Injection and extraction - multi-turn injection

USPAS

by
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Multi-turn injection

- Multi-turn injection is the process of injecting >1 beam bunch into a bucket. Why would we want to do that?
- The injector beam density may be limited by the injector capacity, or by space charge effects
- With multi-turn injection, we can sometimes fill (or paint) the horizontal phase space in the receiving ring to increase injected intensity
  - On the condition that the acceptance of receiving machine larger than delivered beam emittance
- Elements used
  - Septum
  - Fast beam bumpers, made out of 3 or 4 dipoles, to create a local beam bump

Basic concept

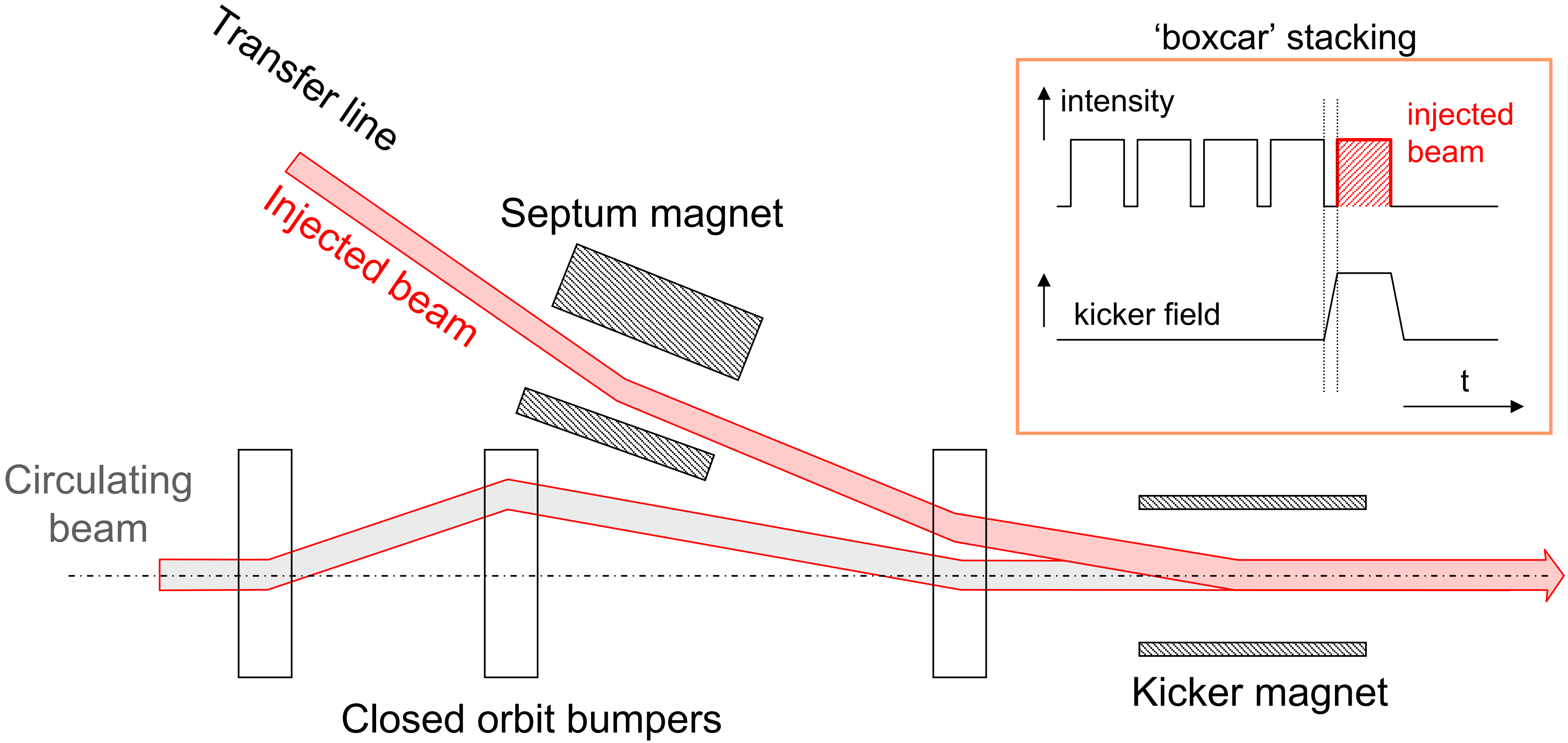
- Multi turn injection is just single turn injection repeated for >1 turn. Kicker magnet is replaced with programmed bump magnets.
- The circulating beam position changes during injection
  - Cannot inject a new bunch directly on top of existing bunch due to conservation of emittance (Liouville's Theorem)
- Multi-turn injection can also be used to paint over the longitudinal phase space (e.g. ramp beam energy during the fill time) (e.g. CERN Booster upgrade)
- First beam goes near the center of the final distribution, each successive injected pulse is placed further and further from the core, like building an onion from the center out
- Typically done in the horizontal plane

Liouville's theorem

- In the absence of collisions and dissipation, the area of an element of phase space along a phase-space trajectory is invariant
- For multi-turn injection, this means that the final emittance of the beam in the ring will be at least the sum of all the emittances of the injected bunches
- Cannot inject a new bunch on top of a circulating bunch

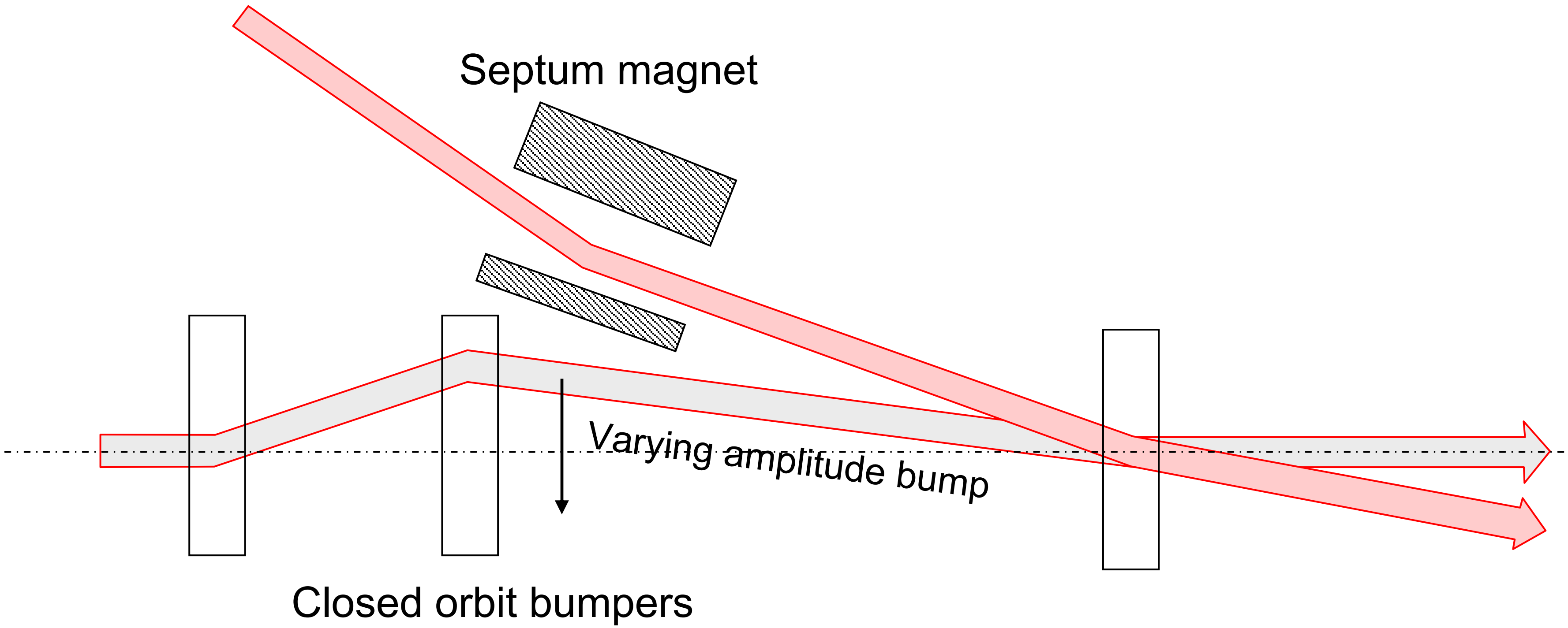
$$\varepsilon_f \geq 1.5 N \varepsilon_i$$ ⟵ (I'm still looking for a good reference for this!)

Single-turn injection



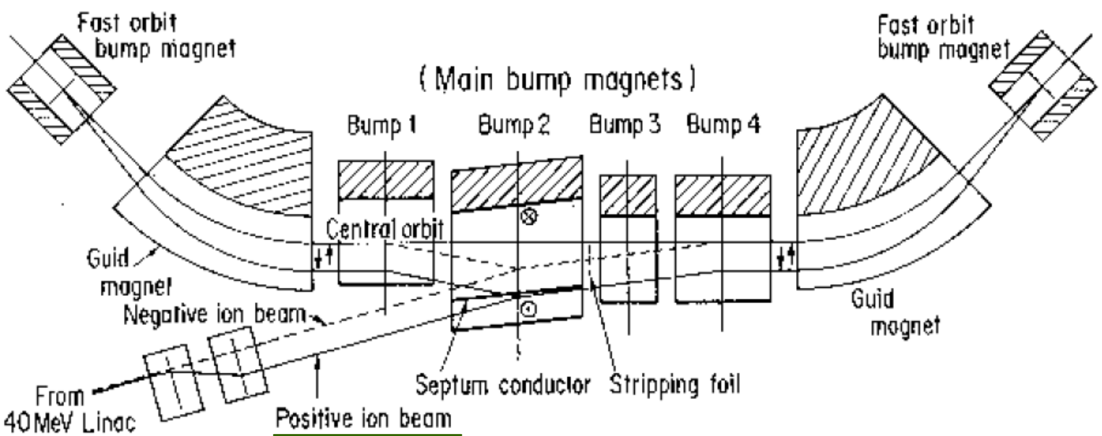
- Septum deflects the beam onto the closed orbit at the center of the kicker
- Kicker compensates for the remaining angle

Multi-turn injection for hadrons



- Bump amplitude varies with time
- Inject a new bunch at each turn
- Phase-space "painting"

Example: KEK Proton Synchrotron



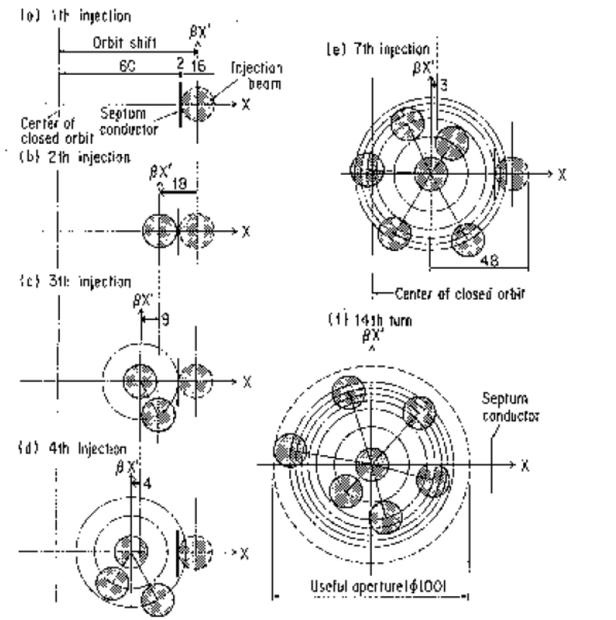


Figure: 2 Injection process in phase space at the septum conductor. (Unit ; mm)

Beam size, horizontal	9 mm (half)
vertical	9 mm (half)
Aperture of the ring, horizontal	50 mm (half)
vertical	20 mm (half)
Revolution frequency (Injection period),	1.1 MHz
Betatron oscillation Q_H / Q_V,	2.17 / 2.30

Both multi-turn and charge exchange injection is possible with this machine

(from I.Sakai et al., EPAC96)

Orbit bumps

- Two magnet bump is simplest
  - Place two magnets $\pi/2$ phase advance upstream and downstream of septum
  - Gives maximum displacement at septum, but no control over angle at septum
- Three magnet bump
  - Don't need a specific phase advance between magnets
  - Still no control over angle
- Four magnet bump
  - Have control over position and angle at the septum for an arbitrary phase advance.

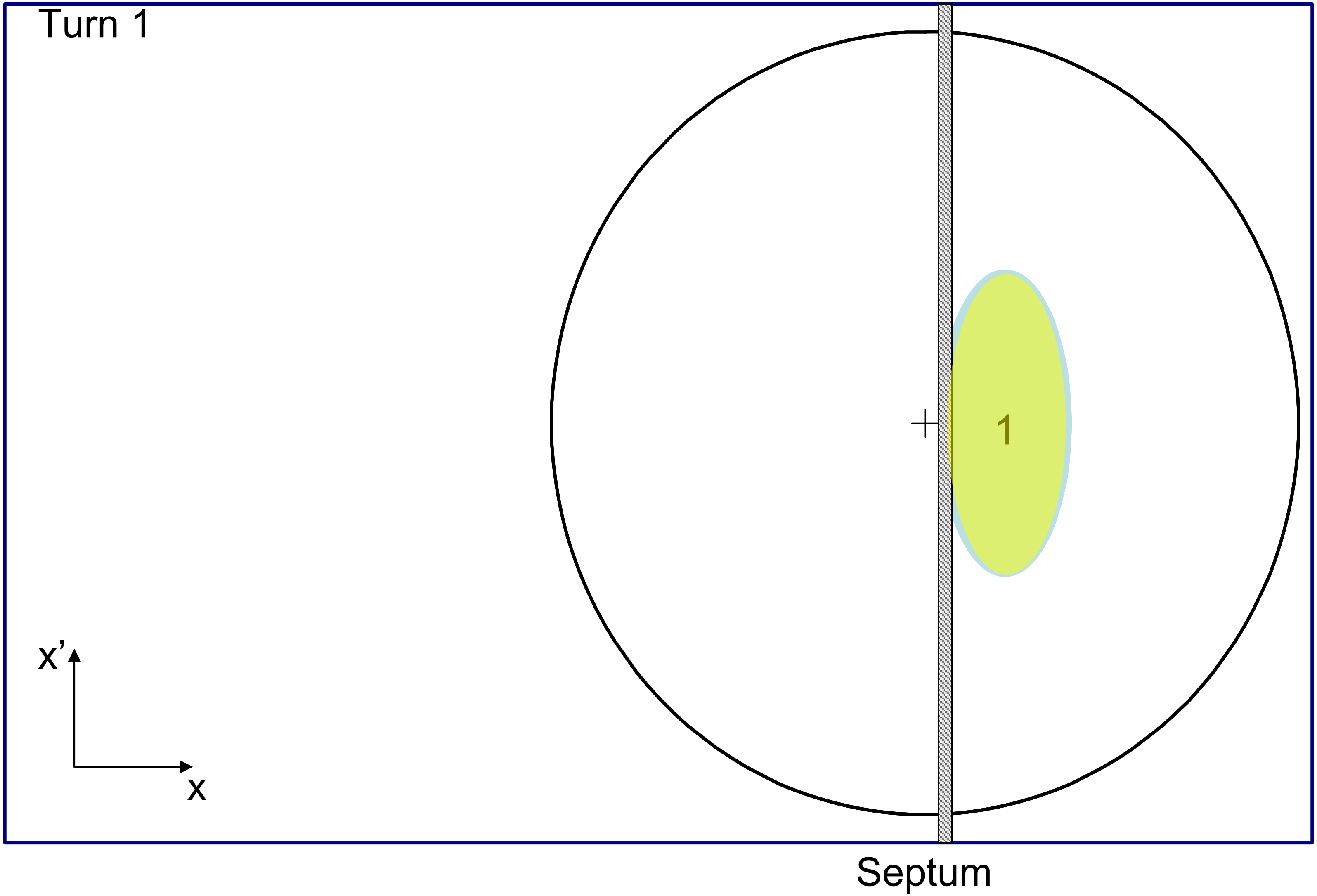
Multi-turn injection for hadrons

- Important aspects of the injection are to:
  - Minimize losses
  - Fill the horizontal phase space most efficiently
- Requirements:
  - Control the tune Q_h accurately
  - Control the bump accurately
  - A thin septum

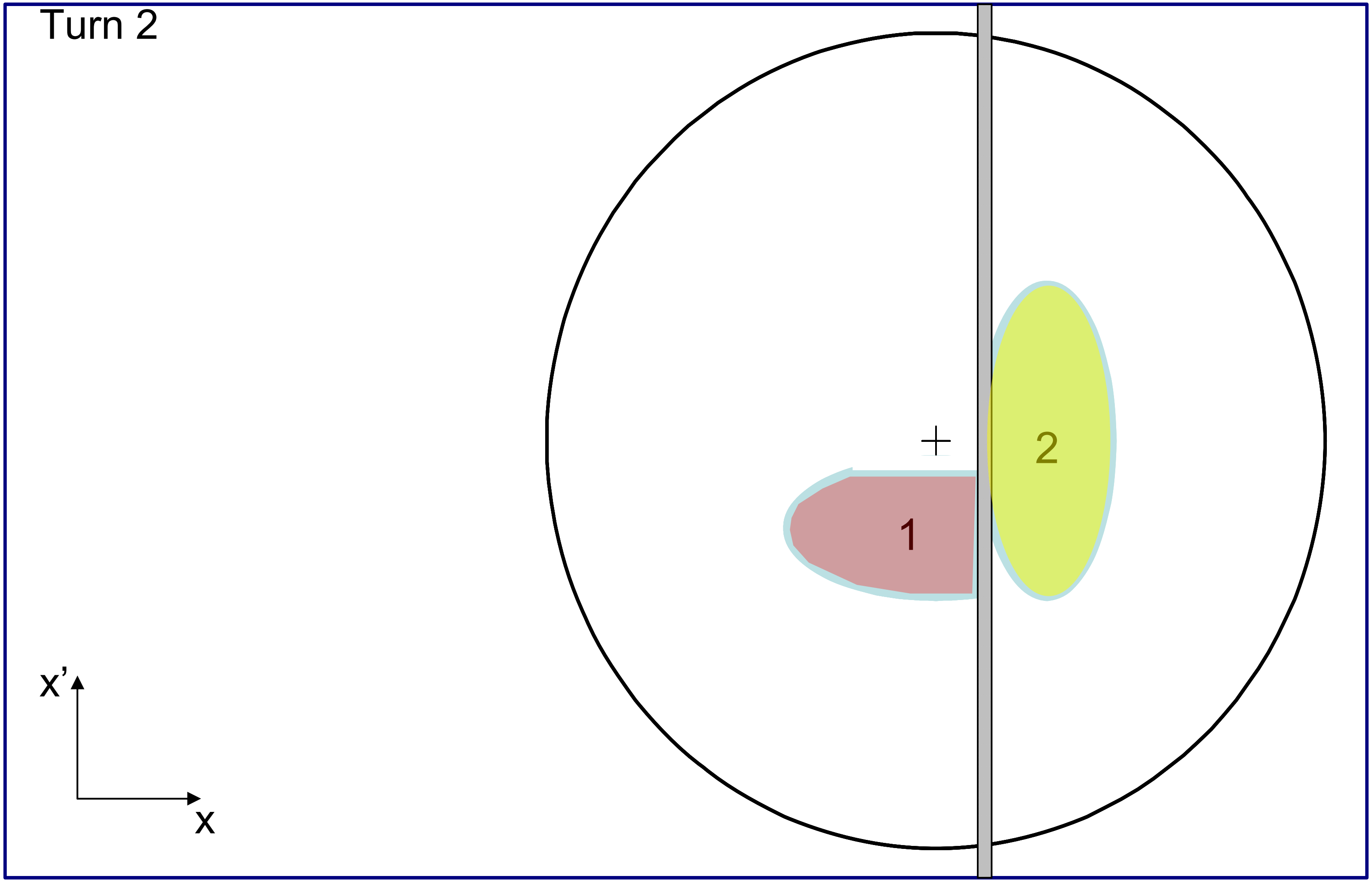
Multi-turn injection for hadrons

- Example: fractional tune $Q_h = 0.25$
  - Beam rotates $\pi/2$ per turn in phase space
- On each turn
  - Inject a new batch
  - Reduce the bump amplitude

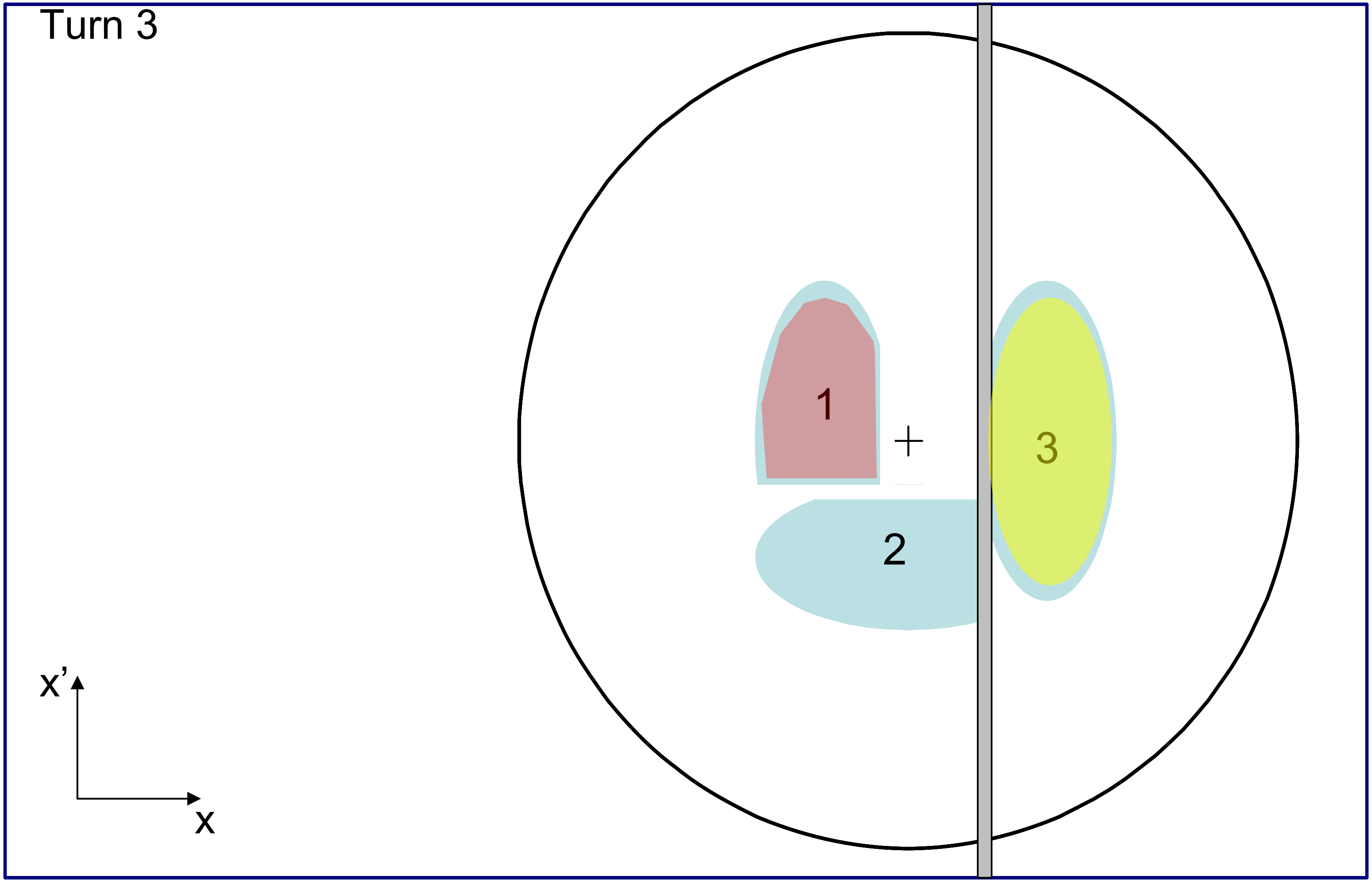
Multi-turn injection for hadrons (B. Goddard)



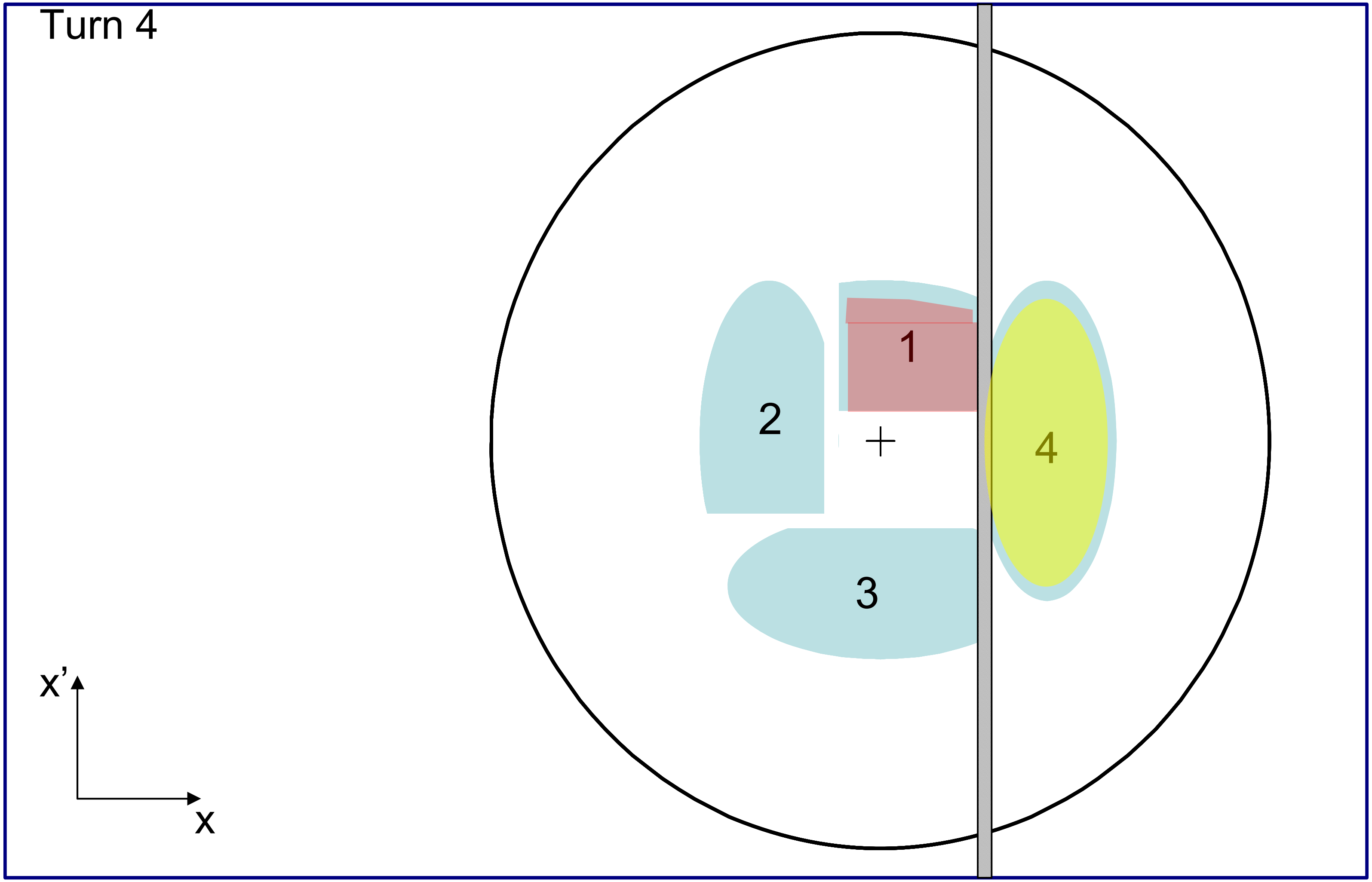
Multi-turn injection for hadrons



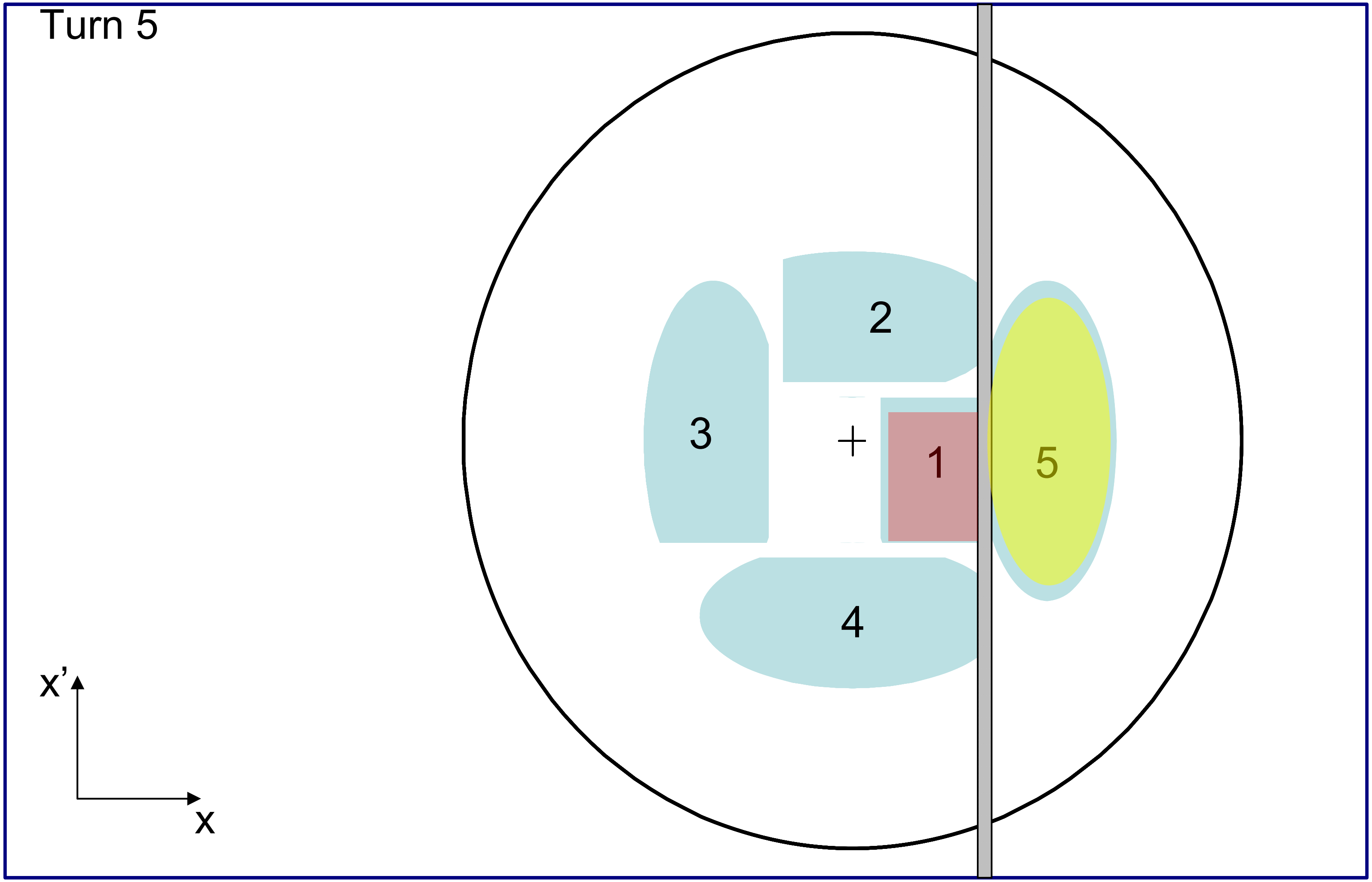
Multi-turn injection for hadrons



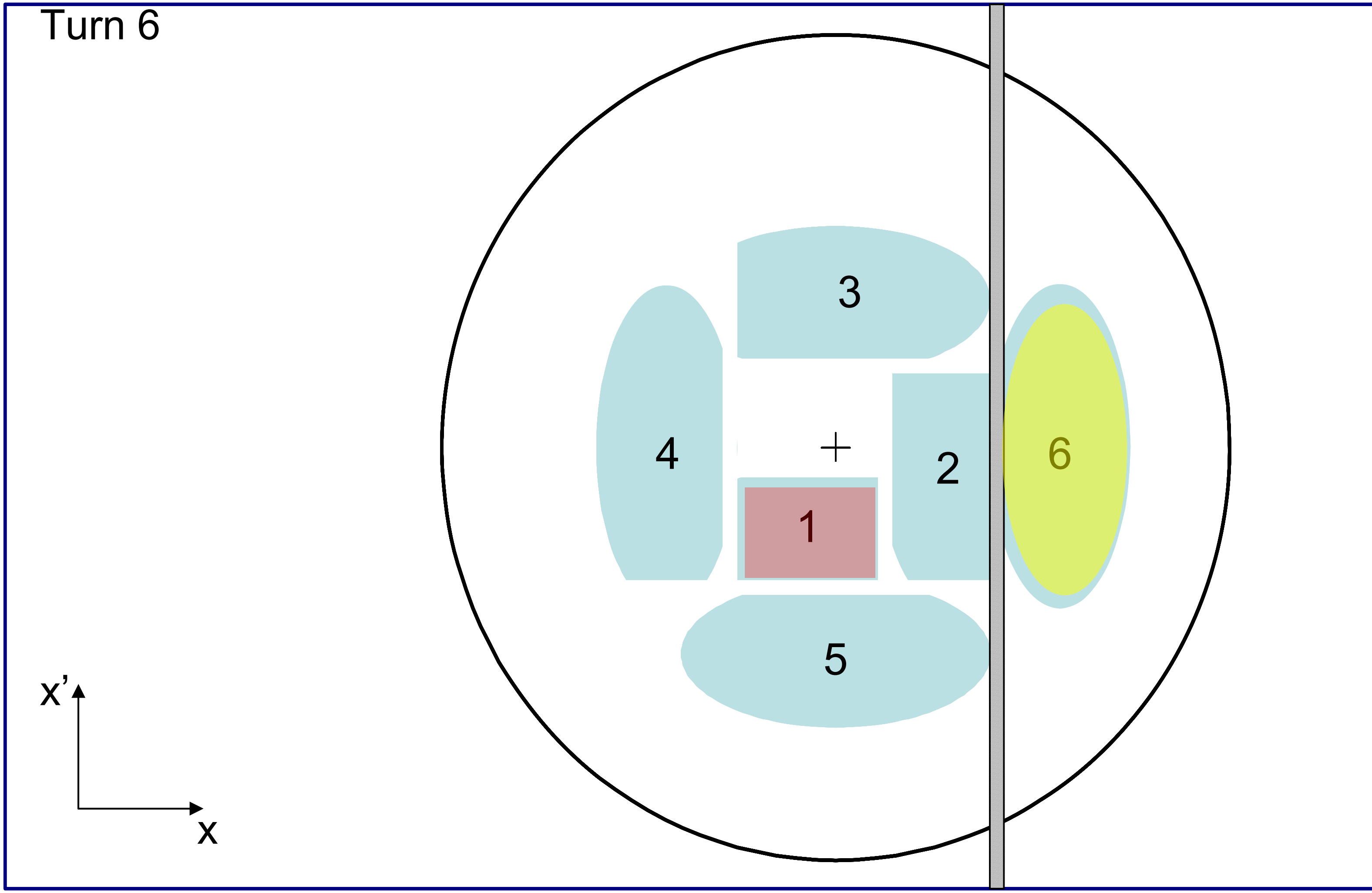
Multi-turn injection for hadrons



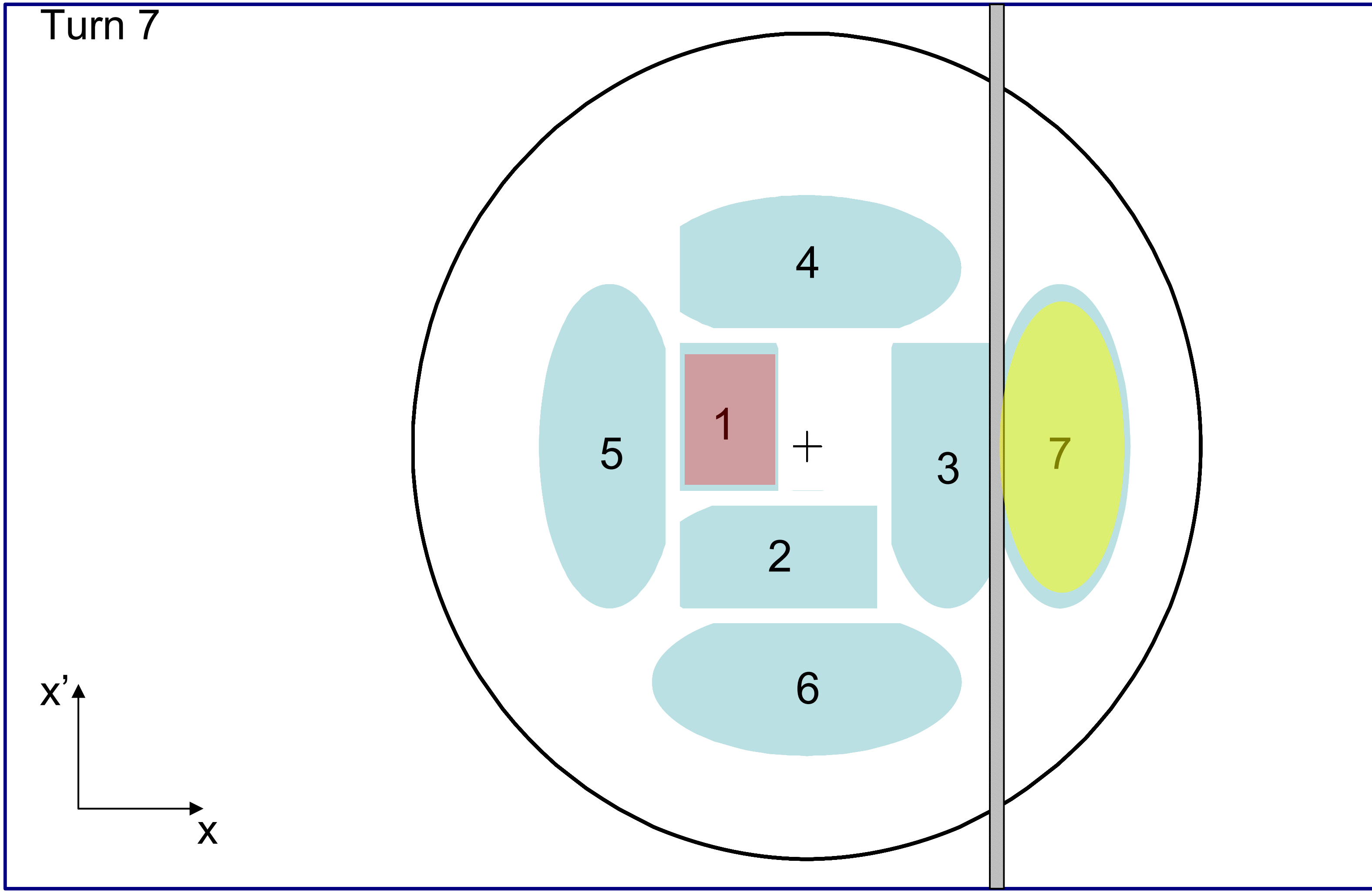
Multi-turn injection for hadrons



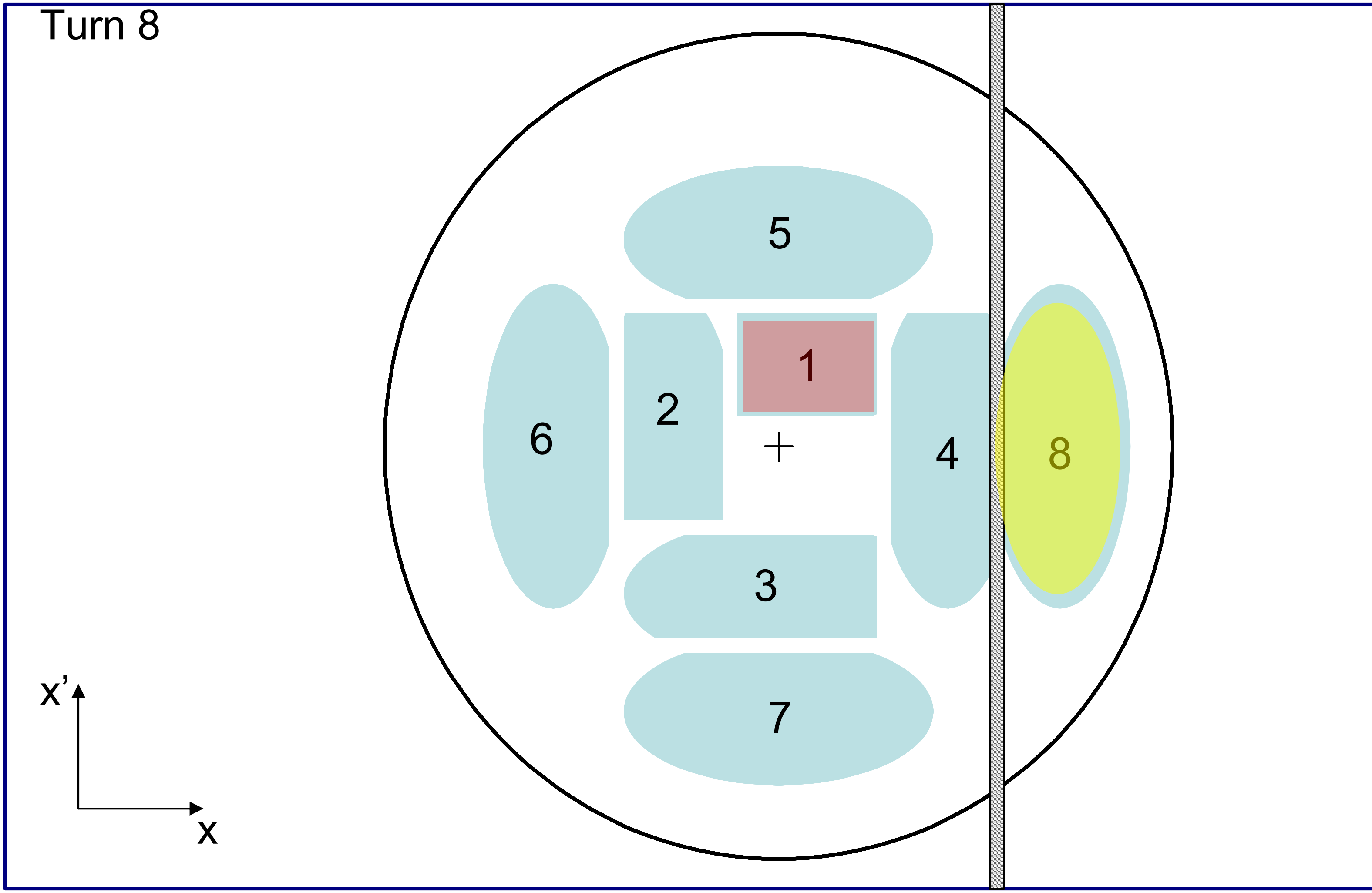
Multi-turn injection for hadrons



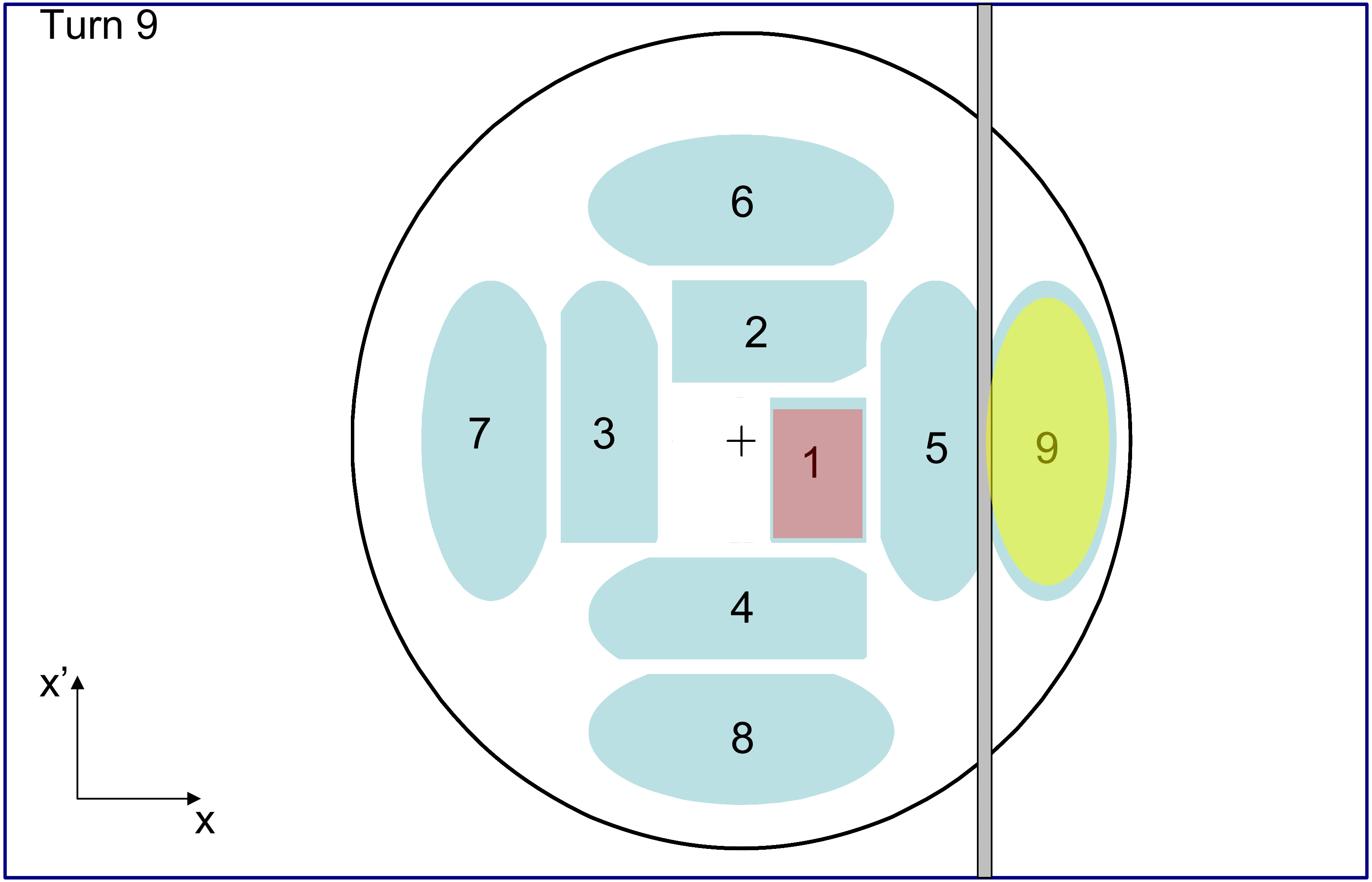
Multi-turn injection for hadrons



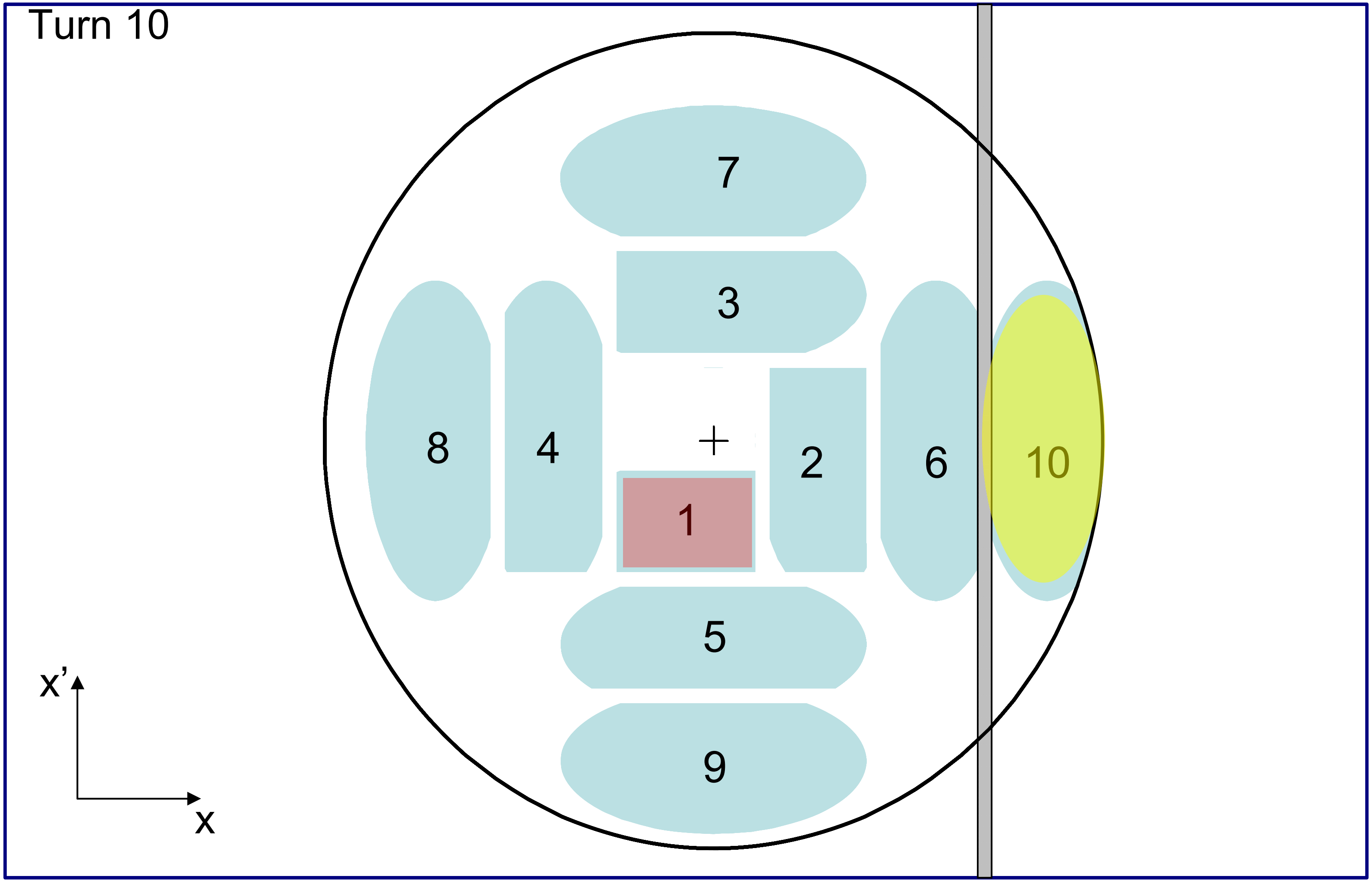
Multi-turn injection for hadrons



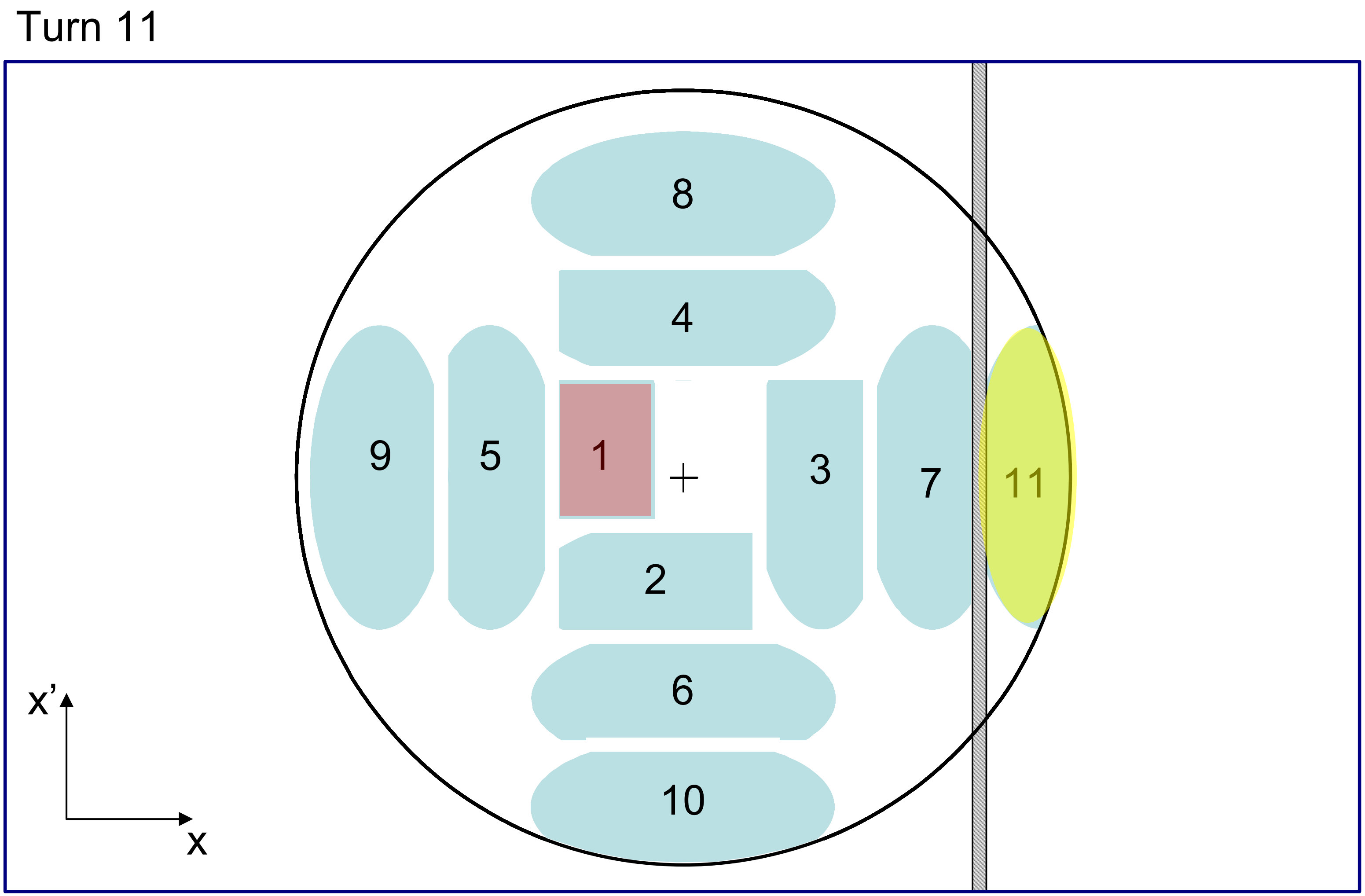
Multi-turn injection for hadrons



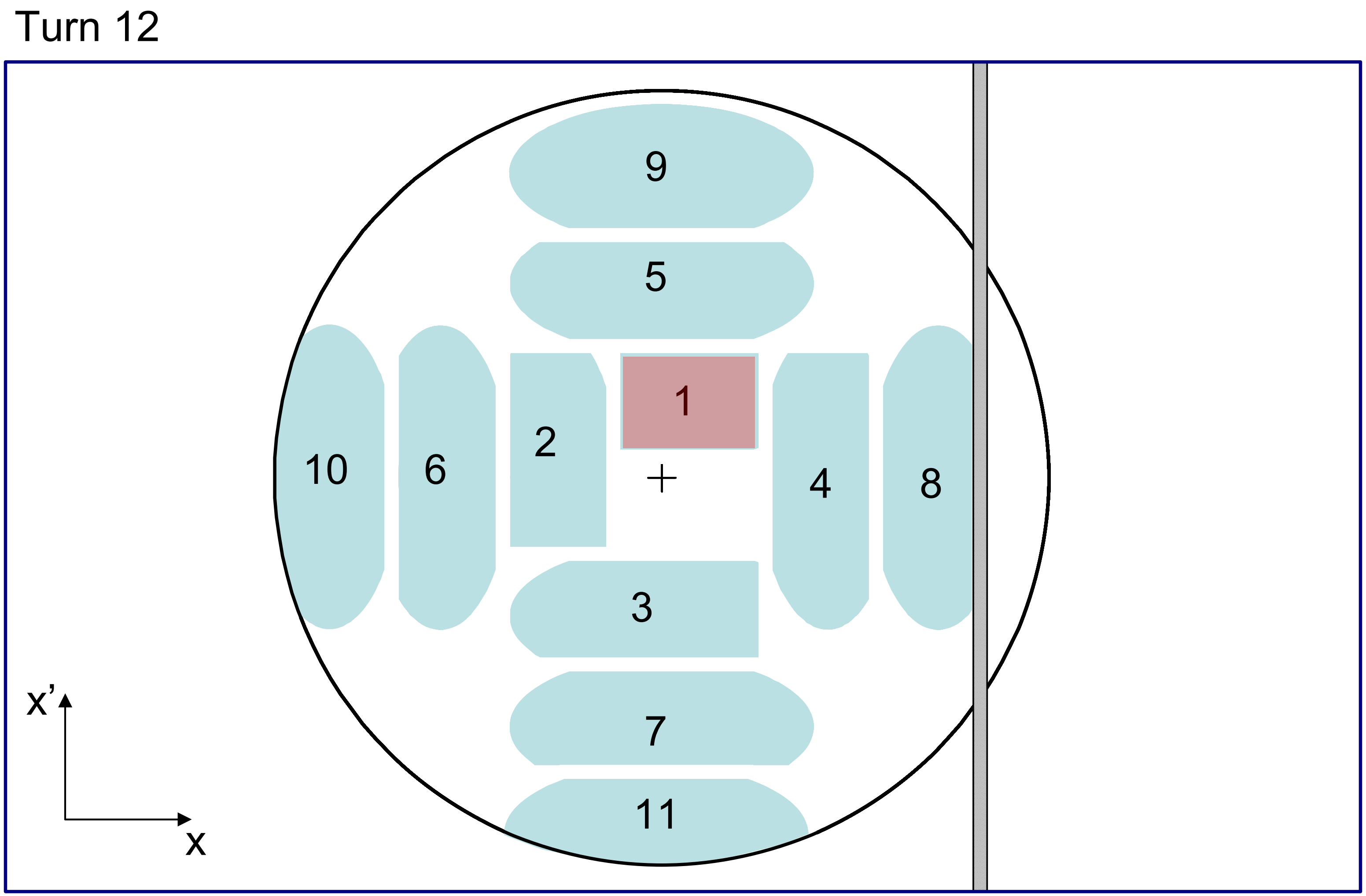
Multi-turn injection for hadrons



Multi-turn injection for hadrons

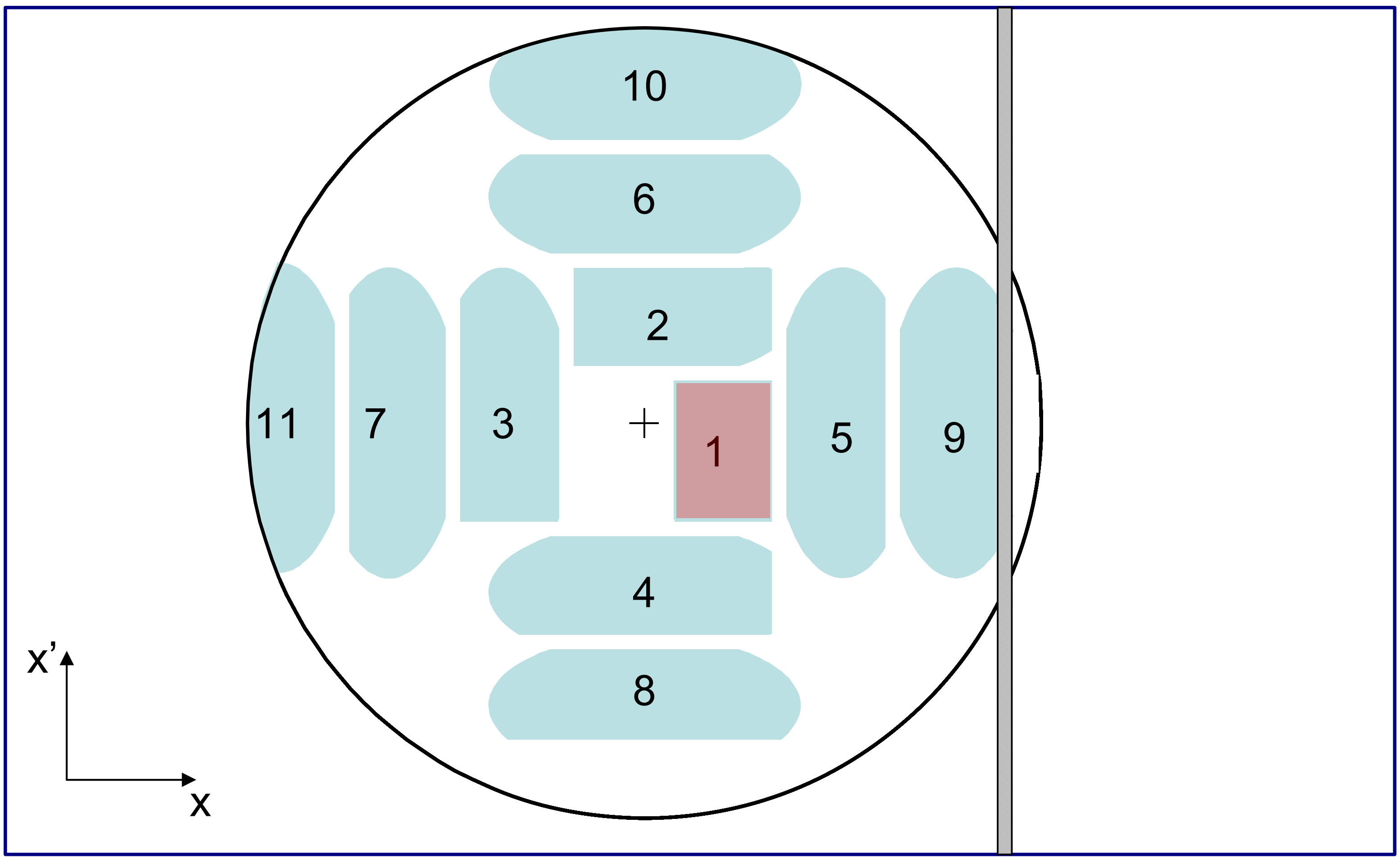


Multi-turn injection for hadrons



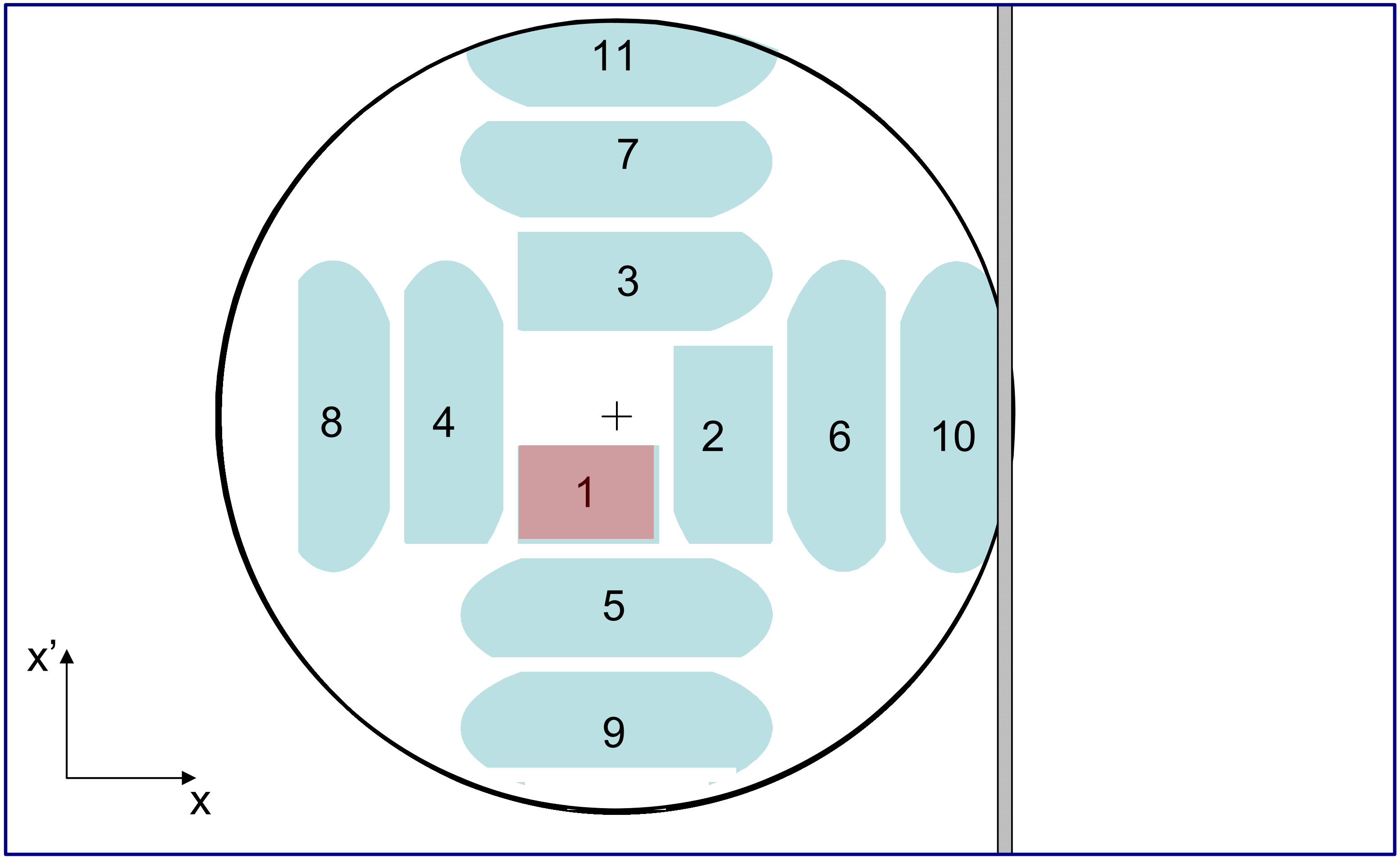
Multi-turn injection for hadrons

Turn 13



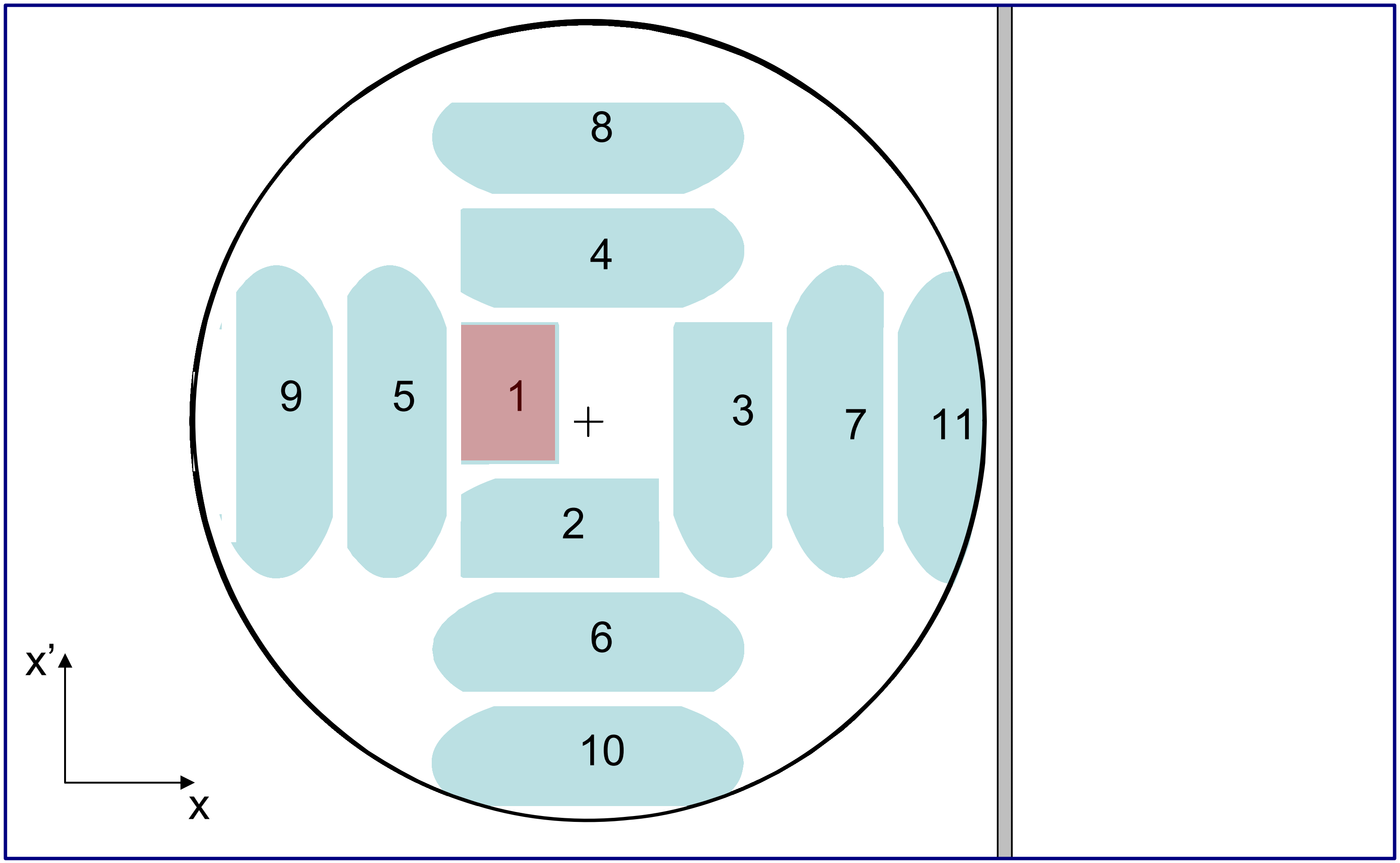
Multi-turn injection for hadrons

Turn 14



Multi-turn injection for hadrons

Turn 15



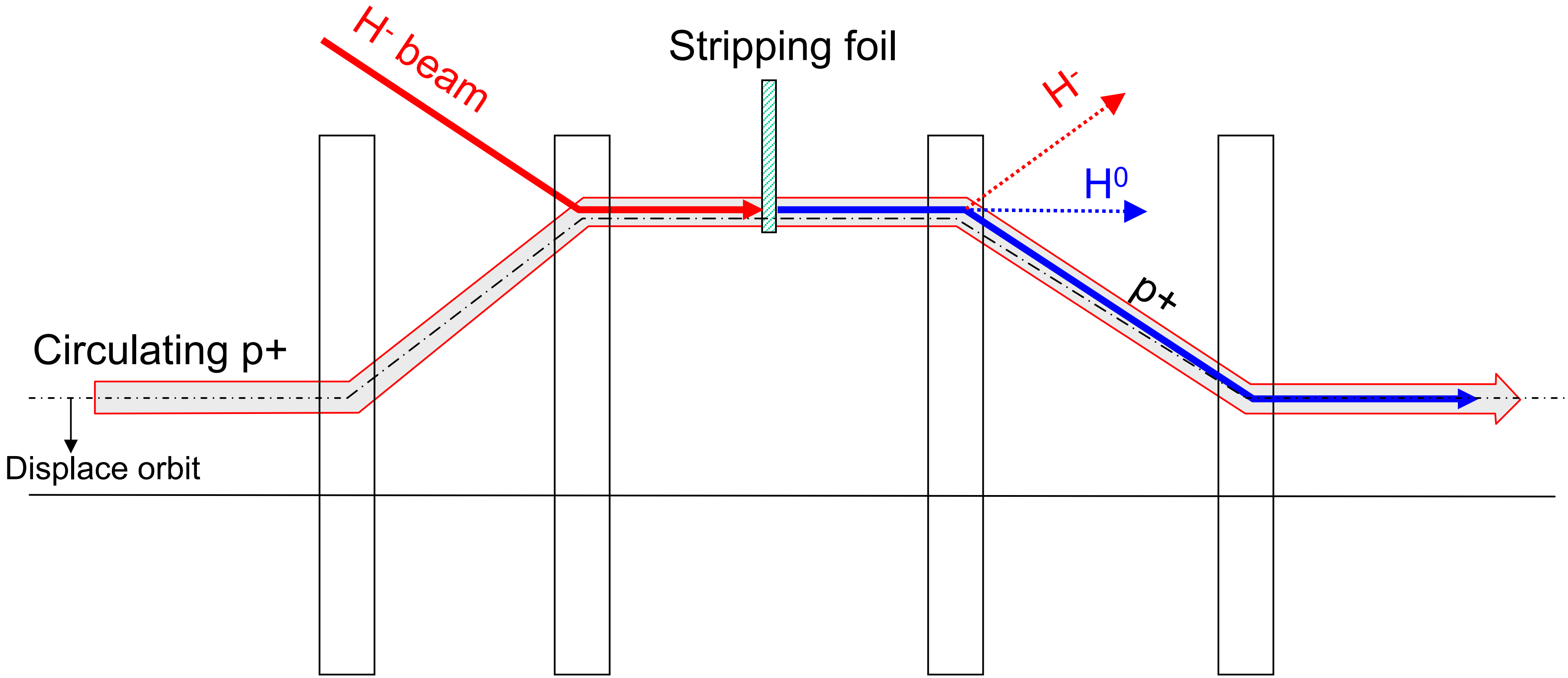
Note: in reality filamentation occurs to produce a quasi-uniform beam

Multi-turn charge-exchange injection

- The concept of Charge Exchange Injection was first discussed in a paper by Budker and Dimov in 1963
- First use of charge exchange injection in ~1968, at Budker Institute, Novosibirsk, USSR (2 stage gas stripping)
- First stripper foil charge exchange injection into the ZGS at Argonne at 50 MeV in 1973 by Ron Martin et al.
- These days many proton synchrotrons and storage rings use charge exchange injection
- Multi-turn injection is an easy way to get around Liouville's theorem

Charge exchange H^- injection

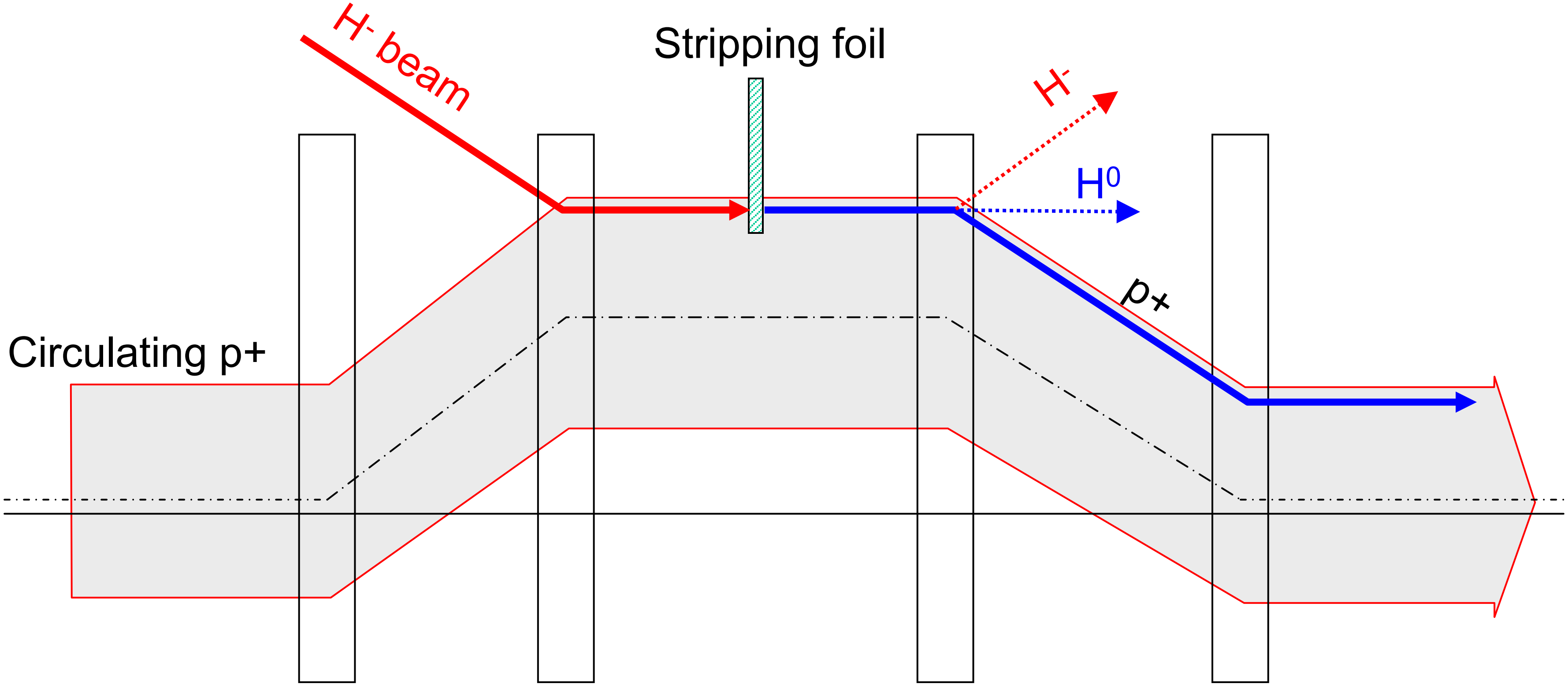
Start of injection process



Injection chicane

Charge exchange H^- injection

End of injection process



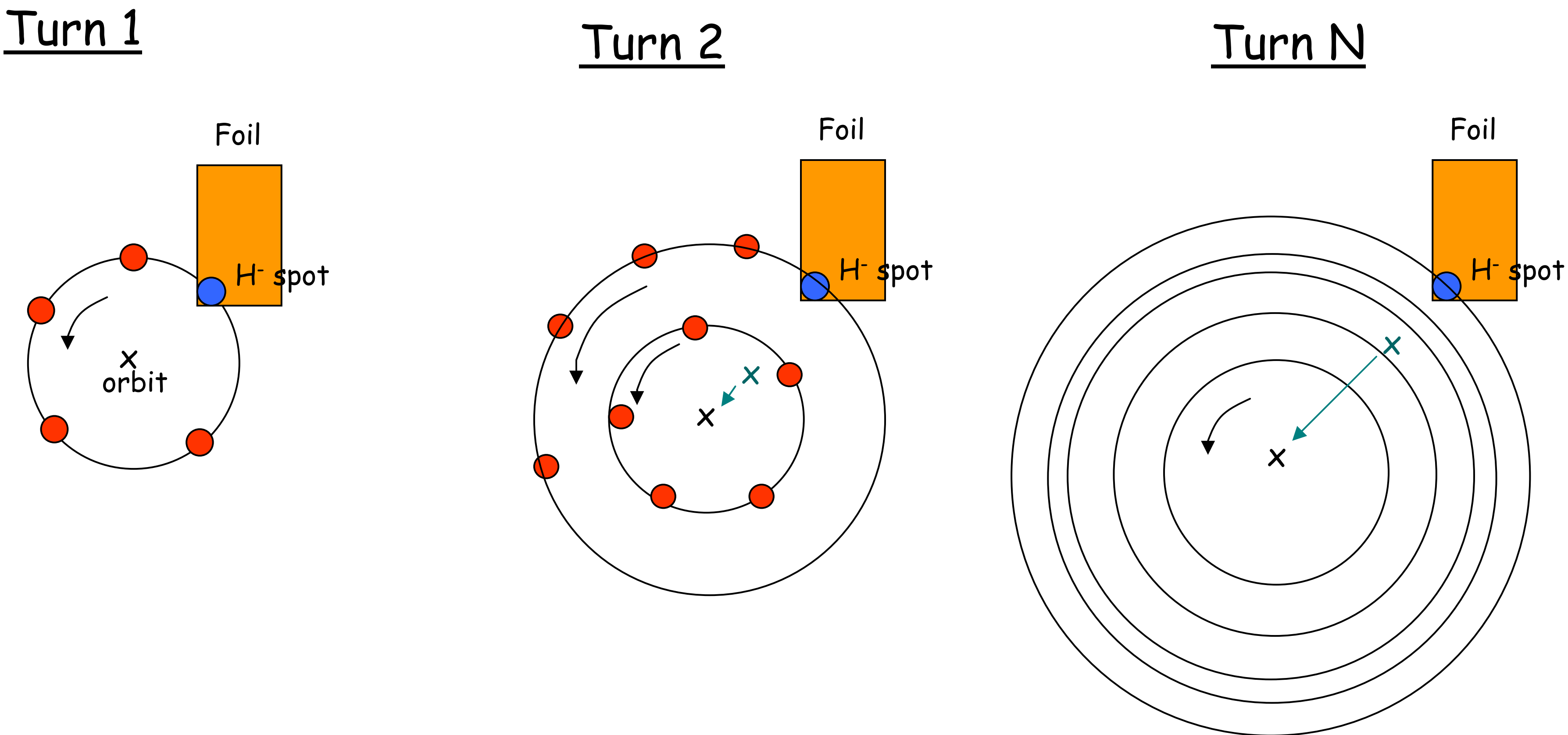
Injection chicane

Charge exchange H^- injection

- The circulating beam orbit is often varied during injection
  - to paint a uniform transverse phase space density to mitigate space charge effects
  - to minimize the number of foil hits, which cause emittance blow up (scattering) and can overheat the foil
- Foil thickness calculated to double-strip most ions (~99%)
  - 50 MeV - 50 $\mu g/cm^2$
  - 800 MeV - 200 $\mu g/cm^2$ (~1 μm of C!)
- Carbon foils generally used – very fragile!
- Injection chicane sometimes reduced or switched off after injection, to avoid excessive foil heating and beam blow up

Injection Painting - transverse

- Transverse painting the beam in the ring allows us to control the size and distribution of the beam.
- This is important for minimizing foil hits (foil heating, emittance growth due to scattering) and controlling space charge effects!



(Courtesy S. Cousineau)

Injection Painting - longitudinal

- Longitudinal painting the beam in the ring allows us to achieve a high momentum spread necessary for beam stability without introducing a momentum tail
- The idea is to vary the injected beam energy during the injection process

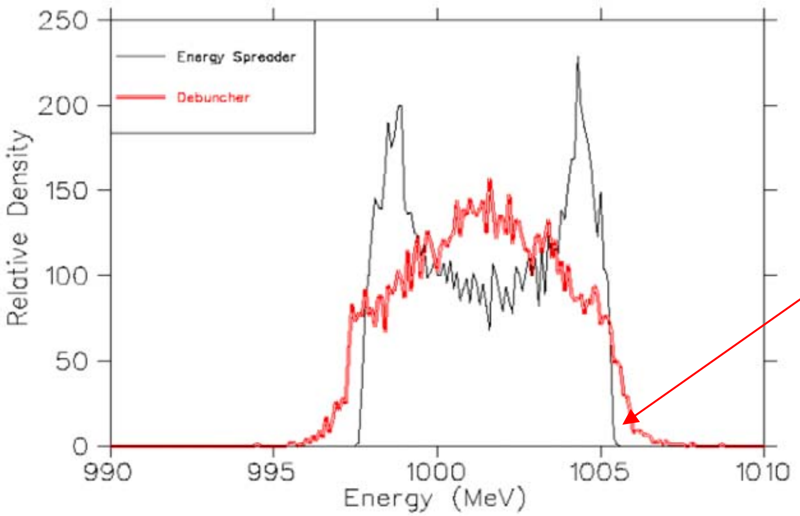
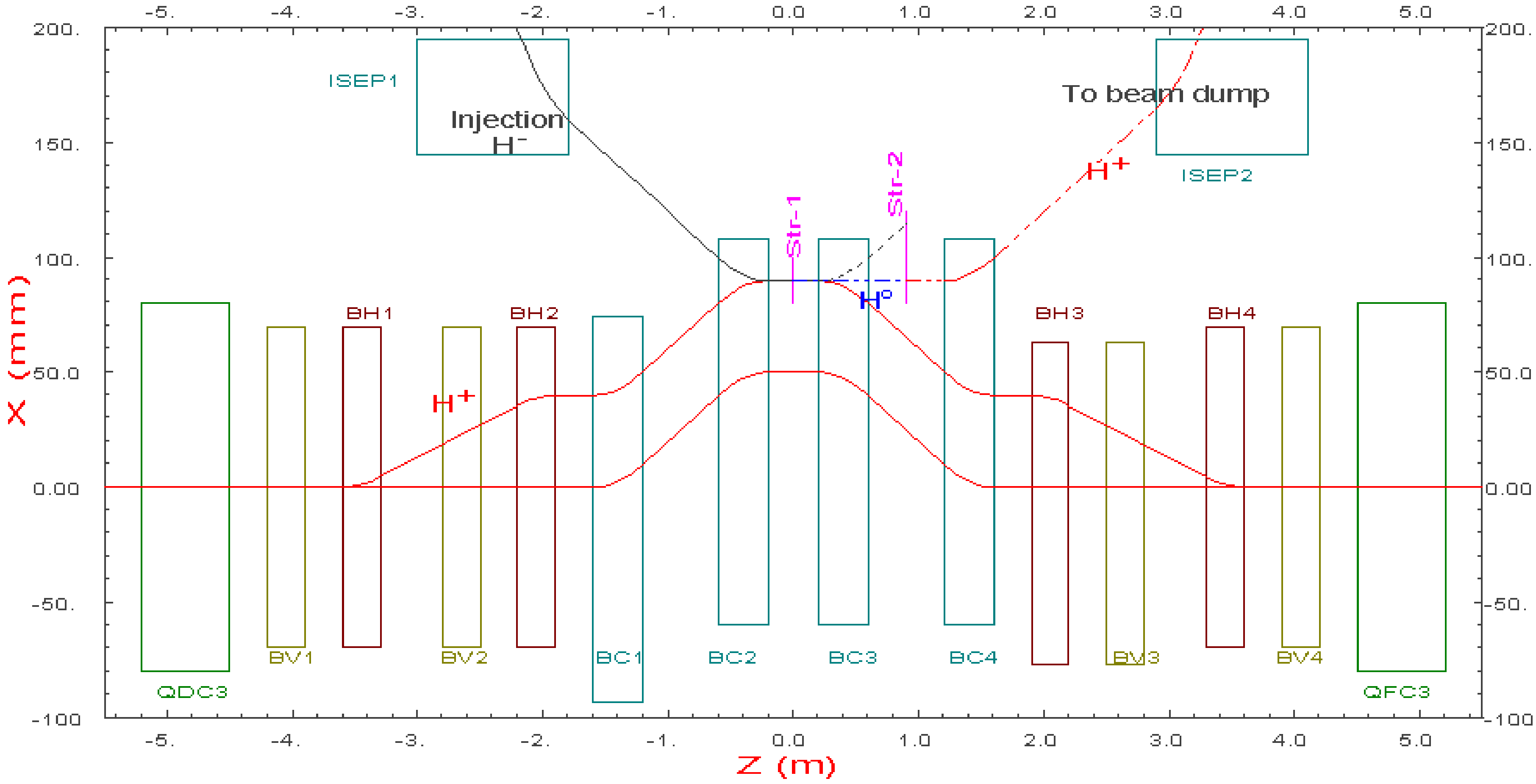


Figure 2. Time integrated energy distribution using constant amplitude energy spreader cavity(black) and debuncher cavity(red).

Note lack of tail for energy spreader case

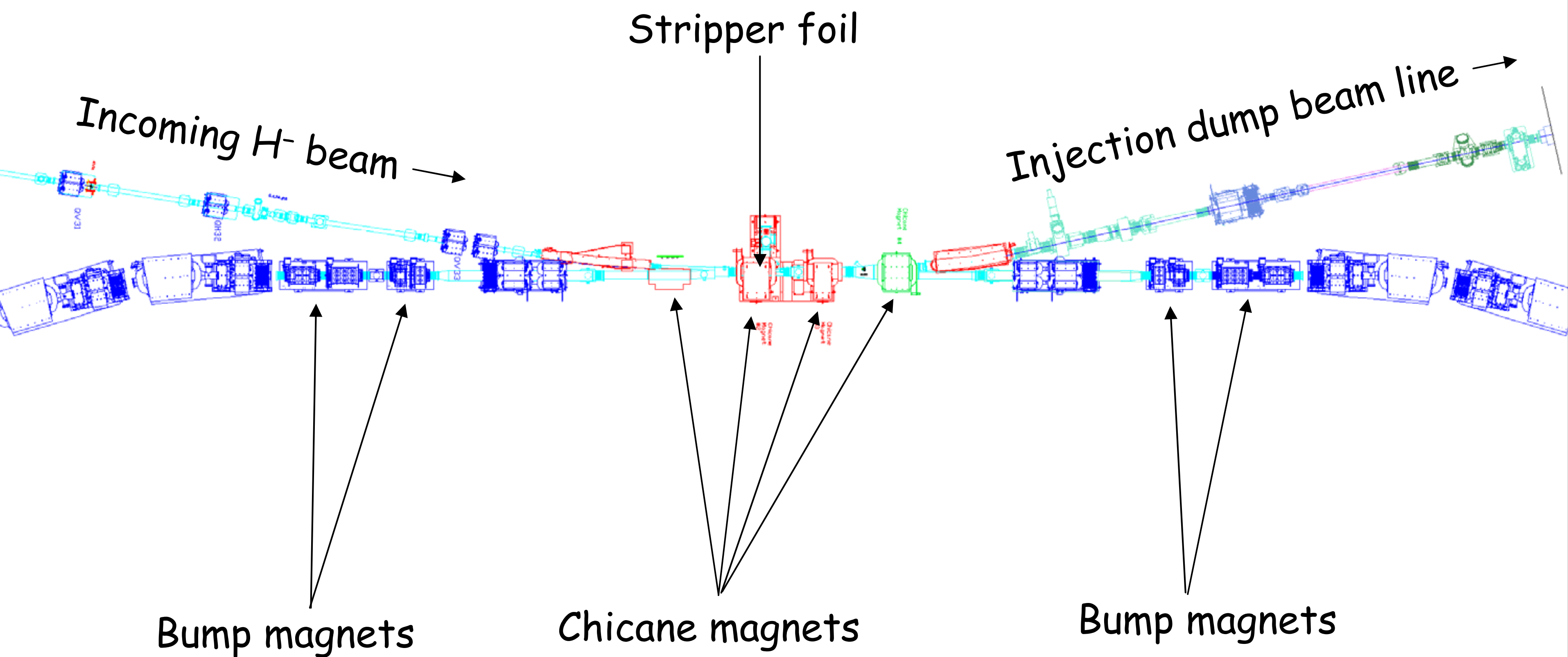
Energy corrector / spreader cavities in original SNS design, Y.Y. Lee, Linac 2002

Example: CSNS



Courtesy J.Y. Tang

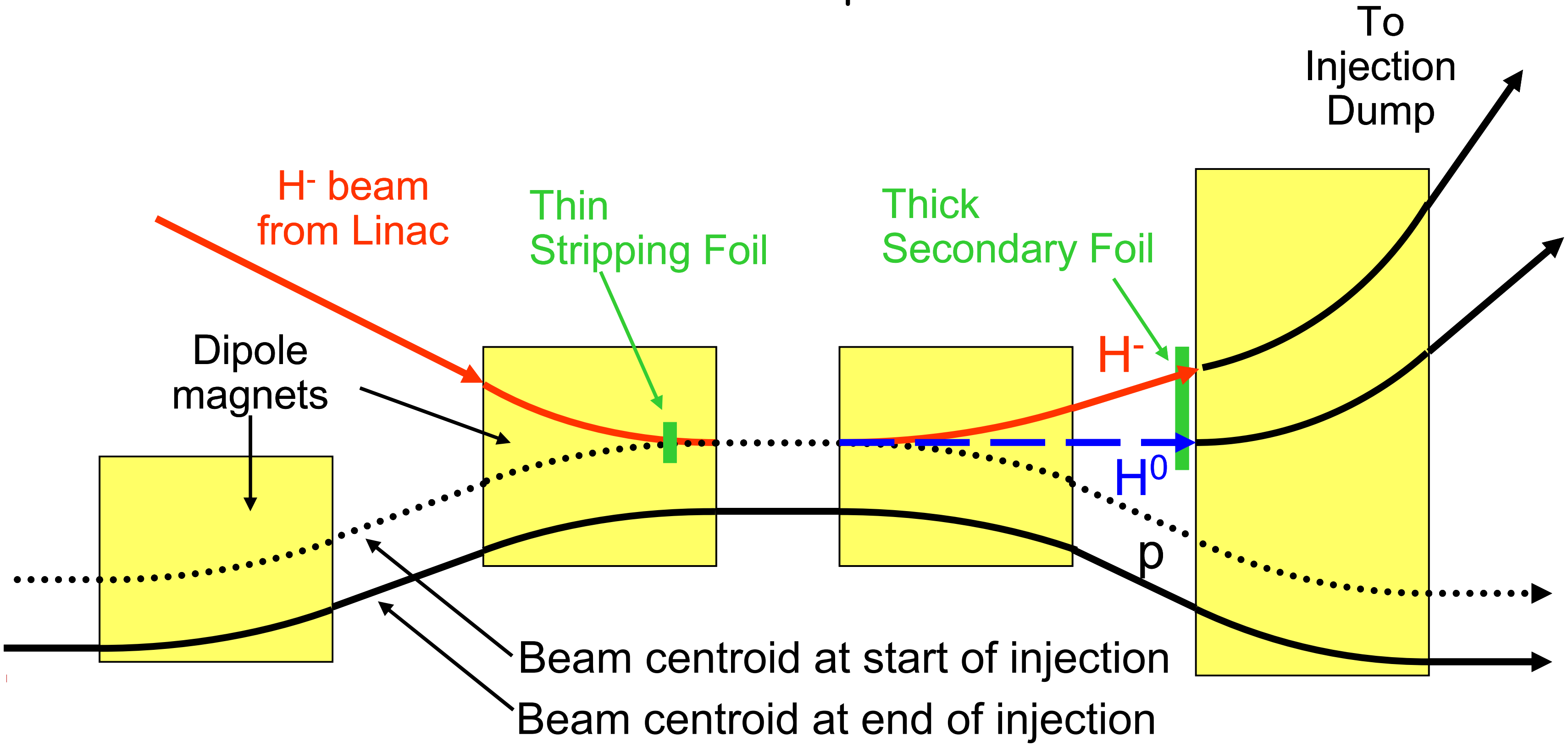
SNS Charge exchange injection



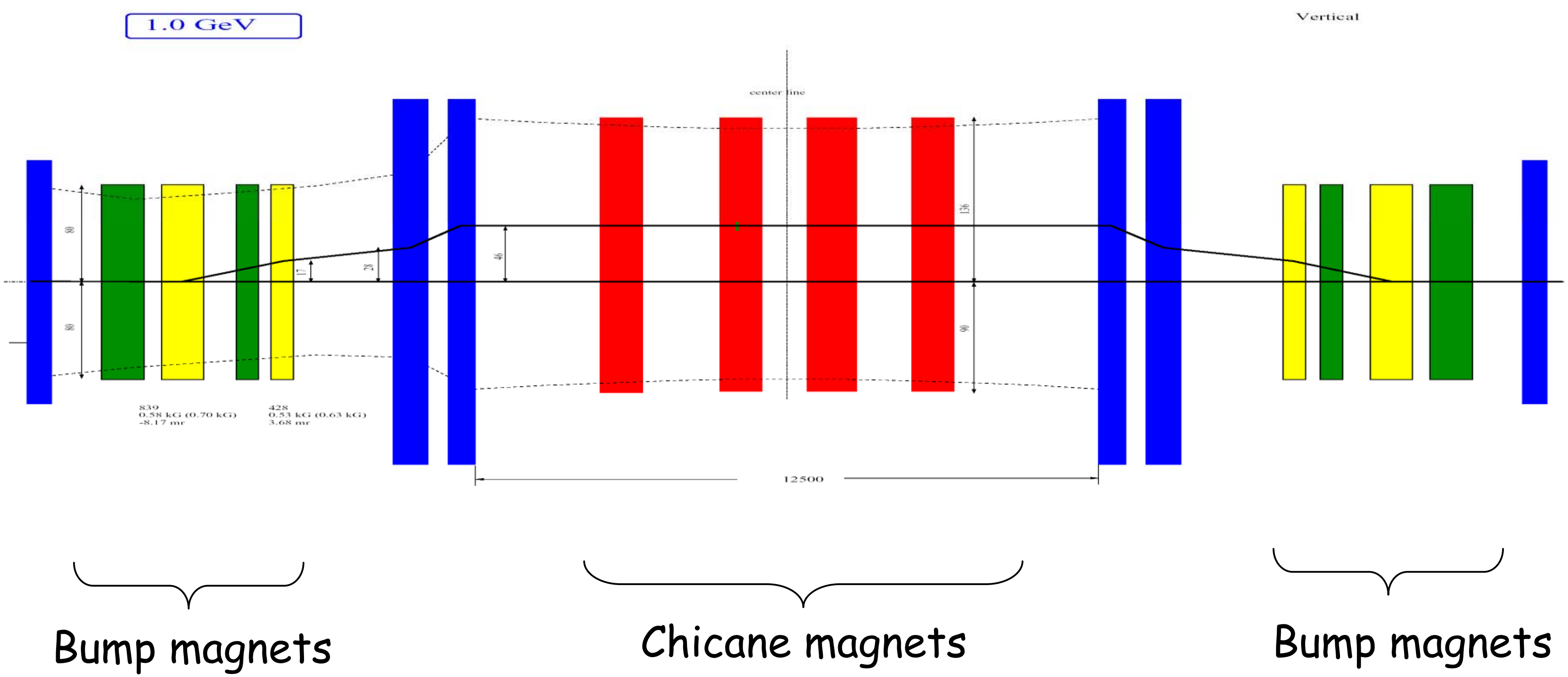
Example – SNS injection scheme

Functions of SNS chicane magnets

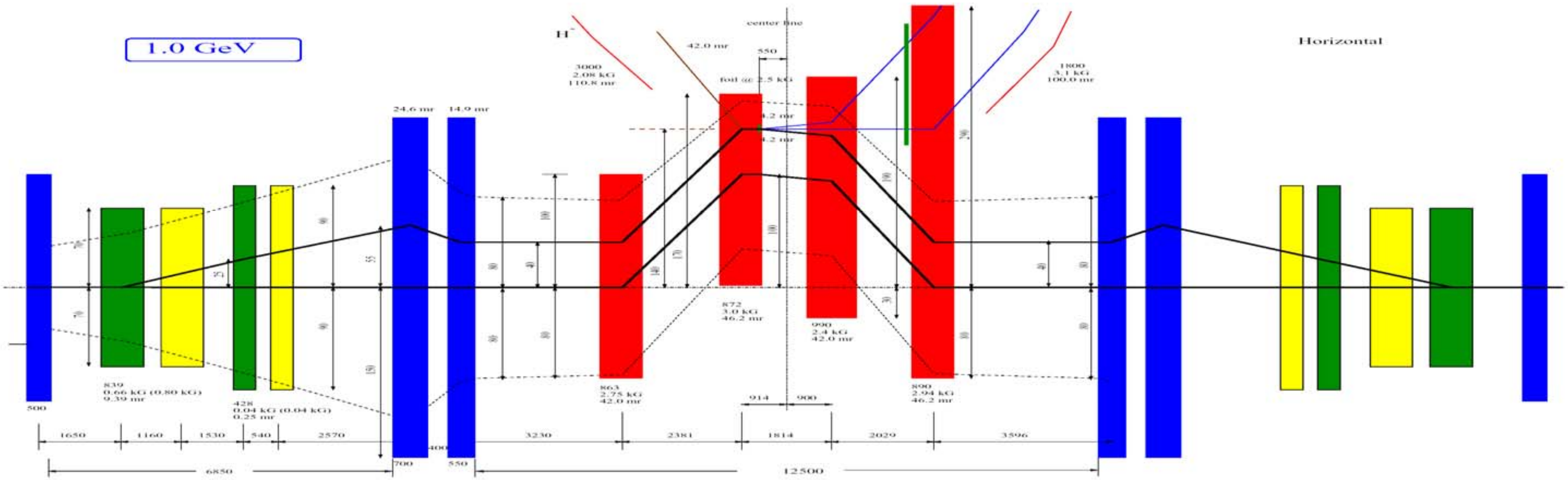
- Closed orbit bump of about 100 mm
- Merge H^- and circulating beams with zero relative angle
- Place foil in 2.5 kG field and keep chicane #3 peak field <2.4 kG for H^0 excited states
- Field tilt [arctan(By/Bz)] >65 mrad to keep electrons off foil
- Funnel stripped electrons down to electron catcher
- Direct H^- and H^0 waste beams to IDmp beam line



SNS vertical injection painting



SNS horizontal injection painting



Bump magnets

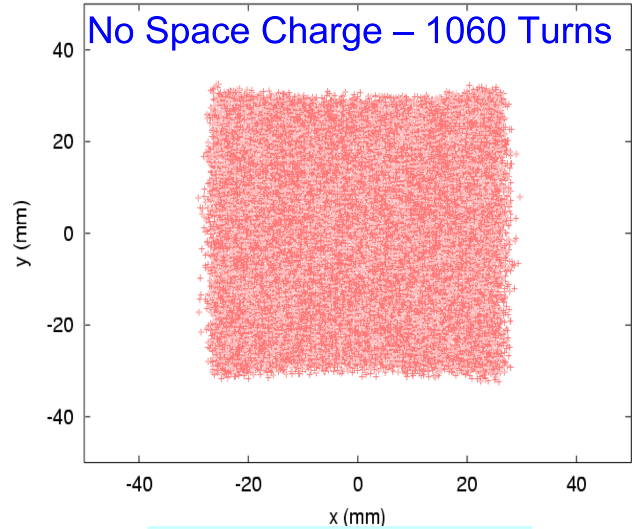
Chicane magnets

Bump magnets

SNS Painting with Space-Charge

USPAS

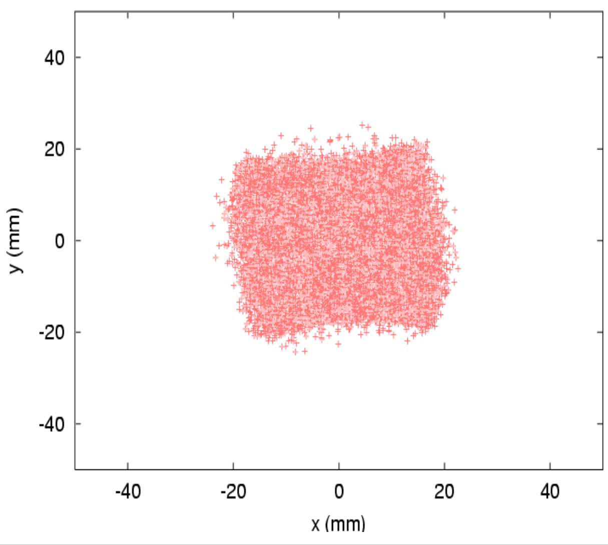
- Injection painting scheme optimized to minimize space charge and beam loss: Paint with a hole in the center to help create uniform density.
- Also try to keep circulating beam foil intercepts to a minimum (~7-10 foil hits per proton).
- Footprint matched to stringent target requirements.

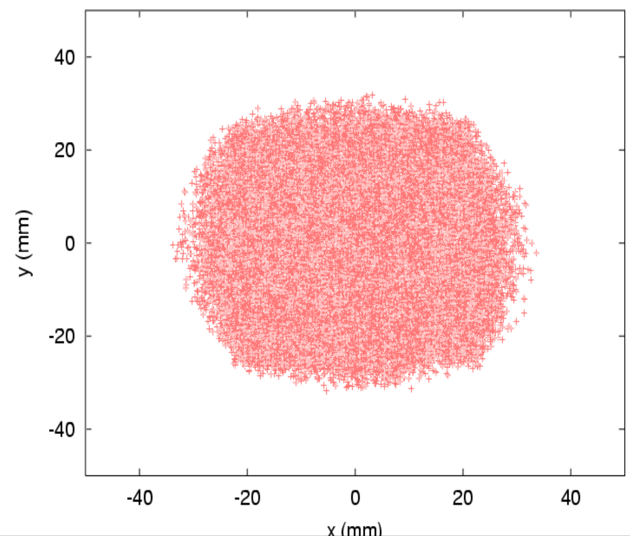


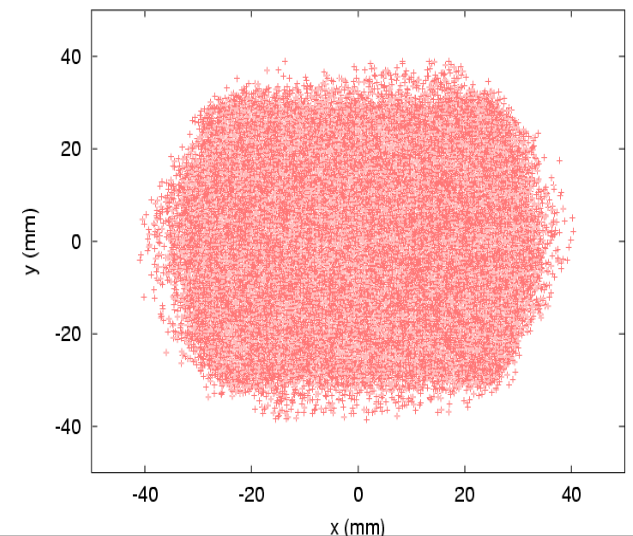
200 Turns

600 Turns

1060 Turns







SNS painting simulations

- Show SNS movie

ISIS Injection Simulation at the foil (from Dean Adams)

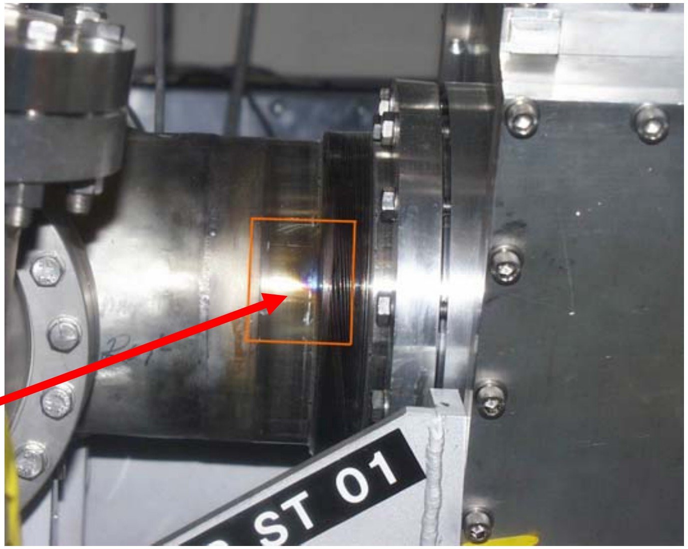
ISIS injection Simulation in the Synchrotron (from Dean Adams)

Injected beam parameters

- We want the injected spot size to be small because this will result in fewer foil hits by the circulating beam
  - The Twiss parameter for this condition is $\alpha_{ix} = \alpha_{iy} = 0$.
- We also want the dispersion of the injection beam line to be zero,
  - to minimize the beam size, and
  - to prevent the beam from moving due to linac energy fluctuations or due to the longitudinal painting process
  - The Twiss parameters for this condition are $D_{ix} = D_{iy} = 0$

Control of stripped electrons

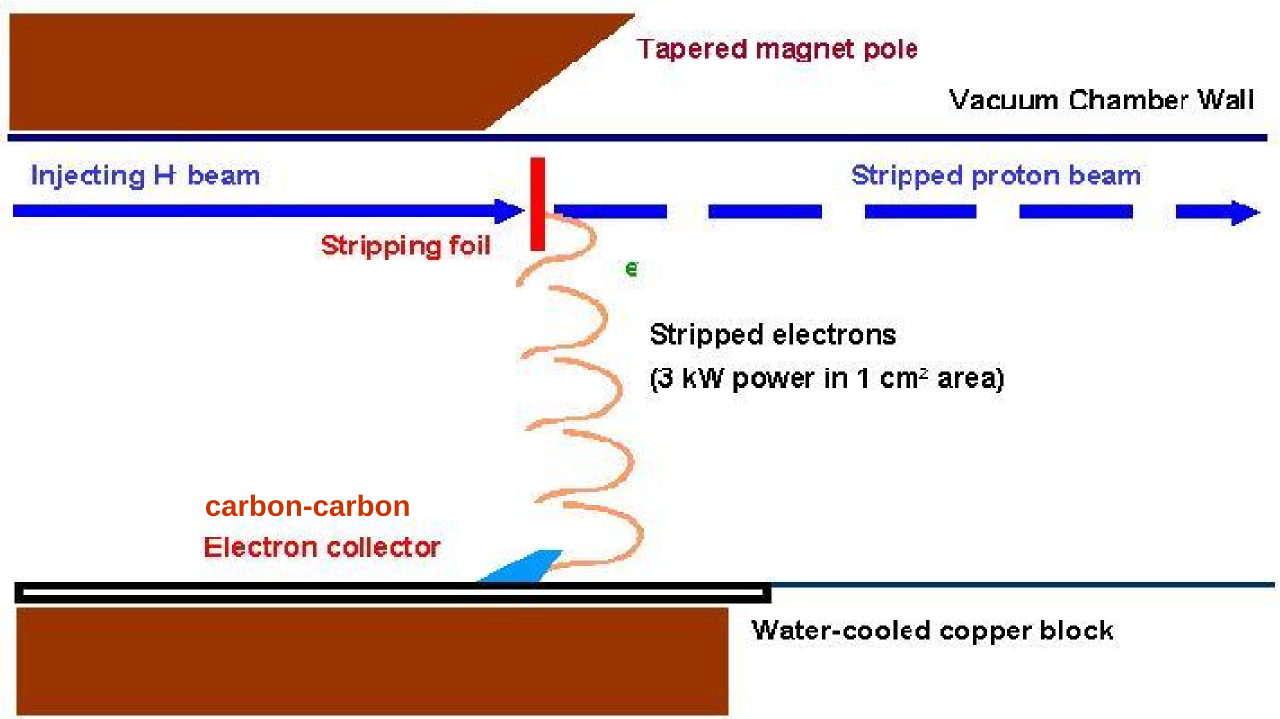
- The power of the stripped electrons can be surprisingly high
- Electron mass is 0.511 MeV, compared to proton mass of 938 MeV (proton mass is 1836 times greater). But there are two electrons stripped, so the power of the electron beam is 918 times less than the H^- beam.
- SNS beam energy is 1.5 MW, so electrons have 1.6 kW of power!



Burn mark from stripped electrons in PSR

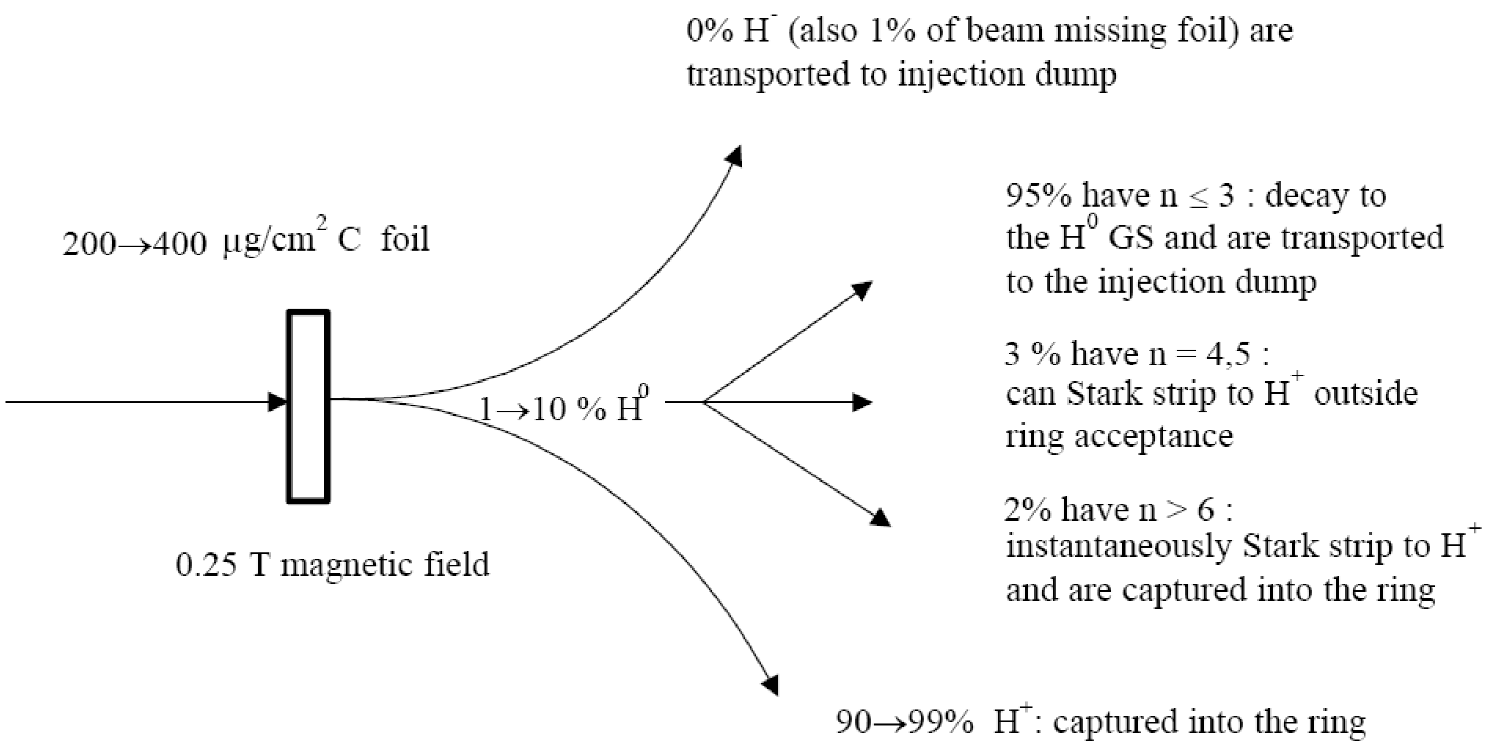
Control of stripped electrons in SNS

- The SNS primary stripper foil is in a tapered magnetic field, which directs the electrons down to a water-cooled electron catcher.



H^0 excited states

- First realization that this was an important issue by R. Hutson at PSR/LANSCE ~1992
- When an H^- beam passes through a thin stripper foil, some of the particles emerge as H^0 excited states
- The lifetimes of these excited states depend on the principle quantum number n (n = 1, 2, 3, …), and the magnetic fields



(Galambos et al., SNS TN002)

H^0 excited state lifetimes

- The H^0 excited states are populated according to the $n^{-2.8}$ law, where $n=1, 2, 3, \ldots$ is the principle quantum number of the H^0 atoms
- When the Ho* pass through a magnetic field, they see an electric field due to a relativistic transformation
  - $E = \gamma\beta c B_{lab}$
- This electric field can strip off the electron (Stark effect)
- If the newly created proton is outside the acceptance of the ring it will create beam loss
- It can be a large fraction of the total loss (e.g. at PSR it is ~15-20% of the total loss)
- SNS was designed specifically to handle these excited states

H^0 excited states at SNS

- At SNS, the stripper foil is located in the falling fringe field of a magnet (simulations show a falling field is best)
- The higher excited states with $n \geq 6$ have short stripping lifetimes and decay practically instantaneously after the foil and are captured into the ring acceptance along with the fully stripped H^+ ions
- The lower excited states with $n \leq 3$ have long stripping lifetimes and survive long enough to be transported along with the ground state H^0 into an injection beam dump and are a controlled loss.
- However, the $n = 4$ and 5 states have the potential of decaying in flight in the magnetic field to H^+ ions far enough downstream from the injection foil such that their resultant deflection puts them on trajectories that do not lie within the ring acceptance

H^0 excited state lifetimes at SNS

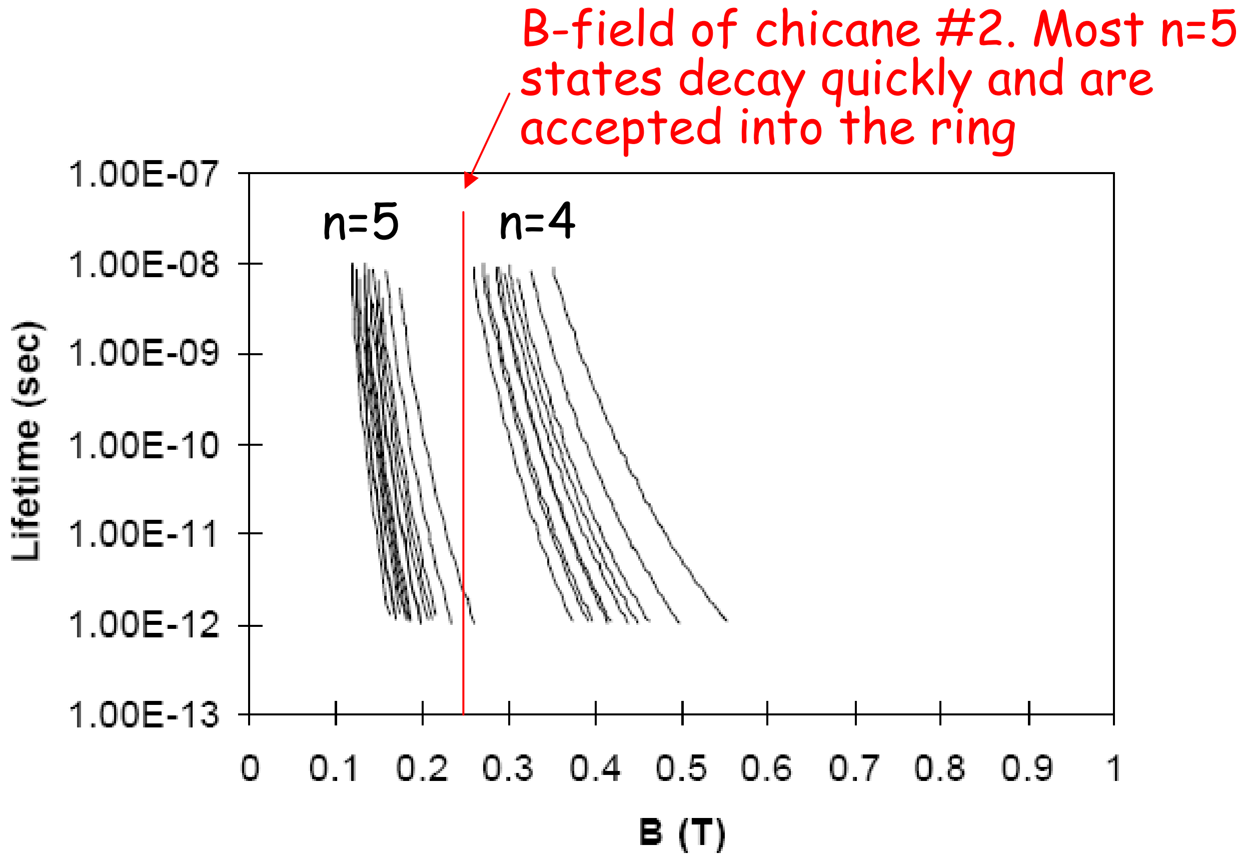
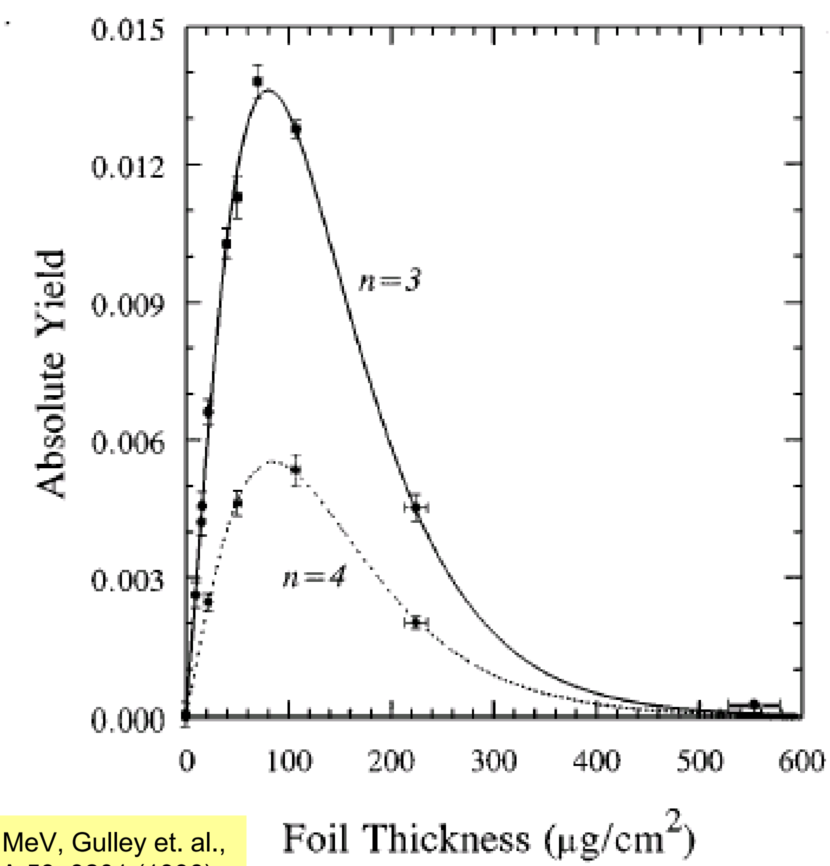


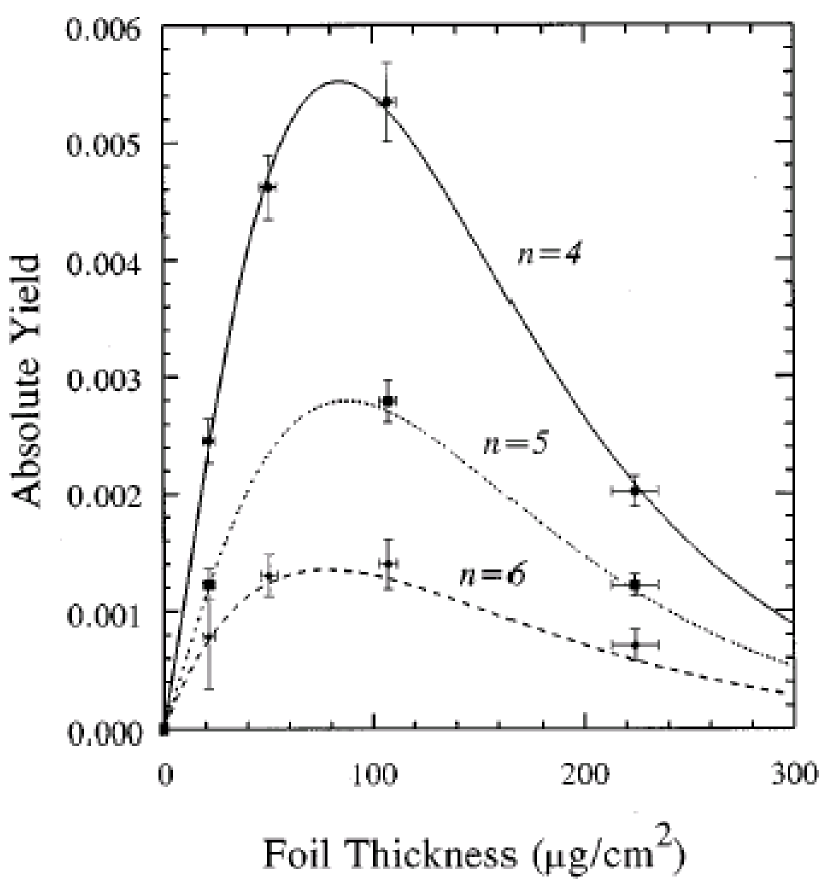
Fig. 4 Lifetimes for 1000 MeV $n = 4$ (band at right) and $n = 5$ (band at left) excited state H^o verses magnetic field level.

(Galambos et al., SNS TN002)

H^0 excited states vs foil thickness

- At SNS, low n states (n ≤ 3) are long-lived and survive to the second foil. High n states (n ≥ 6) are short-lived and are Lorentz-stripped immediately. About 0.01% of the n = 4 and n = 5 are lost.
- Choice of foil thickness should take into account the H^0 excited states





800 MeV, Gulley et. al., PRA 53, 3201 (1996)

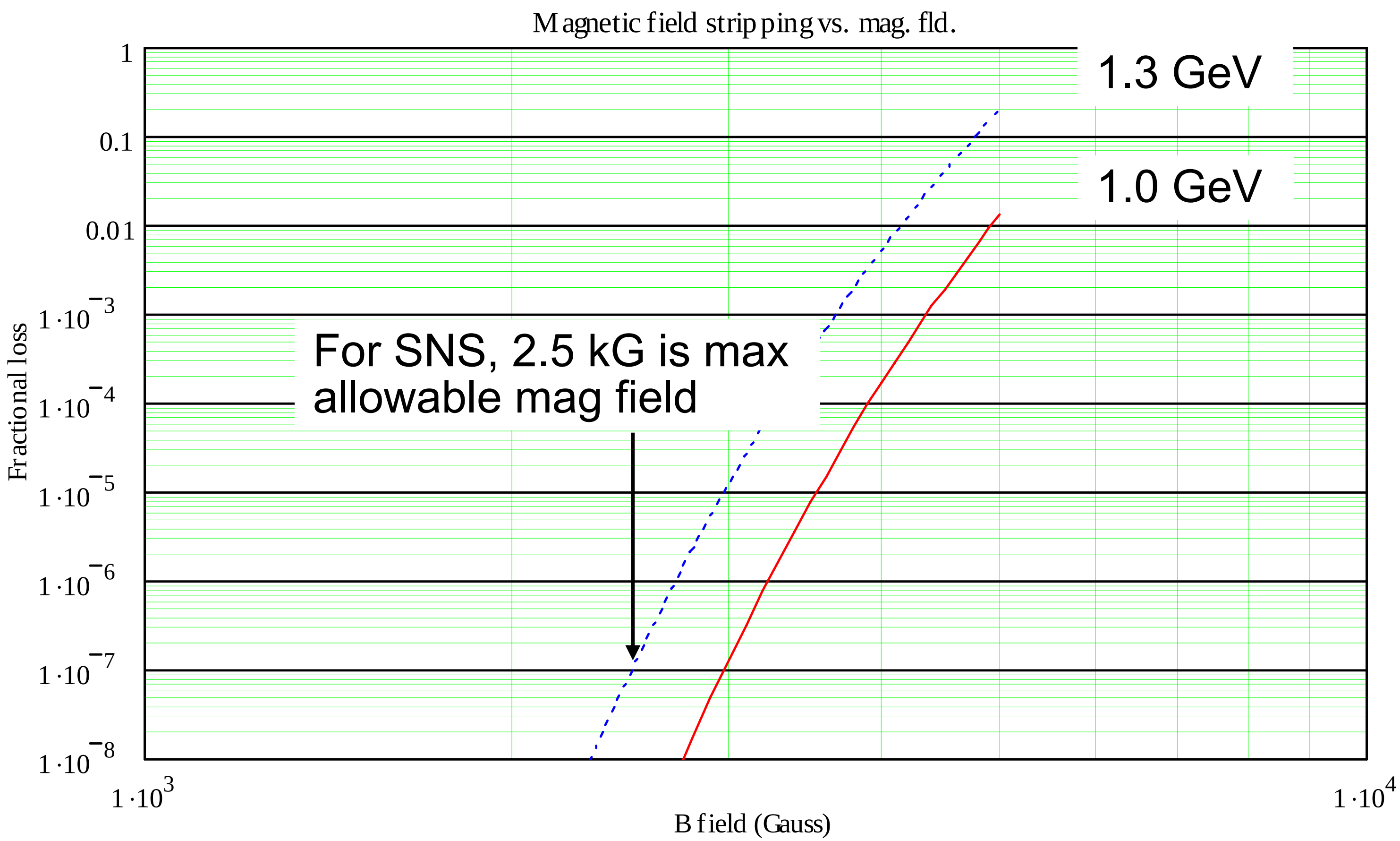
Magnetic stripping

- When an H^- particle encounters a magnetic field, in the rest frame of the particle it sees an electric ***and*** a magnetic field
- Electric fields can easily strip away the weakly-bound, outermost electron on an H^- particle
- H^- accelerators and transport lines must take this effect into account, and ensure the magnetic fields do not get too high
- A reasonable upper limit on the beam loss is 1 W/m
  - Rough rule of thumb is that a 1 W/m beam loss corresponds to approx. 80 mrem/h at 30 cm after 4 h cool-down

Magnetic stripping

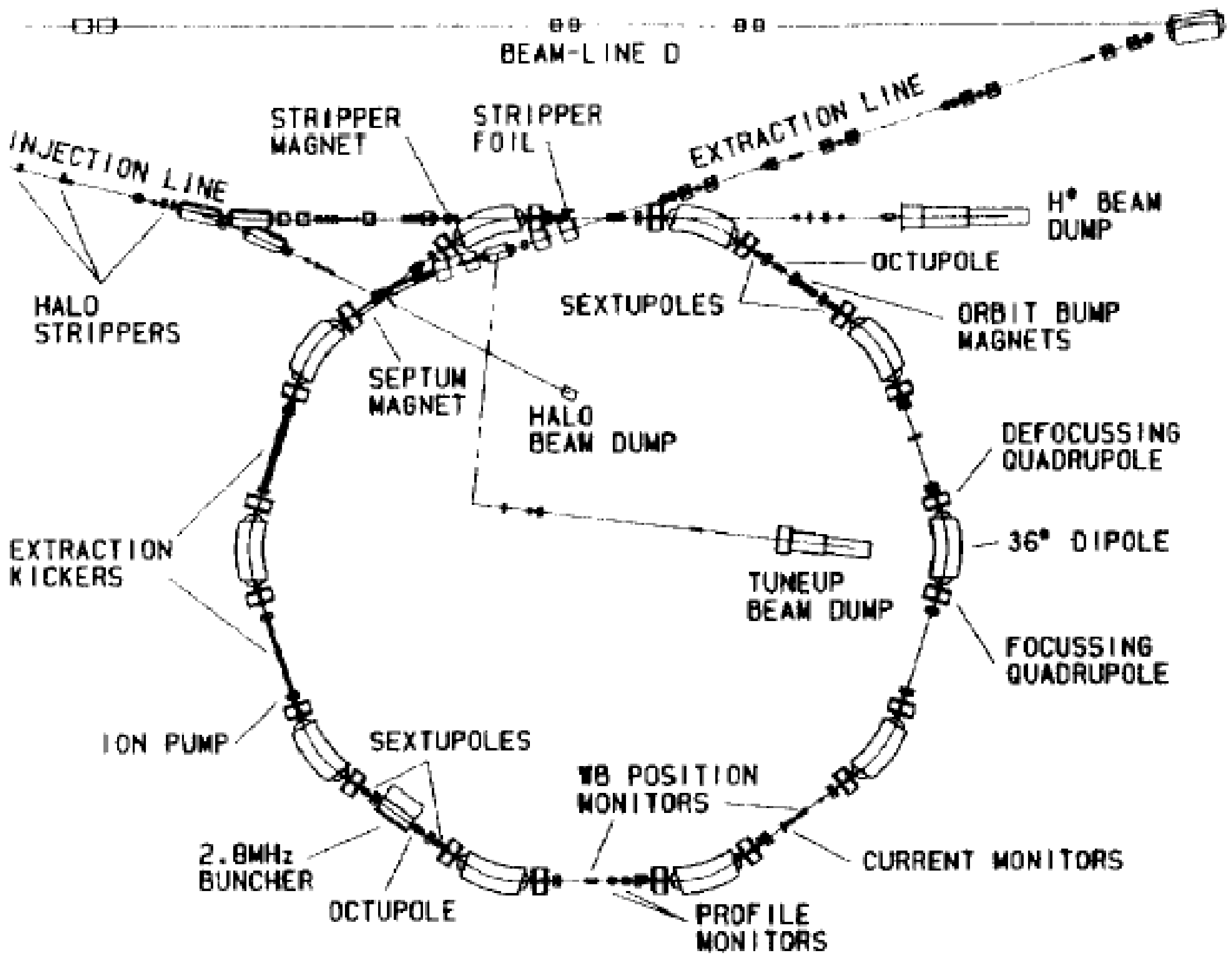
$$\frac{df}{ds} = \frac{B}{A_1} \cdot e^{\frac{-A_2}{\beta\gamma c B}},$$

where A1 = 2.47E-6 V*sec/m, A2 = 4.49E9 V/m, B is the magnetic field seen by the particles (units of Gauss), beta and gamma are the relativistic parameters, and c is the speed of light (A. Jason)



- Fun fact: For 8 GeV beam at Project X, max mag field is ~480 G

Two-step charge exchange injection



Example – Original PSR injection scheme

(G. Lawrence, PAC87)

Two-step charge exchange injection

- The unintended consequence of two-step charge exchange injection was high beam loss in the PSR caused by:
  - Stochastic process of magnetic stripping of H^- to H^0 caused horizontal emittance to grow ~3x
  - No control of Twiss parameters once beam is stripped to H^0, leading to non-ideal Twiss parameters at stripper foil, causing another ~3x growth in emittance
  - In 1998 PSR switched to direct charge exchange injection

Gas stripping

- Residual gas in the beam pipe is like a very thin stripping foil
- If the gas pressure is too high, the beam loss due to stripping will be too high
- Gas stripping cross section proportional to $1/\beta^2$
- Power in stripped beam proportional to beam kinetic energy
- Activation caused by stripped beam increases with beam energy
- Net result is allowable gas pressure decreases as beam energy is increased
- For the case of SNS, the allowable gas pressure ranges from 10^{-6} Torr in RFQ (2.5 MeV) to 10^{-8} Torr in HEBT (1 GeV)

Gas stripping

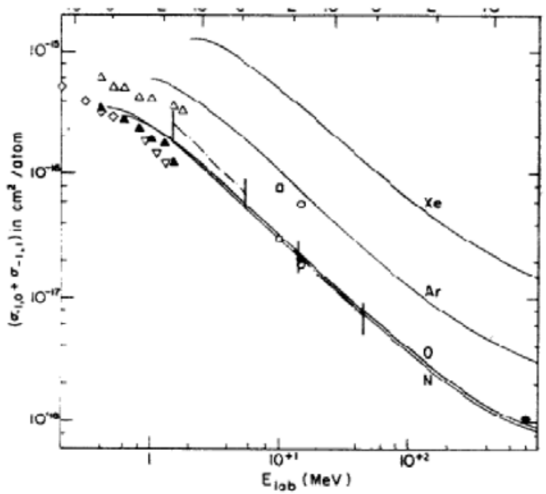


Fig. 1. Figure 1 from Gillespie, Phys ReV A16, page 943 (1977), showing total stripping cross sections for H-minus on nitrogen and oxygen.

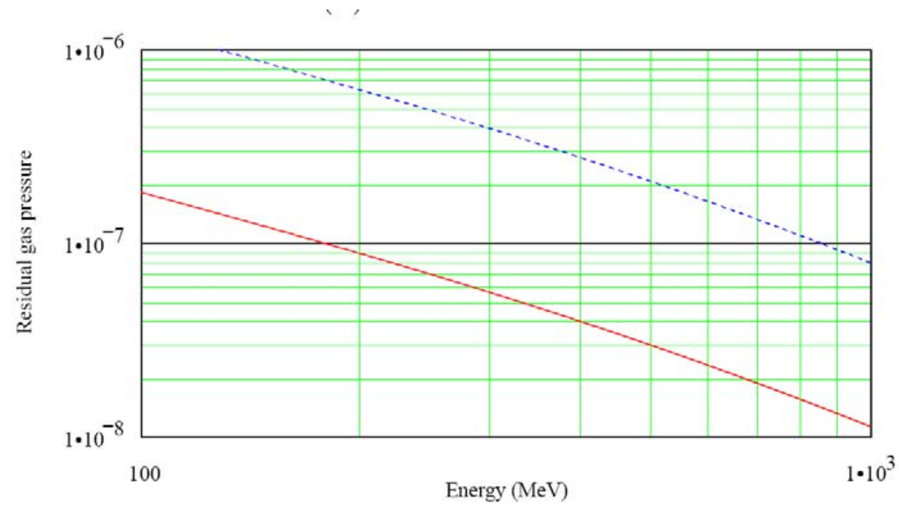


Fig 5. Allowed residual gas pressures for nitrogen (solid line) and hydrogen (dotted line) above 100 MeV

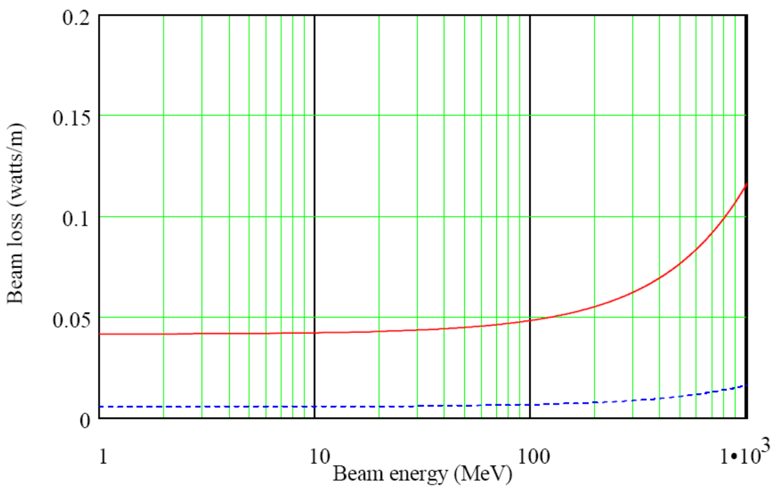


Fig 3. Watts/m beam loss for 1 x 10^{-8} torr nitrogen (solid) or hydrogen (dotted)

As the beam energy is increased, we can tolerate less residual gas pressure

(Figures are from Bob Shafer, for SNS, TN:LANSCE-1:99-085)

Recap

- Liouville's theorem
  - Emittance of circulating beam must increase as inject more and more turns.
  - Unless we use charge exchange injection
- Transverse painting
  - Required for multi-turn non-charge-exchange injection
  - Reduces foil hits for case of charge exchange injection
- High-intensity charge exchange injection
  - Control of stripped electrons - important for component damage
  - Control of H^0 excited states - important for beam losses
  - Magnetic stripping – max B-field decreases as incr. energy
  - Gas stripping – max pressure decreases as increase energy

Acknowledgements

- Thanks to B. Goddard. Many of these slides were copied from his CAS course.
- Thanks to D. Adams for the ISIS simulations

H^0 excited states (cont.)

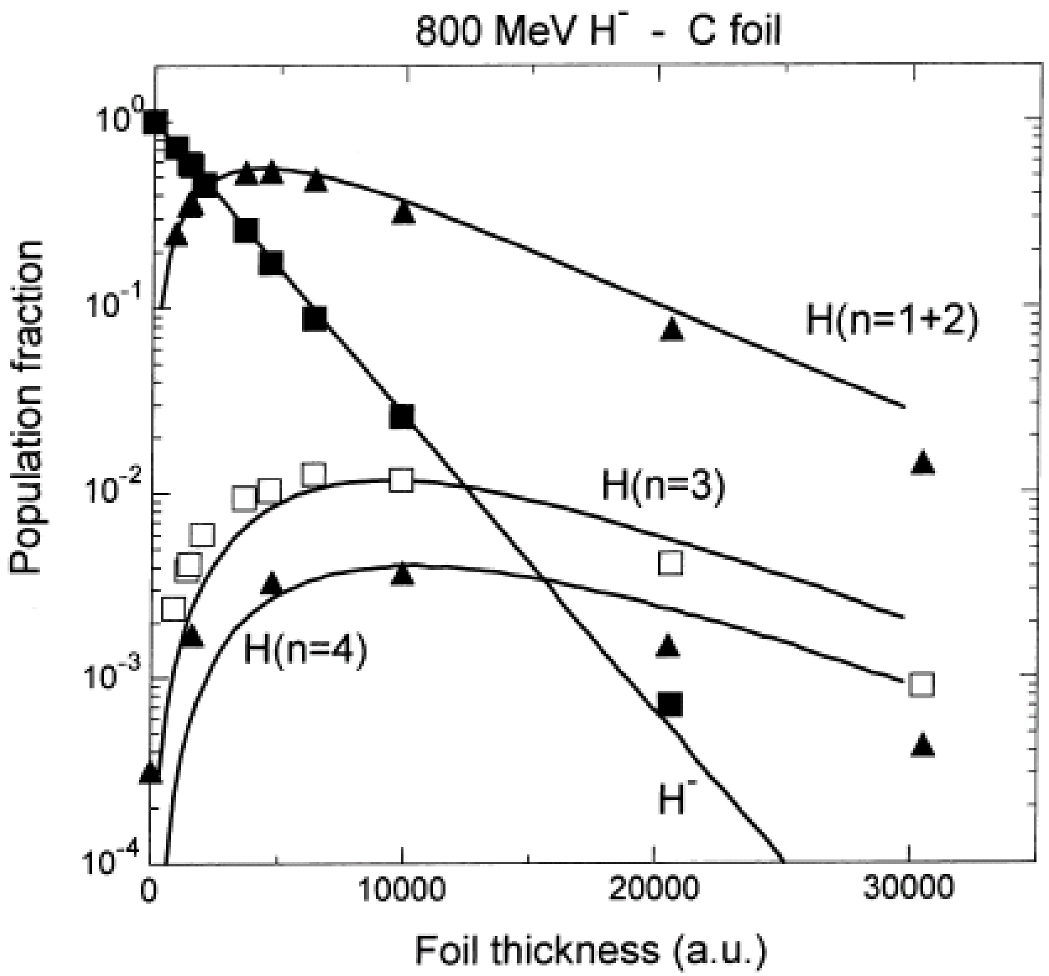


Fig. 2. Fraction of H$^-$, and H ($n = 1,2,3,4$) as a function of foil thickness for a beam energy of 0.8 GeV. The symbols correspond to the experimental data of Gulley et al. [6].

The fraction of partially stripped H^0 particles in excited states scales with the total number of H^0 particles

(Reinhold et al., NIM B146)