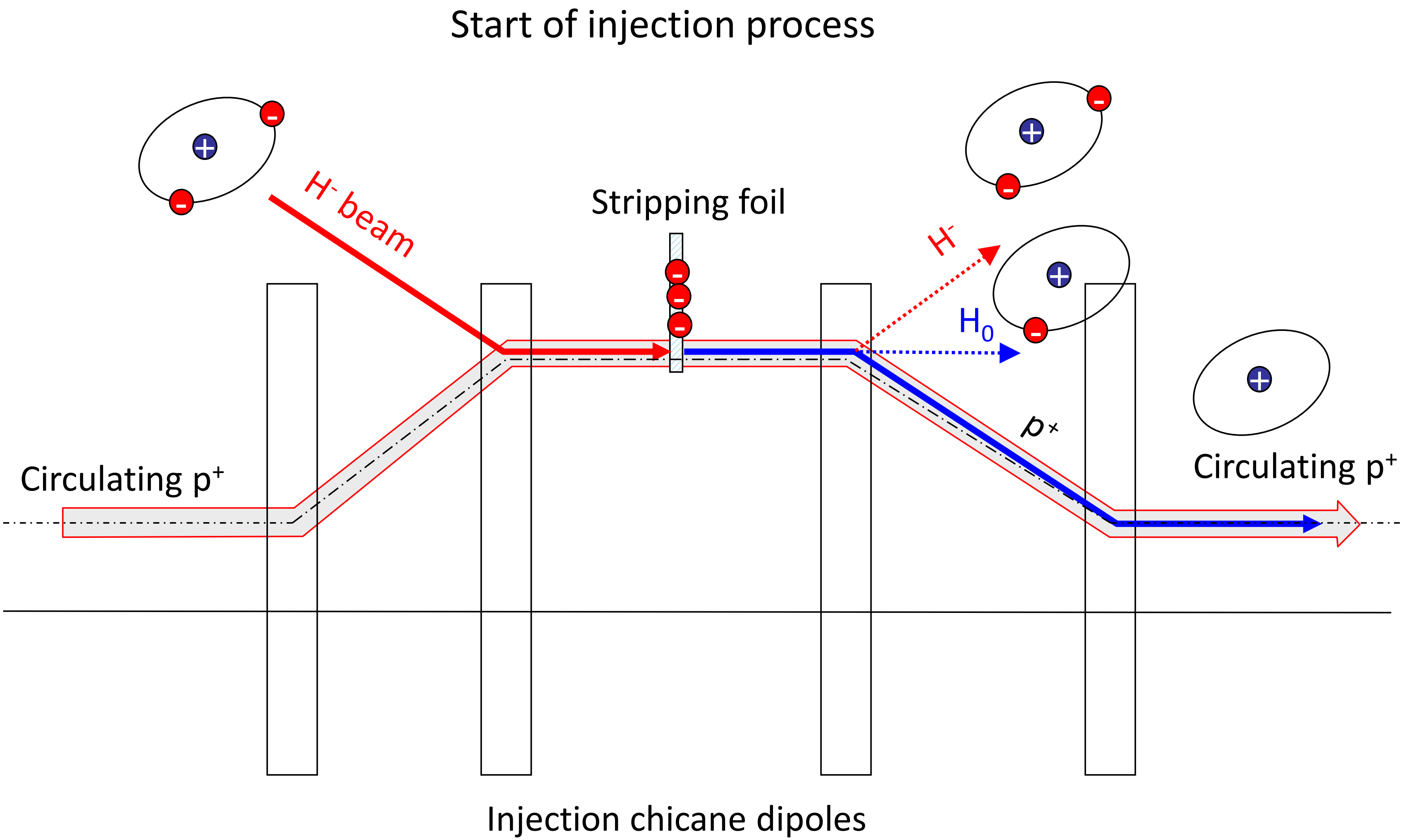


In reality, filamentation (often space-charge driven) occurs to produce a quasi-uniform beam

Charge exchange H- injection

- Multi-turn 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:
    - typically 30 – 40 % for the CERN PSB injection at 50 MeV
  - Limits number of injected turns to 10 - 20
- Charge-exchange injection provides elegant alternative
  - Convert H^- to p^+ using a thin stripping foil, allowing injection into the same phase space area

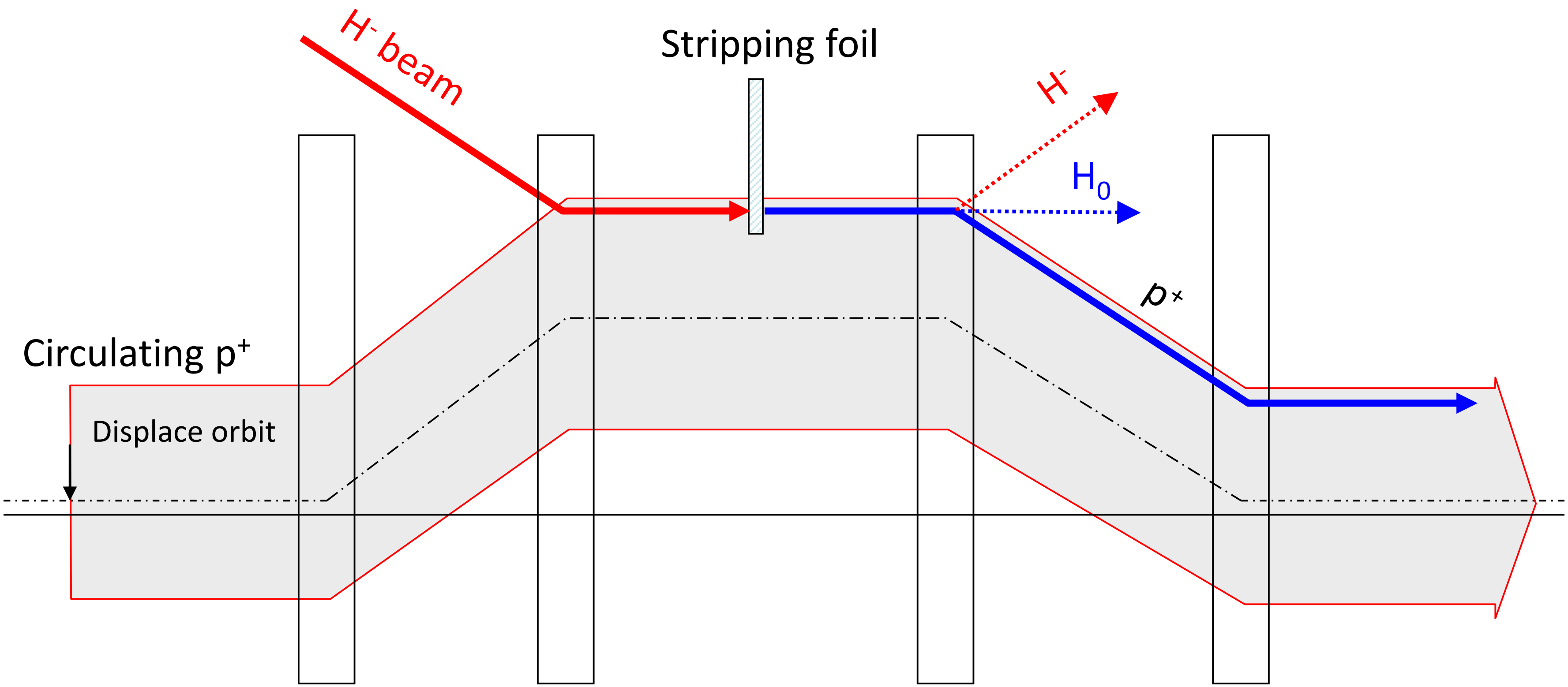
Charge exchange H- injection



C. Bracco's Lecture

Charge exchange H- injection

End of injection process with painting



Injection chicane dipoles

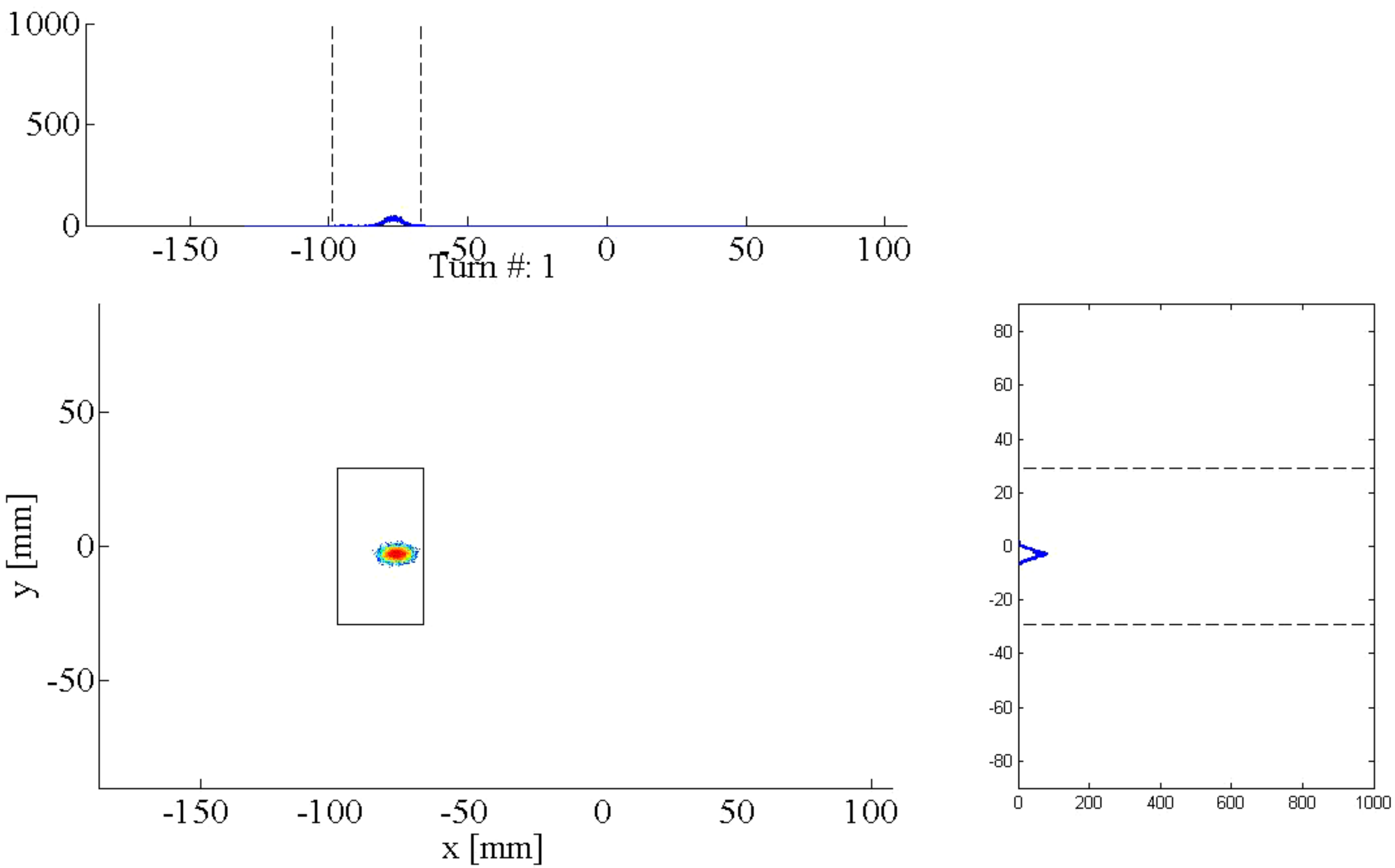
C. Bracco's Lecture

Charge exchange H- injection

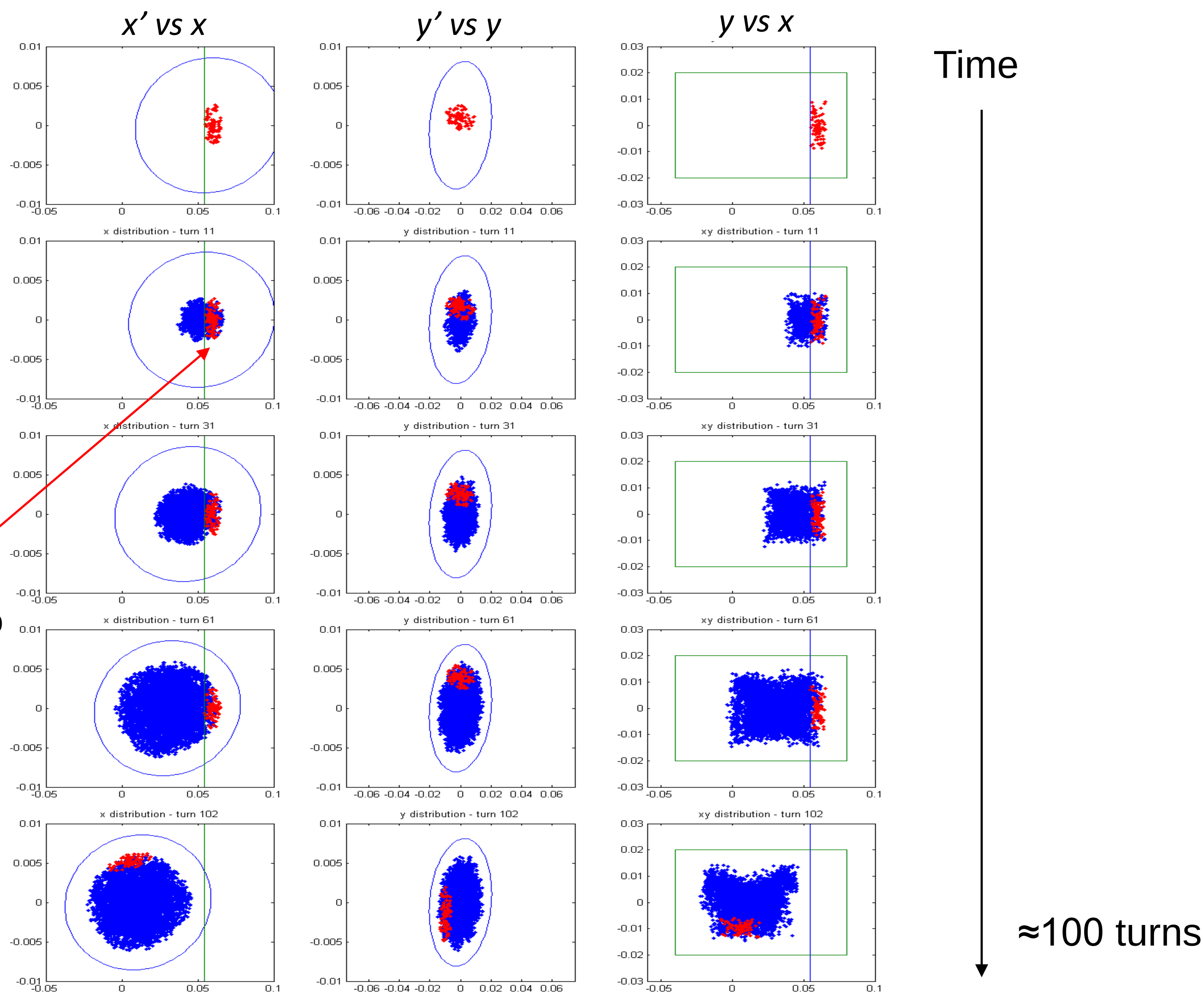
- Paint uniform transverse phase space density by modifying closed orbit bump and steering injected beam
- Foil thickness calculated to double-strip most ions (≈99%)
  - 50 MeV – 50 μg.cm^{-2}
  - 800 MeV – 200 μg.cm^{-2} (≈ 1 μm of C!)
- Carbon foils generally used – very fragile
- Injection chicane reduced or switched off after injection, to avoid excessive foil heating and beam blow-up
- Longitudinal phase space can also be painted turn-by-turn:
  - Variation of the injected beam energy turn-by-turn (linac voltage scaled)
  - Chopper system in linac to match length of injected batch to bucket

Accumulation process on foil

- Linac4 connection to the PS booster at 160 MeV:
  - H^- stripped to p^+ with an estimated efficiency ≈98 % with C foil 200 $\mu g.cm^{-2}$ [14]



H- injection - painting

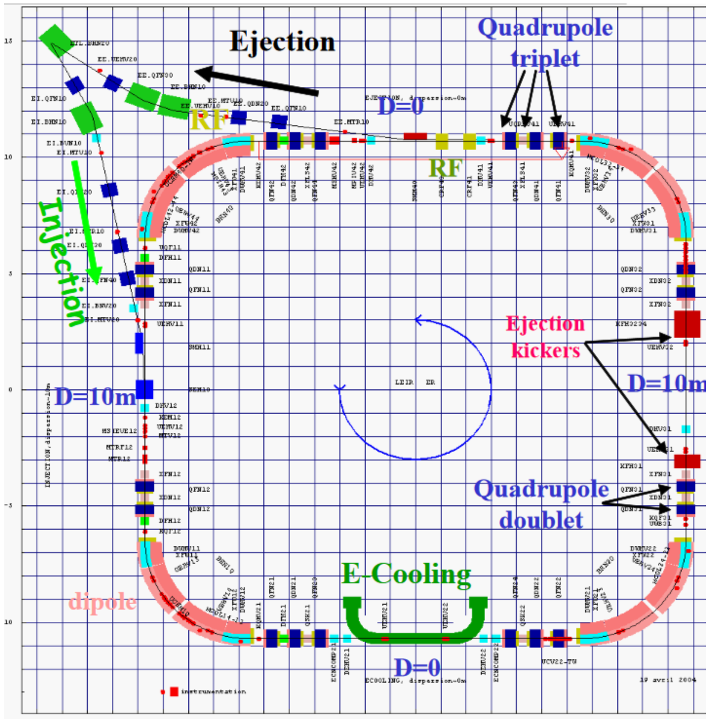


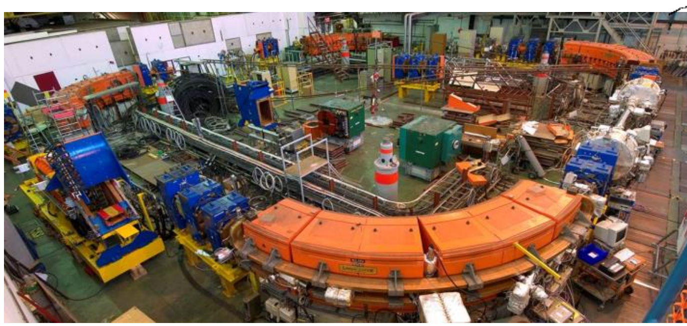
Note injection into same phase space area as circulating beam

Combined longitudinal and transverse multi-turn injection

Used at CERN LEIR to increase intensity of ion bunches

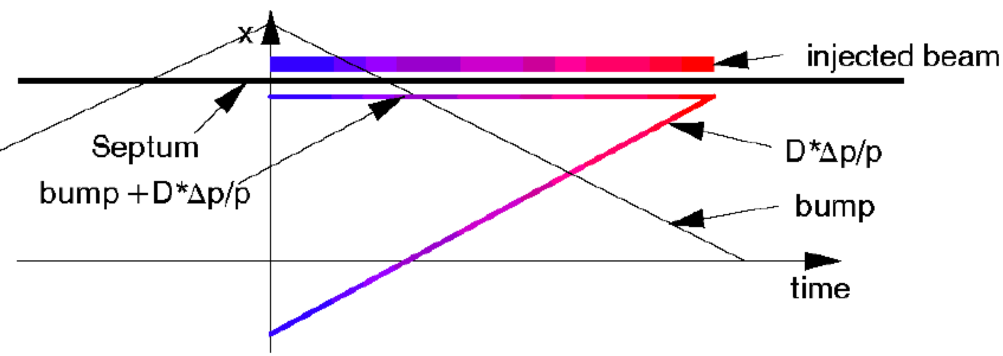
4.2 MeV/nucleon → 72 MeV/nucleon





Combined multi-turn injection and stacking by electron cooling [15].

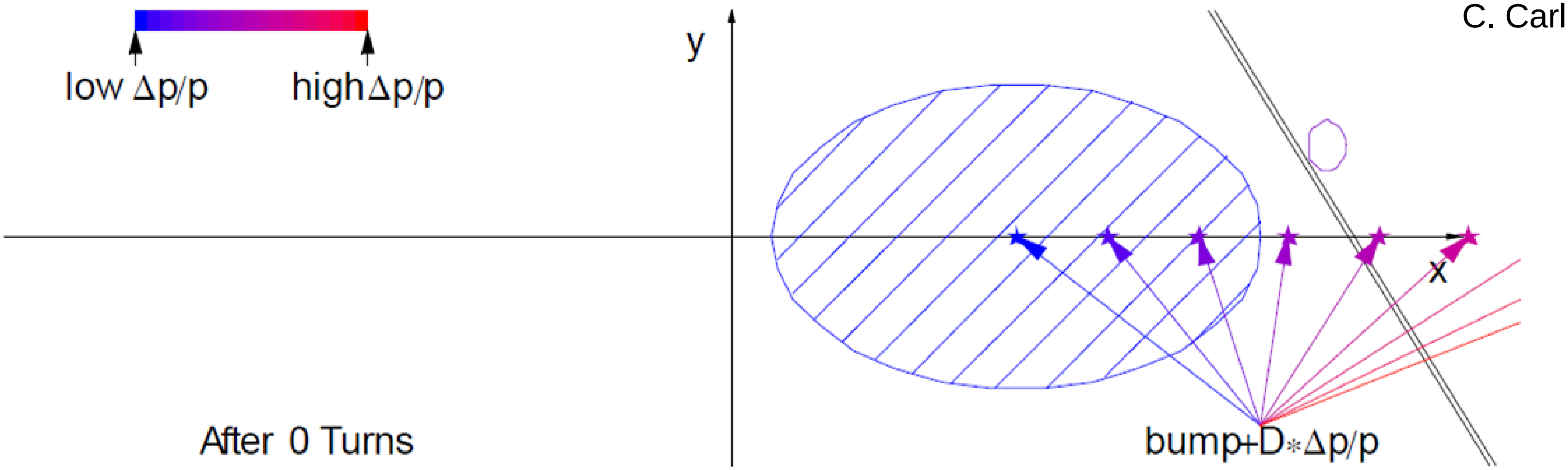
- Injection occurs in a section with large normalised dispersion
- Decrease closed orbit bump
- Ramp momentum of the linac such that the orbit (bump + D Δp/p) stays constant at injection (same betatron amplitude but stacking in momentum)
- After injection the ions cooled and stacked before the new pulse arrives



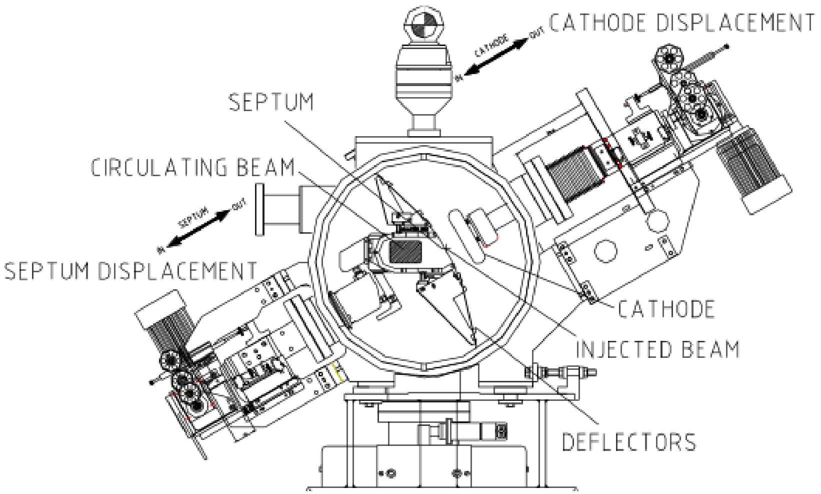
Horizontal Positions during injection

C. Carli

Combined longitudinal and transverse multi-turn injection



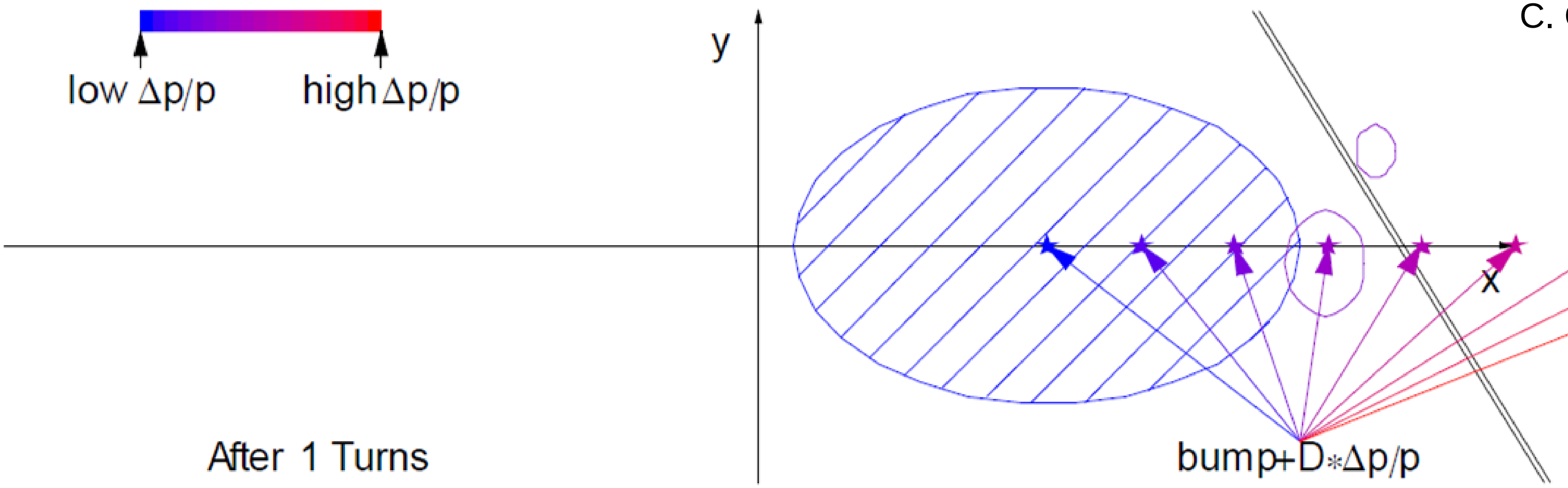
- Stacking in both horizontal and vertical plane requires an inclined electrostatic septum
- The tune has to be optimised to avoid touching the septum blade at each turn
- Injection of 1 pulse from the linac takes ~200 μs (76 turns)
- One injection every 200 ms to allow for cooling (100-150 ms). In total 7 injections to fill LEIR.
- After each injection the momentum offset is reduced from 4‰ down to 1‰ ➔ cooling ➔ move orbit of stack beam to leave room for next injection
- Efficiency: 50- 70%



M. Paraliev's Lecture

Combined longitudinal and transverse multi-turn injection

C. Carli



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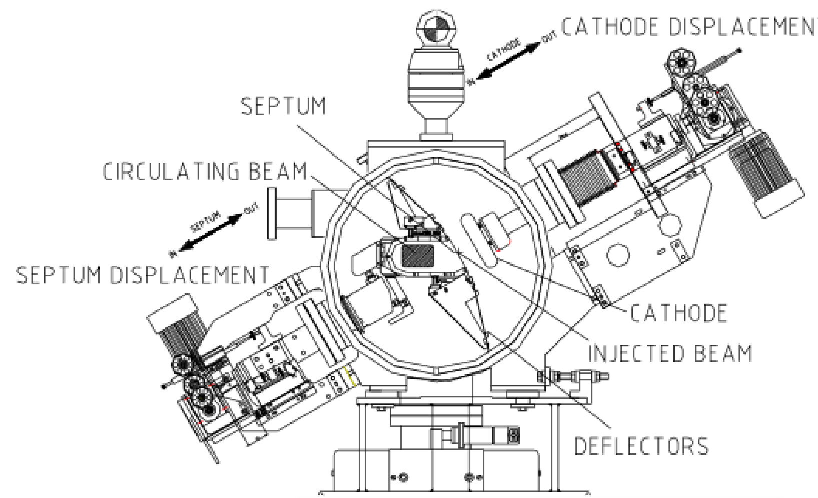
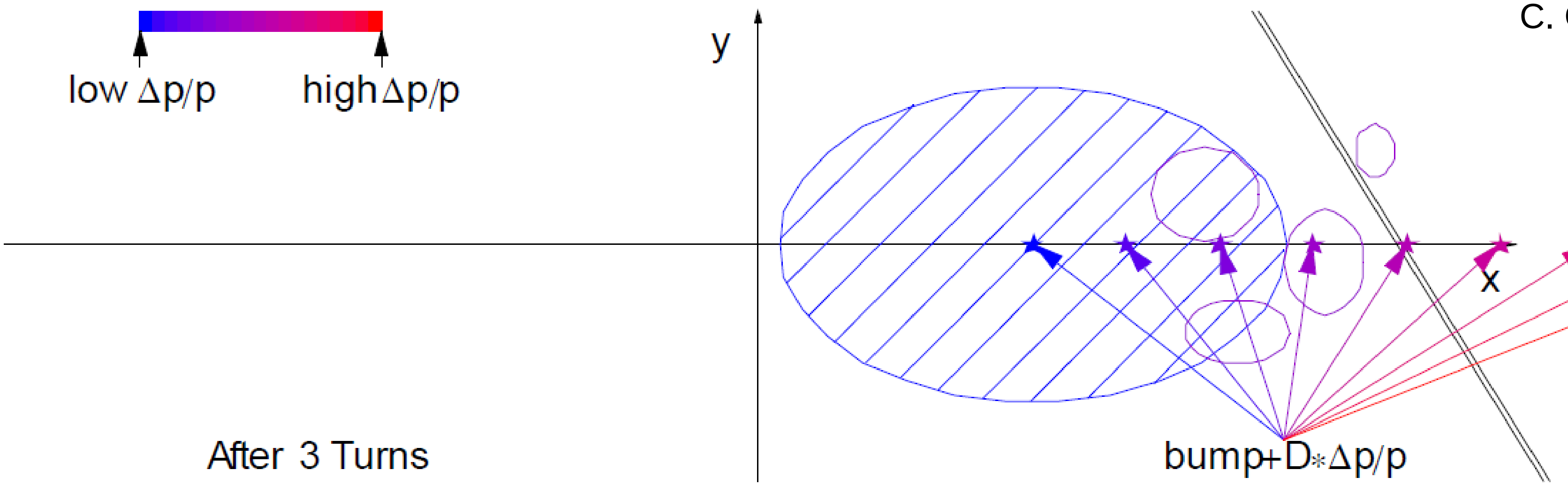


M. Paraliev's Lecture

Combined longitudinal and transverse multi-turn injection



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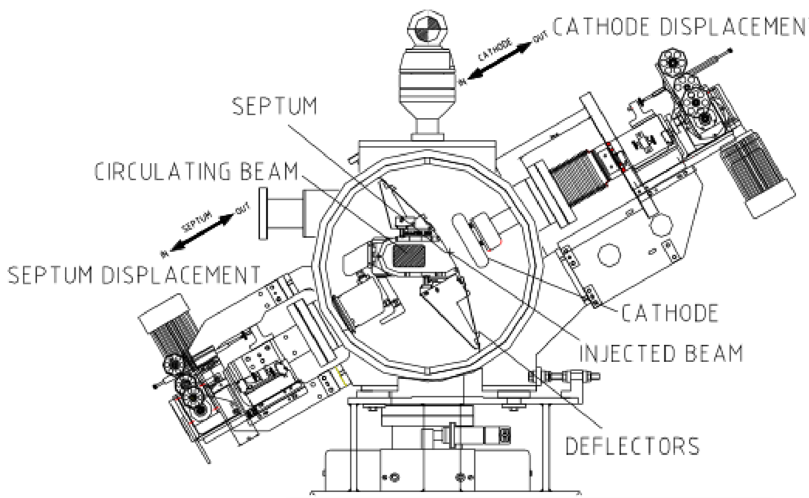

M. Paraliev's Lecture

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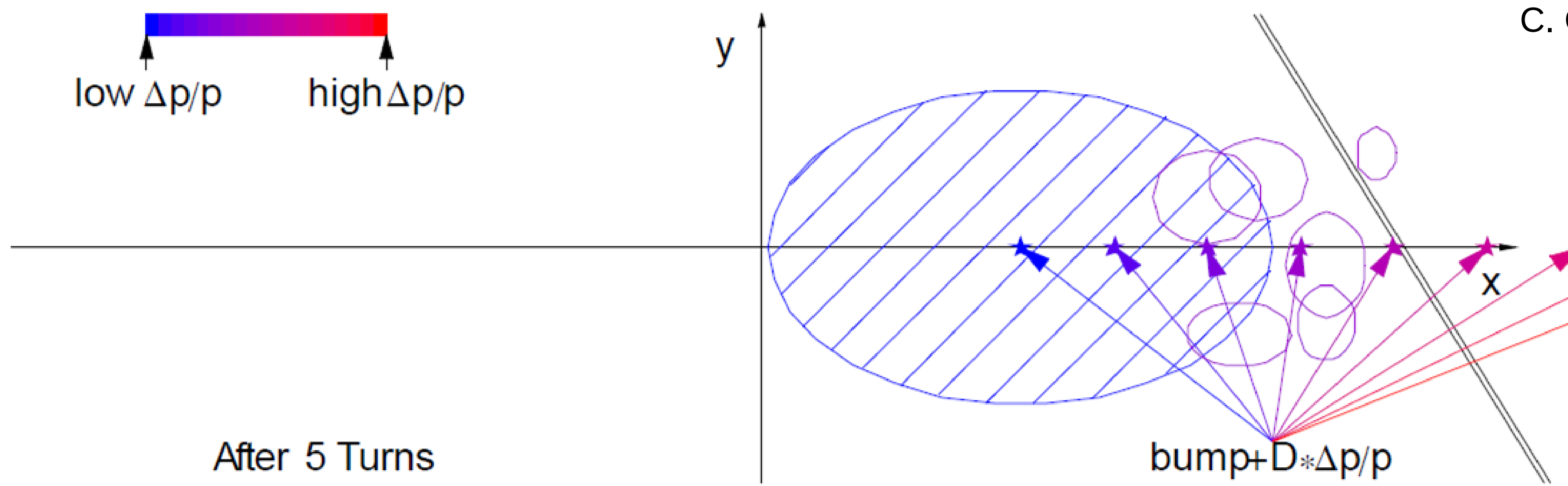

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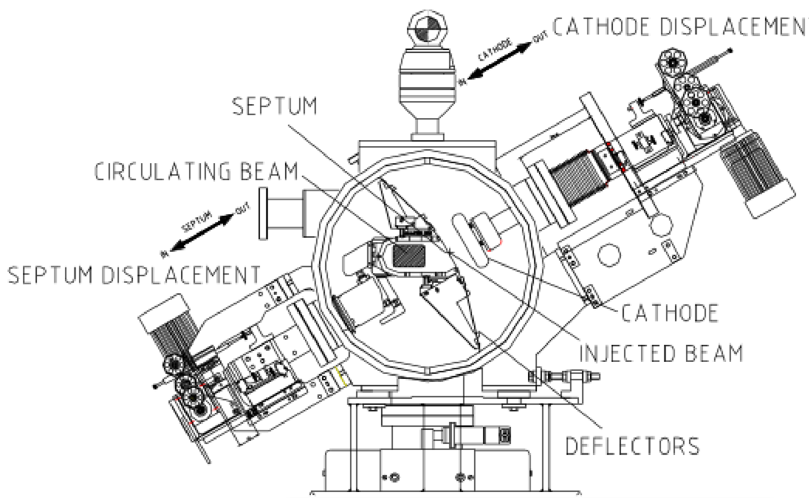
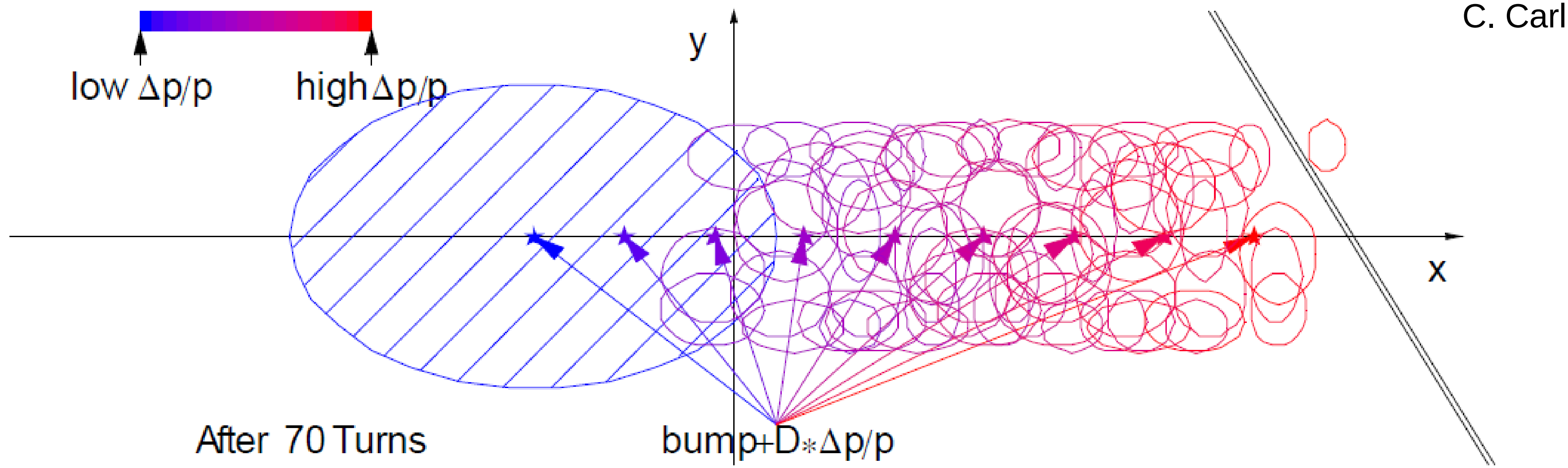


M. Paraliev’s Lecture

Combined longitudinal and transverse multi-turn injection



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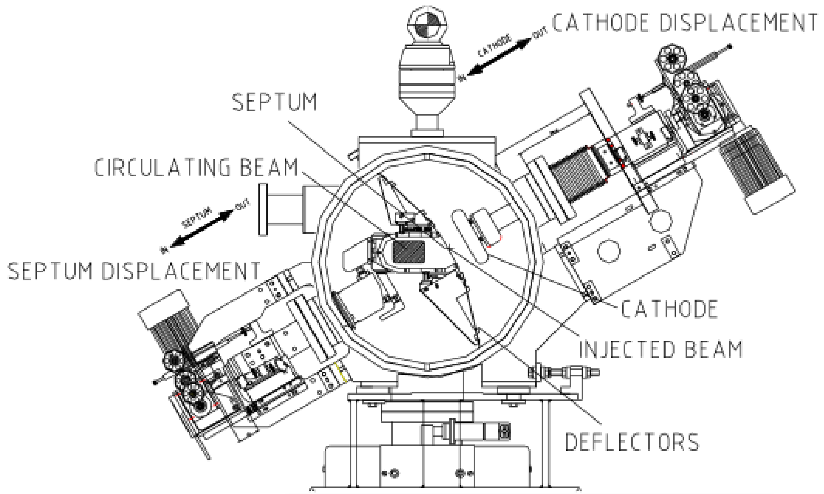
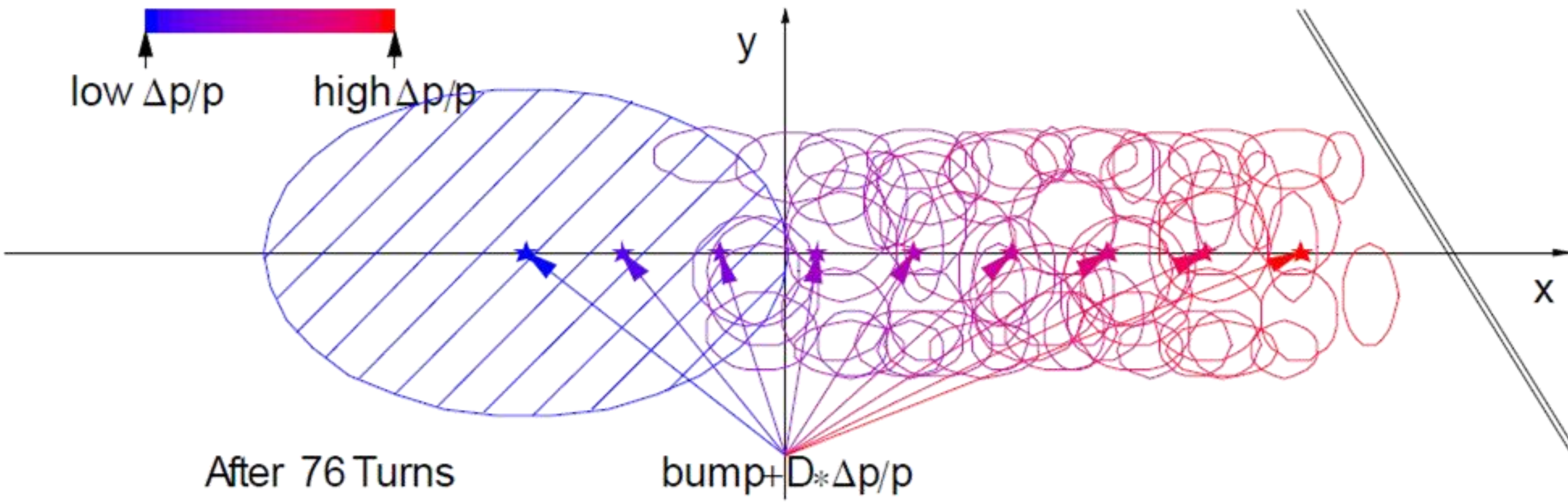


M. Paraliev's Lecture

Combined longitudinal and transverse multi-turn injection

C. Carli



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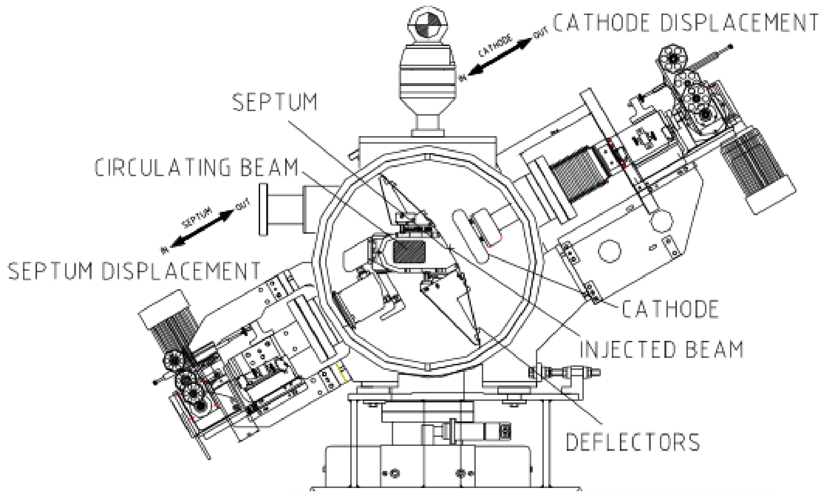

M. Paraliev's Lecture

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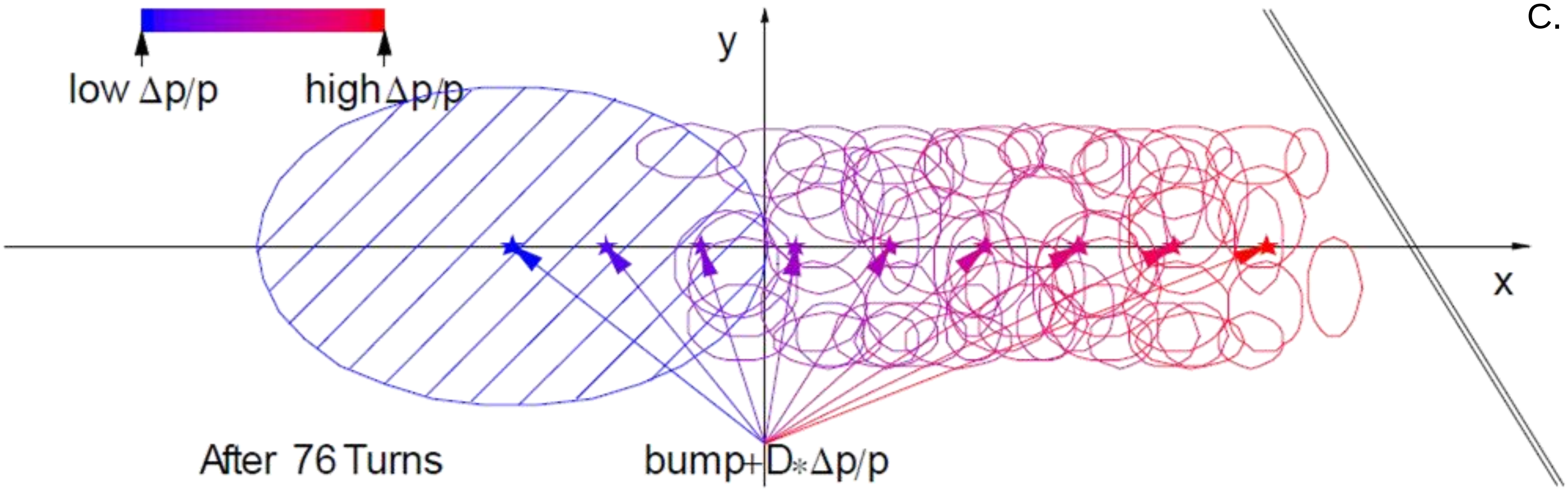

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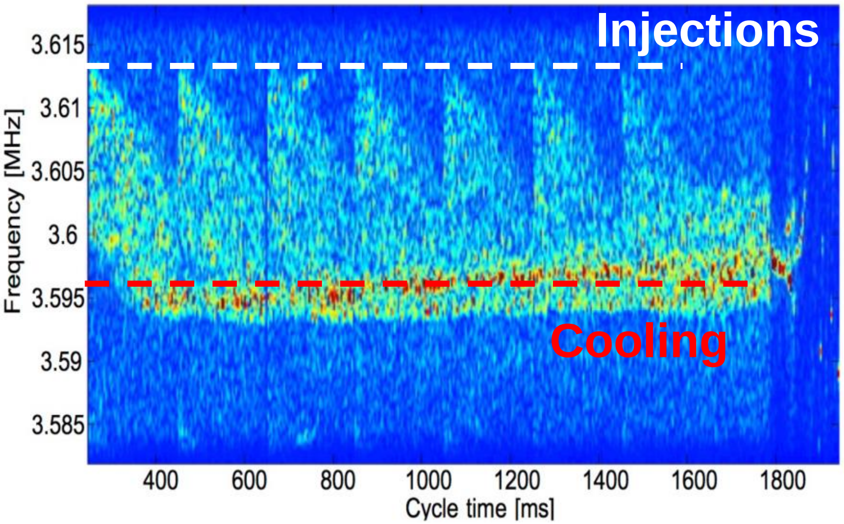


Lessons learnt

Low energy: dominated by space charge ➔ challenging storing high intensity and high brightness beams

- Conventional multi-turn injection with phase space painting: emittance growth, limited by number of turns and injection losses at the septum ➔ charge exchange H^- injection allows to overcome these limitations

High energy: fast process involving handling of high power beams ➔ machine protection concerns!

- Minimize mismatch and injection errors (optimize HW, steering, optics) ➔ reduce losses, injection oscillations and thus emittance blow up
- Need for passive protection elements: aperture, materials and length such to minimize energy deposition on the machine elements and avoid damage while limiting activation

Alternative injection methods:

- Slip-stacking: increasing intensity by accelerating particle beams with different momenta in the same accelerator
- Combined 3-planes multi-turn injection, electron cooling and accumulation

References

[1] D.A. Edwards and M.J. Syphere, “An introduction to the physics of high energy accelerators”, Chapter 6 “intensity dependent effects”, p. 172-186.
[2] J.B. Jeanneret and R. Ostojic: ``Geometrical acceptance in LHC Version 5.0’’, LHC project note 111, 1997
[3] V. Kain, “Machine protection and beam quality during the LHC injection process”, CERN-THESIS-2005-047
[4] R. Bruce et al., “Parameters for aperture calculations at injection for HL-LHC”, CERN-ACC-2016-0328
[5] F. Maria Velotti, “Higher brightness beams from the SPS for the HL-LHC era”, EPFL Ph.D. thesis, to be published.
[6] W. Bartmann et al., “Beam transfer to the FCC-hh collider from a 3.3 TeV booster in the LHC tunnel”, Proceedings of IPAC2015, Richmond, VA, USA.
[7] W. Bartmann et al., “LHC injection and extraction losses”, Proceedings Evian workshop 2010.
[8] O. Stein et al., “Investigation of injection losses at the large hadron collider with diamond based particle detectors”, Proceedings of IPAC2016, Busan, Korea.
[9] L. Drosdal et al., “SPS transverse beam scraping and LHC injection losses”, Proceedings of IPAC 2012, New Orleans, Louisiana, USA.
[10] D. Boussard and Y. Mizumachi, “Production of beams with high line-density by azimuthal combination of bunches in a synchrotron”, IEEE Transaction on Nuclear Science, Vol. NS-26, No. 3, June 1979
[11] T. Argyroupoulos “Slip stacking in the SPS (mode of operation with beam, simulations, scheduled tests and implementation), LIU day 2014, CERN: https://indico.cern.ch/event/299470/contributions/686512/attachments/564153/777111/LIUSlipstacking_2014.pptx
[12] J. Eldred and R. Zwaska, “Slip-stacking dynamics and the 20 Hz Booster”, Fermilab-conf-14-565-APC.
[13] C. Prior, “Ring injection for high intensity accelerators”, CAS on “High power hadron machines”, Bilbao, Spain, 2011.
[14] V. Forte, Performance of the CERN PSB at 160 MeV with H- charge exchange injection, PhD thesis – CERN and Université Blaise Pascal
[15] C. Carli et al., “Combined longitudinal and transverse multi-turn injection in a heavy ion accumulator”, Proceedings of PAC 1997, Vancouver, Canada

Back-up slides

Normalised phase space

- Transform real transverse coordinates (x, x', s) to normalized co-ordinates ($\bar{X}$, $\bar{X}'$, μ) where the independent variable becomes the phase advance μ:

$$\begin{bmatrix} \bar{\mathbf{X}} \\ \bar{\mathbf{X}}' \end{bmatrix} = \mathbf{N} \cdot \begin{bmatrix} x \\ x' \end{bmatrix} = \sqrt{\frac{1}{\beta(s)}} \cdot \begin{bmatrix} 1 & 0 \\ \alpha(s) & \beta(s) \end{bmatrix} \cdot \begin{bmatrix} x \\ x' \end{bmatrix}$$

$$x(s) = \sqrt{\varepsilon}\sqrt{\beta(s)}\cos[\mu(s) + \mu_0]$$

$$x'(s) = -\frac{\sqrt{\varepsilon}}{\sqrt{\beta(s)}}[\alpha(s)\cos(\mu(s) + \mu_0) + \sin(\mu(s) + \mu_0)]$$

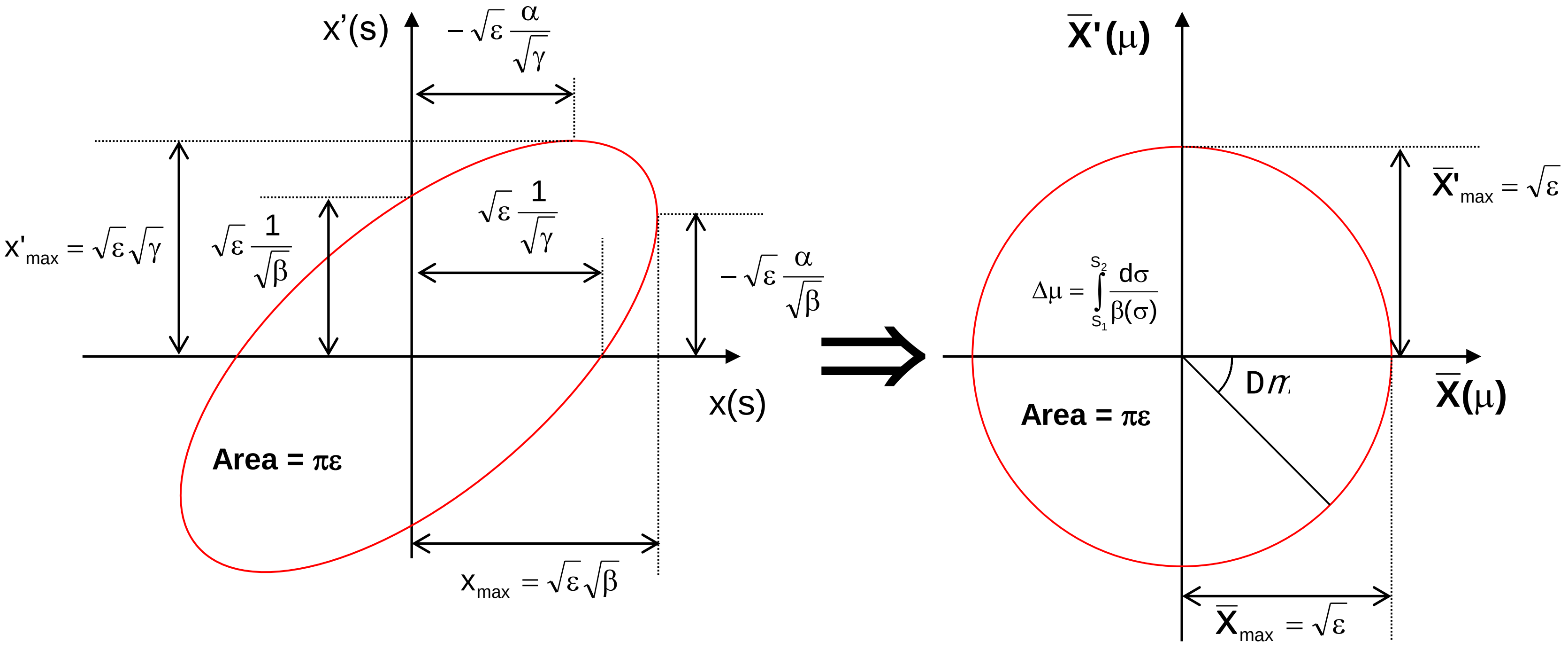
$$\mu(s) = \int_0^s \frac{d\sigma}{\beta(\sigma)}$$

$$\bar{\mathbf{X}}(\mu) = \sqrt{\frac{1}{\beta(s)}} \cdot x = \sqrt{\varepsilon}\cos[\mu + \mu_0]$$

$$\bar{\mathbf{X}}'(\mu) = \sqrt{\frac{1}{\beta(s)}} \cdot \alpha(s)x + \sqrt{\beta(s)}x' = -\sqrt{\varepsilon}\sin[\mu + \mu_0] = \frac{d\bar{\mathbf{X}}}{d\mu}$$

Normalised phase space

Real phase space | Normalised phase space



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

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

Beam position and angle

At the kicker, where $\beta(s) = \beta_k$, we want $x(s) = 0$ and $x'(s) = -\theta_{kicker}$, being μ the phase advance between the septum and the kicker:

$$x(s) = \sqrt{\varepsilon}\sqrt{\beta_k}\cos(\mu + \mu_0) = 0 \longrightarrow \mu + \mu_0 = \frac{\pi}{2}$$

$$x'(s) = -\frac{\sqrt{\varepsilon}}{\sqrt{\beta_k}}[\alpha(s)\cos(\mu + \mu_0) + \sin(\mu + \mu_0)] = -\theta_{kicker} \longrightarrow \sqrt{\varepsilon} = \theta_{kicker}\sqrt{\beta_k}$$

At the septum:

$$x_s = \sqrt{\varepsilon}\sqrt{\beta_s}\cos(\mu_0) = \theta_{kicker}\sqrt{\beta_k\beta_s}\cos(\mu - \frac{\pi}{2}) = \theta_{kicker}\sqrt{\beta_k\beta_s}\sin(\mu)$$

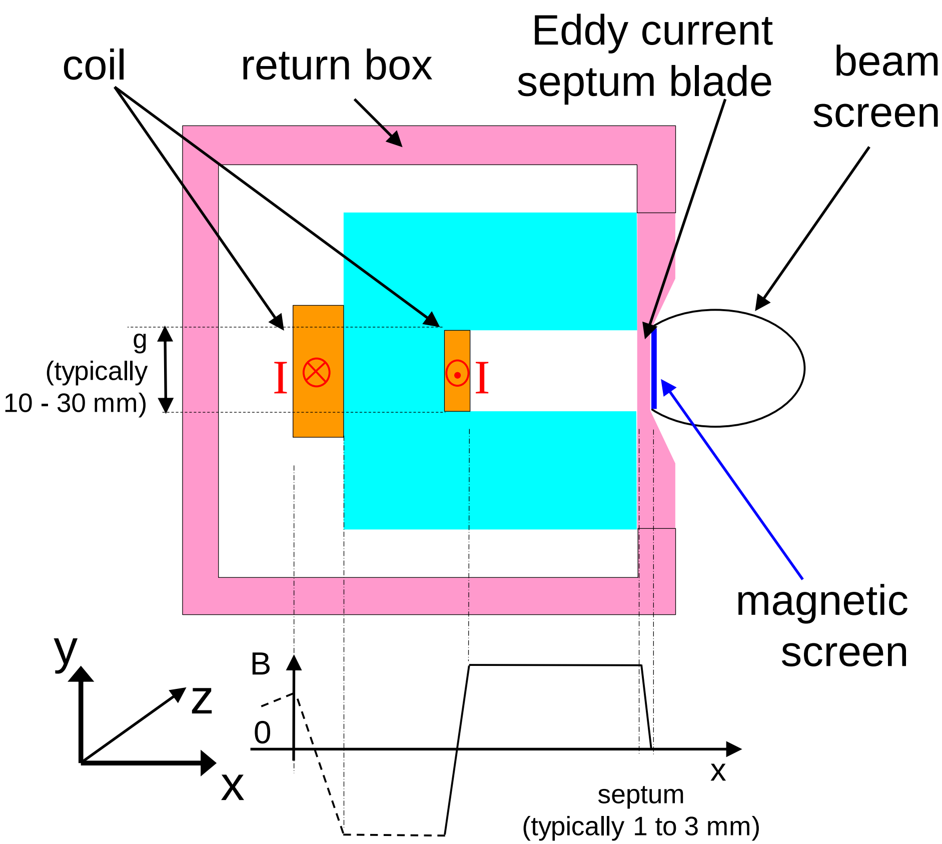
$$x'_s = -\frac{\theta_{kicker}\sqrt{\beta_k}}{\sqrt{\beta_s}}[\alpha_s\sin(\mu) + \cos(\mu)] = -\frac{x_s}{\beta_s}[\alpha_s + \cot g(\mu)]$$

$$\theta_{kicker} = \frac{x_s}{\sqrt{\beta_k\beta_s}\sin(\mu)}$$

A small θ_{kicker} means a reduced cost ➔ we want μ as close as possible to $\pi/2$ and large β_k

Septum leakage field

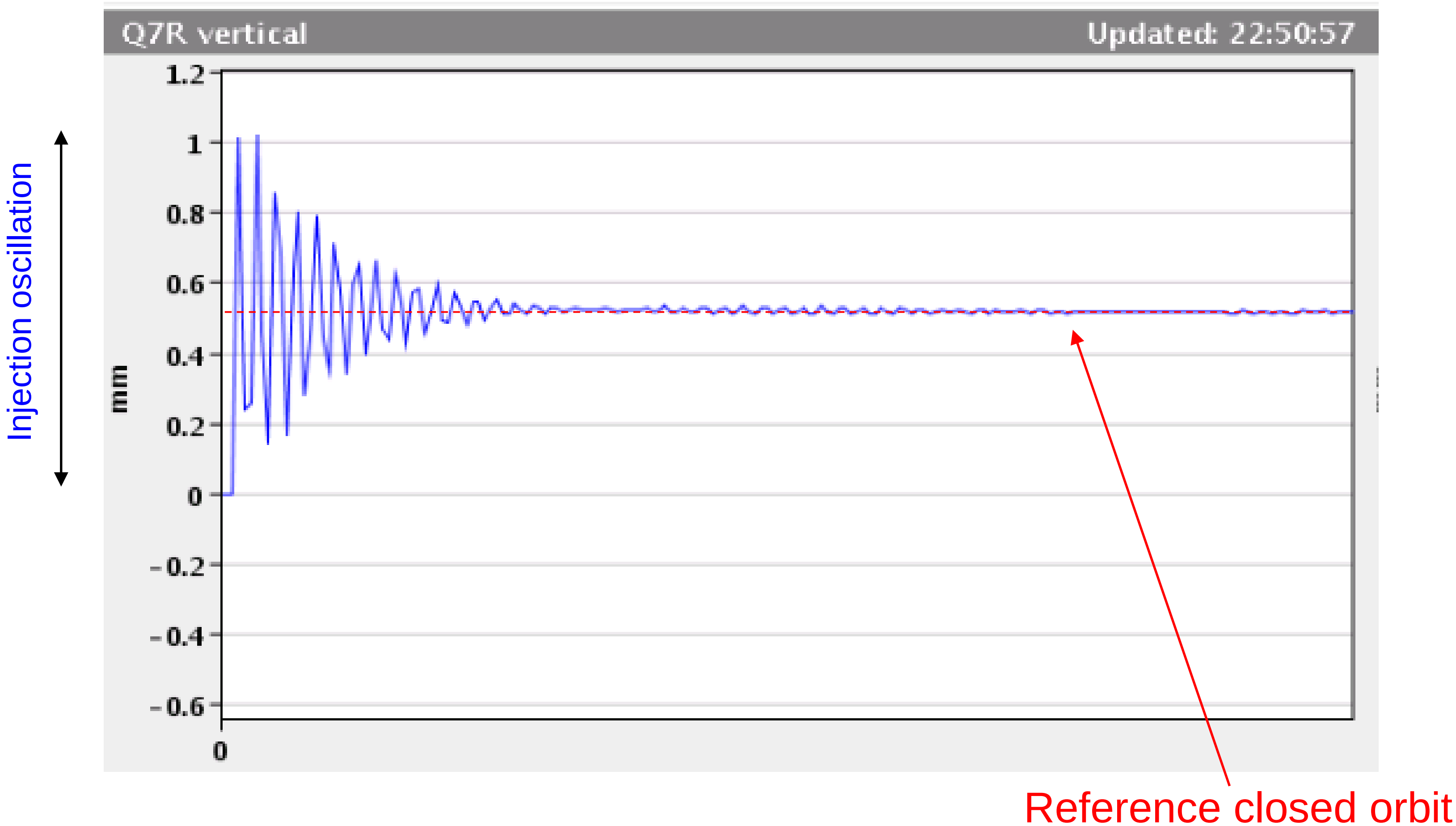
Stray field loss into the “filed-free” region.
Particularly critical for low injection energy ➔ adequate shielding



- Coil removed from septum and placed behind C-core yoke:
  - Coil dimension not critical
  - Very thin septum blade
- Magnetic field pulse induces eddy currents in septum blade
- Eddy currents shield the circulating beam from magnetic field
- Return box and magnetic screen reduce fringe field seen by circulating beam

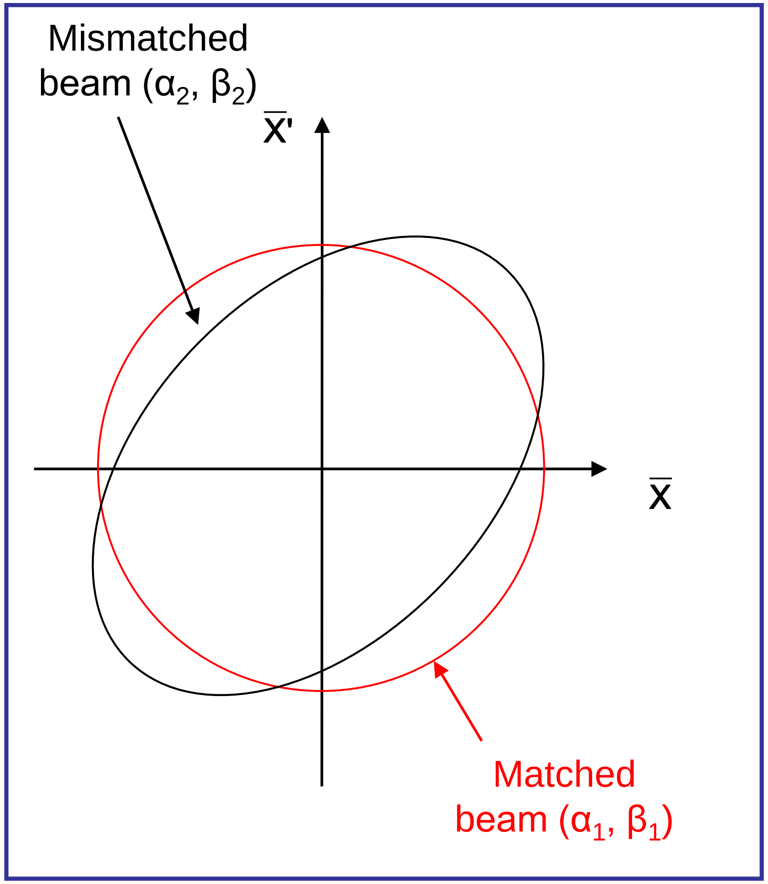
Filamentation

- The residual transverse oscillations lead to an *effective* emittance blow-up through filamentation:

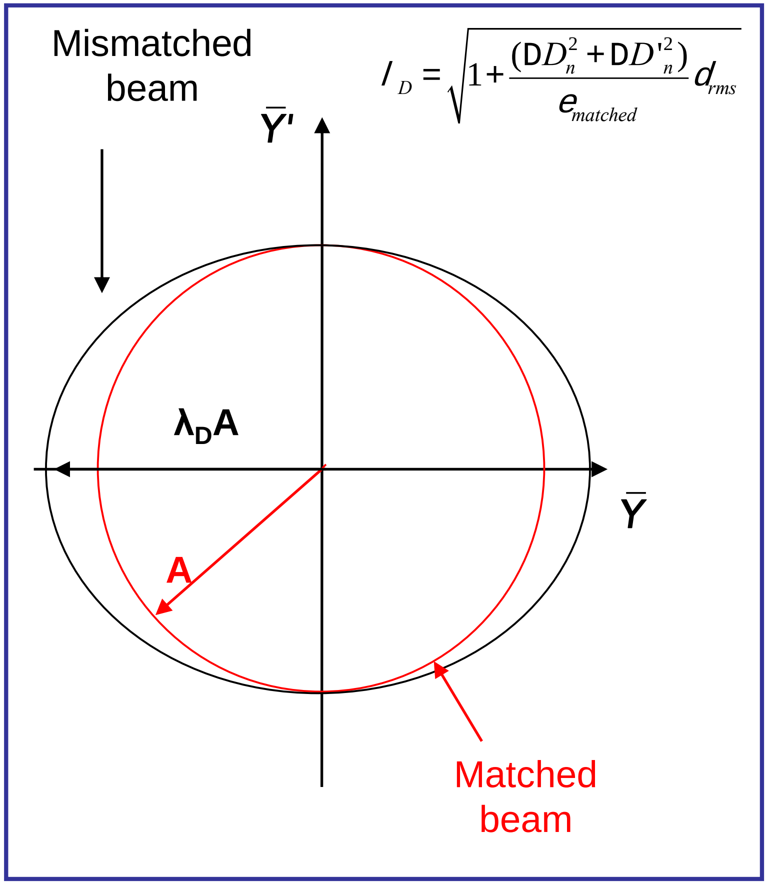


Blow-up from optics mismatch

Betatron mismatch



Dispersion mismatch



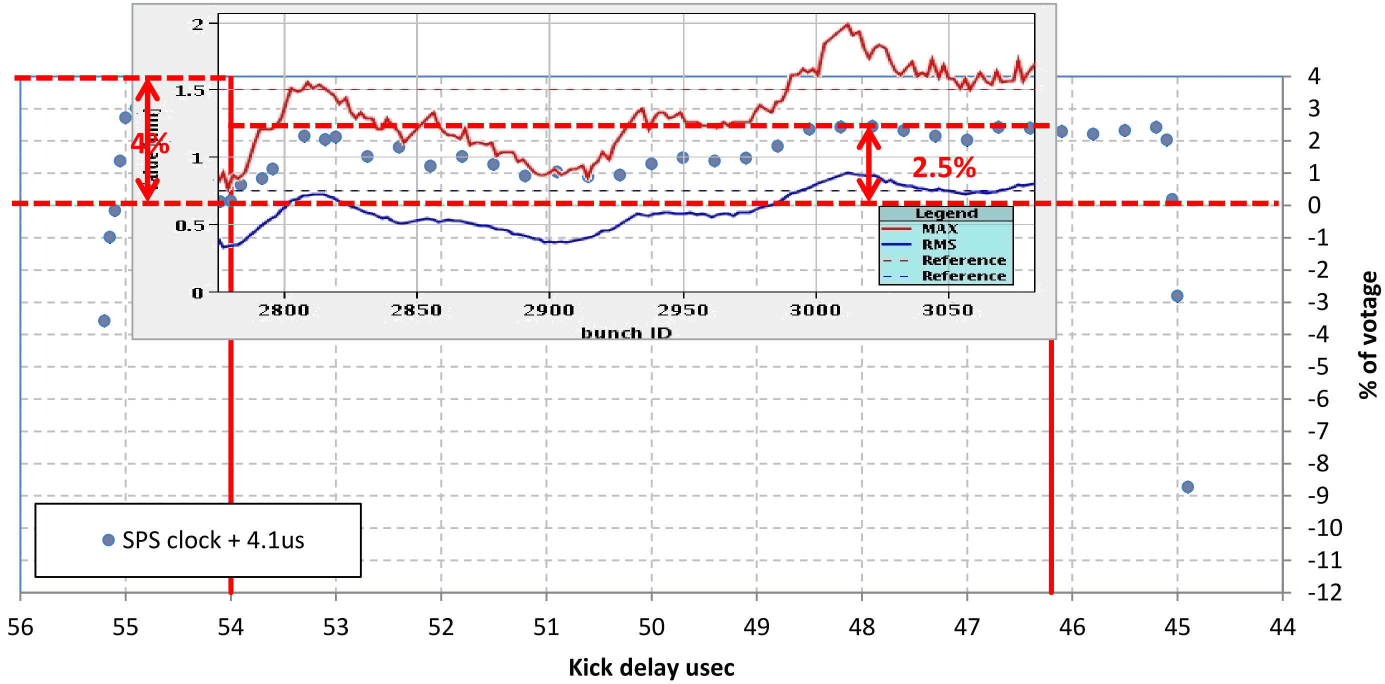
$$\varepsilon_{\text{diluted}} = \frac{1}{2}\left(\frac{\beta_1}{\beta_2} + \frac{\beta_2}{\beta_1}\left(\alpha_1 - \alpha_2\frac{\beta_1}{\beta_2}\right)^2 + \frac{\beta_2}{\beta_1}\right)\varepsilon_{\text{matched}}$$

$$\varepsilon_{\text{diluted}} = \varepsilon_{\text{matched}} + \frac{\Delta D_n^2 + \Delta D_n'^2}{2}\delta_{\text{rms}}^2$$

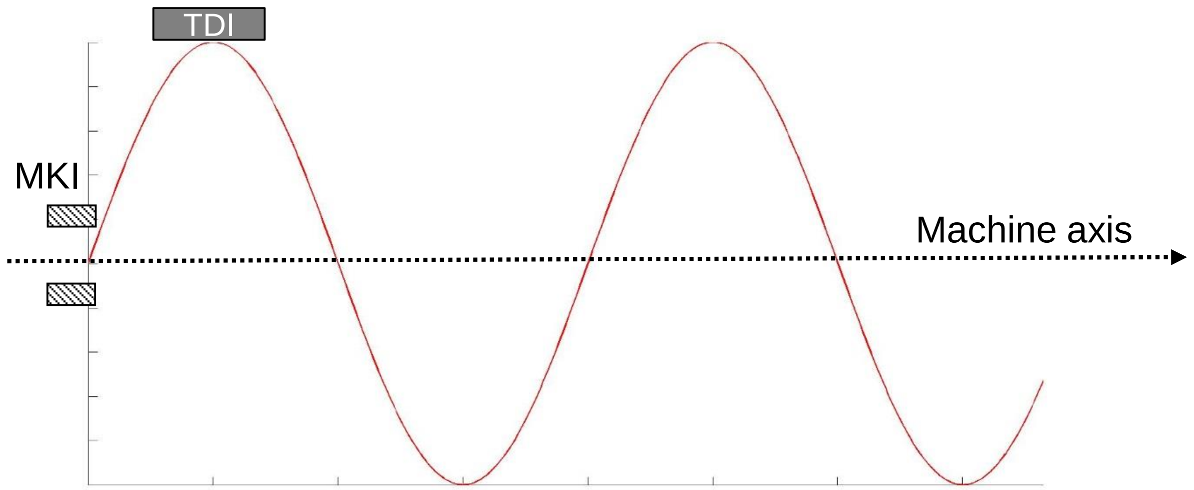
V. Kain's Lecture

SPS extraction kicker waveform

- The kicker waveform shows a ripple varying up to 2.5% of kick (max. to min.) at the flattop (4% at initial overshoot)
- Mitigations:
  - Improve the kicker flat-top ripple
  - Change the delay to move the beam to a flatter part of the waveform (if enough space)

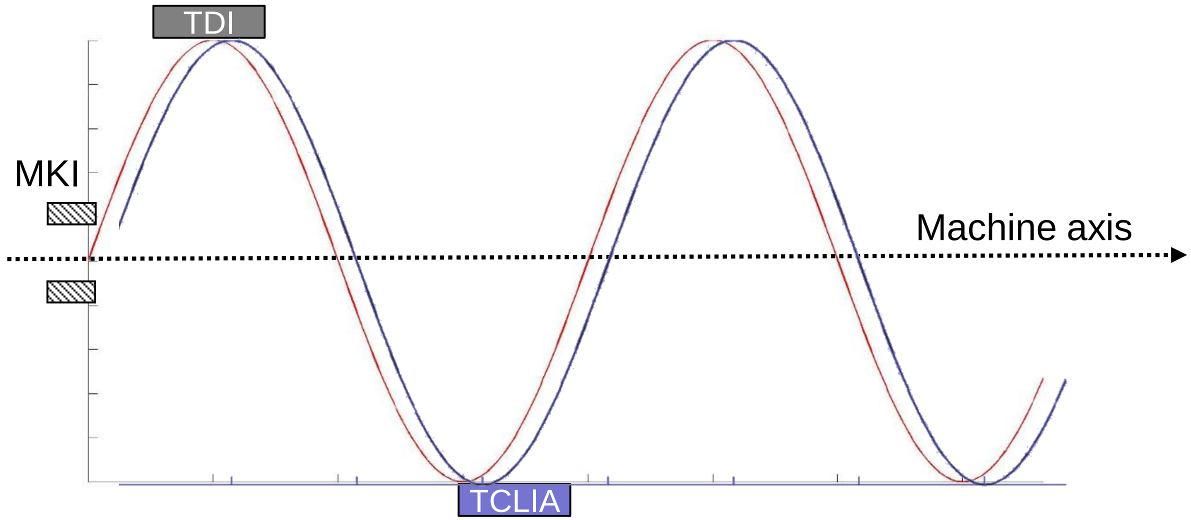


Phase advance for Inj. Protection



90° phase advance MKI ➔TDI

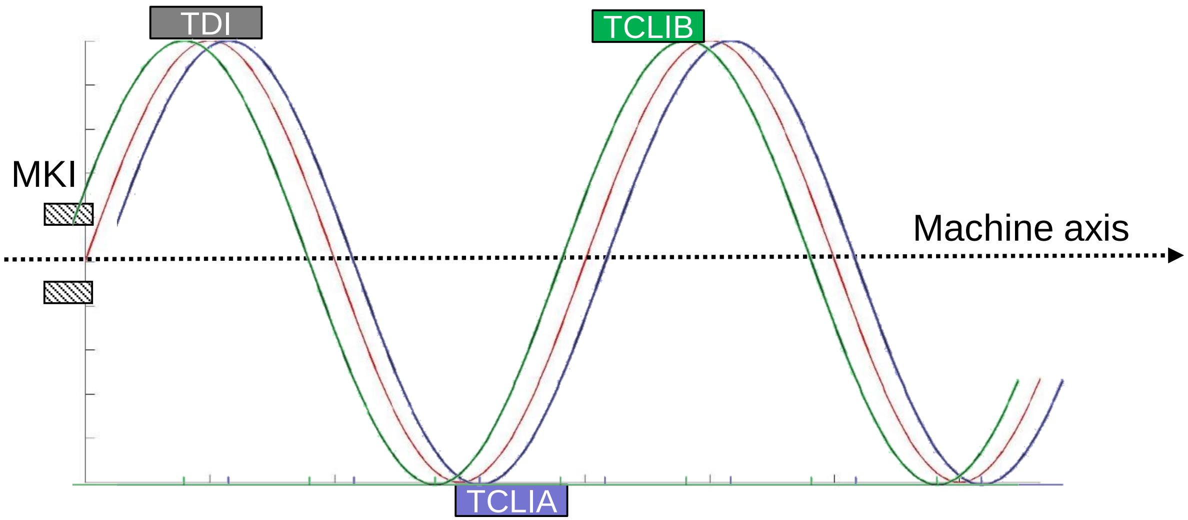
Phase advance for Inj. Protection



90° phase advance MKI ➔TDI

Two auxiliary collimators are installed at 180°+20° (TCLIA)

Phase advance for Inj. Protection

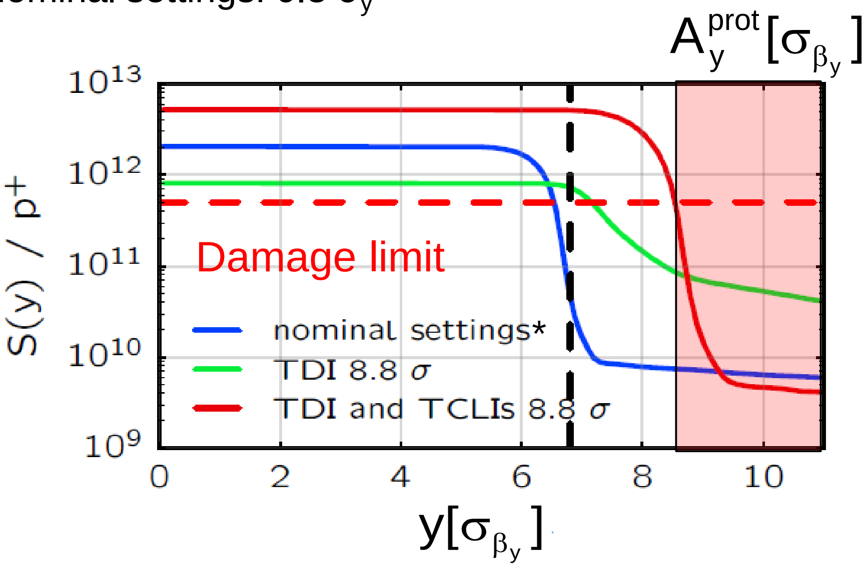


90° phase advance MKI ➔TDI

Two auxiliary collimators are installed at 180°+20° (TCLIA) and 360°-20° (TCLIB) wrt TDI to take into account possible phase-advance errors [3].

Transmission and multi-turns effects

*Nominal settings: 6.8 σ_y



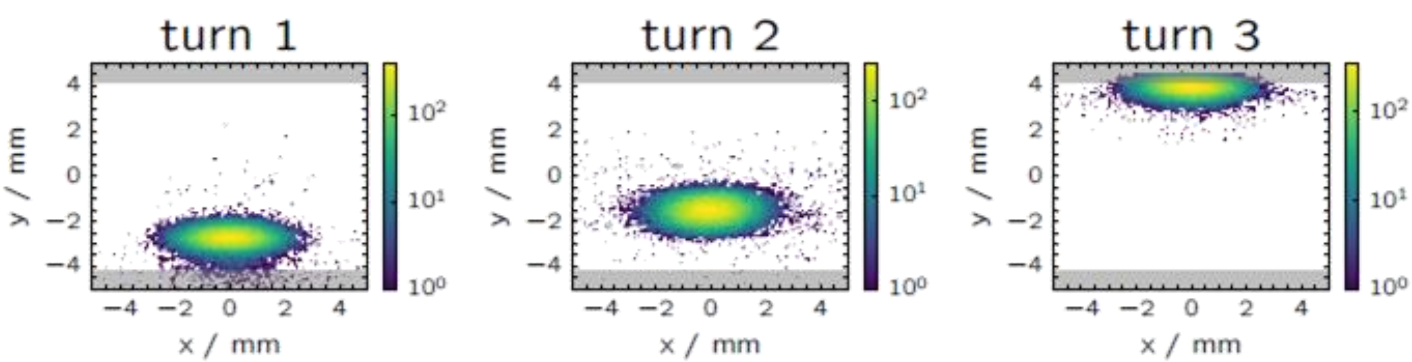
Survival function S(y) normalised to the beam intensity N_p: number of protons escaping the protection devices as a function of the amplitude [4]

$$S(y) \equiv N_p \int_A^{\infty} f(y)dy$$

Where f(y) is the probability density function of the kicked beam

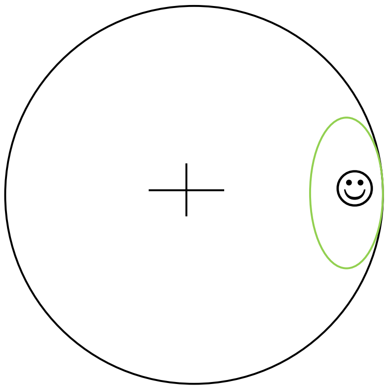
Multi-turn effects: mis-kicked beam escaping the TDI (misaligned by 1 σ) will intercept the TCLIB at the 3rd turn (vertical tune 59.31). Three turns are needed between high loss detection and beam dump [5]!

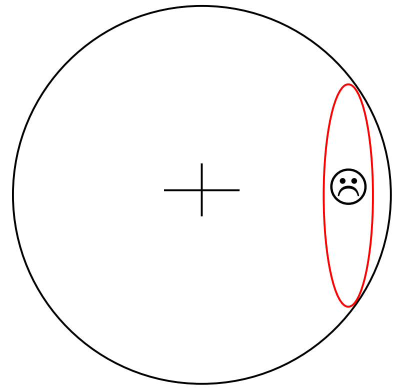
TCLIB

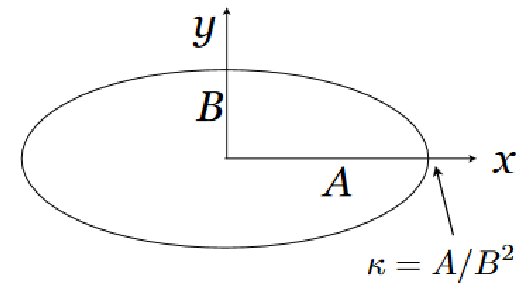


F.M. Velotti

Optimum optics condition for injected beam







Curvature of the ellipse in the ring phase space and normalised coordinates: $k = \frac{1}{\sqrt{\varepsilon}}$ Where $\bar{x}^2 + \bar{x}'^2 = \varepsilon$

The ellipse curvature for the injected beam (assuming upright ellipse) is: $k_i = \left(\frac{\beta_i}{\beta}\right)^{\frac{3}{2}} \frac{1}{\sqrt{\varepsilon_i}}$

Conditions for optimum injection into phase space [13]: $\frac{\alpha_i}{\beta_i} = \frac{\alpha}{\beta} = -\frac{x_i' - x_0'}{x_i - x_0}$ and $\frac{\beta_i}{\beta} \geq \left(\frac{\varepsilon_i}{\varepsilon}\right)^{\frac{1}{3}}$

$(x_0, x_0') =$ Closed orbit

$(x_i, x_i') =$ Centre of injected beam