AXEL-2018

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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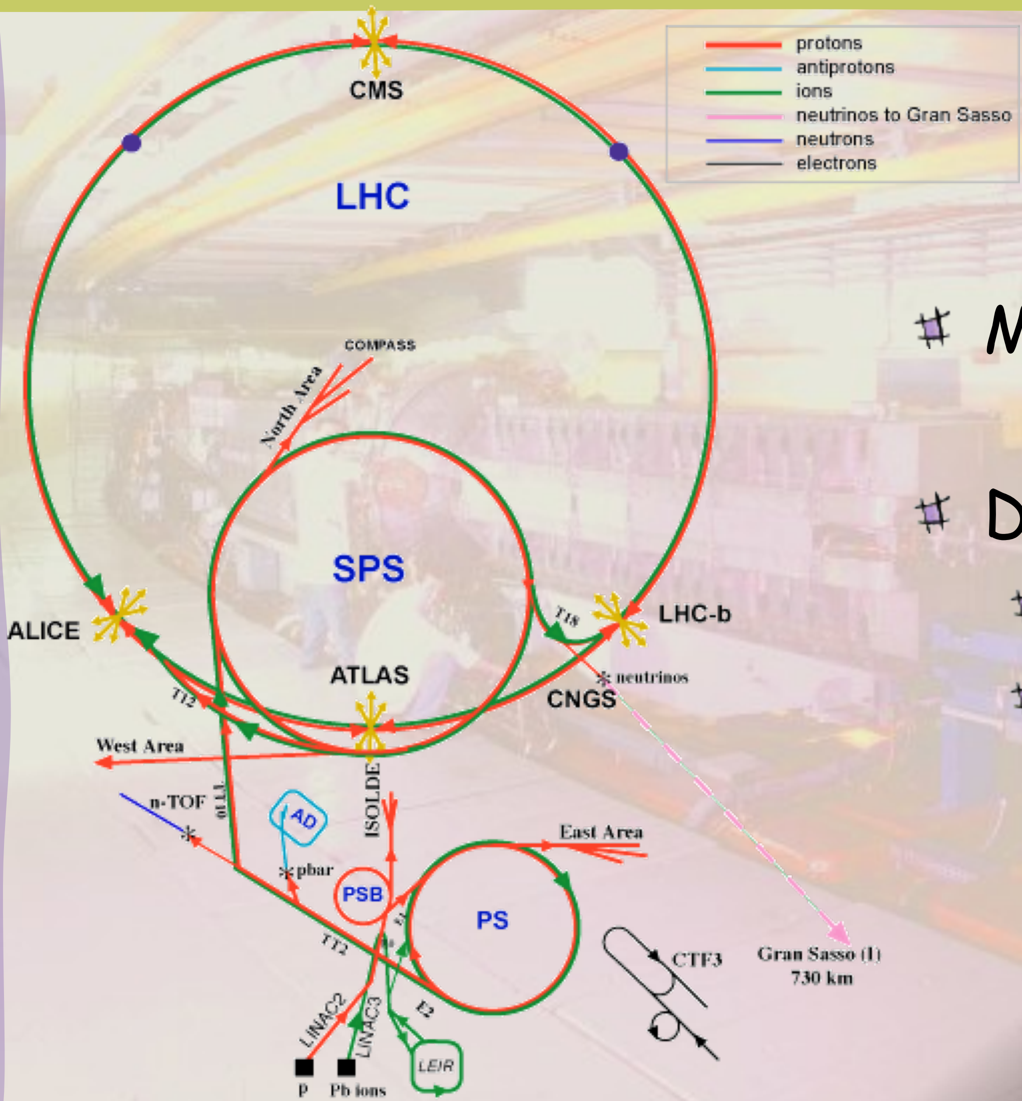
8 March 2018

Overview

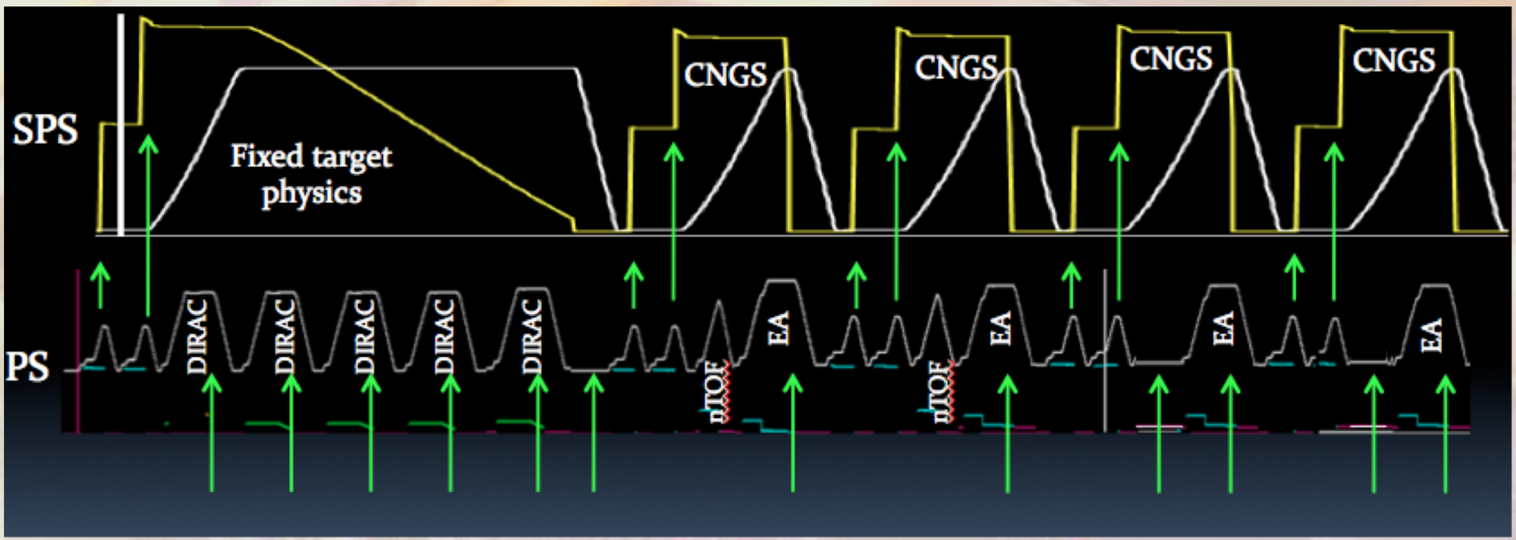
- How to get a beam into and out of circular accelerators and storage rings.
- The wide range of requirements will require different solutions:
  - injection into a synchrotron from a LINAC
  - transfer between two synchrotrons
  - extraction to an end-user facility
  - accumulation of particles, to 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
  - <u>initial lattice parameters ≠ final lattice parameters</u>
- Due to this the transfer matrix gets slightly more complicated.

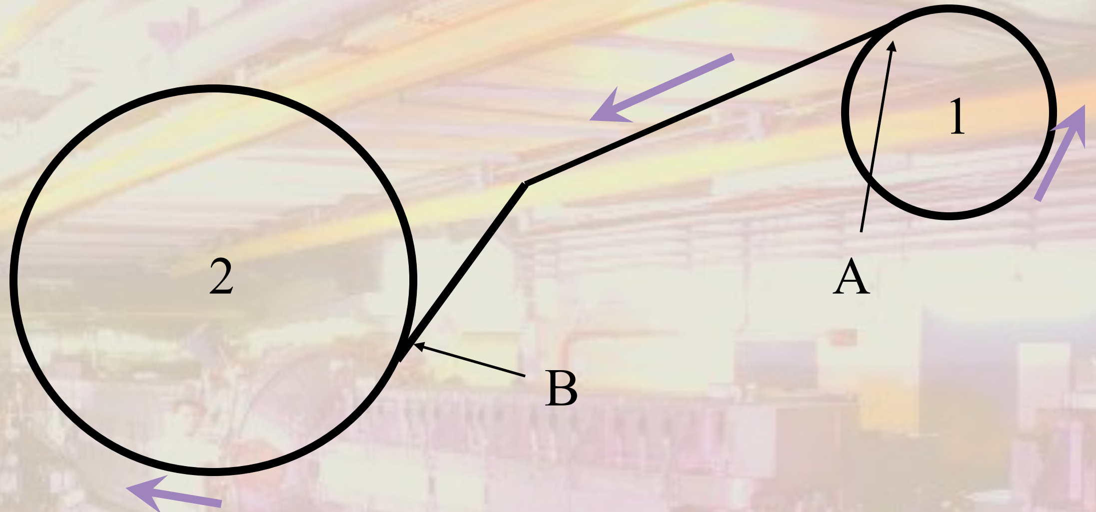
$$\begin{pmatrix} x_2 \\ x'_2 \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{\beta_2}{\beta_1}}(\cos\mu + \alpha_1 \sin\mu) & \sqrt{\beta_1\beta_2}\sin\mu \\ \frac{(1+\alpha_1\alpha_2)\sin\mu + (\alpha_2 - \alpha_1)\cos\mu}{\sqrt{\beta_1\beta_2}} & \sqrt{\frac{\beta_1}{\beta_2}}(\cos\mu - \alpha_2\sin\mu) \end{pmatrix} \times \begin{pmatrix} x_1 \\ x'_1 \end{pmatrix}$$

Transfer Lines (3)

$$\begin{pmatrix} x_2 \\ x'_2 \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{\beta_2}{\beta_1}}(\cos\mu + \alpha_1 \sin\mu) & \sqrt{\beta_1\beta_2}\sin\mu \\ \frac{(1+\alpha_1\alpha_2)\sin\mu + (\alpha_2 - \alpha_1)\cos\mu}{\sqrt{\beta_1\beta_2}} & \sqrt{\frac{\beta_1}{\beta_2}}(\cos\mu - \alpha_2 \sin\mu) \end{pmatrix} \times \begin{pmatrix} x_1 \\ x'_1 \end{pmatrix}$$

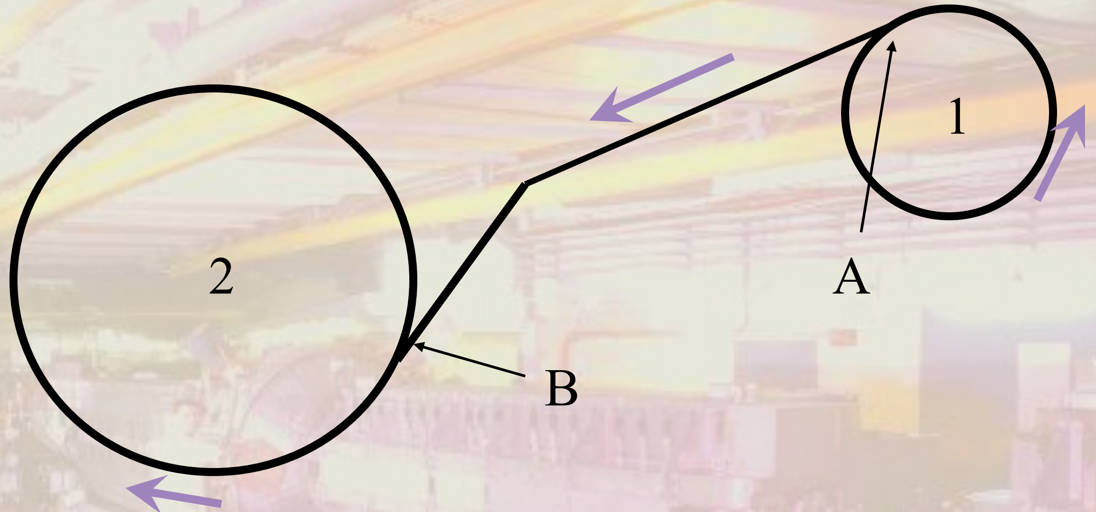
- For $\beta_1 = \beta_2$, $\alpha_1 = \alpha_2$ etc this reduces to the matrix we had for our accelerator, but for transfer lines we must retain the full matrix.
- We can calculate the **Twiss** parameters exactly as for our accelerator.
- However, there are an infinite number of solutions... since for any value β_1 there will give a particular solution for β_2.
- Thus the final α, β, etc. depends on the initial α, β, 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.... <u>what will happen to the beam?</u>

Transverse phase space

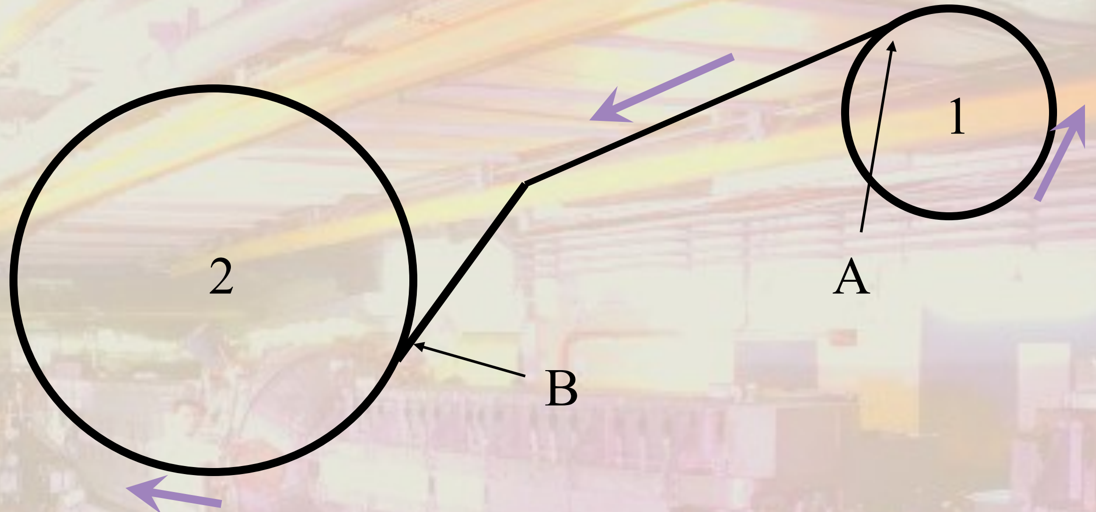
At injection

Injected beam rotates inside the new ellipse

“smear out” of phase space and emittance blow-up begins

emittance blow-up complete

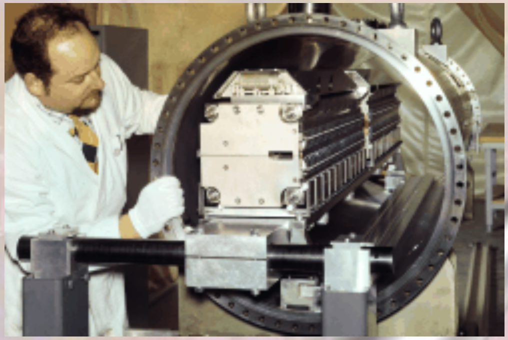
Transverse matching



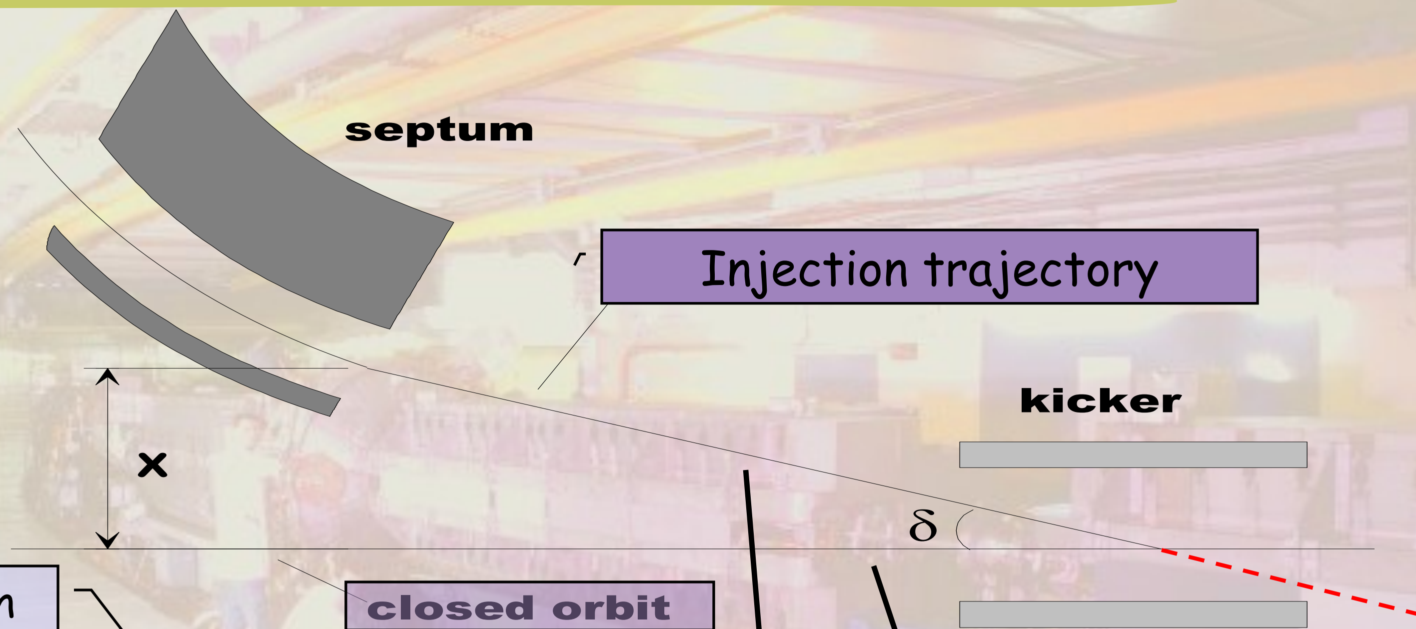
- Set initial $\beta_1, \alpha_1.. = \beta, \alpha$ for machine 1 at point **A**
- Calculate the transfer matrix so that $\beta_2, \alpha_2.. = \beta, \alpha$ for machine 2 at point **B**
- Be careful with the envelope considerations in the transfer line (emittance vs acceptance).
- Variables $\Rightarrow$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



Injection channel

Septum thickness

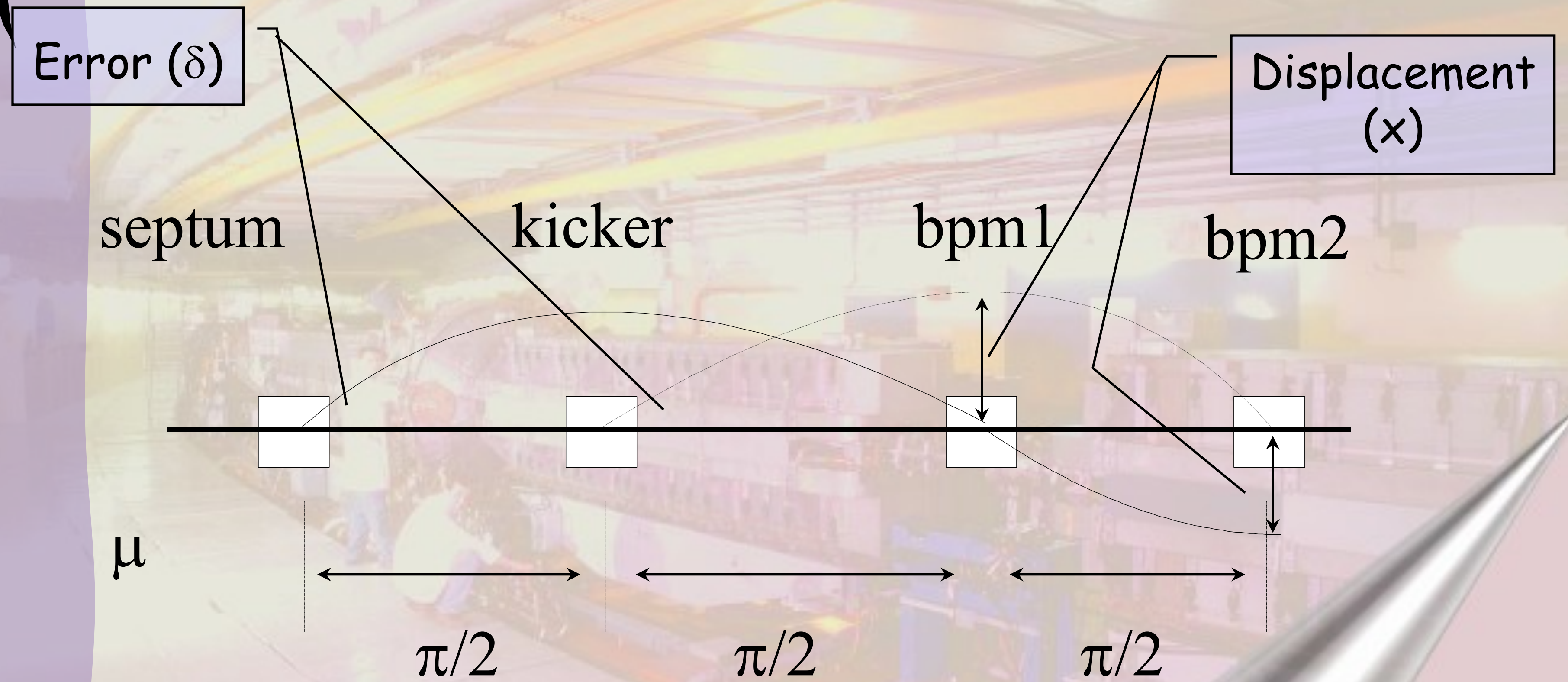
$$x = \sqrt{\beta_s \cdot \varepsilon_i} + \sqrt{\beta_s \cdot \varepsilon} + D_s\left(\frac{dp_i}{p} + \frac{dp}{p}\right) + x_{co} + x_s$$

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

Minimize δ to reduce kicker strength

βs >>
βk >>
μ(s->k) =(2n+1)π/2

Injection oscillations (1)



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

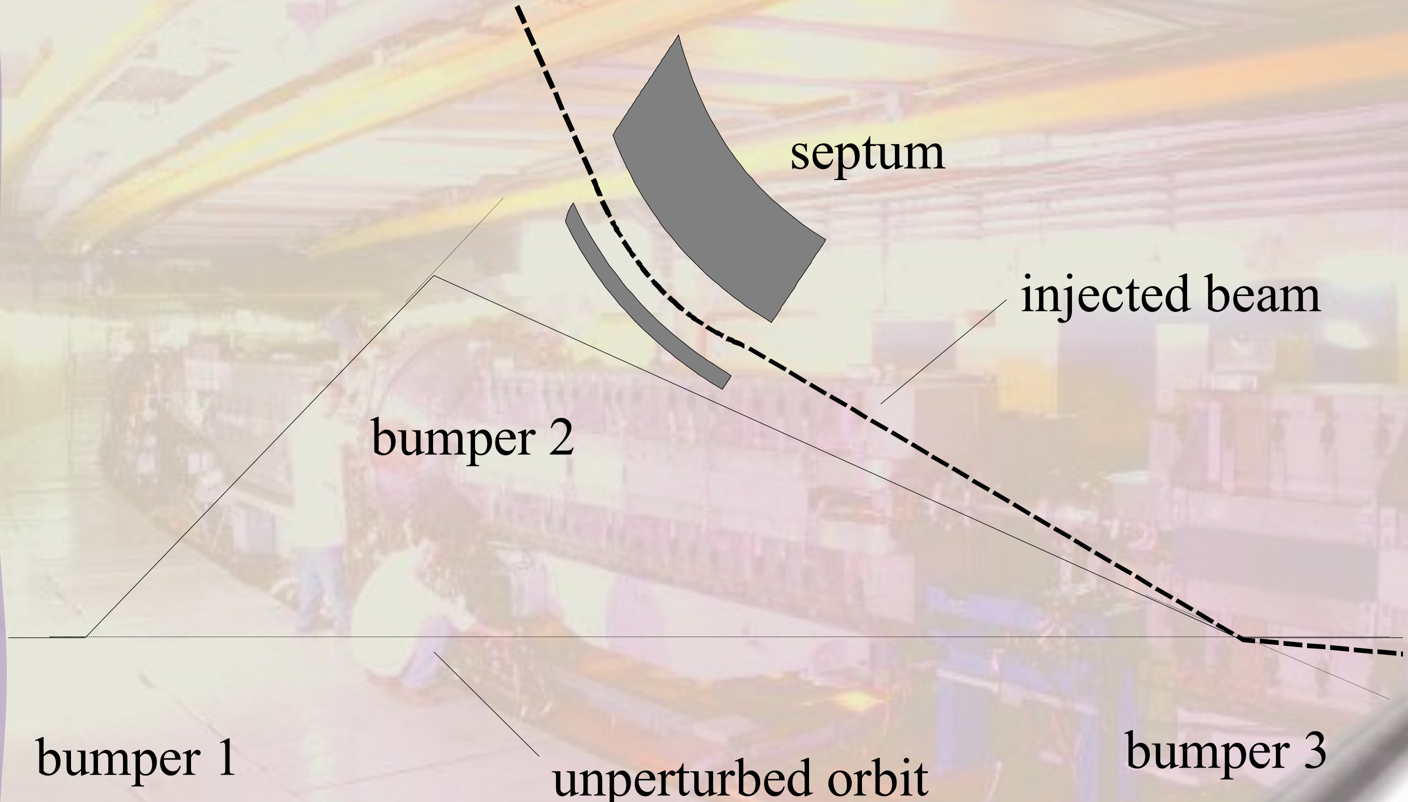
Injection oscillations (2)

- 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

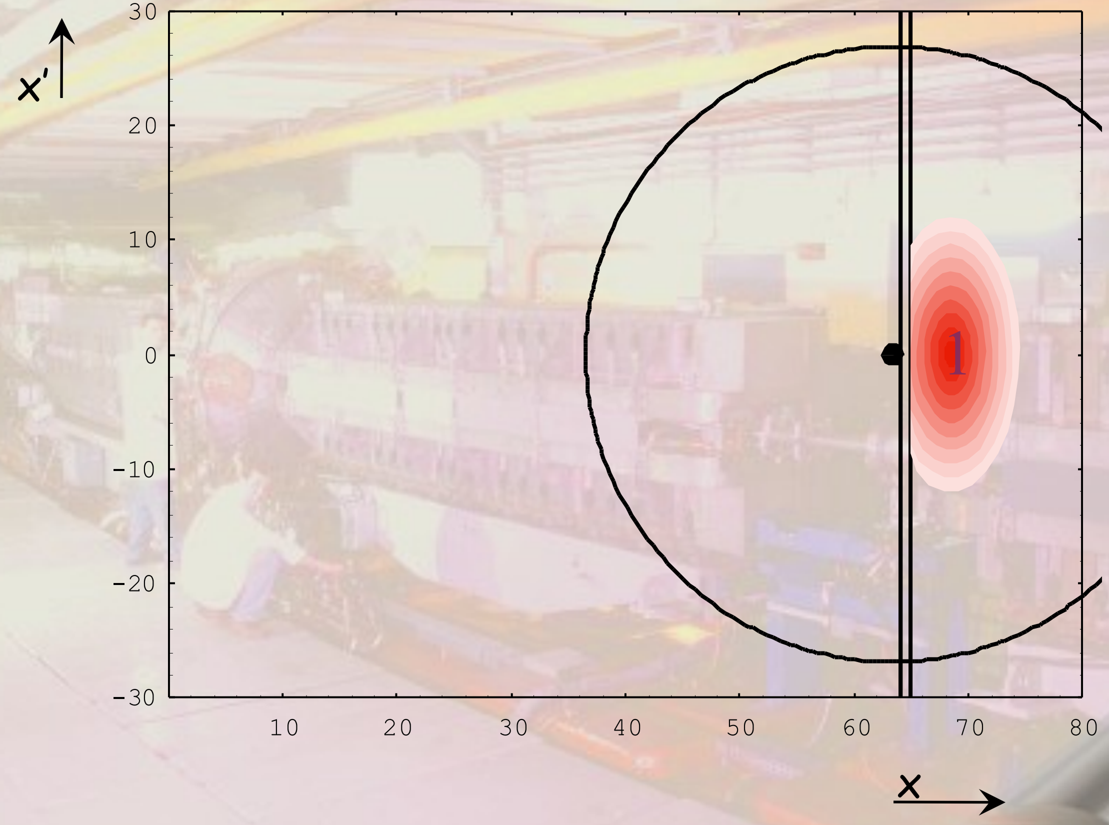
Multi-turn injection for hadrons (2)



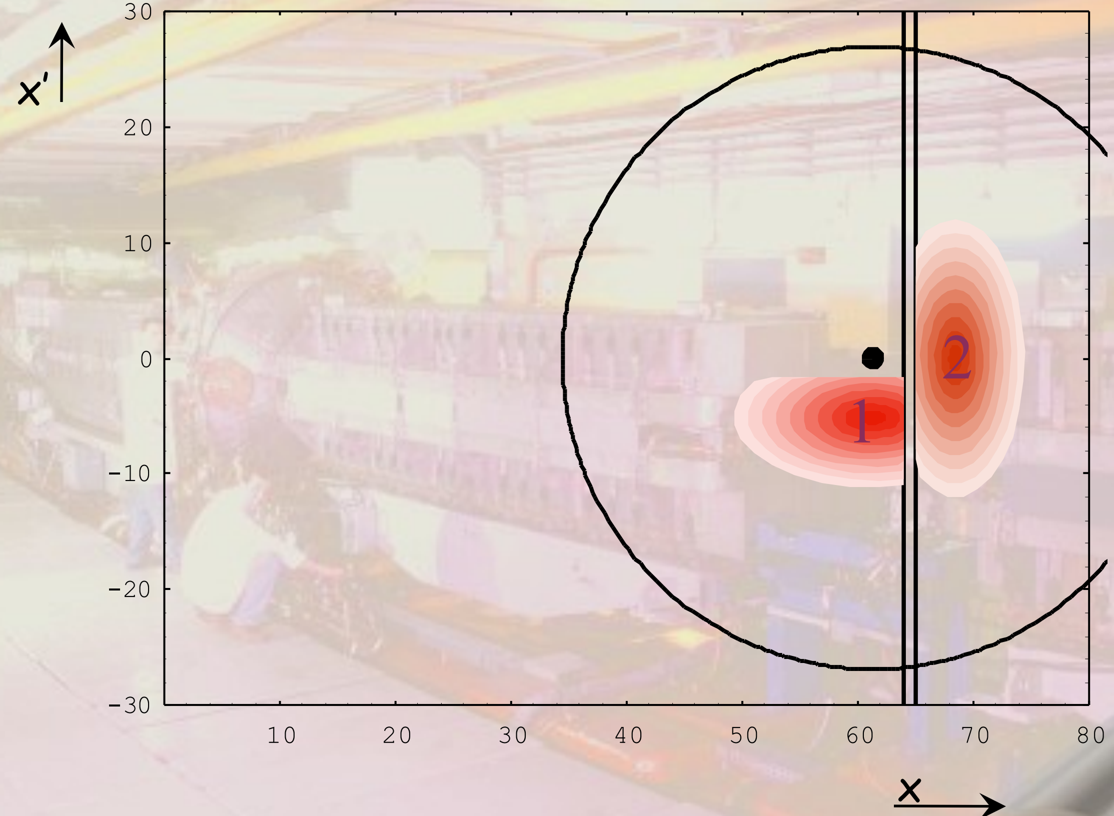
Multi-turn injection for hadrons (3)

- 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

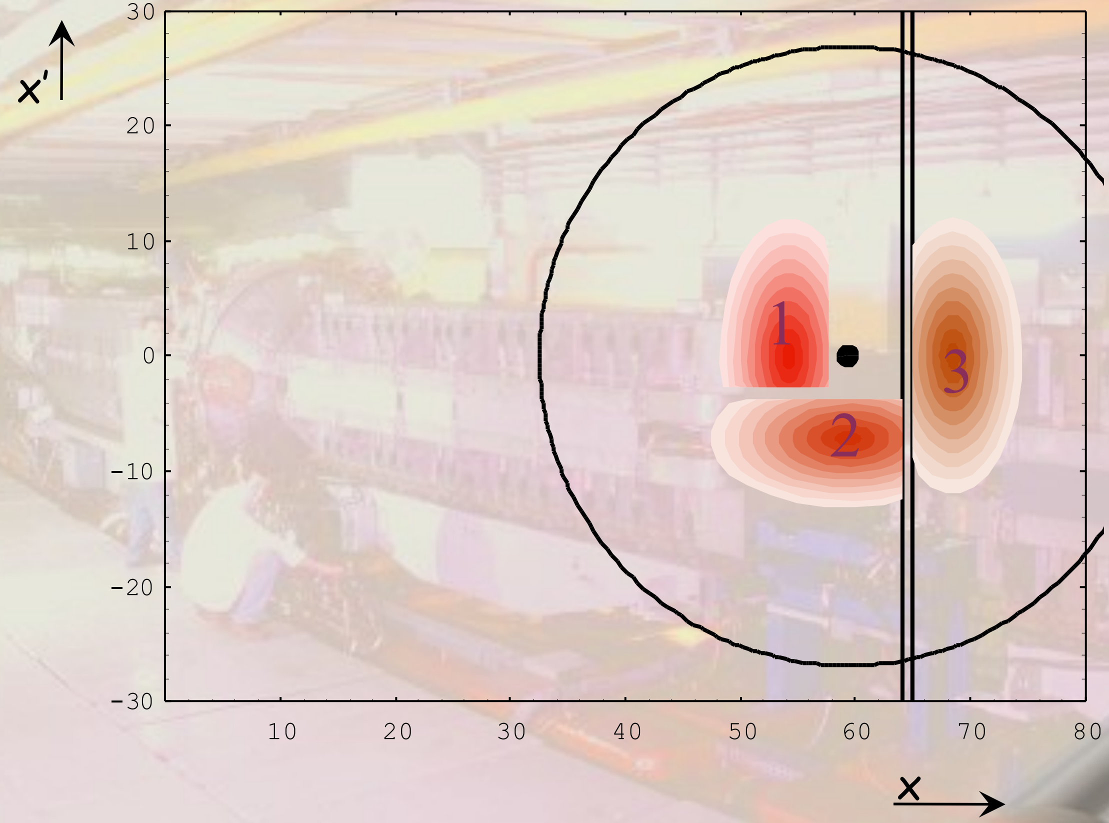
Multi-turn injection for hadrons (4)



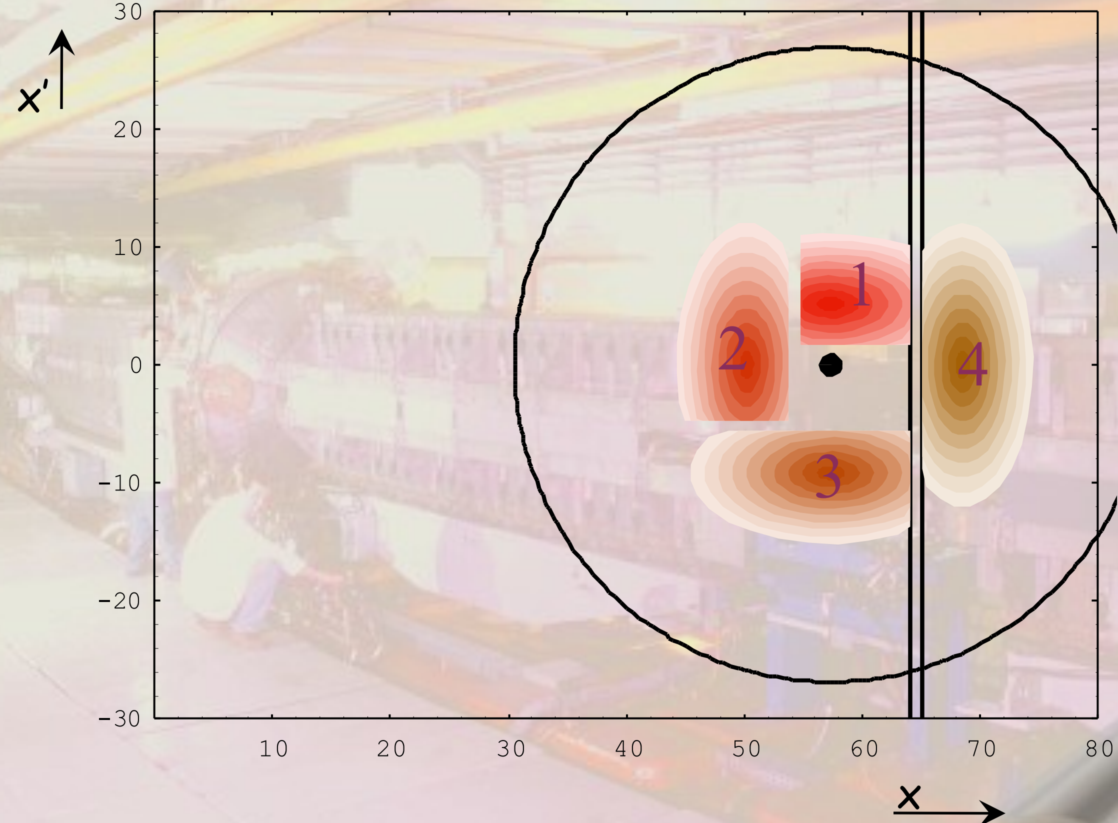
Multi-turn injection for hadrons (5)



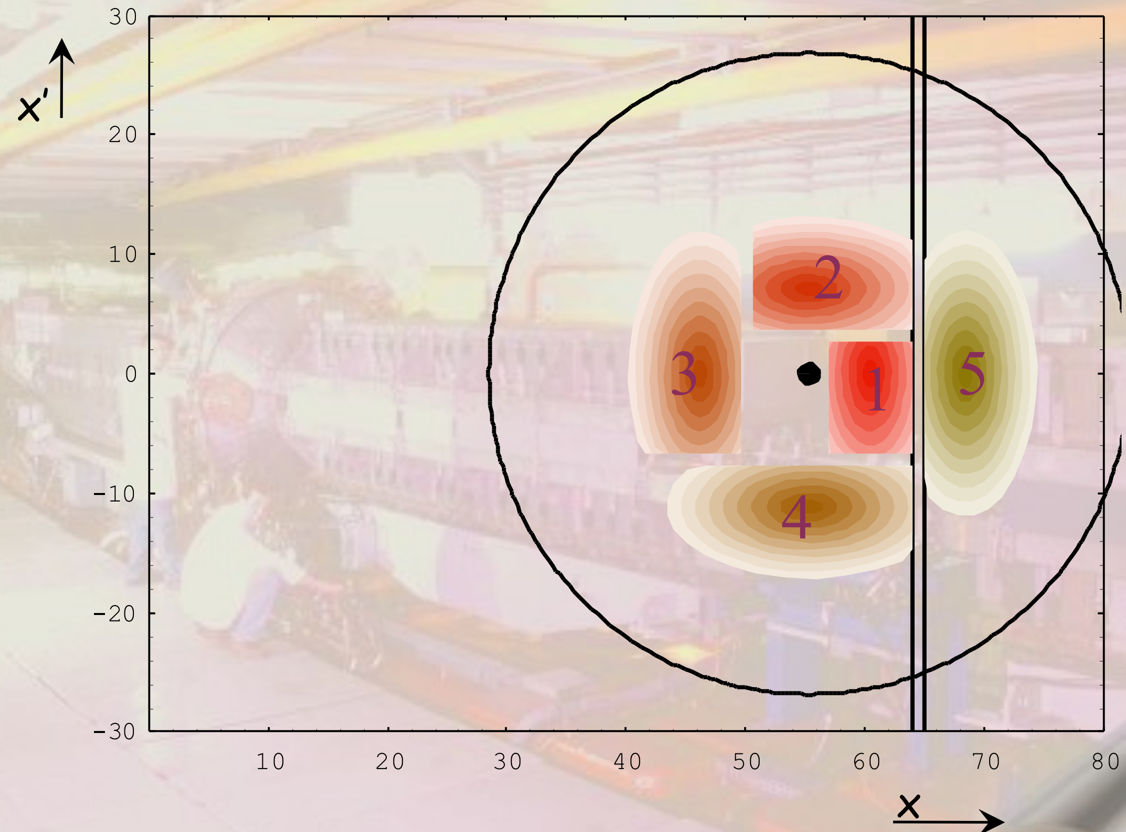
Multi-turn injection for hadrons (6)



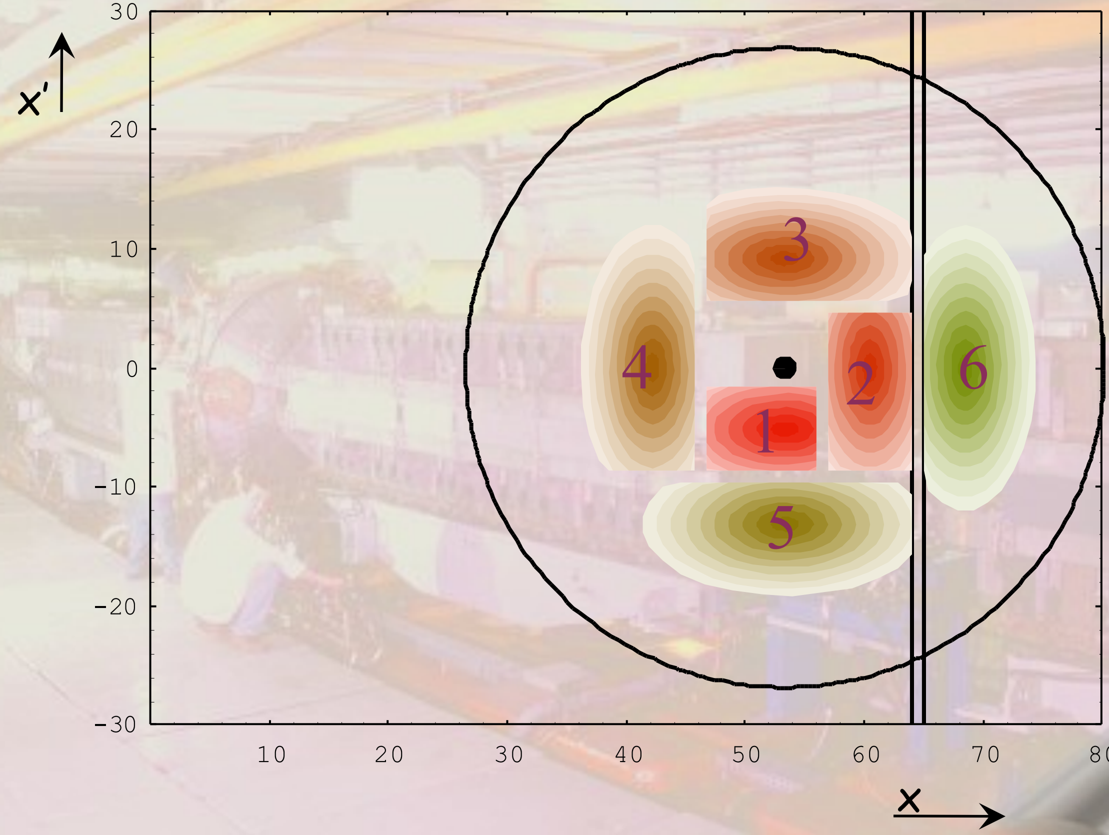
Multi-turn injection for hadrons (7)



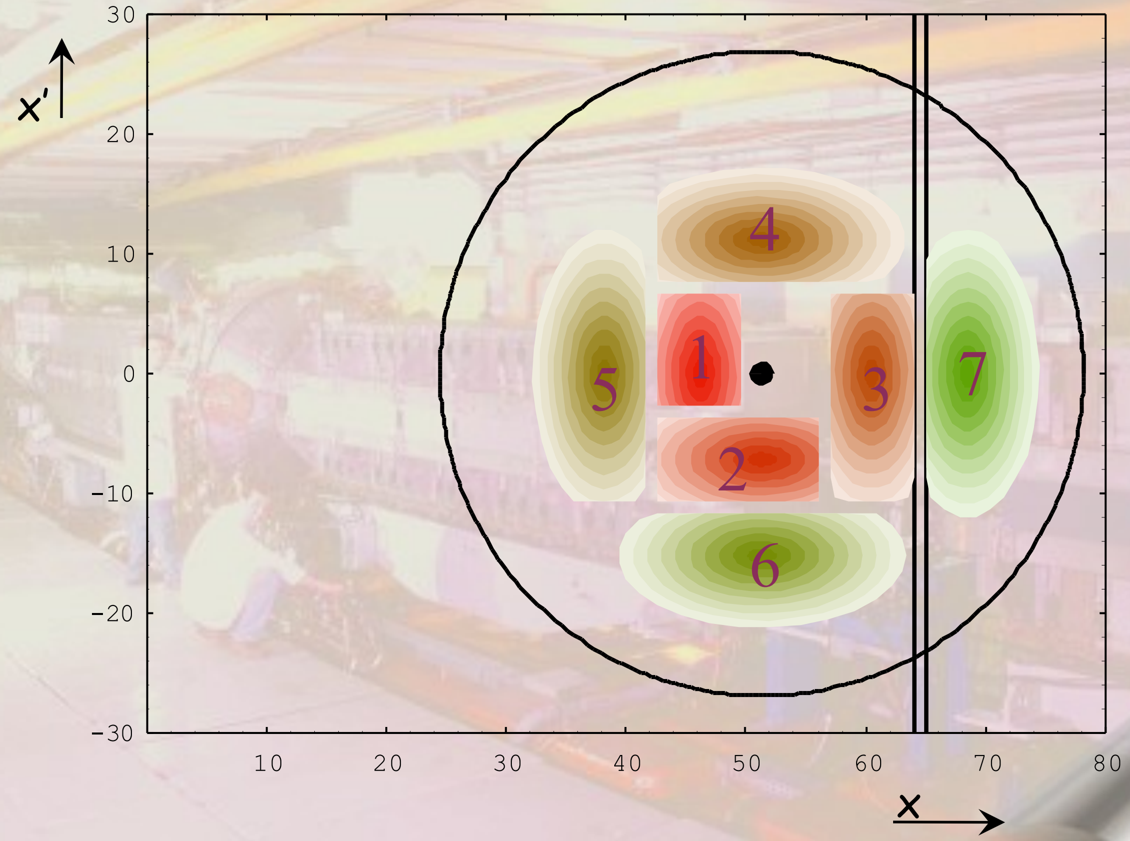
Multi-turn injection for hadrons (8)



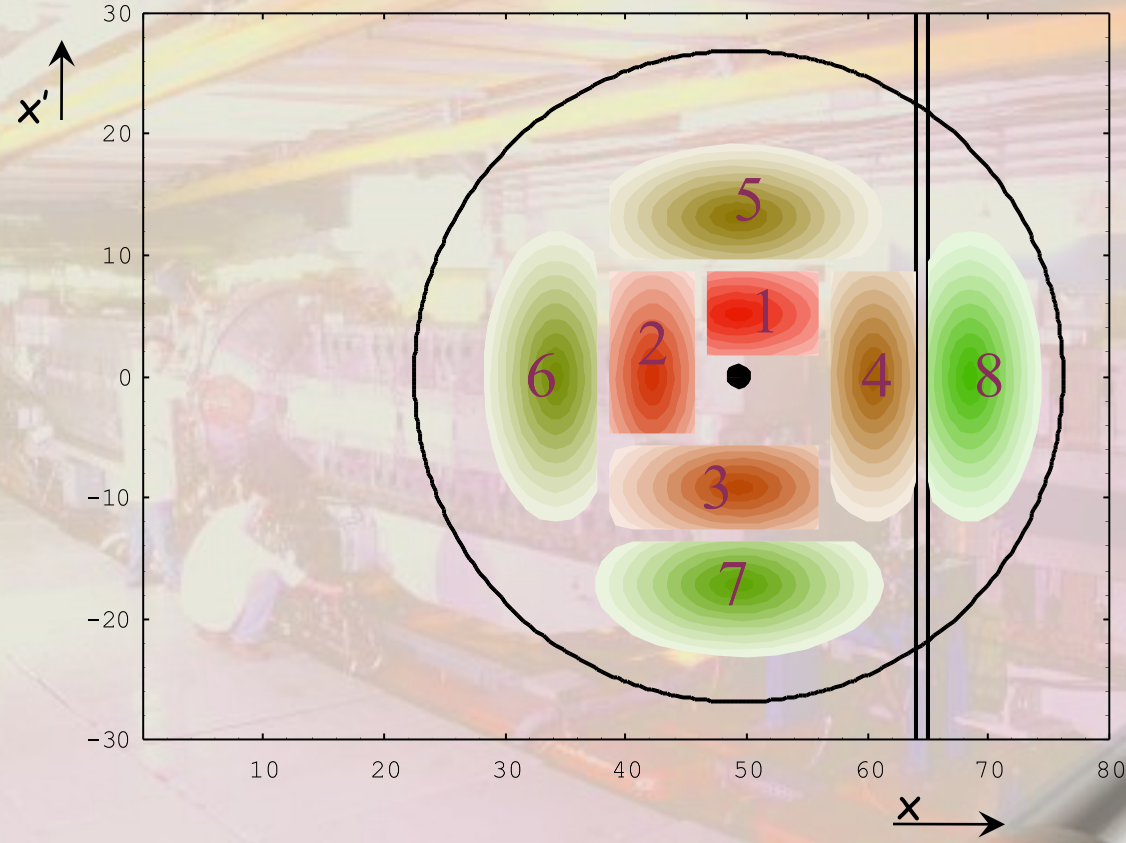
Multi-turn injection for hadrons (9)



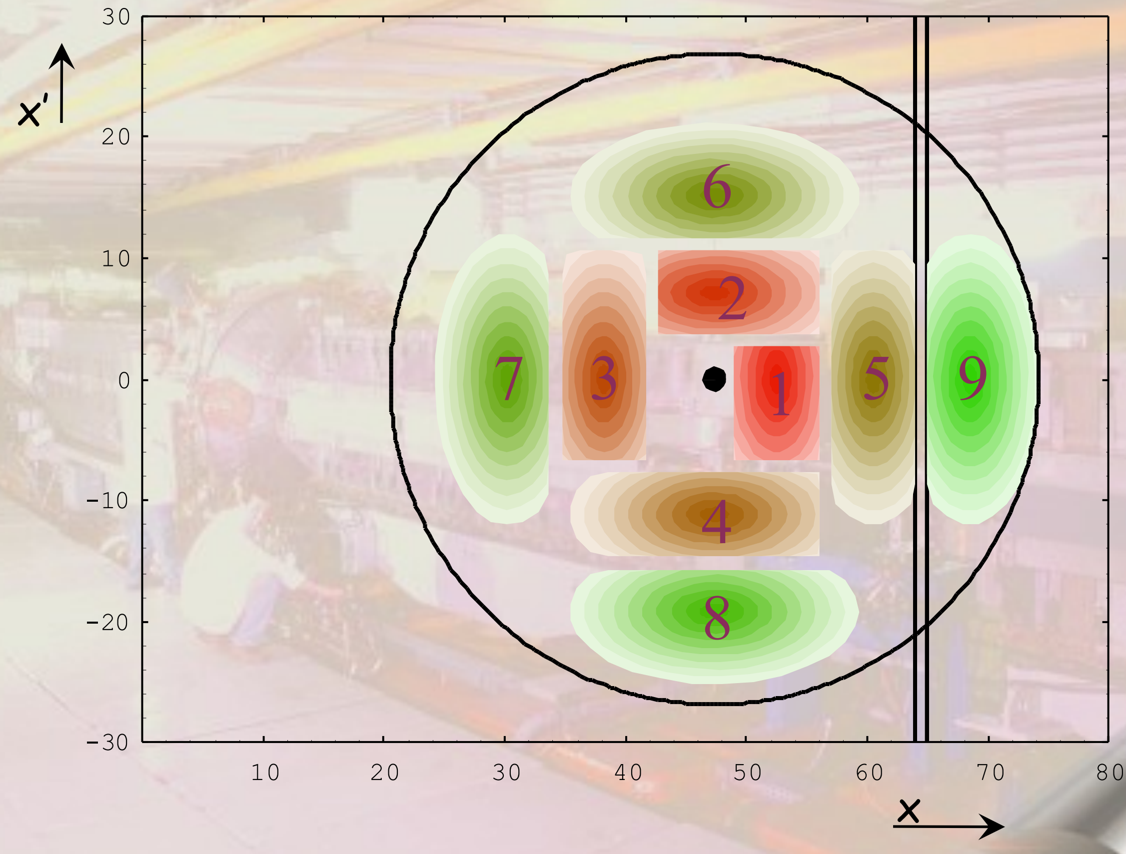
Multi-turn injection for hadrons (10)



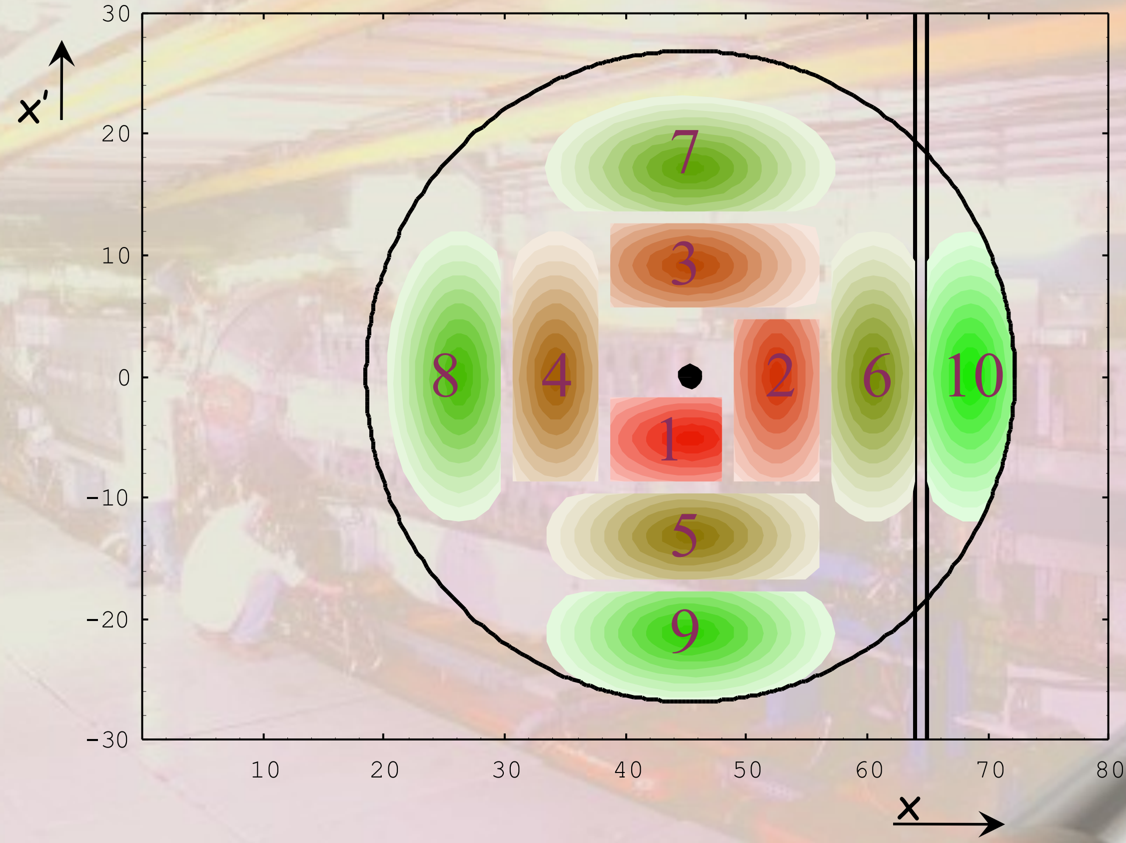
Multi-turn injection for hadrons (11)



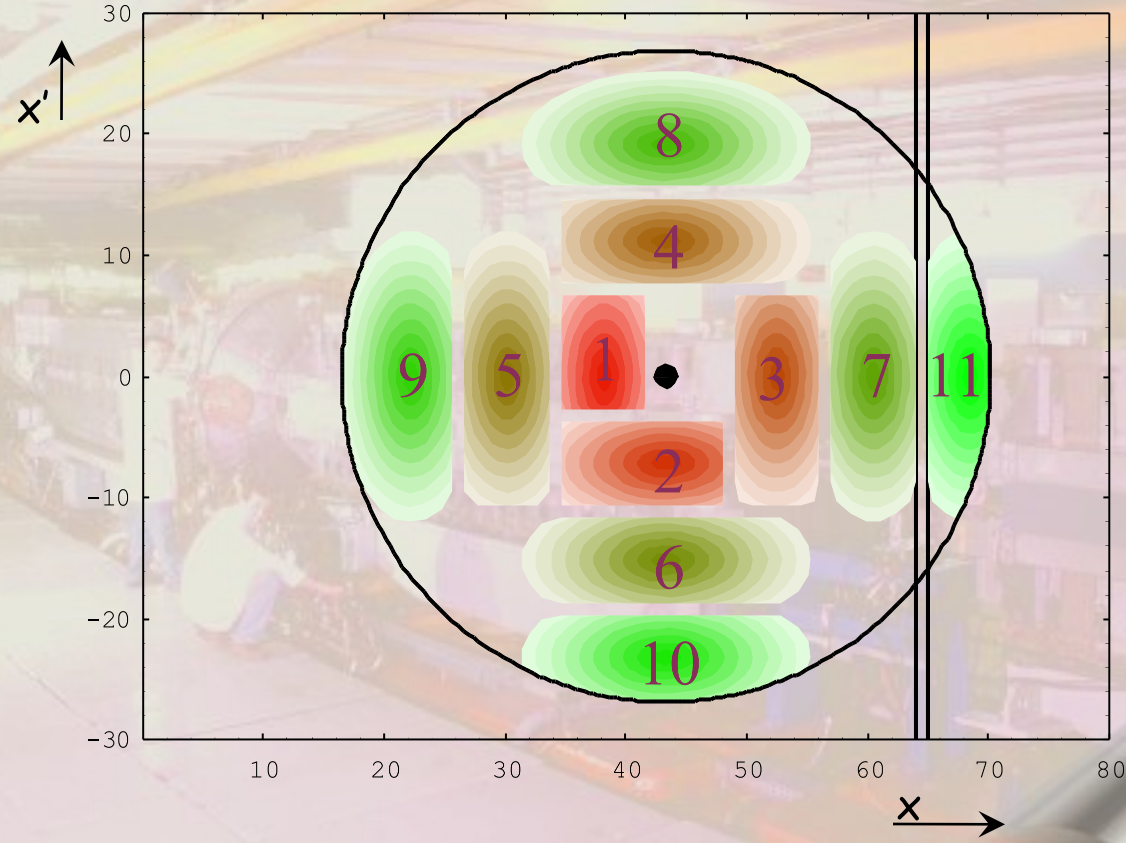
Multi-turn injection for hadrons (12)



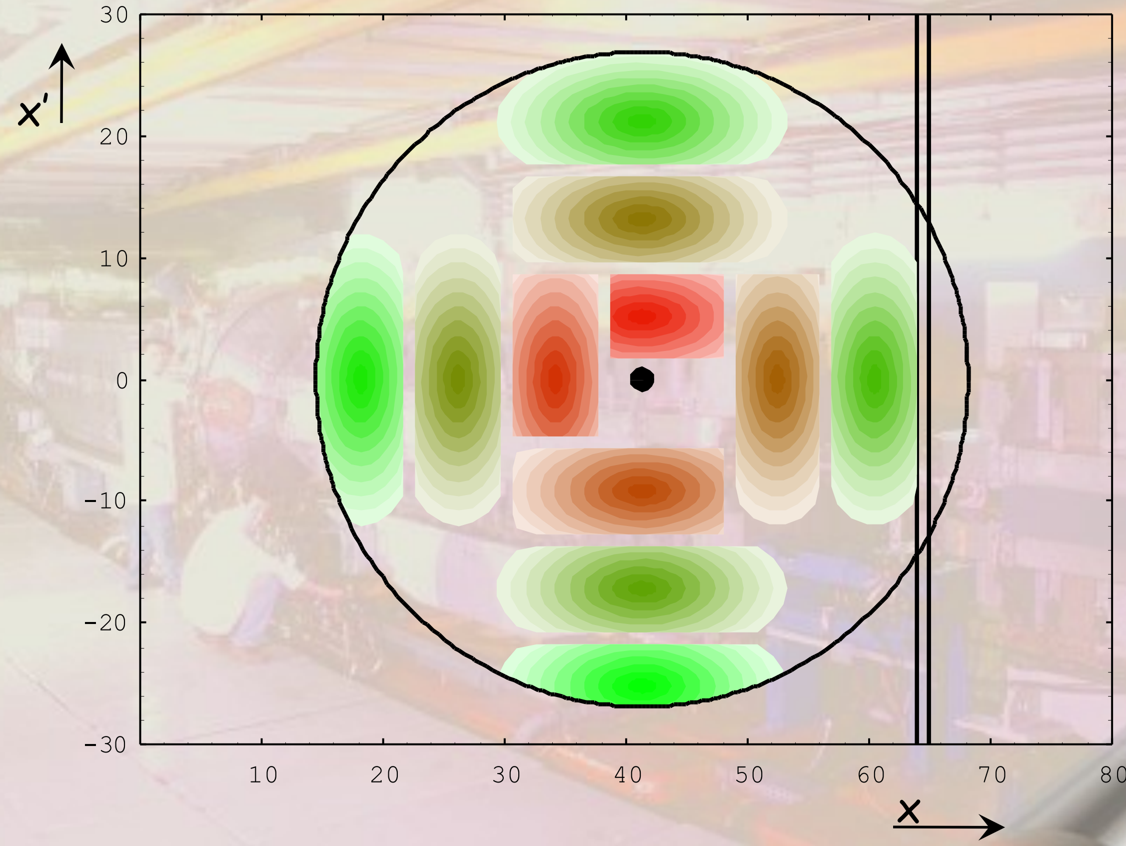
Multi-turn injection for hadrons (13)



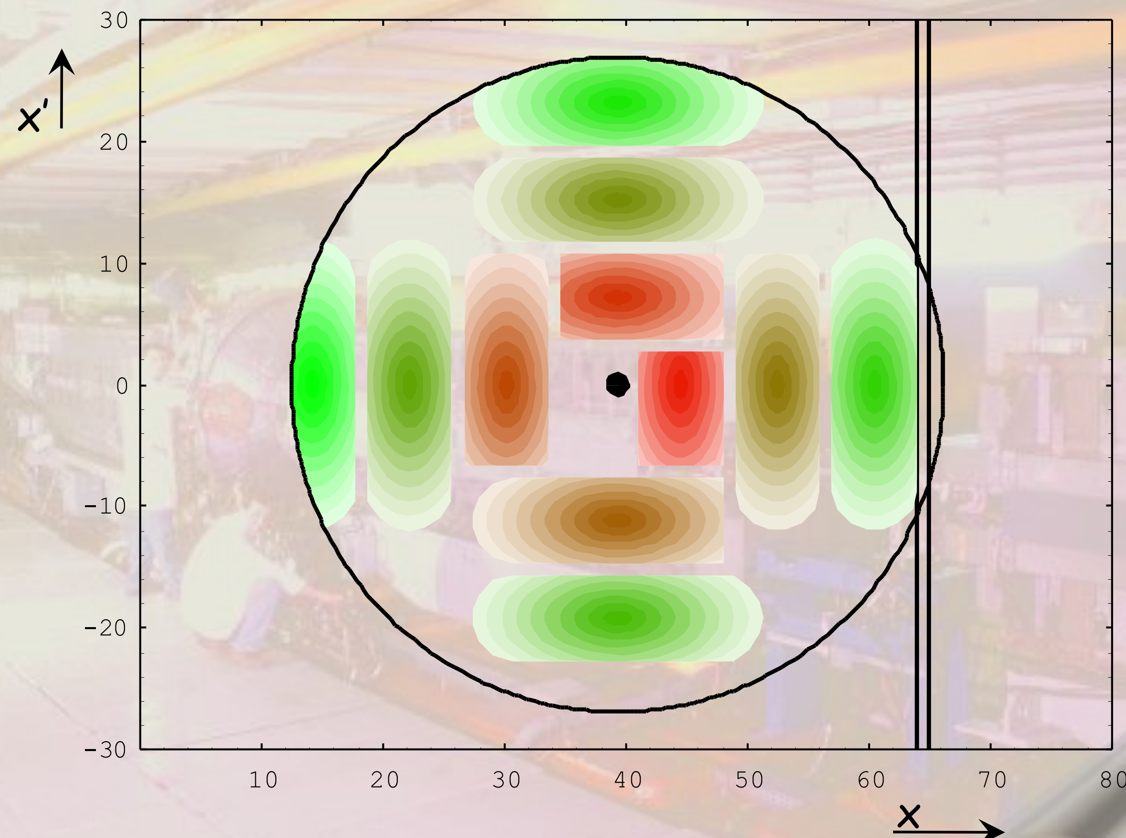
Multi-turn injection for hadrons (14)



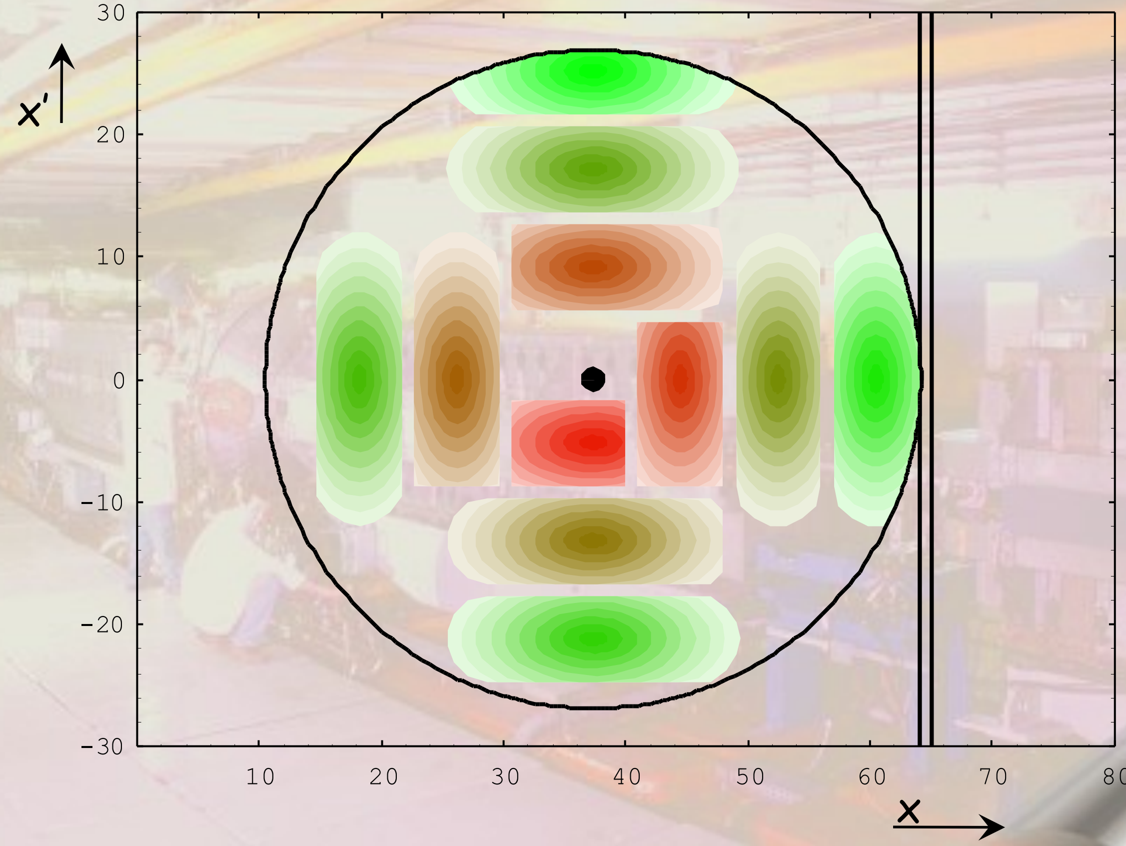
Multi-turn injection for hadrons (15)



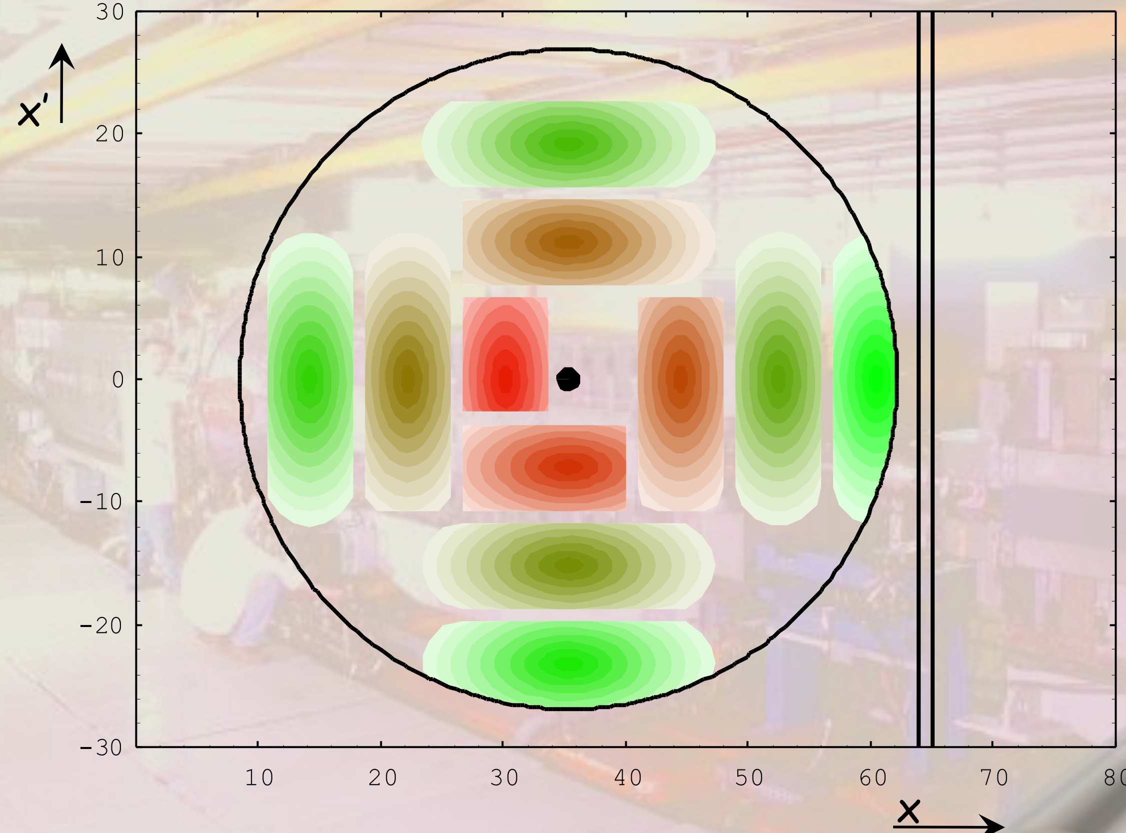
Multi-turn injection for hadrons (16)



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:

$$\frac{1}{0.25}.\left(x_s + \sqrt{\varepsilon_i.\beta} + \sqrt{\varepsilon_h.\beta}\right)$$

Horizontal fractional tune

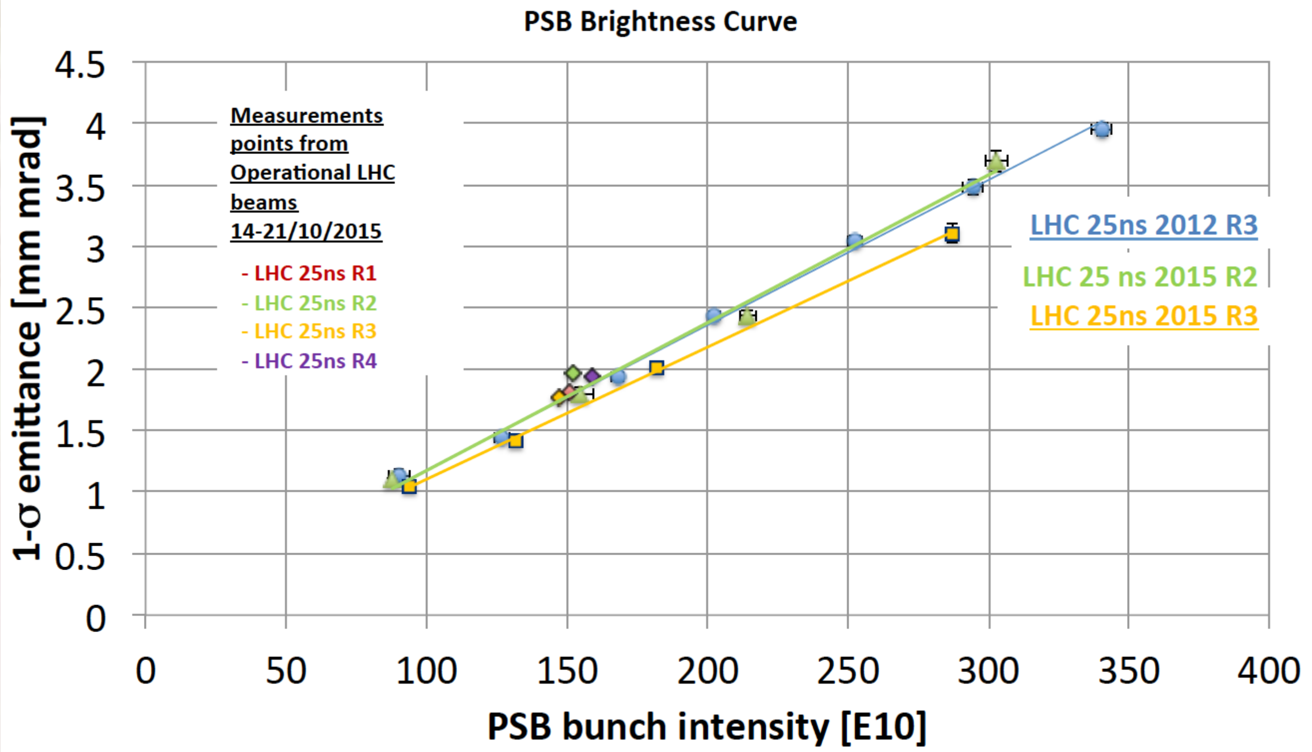
Septum thickness

Beam in the injection channel

Beam in the accelerator

Density with multi-turn injection

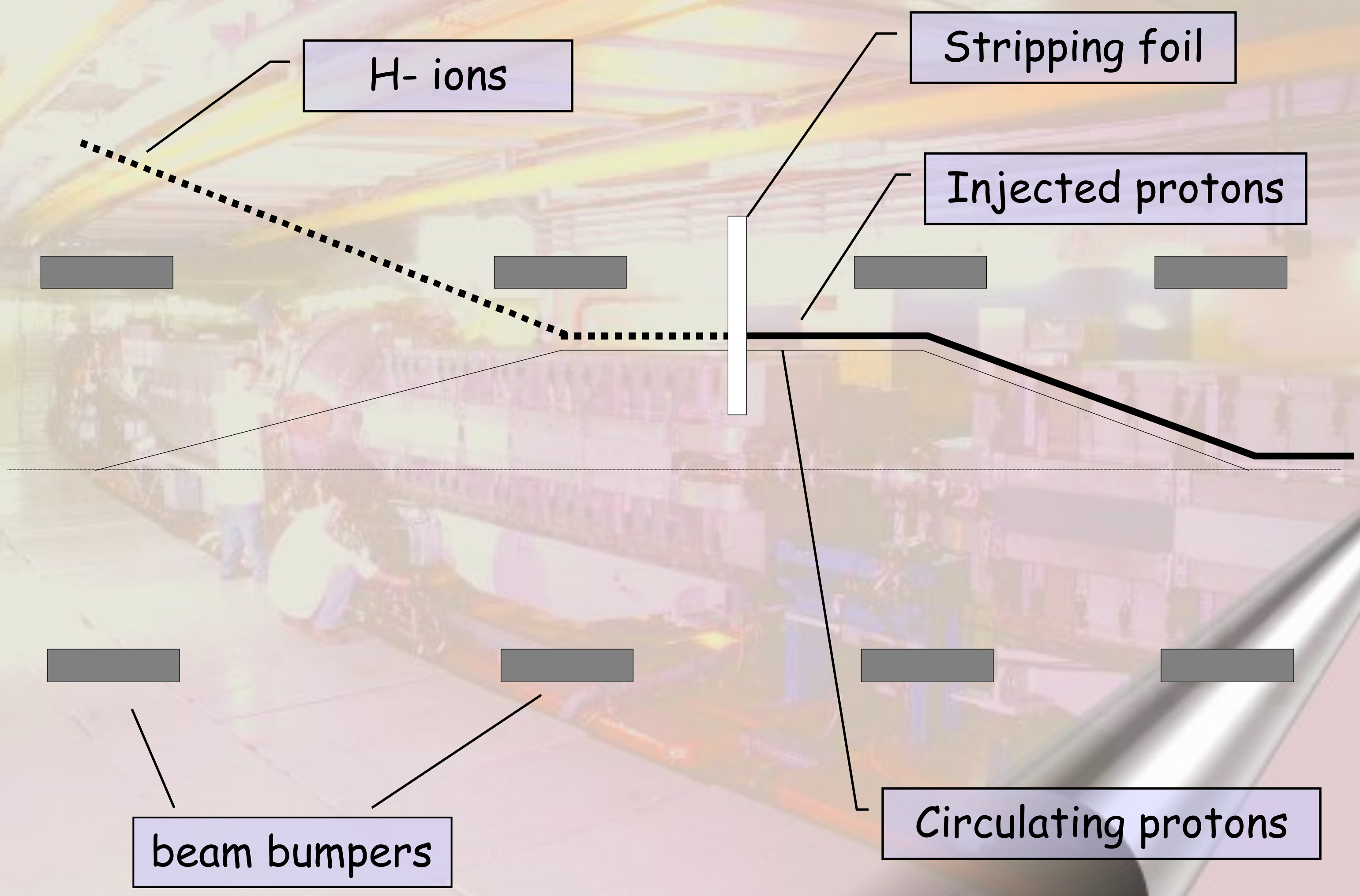
- This multi-turn injection increases intensity with about constant density



Charge exchange injection (1)

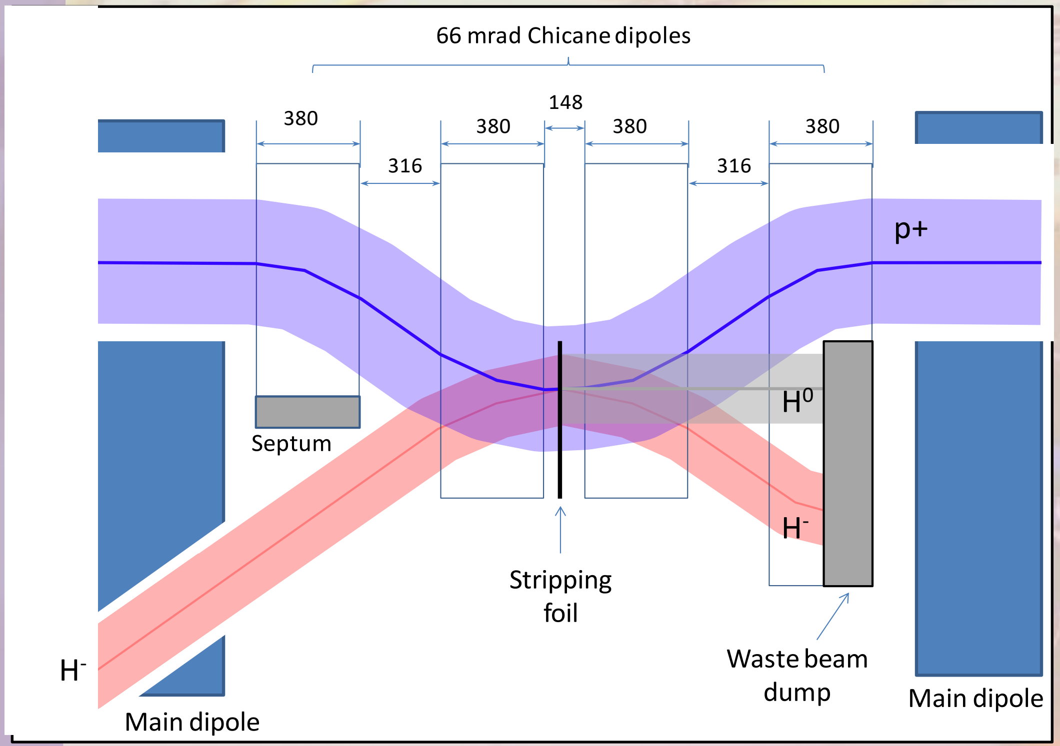
- The charge exchange extraction is already operational in different laboratories around the world.
- At CERN it will be used for the 1st time when Linac 4 will be ready to deliver beam to the PS Booster
- The charge exchange injection works as following:
  - Transport H- ions from the linac to the synchrotron
  - 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)

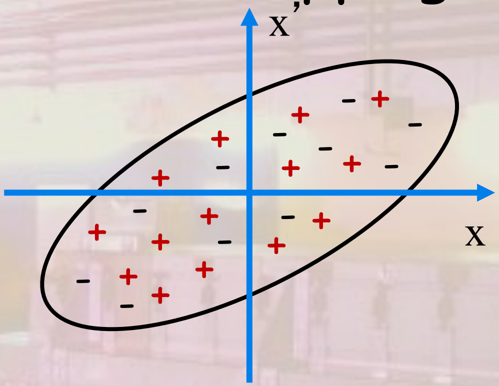


Charge exchange injection (3)

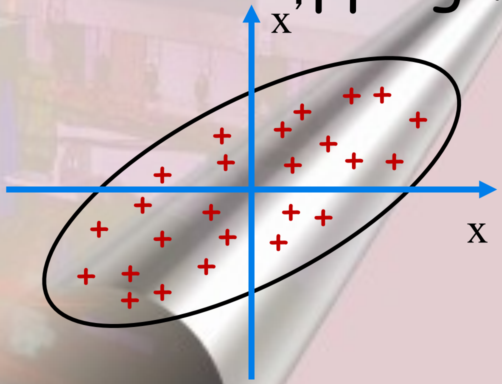
- Use H⁻ beam from LINAC 4



Before stripping foil



Behind stripping foil



- Phase Space Painting is possible (various particle distributions)

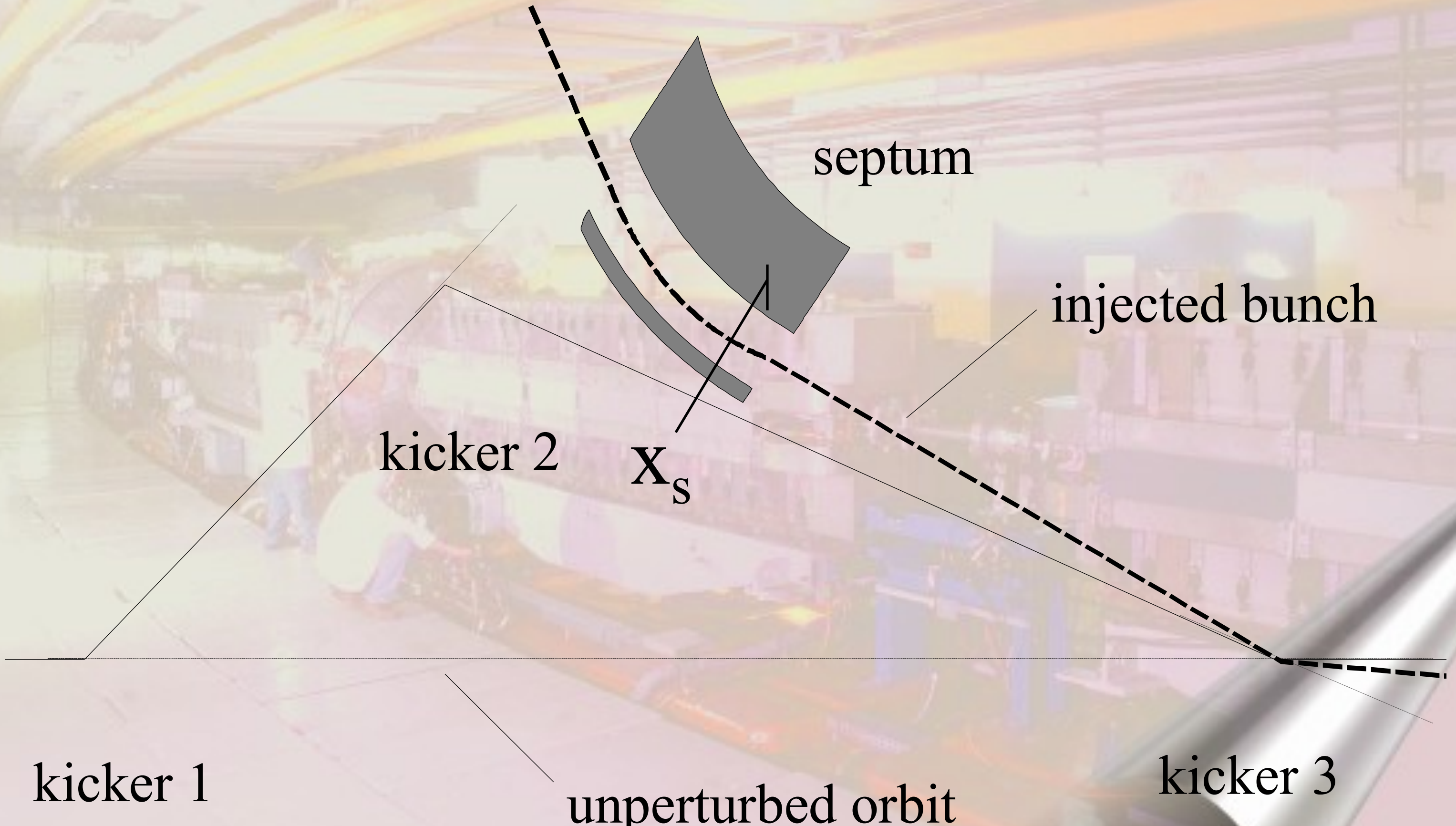
Charge exchange injection (3)

- 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

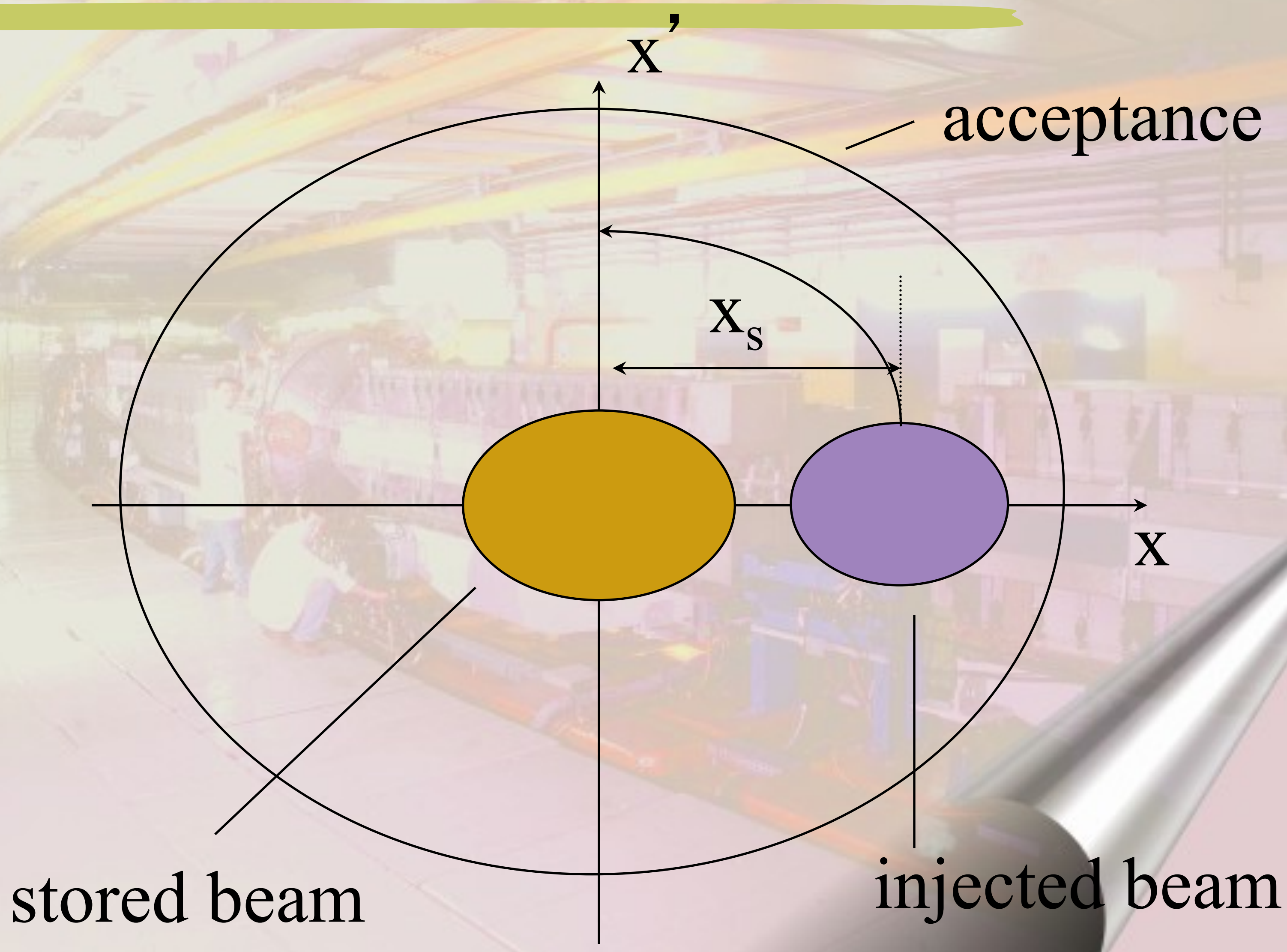
Lepton injection

- 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)

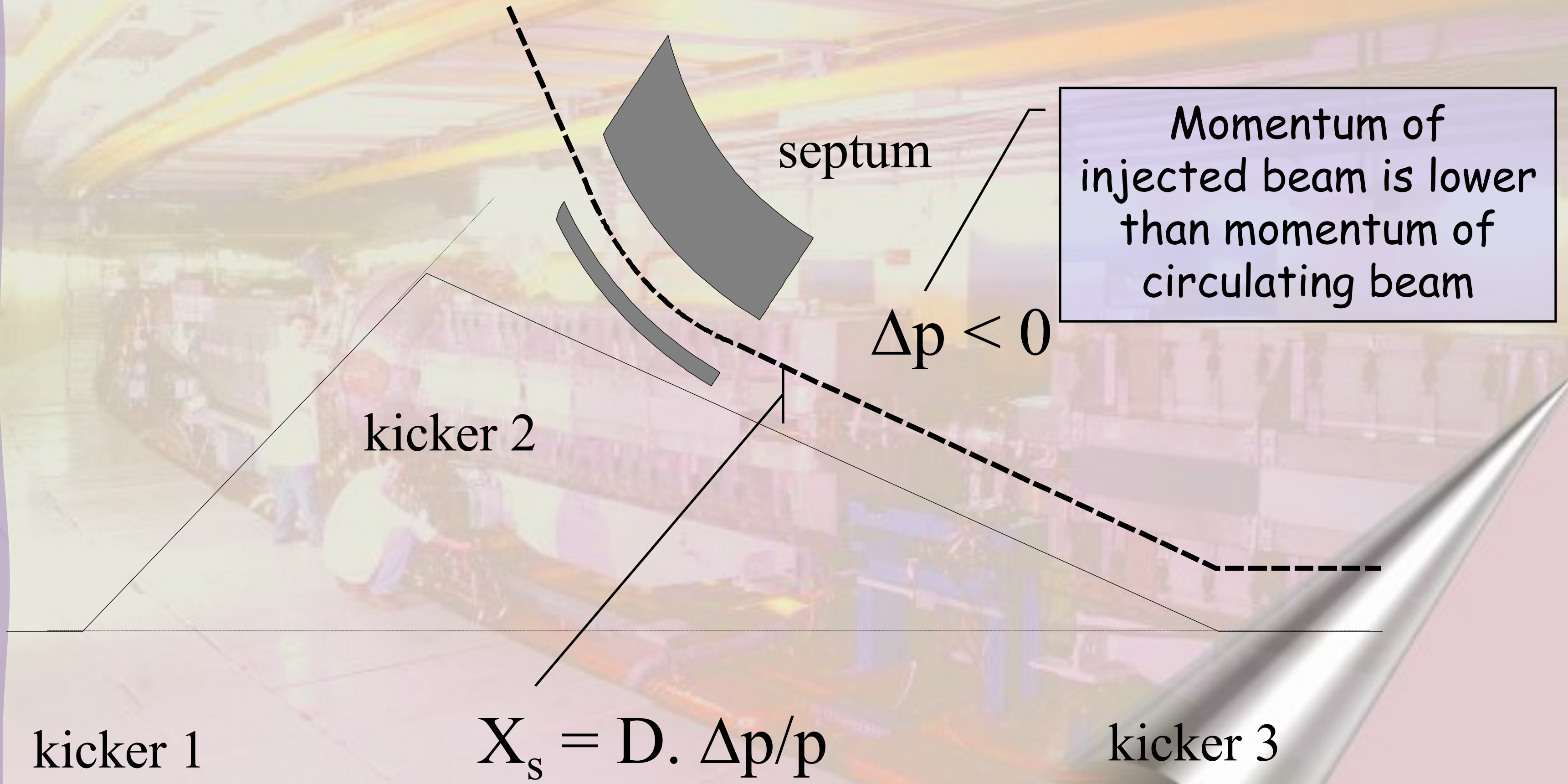
Betatron accumulation (1)



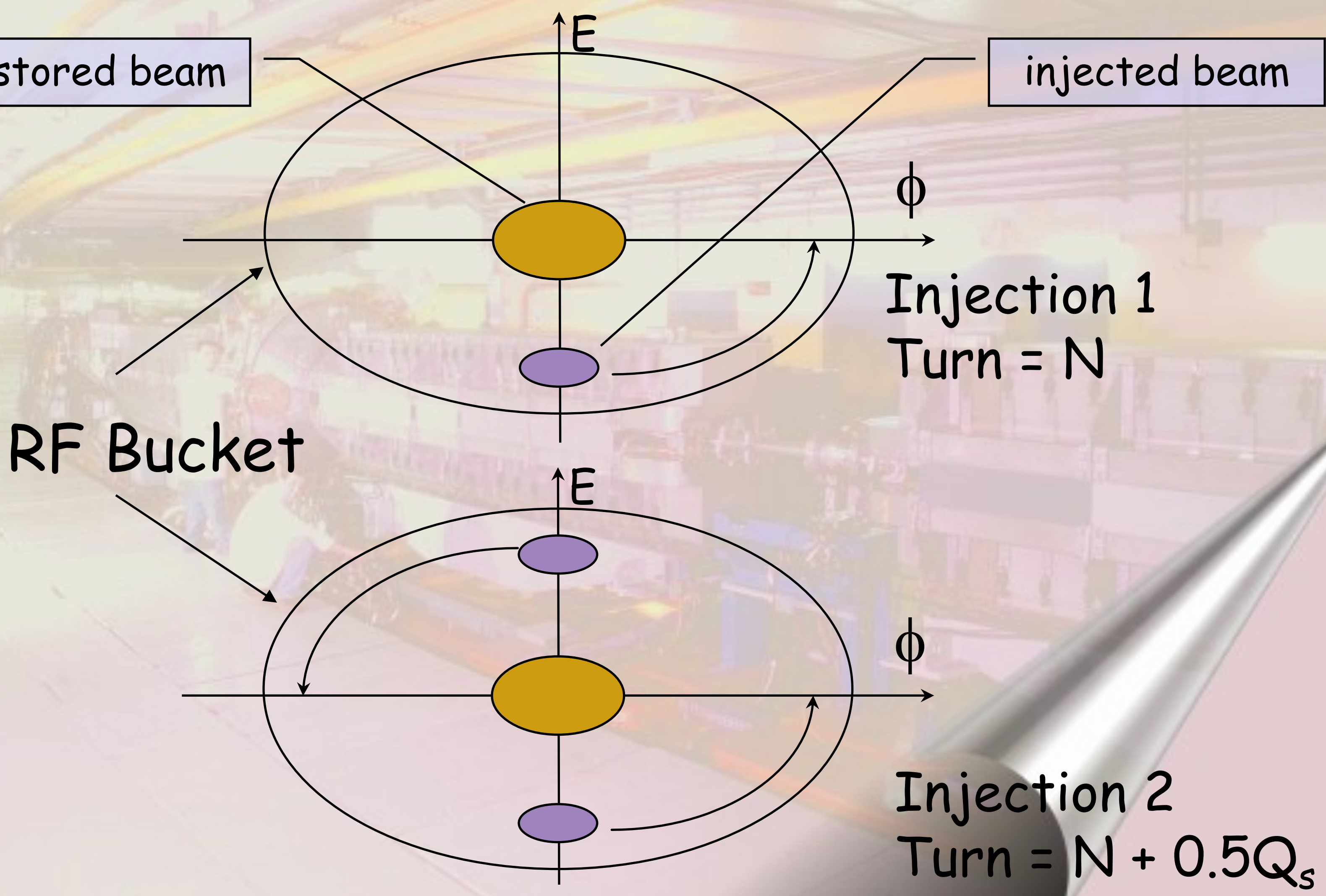
Betatron accumulation (2)



Synchrotron accumulation (1)



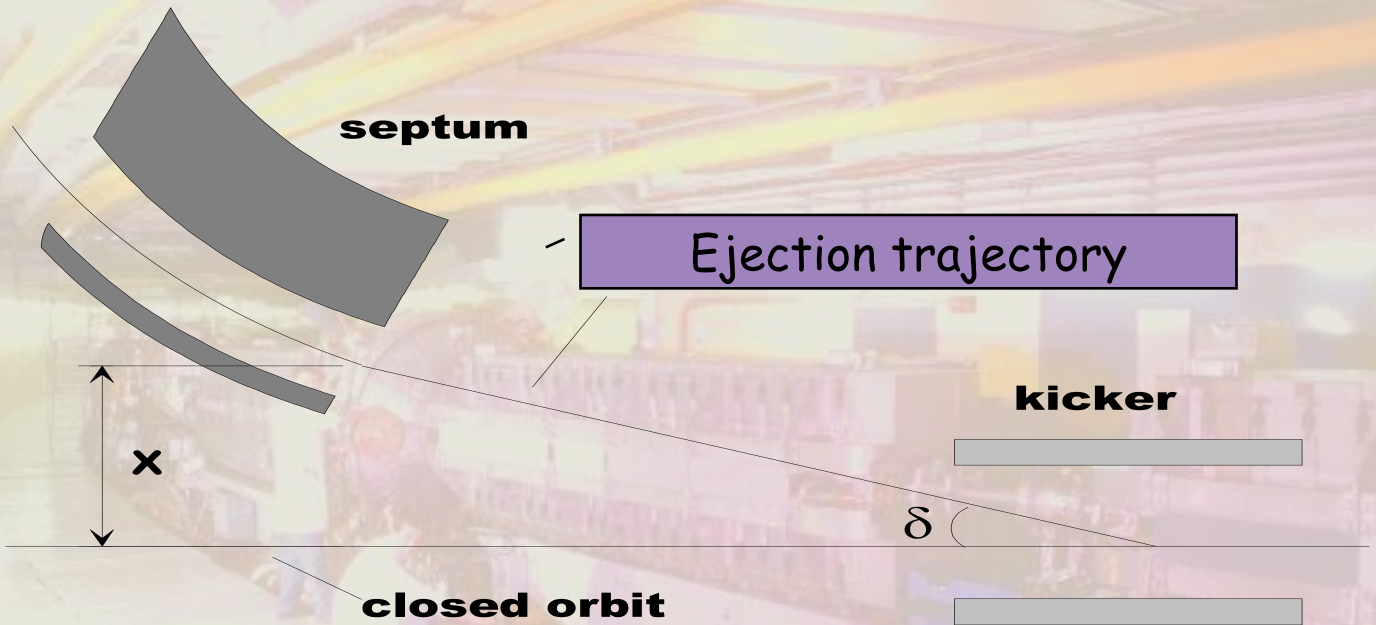
Synchrotron accumulation (2)



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)



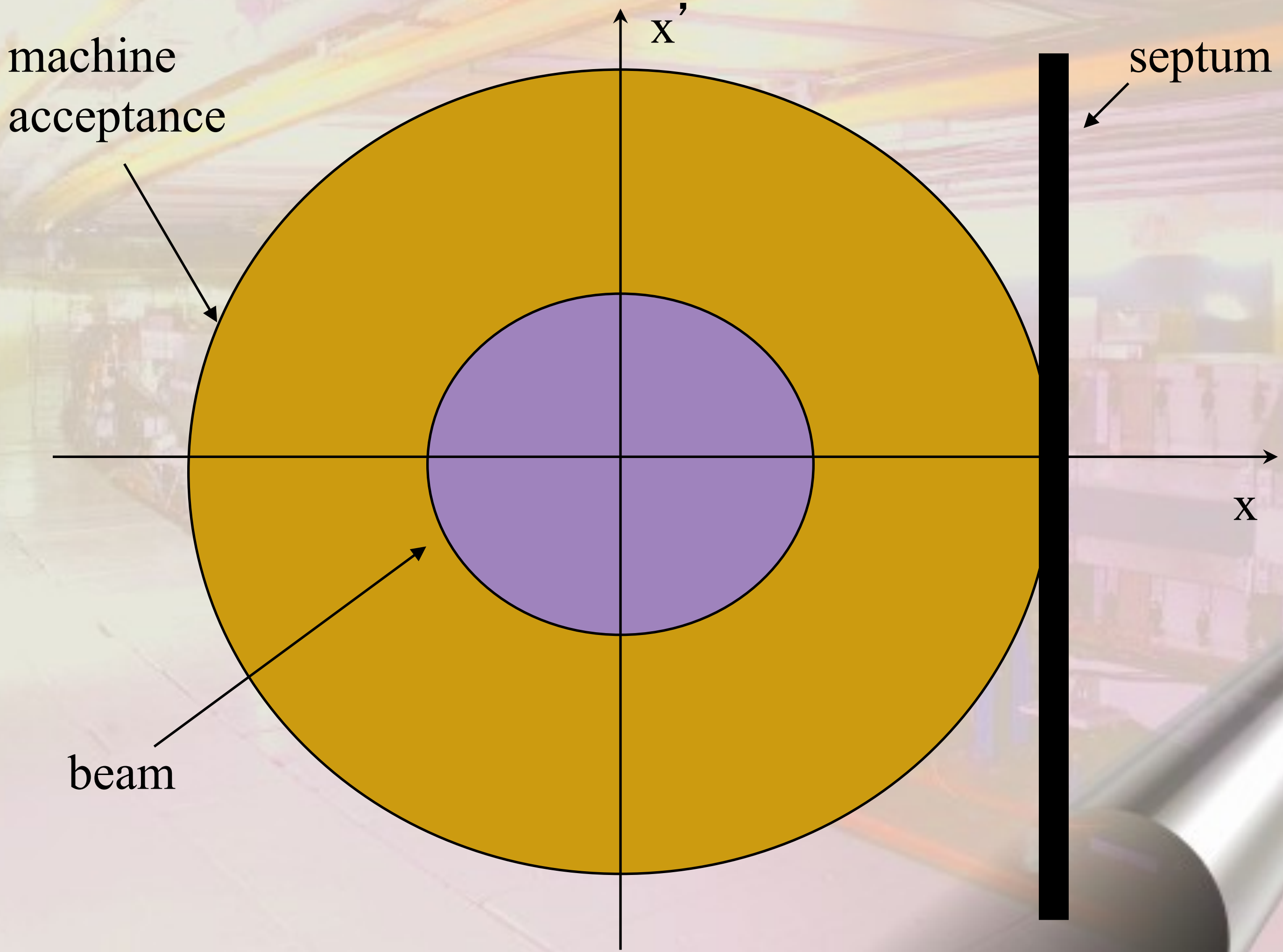
$$x = \sqrt{\beta_s \cdot \varepsilon_e} + \sqrt{\beta_s \cdot \varepsilon} + D_s\left(\frac{dp_e}{p} + \frac{dp}{p}\right) + x_{co} + x_s$$

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

Multi-turn extraction (1)

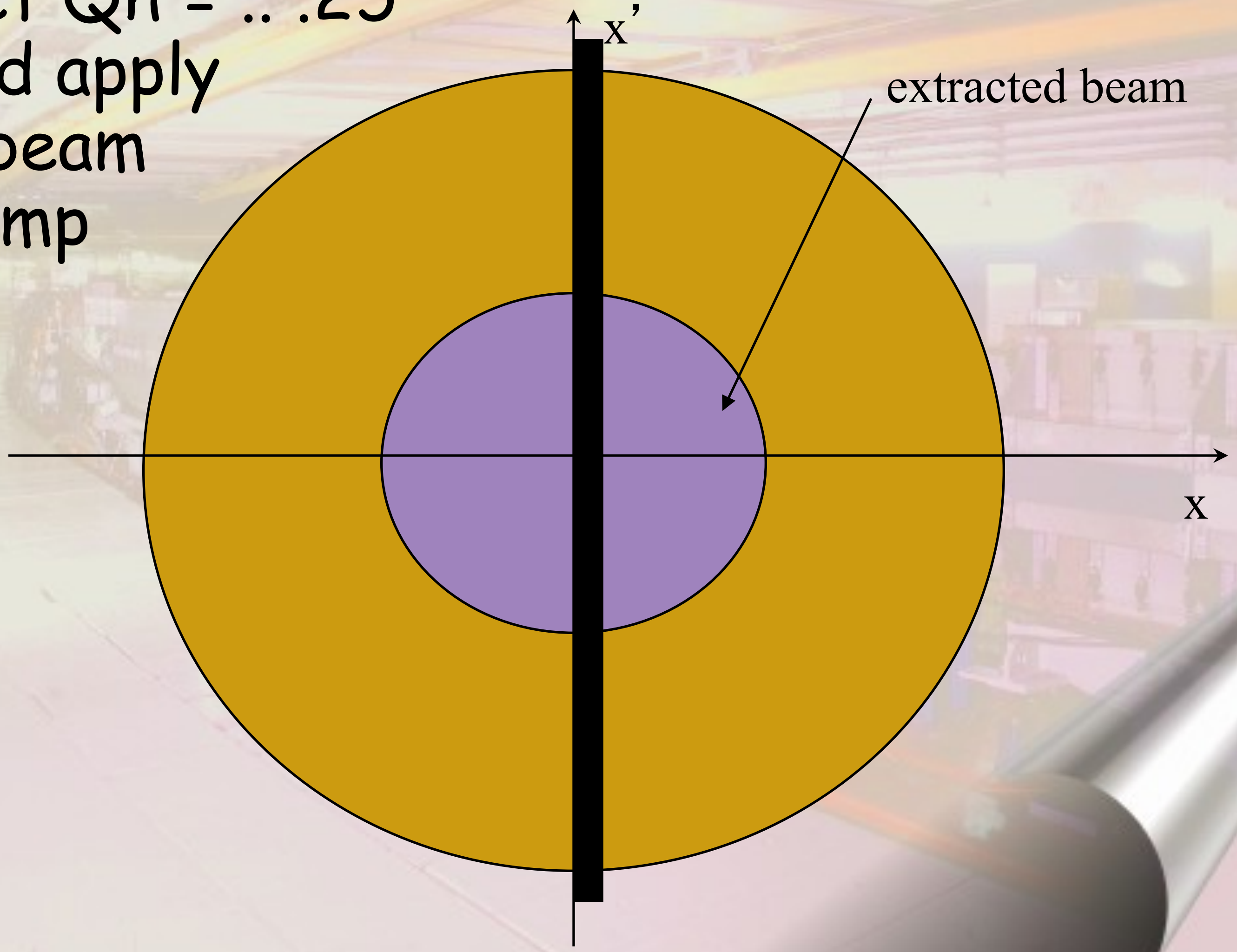
- Many physicists would like to have a continuous flux of particles.
- However, this is not possible with our machines and the way we work.
- We try to approach this using multi-turn extractions
- We know two types of multi turn ejection:
  - Non-Resonant multi-turn ejection (few turns)
    e.g.. PS 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)

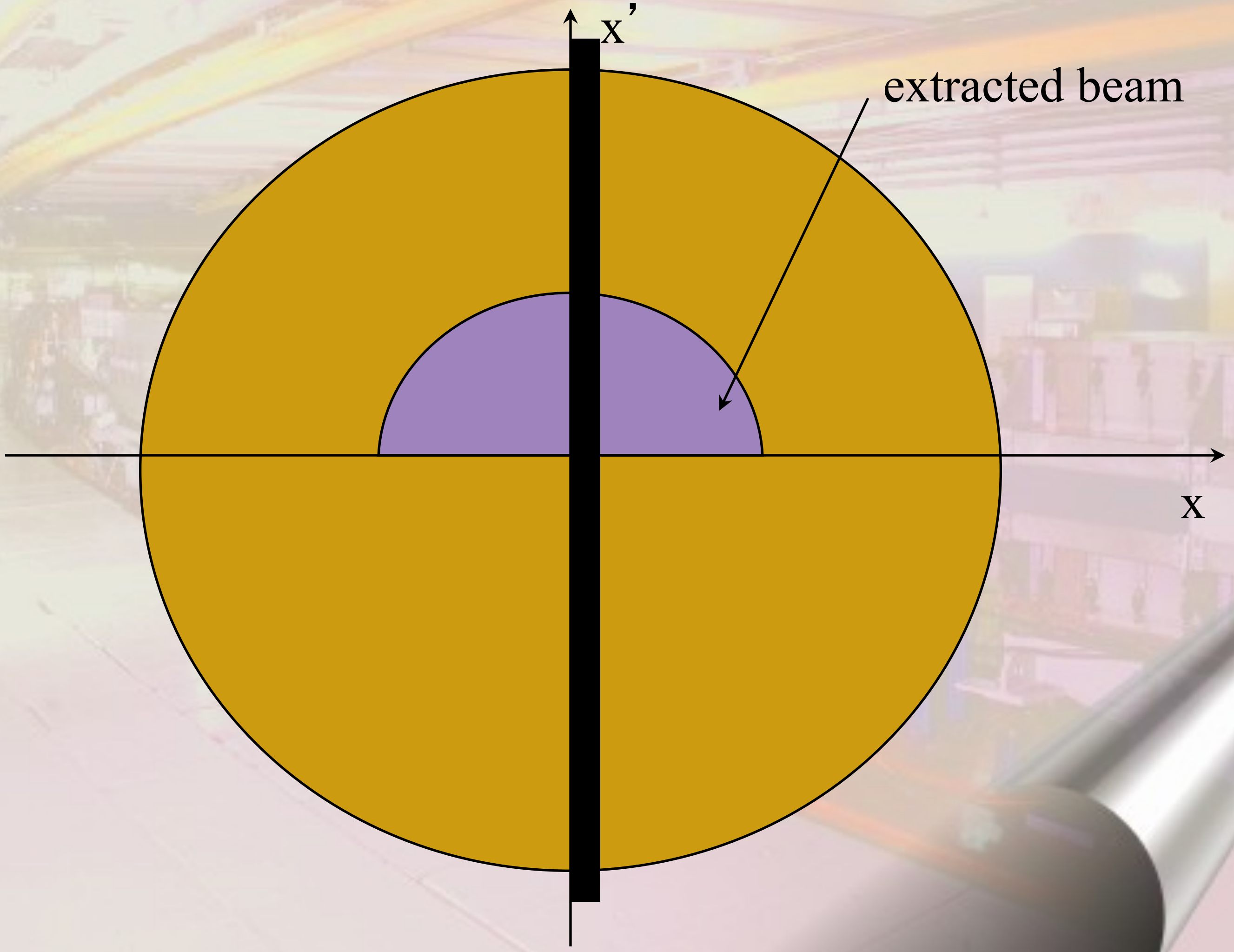


1st turn

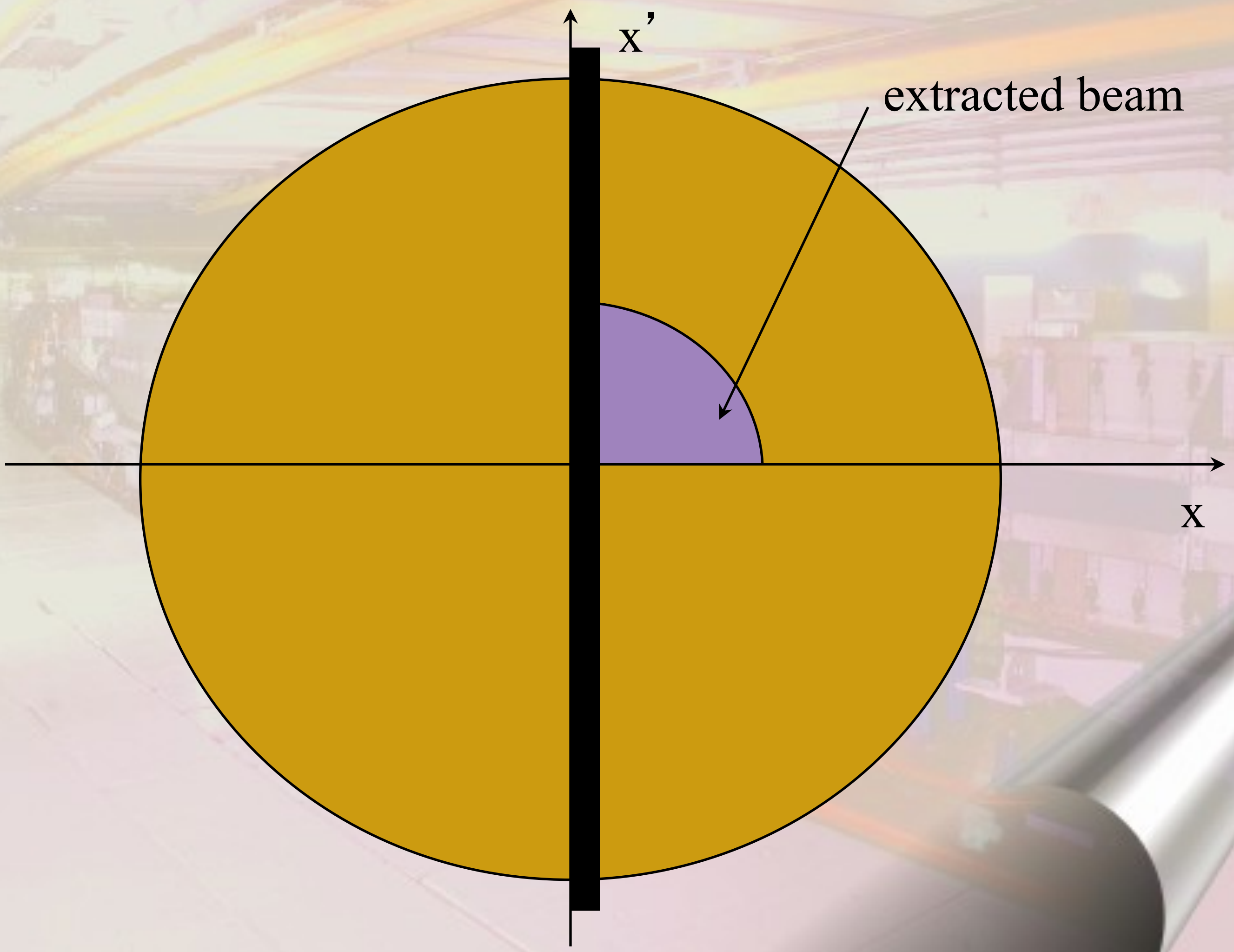
Set Qh = .. .25 and apply a beam bump



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.

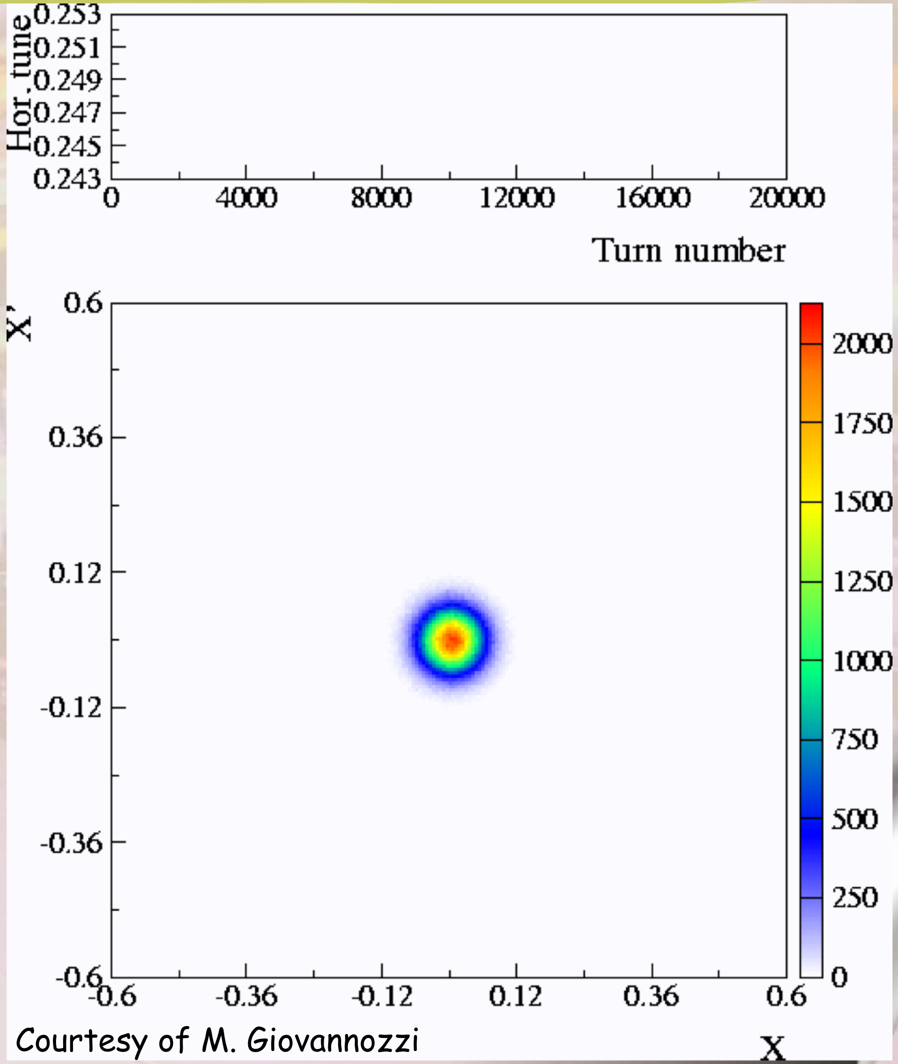
Resonant Multi-Turn Extraction

- 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

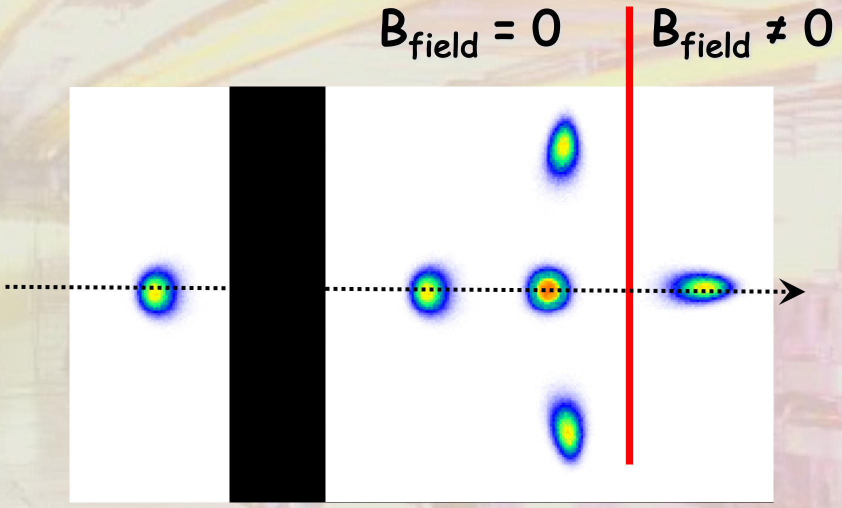
Phase space portrait



Courtesy of M. Giovannozzi

Extract the beam

At the septum location



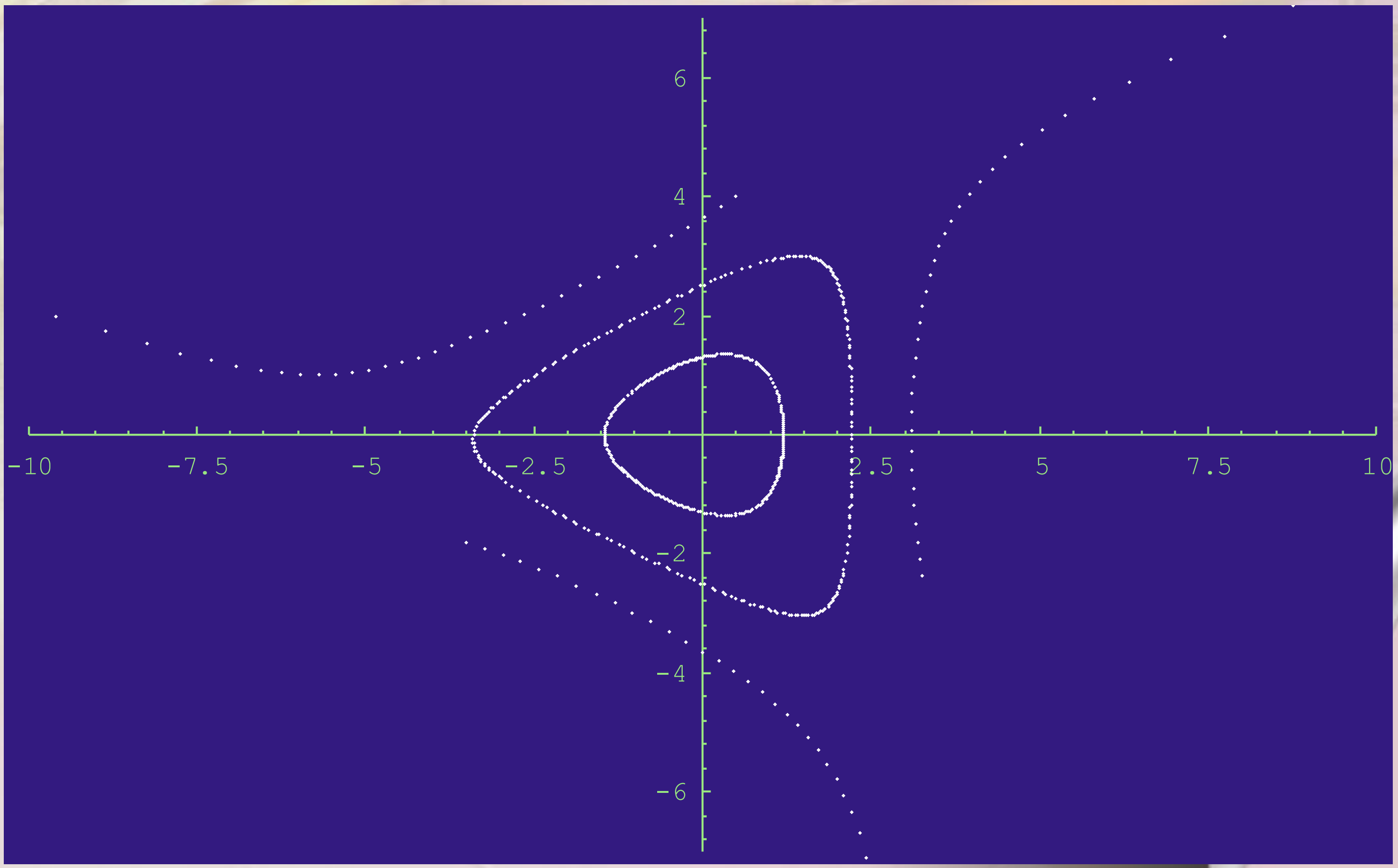
Courtesy of M. Giovannozzi

- 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.

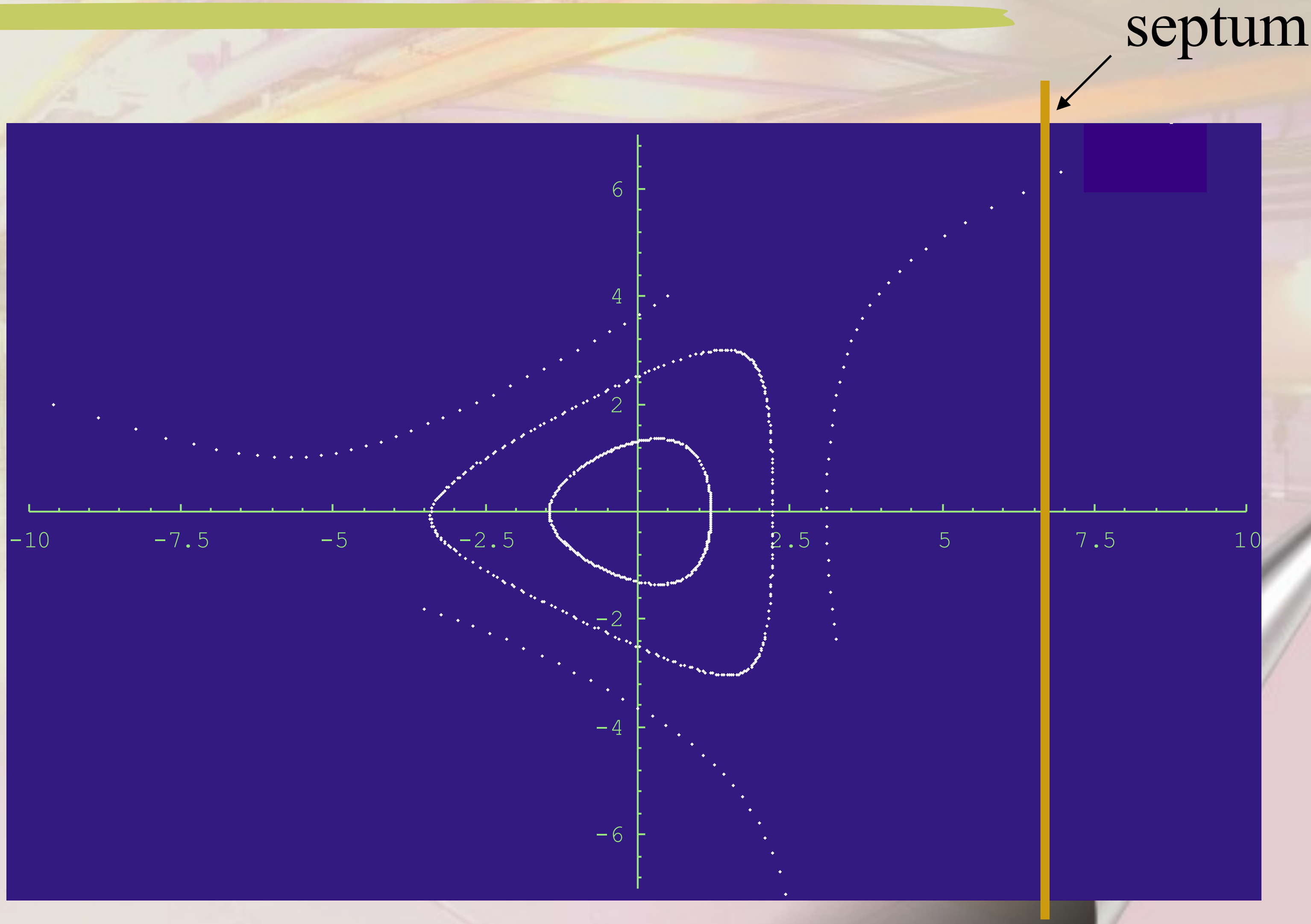
Resonant extraction (1)

- **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

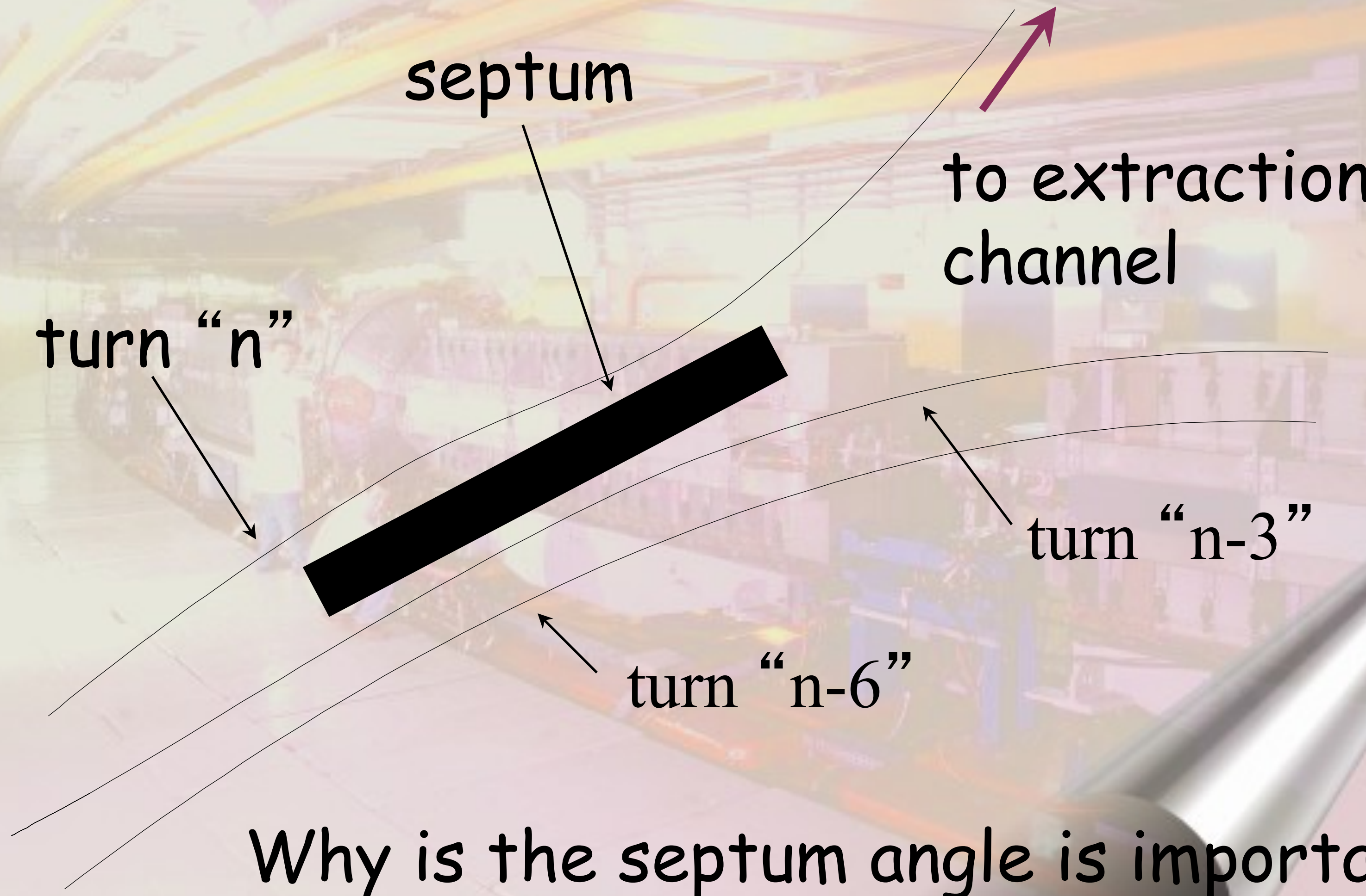
Resonant extraction (2)



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…?