Heavy Ion Therapy Research Integration

Injection into Synchrotrons

ELENA BENEDETTO, SEEIIST
elena.benedetto@cern.ch

HEAVY ION THERAPY MASTERCLASS SCHOOL, MAY 2021

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101008548

INJECTION IS A SPECIAL CASE OF BEAM MANIPULATION

Outline:

- Accelerator physics recap & (x,x')phase-space
- Injection in proton & ion synchrotrons
  - Single turn
  - Multi-turn
  - Charge-exchange multi-turn

(*) The recap uses the same figures and formalism of **yesterday lectures in Accelerator Physics**
(*) A very good reference (from which most of the material comes from) is **the CERN Accelerator School (CAS) on Beam Injection, Extraction and Transfer, 2017**

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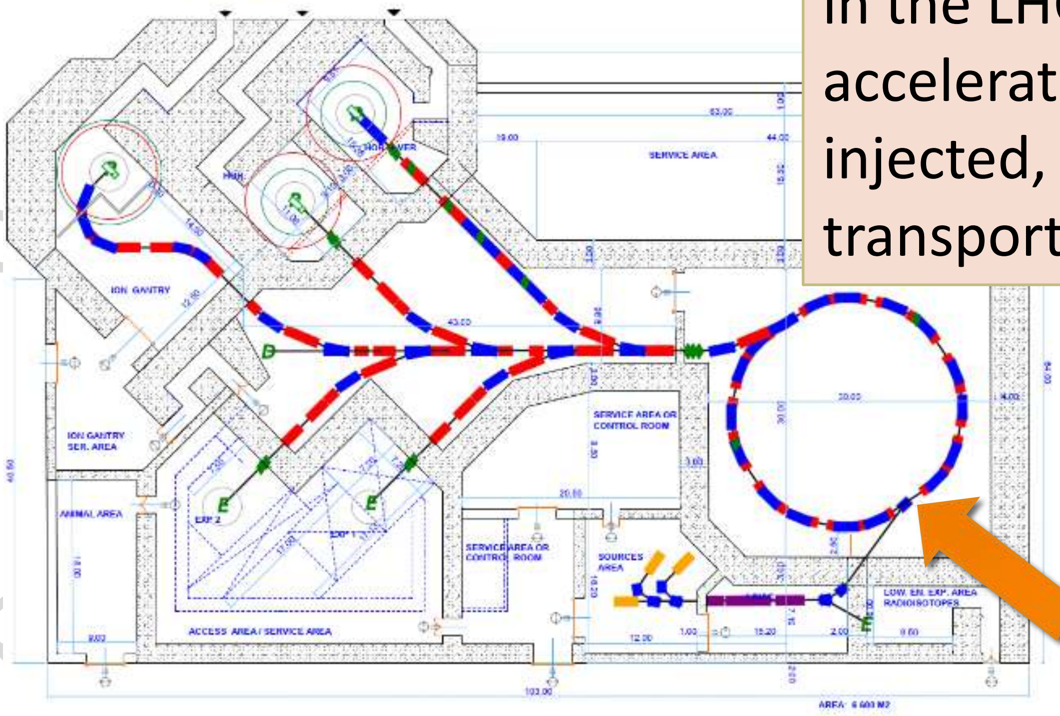
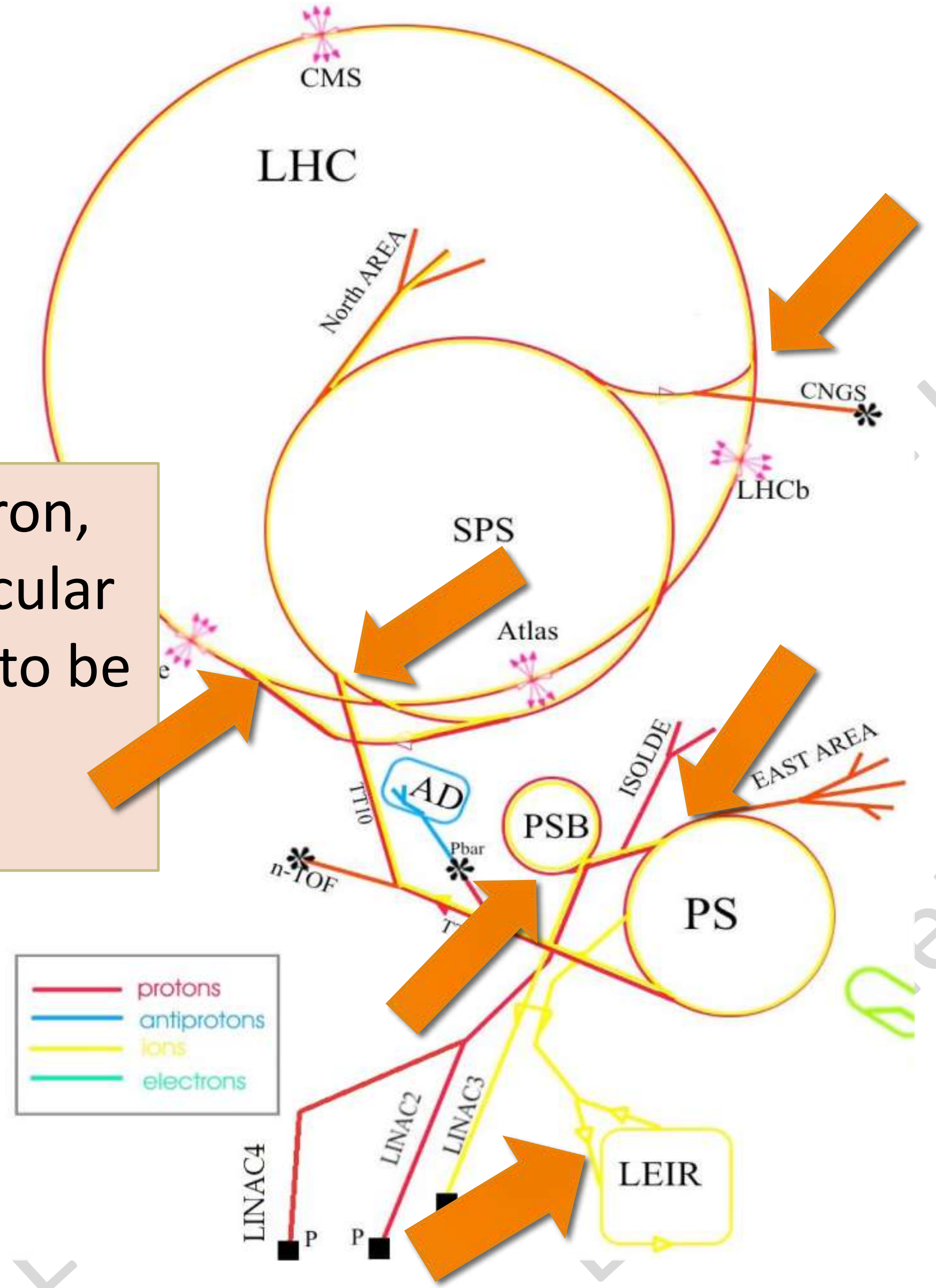


… Be it a in medical synchrotron, in the LHC or in any other circular accelerator, the beam needs to be injected, extracted and transported



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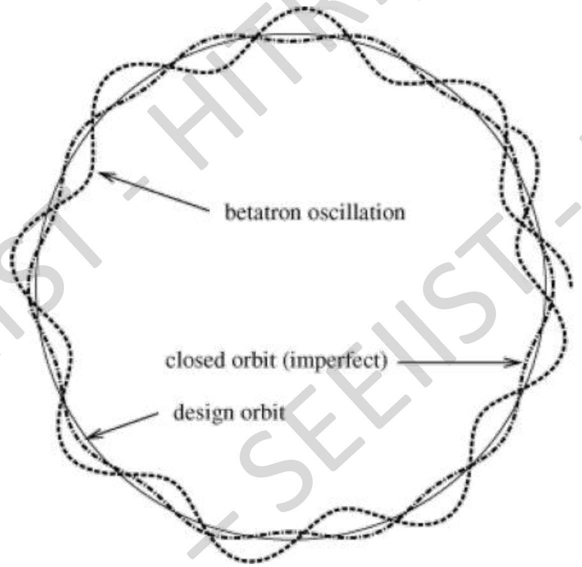
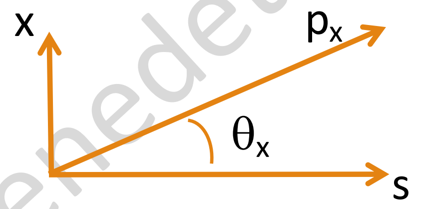
ACCELERATOR PHYSICS - RECAP



- **Reference orbit:** The particles (and the entire beam) oscillate around the synchrotron reference orbit.
- **Tune:** the number of (betatron) oscillations per turn, in x or y
  - must not be an integer N, nor N/2, N/3,…
- **6D phase space**: at a given time t, a particle is identified by its 6 coordinates:
  - Position in x,y,z i.e. the deviation from reference trajectory
  - Divergence x',y' and momentum offset δ
  -

$$x'=dx/ds=\tan(\theta_x)$$



the divergence is ~ the angle of the momentum with respect to the longitudinal coordinate s

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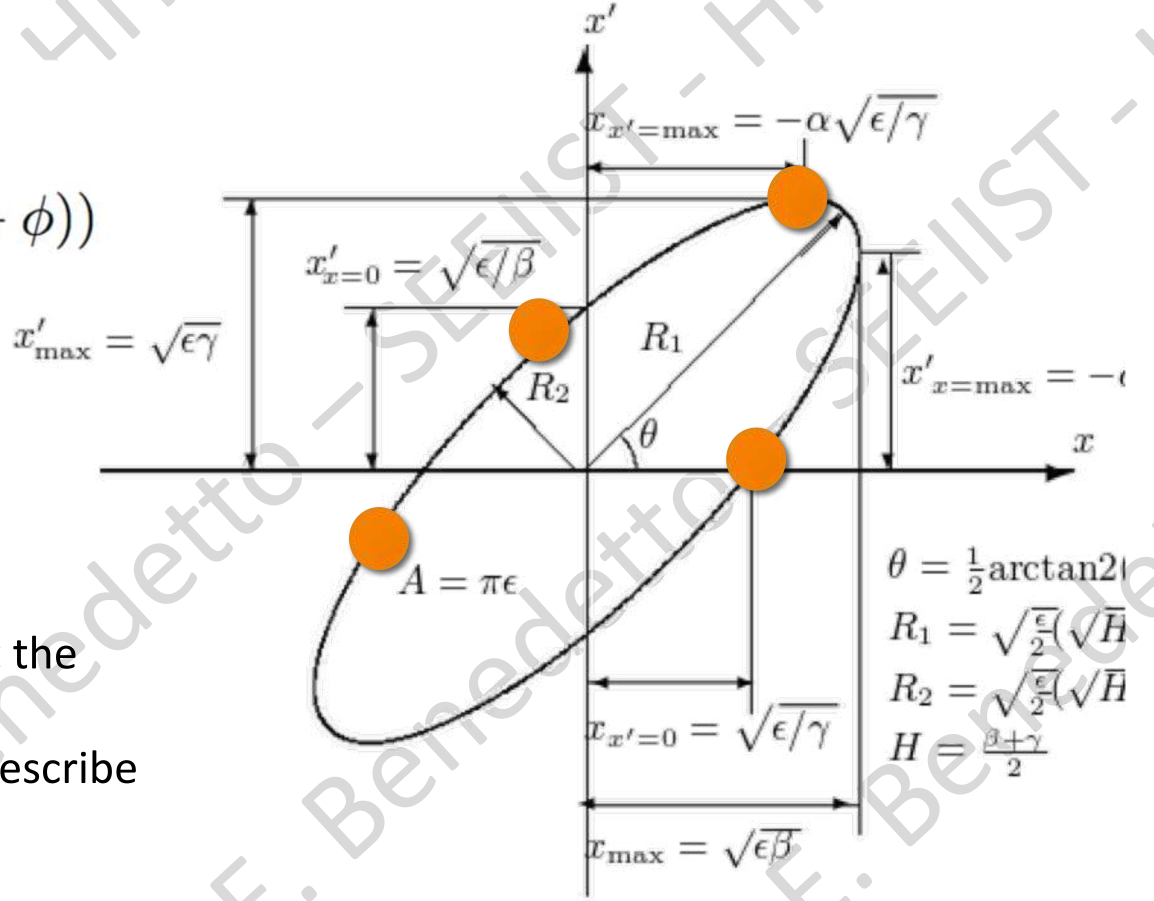
ACCELERATOR PHYSICS - RECAP

- Hills equation: x''(s) + K(s) x(s) = 0   (similar in the y-plane, valid if no coupling)

$$x(s) = \sqrt{2J_x\beta_x(s)}\cos(\psi(s)+\phi)$$

$$x'(s) = -\sqrt{\frac{2J_x}{\beta(s)}}(\alpha(s)\cos(\psi(s)+\phi)+\sin(\psi(s)+\phi))$$



"Accelerator" ellipse:

I sit at a position in the ring and look at the position of a particle, turn after turn.
If the tune is not N, N/2, N/3,… it will describe the entire ellipse

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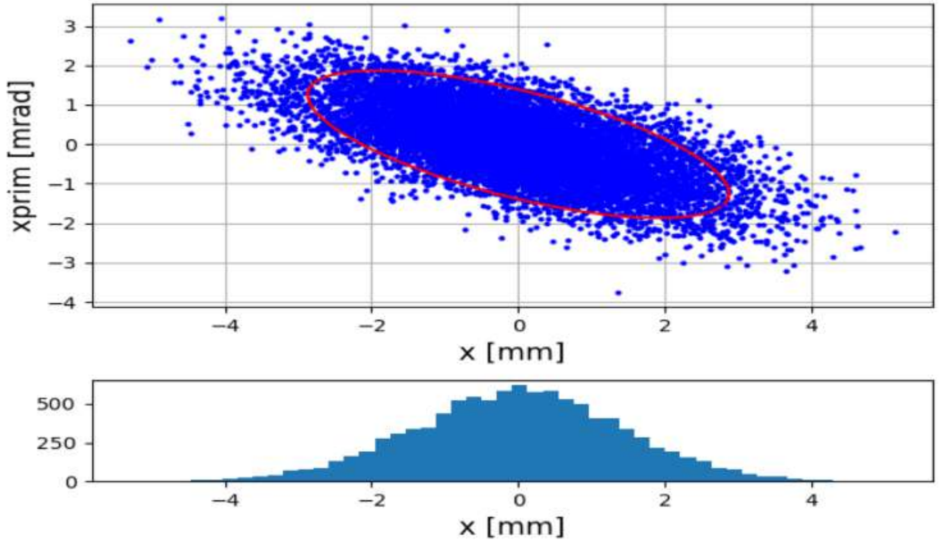
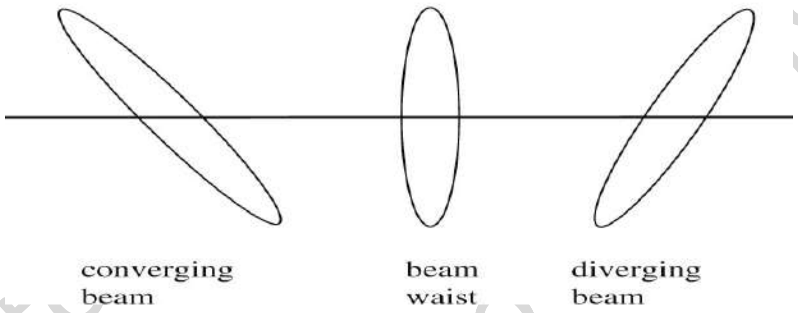
ACCELERATOR PHYSICS - RECAP



"Beam" ellipse:

The ensamble of particles form an ellipse, which area is ~Emittance, constant



In a synchrotron, the two ellipses have the same shape and orientation

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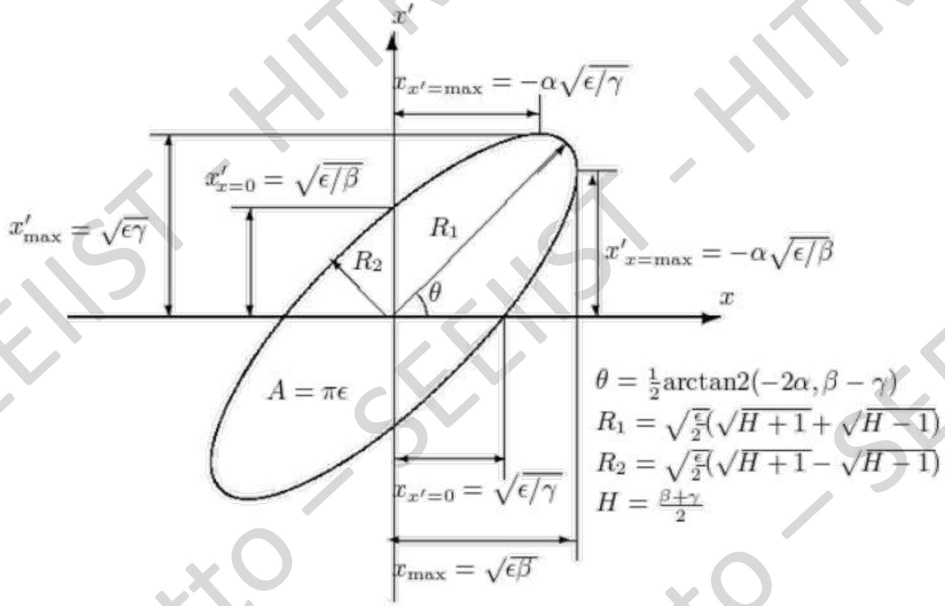
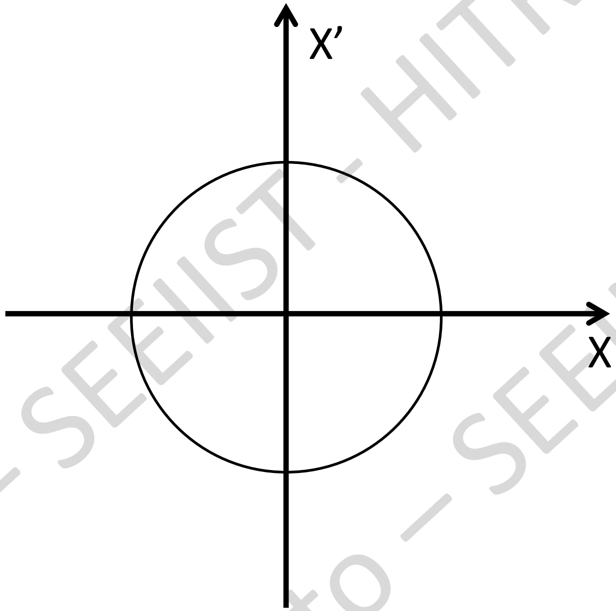
NORMALIZED COORDINATES



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

$$\overline{X}' = \sqrt{\frac{1}{\beta_s}} \cdot \alpha_s x + \sqrt{\beta_s}\, x'$$



Use a coordinate transformation to go from an ellipse to a circle…much easier!!!

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WHAT IS INJECTION?

Filling the synchrotron with charged particles:

- with the correct phase space distribution ("**matched beam**" = the beam ellipse has the same shape and orientation of the accelerator ellipse)
- on the correct **orbit**
- at the correct phase of the RF cavities (for the longitudinal dynamics)

GOAL: Minimize beam losses and emittance blow up

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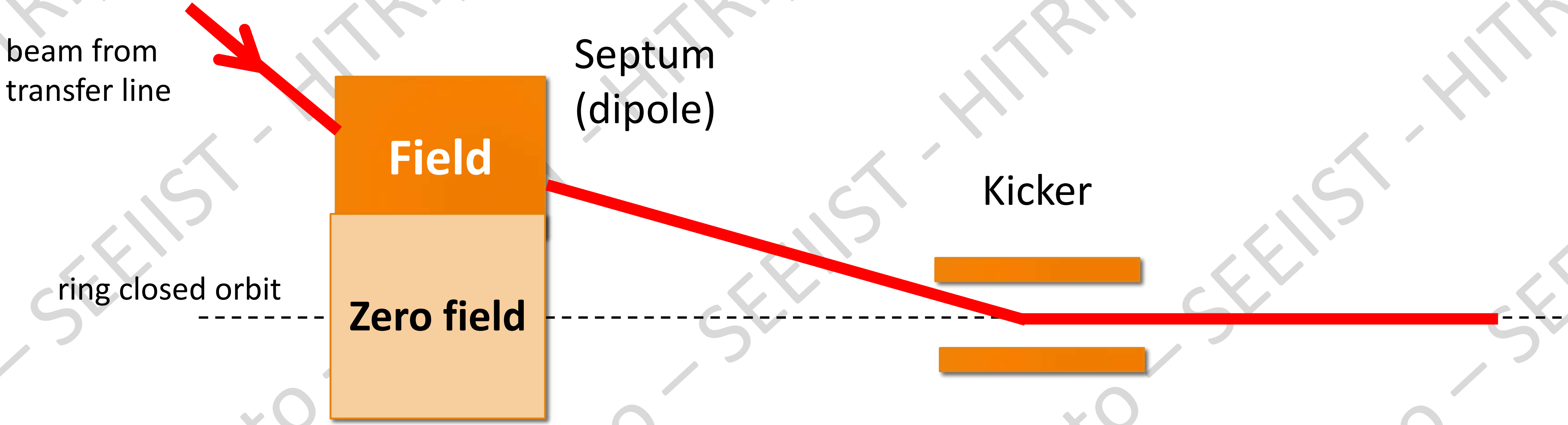
SINGLE TURN INJECTION



Septum dipole filed deflects the beam coming from the transfer line into the ring closed orbit.

“Fast” kicker magnet corrects for the remaining angle and it is so fast that the kick is over when the beam comes back after 1 turn

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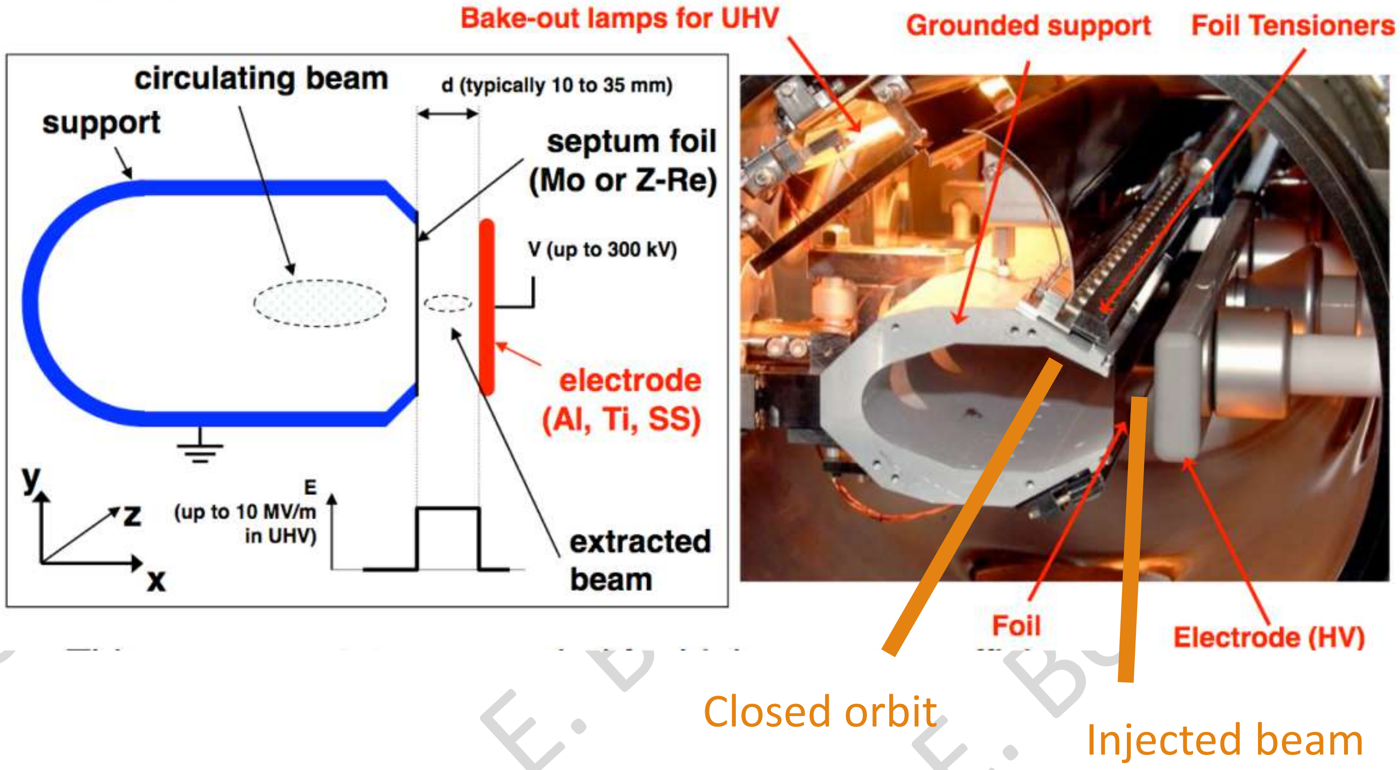
SEPTUM

A “septum” (plural is “septa”) is a thin separation between a region with (electric or magnetic) field and a region without field.

Electrostatic septum



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SEPTUM

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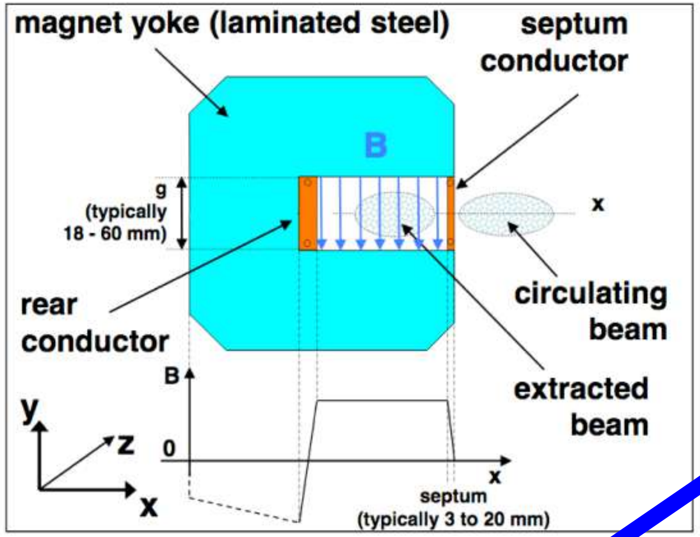
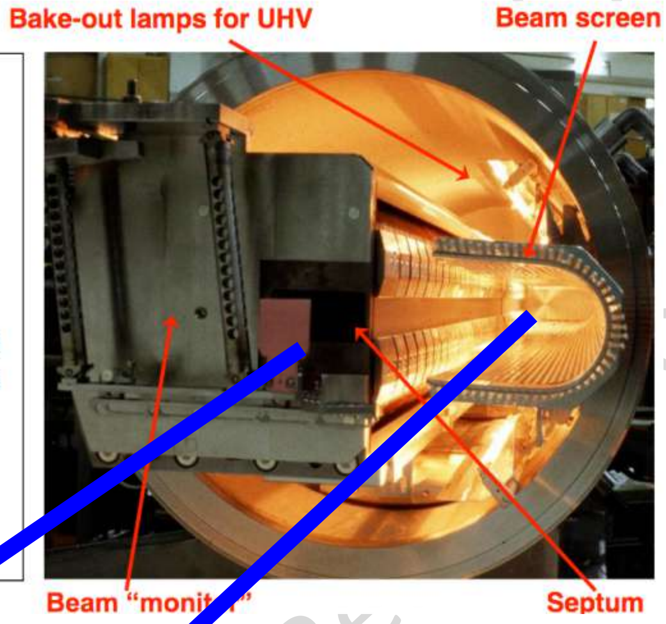
Magnetic septum





Injected beam

Closed orbit

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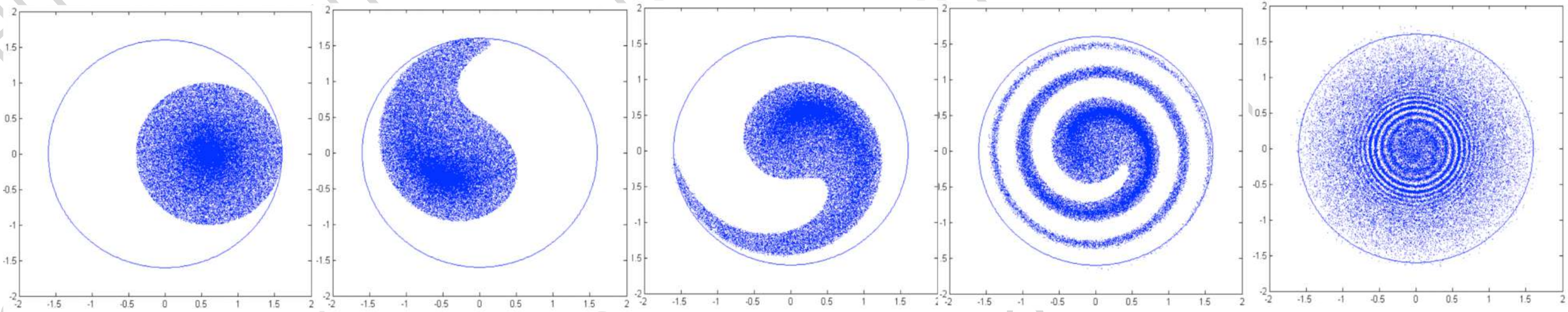
WHAT HAPPENS IF…INJECTION WITH OFFSET

Plots courtesy of C.Bracco



First the beam will start oscillating around the closed orbit

Then, because of non-linearities, it will filament → emittance blow-up

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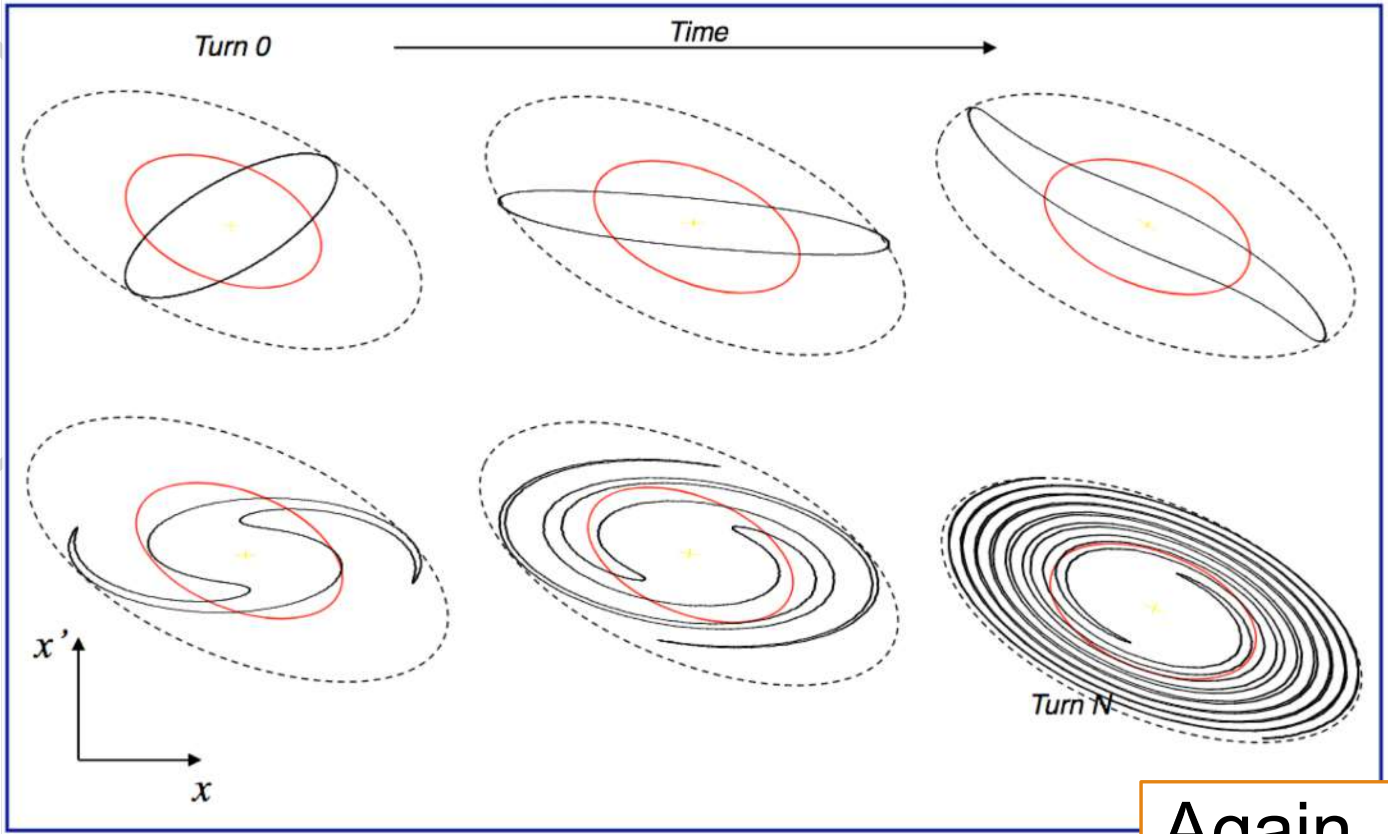
WHAT HAPPENS IF…INJECTION WITH PHASE-SPACE MISMATCH



Plots courtesy of C.Bracco

Again, filamentation and emittance blow-up

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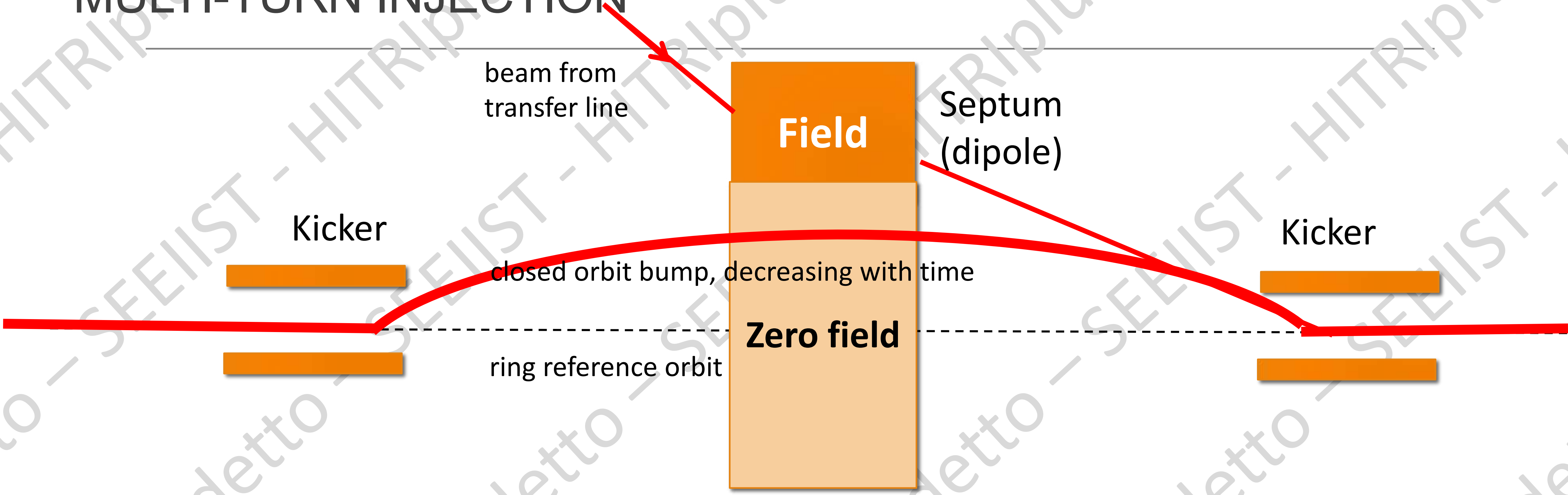
MULTI-TURN INJECTION



Septum to bend the beam into the closed orbit

"Slower" kicker (bumpers) magnets create an closed orbit bump to get close to the septum. turn after turn, the orbit bump decreases and the phase space of the circulating beam is filled.

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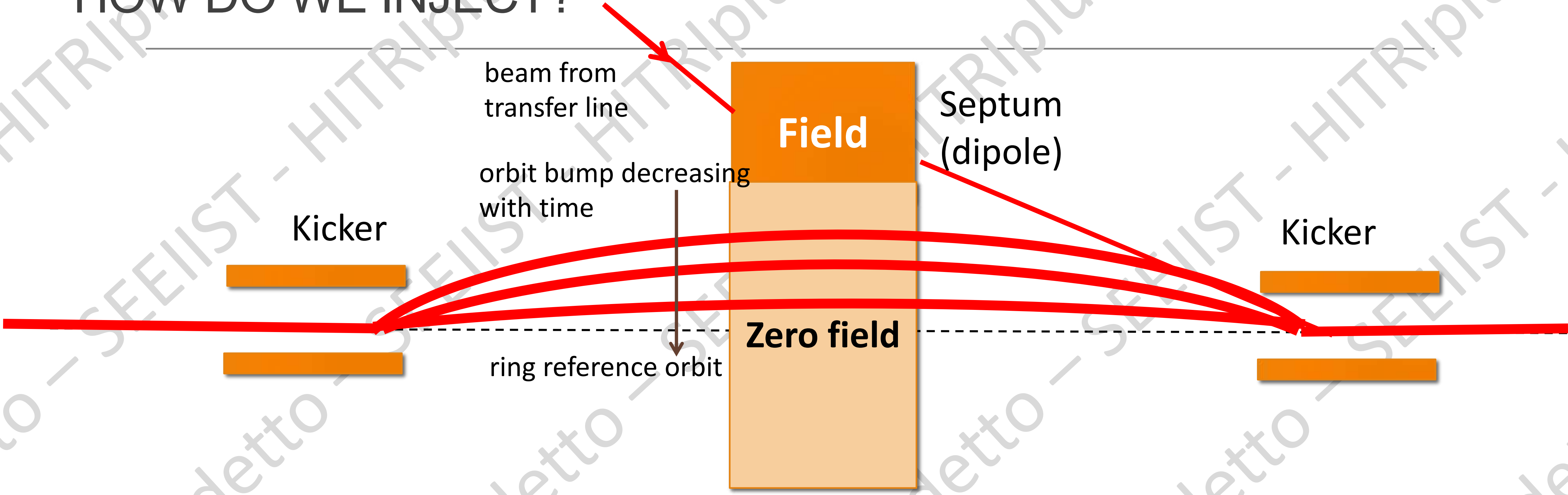
HOW DO WE INJECT?



Multi-turn injection: needs a septum and 2 to 4 “slower” kicker magnet

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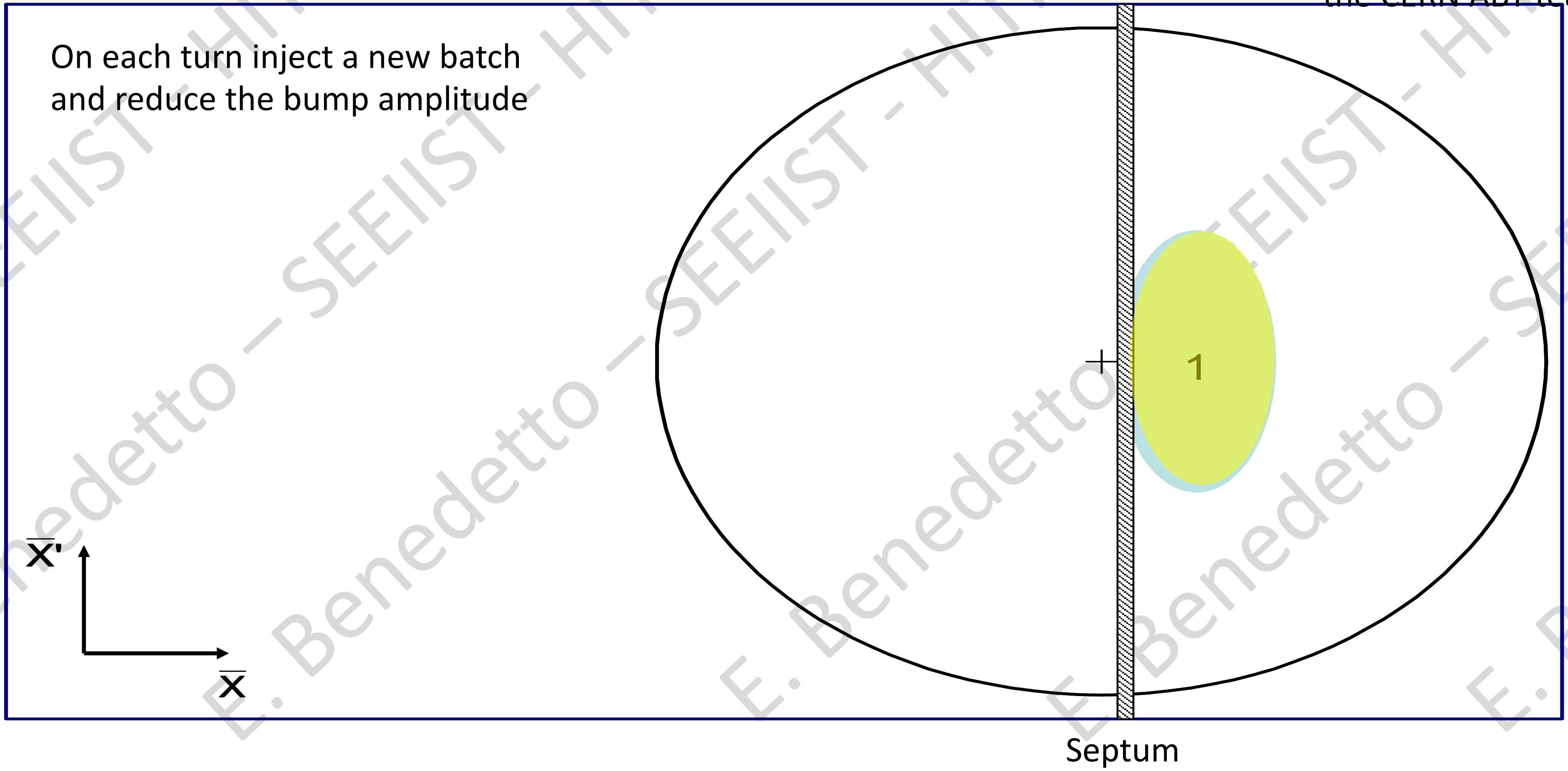
Multi-turn injection for hadrons

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

Animation by C. Bracco and the CERN ABT team

Turn 1

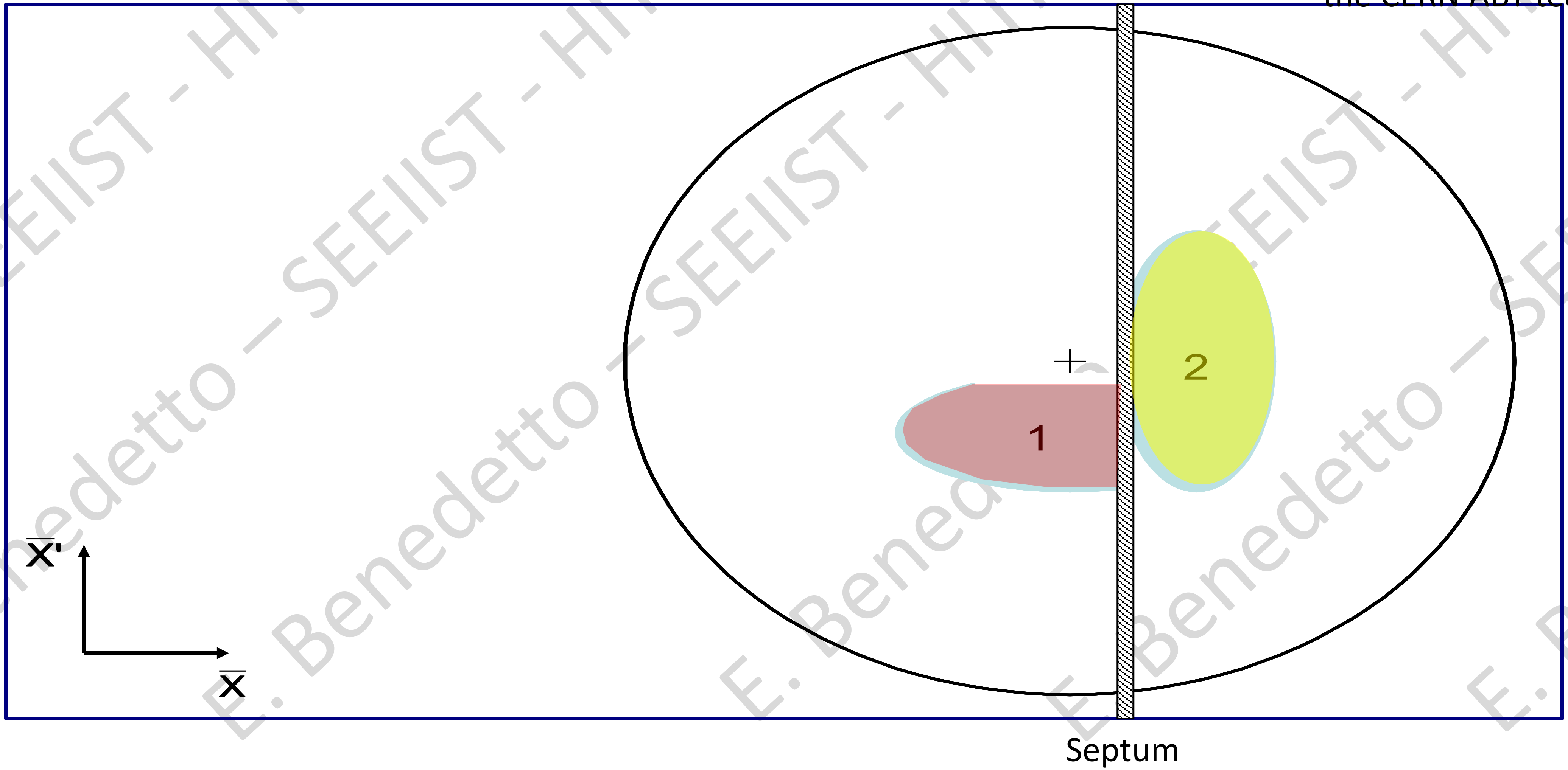


Multi-turn injection for hadrons

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

Turn 2

Animation by C. Bracco and the CERN ABT team

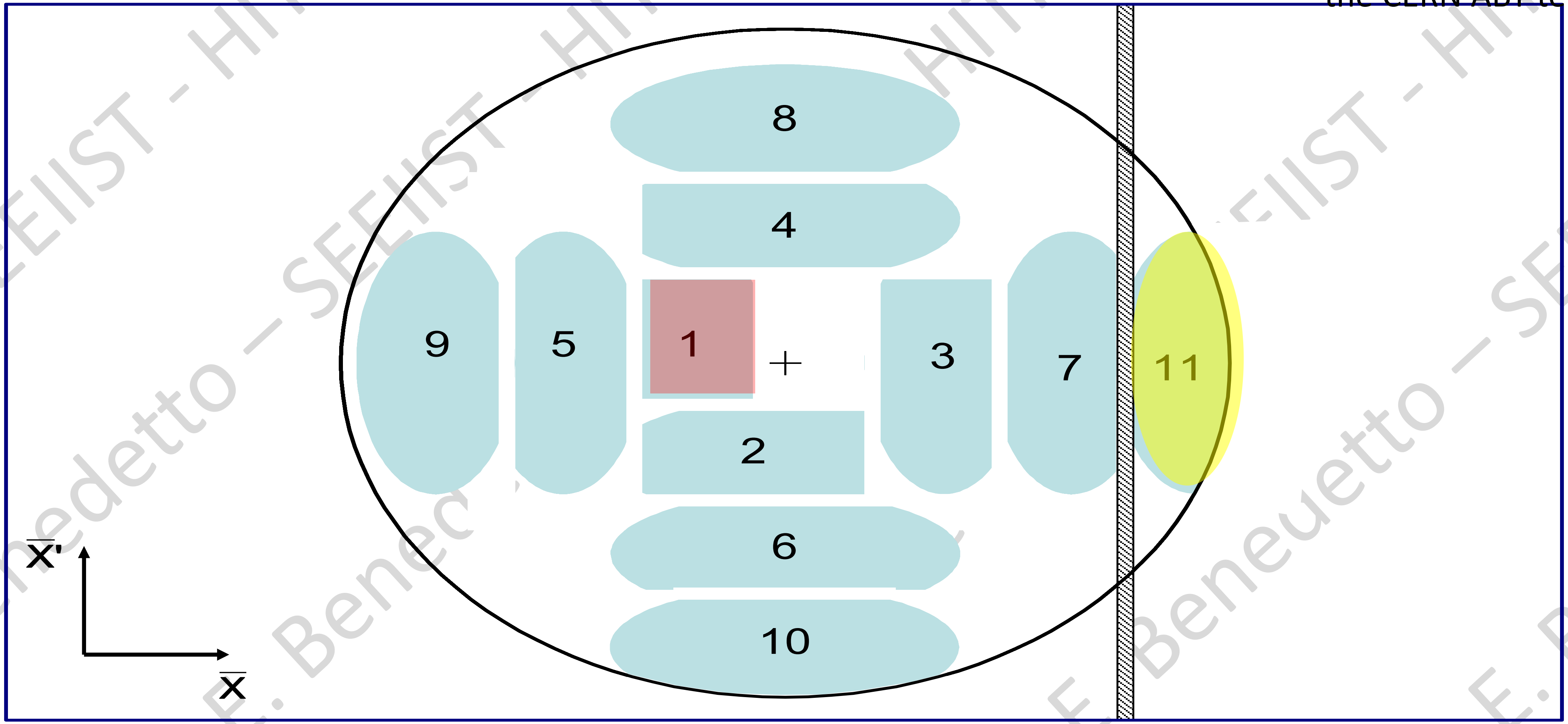


Multi-turn injection for hadrons

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

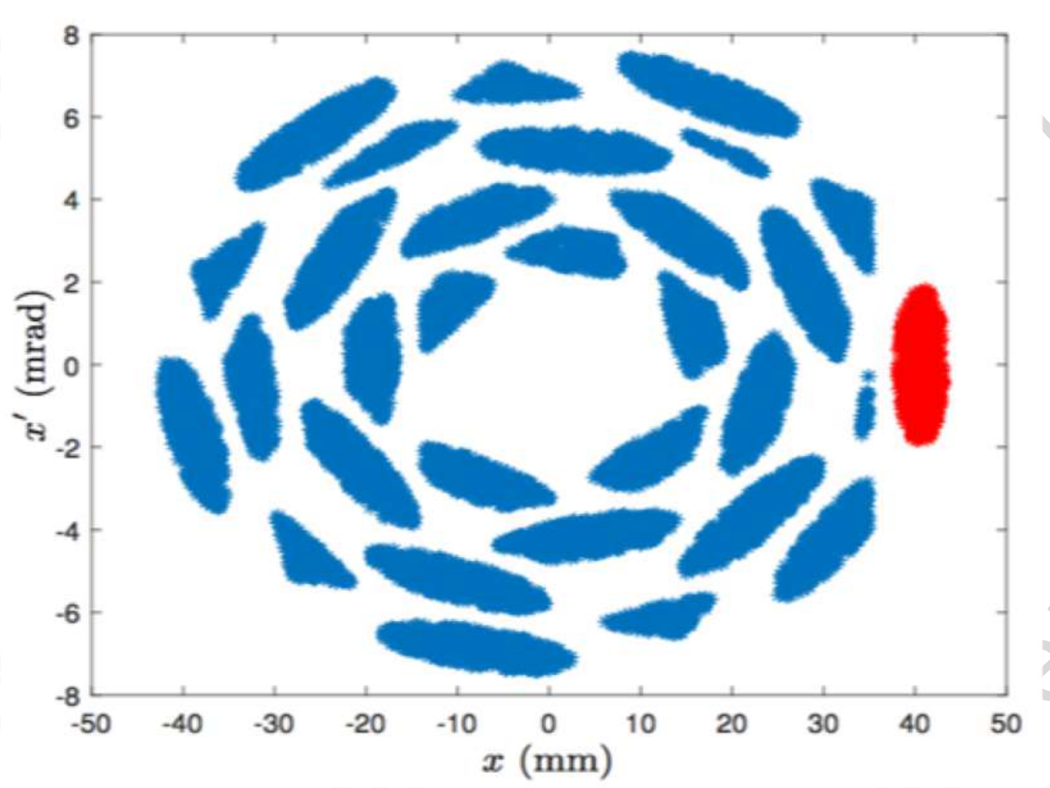
Animation by C. Bracco and the CERN ABT team

Turn 11



MULTI-TURN INJECTION

- Used when need to accumulate higher intensity than what provided by the source:
  - this is the case for SEEIIST synchrotron, design intensity x10 higher than EU medical synchrotrons ...tomorrow you'll discover why
- The final beam emittance will be larger than the source&linac emittance
- Losses occur at the septum, however acceptable at low energy (~60% efficiency)



A. Advic, Master Thesis, University of Sarajevo, 2019

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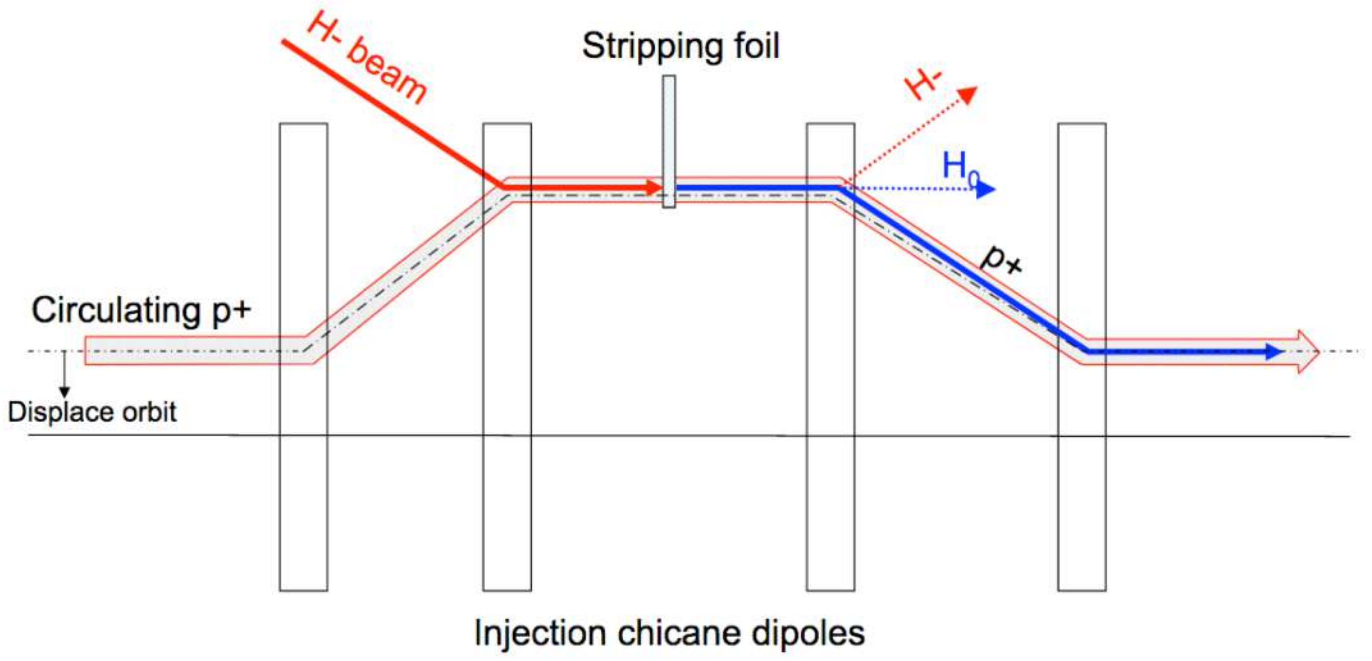
HOW TO DO BETTER? CHARGE-EXCHANGE INJECTION



Possible to inject on the same phase space and increase beam brightness (high intensity and small emittance)

BUT Trajectories (…and transfer lines!) are for one kind of particle only

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CONCLUSIONS

- Injection in a synchrotron must be done carefully to preserve beam emittance and minimize losses
- Representing the beam in (normalized) phase-space (X,X') is convenient to see what happens to the beam

- **Single turn injection** for transfer from one synchrotron to the following
- **Multi-turn injection** if intensity from the source is not enough
- **Charge exchange multi-turn** injection to increase beam brightness

Medical synchrotrons which accelerate different ion species : p, He, C, O, … use Multi-turn injection

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