Single and Multi-turn Fast Extraction

- Introduction
- Single-turn fast extraction:
  - Basic design considerations, principles and concepts
  - Important parameters for kickers and septa
  - Examples: CERN PSB, PS and SPS extraction systems
- Multi-turn fast extraction:
  - Basic principles and concepts
  - Mechanical (non-resonant) splitting vs. magnetic (resonant) splitting
  - Examples: CERN PS CT and MTE extraction systems

Matthew Fraser, CERN (TE-ABT-BTP)

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  } leptons/hadrons
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  - At high energies many kicker and septum modules may be required
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  - Losses and activation are far more important
- Different extraction techniques exist, depending on requirements:
  - **Fast single-turn extraction**: ≤1 turn
    - transfer between machines in complex of synchrotrons, to experimental (production) targets, safely dump the circulating beam (fast abort) etc.
  - **Fast multi-turn extraction:** few turns
    - uniformly fill a synchrotron with a larger circumference or vary spill length
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    - providing experimental target, or patient, with “long” uniform spills
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Design considerations

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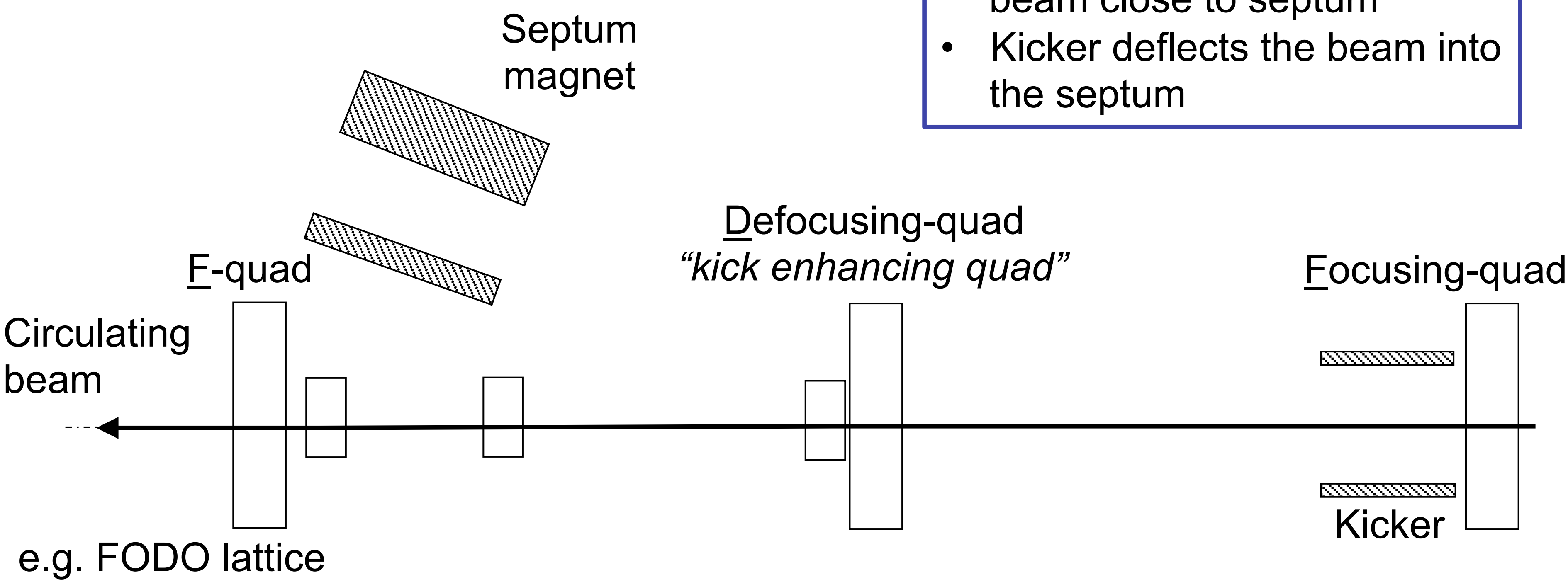
- Important **for high momentum machines** where the layout, performance and protection may be significantly influenced by the extraction system:
  - **destination/user**:
    - precision of beam delivery, tolerated beam loss / emittance blow-up
  - **failure scenarios** and their mitigation (at high energy/intensity):
    - integral part of machine protection system
    - see M. Barnes' lectures: *Kicker Magnets,* A. Nordt's lecture: *Machine Protection and Activation* and W. Bartmann's lectures*: Transfer Line Design…*
  - **insertion regions** may be required to meet specific requirements:
    - optics, integration, aperture, interference with other essential sub-systems
    - see B. Holzer's lectures: *Review of Transverse Dynamics*
- All of the above affect the choice of **hardware employed**: it's an iterative process!

Fast extraction: spatial considerations

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



- Important considerations:
  - optimum phase advance between kicker and septum, e.g. ≈ QD in between: β_x large at F-quads (near kicker and septum in this case)
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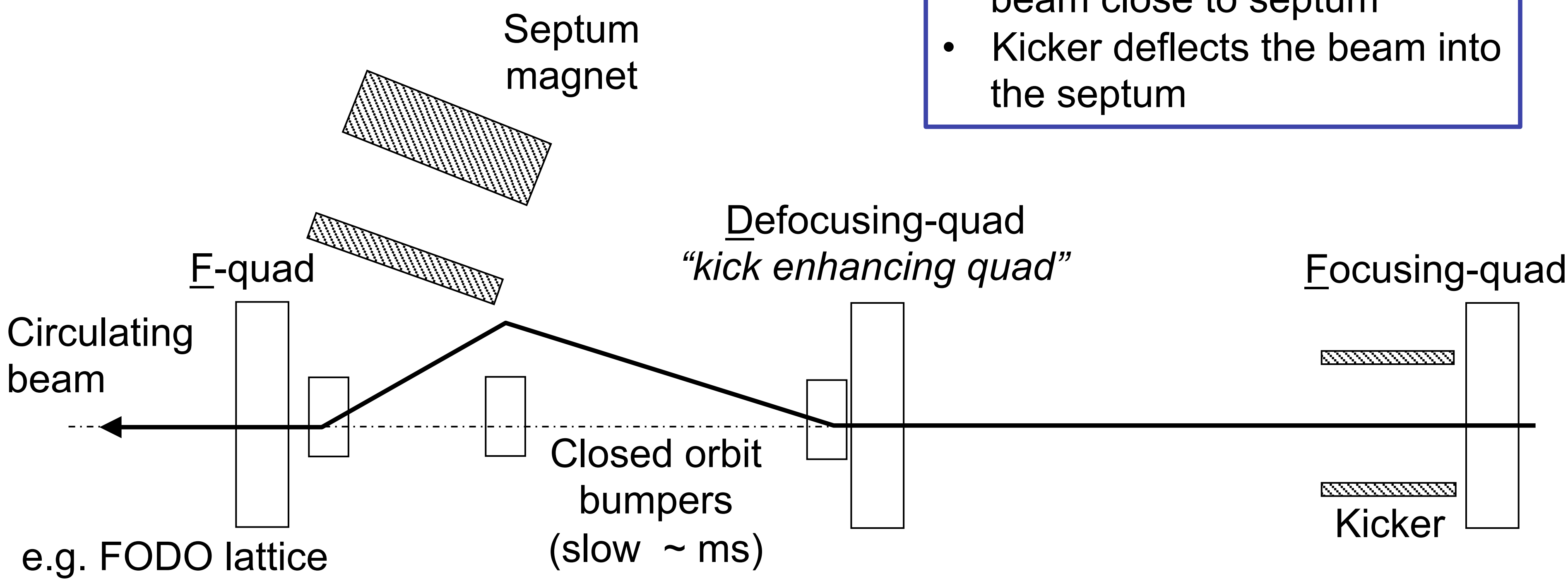

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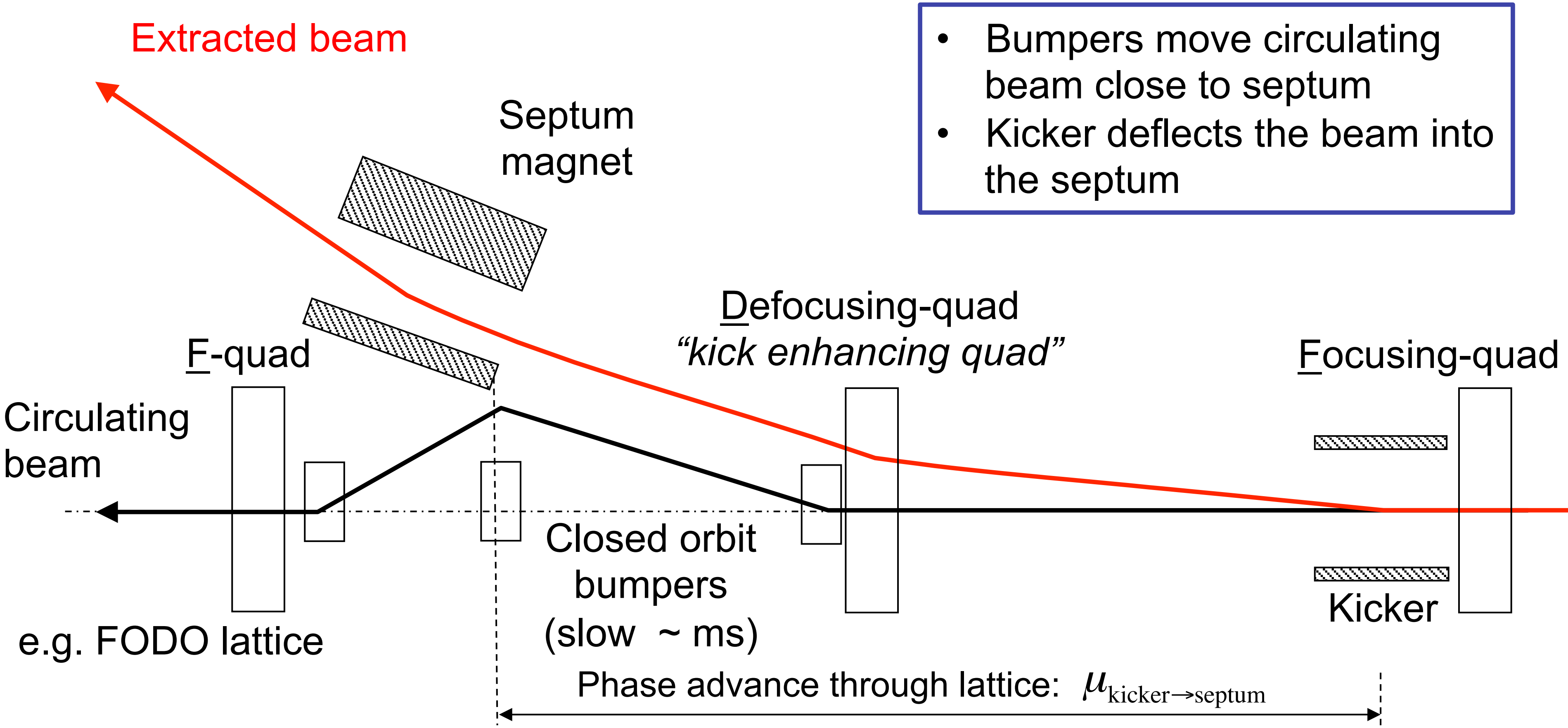

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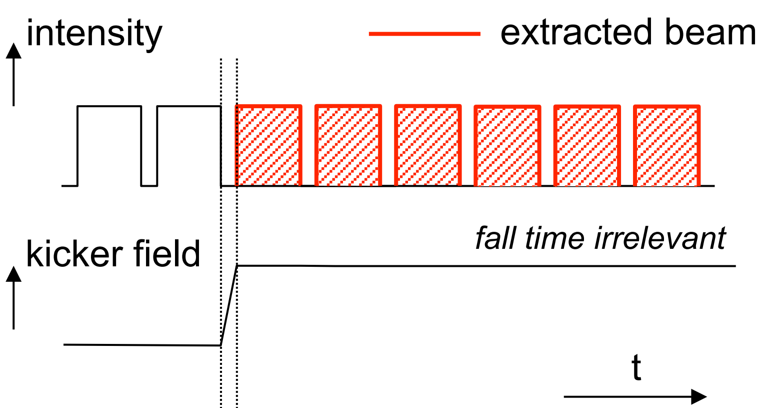
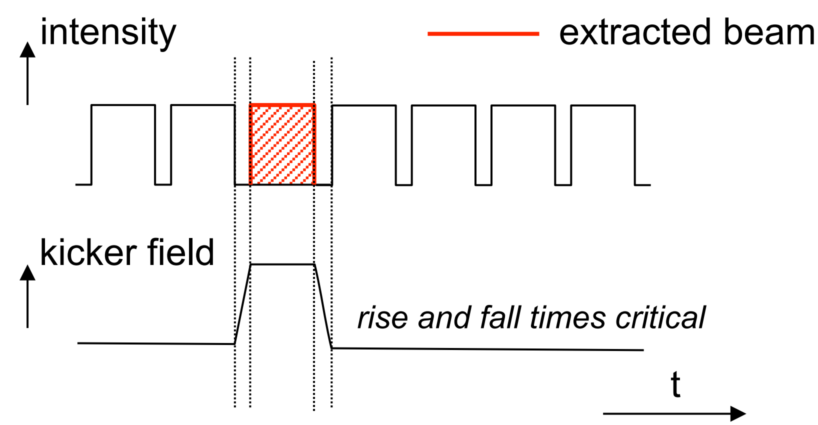
Fast extraction: temporal considerations

- For clean transfer, particle-free gaps in the circulating beam are essential:



single-turn extraction:
transfer between machines or fast-abort



multi-burst or multi-batch extraction:
kicker system must have time to re-charge

  - kicker field must have time to rise (and fall) before it is seen by the beam
  - gaps limit total intensity
  - repetition rate of kicker system: pulsed-power supply must have time to recharge, which typically takes many turns: $t_{recharge} >> t_{rev}$
    - continuous extraction over sequential turns (usually) requires transverse manipulation: *discussed later in this lecture (multi-turn extraction)*

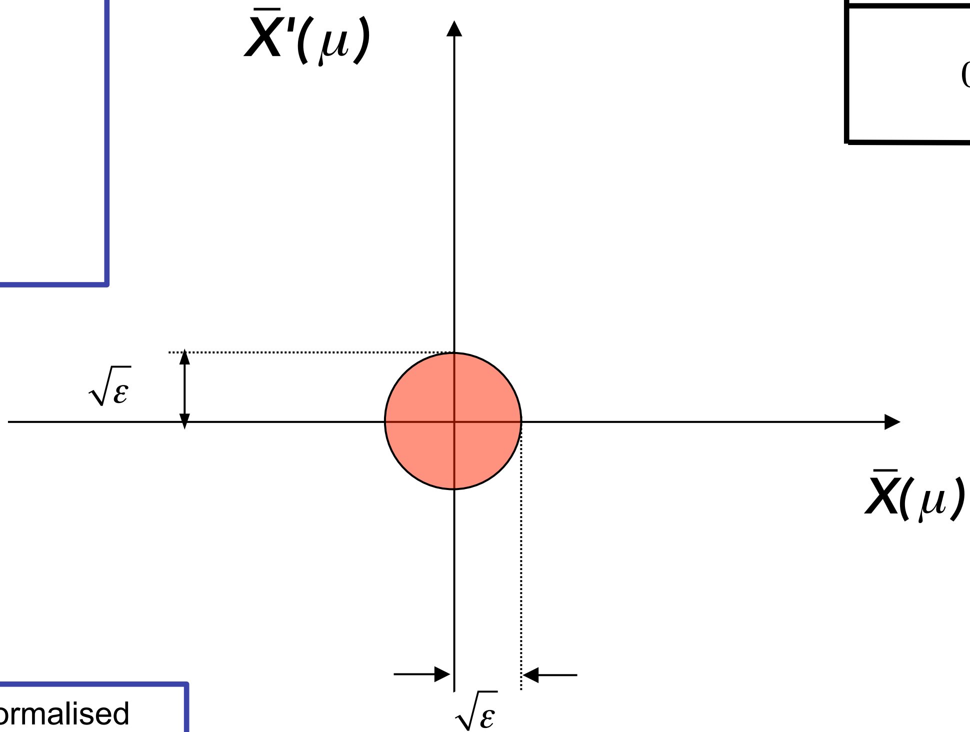
Kick dynamics

Normalised phase space at the kicker location:

$\Delta x'_{\mathrm{kicker}}$	$\Delta \bar{X}'_{\mathrm{kicker}}$
0	0

Kicker strength:

$$\Delta x'_{\mathrm{kicker}} = 0$$



Reminder: transformation to normalised phase space:

$$\begin{bmatrix} \bar{X} \\ \bar{X}' \end{bmatrix} = \mathbf{N}\cdot\begin{bmatrix} x \\ x' \end{bmatrix} = \sqrt{\frac{1}{\beta(s)}}\cdot\begin{bmatrix} 1 & 0 \\ \alpha(s) & \beta(s) \end{bmatrix}\cdot\begin{bmatrix} x \\ x' \end{bmatrix}$$

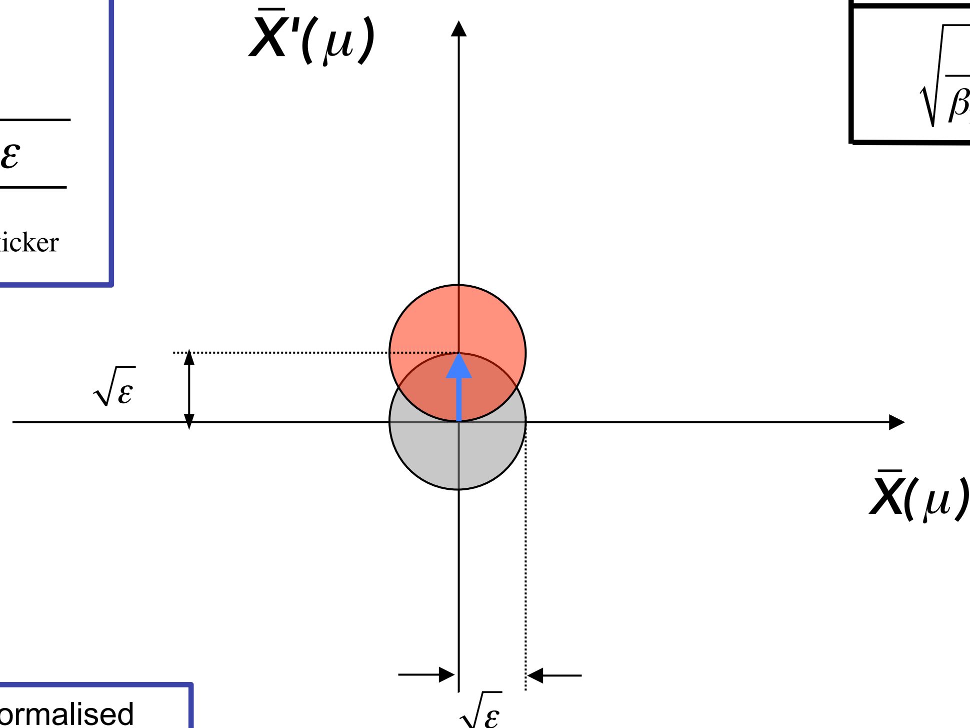
Kick dynamics

Normalised phase space at the kicker location:

$\Delta x'_{\text{kicker}}$	$\Delta \bar{X}'_{\text{kicker}}$
$\sqrt{\frac{\varepsilon}{\beta_{\text{kicker}}}}$	$\sqrt{\varepsilon}$

Kicker strength:

$$\Delta x'_{\text{kicker}}(+1\sigma) = \sqrt{\frac{\varepsilon}{\beta_{\text{kicker}}}}$$



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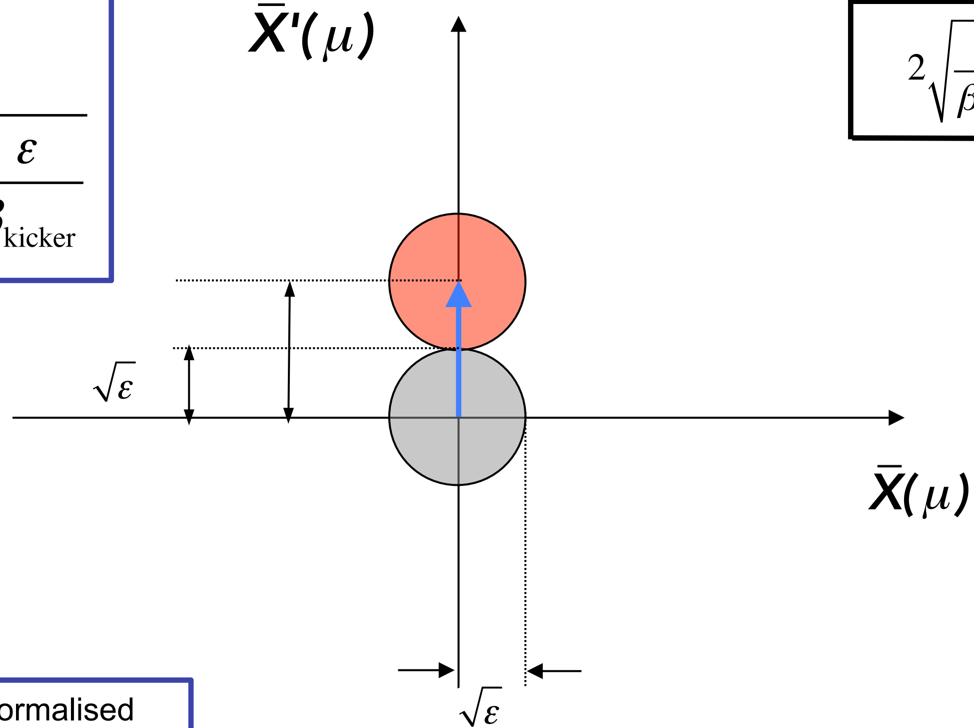
$2\sqrt{\dfrac{\varepsilon}{\beta_{\text{kicker}}}}$	$2\sqrt{\varepsilon}$

Kicker strength:

$$\Delta x'_{\text{kicker}}(+2\sigma) = 2\sqrt{\frac{\varepsilon}{\beta_{\text{kicker}}}}$$



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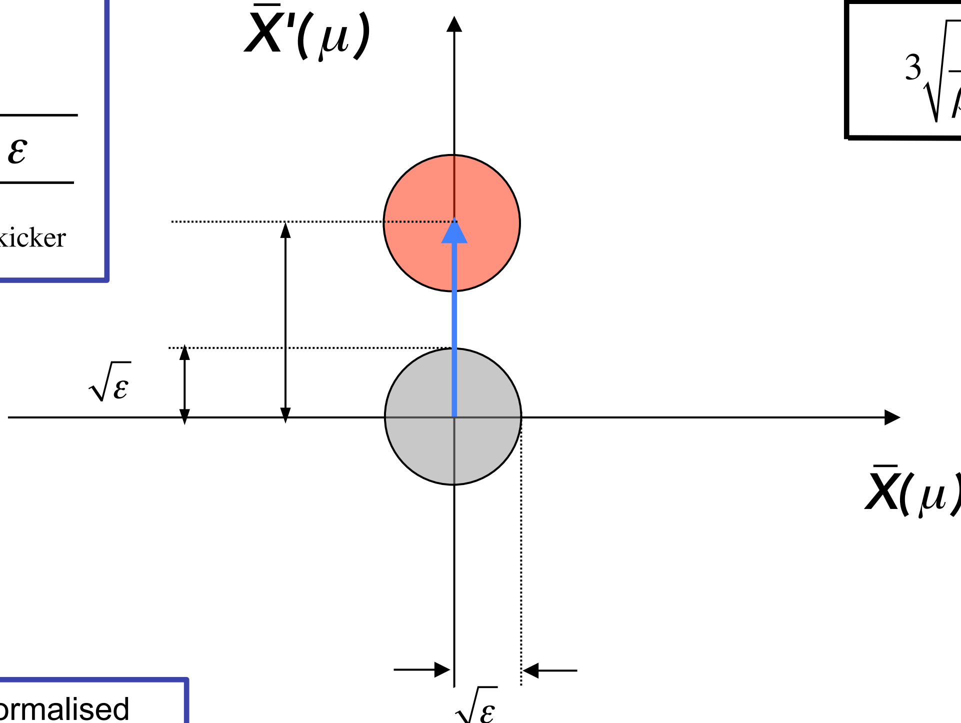
$3\sqrt{\dfrac{\varepsilon}{\beta_{\text{kicker}}}}$	$3\sqrt{\varepsilon}$

Kicker strength:

$$\Delta x'_{\text{kicker}}(+3\sigma) = 3\sqrt{\frac{\varepsilon}{\beta_{\text{kicker}}}}$$



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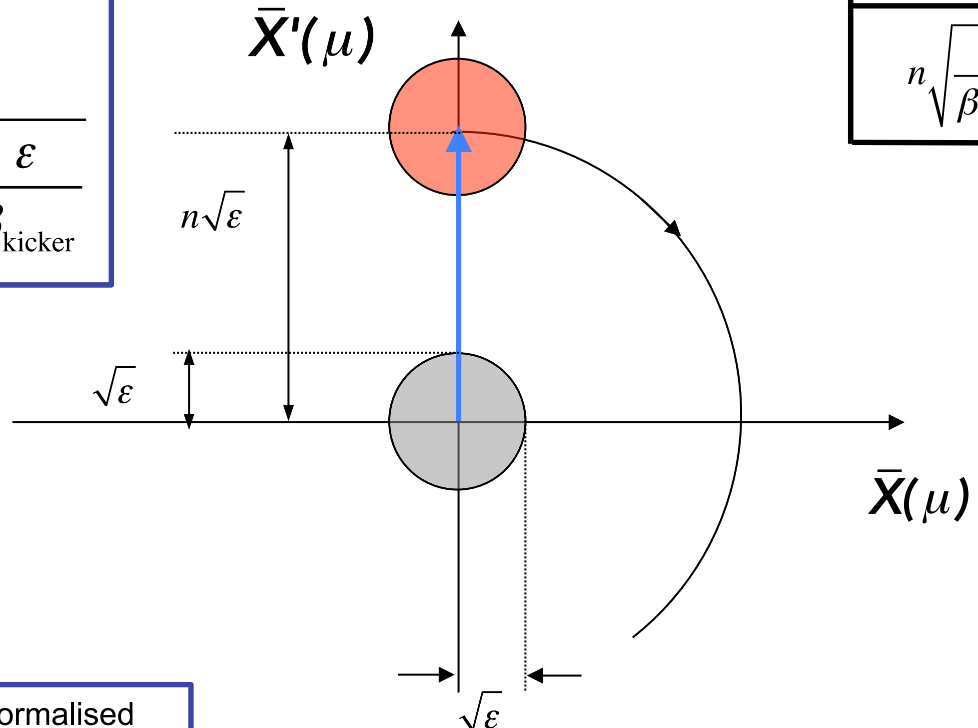

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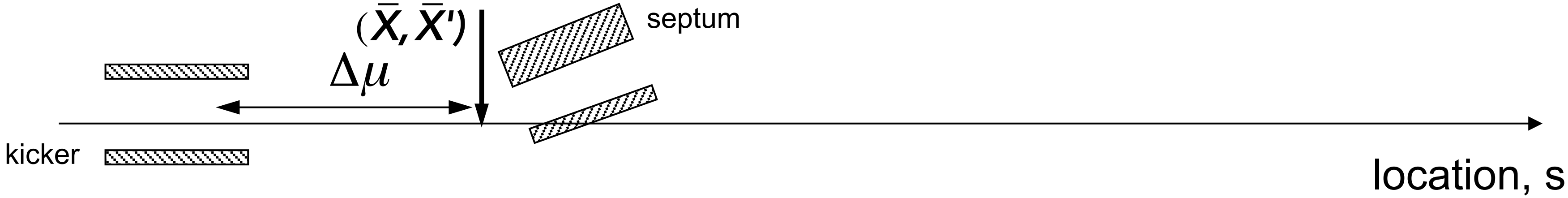

Normalised phase space at the septum location:

Kicker strength:

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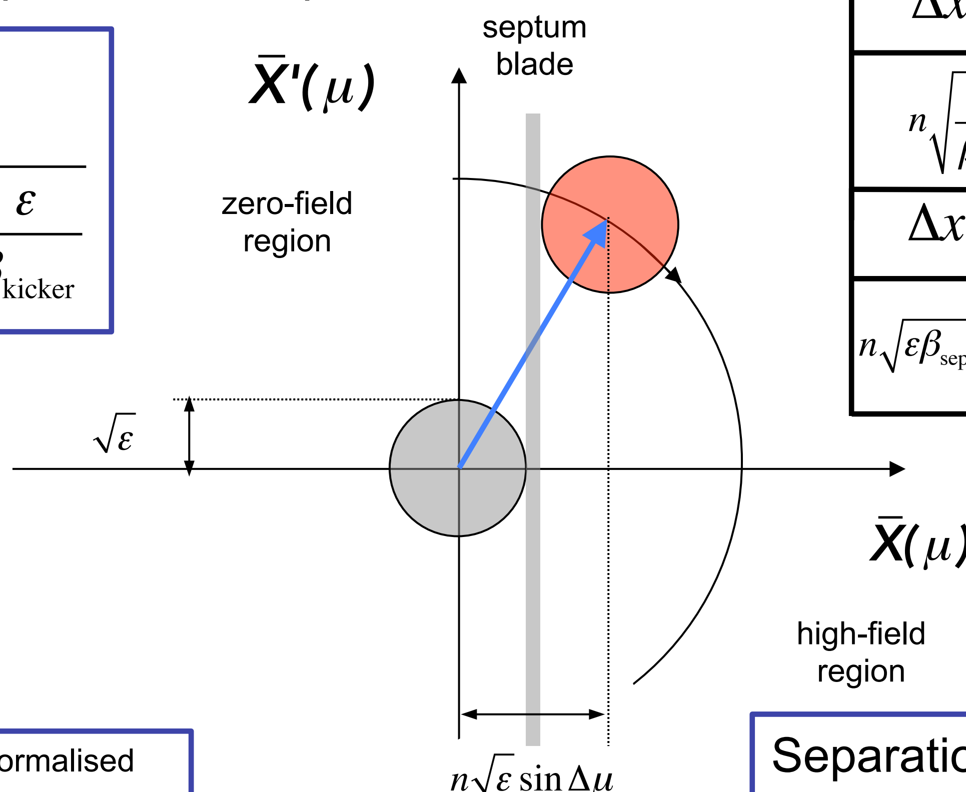

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$$\Delta x_{\text{septum}} = \Delta x'_{\text{kicker}}\sqrt{\beta_{\text{kicker}}\beta_{\text{septum}}}\sin\Delta\mu$$

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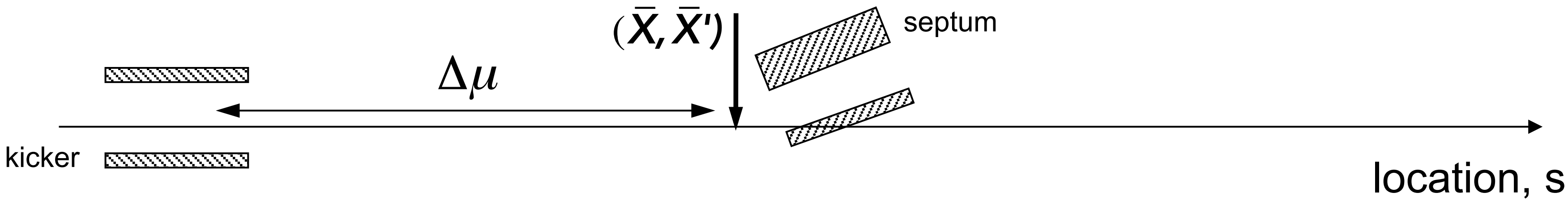

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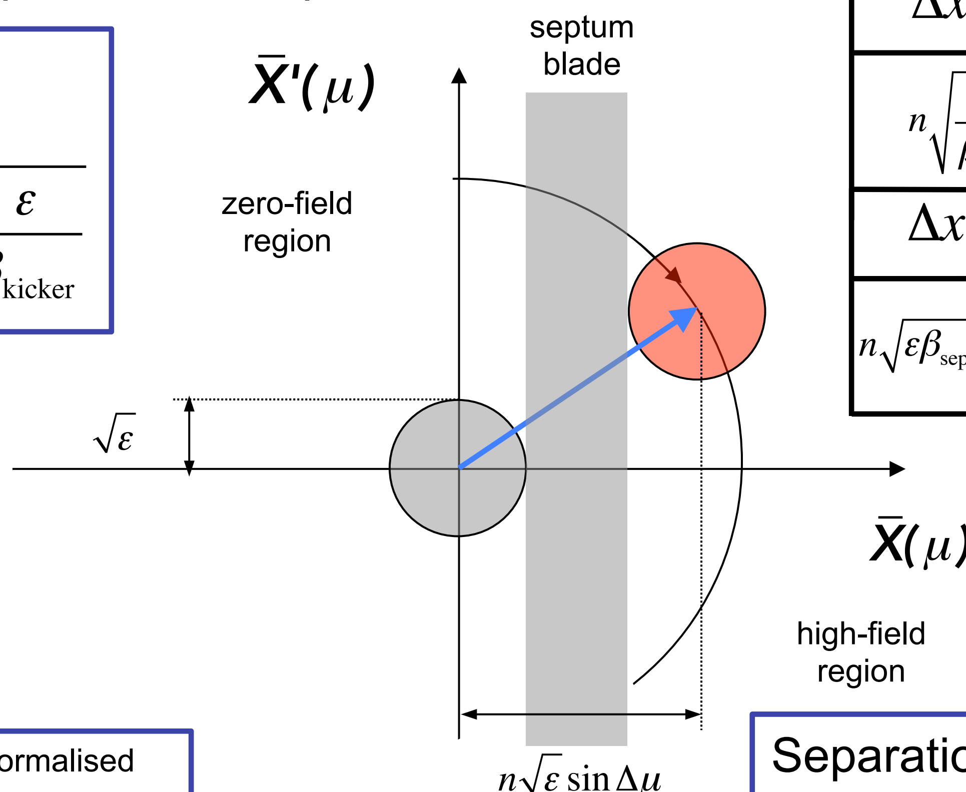

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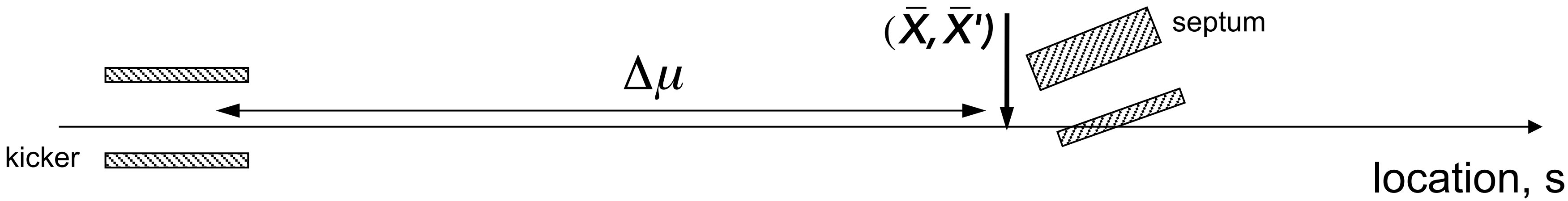

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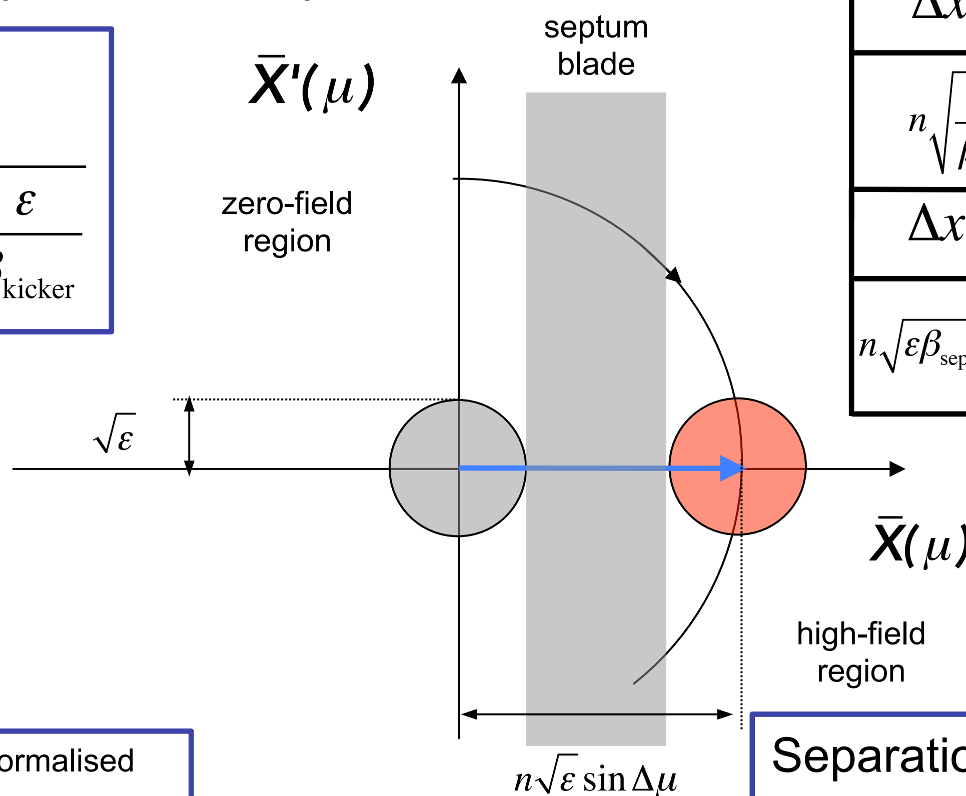

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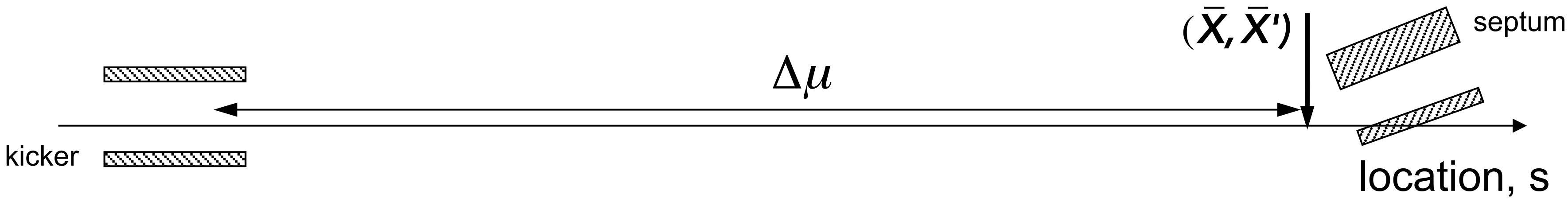

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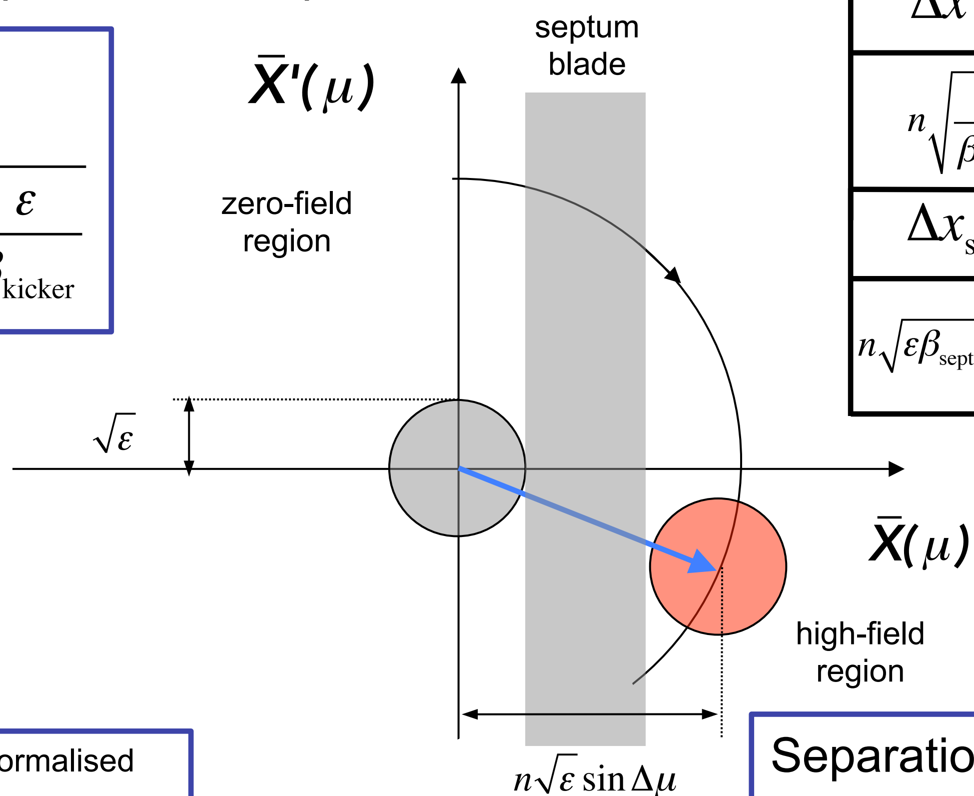

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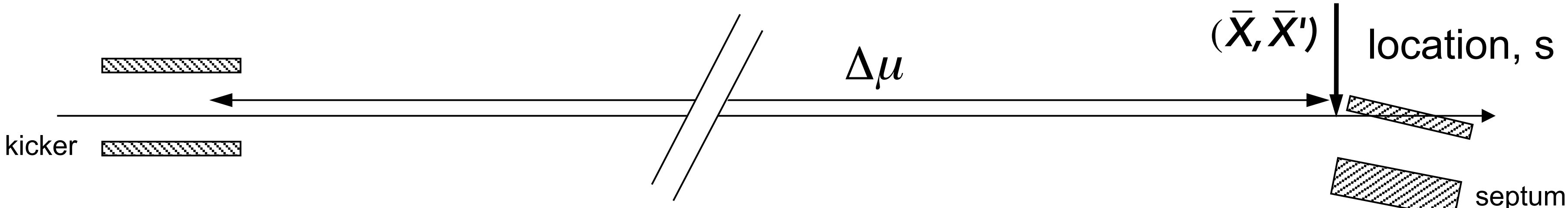

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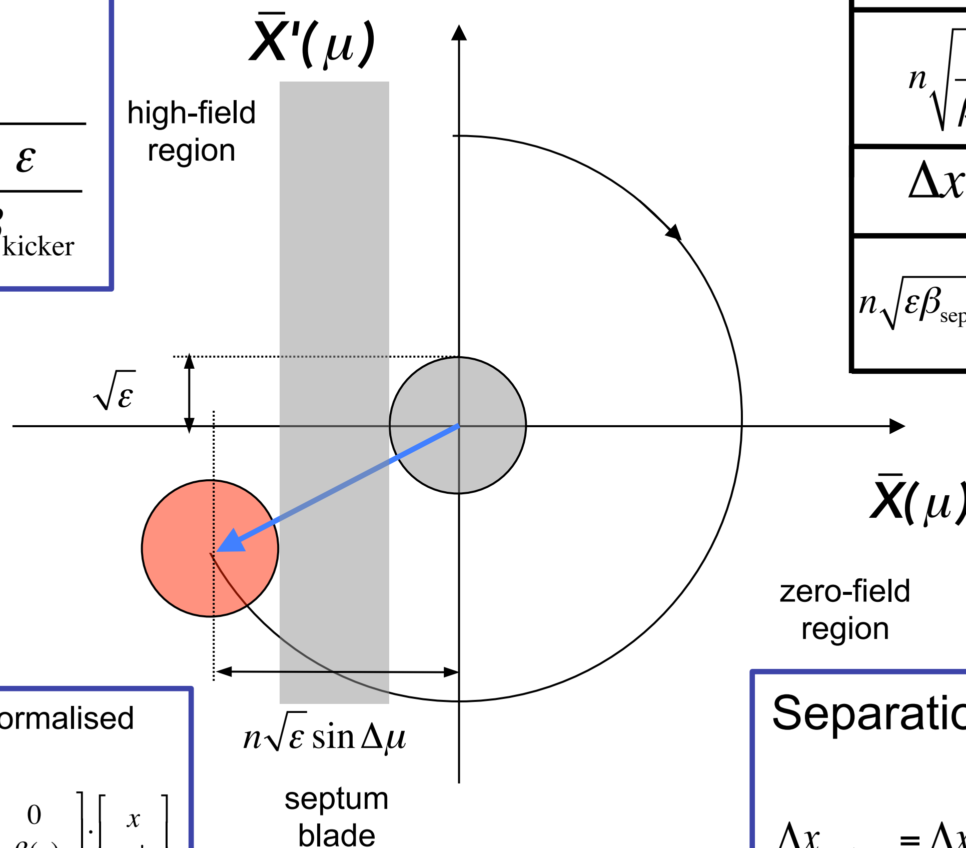

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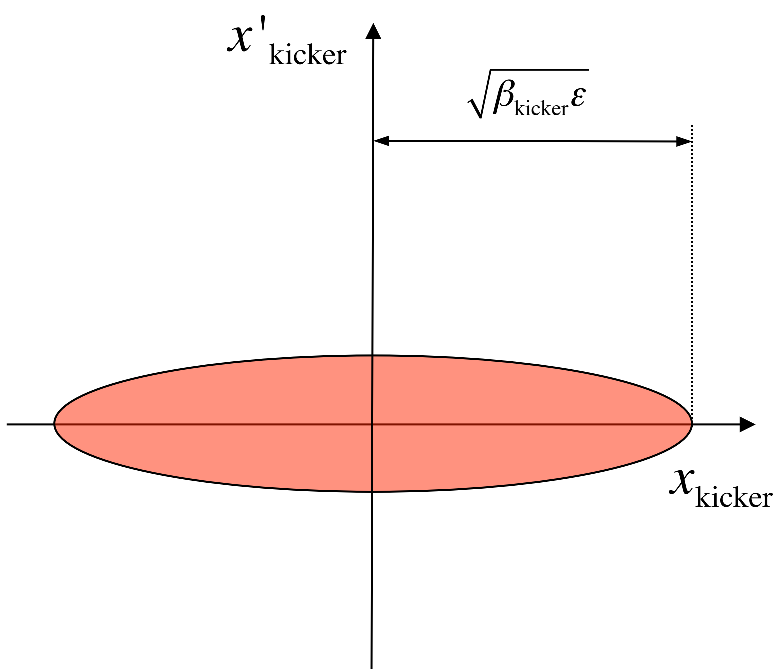
Kick optimisation: β at the kicker

- Intuitively, we can see in **real** phase space why a large β-function at the kicker improves the separation between extracted and circulating beams:

large $\beta_{\text{kicker}}(\alpha_{\text{kicker}}=0):$



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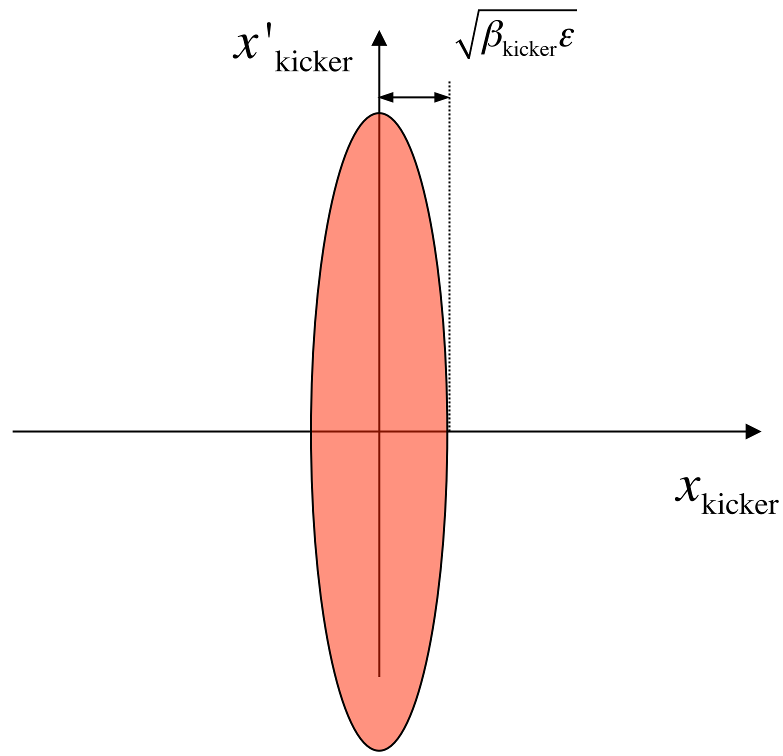

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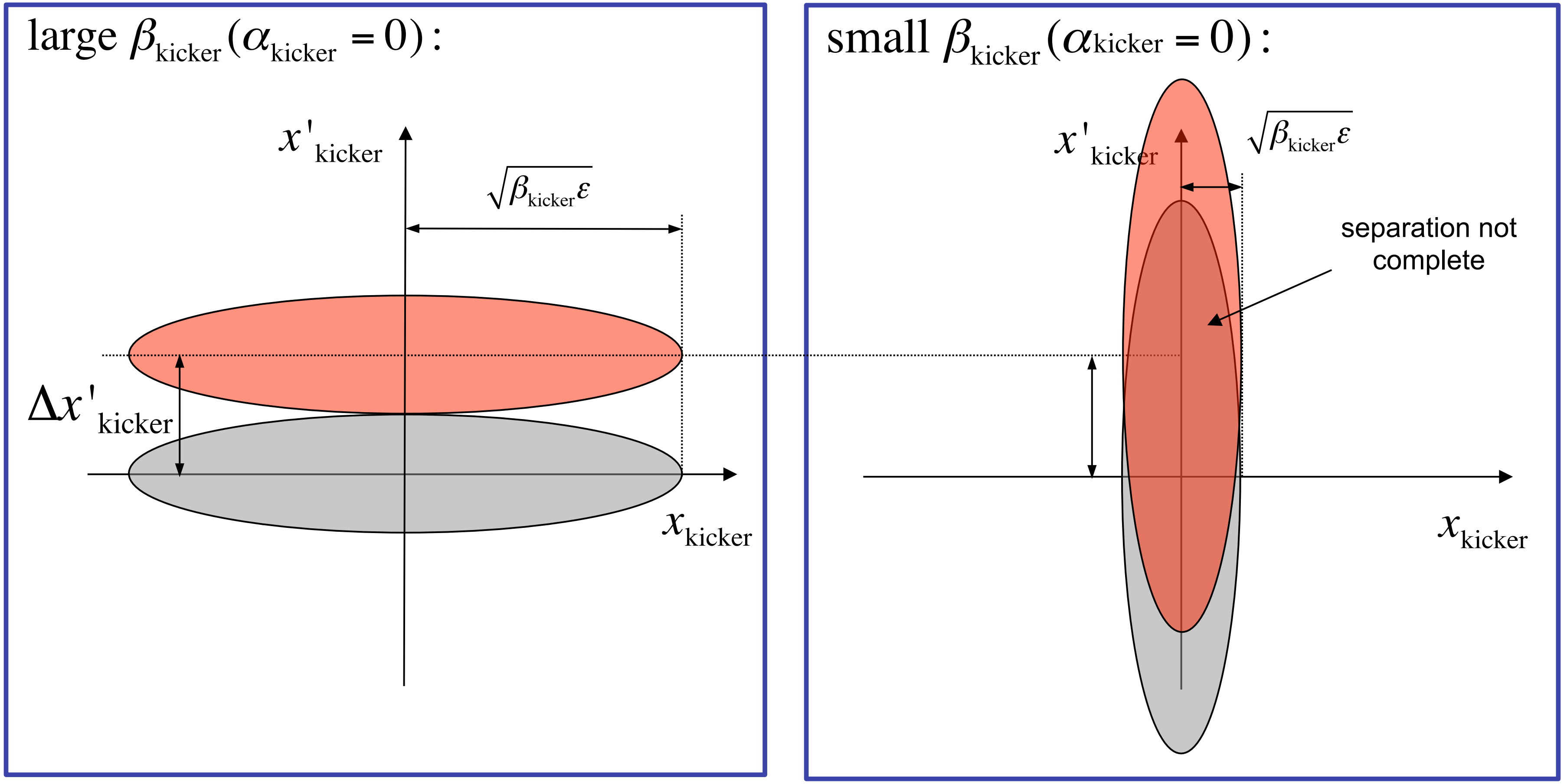

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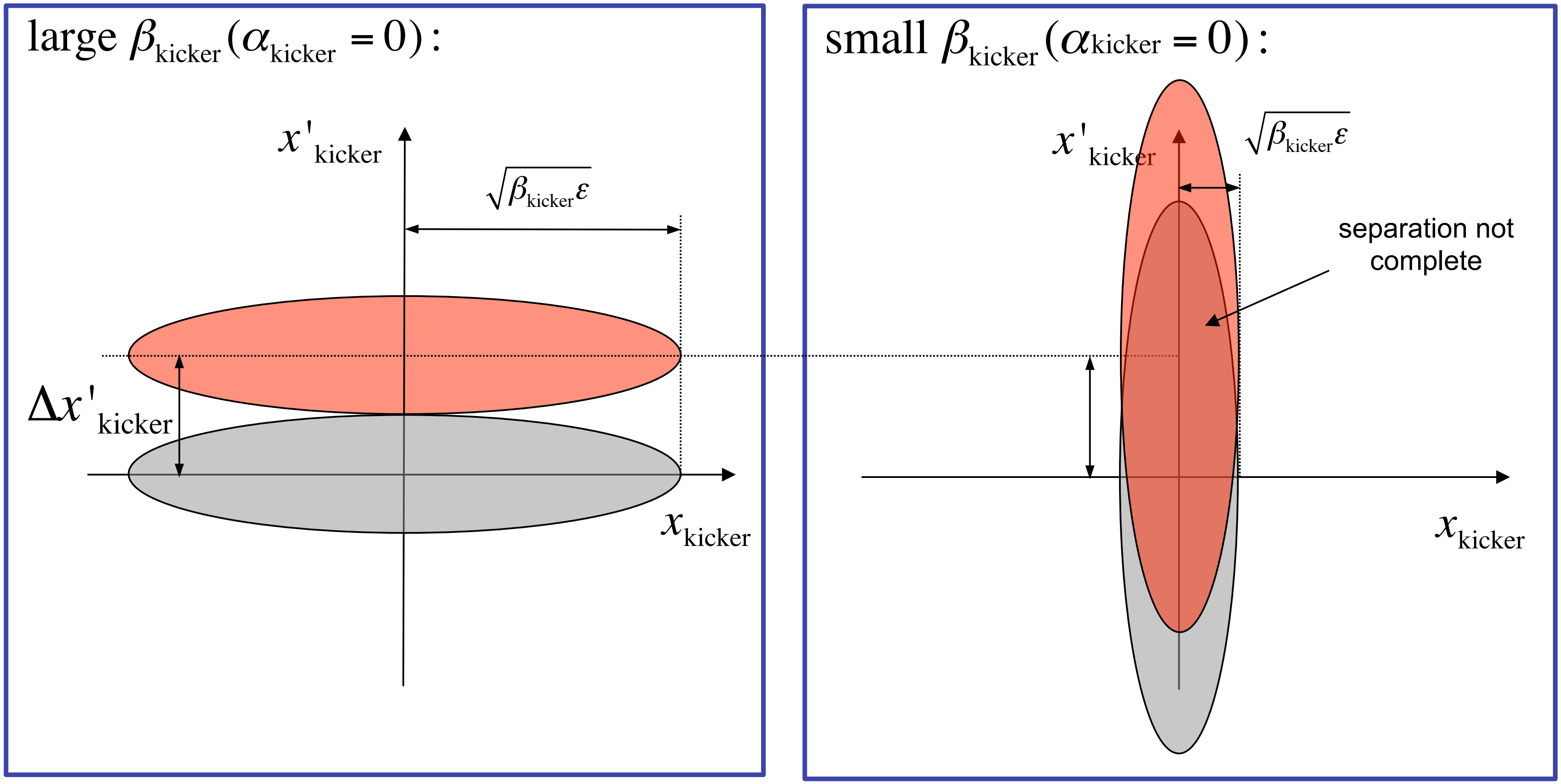
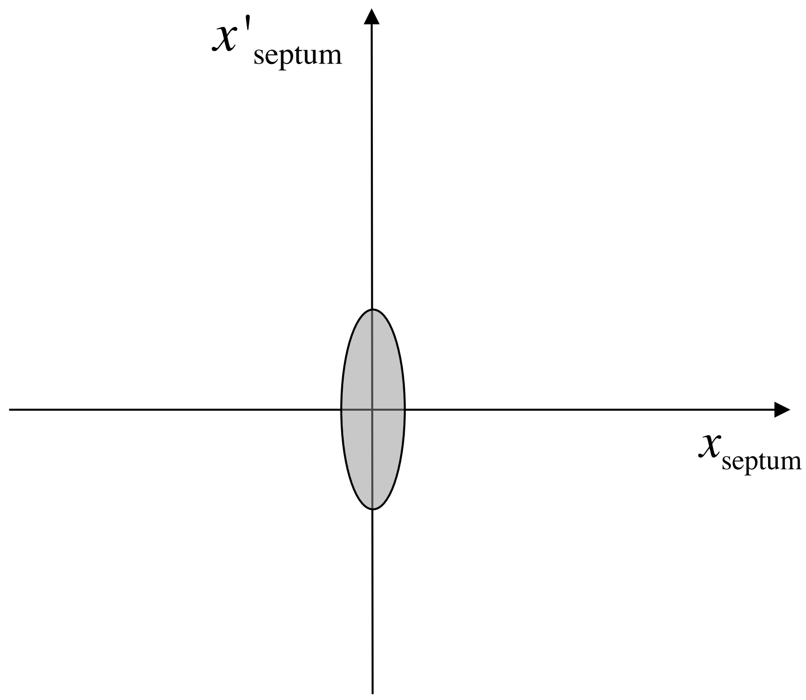


- When the beam divergence is small, we can easily "jump" outside the circulating beam

Kick optimisation: β at the septum

- Again, in **real** phase space we can see why a large β-function improves the spatial separation at the septum, $\Delta\mu_{\text{kicker -> septum}} = \pi/2$:

small β_{septum} $(\alpha_{\text{septum}} = 0)$:



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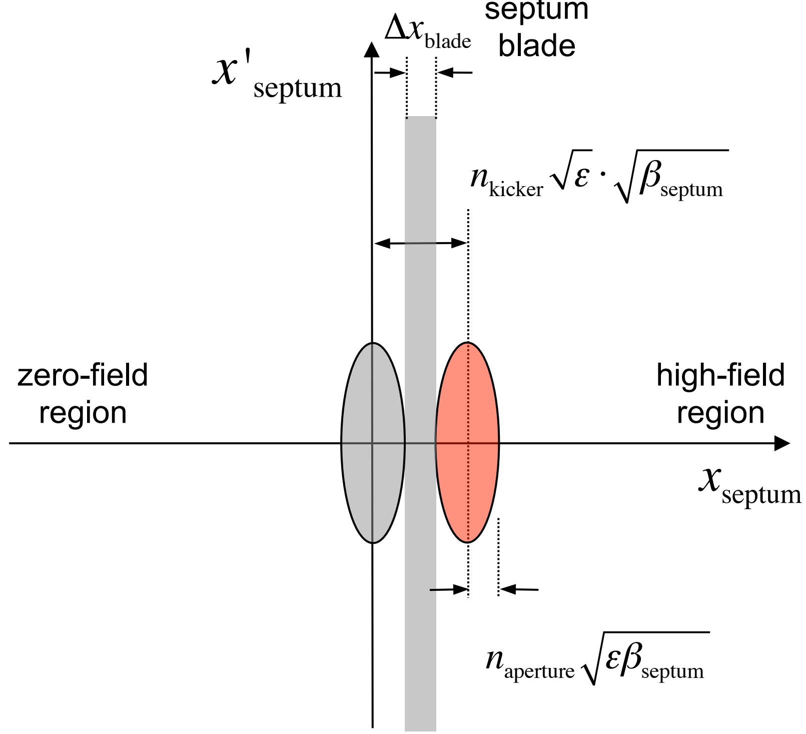
- Again, in **real** phase space we can see why a large β-function improves the spatial separation at the septum, $\Delta\mu_{\text{kicker -> septum}} = \pi/2$:

$$\Delta x_{\text{blade}} \propto \sqrt{\beta_{\text{septum}}}$$

$$\text{small } \beta_{\text{septum}} \quad (\alpha_{\text{septum}} = 0):$$



Space available for the septum blade, for a given beam aperture n_{aperture}:

$$\Delta x_{\text{blade}} = (n_{\text{kicker}} - 2n_{\text{aperture}})\sqrt{\varepsilon}\sqrt{\beta_{\text{septum}}} \propto \sqrt{\beta_{\text{septum}}}$$

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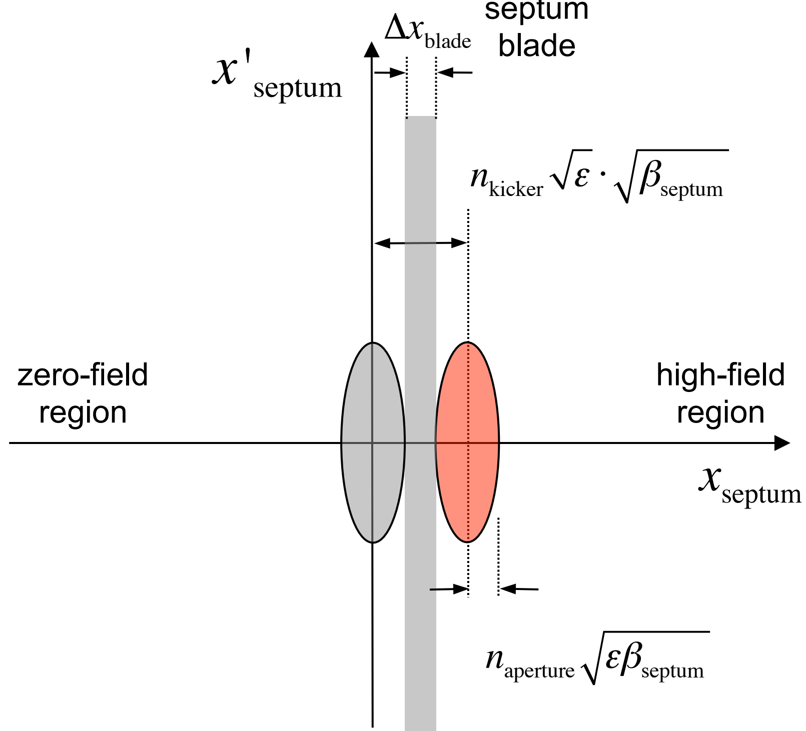

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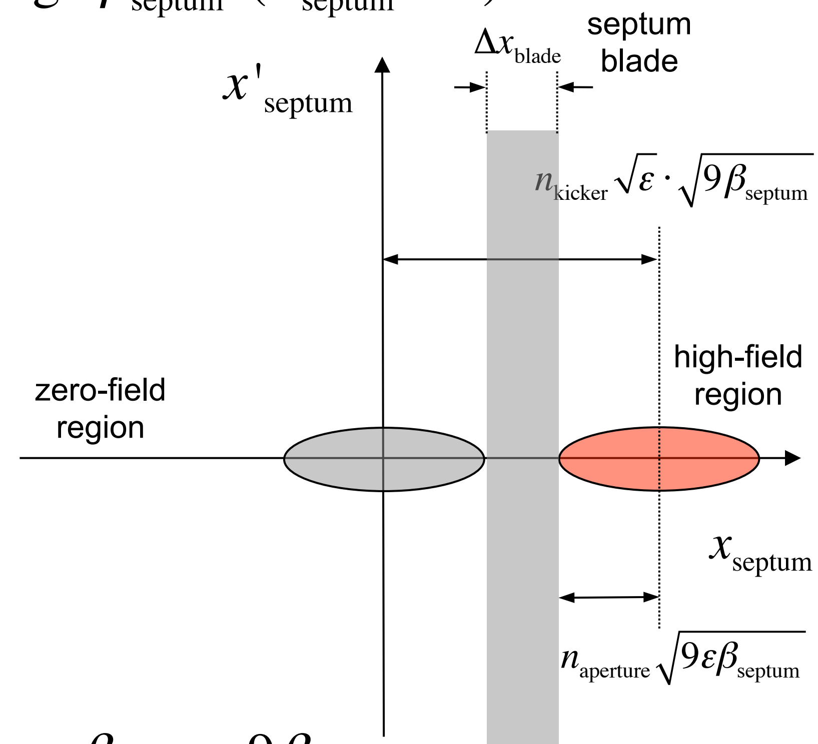
$$\text{large } \beta_{\text{septum}} \quad (\alpha_{\text{septum}} = 0):$$



$$\text{e.g., } \beta_{\text{large}} = 9\beta_{\text{septum}}$$

Kick optimisation: summary

- To minimise the kicker deflection required:

septum blade as thin as possible, septum as close to aperture limit as possible

bump beam as close as possible to septum

$$\Delta x'_{\text{kicker}} = \frac{\overbrace{x_{\text{extr}} - x_{\text{bump}}}^{\Delta x_{\text{kicker}}}}{\sqrt{\beta_{\text{kicker}}\beta_{\text{septum}}}\,\sin\mu_{\text{kicker}\rightarrow\text{septum}}}$$

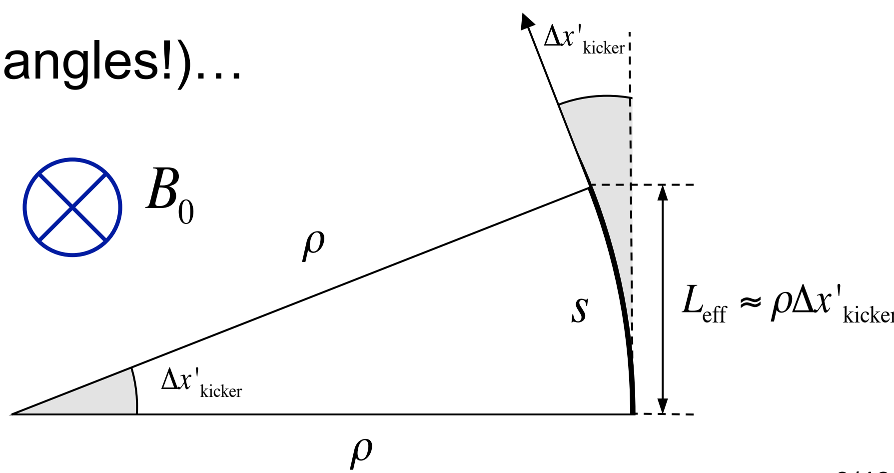
β_{kicker}: as large as possible

β_{septum}: as large as possible

optimize phase advance between kicker and septum ≈ π/2

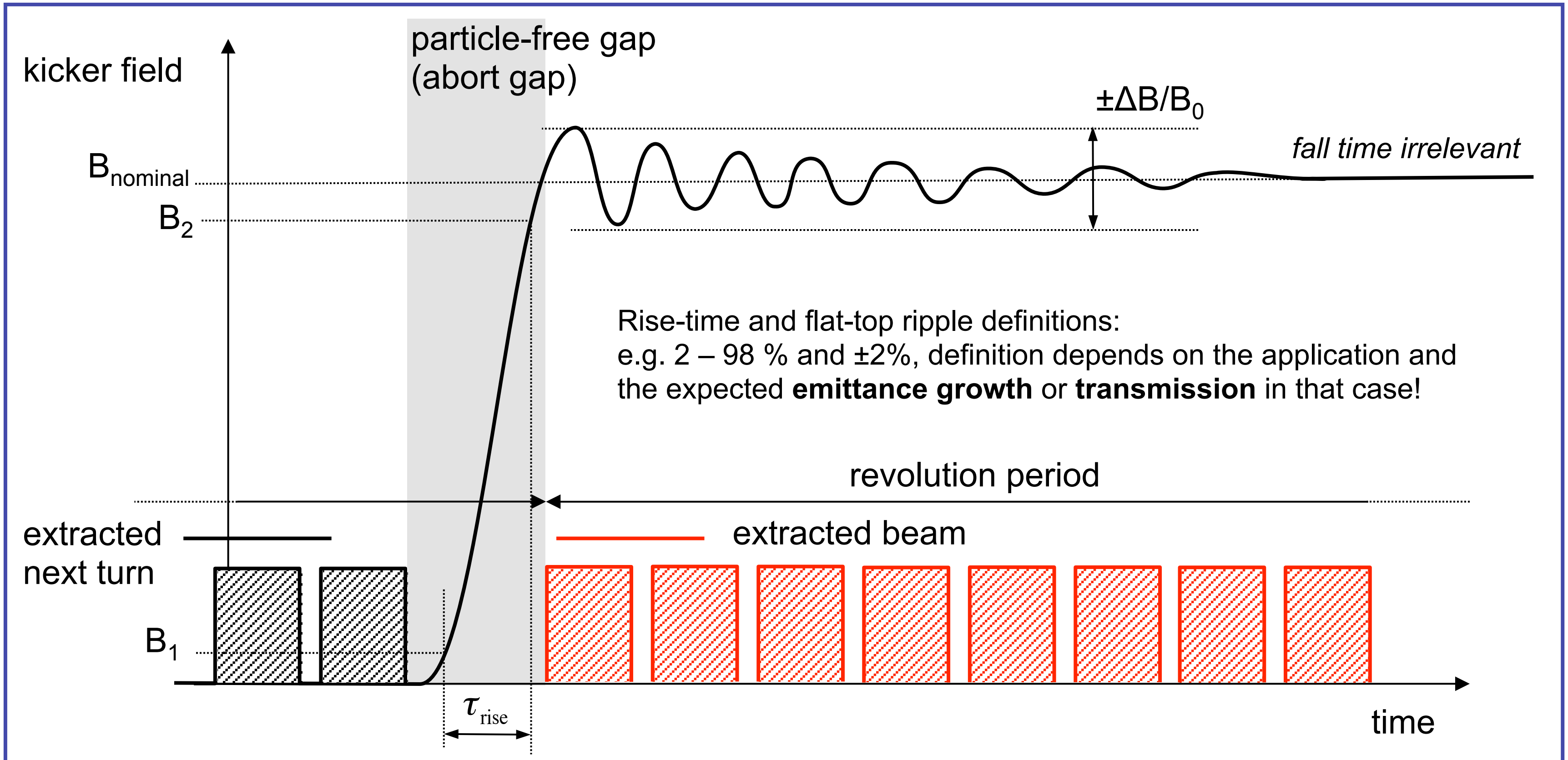
- In terms of integrated field (for small angles!)…

$$\Delta x'_{\text{kicker}} = \frac{s}{\rho} \approx \frac{B_0\int_0^s dl}{B_0\rho} = \frac{q}{p}\int B\,dl = \frac{q}{p}B_0 L_{eff}$$



Kicker parameters: pulse shape

- Definition/parameterization of the kicker pulse depends strongly on the application, some examples:
  - single-turn extraction
  - destination: **transfer between injectors for a high energy collider**



rise-time, τ_{rise} usually defined between given limits [%] of $B_{nominal}$

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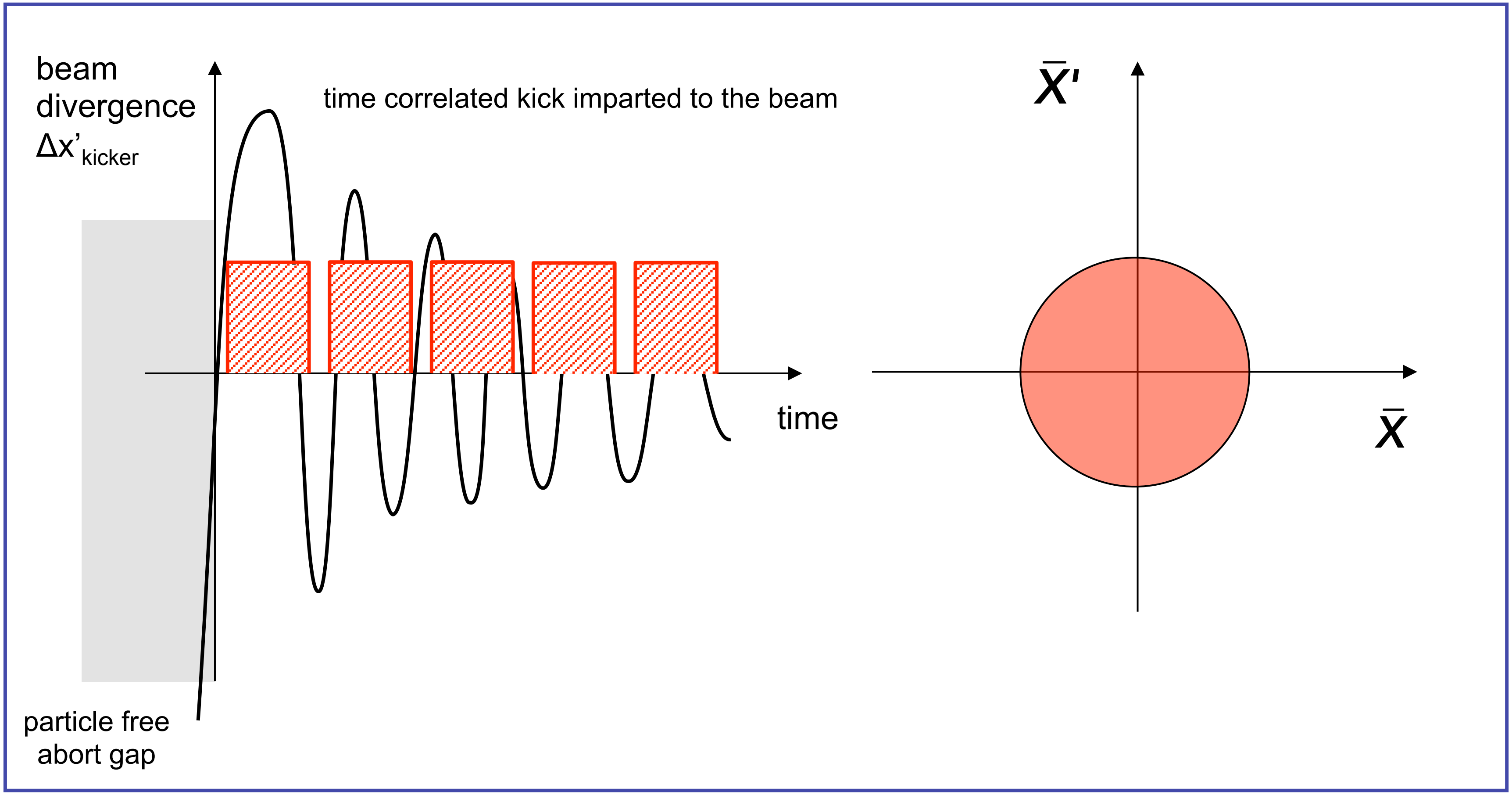

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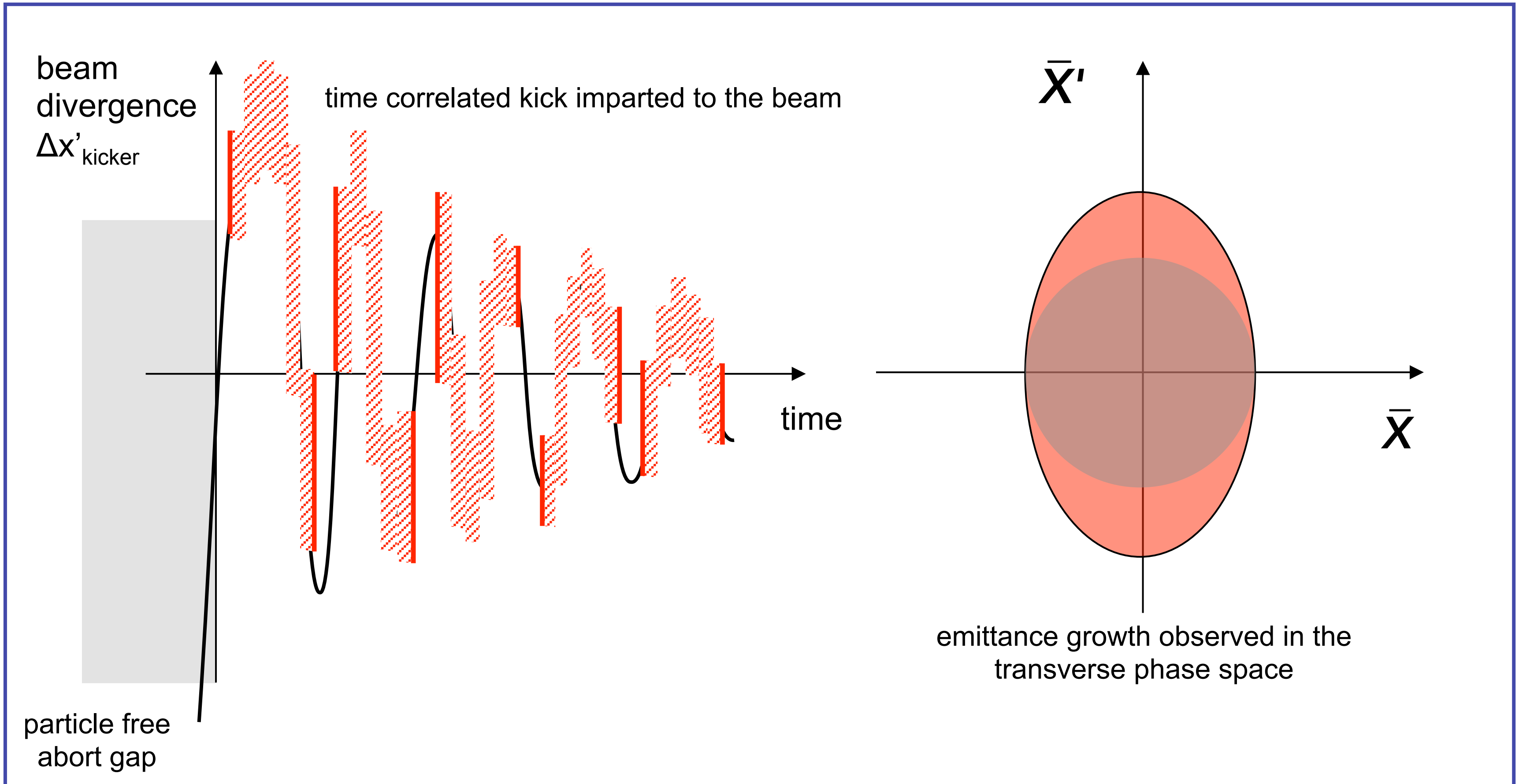

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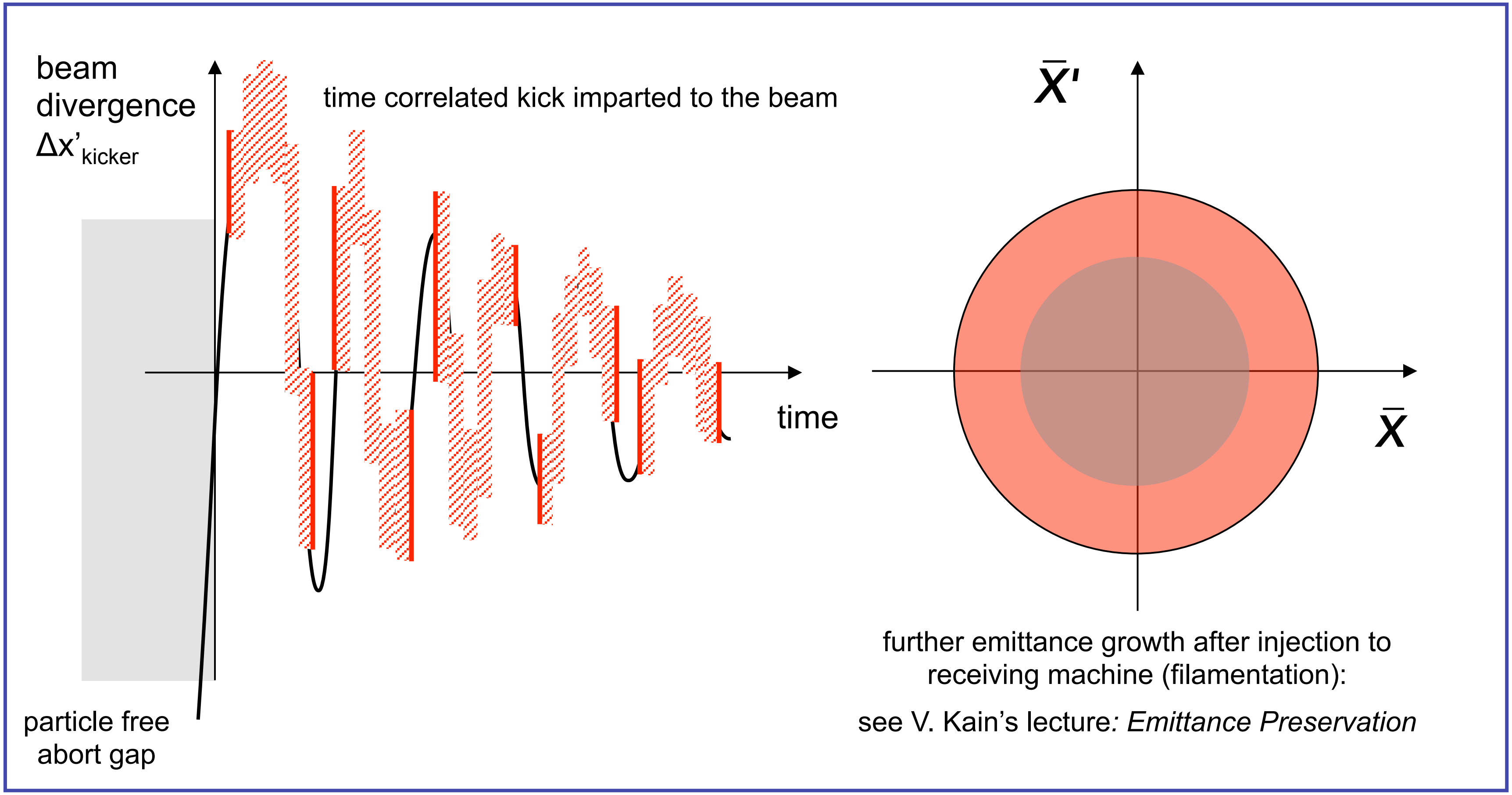

Kicker parameters: pulse shape

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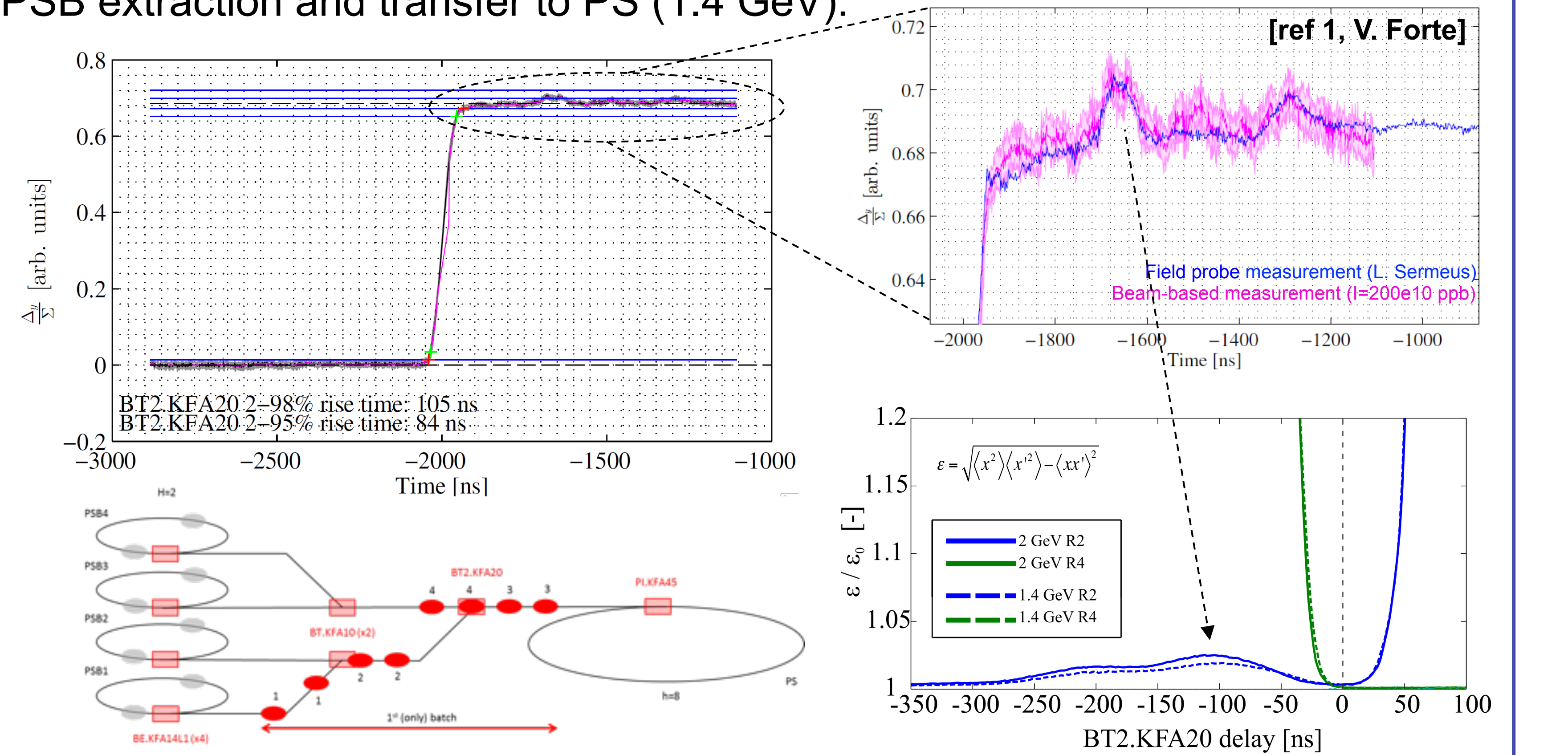
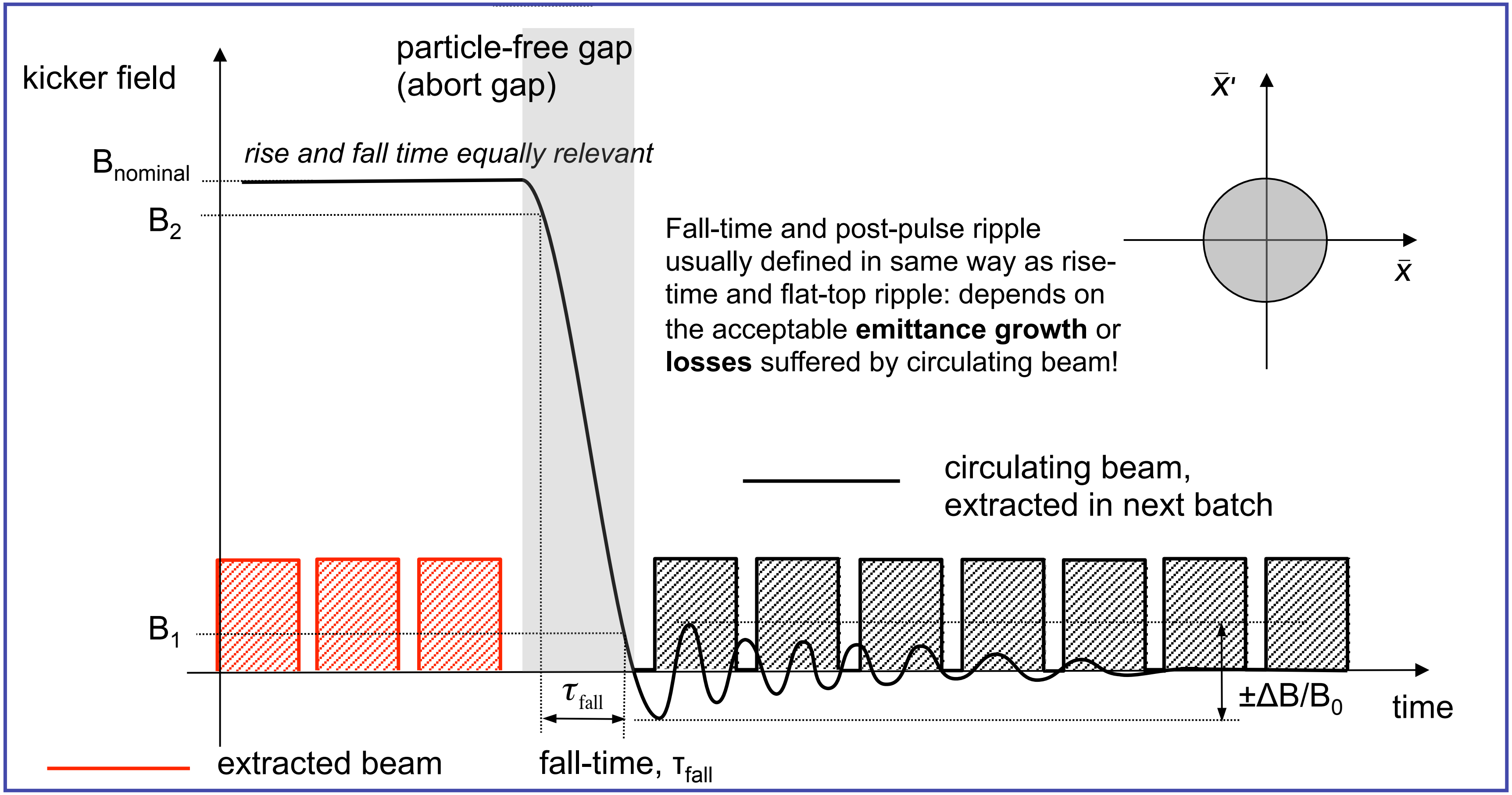
PSB extraction and transfer to PS (1.4 GeV):



Kicker parameters: pulse shape

- Definition/parameterization of the kicker pulse depends strongly on the application, some examples:
  - multi-burst extraction
  - destination: **fixed target physics programme/high-energy collider filling**



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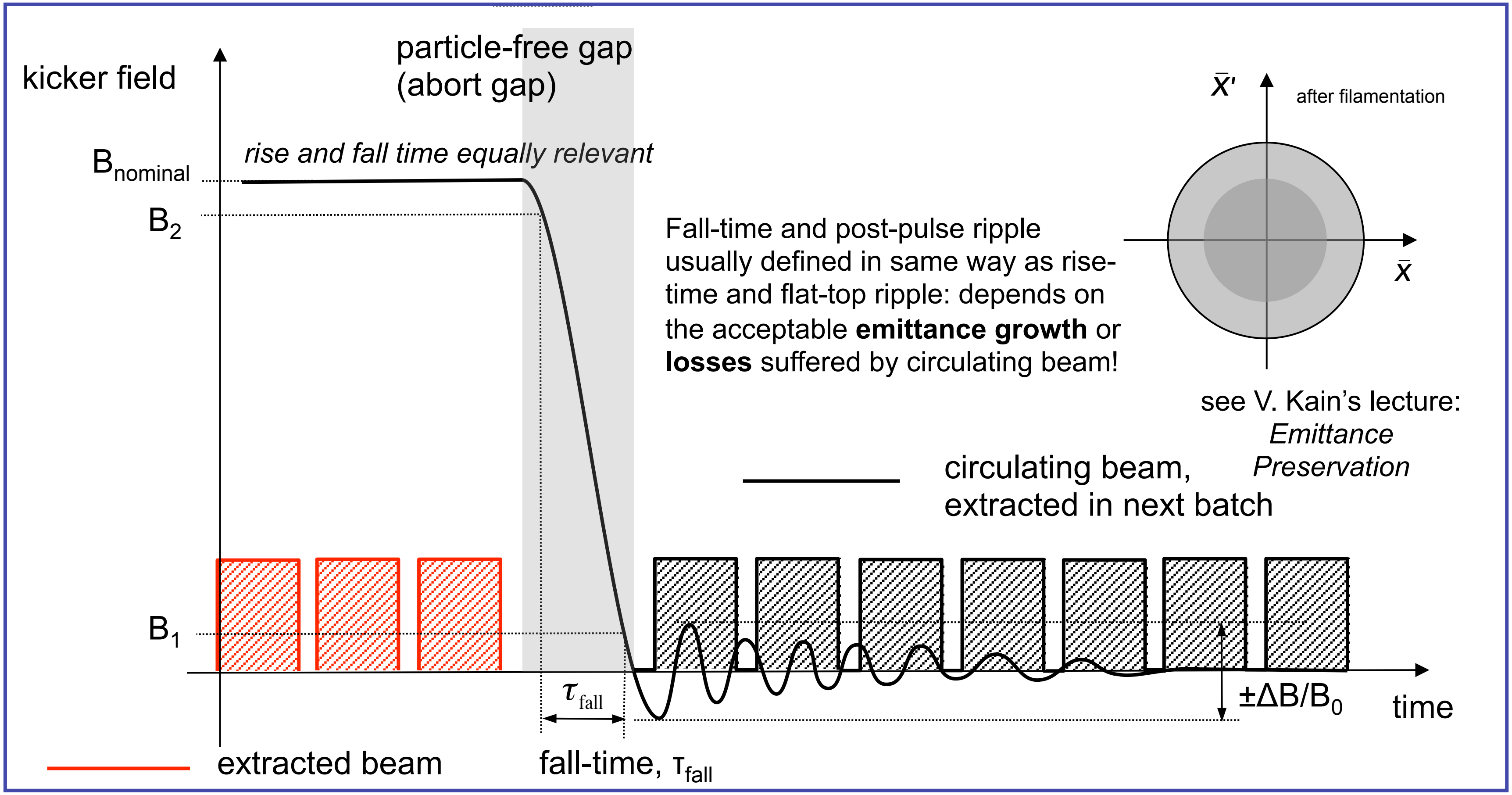
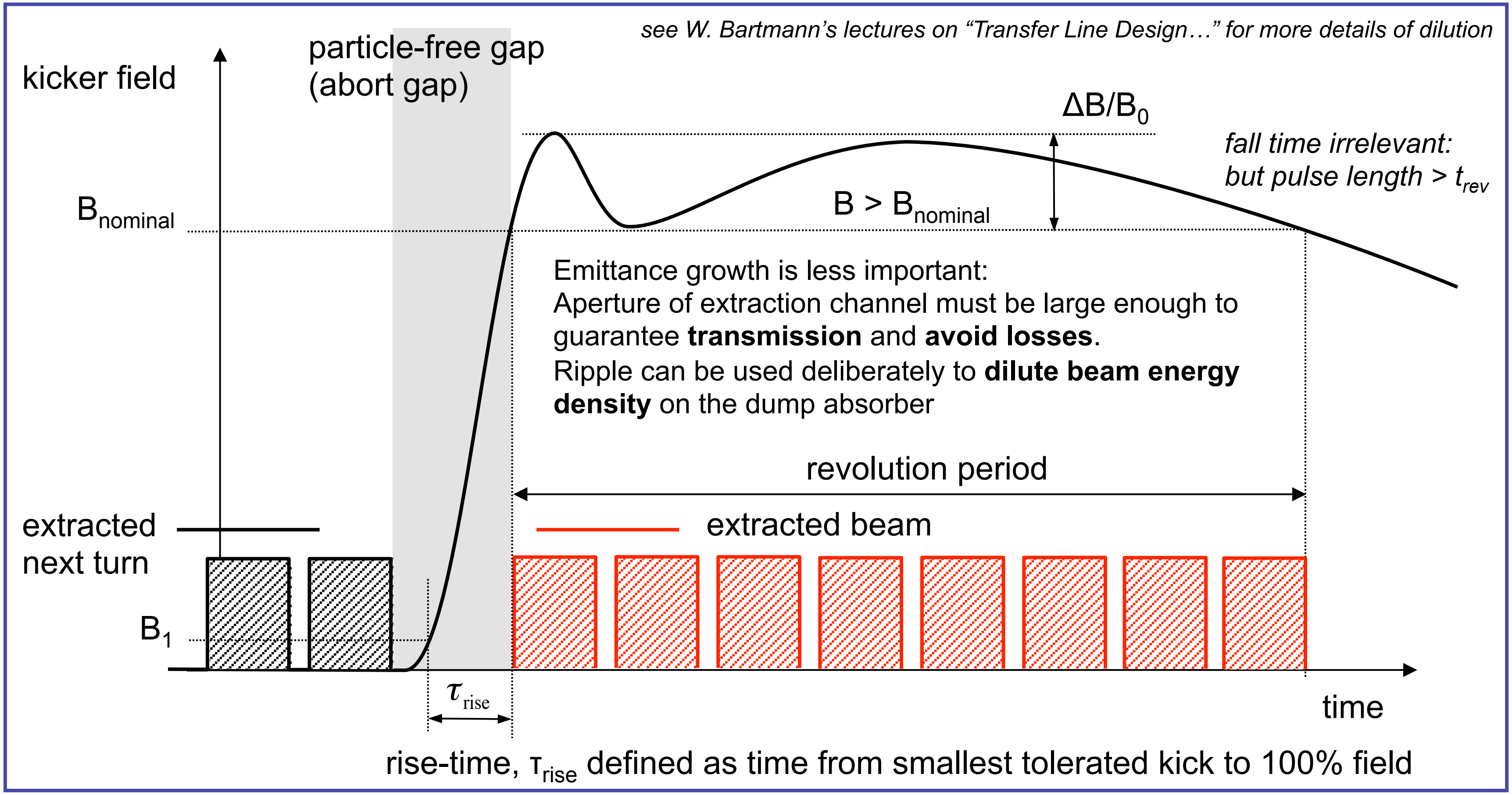


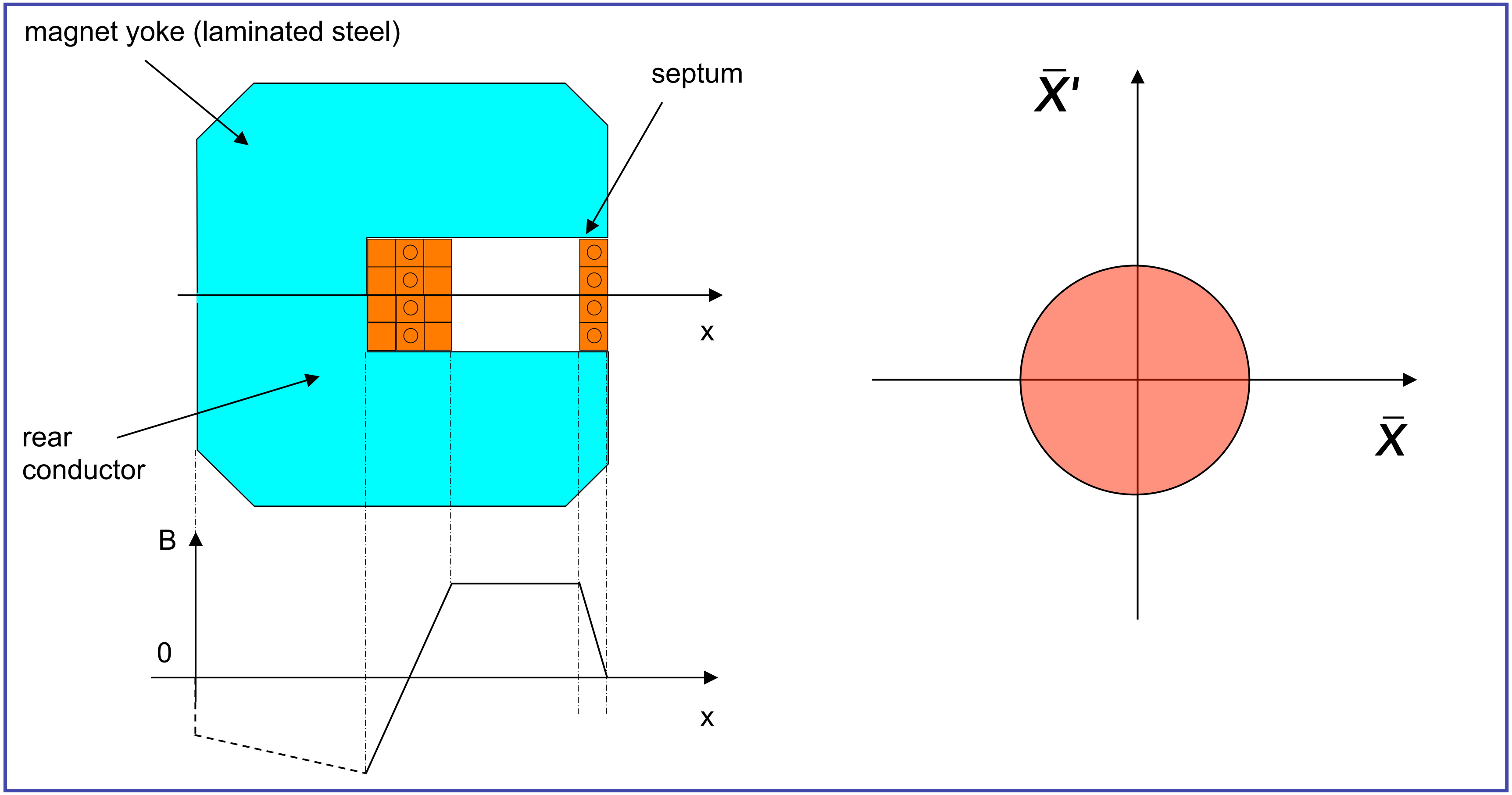
Kicker parameters: pulse shape

- Definition/parameterization of the kicker pulse depends strongly on the application, some examples:
  - single-turn extraction
  - destination: **to a dump for fast beam abort**



Septa parameters: field quality

- Although the field homogeneity is also a design consideration for kickers, due to the relative strength of septa (typically 10x stronger), it is more critical for septa:
  - field homogeneity, shot-to-shot jitter (power converter pulse timing)



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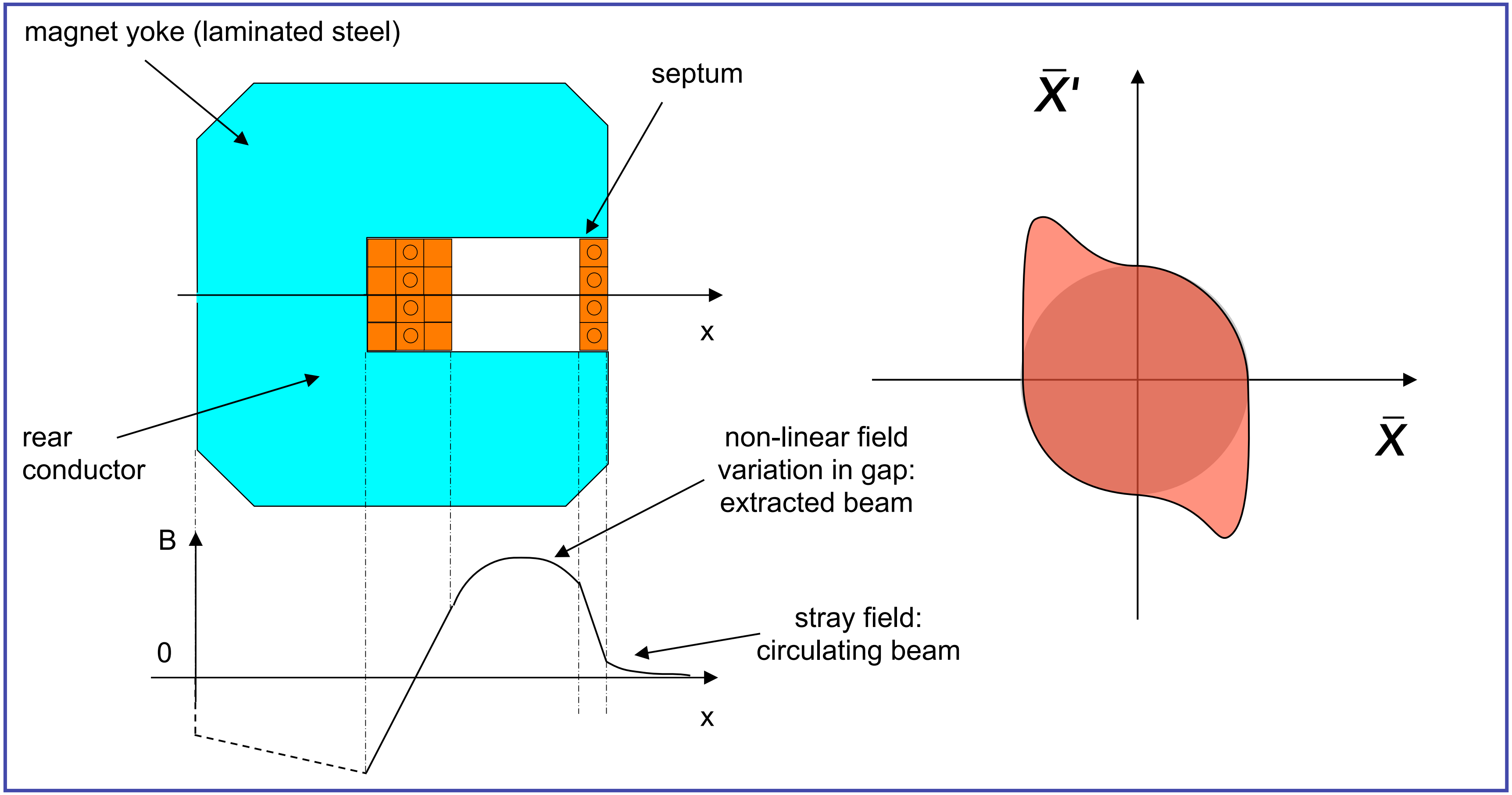

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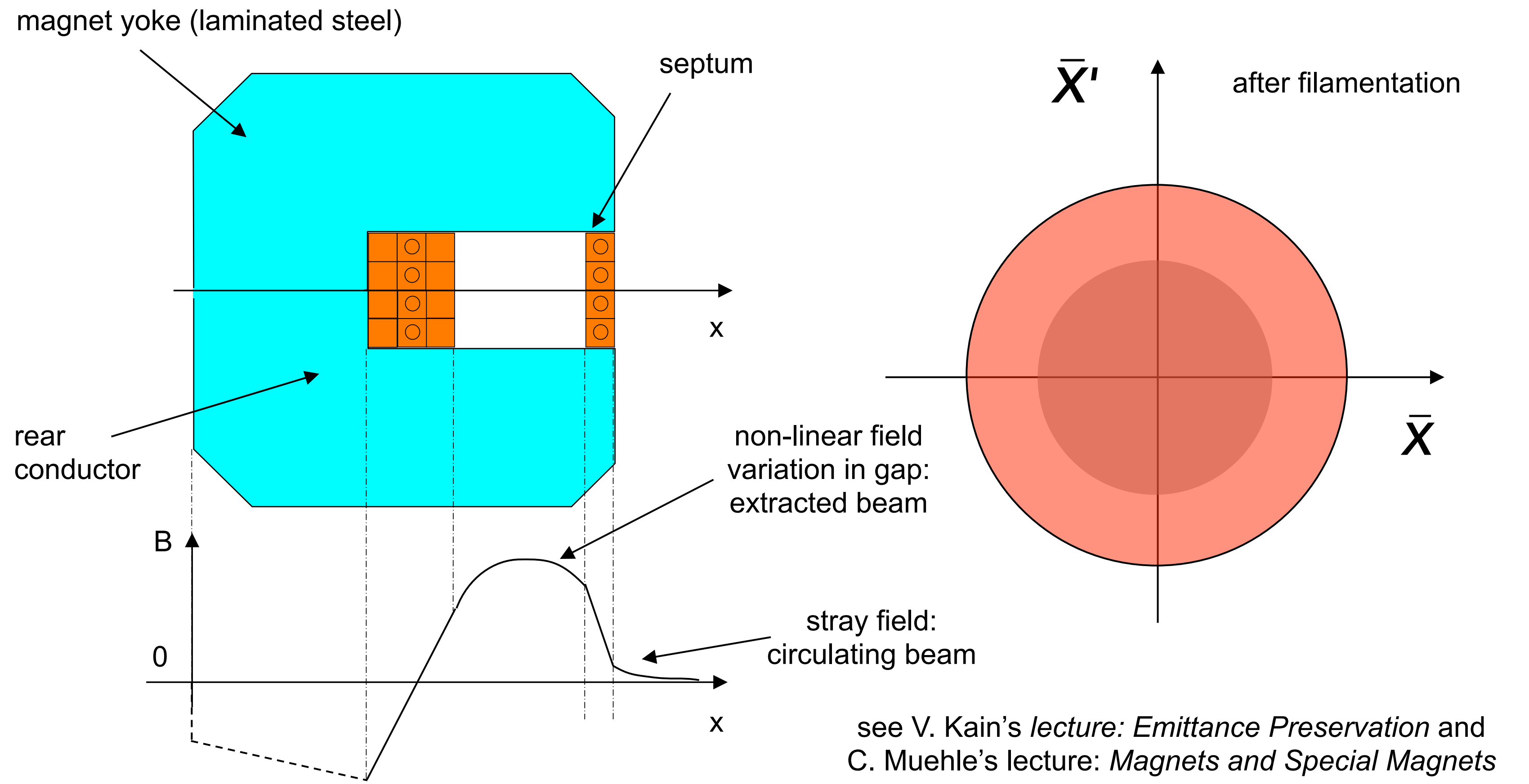


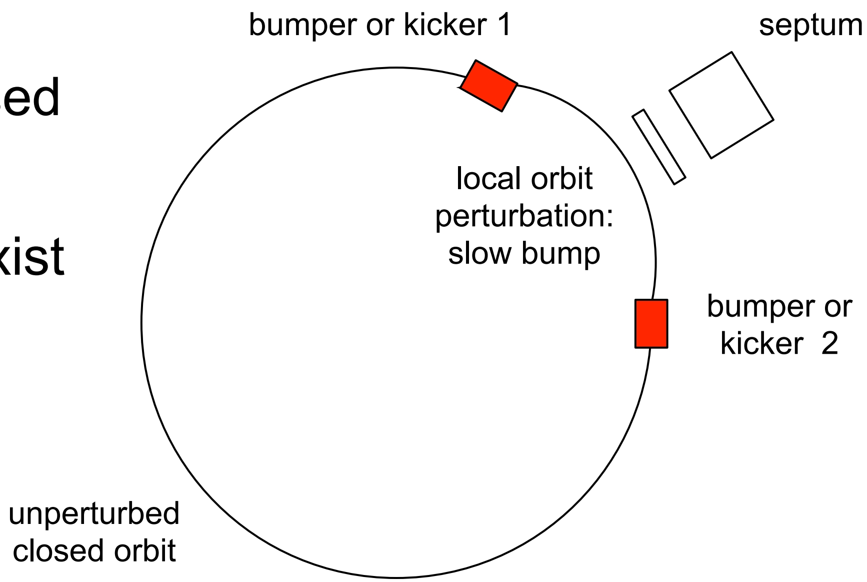
see V. Kain's *lecture: Emittance Preservation* and C. Muehle's lecture: *Magnets and Special Magnets*

Other constraints…

- We must also not forget…
  - **integration** constraints: can the extraction equipment fit in the machine?
  - **mechanical aperture** of the machine… see the appendix for more details
  - **failure scenarios**
  - **beam size at beam intercepting devices**

Closed-orbit bumps

- Local, closed-orbit bumps are regularly used during extraction:
  - to bring the circulating beam close to the septum (slow bump) reducing the kicker strength
  - to control multi-turn extraction (intensity and emittance) by shaving the beam on a septum turn-by-turn (fast bump)
- Closed-orbit bumps are also commonly used for injection
- Dipole "bumper" magnets used to steer the closed-orbit away from the nominal trajectory in a localised part of the synchrotron.
- Standard bump configurations exist for different requirements:
  - π-bump
  - 3 and 4-magnet bumps



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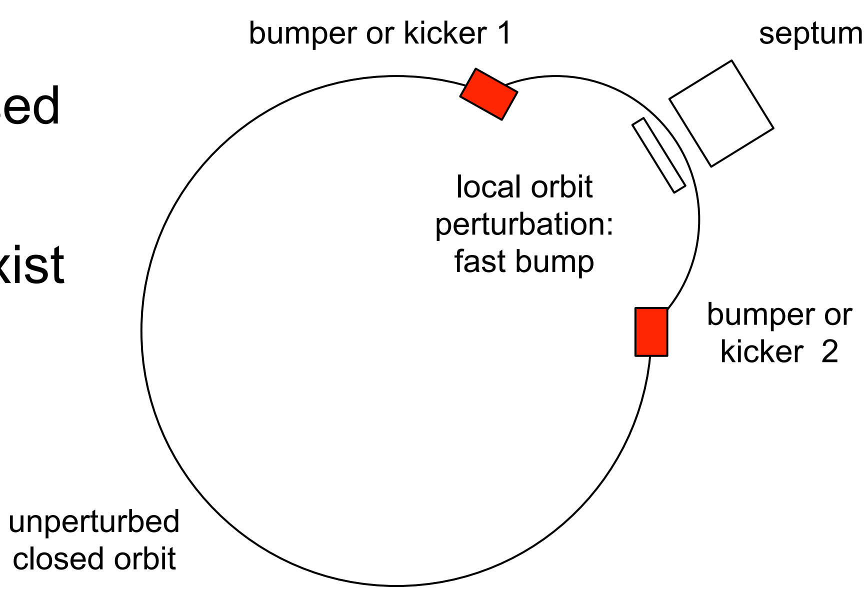

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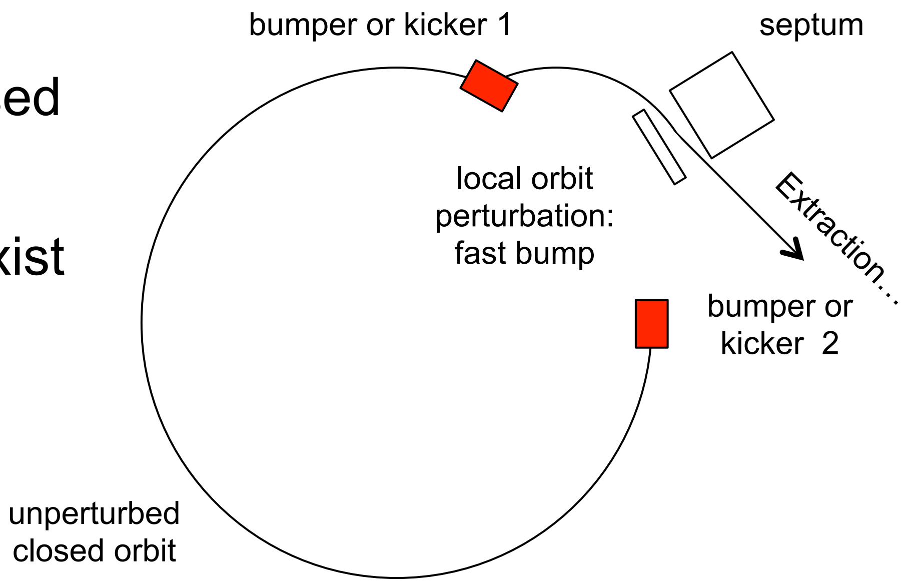
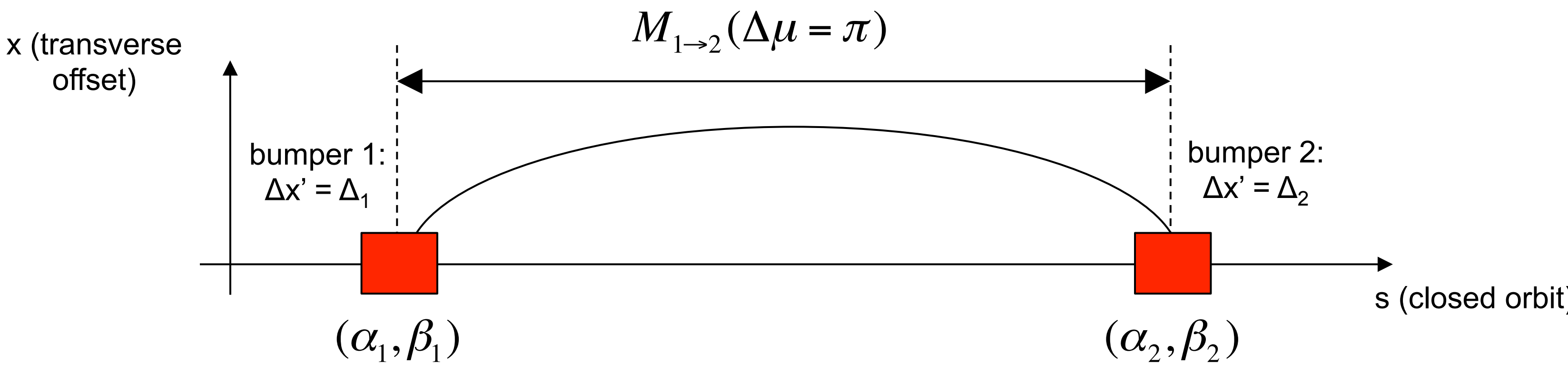
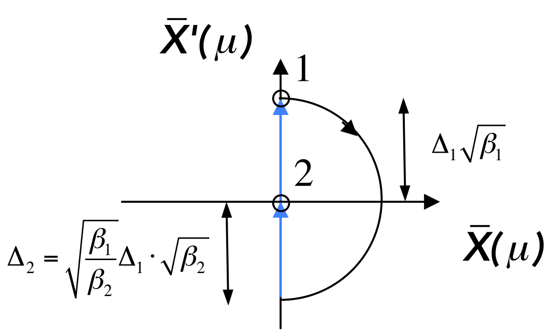


π-bump

- The simplest closed bump, the π-bump, is constrained by a phase advance of 180° between two dipole bumper magnets
  - first magnet opens the bump (kick = Δ_1), the second closes it (kick = Δ_2)



In normalised phase space:



$$X_2 = M_{1\to 2}(\Delta\mu = \pi) X_1$$

$$= \begin{pmatrix} -\sqrt{\frac{\beta_2}{\beta_1}} & 0 \\ \frac{\alpha_2 - \alpha_1}{\sqrt{\beta_1\beta_2}} & -\sqrt{\frac{\beta_1}{\beta_2}} \end{pmatrix} \begin{pmatrix} 0 \\ \Delta_1 \end{pmatrix}$$

$$= \begin{pmatrix} 0 \\ -\sqrt{\frac{\beta_1}{\beta_2}}\Delta_1 \end{pmatrix}$$

$$\begin{pmatrix} -\sqrt{\frac{\beta_2}{\beta_1}}(\cos\Delta\mu + \alpha_1 \sin\Delta\mu) & \sqrt{\beta_2\beta_1}\sin\Delta\mu \\ \frac{(\alpha_1 - \alpha_2)\cos\Delta\mu - (1 + \alpha_1\alpha_2)\sin\Delta\mu}{\sqrt{\beta_1\beta_2}} & \sqrt{\frac{\beta_1}{\beta_2}}(\cos\Delta\mu - \alpha_2 \sin\Delta\mu) \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}$$

Bumper 2 compensates the angle created by bumper 1 still remaining after Δμ = π:

$$\Delta_2 = +\sqrt{\frac{\beta_1}{\beta_2}}\Delta_1$$

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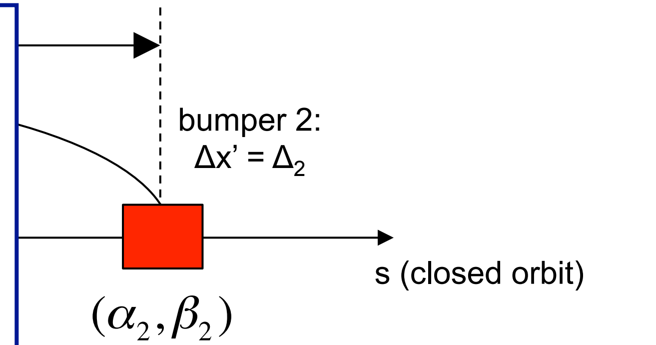

$$\begin{pmatrix} -\sqrt{\frac{\beta_2}{\beta_1}}(\cos\Delta\mu+\alpha_1\sin\Delta\mu) & \sqrt{\beta_2\beta_1}\sin\Delta\mu \\ \frac{(\alpha_1-\alpha_2)\cos\Delta\mu-(1+\alpha_1\alpha_2)\sin\Delta\mu}{\sqrt{\beta_1\beta_2}} & \sqrt{\frac{\beta_1}{\beta_2}}(\cos\Delta\mu-\alpha_2\sin\Delta\mu) \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}$$

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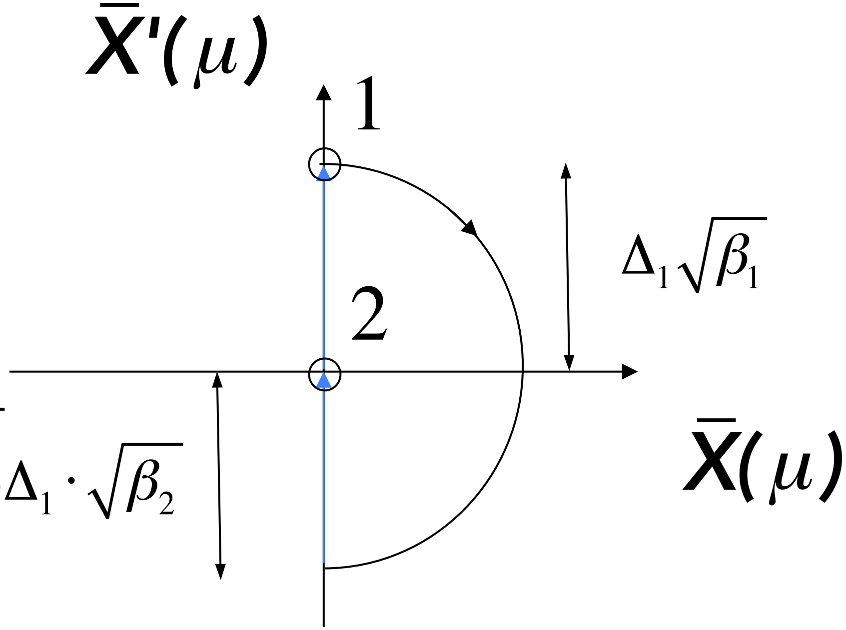


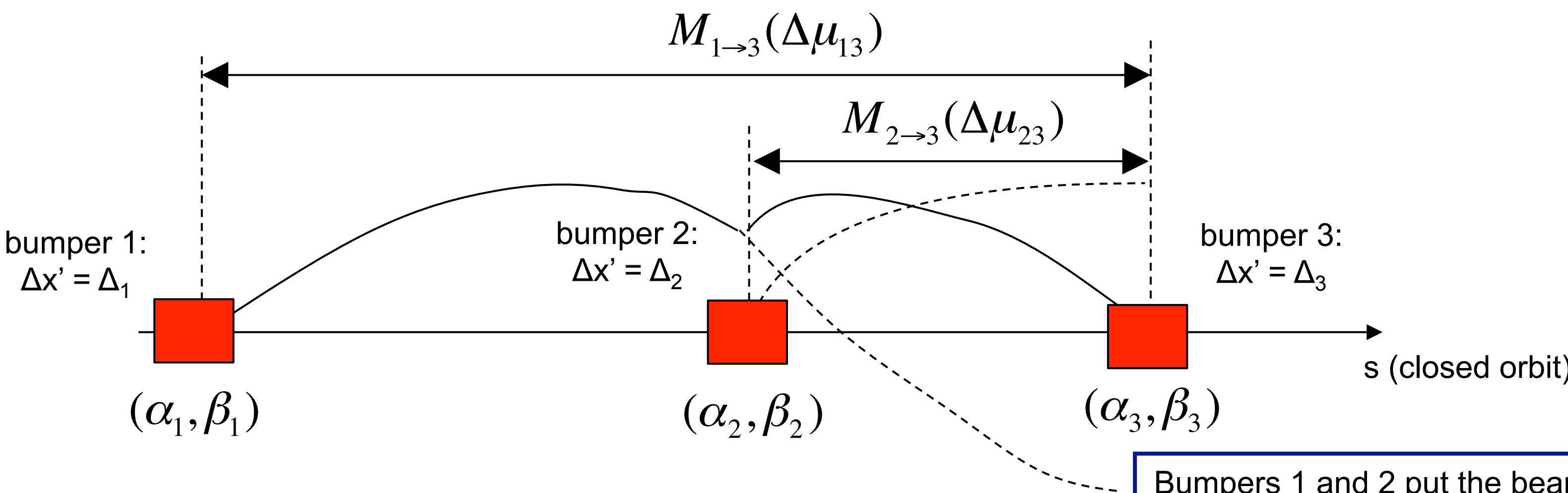
$$\Delta_2 = \sqrt{\frac{\beta_1}{\beta_2}}\Delta_1 \cdot \sqrt{\beta_2}$$

Bumper 2 compensates the angle created by bumper 1 still remaining after Δμ = π:

$$\Delta_2 = +\sqrt{\frac{\beta_1}{\beta_2}}\Delta_1$$

3-magnet ("coil") bump

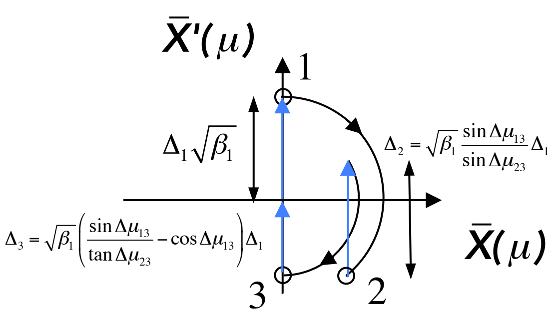
- In a real accelerator more degrees of freedom are often needed…
  - a third magnet can be added to close the bump for (almost) any value of phase advance, Δμ: either the **position or angle** can be matched



Bumpers 1 and 2 put the beam on axis at bumper 3:

$$\Delta_2 = -\frac{M_{1\to3,12}}{M_{2\to3,12}}\Delta_1 = -\sqrt{\frac{\beta_1}{\beta_2}}\frac{\sin\Delta\mu_{13}}{\sin\Delta\mu_{23}}\Delta_1$$

In normalised phase space:



$$X_3 = M_{1\to3}(\Delta\mu_{13})X_1 + M_{2\to3}(\Delta\mu_{23})X_2$$

$$= M_{1\to3}(\Delta\mu_{13})\begin{pmatrix}0\\ \Delta_1\end{pmatrix} + M_{2\to3}(\Delta\mu_{23})\begin{pmatrix}0\\ \Delta_2\end{pmatrix}$$

Summing kicks from each bumper gives 2 simultaneous equations:

$$0 = M_{1\to3,12}\Delta_1 + M_{2\to3,12}\Delta_2$$

$$-\Delta_3 = M_{1\to3,22}\Delta_1 + M_{2\to3,22}\Delta_2$$

Bumper 3 compensates the angle:

$$\Delta_3 = M_{1\to3,22}\Delta_1 - M_{2\to3,22}\Delta_2$$

$$= \sqrt{\frac{\beta_1}{\beta_3}}\left(\frac{\sin\Delta\mu_{13}}{\tan\Delta\mu_{23}} - \cos\Delta\mu_{13}\right)\Delta_1$$

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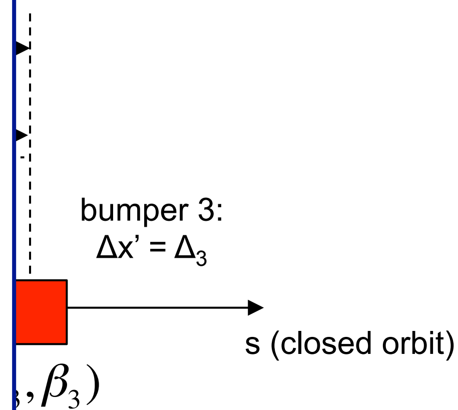

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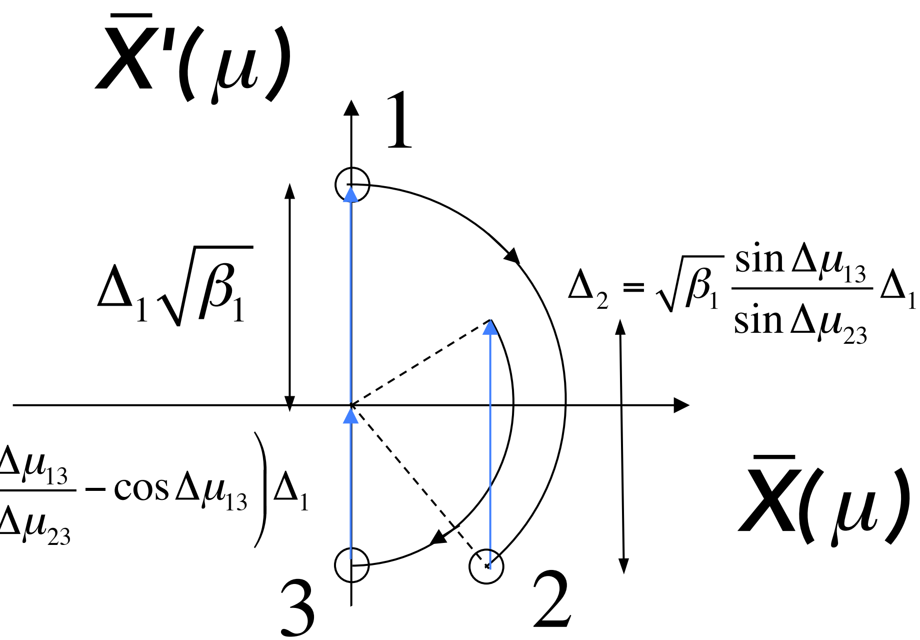

$$\Delta_1 \sqrt{\beta_1}$$

$$\Delta_2 = \sqrt{\beta_1} \frac{\sin \Delta\mu_{13}}{\sin \Delta\mu_{23}} \Delta_1$$

$$\Delta_3 = \sqrt{\beta_1} \left(\frac{\sin \Delta\mu_{13}}{\tan \Delta\mu_{23}} - \cos \Delta\mu_{13} \right) \Delta_1$$

Bumpers 1 and 2 put the beam on axis at bumper 3:

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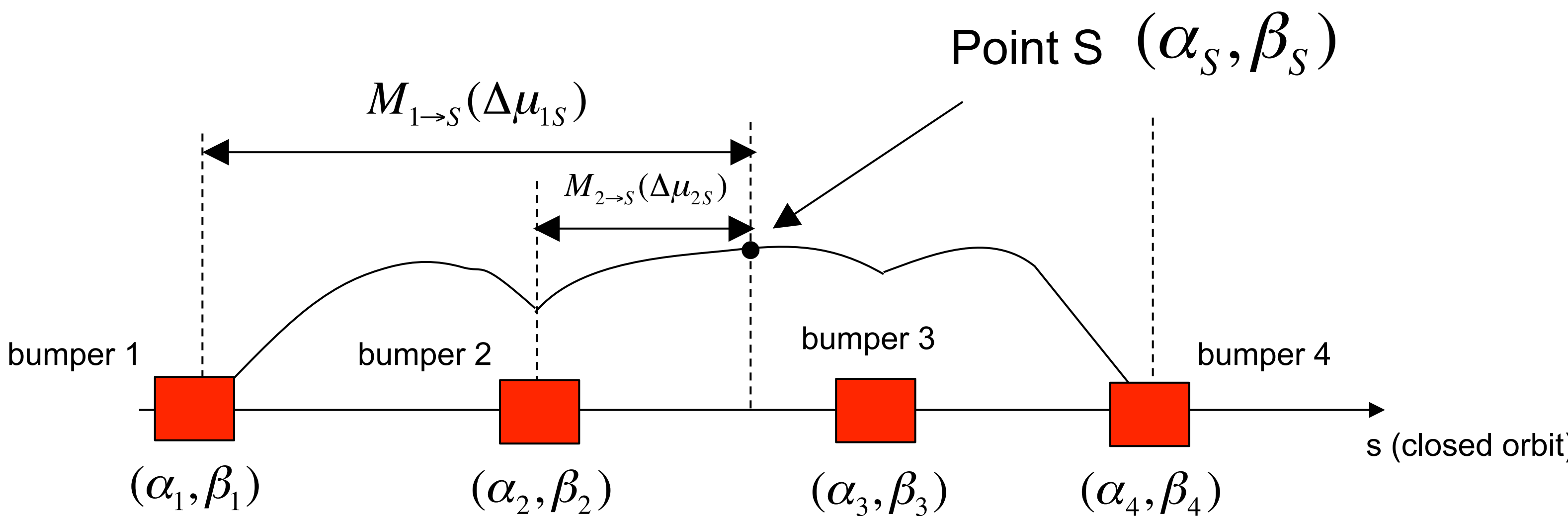
Bumper 3 compensates the angle:

$$\Delta_3 = M_{1\to3,22}\Delta_1 - M_{2\to3,22}\Delta_2$$

$$= \sqrt{\frac{\beta_1}{\beta_3}} \left(\frac{\sin \Delta\mu_{13}}{\tan \Delta\mu_{23}} - \cos \Delta\mu_{13} \right) \Delta_1$$

4-magnet ("coil") bump

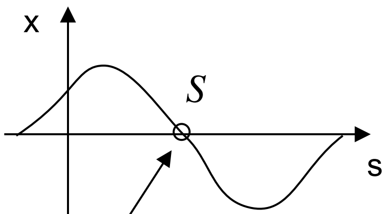
- To control both **position and angle** (x_S, x'_S) at a given point a fourth magnet is needed:



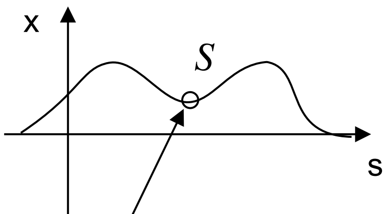
- The first two bumpers select position and angle at a given location, e.g. at the extraction septum or Point S in this case
- The second two bumpers ensure closure, returning the beam onto the closed orbit:
  - see the appendix for more details…

Closed-orbit bumps: other considerations

- Typically, we use optics codes (e.g. MADX) to match bumps and to include more constraints:
  - usually mechanical aperture in the extraction region is of concern and the position of the bumped beam must be controlled at multiple points S_1, S_2…
    - …more bumper magnets may be needed
- Many other topics can be discussed:
  - orthogonal 4-magnet bumps:
    - “Odd” and “even” bumps can be superimposed to move the beam’s position and angle independently at a given point S:



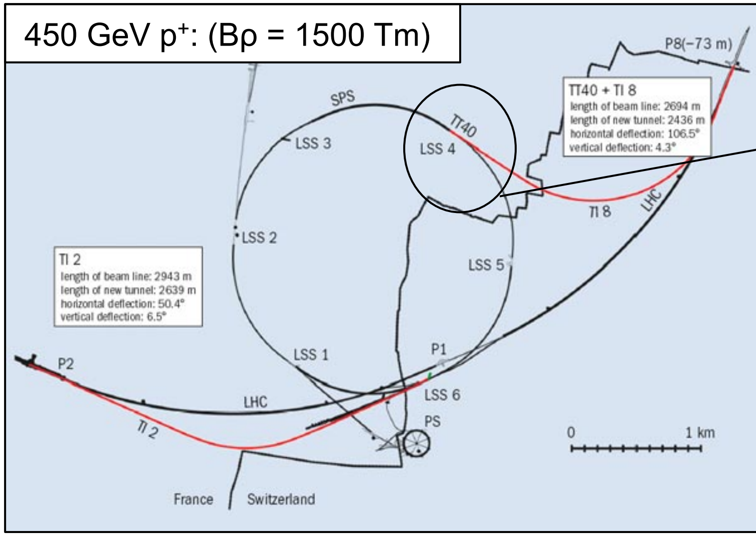
$$\begin{pmatrix} x \\ x' \end{pmatrix}_{S,\,\mathrm{odd}} = \begin{pmatrix} 0 \\ \Delta x' \end{pmatrix}$$

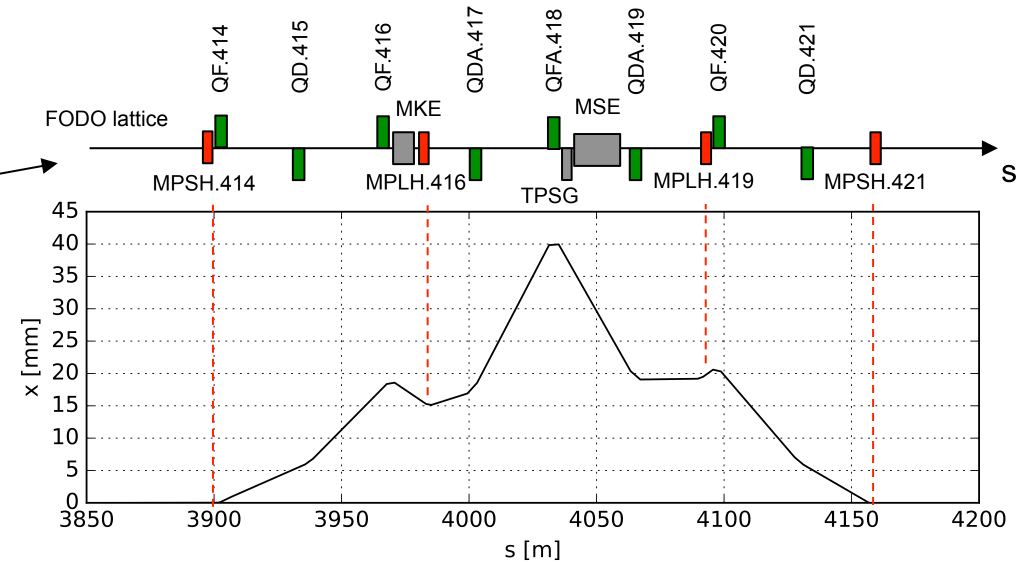


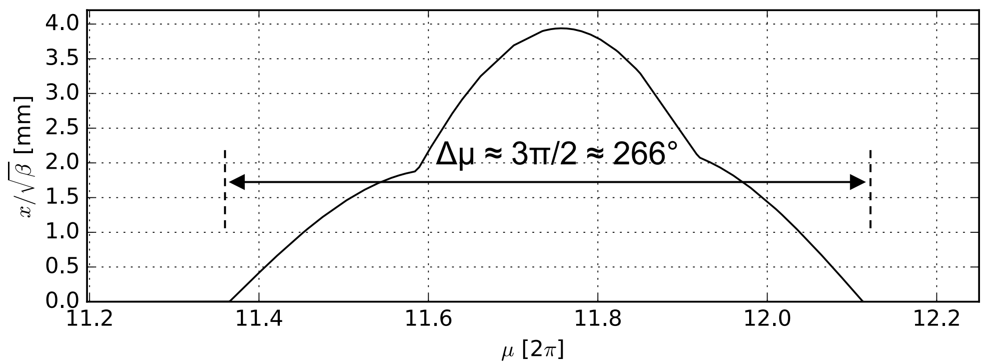
$$\begin{pmatrix} x \\ x' \end{pmatrix}_{S,\,\mathrm{even}} = \begin{pmatrix} \Delta x \\ 0 \end{pmatrix}$$

  - non-closure of bumps:
    - a mismatched bump will look like a dipole error steering
  - sensitivity to machine working point:
    - a bump is closed for a given tune (phase advance)… if the working point of the machine is changed, the magnet strengths should be adjusted accordingly.

Example: SPS fast extraction to LHC (1)



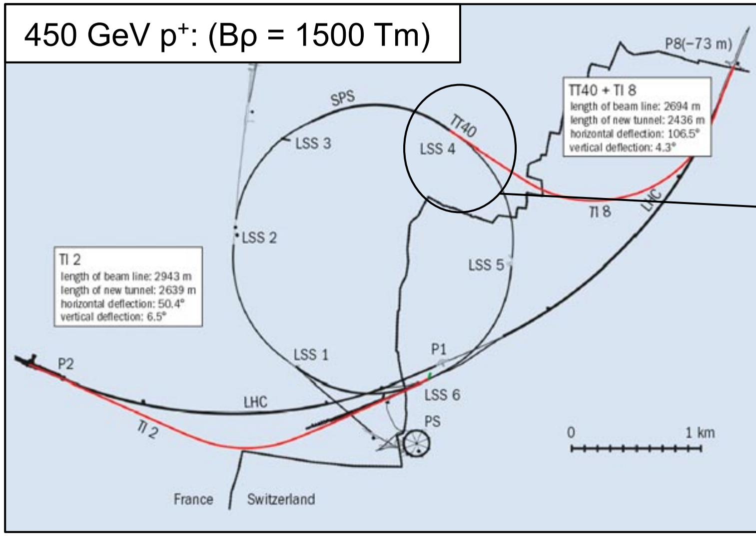


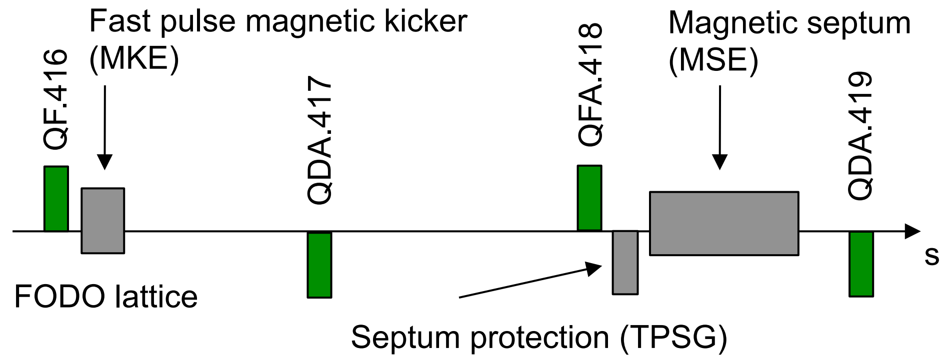


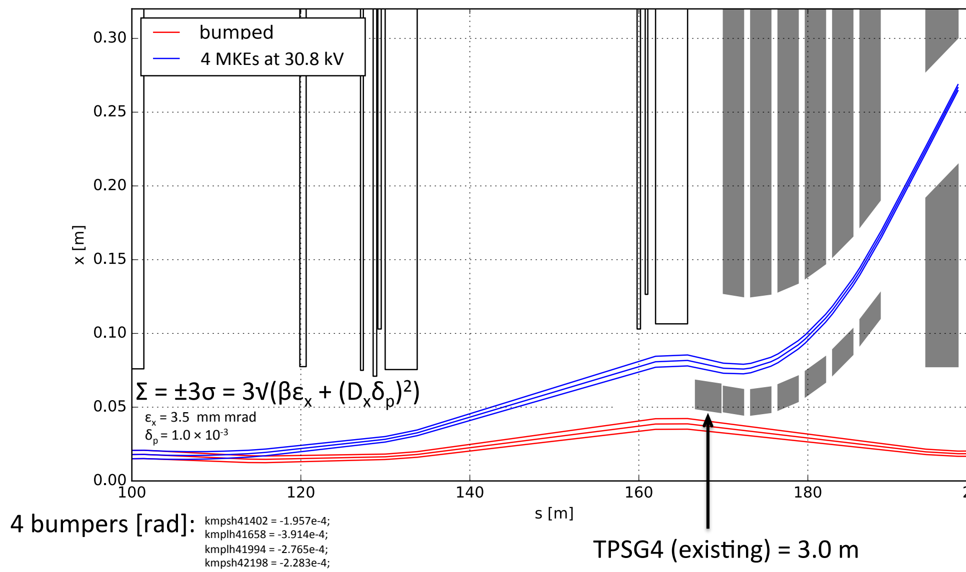
- Things to note:
  - 4-magnet bump
  - deflection in quads
  - almost symmetric
  - maximum amplitude close to septum
  - normalized phase space variables can be intuitive!

Optics parameter	MPSH.414	MPLH.416	MPLH.419	MPSH.421
β_x [m]	96.62	60.92	88.10	95.40
α_x	-1.75	1.27	-1.67	-1.79
$\Delta\mu_x$ [deg.]	0	79.2	198.0	266.4
$\Delta x'$ [mrad]	0.172	0.345	0.253	0.192

Example: SPS fast extraction to LHC (2)







- Things to note:
  - large β_x at MKE and MSE
  - $\Delta\mu_{kicker\text{->}septum} \approx 67°$
  - enlarged aperture of QDA.419
  - extracted beam passes through a window in quad coil!

Optics parameter*	MKE	TPSG	MSE	QF / QD
β_x [m] (Q20 optics)	97.0	100.2	88.4	105 / 32
$\Delta\mu_x$ [deg.]	0	64.8	66.8	32 (per half-cell)
$\Delta x'$ [mrad]	0.42	-	≈ 12	-

*given at upstream end of element

“Non-local” extraction concept

- A fast extraction system can be designed to extract using a single kicker system through different septa to different extraction lines:

To SMH58: $\Delta x'_{\text{kicker}} < 0$

$$\mu_{\text{kicker}\rightarrow\text{septum}} \approx \frac{15}{2}\pi = 3.75\lambda_\beta$$

CERN PS, 1963
(kicker in SS97
no longer in operation)

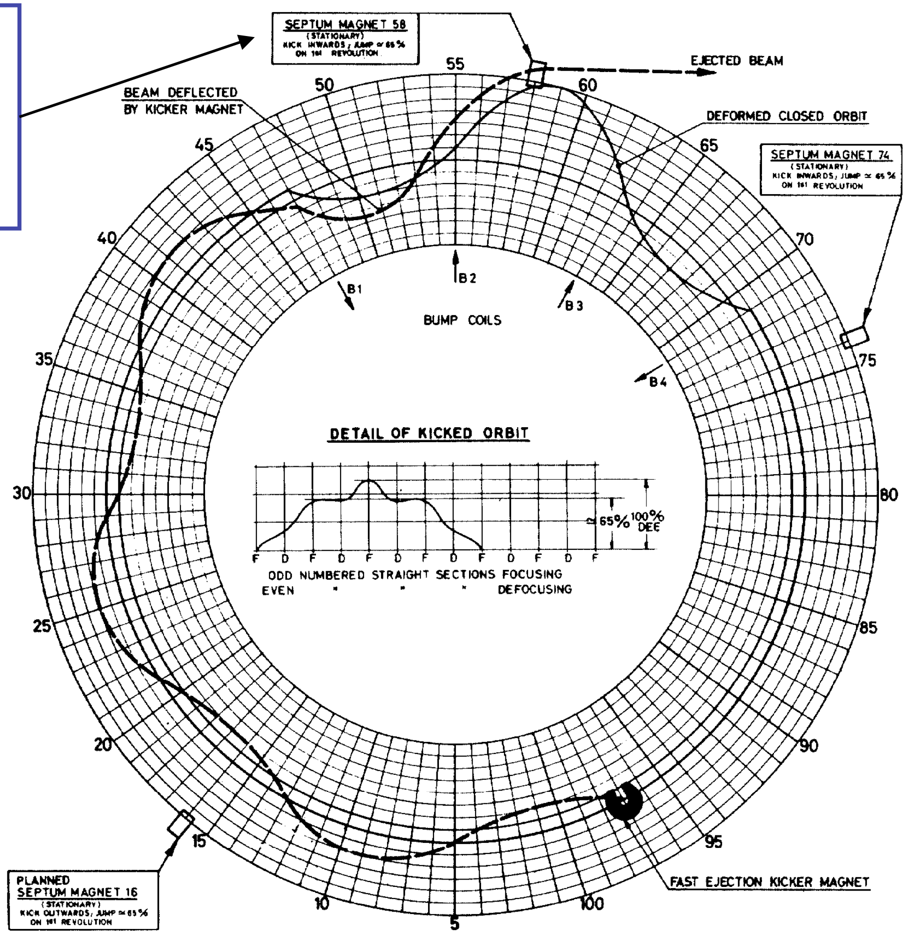


Figure 1 : Fast ejection from straight section 58 into the east experimental area

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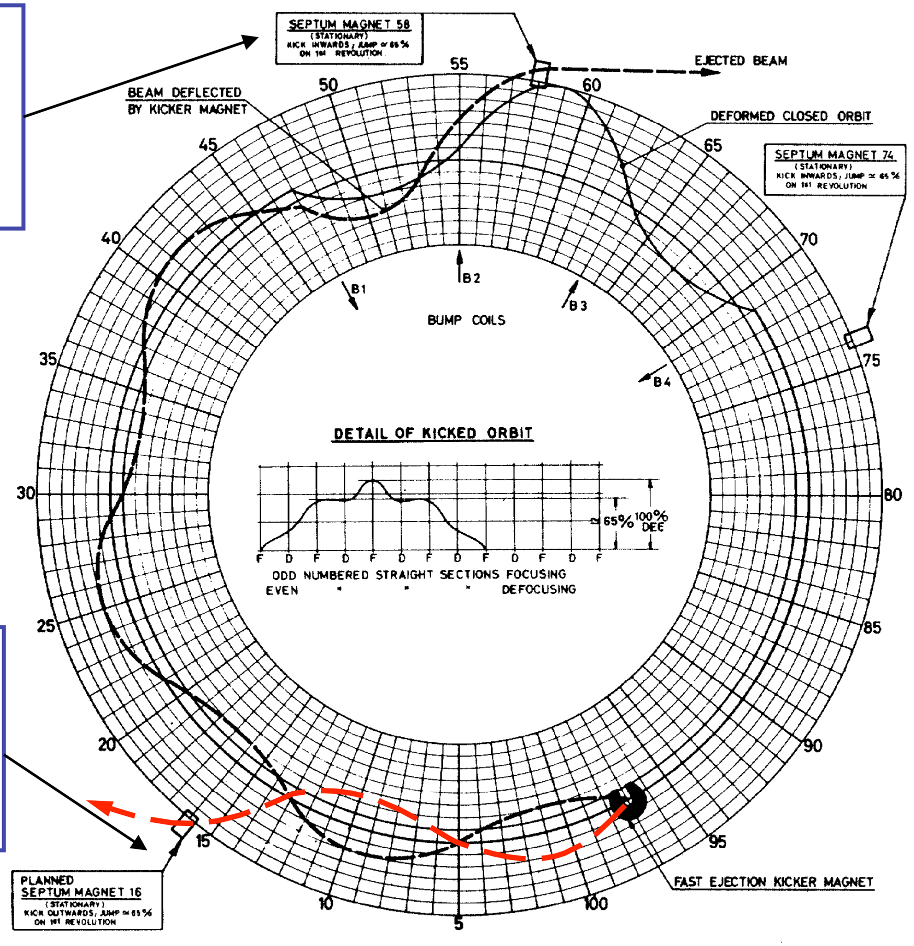
CERN PS, 1963
(kicker in SS97
no longer in operation)

To SMH16: $\Delta x'_{\text{kicker}} > 0$

$$\mu_{\text{kicker}\to\text{septum}} \approx \frac{5}{2}\pi = 1.25\lambda_\beta$$



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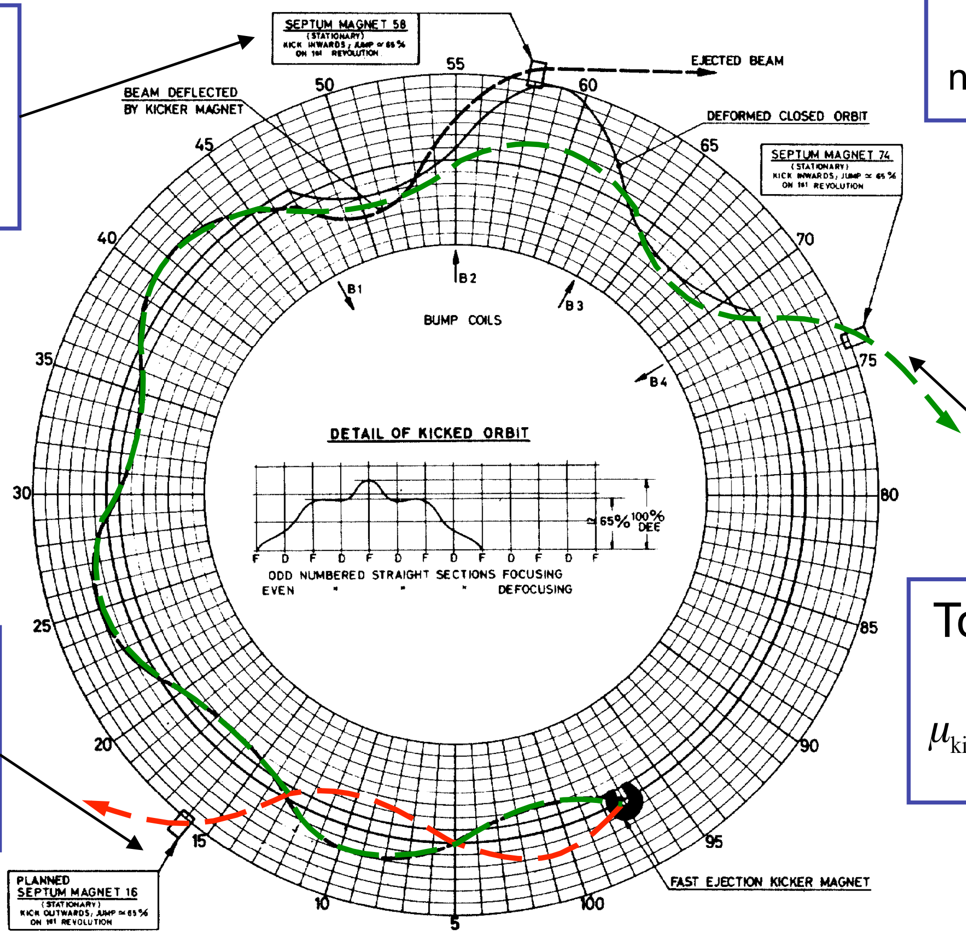


Figure 1 : Fast ejection from straight section 58 into the east experimental area

To SMH74: $\Delta x'_{\text{kicker}} < 0$

$$\mu_{\text{kicker}\rightarrow\text{septum}} \approx \frac{19}{2}\pi = 4.75\lambda_\beta$$

To SMH16: $\Delta x'_{\text{kicker}} > 0$

$$\mu_{\text{kicker}\rightarrow\text{septum}} \approx \frac{5}{2}\pi = 1.25\lambda_\beta$$

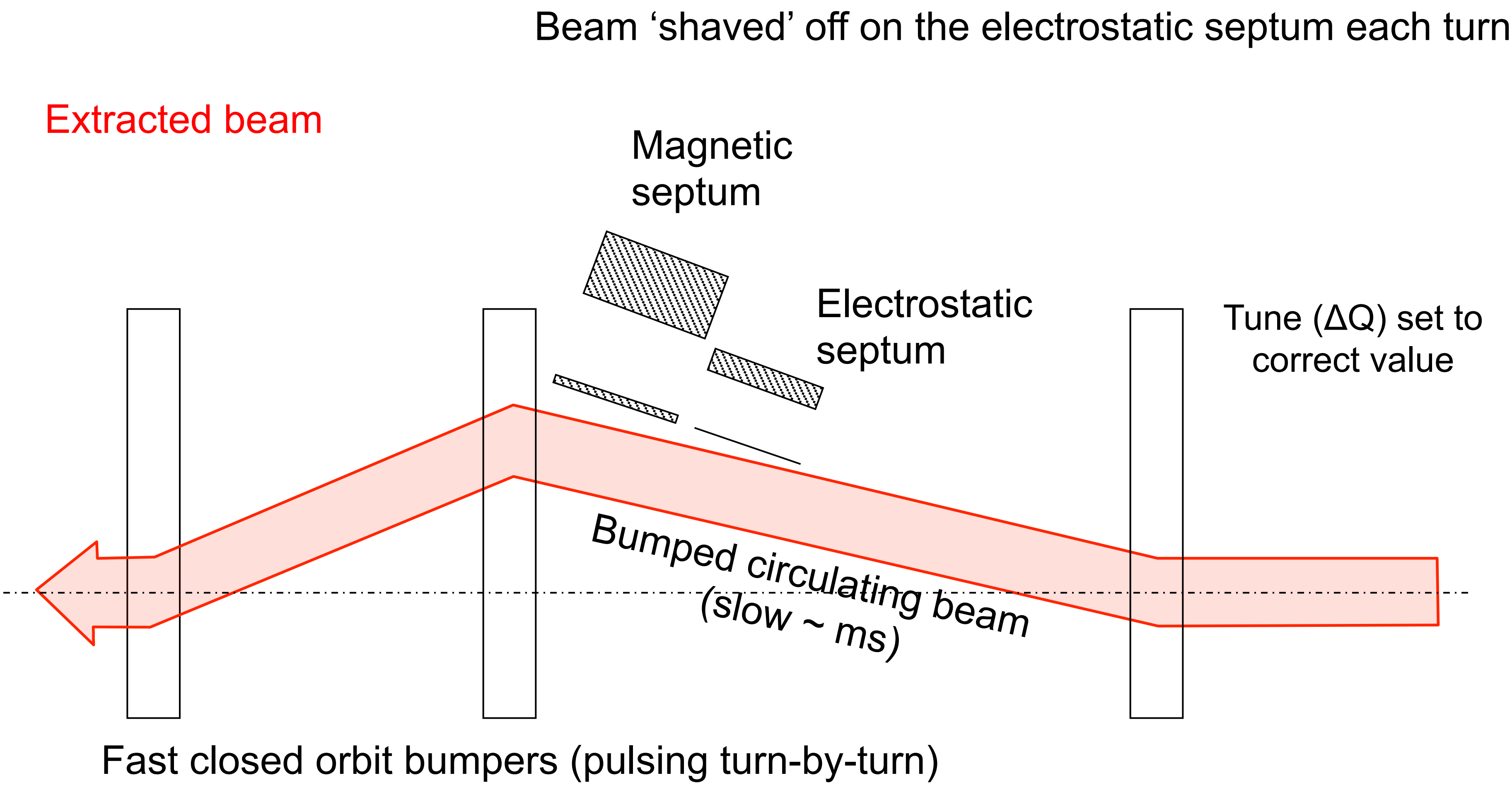
“Non-local” extraction concept

- Kickers and septa may be separated by large distances around a synchrotron, with the correct phase advance. For septa on the outside, i.e. x > 0:

$$\Delta x_{\text{septum}} = (-1)^{n-1} \left| \Delta x'_{\text{kicker}} \right| \sqrt{\beta_{\text{kicker}} \beta_{\text{septum}}} \sin(\mu_{\text{kicker} \rightarrow \text{septum}}) \quad \text{where} \quad \mu_{\text{kicker} \rightarrow \text{septum}} = \frac{2n-1}{2}\pi, \text{ where } n = 1, 2, 3 \ldots$$

- A single kicker system can service different extraction channels located around the synchrotron:
  - destination of beam chosen by kicker polarity and energizing local bump
  - might be a necessity in smaller machines where space is limited
- Implications:
  - reduced cost and maintenance
  - reduced impedance
  - reduced acceptance and stability of extracted beam
- See the appendix for a recent proposal at SPS

Multi-turn fast extraction



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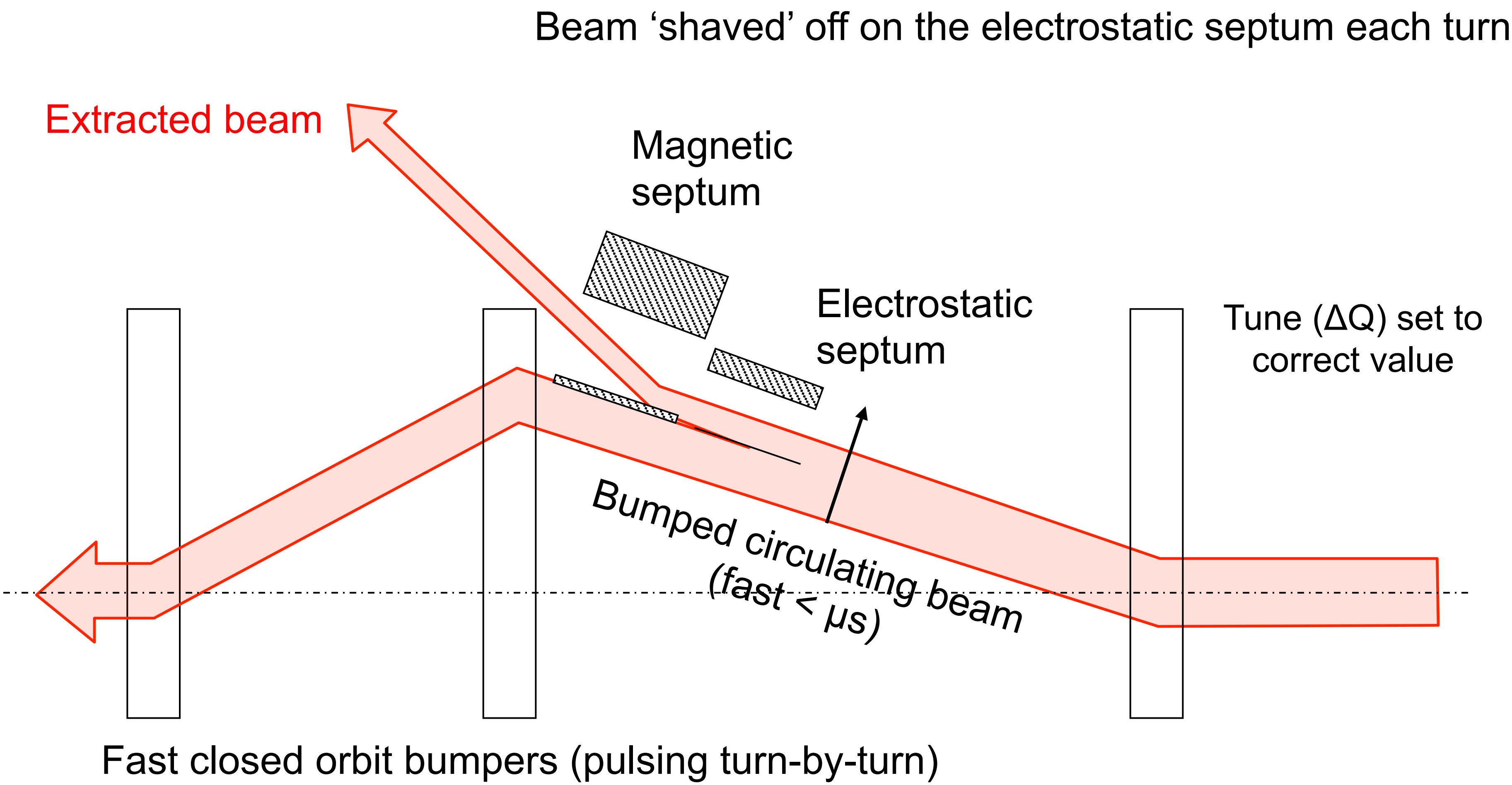

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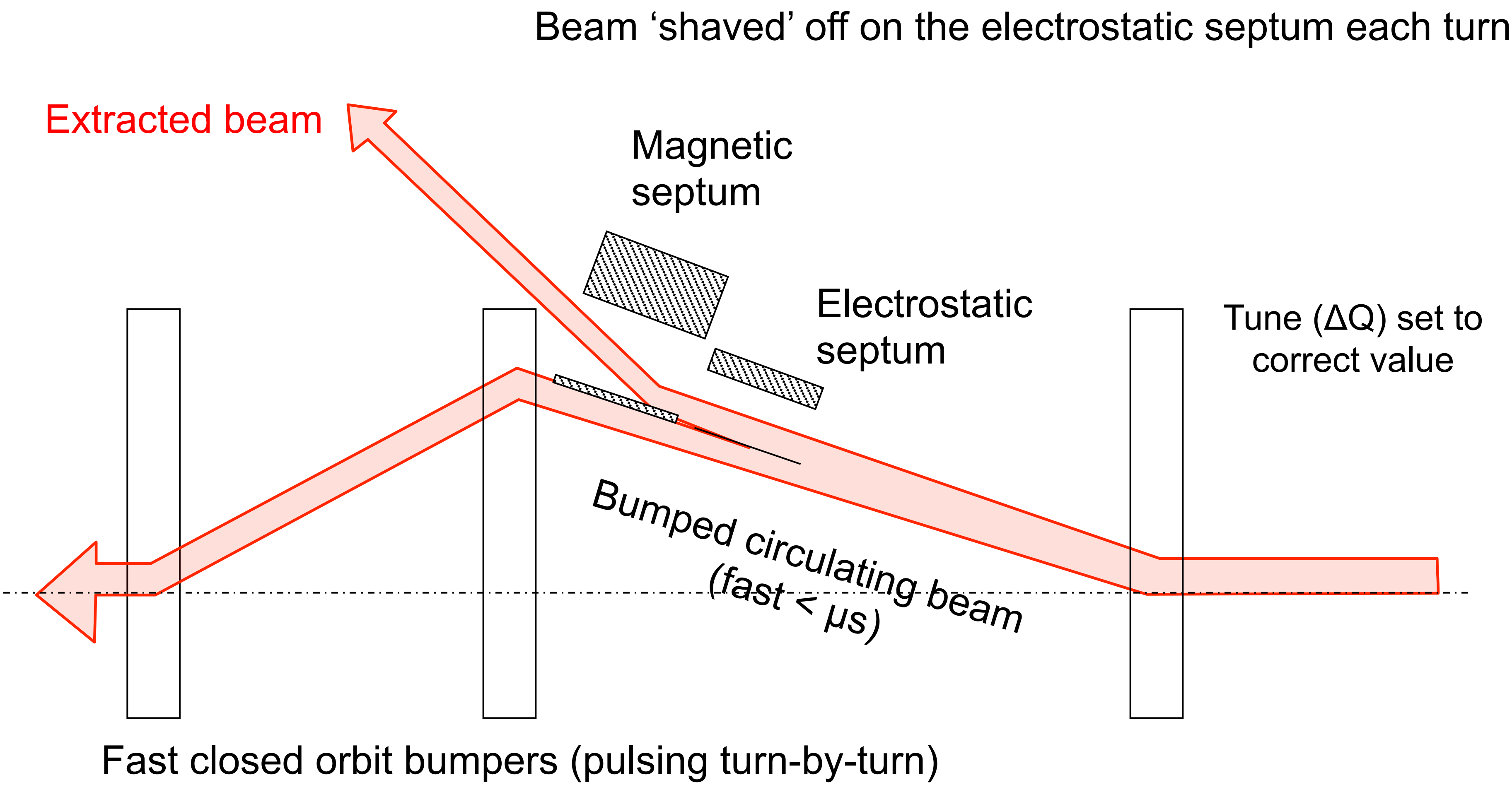

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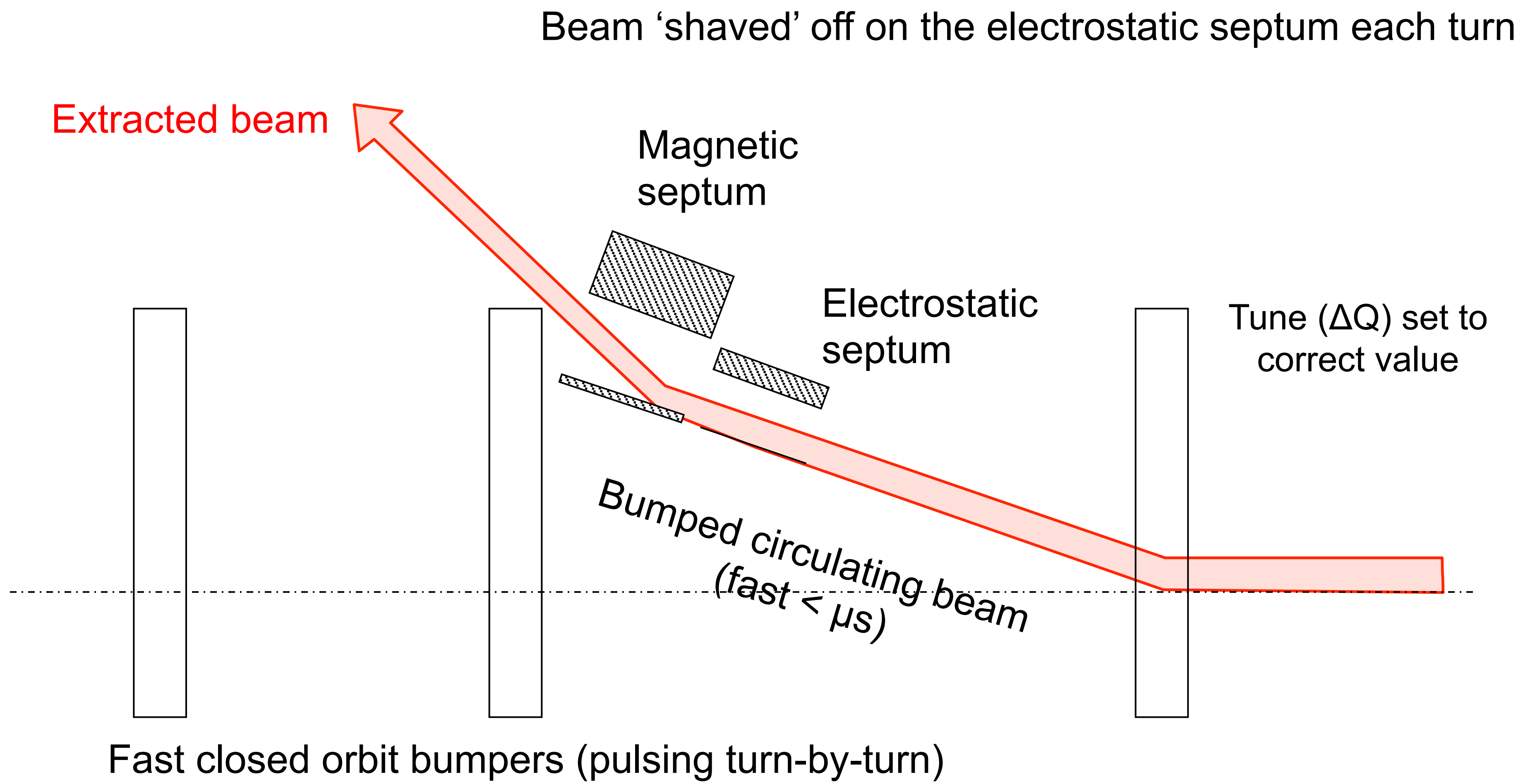

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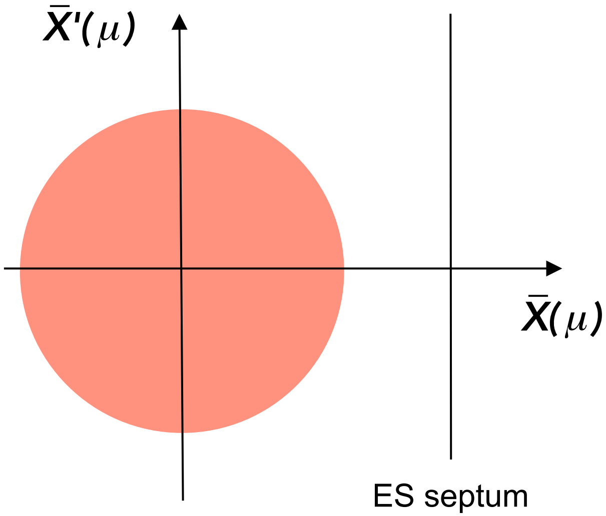

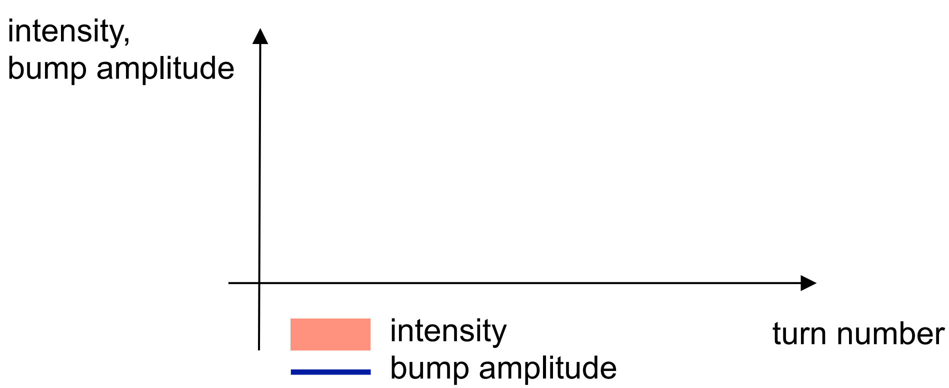

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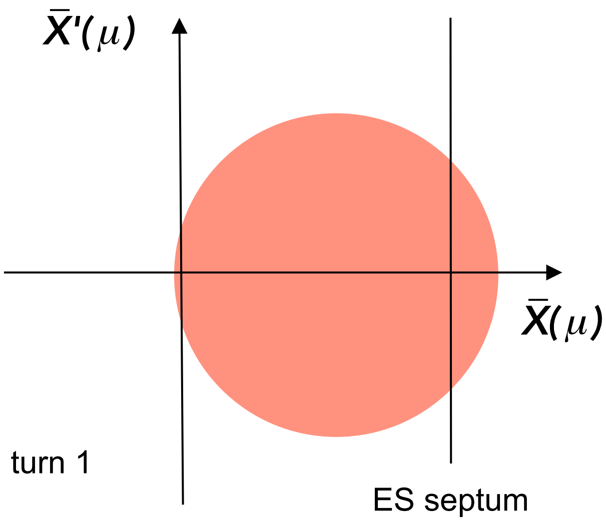

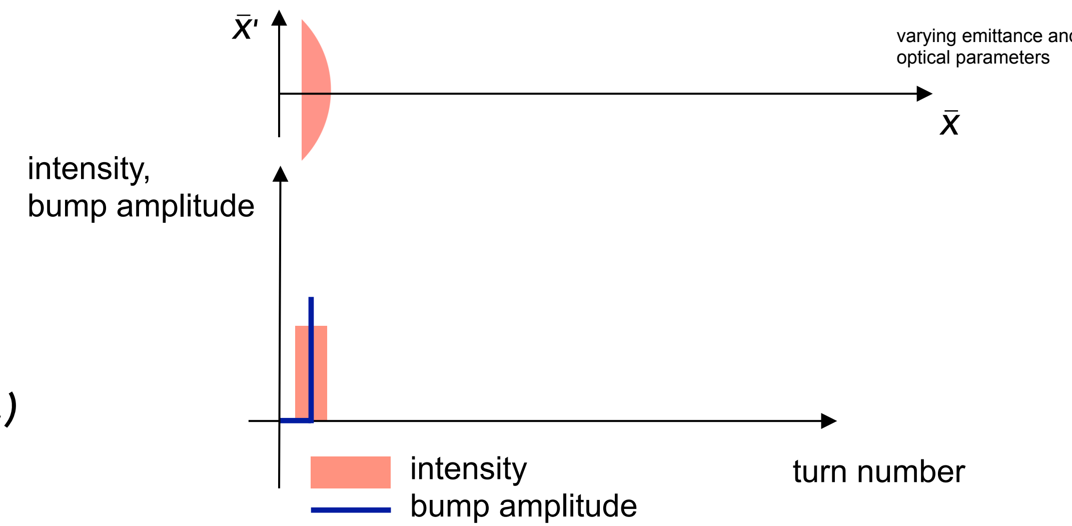

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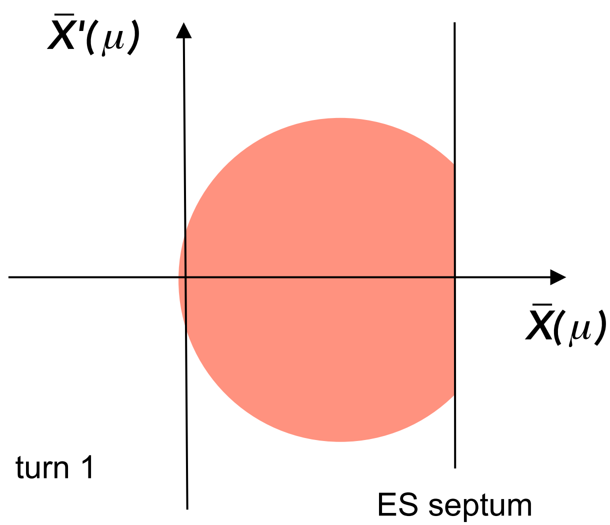

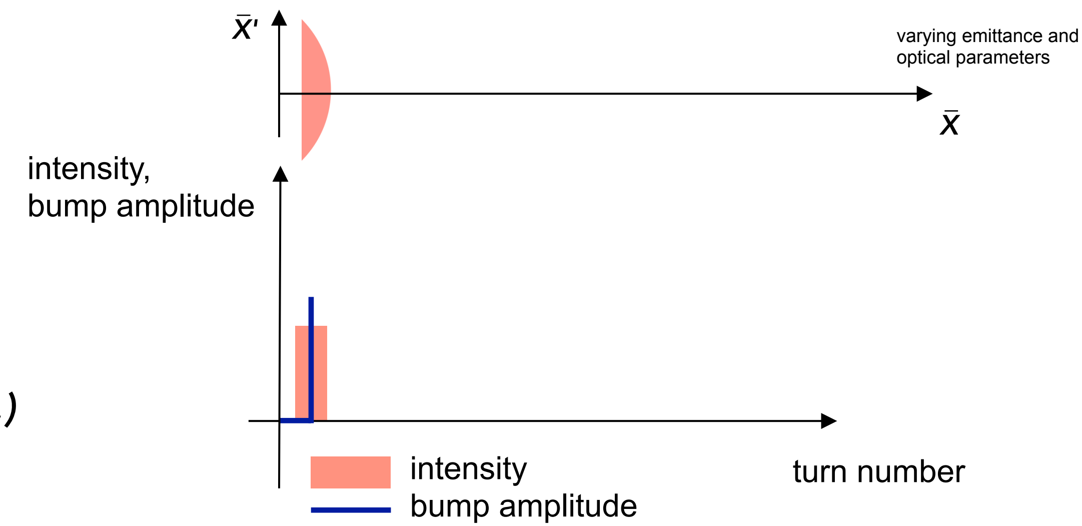

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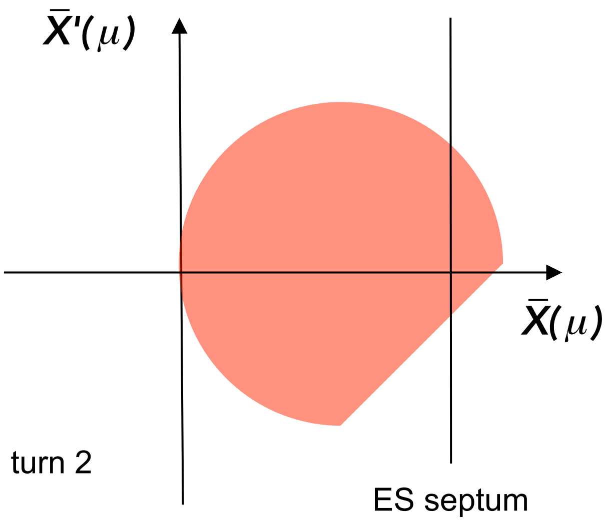

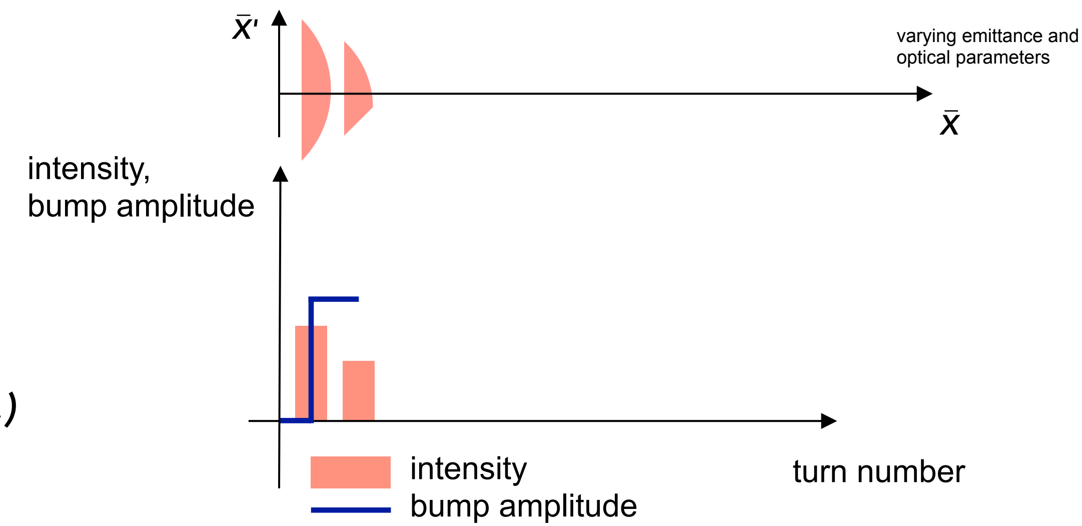

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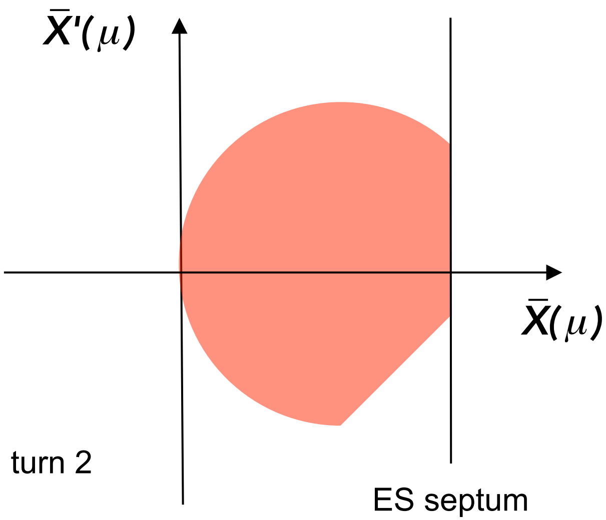

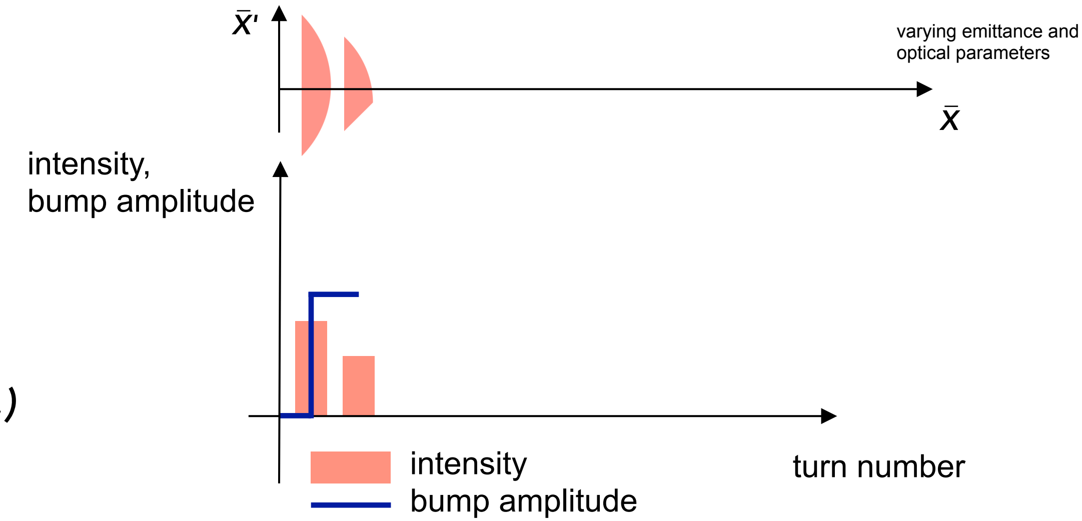

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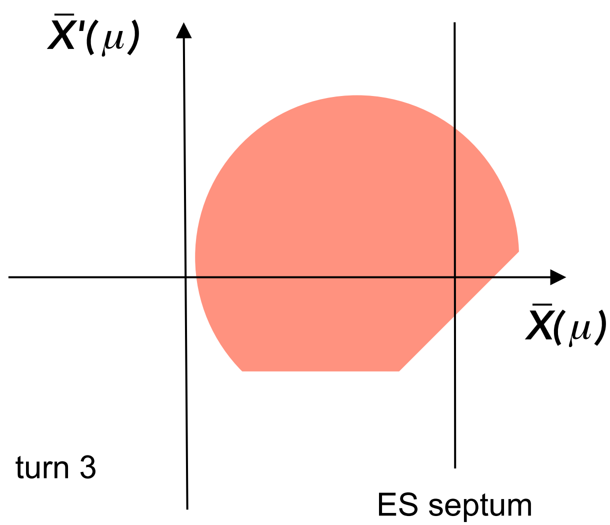

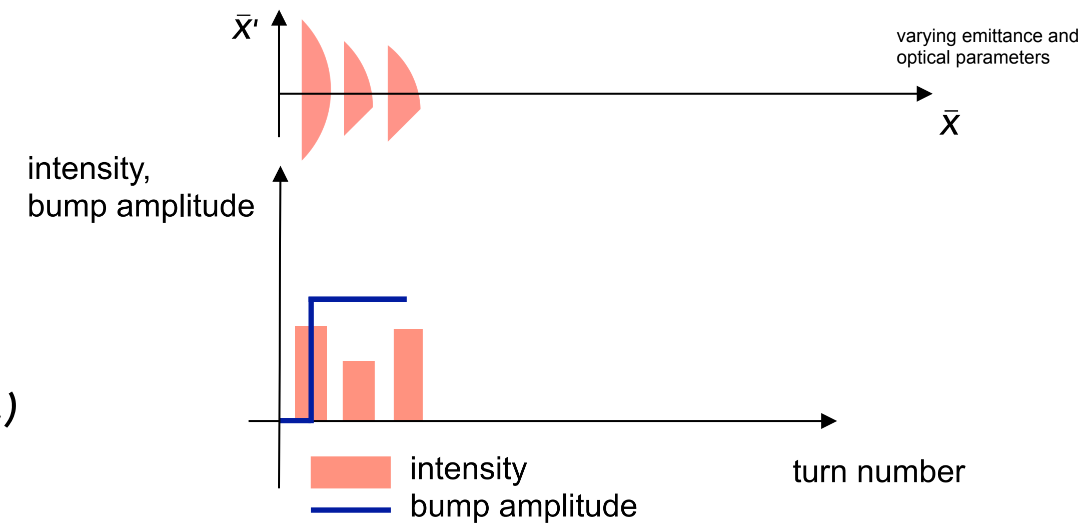

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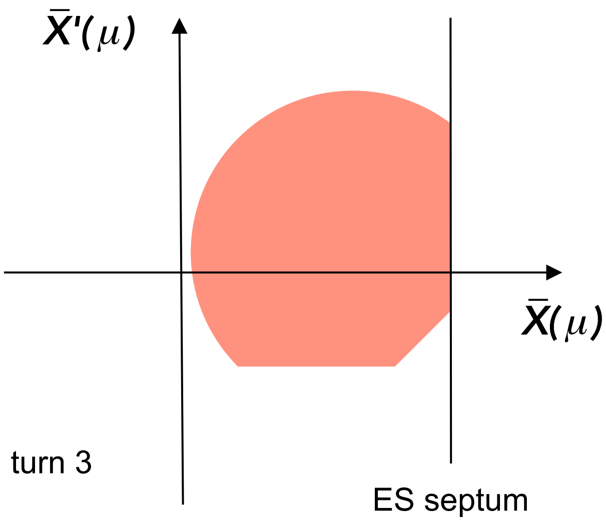

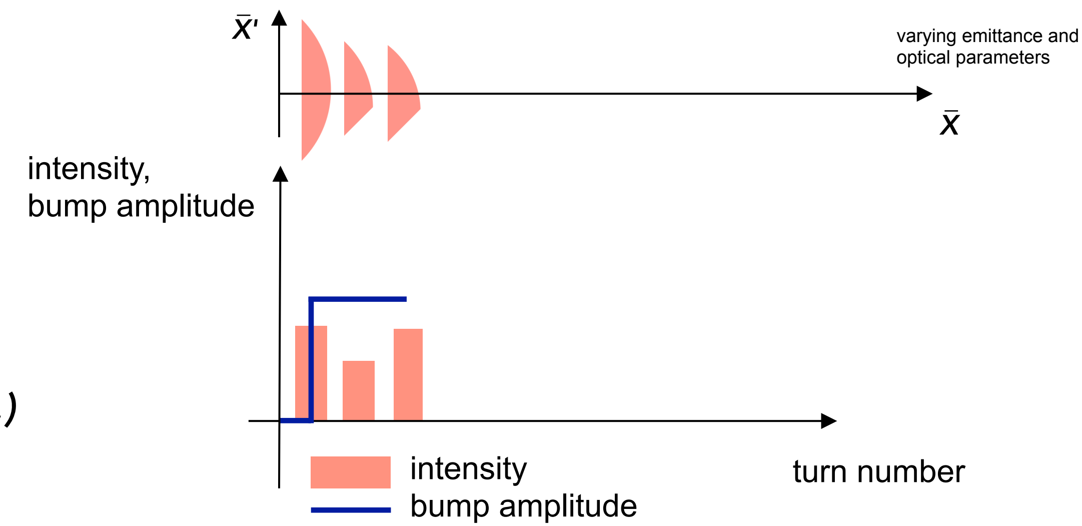

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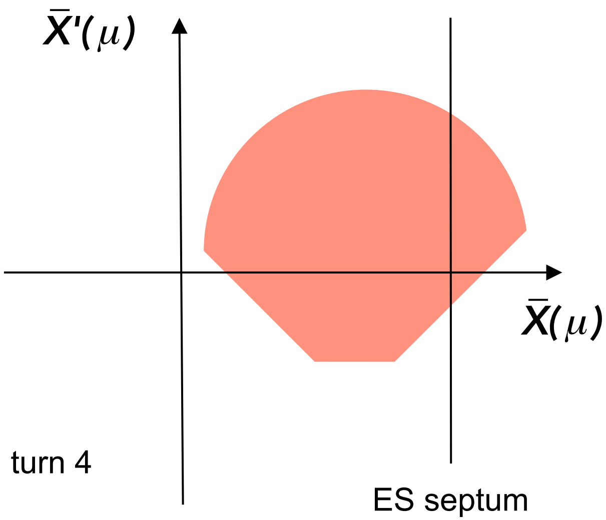

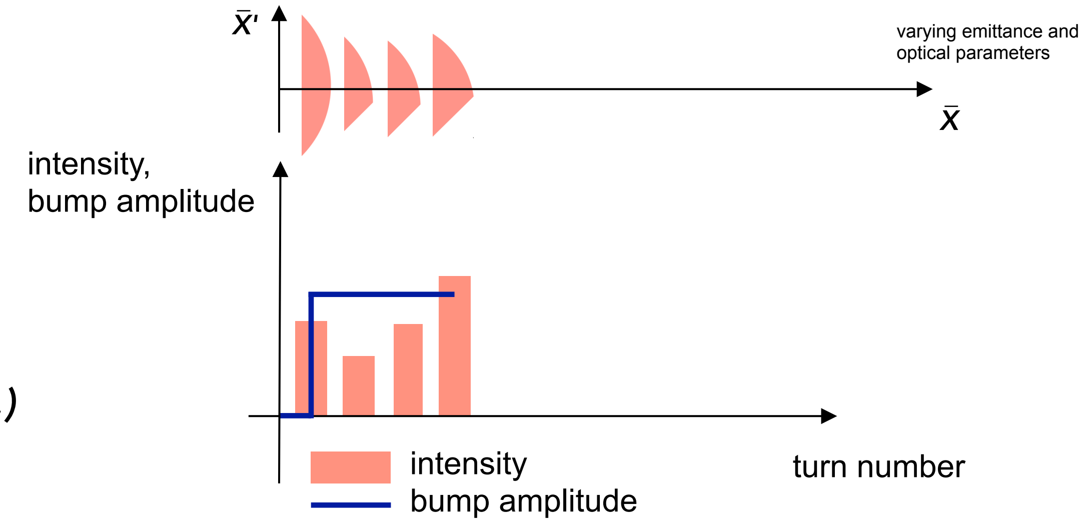

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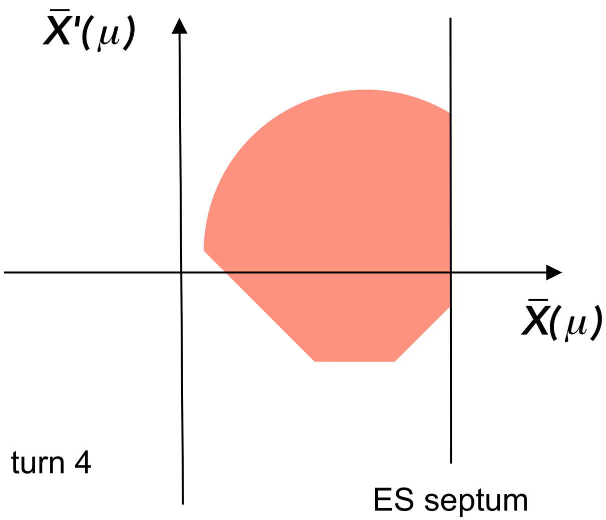

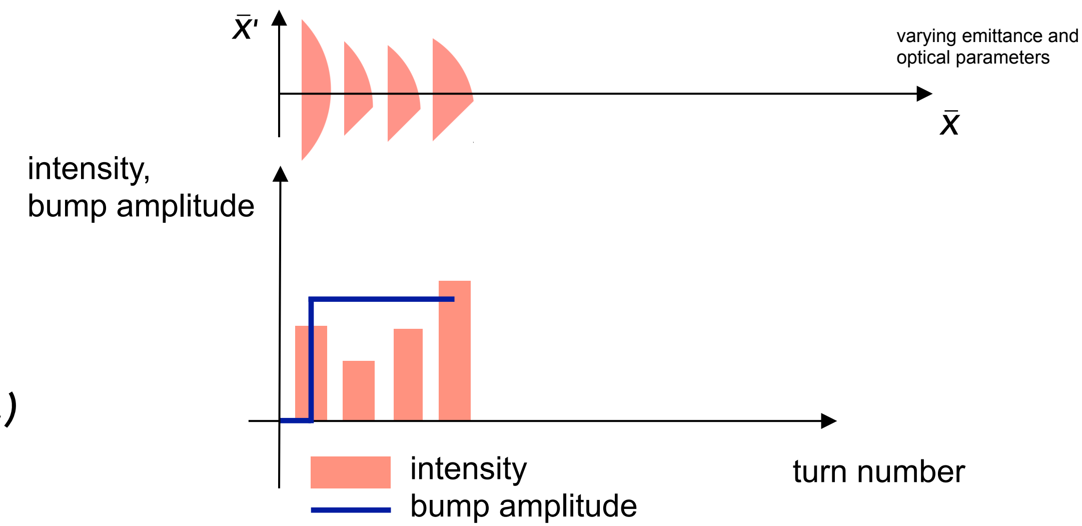

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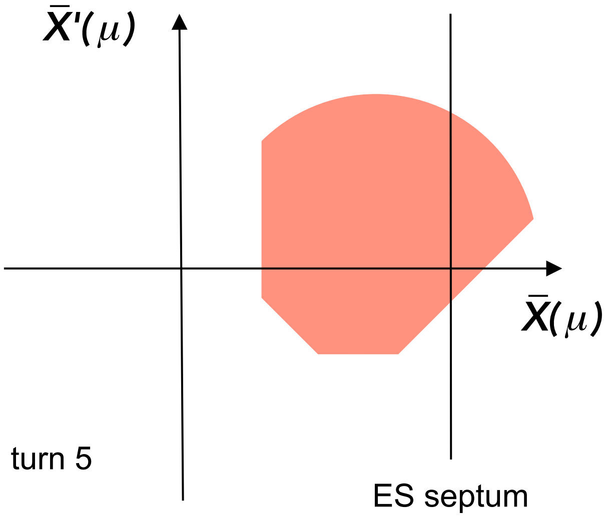

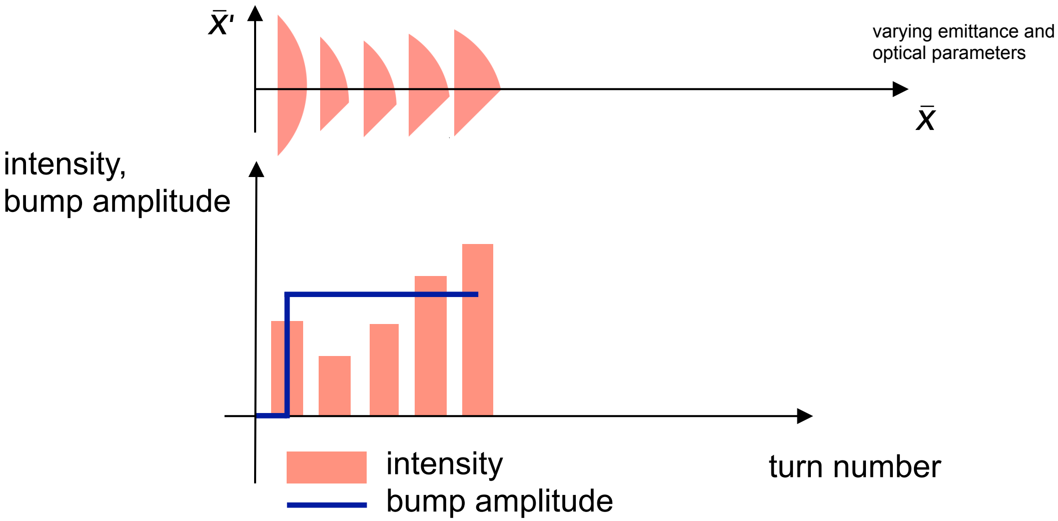

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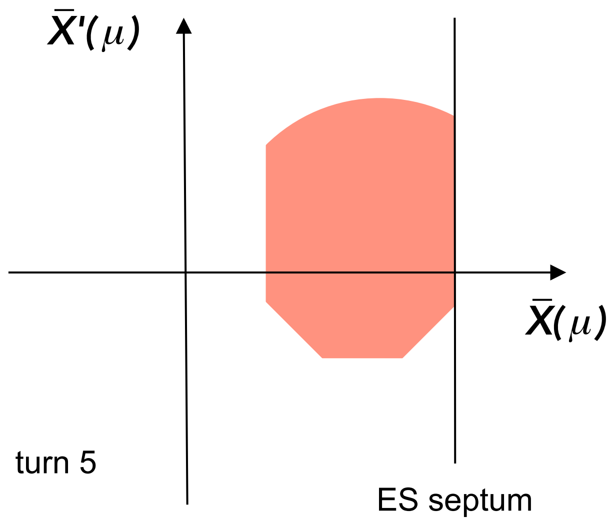

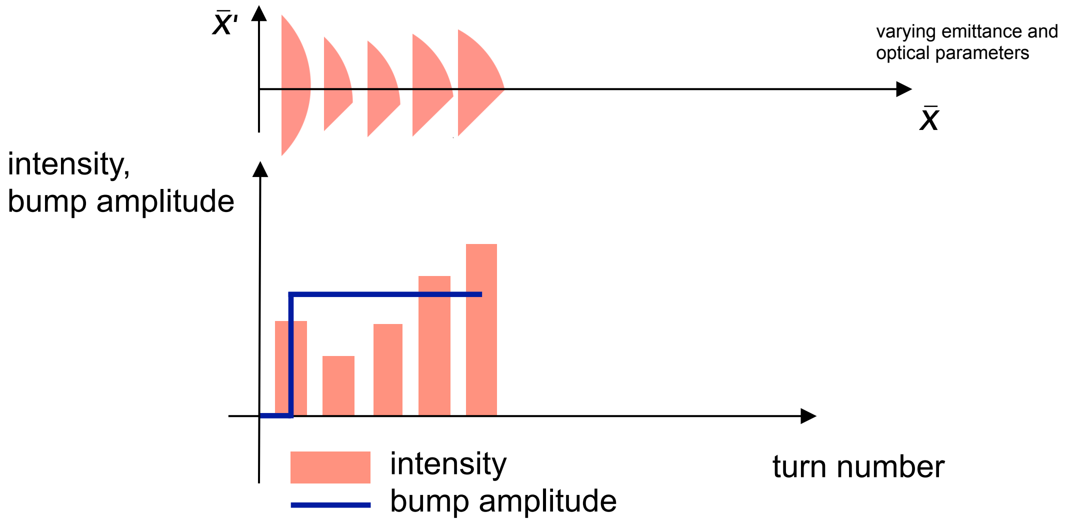

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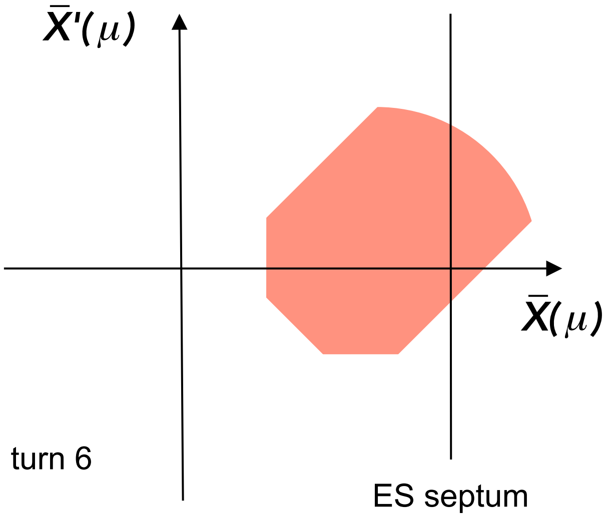

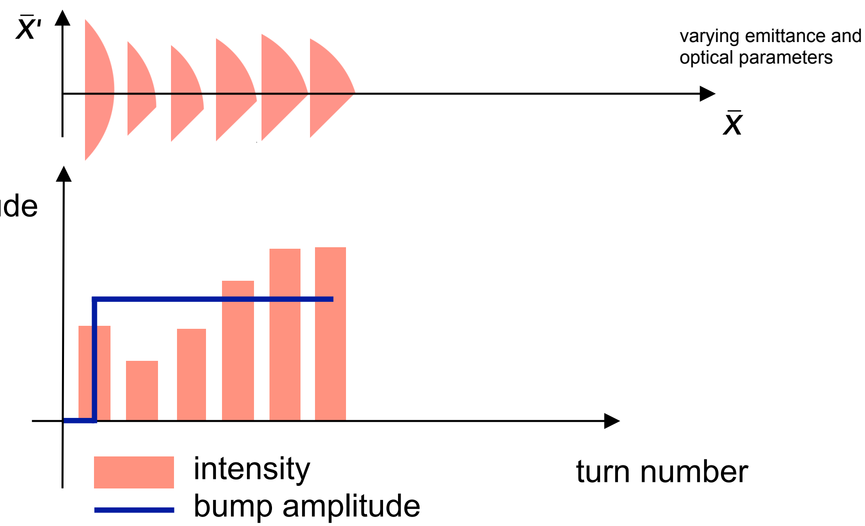

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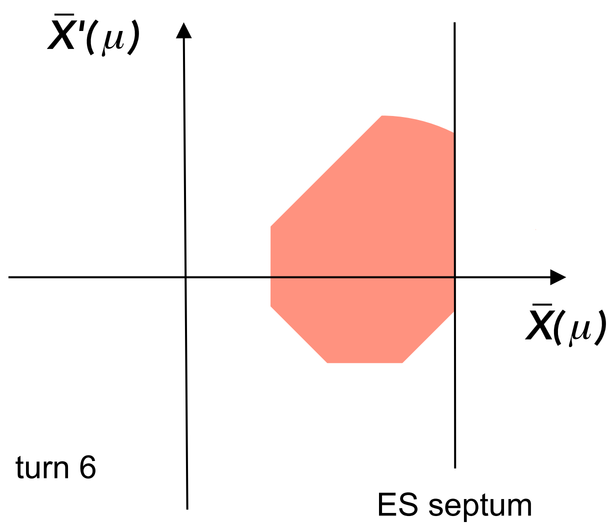

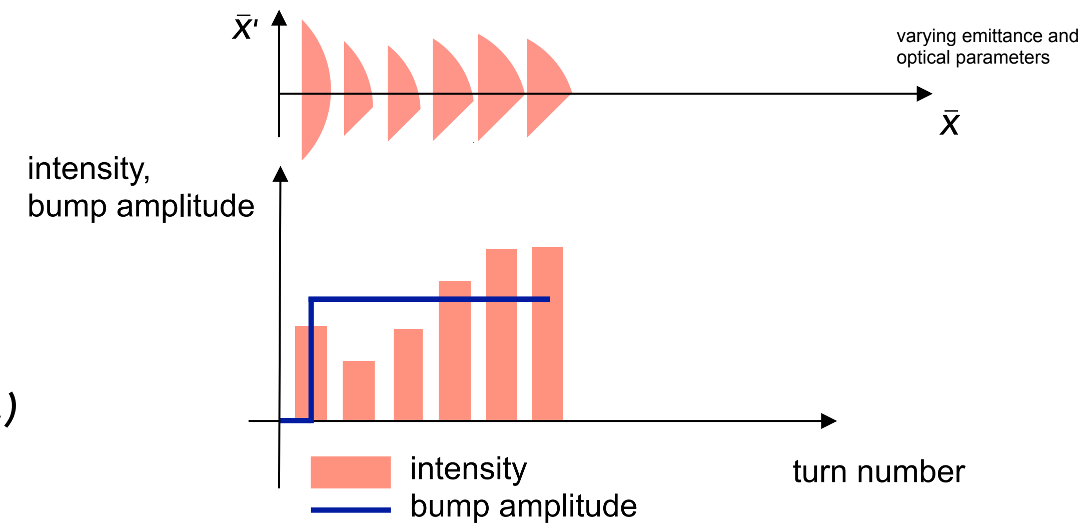

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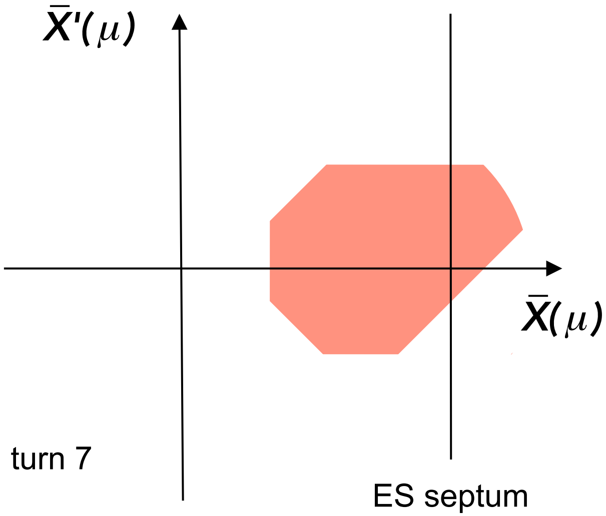

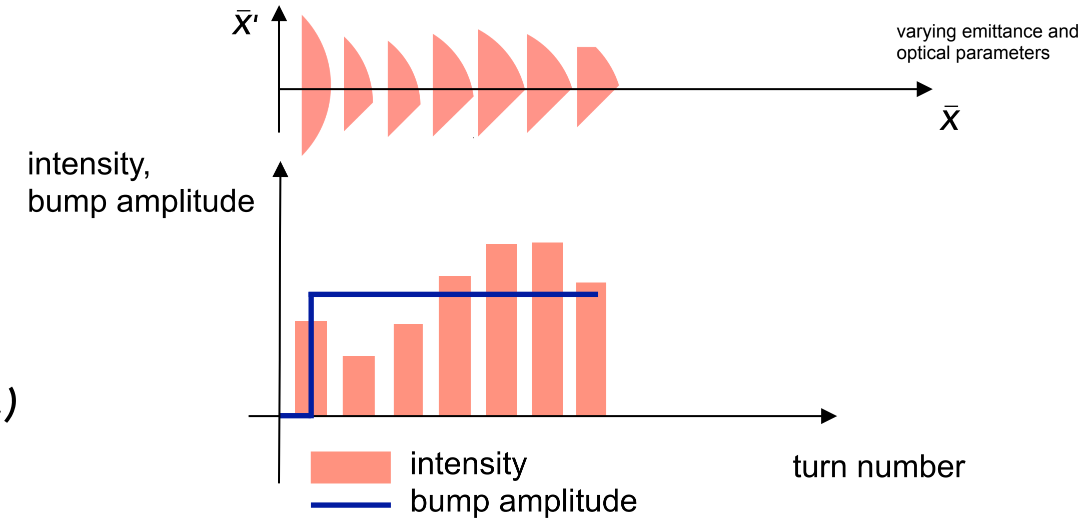

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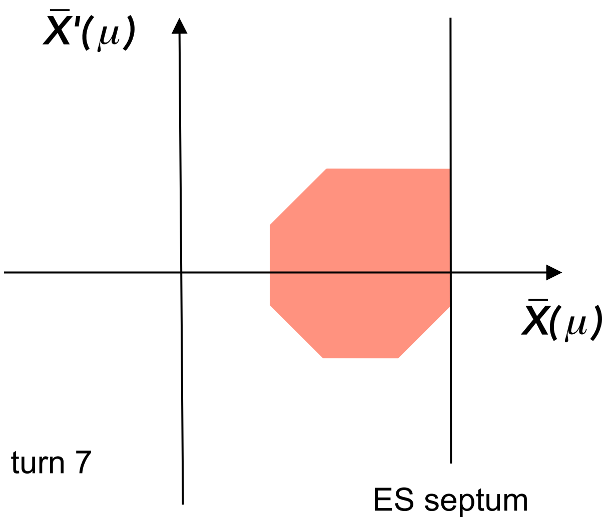

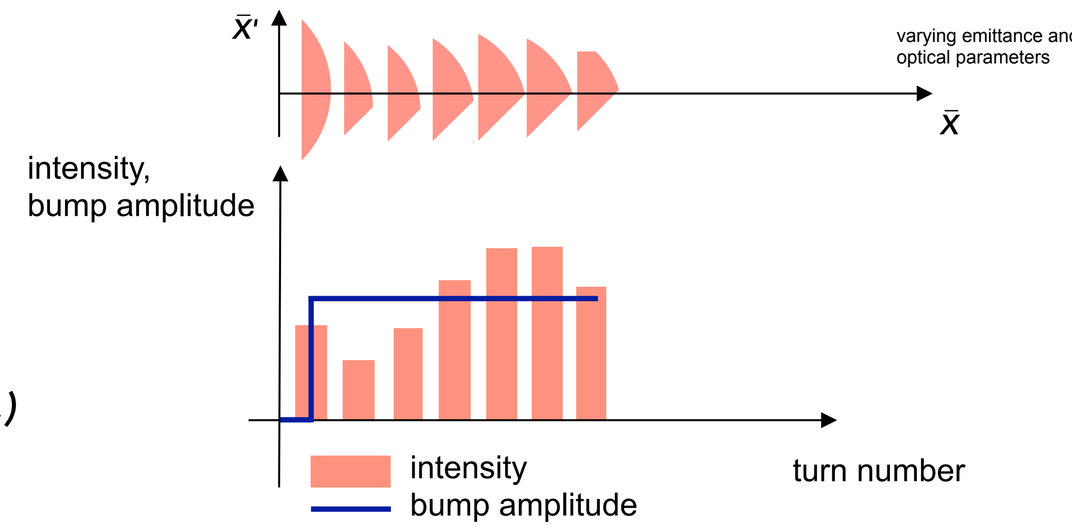

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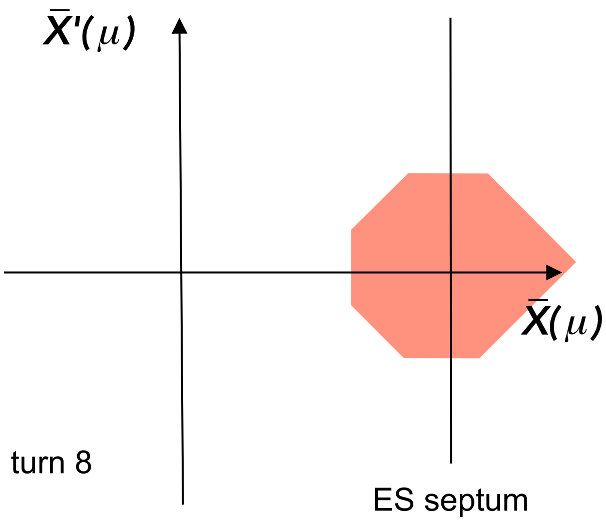

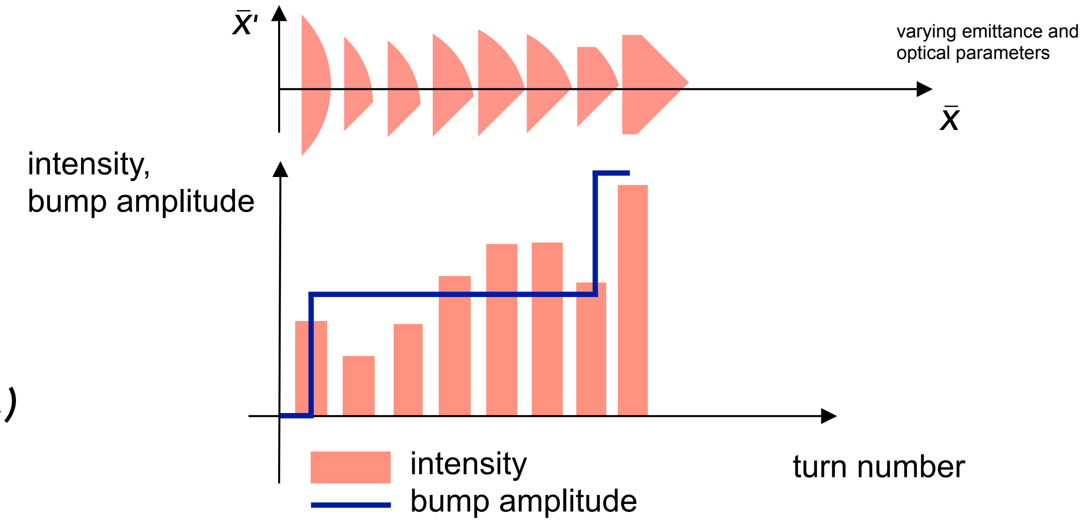

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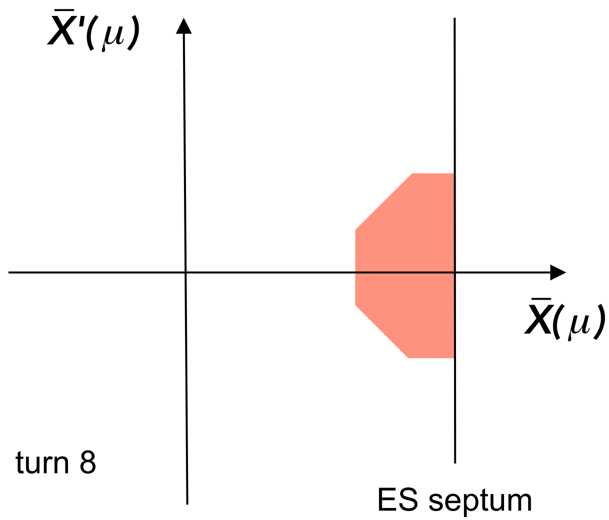

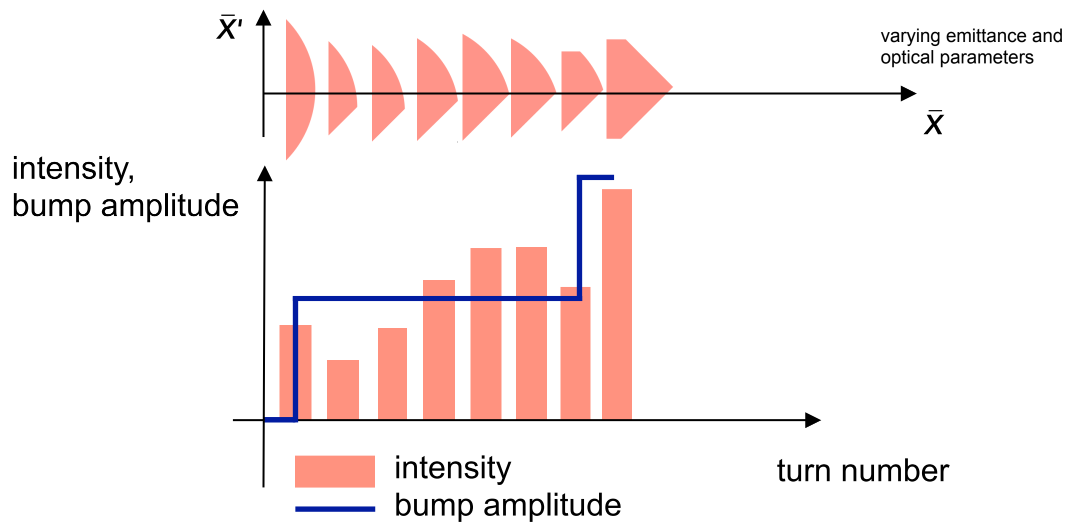

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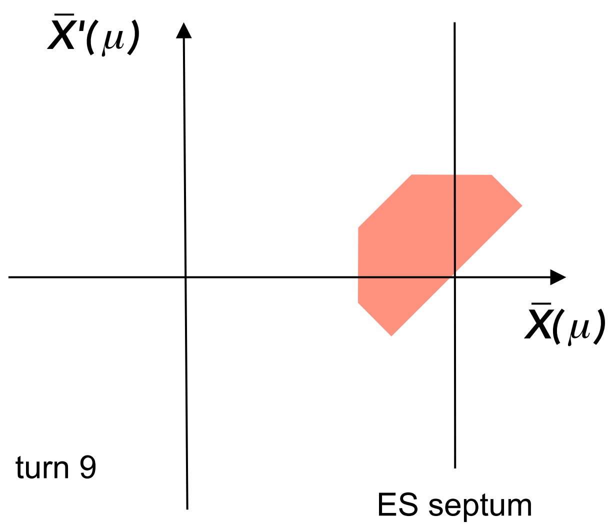

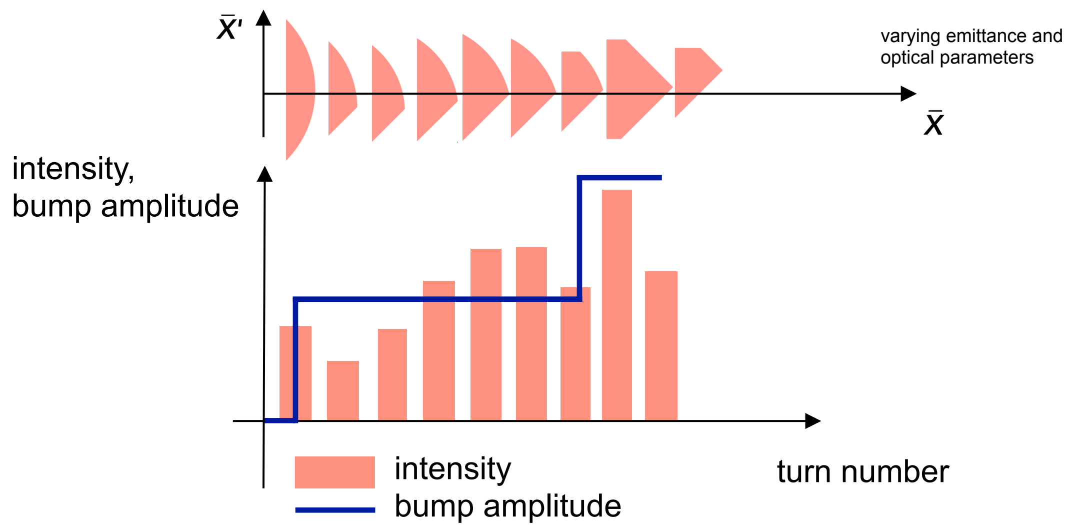

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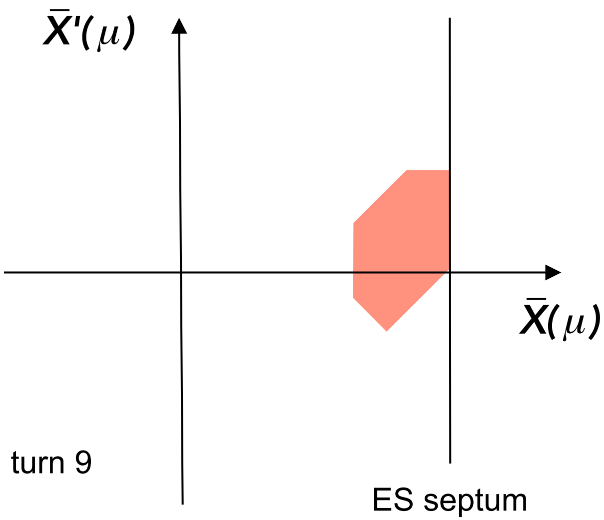

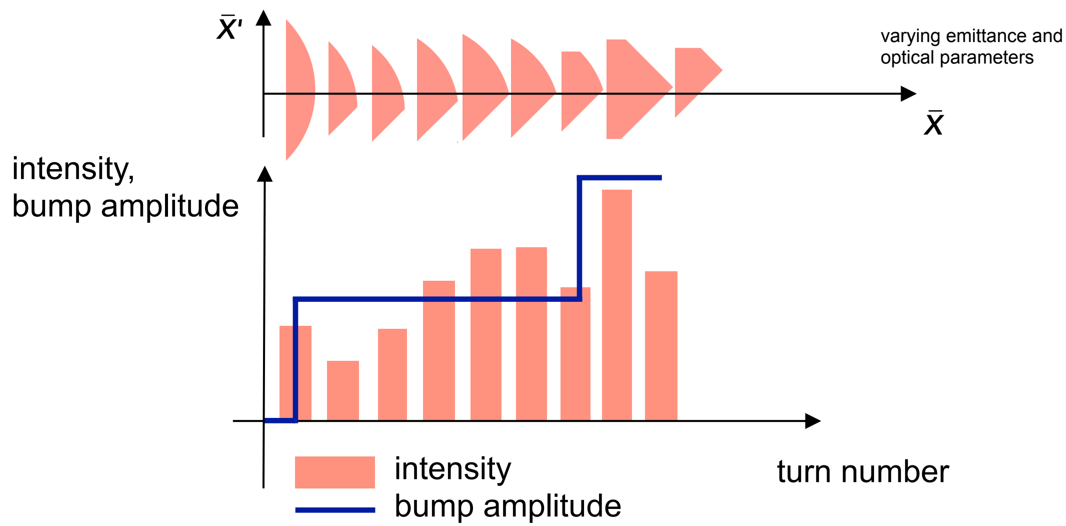

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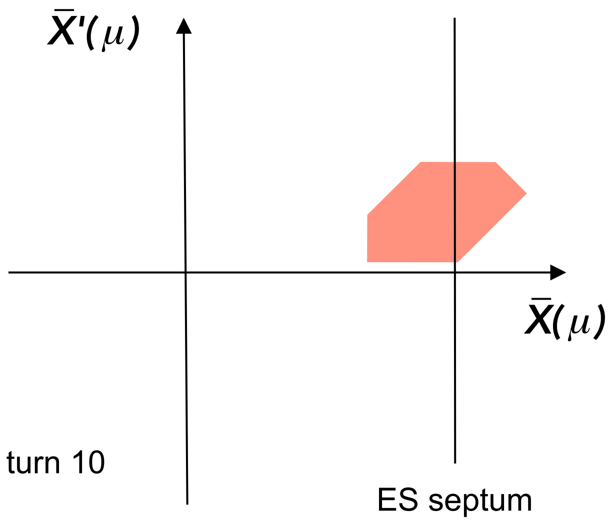

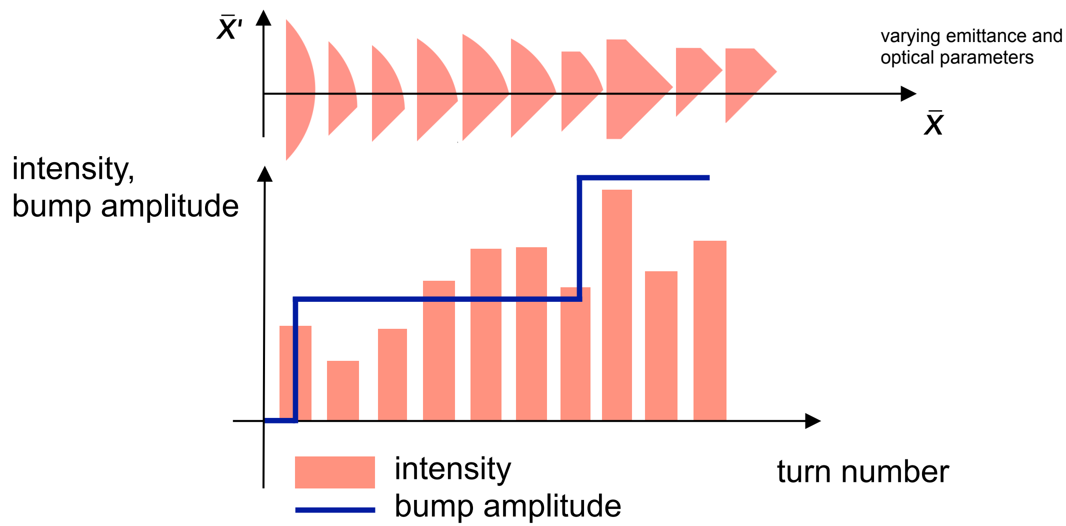

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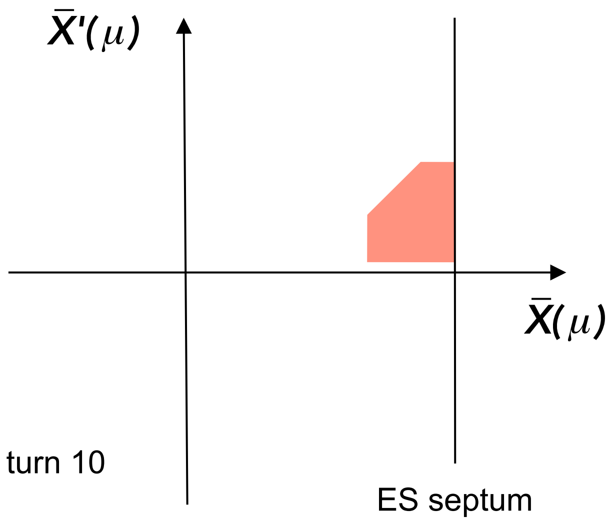
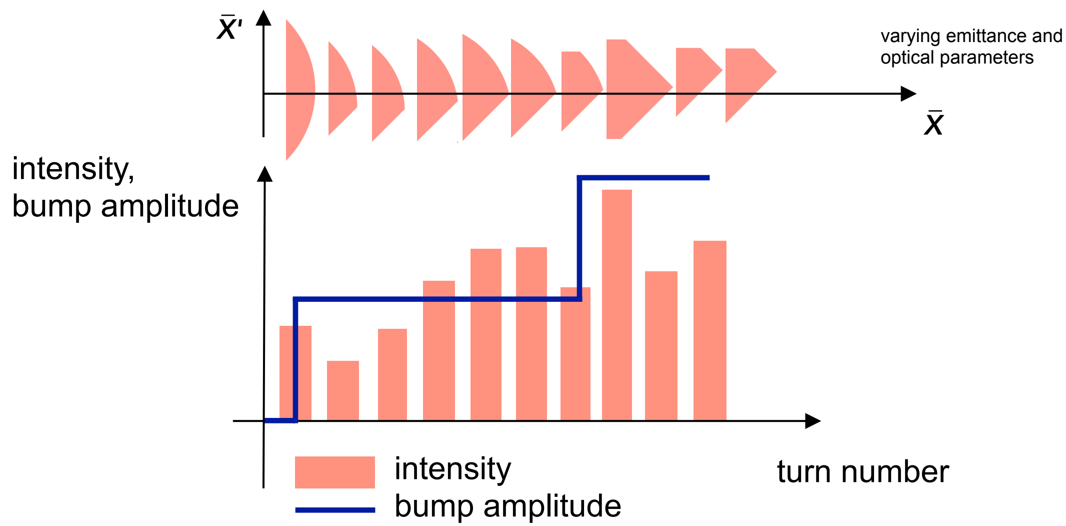
- A brute force method used to lengthen the spill from a synchrotron:
  - useful for filling a larger synchrotron (reduce filling time)
  - or… providing experiments with spills over a few turns: < 15 turns
- The circulating beam is “shaved” on a turn-by-turn basis by a septum:
  - the spill length and intensity is controlled by…
  - …a fast programmable closed-bump: forces the beam into the septum
  - …the fractional part of the tune ΔQ: rotates the beam into the septum





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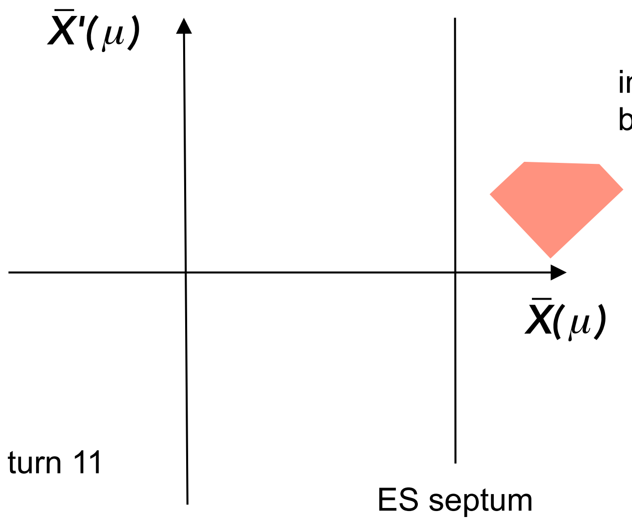

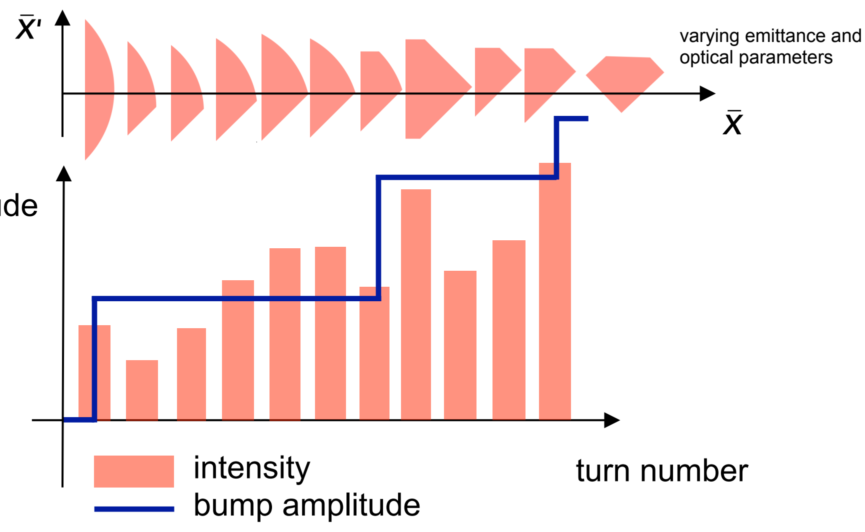

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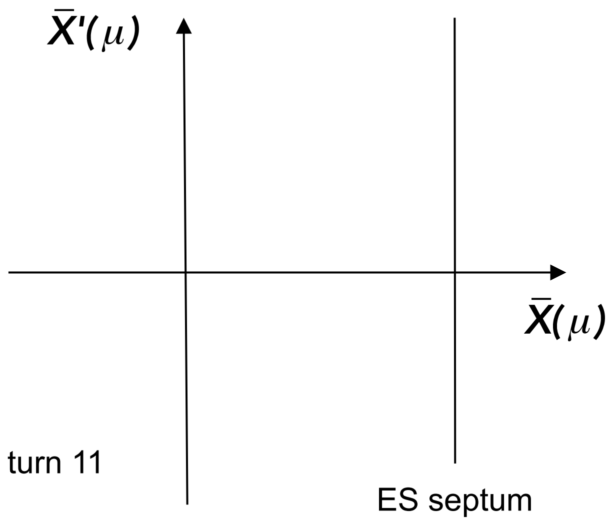

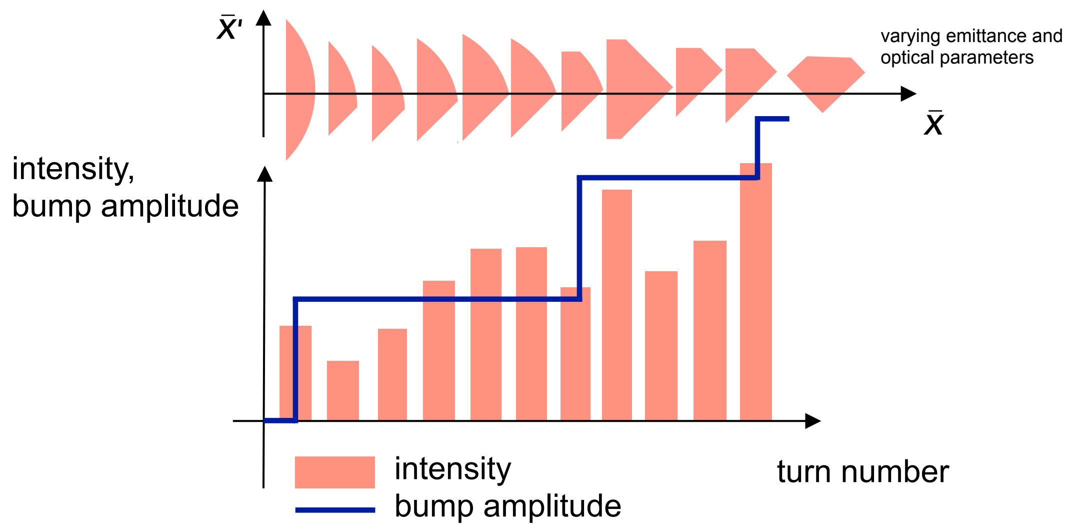

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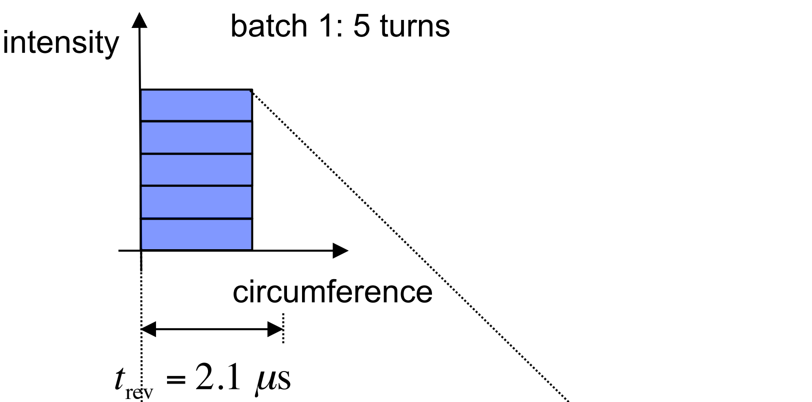
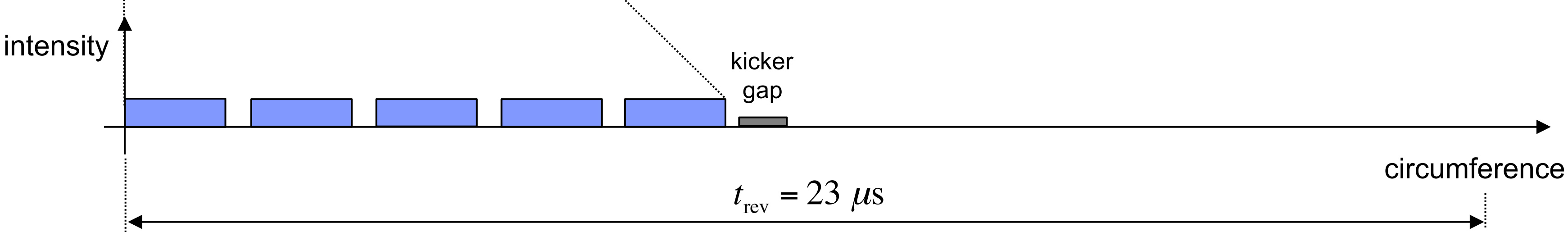
Continuous Transfer at the CERN PS

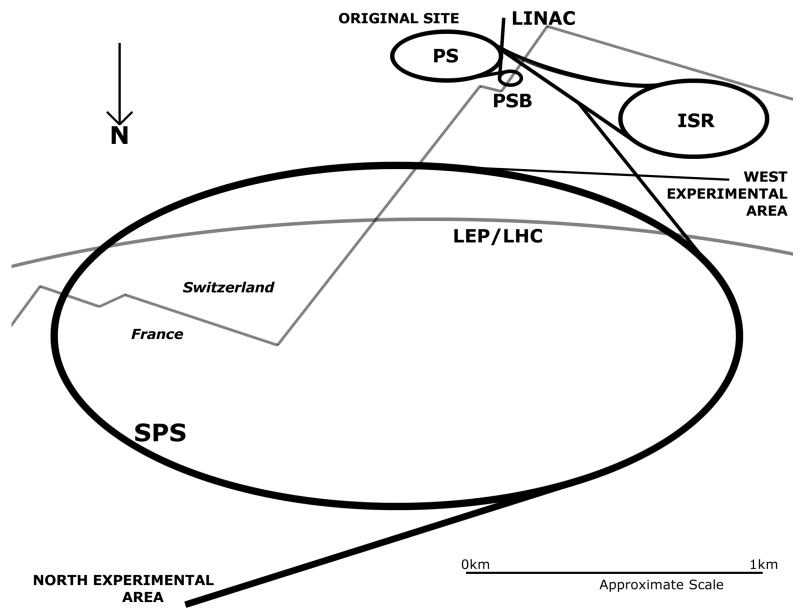
- Continuous Transfer was used at the CERN PS to fill the SPS **uniformly**:
  - filling time and resulting duty cycle (and thus protons on target) is optimized with 2 transfers of **5-turns** each at **14 GeV** in SPS:

PS: $I_{PS} = 0.1 - 3.3 \times 10^{13}\ p^{+}$ per batch

SPS: $C_{SPS} = 11 C_{PS}$







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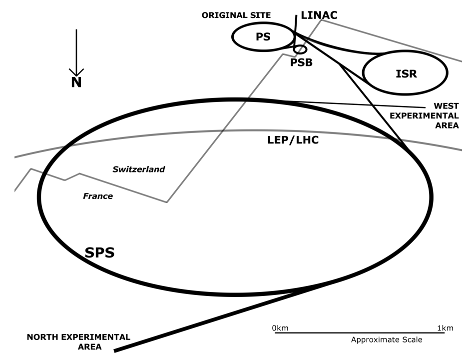

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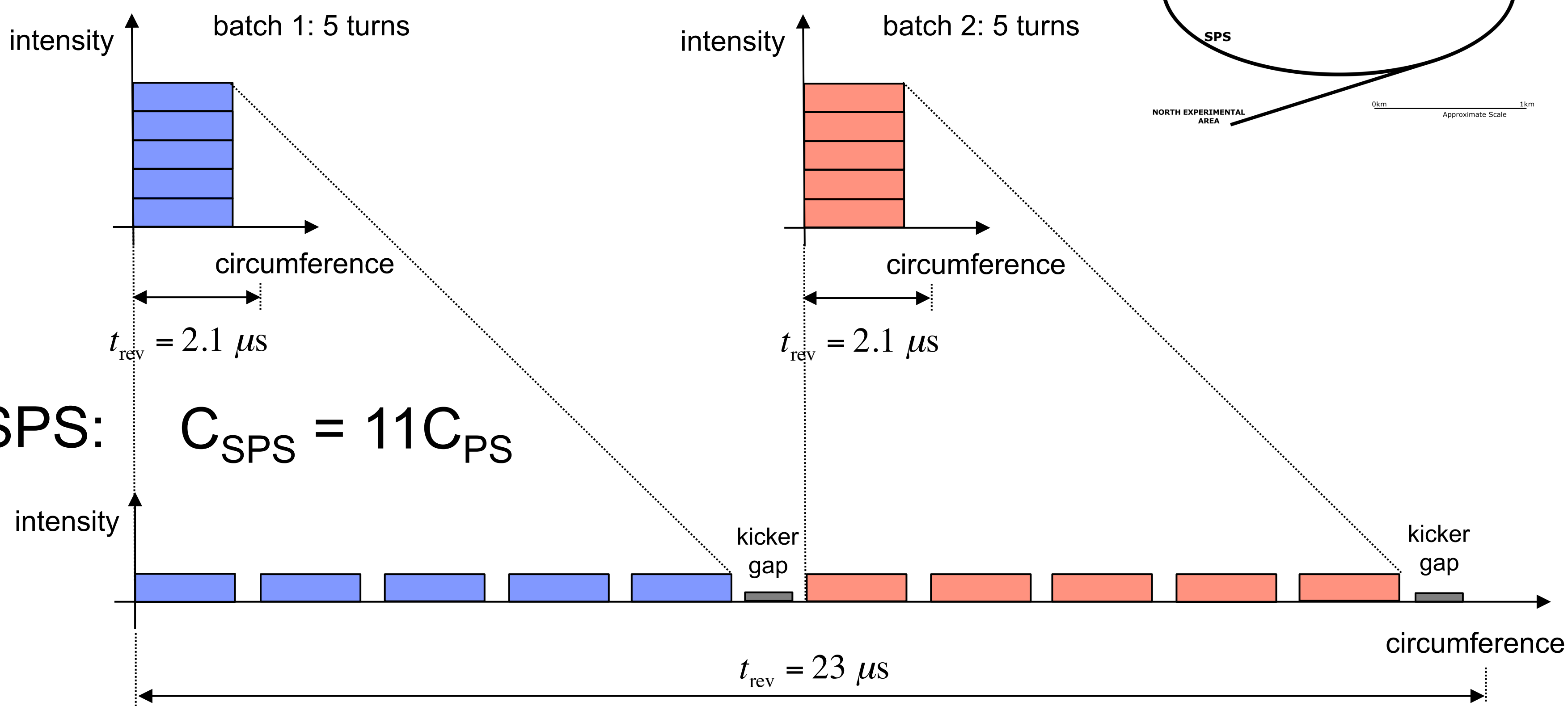
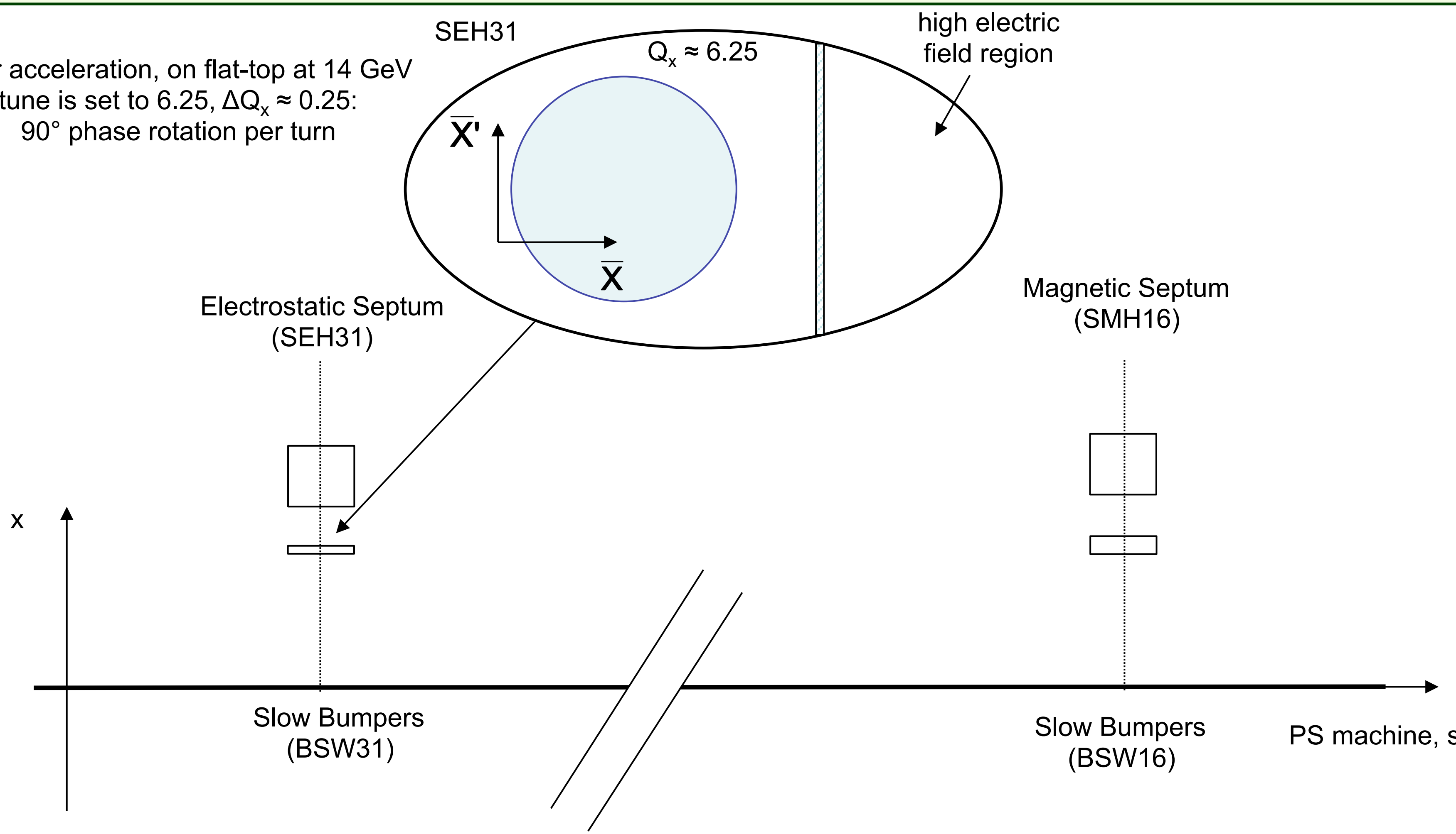


CT: operational implementation

After acceleration, on flat-top at 14 GeV
tune is set to 6.25, $\Delta Q_x \approx 0.25$:
90° phase rotation per turn



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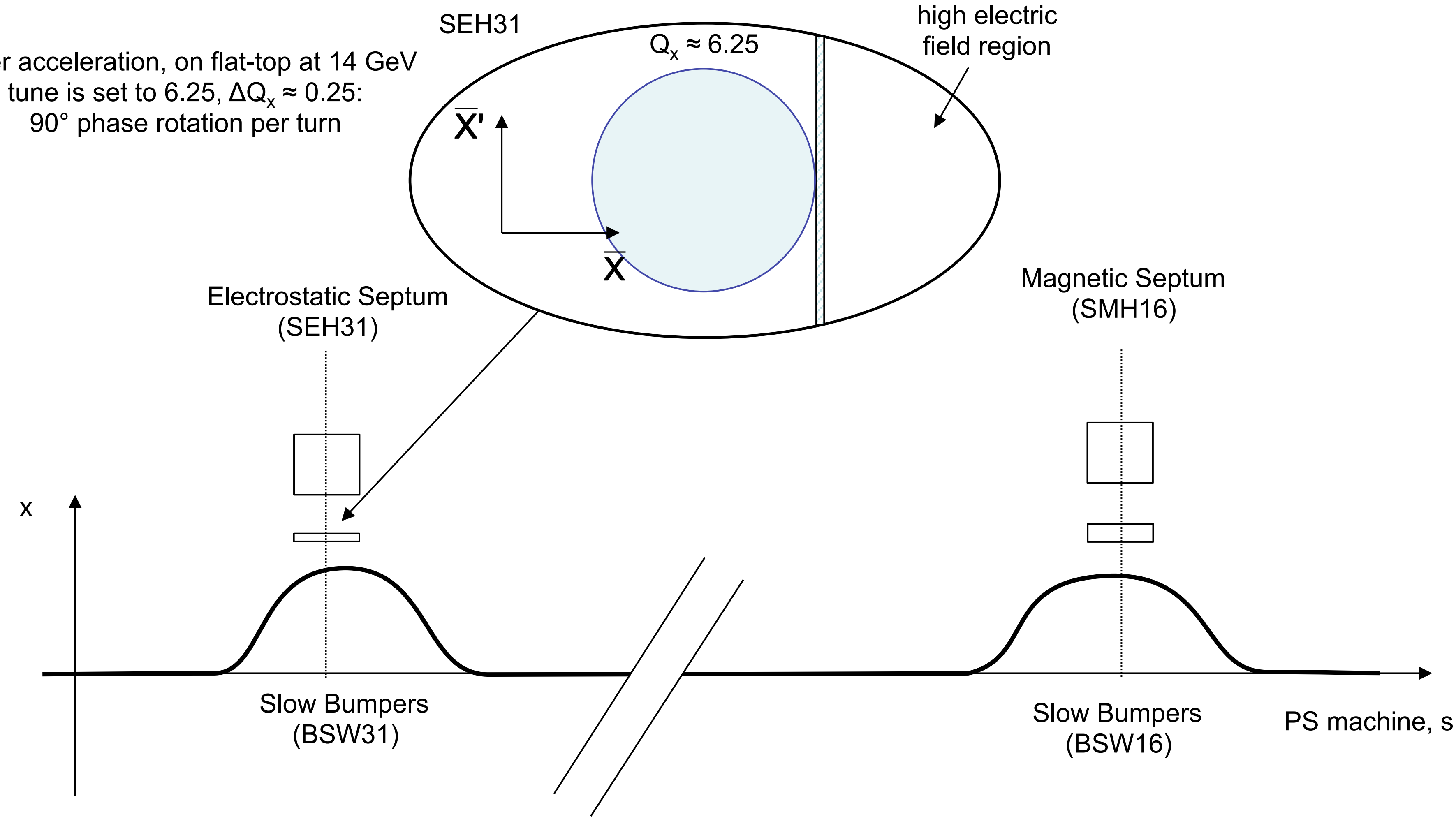

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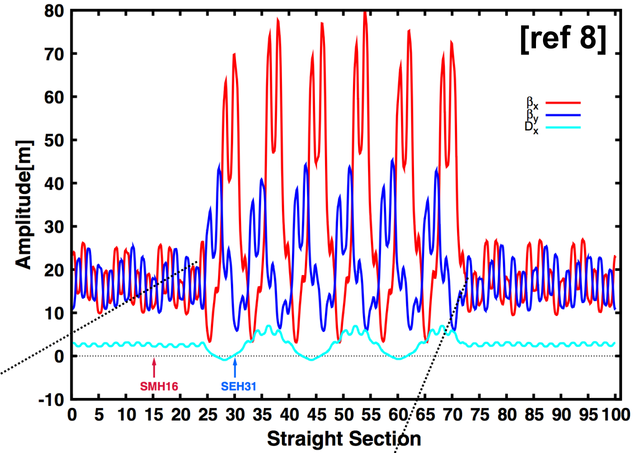
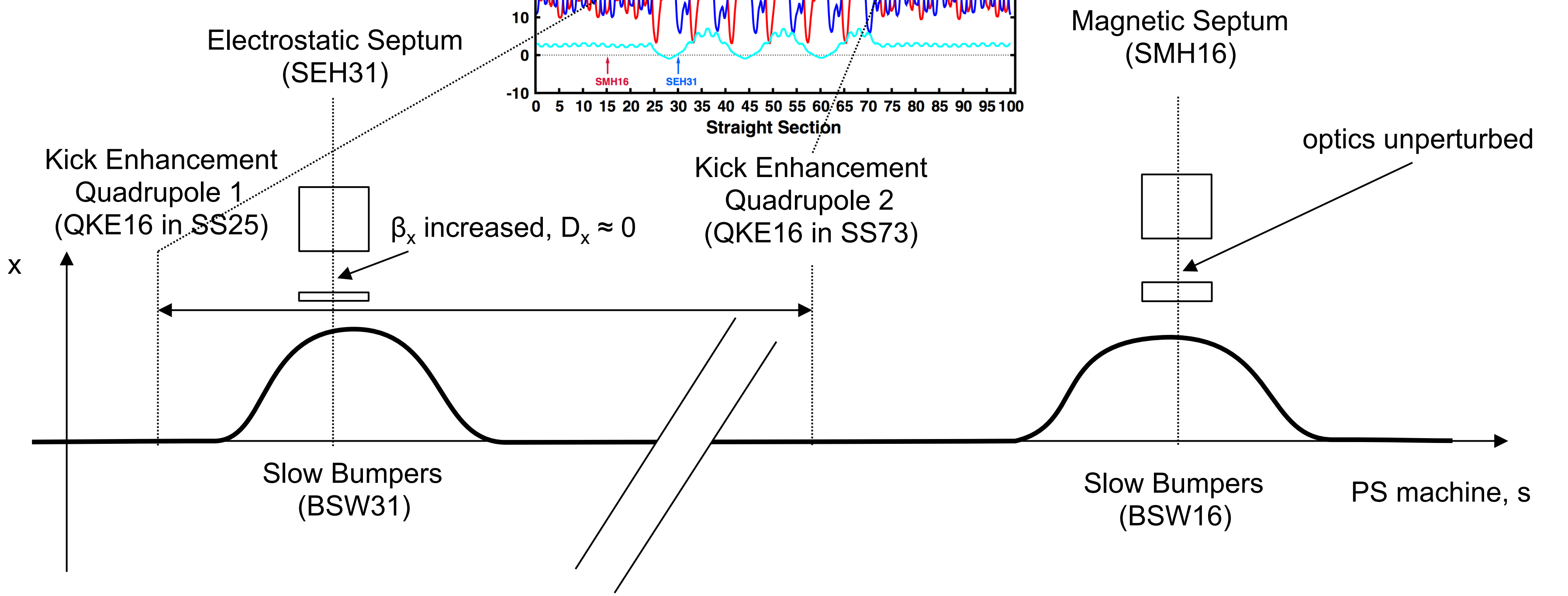
- Large β_x (beam size) reduces the density at the septum blade and reduces the number of particles lost
- $D_x \approx 0$ reduces correlation between momentum and extracted slice





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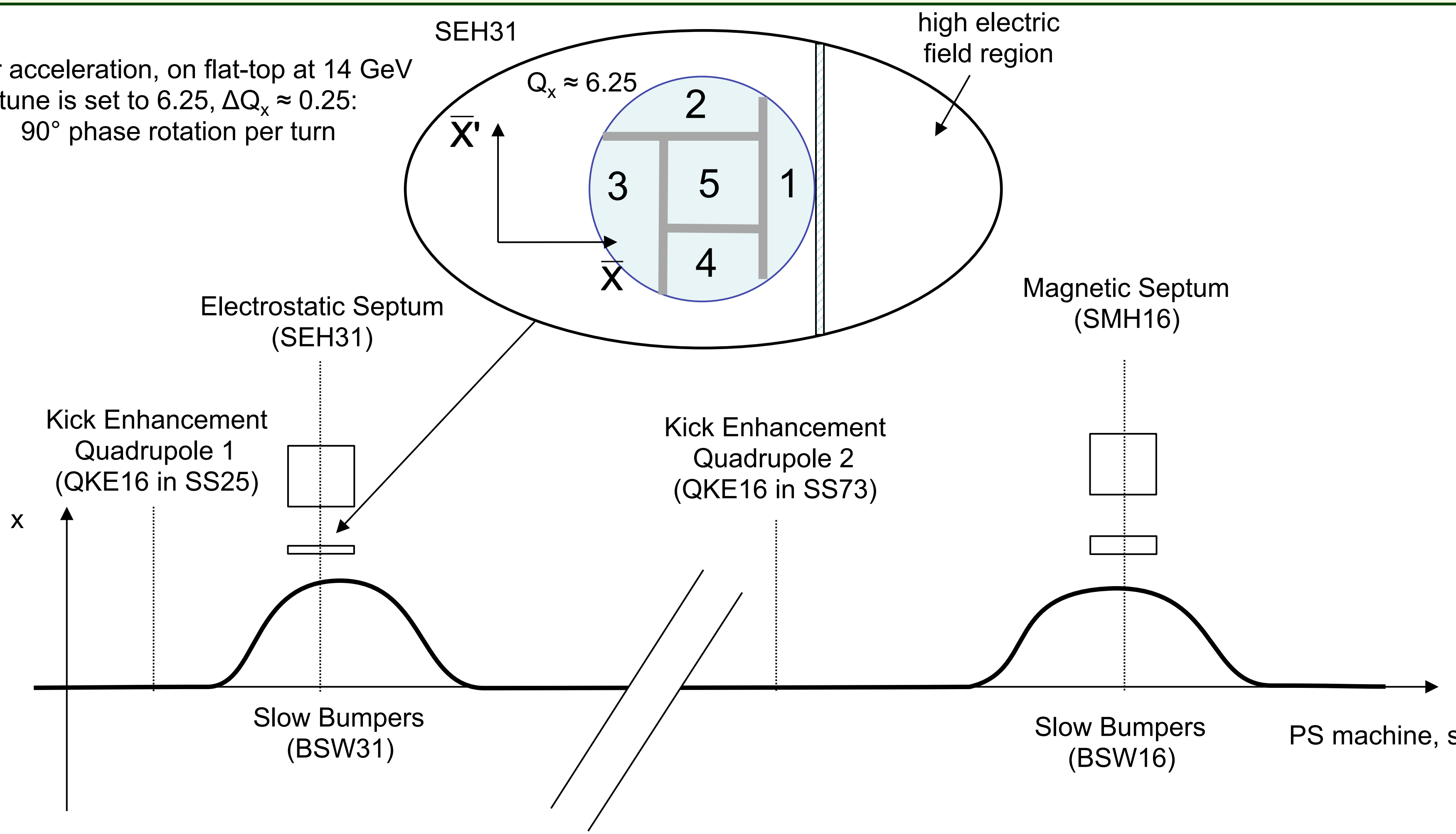

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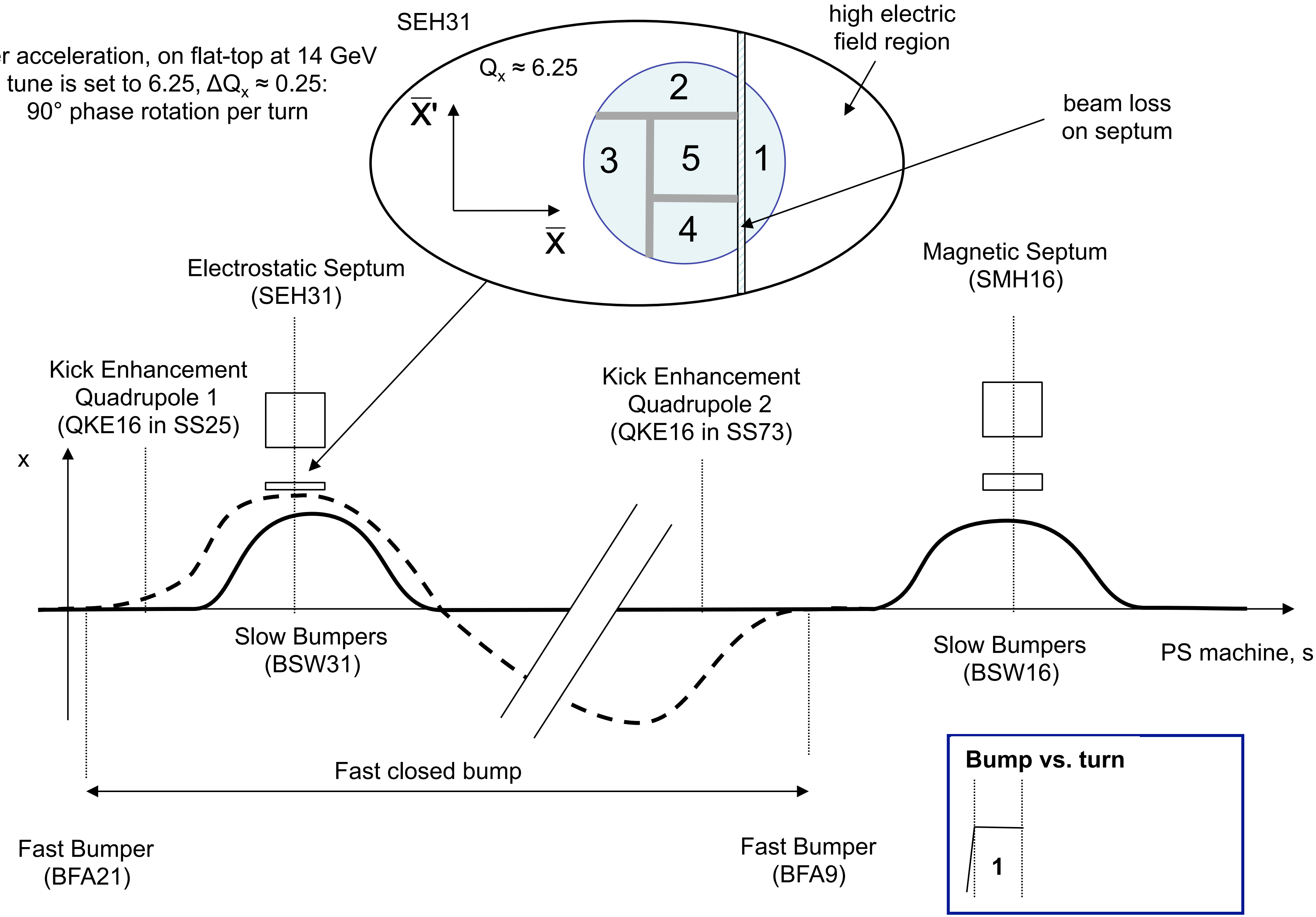

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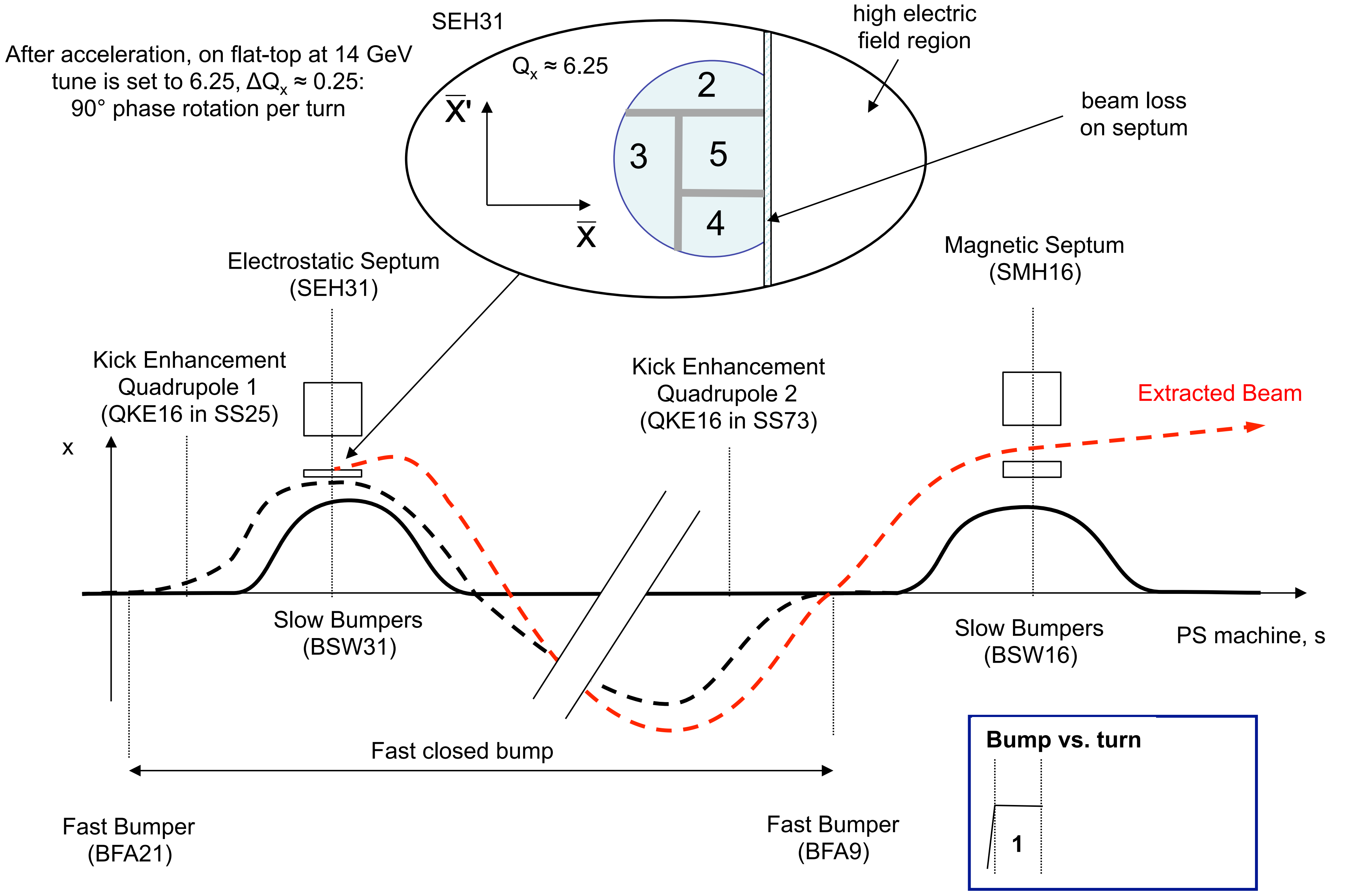

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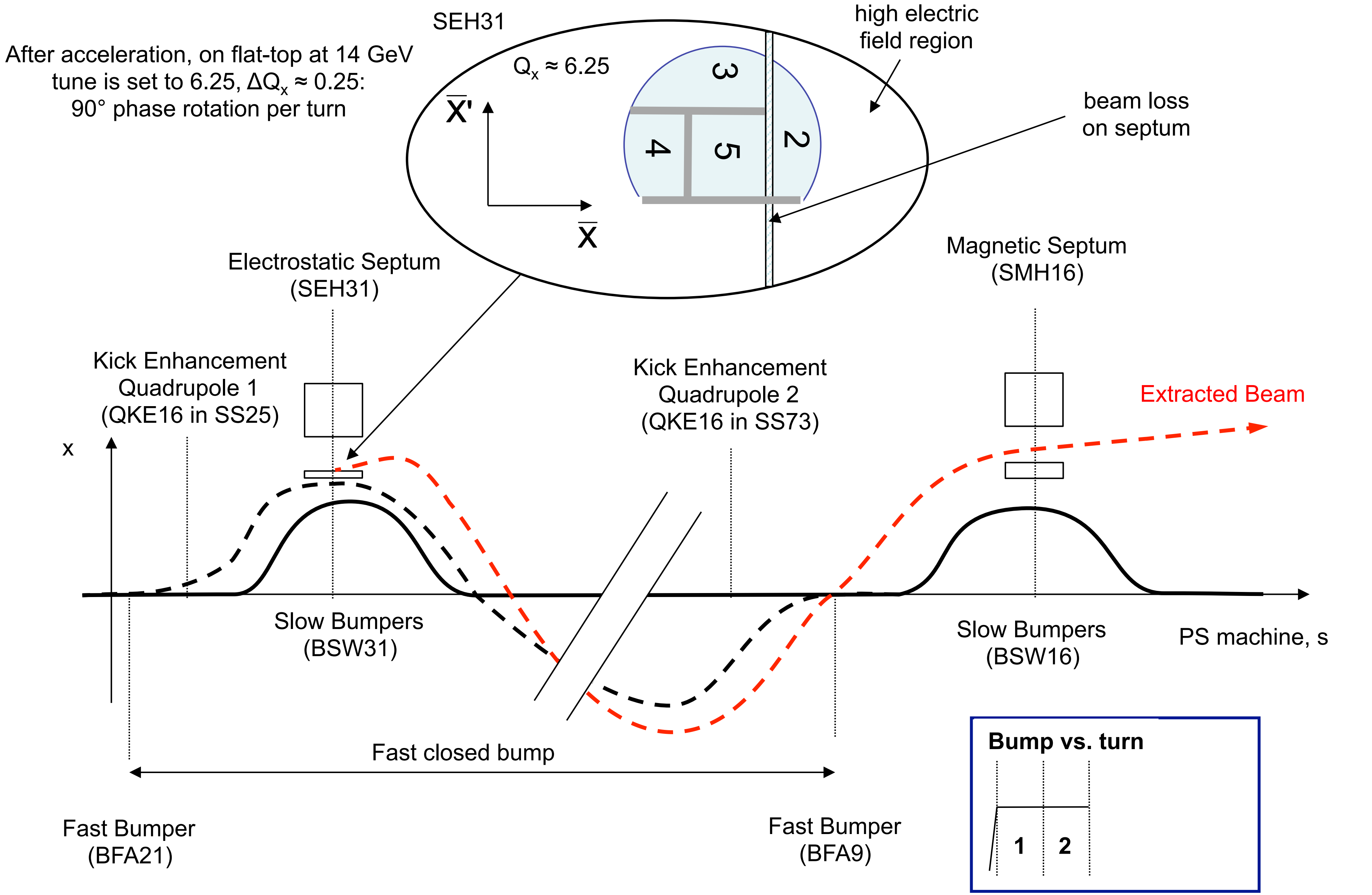

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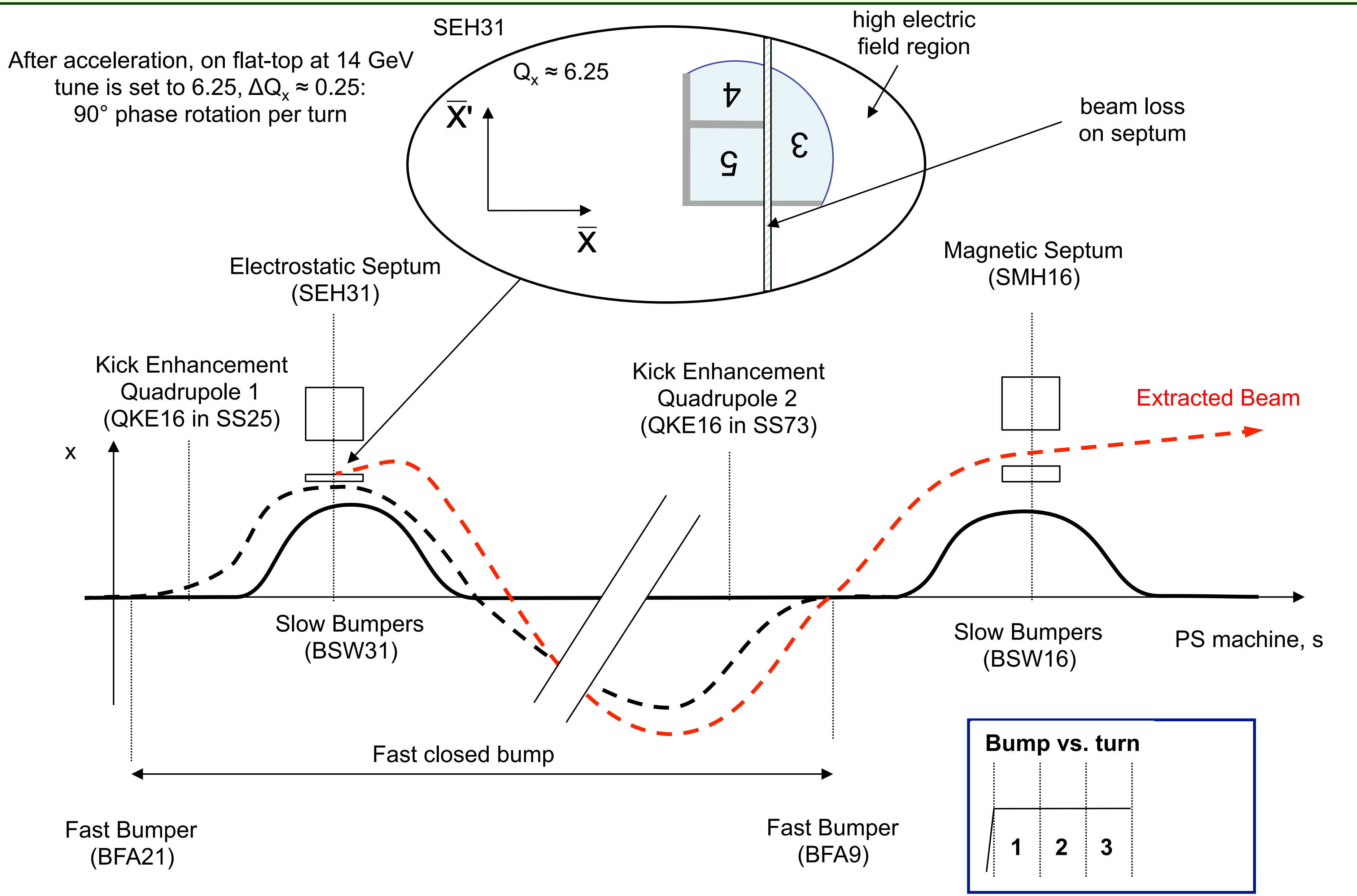

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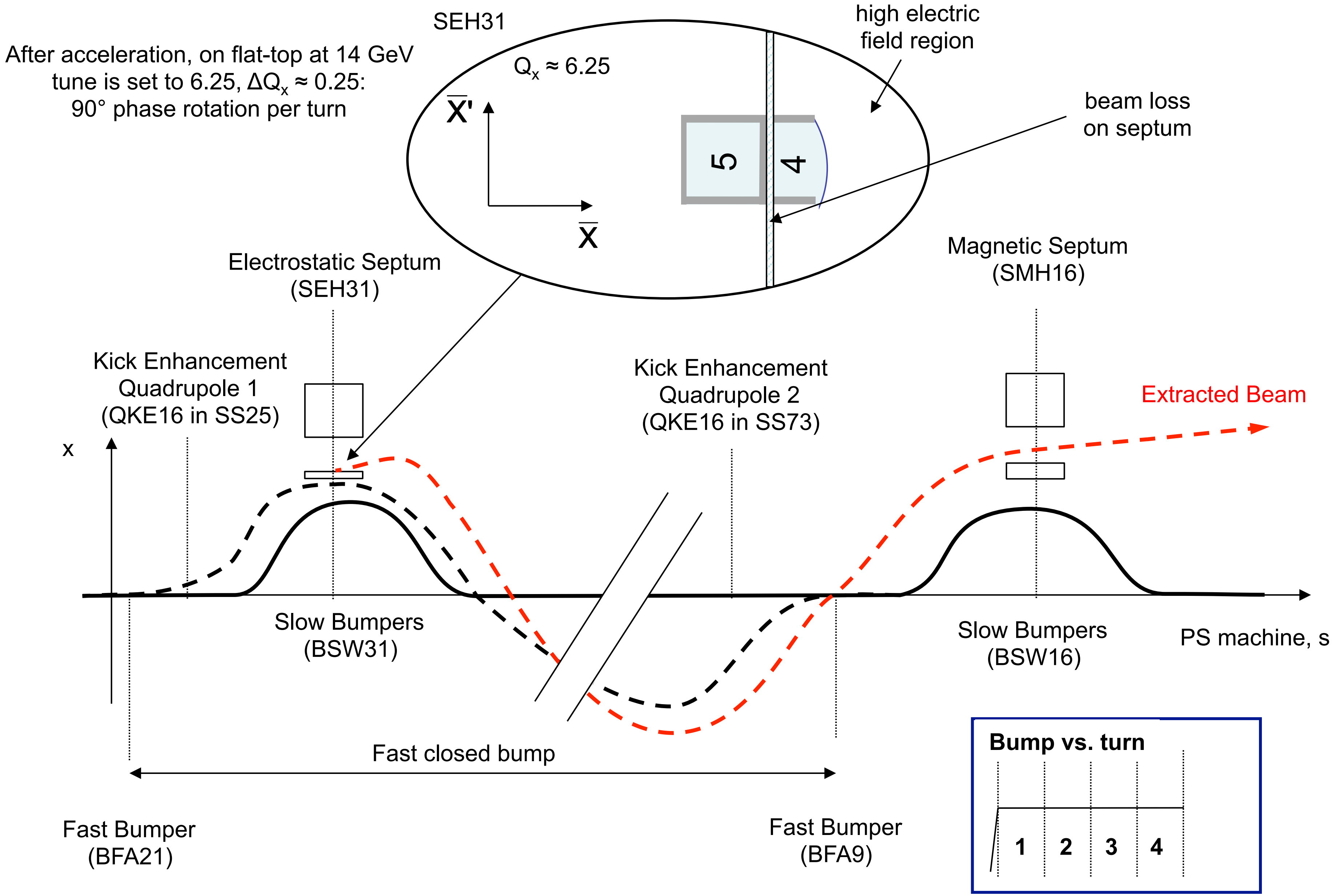

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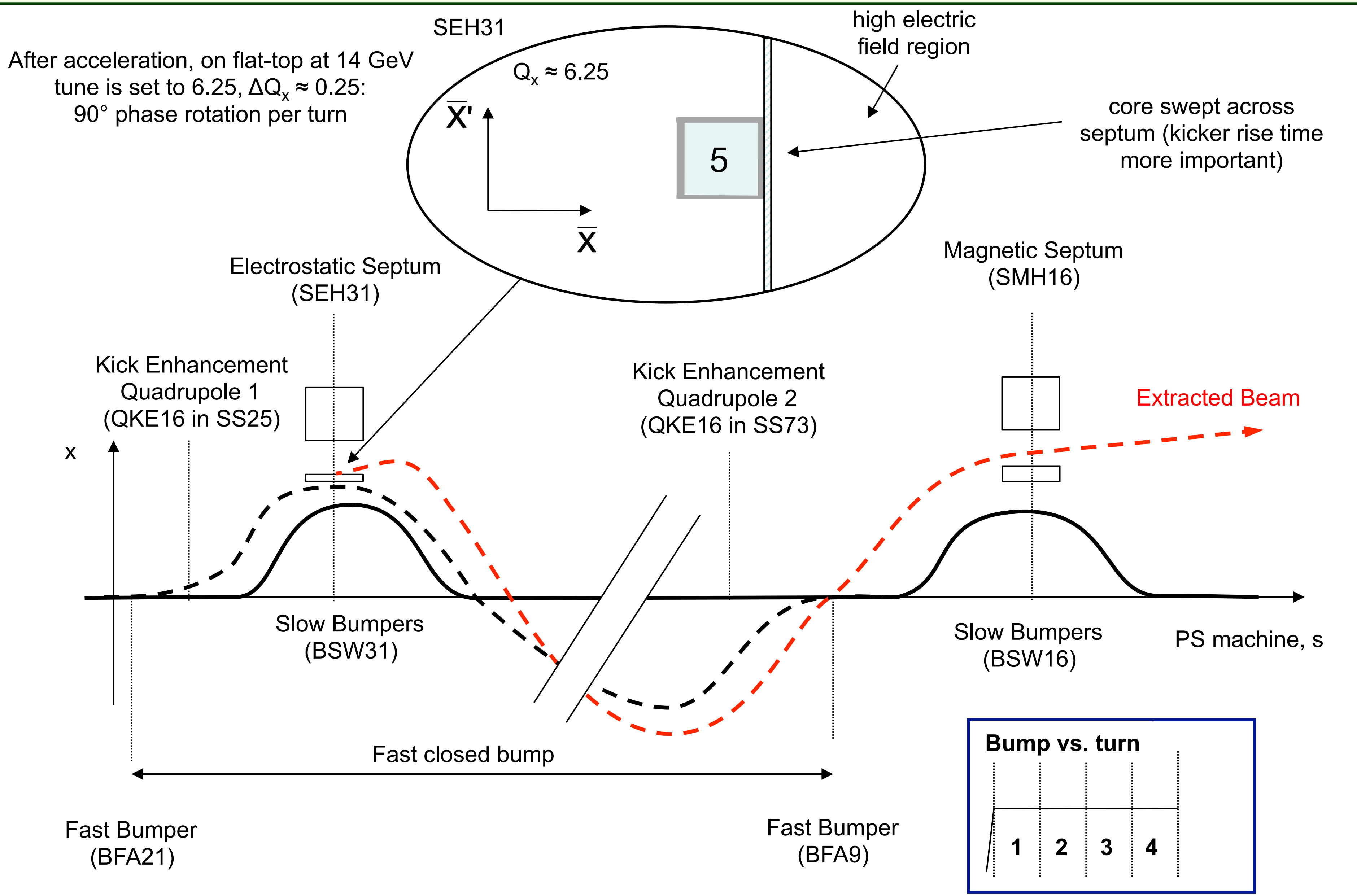

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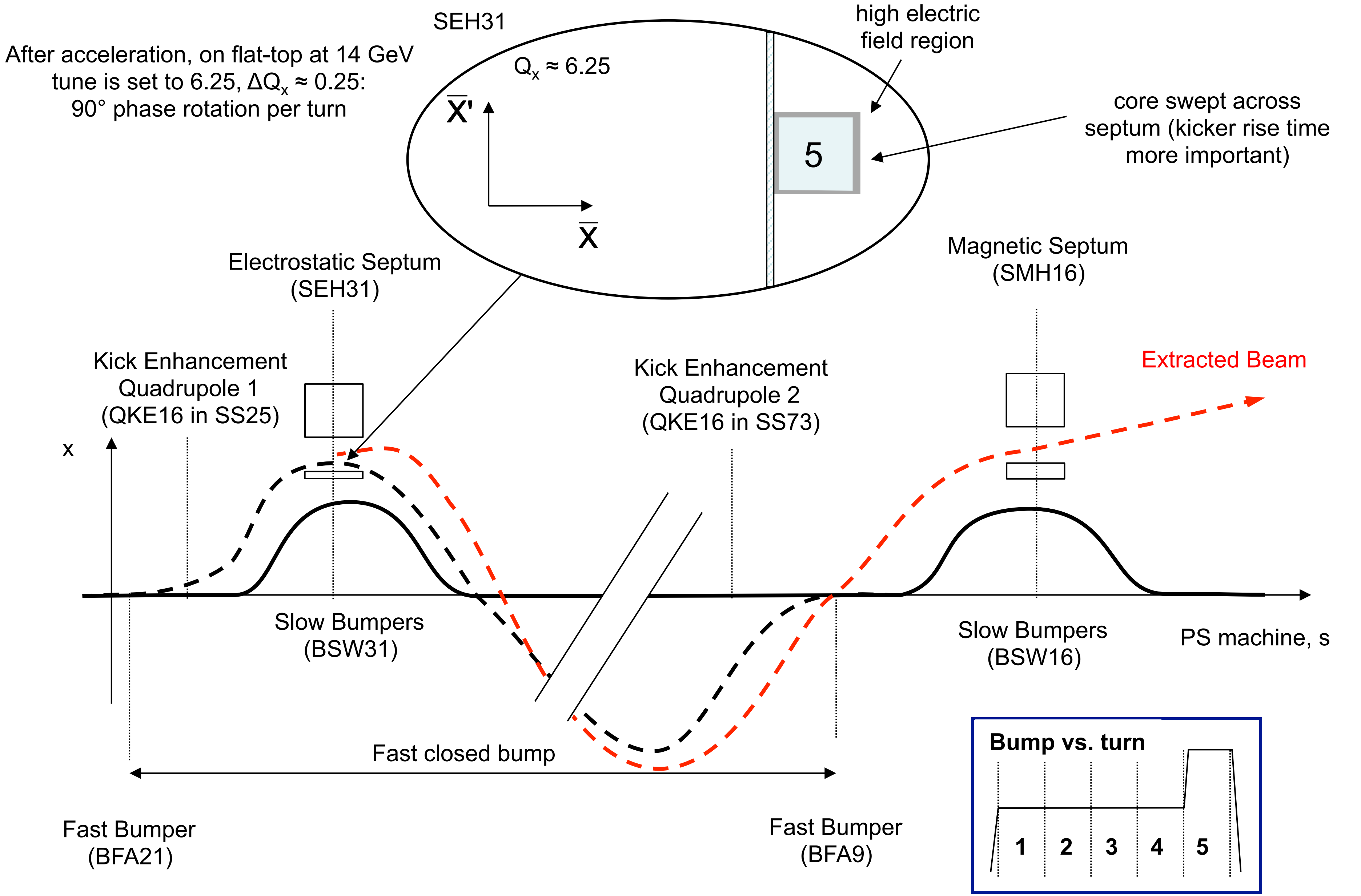

CT: performance aspects

- CT results in a **smaller emittance** in the plane that is "sliced":
  - exploited to overcome the vertical aperture limitation in the SPS
  - horizontal and vertical emittances are exchanged in the transfer line:
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  - electrostatic septum is irradiated making **hands-on maintenance** difficult
  - potential **limit for total intensity** throughput:
    - ≈ 40% of the all losses along the accelerator chain for the SPS FT physics programme occur at the PS electrostatic septum
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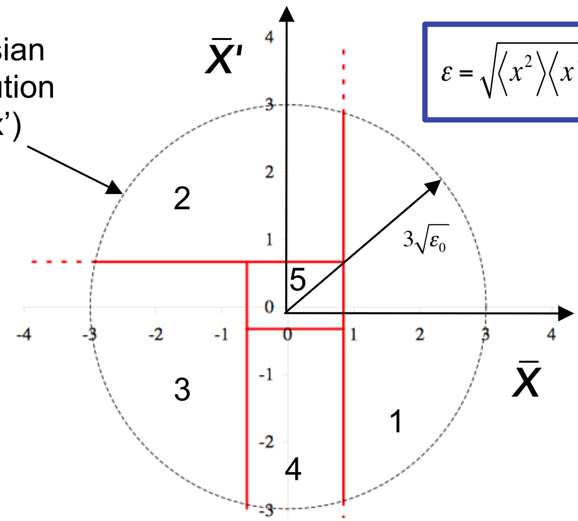
- Turn-by-turn **mismatch** causes emittance growth in receiving machine:
  - each slice has a **different emittance** and **optical parameters**
  - each slice has a **different centroid** and **trajectory error**
  - spills with **both uniform intensity** and **emittance are not possible**

CT: constant intensity vs. emittance

- The fast closed bump can be adjusted turn-by-turn giving 4 free parameters when slicing:

Constant **intensity** per slice = $I_0/5$

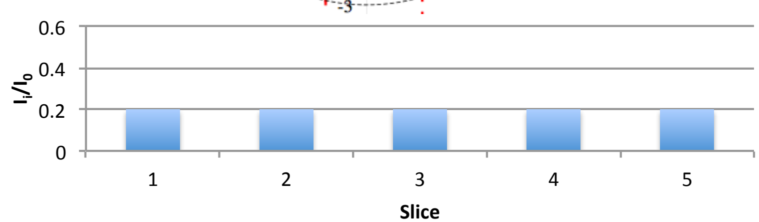
Gaussian distribution ρ(x,x')



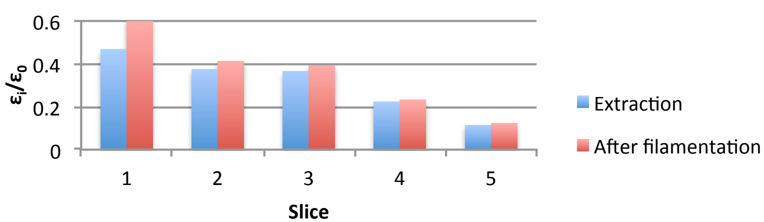
$$\varepsilon = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

[ref 10]

Intensity:



Emittance, (filamentation in SPS due to betatron mismatch):



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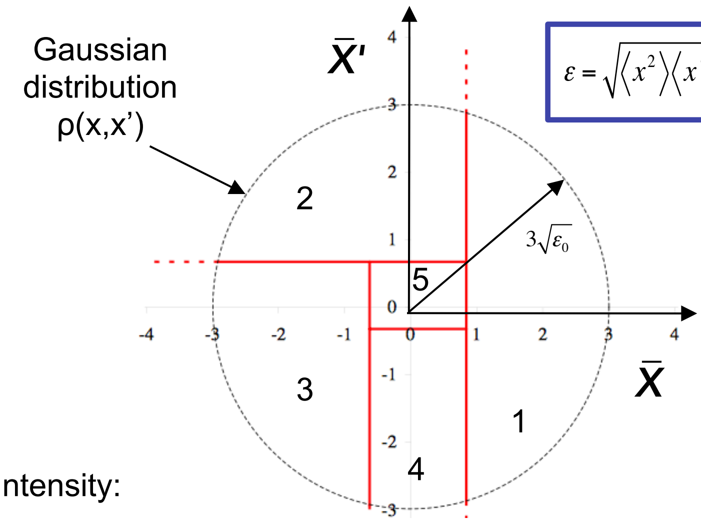

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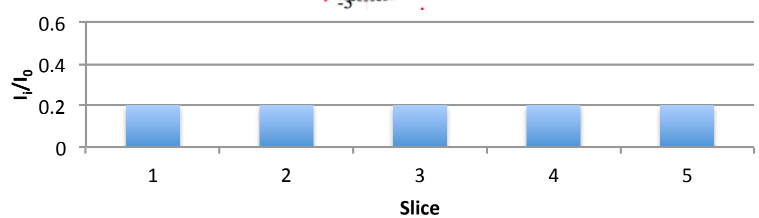

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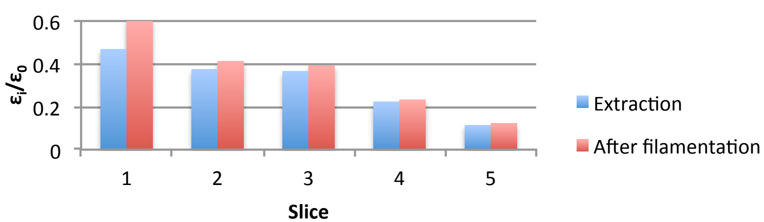
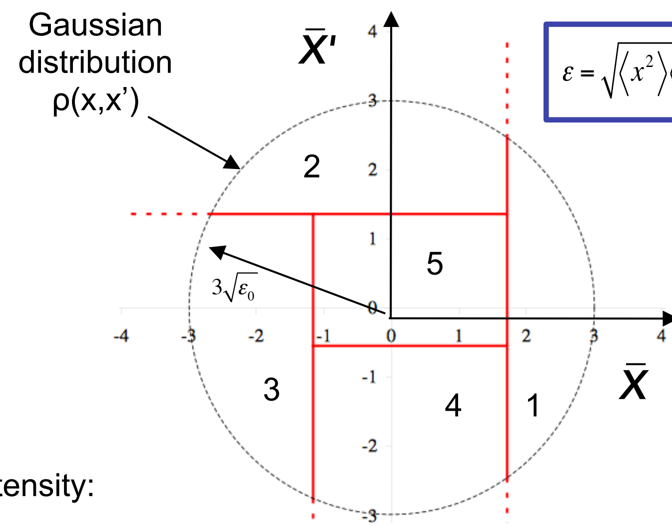


Constant **emittance** per slice = $\varepsilon_0/2.75 \neq \varepsilon_0/5$

$$\varepsilon = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$



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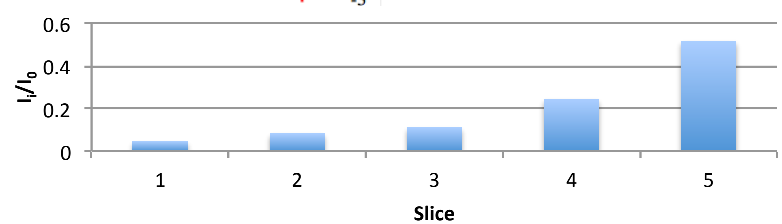

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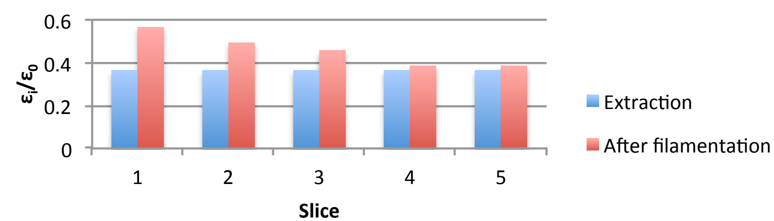
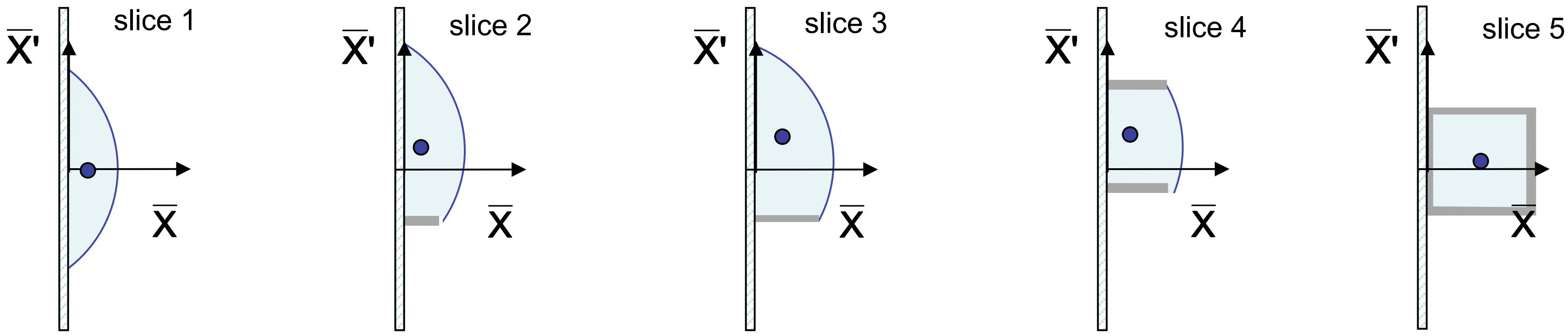


CT: turn-by-turn trajectory variation

- Turn-by-turn variation in the extracted beam centroid:



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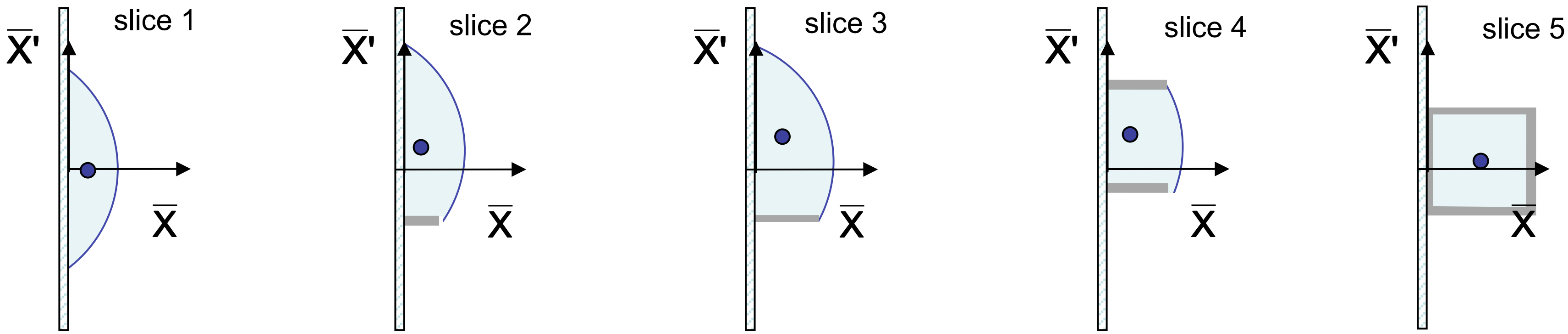
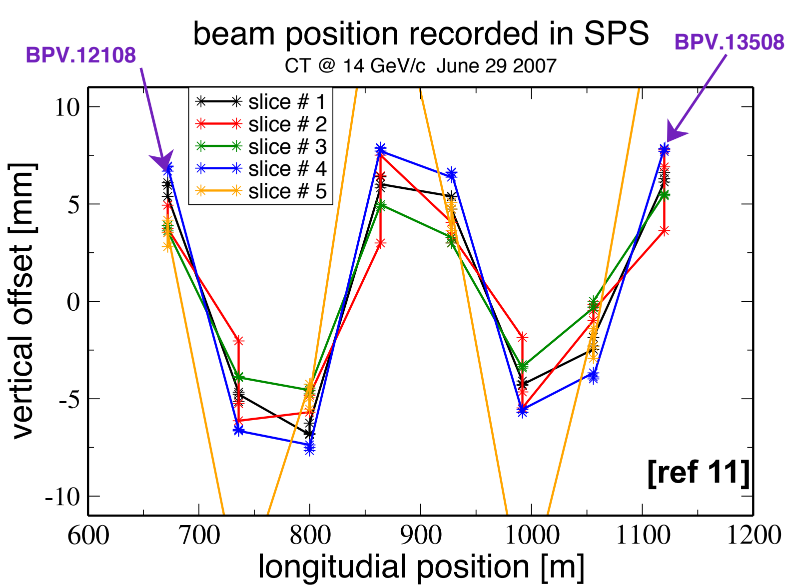


Before correction trajectory:



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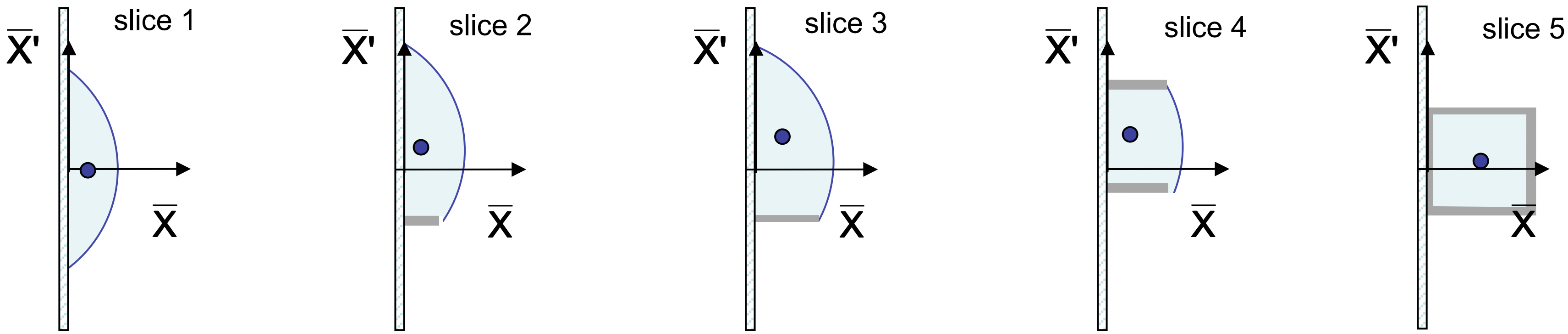

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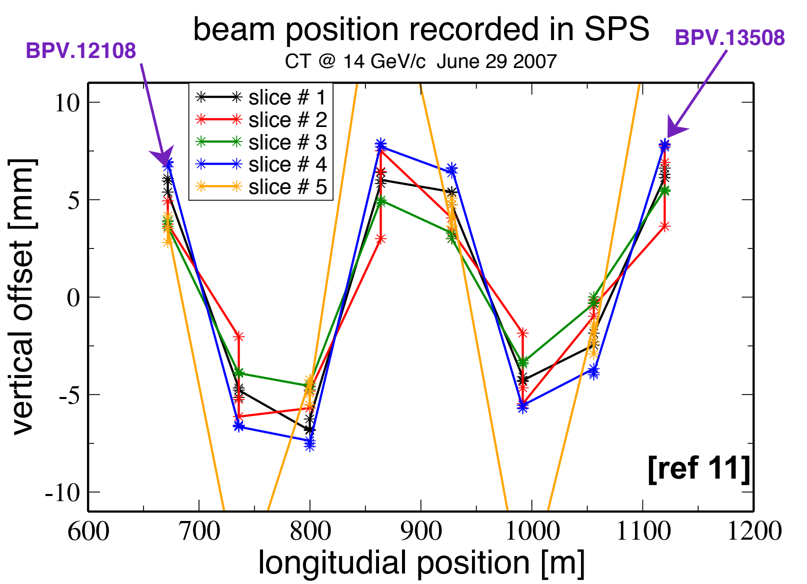
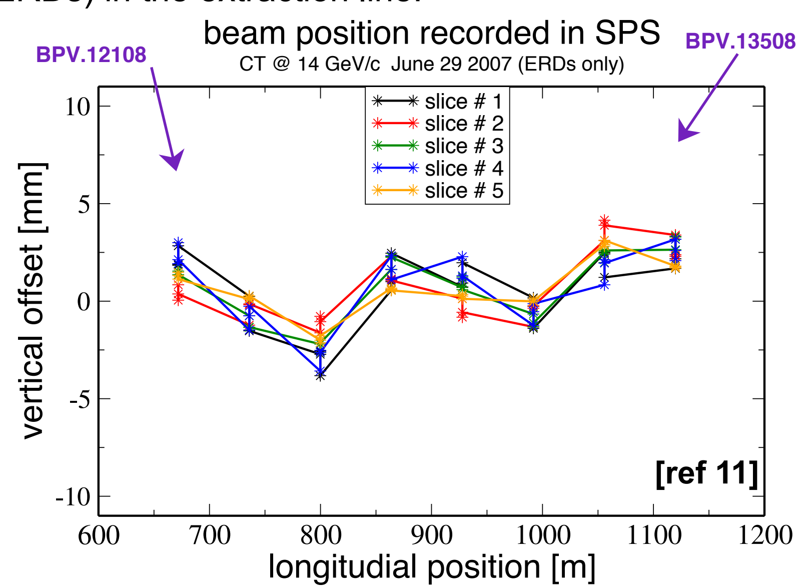


After turn-by-turn correction with 2 fast-pulsed kickers (ERDs) in the extraction line:



CT: losses

- Typically ~ 6% of the beam is lost around the ring during extraction, depending on how well the extraction has been optimised:

Magnetic splitting: motivation

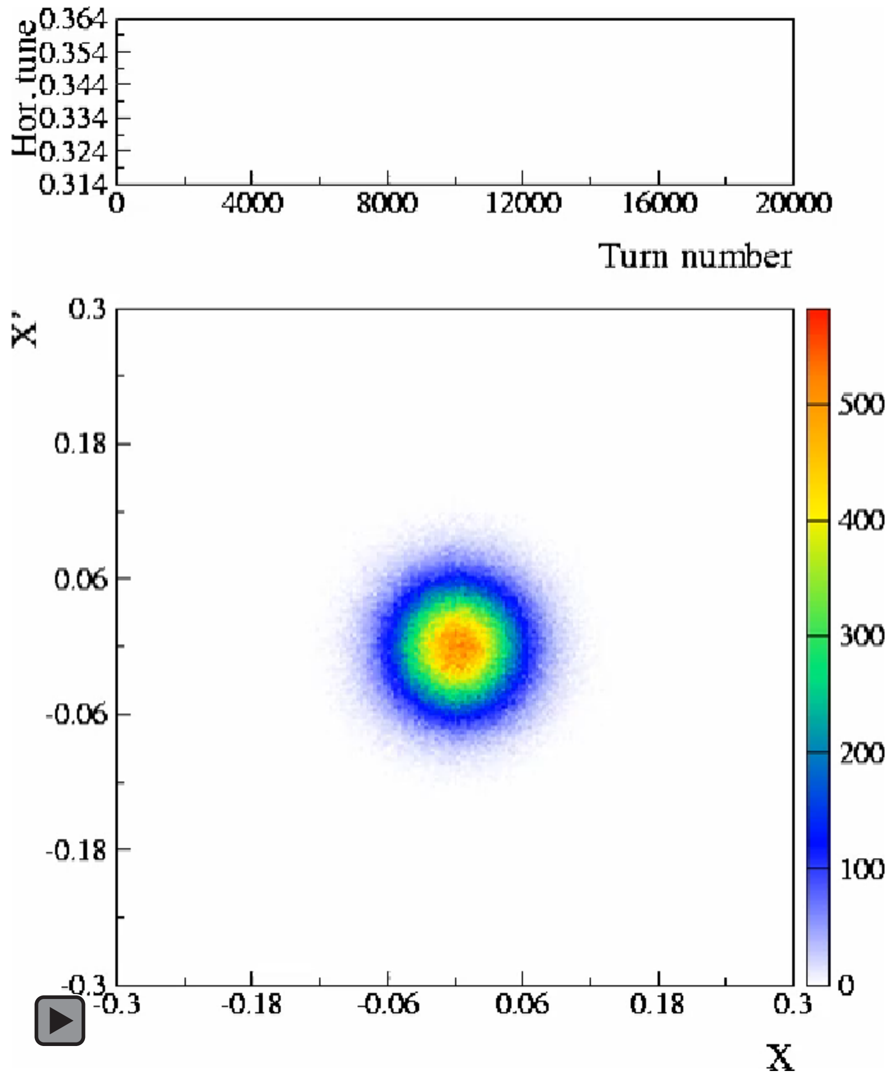
- Aim to do away with mechanical splitting, with several advantages:
  - Losses reduced significantly (no need for an electrostatic septum)
    - attractive for higher energy applications
  - Phase space matching improved with respect to CT
    - ‘beamlets’ have same emittance and optical parameters at extraction

Magnetic splitting

[ref 13]

- **Non-linear fields** can be used to split a beam in phase space:
  - **Sextupoles** and **octupoles** can be used to create **islands of stability** inside the circulating beam
  - A slow (adiabatic) tune variation across a resonance can **capture** particles into **separate islands**
  - Variation of the **tune** moves the islands to large amplitudes
- Pioneered over the last 25 years at CERN:
  - for further reading a **list of references** is found at the end of the talk **[ref 20-25]**
  - see appendix for measurement results carried out in the PS!

An example of splitting a beam into three stable islands $\Delta Q_x \approx 0.33$



Non-linear beam dynamics (1)

- A vast subject (out of the scope of this lecture!) to solve the non-linear equation of motion (a driven simple harmonic oscillator):

$$\frac{d^2\overline{X}}{d\phi^2} + Q^2\overline{X} = -Q^2\beta^{3/2}\overbrace{\frac{\Delta B(\overline{X},\phi)}{(B\rho)}}^{\text{perturbing fields}}$$

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$$= -\frac{Q^2 B_0}{(B\rho)}\Big[\underbrace{\underbrace{(\beta^{3/2}b_0) + (\beta^{4/2}b_1)\bar{X}}_{\text{linear imperfections: integer and 1/2-integer}} + \underbrace{(\beta^{5/2}b_2)\bar{X}^2 + (\beta^{6/2}b_3)\bar{X}^3}_{\text{non-linear imperfections: sextupole (1/3-integer) and octupole (1/4-integer)}} + \ldots}_{\ldots\text{these terms include harmonic functions of } \phi\text{, driving resonances}}\Big]$$

- Many mathematical tools exist to help understand such dynamics:
  - the Hamiltonian
  - Taylor maps and Lie transformations
  - Perturbation theory, normal form analysis, etc.
- However, nowadays we can "cheat" and solve the equation of motion by integrating it numerically to gain insight:
  - one turn map + non-linear thin lens kick (sextupole and/or octupole)

Non-linear beam dynamics (2)

- We can learn a lot by tracking a few particles over a few 100 turns:

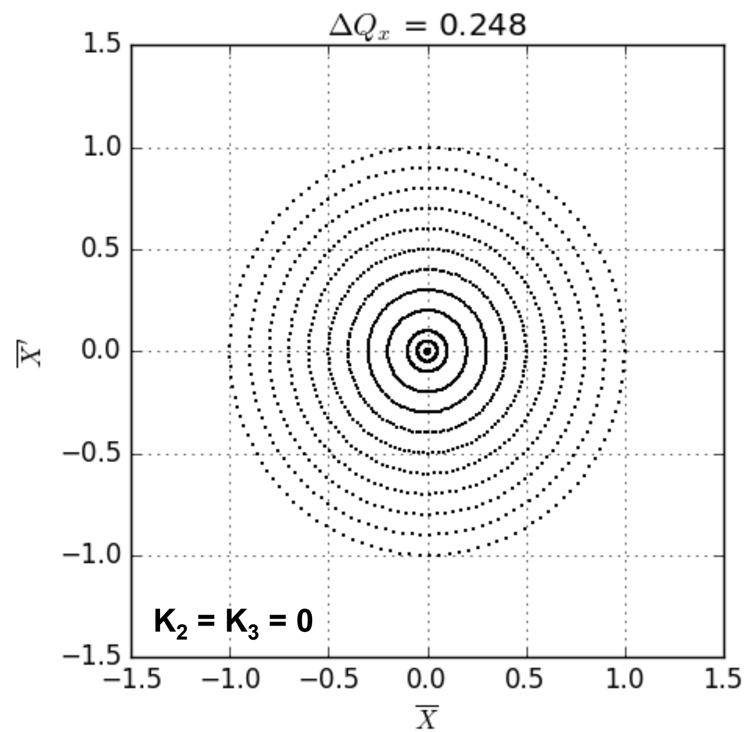
one-turn map, function of the machine tune

thin lens approximation of a sextupole and octupole at the same location in the ring

$$\begin{pmatrix} \bar{X} \\ \bar{X}' \end{pmatrix}_{n+1} = R(2\pi Q)\begin{pmatrix} \bar{X} \\ \bar{X}' + K_2\bar{X}^2 + K_3\bar{X}^3 \end{pmatrix}_n$$

…a Hénon map

- Example:
  - Crossing **1/4 - integer resonance**
    - i.e. Q_x = integer + 0.25
  - **Sextupole OFF and octupole OFF:**
    - $\mathbf{K_2 = K_3 = 0}$
  - Ramping tune from below resonance:
    - ΔQ_x = 0.248 to 0.252
  - 12 particles, 1000 turns



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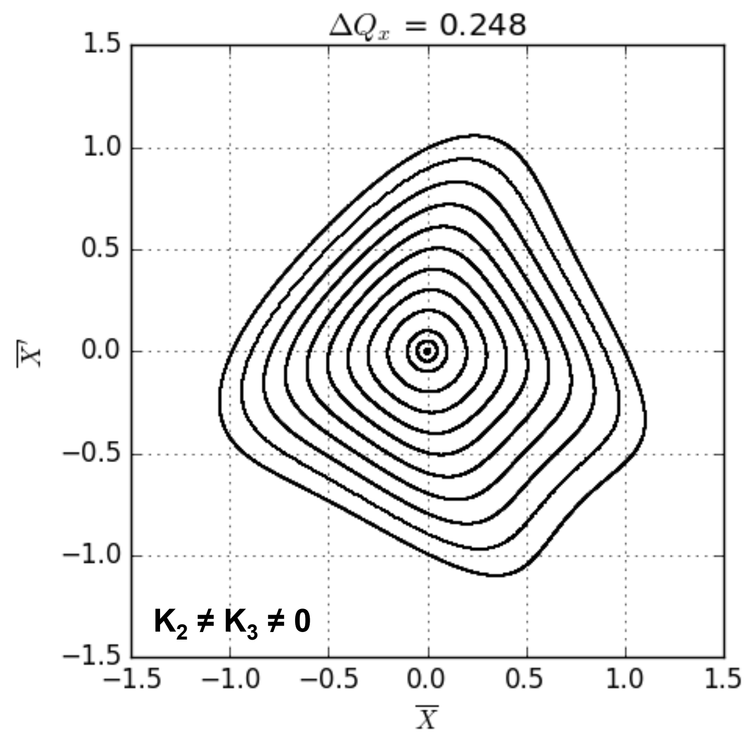

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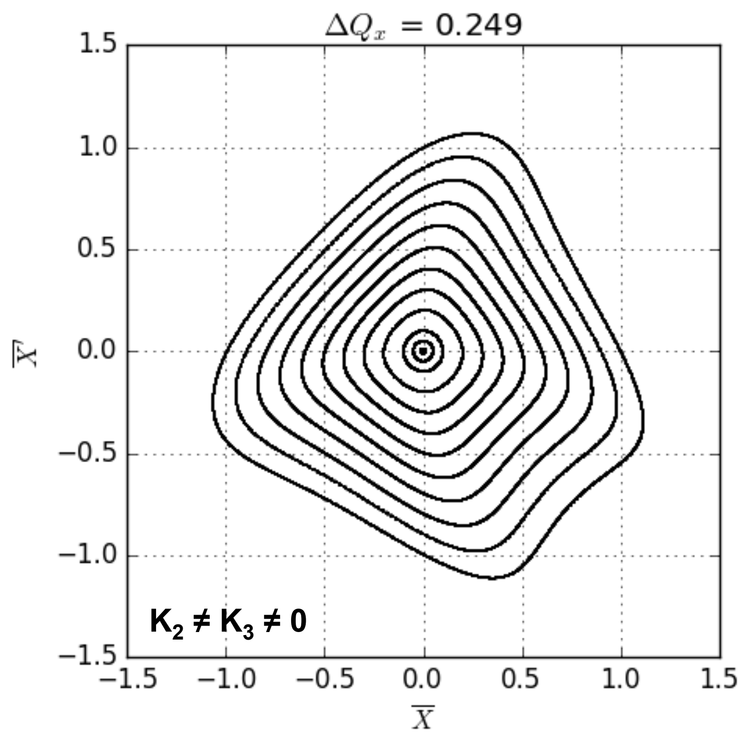

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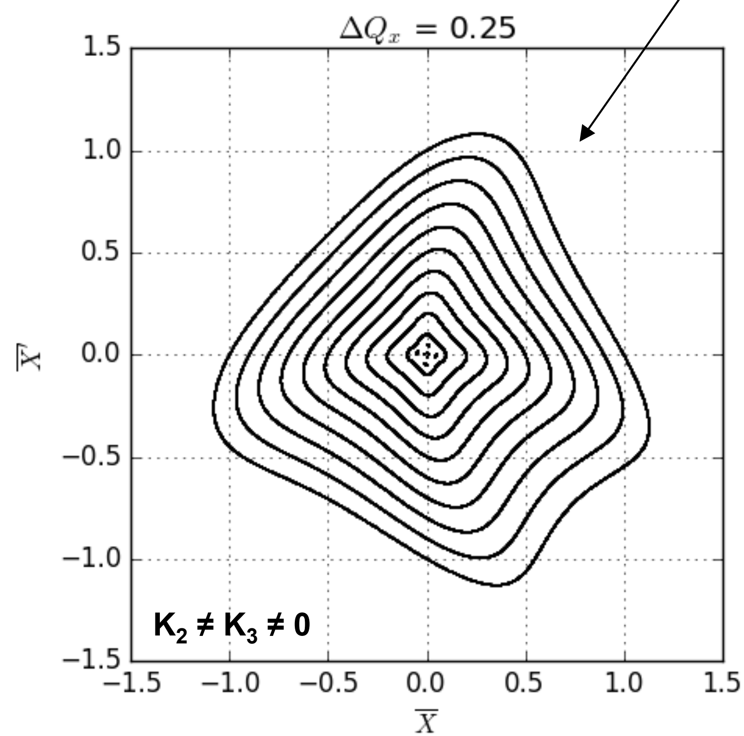
Ratio of K_2/K_3 can be used to tailor the phase space and size of the islands

- Example:
  - Crossing **1/4 - integer resonance**
    - i.e. Q_x = integer + 0.25
  - **Sextupole ON and octupole ON:**
    - $\mathbf{K_2 \neq K_3 \neq 0}$
  - Ramping tune from below resonance:
    - ΔQ_x = 0.248 to 0.252
  - 12 particles, 1000 turns



Non-linear beam dynamics (2)

- We can learn a lot by tracking a few particles over a few 100 turns:

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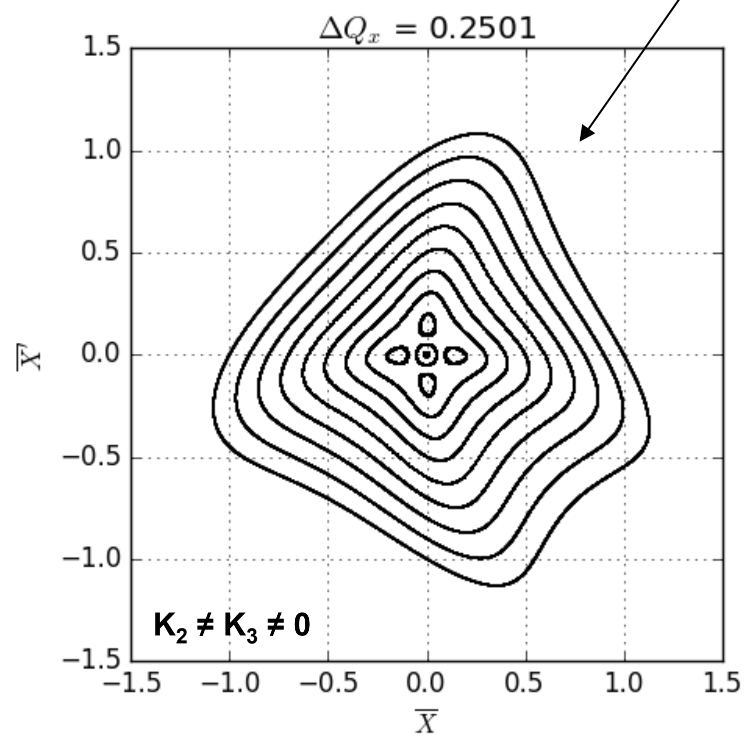

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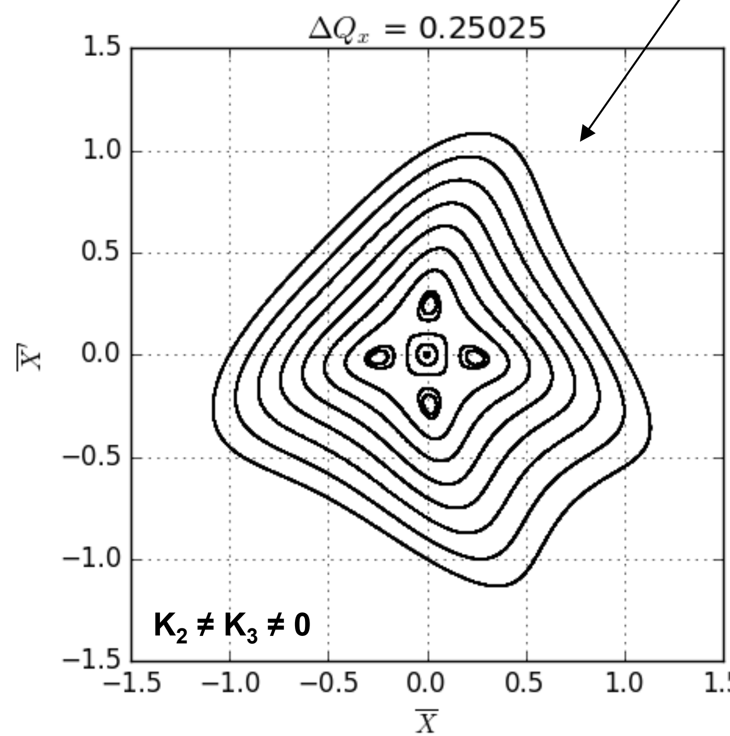

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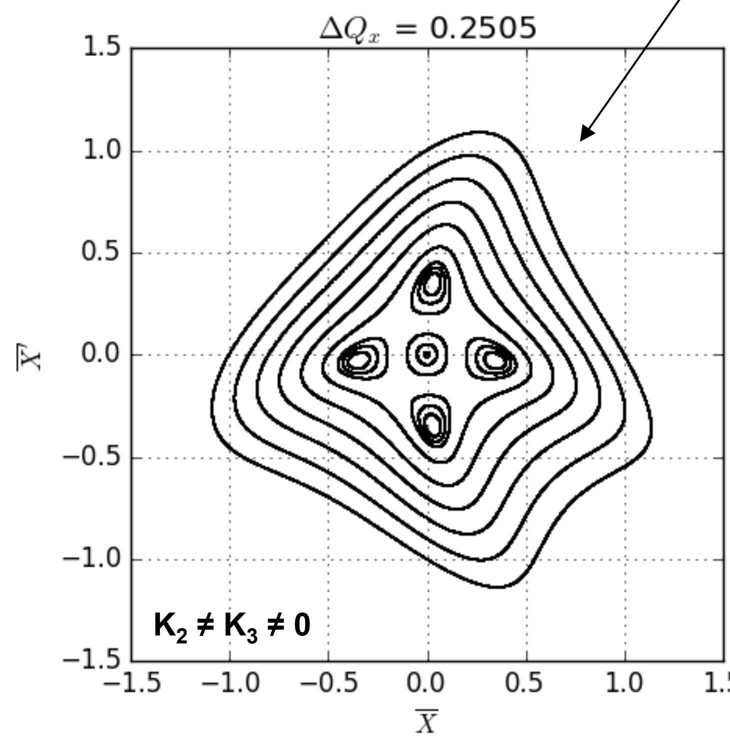

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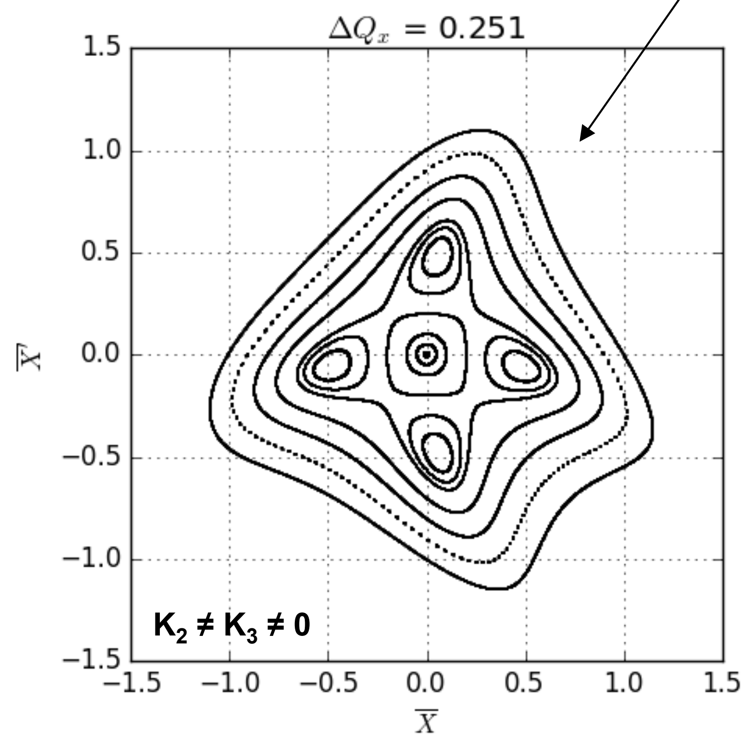

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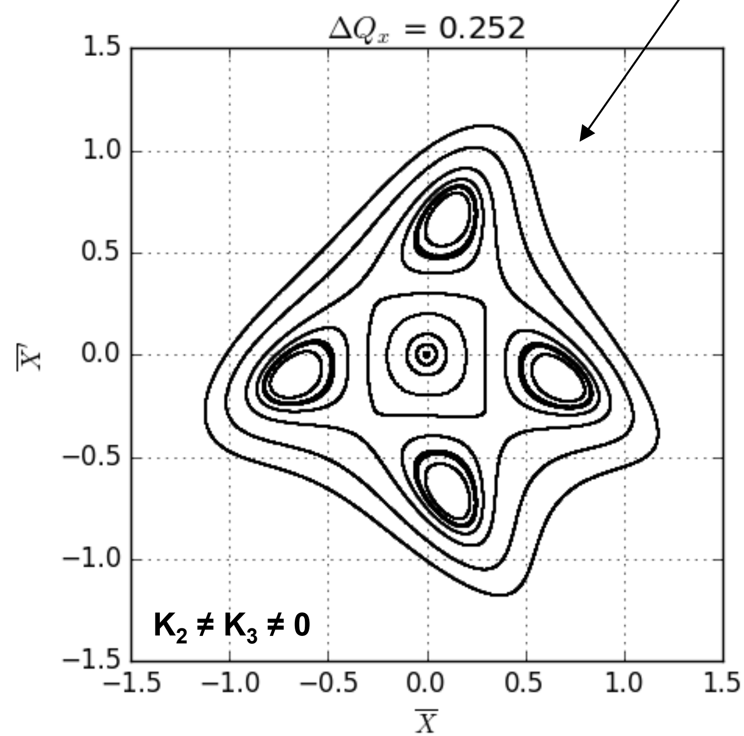
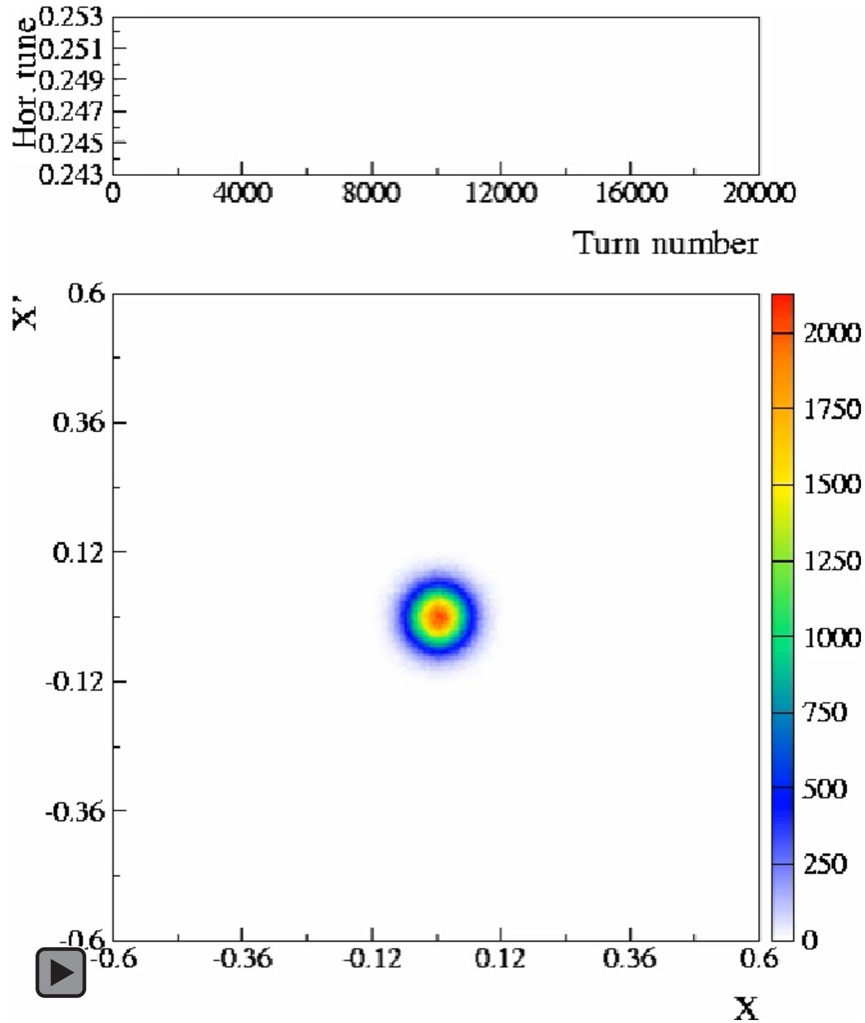


Multi-turn extraction suitable for the PS

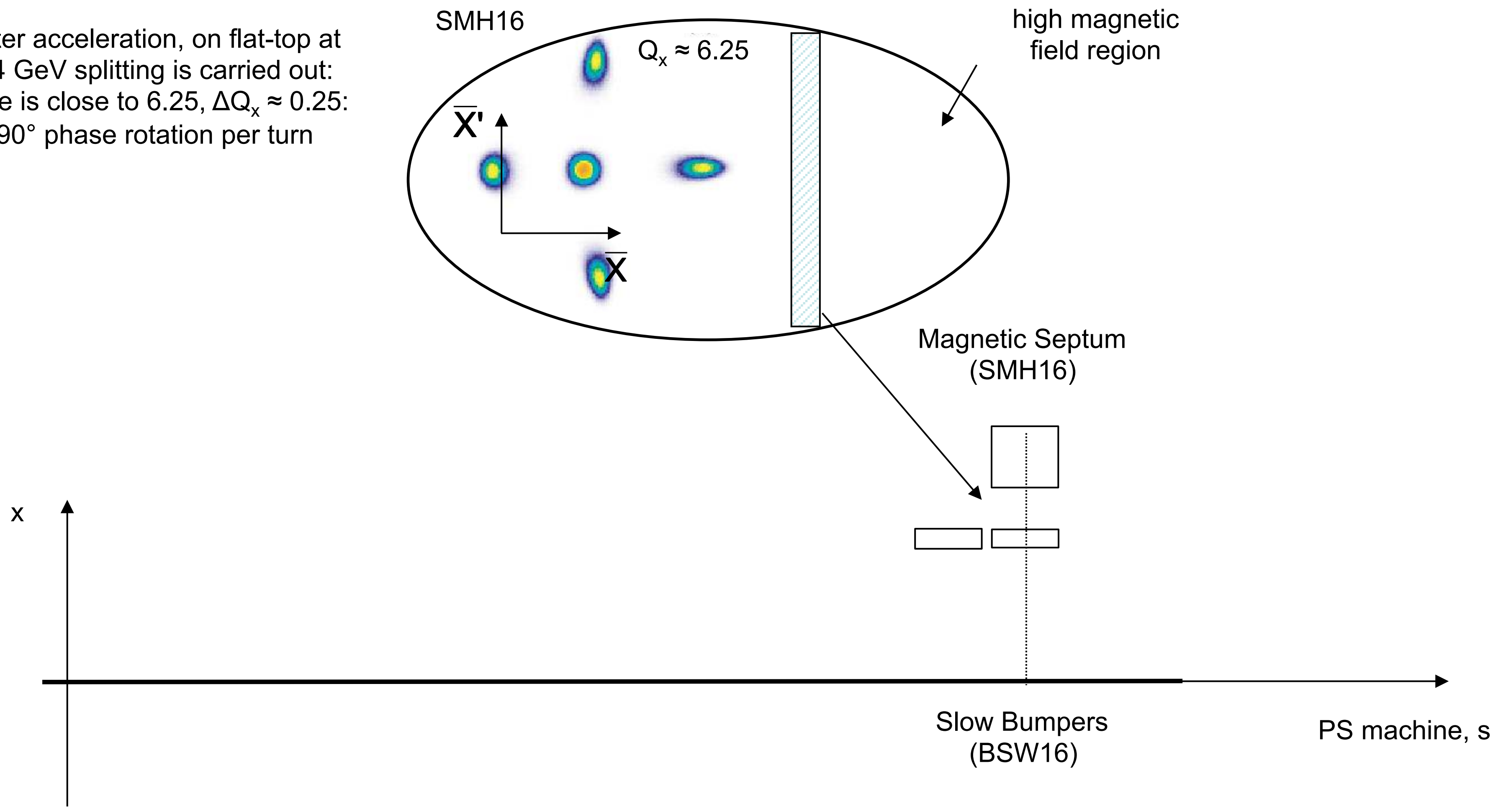
- For an n^{th} order stable resonance $n + 1$ islands will be created:
  - the 4^{th} order resonance works for the CERN PS scenario:



[ref 13]

MTE: operational implementation

After acceleration, on flat-top at 14 GeV splitting is carried out: tune is close to 6.25, $\Delta Q_x \approx 0.25$: 90° phase rotation per turn



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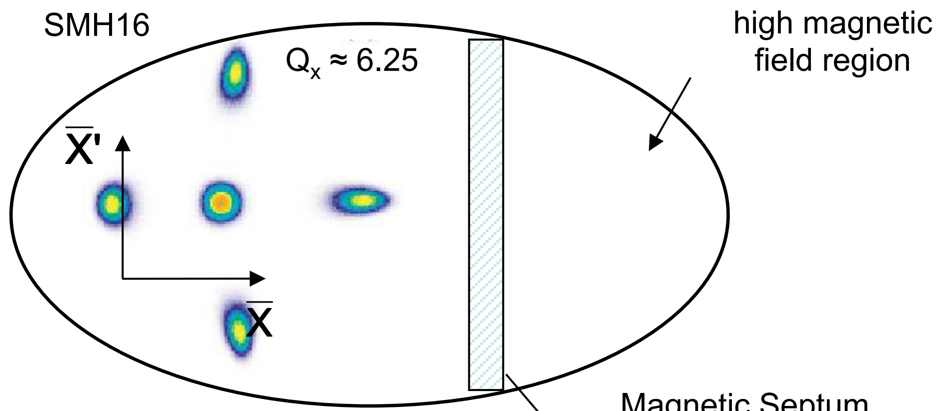
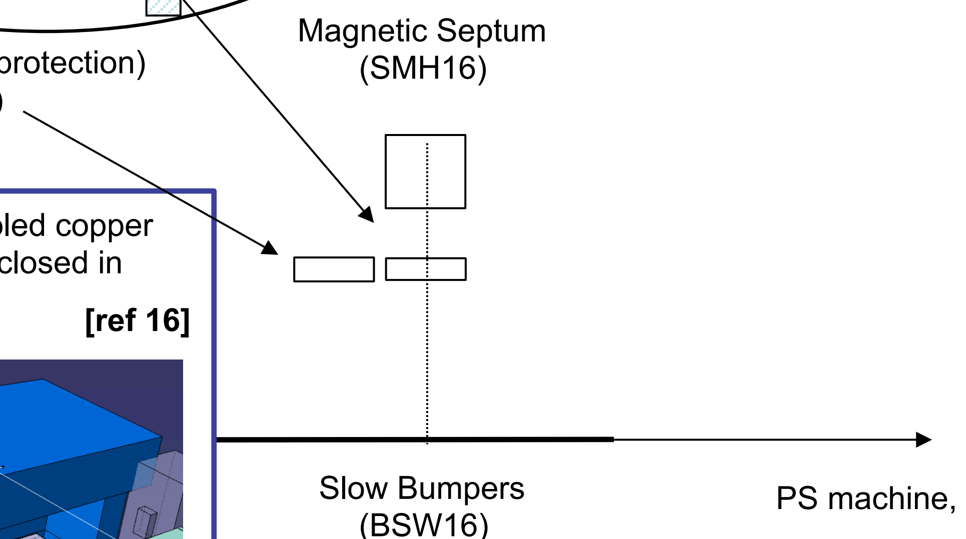
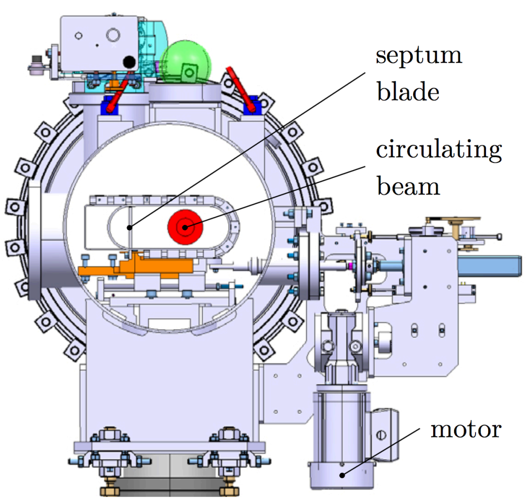
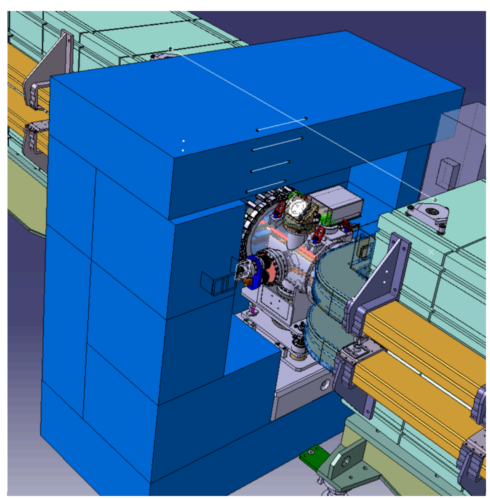




SPS requests de-bunched beam (no kicker gaps), so a cooled copper blade protecting downstream septum is required, and is enclosed in shielding:

[ref 16]





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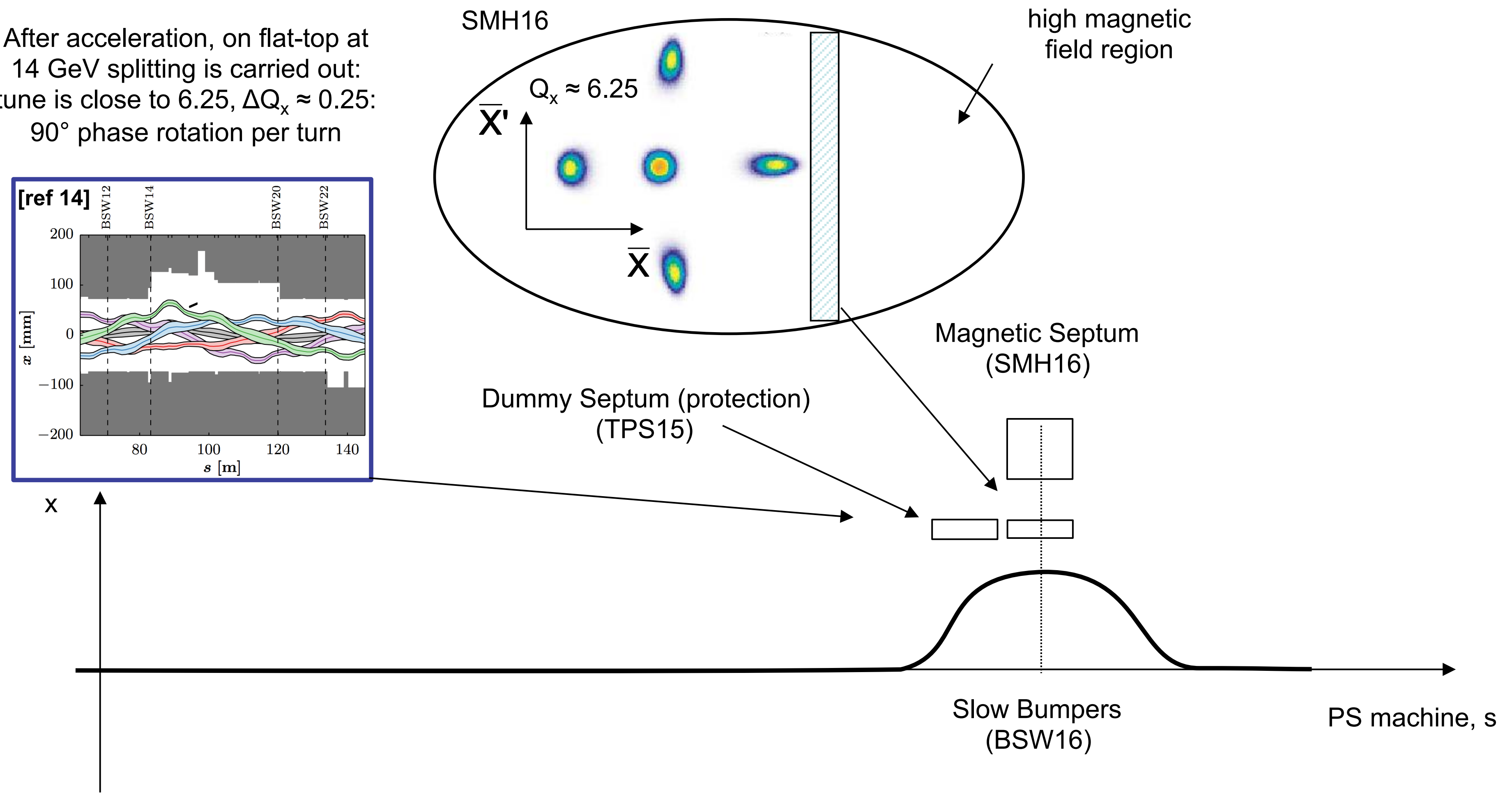

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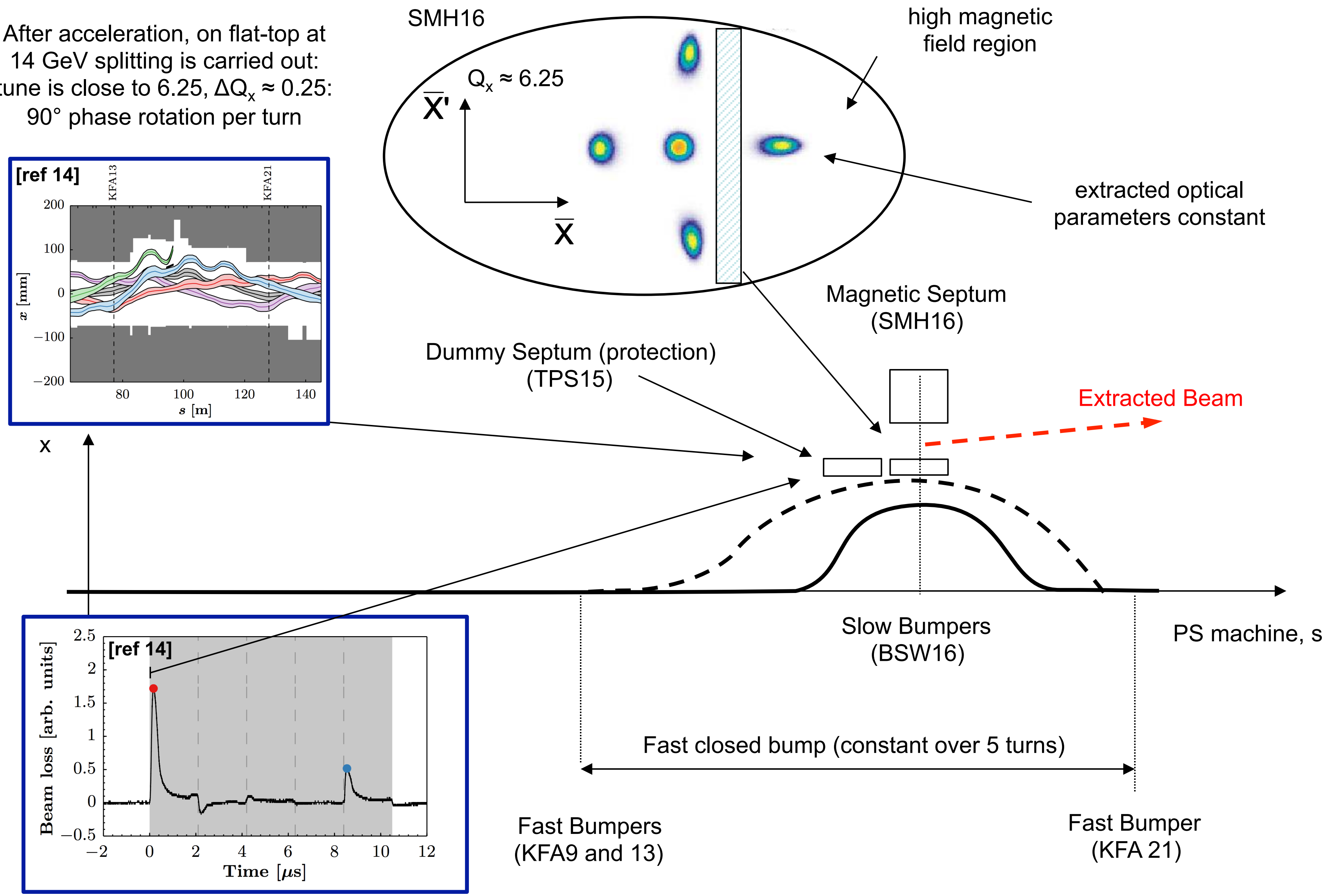

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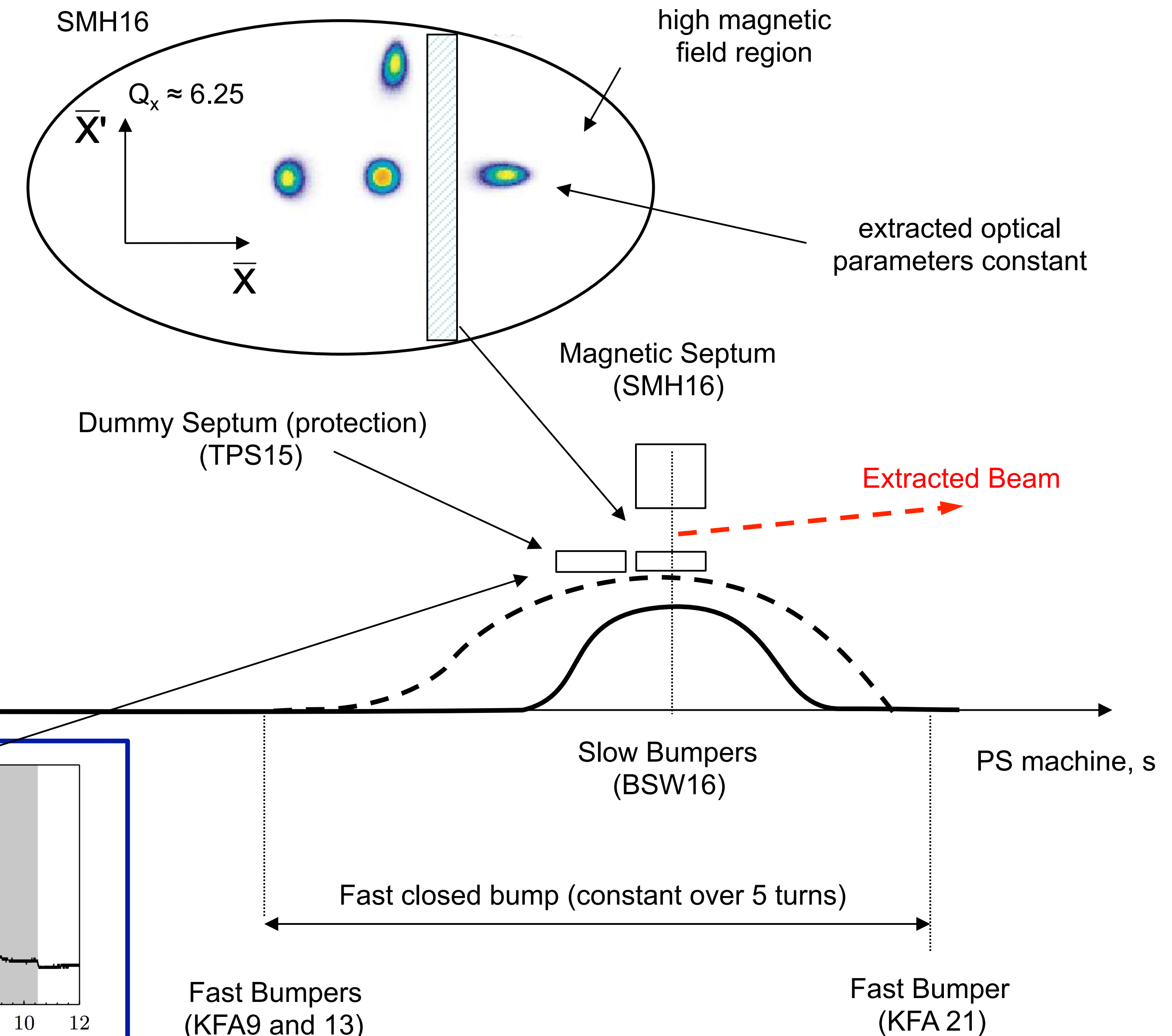

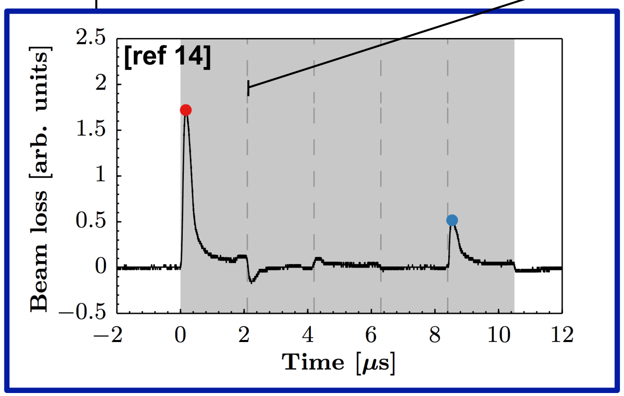

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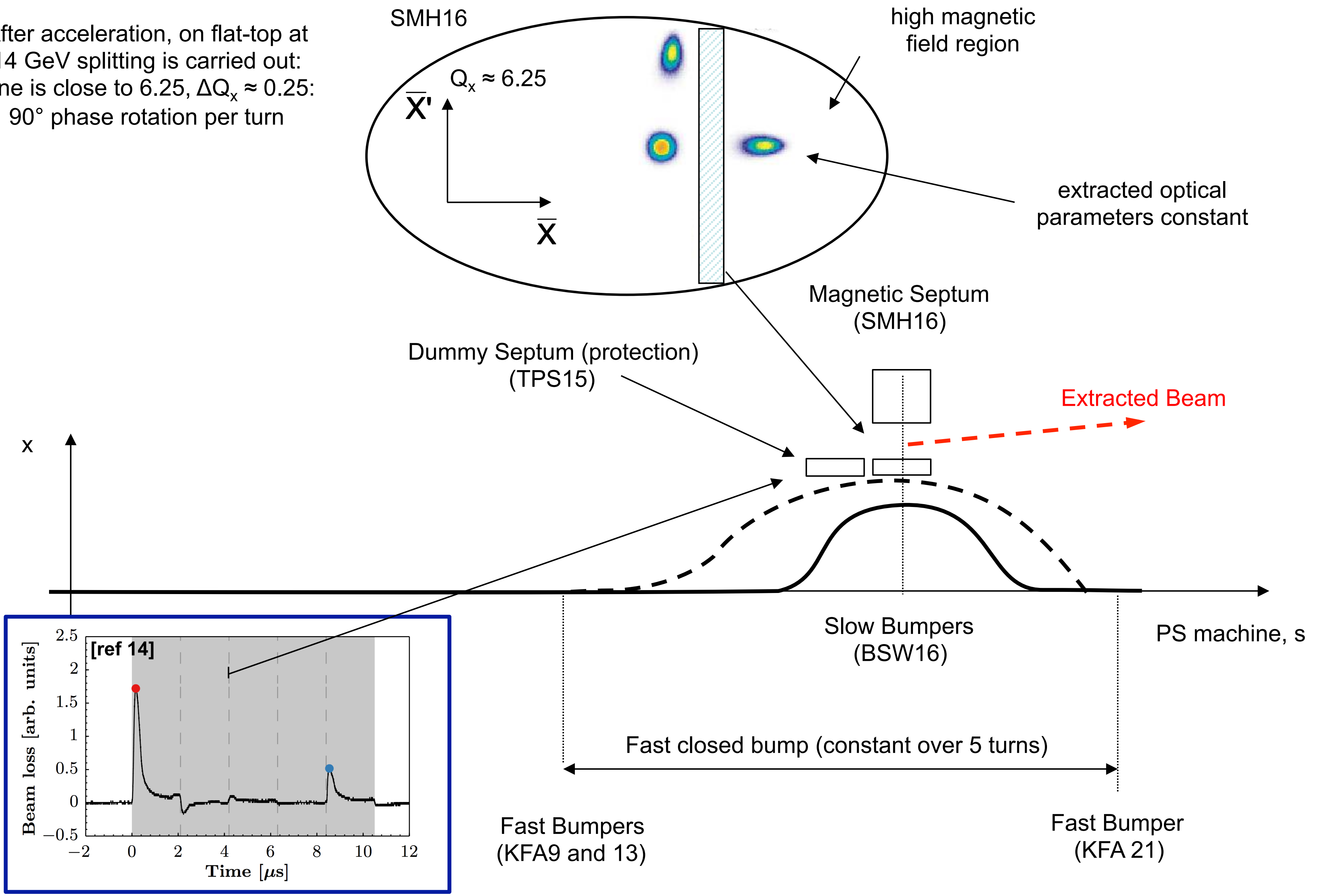

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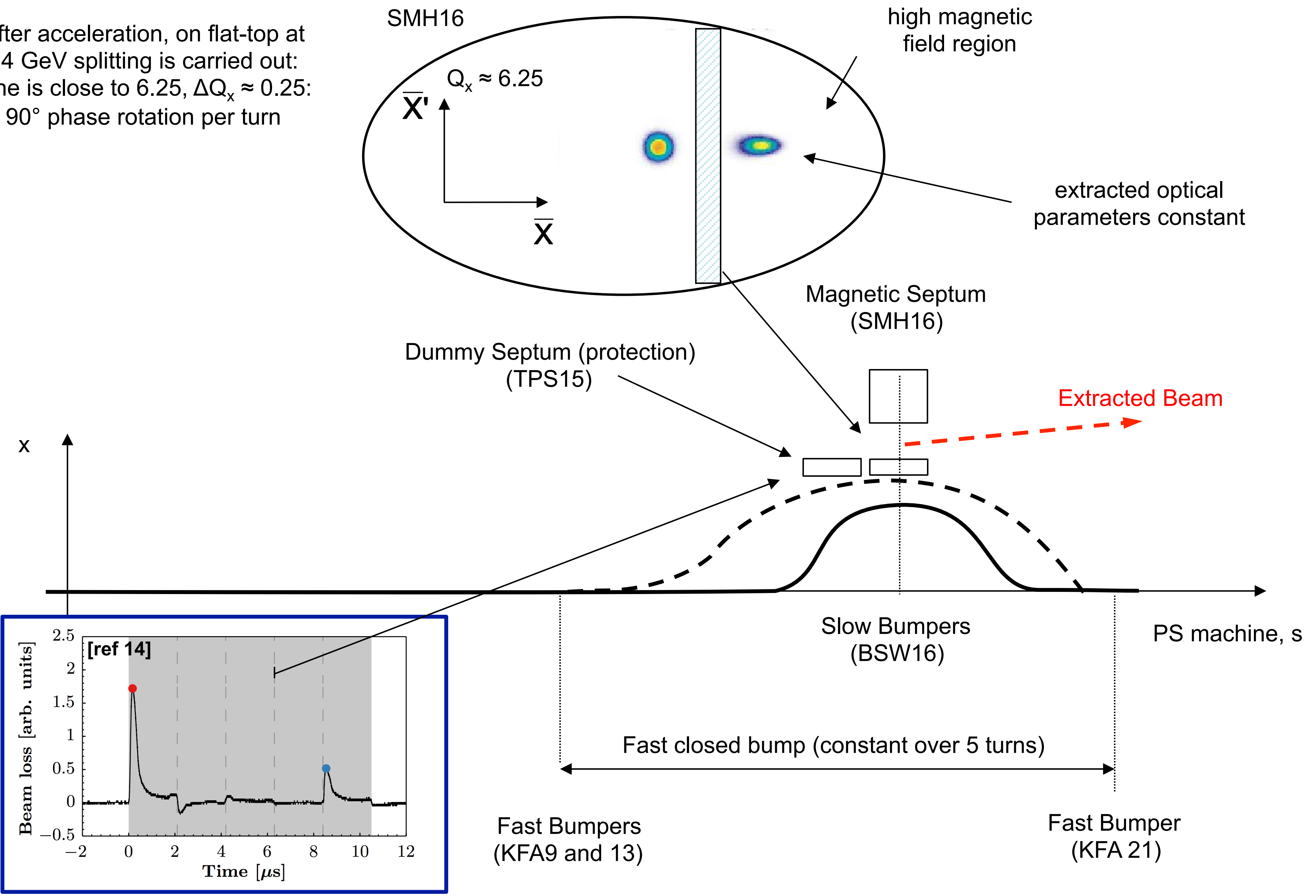

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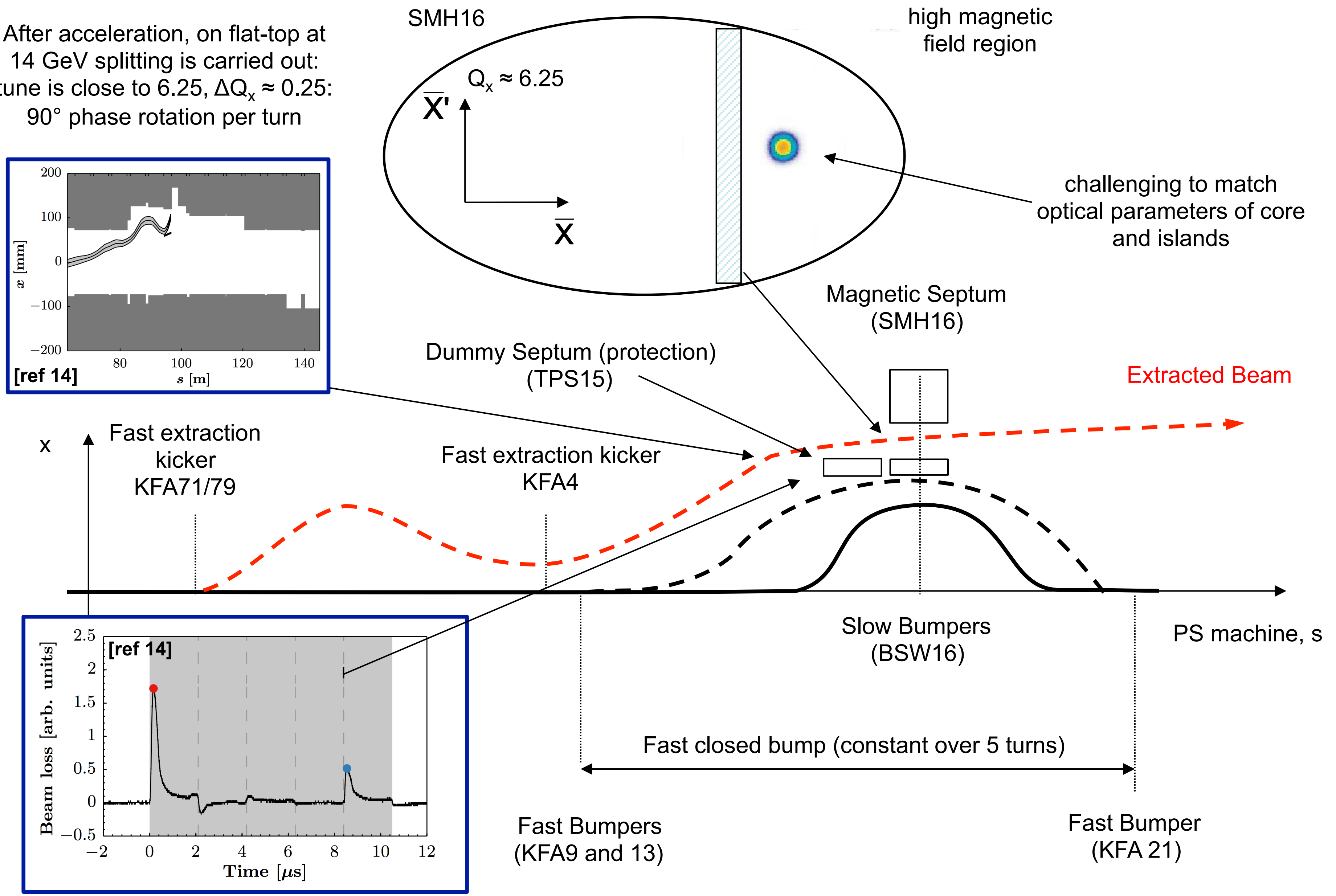
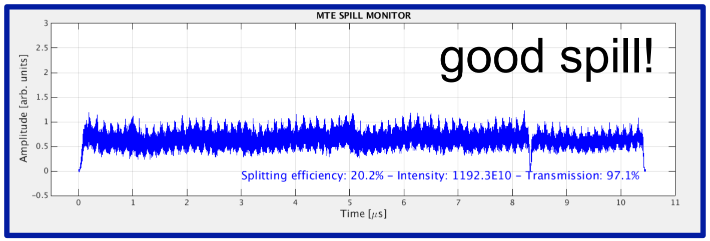


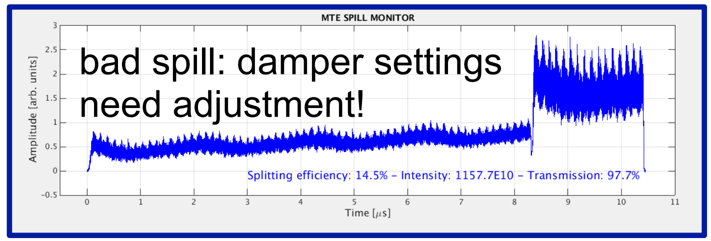
MTE: performance aspects (1)

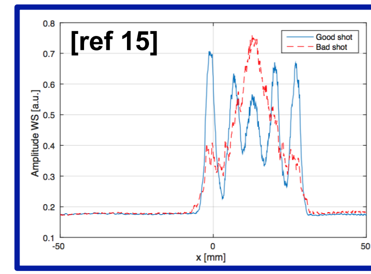
- MTE is complex and operational implementation faced many challenges:
  - Fluctuations in splitting efficiency:

$$\eta_{MTE} = \frac{\langle I_{\text{island}} \rangle}{I_{\text{total}}}$$

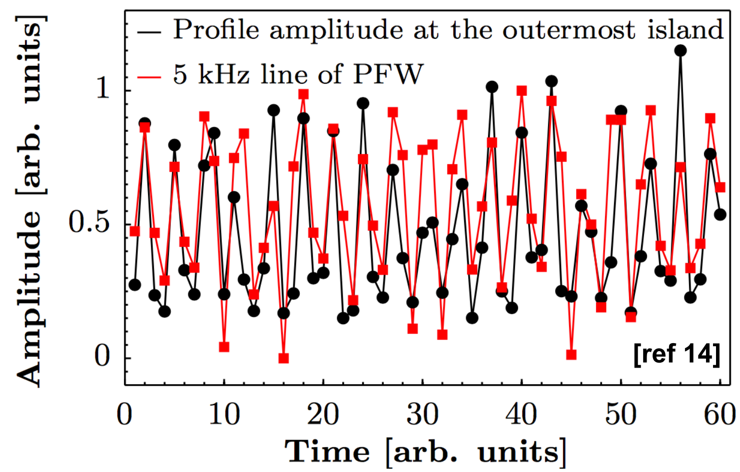
    - aim for (20 ± 1) % of the beam in each island (imposed by SPS)





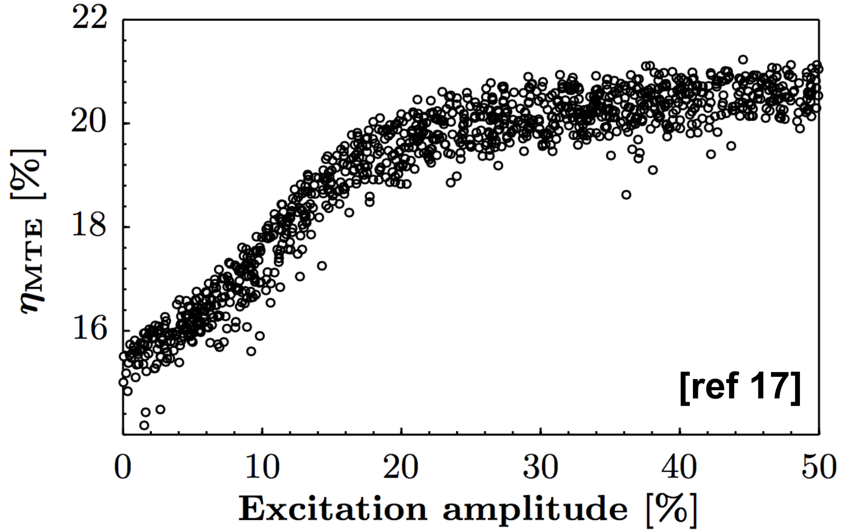


  - Sensitivity to power converter ripple:
    - fluctuations shown to be correlated to low frequency noise (≈ 5 kHz) on unsynchronized power converters, affecting the machine tune
    - ripple reduced, power converters to be synchronised and their (step-mode) frequency to be increased to ≈ 10 kHz



MTE: performance aspects (2)

- MTE is complex and operational implementation faced many challenges:
  - Transverse damper excitation is imperative to increase the capture probability during island formation:



    - theoretical studies on-going to understand the mechanism

  - Vertical emittance and transmission at low-energy in SPS:
    - work is on-going to create and preserve smaller emittances throughout the accelerator chain
    - charge exchange injection in the PSB will help in the long term

MTE: performance aspects (3)

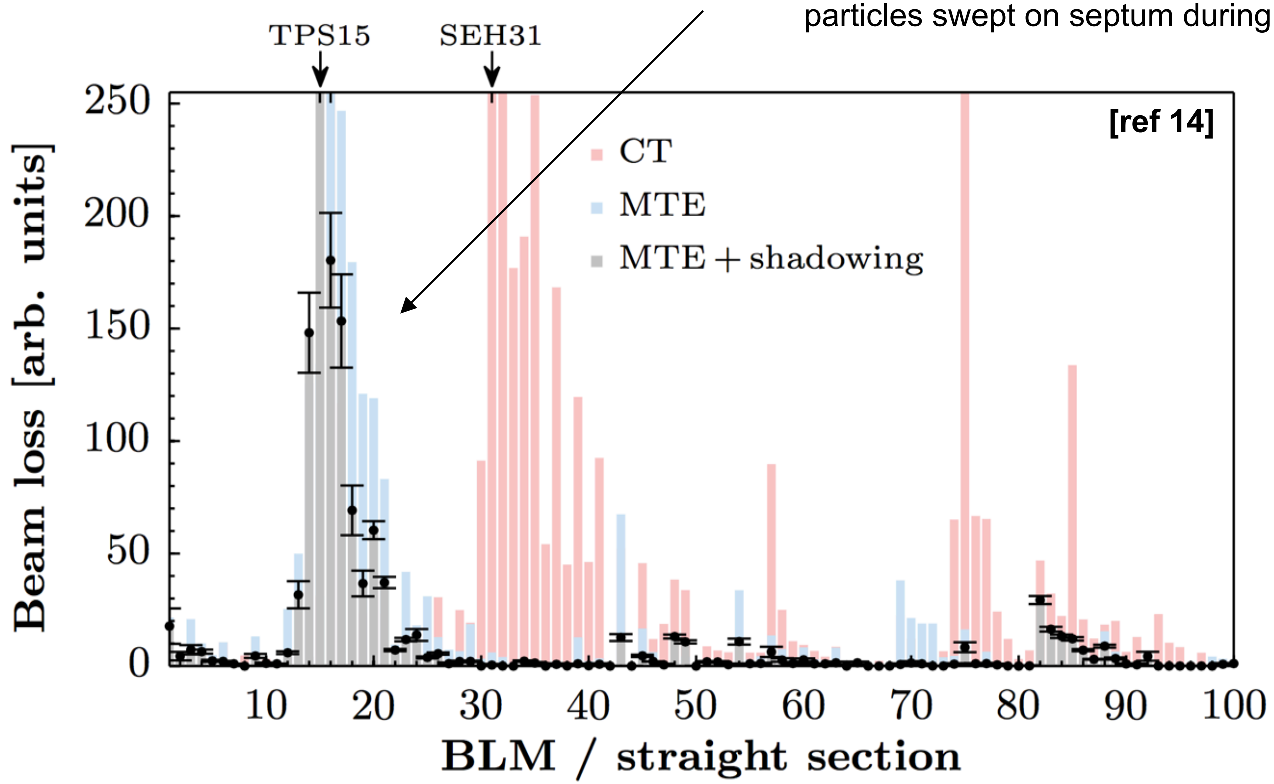
- There are many other issues too detailed for this lecture:
  - available mechanical aperture
  - operation of a dummy septum with other beam types whilst shadowing the septum for MTE
  - control of magnetic reproducibility and stability for splitting:
    - non-linear coupling, chromaticity and energy spread
    - rotation of the islands after splitting for correct presentation at septum
  - control of tune as slow bump turned on (to better than 10^{-3})
  - turn-by-turn extraction trajectory differences

… consult reference list for more information!

Losses: CT vs. MTE

- Beam is requested **de-bunched** by the SPS (no particle-free abort gap)
  - islands and core swept over the magnetic septum as the kicker field rises: local shielded protection installed upstream to absorb losses
  - losses in PS improved from ~ 6% to < 2%

MTE losses due to **de-bunched longitudinal structure**: particles swept on septum during kicker rise-time



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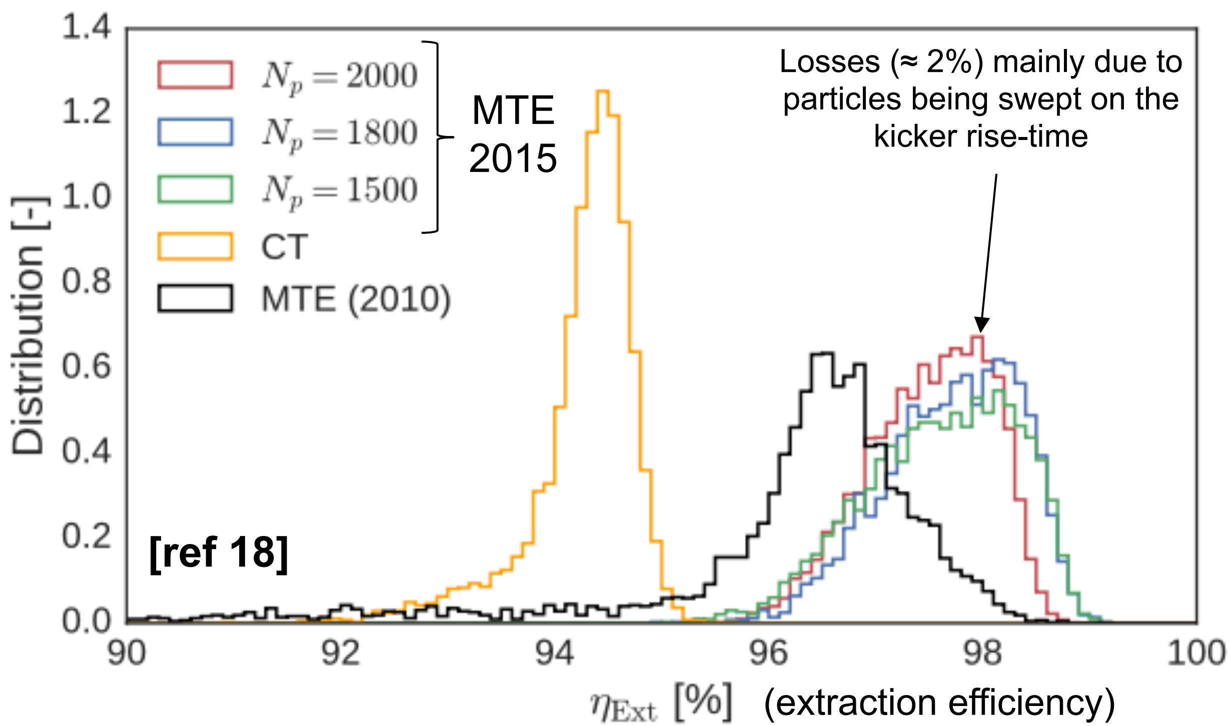
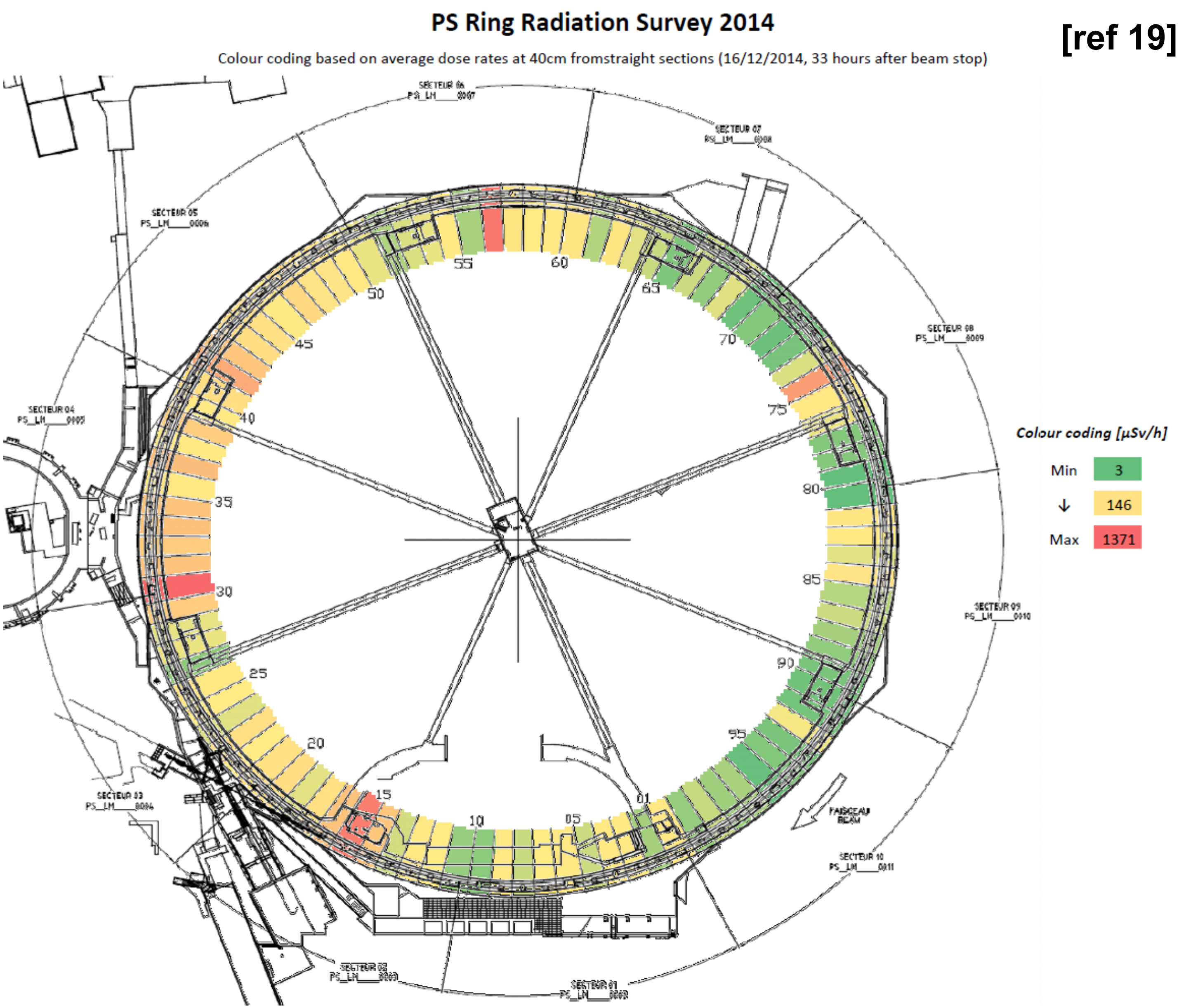


Activation: after CT operation

[ref 19]



Activation: after MTE operation

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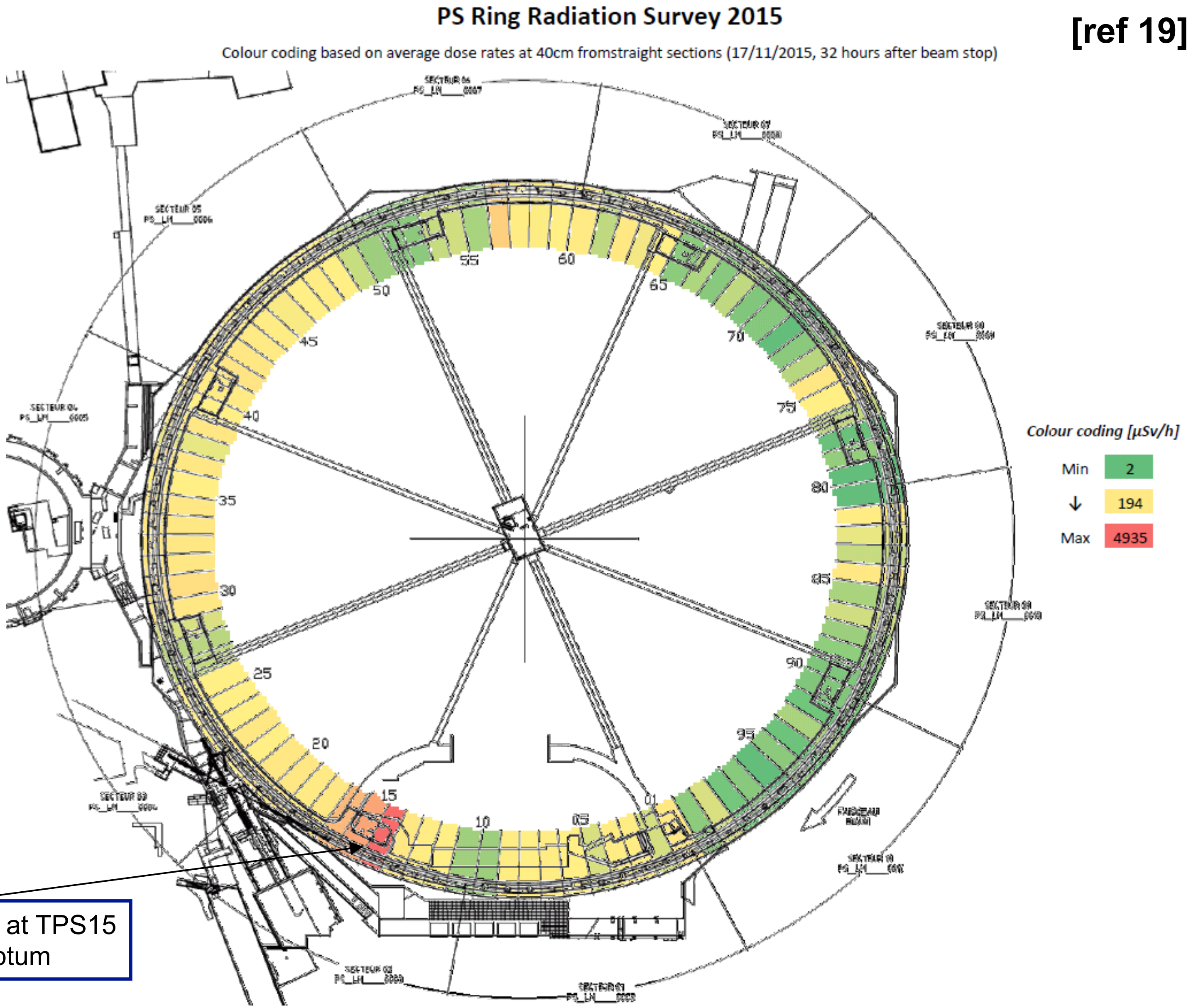

Summary

- The basic principles and design considerations for **fast extraction** were reviewed:
  - kick optimisation
  - important design parameters for kickers and septa
  - bumps and “non-local” extraction
- Two different techniques for **multi-turn fast extraction** were described:
  - **mechanical splitting** vs. **magnetic splitting**
- Examples of extraction systems at CERN were given to illustrate the different **fast extraction techniques**

Acknowledgements

- A large amount of material in this presentation was provided by colleagues at CERN including **D. Cotte**, **S. Gilardoni, M. Giovannozzi, B. Goddard** and **G. Sterbini** to name just a few…!

- A special thanks to **A. Huschauer** and **F. Velotti** for their comments on the final draft!

Thanks for your attention!

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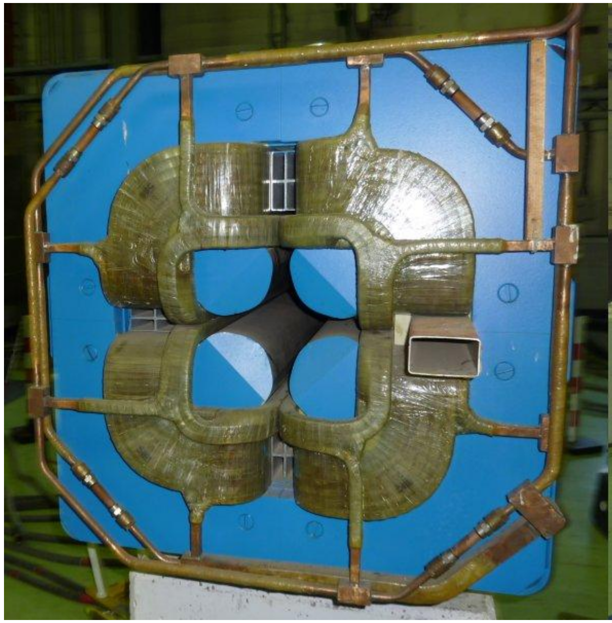
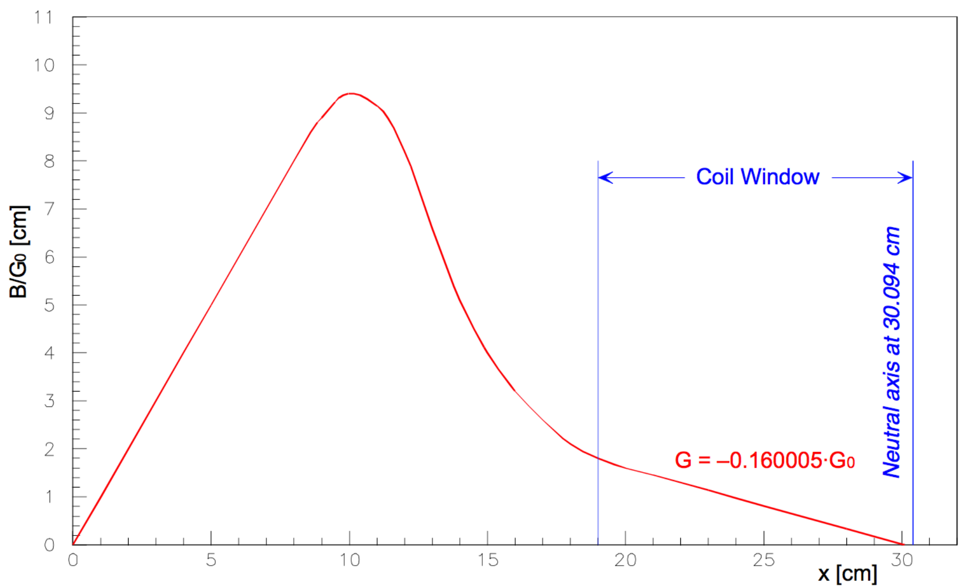
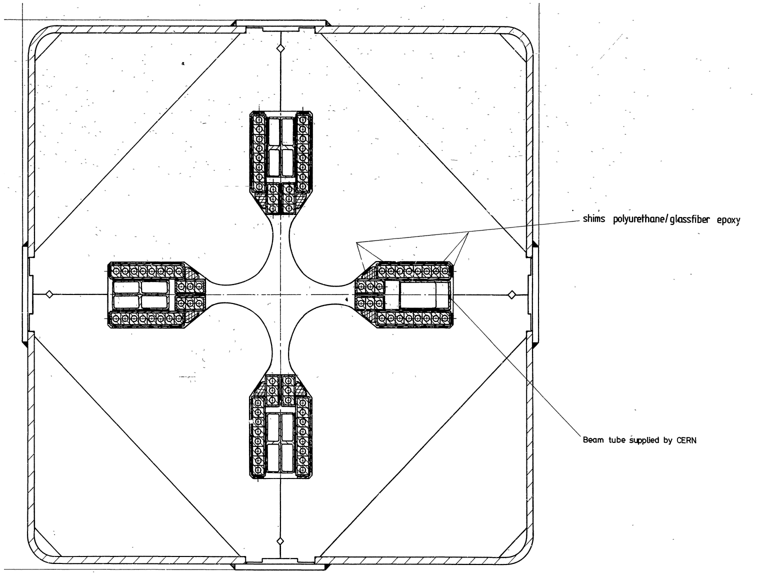
Appendix

SPS QDA coil window

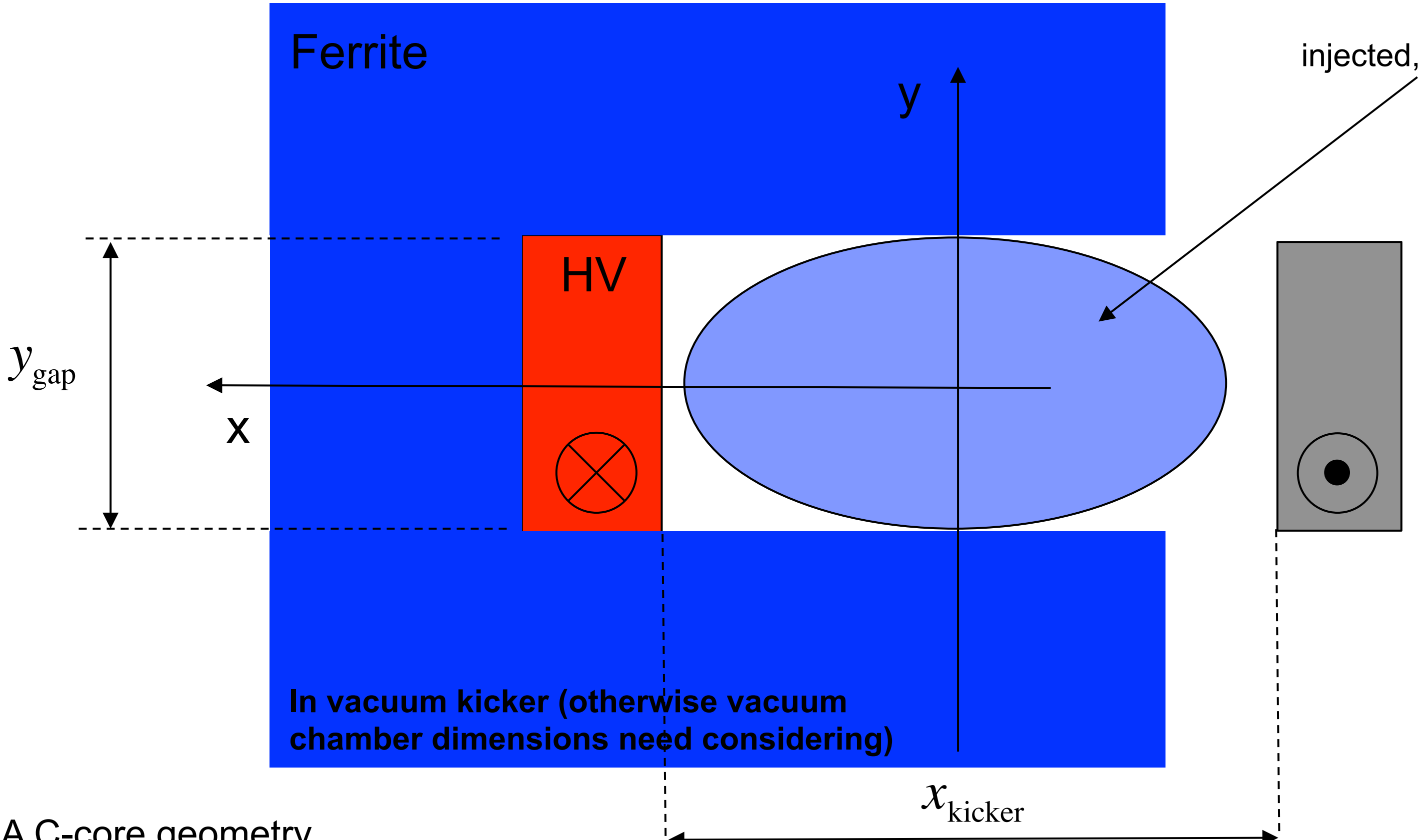






Aperture considerations: kicker

- Extraction kicker is usually positioned on the circulating beam and therefore its vertical aperture is constrained by the injected beam size:
  - see C. Bracco's lecture: *Injection: Hadron Beams* and the appendix for more details



A C-core geometry, commonly used at CERN

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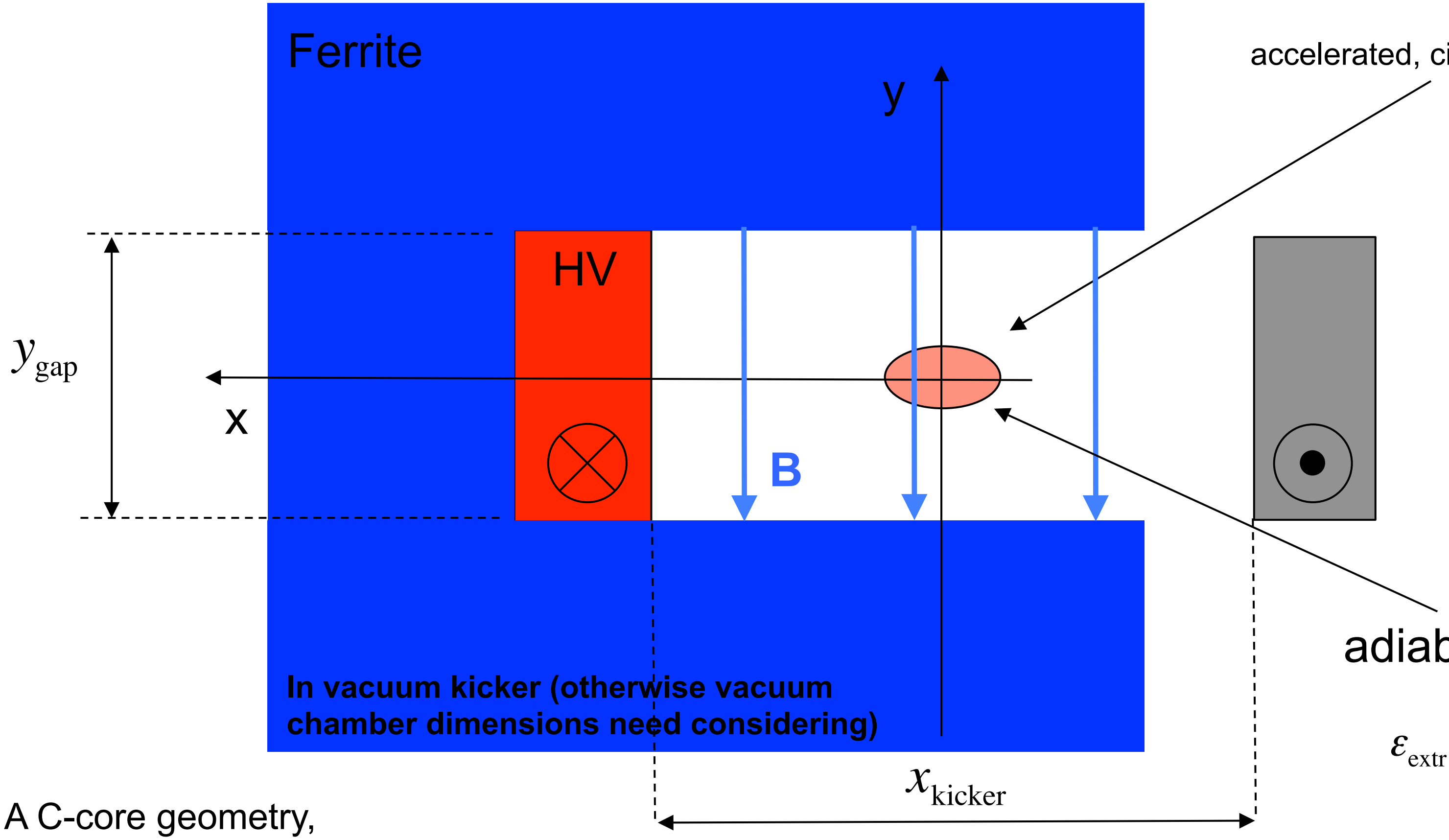

adiabatic damping:

$$\varepsilon_{extr} = \frac{\beta_{inj}\gamma_{inj}}{\beta_{ext}\gamma_{ext}}\varepsilon_{inj}$$

A C-core geometry, commonly used at CERN

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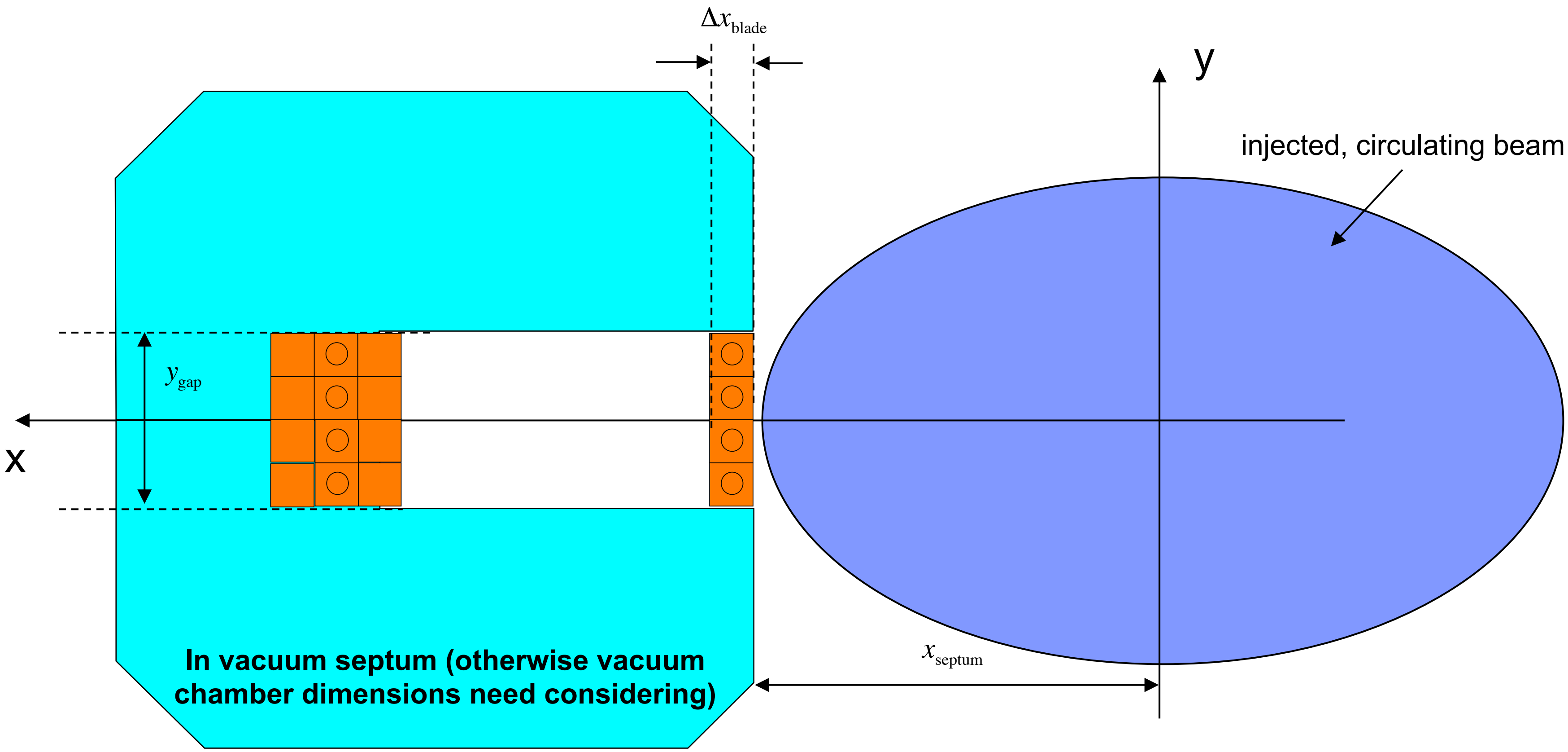

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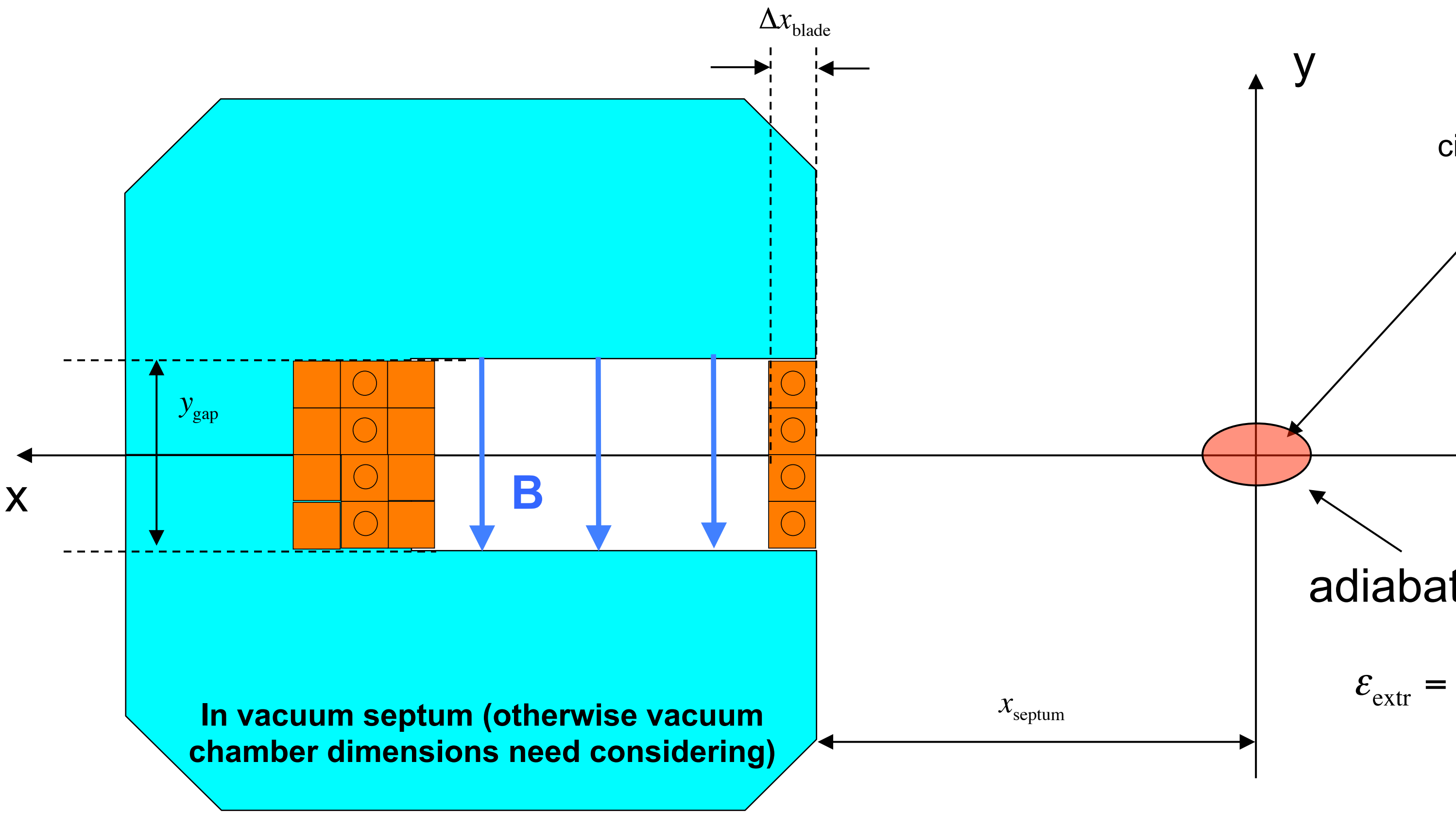

adiabatic damping:

$$\varepsilon_{\text{extr}} = \frac{\beta_{inj}\gamma_{\text{inj}}}{\beta_{\text{ext}}\gamma_{\text{ext}}}\varepsilon_{\text{inj}}$$

Aperture considerations: septum

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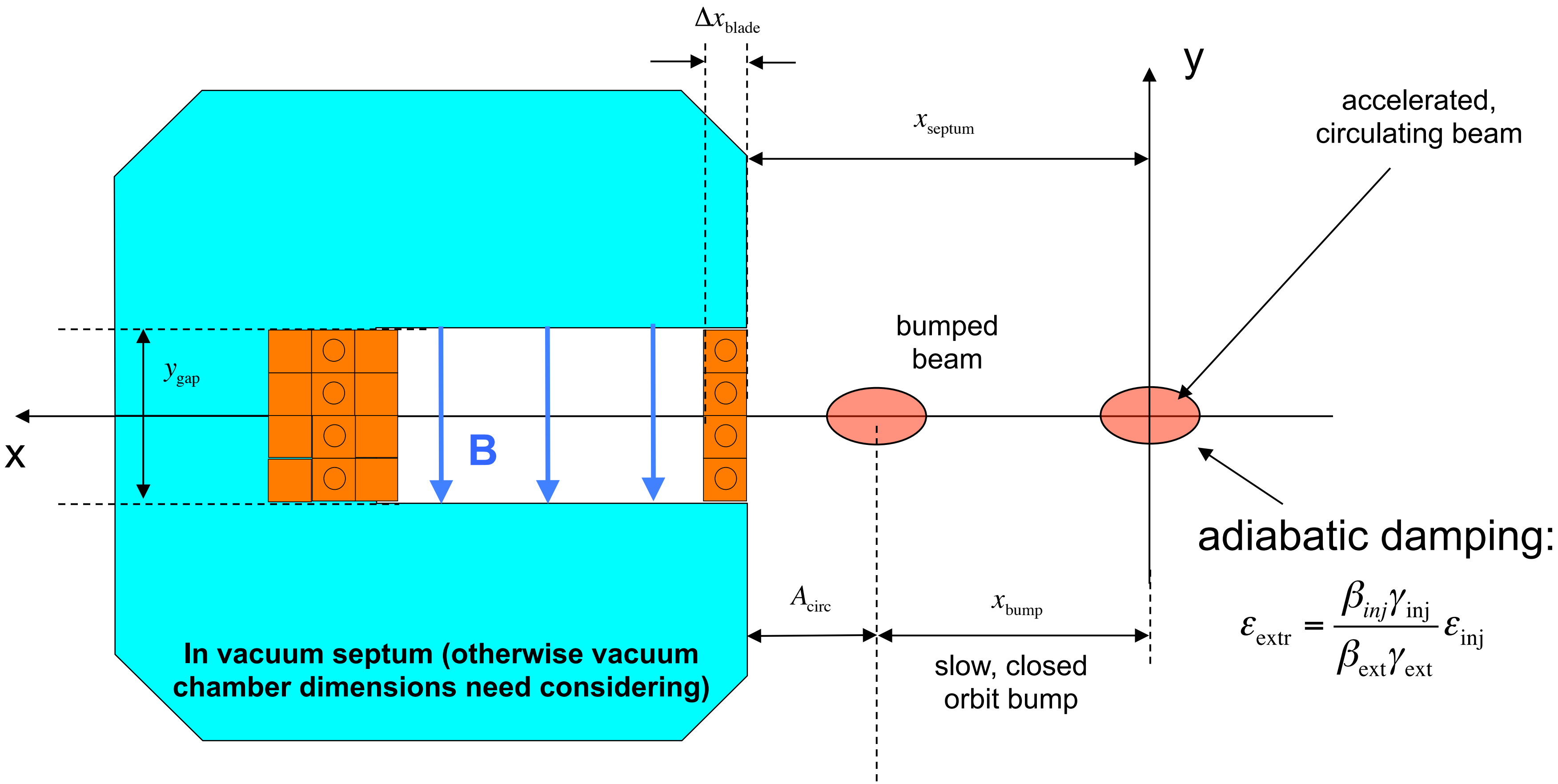
  - slow orbit bumps are used instead to move the beam to the septum



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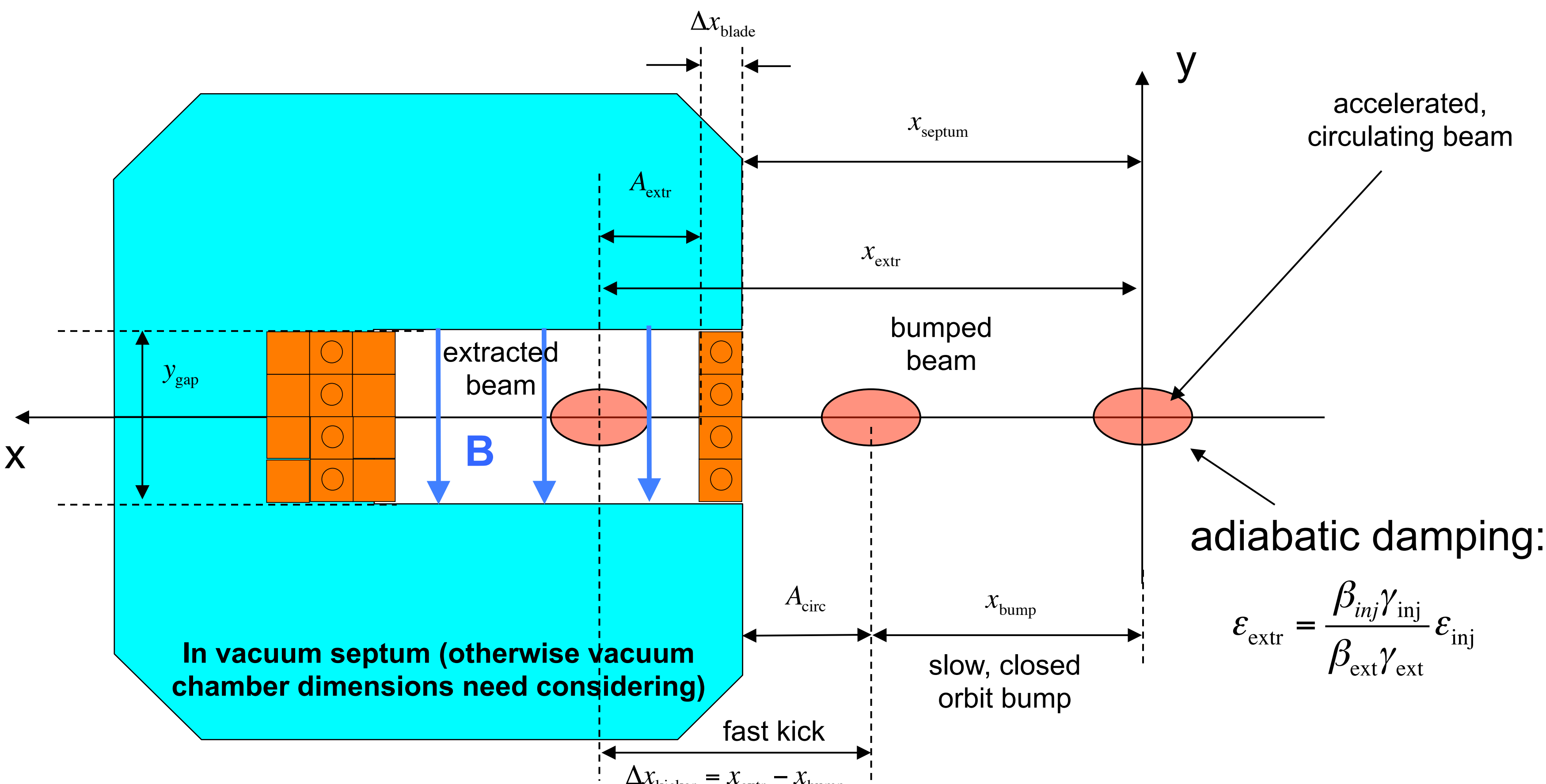


Extraction aperture and tolerances (1)

- The main concerns for the extraction aperture are **beam loss induced heating** (cooling) and **activation** (maintenance/damage) of the septum
- Aperture is usually written in terms of the betatron beam size:

$$\sigma_x = \sqrt{K_\beta \beta_x \varepsilon_x}$$

Take care, sometimes aperture (n_σ) includes dispersion: $\sigma_x = \sqrt{K_\beta \beta_x \varepsilon_x + K_D D_x^2 \delta_{\Delta p,\mathrm{beam}}^2}$

  - where the symbols have their usual meaning and K_β and K_D are safety factors, generally taken as ≈ 1.2

- Bumped, circulating beam aperture:

$$n_{\sigma_x,\mathrm{bumped}} = \frac{\overbrace{x_{\mathrm{septum}} - x_{\mathrm{bump}}}^{A_{\mathrm{circ}}} - \delta_{x,\mathrm{CO}} - \delta_{x,\mathrm{alignment}} - (\delta_{\Delta p,\mathrm{offset}} + \delta_{\Delta p,\mathrm{beam}}) K_D D_x}{\sigma_x}$$

  - where:
    - $\delta_{x,\mathrm{CO}}$ is the error on the closed-orbit position
    - $\delta_{x,\mathrm{alignment}}$ is the mechanical alignment tolerance of septum position
    - $\delta_{\Delta p,\mathrm{offset}}$ and $\delta_{\Delta p,\mathrm{beam}}$ are the momentum offset error and spread of the beam

Extraction aperture and tolerances (2)

- Circulating beam aperture:
  - usually only a concern at injection
  - larger ε, larger closed-orbit errors due to injection oscillations
- Extracted beam aperture:

$$n_{\sigma_x,\mathrm{extr}} = \frac{\overbrace{\Delta x_{\mathrm{kicker}} + x_{\mathrm{bump}} - (\Delta x_{\mathrm{blade}} + x_{\mathrm{septum}})}^{A_{\mathrm{extr}}} - \delta_{x,\mathrm{CO}} - \delta_{x,\mathrm{alignment}} - (\delta_{\Delta p,\mathrm{offset}} + \delta_{\Delta p,\mathrm{beam}}) K_D D_x}{\sigma_x}$$

  - dependent on the kick strength and septum blade thickness
- The vertical aperture for the extracted beam is usually critical because of the narrow septum gap:

$$n_{\sigma_y,\mathrm{extr}} = \frac{y_{gap}/2 - \delta_{y,\mathrm{CO}} - \delta_{y,\mathrm{alignment}}}{\sigma_y}$$

  - typically no dispersion in the non-bending plane of synchrotron
  - vertical aperture not always the most critical, see the Lambertson septum

Kickers: electric vs. magnetic

- A quick comparison between the highest and lowest energy extraction systems at CERN:

  ELENA: 100 keV antiprotons: Bρ = 45.7 mT m

  LHC Beam Dump: 7 TeV protons: Bρ = 23.4 kT m

  ↕ factor of ≈ 500,000

- Kickers do not have to be magnets…
  – at low kinetic energy, i.e. at small beam velocities *v*, the electric force is more efficient than the magnetic force
  – electrostatic rigidity vs. magnetic rigidity:

$$\chi_e = E_0\rho = \frac{pv}{q}\ [\mathrm{V}] \qquad \Delta x'_{\mathrm{kicker}} = \frac{E_0 L_{eff}}{\chi_e}$$

$$\chi_m = B\rho = \frac{p}{q}\ [\mathrm{Tm}] \qquad \Delta x'_{\mathrm{kicker}} = \frac{B_0 L_{eff}}{\chi_m}$$

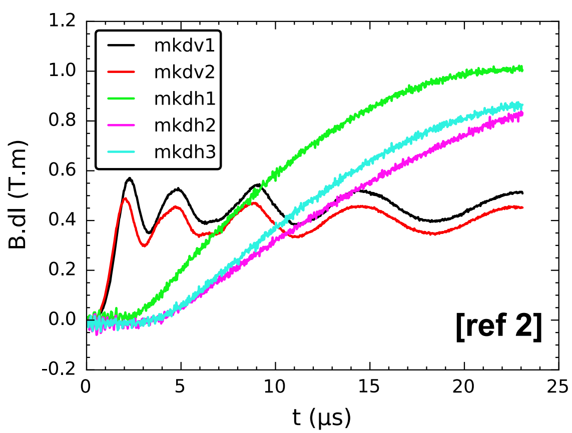
ELENA: 100 keV antiprotons: Eρ = 45.7×10^{-3} x 0.0146*c* = 200 kV ← deflectors with ~10 kV feasible!

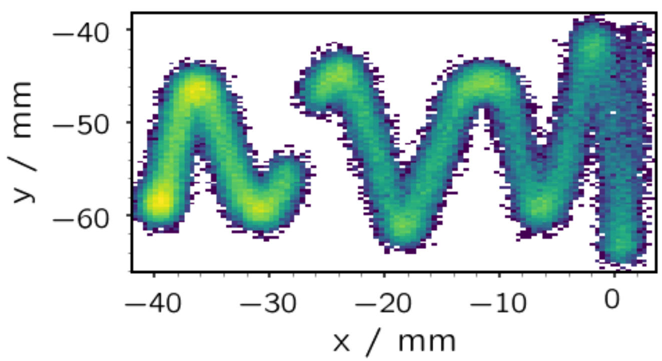
LHC Beam Dump: 7 TeV protons: Eρ = 23.4×10^{3} x *c* = 7.02 TV ← ~ 4 MV an enormous voltage to hold-off and switch! 30 kV is already challenging enough!

Kicker parameters: pulse shape

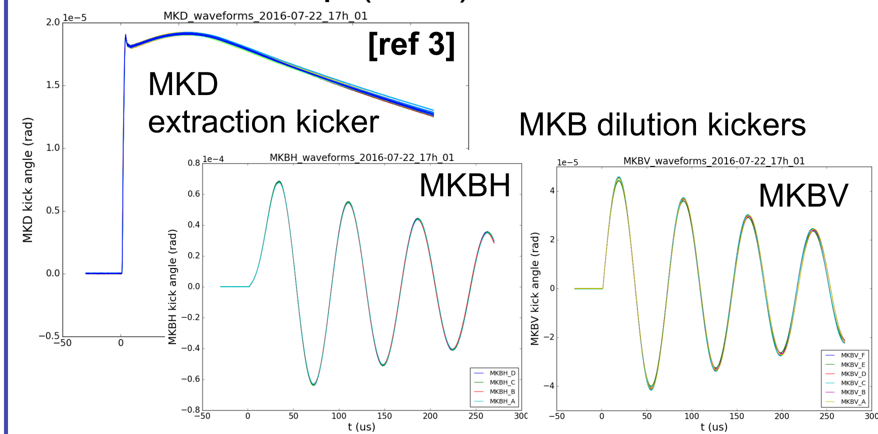
- Definition/parameterization of the kicker pulse depends strongly on the application, some examples:
  - single-turn extraction
  - destination: **to an absorber/beam dump**

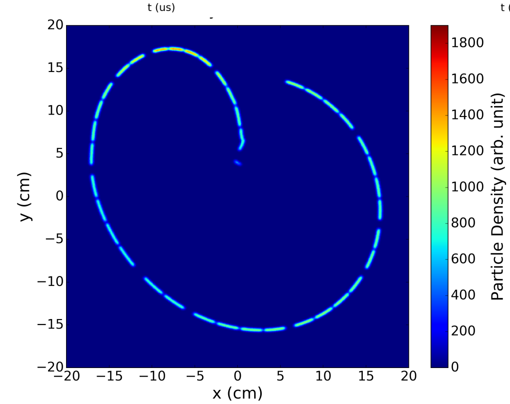
SPS beam dump (TIDVG) ≈ 3 MJ:





LHC beam dump (TDE): ≈ 350 MJ



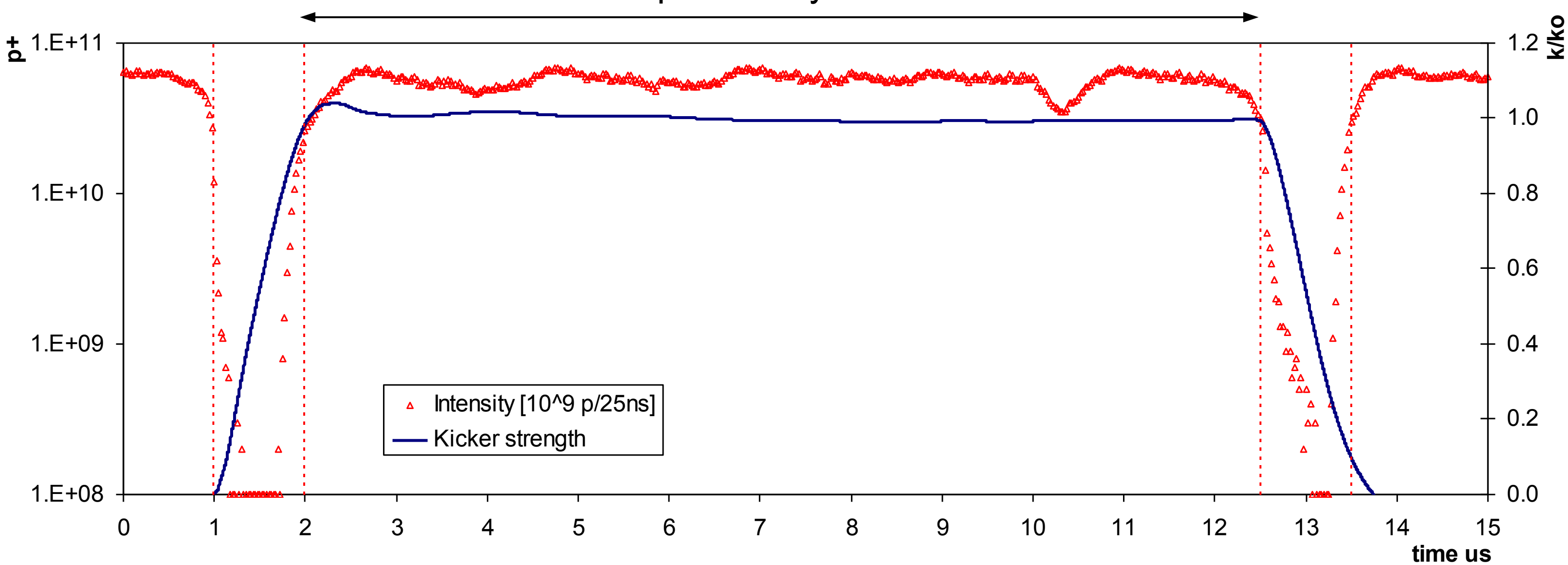


Kicker parameters: pulse shape

- Definition/parameterization of the kicker pulse depends strongly on the application, some examples:
  - multi-burst extraction
  - destination: **fixed target physics programme**

CERN Neutrinos to Gran Sasso (CNGS) SPS extraction (400 GeV):

2 batches of 10.5 μs containing 2.4×10^{13} p+ (nominal)
separated by 50 ms



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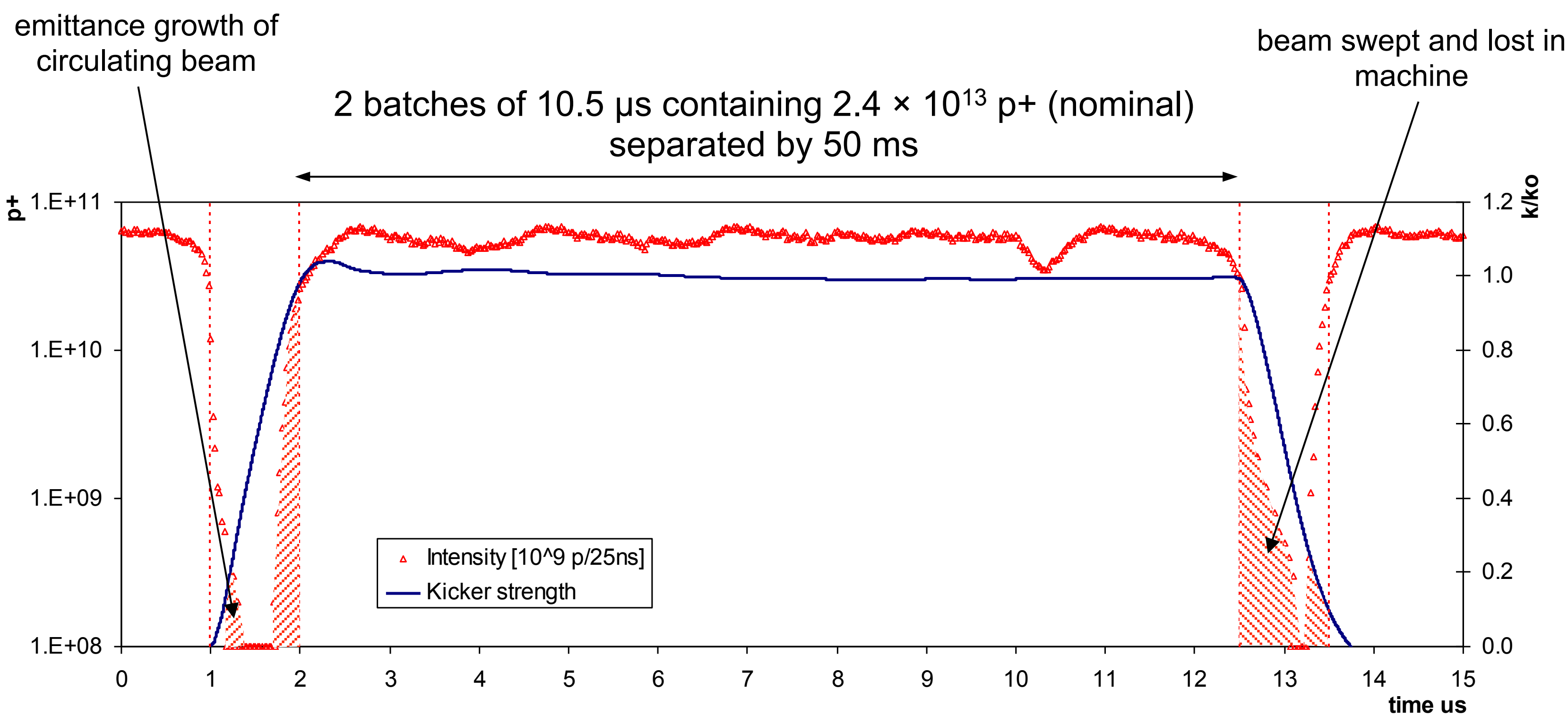
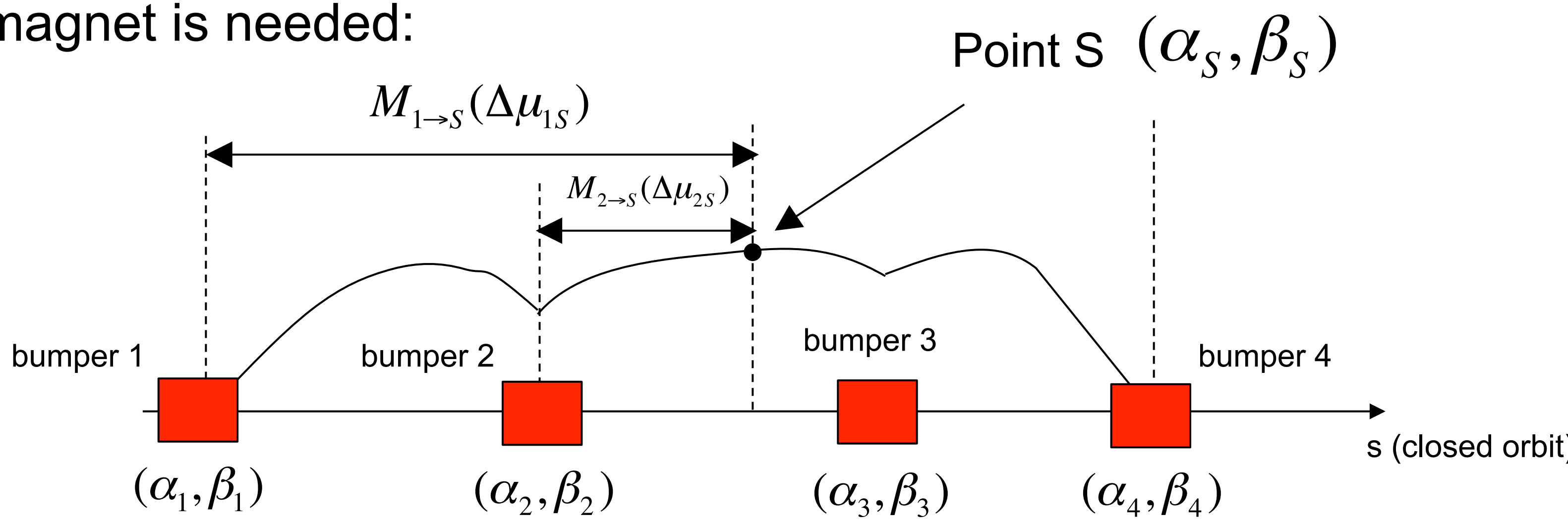


4-magnet ("coil") bump

- To control both **position and angle** (x_S, x'_S) at a given point a fourth magnet is needed:



First two bumpers select the position and angle at point S:

$$\begin{pmatrix} x_s \\ x'_s \end{pmatrix} = M_{1\to S}\begin{pmatrix} 0 \\ \Delta_1 \end{pmatrix} + M_{2\to S}\begin{pmatrix} 0 \\ \Delta_2 \end{pmatrix}$$

$$= \begin{pmatrix} M_{1\to 3,12}\Delta_1 + M_{2\to 3,12}\Delta_2 \\ M_{1\to 3,22}\Delta_1 + M_{2\to 3,22}\Delta_2 \end{pmatrix}$$

Summing kicks from each bumper gives 2 simultaneous equations:

$$x_s = M_{1\to 3,12}\Delta_1 + M_{2\to 3,12}\Delta_2$$
$$x'_s = M_{1\to 3,22}\Delta_1 + M_{2\to 3,22}\Delta_2$$

Solving for the bumper kick strengths one can write:

$$\Delta_1 = \frac{1}{\sqrt{\beta_1\beta_S}}\frac{\cos\Delta\mu_{2S} - \alpha_S\sin\Delta\mu_{2S}}{\sin\Delta\mu_{12}}x_s - \sqrt{\frac{\beta_S}{\beta_1}}\frac{\sin\Delta\mu_{2S}}{\sin\Delta\mu_{12}}x'_s$$

$$\Delta_2 = -\frac{1}{\sqrt{\beta_2\beta_S}}\frac{\cos\Delta\mu_{1S} - \alpha_S\sin\Delta\mu_{1S}}{\sin\Delta\mu_{12}}x_s + \sqrt{\frac{\beta_S}{\beta_2}}\frac{\sin\Delta\mu_{1S}}{\sin\Delta\mu_{12}}x'_s$$

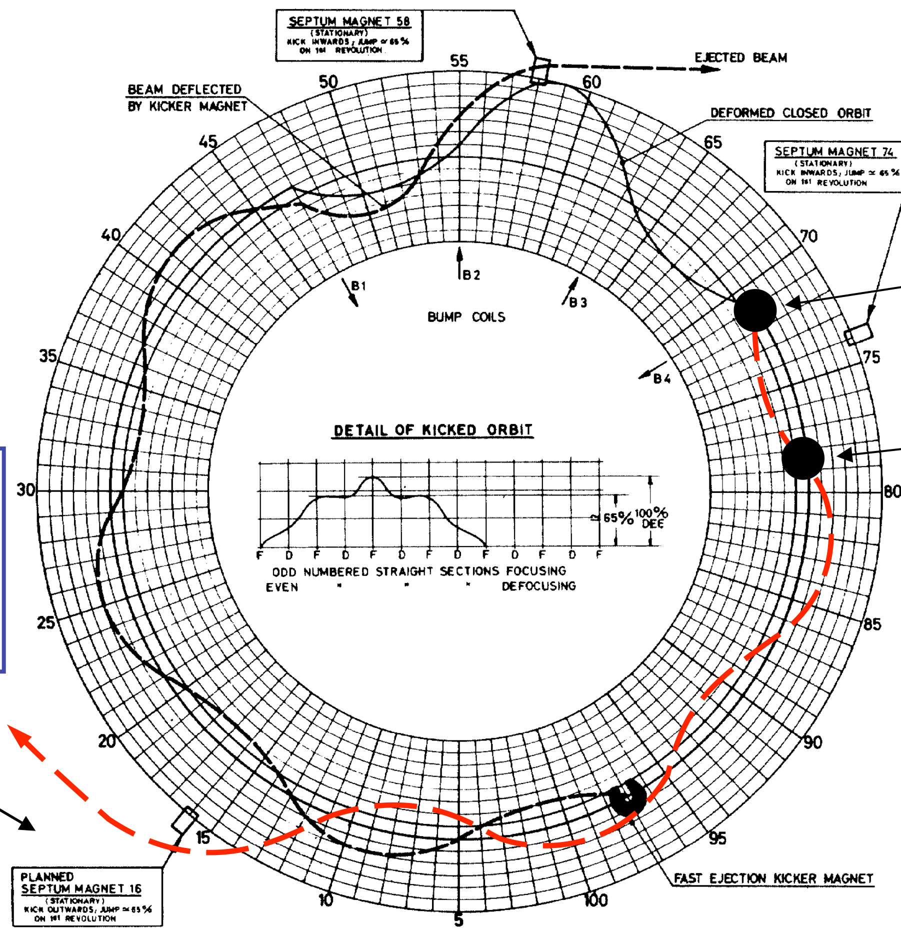
One can derive by symmetry the strengths of Δ_3 and Δ_4 by applying the following transformations to the above equations:

$$\beta_1 \to \beta_4,\ \beta_2 \to \beta_3,\ \alpha_S \to -\alpha_S,\ x_S \to -x_S,\ \Delta\mu_{1S} \to \Delta\mu_{S4},\ \Delta\mu_{2S} \to \Delta\mu_{S3}$$

“Non-local” extraction concept

- A fast extraction system can be designed to extract using a single kicker system through different septa to different extraction lines:

CERN PS, today
(kicker in SS71/79)



Fast ejection kicker magnet: KFA71 ($\Delta x'_{kicker} < 0$)

Fast ejection kicker magnet: KFA79 ($\Delta x'_{kicker} > 0$)

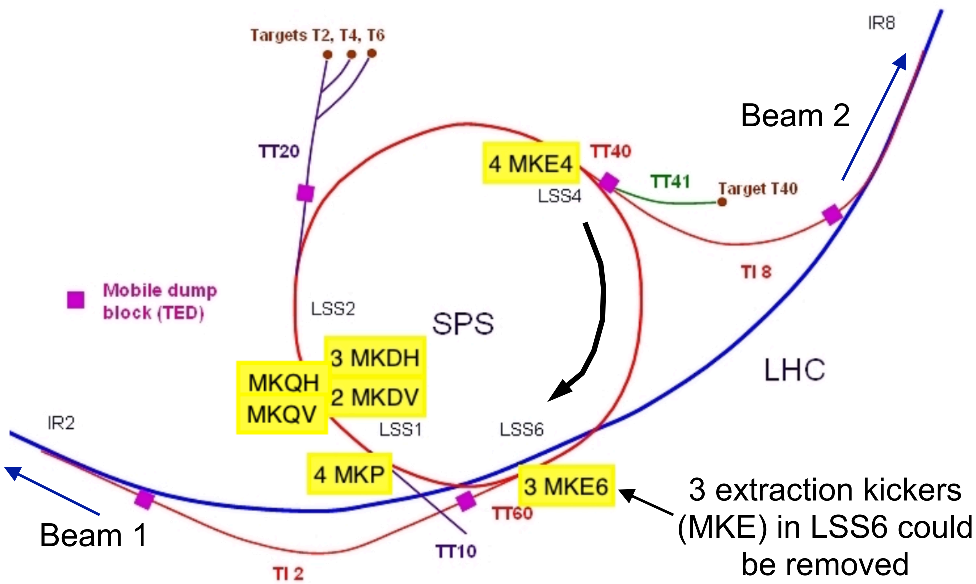
To SMH16: $\Delta x'^{KFA71}_{kicker} < 0$

$$\mu_{kicker \rightarrow septum} \approx \frac{11}{2}\pi = 2.75\lambda_\beta$$

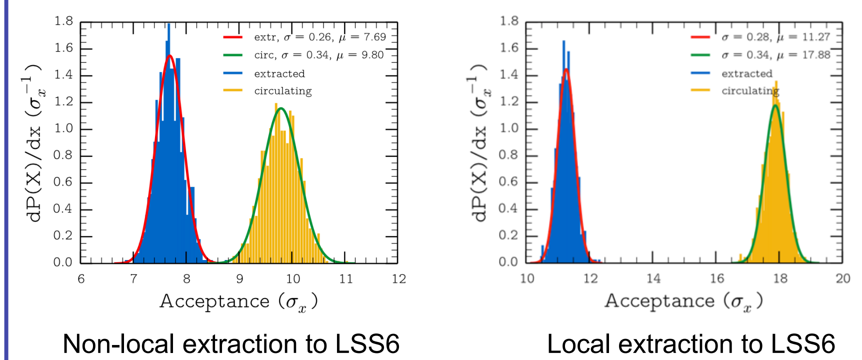
Figure 1 : Fast ejection from straight section 58 into the east experimental area

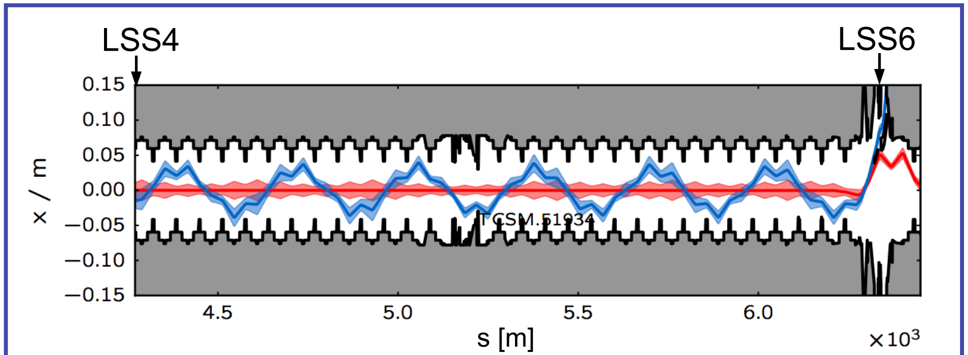
Example: potential upgrade at SPS

- SPS impedance could be reduced by removing extraction kickers (MKE) from LSS6:
  - Kickers in LSS4 used to extract both LHC beams from LSS4 and LSS6

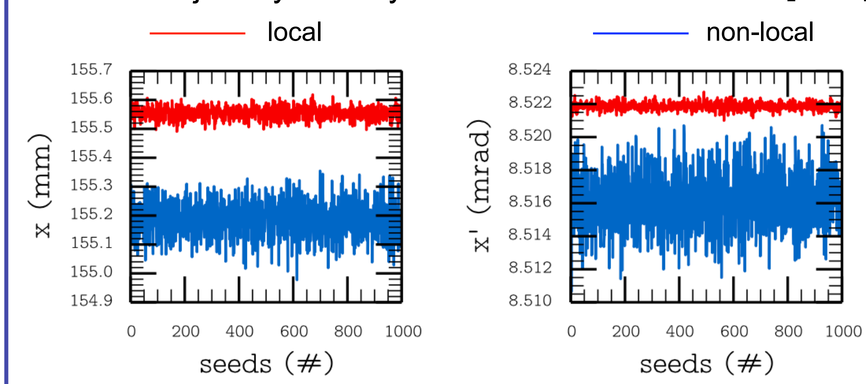


Effect on acceptance: **[ref 4]**





Effect on trajectory stability in LSS6: **[ref 4]**



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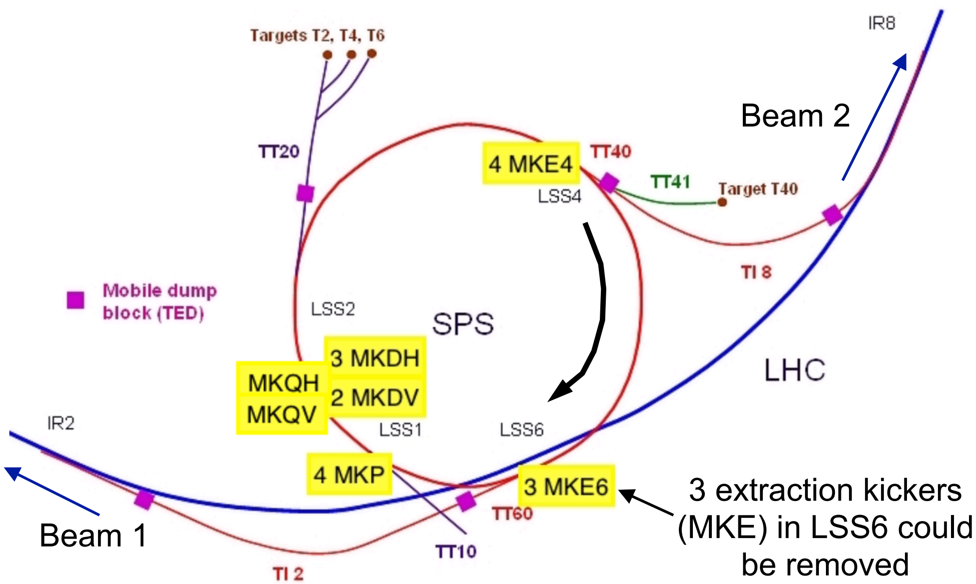
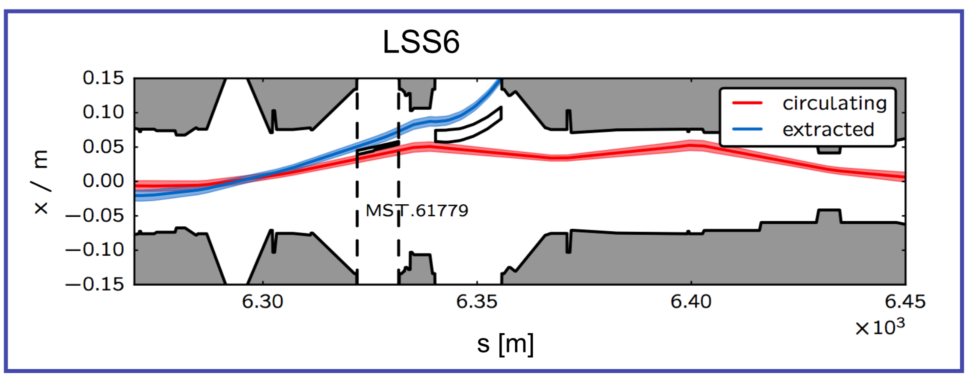
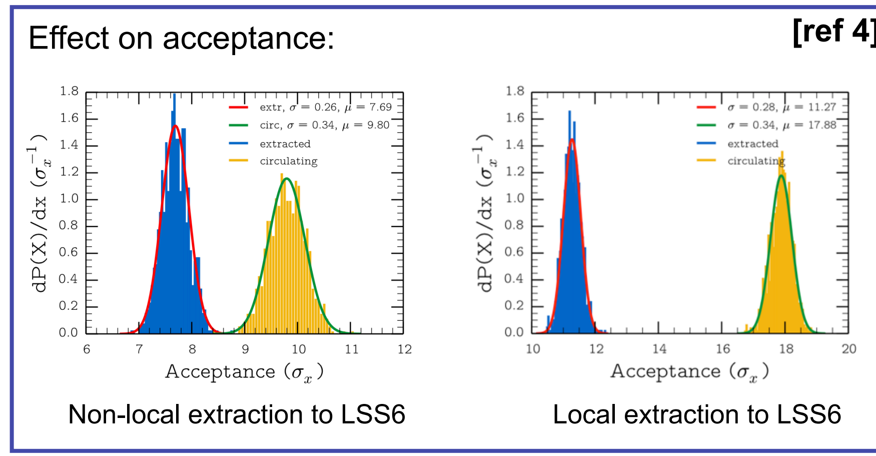
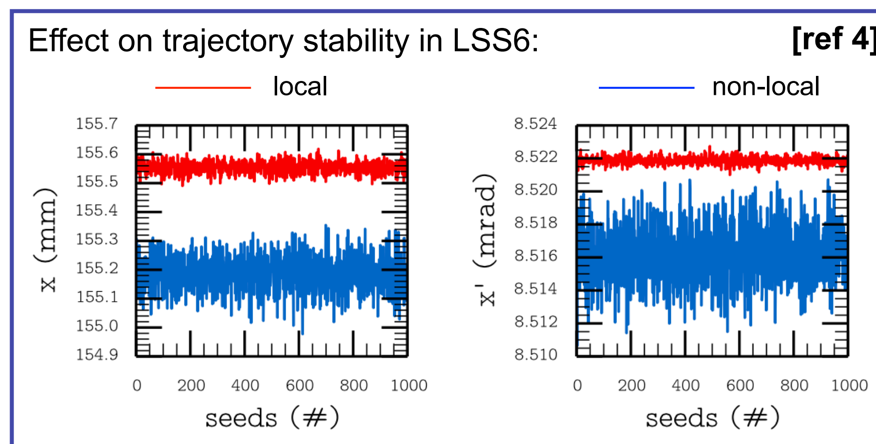








No turn-on of kicker

- For a fail-safe beam abort system **passive redundancy** must be built into the design:
  - multiple, independently powered kicker modules can be employed
  - redundancy in the power module circuitry, e.g. two switches in parallel
  - multiple trigger signals generated by redundant control electronics
  - aperture and kick strength over-specified to allow clean extraction even with missing kicker module(s)
- As well as **active interlock** and **monitoring** systems:
  - kicker voltage (and all other critical systems, septum current etc.) surveyed and compared to the measured beam rigidity:
    - synchronous beam dump immediately triggered if voltage of kicker power module is out of tolerance
  - check for **cable connectivity**:
    - synchronous beam dump if cable disconnected or connectivity lost
  - **post-operational checks** after each dump is executed:
    - identify any changes or non-conformity in the dump system (not only the kickers) before it is armed and readied again

What can go wrong?

- When the **beam energy exceeds ≈ 200 kJ** the risk of damaging the accelerator is significant:
  - Damage evident on copper for > 2×10^{12} p^+ at 450 GeV with $\sigma_{x,y} \approx 1$ mm
    - *see A. Nordt's lecture "Machine Protection and Activation"*
- Failures associated with beam extraction equipment are typically very fast and difficult to catch, for example:
  - No turn-on of kicker: missing kick strength, *see appendix for more details!*
  - **Erratic turn-on of kicker:** sweep circulating beam in the machine
  - Asynchronous triggering of kicker, flash-over (short-circuit) in kicker, magnet failure (e.g. septum)
- At high energy **failure is not an option:**
  - mitigation techniques need considering from the design stage
- At lower energy/intensity the **induced activation** is the main concern:
  - Beam inhibited by BLMs or RP monitors only after the failure has occurred, e.g. beam lost in septum due to power converter failure

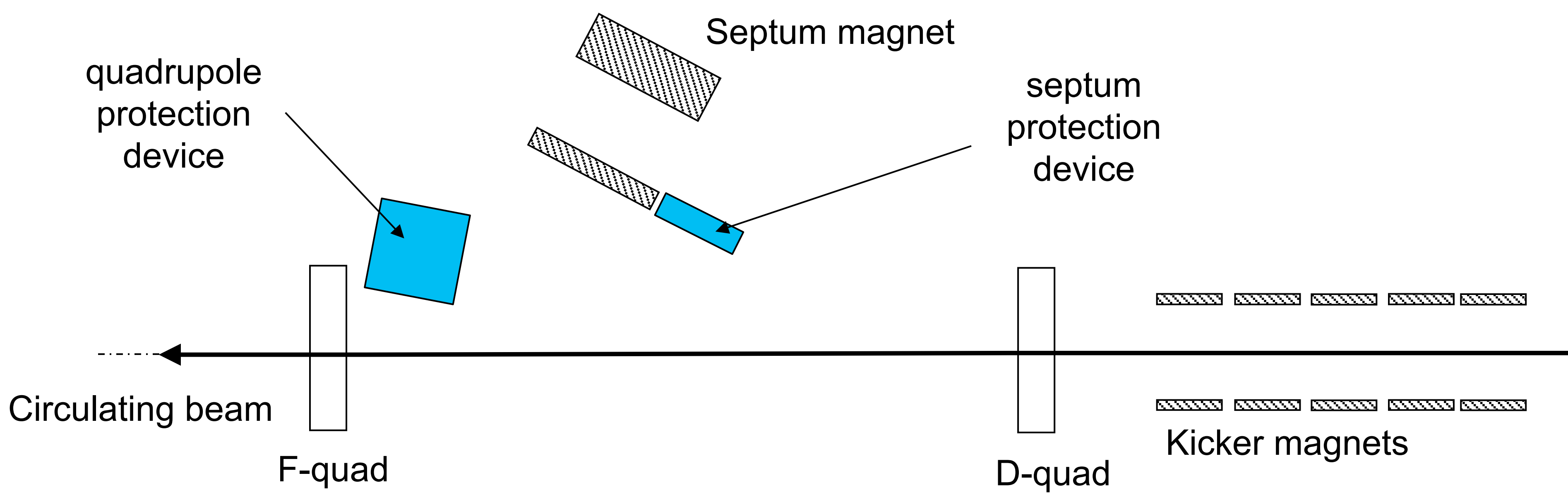
Erratic turn-on of kicker

- Extraction system for a high energy collider needs to abort at any moment throughout the cycle (injection, ramp, beams in collision):
  - switches of kicker power supply must be held at high voltage for long periods of time
  - erratic triggering of the kicker will happen sooner or later…

- Consequences depend on the total number of independently powered kicker modules in the dump system:
  - **One power module**: beam swept across entire machine aperture, septum and into the extraction channel:
    - beam extracted in an asynchronous dump
  - **A few power modules**: single kicker erratic will steer the beam directly into the machine aperture:
    - quick re-triggering of other kickers important to safely extract beam
  - **A very large number of power modules**: single kicker erratic results in a minor perturbation to closed orbit:
    - beam safely steered inside machine aperture and dumped synchronously later

Erratic turn-on of kicker

- If a single kicker module turns on erratically the others must re-trigger quickly to keep sweep speed of the beam fast on the machine aperture:
  - Quick fail-safe re-trigger system ($t_{retrigger}$ < kicker rise-time!)
  - Passive protection devices must be used to mask sensitive equipment if energy deposition during sweep is above the damage limit
  - Load taken by passive protection devices must be taken into account



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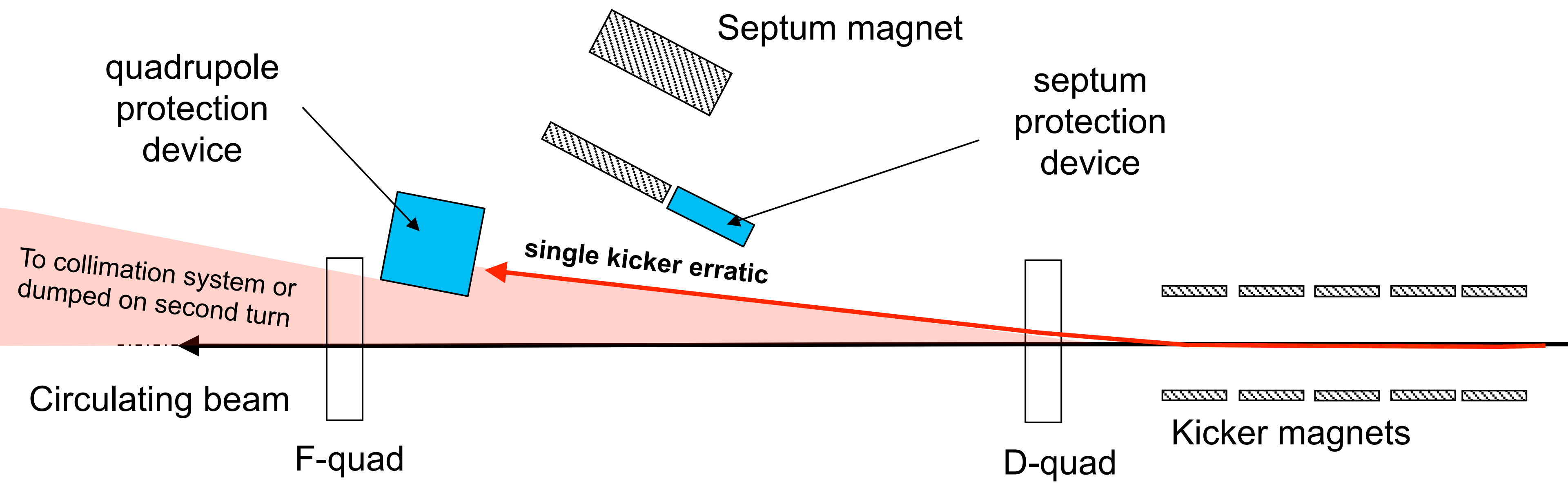

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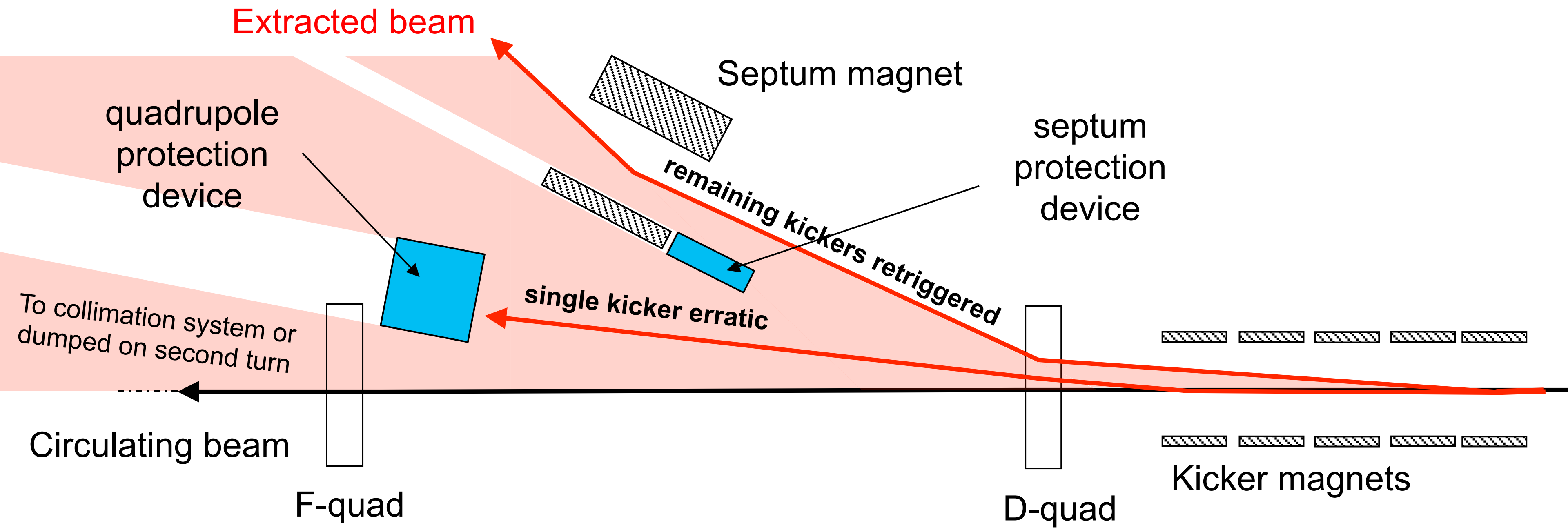
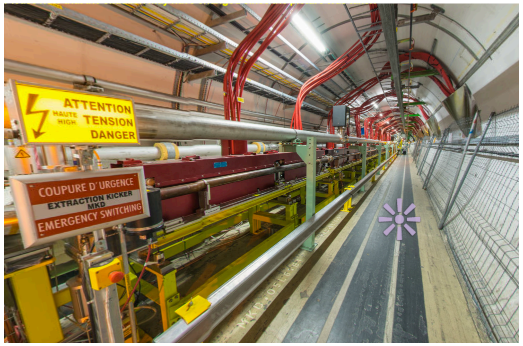
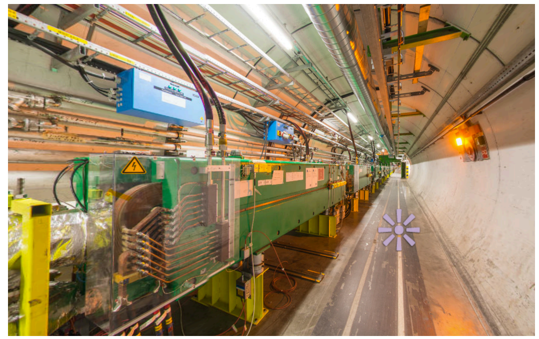


Example: LHC beam dump (1)

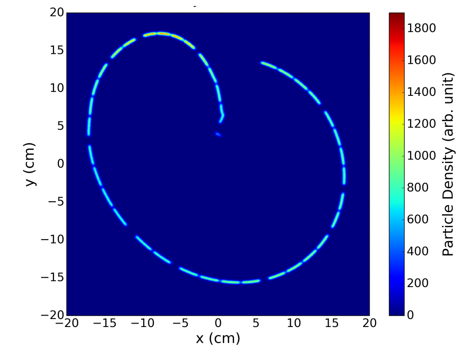
Kicker (MKD): 15 independently powered magnets, each 1.85 m long, delivering a total of 0.275 mrad: BL_{eff} = 6.4 Tm and τ_{rise} < 3 μs:

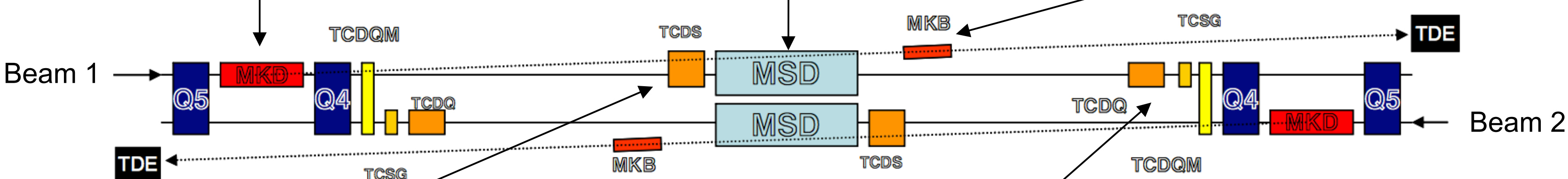


Septum (MSD): Normal conducting Lambertson (vertical deflection) powered in DC: 15 magnets each 5 m long, total length of 75 m: BL_{eff} = 56 Tm, septum width ranges from 6 – 18 mm:

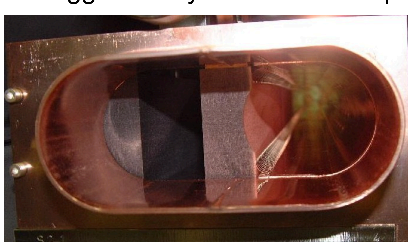


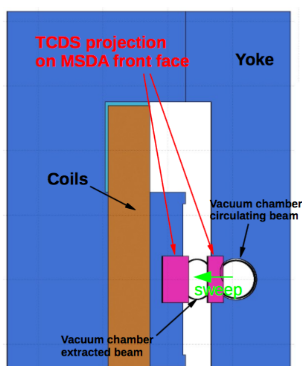
Dilution kickers (MKB): Vertical and horizontal deflection oscillating at 13 kHz to dilute beam on carbon beam dump (TDE):



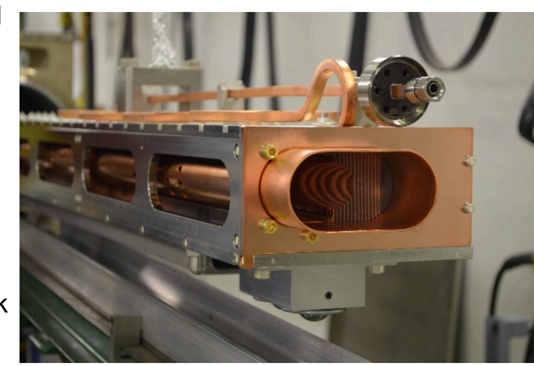


Septum protection (TCDS): fixed 6 m long absorber of carbon (graphite/2D CfC) and Ti-alloy reducing energy deposited in septum in the event erratic kicker trigger or asynchronous dump:

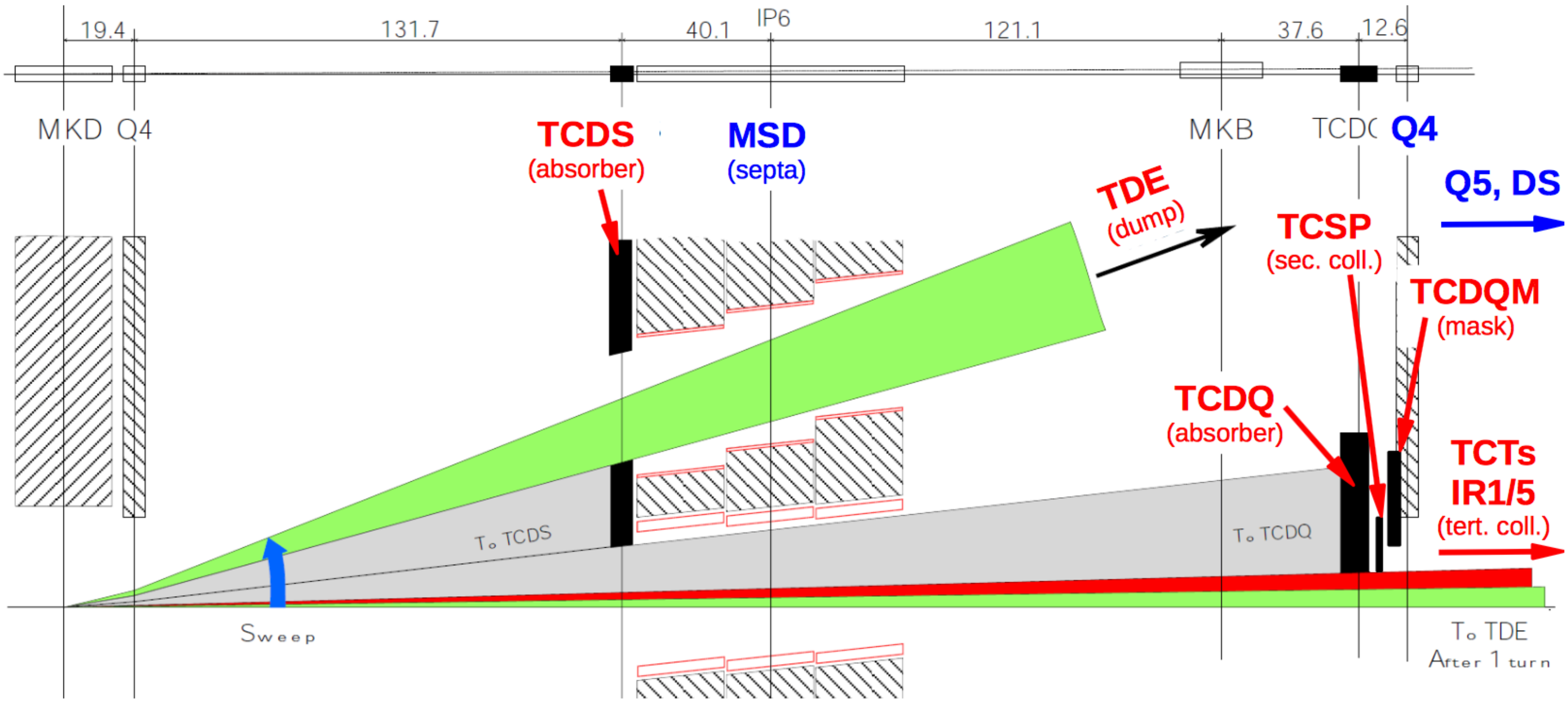




Quad protection (TCDQ): mobile 9 m long single-sided absorber of carbon fibre reinforced carbon (CfC) designed to protect downstream superconducting quadrupole in the event of an erratic kicker trigger or asynchronous dump. TCDQ is combined with a downstream fixed steel mask TCDQM:



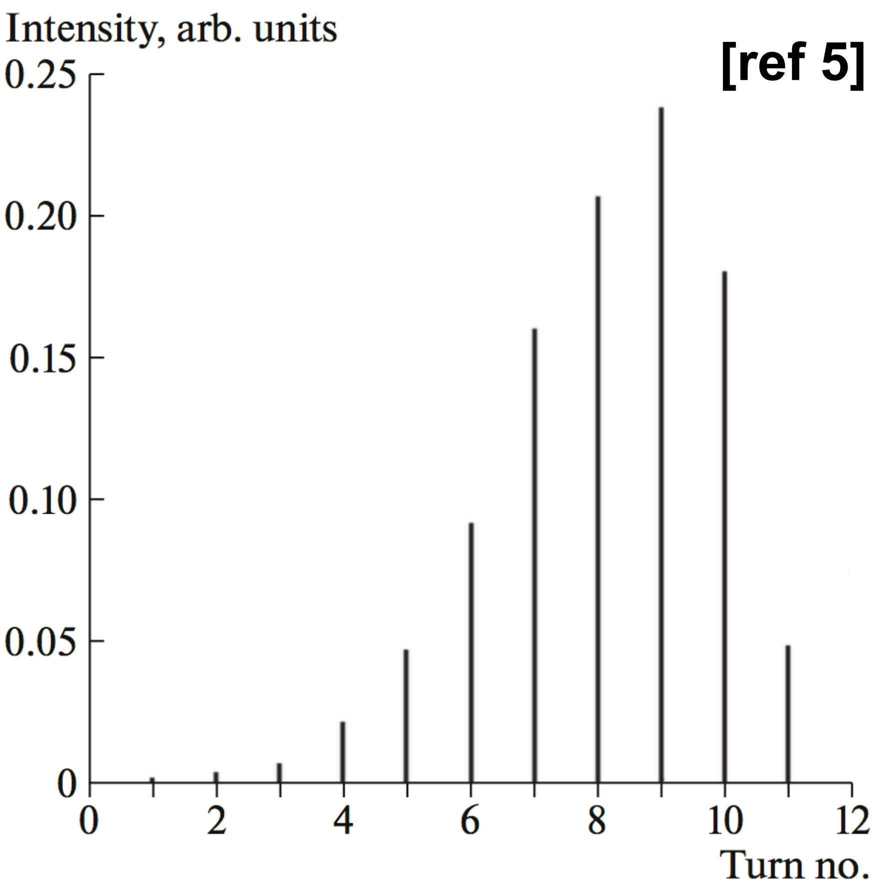
Example: LHC beam dump (2)

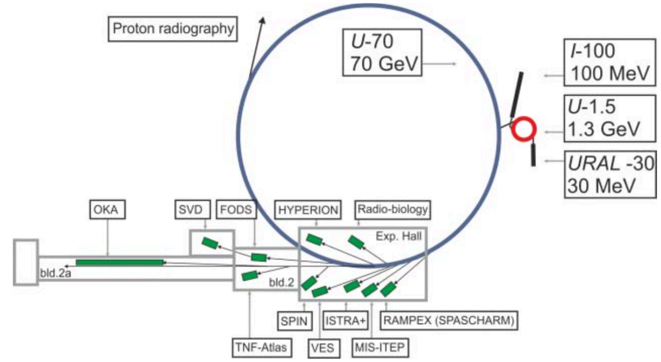


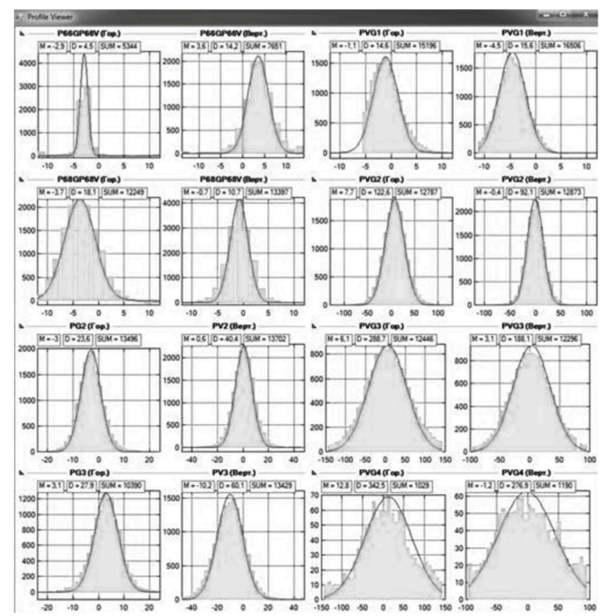
Example: U-70 IHEP-Protvino (MFE)

- Recent tests to provide a proton radiography facility with spills from the U-70 synchrotron at 70 GeV over 10 turns (≈ 50 μs):

[ref 5]



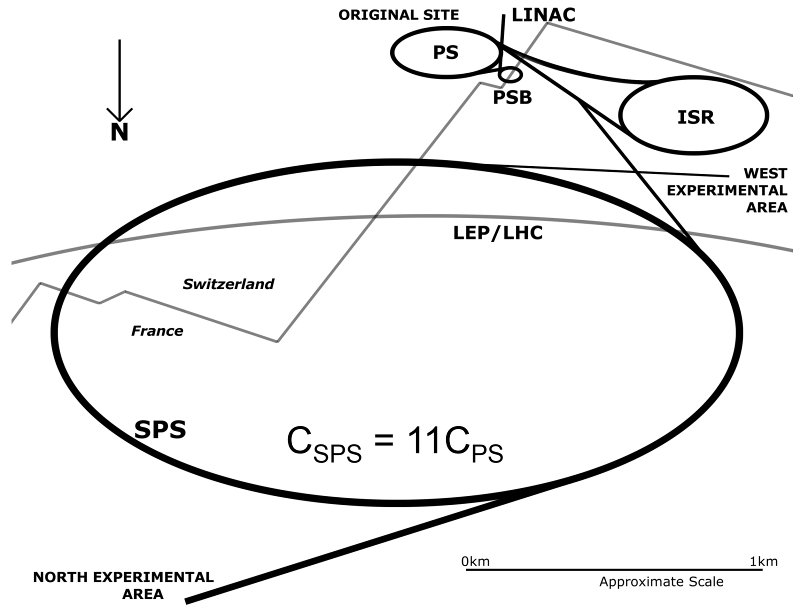




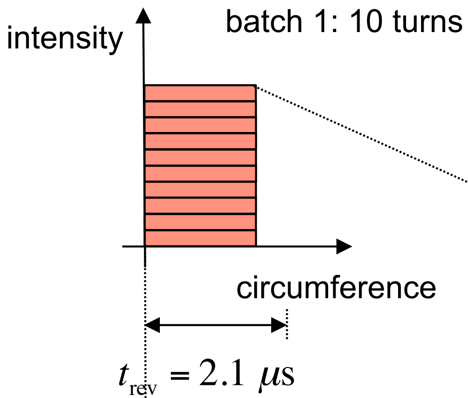
Turn-by-turn beam profiles measured in the extraction beam line

Continuous Transfer at the CERN PS

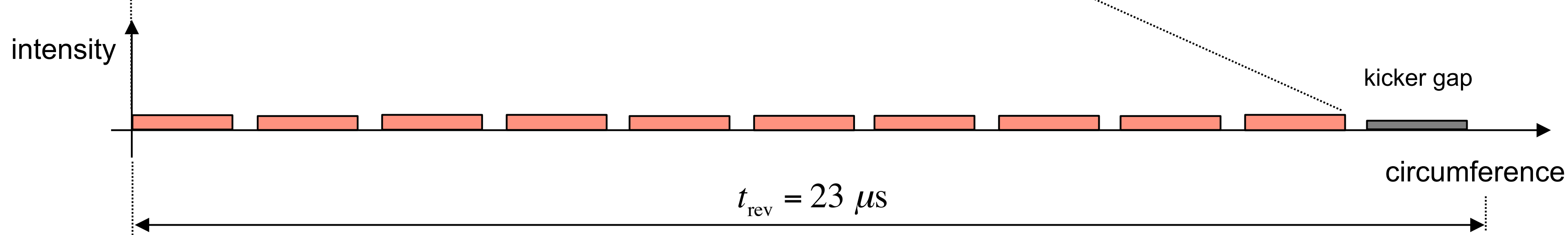
- Continuous Transfer was used at the CERN PS to fill the SPS **uniformly**:
  - a **single 10-turn transfer** was first operational with protons at **10 GeV**



PS: $I_{PS} \approx 0.7 \times 10^{12}$ p^+ per batch



SPS: $C_{SPS} = 11C_{PS}$



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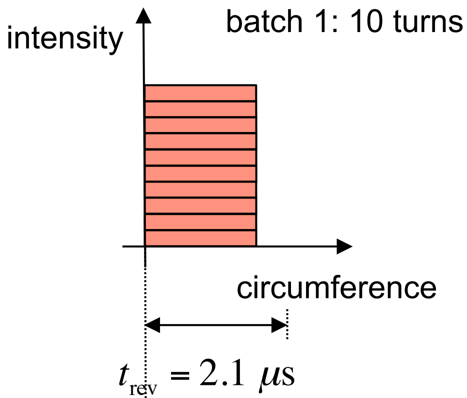


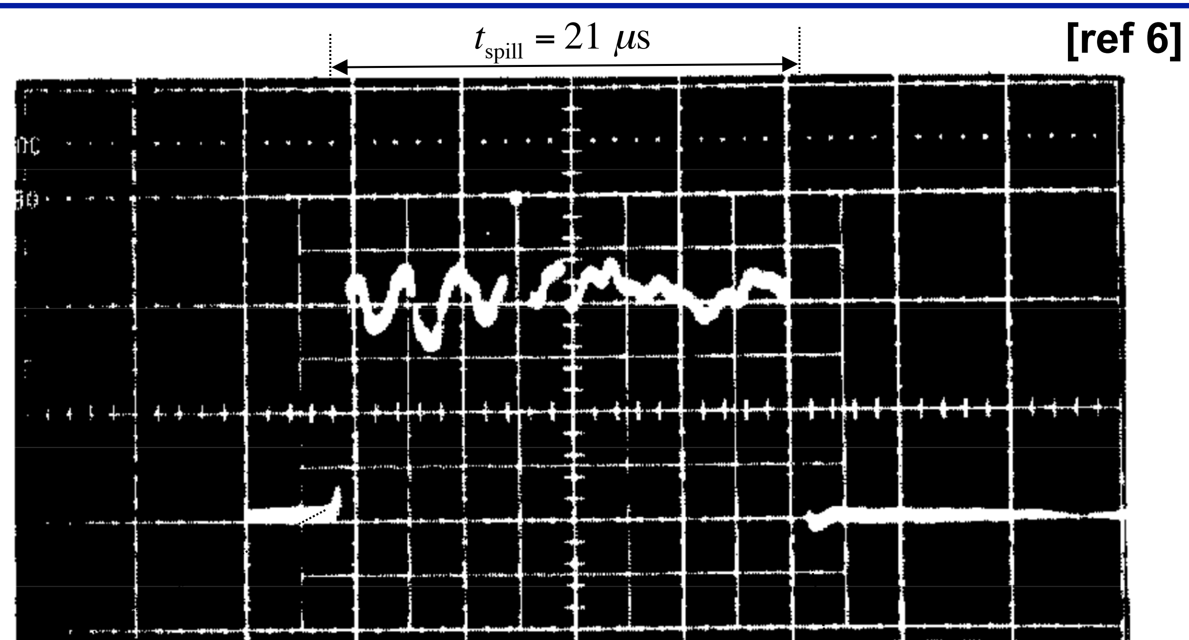
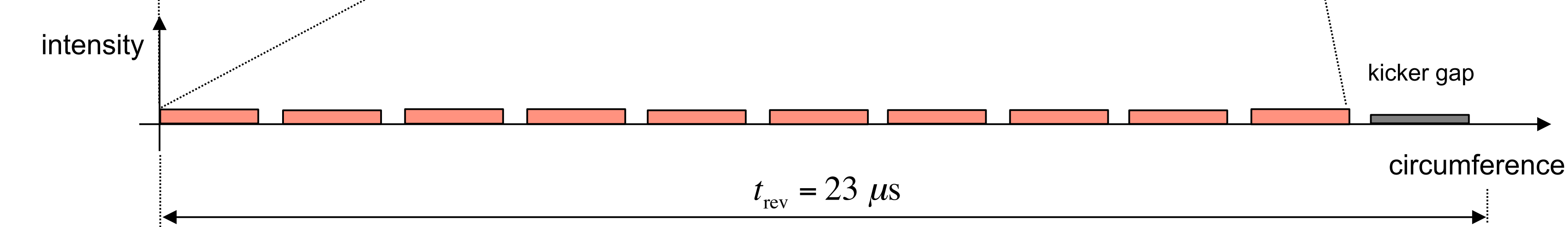


Fig. 7. Typical Ejected Beam Current 5 µs/div.

SPS: $C_{SPS} = 11 C_{PS}$



CT: extraction system layout

[ref 7]

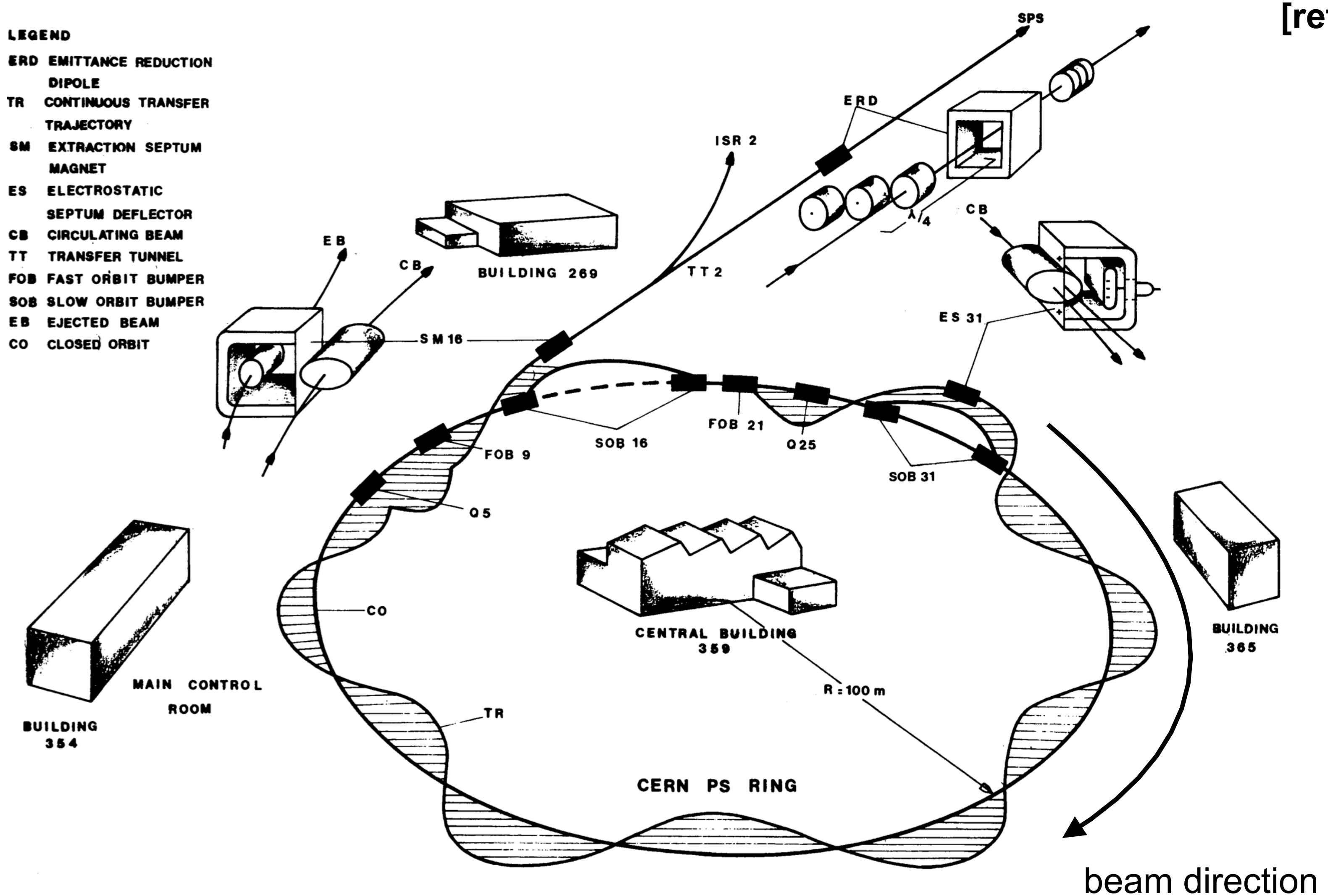
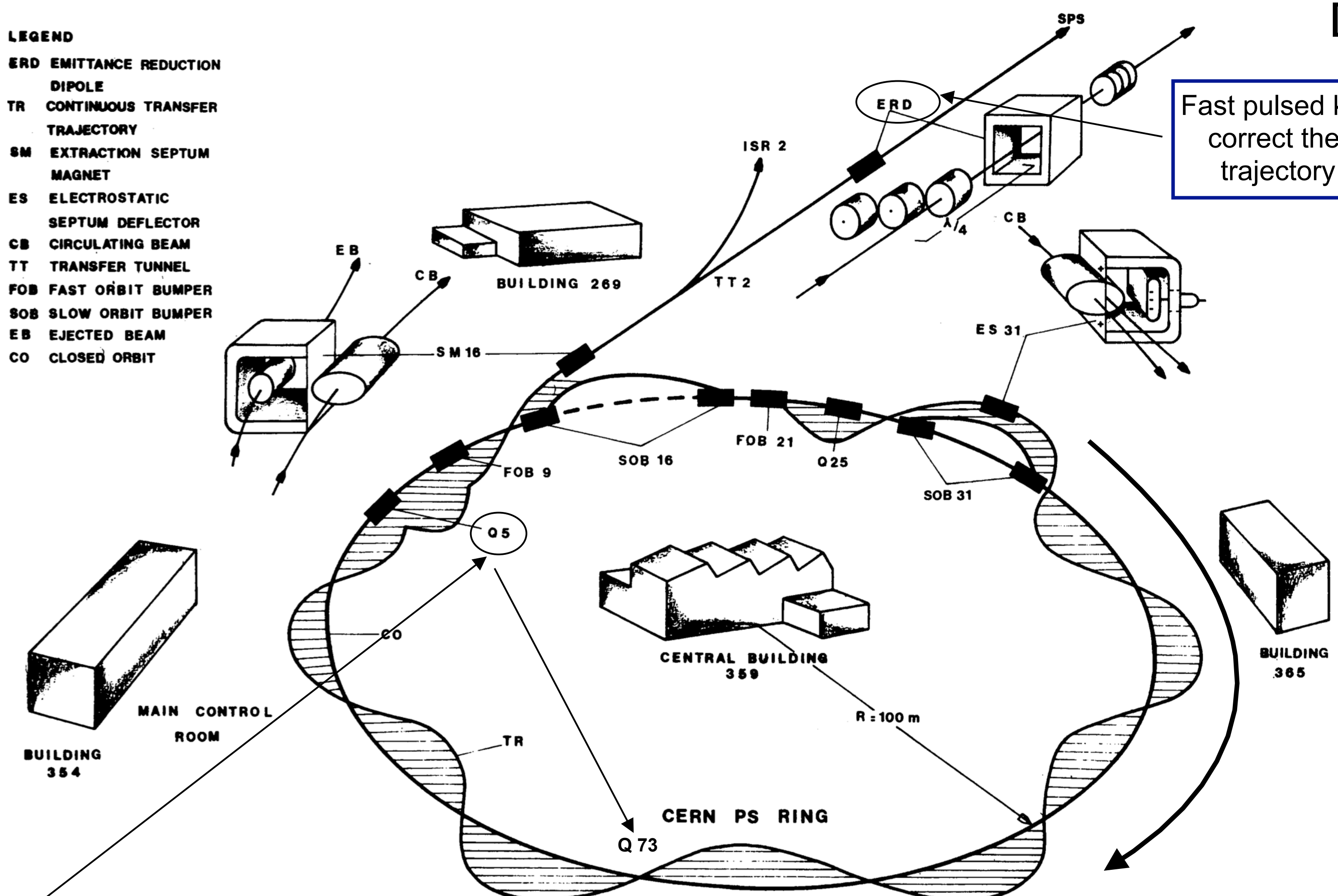


Fig. 1 Synoptic diagram of continuous transfer process

(slightly out of date… see next schematic!)

CT: extraction system layout (2)

[ref 7]



Fast pulsed kickers used to correct the turn-by-turn trajectory differences

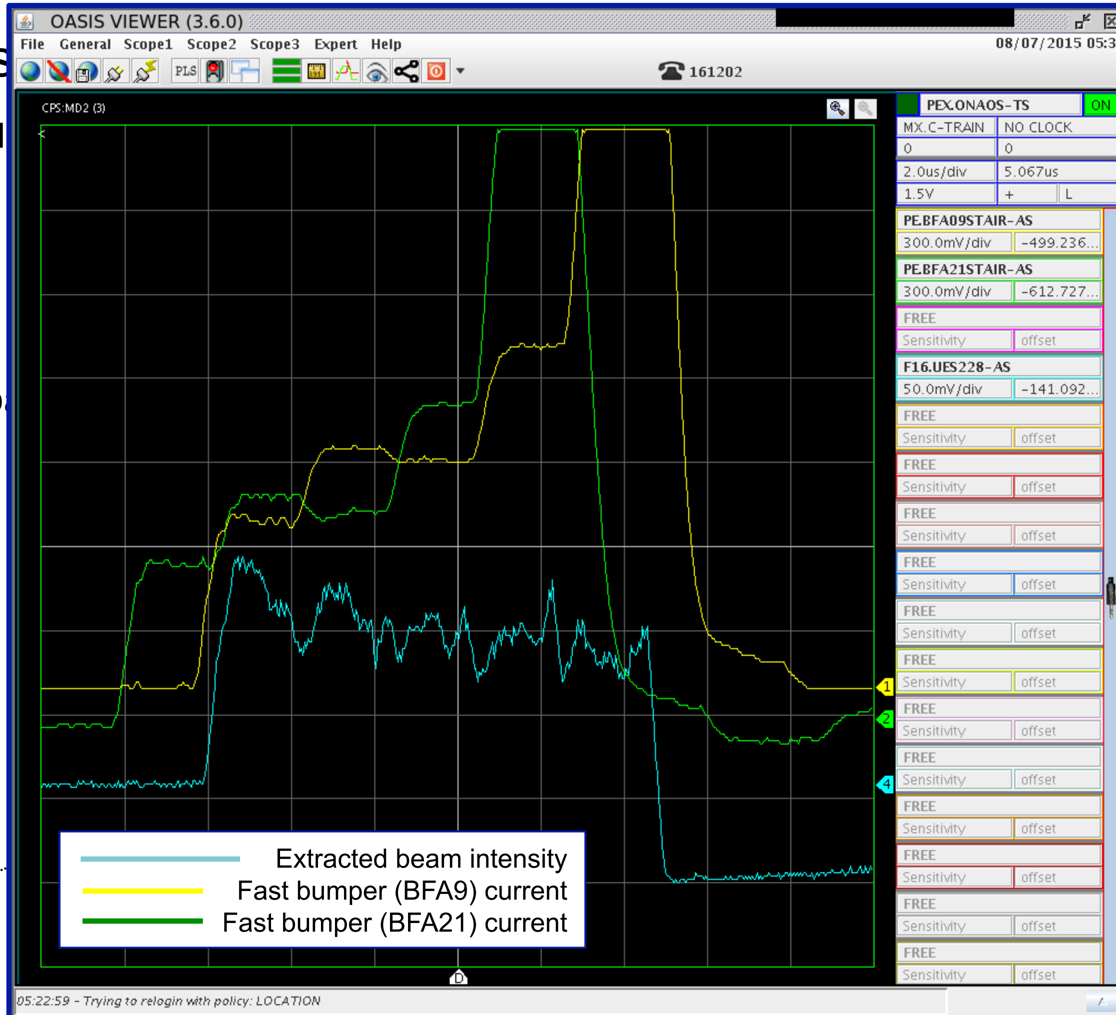
beam direction

Now moved 4π upstream to SS73 to displace losses to more shielded locations

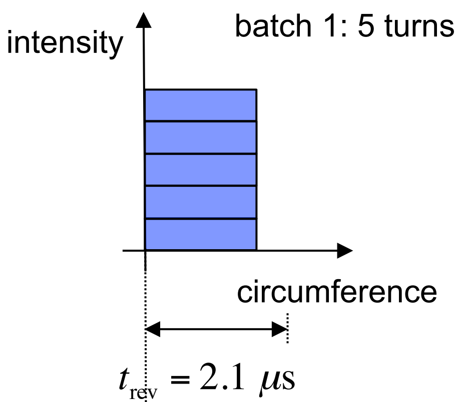
Fig. 1 Synoptic diagram of continuous transfer process

Continuous Transfer at the CERN PS

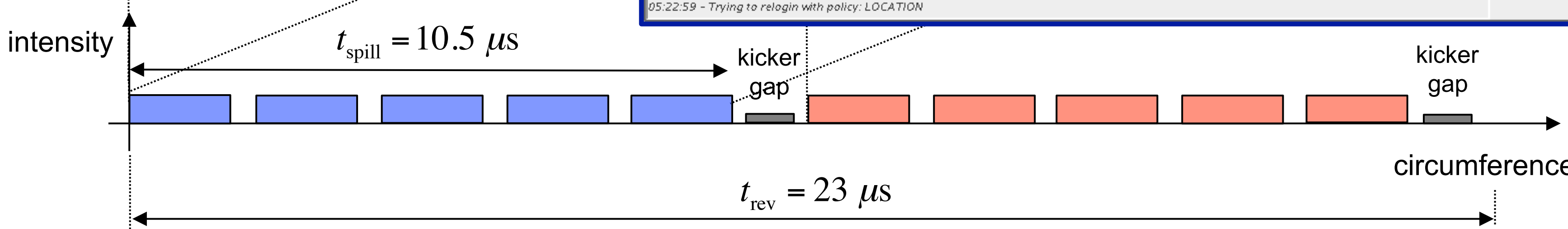
- Continuous Transfer was us
  - filling time and resulting du with 2 transfers of **5-turns**



PS: $I_{PS} = 0.1 - 3.3 \times 10^{13}$ p^+ per b



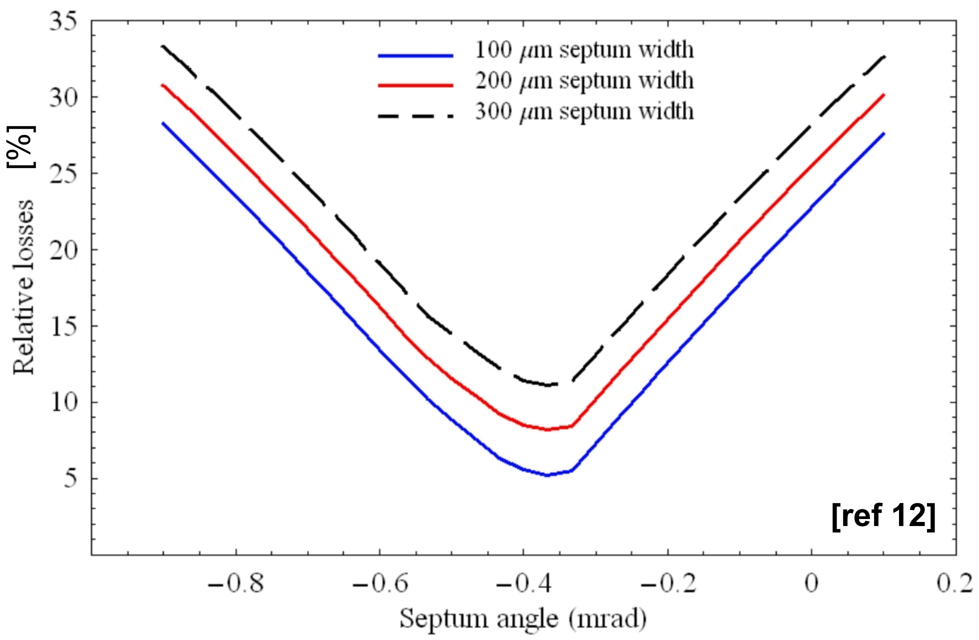
SPS: $C_{SPS} = 11C_{PS}$



CT: losses (2)

- Losses on the electrostatic septum can be understood with simple, and more advanced, simulation models:

Analytic model taking a Gaussian distribution and counting impacting particles as lost. Sensitivity to septum (SEH31) thickness and alignment evident:



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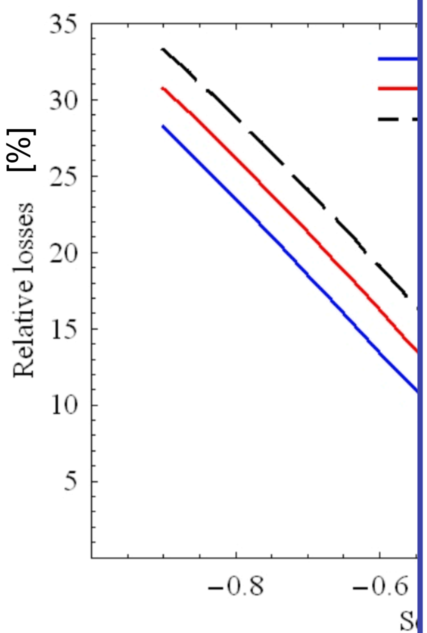
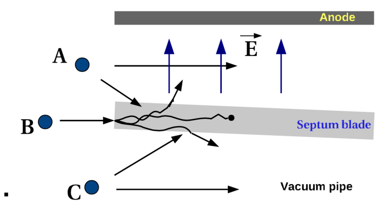
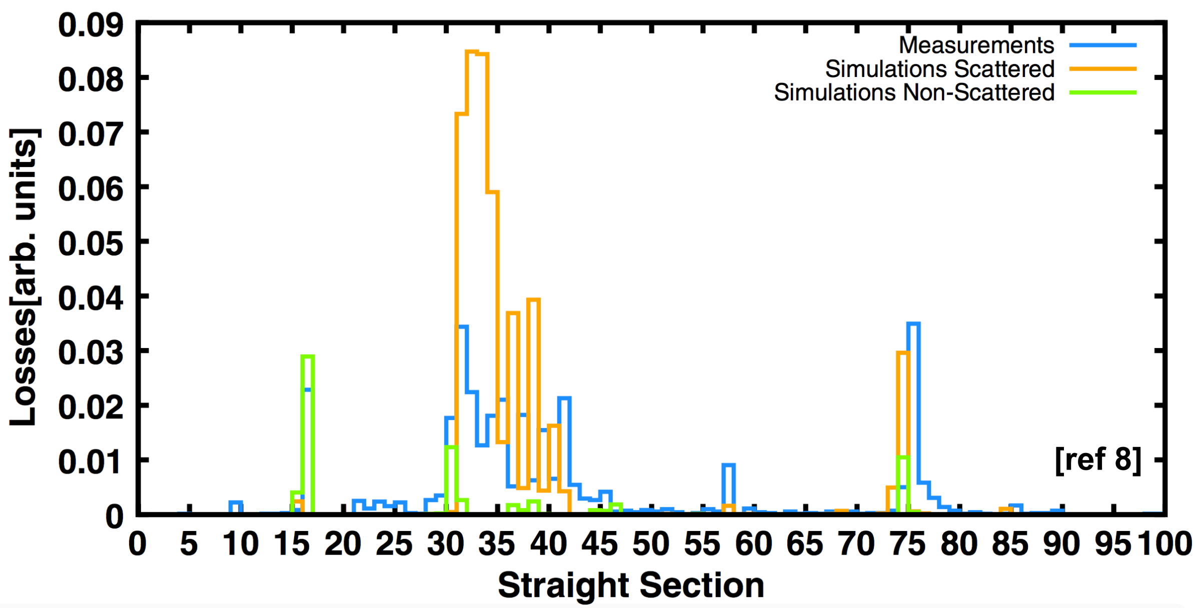


Including the scattering processes at the septum (multiple Coulomb scattering, ionization energy loss, and nuclear interactions) the loss location in the ring could be understood with tracking simulations using an aperture model (SIXTRACK):



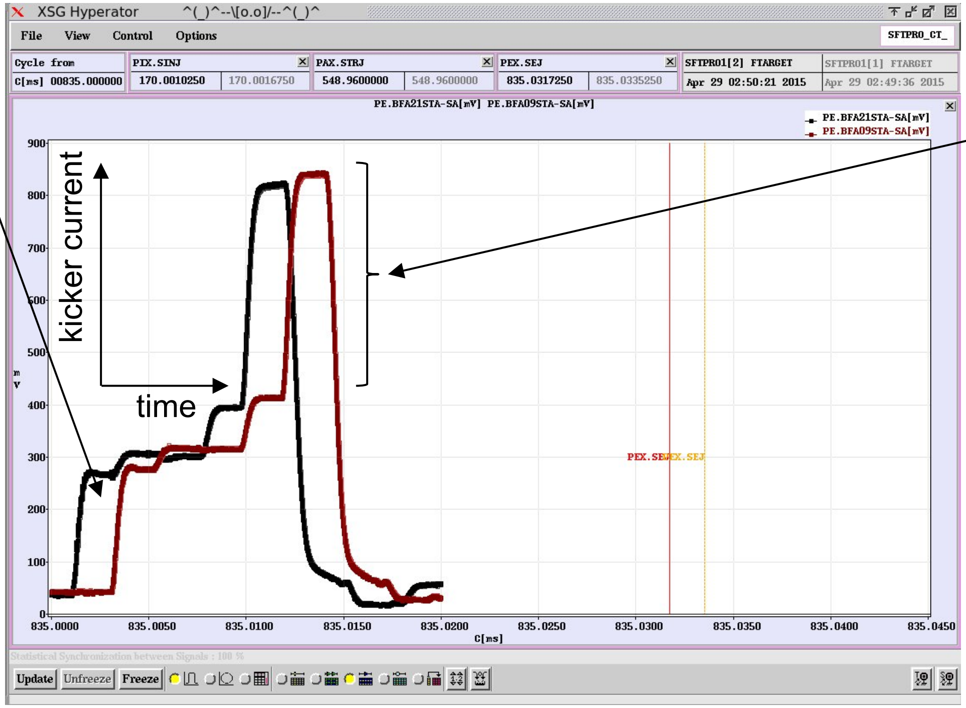


CT: operational aspects

- Electrostatic septum angle (SEH31) must be well aligned to reduce beam loss, *see the appendix for more details!*

- Spill adjusted with slow bump (BSW31) and turn-by-turn adjustment of fast bump (BFA21 – 9):

Time-of-flight between fast bumpers is important to keep bump closed turn-by-turn



Larger kick required to push 5th turn over the septum

CT: operational aspects

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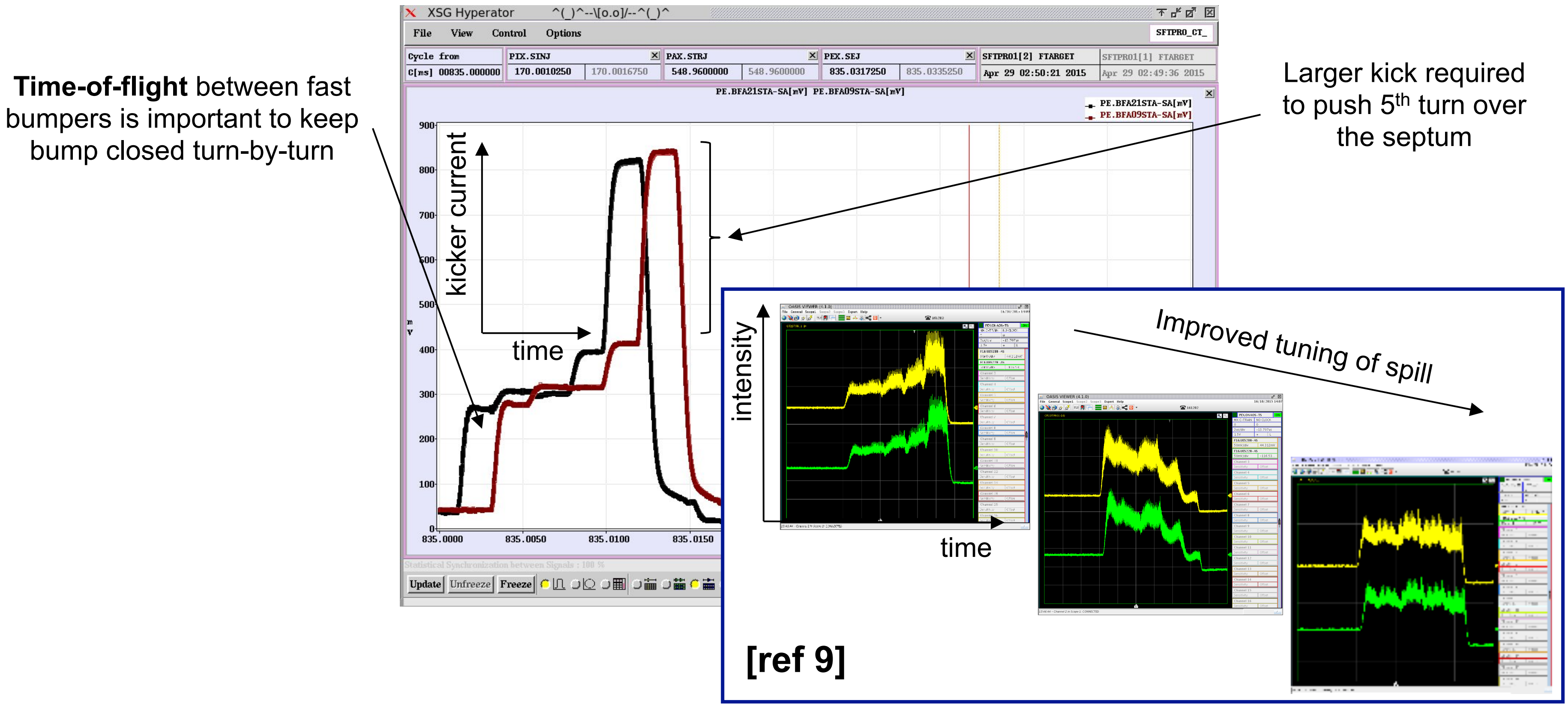
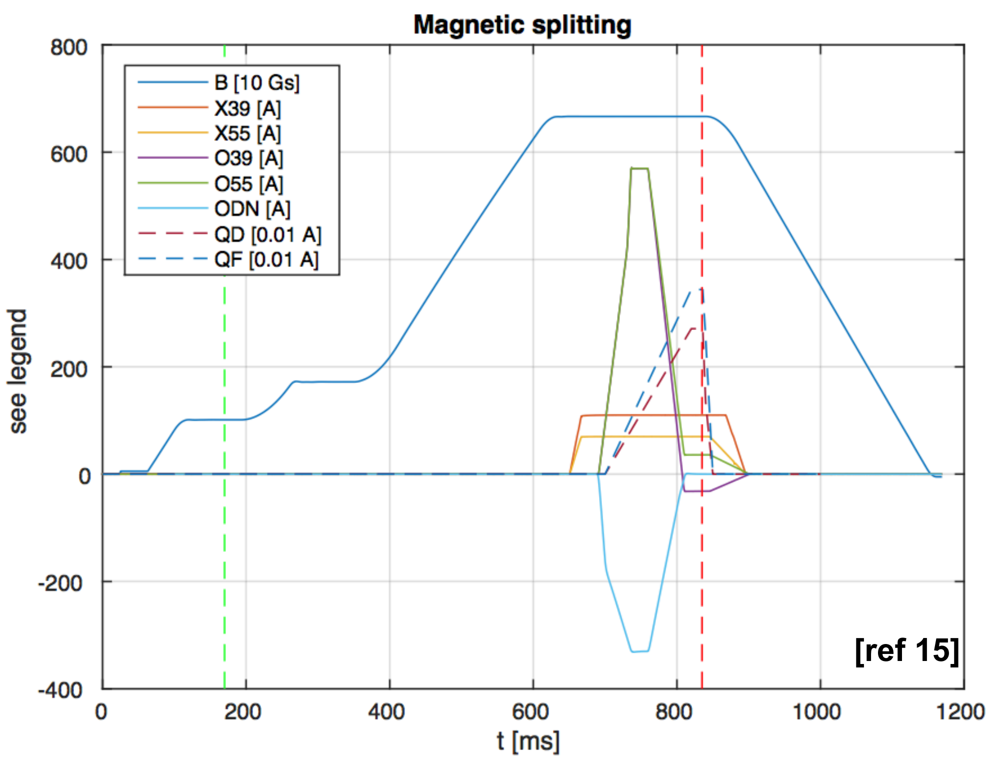
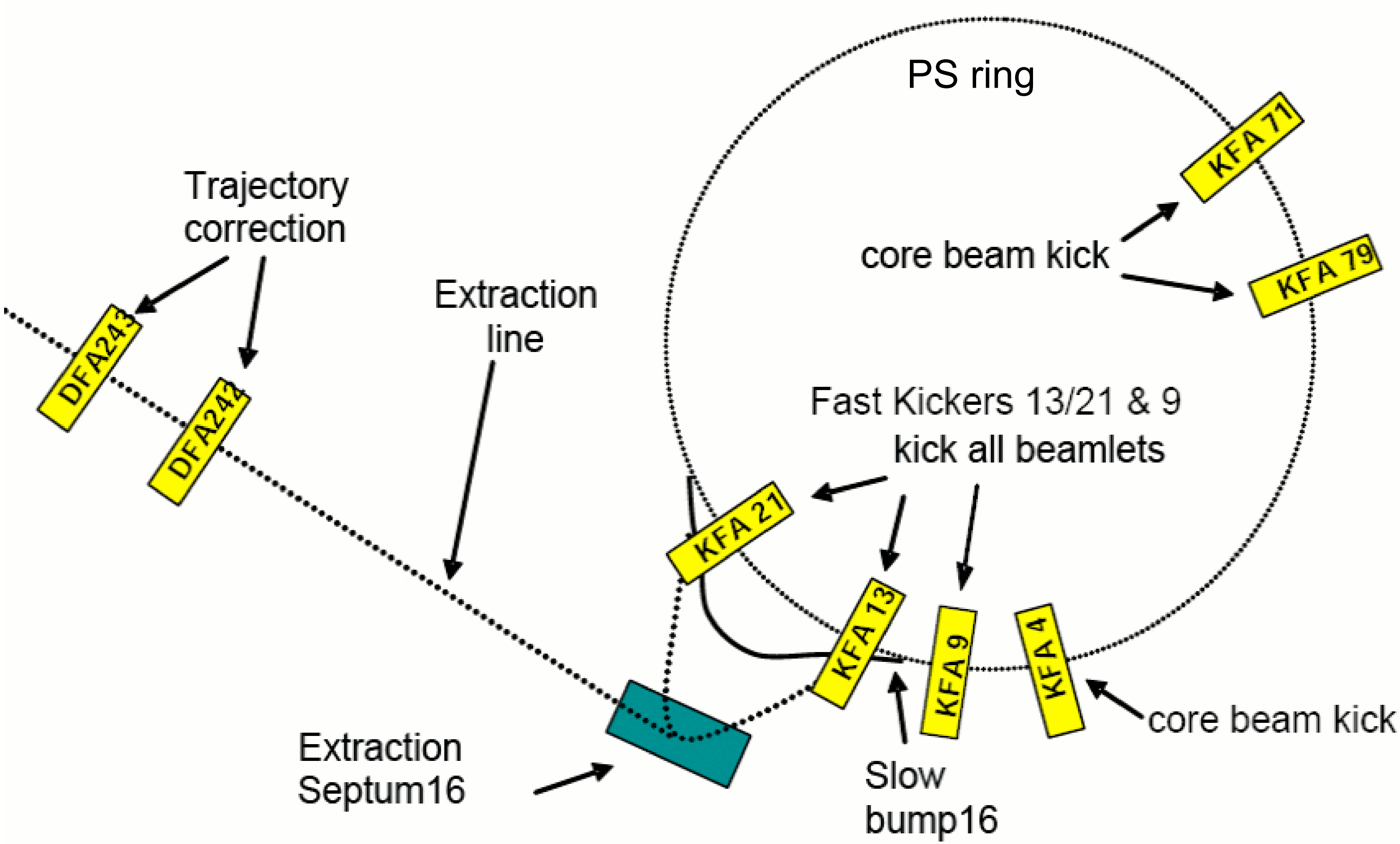


MTE cycle

- Splitting is carried out at flat-top (14 GeV):
  - non-linearities are applied (seXtupoles and Octupoles)
  - tune is swept (Quadrupoles)
  - excitation from damper applied
  - beam adiabatically debunched and partially recaptured at 200 MHz



MTE: extraction system layout



[ref 9]

Non-linear beam dynamics (2)

- We can learn a lot by tracking a few particles over a few 100 turns:

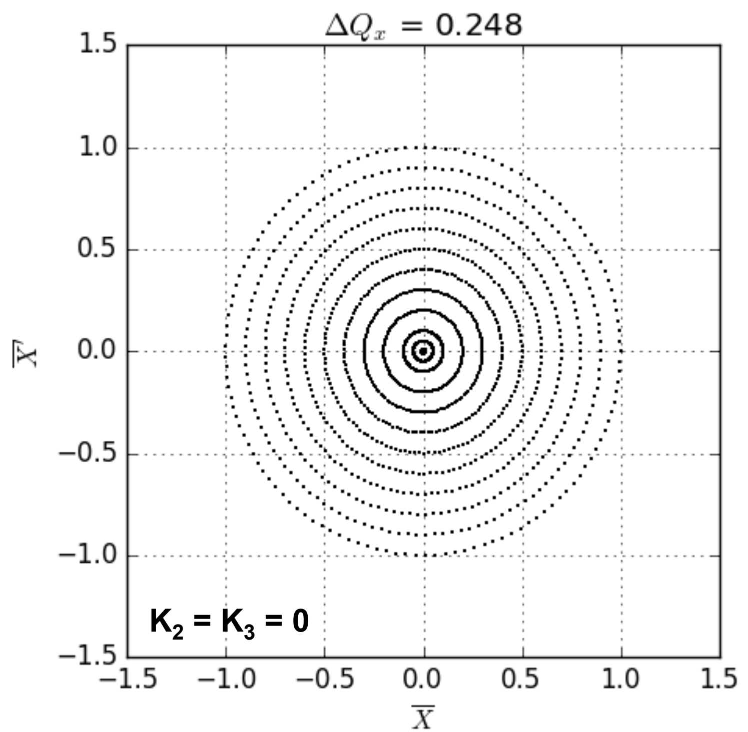
one-turn map, function of the machine tune

thin lens approximation of a sextupole and octupole at the same location in the ring

$$\begin{pmatrix} \bar{X} \\ \bar{X}' \end{pmatrix}_{n+1} = R(2\pi Q) \begin{pmatrix} \bar{X} \\ \bar{X}' + K_2 \bar{X}^2 + K_3 \bar{X}^3 \end{pmatrix}_n$$

…a Hénon map

- Example:
  - Crossing **1/4 - integer resonance**
    - i.e. Q_x = integer + 0.25
  - **Sextupole OFF and octupole OFF:**
    - $\mathbf{K_2 = K_3 = 0}$
  - Ramping tune from below resonance:
    - ΔQ_x = 0.248 to 0.252
  - 12 particles, 1000 turns



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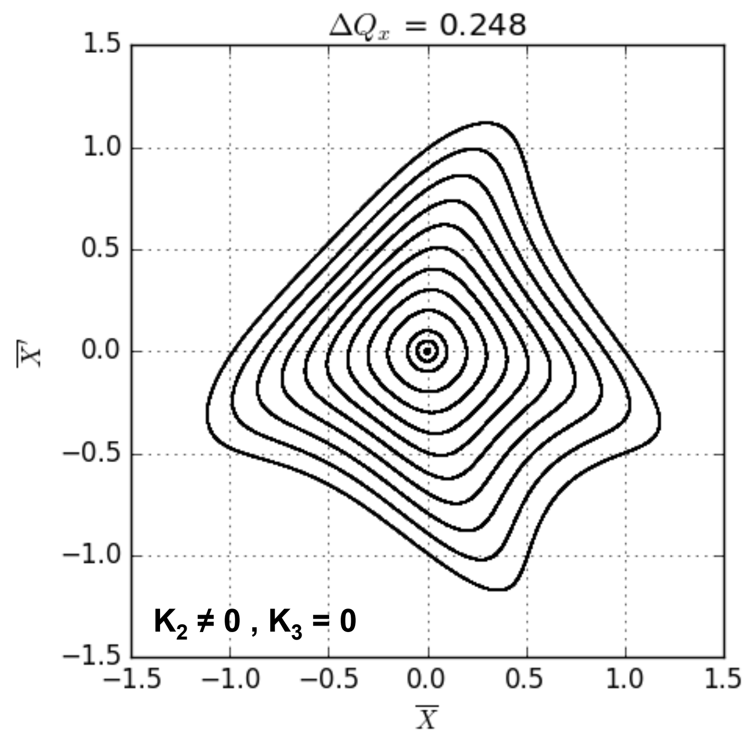

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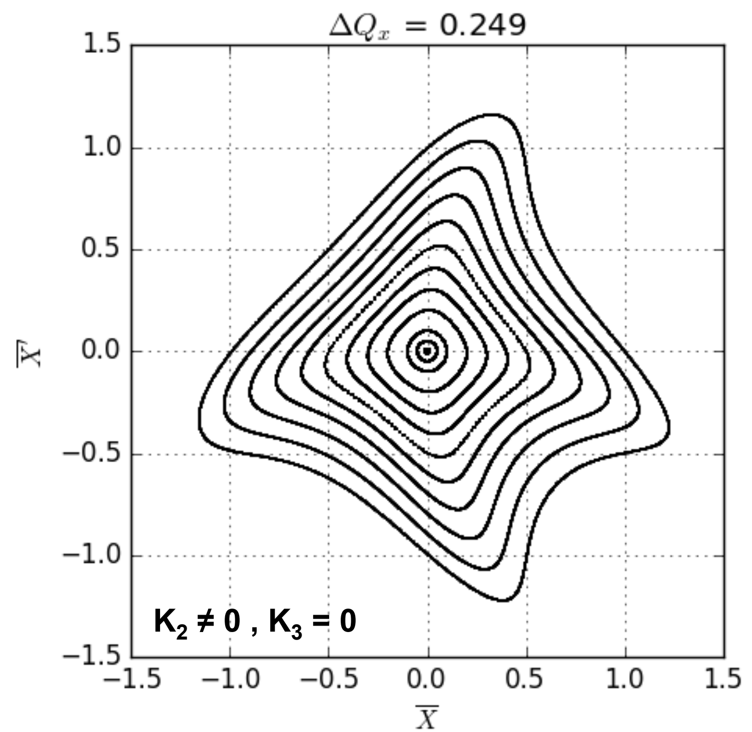

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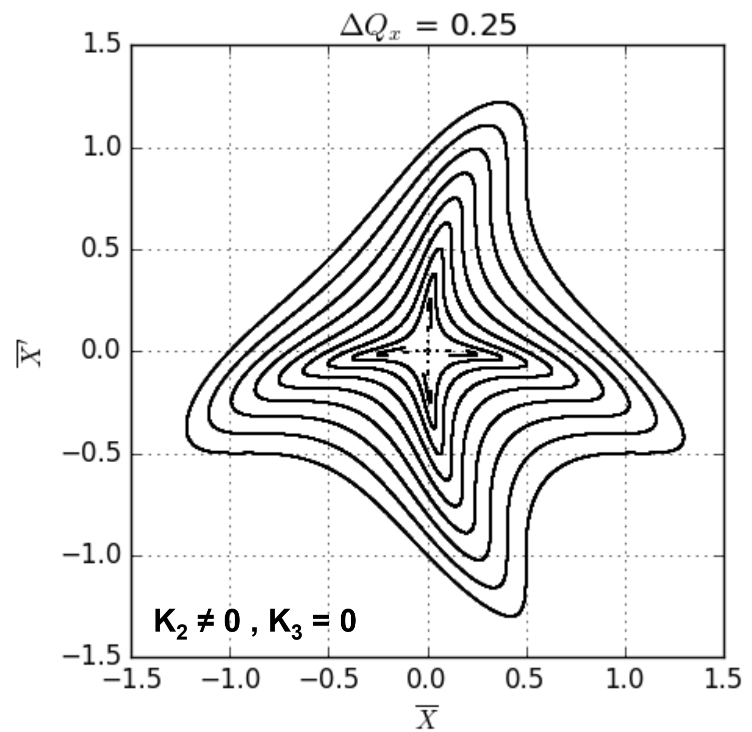

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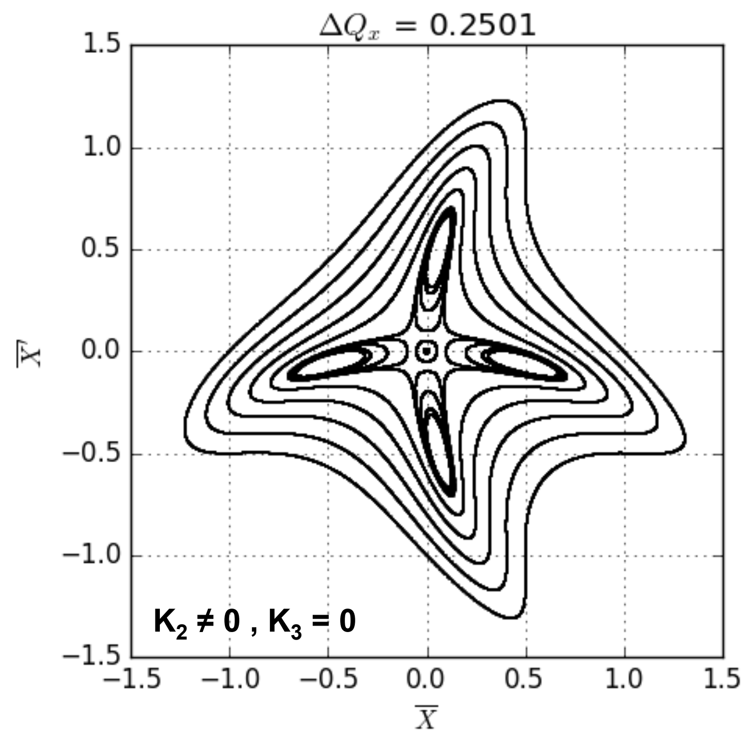

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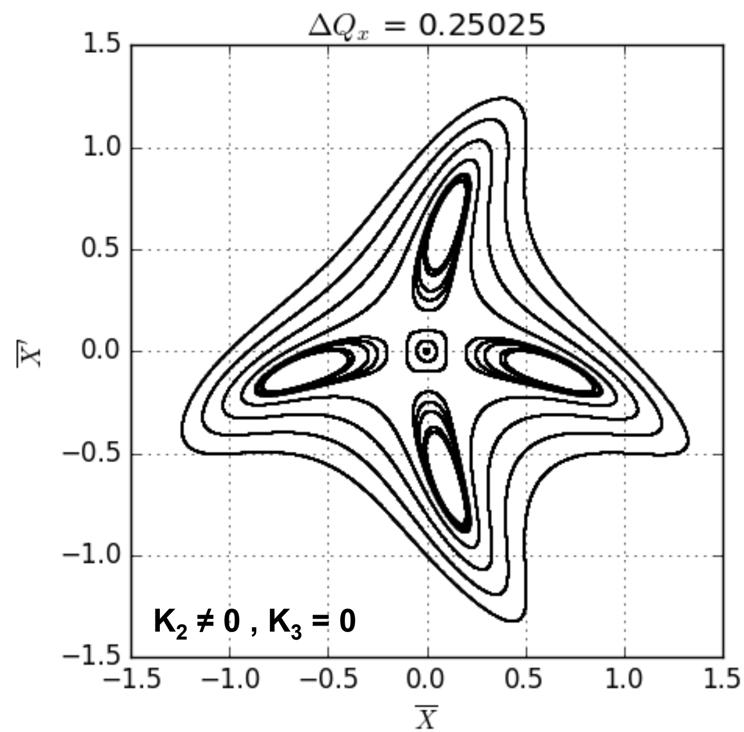

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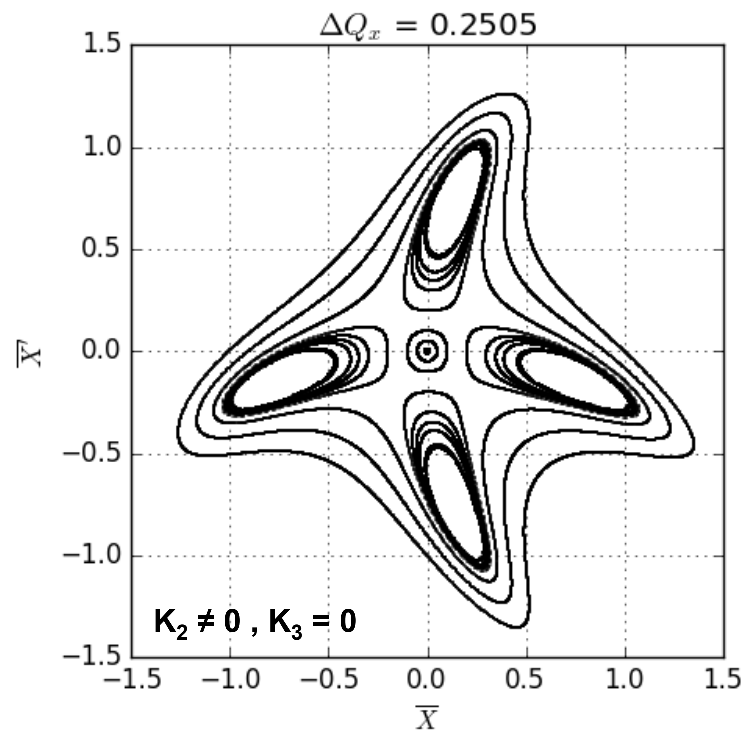

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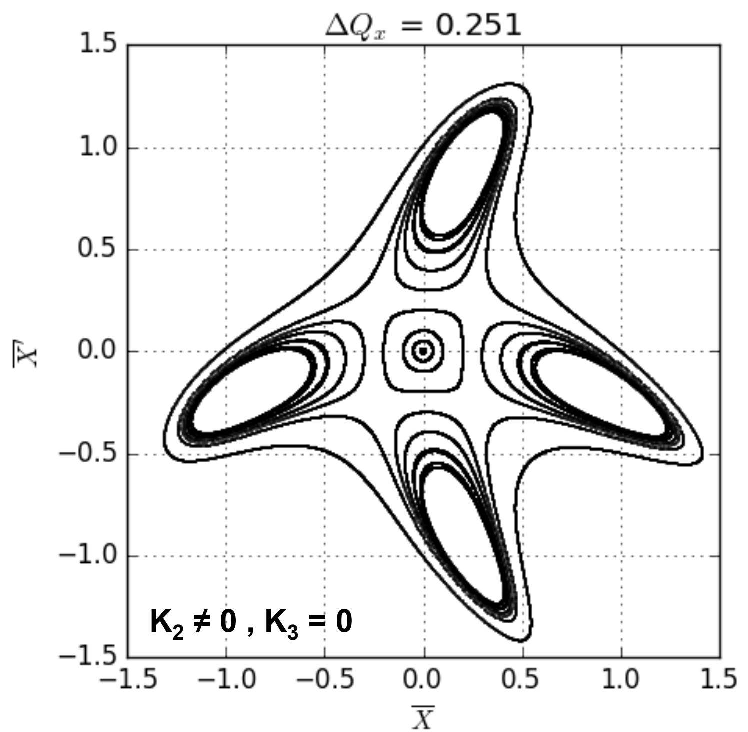

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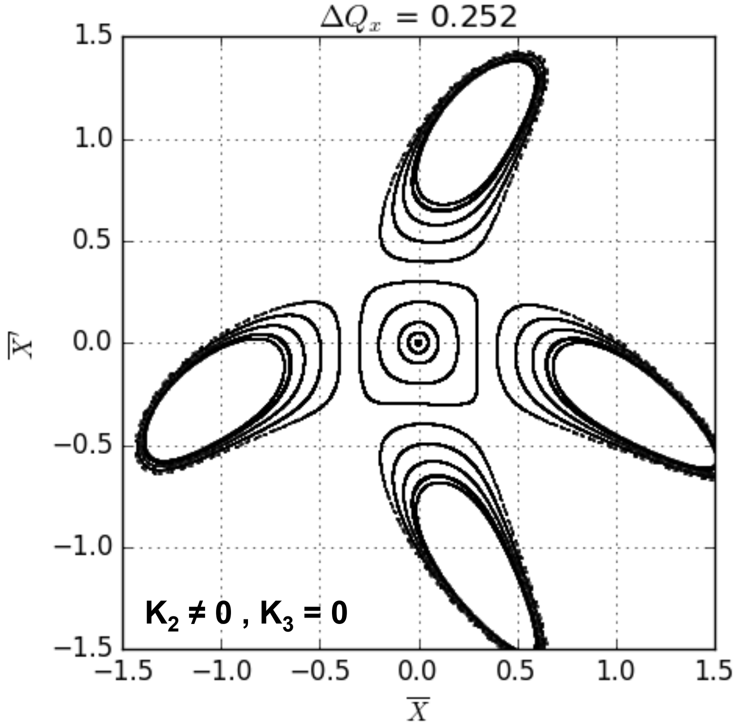
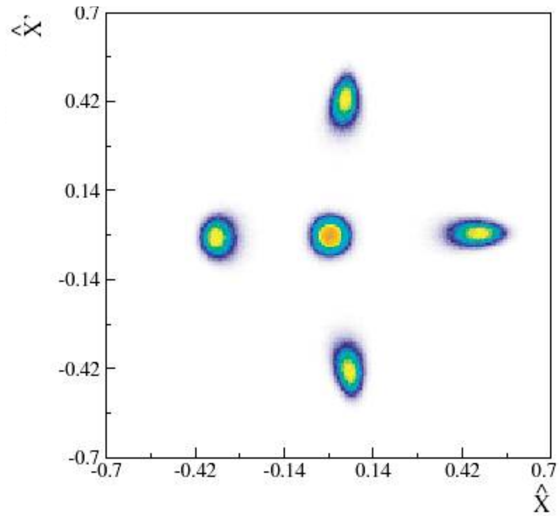
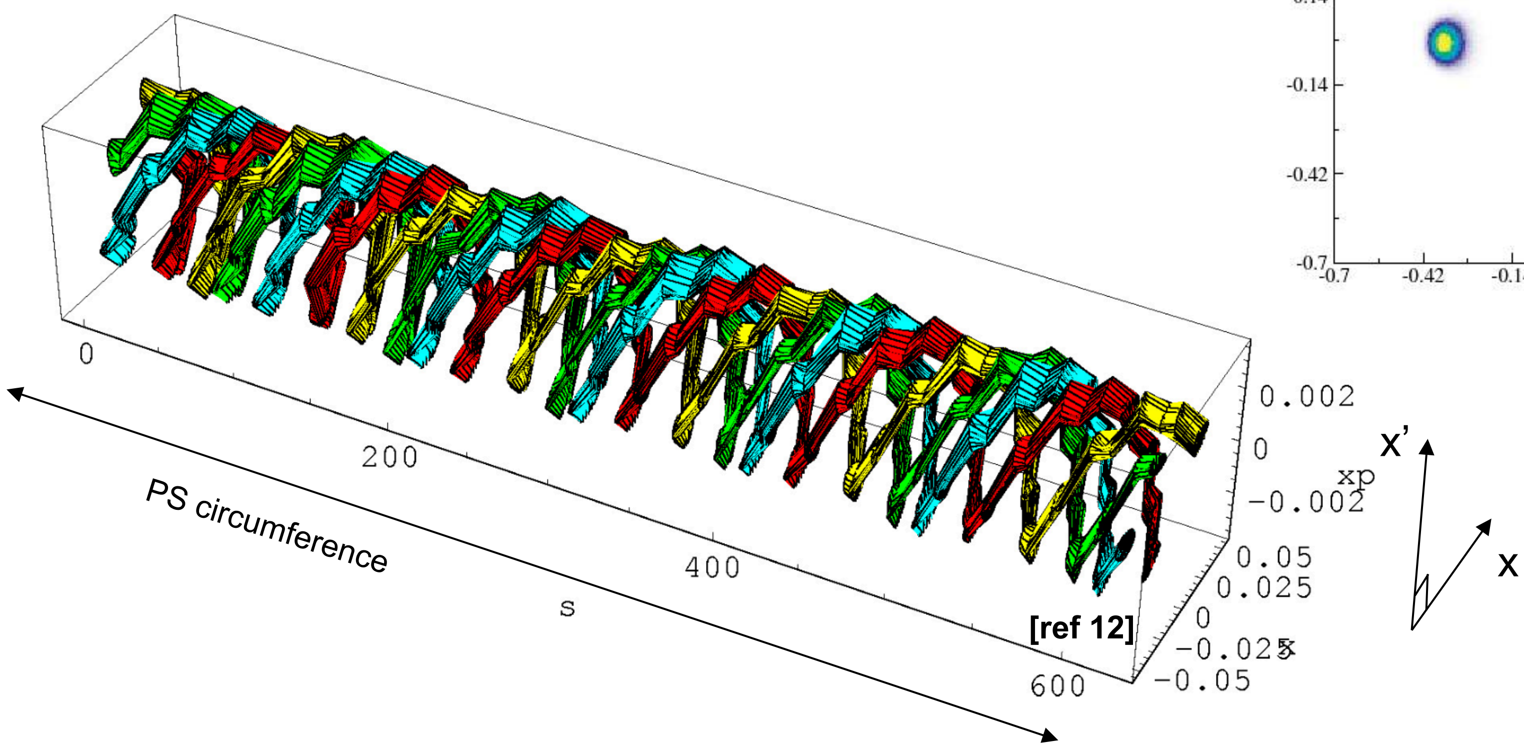


How many beams ?!

- In the PS case we end up with two beams circulating on distinct closed orbits in the machine (in the horizontal plane):
  - the islands are a separate, continuous entity (if de-bunched) wrapped around the machine circumference 4 times
  - the core circulates as usual
- Two fast "kicks" (islands + core) to extract





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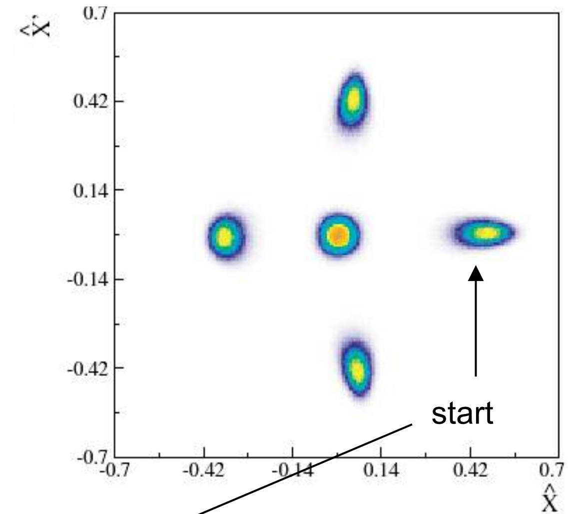

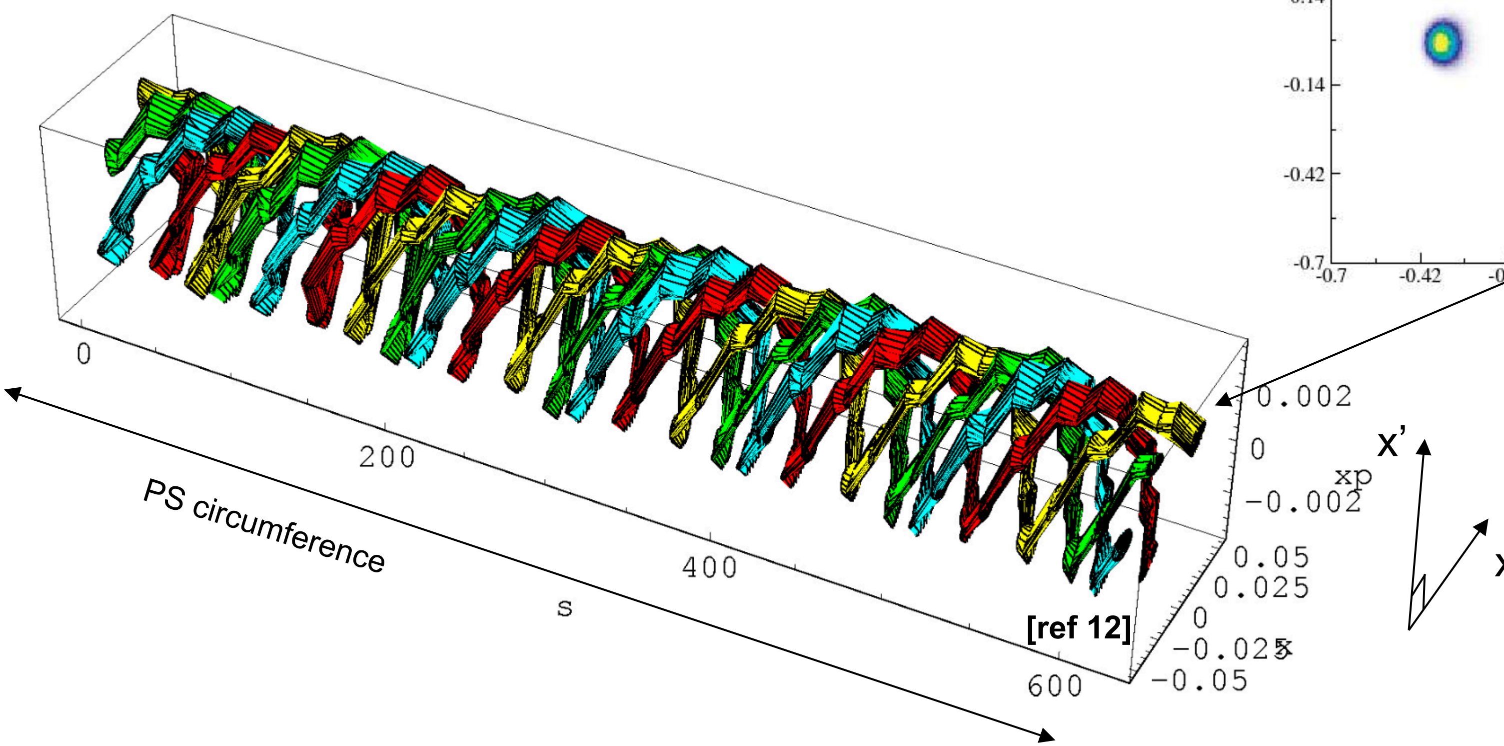

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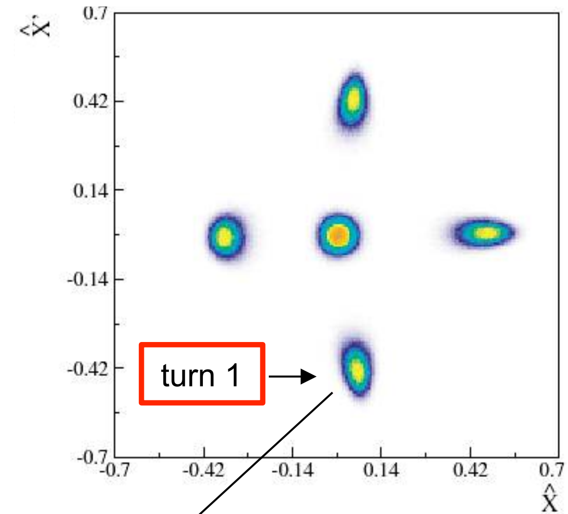

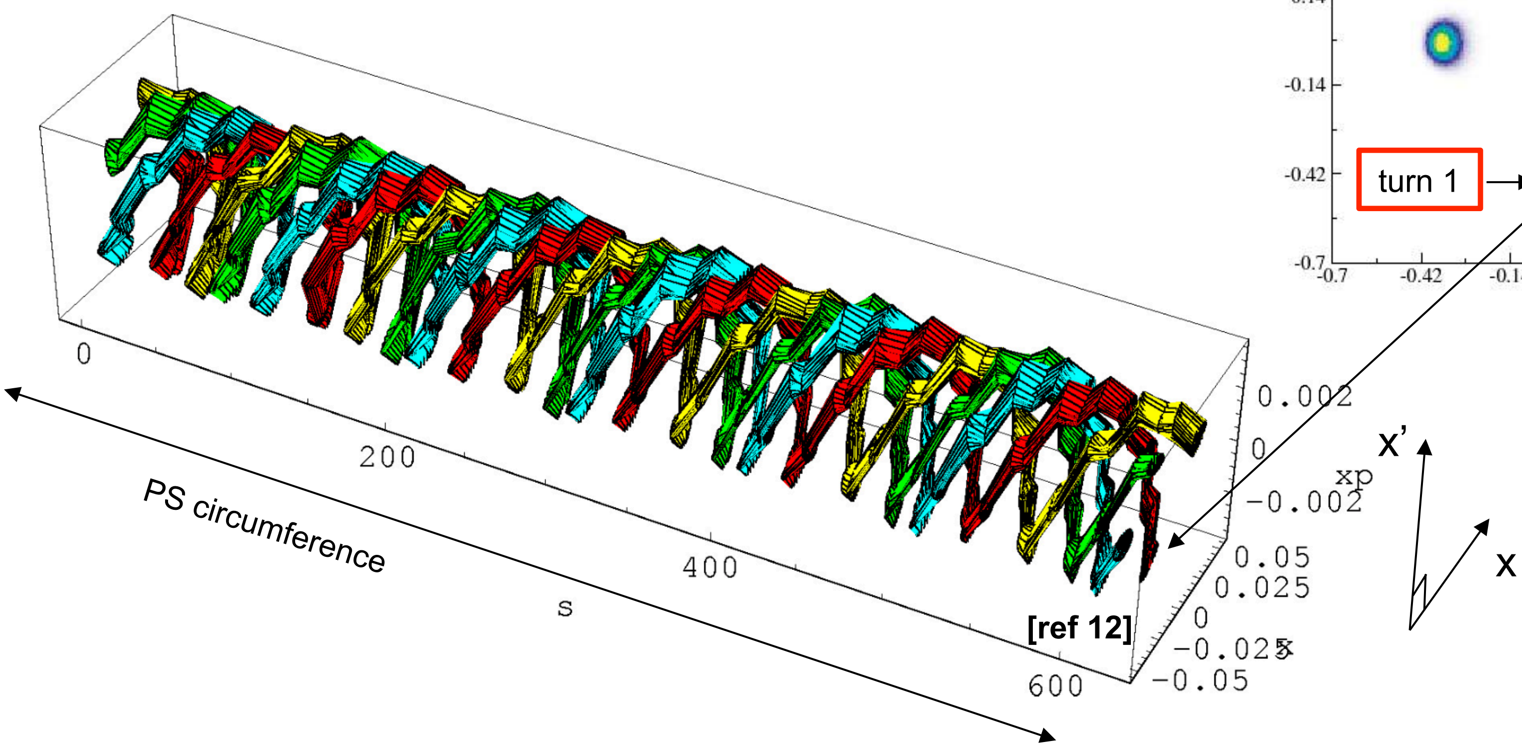

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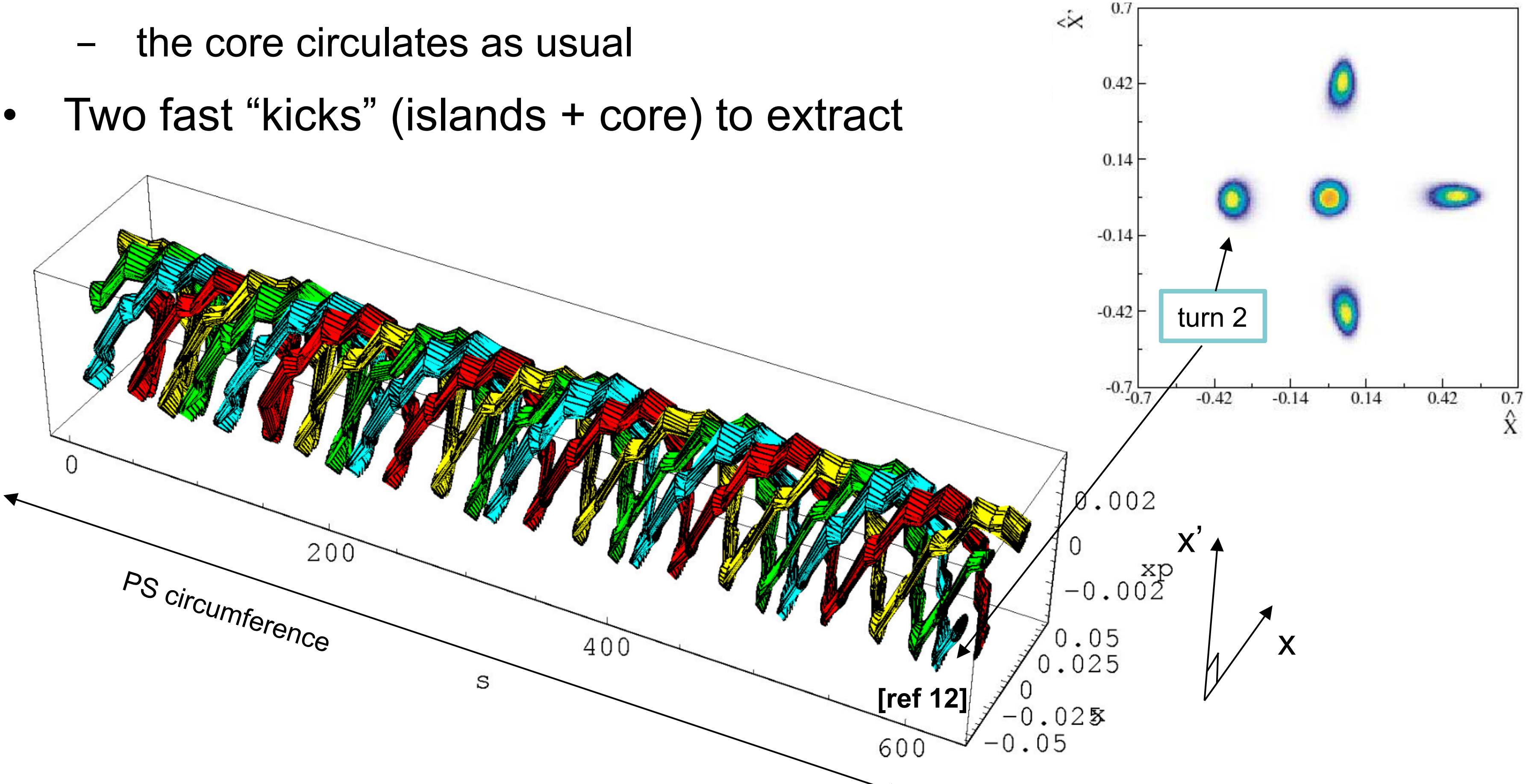

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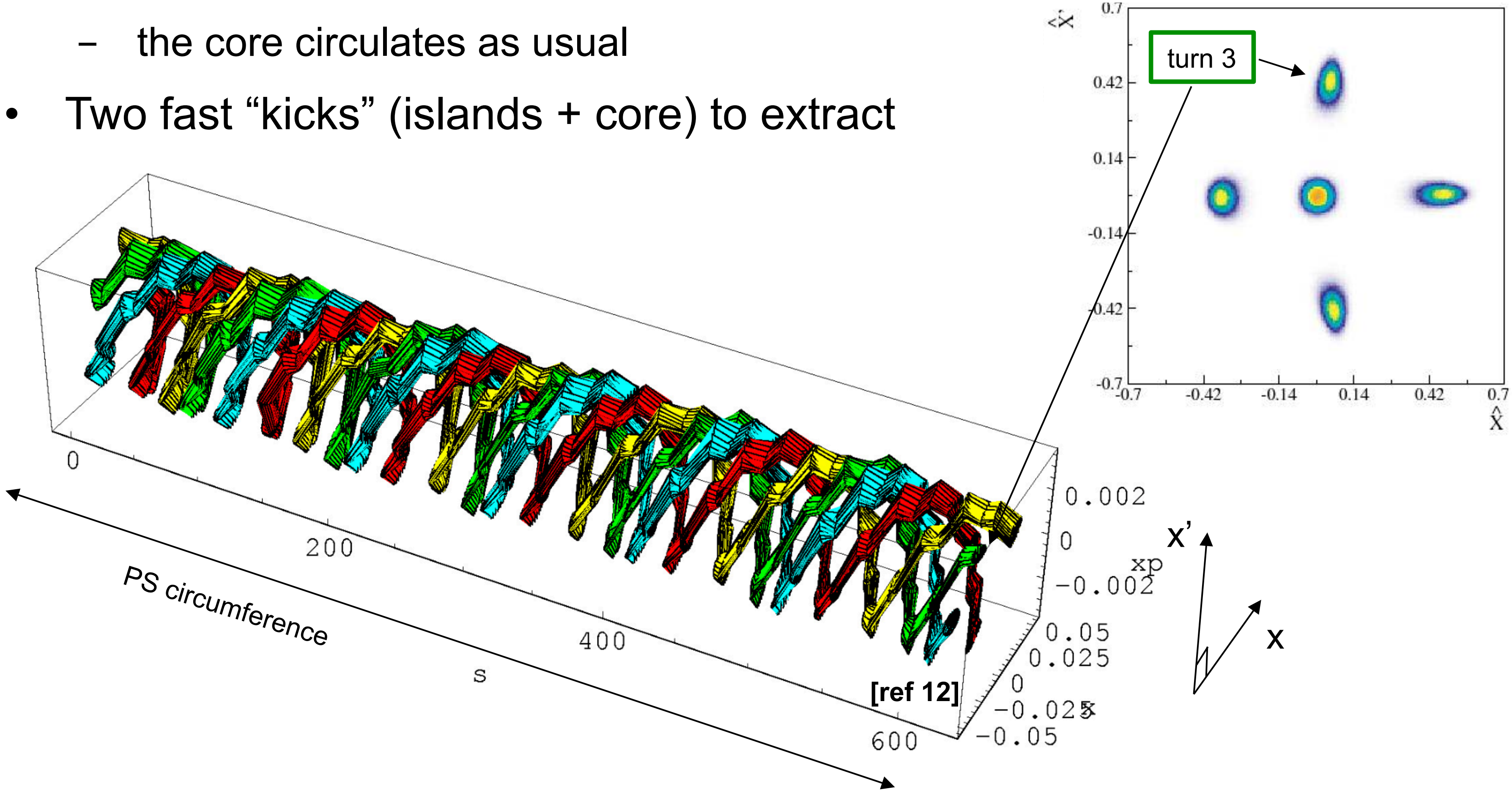

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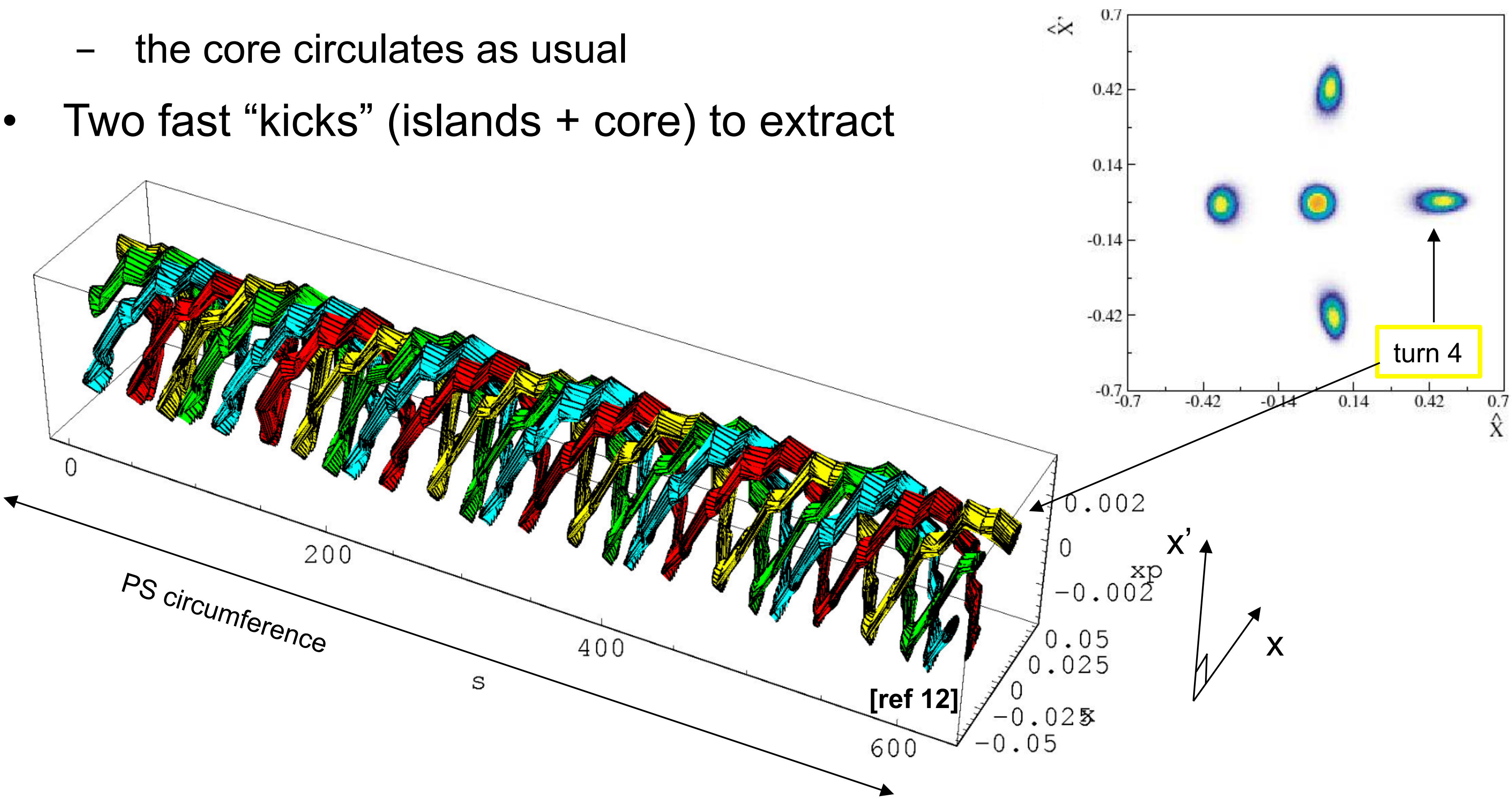
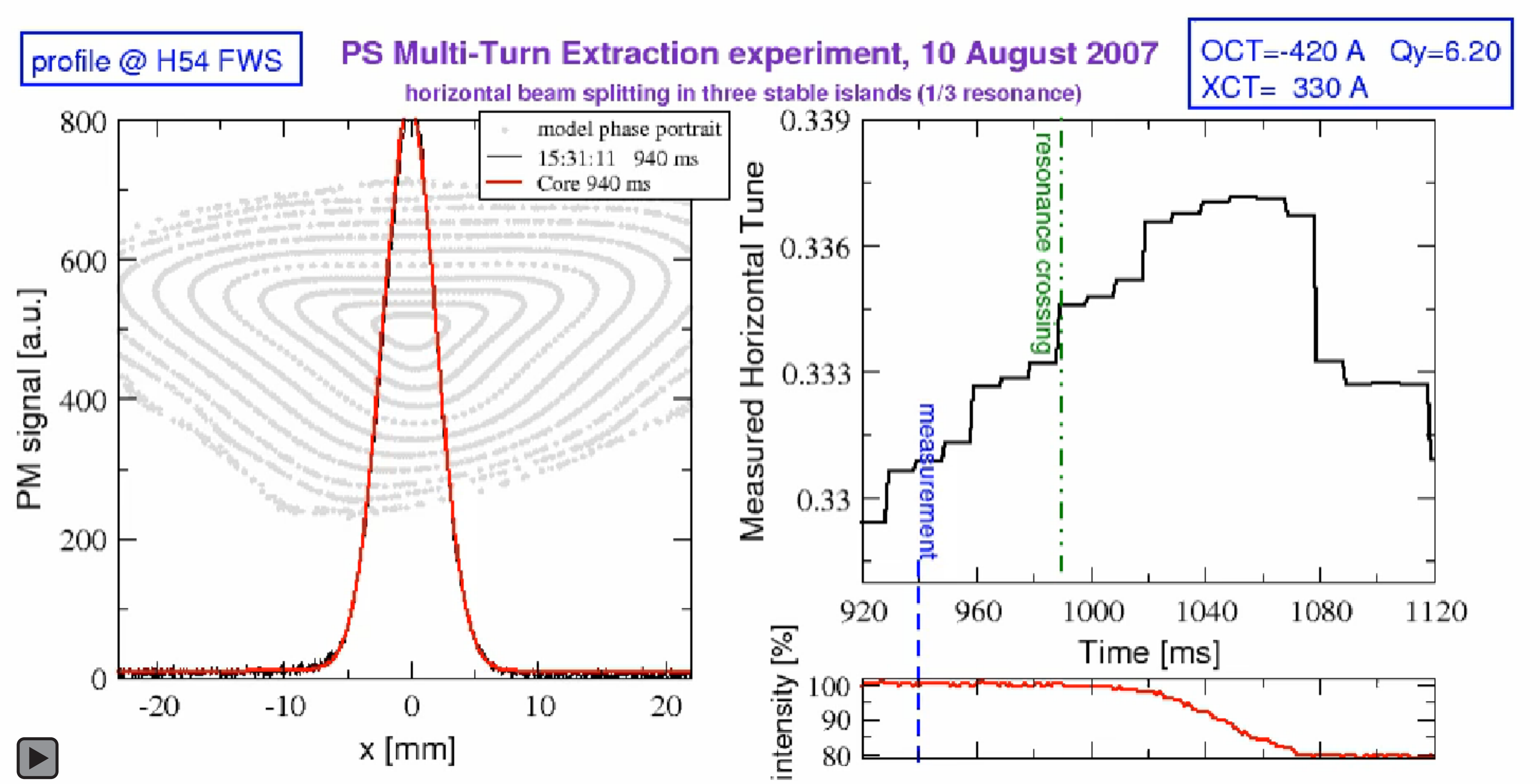


PS test: splitting in three stable islands **[ref 13]**

Exciting the unstable 1/3rd resonance the central island (beam core) is depleted. In the movie the evolution of the beam profile is shown. It was measured at a single machine section by means of horizontal flying wire installed in section 54 of the CERN Proton Synchrotron. Essentially no losses are observed for a moderate separation of the beamlets. No optimization of the working point was performed due to problems with the beam instrumentation. The beam used is a **single-bunch**, **medium-intensity** (about 2.6×10^{12}) proton beam.



PS test: splitting into six stable islands **[ref 13]**

The 1/5th stable resonance was also crossed. No beam losses were observed. The beam used is a **single-bunch**, **medium-intensity** (about 2.6x10^{12}) proton beam. The movie shows a superposition of different measurements in terms of the octupole settings during the trapping process