CERN

Injection and extraction

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with material from past and current members of the ABT group

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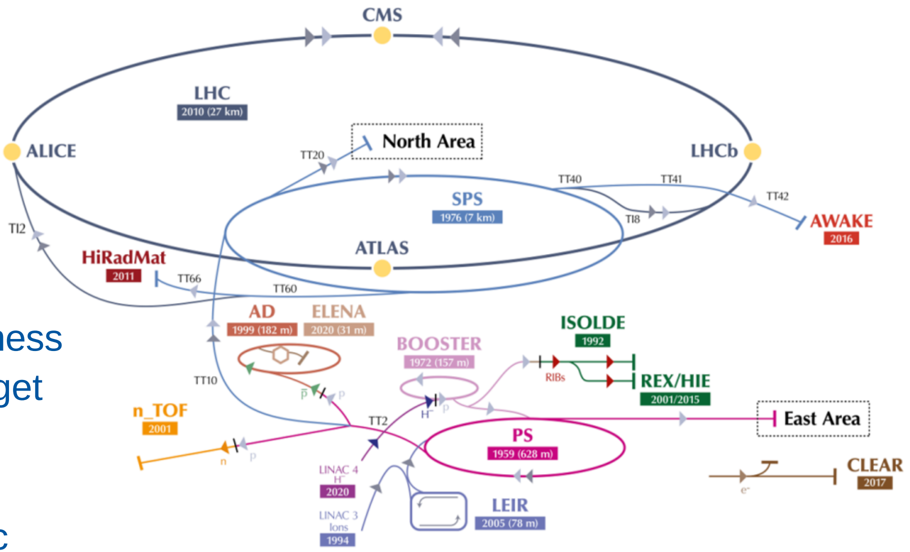
Layout

- Introduction
- Injection techniques
  - Fast injection
    - Errors, filamentation and blow-up
  - Multi-turn injection
  - Charge exchange technique
  - Lepton injection
- Extraction techniques
  - Fast extraction
  - Multi-turn extraction
  - Resonant extraction
- Conclusion

Introduction

- Accelerators have limited ranges of energies
  - A synchrotron have a typical range of energy of 20
    - LHC from 450GeV to 7000TeV for protons (x15)
    - SPS from 14GeV to 450GeV for protons (x30)
  - Particles get accelerated in a chain of accelerators
- Injection and extraction between stage needs careful consideration
  - to maintain the beams properties, in particular brightness
  - To deliver beams with required properties to fixed target experiments
- The limits of this lecture
  - No (synchro-)cyclotrons, rodhotron, FFA, electrostatic
  - Most principles discussed here are applicable to any type of accelerator
  - Focus synchrotrons, more specifically alternating gradient synchrotrons



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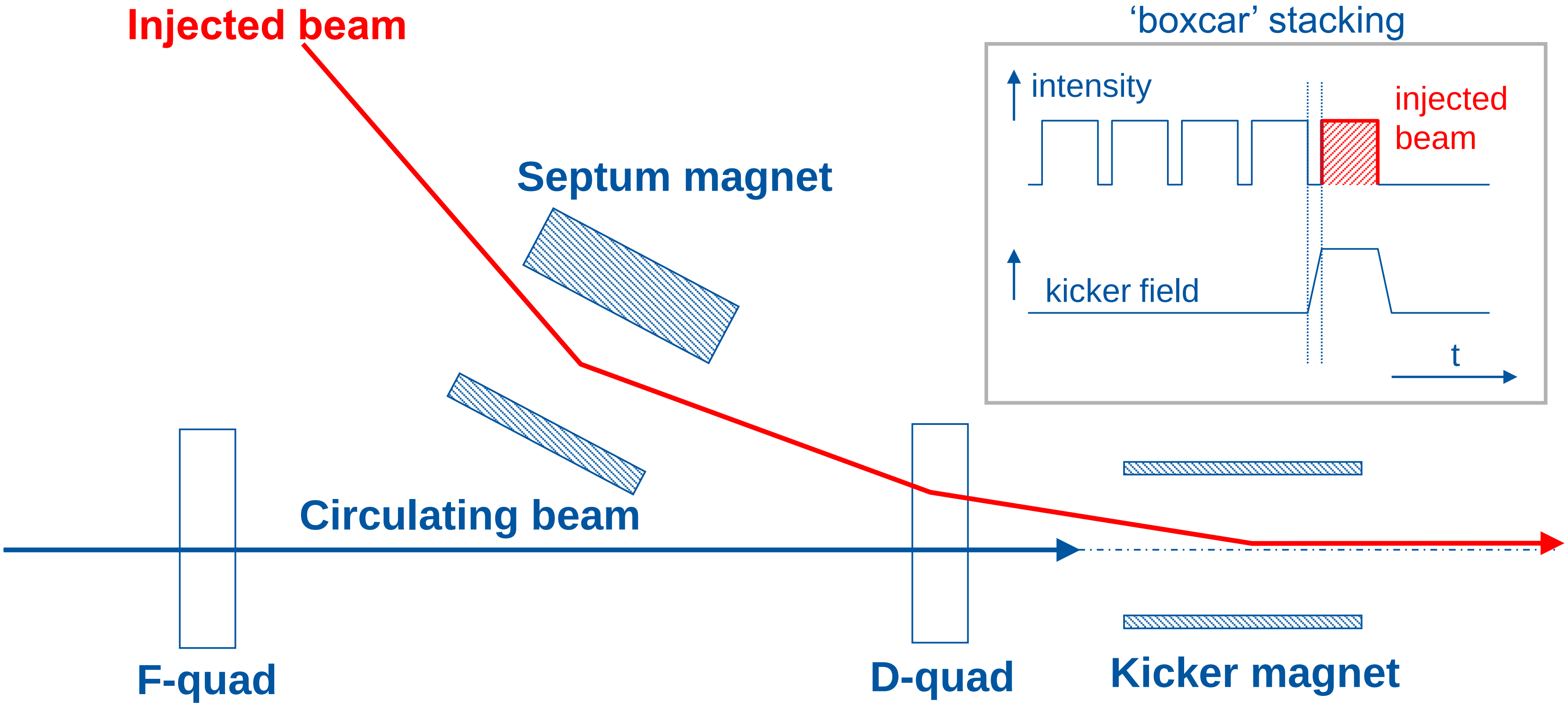
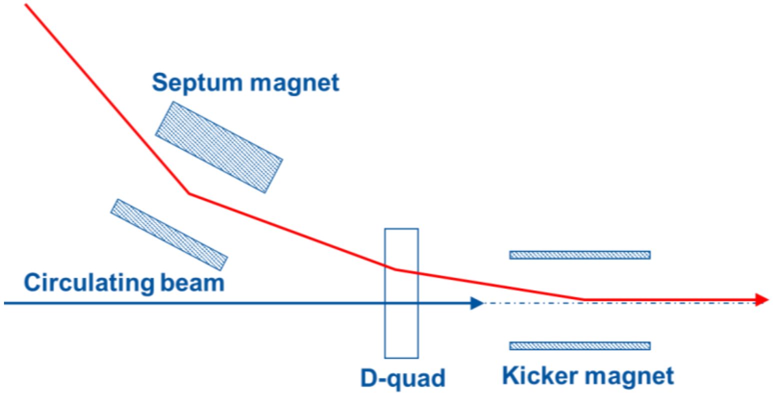
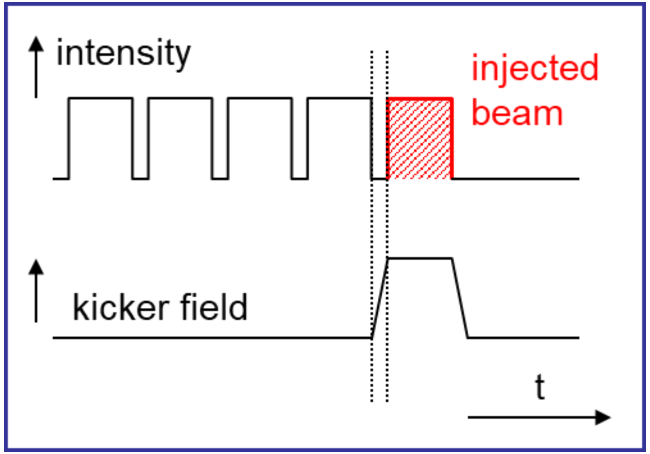
Injection techniques : Fast injection



Injection techniques : Fast injection

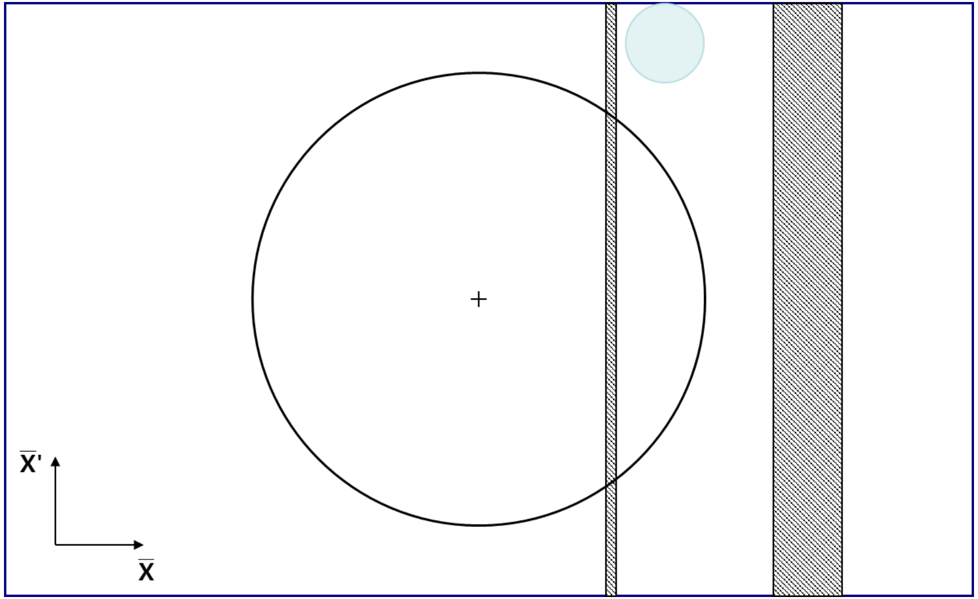
- Principle
  - Injected beam is directly injected into the ring
  - Conservation of the beam brightness in all 3 phase spaces
- Challenges
  - Injected beam needs to be matched and aligned to the lattice and trajectory of the ring
  - Injection kicker(s) needs to be fast enough to deflect only the injected beam
- Applications
  - At LEIR to PS, PS to SPS and SPS to LHC

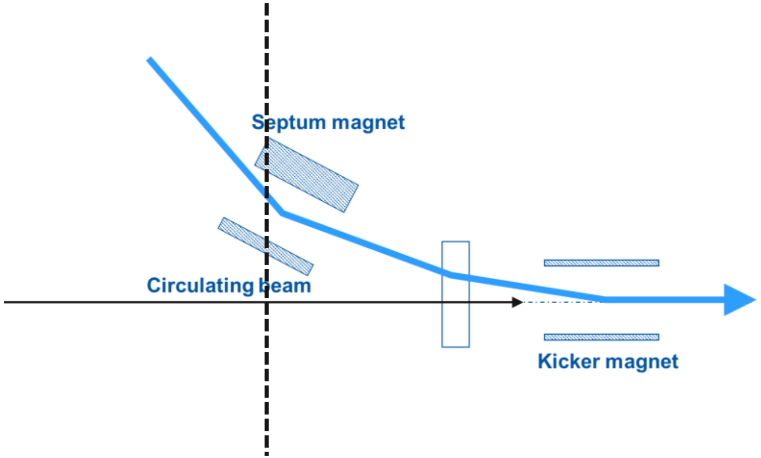




Injection techniques : Fast injection

- Seen from the ring
  - in the normalized transverse phase space in the plane of injection





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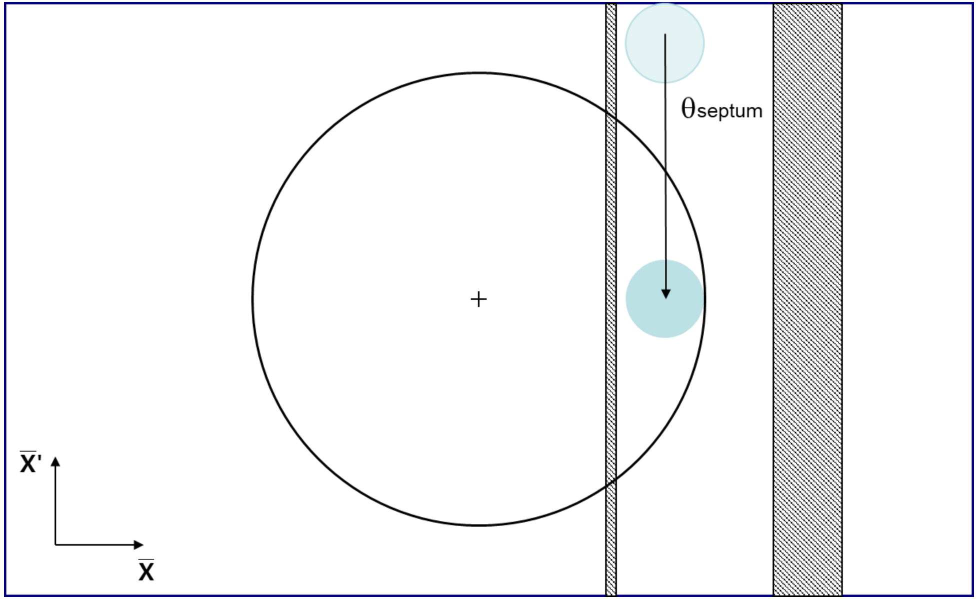

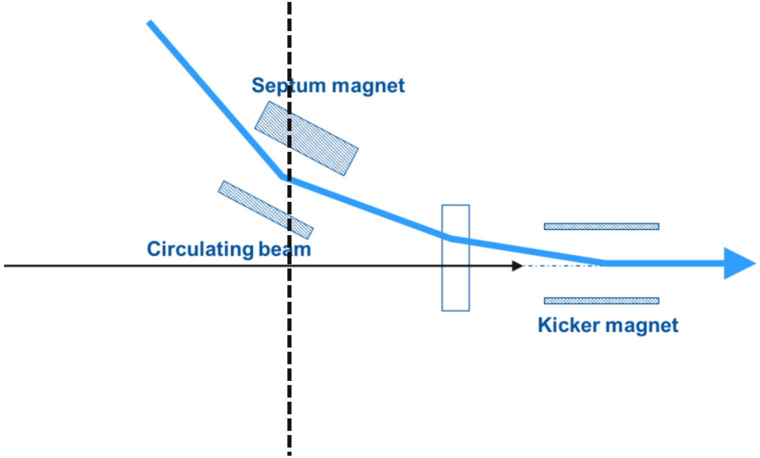

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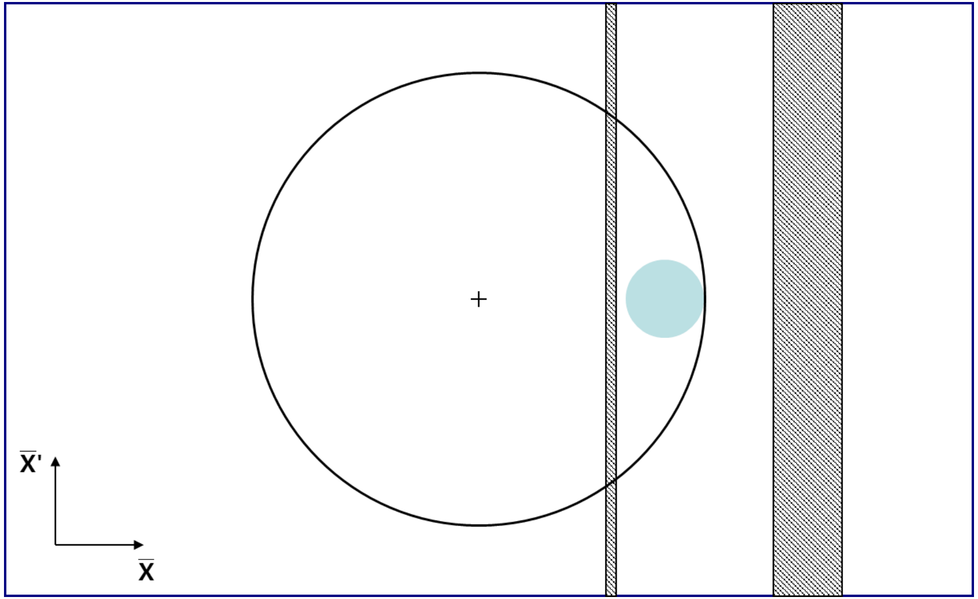

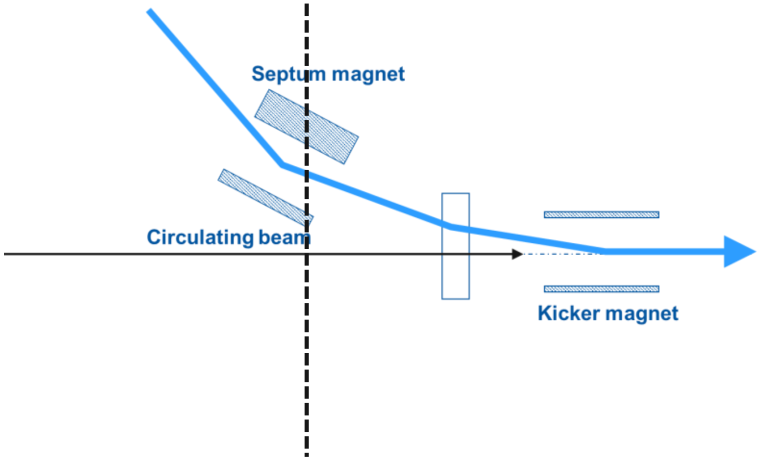

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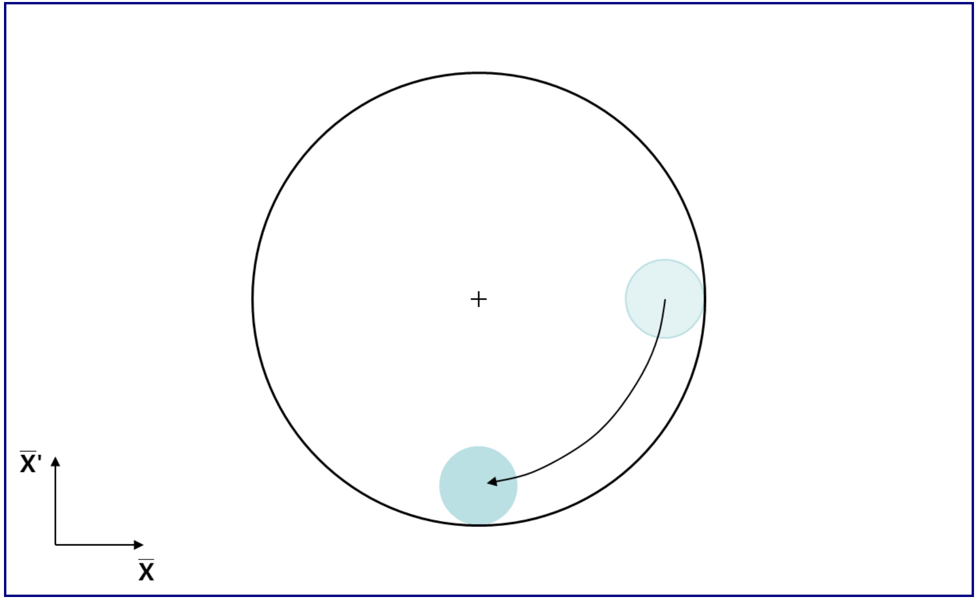

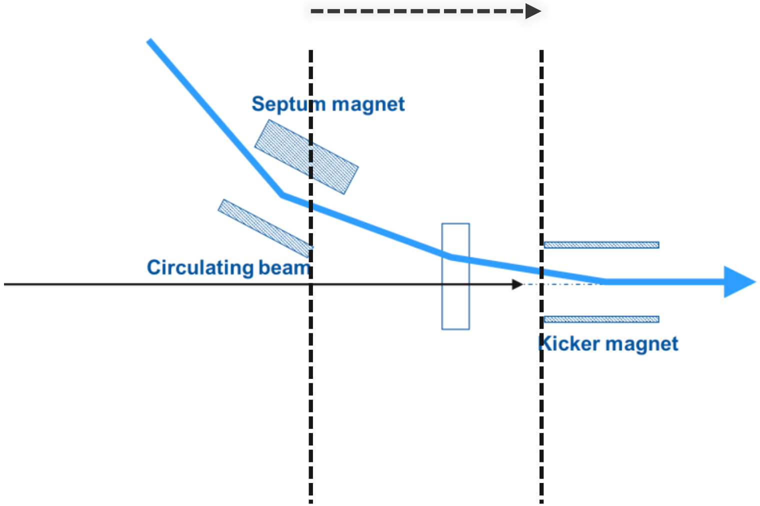

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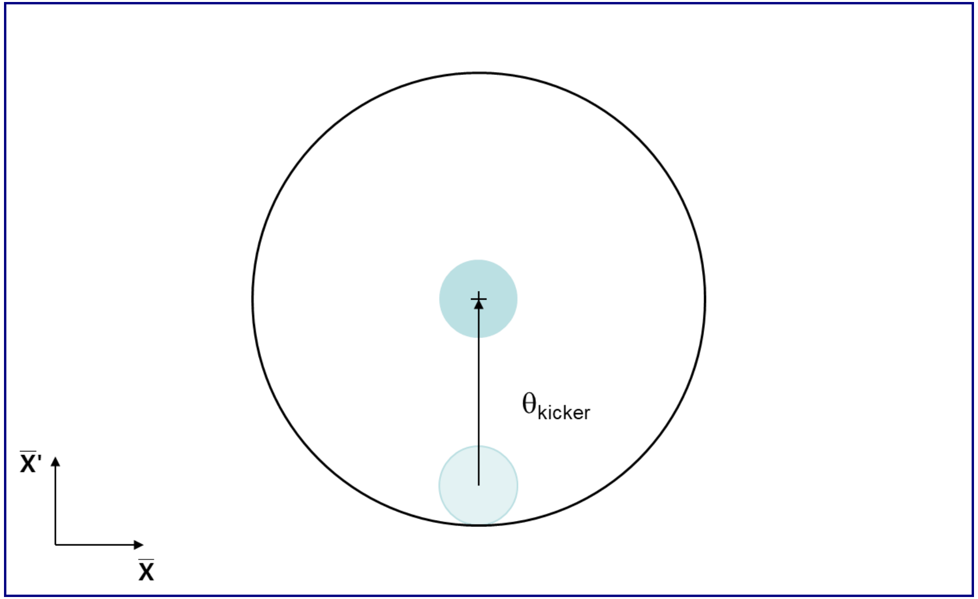
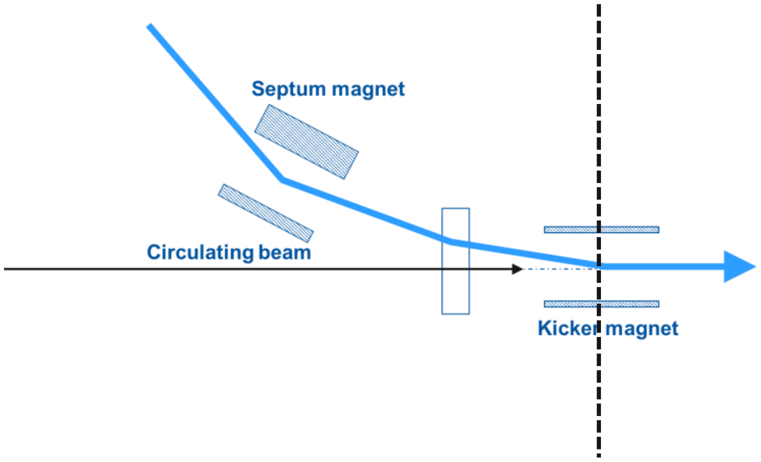




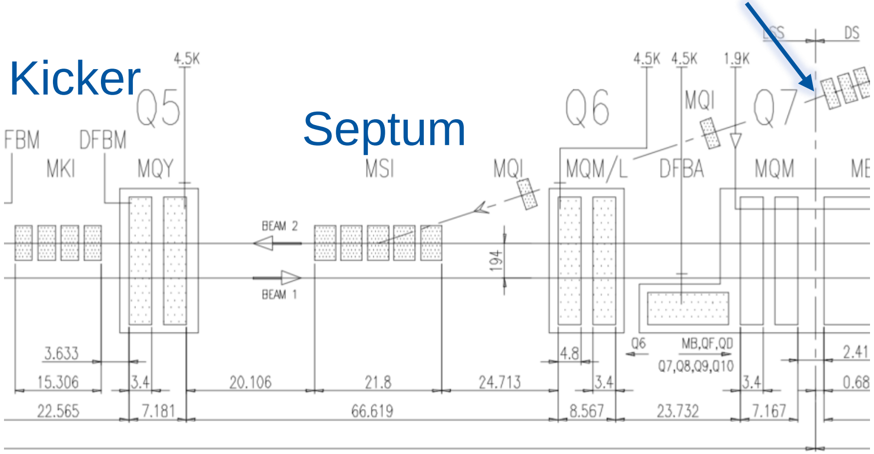
Injection techniques : Fast injection

- Example of the LHC injection

Injected beam

Kicker

Septum



MSIs (P8)

MQY
(superconducting LHC quadrupole)

MKIs

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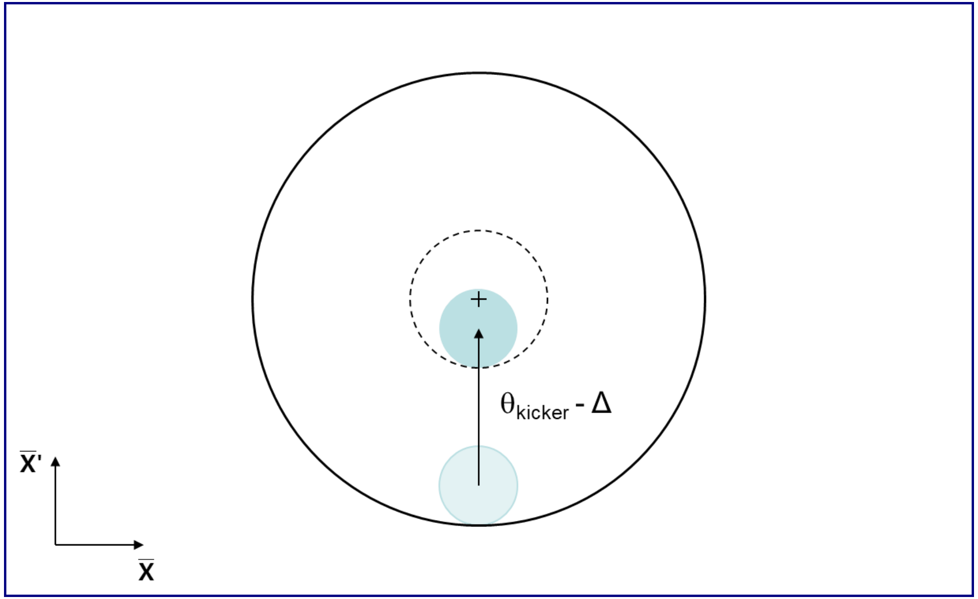
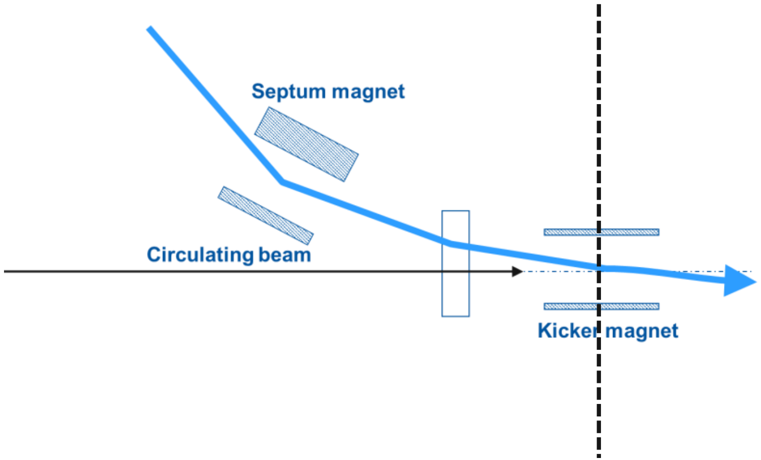
Injection techniques : Fast injection

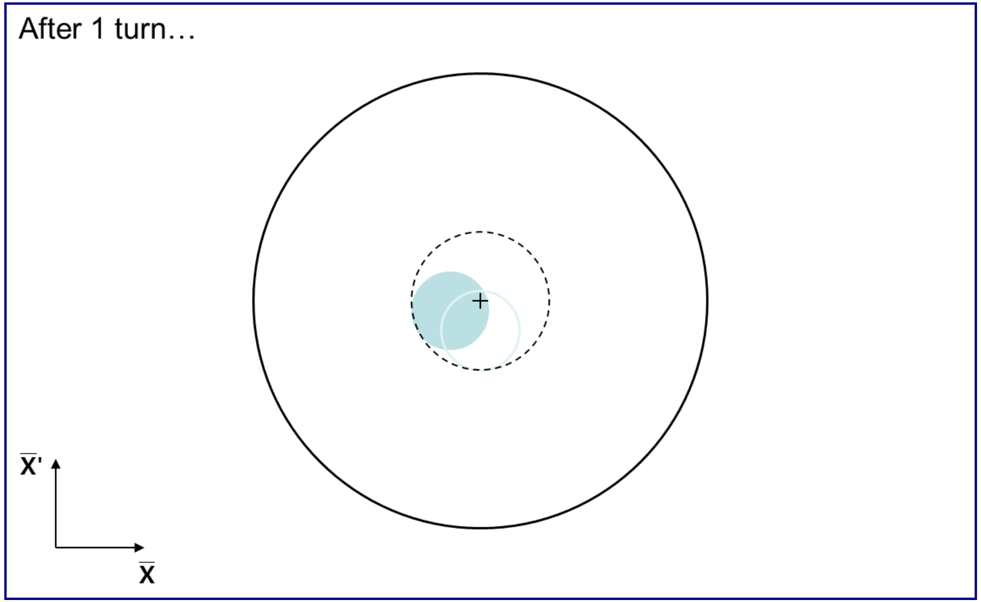
- Injection with an error, here of Δ in angle at the kicker

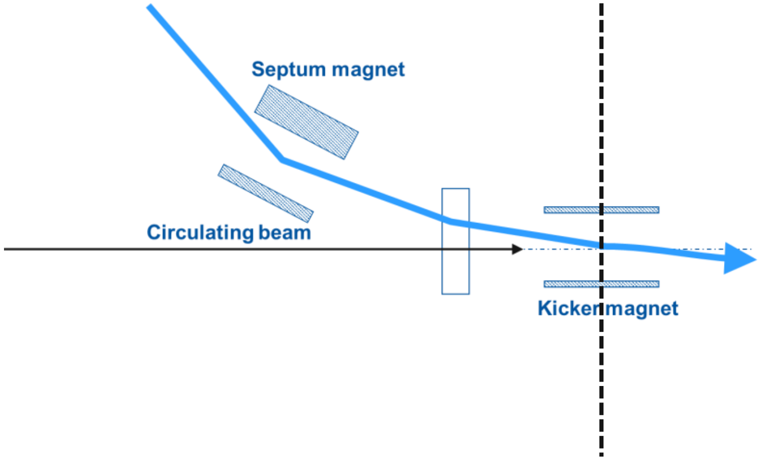




Injection techniques : Fast injection

- In the normalized phase space
  - The beam rotates around the closed orbit





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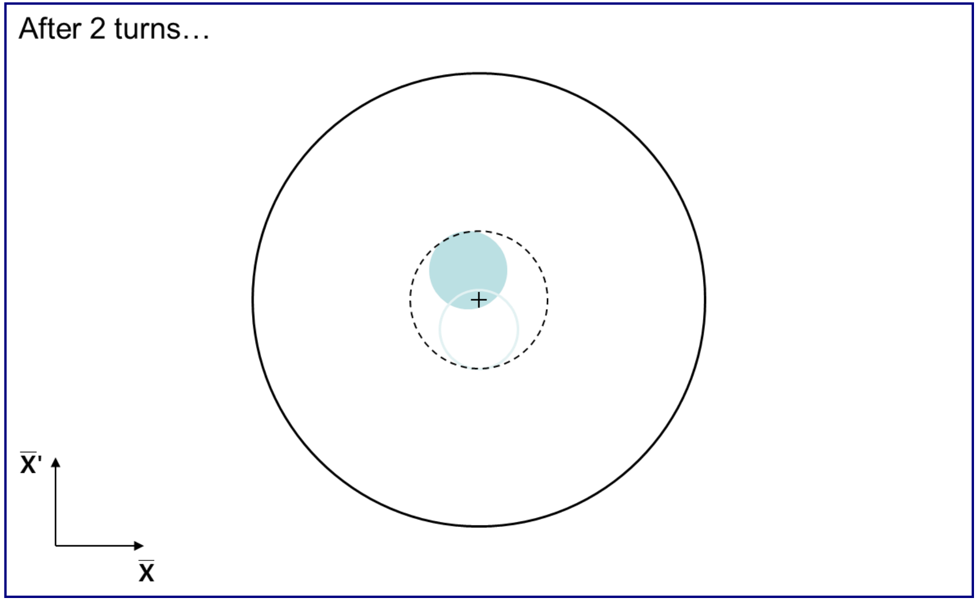

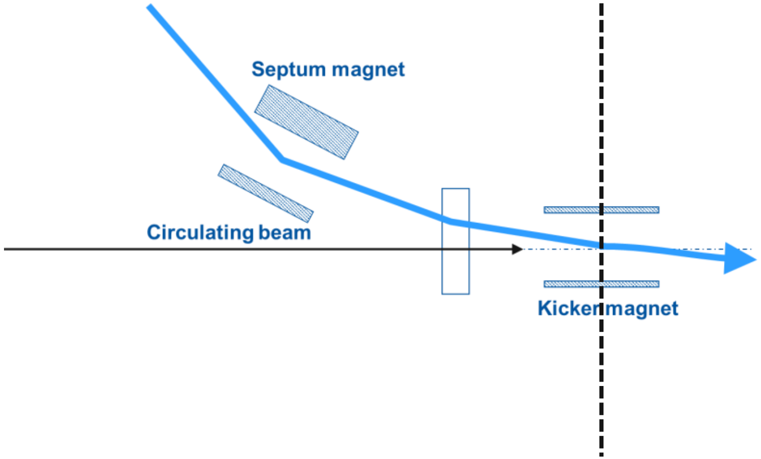

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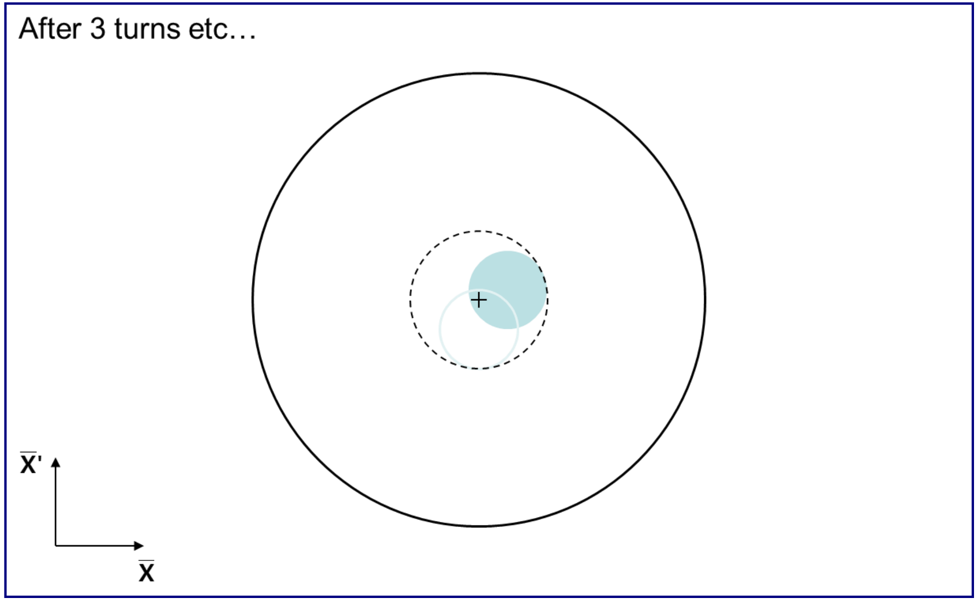
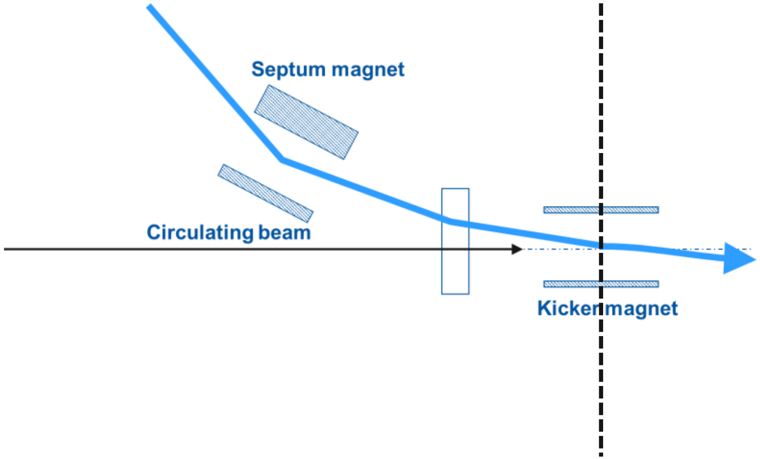
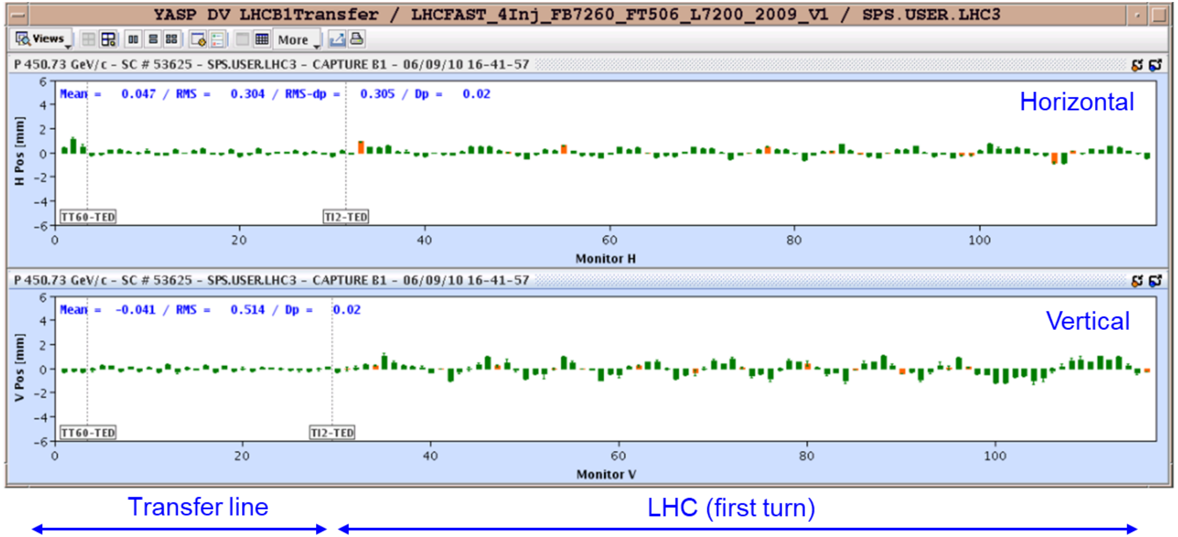




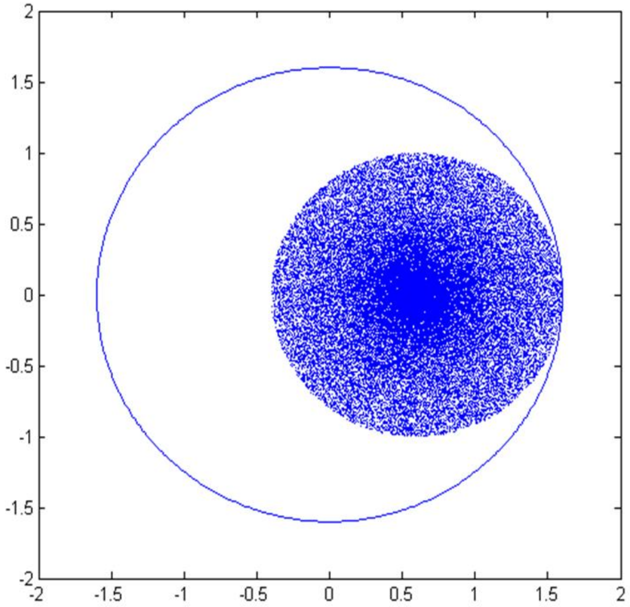
Injection techniques : Fast injection

- Example of such effect observed, at the SPS to LHC injection



Injection techniques : Fast injection

- Filamentation
  - Mismatch between the injected position and ring closed orbit leads to a dipole oscillation around the closed orbit
  - Mismatch between the injected shape and ring closed solution leads to a quadrupole oscillation of the beam
  - Both errors lead to filamentation, and a reduction of the beam brightness
- Turn after turn the brightness of the beam decreases as its emittance increases
  - This effect is due to non-liner behaviour: particles at different distances from the center do no rotate at the same speed



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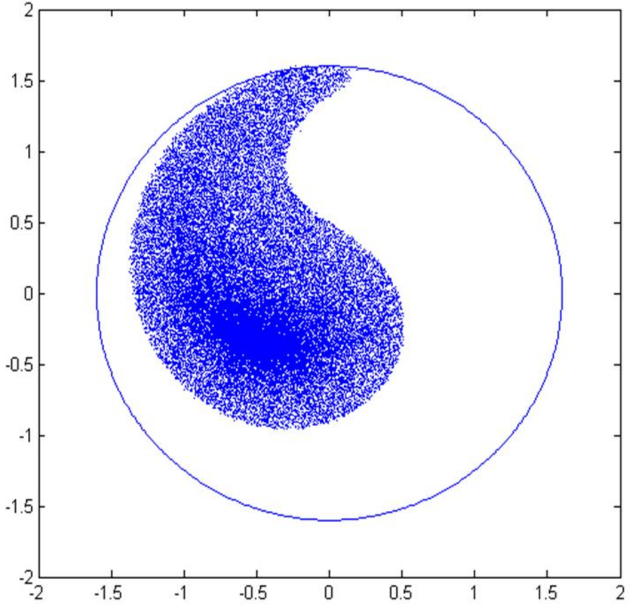

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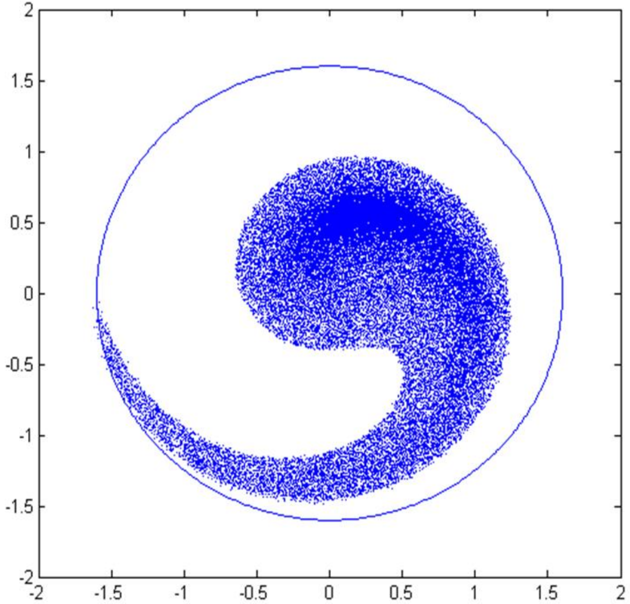

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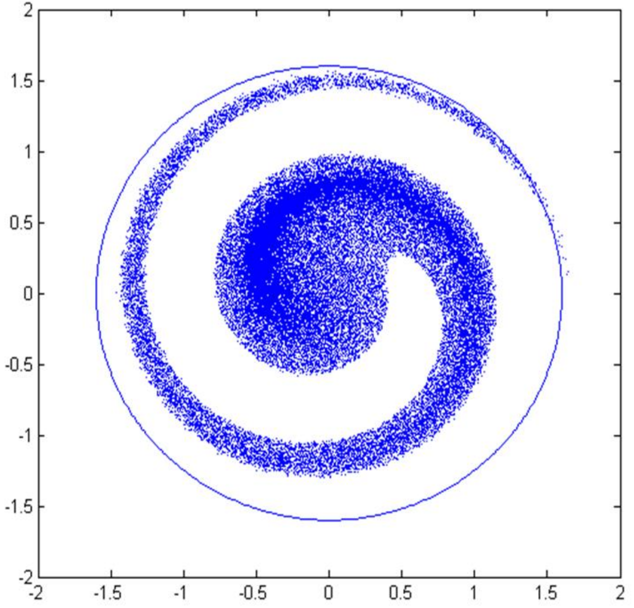

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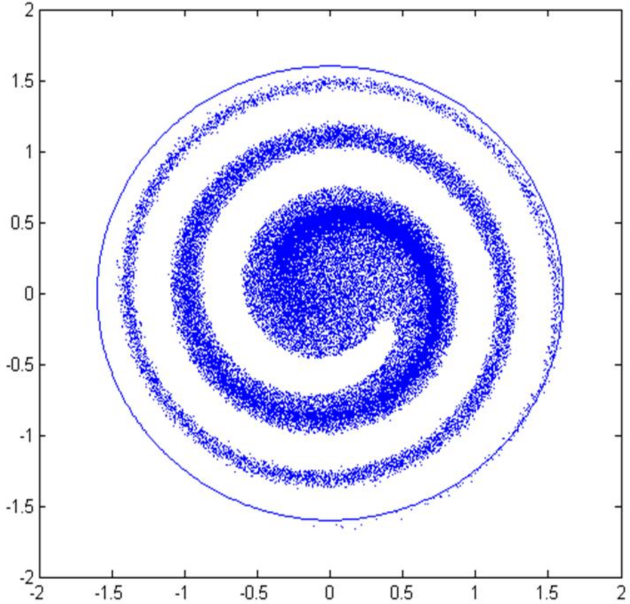

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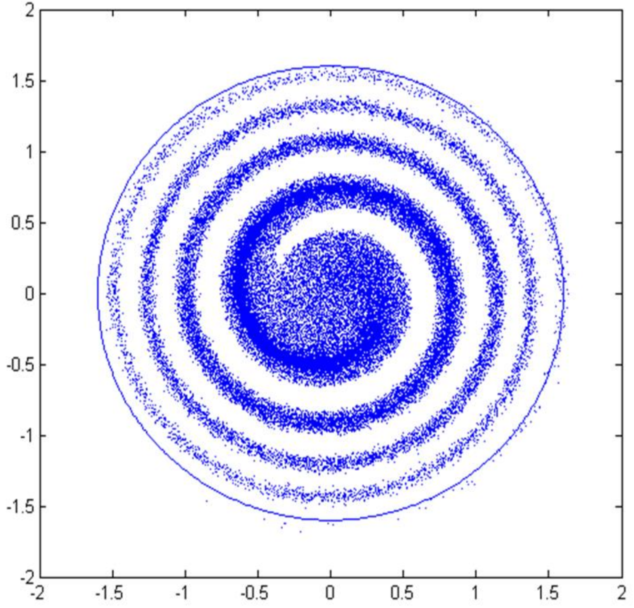

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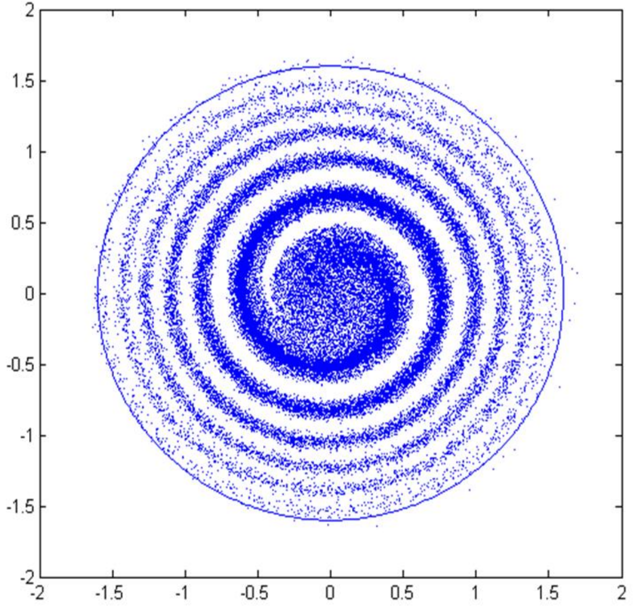

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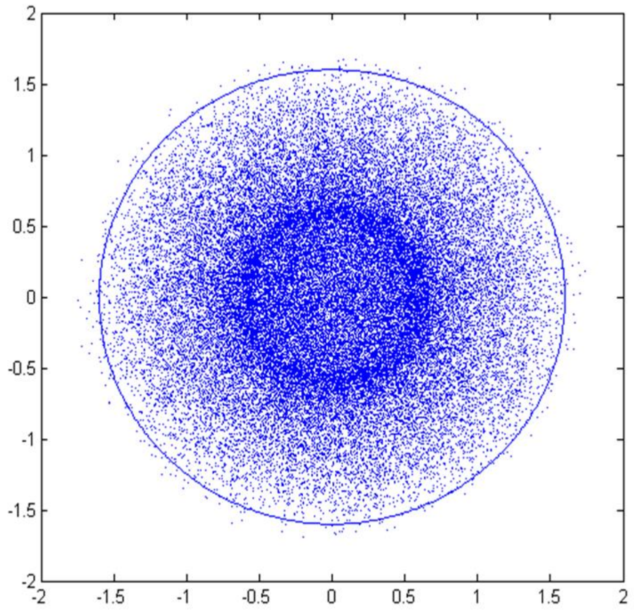
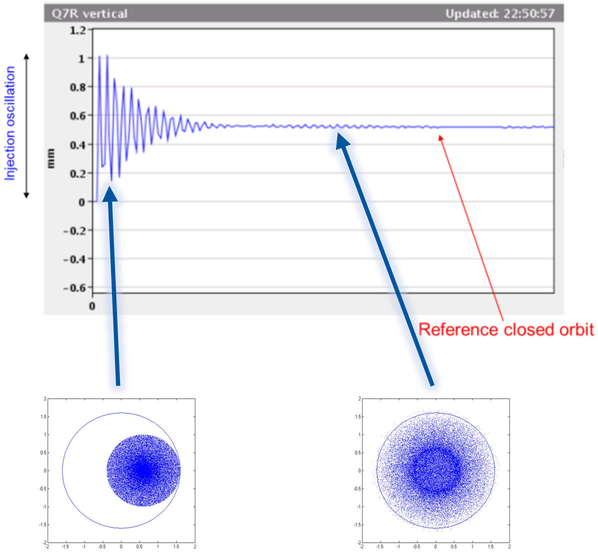


Injection techniques : Fast injection

- Observables
  - For a steering error the beam centroid oscillate around the closed orbit, which can be observed using a BPM
  - For a shape, or optical mismatch
    - the beam profile needs measured turn after turn for a direct measurement
    - Indirectly, by comparing the measured beam equilibrium emittance to expected values
- Important point
  - Any error and the induced filamentation will lead to an increase in emittance and a loss of brightness
  - This applies to both transverse and longitudinal phase spaces
- Mitigation techniques
  - Measurement of injected beam shape and trajectory correction and their correction
  - Transverse damper can mitigate the effect of filamentation by damping the injection oscillations

Position as a function of time at one BPM



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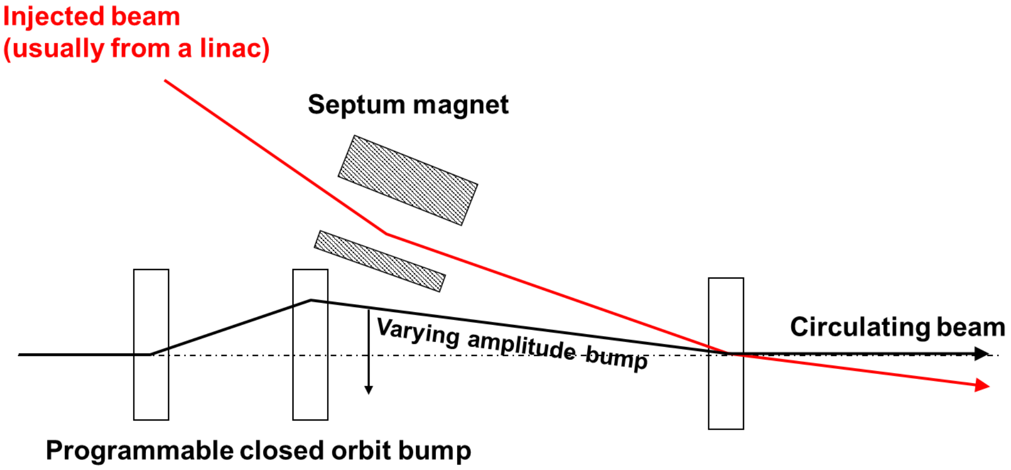
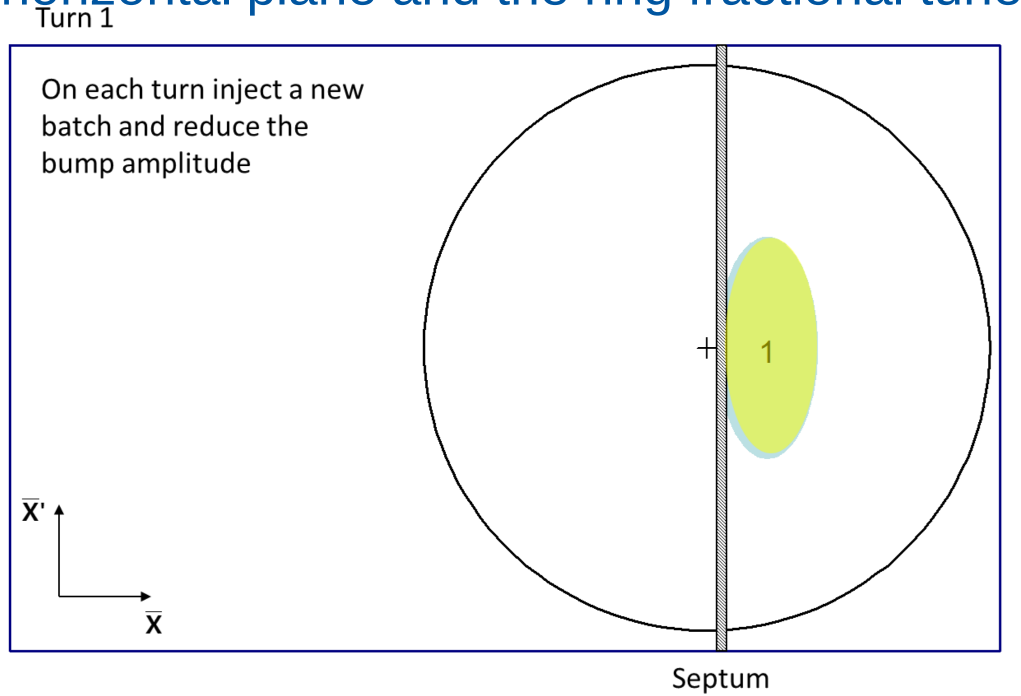
Injection techniques : Multi-turn injection

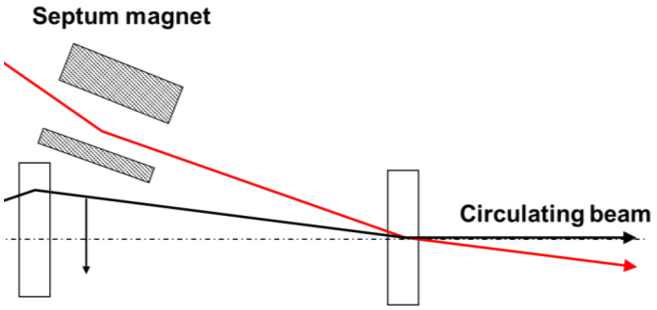
- Principle
  - Injected beam is injected in a small part of the available phase space
  - The injected trajectory is moved relative to the closed orbit during the injection process
  - Allows to accumulate intensity and `paint` the phase space with a beam smaller than the available ring acceptance, typically from a linac to a ring
- Challenges
  - Complex manipulation of the injected beam and ring closed orbit during the injection process
- Applications
  - At CERN PSB until LS2
  - At GSI SIS18 heavy ions injection



Injection techniques : Multi-turn injection

- In the case of the PSB (pre-LS2) the beam is injected in the horizontal plane and the ring fractional tune is close to 0.25





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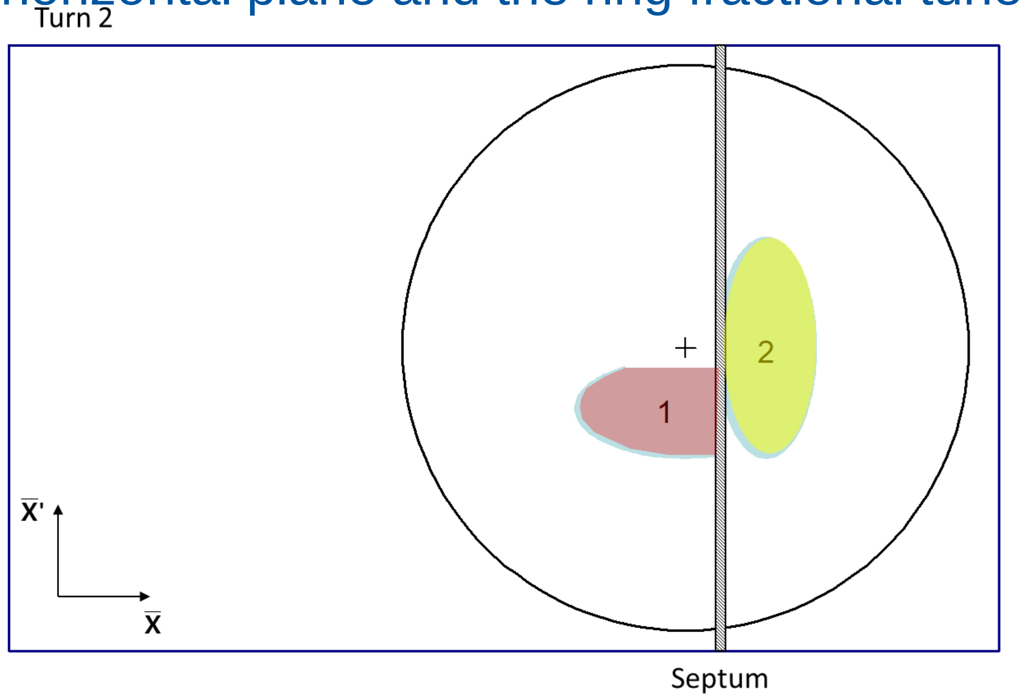

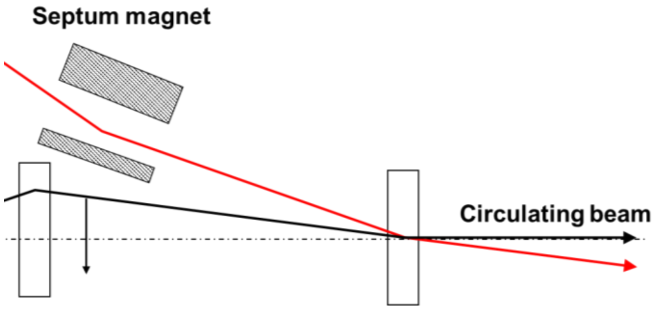

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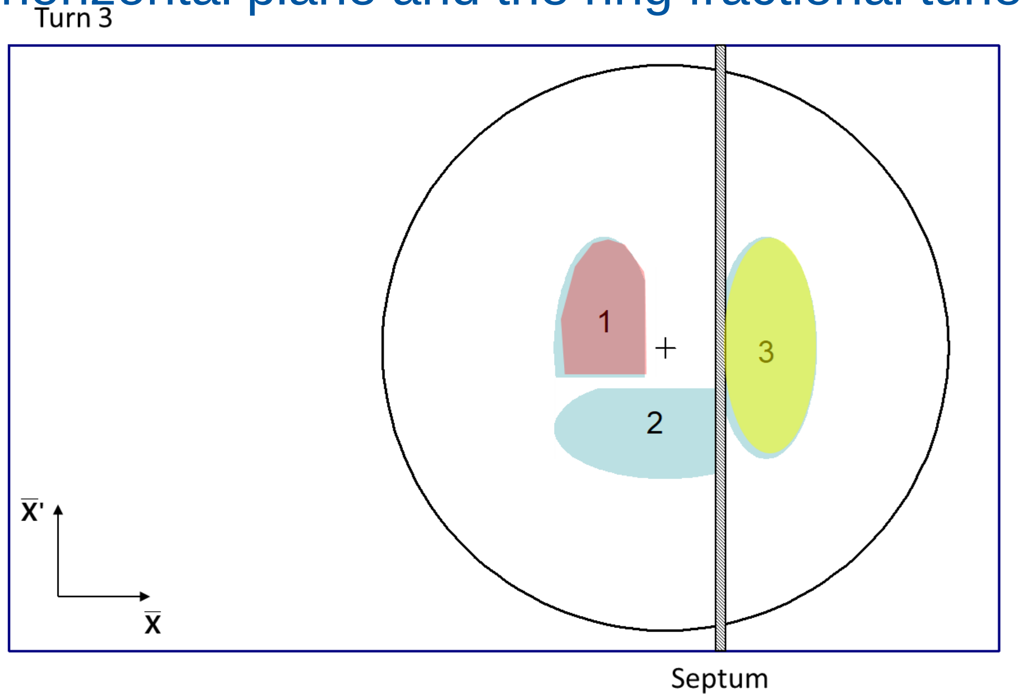

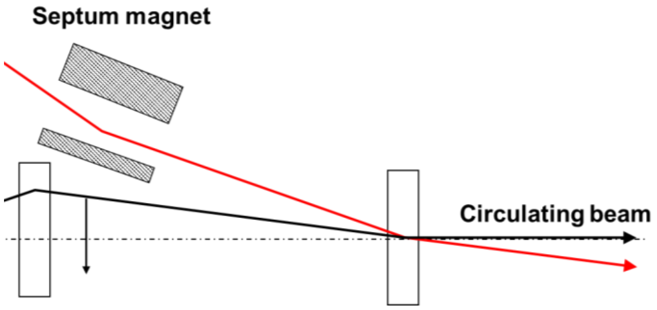

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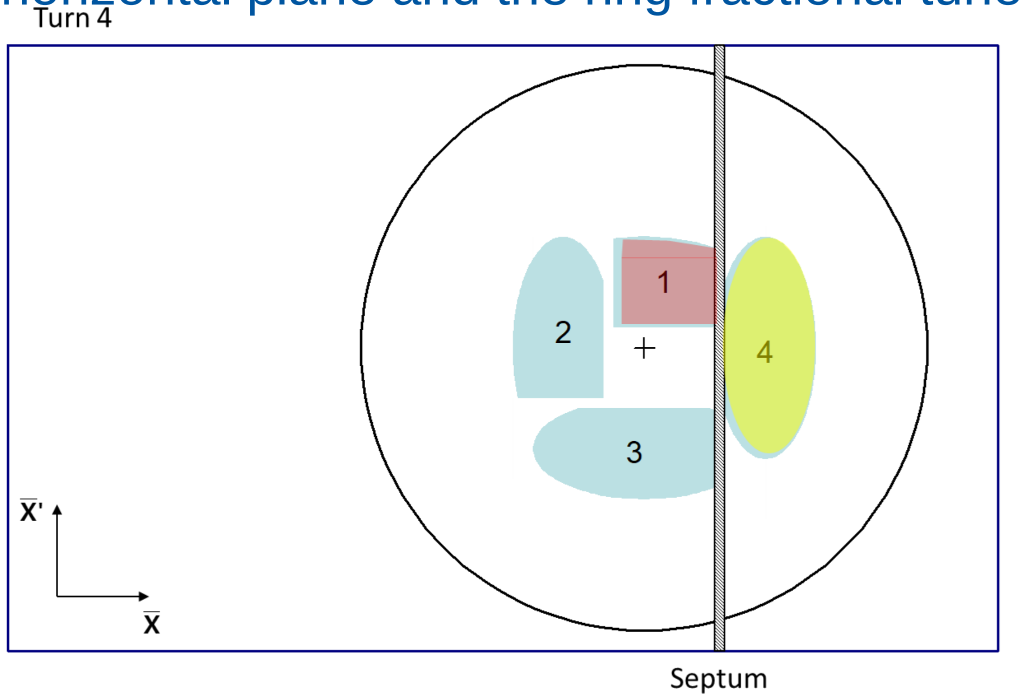

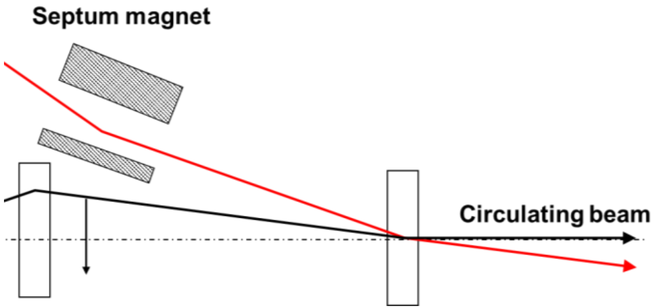

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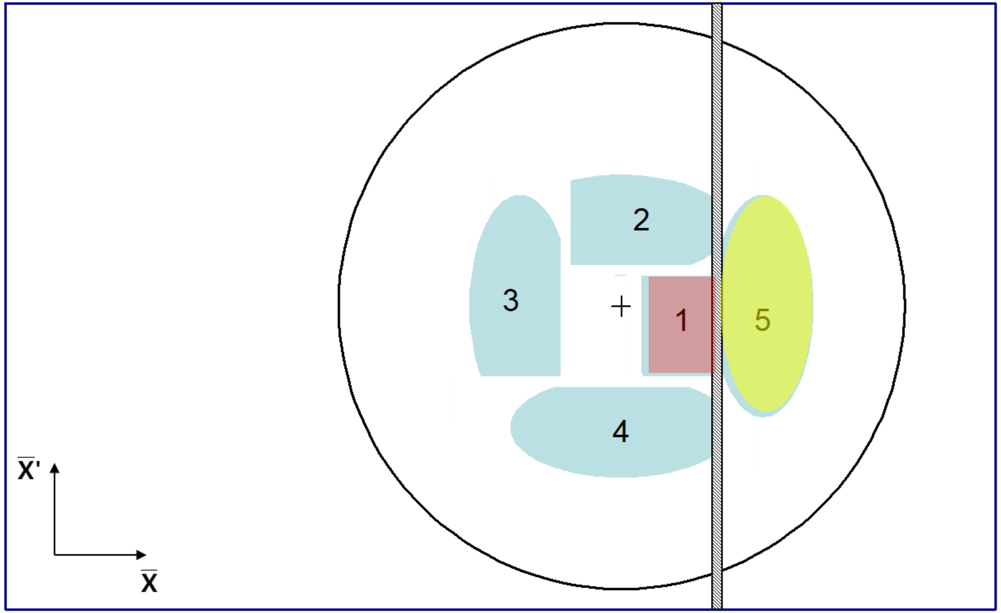
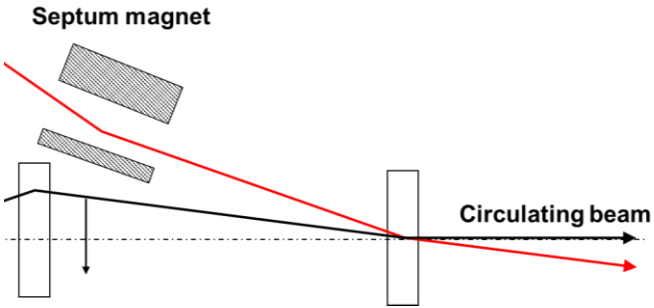
Turn 5



Septum



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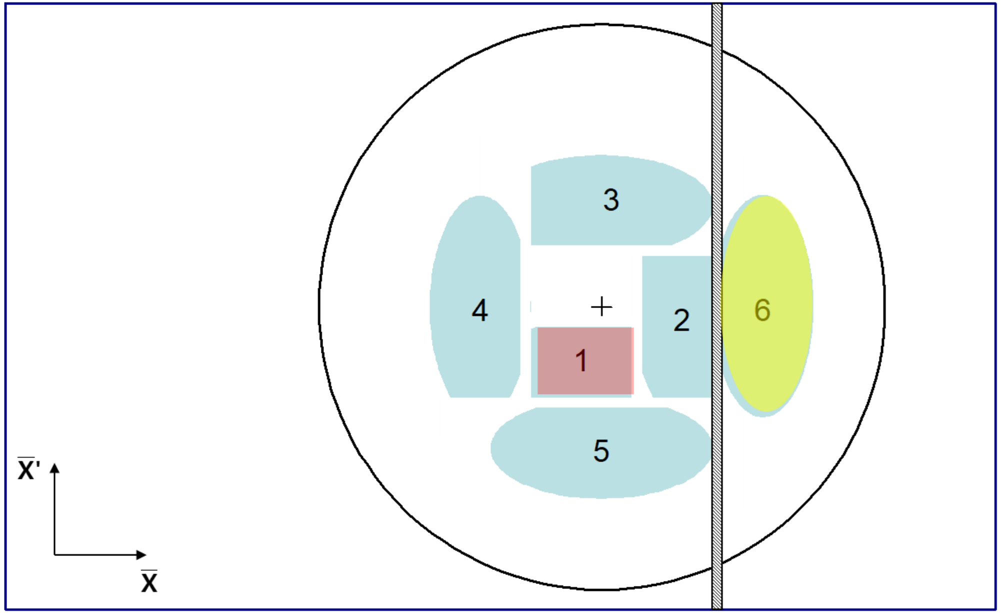
Turn 6



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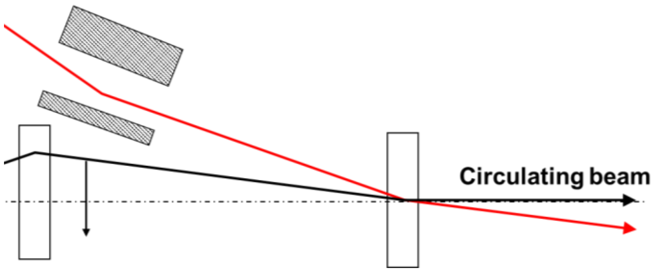

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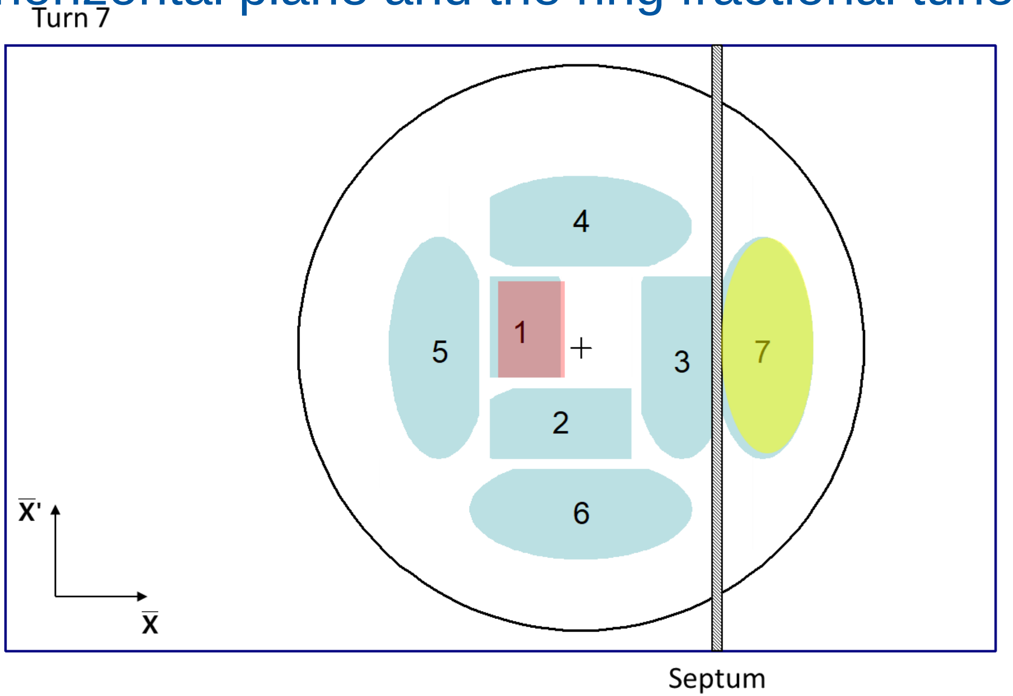

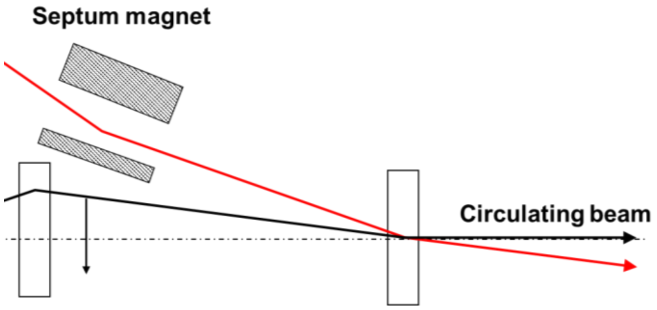

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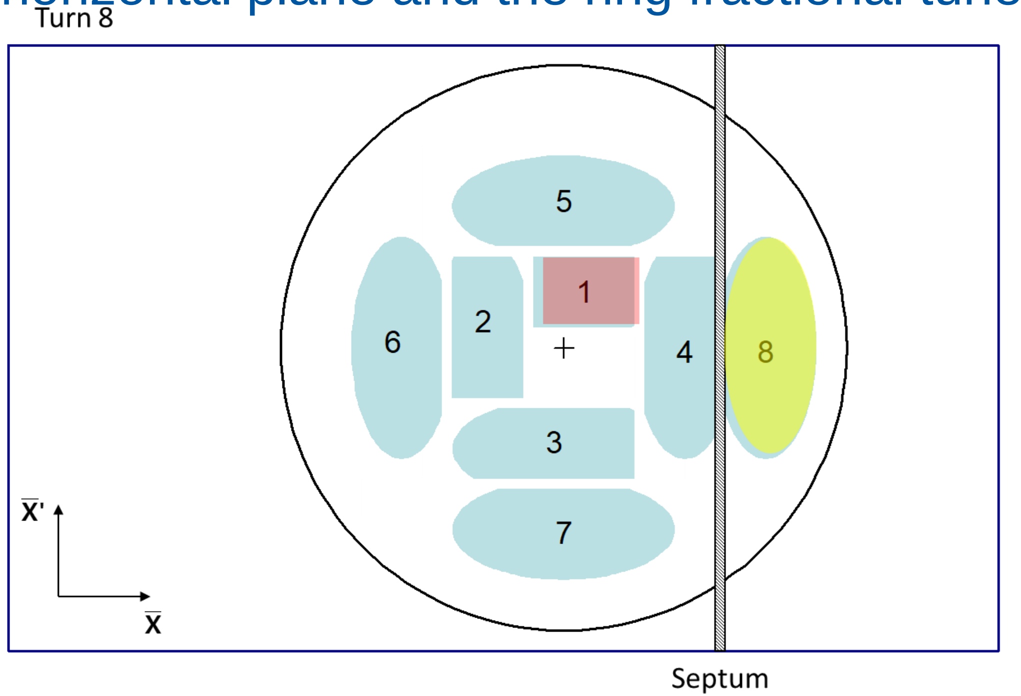

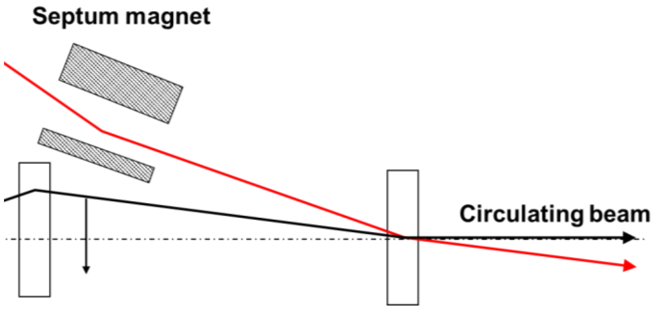

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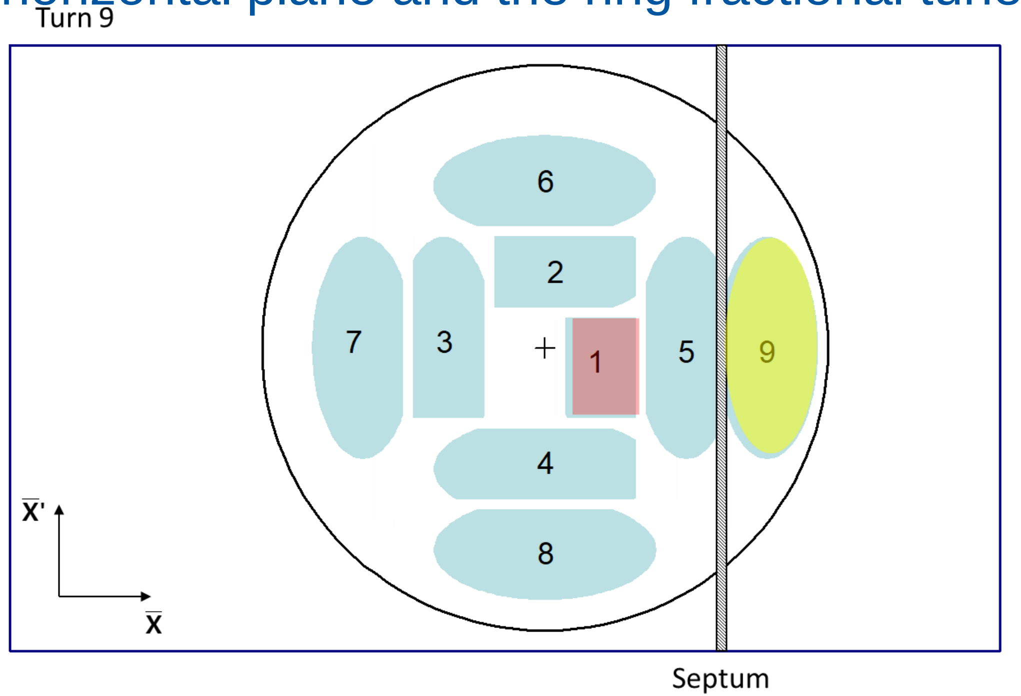

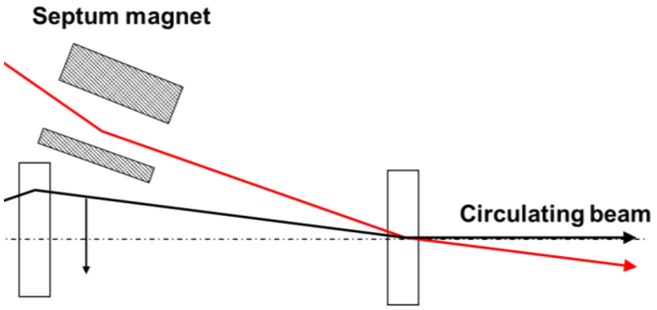

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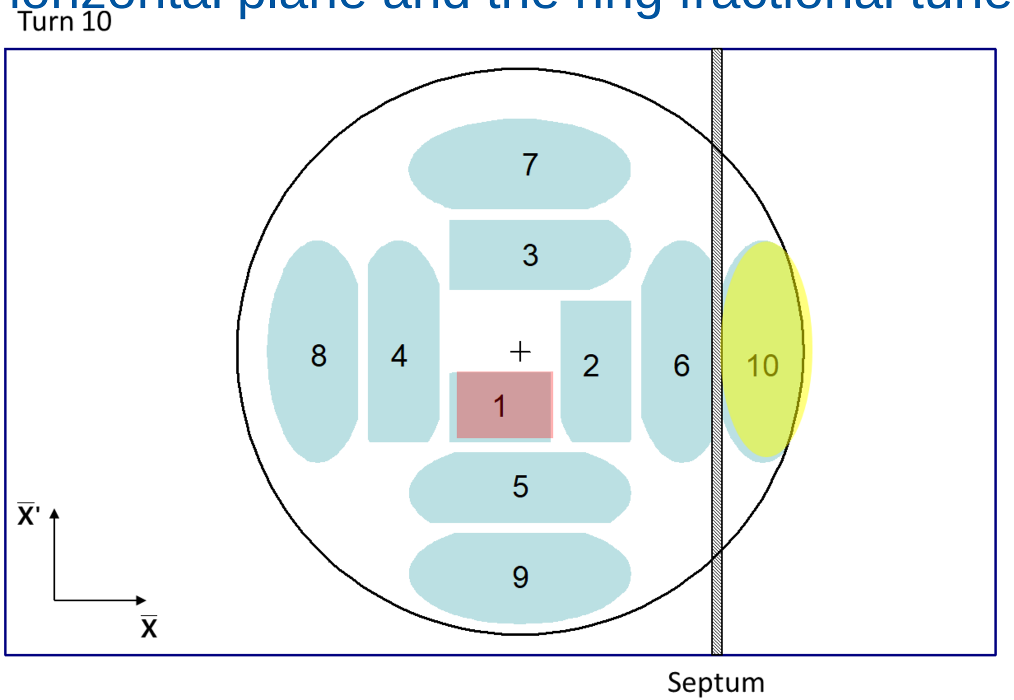
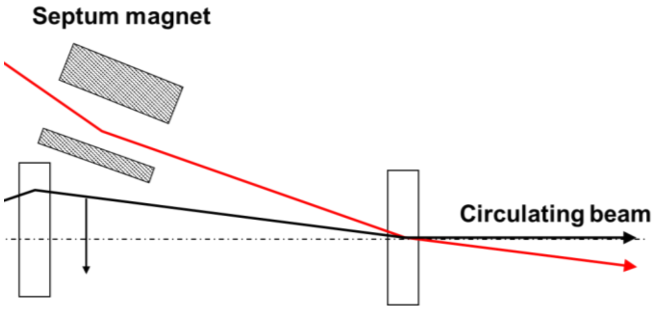
- In the case of the PSB (pre-LS2) the beam is injected in the horizontal plane and the ring fractional tune is close to 0.25





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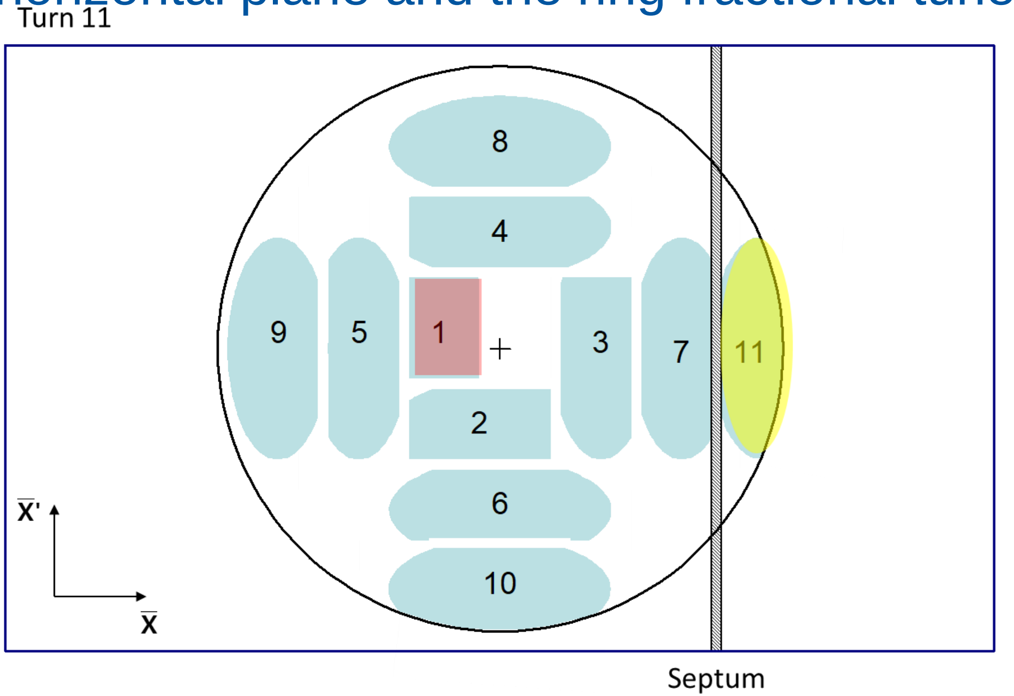

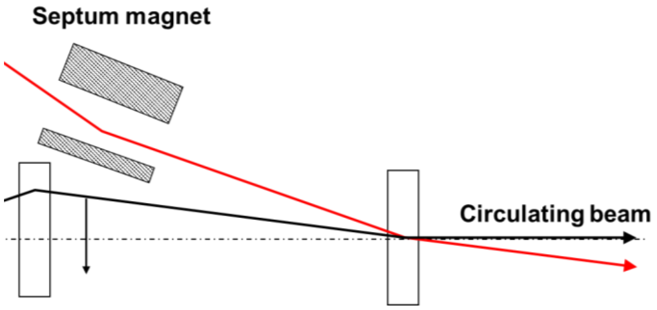

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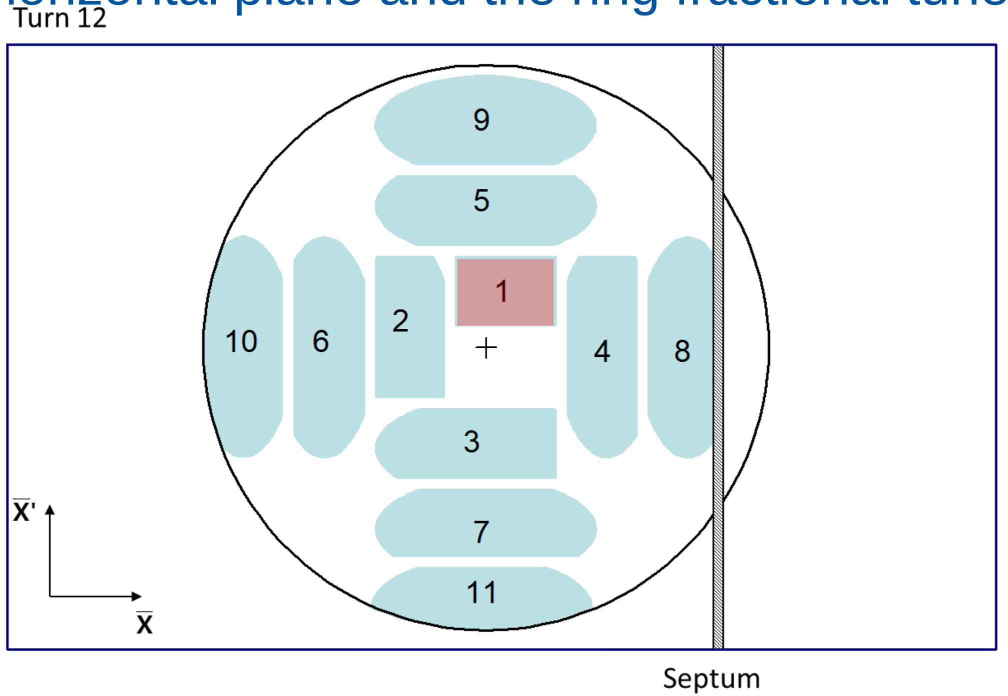

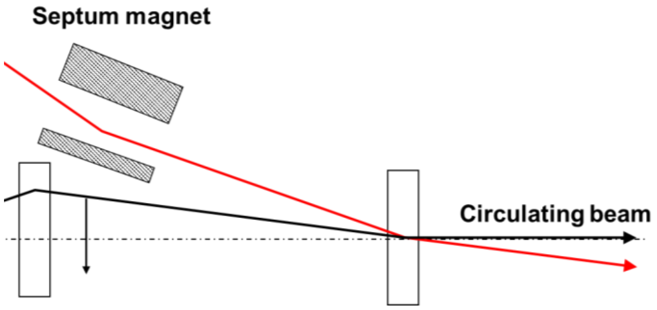

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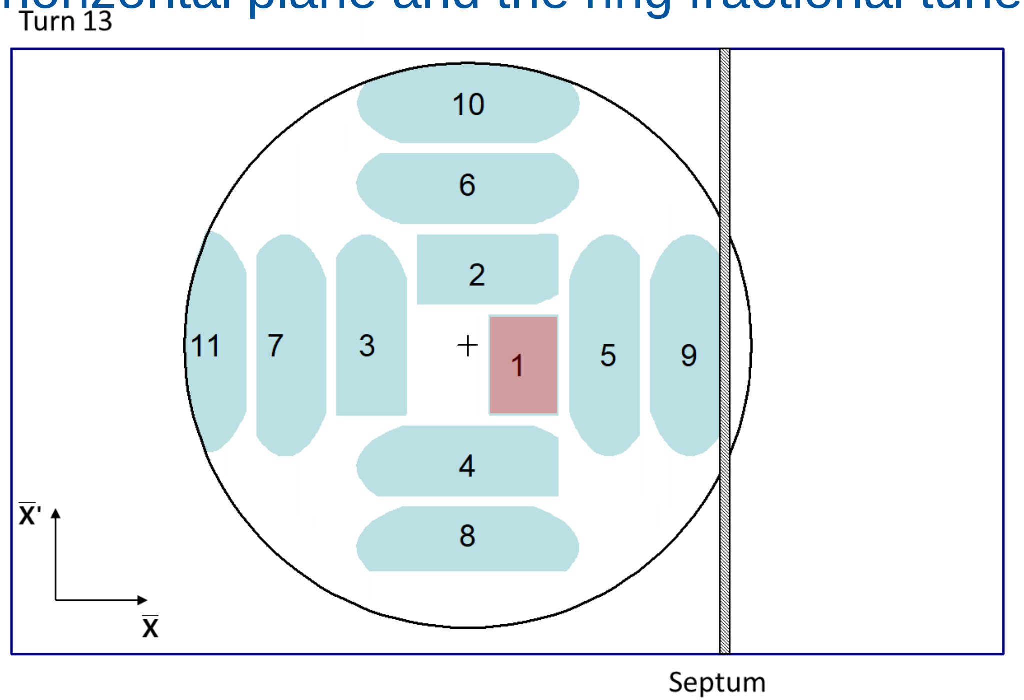

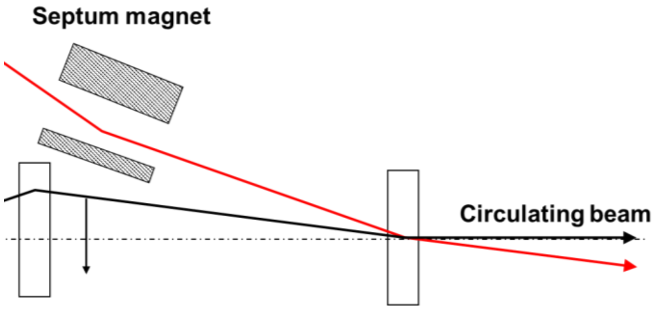

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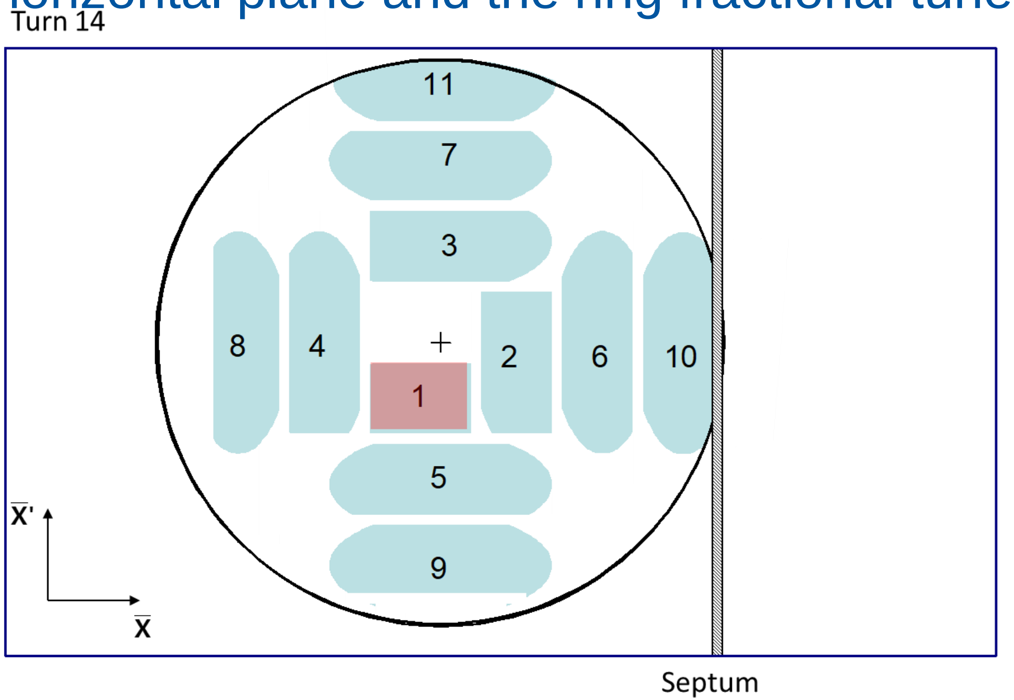

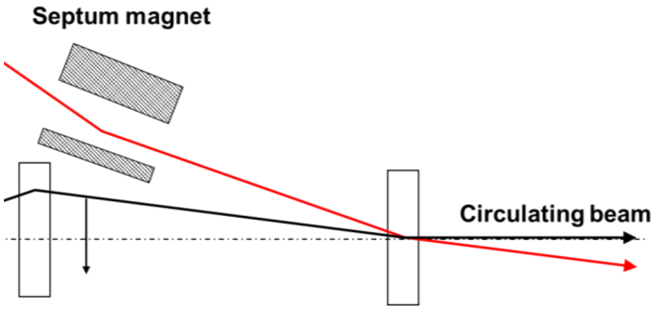

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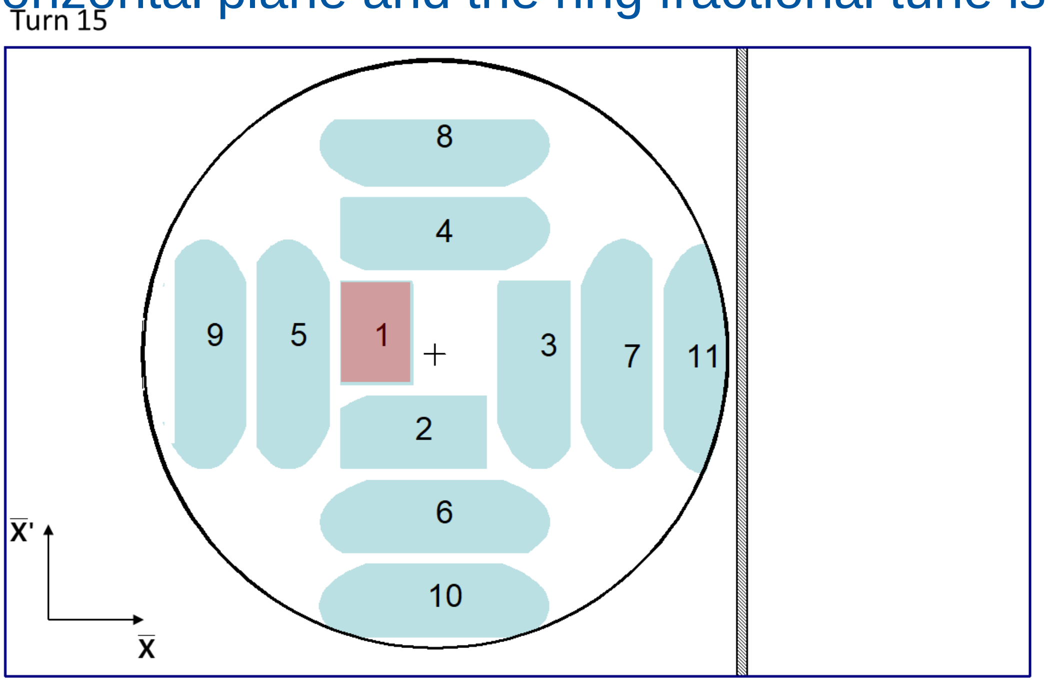

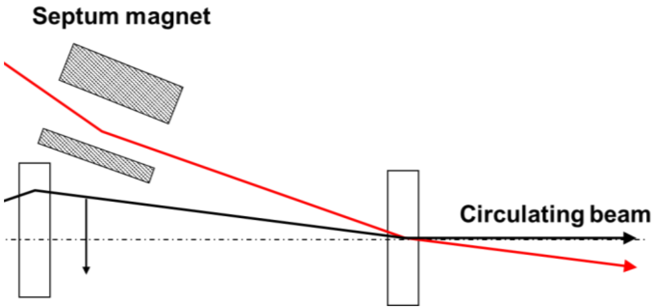

Injection techniques : Multi-turn injection [1]

- Other example at the GSI SIS18, injection of heavy ions from the UNILAC

- Conclusion
  - Disadvantages inherent in using an injection septum:
    - Width of several mm reduces aperture
    - Beam losses from circulating beam hitting septum:
      - Typically 30 – 40 % for the CERN PSB injection pre-LS2
    - Limits number of injected turns to 10 - 20
  - Allows to accumulate intensity into a ring, from a much smaller beam source, typically a linear accelerator
  - Is complex to optimize, with few observables as individual beamlets cannot be measured

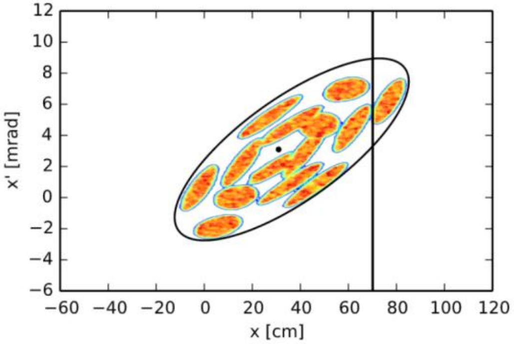

Fig. 5. Snapshot of an MTI simulation with GA optimized injection parameters. The inner beamlets do not overlap through earlier loss at the septum.

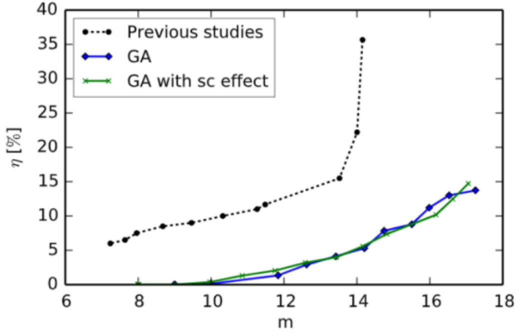

Fig. 7. The PA front for the multiplication factor and MTI loss. GA found a much better PA front than the previous simulation studies.

[1]S. Appel, O. Boine-Frankenheim, and F. Petrov, 'Injection optimization in a heavy-ion synchrotron using genetic algorithms', Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 852, pp. 73–79, Apr. 2017, doi: 10.1016/j.nima.2016.11.069.

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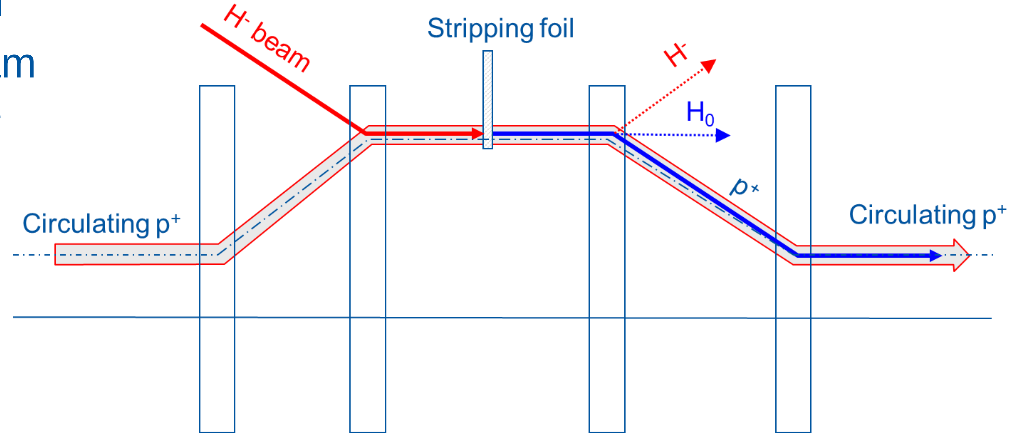
Injection techniques : Charge exchange

- Principle
  - Injected beam changes charge states through stripping in the injection region
  - Since both injected and circulating beam can cross the same space at the same time, longer injection times and higher brightness are reachable
- Challenges
  - More elements than in other injection scheme
- Applications
  - At CERN PSB since 2020
  - At BNL AGS-Booster since the 1992



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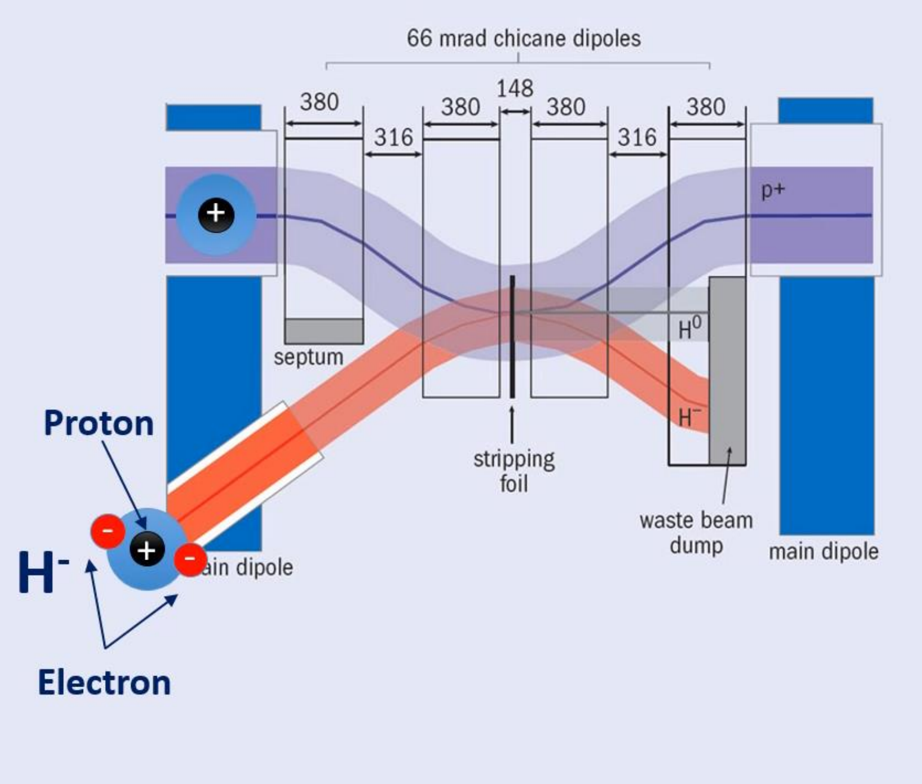
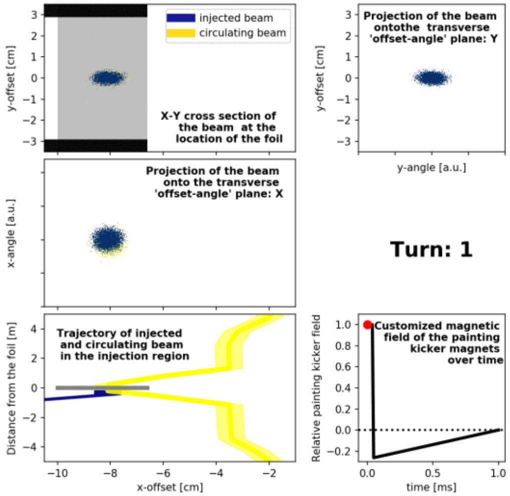
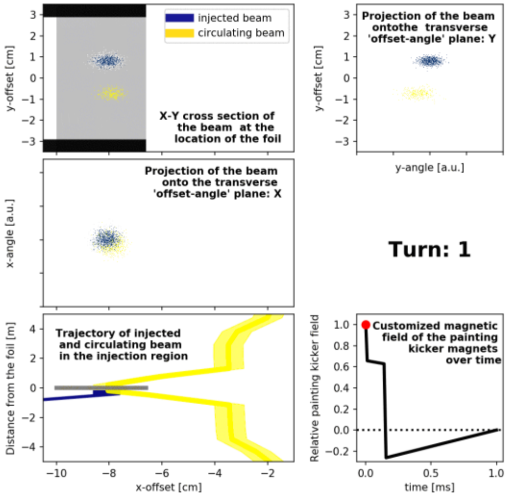


E. Renner, SY-ABT-BTP

Injection techniques : Charge exchange

- Carefull adjustment of the injection parameters allow to produce very different beams





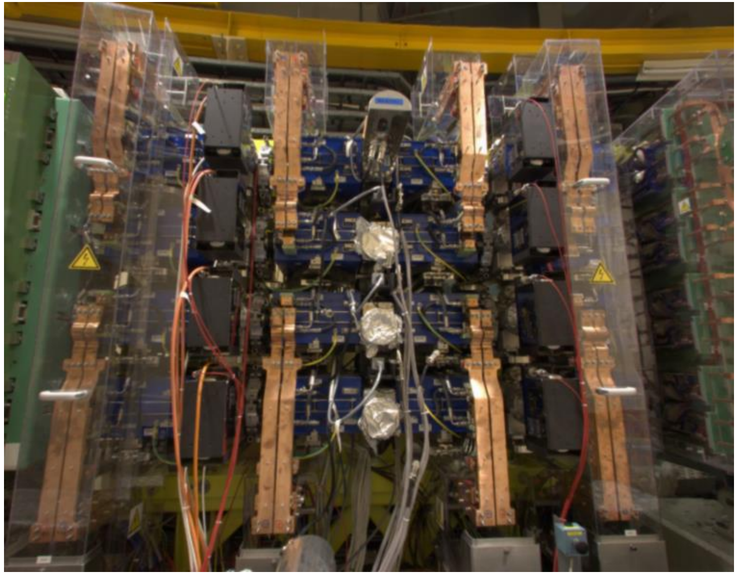
This beam has a high intensity at a small beam size. This maximum density beam is called high brightness beam and is required for the LHC experiments.

This beam has a large beam size to accommodate a very high intensity (large number of protons).
The large beam size is required to avoid that the protons repel each other.
Similar high intensity beams are required for experiments in the ISOLDE facility.

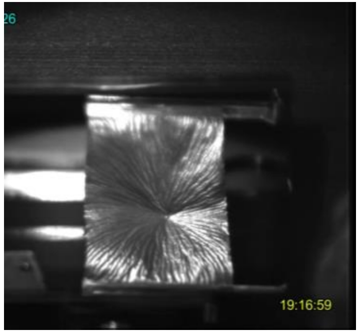
Injection techniques : Charge exchange

- Example of the PSB
  - Paint uniform transverse phase space density by modifying closed orbit bump and steering injected beam
  - Foil thickness calculated to double-strip most ions (≈99%)
    - 200 μg.cm^{-2} (≈ 1 μm of C!)
    - Carbon foils generally used – very fragile
  - Injection chicane reduced or switched off after injection, to avoid excessive foil heating and beam blow-up

PSB injection 4 rings stacked



Foils cassette developed by SY-ABT



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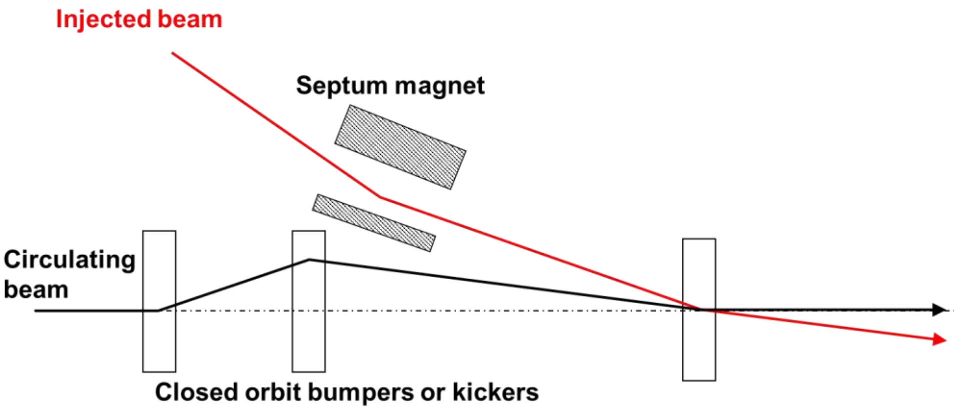
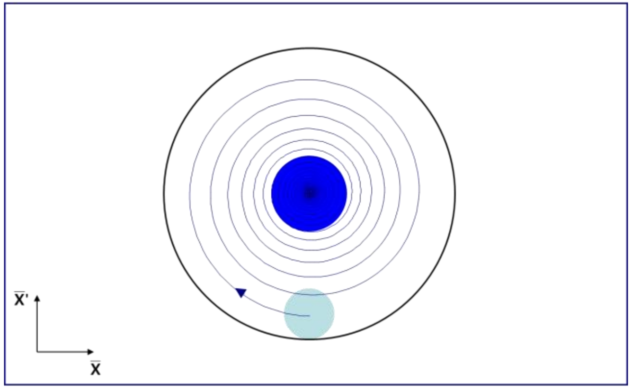
Injection techniques : Lepton Injection

- Principle
  - In a synchrontron-radiation dominated lepton ring one can take advantage of the fast damping of oscillations
  - Can use transverse or longitudinal damping:
    - Transverse - Betatron accumulation
    - Longitudinal - Synchrotron accumulation
- Challenges
  - Injection scheme and model needs to account for the synchrotron radiation damping experienced by the beam
- Applications
  - At CERN LEP injection
  - In most synchrotron light sources, where it Allows continuous injection, allowing continuous operation ~constant current





Injection techniques : Summary

- Several different techniques using kickers, septa and bumpers:
  - Single-turn injection for hadrons
    - Boxcar stacking: transfer between machines in accelerator chain
    - Angle / position errors $\Rightarrow$ injection oscillations
    - Uncorrected errors $\Rightarrow$ filamentation $\Rightarrow$ emittance increase
  - Multi-turn injection for hadrons
    - Phase space painting to increase intensity
    - H- injection allows injection into same phase space area
  - Lepton injection: take advantage of damping
    - Less concerned about injection precision and matching

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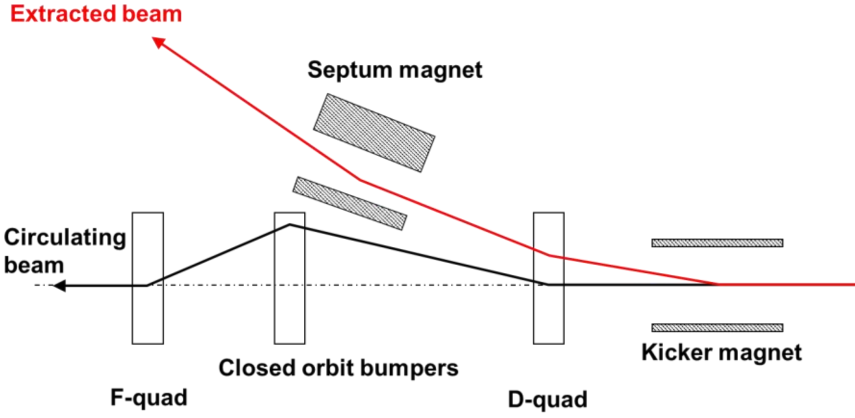
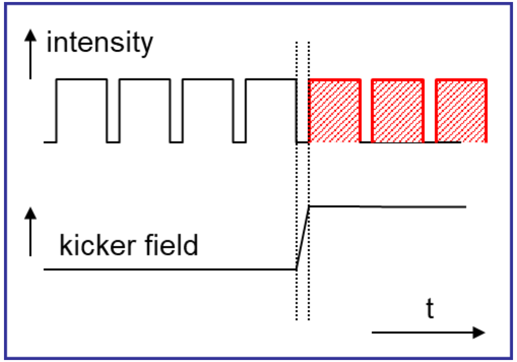
Extraction techniques : Fast extraction

- Principle
  - Mirror of the fast injection thechnique
  - Circulating beam is moved close to the septum magnet
  - A fast kicker magnet imparts a final deflection to channel the beam towards the septum aperture and the extraction line
- Challenges
  - Higher energies require stronger elements than for injection
- Applications
  - At CERN PSB, SPS, AD and more
  - At many other synchrotrons around the world





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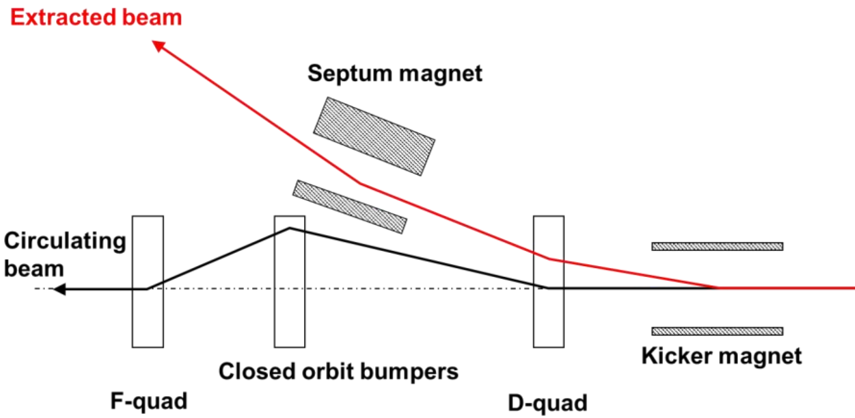
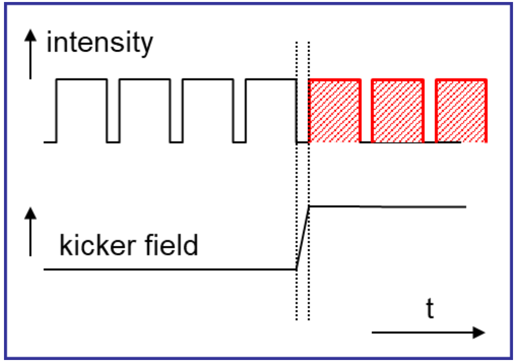
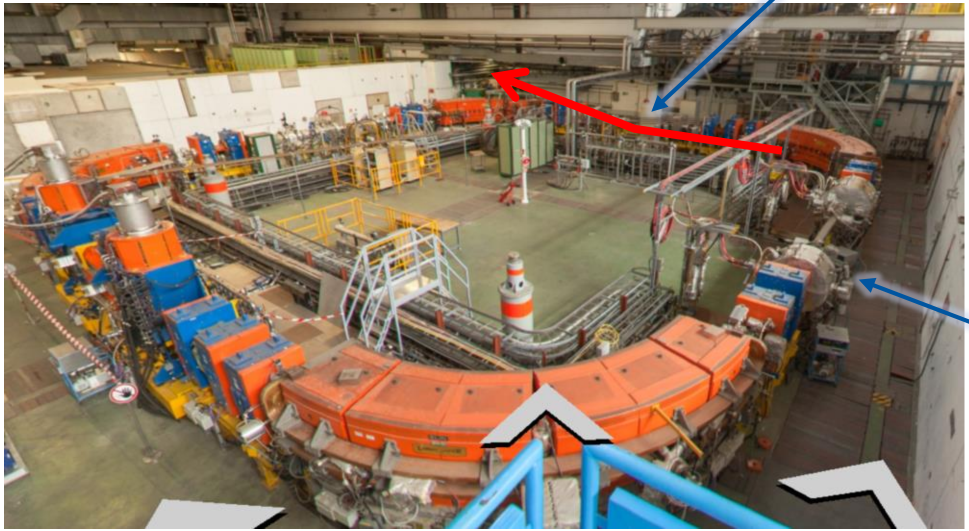




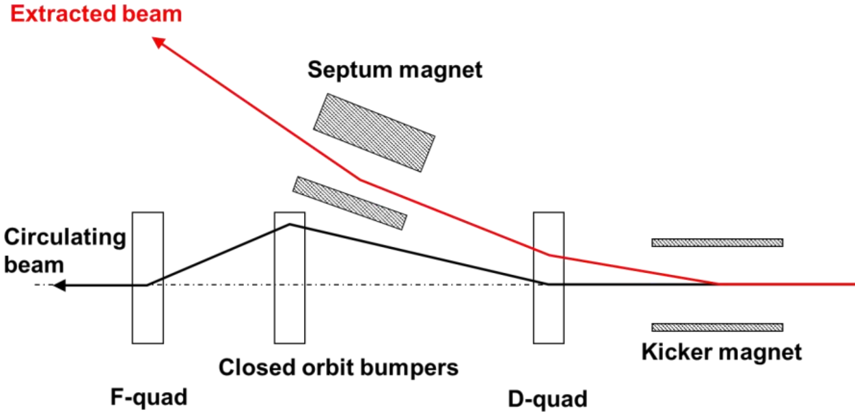
Extraction techniques : Fast extraction

- Example of the LEIR extraction

Septum



Kicker



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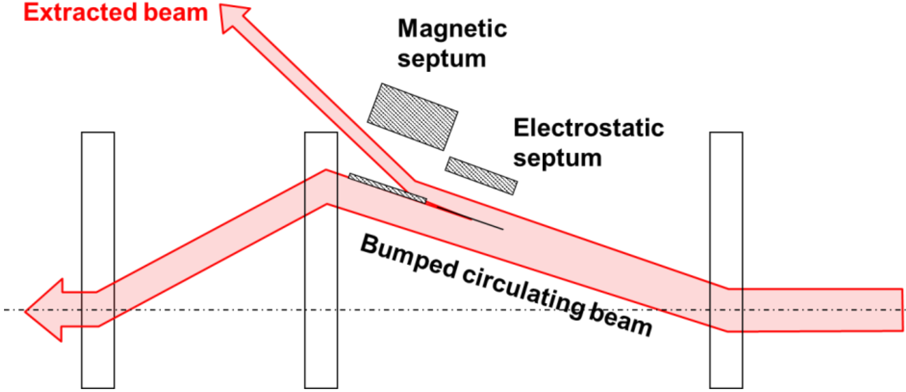
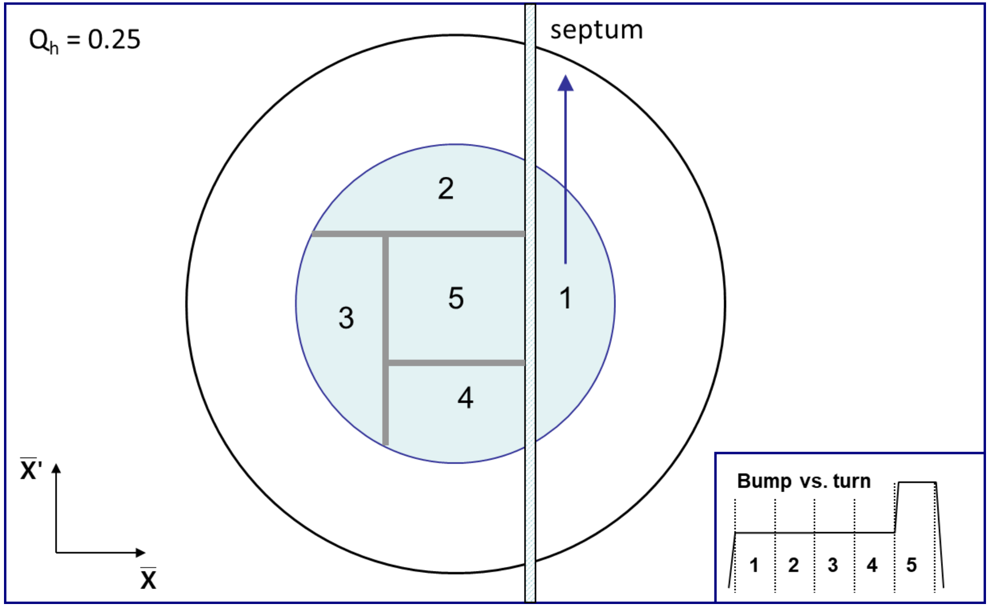
Extraction techniques : Multi-turn extraction

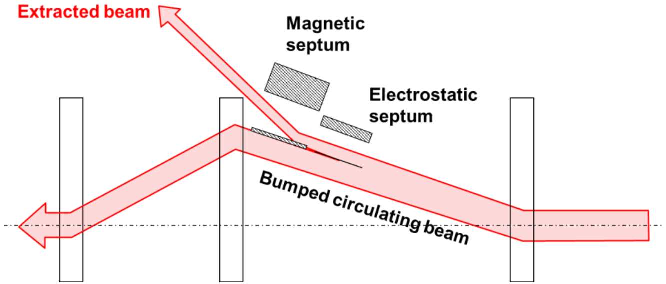
- Principle
  - Somewhat mirrors the principle of multi-turn injection
  - Circulating beam is brought close to an electrostatic septum and partially pushed trough using fast kicker
  - The beam is shaved over a few turns
- Challenges
  - The electrostatic septum is used for its thin blade (down to a few tens of um), but limited effect on high energy beams
  - This scheme is intrinsically lossy and will create activation around the extraction elements, and in particular the electrostatic septum
- Applications
  - At CERN PS until 2015



Extraction techniques : Multi-turn extraction

- CERN PS to SPS: 5-turn continuous transfer





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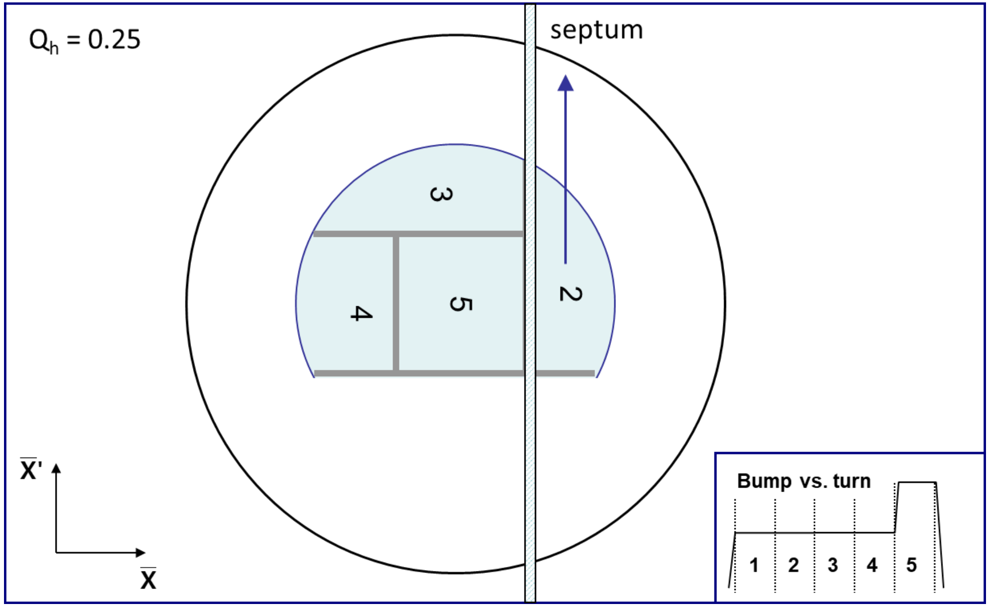

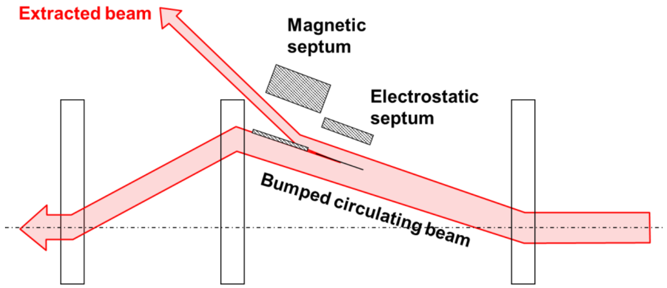

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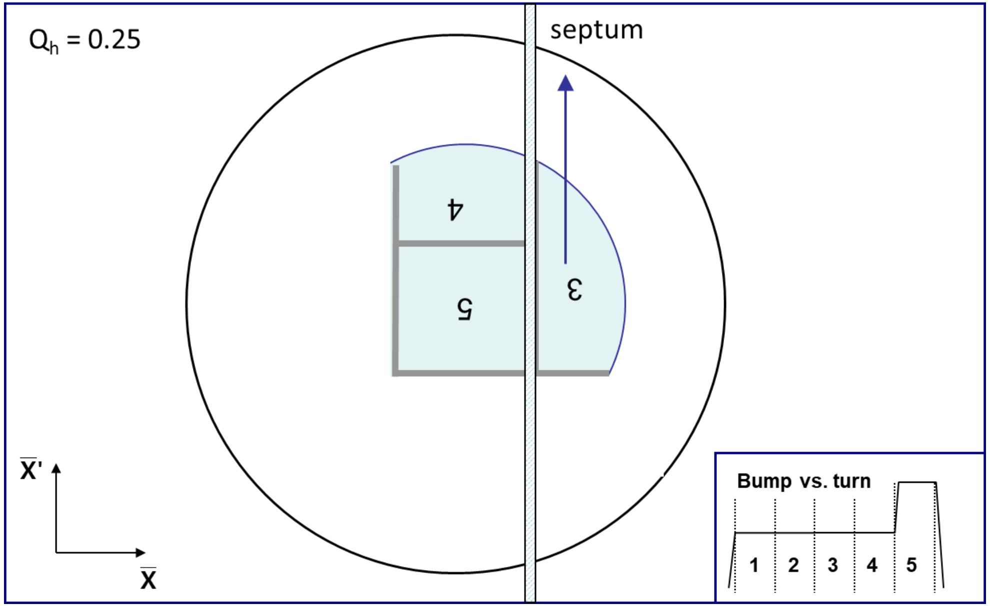

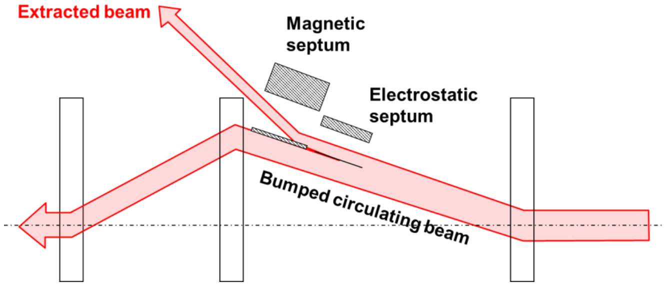

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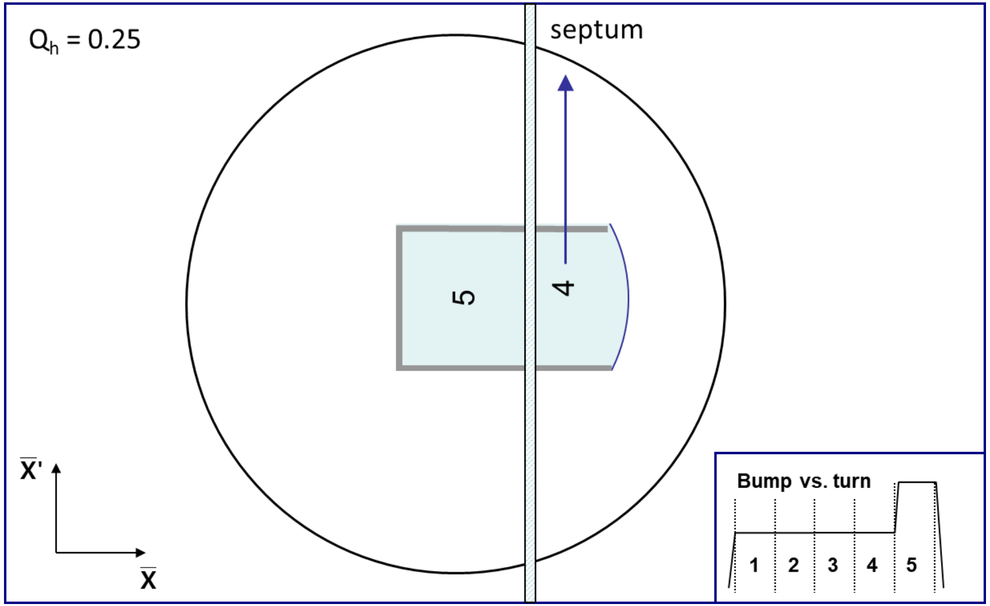

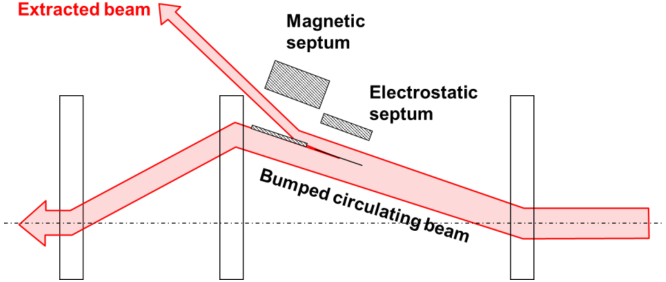

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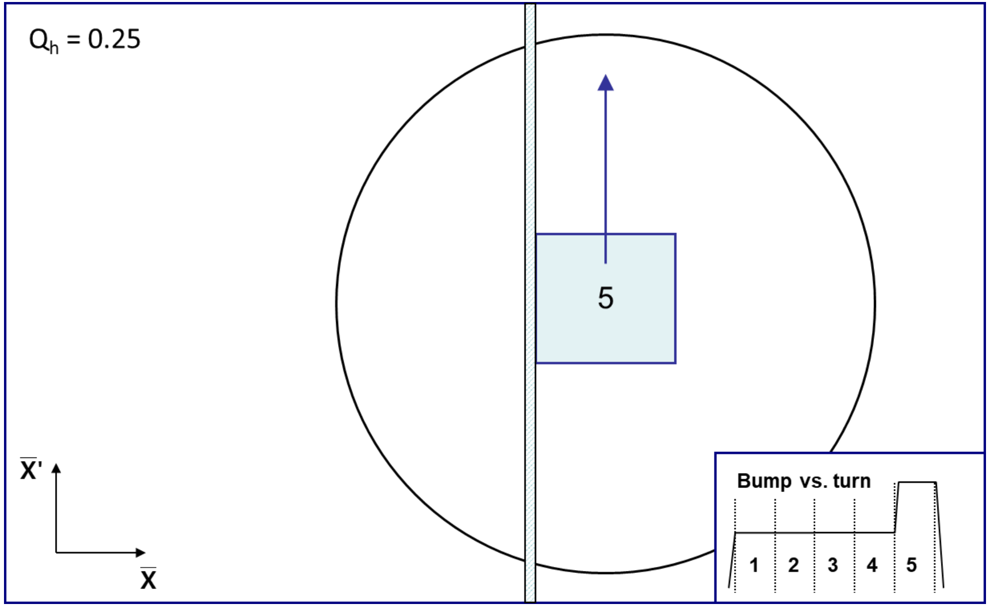

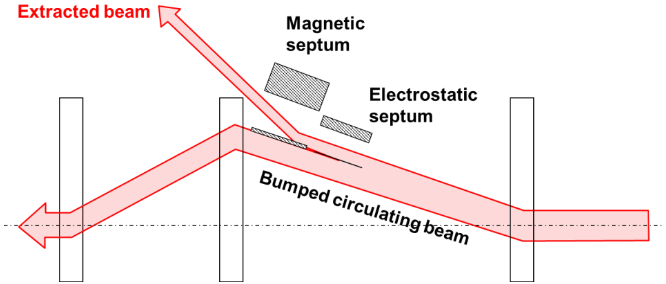

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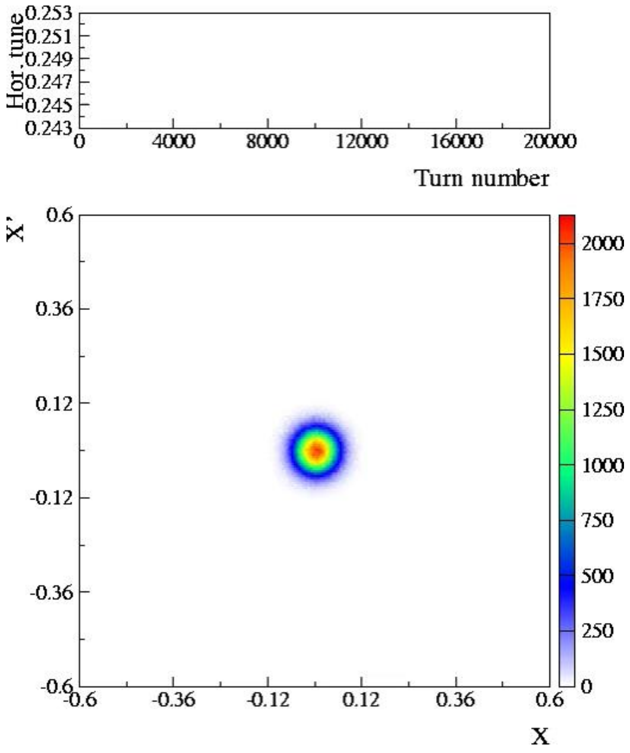
Extraction techniques : Resonant extraction, Multi-turn extraction

- Principle
  - Direct evolution of the PS continuous extraction,
    - significantly lower losses (no particles at the septum in transverse plane)
    - Phase space matching improved with respect to existing non-resonant multi-turn extraction - ‘beamlets’ have similar emittance and optical parameters
  - Adiabatic capture of beam in stable “islands”
    - Use non-linear fields (sextupoles and octupoles) to create islands of stability in phase space
    - A slow (adiabatic) tune variation to cross a resonance and to drive particles into the islands (capture) with the help of transverse excitation (using damper)
    - Variation of field strengths to separate the islands in phase space
- Challenges
  - Highly non-linear, and complex, beam-dynamics
- Applications
  - At CERN PS

Extraction techniques : Resonant extraction, PS Multi-turn extraction (MTE)



a. Unperturbed beam

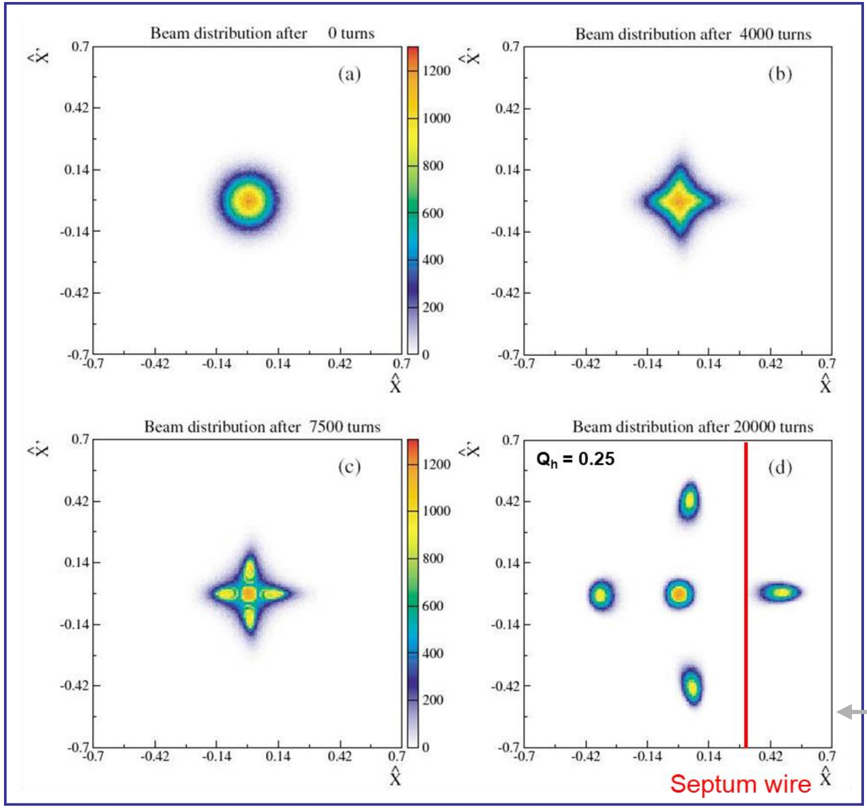
b. Increasing non-linear fields

a. Beam captured in stable islands

b. Islands separated and beam bumped across septum – extracted in 5 turns

Courtesy M. Giovannozzi: MTE Design Report, CERN-2006-011, 2006

Extraction techniques : Resonant extraction, PS Multi-turn extraction (MTE)



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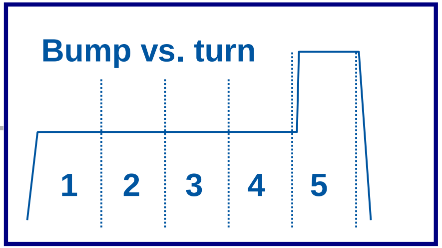
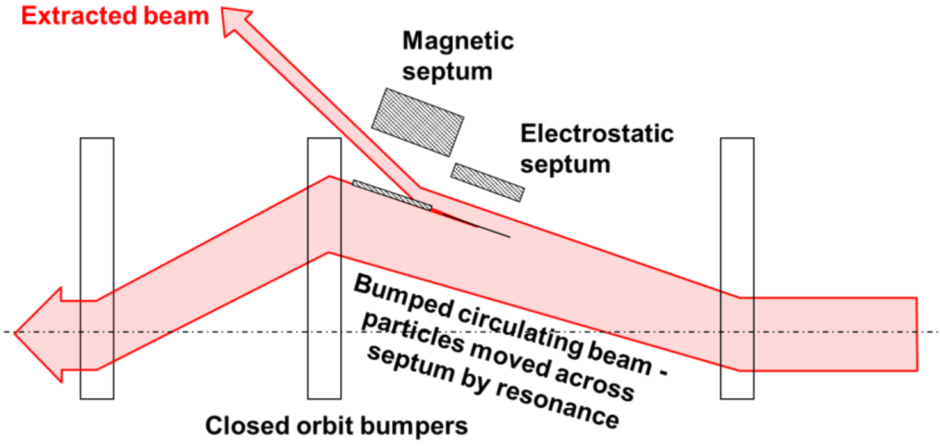


Courtesy M. Giovannozzi: MTE Design Report, CERN-2006-011, 2006

Extraction techniques : Resonant extraction, slow extraction

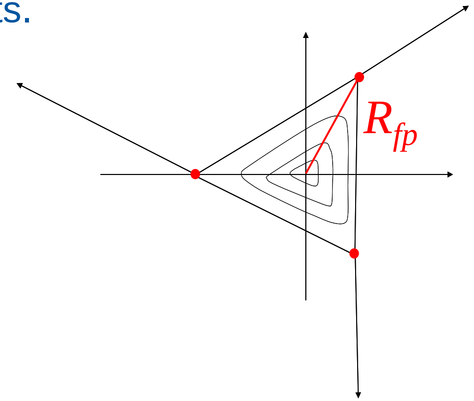
- Principle
  - Slow bumpers move the beam near the septum
    - Tune adjusted close to nth order betatron resonance
    - Multipole magnets excited to define stable area in phase space, size depends on $\Delta Q = Q - Q_r$
  - Provides a continuous beam ‘spill’ to experiments, over any length of times from milliseconds to hours
- Challenges
  - Non-linear beam dynamics
  - Lossy process
- Applications
  - At CERN PS and SPS
  - At BNL AGS until 2000 and Booster



Extraction techniques : Resonant extraction, slow extraction

- 3rd order resonances
  - Sextupole fields distort the circular normalised phase space particle trajectories.
  - Stable area defined, delimited by unstable Fixed Points.

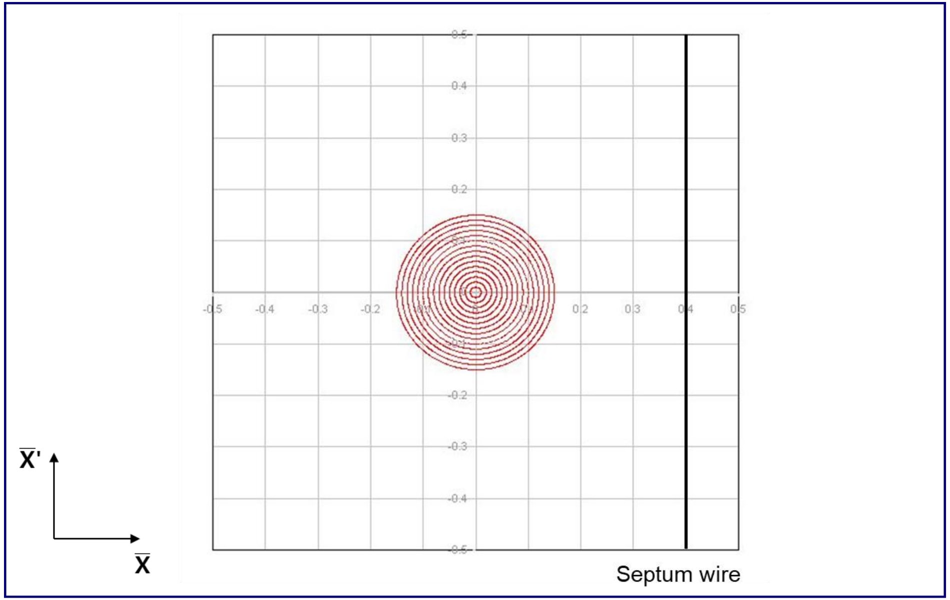
$$R_{fp}^{1/2} \propto \Delta Q \cdot \frac{1}{k_2}$$

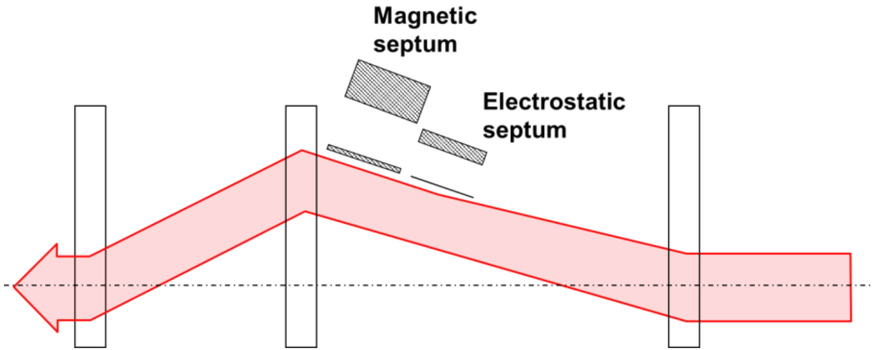


- Sextupole magnets arranged to produce suitable phase space orientation of the stable triangle at thin electrostatic septum
- Stable area can be reduced by…
  - Increasing the sextupole strength, or…
  - Fixing the sextupole strength and scanning the machine tune Qh (and therefore the resonance) through the tune spread of the beam

Extraction techniques : Resonant extraction, slow extraction

- Evolution of the phase space for slow extraction





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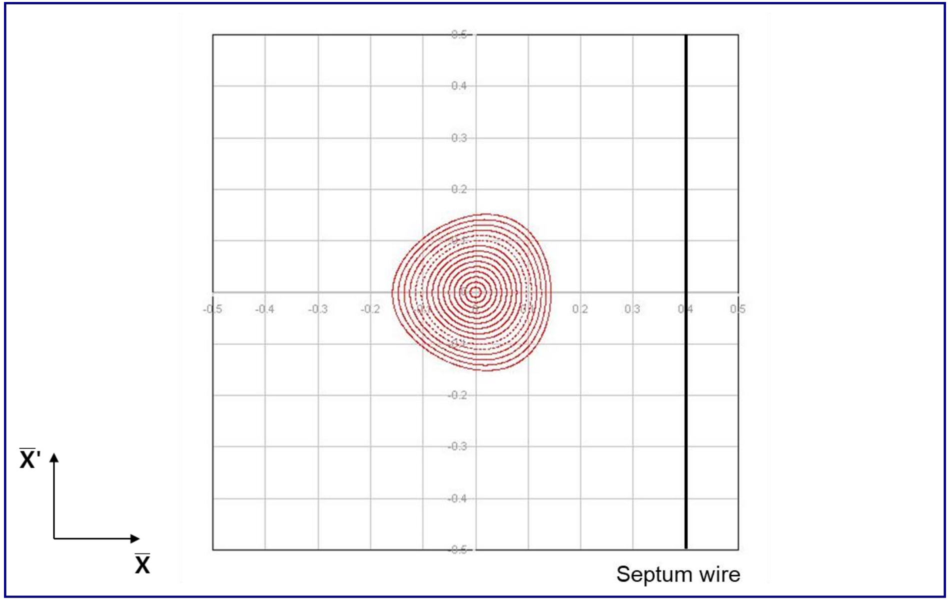

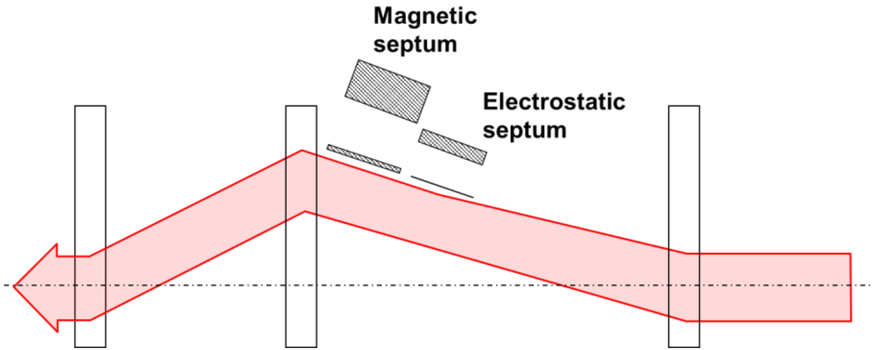

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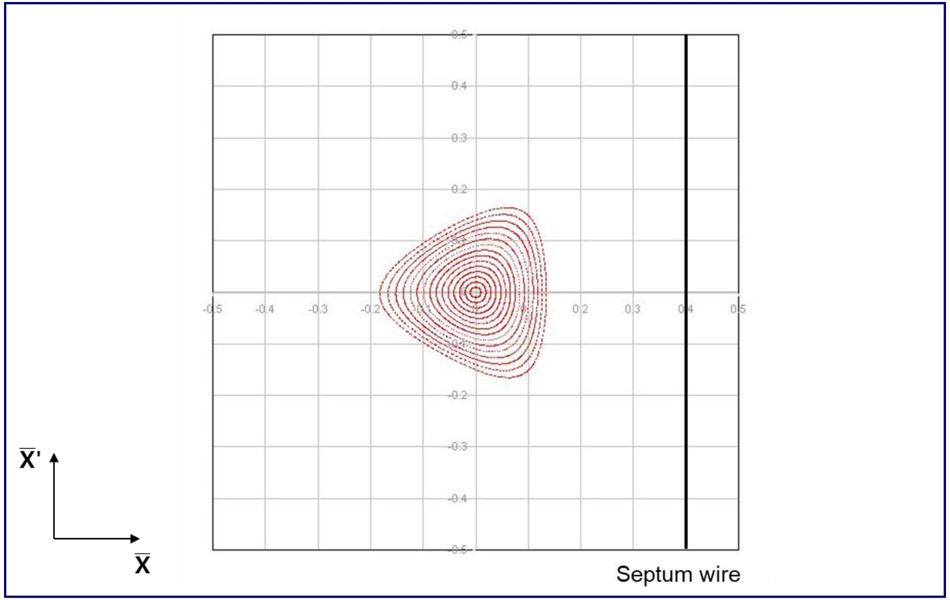
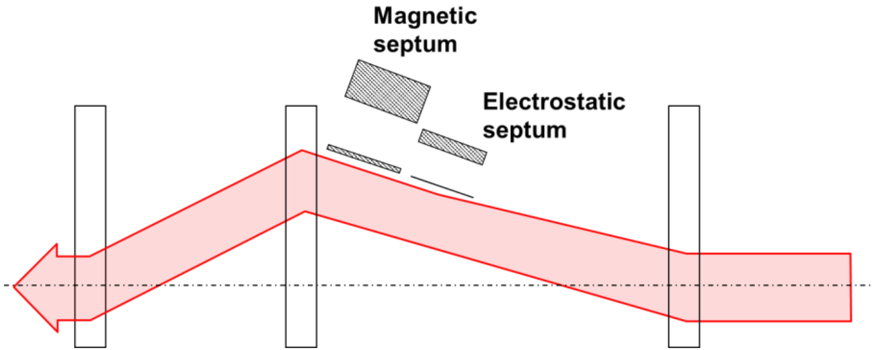
- Evolution of the phase space for slow extraction





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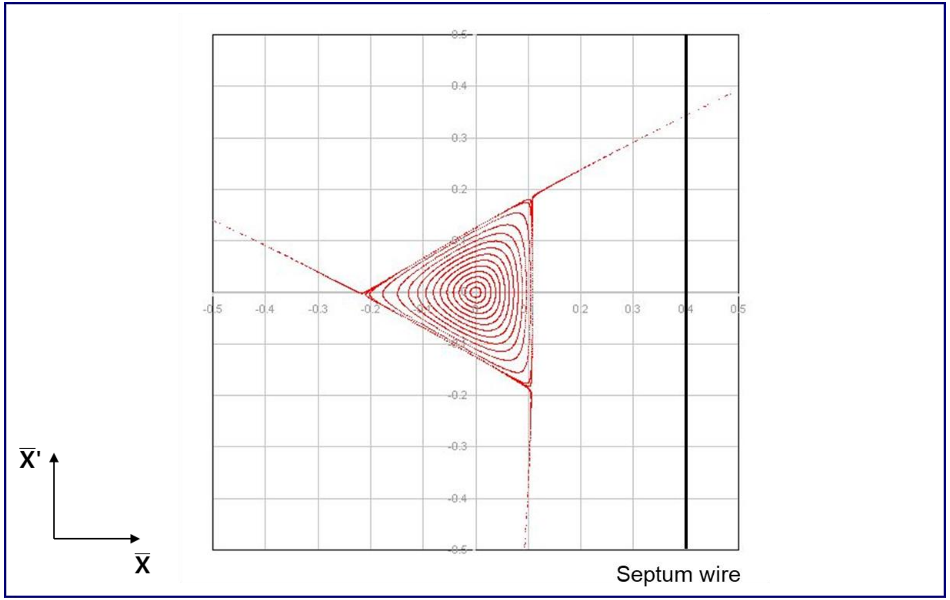

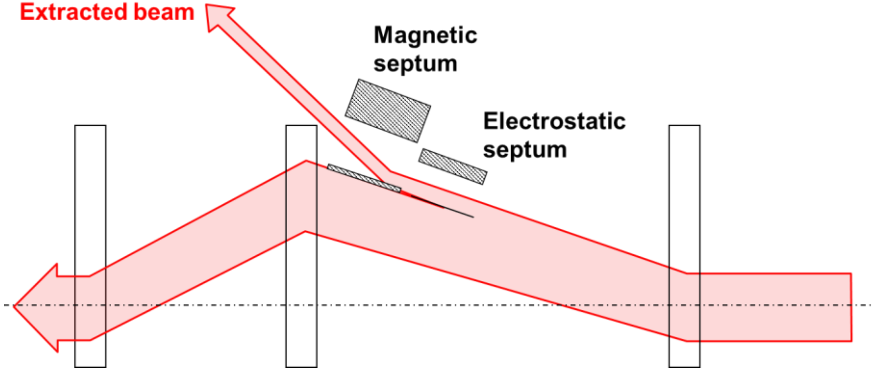

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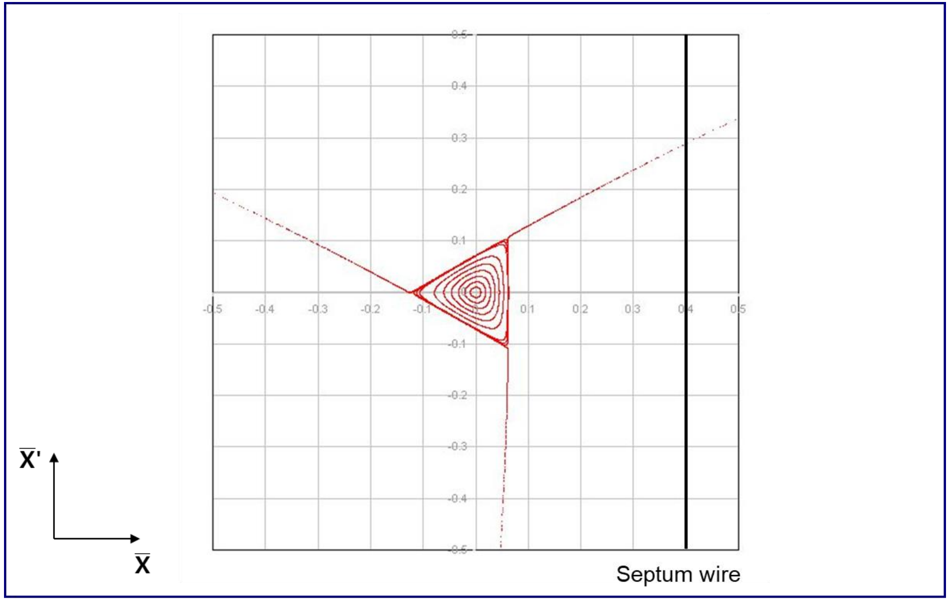

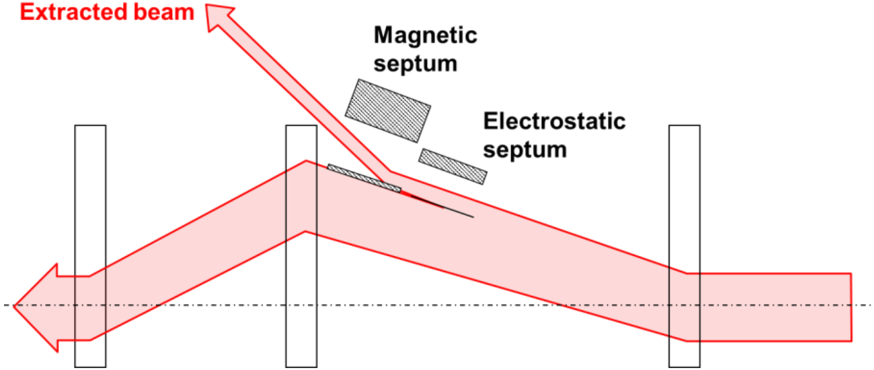

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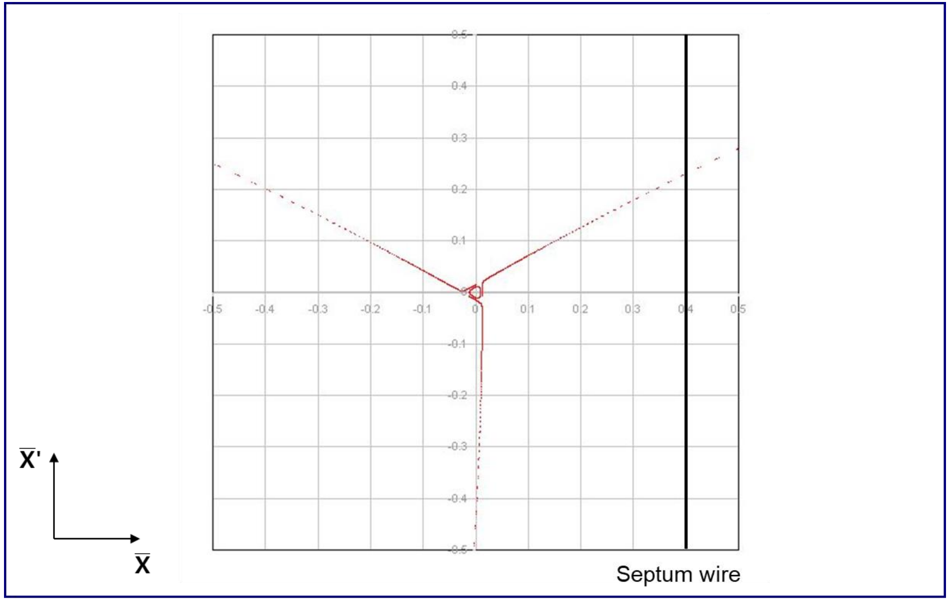
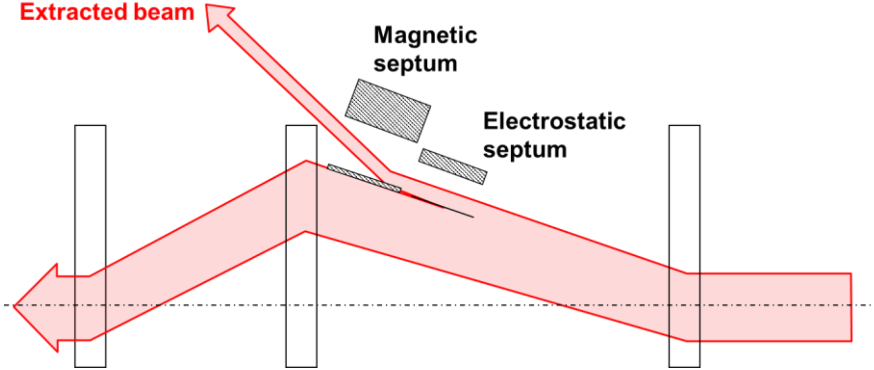
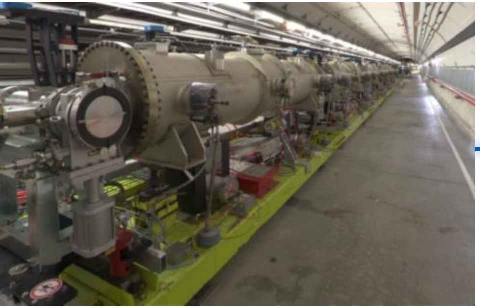
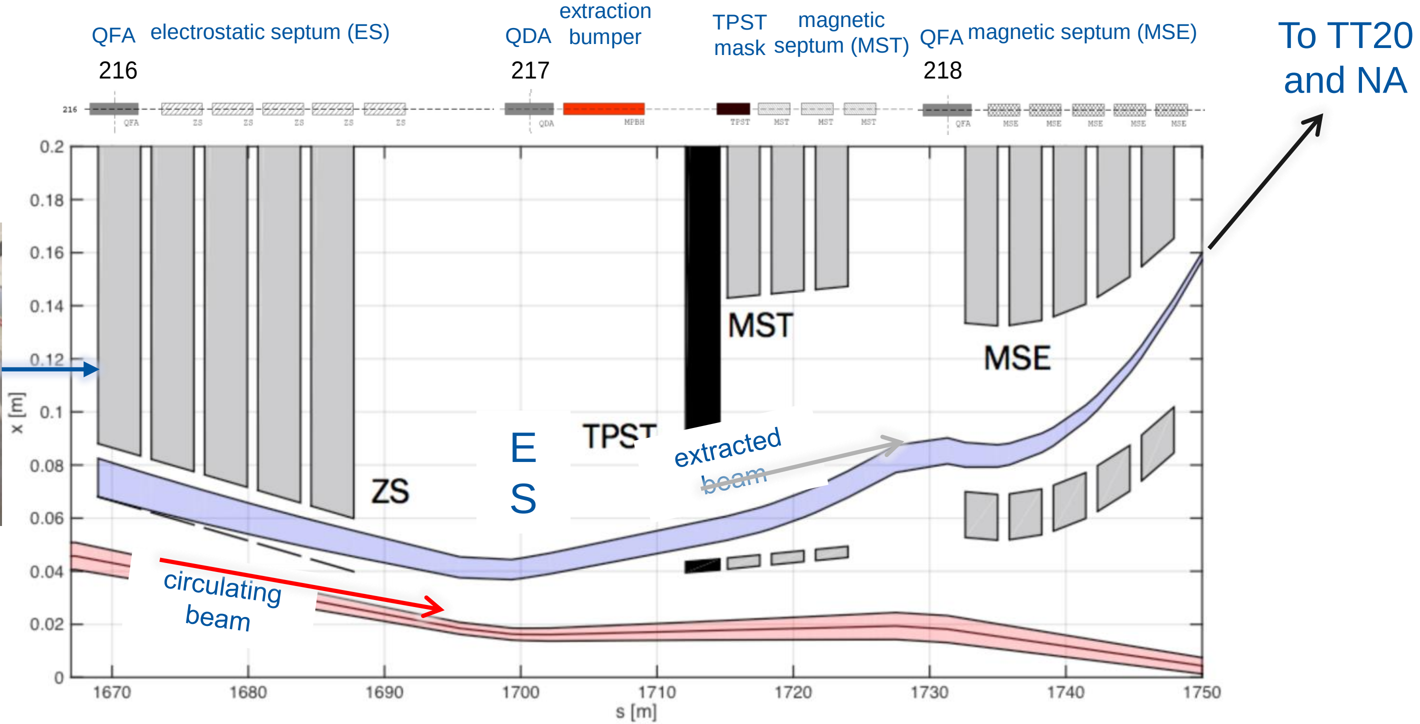




Extraction techniques : Resonant extraction, slow extraction from the SPS





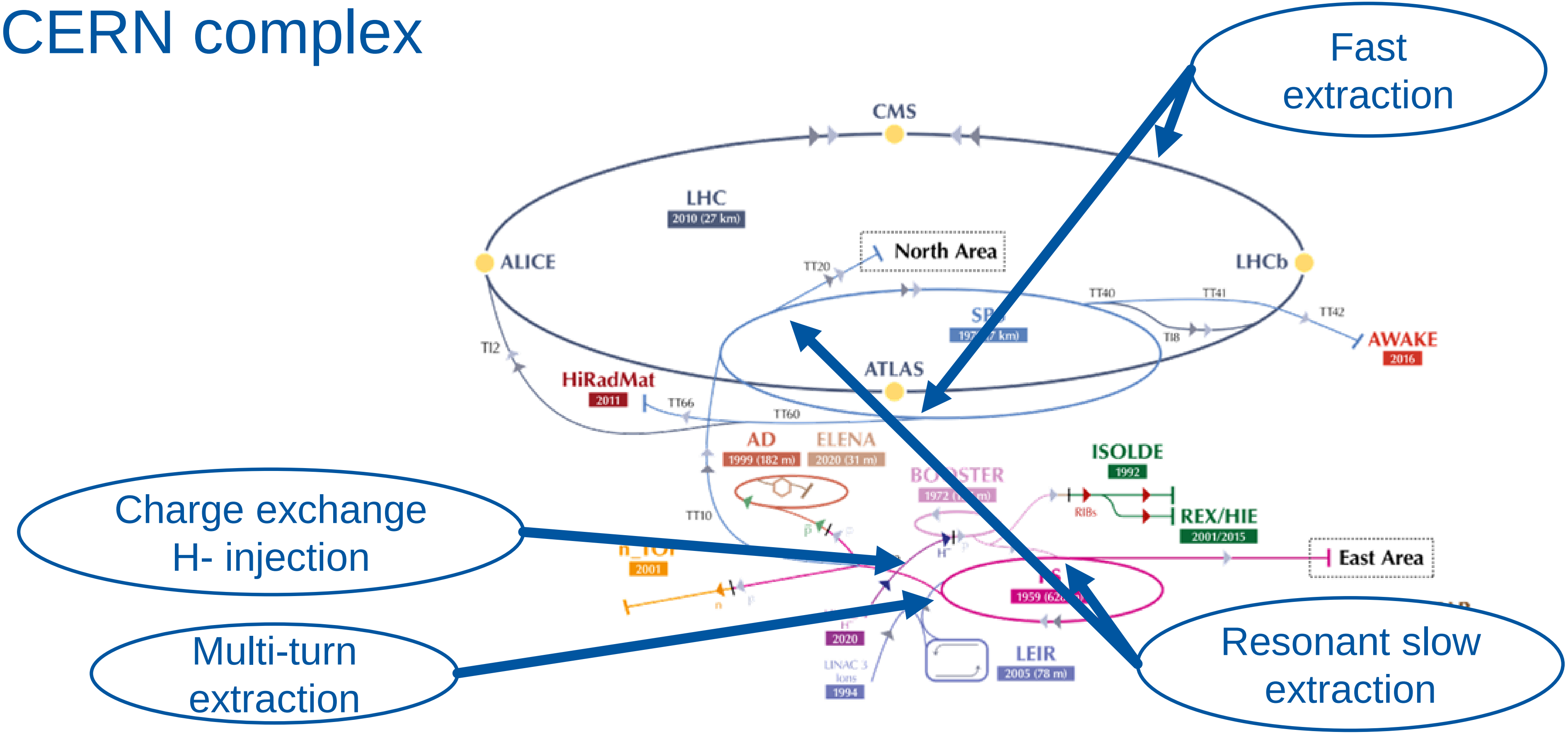
Extraction techniques : Summary

- Single-turn fast extraction:
  - for transfer between machines in accelerator chain, beam abort, etc.
- Non-resonant (fast) multi-turn extraction
  - slice beam into equal parts for transfer between machine over a few turns.
- Resonant low-loss (fast) multi-turn extraction
  - create stable islands in phase space: slice off over a few turns.
- Resonant (slow) multi-turn extraction
  - create stable area in phase space and slowly drive particles into resonance →long spill over many thousand turns.

Layout

- Introduction
- Injection techniques
  - Fast injection
    - Errors, filamentation and blow-up
  - Multi-turn injection
  - Charge exchange technique
  - Lepton injection
- Extraction techniques
  - Fast extraction
  - Multi-turn extraction
  - Resonant extraction
- Conclusion

CERN complex



Further reading (with the formulae !), and ressources

- CAS 2017 on Beam injection, extraction and transfer at https://indico.cern.ch/event/451905/
  - This talk, more detailed and with formulae by M. Fraser https://indico.cern.ch/event/451905/contributions/2159062/
  - Overlooked here, timing and synchronization by RF expert H. Damerau https://indico.cern.ch/event/451905/contributions/2159053/
  - Detailed talk on resonant slow extraction by P. Bryant https://indico.cern.ch/event/451905/contributions/2159064/
  - Exotic extraction methods that discuss all the possibilities overlooked here by B. Goddard https://indico.cern.ch/event/451905/contributions/2159103
- This CAS lecture on Kickers and Septa by M. Barnes https://indico.cern.ch/event/1018359/contributions/4312229
- CERN GIS machine portal https://gis.cern.ch/gisportal/Machine.htm

Thank you