Injection and extraction - extraction

USPAS

by
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Differences between inj. and extr.

- In accelerating rings
  - space charge is less of a concern due to the higher beam energies
  - need more ∫B.dl to get the same amount of deflection, so may need multiple kickers and septum magnets
- In accumulator rings
  - space charge can be more of a concern due to higher beam charge
  - aperture requirement can be greater due to painting
  - beam leaking into the gap can cause excessive beam loss during extraction
- In contrast to charge exchange injection, if the particles are fully stripped then don't have to worry about magnetic and gas stripping (e.g. H^- injection, proton extraction)

Extraction

- Different extraction techniques exist, depending on requirements
  - Charge-exchange: (e.g cyclotron accelerating an H^- beam)
    - Beam is extracted when radius increases to location of stripping foil
  - Fast extraction: ≤1 turn
    - Whole beam kicked into septum gap and extracted
  - Non-resonant multi-turn extraction: few turns
    - Beam kicked to septum; part of beam 'shaved' off each turn.
  - Resonant multi-turn extraction: many thousands of turns
    - Non-linear fields excite resonances which drive the beam slowly across the septum.
  - Resonant low—loss multi-turn extraction: few turns
    - Non-linear fields used to trap 'bunchlets' in stable islands. Beam then kicked across septum and extracted in a few turns.
  - Other exotic technologies: (e.g. bent crystal)

Charge exchange extraction

- In a cyclotron, beam radius increases as the beam is accelerated
- If an ion beam is accelerated, a stripper foil located near the outer radius will intercept the beam, change the charge state, and deflect the beam to an extraction channel
- Drawbacks include
  - Activation due to scattering
  - Stripper foil heating
- Not in wide use today. As beam powers and beam intensities have increased, high-efficiency extraction has become more and more important.
- High intensity machines require extraction efficiencies of ~100%

Fast single turn extraction

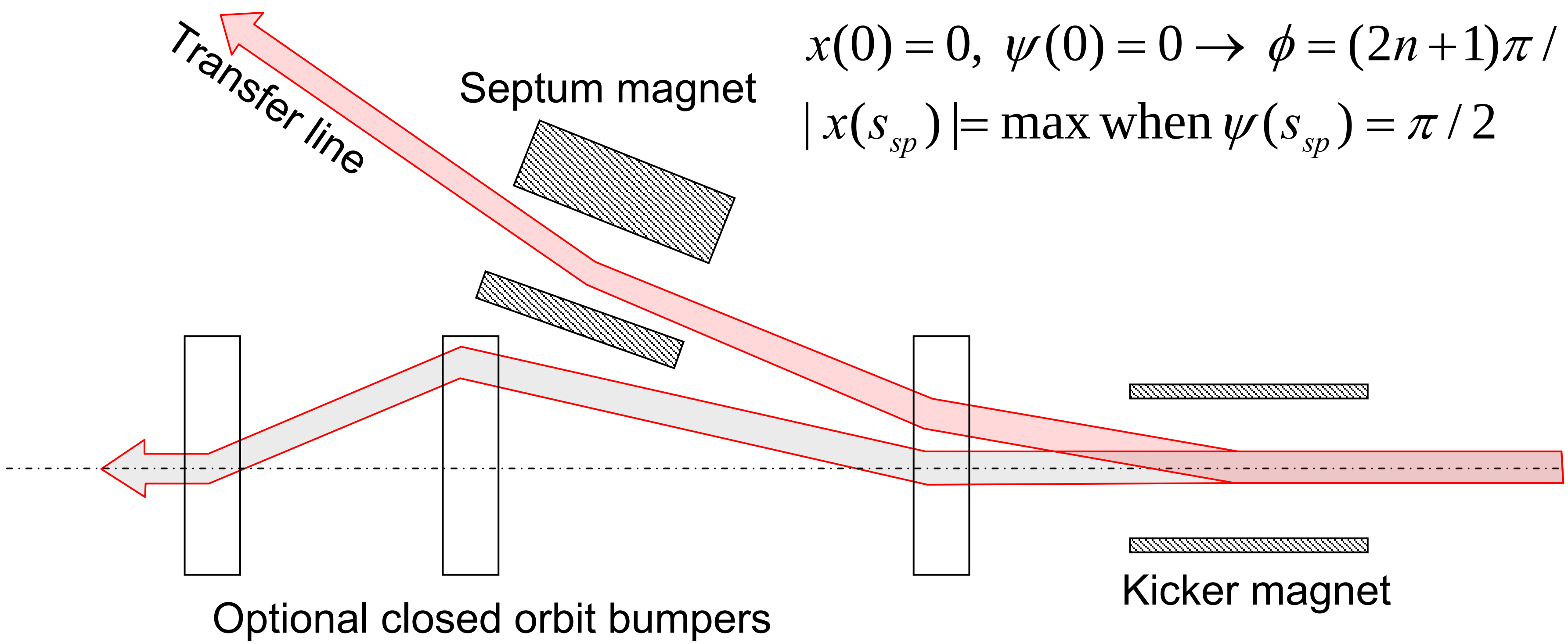
- Commonly used to transfer the entire beam from one circular accelerator to another
  - e.g. box-car stacking of a main ring from a booster ring
- Or for particle production targets
  - e.g. neutron spallation, neutrino production
- Fast rise time must be less than the beam-free gap. If extract all the beam bunches, then fall time can be slow.
- Can also extract single beam bunches from a multi-bunch ring if the kicker system is fast enough
  - Rise time and fall time must fit within inter-bunch spacing
- Septum deflection may be in the other plane to the kicker deflection

Fast single turn extraction

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

$$x(0)=0,\ \psi(0)=0 \rightarrow \phi=(2n+1)\pi/2$$

$$|x(s_{sp})| = \max \text{ when } \psi(s_{sp}) = \pi/2$$



- Kicker deflects the entire beam into the septum in a single turn
- Septum deflects the entire beam into the transfer line
- Most efficient (lowest deflection angles required) for $\pi/2$ phase advance between kicker and septum

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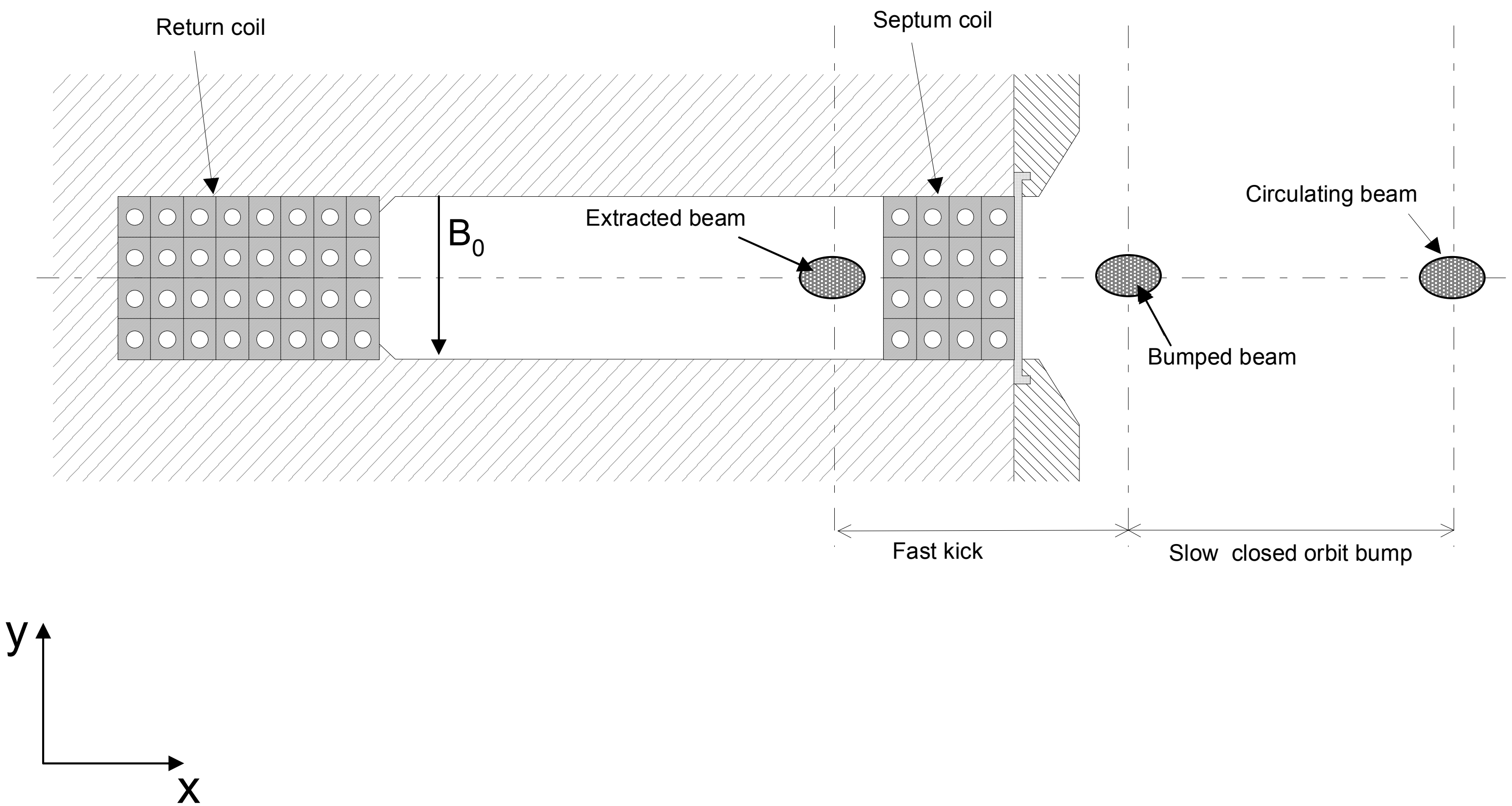
Fast single turn extraction



- View at the septum entrance. Here the clearances are the smallest.
- For high energies / intensities, beam loss and machine protection becomes an issue.

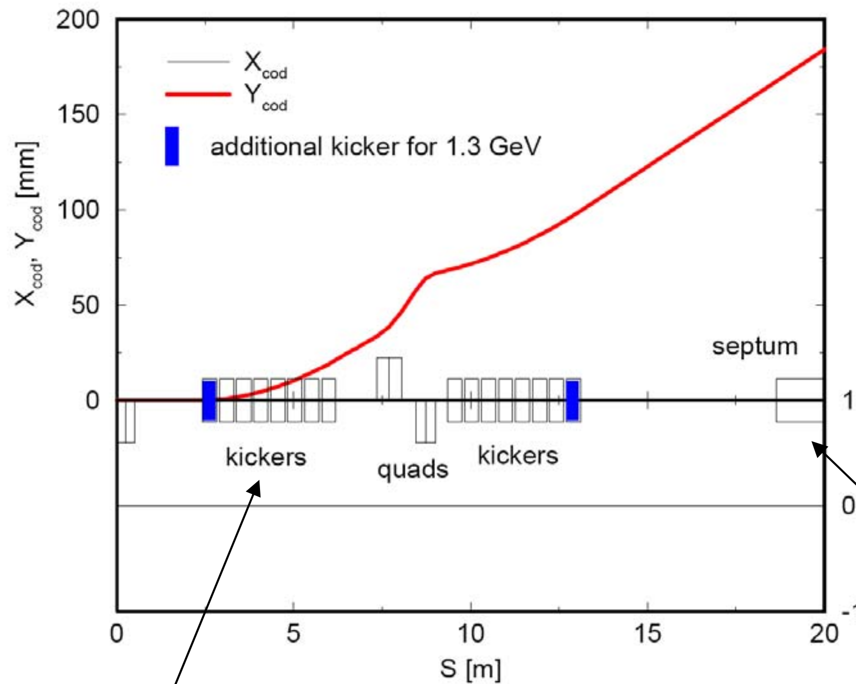
Lambertson septum magnet

- Has coil package on just one pole tip – no coil between the two beams

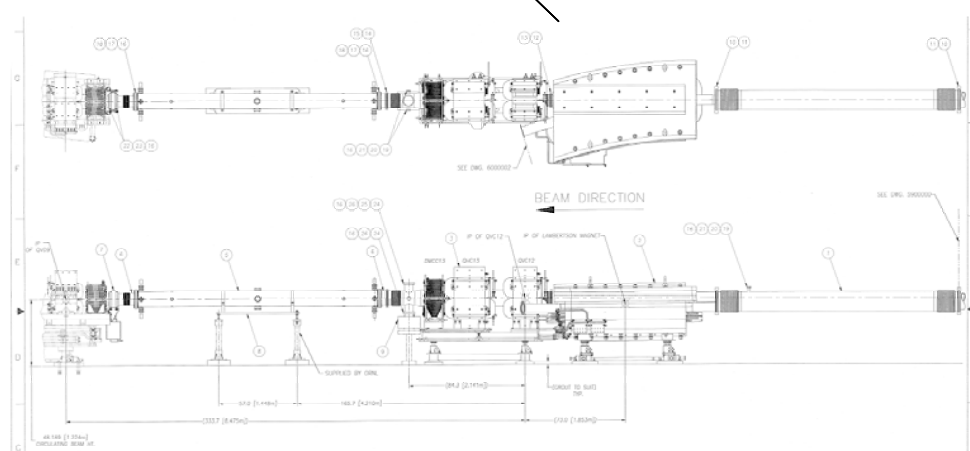
Photos of SNS Lambertson septum magnet

(D. Raparia, PAC 2005)

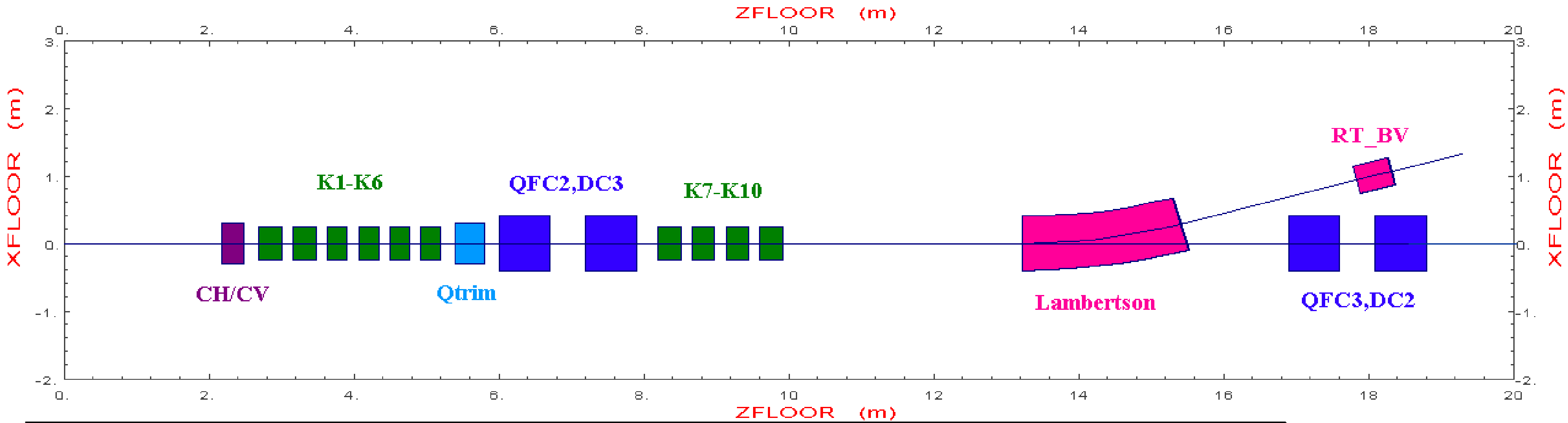
Example: SNS



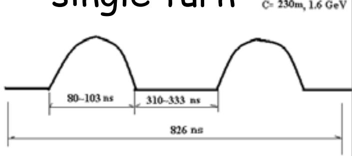
14 ferrite kickers are used to achieve the required deflection



Example: CSNS



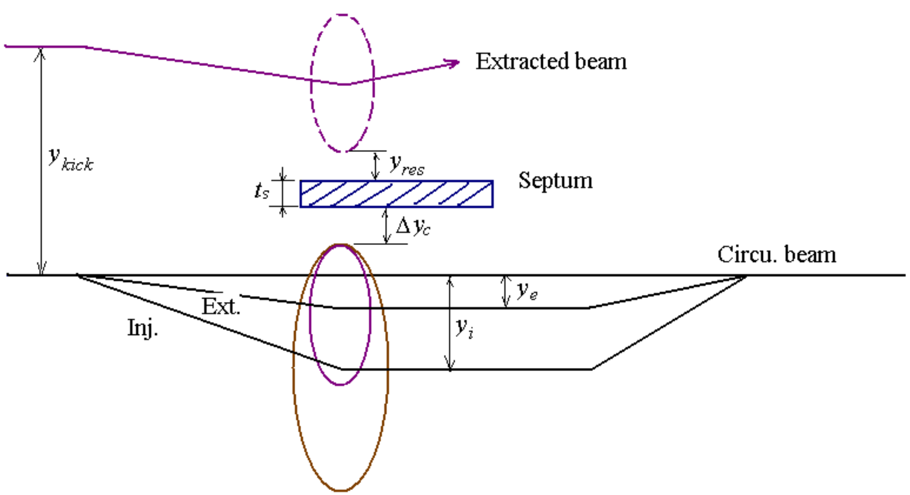
2 bunches extracted in a single turn

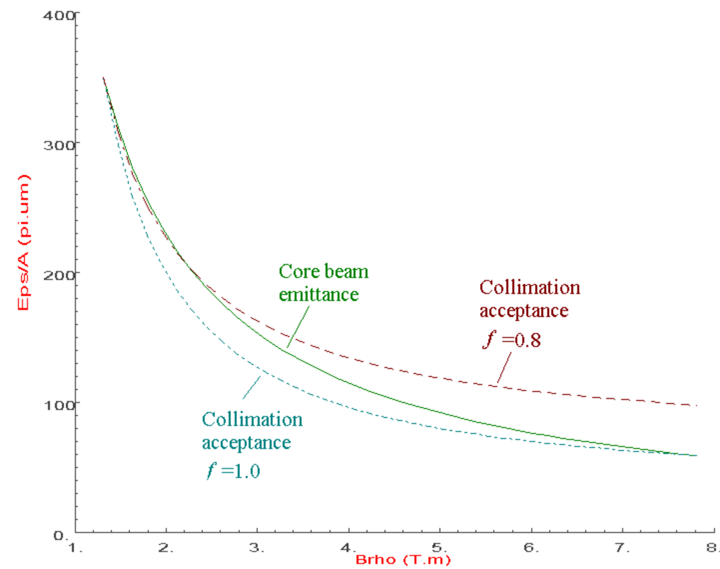


Courtesy J.Y. Tang

Example: CSNS (cont.)

- Another method using DC bump magnets for the extraction has been studied
  - DC bump magnets at both the extraction septum and the transverse collimators
  - Reducing the requirement to the kickers and beam losses in RTBT
  - Halo collimation at low energy
- Potentially applicable at the CSNS
  - Acceptance reduced from 350 pi to 100~120 pi, 30% in kicking strength





Courtesy J.Y. Tang

Kick angle

To achieve a deflection amount y at the septum entrance, the kicker(s) must deflect the beam through angle θ

$$\theta = \frac{y}{\sqrt{\beta_{y,k}\beta_{y,s}}\,\sin\mu_y}$$

lattice function at kicker

lattice function at septum

phase advance from kicker to septum

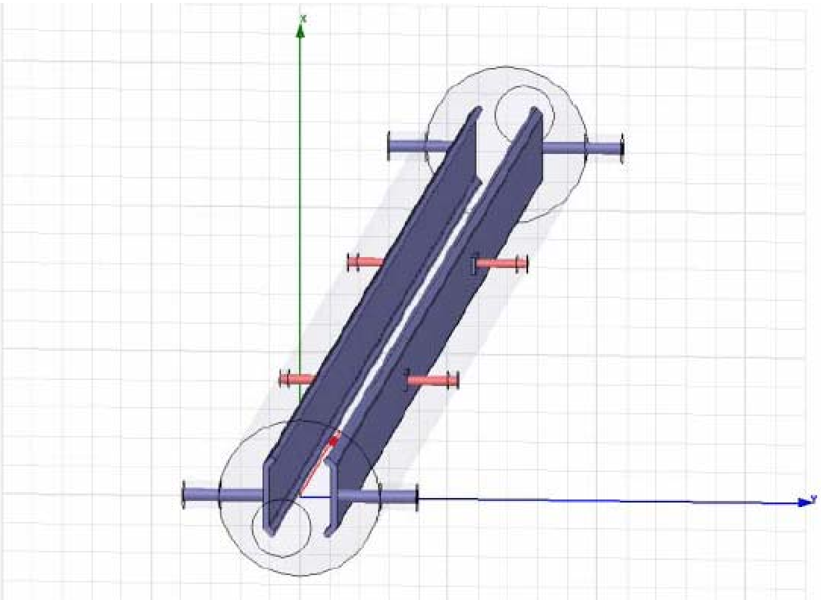
To minimize the required deflection angle, make the phase advance $\mu = \pi/2$

The beam separation y must be greater than

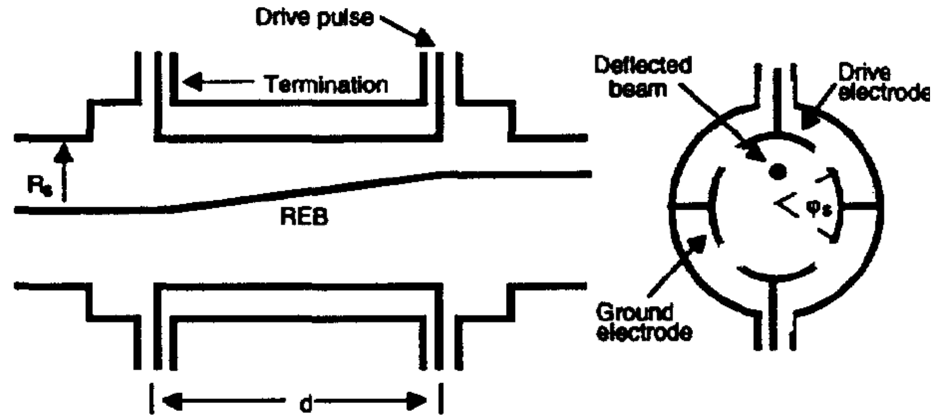
$$n\sqrt{\varepsilon\beta_{y,s}} + m\sqrt{\varepsilon\beta_{y,s}} + \text{dispersion} + \text{septum thickness} + \text{errors}$$

(where n and m are factors to include beam tails, just like case of injection)

Stripline kicker

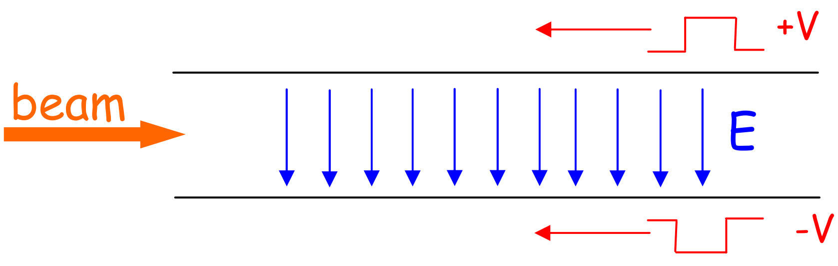


(I. Rodríguez, EPAC06)

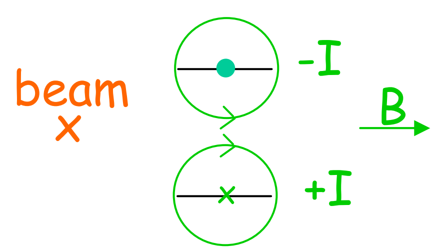


(B.R. Poole et al., UCRL-JC-126075 Rev 1)

Drive the kicker from the downstream end to get the electric and magnetic fields to add



side view



end view

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Stripline kicker

$F = qV(1 \pm \beta)/g$ force on the beam particles (+ for drive from downstream end)

$\theta = \tan^{-1}(Fl/p\beta c) \approx Fl/p\beta c$ deflection angle

$\tau = \frac{l}{\beta c}(1+\beta)$ rise time (drive from downstream end)

$l =$ electrode length

$g =$ electrode separation

$V =$ voltage between electrodes (e.g. V/2 on each one)

- You can string as many kickers of length l together as you like, and still have an overall rise time equal to that of a single kicker
- By terminating the striplines in their characteristic impedance, the rise and fall times can be very fast
- For high energy (stiff) beams stripline kickers may be impractical due to high voltages and currents

Ferrite kickers

- If the ferrite kicker is outside the vacuum envelope, you must take into account eddy current effects
- If the ferrite kicker is inside the vacuum envelope you must take into account ferrite out gassing

Example: SNS extraction kicker magnets (inside the vacuum envelope)

Pulse rise time: 200 nS (1% - 95%)

Kicker strength: 1.276 to 1.775 mrad

Kicker horizontal aperture: 120 mm to 211.3 mm

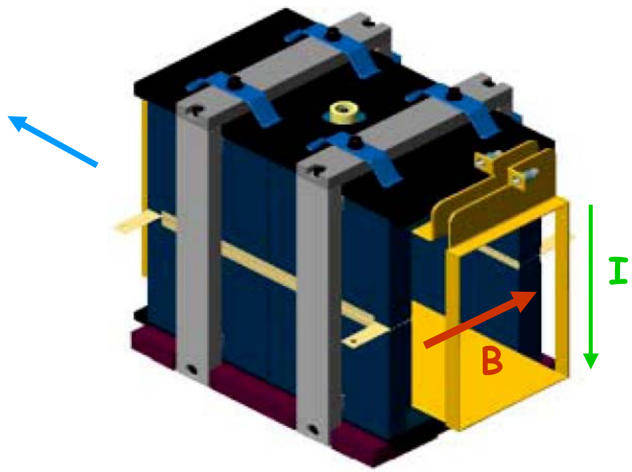
Kicker vertical aperture: 166 mm to 243 mm

Kicker length: 390 mm to 505 mm per

Kicker magnet inductance: 695 nH to 789 nH

Operating voltage < 35 kV per section

Operating current < 2.5 kA per section



(C. Pai, PAC03)

Ferrite kickers

$F = \dfrac{qI\beta\mu_0 c}{g}$ force on beam particle of charge q

$L = \dfrac{\mu_0 wl}{g}$ inductance

$\tau = L/Z_0$ rise time

$I = V/Z_0$ current

$B = \mu_0 I/g$ (one turn magnet)

$\theta \approx Bl/(B\rho) = 0.2997925\; Bl/p \quad [T\; m/GeV/c]$ deflection angle

ferrite length l, gap g, and width w

$Z_0 =$ characteristic impedance of cables

As in the case of the stripline kickers, you can string as many kickers of length l together as you like, and still have an overall rise time equal to that of a single kicker – but beware of changes in phase advance between the kickers and the septum magnet

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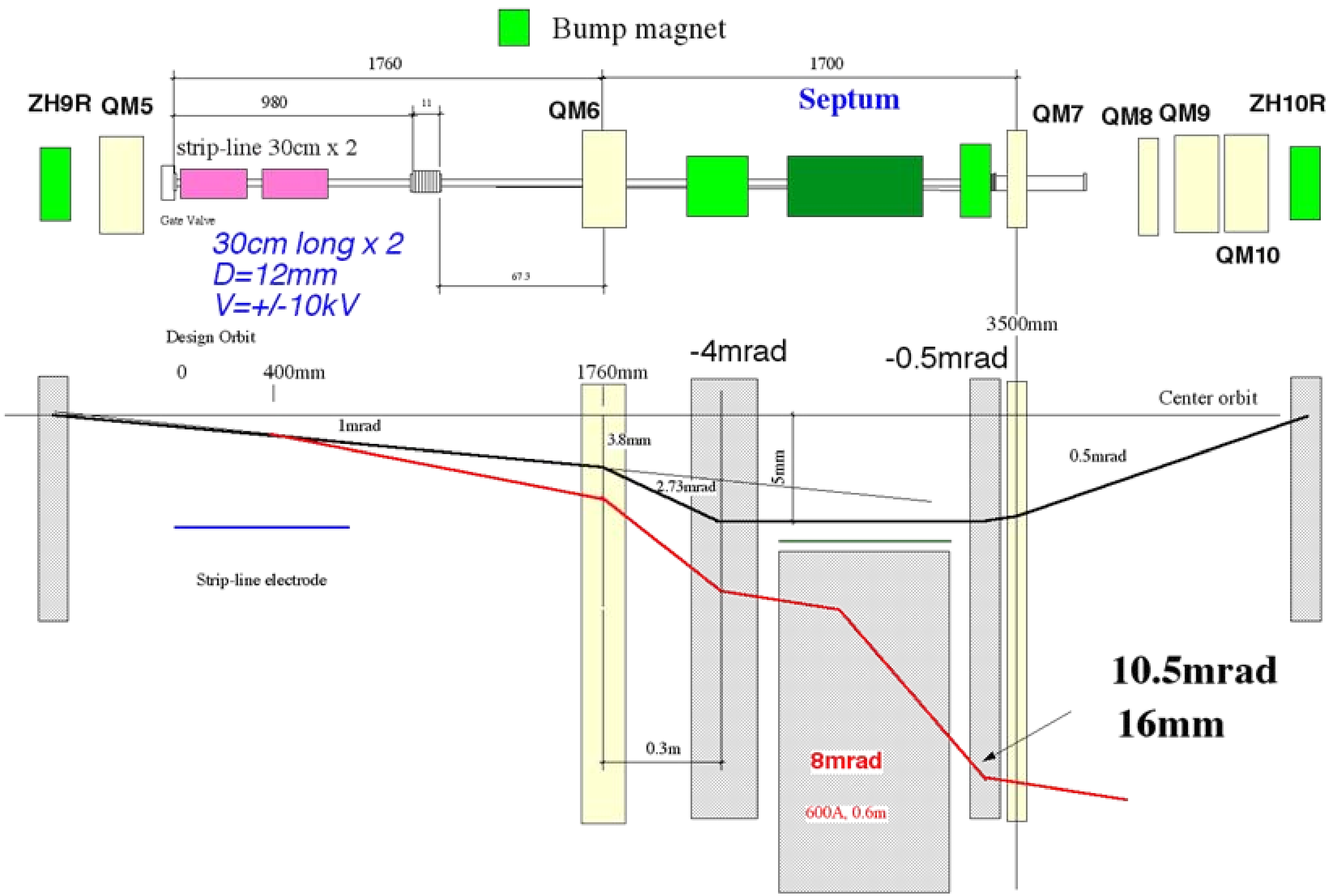
Ferrite vs. stripline kicker

Stripline	Ferrite
$F_E = qV(1+\beta)/g$	$F_B = qvB = q\beta c\mu_0 I/g = q\beta c\mu_0 V/(Z_0 g)$ $= (qV/g)(\mu_0\beta c/(Z_0))$ Assume $Z_0 = 12\ \Omega$ *(take credit for 2 cables and voltage doubling at magnet)* $F_B \approx 31\ F_E\ \beta/(1+\beta)$
Fast rise and fall time	Fast rise time, big kick, hard to get fast fall time Can present large beam impedance

For a given length, voltage, and current, the bend angle from a ferrite kicker can be up to 15x more than from a stripline kicker!

Example from ILC



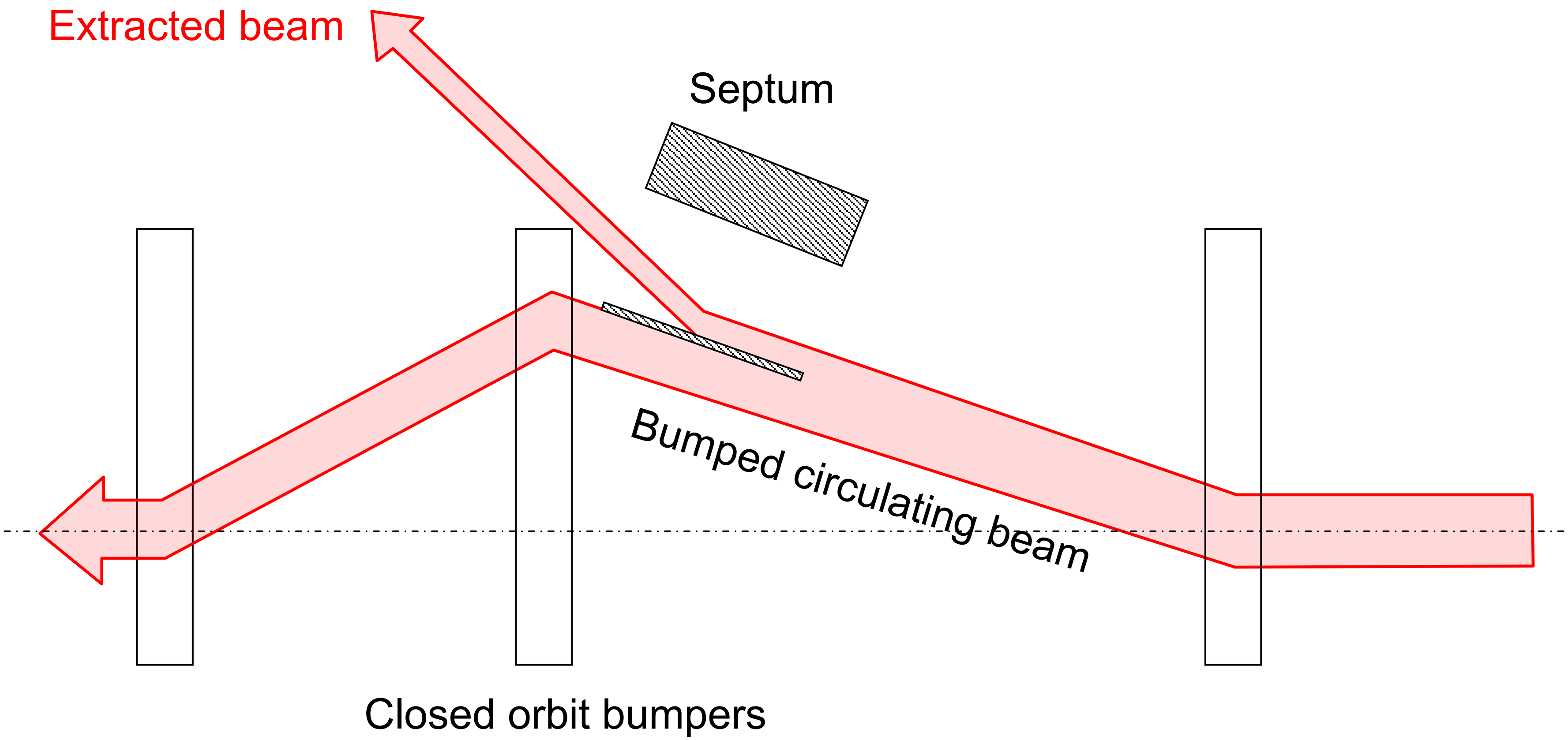
(T.Naito, ILC kicker, PAC07)

Multi-turn extraction

- Some filling schemes require a beam to be injected over several turns into a larger machine…
- And, fixed target physics experiments often need a continuous flux of particles…

- Multi-turn extraction…
  - Non-Resonant multi-turn ejection (few turns) for filling
    e.g. PS to SPS at CERN for high intensity proton beams (>2.5 • 10^{13} protons)
  - Resonant extraction (ms to hours) for experiments

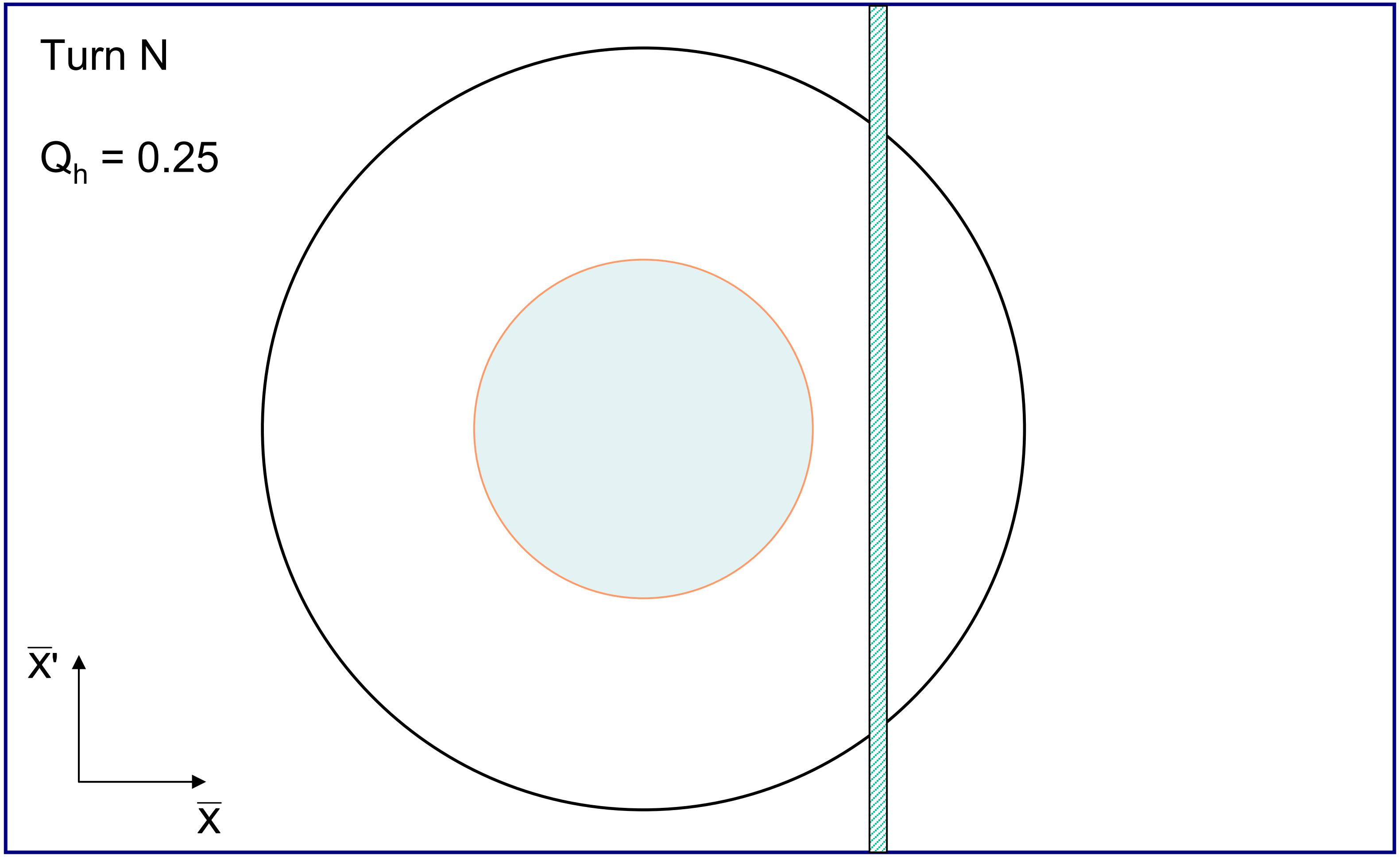
Non-resonant multi-turn extraction



- Fast bumper deflects the whole beam onto the septum
- Beam extracted in a few turns, with the machine tune rotating the beam
- Intrinsically high-loss process – thin septum essential

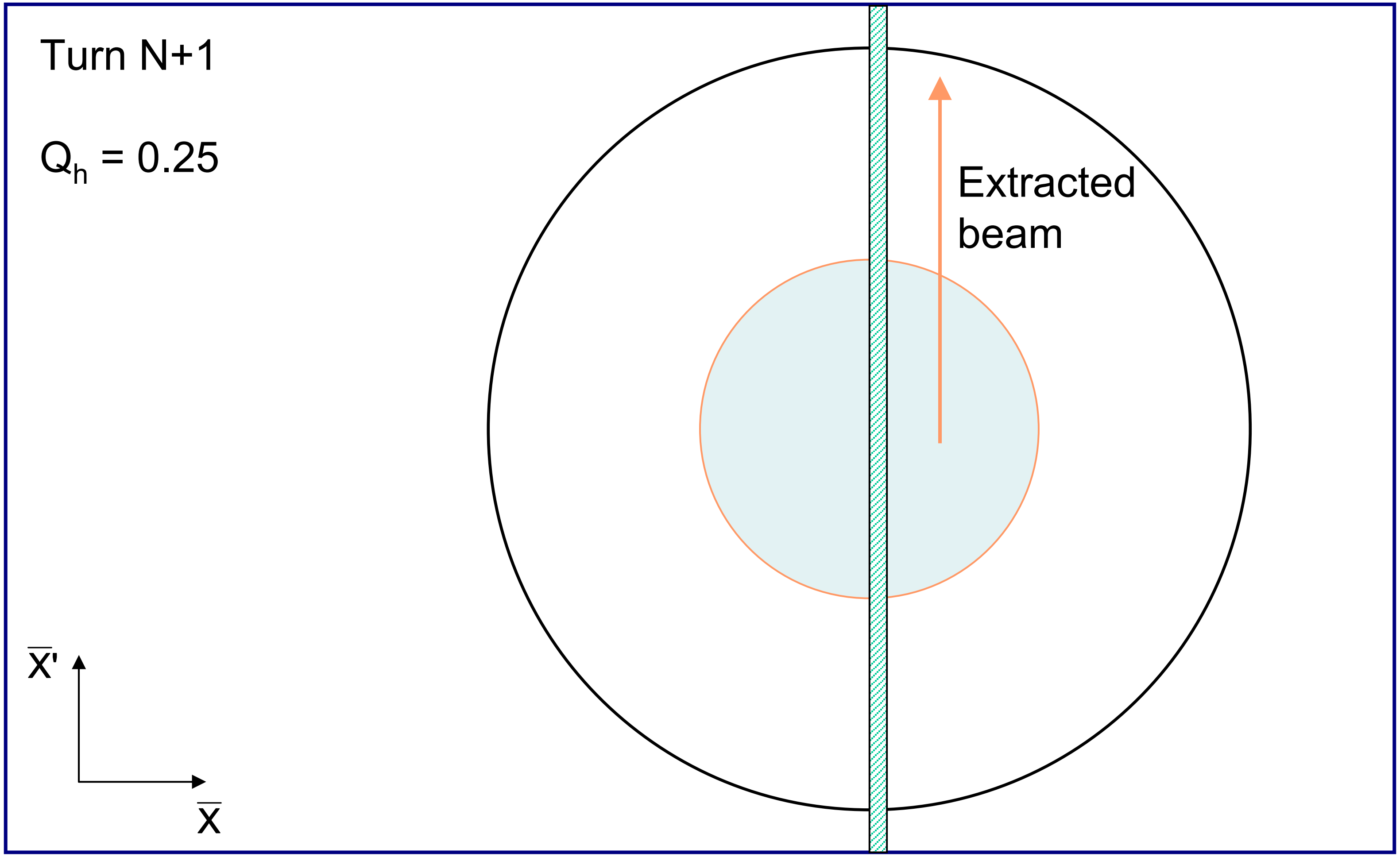
Non-resonant multi-turn extraction

Just before extraction….



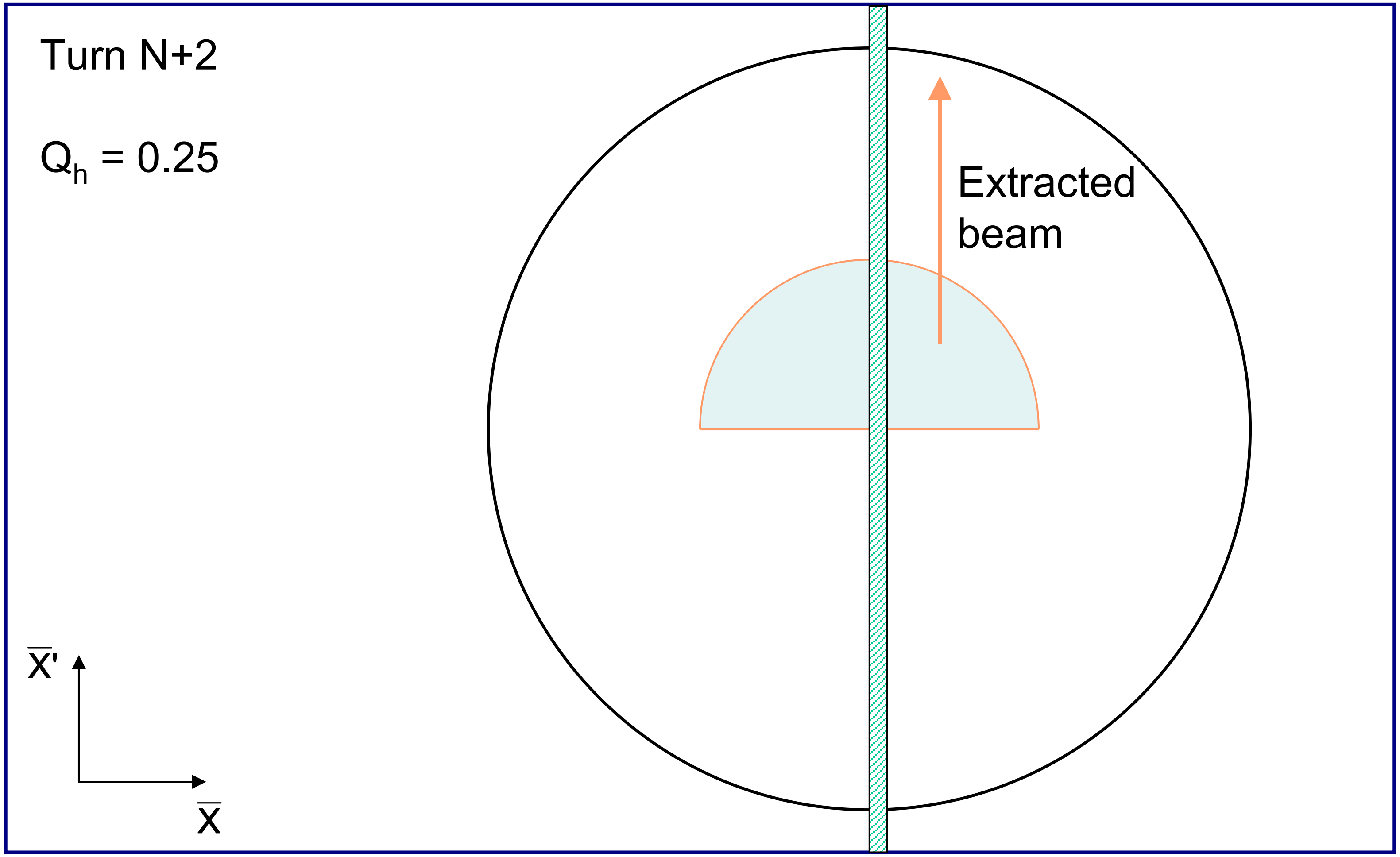
Non-resonant multi-turn extraction

Fast closed orbit bump moves part of the beam across the septum



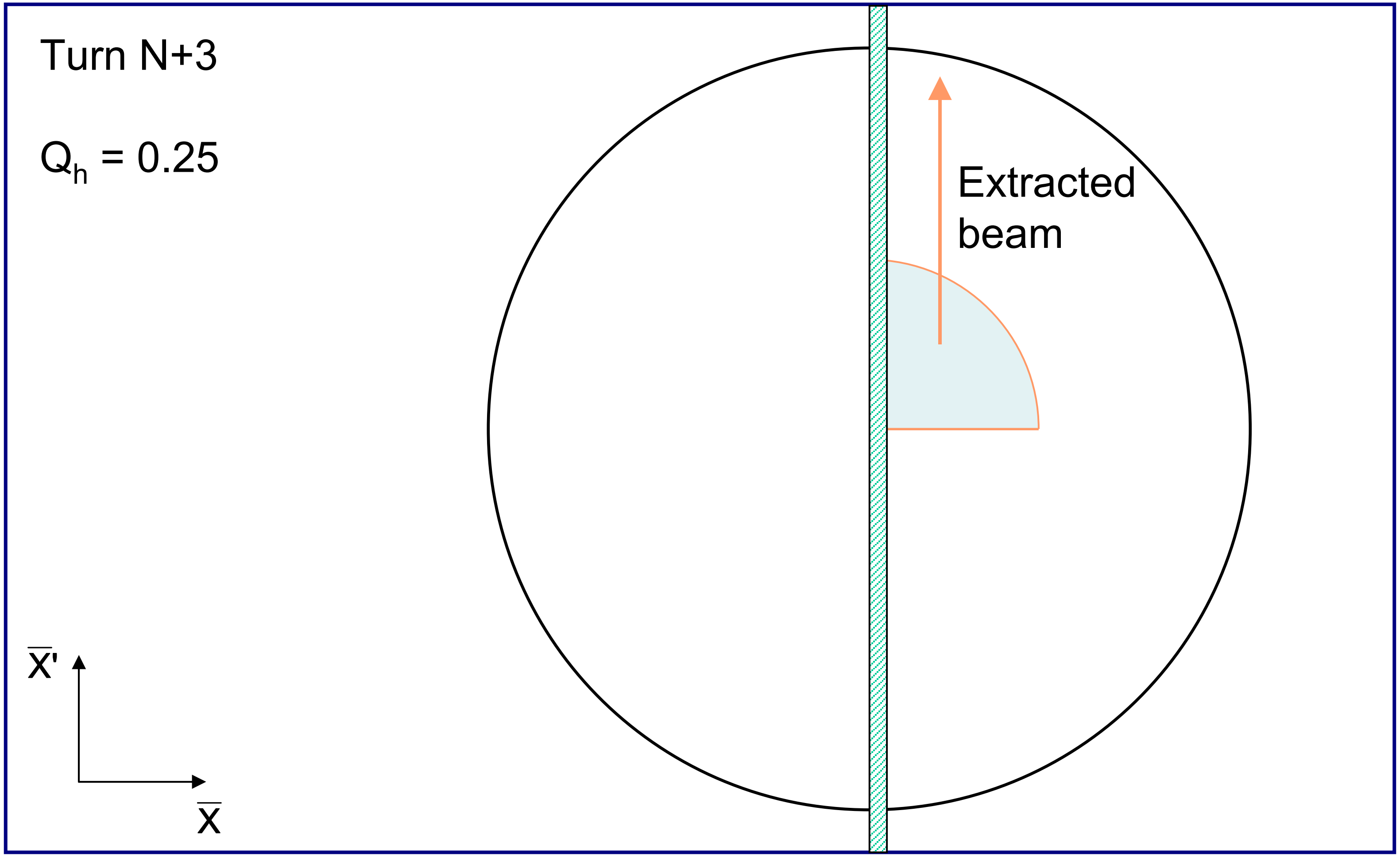
Non-resonant multi-turn extraction

The beam rotates across the septum….



Non-resonant multi-turn extraction

…and the last part is extracted on the final turn.

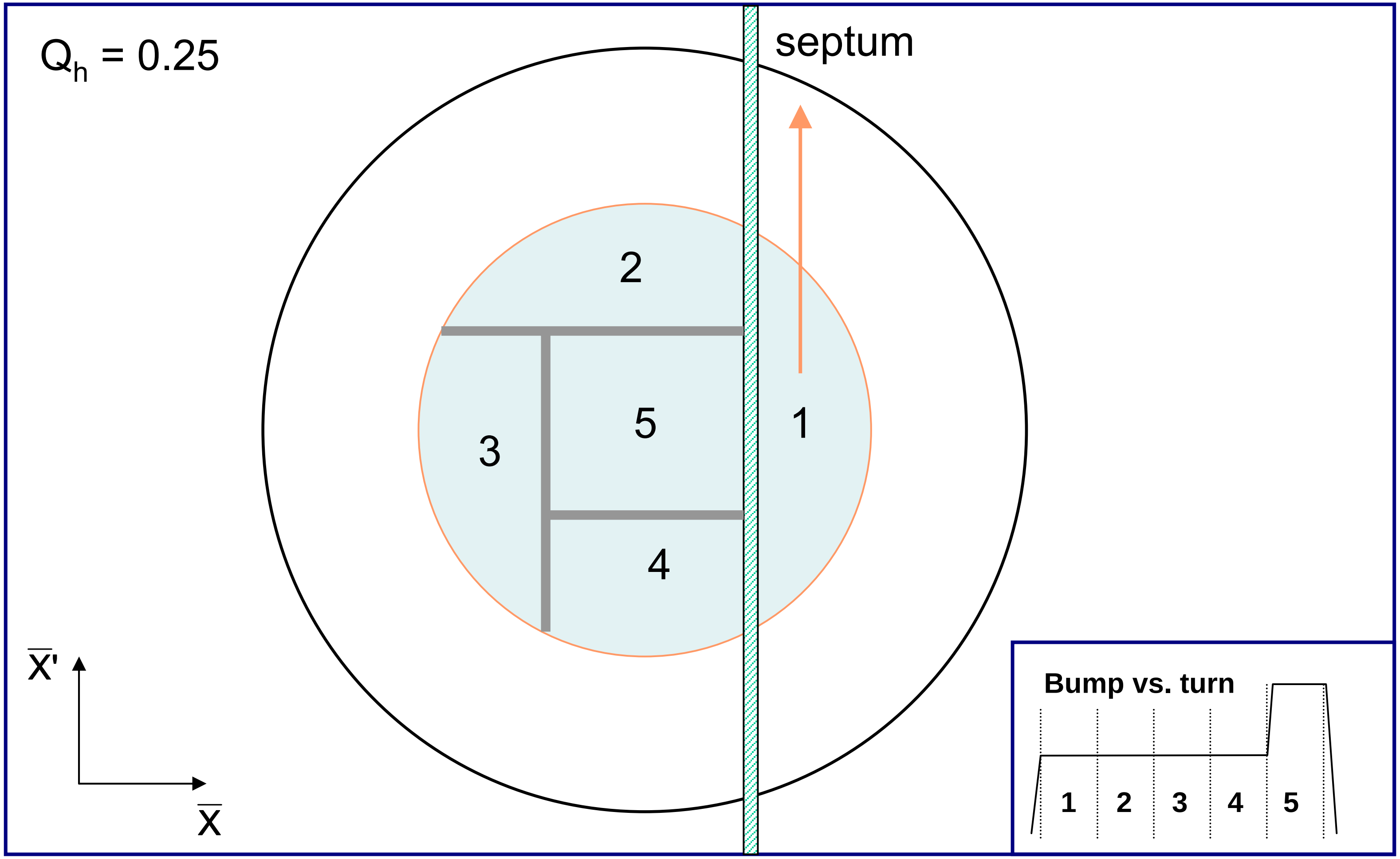


Non-resonant multi-turn extraction

- Example system: CERN PS to SPS Fixed-Target 'continuous transfer'
  - Accelerate beam in PS to 14 GeV/c
  - Empty PS machine (2.1 μs long) in 5 turns into SPS
  - Do it again
  - Fill SPS machine (23 μs long)
  - Quasi-continuous beam in SPS (2 x 1 μs gaps)
  - Total intensity per PS extraction ≈ 3×10^{13} p+
  - Total intensity in SPS ≈ 5×10^{13} p+

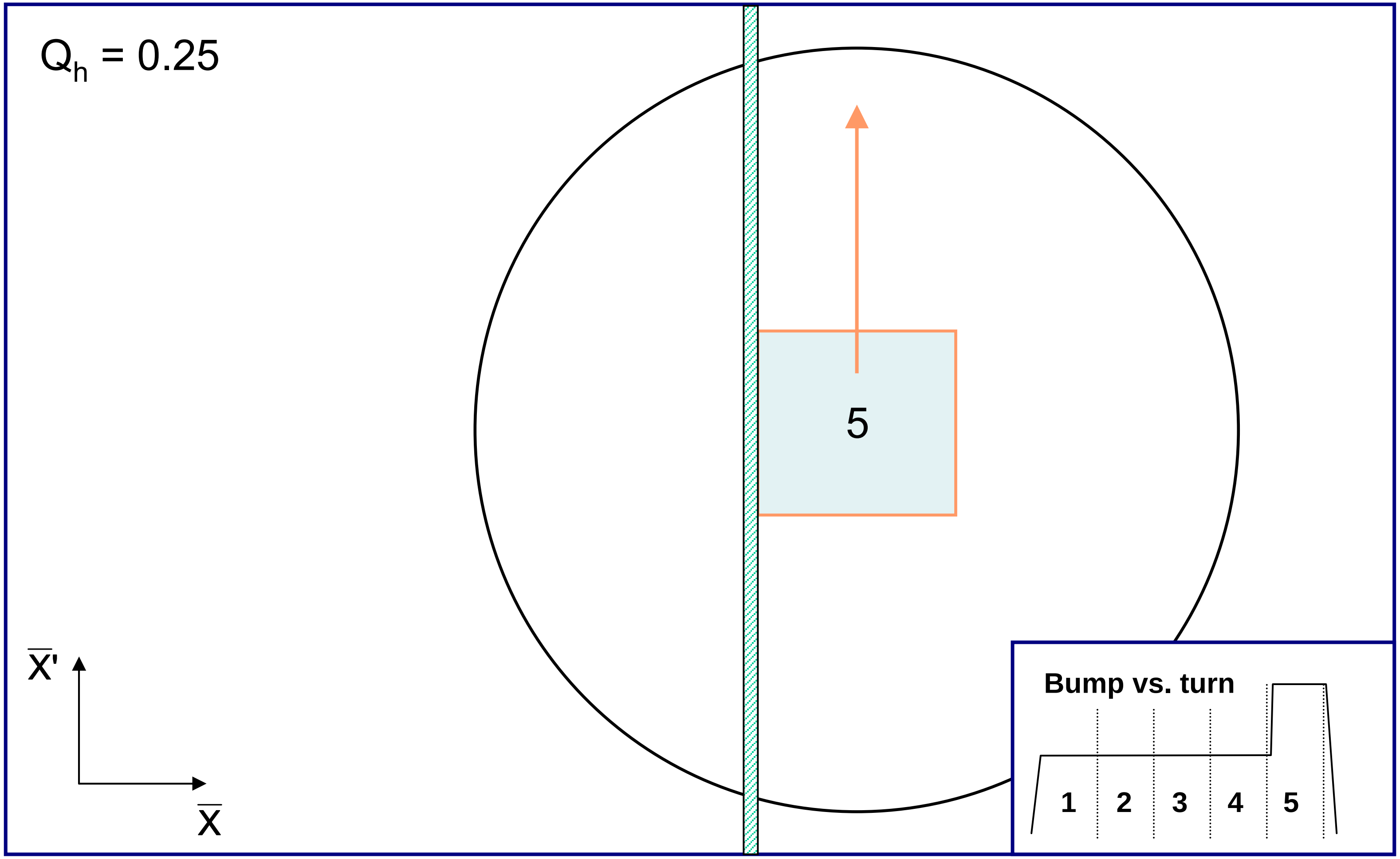
Non-resonant multi-turn extraction

CERN PS to SPS: 5-turn continuous transfer



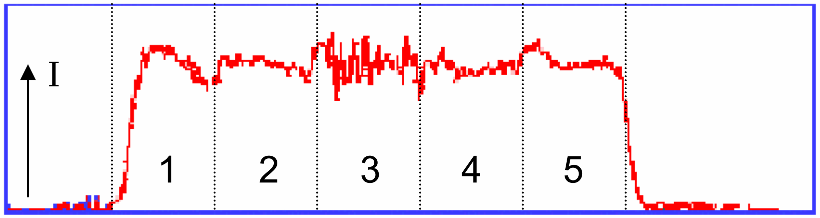
Non-resonant multi-turn extraction

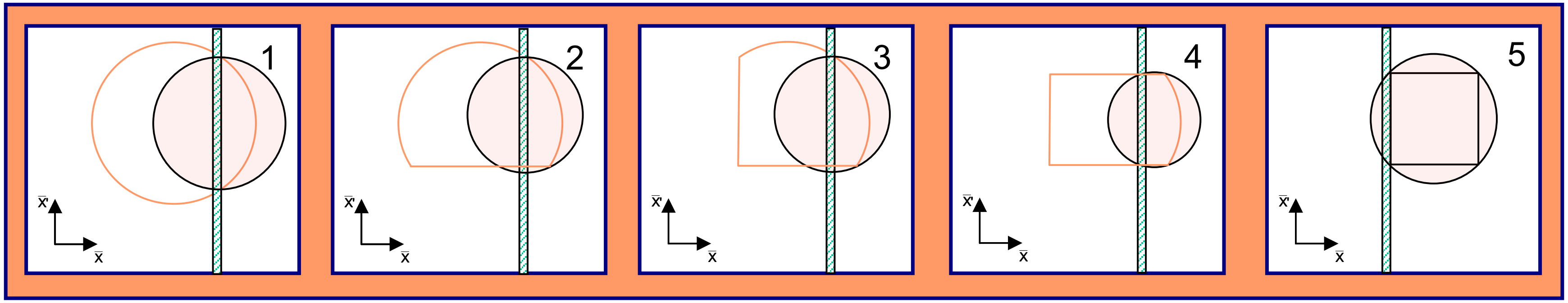
CERN PS to SPS: 5-turn continuous transfer – 5th turn



Non-resonant multi-turn extraction

- CERN PS to SPS: 5-turn continuous transfer
  - Losses require thin (ES) septum… second septum needed
  - Still about 15 % of beam lost in PS-SPS transfer
  - Difficult to get equal intensities per turn
  - Different trajectories for each turn
  - Different emittances for each turn





Resonant multi-turn extraction

Will be covered by Uli

Recap

- Single turn extraction is a lot like single turn injection
- Optimum phase advance from kicker to septum is $\pi/2$
- Ferrite kickers more efficient than stripline kickers
  - But striplines best for fast rise and fall times
- There are two main types of multi-turn extraction
  - Non-resonant – most straightforward
  - Resonant – more complicated but can get longer spill times

Acknowledgements

- Thanks to B. Goddard. Many of these slides were copied from his CAS course.