# AXEL-2023

## Introduction to Particle Accelerators

## *Transfer lines, injection and ejection*

- ✓ *Transfer lines: Transverse matching*
- ✓ *Single turn injection*
- ✓ *Multi-turn injection for protons and heavy ions*
- ✓ *Charge exchange injection for protons*
- ✓ *Leptons, betatron and synchrotron injection*
- ✓ *Single-turn & multi-turn extraction*

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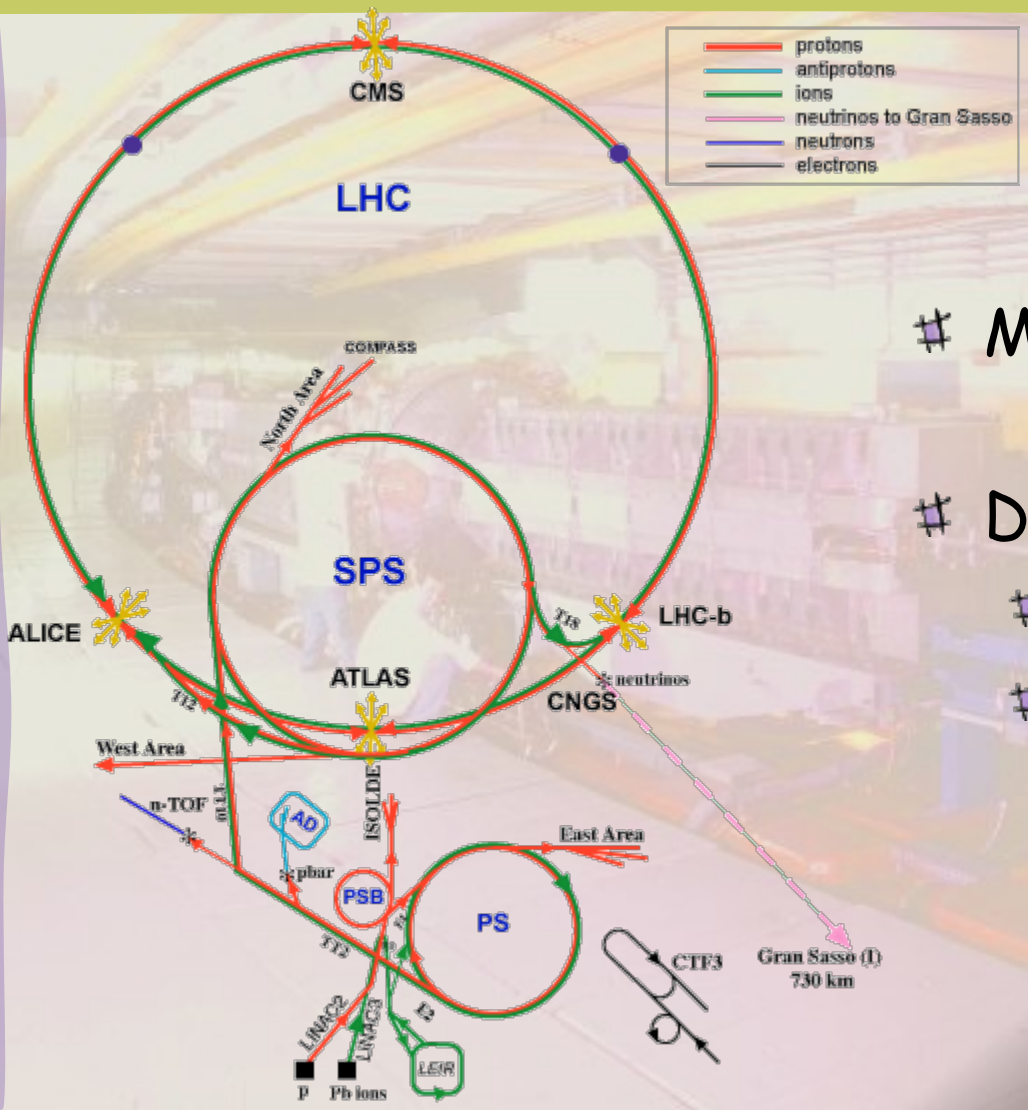
# Overview

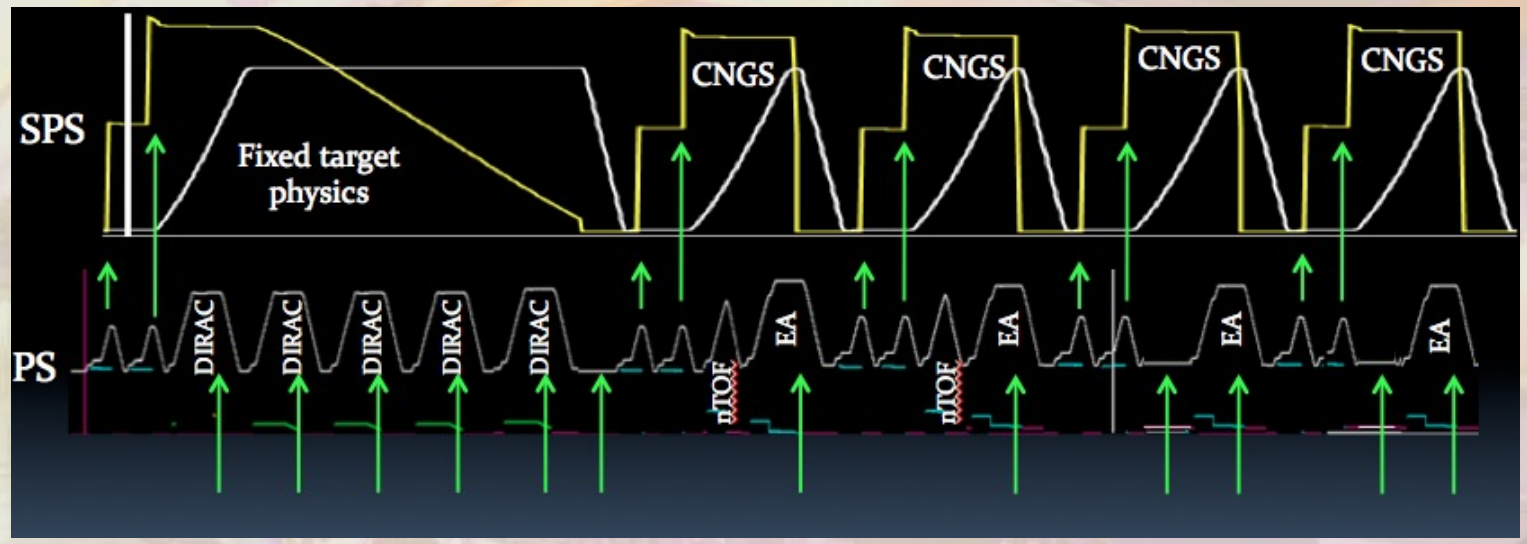
- How to get a beam into and out of circular accelerators and storage rings.
- The wide range of requirements will require different solutions:
  - injection into a synchrotron from a LINAC
  - transfer between two synchrotrons
  - extraction to an end-user facility
  - accumulation of particles, to increase intensity
  - dealing with different particles

# CERN Accelerators




- Many transfer lines.
- Different types of:
  - Injection
  - Ejection

# Cycling the CERN Accelerators




- Time sharing to serve all experiments and accelerators.
- Fast and slow extraction can be clearly distinguished

# Transfer Lines (1)

- Particles trajectories in transfer lines are treated the same way as in a circular machine, with the only difference that they pass only once.
- We use:
  - Dipoles to deflect particles
  - Quadrupoles to focus particles transversely
- This leads to betatron oscillations and functions
- We can use the 2x2 matrices to describe the transverse motion of the particle

$$\begin{pmatrix} x_2 \\ x'_2 \end{pmatrix} = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \begin{pmatrix} x_1 \\ x'_1 \end{pmatrix}$$

- But… **the transfer line is not closed up on itself !**

# Transfer Lines (2)

- The particles trajectories in transfer lines are not closed
- This means that the
  - initial lattice parameters ≠ final lattice parameters
- Due to this the transfer matrix gets slightly more complicated.

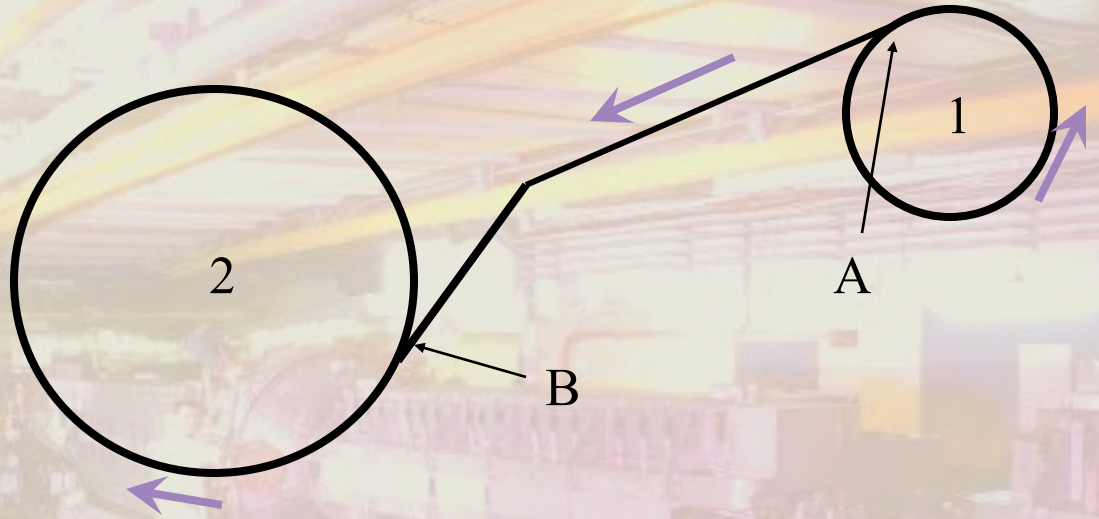
$$\begin{pmatrix} x_2 \\ x_2' \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{\beta_2}{\beta_1}}(\cos\mu + \alpha_1 \sin\mu) & \sqrt{\beta_1\beta_2}\sin\mu \\ \frac{(1+\alpha_1\alpha_2)\sin\mu + (\alpha_2 - \alpha_1)\cos\mu}{\sqrt{\beta_1\beta_2}} & \sqrt{\frac{\beta_1}{\beta_2}}(\cos\mu - \alpha_2 \sin\mu) \end{pmatrix} \times \begin{pmatrix} x_1 \\ x_1' \end{pmatrix}$$

# Transfer Lines (3)

$$\begin{pmatrix} x_2 \\ x_2' \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{\beta_2}{\beta_1}}(\cos\mu + \alpha_1 \sin\mu) & \sqrt{\beta_1\beta_2}\sin\mu \\ \frac{(1+\alpha_1\alpha_2)\sin\mu + (\alpha_2 - \alpha_1)\cos\mu}{\sqrt{\beta_1\beta_2}} & \sqrt{\frac{\beta_1}{\beta_2}}(\cos\mu - \alpha_2 \sin\mu) \end{pmatrix} \times \begin{pmatrix} x_1 \\ x_1' \end{pmatrix}$$

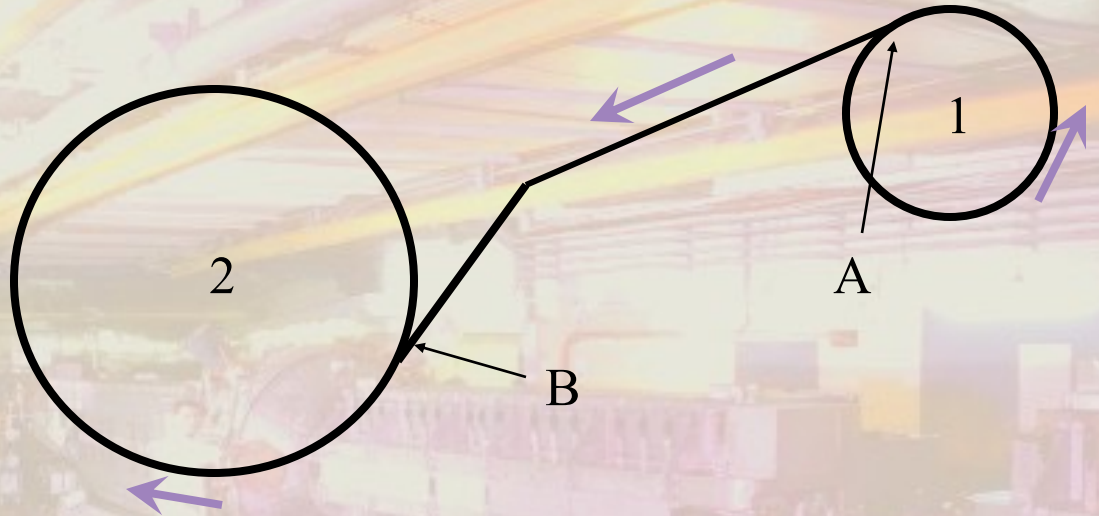
- For $\beta_1 = \beta_2$, $\alpha_1 = \alpha_2$ etc this reduces to the matrix we had for our accelerator, but for transfer lines we must retain the full matrix.
- We can calculate the **Twiss** parameters exactly as for our accelerator.
- However, there are an infinite number of solutions... since for any value $\beta_1$ there will give a particular solution for $\beta_2$.
- Thus the final $\alpha$, $\beta$, etc. depends on the initial $\alpha$, $\beta$, etc.

# Transfer between machines (1)



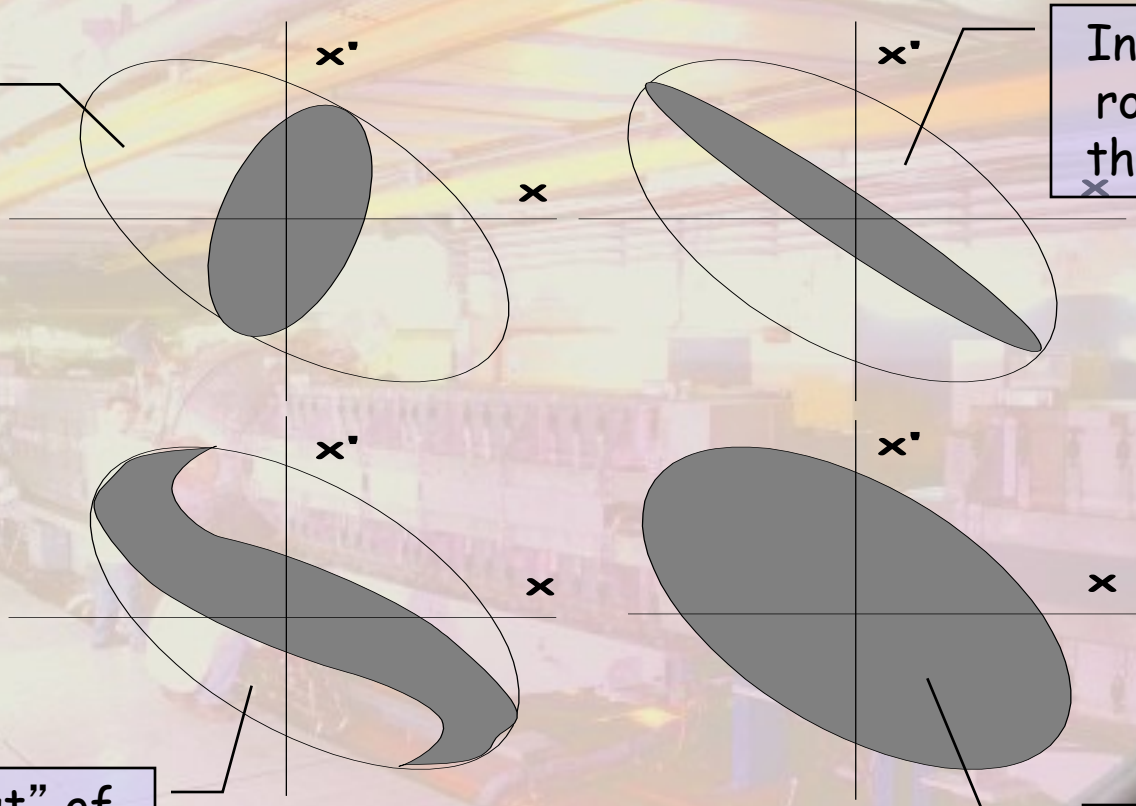

- The initial phase space ellipse will be determined by the accelerator (1), from which the beam is being extracted. (point A)
- Then we calculate the transport matrix that describes the transport line and we calculate the final ellipse at point B

# Transfer between machines (2)




- However, machine (2) will have it's own predetermined transverse phase space ellipse at B.
- If the phase space ellipse, which arrives from the transfer line is different (which can be the case) then.... what will happen to the beam?

# Transverse phase space



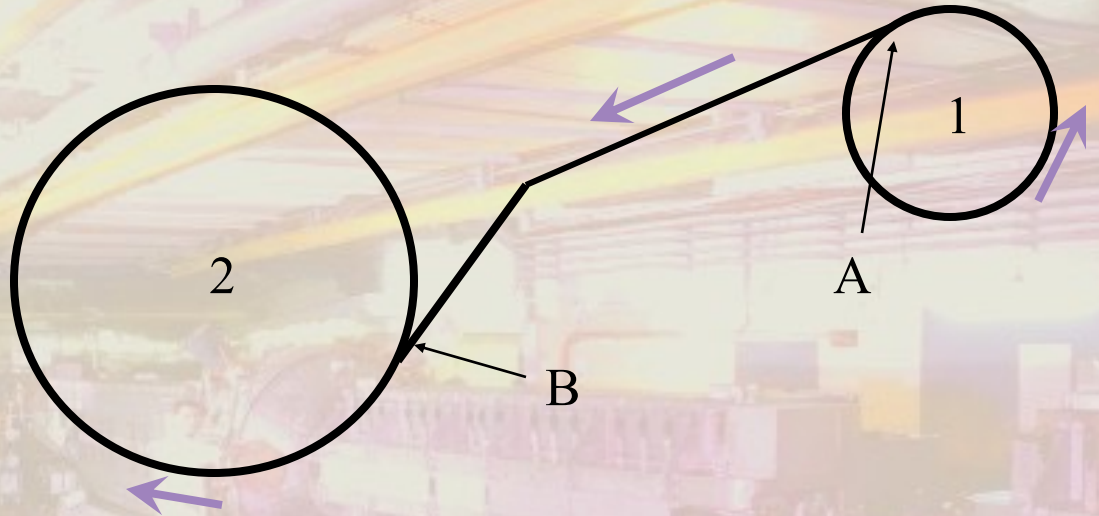

At injection

Injected beam rotates inside the new ellipse

"smear out" of phase space and emittance blow-up begins

emittance blow-up complete

# Transverse matching

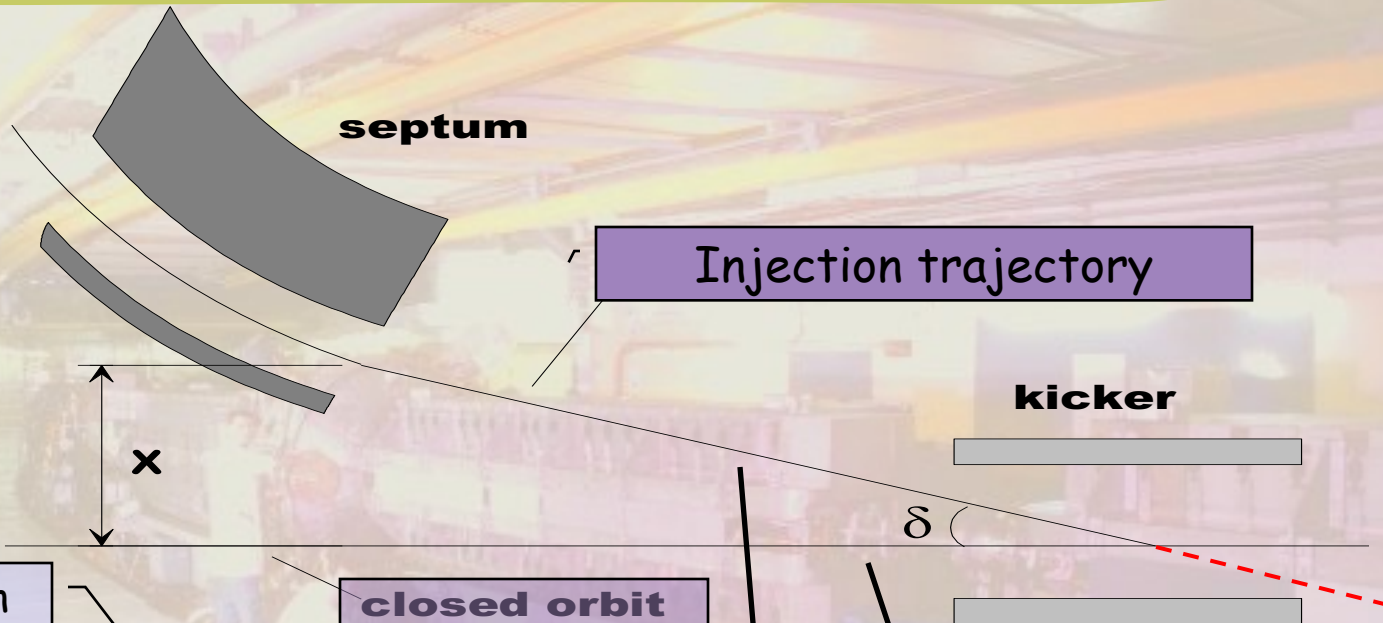



- Set initial $\beta_1, \alpha_1.. = \beta, \alpha$ for machine 1 at point **A**
- Calculate the transfer matrix so that $\beta_2, \alpha_2.. = \beta, \alpha$ for machine 2 at point **B**
- Be careful with the envelope considerations in the transfer line (emittance vs acceptance).
- Variables $\Rightarrow$ quadrupole strengths and positions

# Single turn injection (1)

- With a single turn injection we inject one or more bunches into a synchrotron in a single turn. (revolution period of receiving machine)
- Elements involved:
  - Transfer line
  - Septum magnet
  - Fast kicker magnet
  - Synchrotron (receiving machine)

# Single turn injection (2)



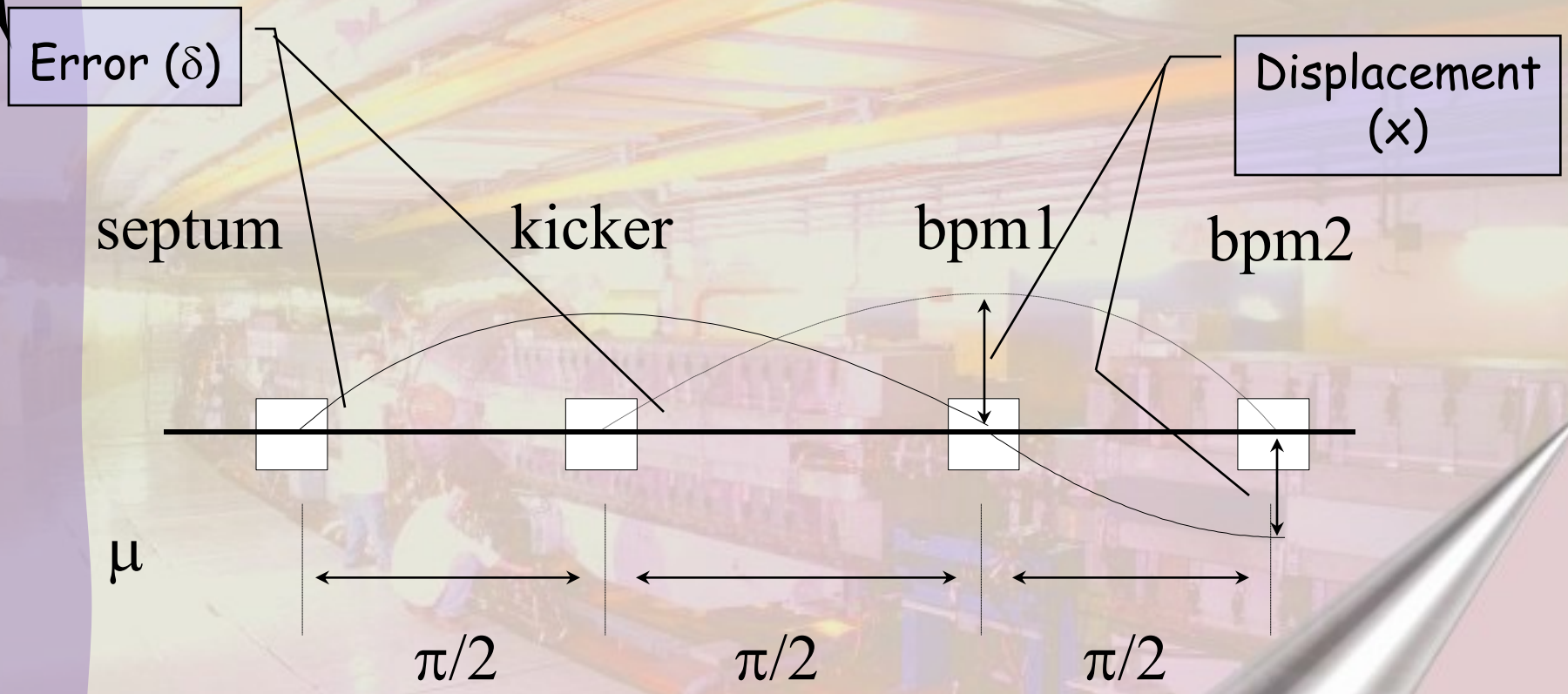

$$x = \sqrt{\beta_s \cdot \varepsilon_i} + \sqrt{\beta_s \cdot \varepsilon} + D_s\left(\frac{dp_i}{p} + \frac{dp}{p}\right) + x_{co} + x_s$$

$$\delta = \frac{x}{\sqrt{\beta_s \cdot \beta_k} \cdot \sin(\mu_{(s \to k)})}$$

Minimize δ to reduce kicker strength

βs >>
βk >>
μ(s->k) =(2n+1)π/2

# Injection oscillations (1)




$$\delta = \frac{x}{\sqrt{\beta_a . \beta_b}\,\sin(\mu)}$$

=1

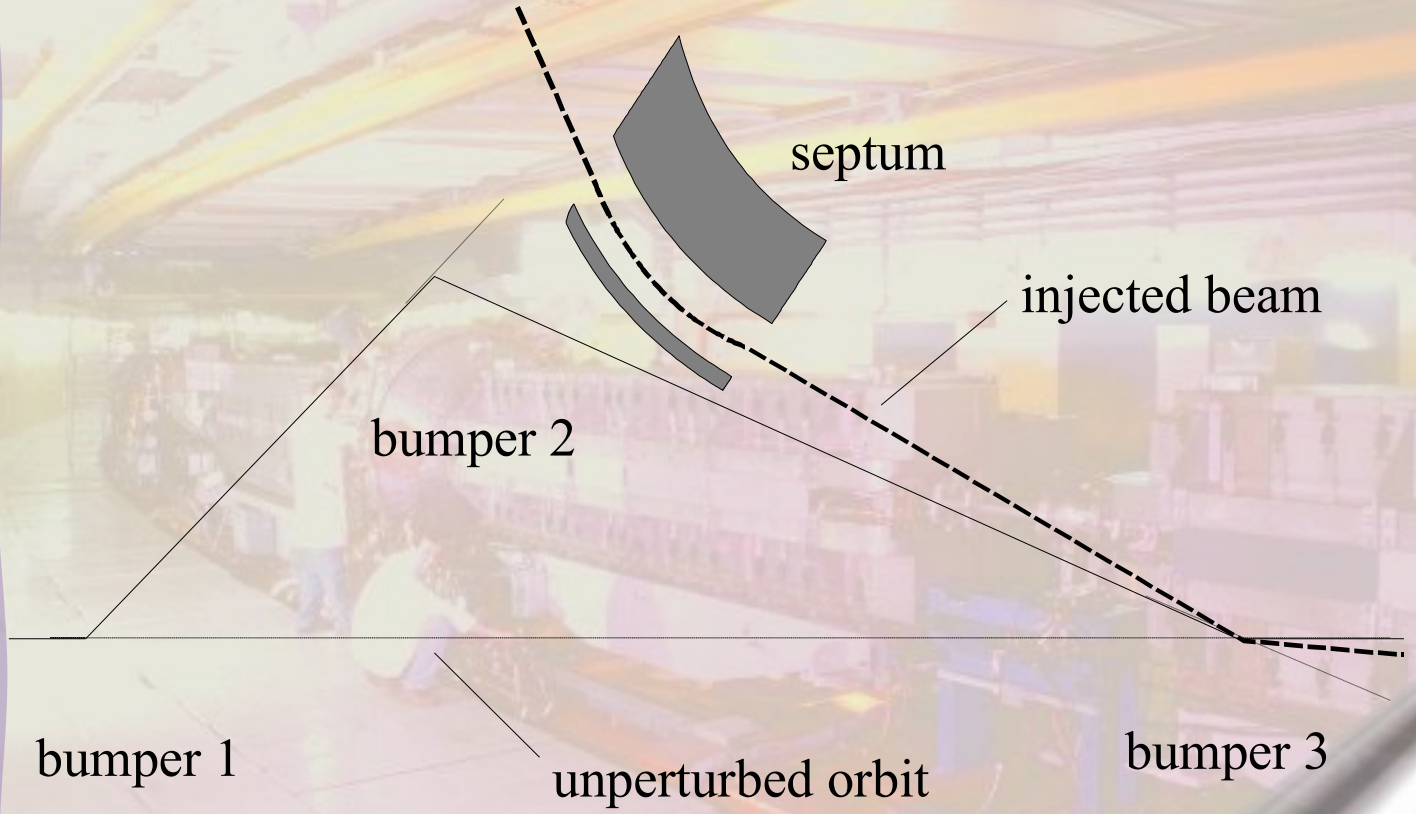
# Injection oscillations (2)

- Any residual transverse oscillation will lead to an emittance blow-up
- Measurement methods, FFT analysis of one BPM signal, compare single-turn and closed orbit
- Possible that injection is well corrected, but there is still an emittance blow-up
- Matching…

# Multi-turn injection for hadrons (1)

- For hadrons the beam density at injection is either limited by space charge effects or by the injector (heavy ions…)
- Usually we inject from a LINAC into a synchrotron
- We cannot increase charge density, so we fill the horizontal phase space to increase injected intensity.
- Elements used
  - Septum
  - Fast beam bumpers, made out of 3 or 4 dipoles for more flexibility, to create a local beam bump

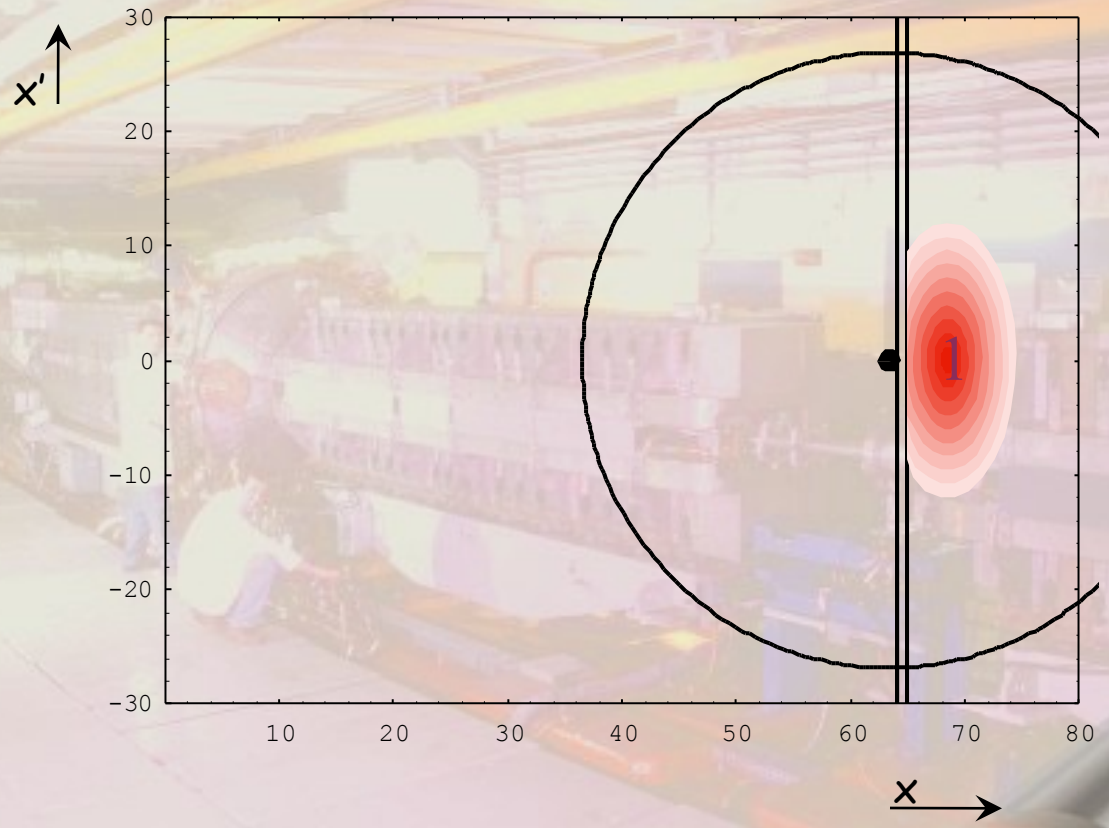
# Multi-turn injection for hadrons (2)



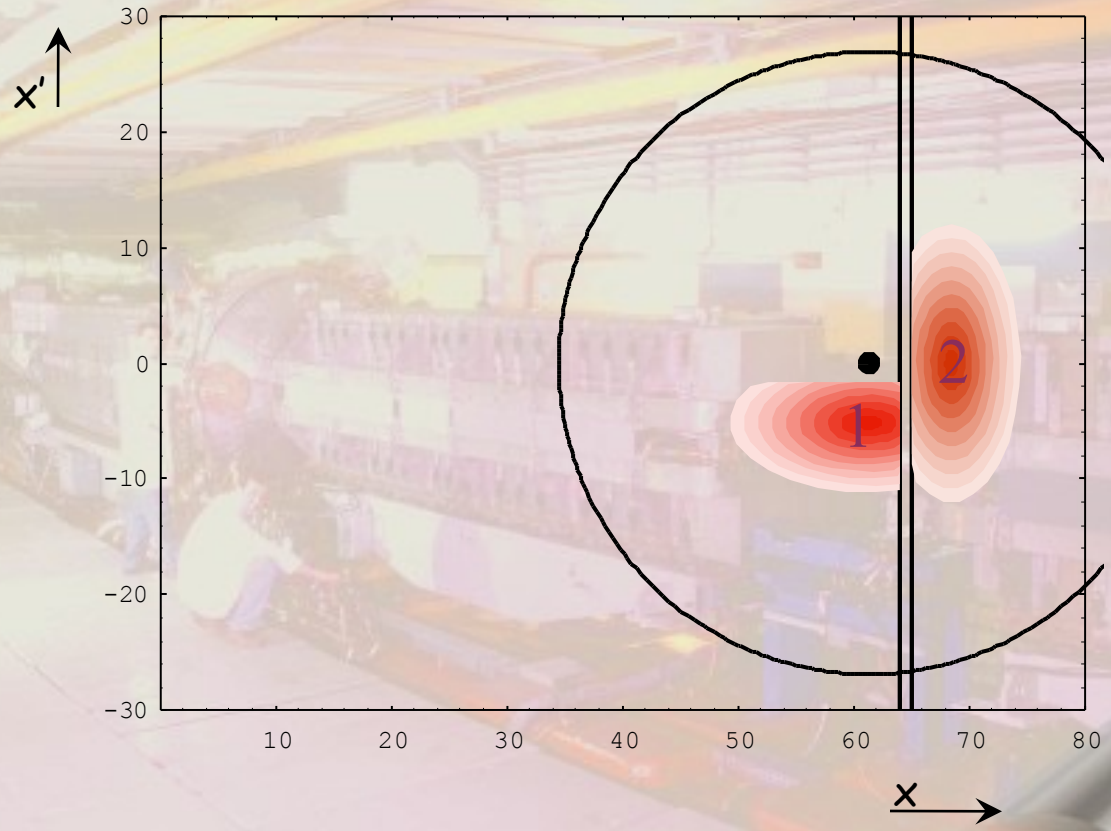
# Multi-turn injection for hadrons (3)

- Lets have a look at a real example…
- Could be the PS Booster
- Let qh = .25 (fractional tune)
- Let us have a look what happens in phase space turn after turn

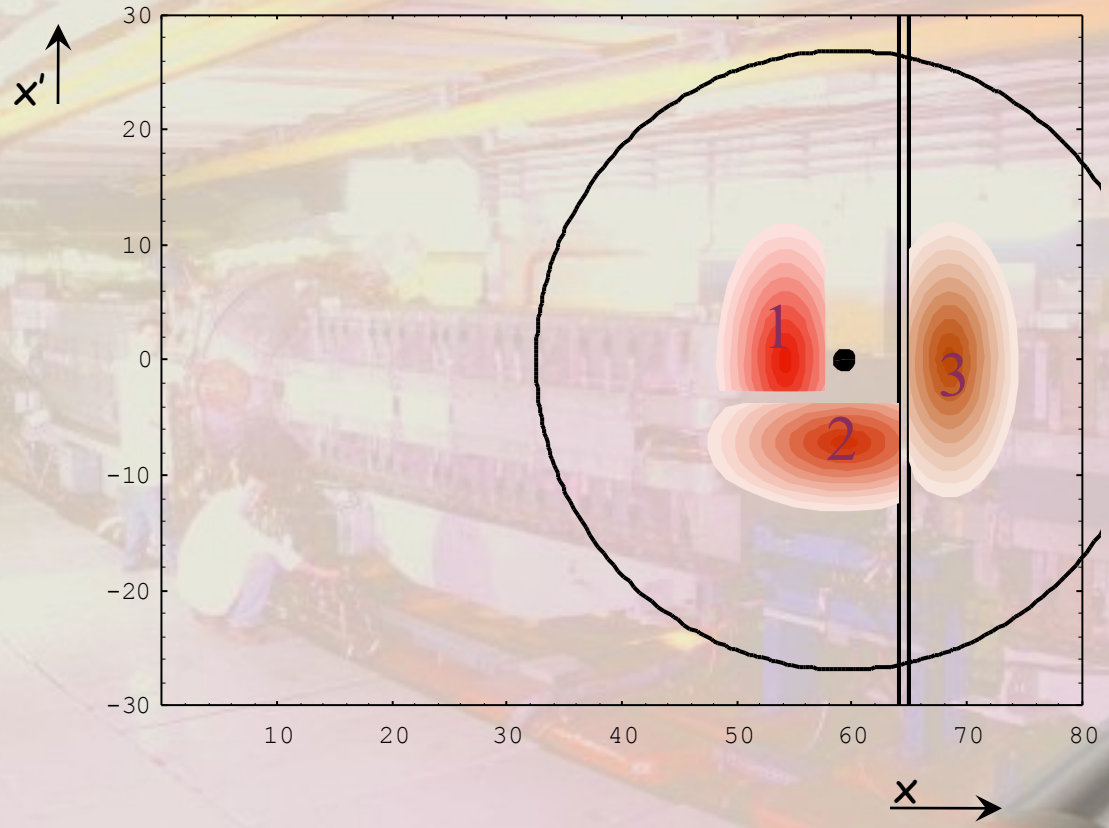
# Multi-turn injection for hadrons (4)



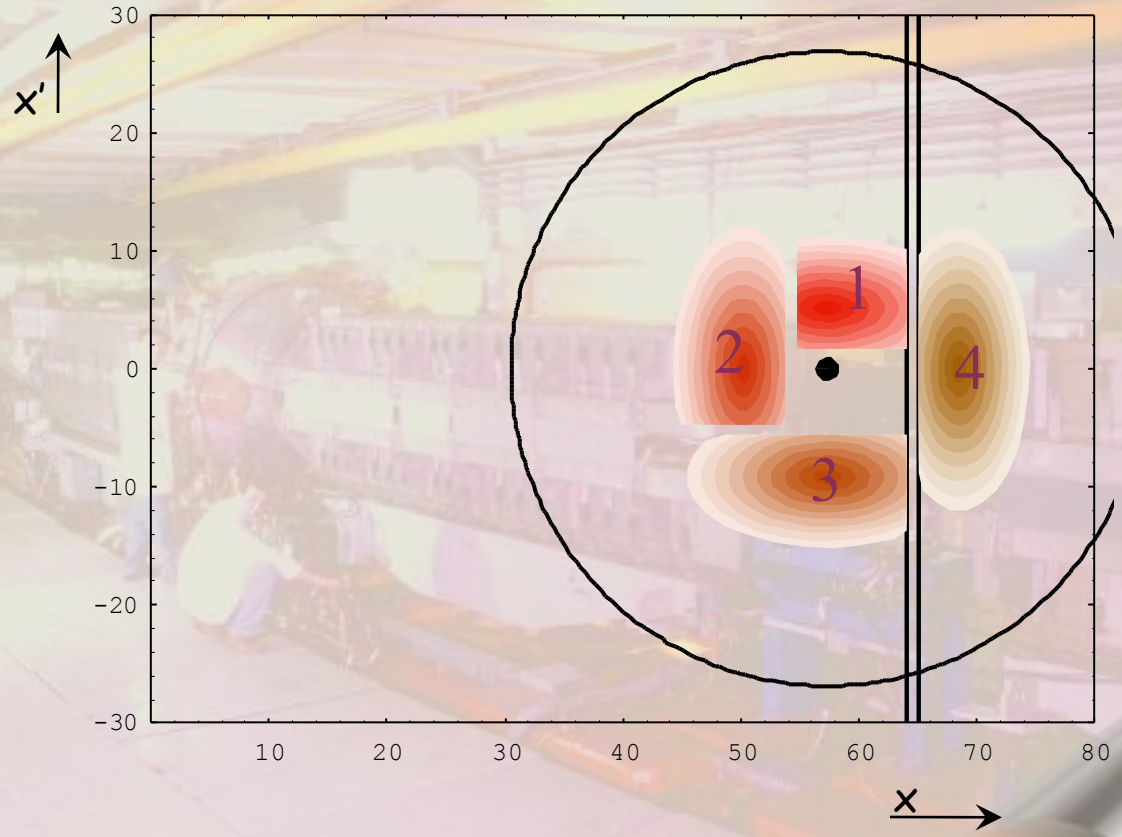
# Multi-turn injection for hadrons (5)



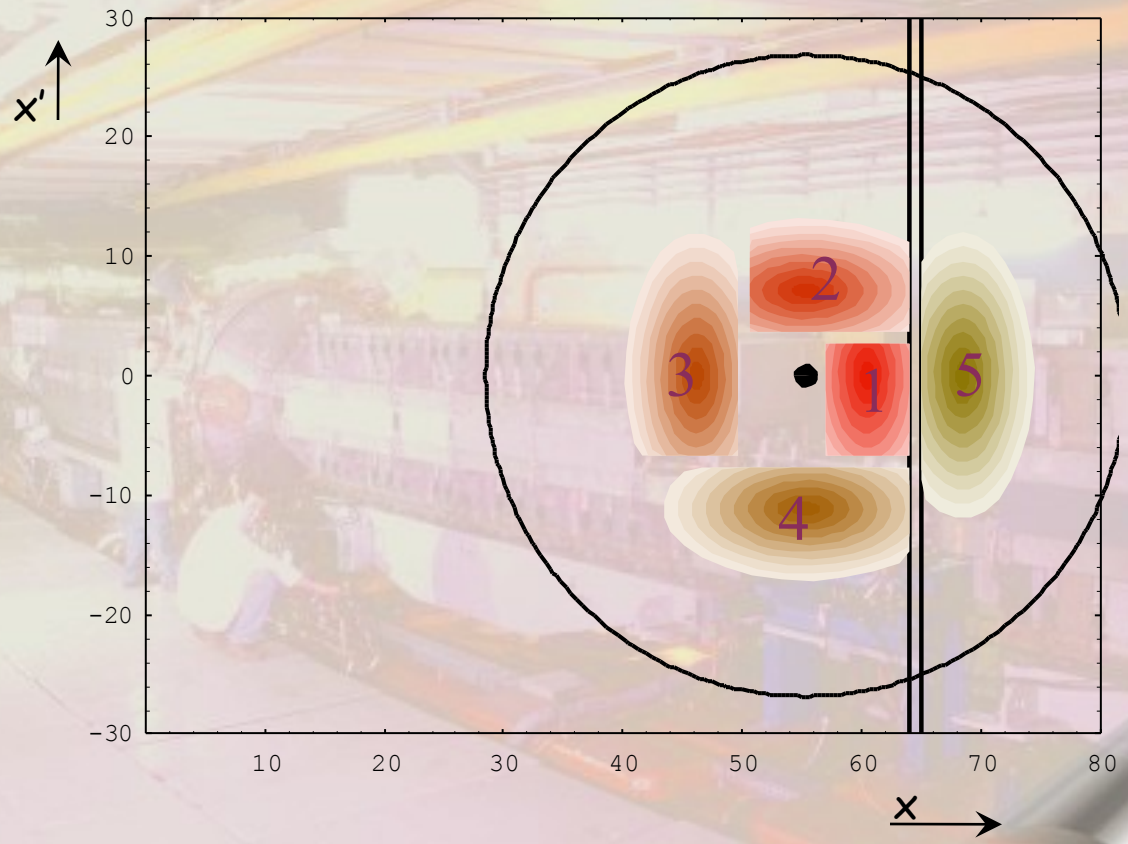
# Multi-turn injection for hadrons (6)



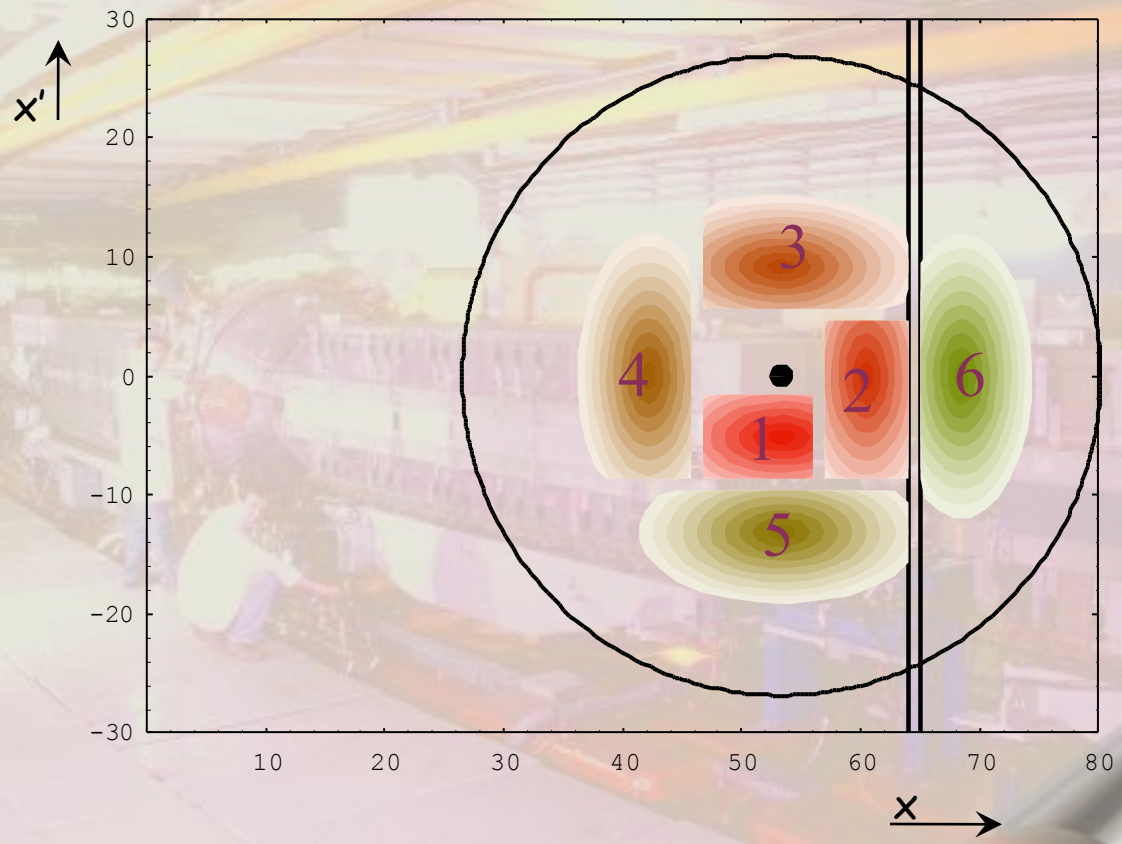
# Multi-turn injection for hadrons (7)



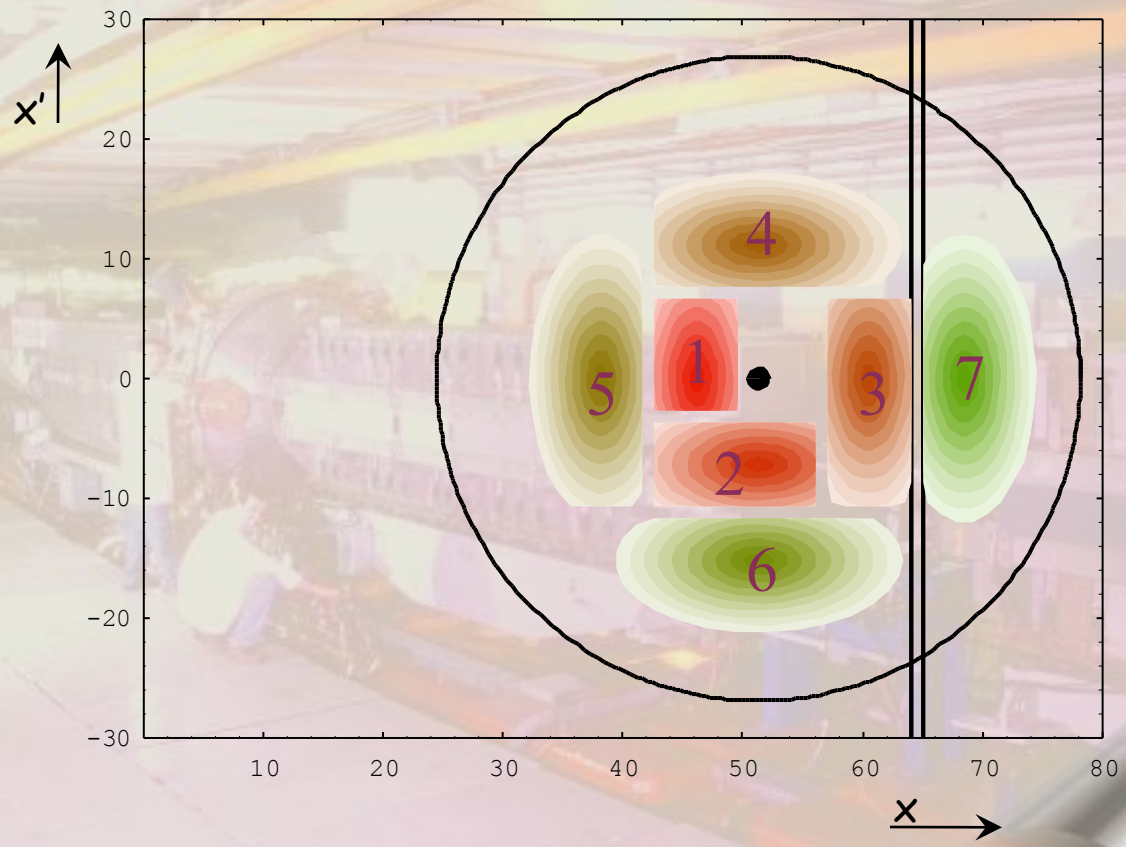
# Multi-turn injection for hadrons (8)



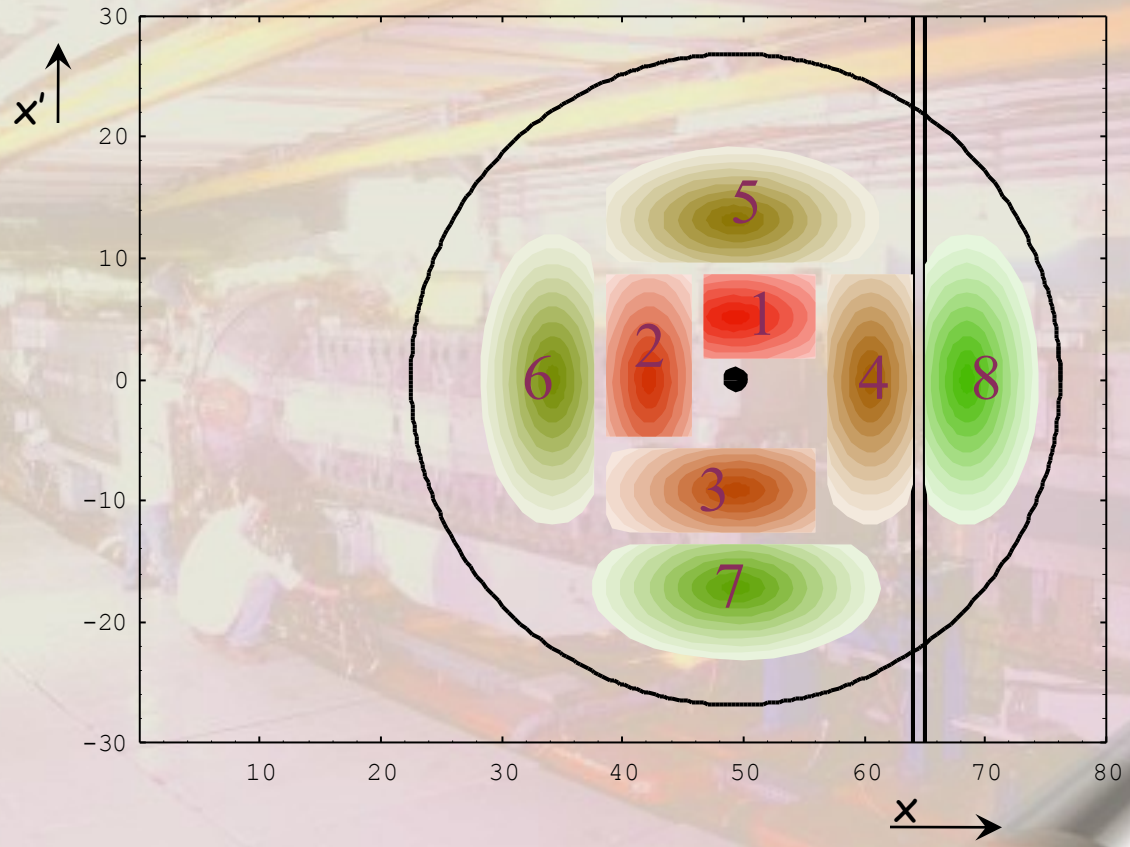
# Multi-turn injection for hadrons (9)



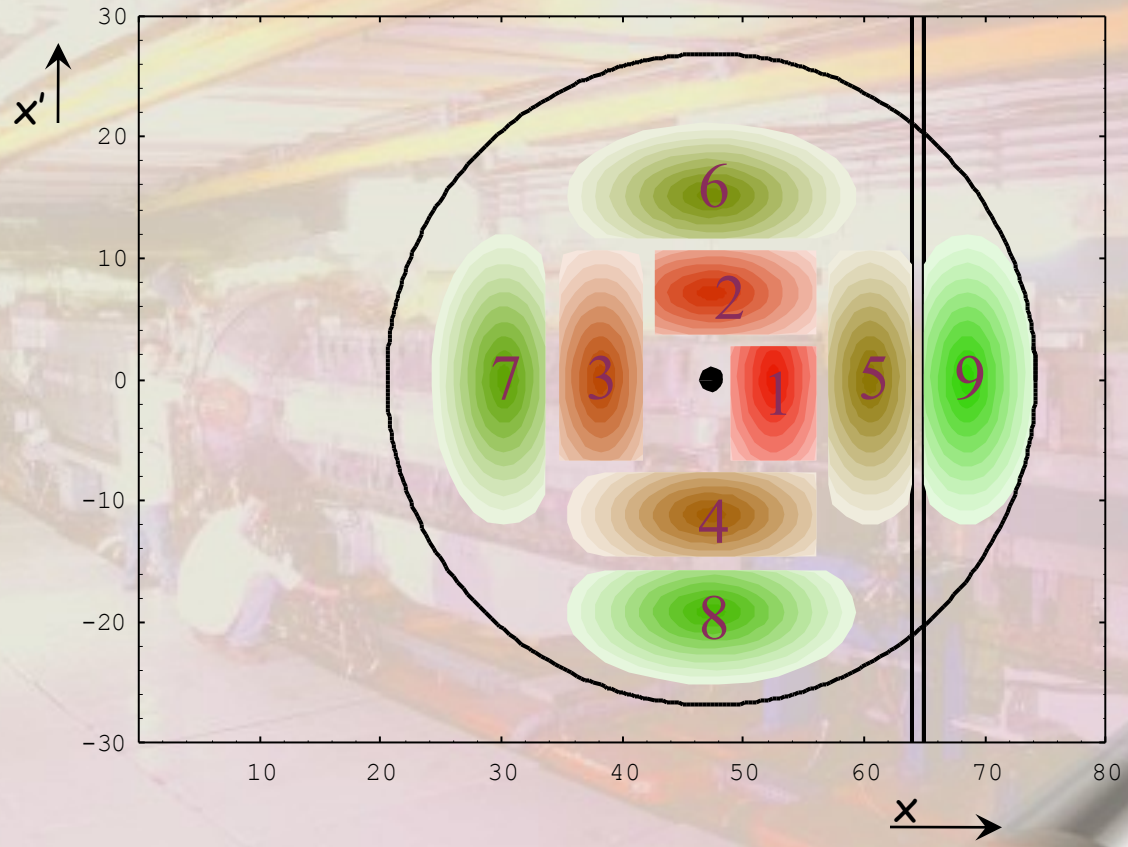
# Multi-turn injection for hadrons (10)



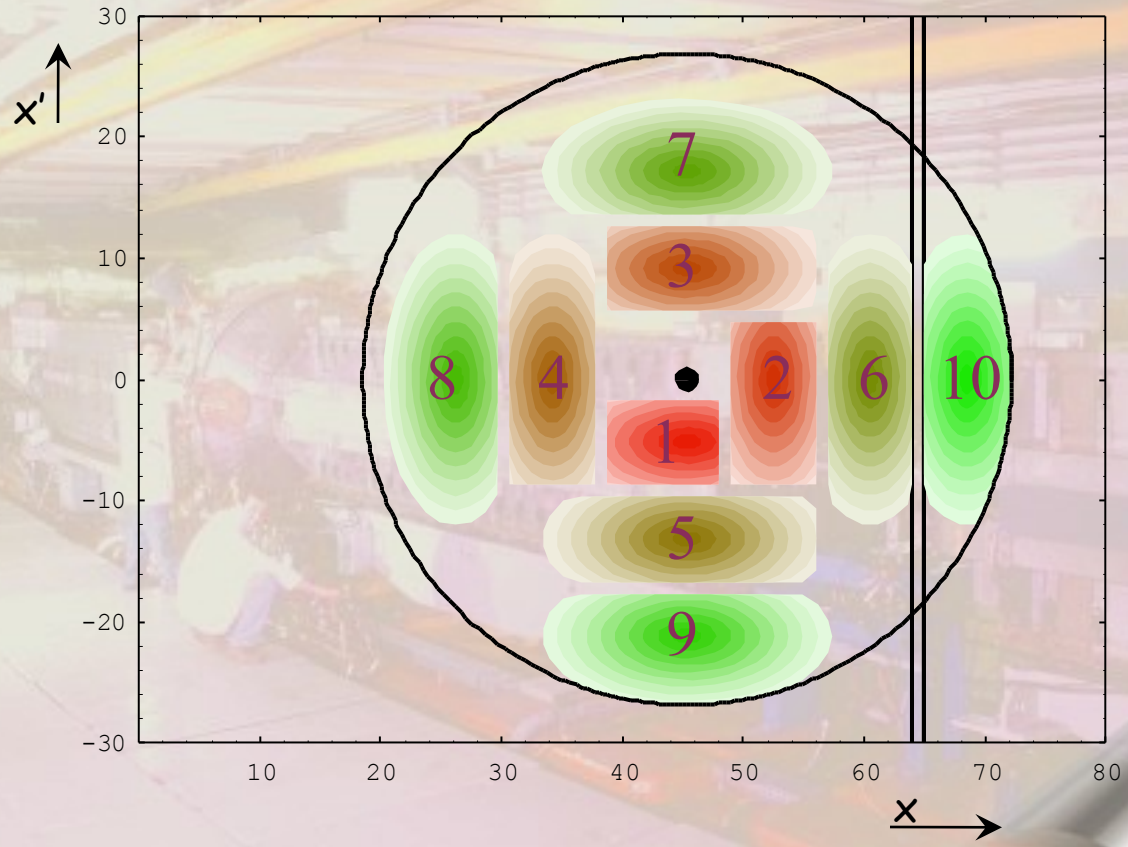
# Multi-turn injection for hadrons (11)



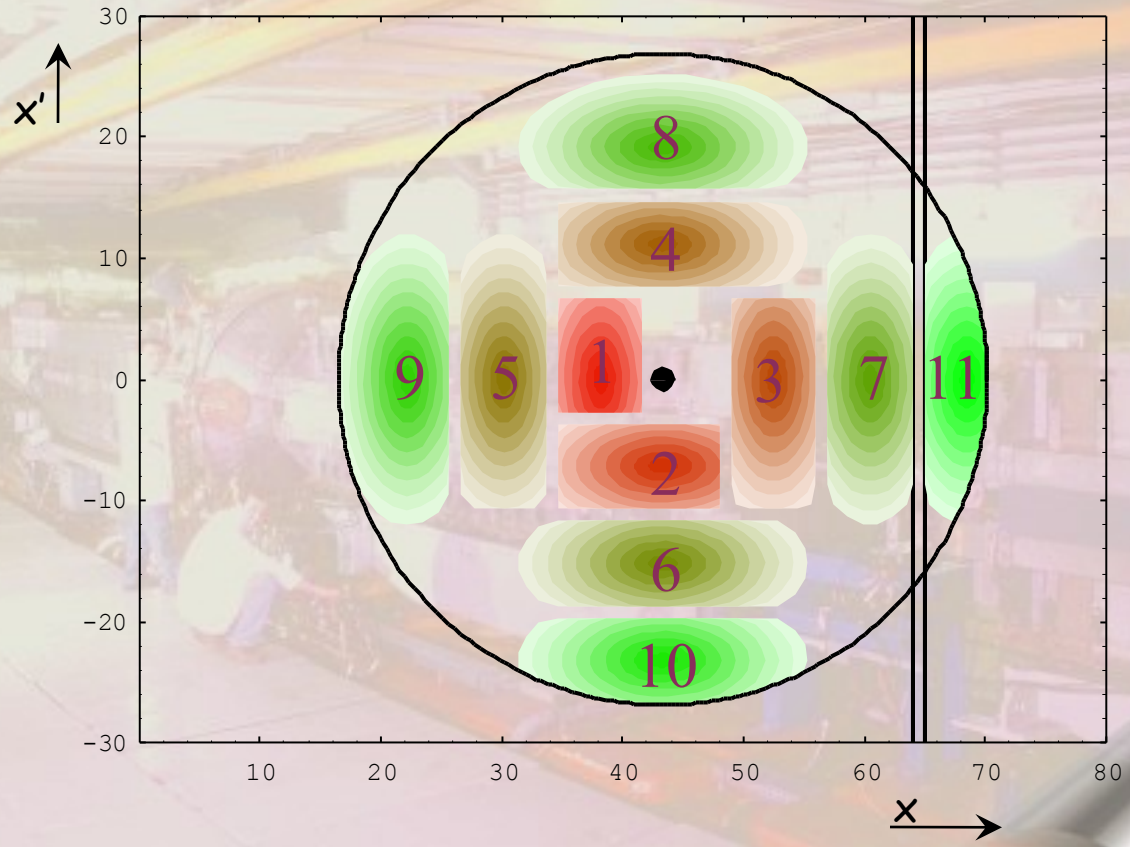
# Multi-turn injection for hadrons (12)



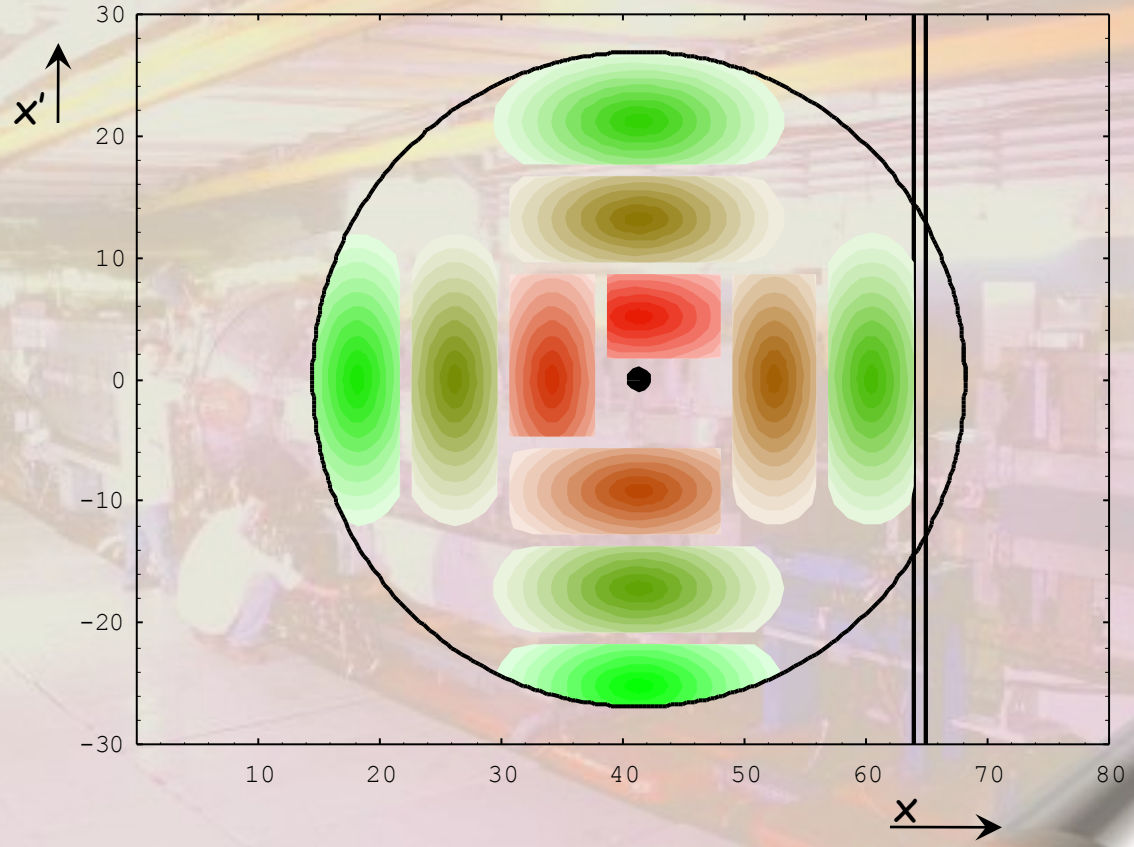
# Multi-turn injection for hadrons (13)



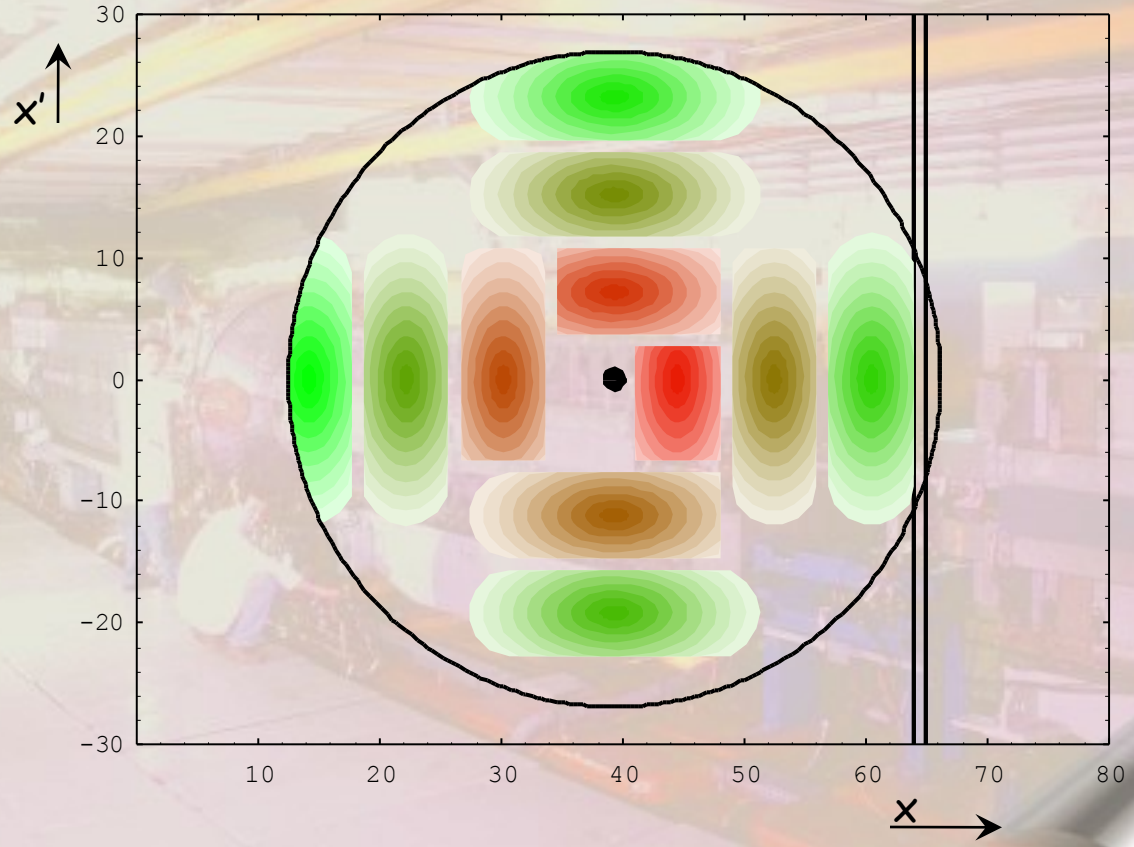
# Multi-turn injection for hadrons (14)



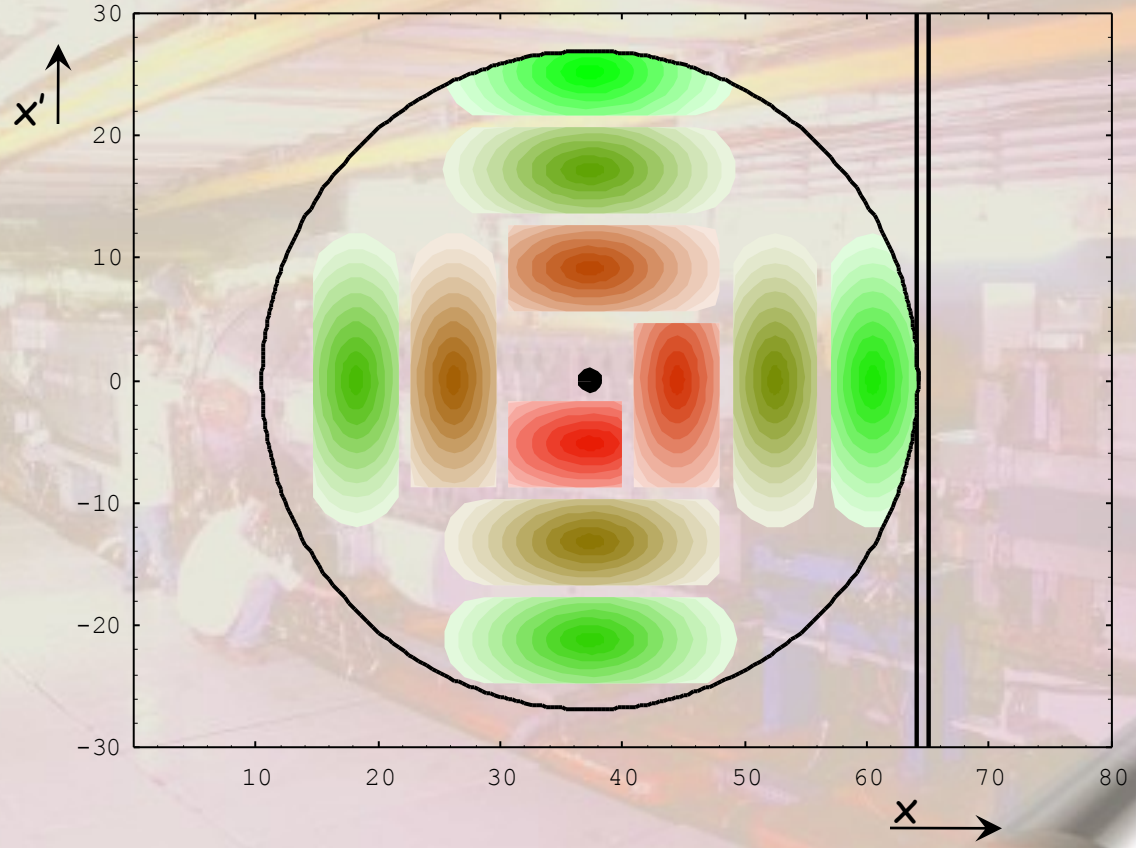
# Multi-turn injection for hadrons (15)



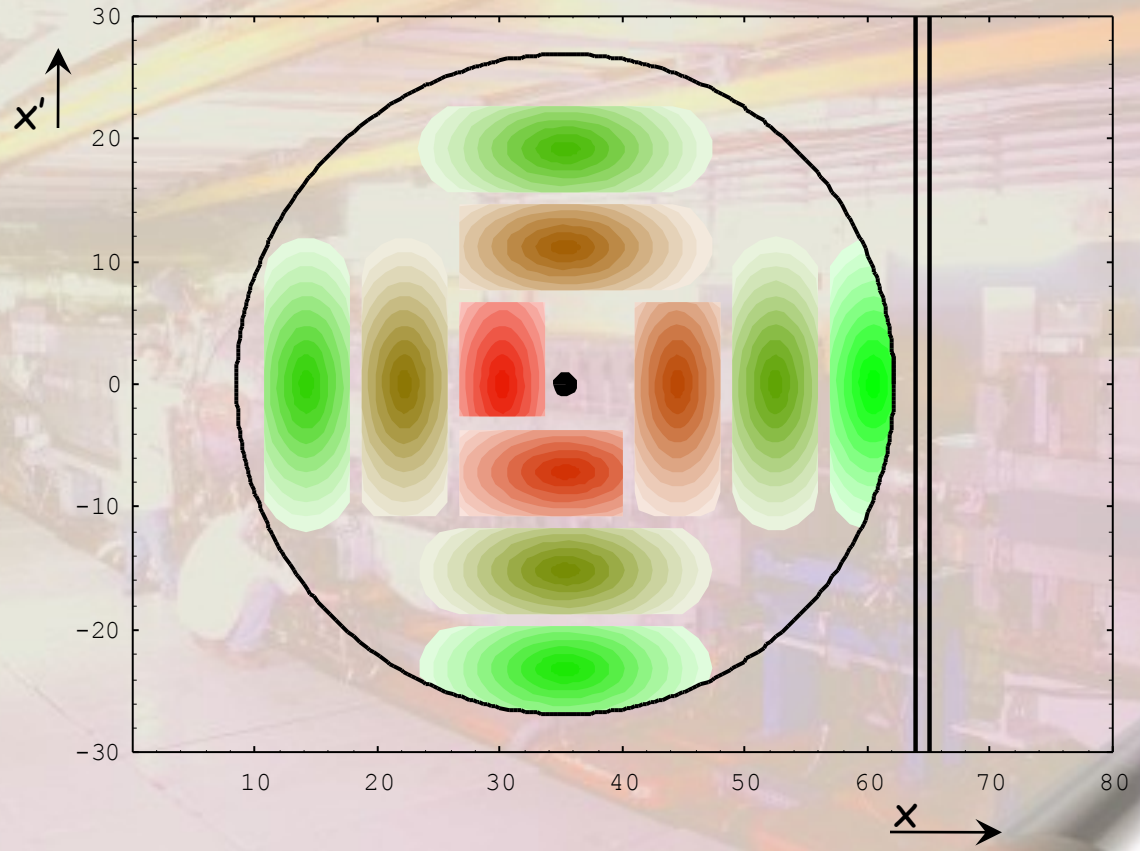
# Multi-turn injection for hadrons (16)



# Multi-turn injection for hadrons (17)



# Multi-turn injection for hadrons (18)



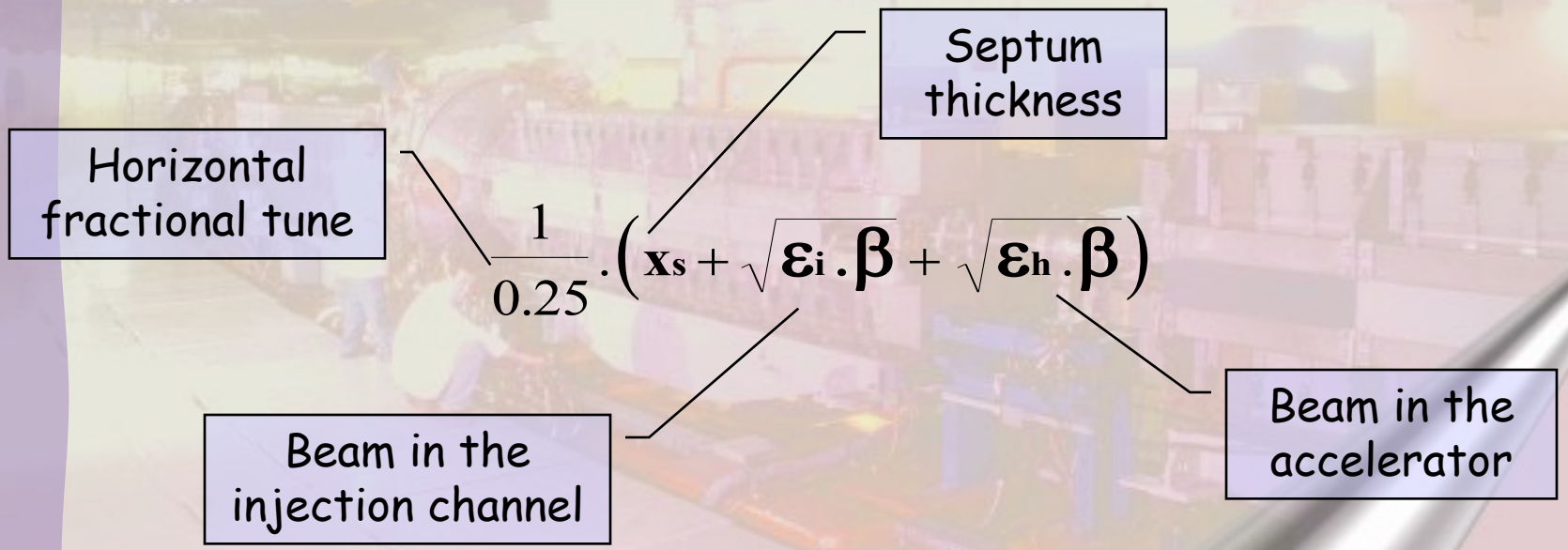

- Now the horizontal phase acceptance is completely filled and acceleration can start

# Multi-turn injection for hadrons (19)

- We need to control the tune Qh and the beam bump accurately
  - in order to reduce losses
  - in order to fill the horizontal phase space most efficiently
- We need a very thin septum
  - in order to minimize the losses on subsequent turns
  - in order to reduce phase space dilution.

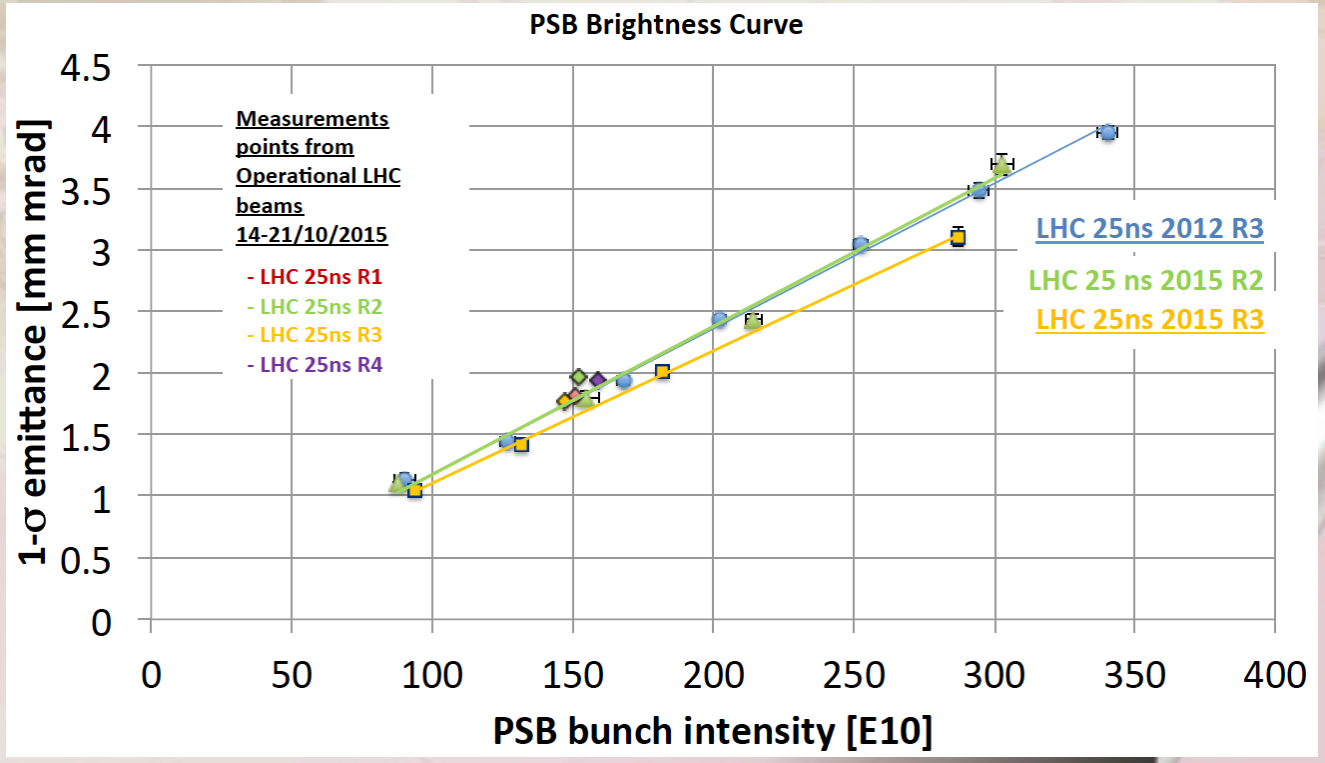
# Multi-turn injection for hadrons (20)

- The optimum reduction in the orbit bump/turn can be calculated using:



# Density with multi-turn injection

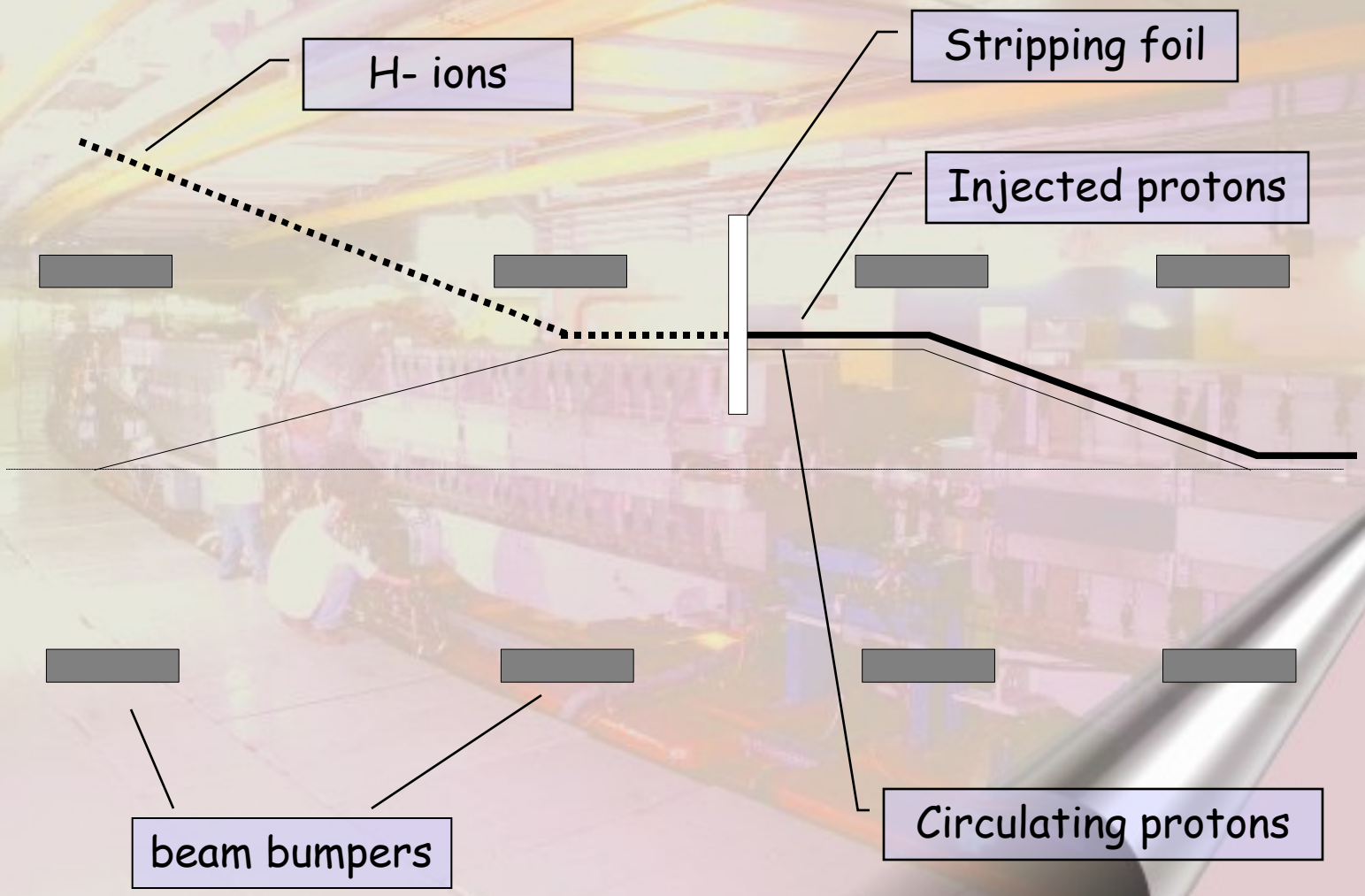
- This multi-turn injection increases intensity with about constant density



# Charge exchange injection (1)

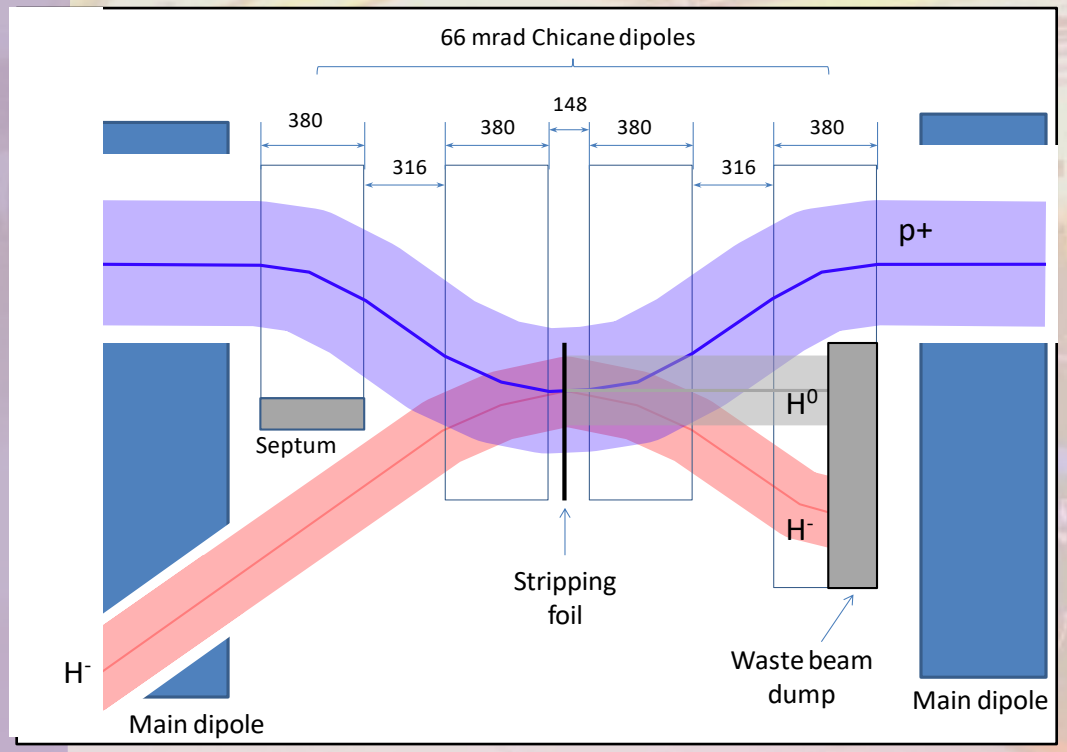
- The charge exchange extraction is already operational in different laboratories around the world.
- At CERN it will be used for the 1st time when Linac 4 will be ready to deliver beam to the PS Booster
- The charge exchange injection works as following:
  - Transport H- ions from the linac to the synchrotron
  - Strip the H- ions to protons inside the ring acceptance
- In order to strip the ions, but no to blow-up the beam to much we carefully need to consider the stripping foil requirements
- It has advantages over normal multi-turn proton injection

# Charge exchange injection (2)

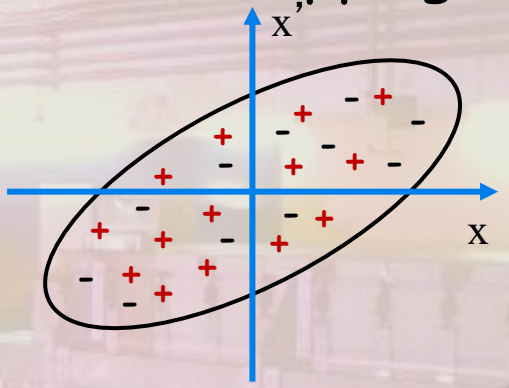


# Charge exchange injection (3)

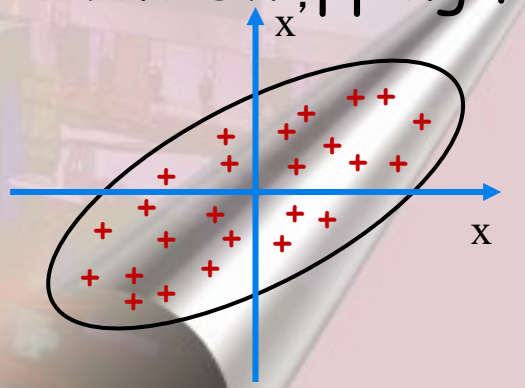
- Use $H^-$ beam from LINAC 4




Before stripping foil




Behind stripping foil




- Phase Space Painting is possible (various particle distributions)

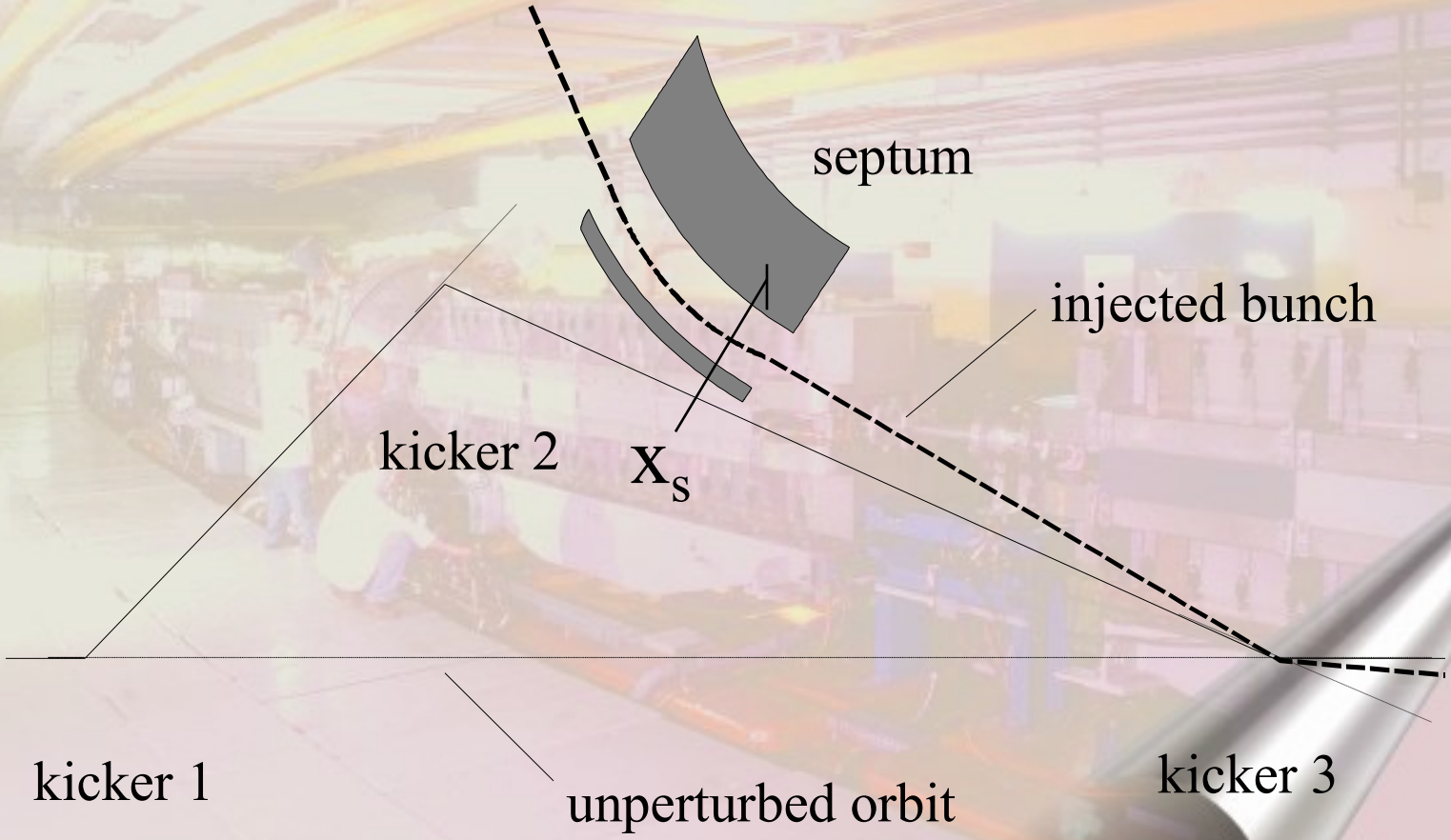
# Charge exchange injection (3)

- It makes it possible to "beat" Liouville's theorem, which says that emittance is conserved.
- We paint a uniform transverse phase space density by modifying the beam bump and by and changing the steering of the injected beam
- The foil thickness should be calculated to strip most ions (99%)
  - 50 MeV - 50 ug.cm$^{-2}$
  - 800 MeV - 200 ug.cm$^{-2}$
- Types of foils that can be used:
  - Carbon
  - Aluminum
- To avoid excessive foil heating and unnecessary beam blow up the injection bump is reduced to zero as soon as the injection is finished

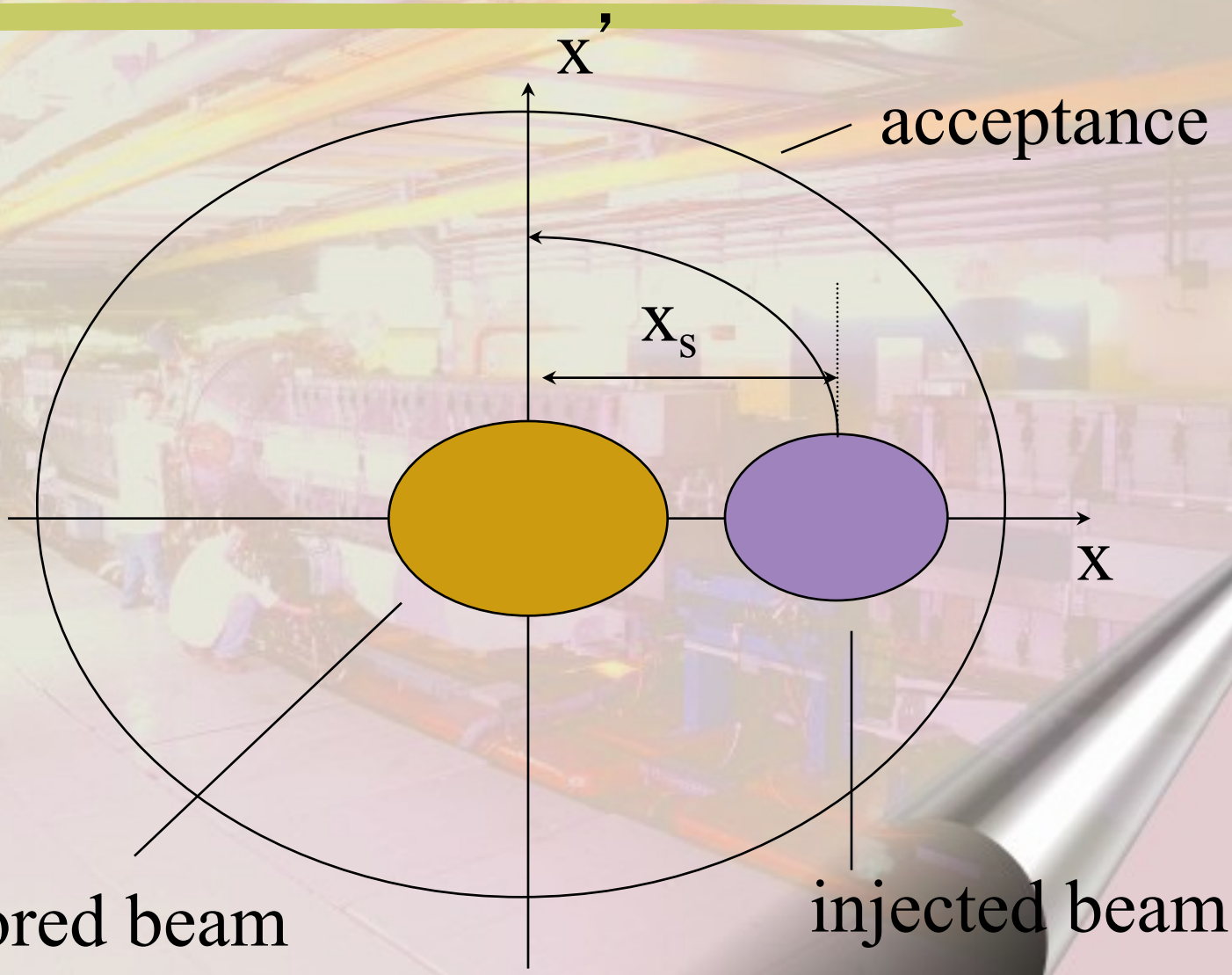
# Lepton injection

- We can apply the same fast injection as for protons however, there are differences with respect to proton or ion injection
- Lepton motion is damped in our accelerator
- We can use transverse and longitudinal damping to perform:
  - Betatron accumulation (most lepton machines)
  - Synchrotron accumulation (was used in LEP)

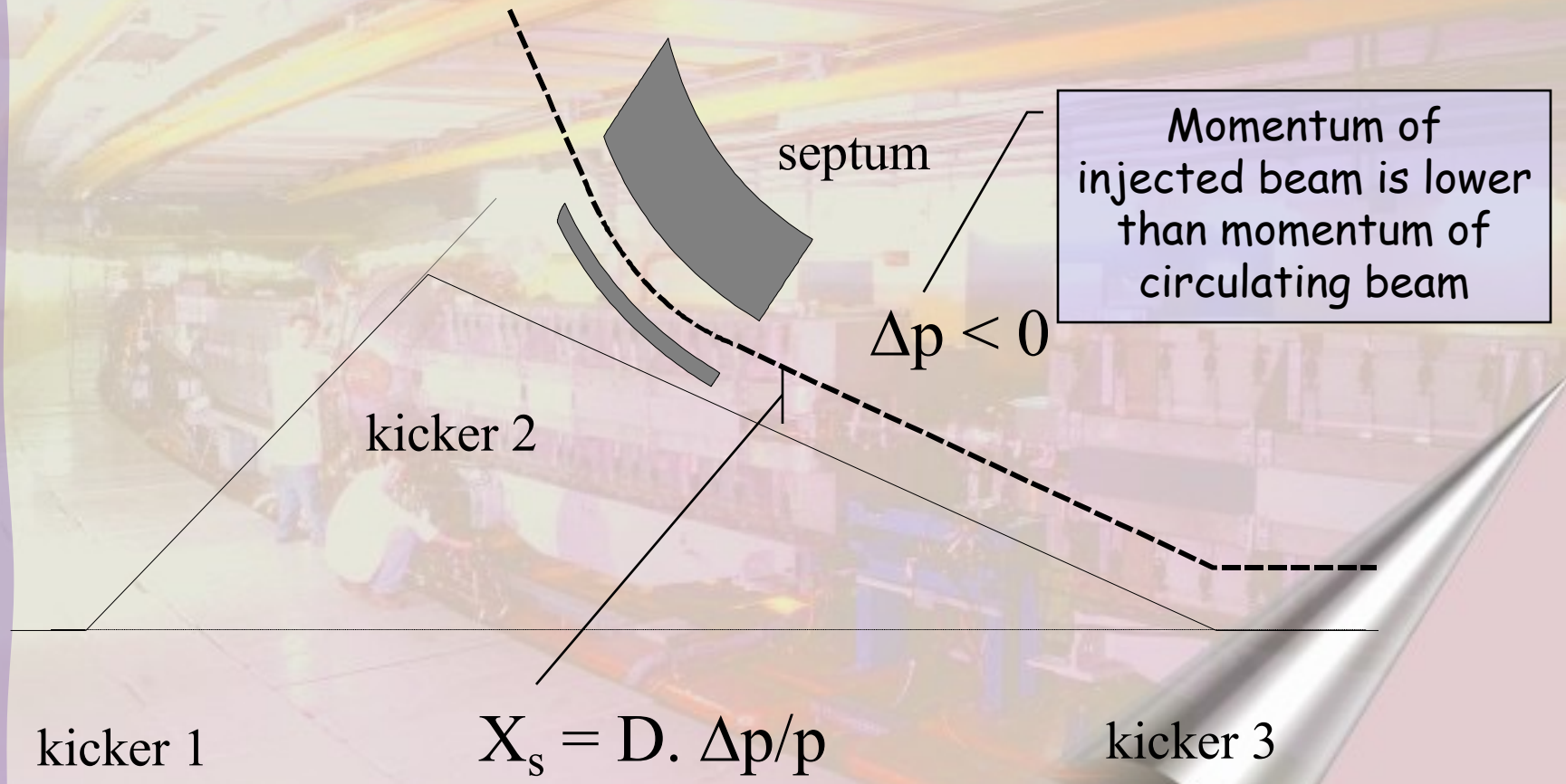
# Betatron accumulation (1)



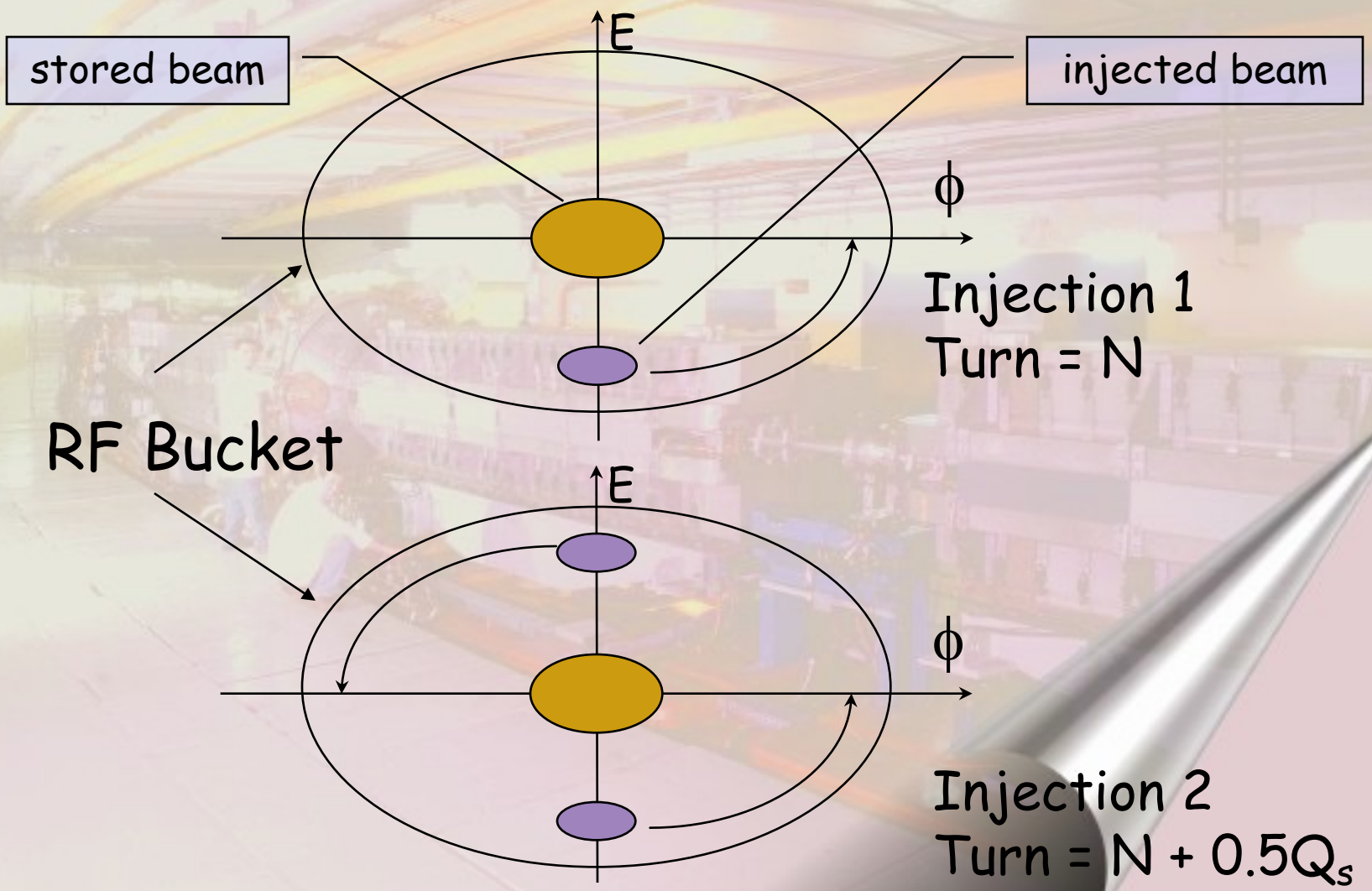
# Betatron accumulation (2)



# Synchrotron accumulation (1)



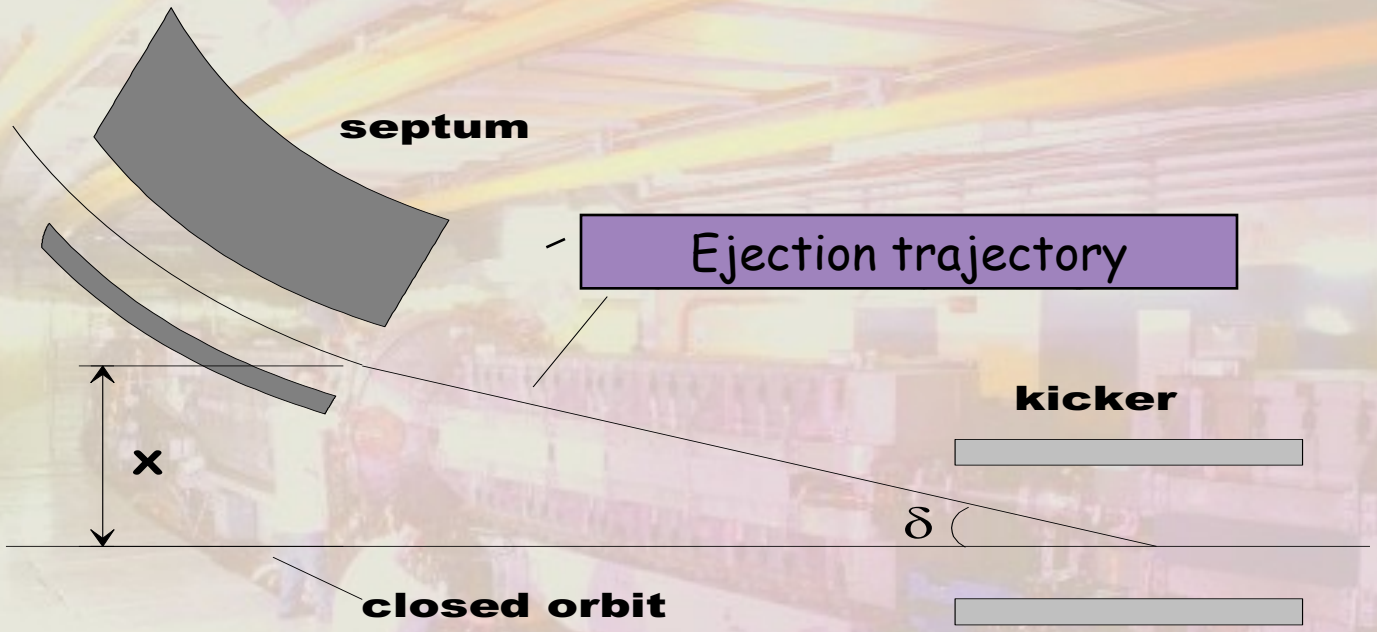
# Synchrotron accumulation (2)



# Single turn ejection (1)

- With a single turn ejection we eject one or more bunches out of a synchrotron in a single turn. (revolution period)
- Elements involved:
  - Synchrotron
  - Bumper
  - Septum magnet
  - Fast kicker magnet
  - Ejection synchronization

# Single turn ejection (2)



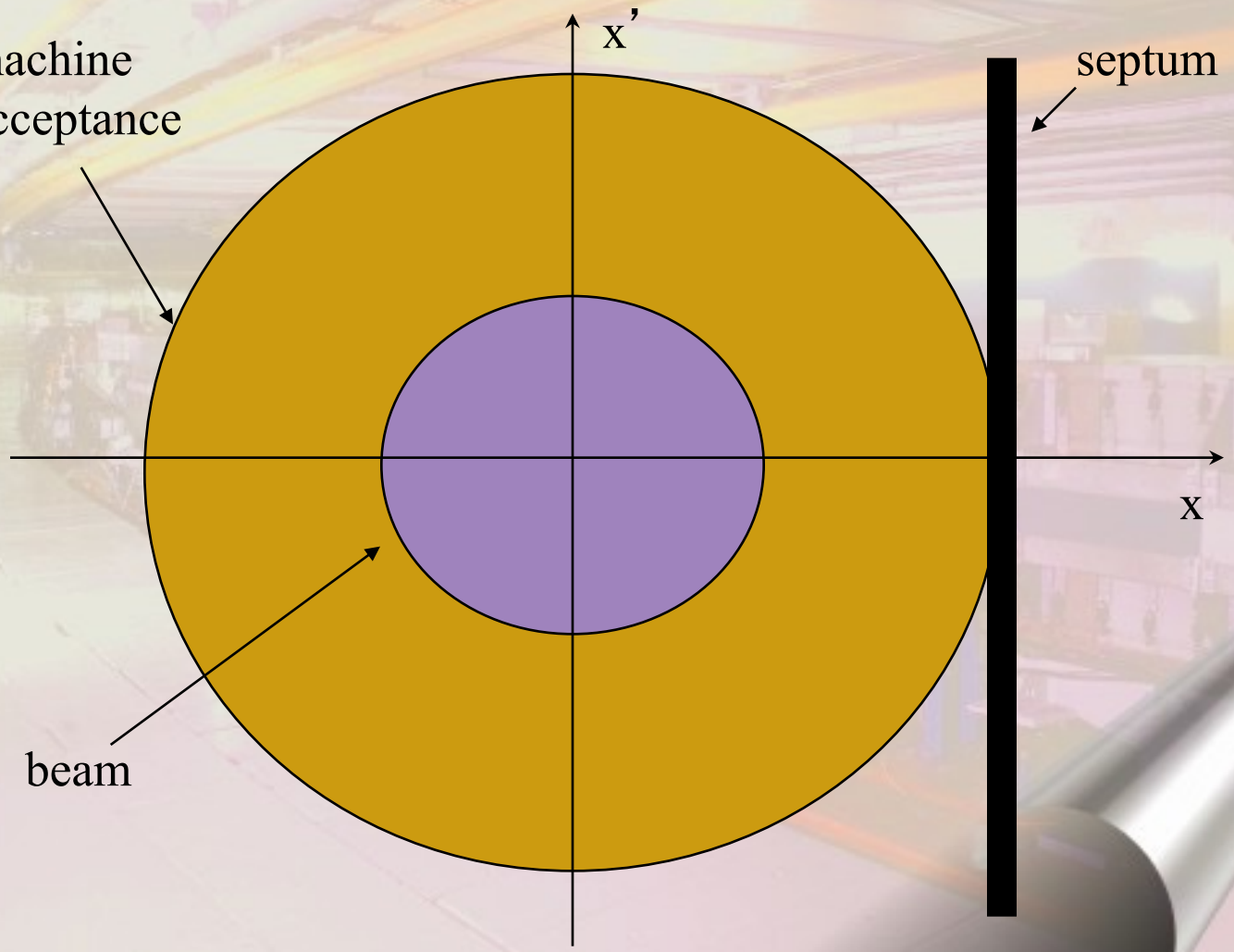

$$x = \sqrt{\beta_s \cdot \varepsilon_e} + \sqrt{\beta_s \cdot \varepsilon} + D_s\left(\frac{dp_e}{p} + \frac{dp}{p}\right) + x_{co} + x_s$$

$$\delta = \frac{x}{\sqrt{\beta_s \cdot \beta_k} \cdot \sin(\mu_{(k \to s)})}$$

# Multi-turn extraction (1)

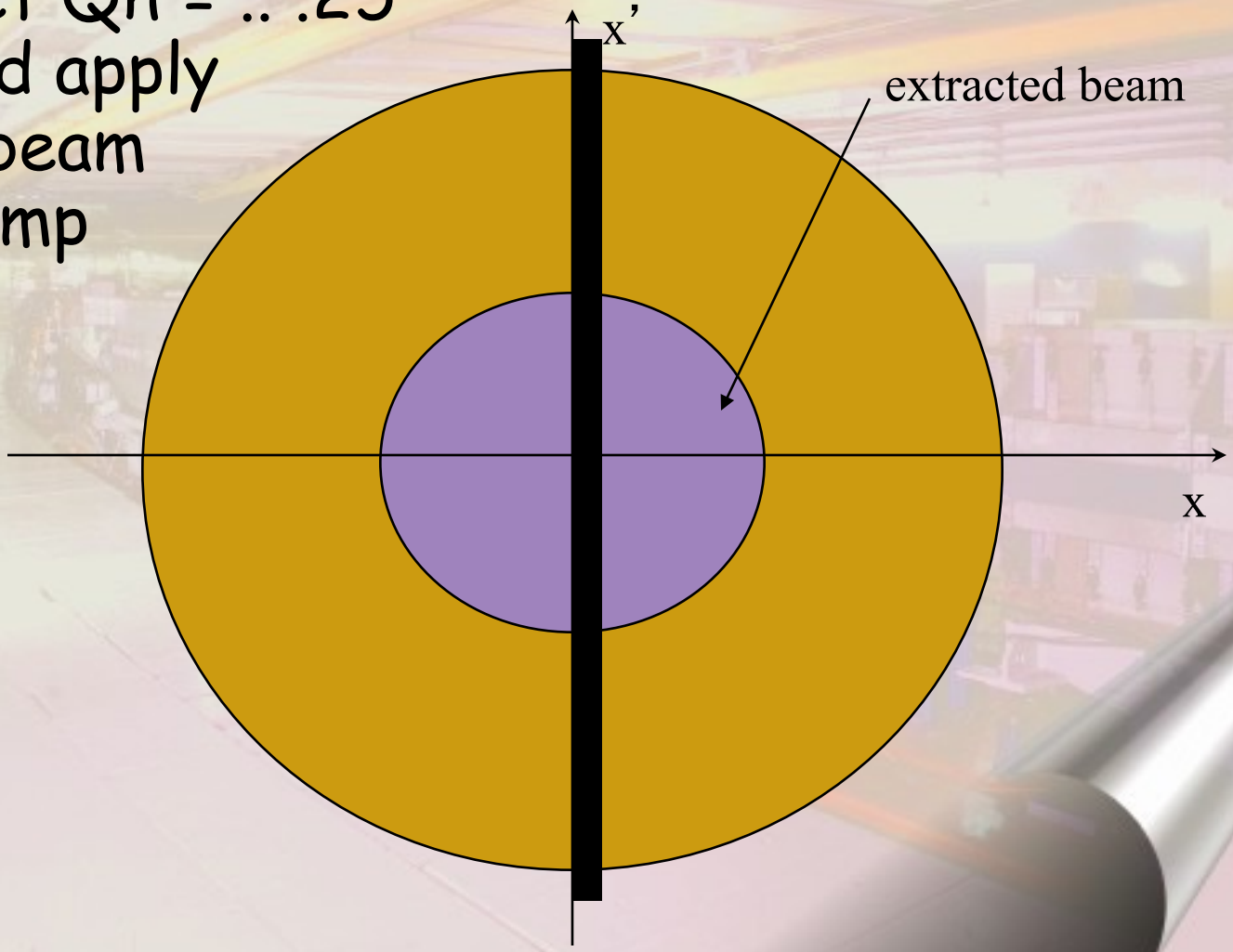
- Many physicists would like to have a continuous flux of particles.
- However, this is not possible with our machines and the way we work.
- We try to approach this using multi-turn extractions
- We know two types of multi turn ejection:
  - Non-Resonant multi-turn ejection (few turns)
    e.g.. PS to SPS at CERN for high intensity proton beams (>2.5 $10^{13}$ protons)
  - Resonant extraction (millisecs to hours)
    Spills to experiments from a synchrotron

# Non-resonant multi-turn extraction (1)

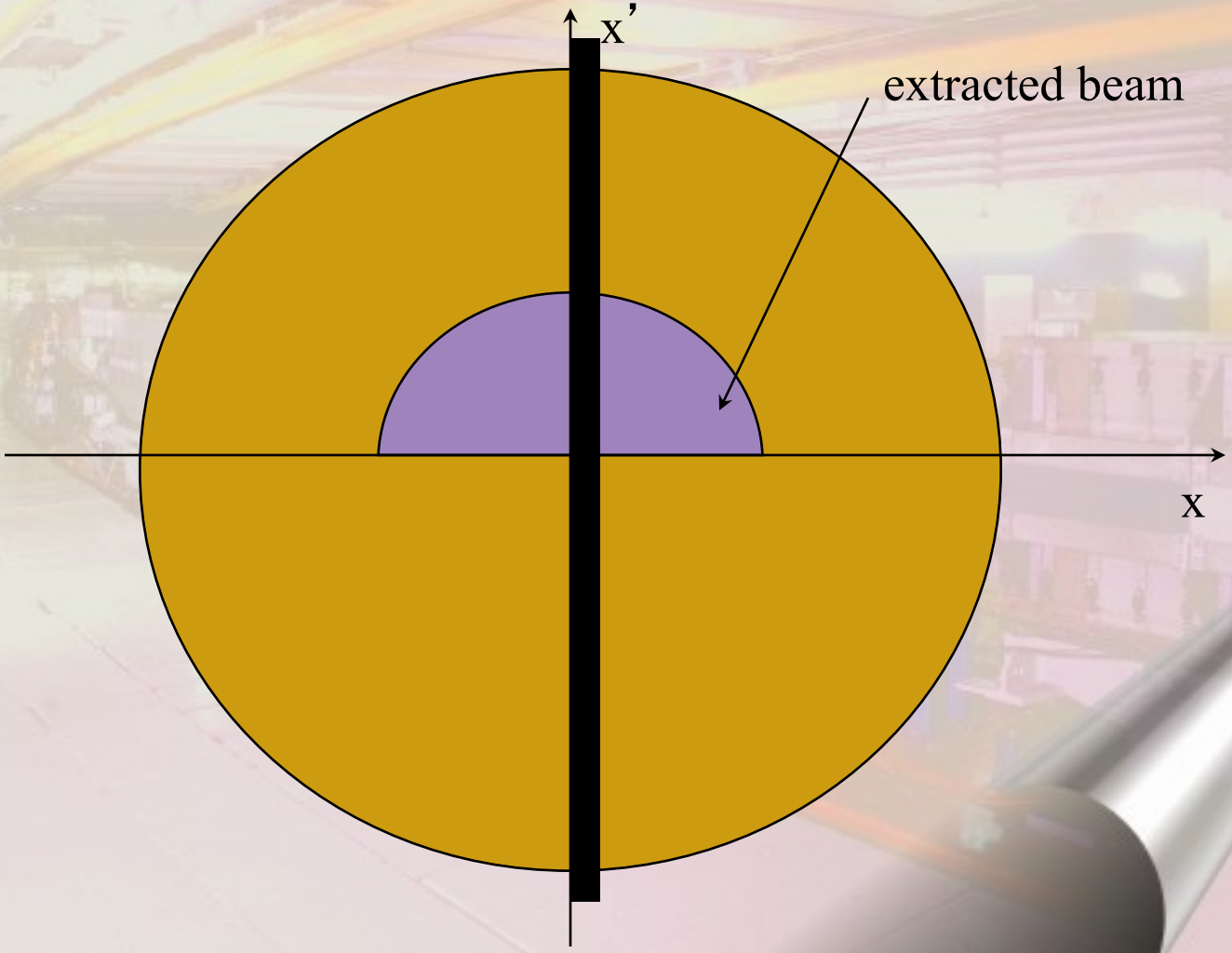


# 1st turn

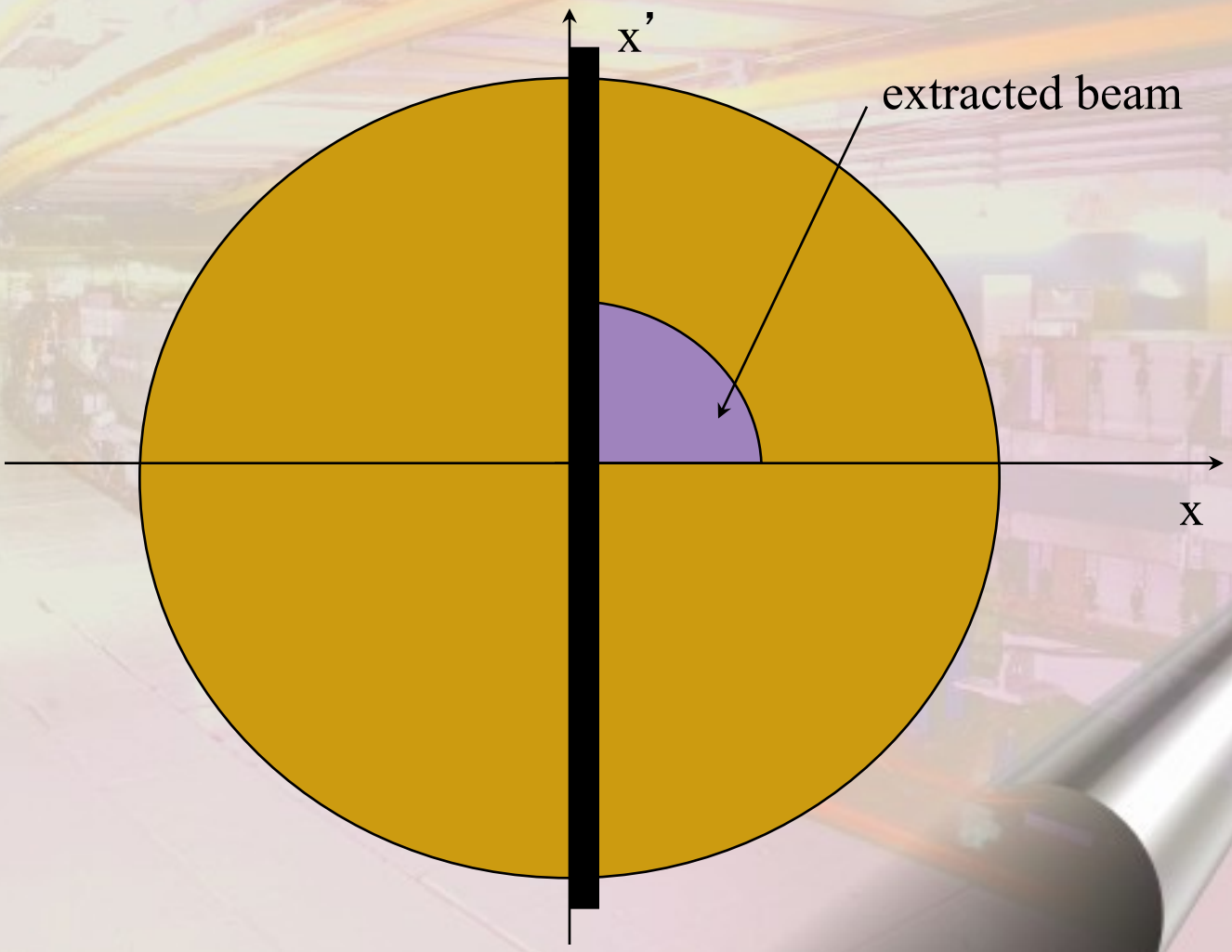
Set Qh = .. .25
and apply
a beam
bump



# 2nd turn



# 3rd turn



# Non-resonant multi-turn extraction (2)

- Particularities:
  - Use a thin septum, to minimise losses
  - Use two types of septa (electro-static, magnetic)
  - First septum is moveable, position and angle
  - Only gives a few turns… (>>$10^{10}$ particles/turn)
  - Many users need <$10^{6}$ particles/second
- For very high intensity beams the beam losses may be too important to use this method.
- Hands on maintenance becomes difficult.

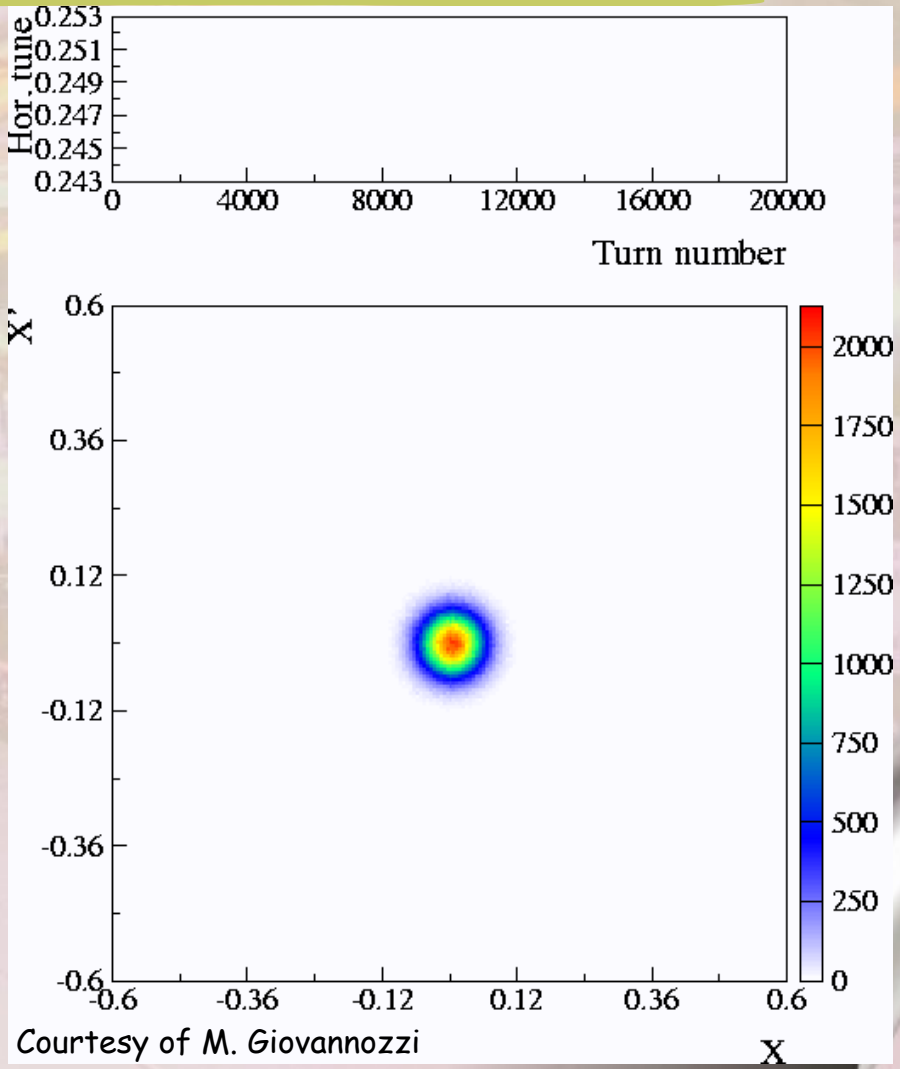
# Resonant Multi-Turn Extraction

- The majority of the losses are produced on the thin septum and are a function of beam intensity and density
- If we could de-populate the beam at the places where the septum will slice the beam, we could reduce these losses.
- Using strong non-linear elements like sextupoles and octupoles and programming the correct tune, one can create stable islands in phase space.
- The trick now is to capture beam in these stable islands and to have no particles in between the islands.

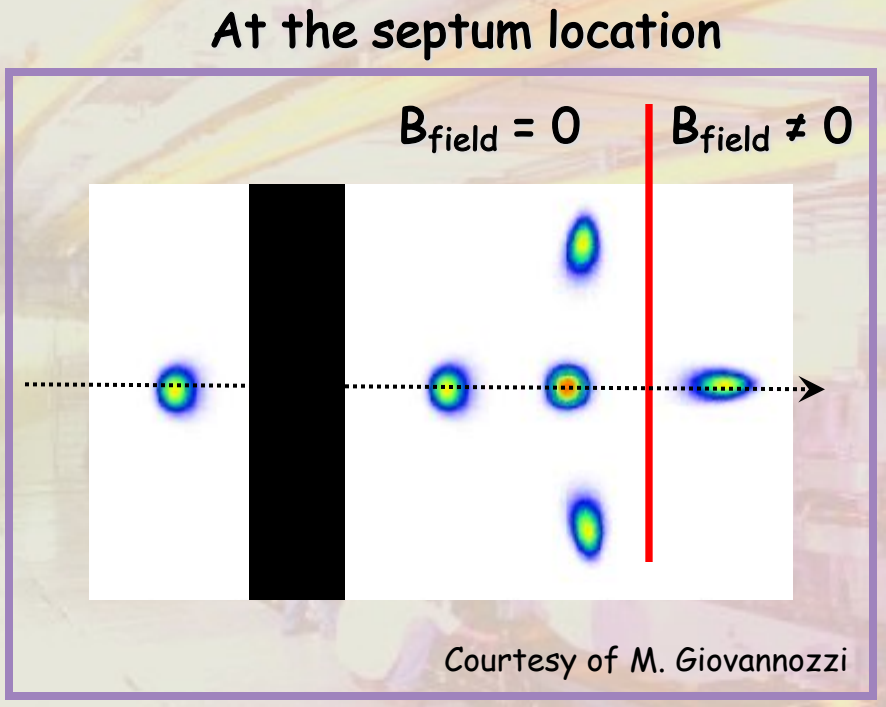
# Capture beam in stable islands

Tune variation

Phase space portrait



# Extract the beam



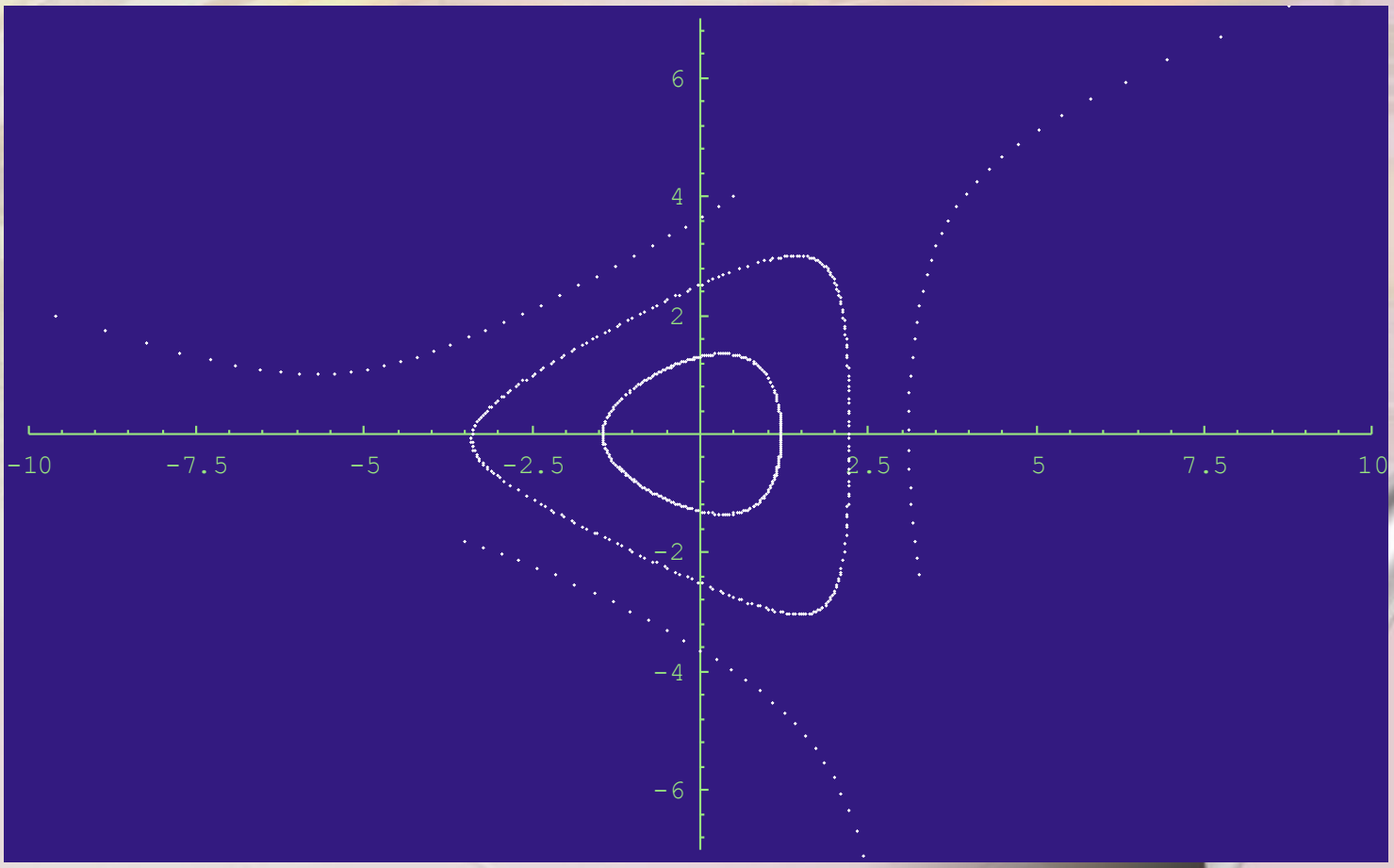

- A slow bump moves the islands towards the septum
- A fast bump makes the island jump to the other side of the septum
- The tune of 6.25 makes that the beam rotates 90 degrees in phase space each revolution period
- The four islands will be extracted

- The central part will be extracted using a fast kicker
- This way there are no particles lost on the septum blade.
- This extraction is operationally used since 2015 to deliver the North Area physics beam to the SPS.

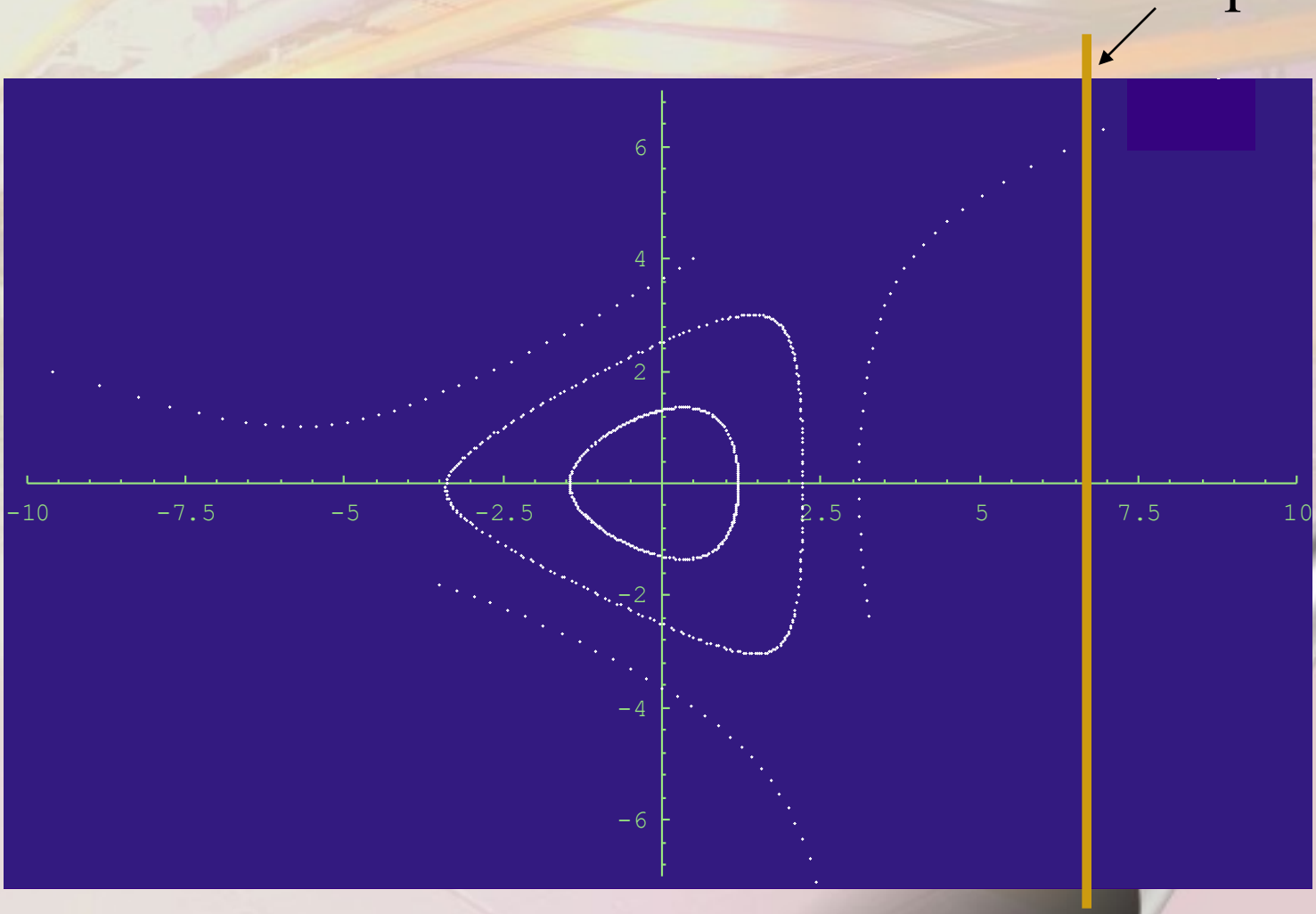
# Resonant extraction (1)

- **How to extract beam over thousands of turns ?**
- The idea is that few particles jump to the other side of the septum every revolution period
- Resonant transverse motion makes the beam size increase
- Set $3Q_h$ = integer (third order resonance)
- Use sextupoles to excite this resonance with correct phase…
- Use a horizontal beam bump at the extraction septum, to ensure that the septum is the aperture limitation

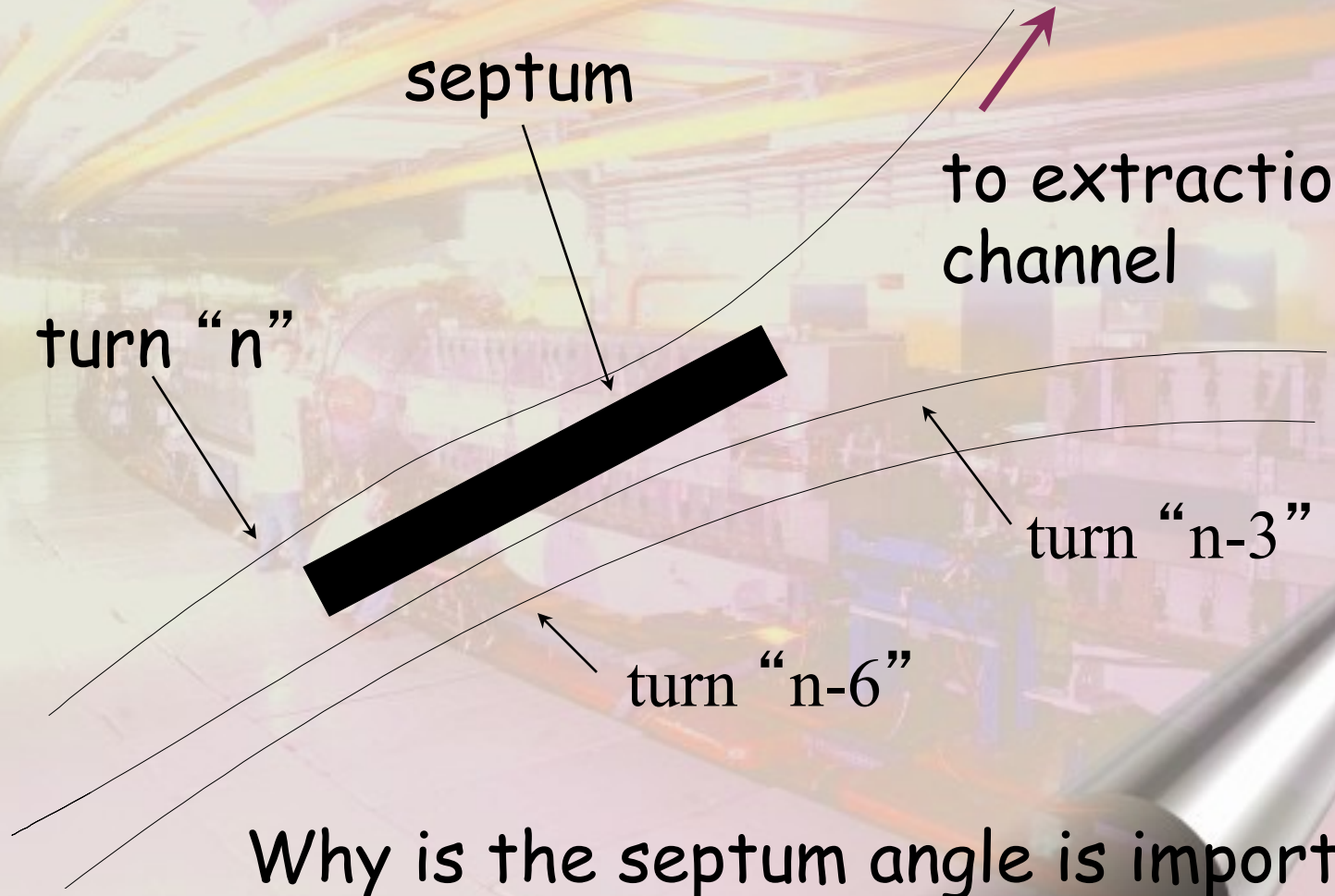
# Resonant extraction (2)



# Resonant extraction (3)



# Resonant extraction (4)




Why is the septum angle is important?

# Resonant extraction (5)

- The beam can be extracted in different ways:
  - Move the resonance into the beam (change the current in the quadrupoles)
  - Move the particles onto the resonance (change the radial position of the beam)
- Both principles can generate beam spills ranging from several milliseconds up to several hours.

# Questions….,Remarks…?