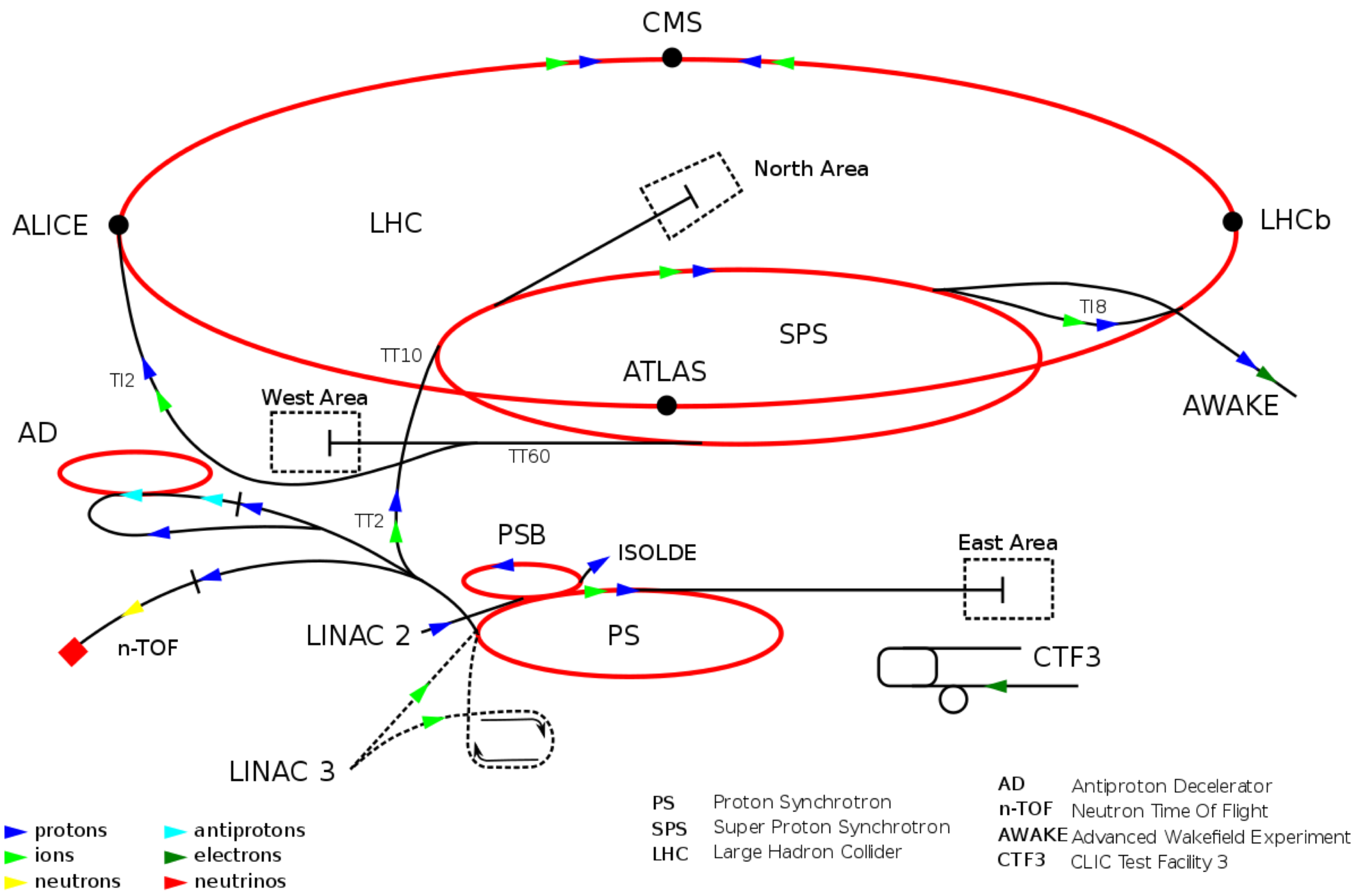
Proton Synchrotron

Example: LHC Accelerator Complex

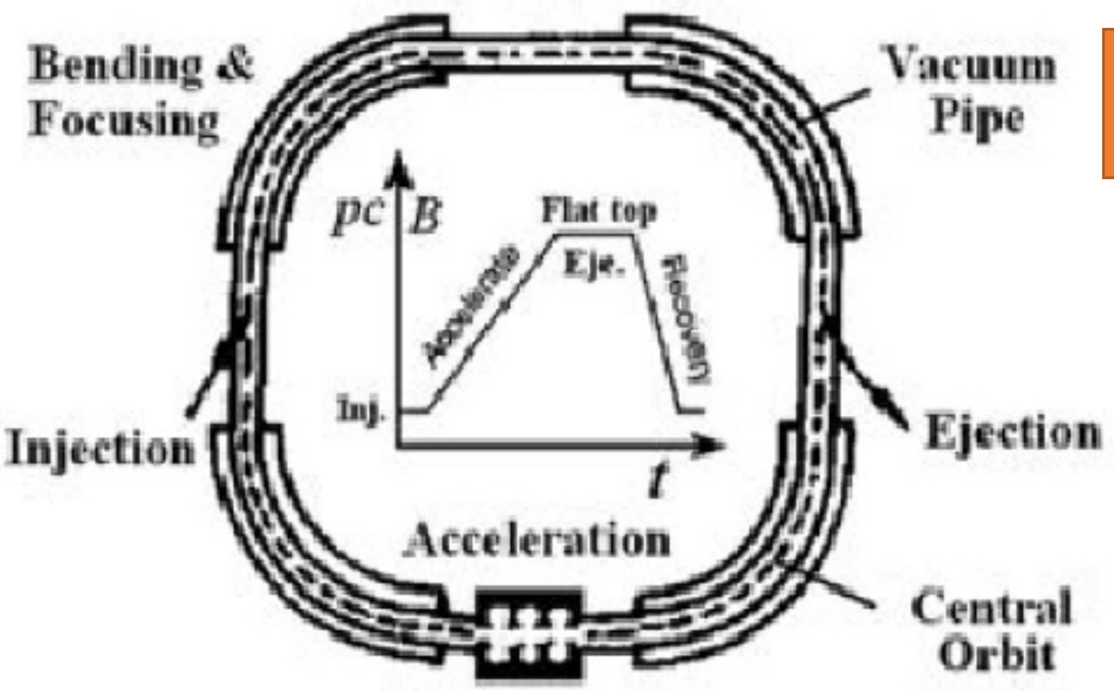


Why Synchrotron?

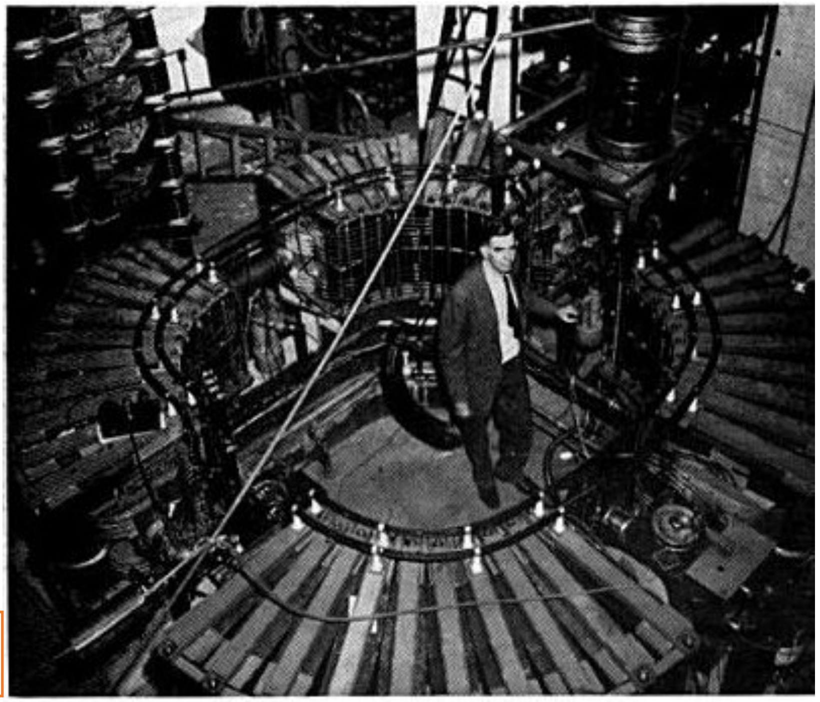
Angular frequency:

$$\omega = \frac{qB}{m\gamma}$$

	Magnetic Field	Frequency	Orbit
Cyclotron	Fixed	Change for relativistic particle.	Increase with ascending energy
Synchrotron	Vary	Keep Constant	Keep Constant



Achieve high energy in circular ring

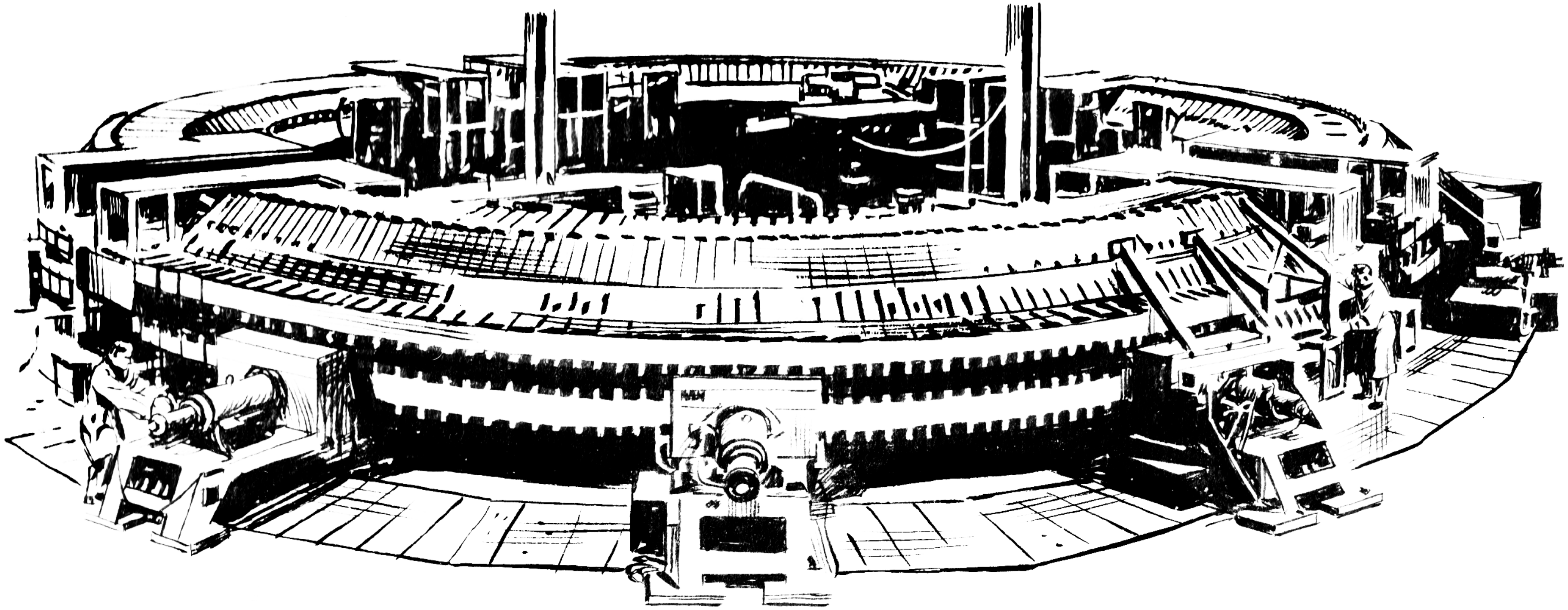


First synchrotron

Outlines

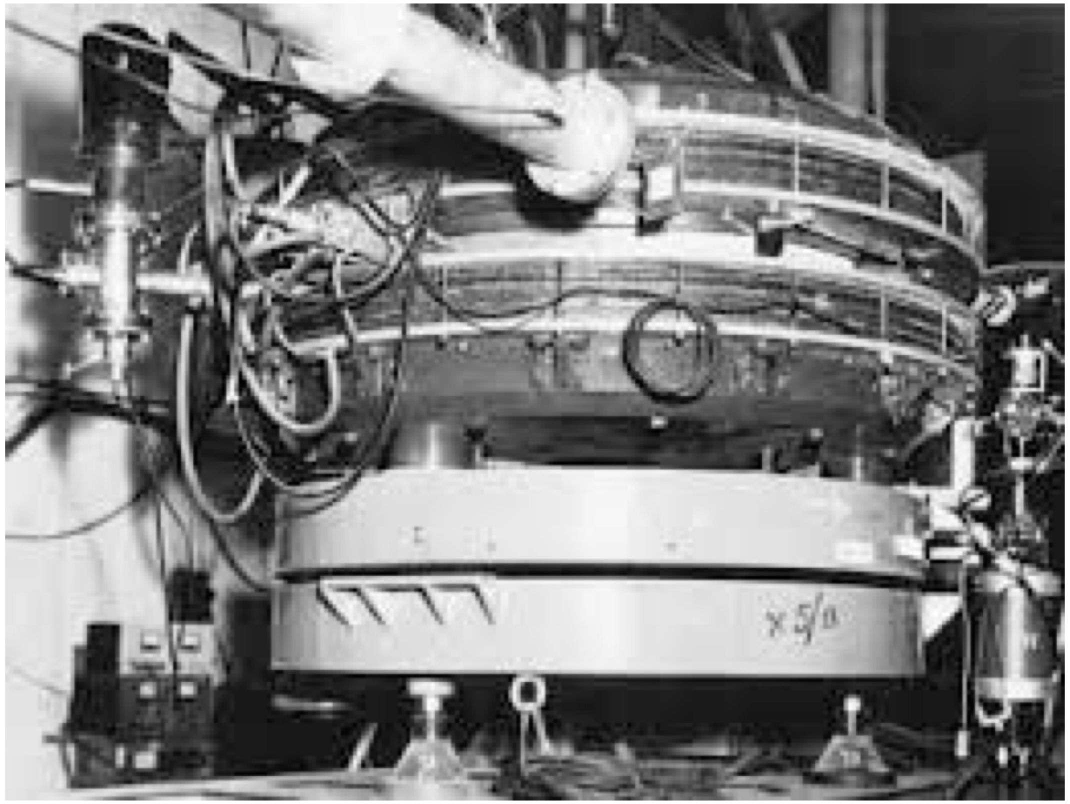
- Earlier synchrotrons
- Principle of operation
- Synchrotron motions
- Injection
- Extraction

Earlier stage



Cosmotron at Brookhaven National Laboratory, 1948-1968, reach 3.3 GeV proton, Weak focusing accelerator.

Earlier Stage



ADA collider at LNF in Frascati (1961-1964), reaches 250 MeV and achieve electron-position collision.

Operation principle

- As the energy/momentum of the particle increases, the magnetic field is also ramped so that the following relation holds:

$$P(t) = qB(t)\rho \longrightarrow \beta(t)\gamma(t)mc = qB(t)\rho$$

- The angular frequency gives

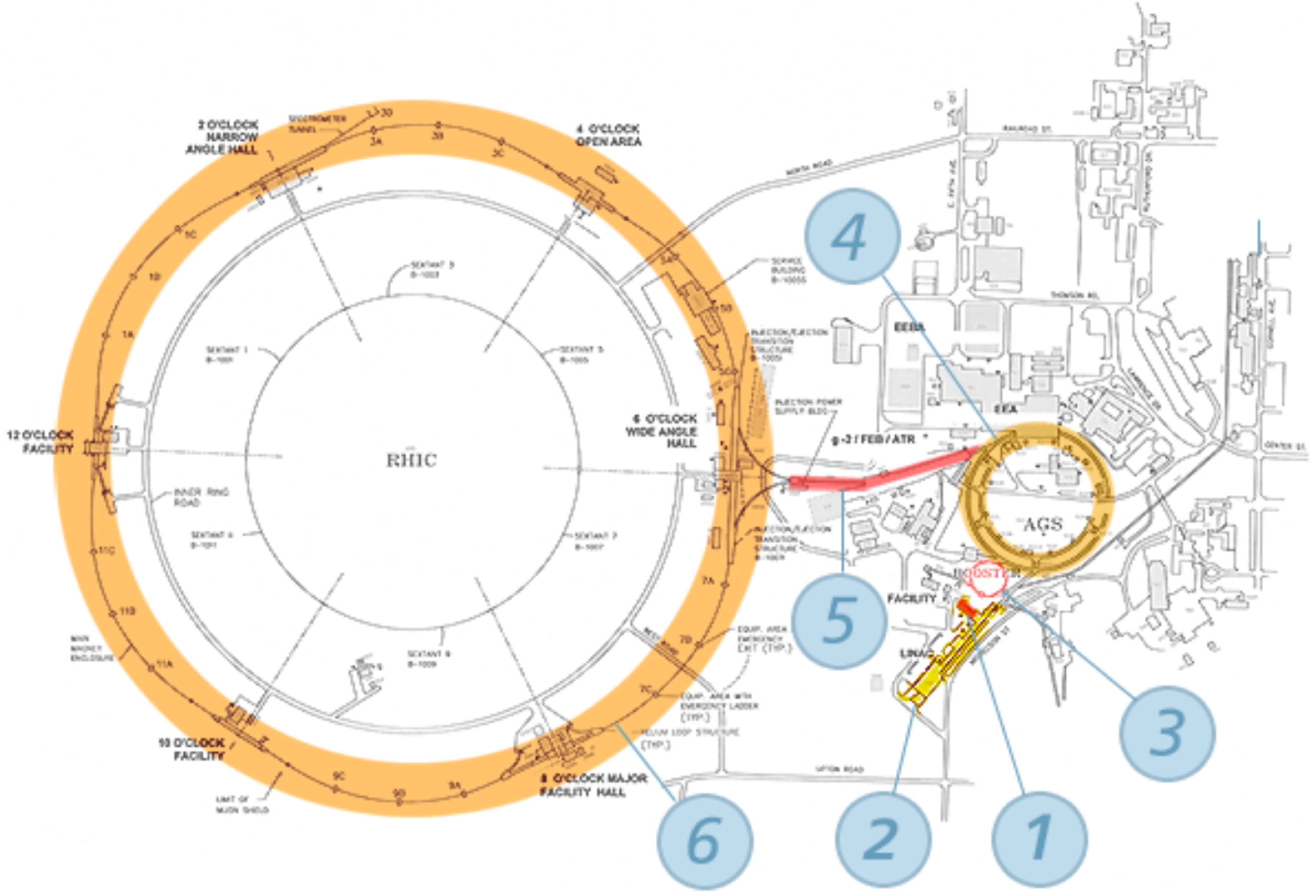
$$\omega(t) = \frac{qB(t)}{m\gamma(t)} = \frac{\beta(t)c}{\rho}$$

- Only in ultra-relativistic case, the orbit and frequency can be 'synchronized' together.

Energy Dynamic Range

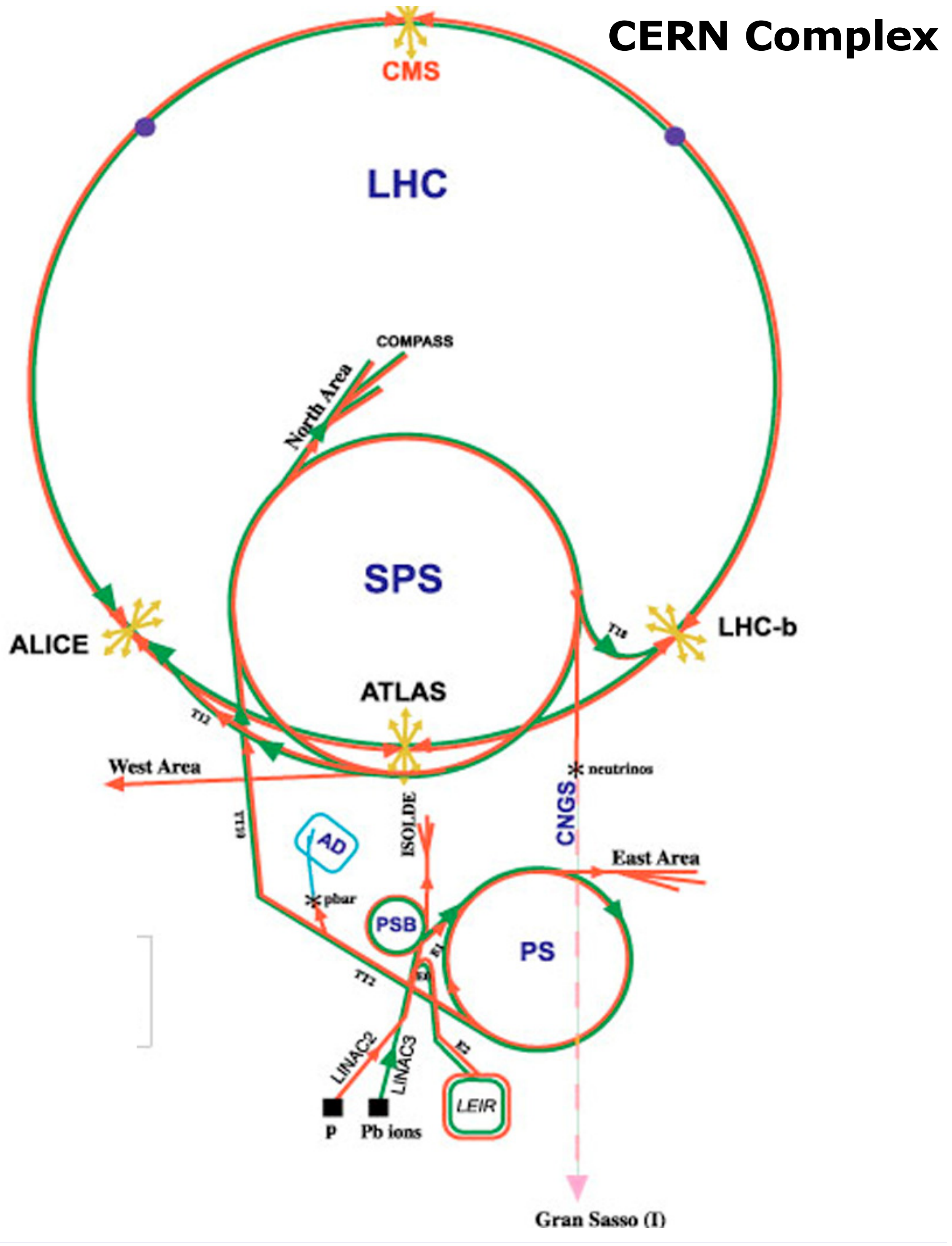
- There is no one accelerator to accelerate the particle from source all the way to the top energy (>GeV level)
  - Frequency changes a lot.
  - Space charge at low energy.
- Linac handles up to ~MeV
- One synchrotron can boost the energy up 10x-100x, from its injection energy to the top energy
- Need accelerator complex to achieve high energy
- Injection and Extraction are important.

Accelerator complex

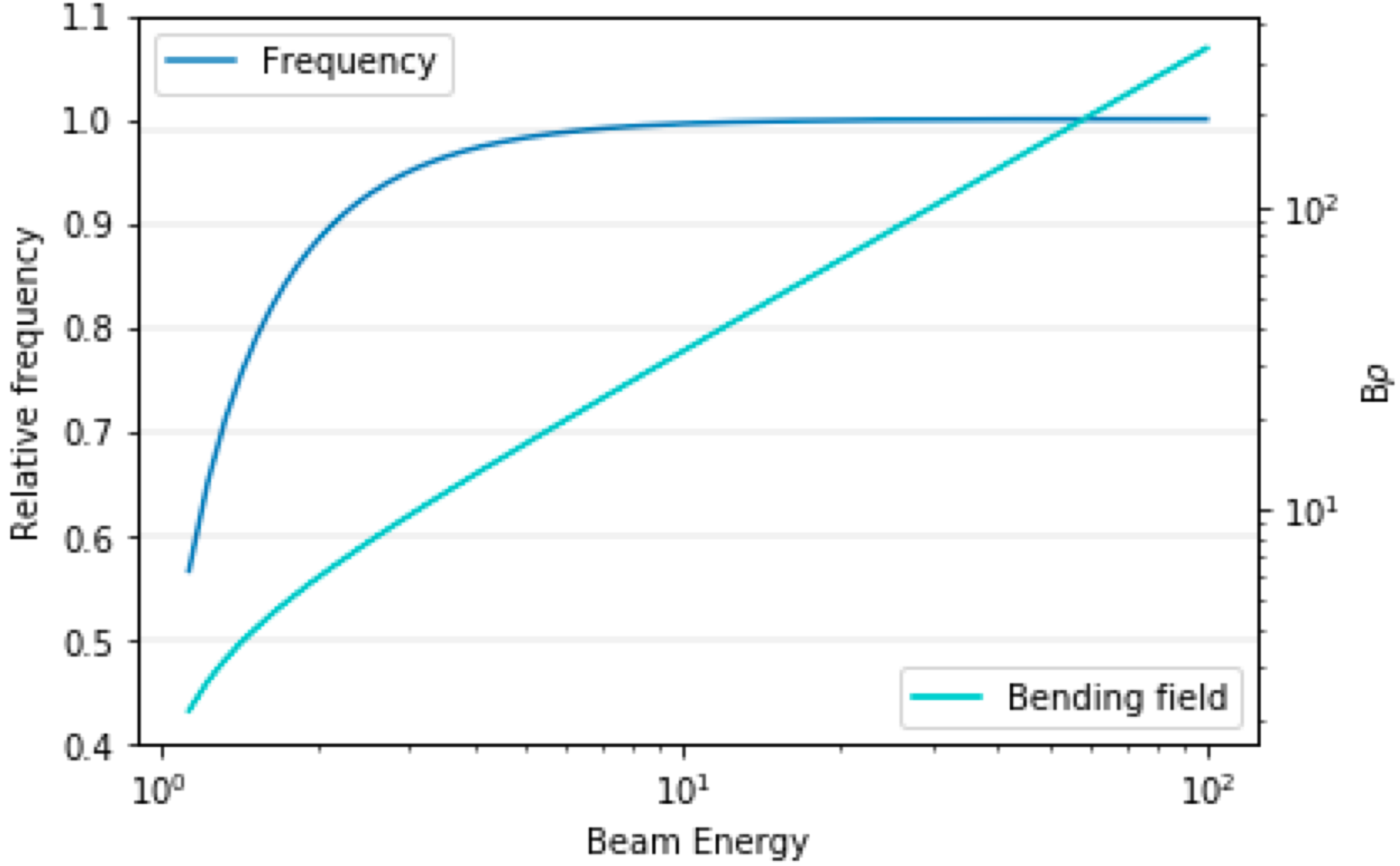


Relativistic Heavy Ion Collider complex:

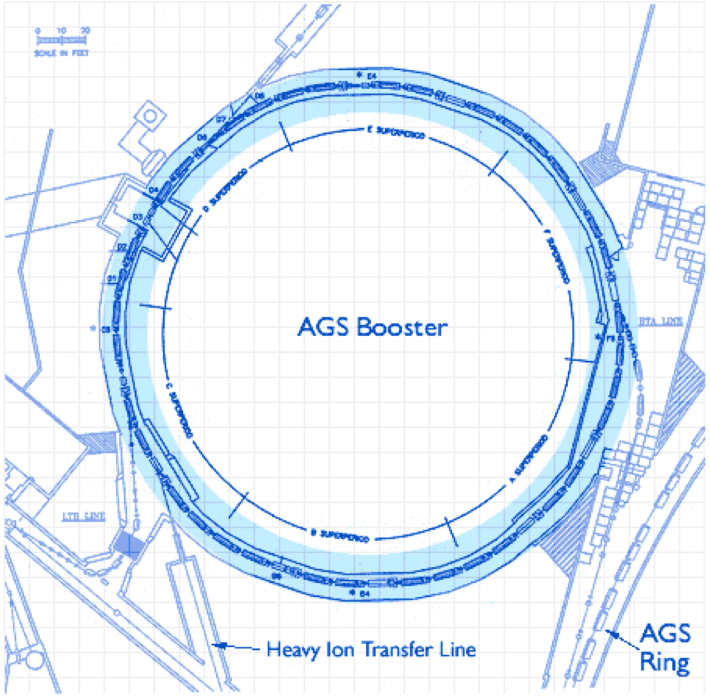
1. EBIS (Electron Beam Ion Source); 2. Linac Accelerator
3. Booster 4. AGS (Alternating Gradient Synchrotron)
5. AGS to RHIC Line 6. RHIC

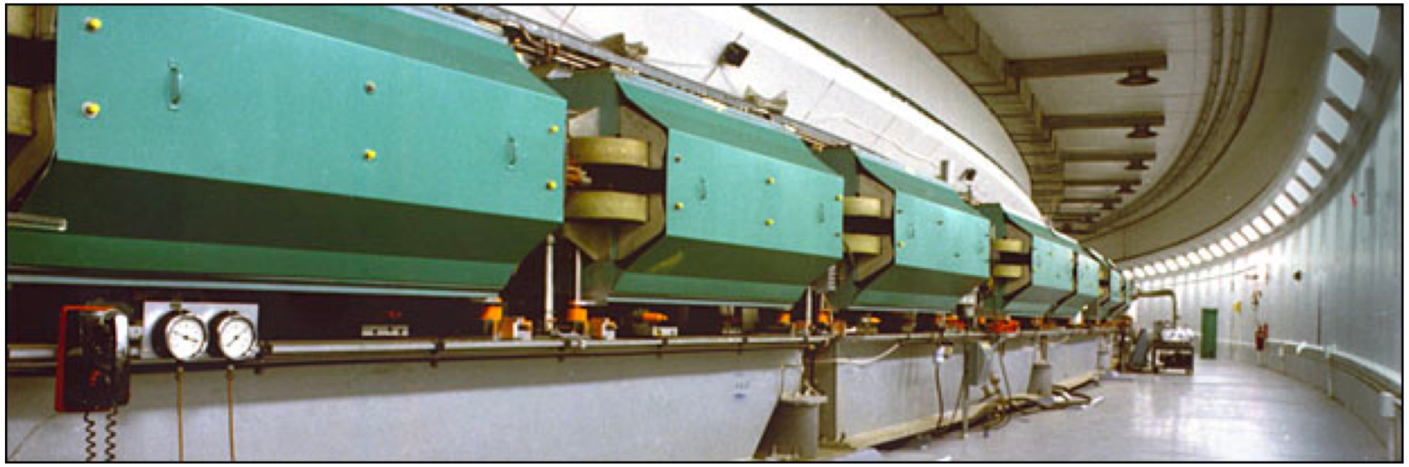


Synchronization



Synchrotrons in RHIC complex

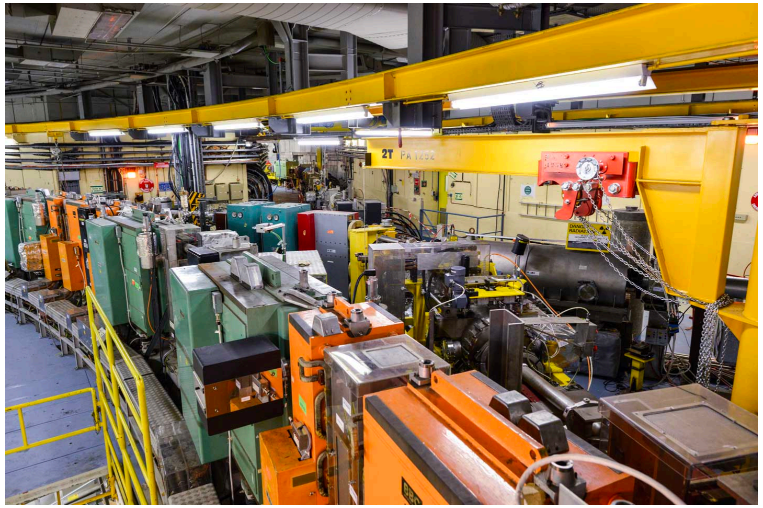




Booster, from 200 MeV proton/
2MeV ion to 100MeV/nucleon

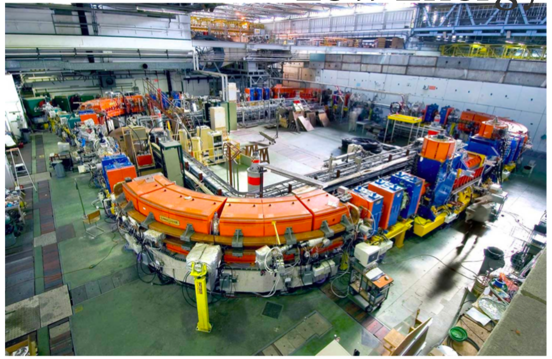
Alternative Gradient Synchrotron, accelerate to ~9 GeV/ nucleon.

Synchrotrons in LHC complex

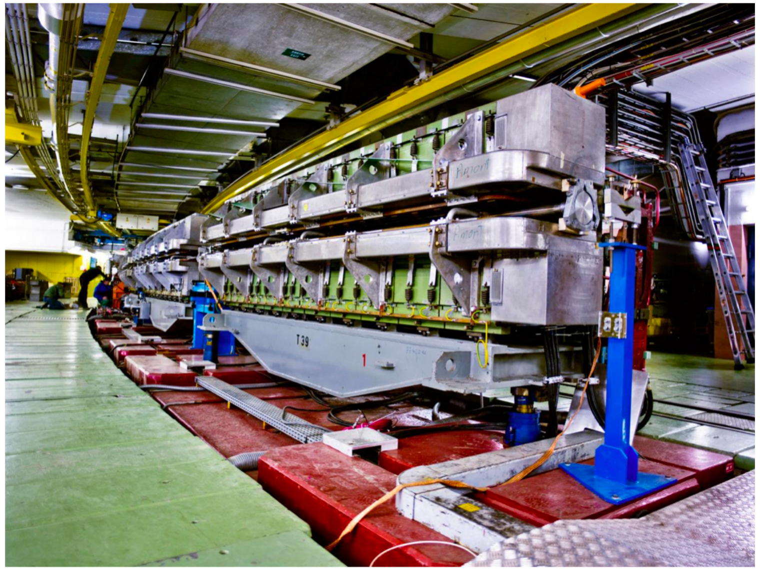


Proton Synchrotron Booster (50MeV to 1.4 GeV)

Low Energy Ion Ring



Proton Synchrotron (1.4 GeV to 25 GeV), 628m

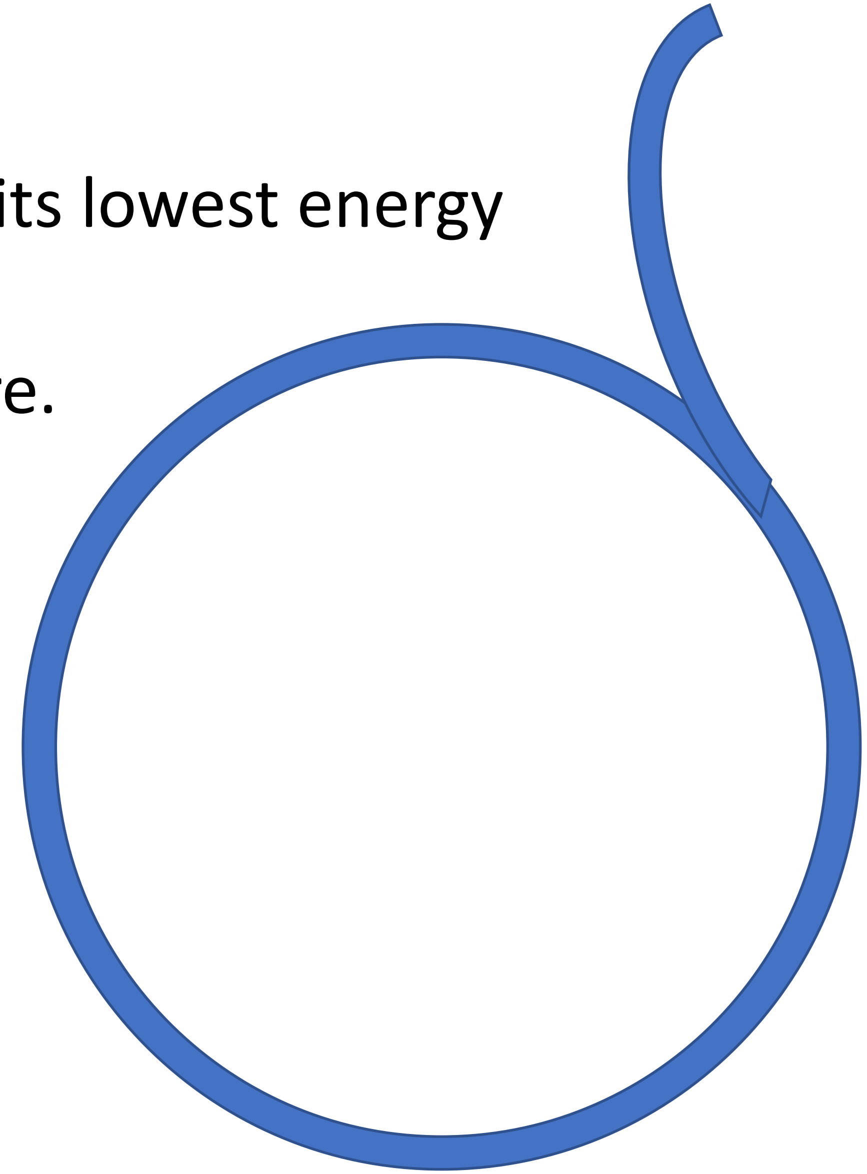


Super Proton Synchrotron (25 GeV to 450 GeV), 7 km

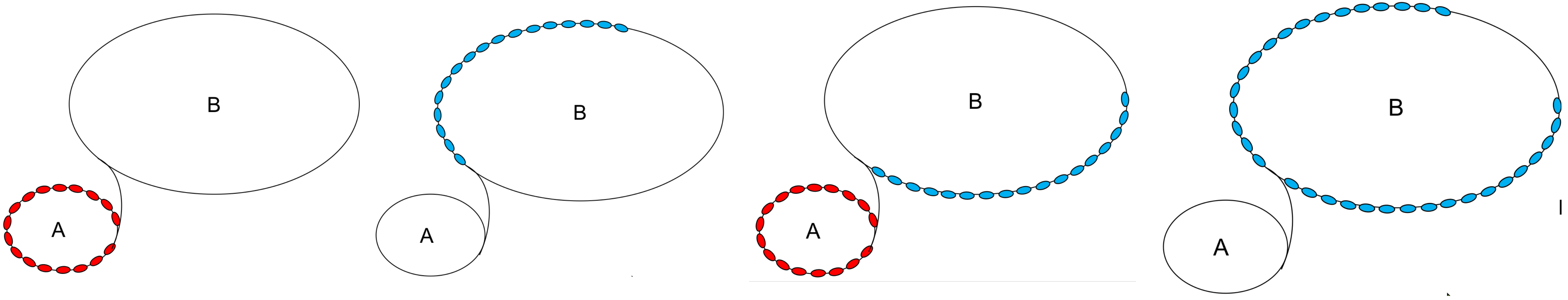
Injection

Simple goals

- Simple Goal: “Put beam in to synchrotron at its lowest energy (injection energy).”
- To the zero’s order, it looks like the right figure.
- More requirements:
  - Need to inject h particles, h>>1
  - The i^{th} injected bunch not affect 1…i-1 bunches
  - Need time-depend kicks

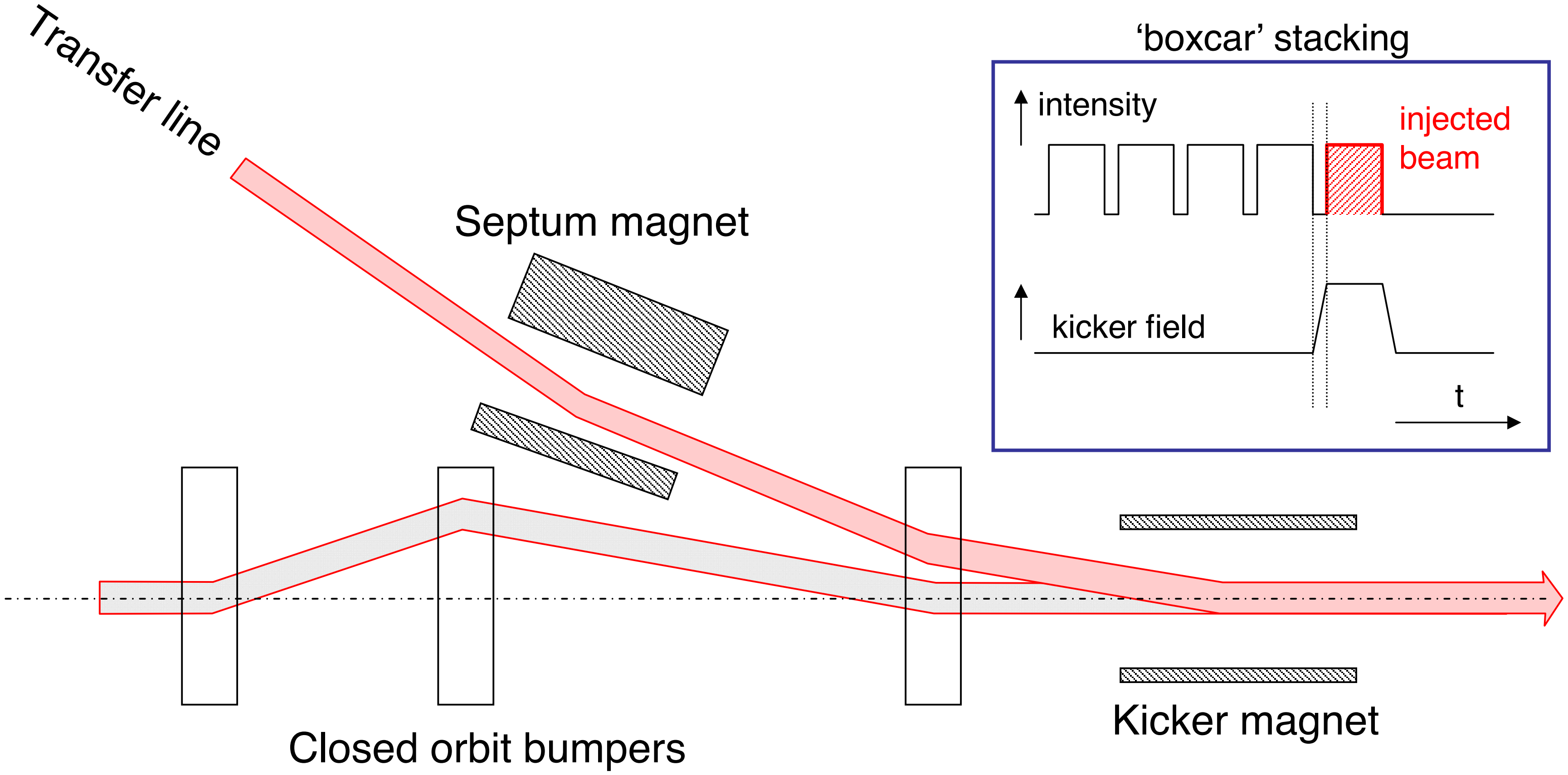


Bunch Filling



One-turn injection

- The simplest scheme:



Real layouts

RHIC

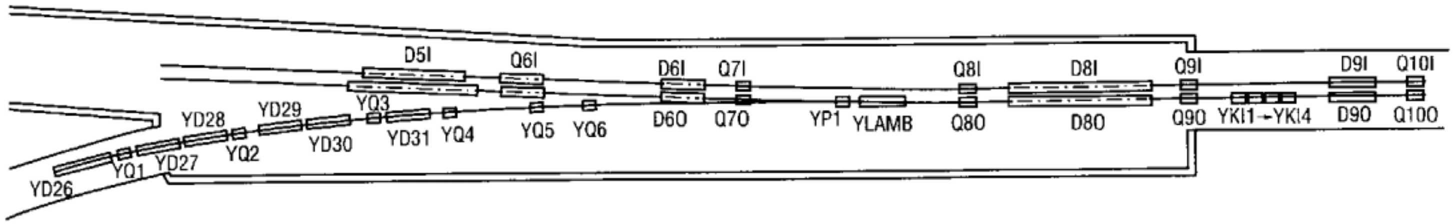
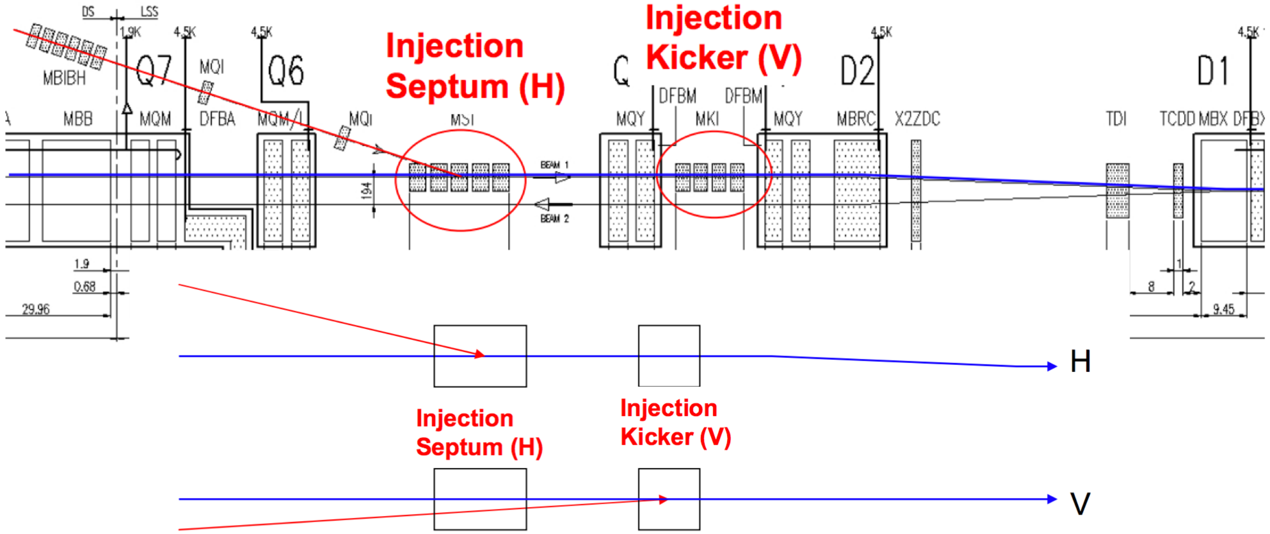


Fig. 5-2. Six o'clock insertion with location of yellow ring injection equipment.

LHC



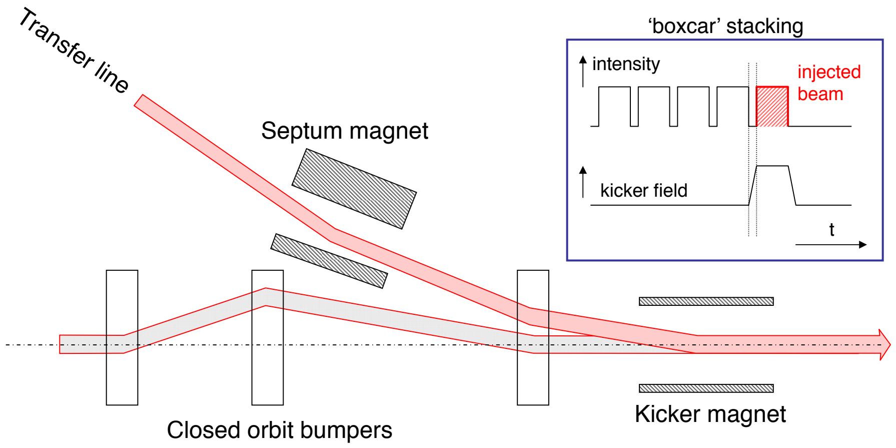
Transfer Matrix

If we know the twiss parameter of both end and phase advance in between

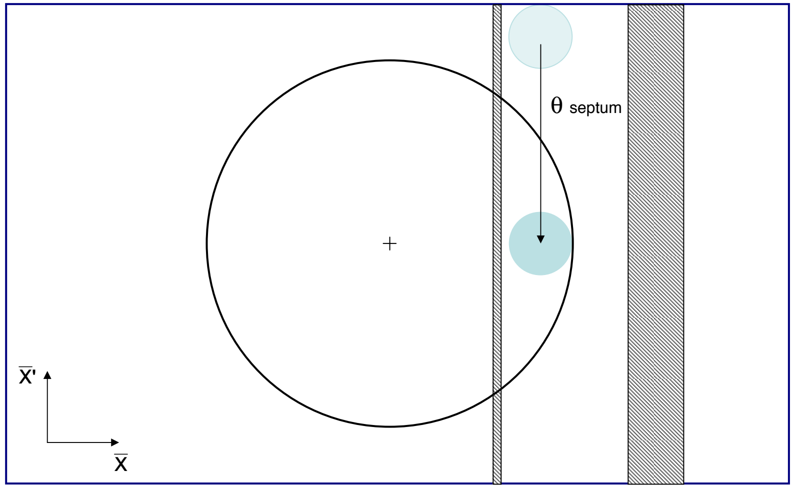
$$M\left(s_1 \mid s_0\right) = \begin{pmatrix} \sqrt{\frac{\beta_1}{\beta_0}}\left(\cos\psi + \alpha_0 \sin\psi\right) & \sqrt{\beta_0\beta_1}\sin\psi \\ -\frac{1+\alpha_0\alpha_1}{\sqrt{\beta_0\beta_1}}\sin\psi + \frac{\alpha_0-\alpha_1}{\sqrt{\beta_0\beta_1}}\cos\psi & \sqrt{\frac{\beta_0}{\beta_1}}\left(\cos\psi - \alpha_1\sin\psi\right) \end{pmatrix}$$

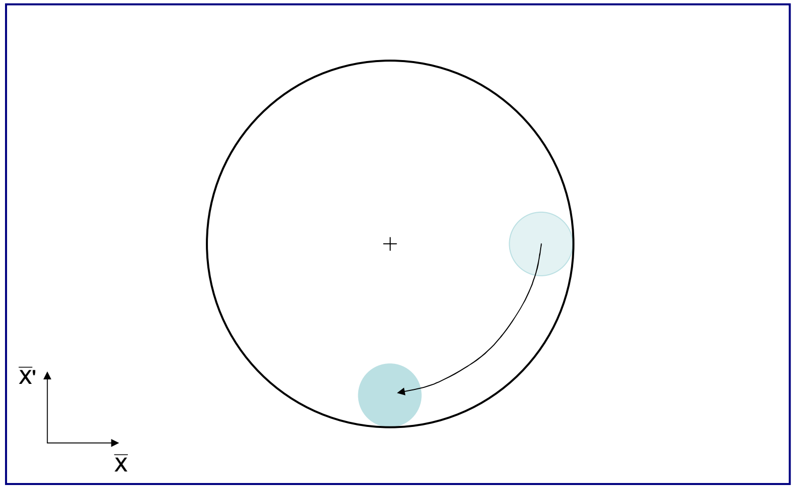
S_1 represents the kicker.

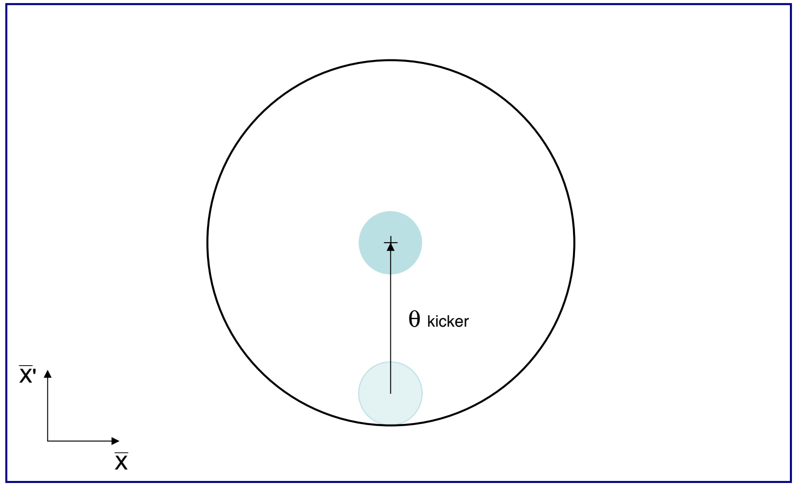
S_0 represents the septum.



What happened in phase space





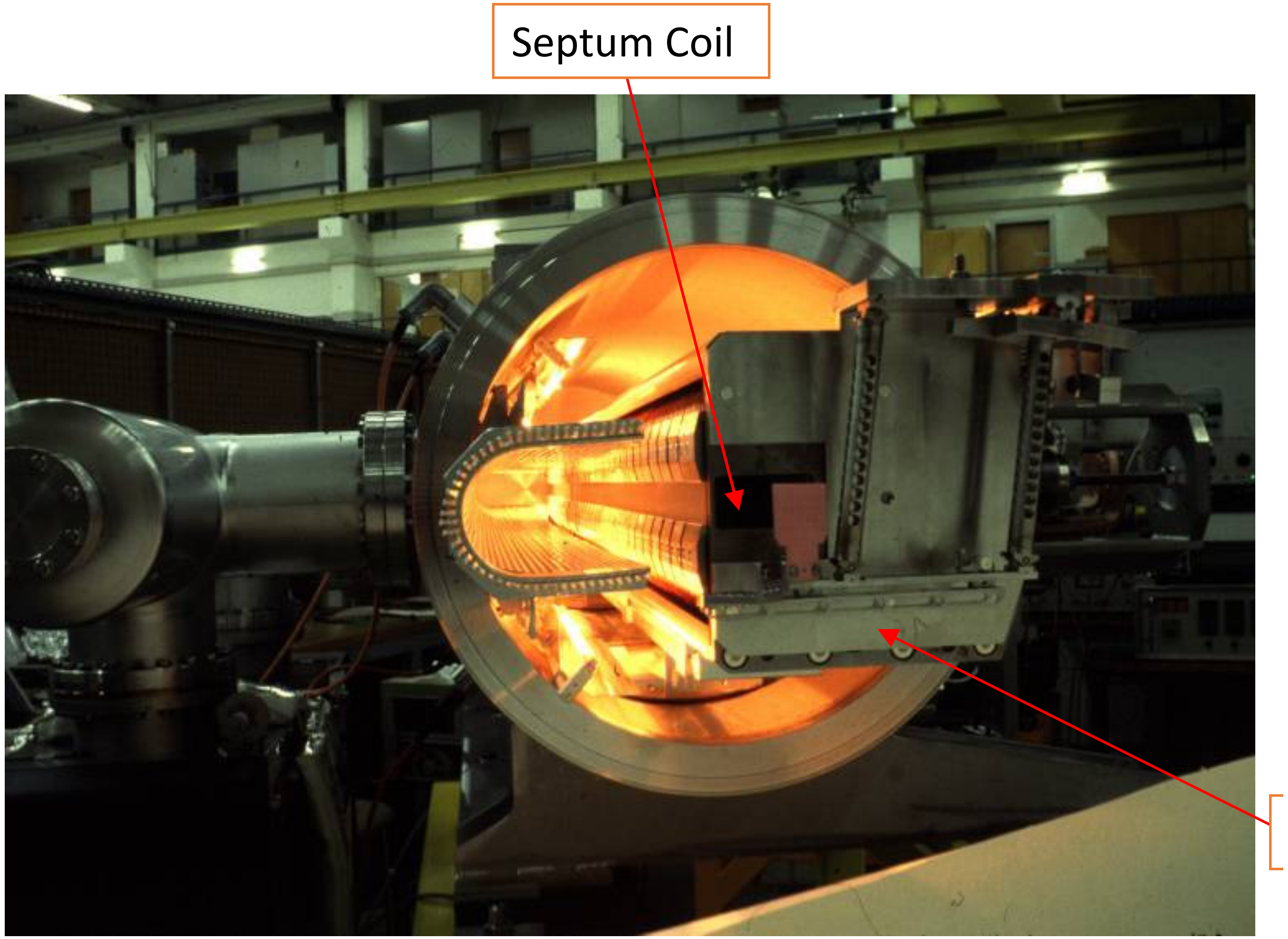


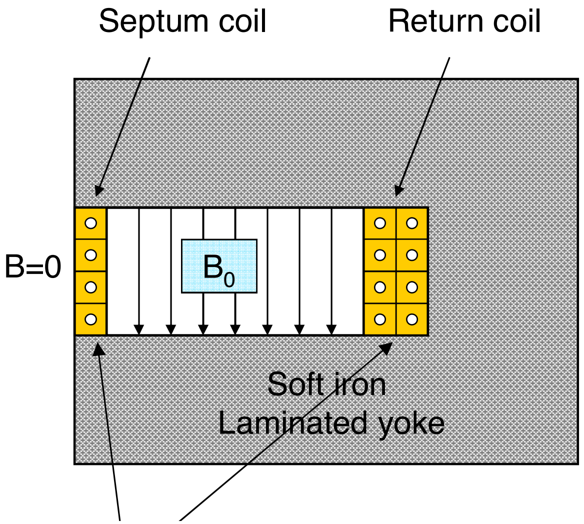
The injected bunch experience three necessary steps in phase space, which put the bunch exactly same location in phase space, as other circulating bunches.

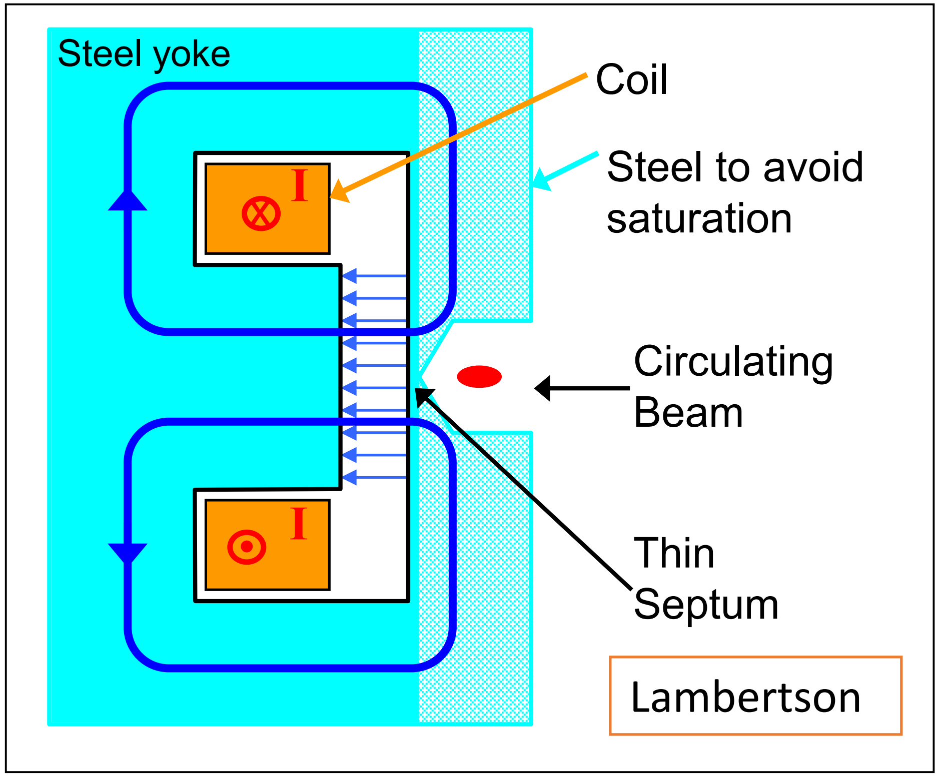
The circulating bunch does not experience this due to

- Spatial separation at septum magnet
- Time separation at injection kicker.

Septum

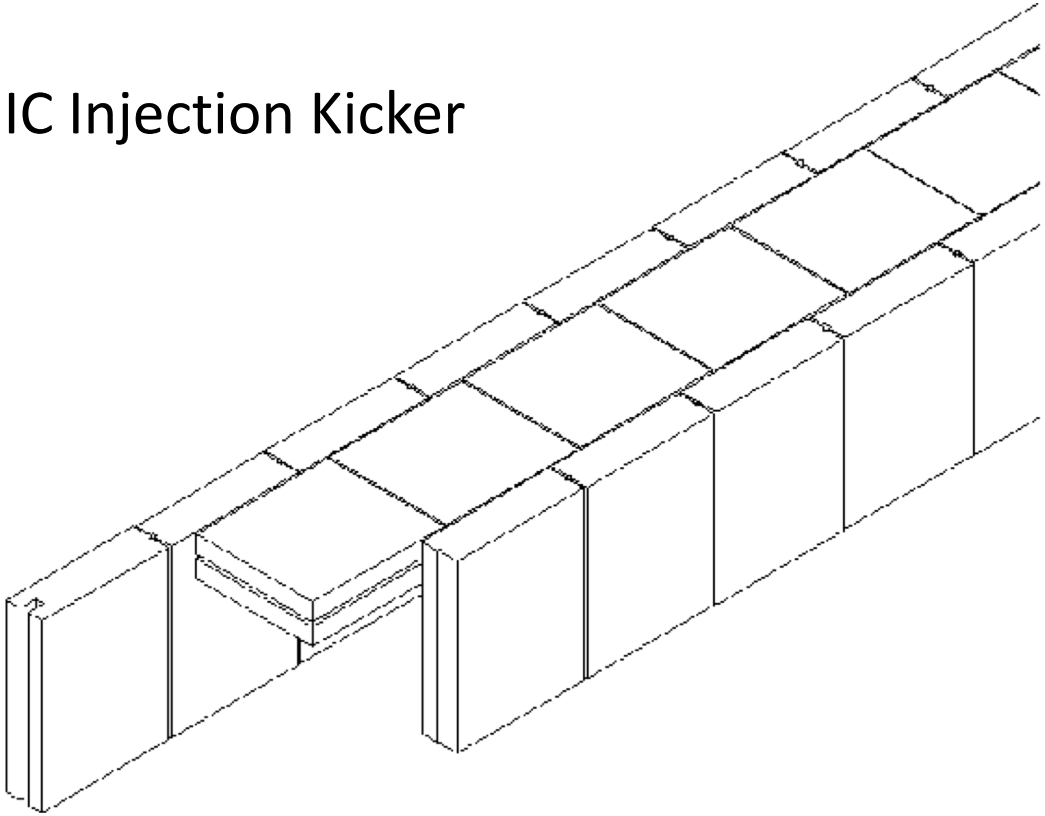

Septum Coil

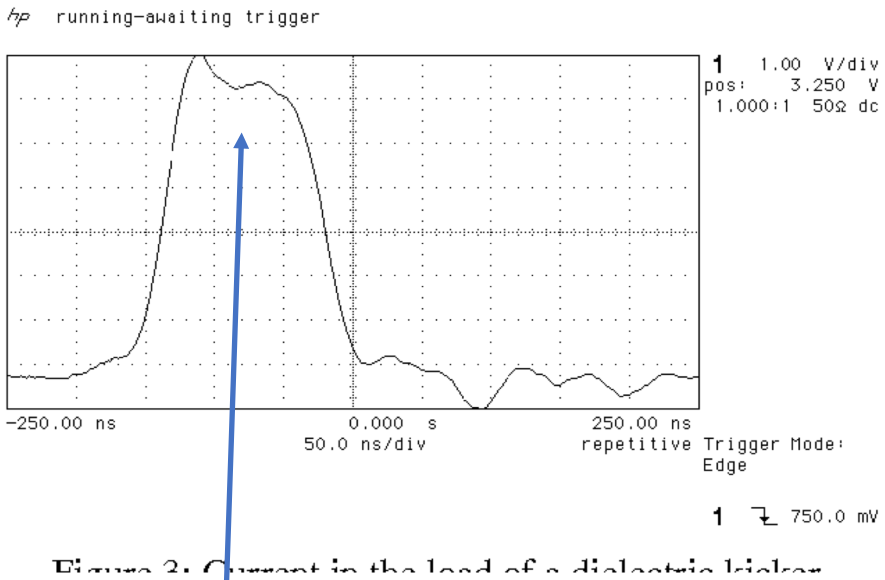

Septum coil
Return coil
B=0
B_0
Soft iron
Laminated yoke


Steel yoke
Coil
Steel to avoid saturation
I
I
Circulating Beam
Thin Septum
Lambertson

Injection Kicker

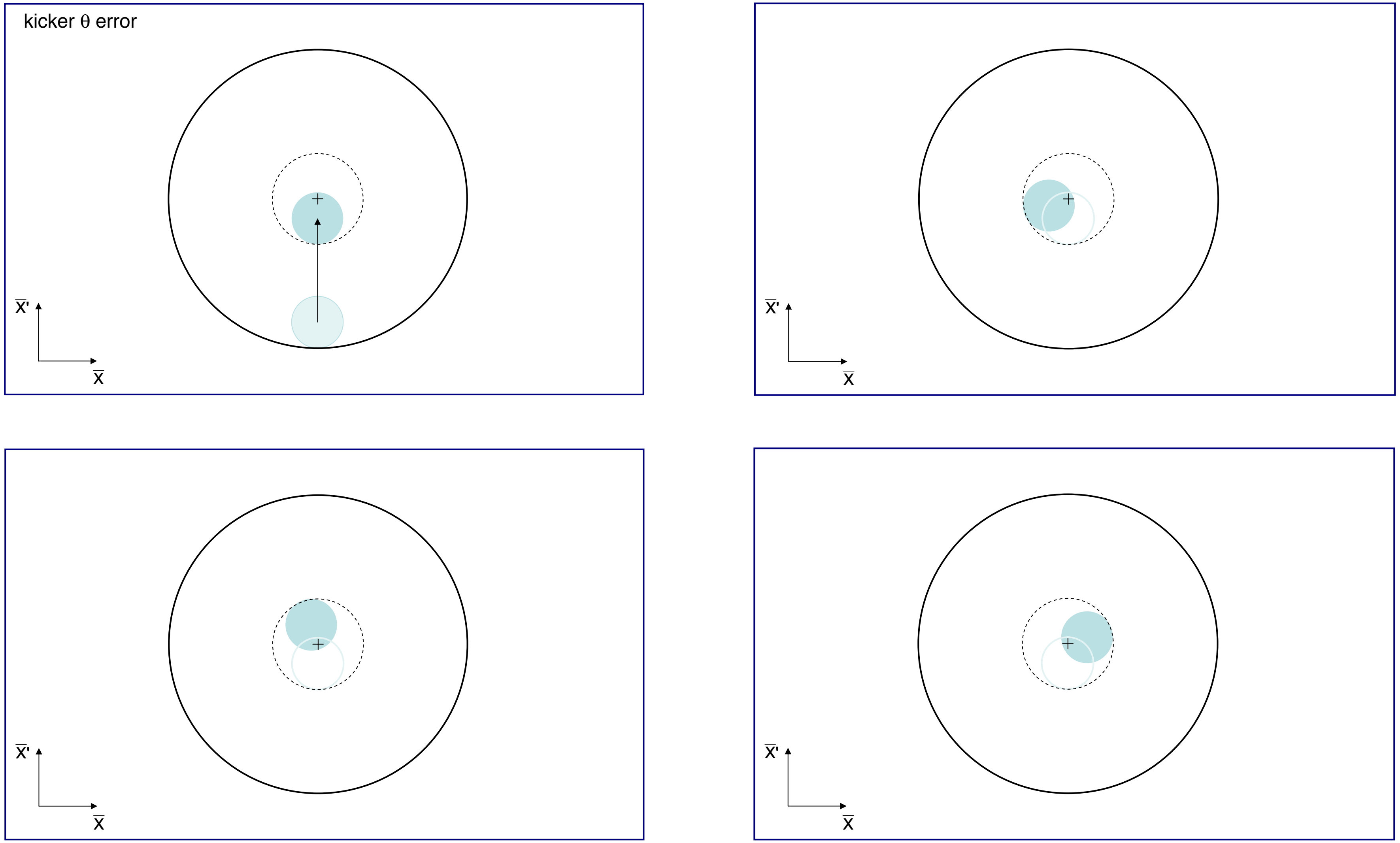
RHIC Injection Kicker



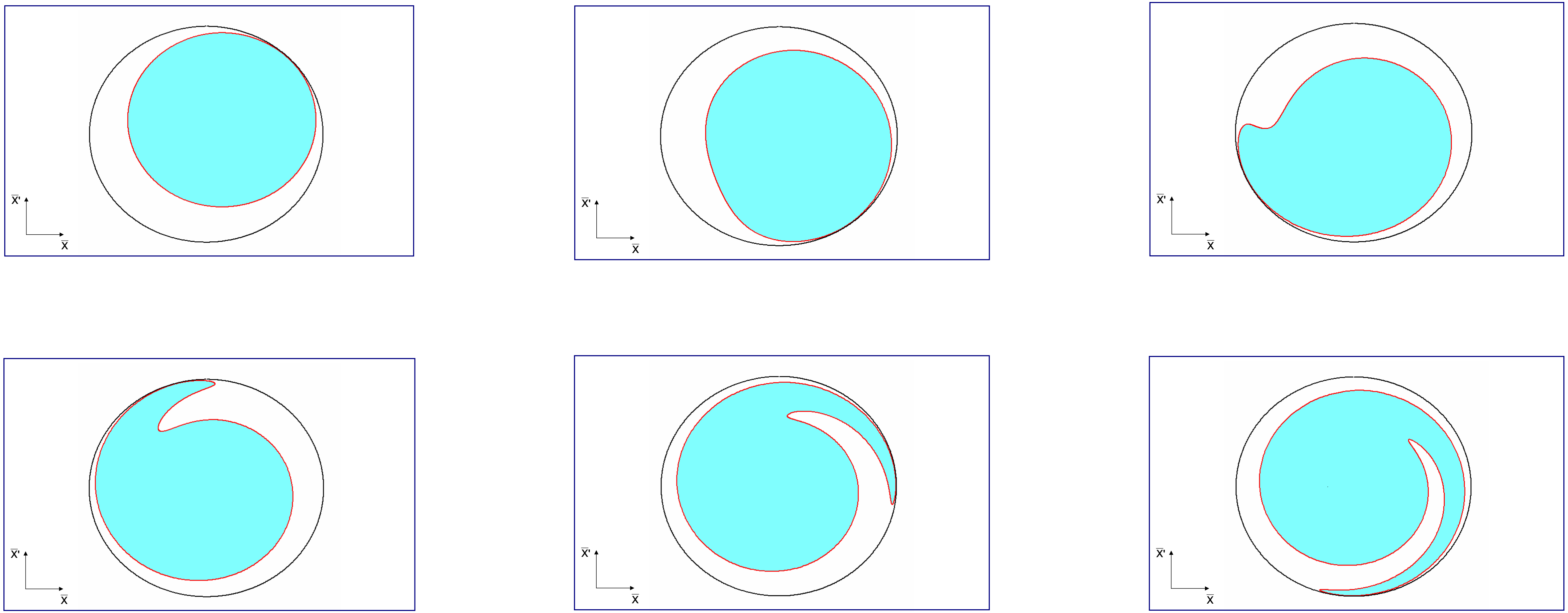


Time for injecting the bunch

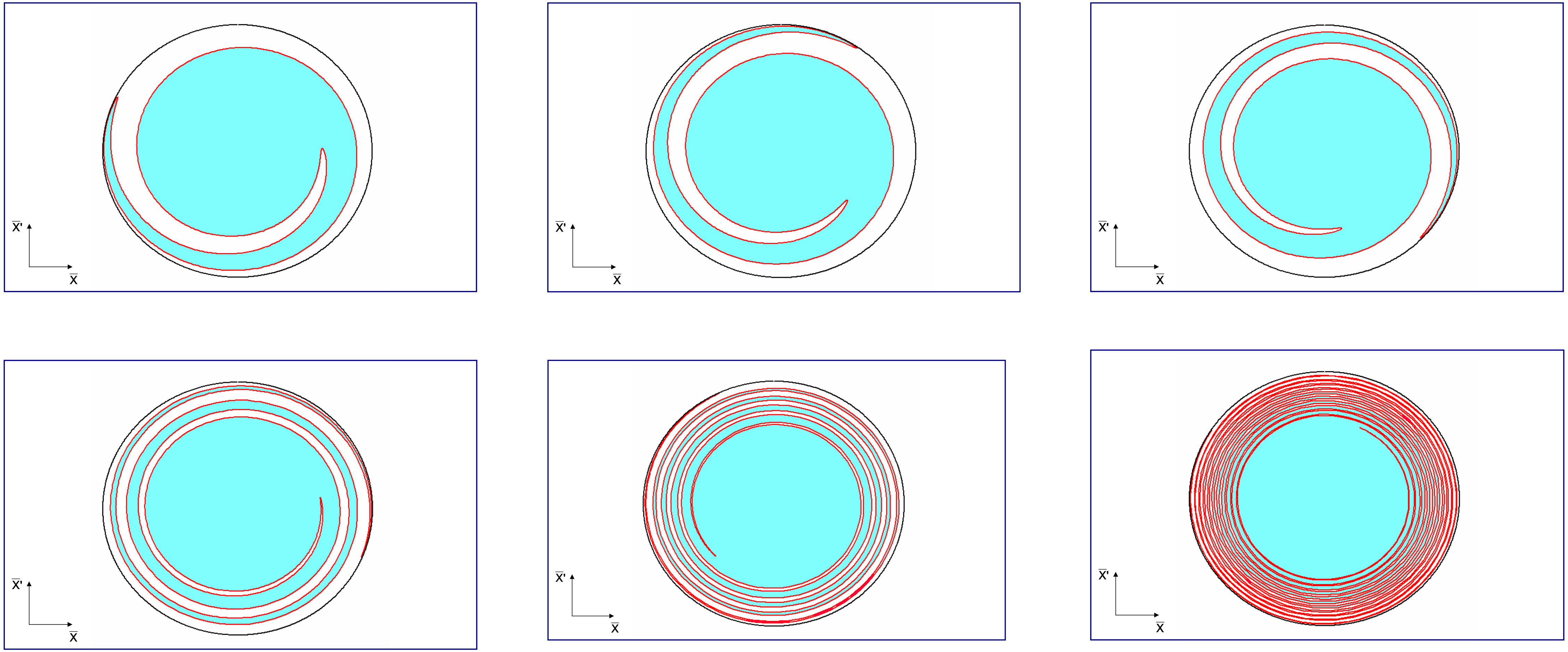
Injection Errors, Oscillations



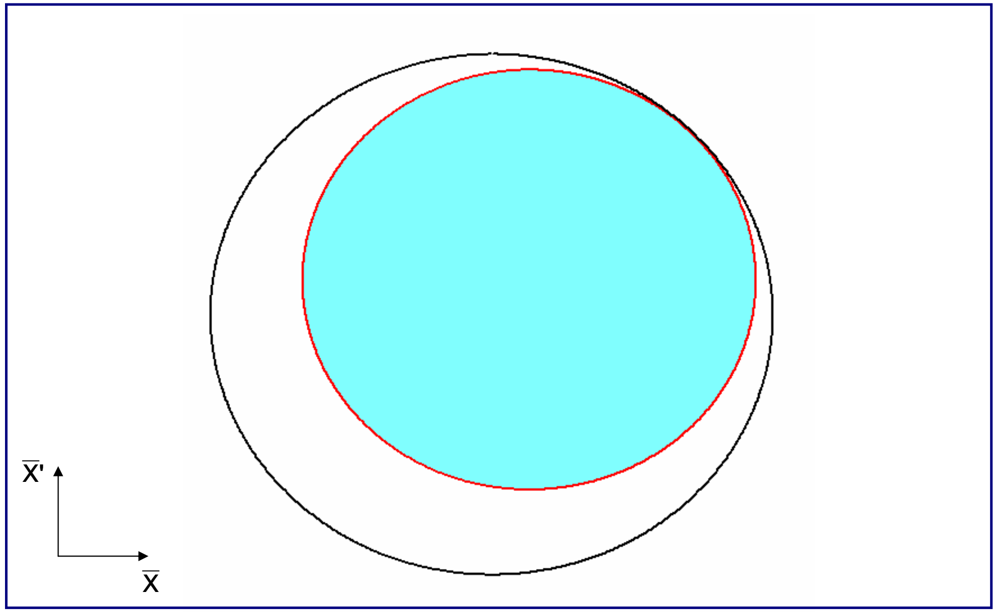
Injection Error, Filamentation

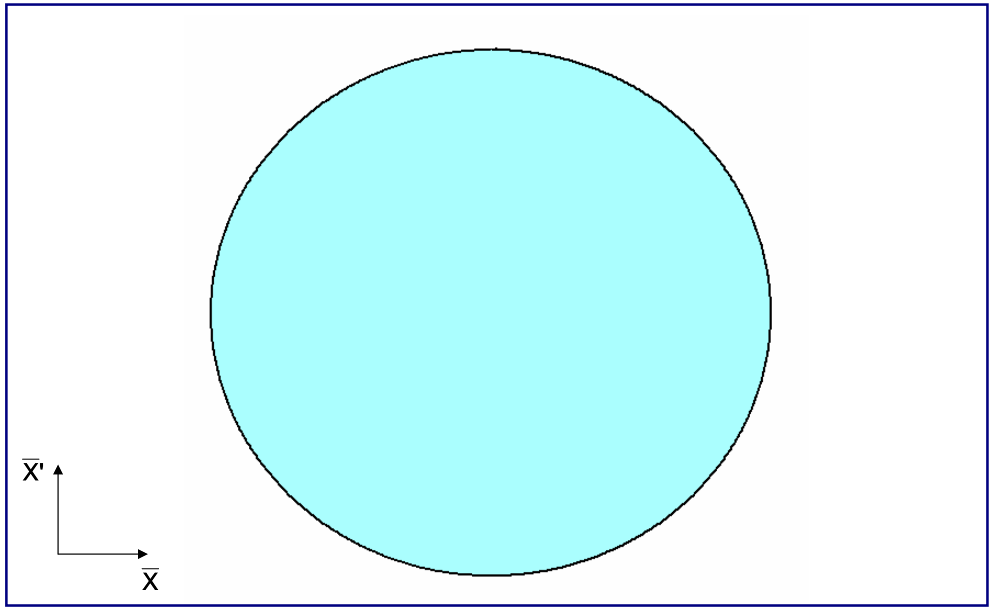


Injection Error, Filamentation

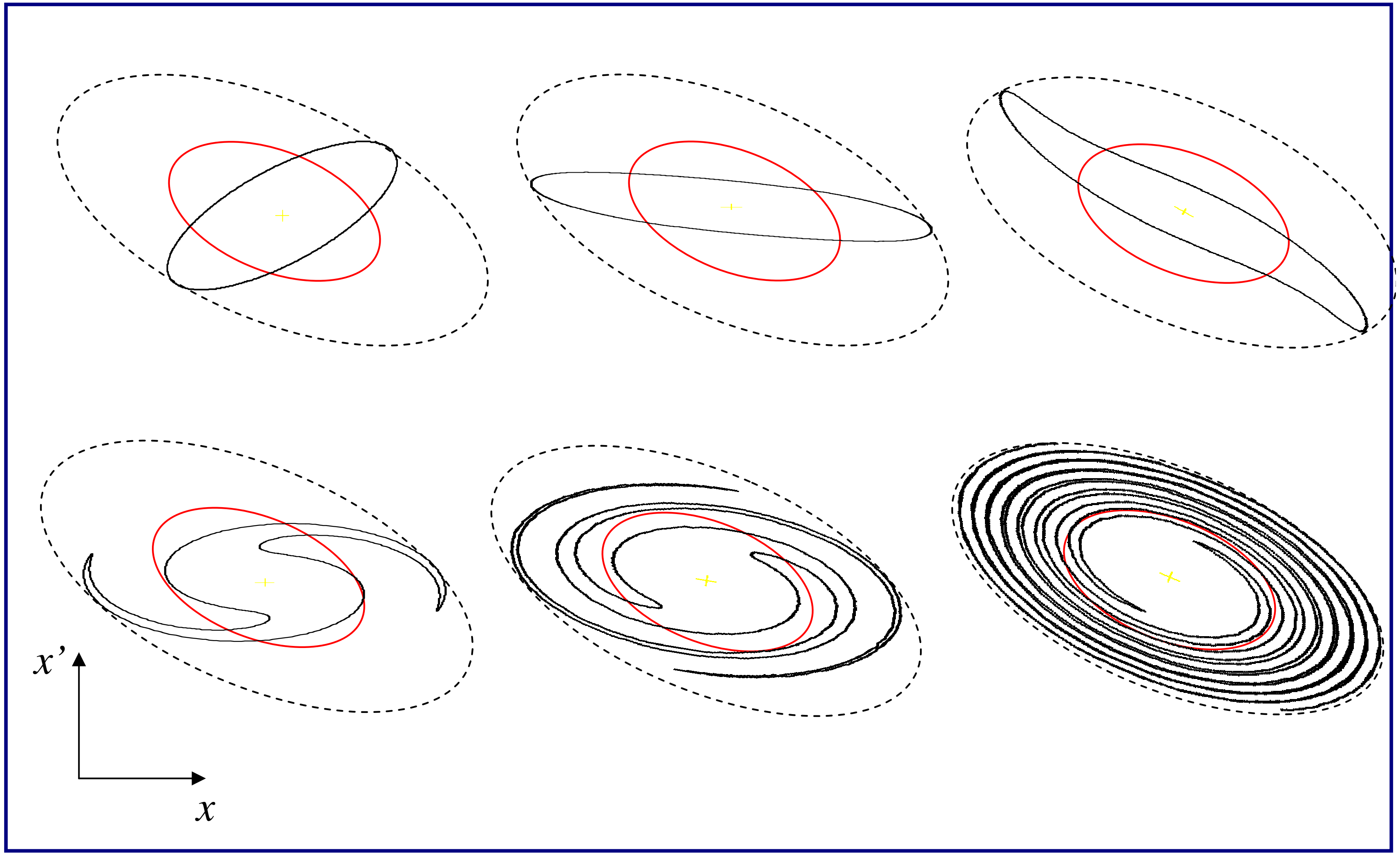


Injection Error, Filamentation





Injection Error, Mismatch



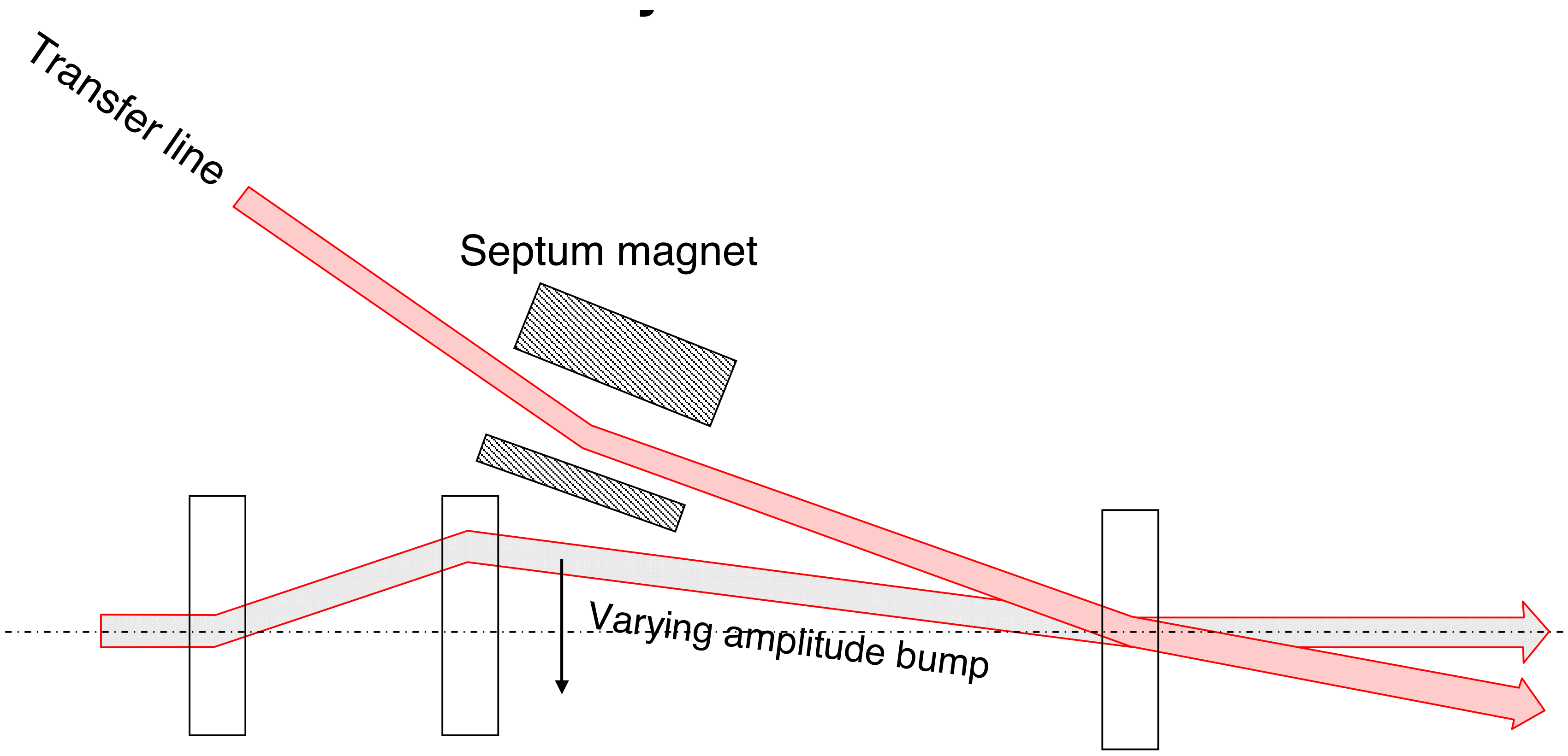
Emittance Blowup

- Both Injection angle/position error and mismatch cause emittance blowup
- The Blowup is due to filamentation
- Filamentation is due to the frequency spread of the particles
  - Nonlinearity
  - Chromatic effect
- Have to correct both the injection orbit and optical mismatch to avoid emittance growth.

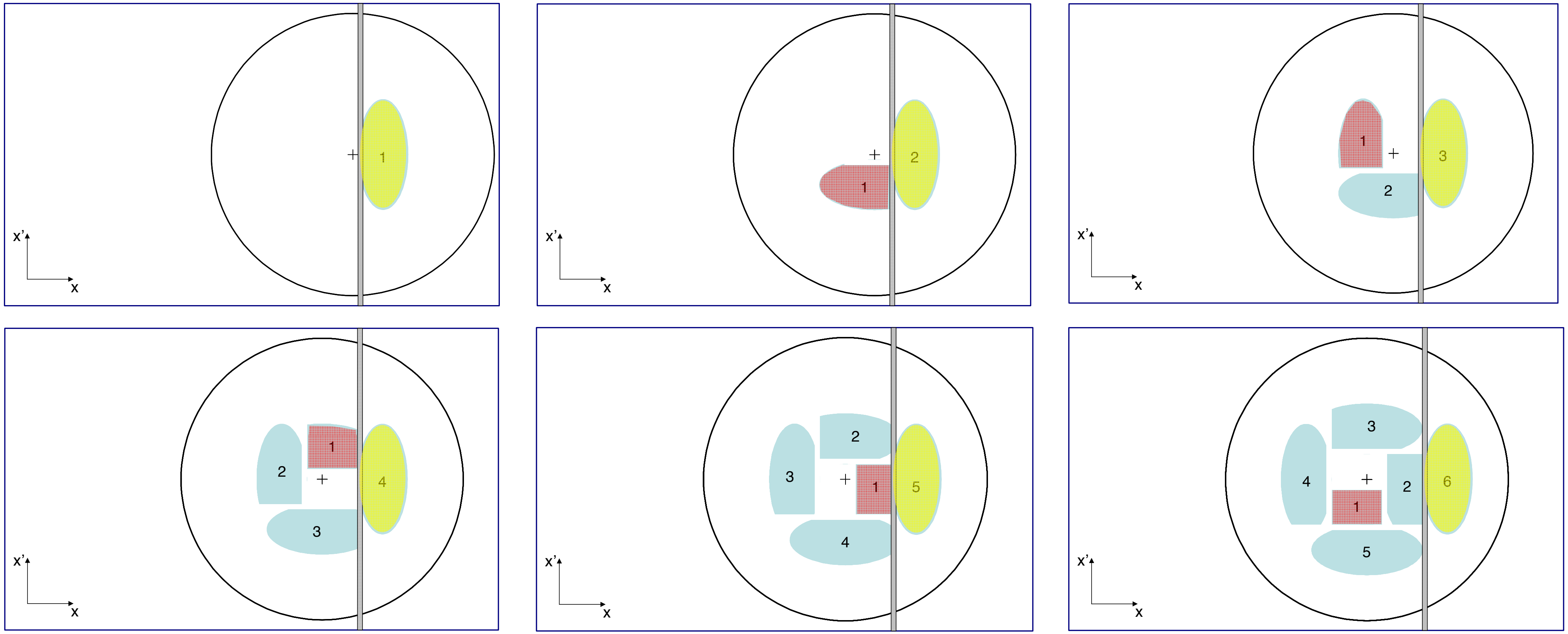
Multi-turn injection

- Some times it is impossible to have high intensity one-turn injection
  - Limited by the intensity of previous accelerator or source
  - Limited from space charge effect
- Solution: Multi-turn injection
- Instead of one kicker, we need several fast dipole to create ‘bump’
- These fast dipole create varying bump strength throughout the injection process
- Well controlled transverse tune.
- This is the process of ‘Painting in transverse phase space’

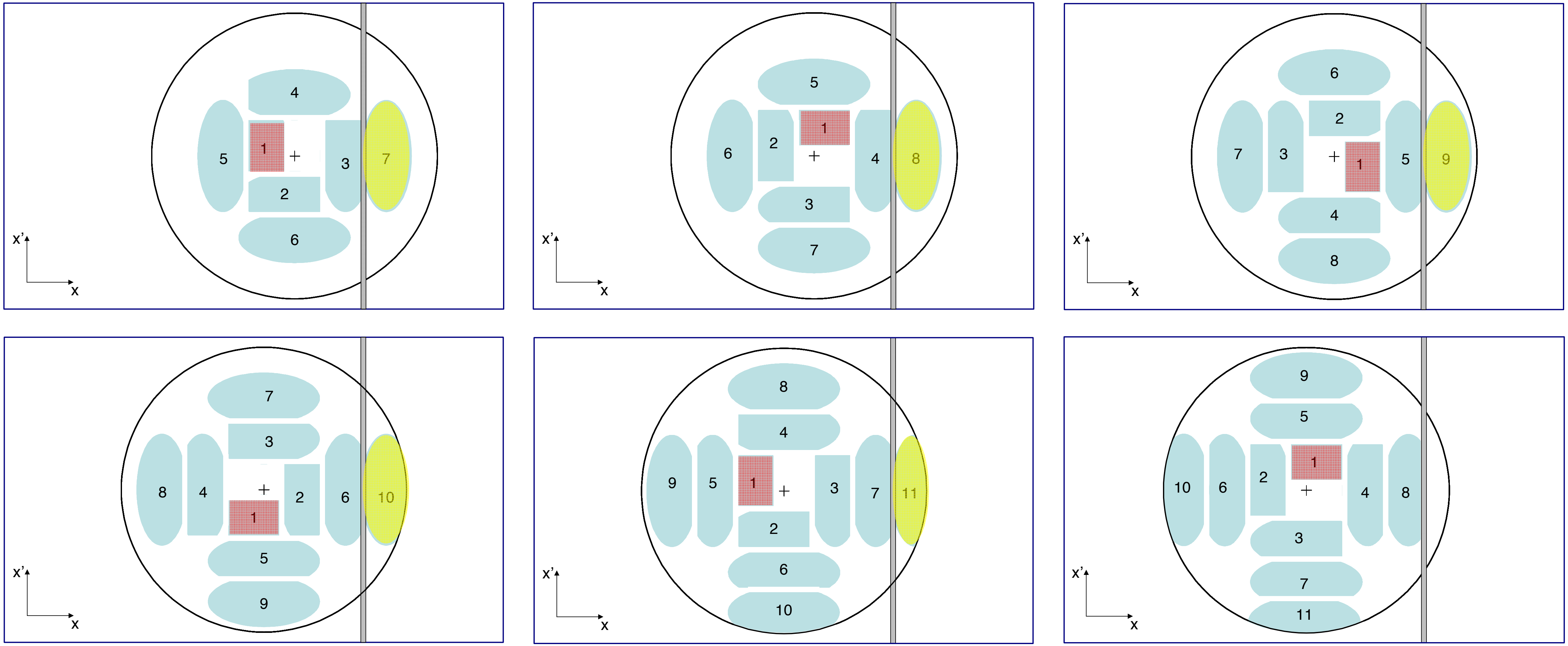
Multi-Turn Idea



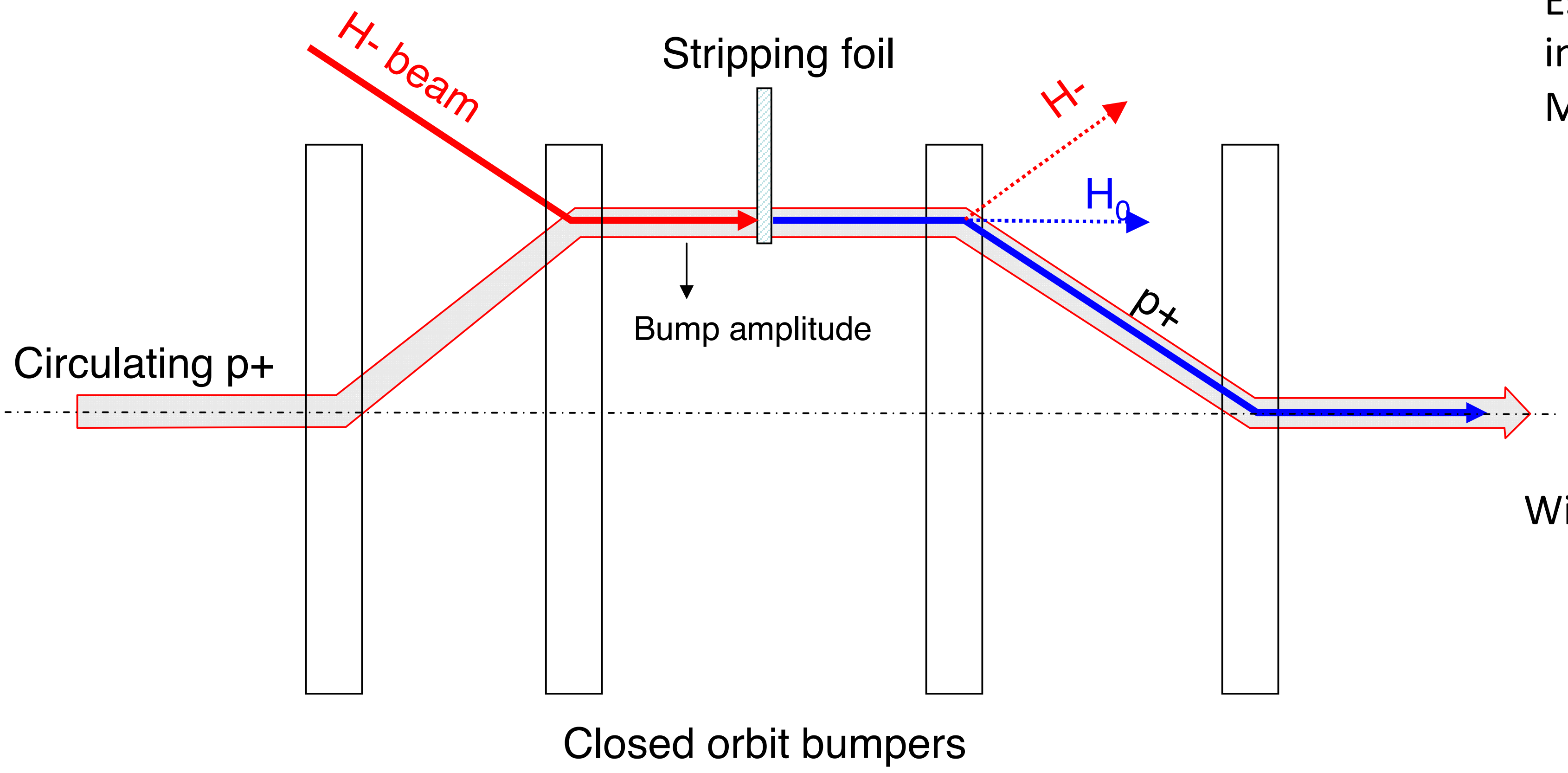
Multi-turn Injection



Multi-turn Injection



Charge exchange H- Injection



Essential for low loss injection for high intensity beam.
May achieve ~0.02%

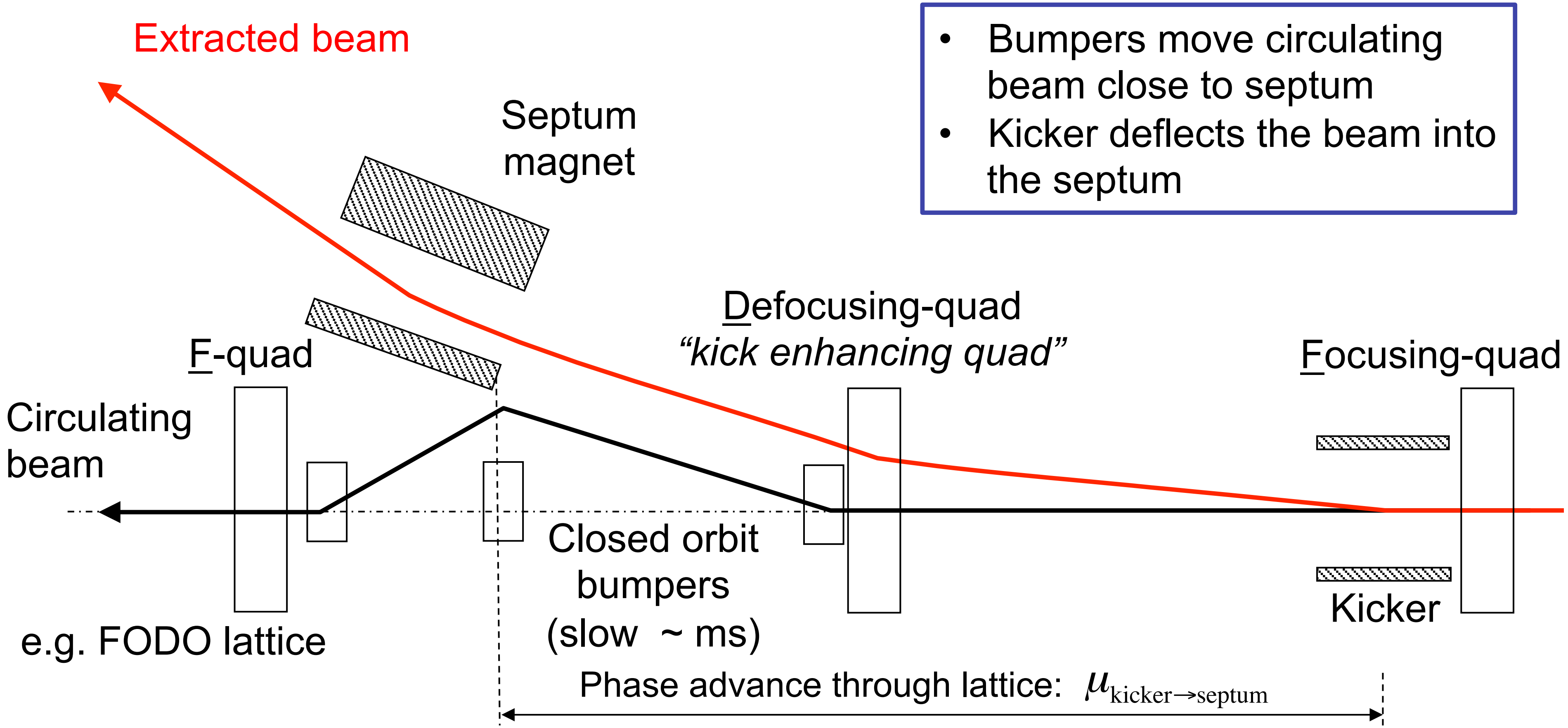
Without CEI, the best loss is 10%.

Extraction

Schemes

- Treat extraction as reverse procedure of Injection (fast)
  - Single turn extraction
  - Multi-turn extraction (No resonance)
- We can play more tricks with using nonlinear resonance
  - Nonlinear resonance slow extraction
  - Nonlinear low-loss extraction

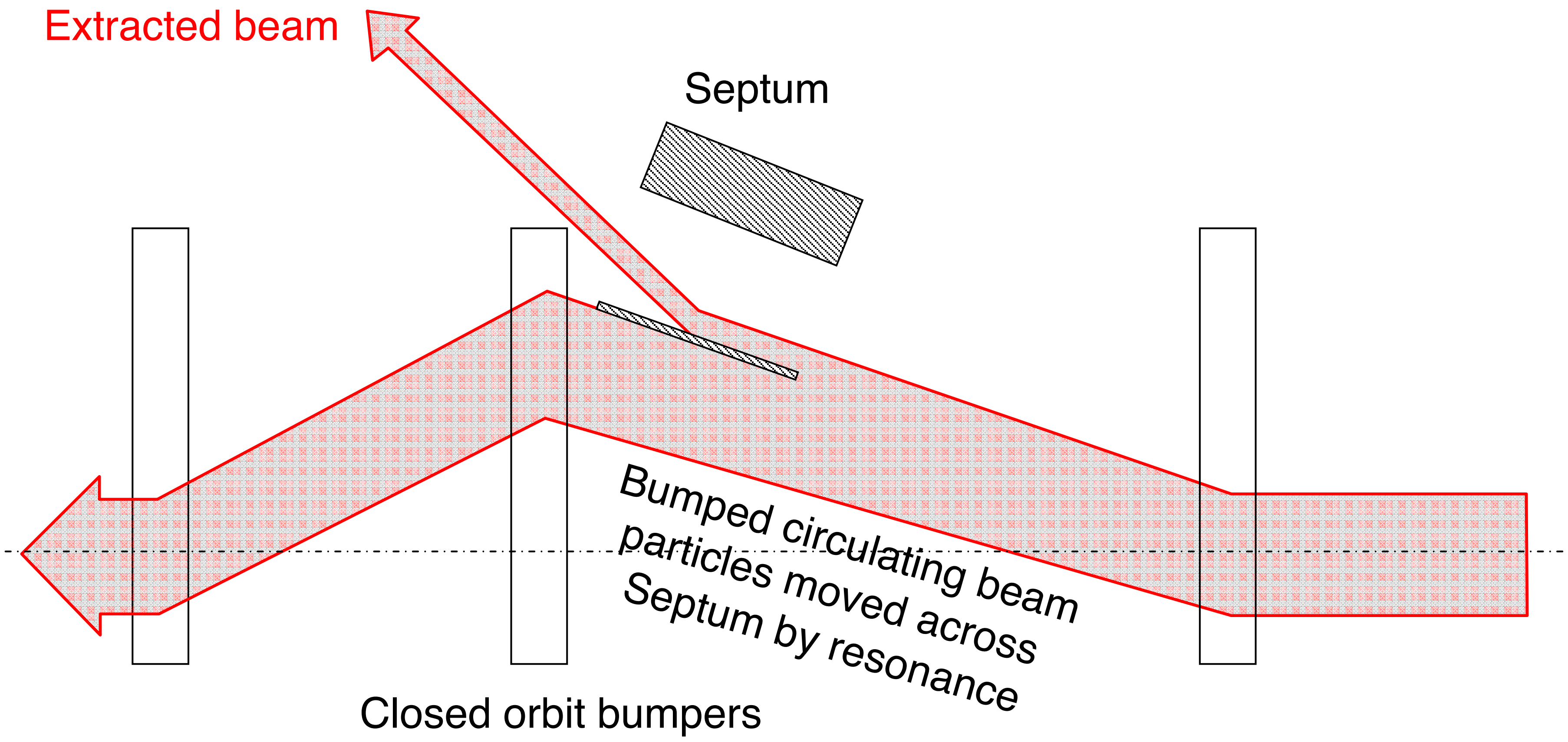
Single Turn Extraction



- Bumpers move circulating beam close to septum
- Kicker deflects the beam into the septum

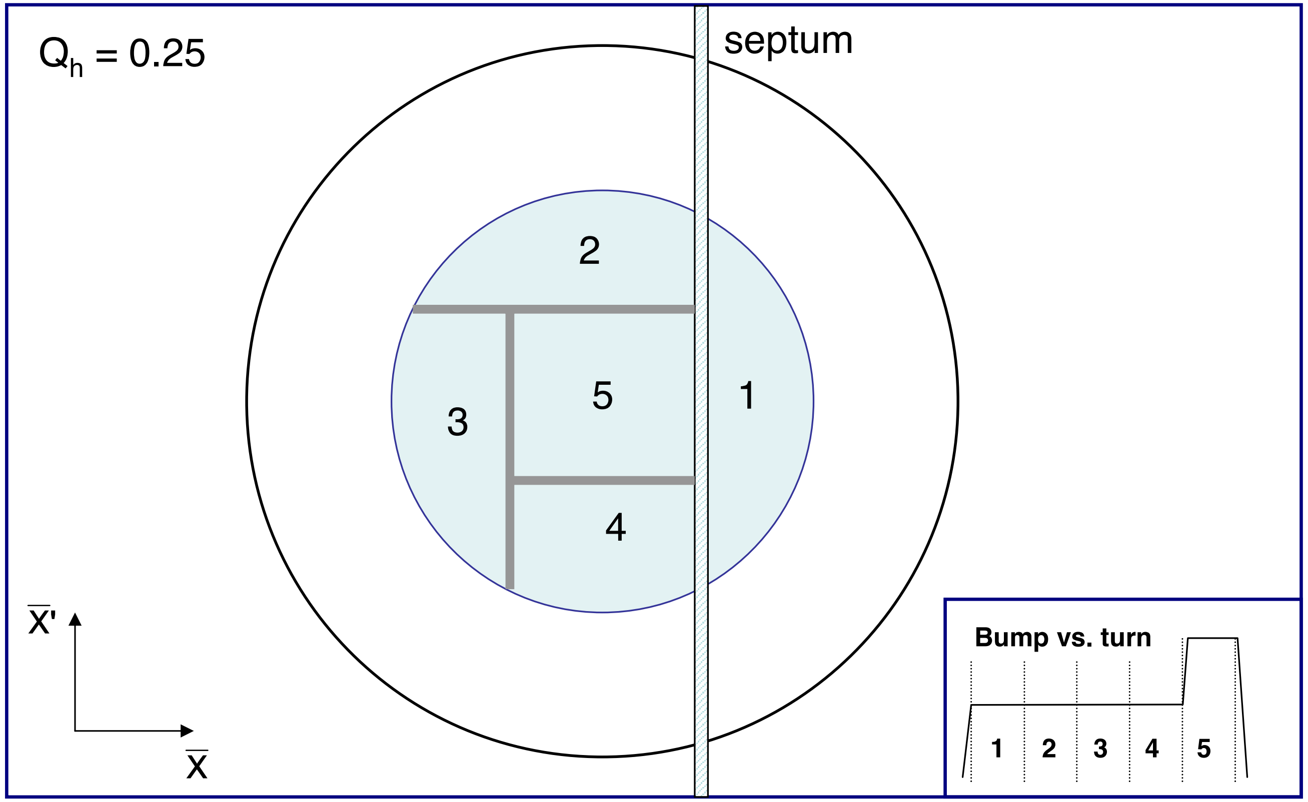
@ Matthew Fraser, CERN ACC. School, 2017

Multi-Turn extraction (Non-resonance)



Multi-Turn extraction (Non-resonance)

CERN PS to SPS: 5-turn continuous transfer

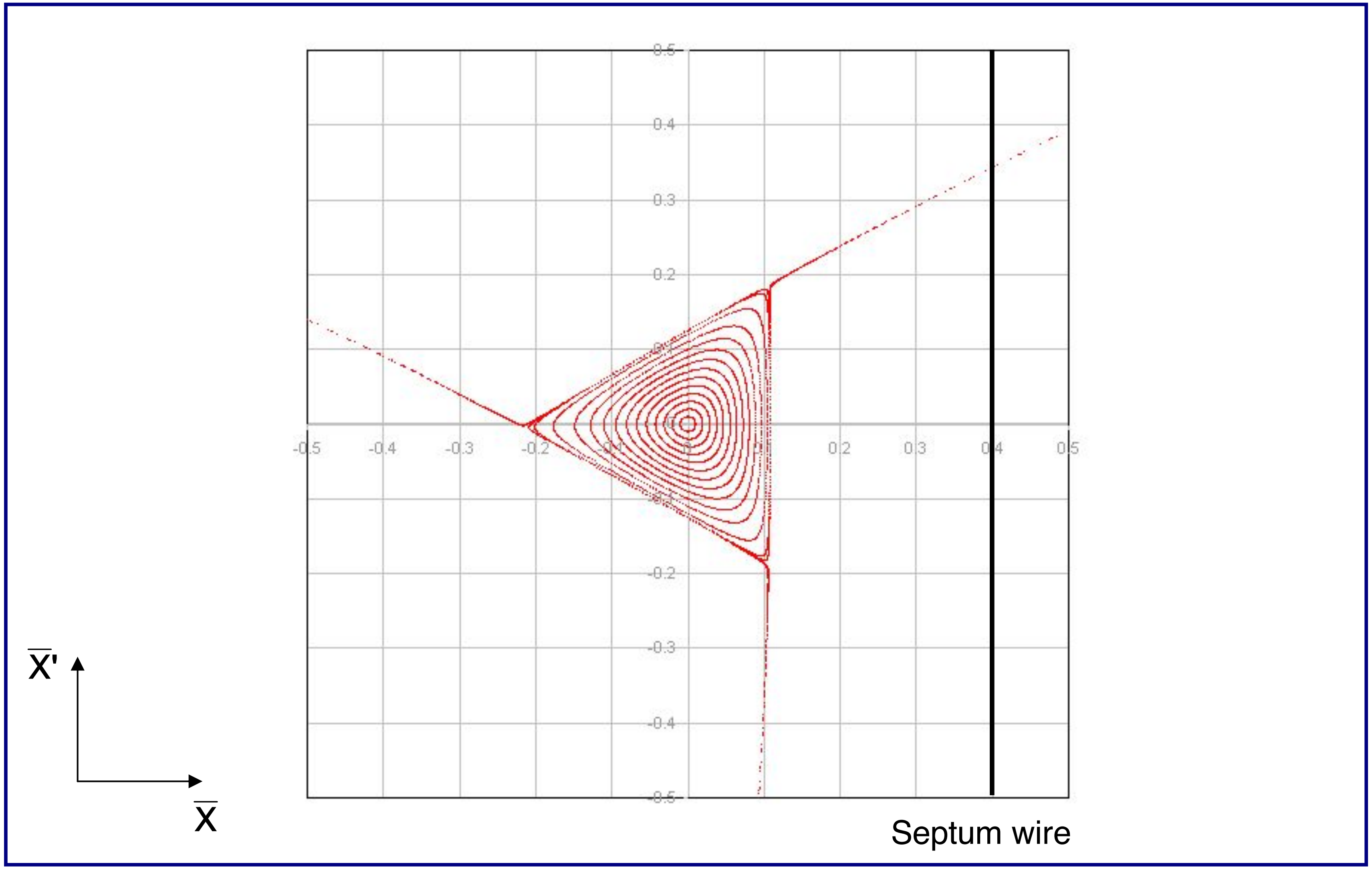


Multi-turn extraction (Non-resonance)

- This scheme will extract the beam within few turns.
- Beam loss is an issue.
- Septum need to be very thin.
- It is hard to have same intensity, emittance, centroid for every part of the beam.

- We can use nonlinear resonance to do a better job.

Resonance (slow) extraction



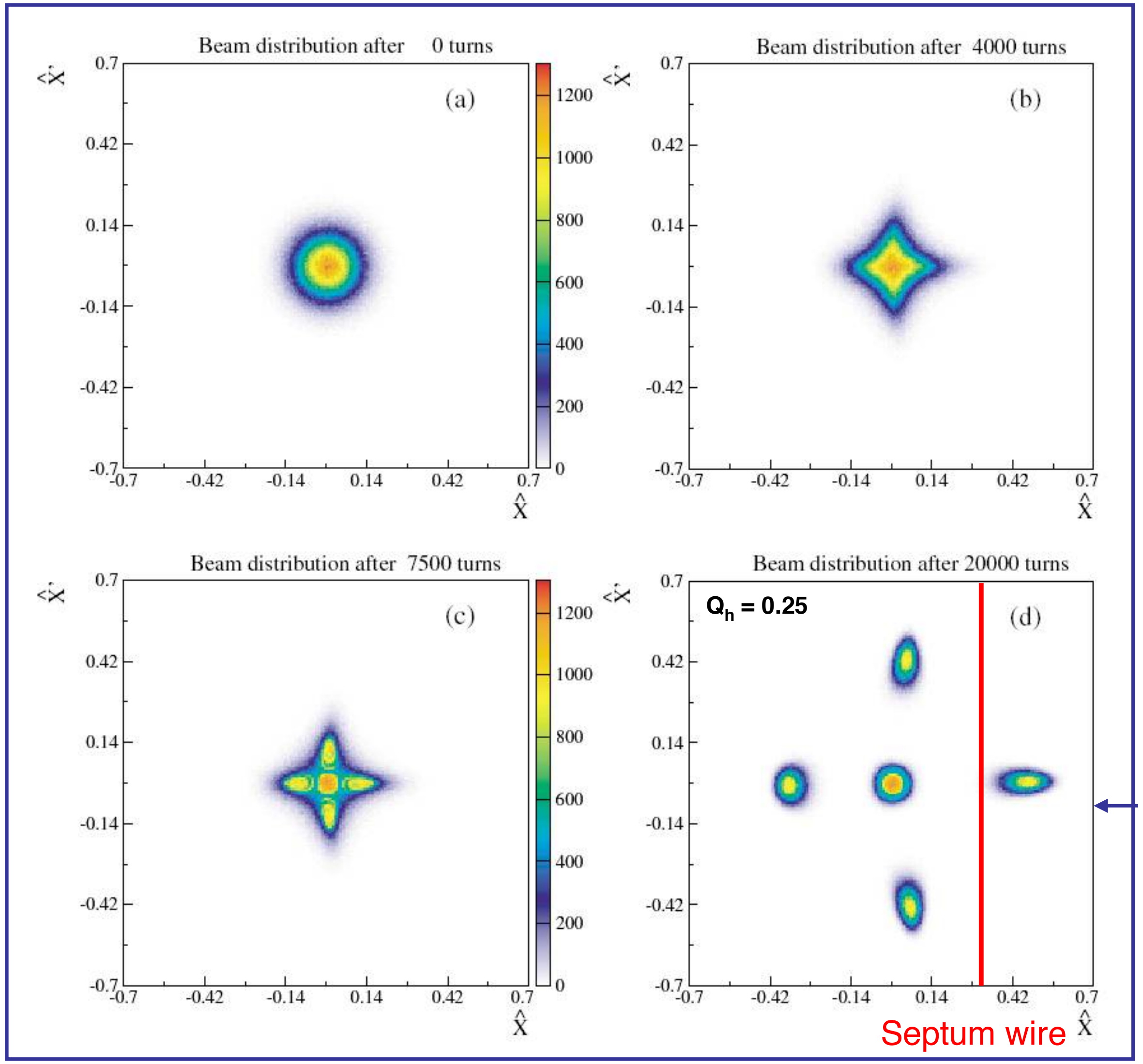
Very slow extraction ~1000 turns, perfect for low dose applications like medical applications

This example is third order resonance, when the tune is about 1/3 or 2/3

Still have loss at septum

Resonance Low Loss Extraction

- Use sextrupole and Octupole to control the nonlinear island.
- The beam is split into many, usually 4 equally populated island and then use septum wire to extract them.



More readings

- Injection and extraction material are largely borrowed from:
- http://cas.web.cern.ch/schools/erice-2017