ELENA BENEDETTO, SEEIIST ASSOCIATION

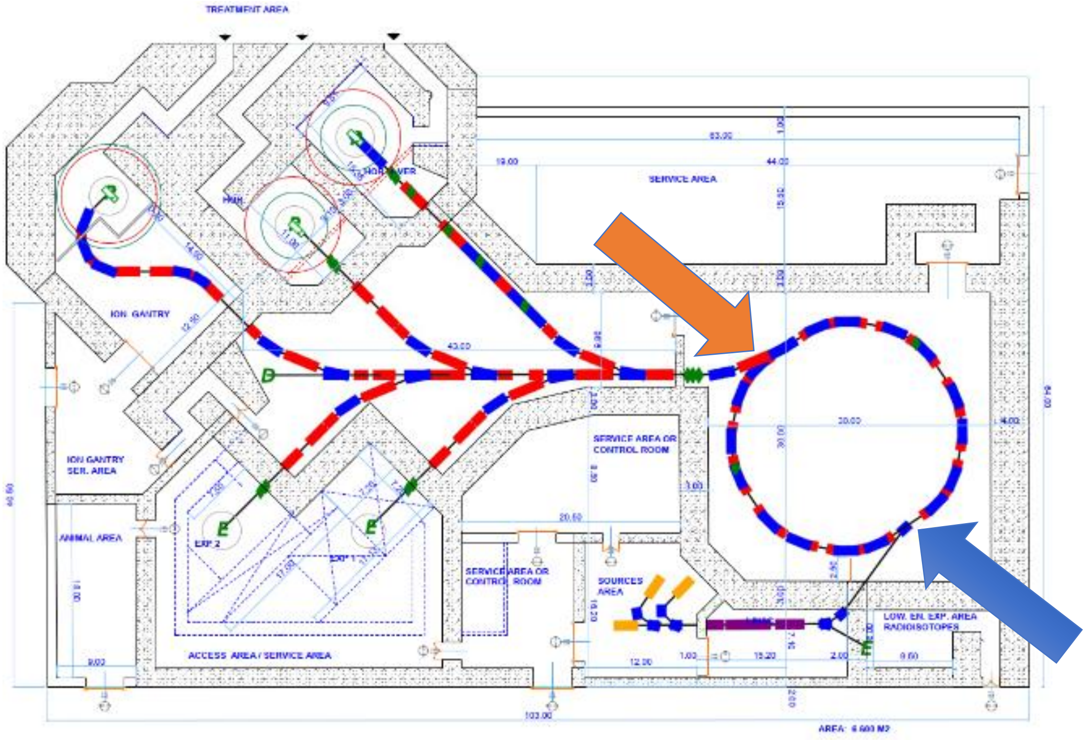
@BALTIC PhD COURSE "ACCELERATOR TECHNOLOGIES" (HEP700) , 10 MAY 2022

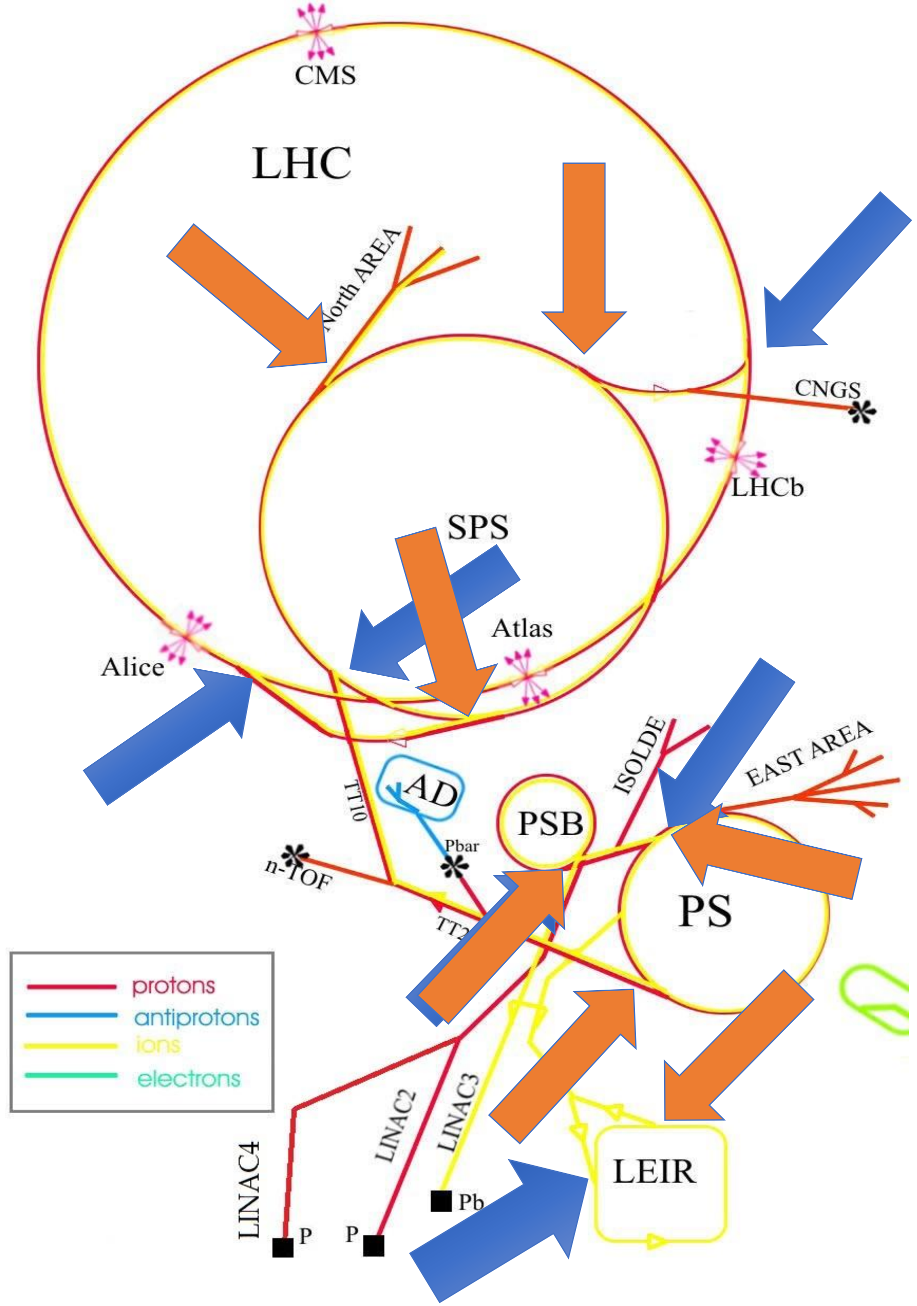
Injection, extraction and beam transfer

SEE ST
South East European International Institute for Sustainable Technologies

Architectural design by Kaprinis Architects

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





INJECTION, EXTRACTION, BEAM TRANSFER

….No extra physics, application of the concepts you have learned in the previous lectures

OUTLINE

- Accelerator physics: recap
- Injection in proton & ion synchrotrons
  - Single turn
  - Multi-turn
- Beam transfer and emittance preservation
- Extraction
  - Single turn
  - Multi-Turn (and Resonant MTE)
  - Slow
- Longitudinal synchronization

(*) The recap uses the same figures and formalism of A. Latina, Transverse beam dynamics course

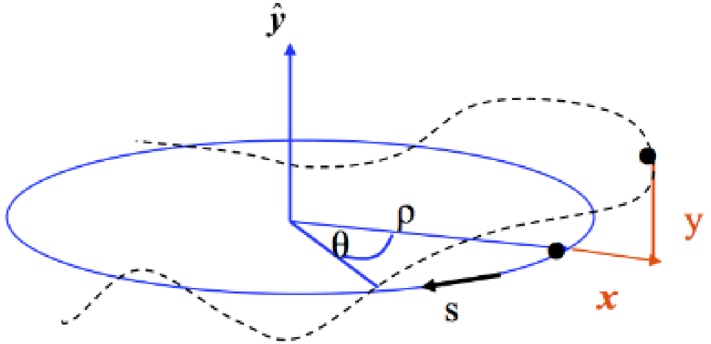
(*) A very good reference (from which most of the material comes from) is **the CERN Accelerator School (CAS) on Beam Injection, Extraction and Transfer, 2017:**

Indico: https://indico.cern.ch/event/451905/timetable/

Proceedings: https://e-publishing.cern.ch/index.php/CYRSP/issue/view/62

ACCELERATOR PHYSICS - RECAP

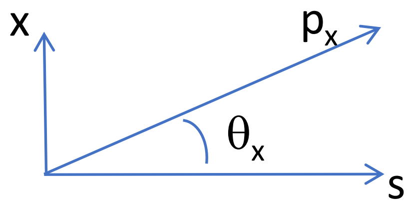
- **Reference orbit:** The particles (and the entire beam) oscillate around the synchrotron reference orbit.



- **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

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

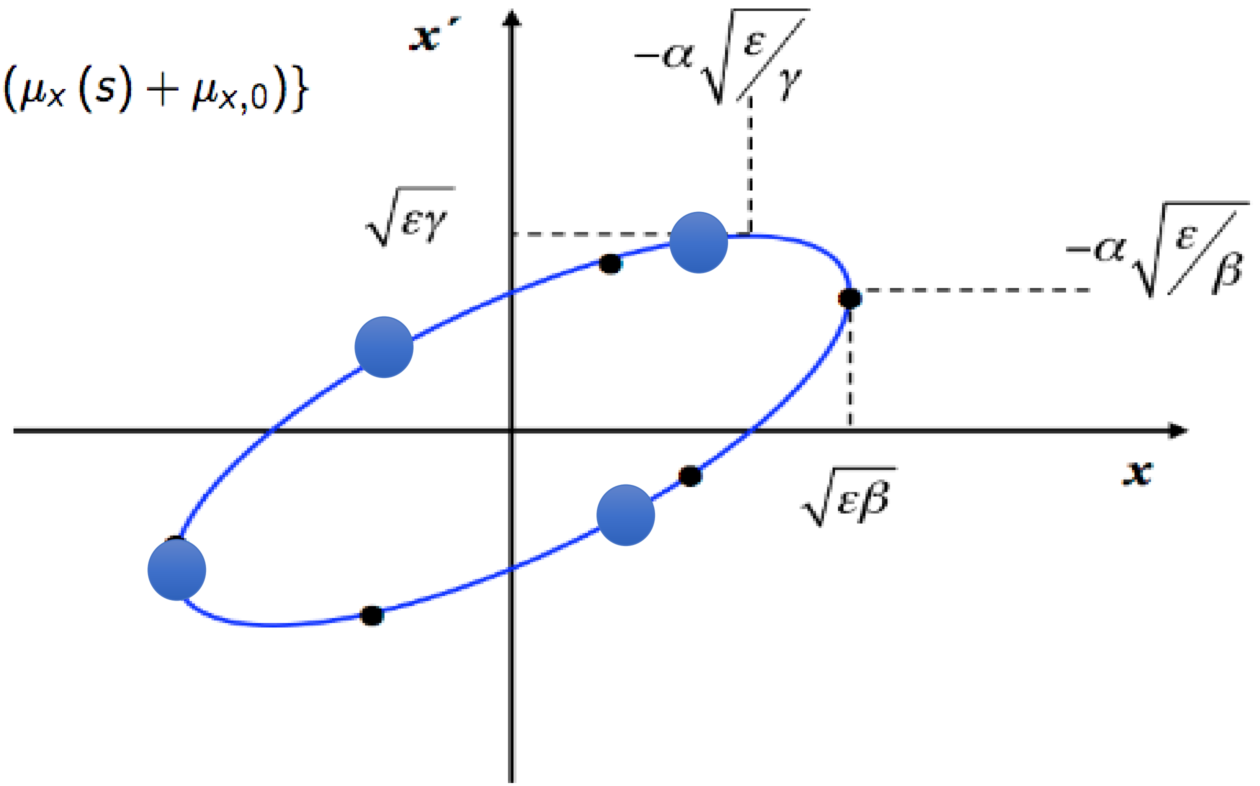


the divergence is ~ the angle of the momentum with respect to the longitudinal coordinate s

ACCELERATOR PHYSICS - RECAP

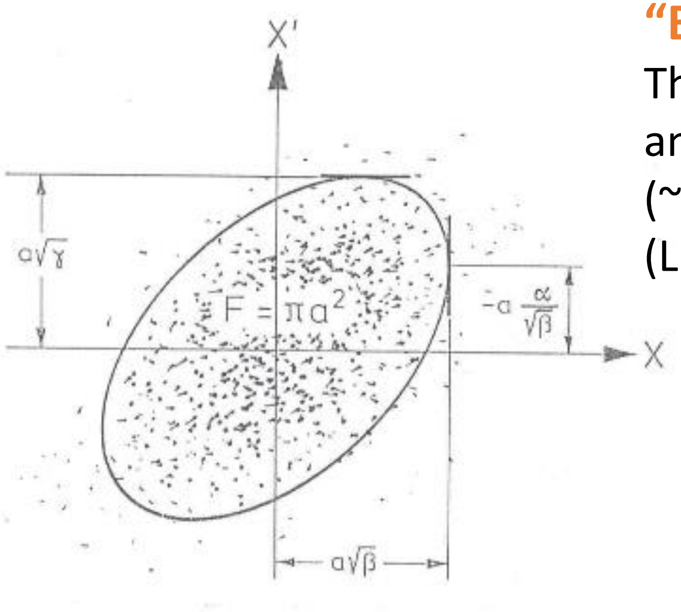
- Hills equation: x''(s) + K(s) x(s) = 0   (similar in the y-plane, valid if no coupling)

$$\begin{cases} x(s) &= \sqrt{\beta_x(s) J_x} \cos(\mu_x(s) + \mu_{x,0}) \\ x'(s) &= -\dfrac{\sqrt{J_x}}{\sqrt{\beta_x(s)}} \{\alpha_x(s) \cos(\mu_x(s) + \mu_{x,0}) + \sin(\mu_x(s) + \mu_{x,0})\} \end{cases}$$



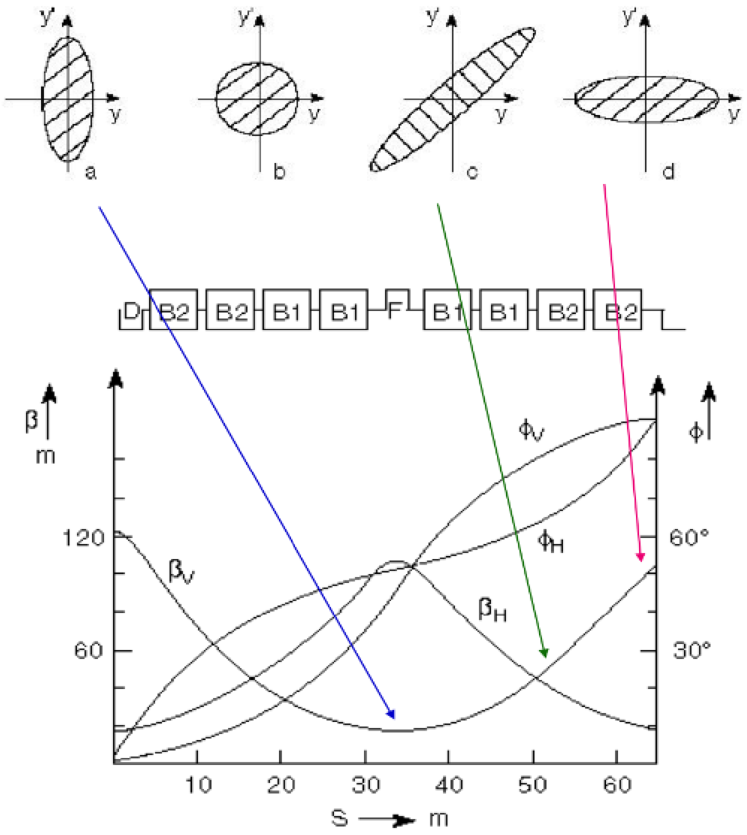
“Accelerator” ellipse:
I sit at a position in the ring and look at the position of a particle, turn after turn.
If the tune is not N, N/2, N/3,… it will describe the entire ellipse

ACCELERATOR PHYSICS - RECAP



"Beam" ellipse:
The ensemble of particles form an ellipse, which area (~Emittance), is constant (Liouville).

In a synchrotron, the "accelerator" and the "beam" ellipse have the same shape and orientation

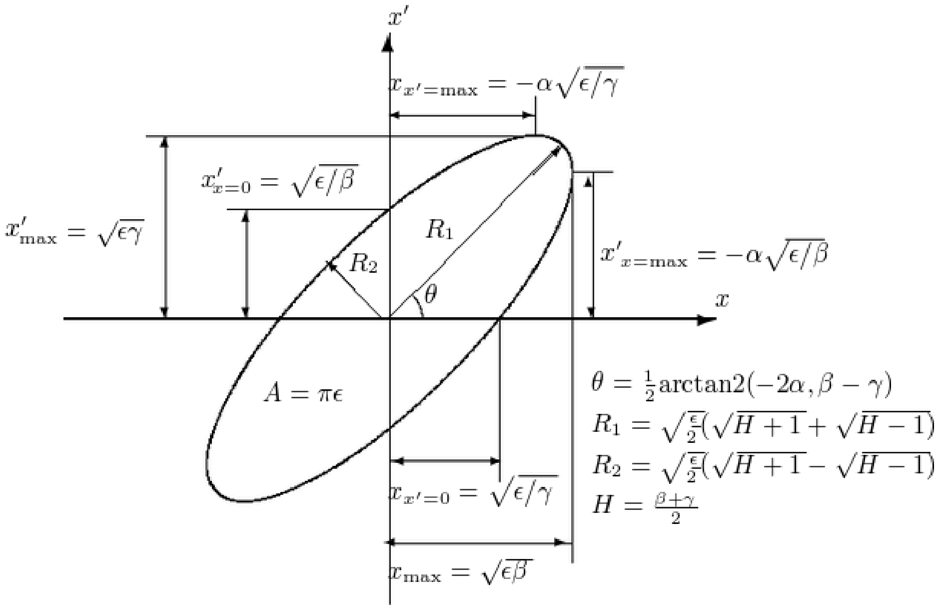


Beam envelope: proportional to ~Sqrt(Beta function):

- periodic in a ring
- dependent on initial condition in a transfer line!!!

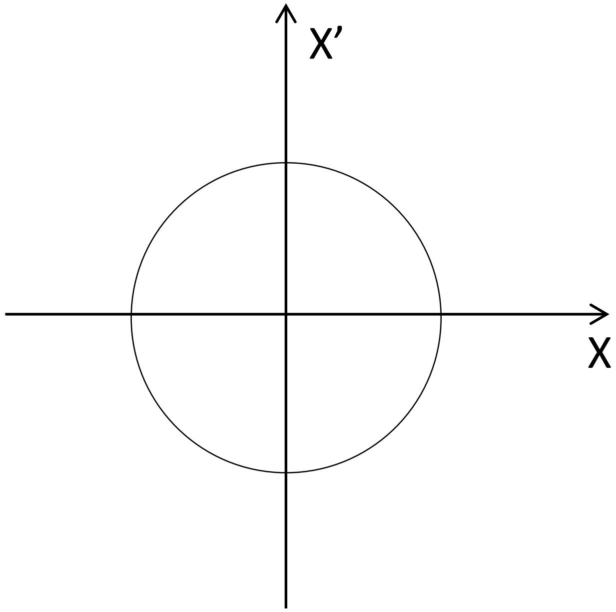
NORMALIZED COORDINATES

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



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

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

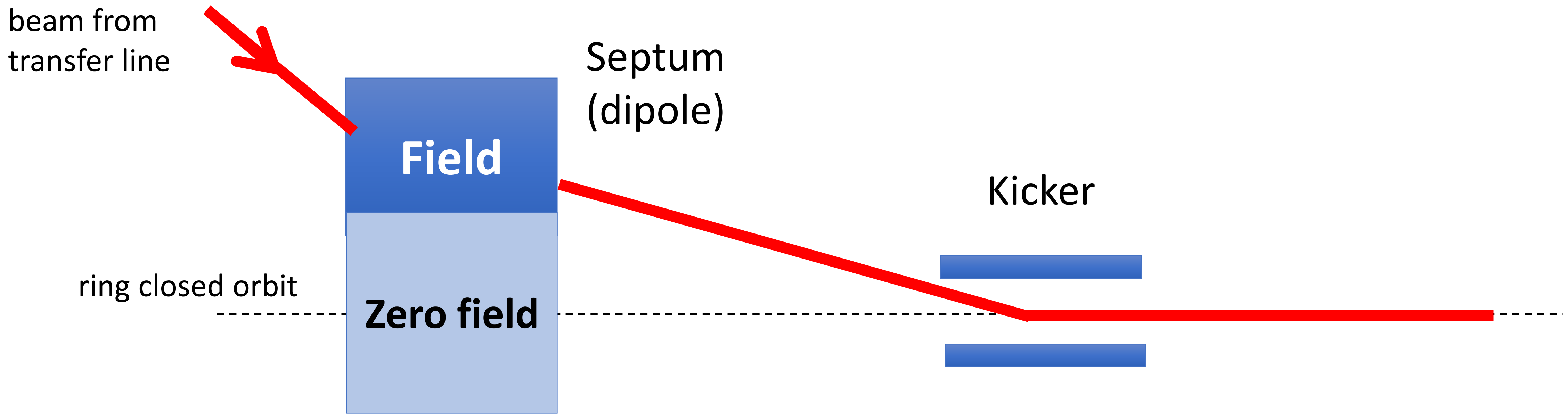


WHAT IS INJECTION?

- 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

SINGLE TURN INJECTION



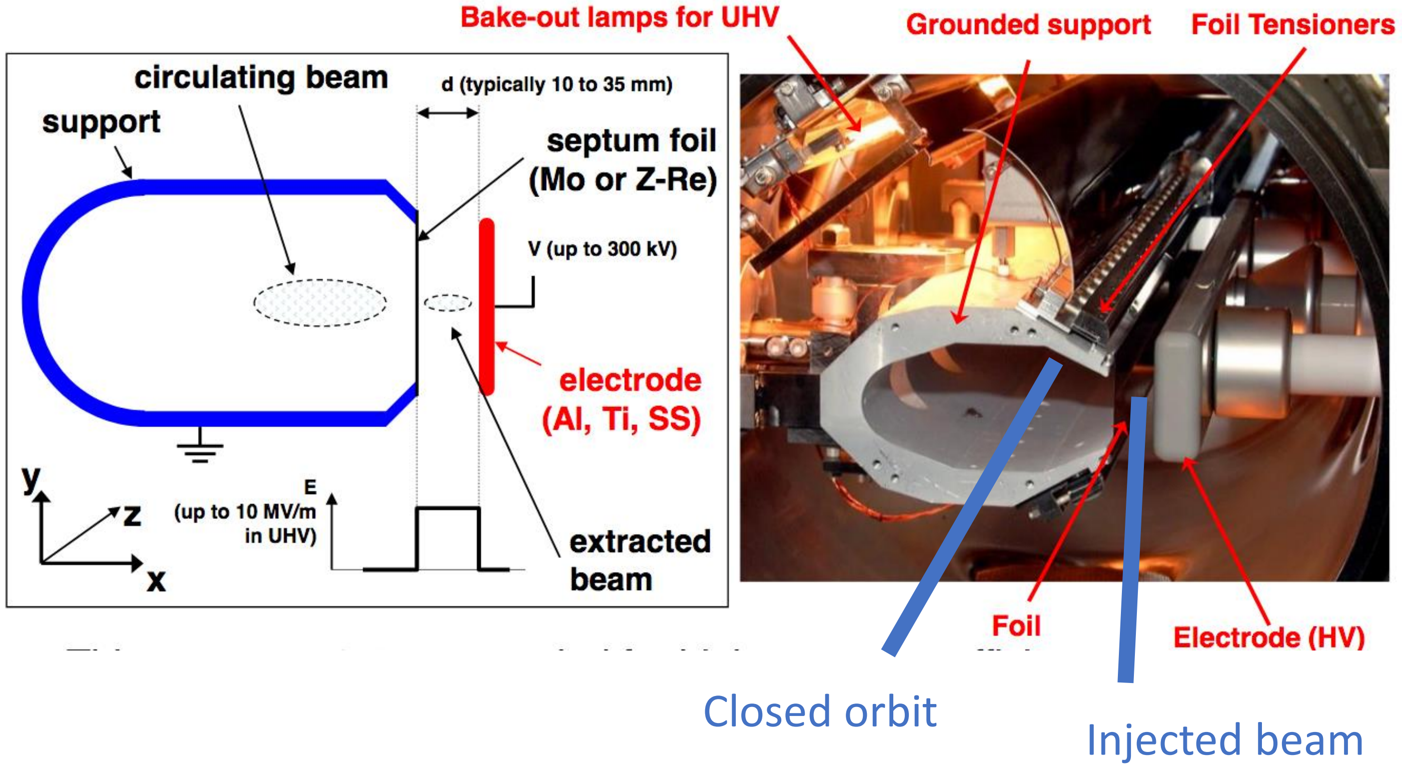
- **Septum** dipole field deflects the beam coming from the transfer line into the ring closed orbit.
- **“Fast” kicker** magnet corrects for the remaining angle and it is so fast that the kick is over when the beam comes back after 1 turn

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

very thin ~0.1mm septum foil, which separates zero field and high field region

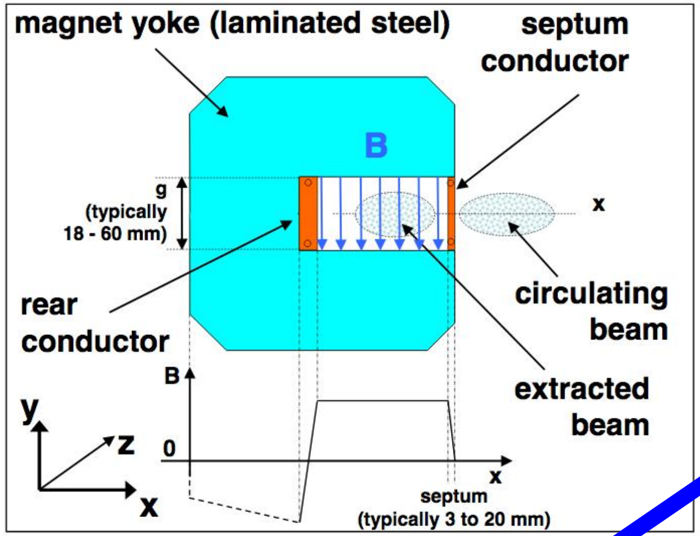


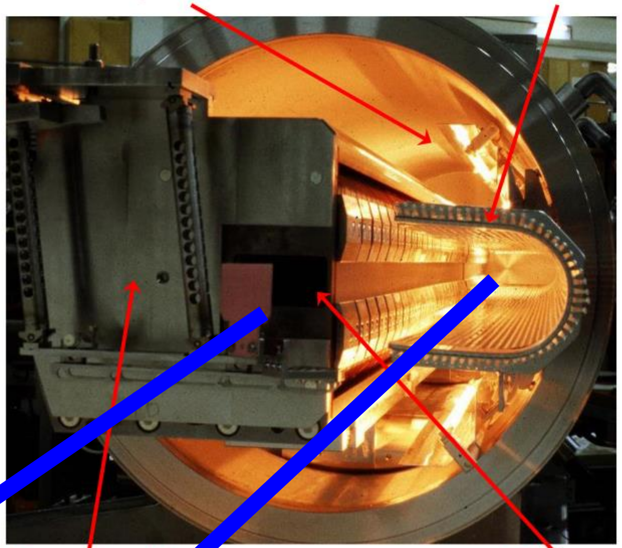
SEPTUM

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

Magnetic septum

thicker septum ~2-20mm





Injected beam

Closed orbit

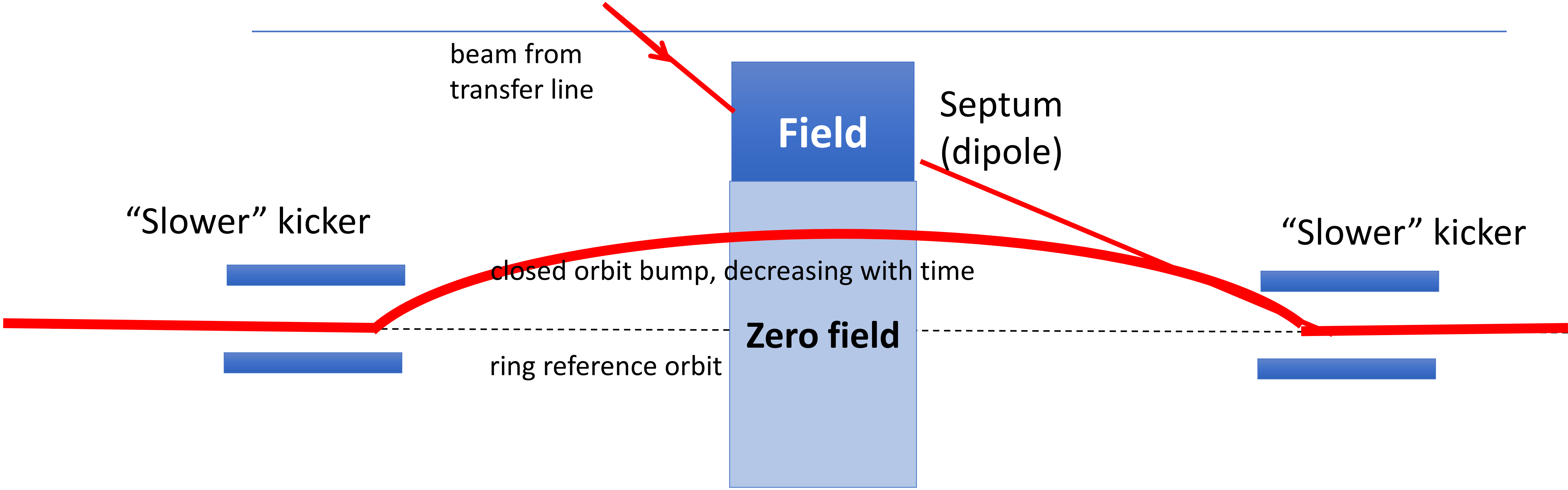
KICKER

- Pulsed dipole
- Active on ~100ns to ~us time scale

MULTI-TURN INJECTION

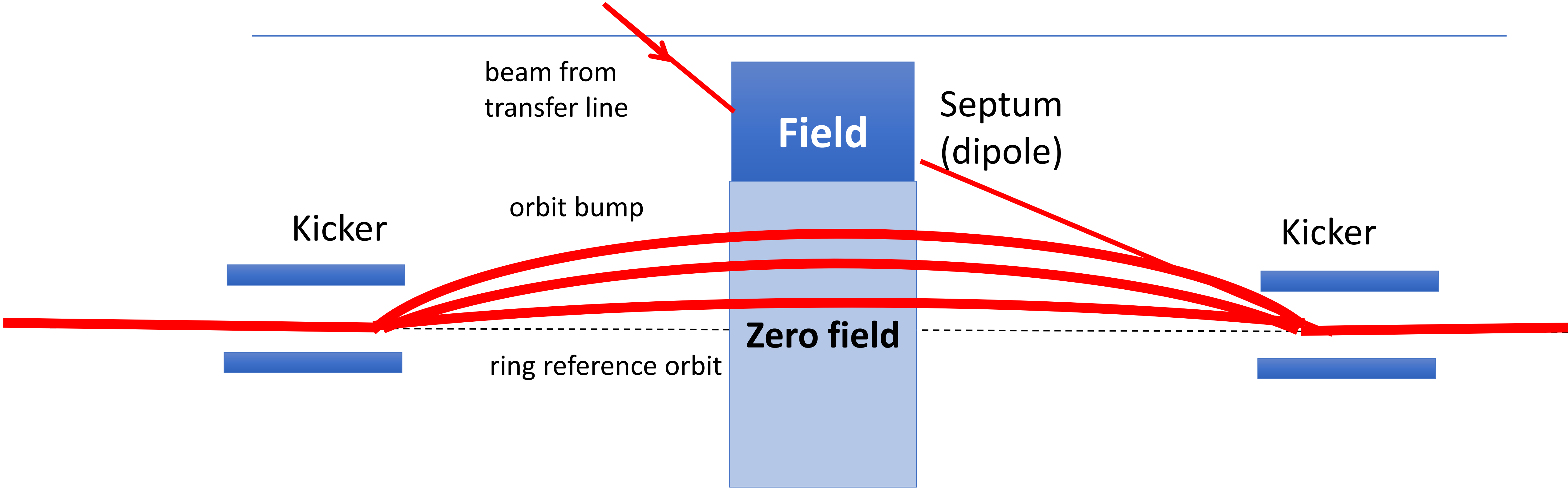
- Used when need to accumulate intensity higher than what provided by the source:
  - this is the case for medical synchrotron, design intensity x10 higher than EU medical synchrotrons ...tomorrow you'll discover why
- The final beam emittance will be larger than the source&linac emittance
- Losses occur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

MULTI-TURN INJECTION



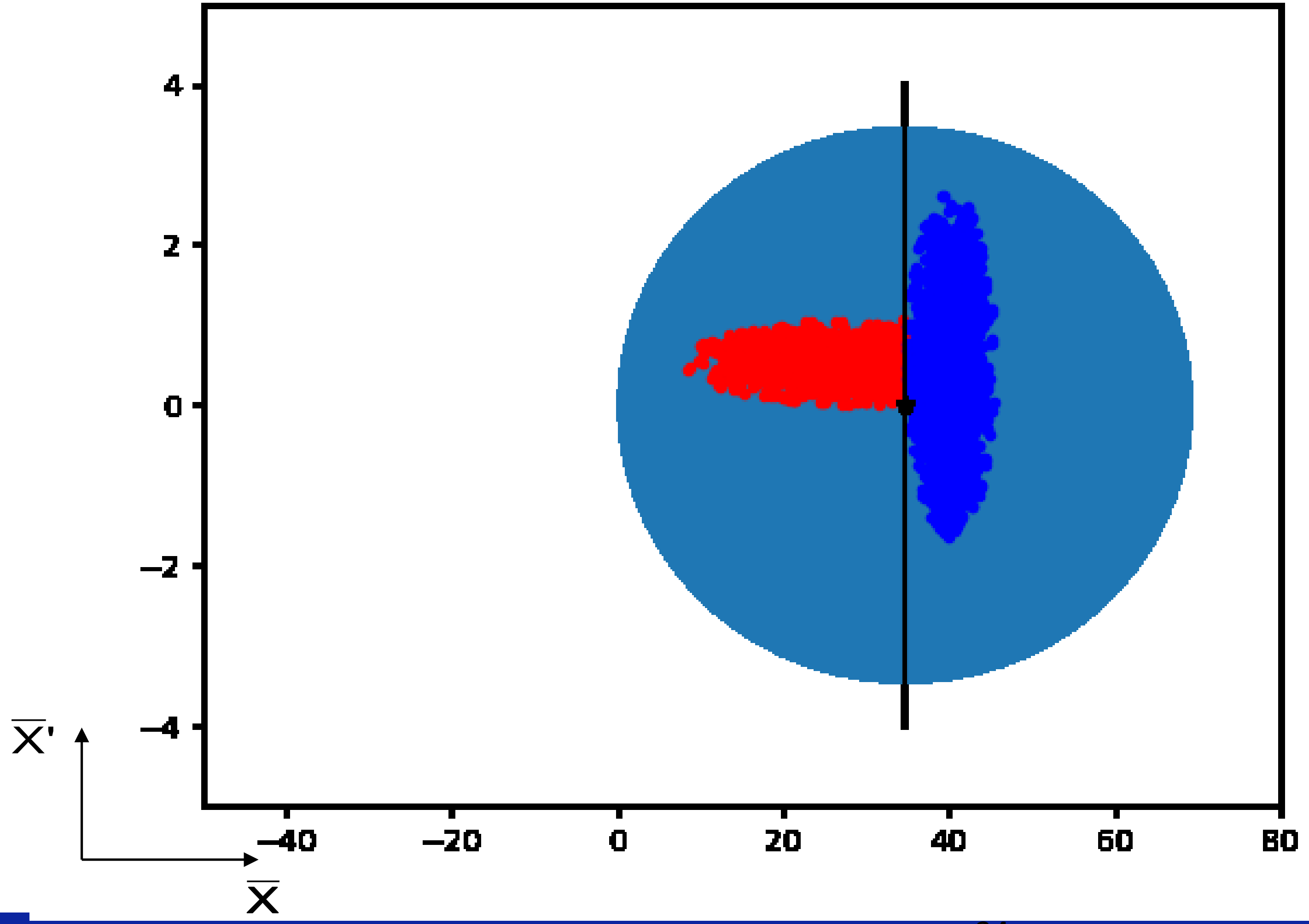
- **Septum** to bend the beam into the closed orbit
- **"Slower" kicker (bumpers) magnets** create an closed orbit bump to get close to the septum. turn after turn, the orbit bump decreases and the phase space of the circulating beam is filled (time ~100us).

HOW DO WE INJECT?



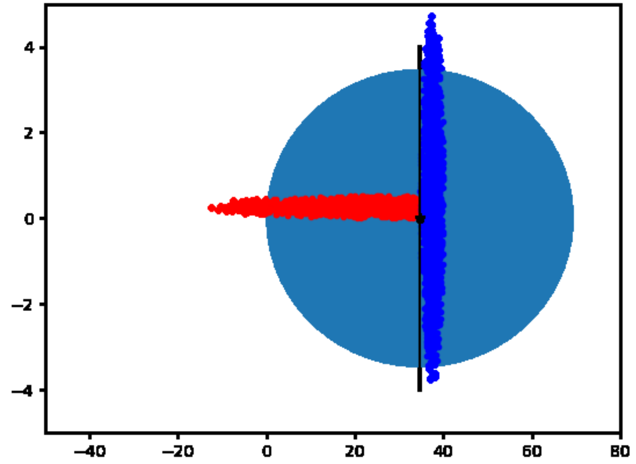
Multi-turn injection for hadrons

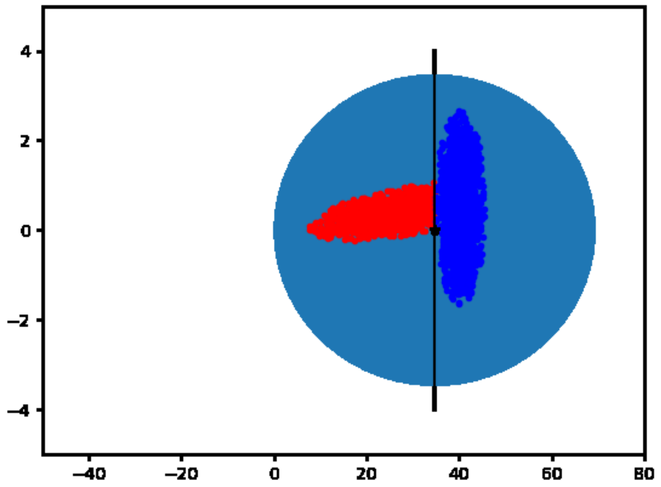
On each turn inject a new batch and reduce the bump amplitude

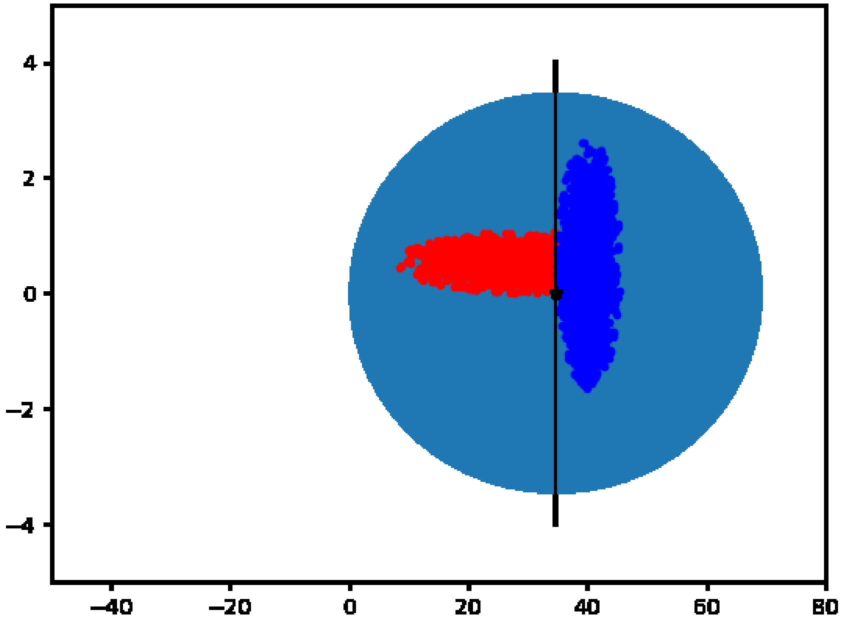


Multi-turn injection for hadrons

- Question: What did it change here?

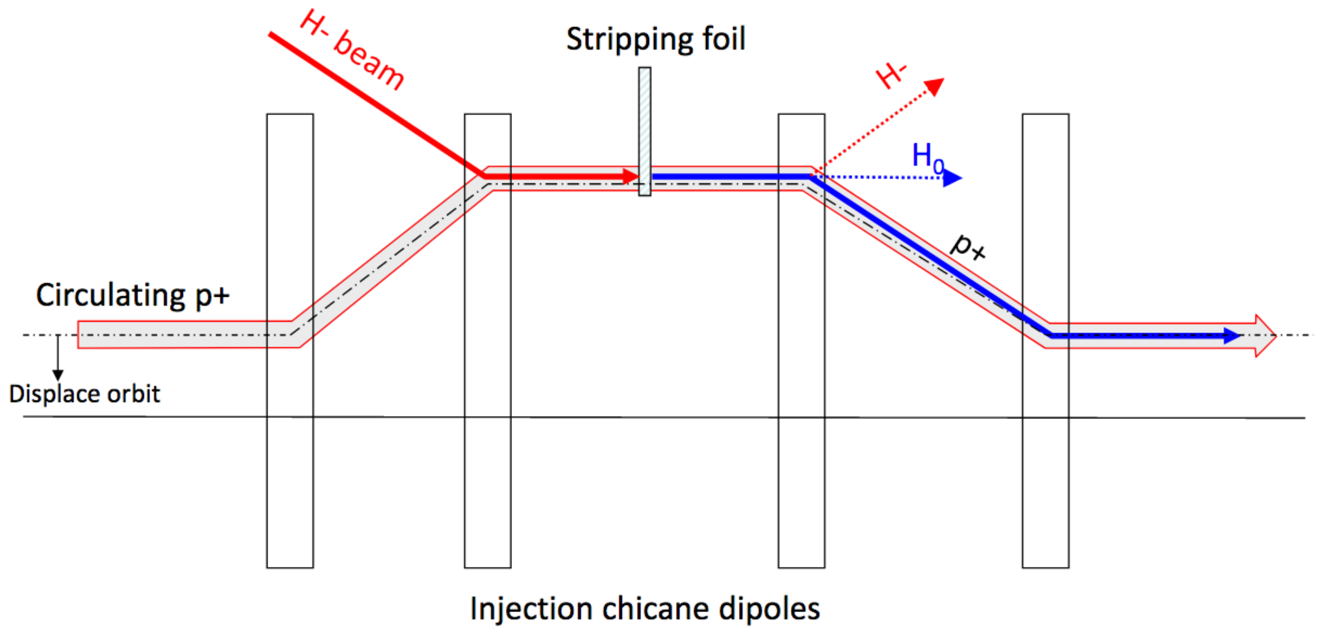


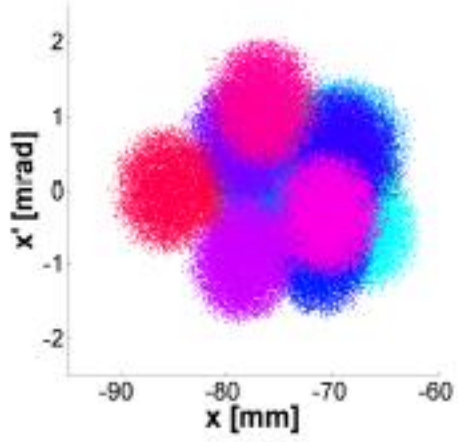




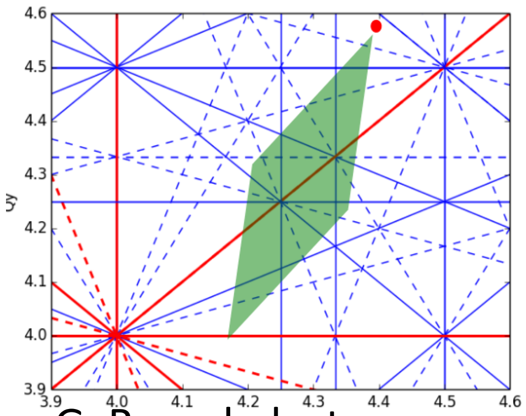
HOW TO DO BETTER? CHARGE-EXCHANGE INJECTION

- **Cheating Liouville!**: Possible to inject in the same phase space → increase beam brightness (high intensity and small emittance)





PSB H- injection ...up to the space charge limit!



see G. Rumolo lecture

Challenges: stripping foil heating, foil scattering, valid for 1 species only

→ **Laser stripping**

What about leptons?

- Radiation damping:
  - because of synchrotron radiation, transverse motion is damped and the beam is "cooled"

  - → Less concern for emittance growth during injection

EMITTANCE CONTROL

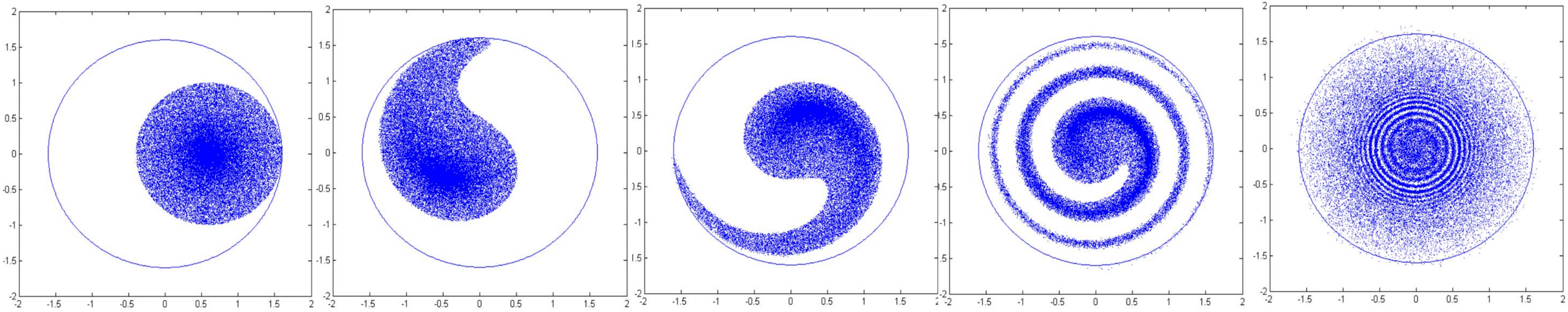
- Luminosity in colliders depends on beam emittance (see E. Metral lecture):

$$L_0 = \frac{M\, N_b^2\, f_{rev}\, \beta\, \gamma}{4\, \pi\, \beta^*\, \varepsilon_n}$$

- In hadron machine, there is no radiation damping → emittance blowup along the chain cannot be recovered
- Causes of emittance blow-up:
  - space-charge (at injection! ;)) and collective effects
  - beam transfer from one ring to the other
  - …

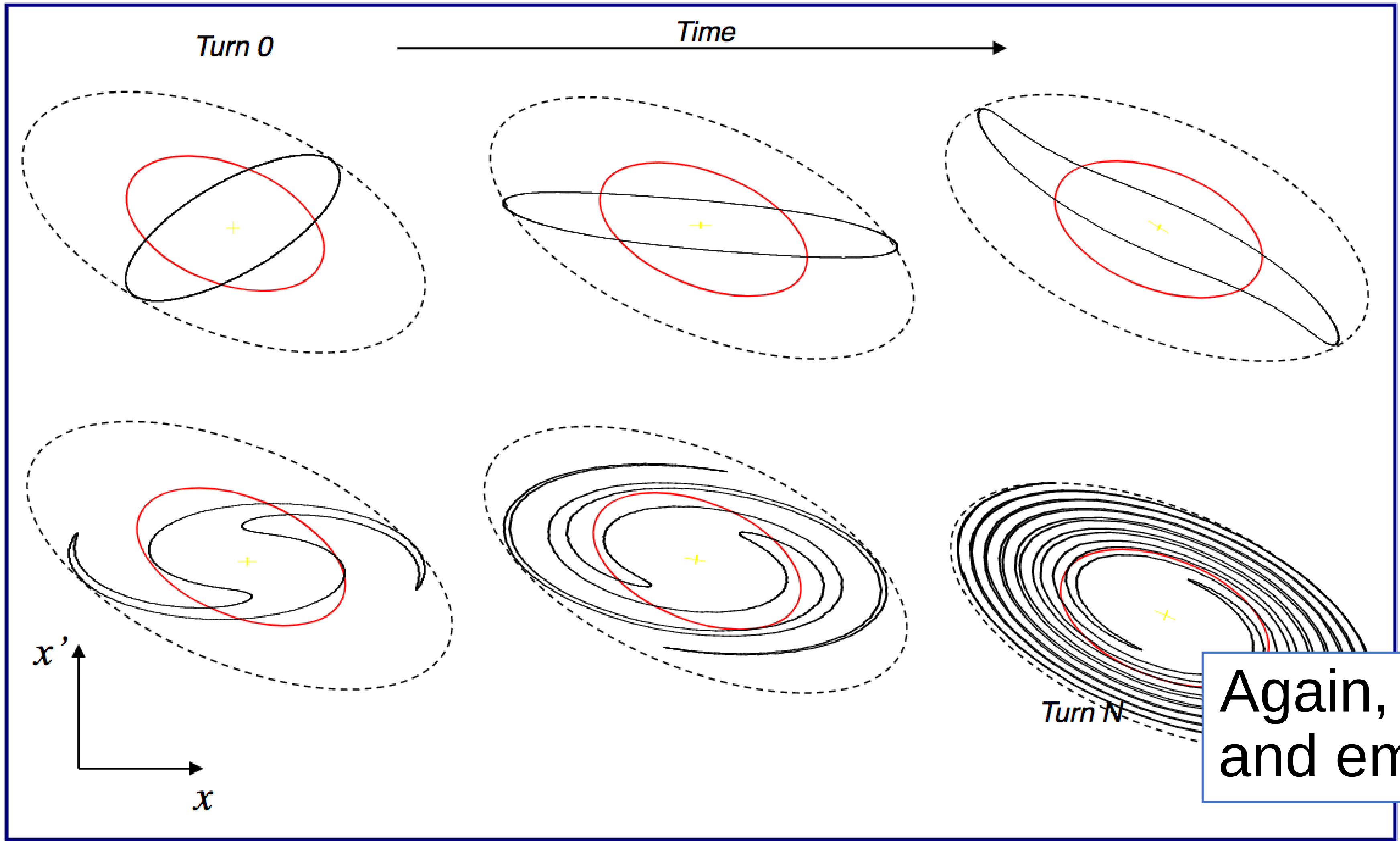
WHAT HAPPENS IF…INJECTION WITH OFFSET

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

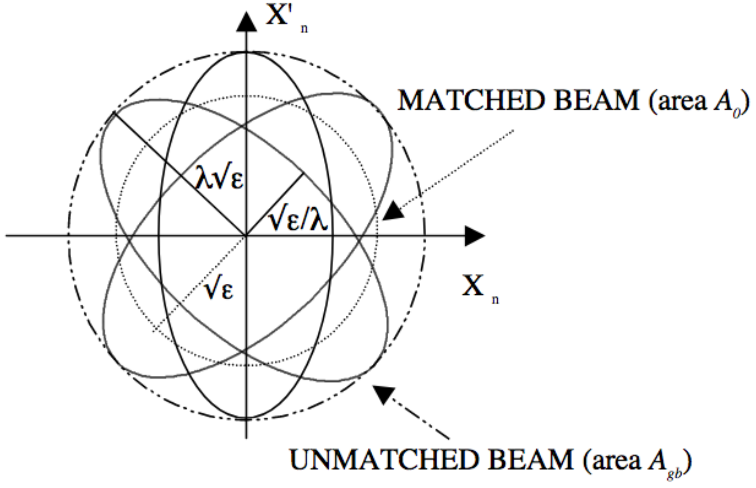
WHAT HAPPENS IF…INJECTION WITH PHASE-SPACE MISMATCH



Plots courtesy of C.Bracco

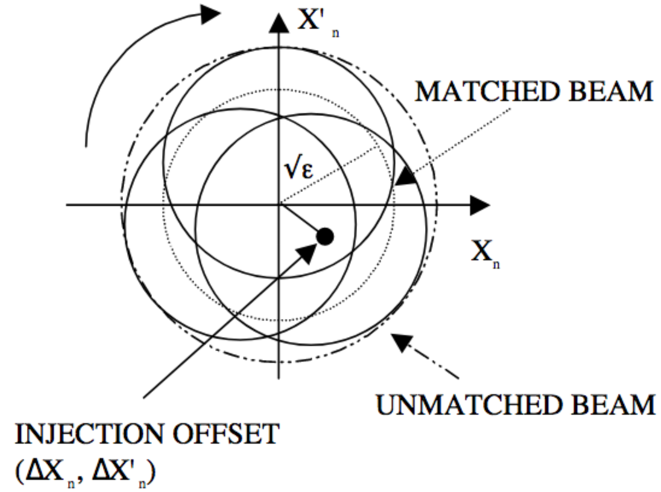
Again, filamentation and emittance blow-up

Injection error blow-up



Betatron mismatch

$$H = \frac{1}{2}\left(\lambda^2 + \frac{1}{\lambda^2}\right) = \frac{1}{2}\left(G + \frac{1}{G}\right) = \frac{1}{2}\left[\frac{\beta_0}{\beta_m} + \frac{\beta_m}{\beta_0} + \left(\alpha_0\sqrt{\frac{\beta_m}{\beta_0}} - \alpha_m\sqrt{\frac{\beta_0}{\beta_m}}\right)^2\right]$$



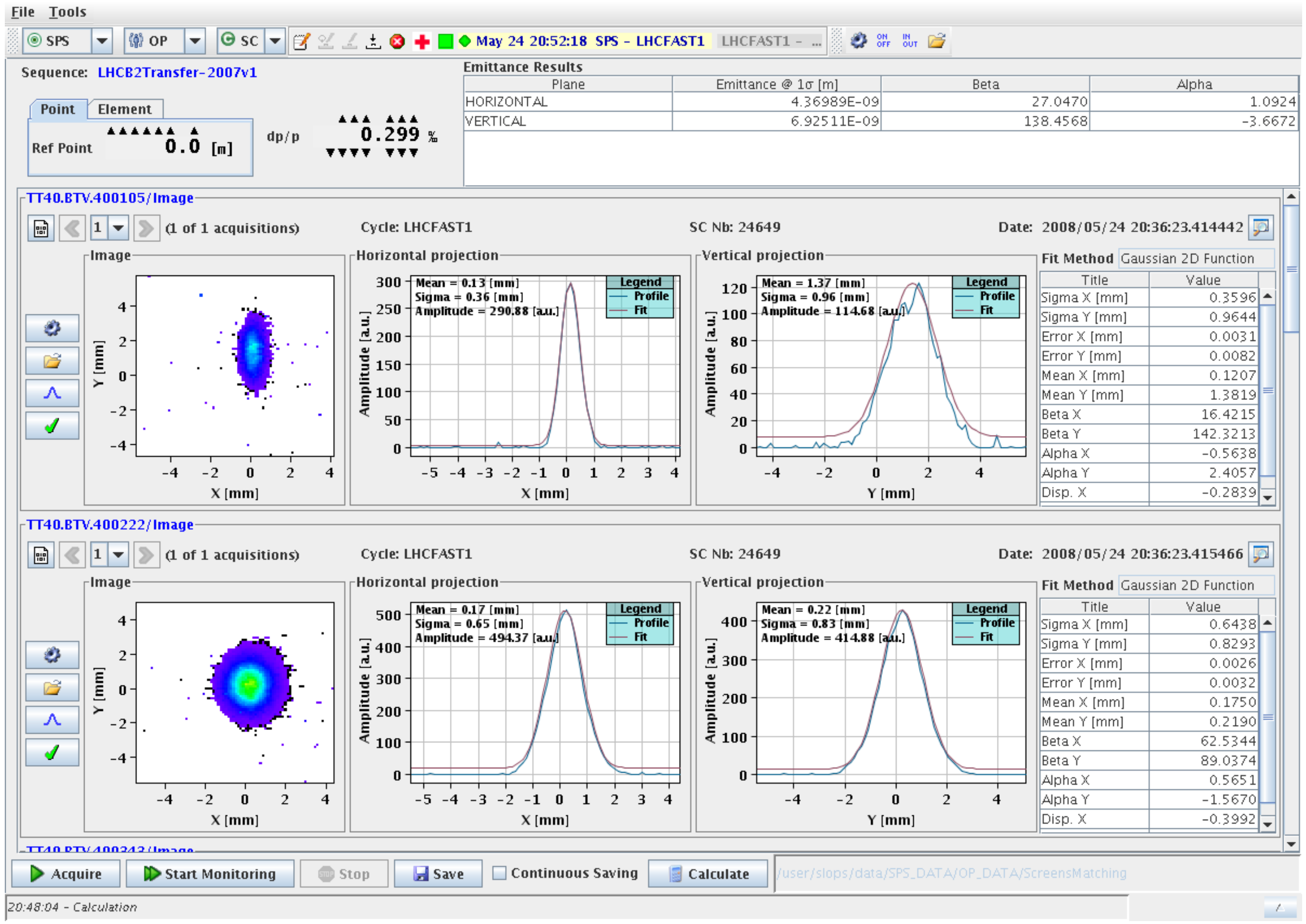
Injection offset (or energy offset – coupled via the dispersion)

$$H_{inj.} = 1 + \frac{\Delta X_n^2 + \Delta X_n'^2}{2\varepsilon}$$

IMPORTANT TO "MATCH" THE BEAM

- Adapt the optics of the line to arrive in the downstream ring with the correct phase-space ellipse orientation

Matching measurements



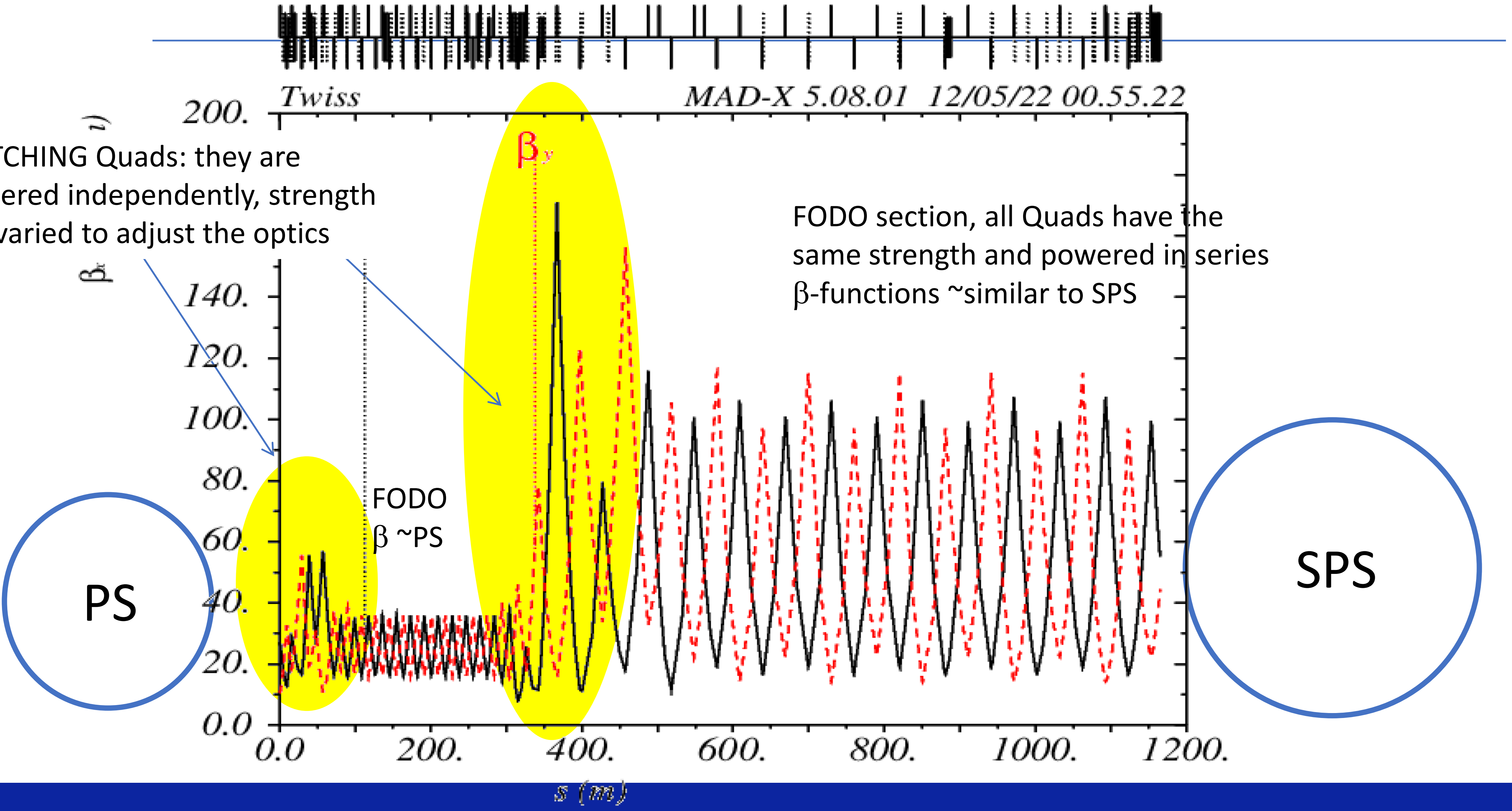
At least 3 screens:
→ beam sizes at 3 different locations on the line & knowledge of the transfer matrix between them
→ give alpha, beta, emittance

Matching measurements

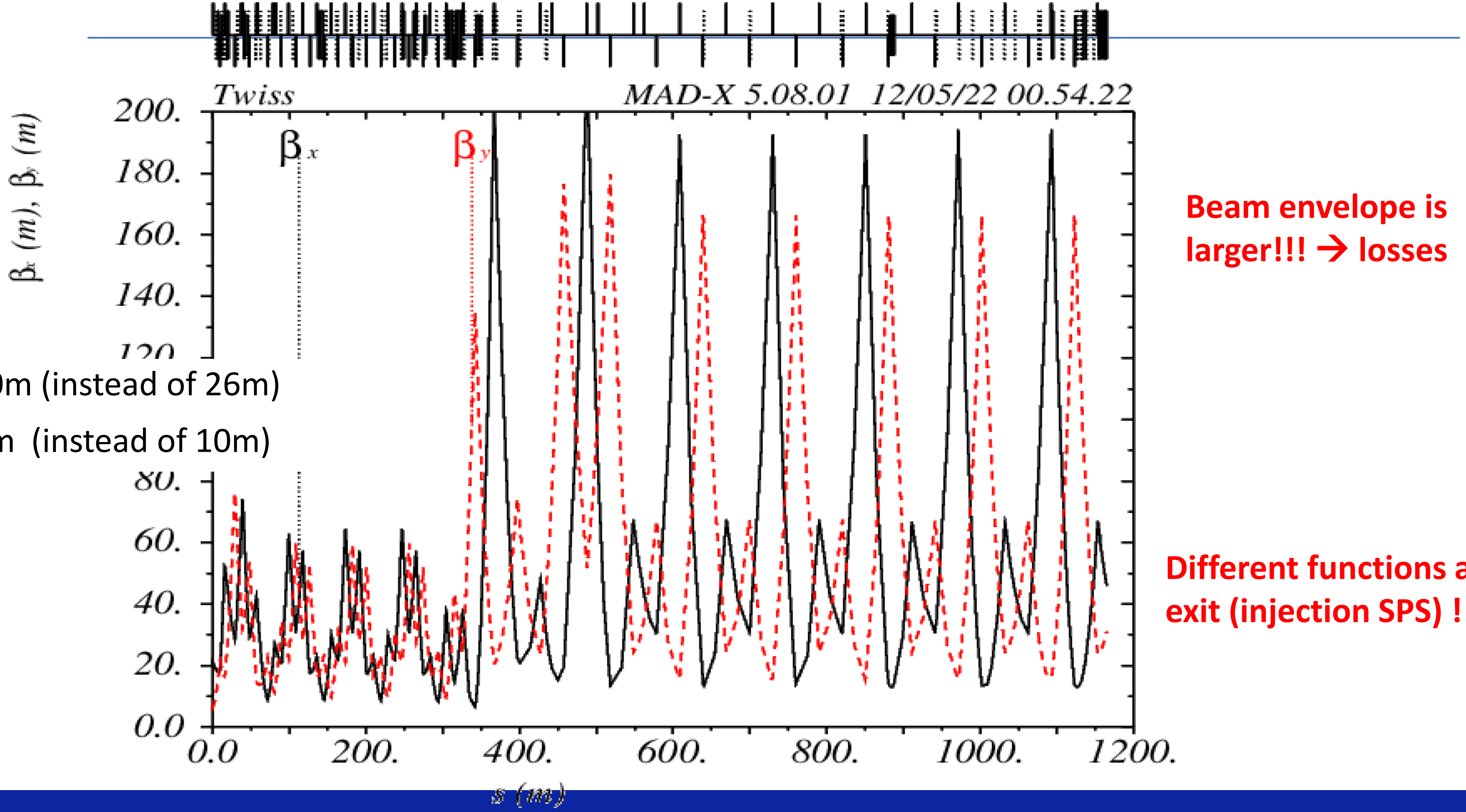
Answer:

$$\begin{pmatrix} C_1^2 & -2C_1S_1 & S_1^2 \\ C_2^2 & -2C_2S_2 & S_2^2 \\ C_3^2 & -2C_3S_3 & S_3^2 \end{pmatrix} \begin{pmatrix} \varepsilon\beta_0 \\ \varepsilon\alpha_0 \\ \varepsilon\gamma_0 \end{pmatrix} = \begin{pmatrix} \sigma_{\beta,1}^2 \\ \sigma_{\beta,2}^2 \\ \sigma_{\beta,3}^2 \end{pmatrix}$$

Matching of a transfer line (example of the PS to SPS)



Wrong beta at entrance (extraction from PS)



βx_0=20m (instead of 26m)

βy_0=7m (instead of 10m)

Beam envelope is larger!!! → losses

Different functions at exit (injection SPS) !!!

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

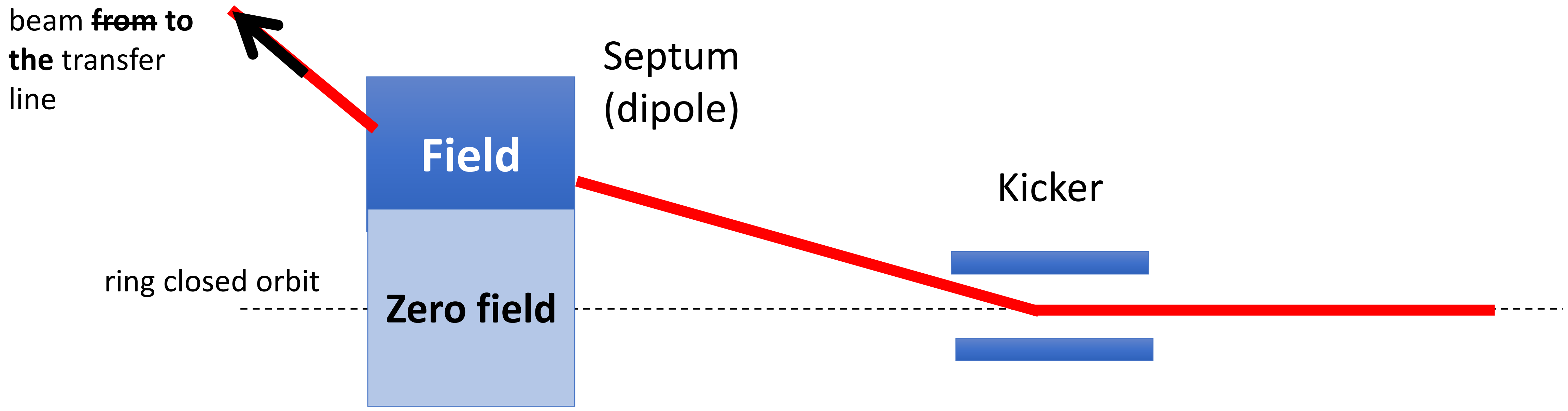
- **Single turn injection** for transfer from one synchrotron to the following
- **Multi-turn injection** if intensity from the source is not enough
- **Charge exchange multi-turn** injection to increase beam brightness

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

OUTLINE

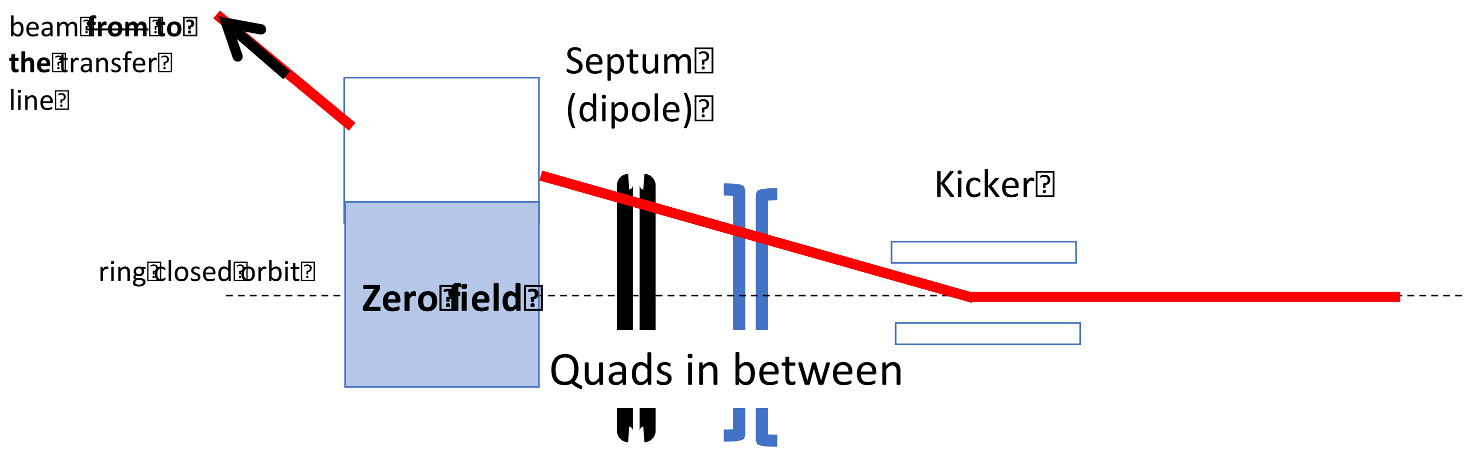
- Accelerator physics: recap
- Injection in proton & ion synchrotrons
  - Single turn
  - Multi-turn
- Beam transfer and emittance preservation
- Extraction
  - Single turn
  - Multi-Turn (and Resonant MTE)
  - Slow
- Longitudinal synchronization

EXTRACTION…the inverse of injection!



- Beam momentum is higher (Brho) → need stronger fields (and/or >1 septa)
- No space-charge
- Slow bump to move orbit toward septum + Kicker (rise-time < bunch spacing, i.e. 50-150ns)

SINGLE TURN EXTRACTION: Exercise

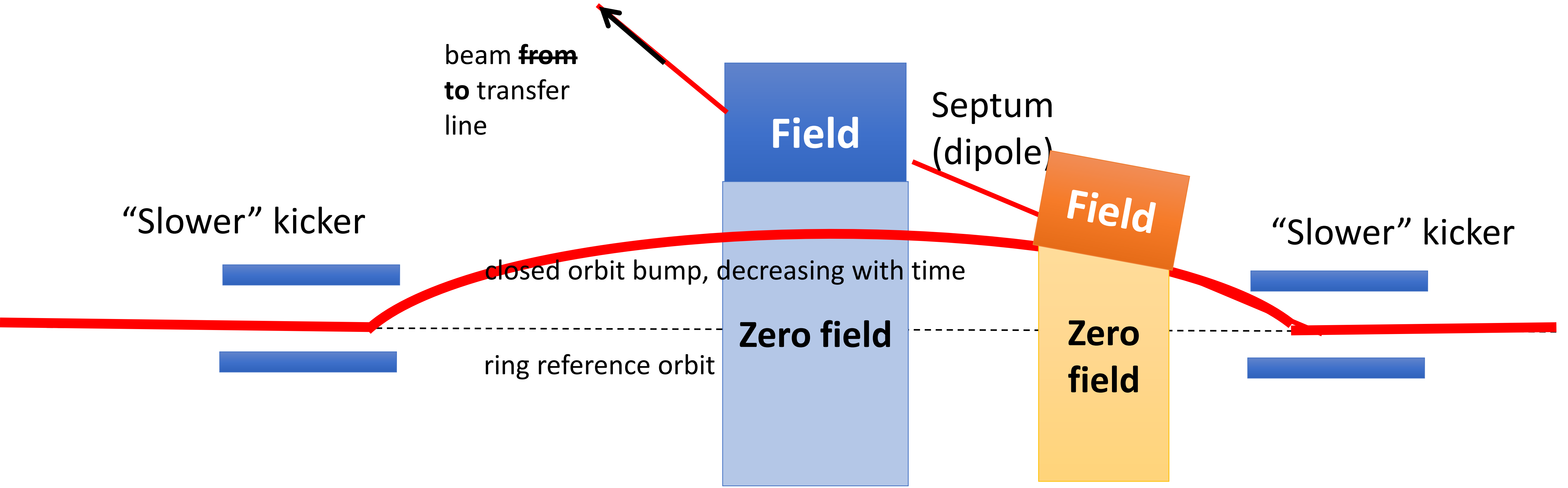


- What is the angular kick needed at the kicker? How to minimize the kick?

$$\begin{pmatrix} x \\ x' \end{pmatrix}_s = M \begin{pmatrix} x \\ x' \end{pmatrix}_0 \rightarrow M = \begin{pmatrix} \sqrt{\frac{\beta_s}{\beta_0}}(\cos\mu_s + \alpha_0 \sin\mu_s) & \sqrt{\beta_s\beta_0}\sin\mu_s \\ \frac{(\alpha_0-\alpha_s)\cos\mu_s-(1+\alpha_0\alpha_s)\sin\mu_s}{\sqrt{\beta_s\beta_0}} & \sqrt{\frac{\beta_0}{\beta_s}}(\cos\mu_s - \alpha_s\sin\mu_s) \end{pmatrix}$$

$$\theta_{kicker} = \frac{x_{septum}}{\sqrt{\beta_{kicker}\beta_{septum}}\sin(\mu)}$$

MULTI-TURN and SLOW EXTRACTION

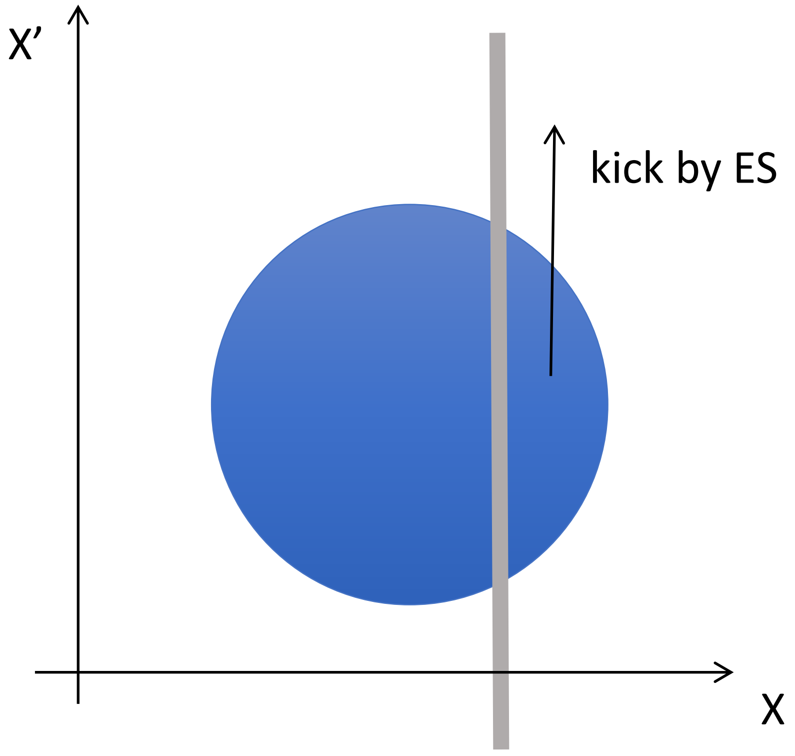


- Electrostatic Septum (EM) which is thin gives a first (small) kick
- Magnetic Septum gives a second kick

MULTI-TURN EXTRACTION

- When single-bunch pulse is too short
- 5 turns (in this case) to extract

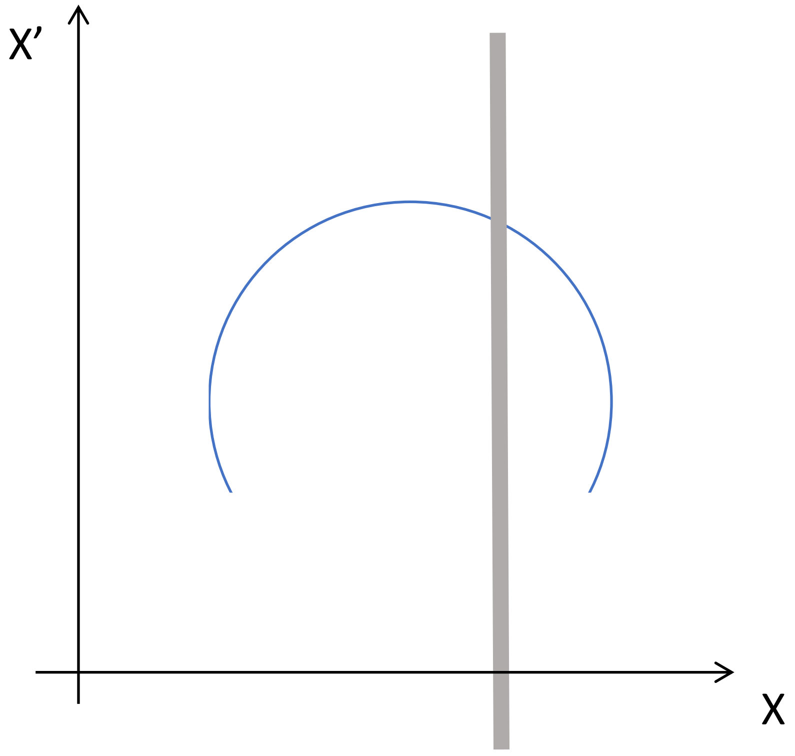
- ES is "cutting" the beam
- The fraction outside gets a kick
- …and a further deviation by a MS



MULTI-TURN EXTRACTION

- When single-bunch pulse is too short
- 5 turns (in this case) to extract

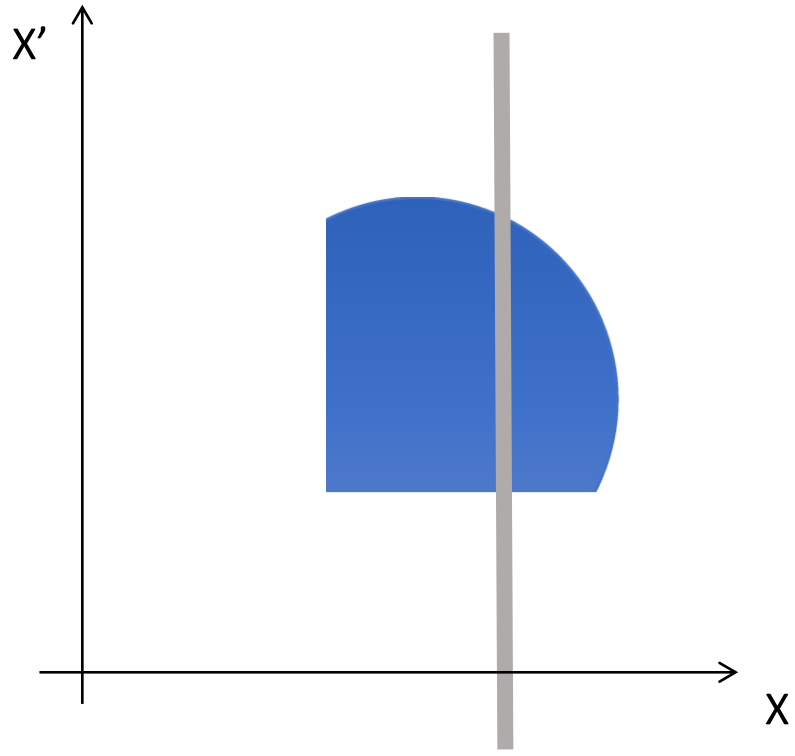
- ES is “cutting” the beam
- The fraction outside gets a kick
- …and a further deviation by a MS



MULTI-TURN EXTRACTION

- When single-bunch pulse is too short
- 5 turns (in this case) to extract

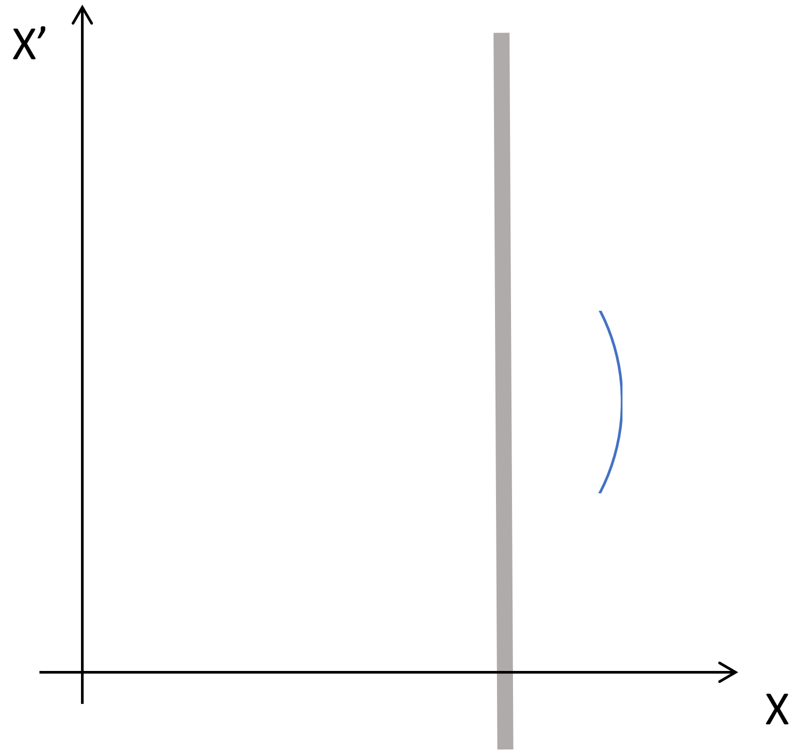
- ES is “cutting” the beam
- The fraction outside gets a kick
- …and a further deviation by a MS



MULTI-TURN EXTRACTION

- When single-bunch pulse is too short
- 5 turns (in this case) to extract

- ES is "cutting" the beam
- The fraction outside gets a kick
- …and a further deviation by a MS

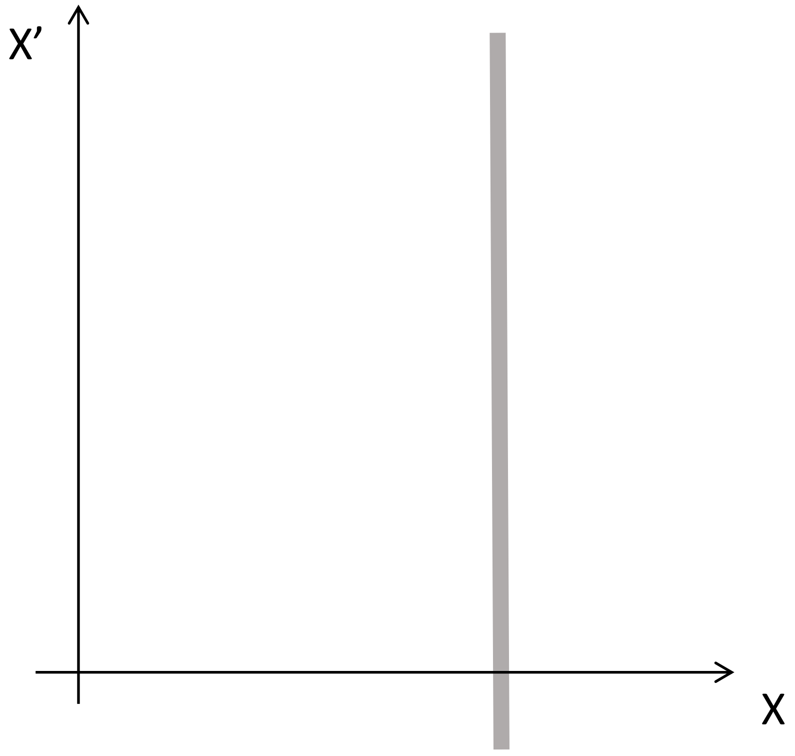


MULTI-TURN EXTRACTION

- When single-bunch pulse is too short
- 5 turns (in this case) to extract

- ES is “cutting” the beam
- The fraction outside gets a kick
- …and a further deviation by a MS

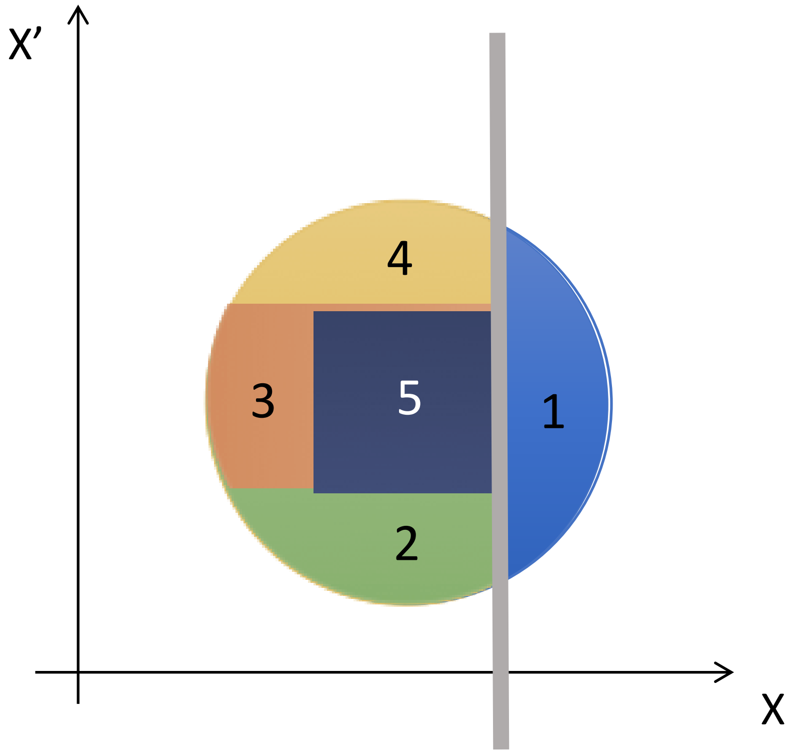
- this 5th beamlet needs to be kicked out



MULTI-TURN EXTRACTION

- When single-bunch pulse is too short
- 5 turns (in this case) to extract

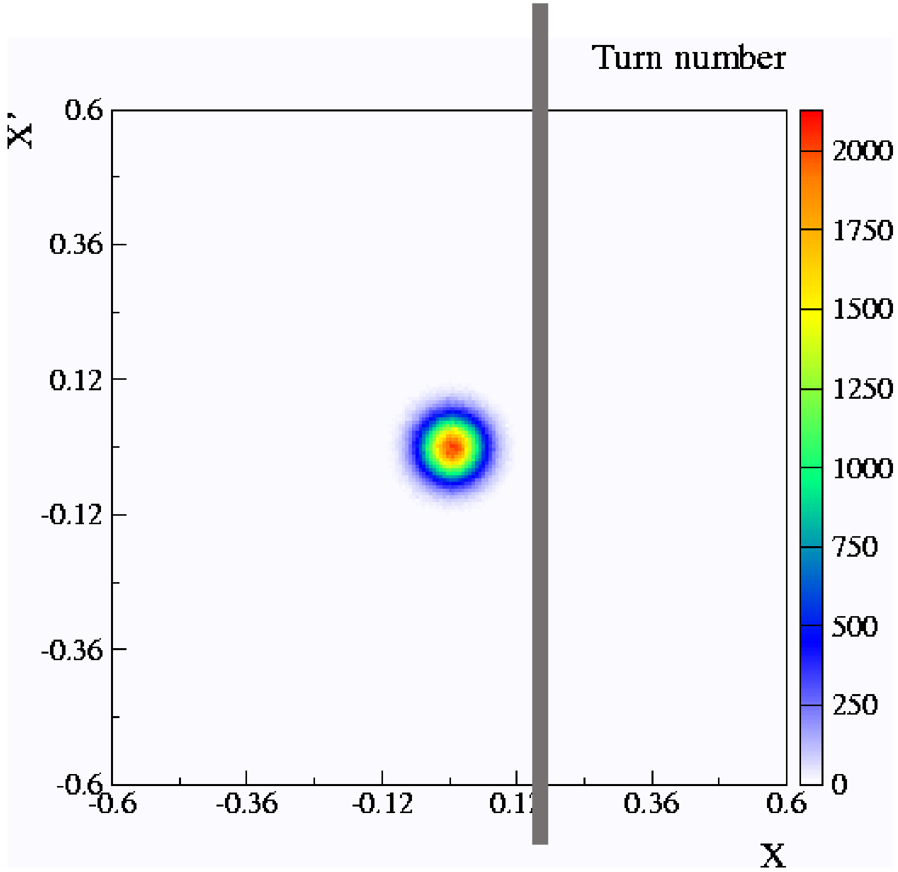
- ES is “cutting” the beam
- The fraction outside gets a kick
- …and a further deviation by a MS

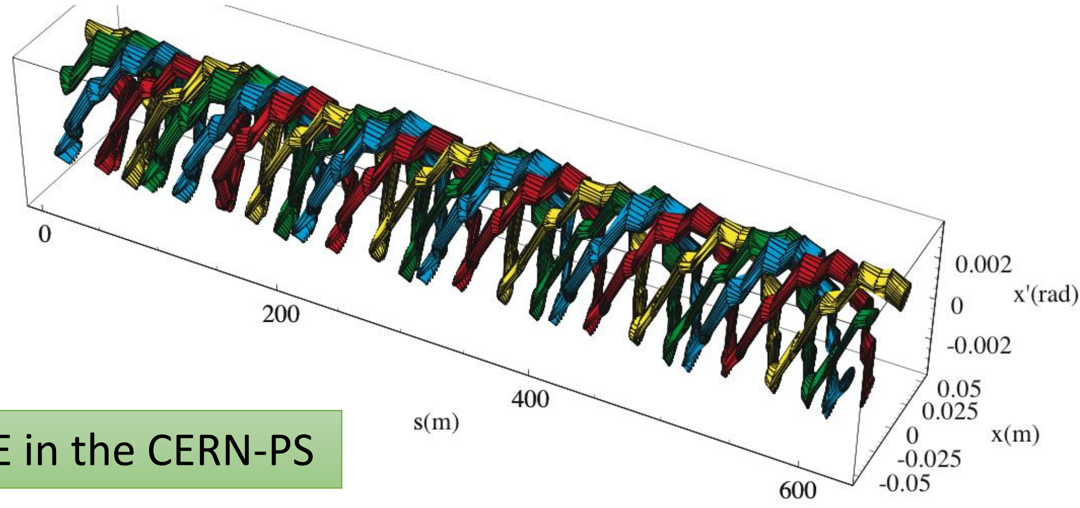


- Losses at the Electrostatic Septum (ES), where the beam is cut

RESONANT MULTI TURN EXTRACTION (MTE)

Imagine we can split the beam in a different way and avoid losses at the ES…





M. Giovannozzi, MTE in the CERN-PS

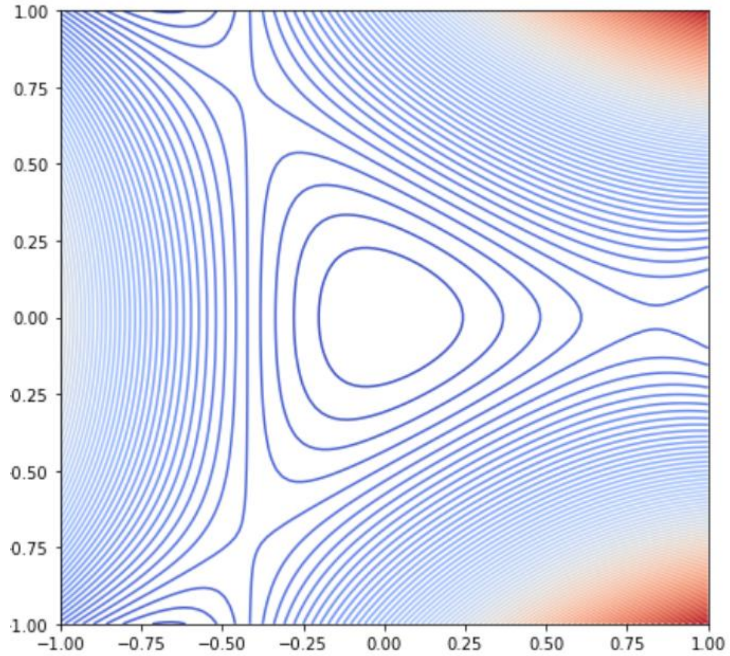
Beam manipulation on the 4th order resonance:

- Using strong non-linear elements (Octupoles + Sextupoles) and a proper tune → creation of stable islands
- Slow bump + fast kick to move the island to the septum

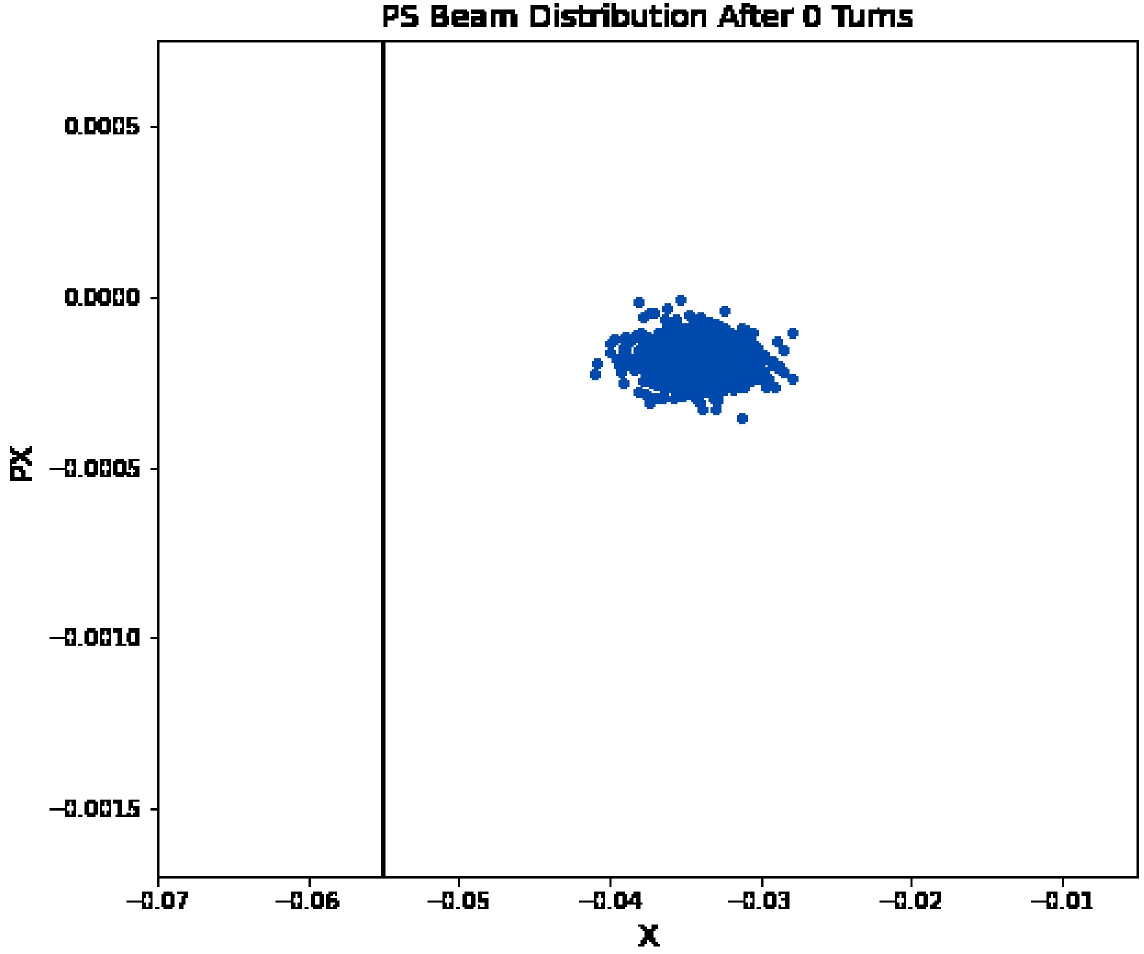
SLOW RESONANT EXTRACTION

Beam manipulation on the 3rd order resonance

- Using sextupoles and tune close to Qx=#.33 or #.67



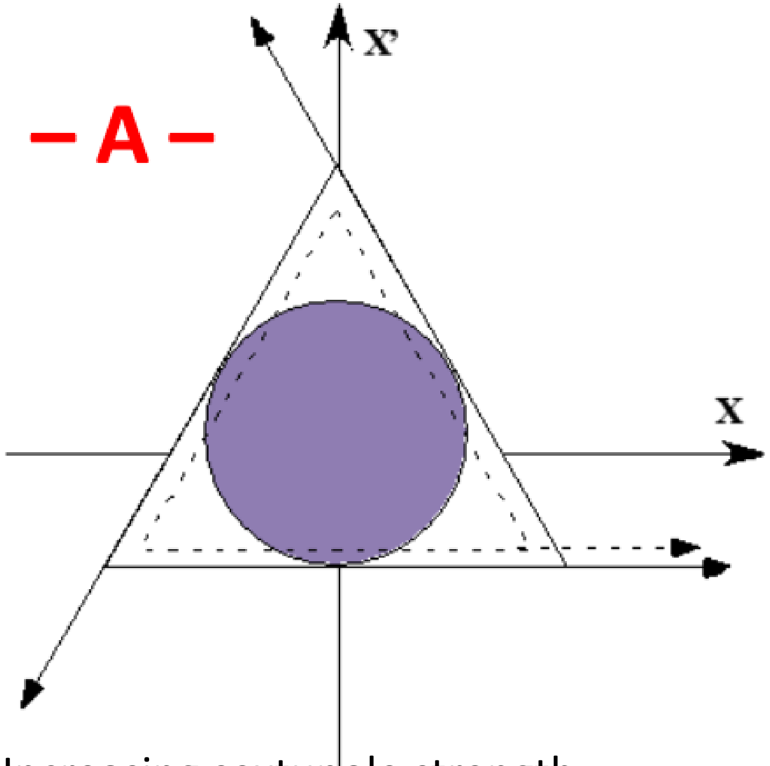
R. Taylor



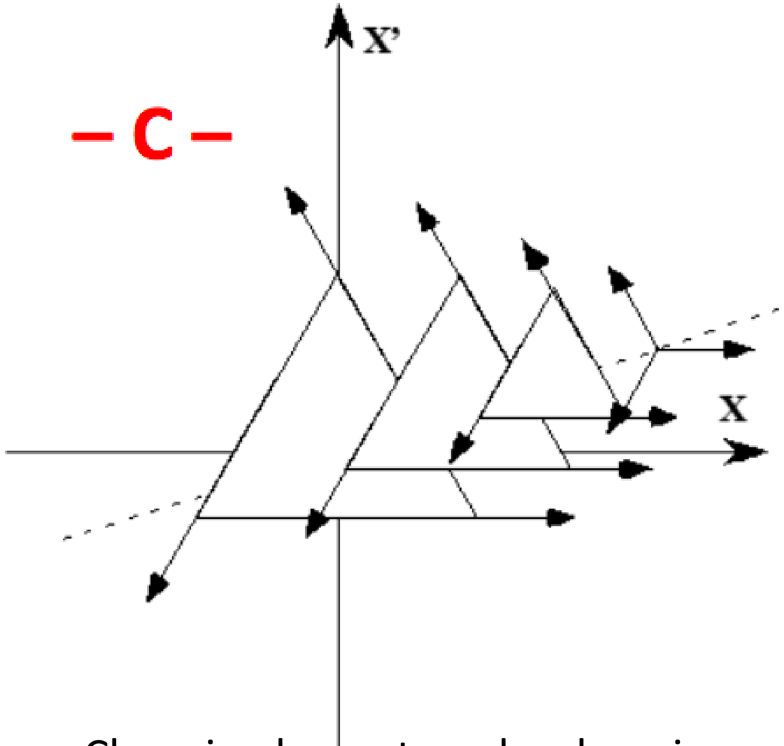
PUSH PARTICLES OUTSIDE THE STABLE TRIANGLE

- Several ways:

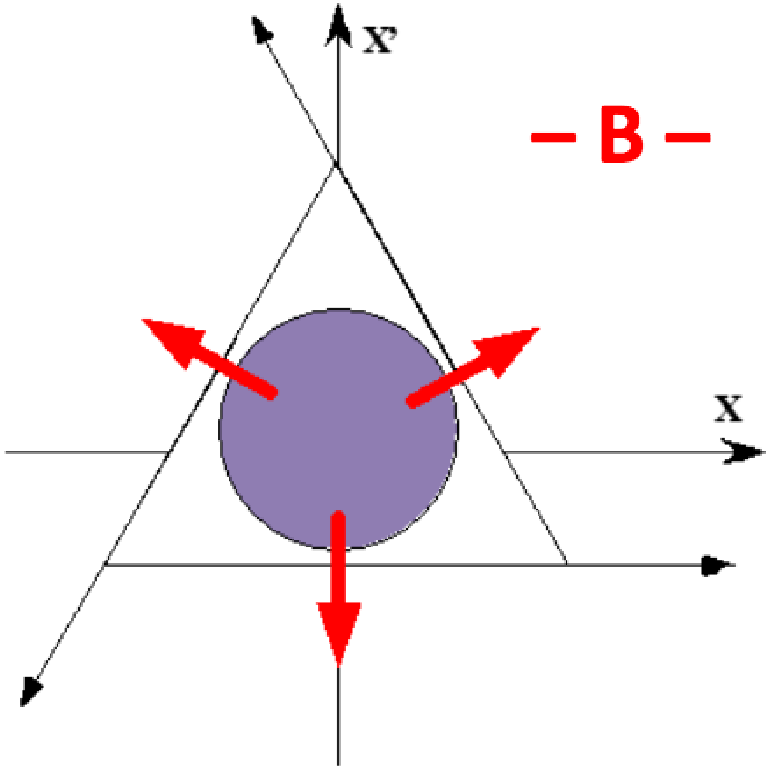
K. Noda



Increasing sextupole strength, changing tune to approach resonance



Changing beam tune by changing momentum (chromaticity)
→**Betatron core** (e.g. at CNAO)



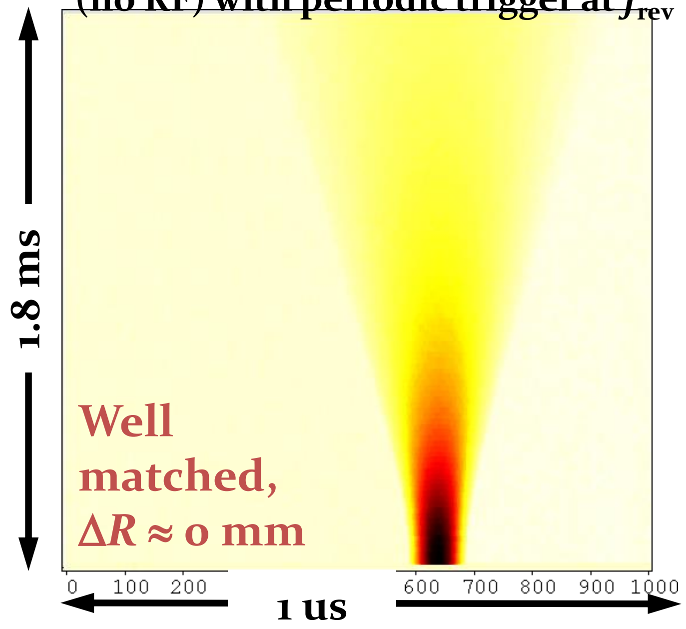
Increasing beam emittance by exciting particles with **RF-KO** signal

SYNCHRONISATION & LONGITUDINAL ASPECTS

H. Damerau @ CAS Erice

- Longitudinal plane: longitudinal coordinate ~ phase ~ time
- When transfer from one ring to the next, need to assure that:
  - the beam has the right energy
  - the hardware (kickers, bumps, monitors) **triggers!**
  - RF cavities have the correct phase to accelerate the beam
- Injection:
  - Multi-turn with RF on / RF off
  - Single-turn (bunch to bucket)
- Leptons: less of a problem, damping

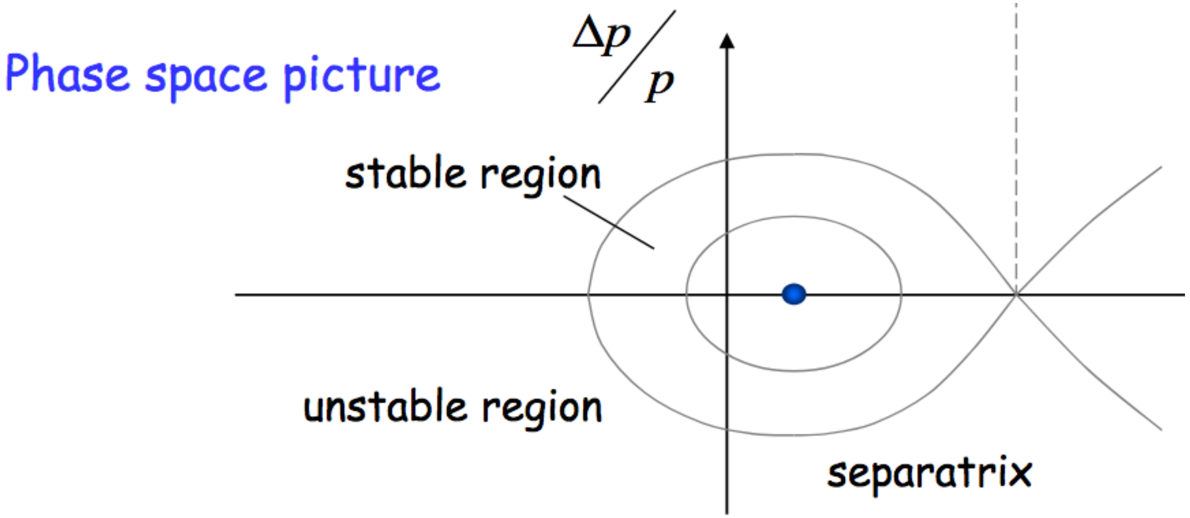
S. Hancock: Observe de-bunching (no RF) with periodic trigger at f_{rev}



MULTI-TURN INJ. (from the longitudinal point of view)

The beam is injected multi-turn, BUT in time (longitudinal) it is continuous

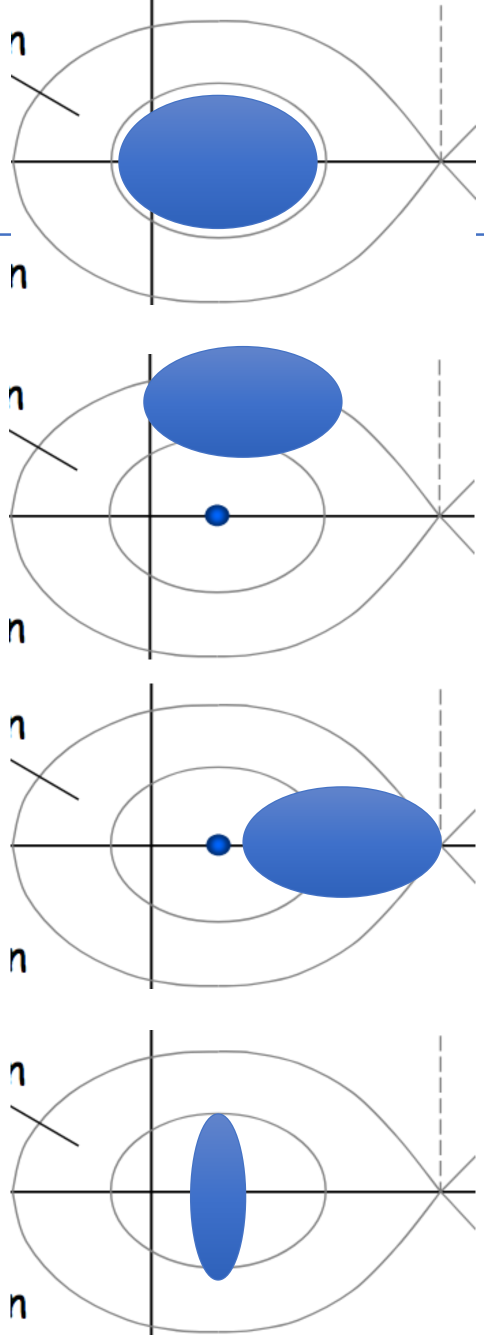
- Either chopper in the Linac to create “holes” (+ synchronization)
- Or injection with RF cavities OFF, then adiabatically ramped up to capture the beam inside the bucket & accelerate it



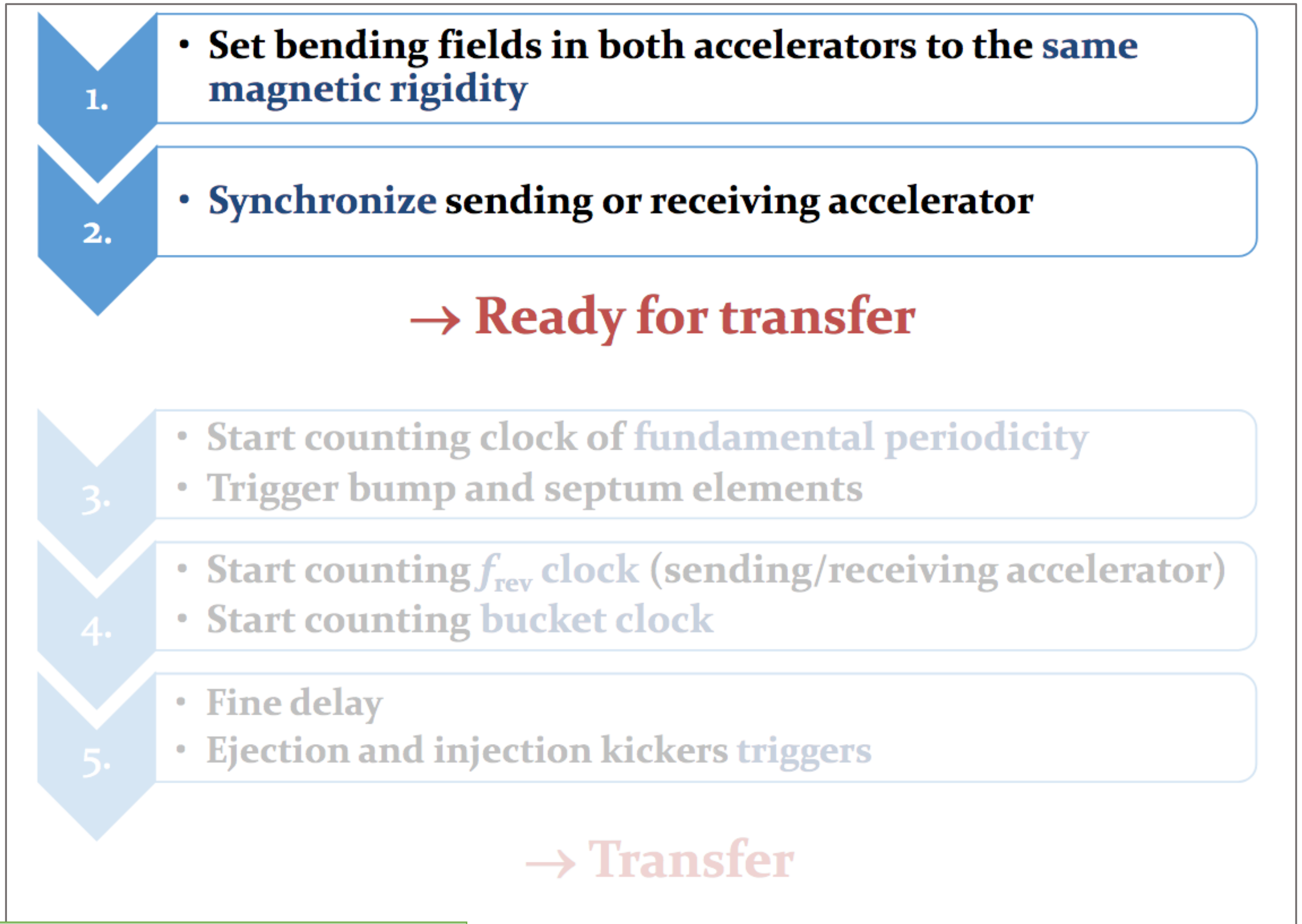
SINGLE-TURN (BUNCH TO BUCKET)

Need to assure that:

- the beam has the correct energy …or that the cavity has the correct frequency!
- the phase is correct
- the shape is "matched" (otherwise…filamentation)

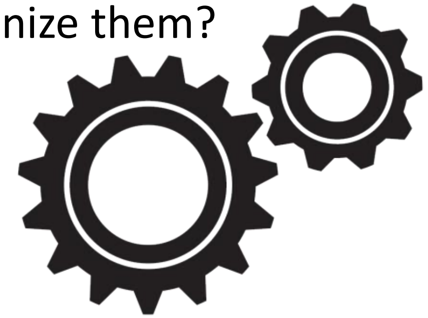


Steps of beam transfer synchronization



H. Damerau @ CAS Erice

- In theory upstream and downstream synchrotron have multiples of the same revolution frequency
- In practice it is never the case.
- How to synchronize them?



- (Bfield, Frev, Radial position, Beam Momentum) are interrelated
- Change slightly beam revolution frequency by changing the energy, and the radial position (B=const), until it has the correct azimuth position
- Lock the phase of the 2 ring, so that from now on they move together (master/slave)
- Adjust radial position of the beam (therefore energy), so that the revolution frequency is now fine

Summary

- Injection, extraction, beam transfer …application of different accelerators physics disciplines (transverse/longitud dynamics, non –linear beam manipulation, space-charge, special hardware, timings)
- Injection/extraction: bunch-to-bucket or multi-turn
- Use of special magnets: kickers, septa, orbit bumps