CERN PS MULTI TURN EXTRACTION

Manipulation of transverse beam distribution in circular accelerators: beam splitting by particles' trapping into resonance islands

M. Giovannozzi

Summary:

- Introduction
- Present multi-turn extraction
- New multi-turn extraction (MTE)
- Other applications
- Measurement results
- Conclusions

Introduction - I

Three approaches are normally used to extract beam from a circular machine:

Fast Extraction (one turn)

- A kicker (fast dipole) displaces the beam from nominal closed orbit.
- A septum magnet deflects displaced beam towards transfer line.
- This extraction can be used both to transfer beam towards a ring or an experimental area.

Multi-turn!

What is in between?

Slow Extraction (millions turns)

- The separatix of the third-order resonance increases particles' amplitude until they jump beyond the septum.
- The tune is changed to shrink the stable region, thus pushing the particles towards larger amplitudes.
- This extraction is used to transfer beam towards an experimental area.

Introduction - II

Multi-turn extraction

- The beam has to be "manipulated" to increase the effective length beyond the machine circumference.
- This extraction mode is used to transfer beam between circular machines.
- AT CERN this mode is used to transfer the proton beam between PS and SPS. In the SPS the beam is used for
  - Fixed Target physics (broad sense)
  - Neutrino experiments (until 1998)
  - CERN Neutrino to Gran Sasso (CNGS) (from 2006)
- These beams are high-intensity (about 3×10^{13} p in the PS).

Present multi-turn extraction - I

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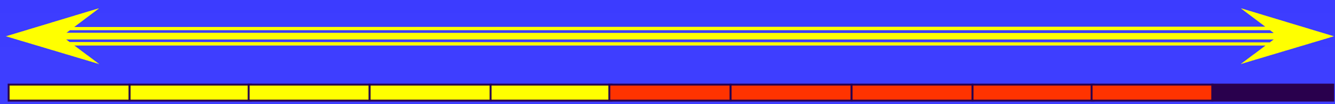
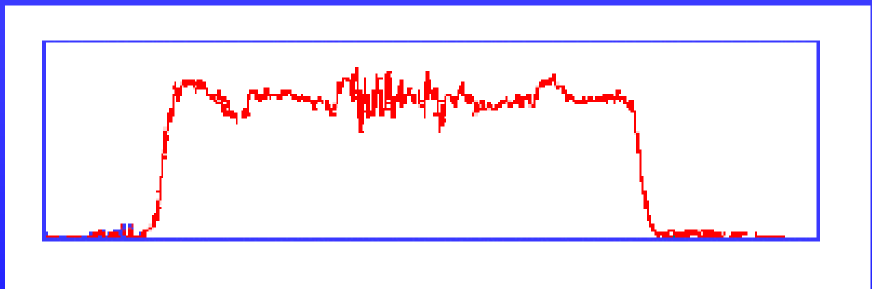
$C_{SPS} = 11\ C_{PS}$

PS PS

SPS circumference



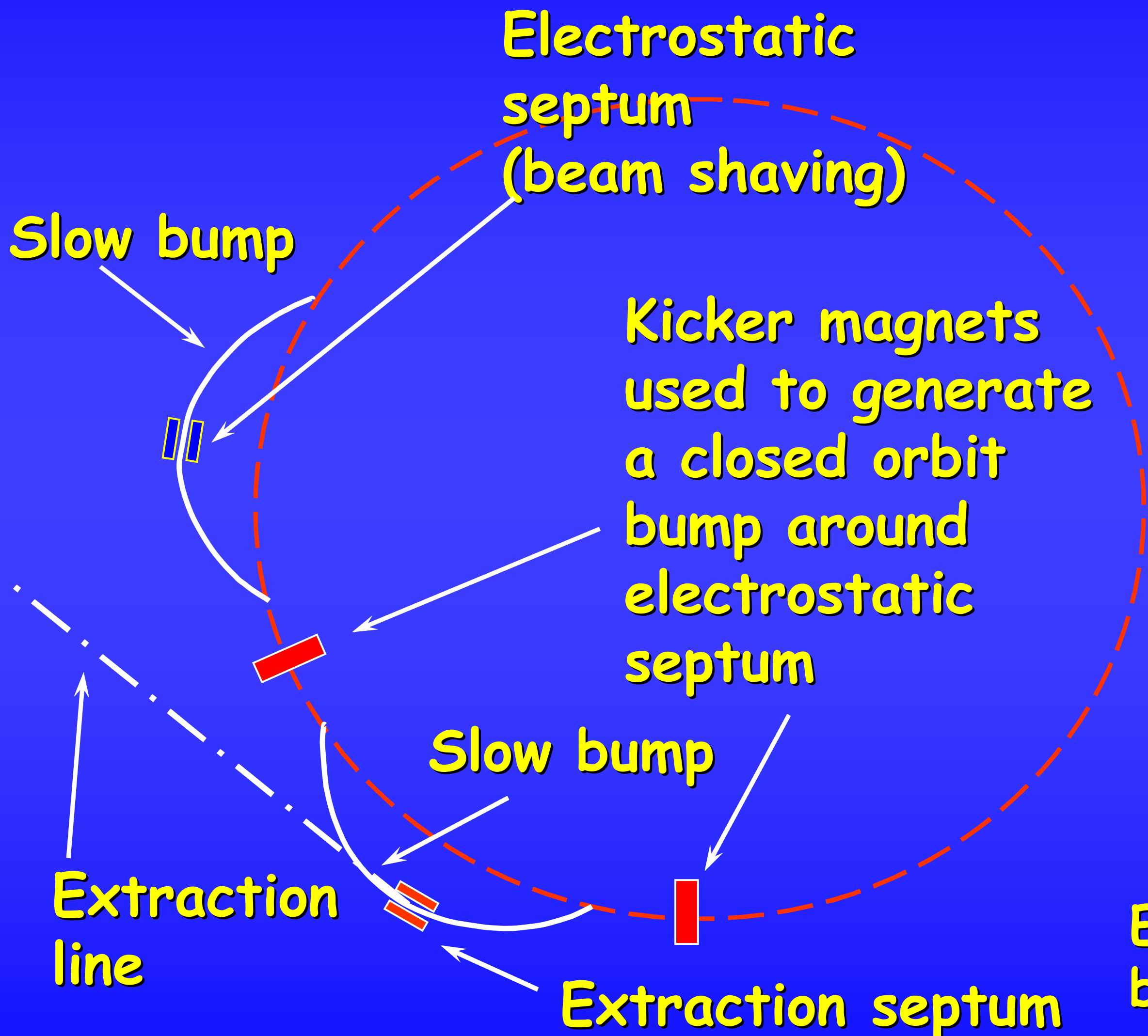
First PS batch Second PS batch Gap for kicker

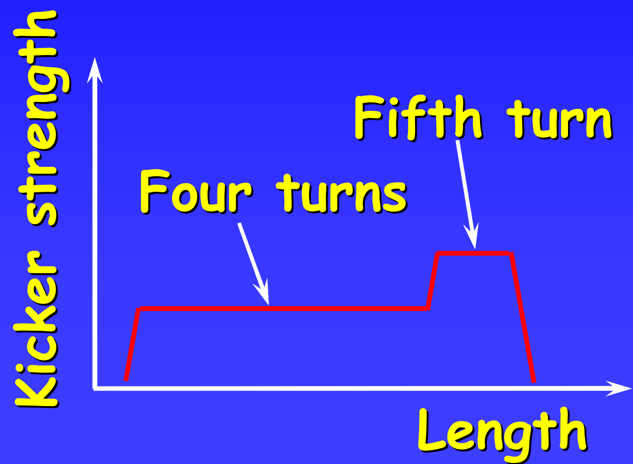


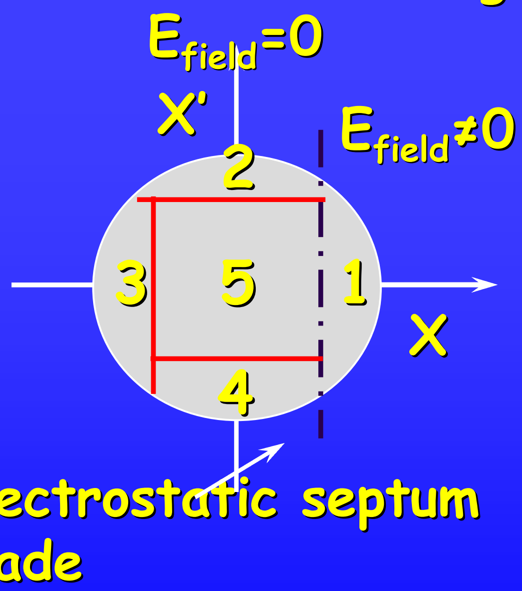
Beam current transformer in the PS/SPS transfer line

1 2 3 4 5 (total spill duration 0.010 ms)

Present multi-turn extraction - II







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Present multi-turn extraction –III

The main drawbacks of the present scheme are:

- Losses (about 15% of total intensity) are unavoidable due to the presence of the electrostatic septum used to slice the beam.
- The electrostatic septum is irradiated. This poses problems for hands-on maintenance.
- The phase space matching is not optimal (the various slices have "fancy shapes"), thus inducing betatronic mismatch in the receiving machine, i.e. emittance blow-up.
- The slices have different emittances and optical parameters.

Novel multi-turn extraction – I

The main ingredients of the novel extraction:

- The beam splitting is not performed using a mechanical device, thus avoiding losses. Indeed, the beam is separated in the transverse phase space using
  - Nonlinear magnetic elements (sextupoles ad octupoles) to create stable islands.
  - Slow (adiabatic) tune-variation to cross an appropriate resonance.
- This approach has the following beneficial effects:
  - Losses are reduced (virtually to zero).
  - The phase space matching is improved with respect to the present situation.
  - The beamlets have the same emittance and optical parameters.

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Model used in numerical simulations

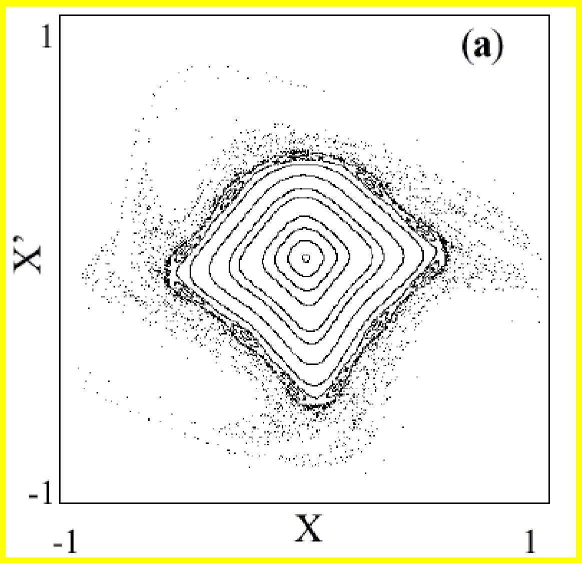
- Standard approach: nonlinear elements represented as a single kick at the same location in the ring (Hénon-like polynomial maps).
- Vertical motion neglected.
- Normalised (adimensional co-ordinates).

The linear tune is time-dependent

$$\begin{pmatrix} \hat{X} \\ \hat{X}' \end{pmatrix}_{n+1} = \mathbf{R}(\omega) \begin{pmatrix} \hat{X} \\ \hat{X}' + \hat{X}^2 + \kappa \hat{X}^3 \end{pmatrix}_n \qquad \kappa = \frac{2}{3} \frac{K_3}{K_2^2 \beta_x}$$

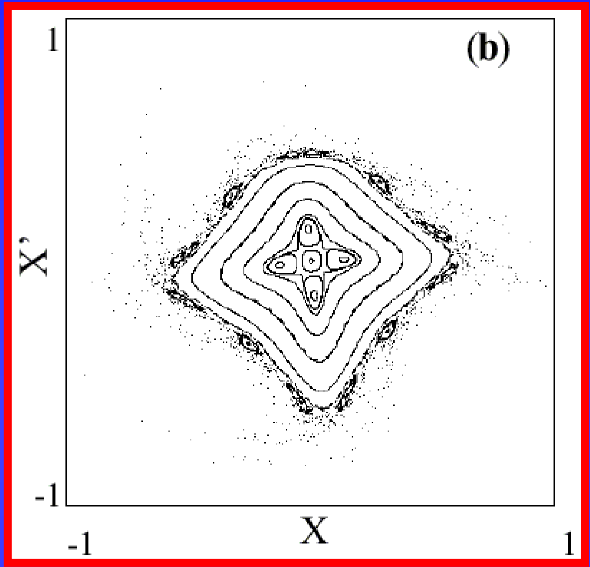
Quadrupoles Sextupole Octupole

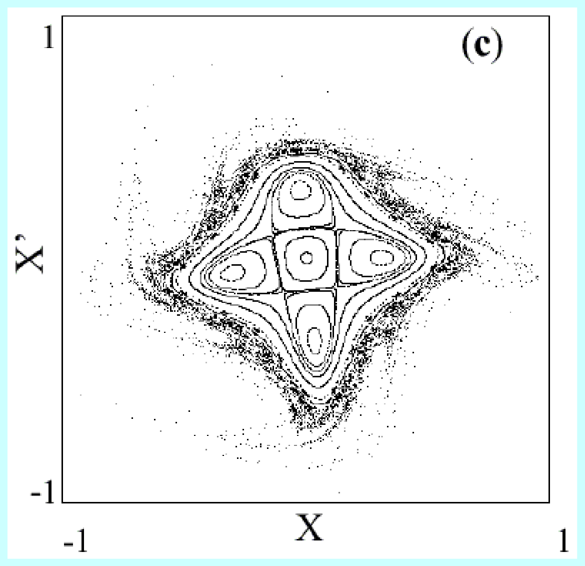
Novel multi-turn extraction – II



Left: initial phase space topology. No islands.

Right: intermediate phase space topology. Islands are created near the centre.



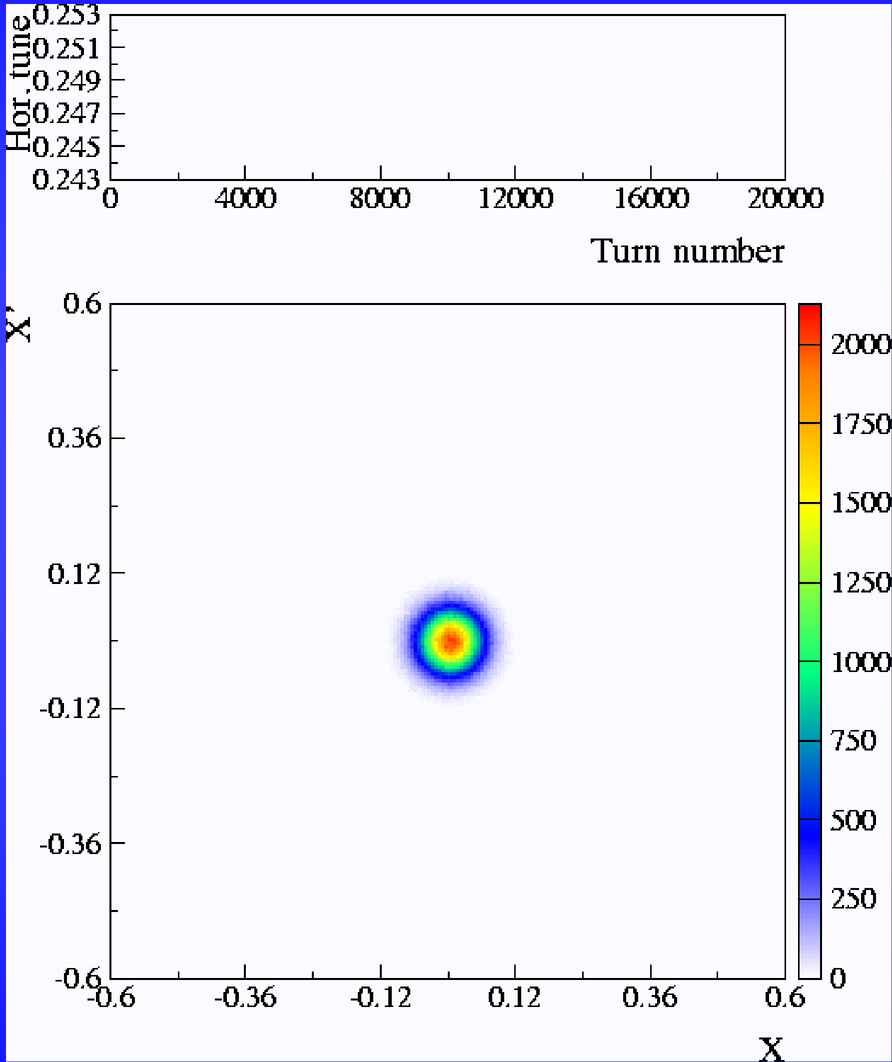


Bottom: final phase space topology. Islands are separated to allow extraction.

Novel multi-turn extraction - III

Tune variation

Phase space portrait



Simulation parameters:

Hénon-like map (i.e. 2D polynomial - degree 3 - mapping) representing a FODO cell with sextupole and octupole

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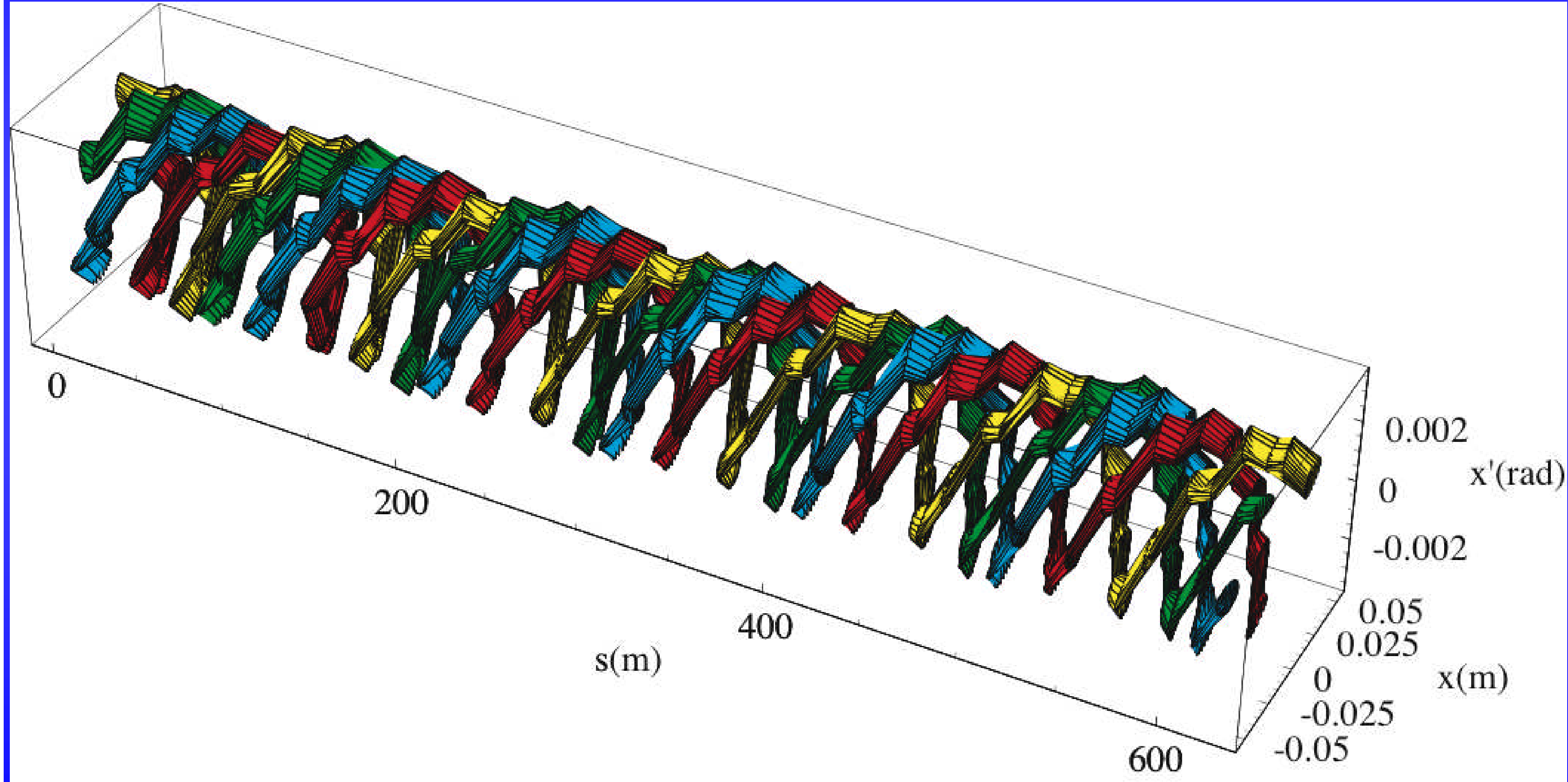
Novel multi-turn extraction – IV

Final stage after 20000 turns (about 42 ms for CERN PS)



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Novel multi-turn extraction - V

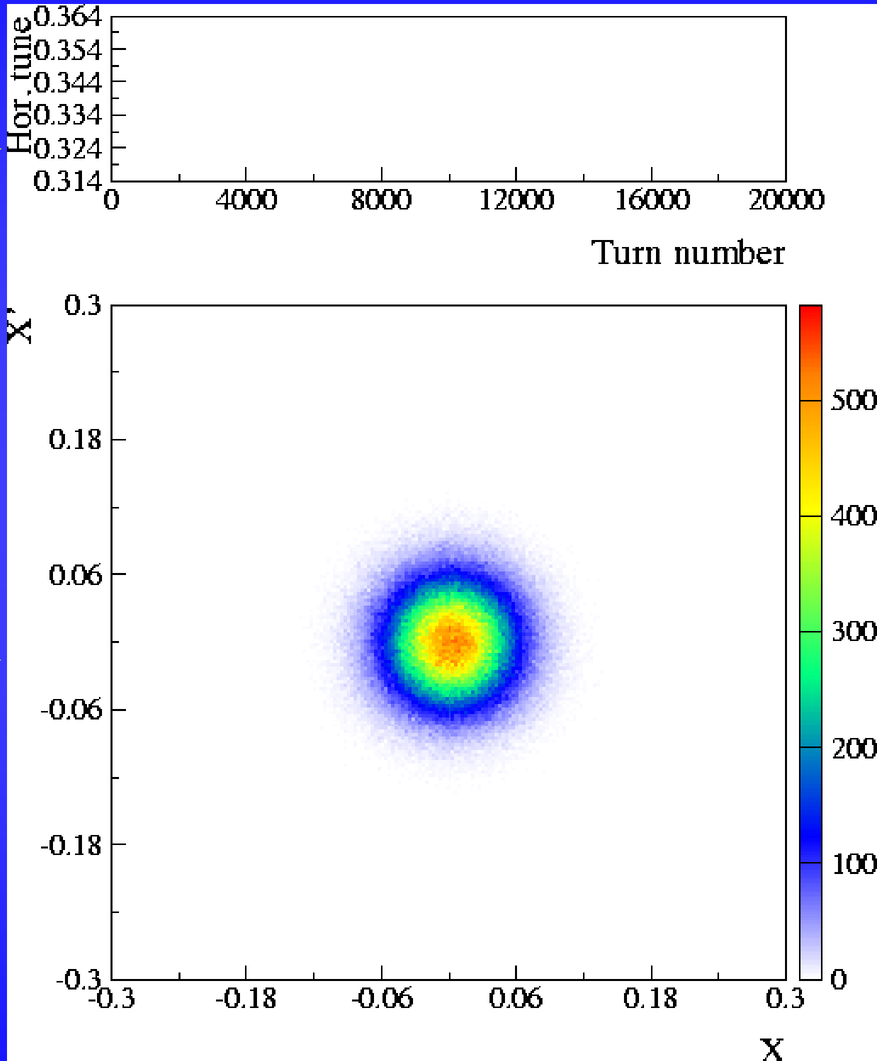
The original goal of this study was to find a replacement to the present Continuous Transfer used at CERN for the high-intensity proton beams. However the novel technique proved to be useful also in different context, e.g.

- The same approach can be applied for multi-turn injection (time-reversal property of the physics involved).
- multi-turn extraction over a different number of turns can be designed, provided the appropriate resonance is used.
- Multiple multi-turn extractions could be considered, e.g. to extract the beam remaining in the central part of phase space.

Novel multi-turn extraction with other resonances - I

Tune variation

Phase space portrait



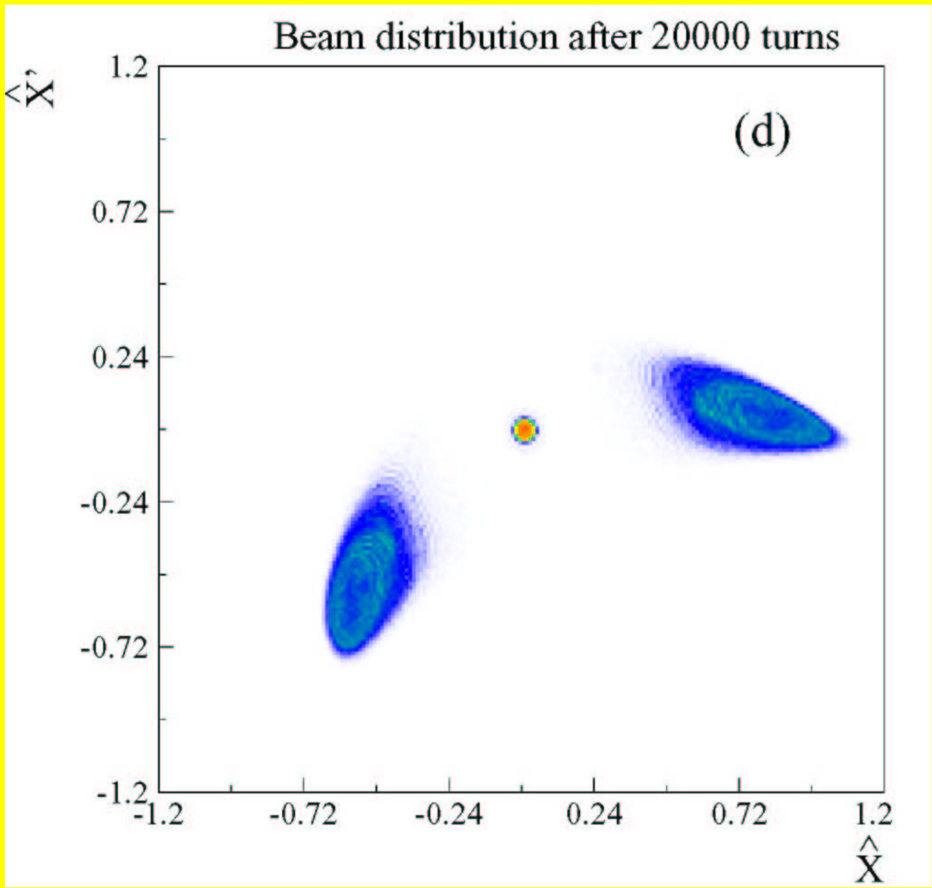
Simulation parameters:

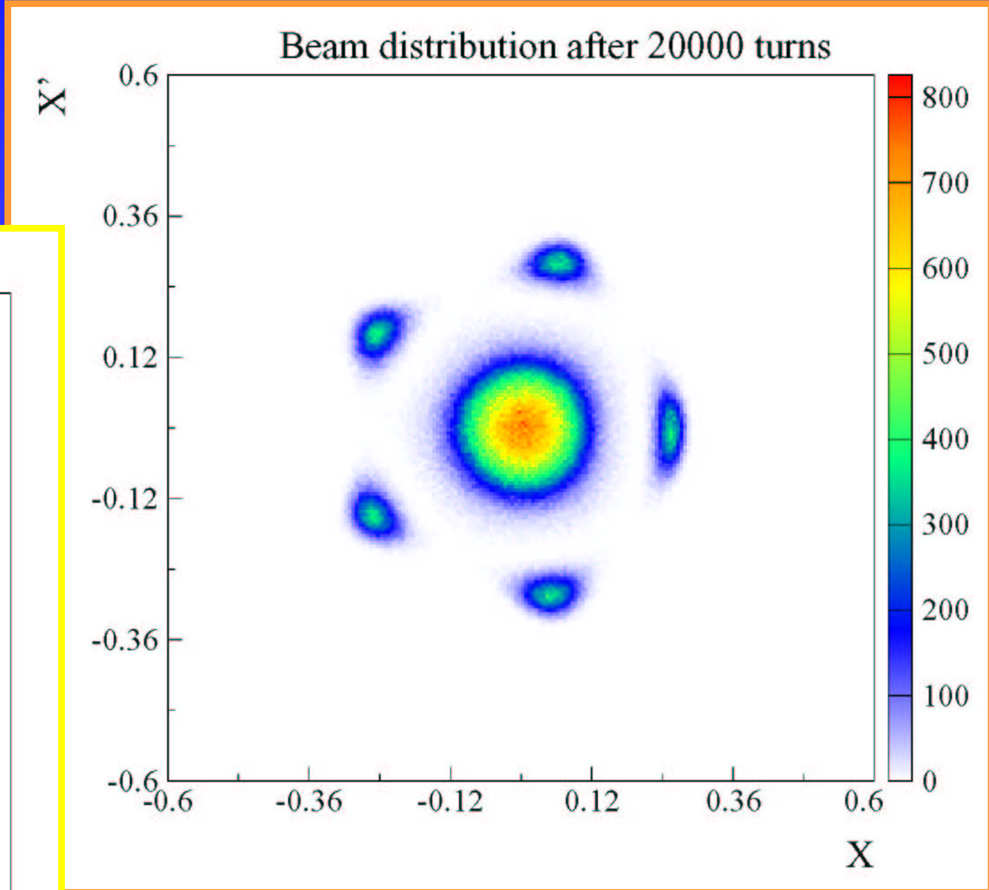
Hénon-like map with sextupole and octupole

The third-order resonance is used, thus giving a three-turn extraction

Novel multi-turn extraction with other resonances - II

The second-order resonance is used, thus giving a two-turn extraction





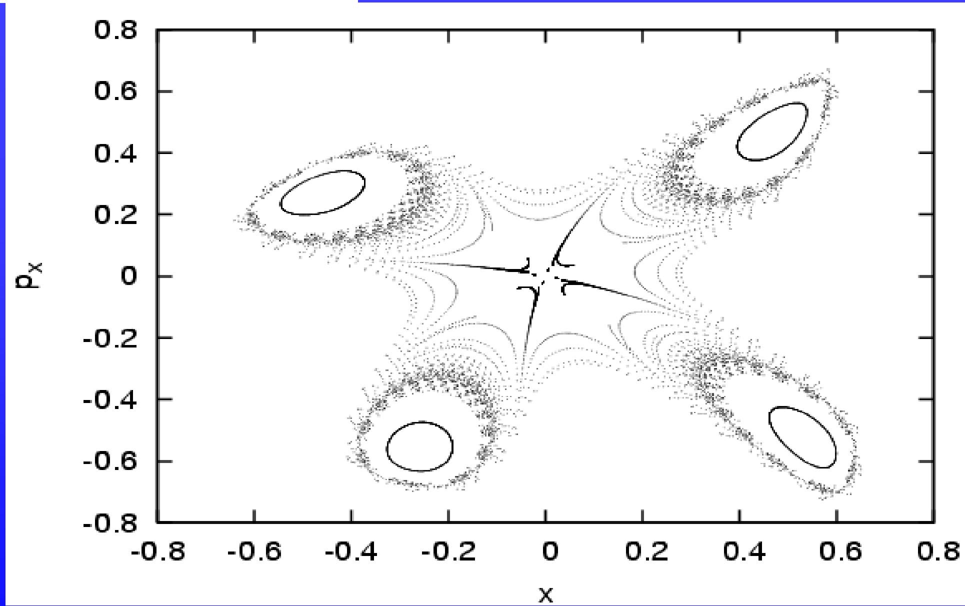
The fifth-order resonance is used, thus giving a six-turn extraction

Novel multi-turn extraction: 4th order unstable resonance - new application!

- Non-linear elements can be used to make the fourth-order resonance unstable by canceling the amplitude detuning.

$$\nu_x = \nu_{x,0} + \Omega_2 A_x \quad \rightarrow \quad \Omega_2 = 0$$

- Possible applications:
  - Four-turn extraction.
  - Deplete the core region to achieve a better intensity sharing.



Master thesis Diego Quatraro

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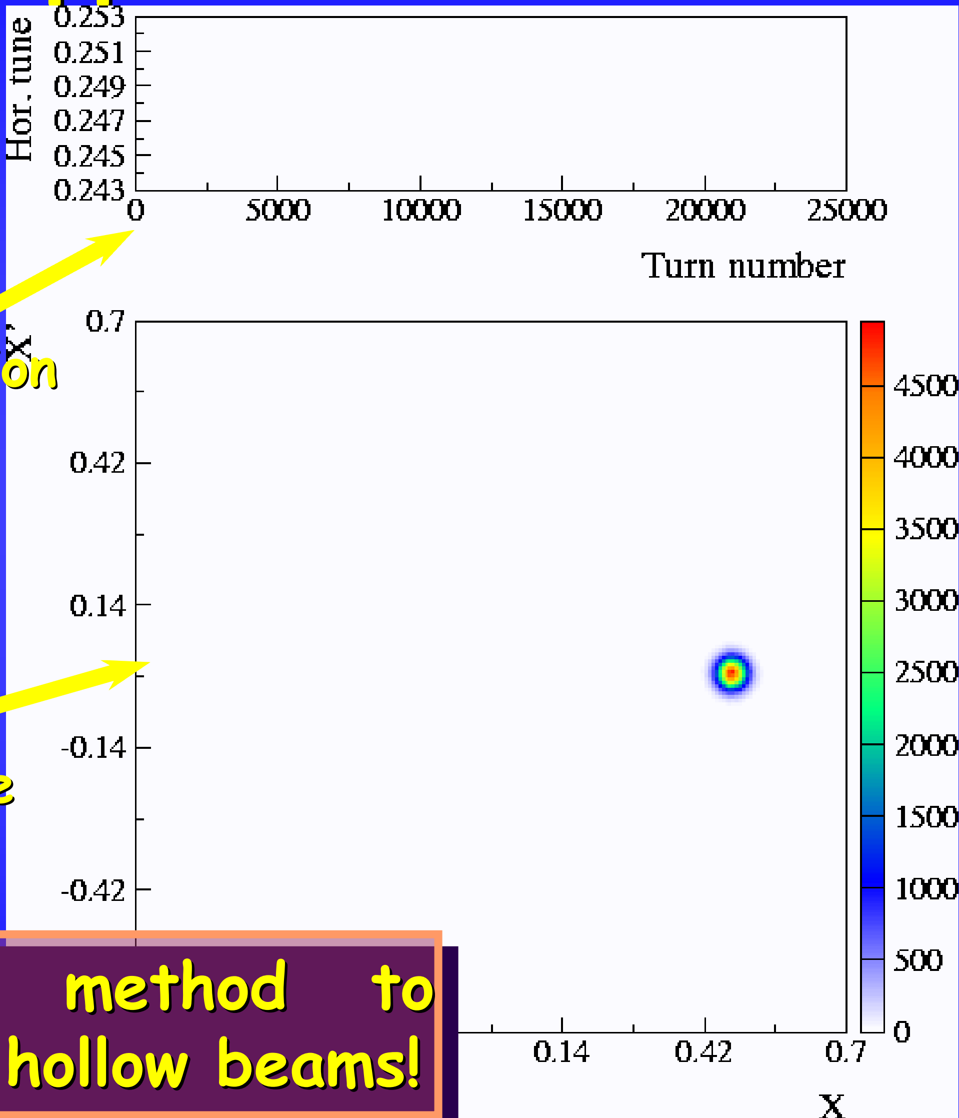
Novel multi-turn injection: new application!



Tune variation

Phase space portrait

Efficient method to generate hollow beams!

Simulation parameters:

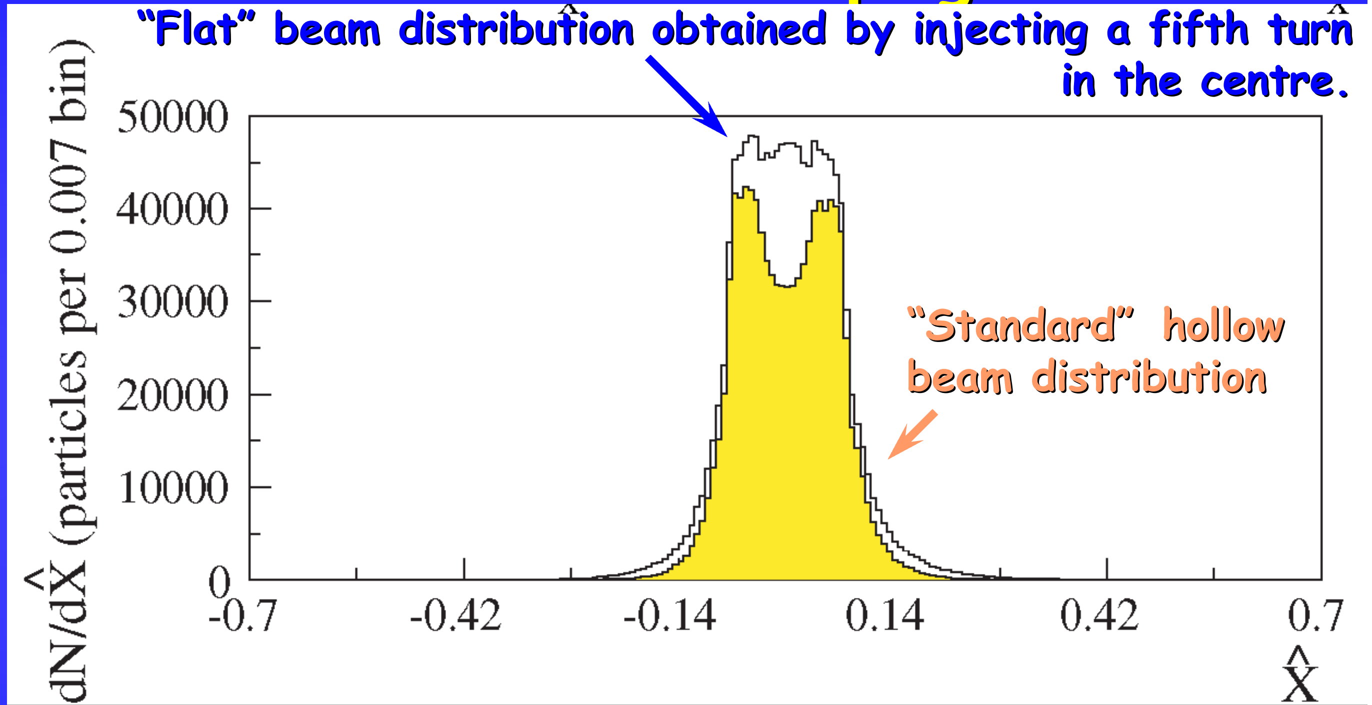
Third-order polynomial map representing a FODO cell with sextupole and octupole

The fourth-order resonance is used for a four-turn injection

CERN PS Multi Turn Extraction

Novel multi-turn injection: new application!

- Possible applications: transverse shaping of beam distribution.



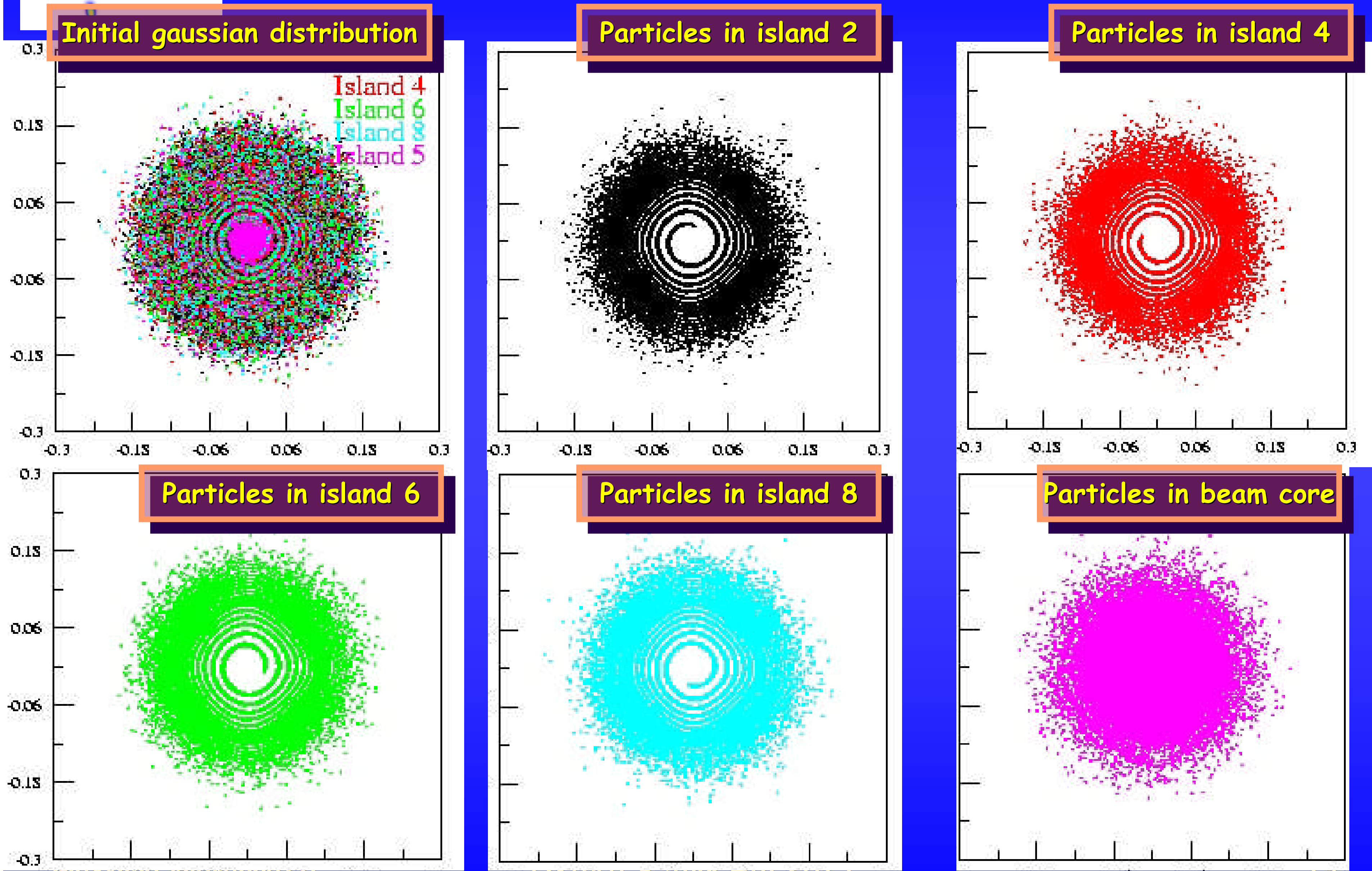
- Observation: the proposed method seems to be more efficient in generating smaller emittance beams than standard multi-turn injection!

M. Giovannozzi, J. Morel, PRST-AB, 10, 034001 (2007)

The capture process - I

- Quantitative analysis needed:
  - To control sharing between core and beamlets.
  - To control the emittance sharing.
- Adiabatic theory is the key concept:
  - Probability trapping is proportional to the speed of variation of the island's surface.
  - It is possible to account for the loss of adiabaticity close to the separatrix.
- 2D case seems under control.
- The 4D case requires the usual conditions:
  - weak coupling between the two degrees of freedom
  - no low order resonances in the vertical plane

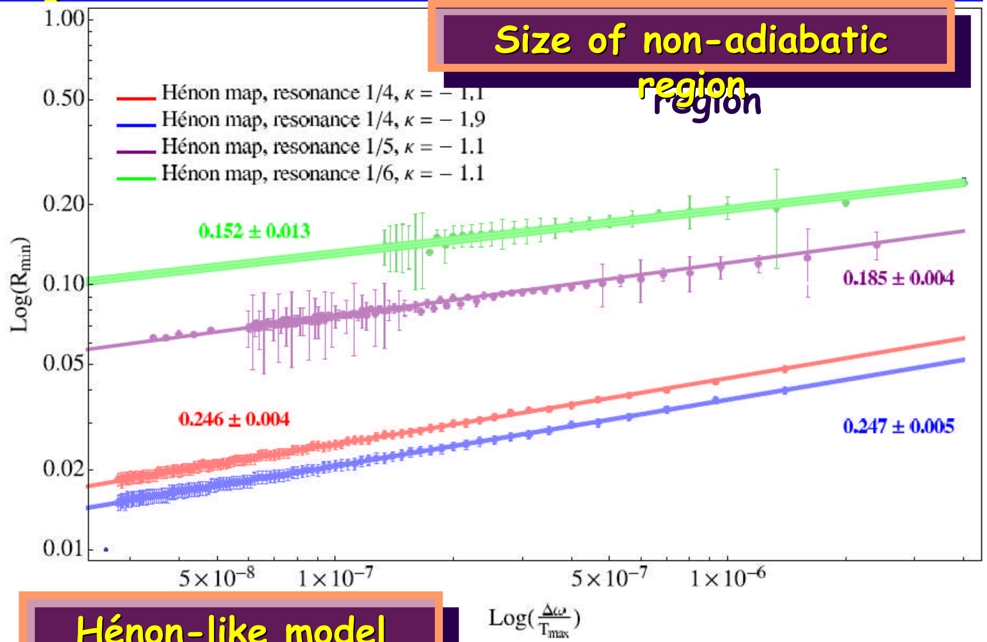
The capture process - II



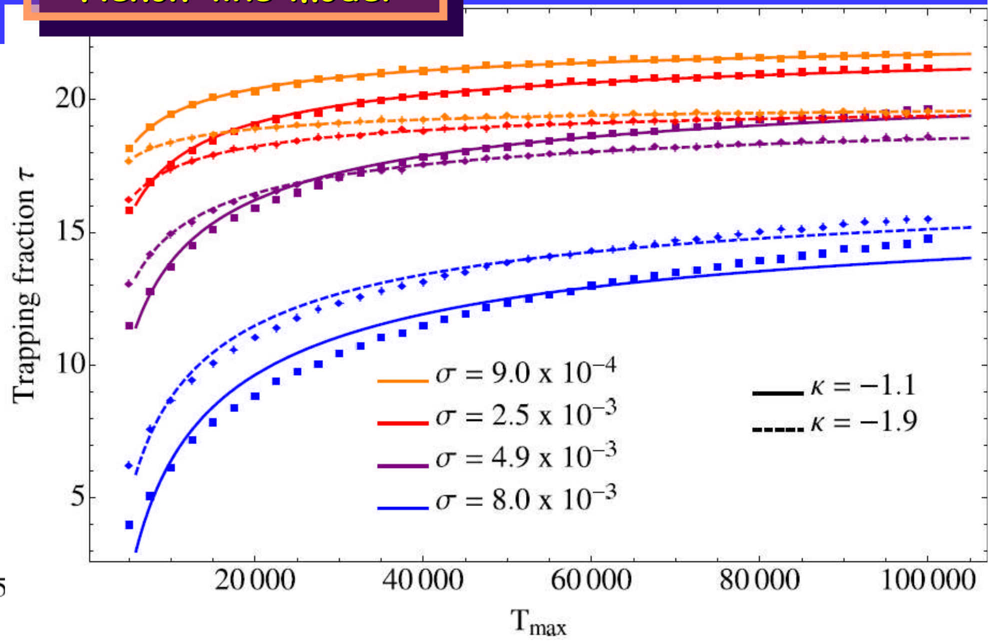
The capture process - III

- Under these conditions:
  - Scaling law for the size of the adiabatic region is well-reproduced.
  - Trapping probability is well-described.

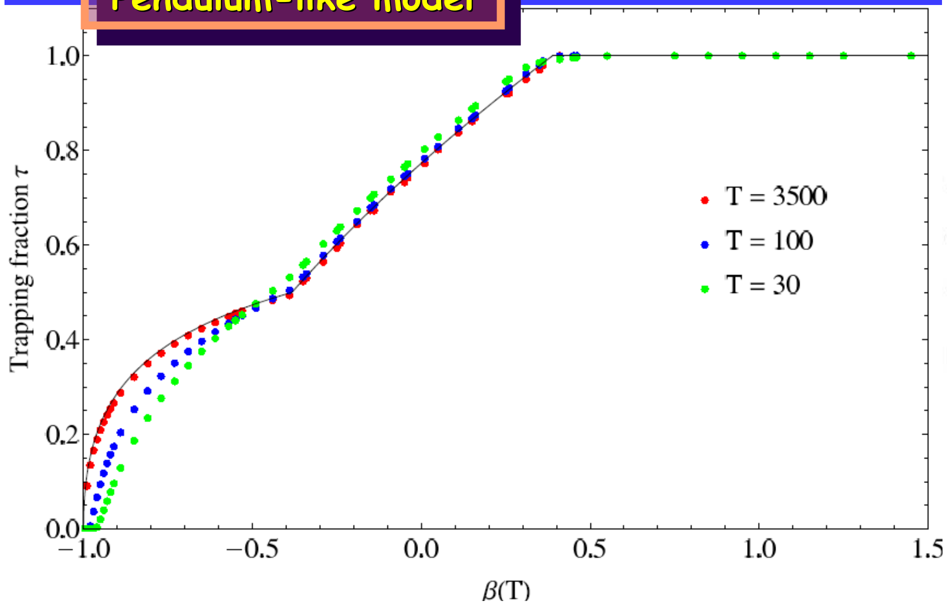
Size of non-adiabatic region



Hénon-like model



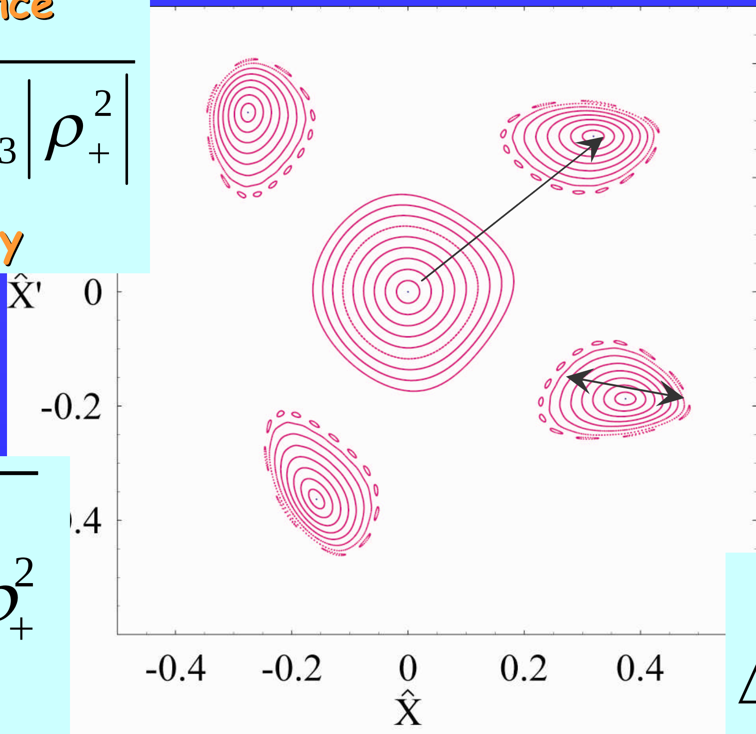
Pendulum-like model



Analytical computation of island's parameters

Using perturbative theory (normal forms) it is possible to derive analytical estimate of island's parameters.

Normalised phase space



Distance from resonance

$$\omega_{\text{sec}} = 4\sqrt{\left|\Omega_2 \varepsilon\right| \left|u_{0,3}\right| \rho_+^2}$$

Secondary frequency

$$\rho_+ = -\frac{\varepsilon}{\Omega_2 + 2\varepsilon \left|u_{0,3}\right|}$$

Distance of fixed points from origin of phase space

$$\Sigma = 16\sqrt{\left|\frac{\varepsilon}{\Omega_2}\right| \left|u_{0,3}\right| \rho_+^2}$$

Island's surface

$$\Delta = 4\sqrt{\left|\frac{\varepsilon}{\Omega_2}\right| \left|u_{0,3}\right| \rho_+^2}$$

Distance between separatices

Operational implementation - I

Sextupoles and octupoles are used to

- Generate stable islands
- Control size/position of islands
- Control linear chromaticity
- Control non-linear coupling (using an additional set of octupoles, normally used to combat instabilities)

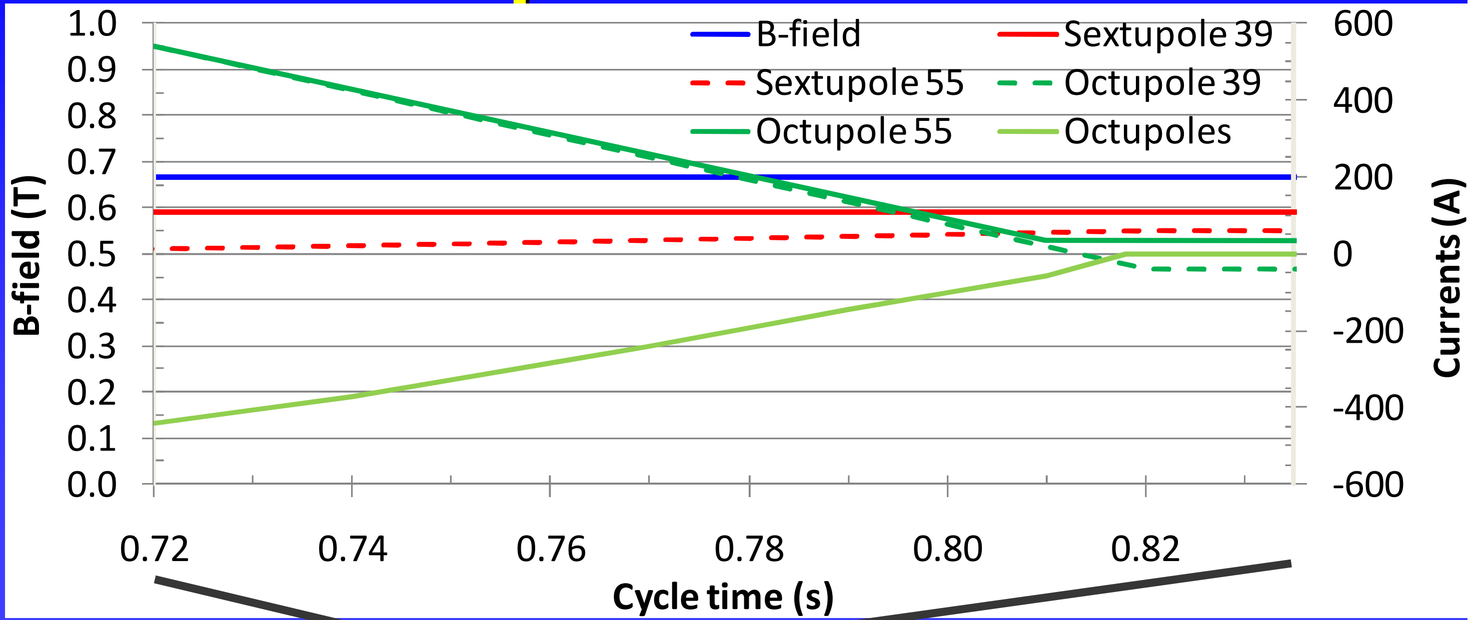
$$\delta Q_x = h_{2,0}\, J_x + h_{1,1}\, J_y$$
$$\delta Q_y = h_{1,1}\, J_x + h_{0,2}\, J_y$$

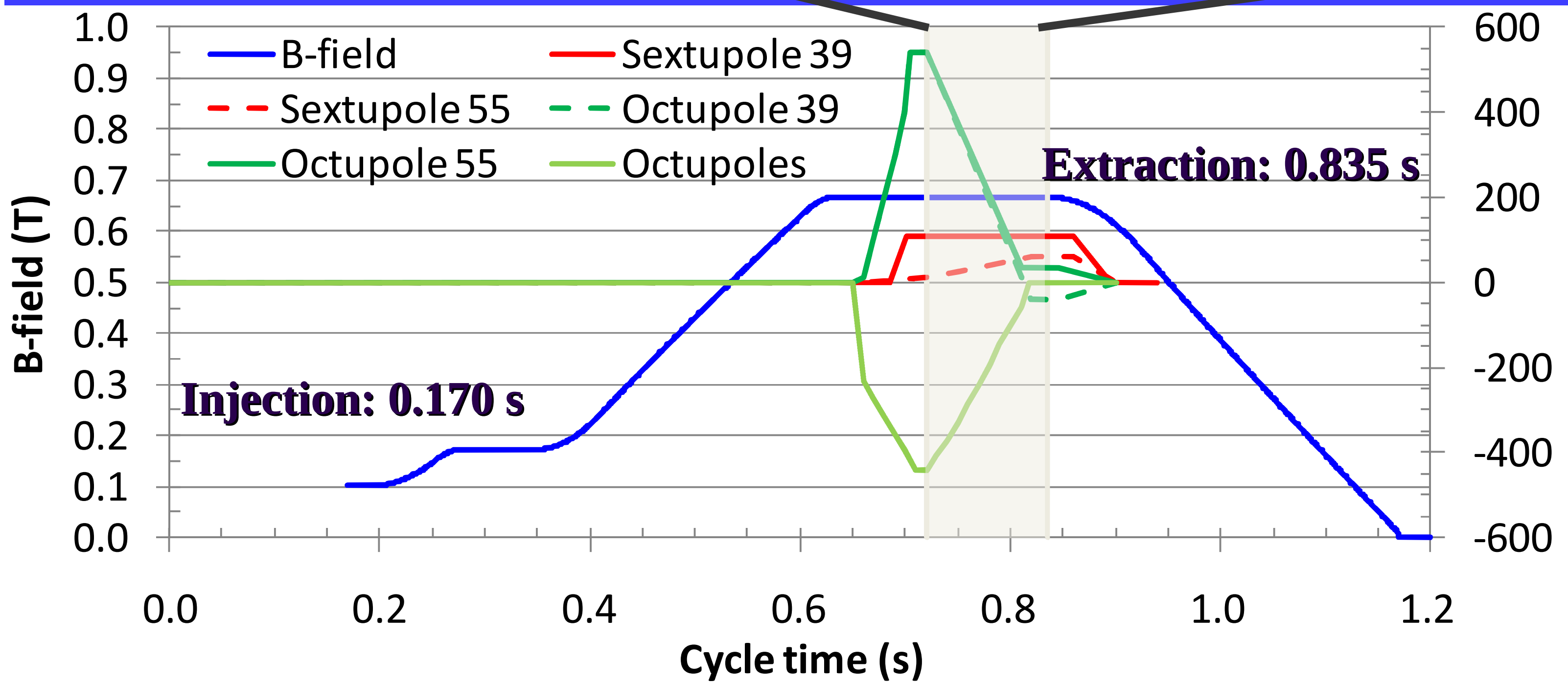
$h_{2,0}$ -> detuning with amplitude (H-plane) -> $\propto \beta_x^2 K_3$

$h_{1,1}$ -> non-linear coupling -> $\propto \beta_x\beta_y K_3$

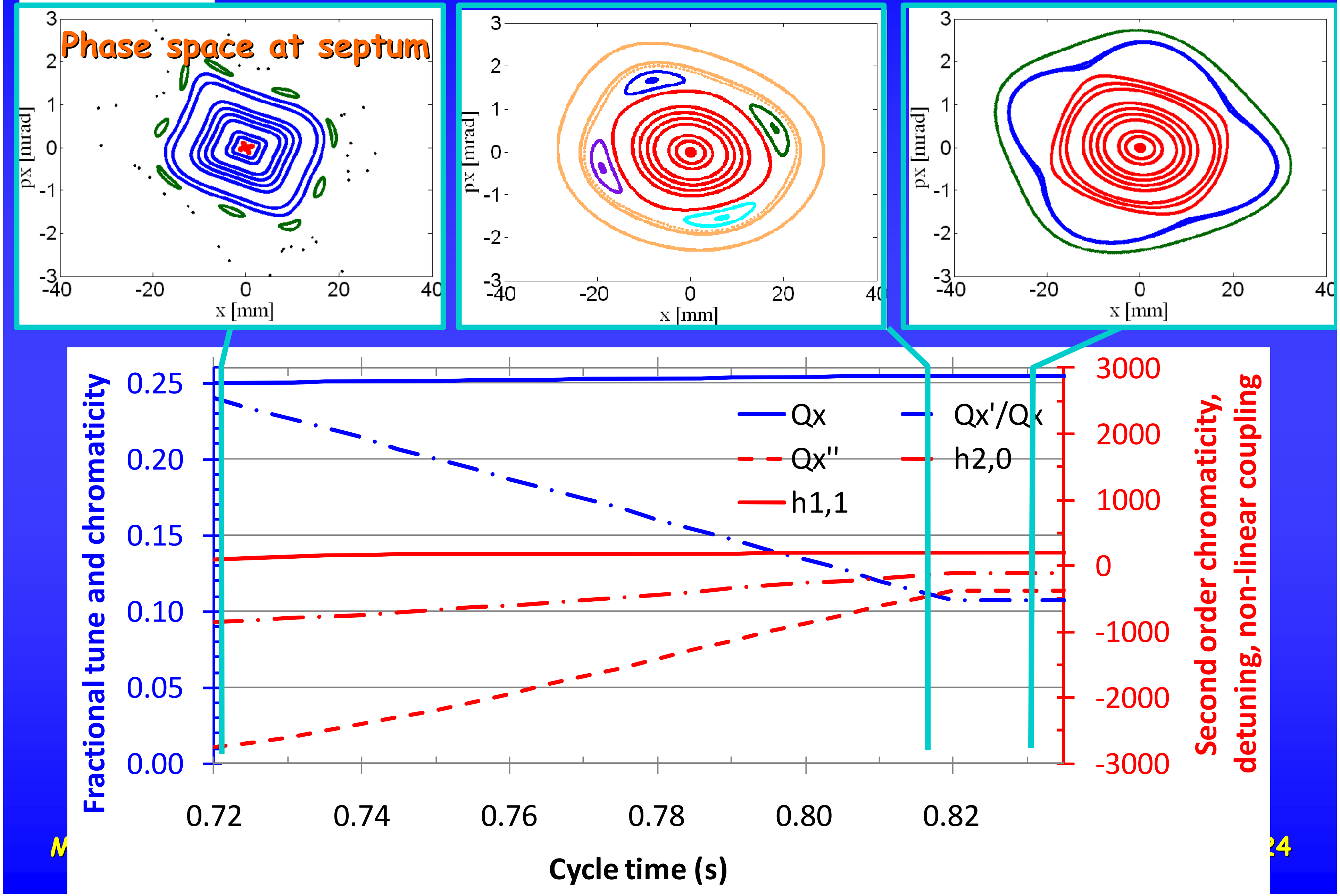
$h_{0,2}$ -> detuning with amplitude (V-plane) -> $\propto \beta_y^2 K_3$

Operational implementation - II



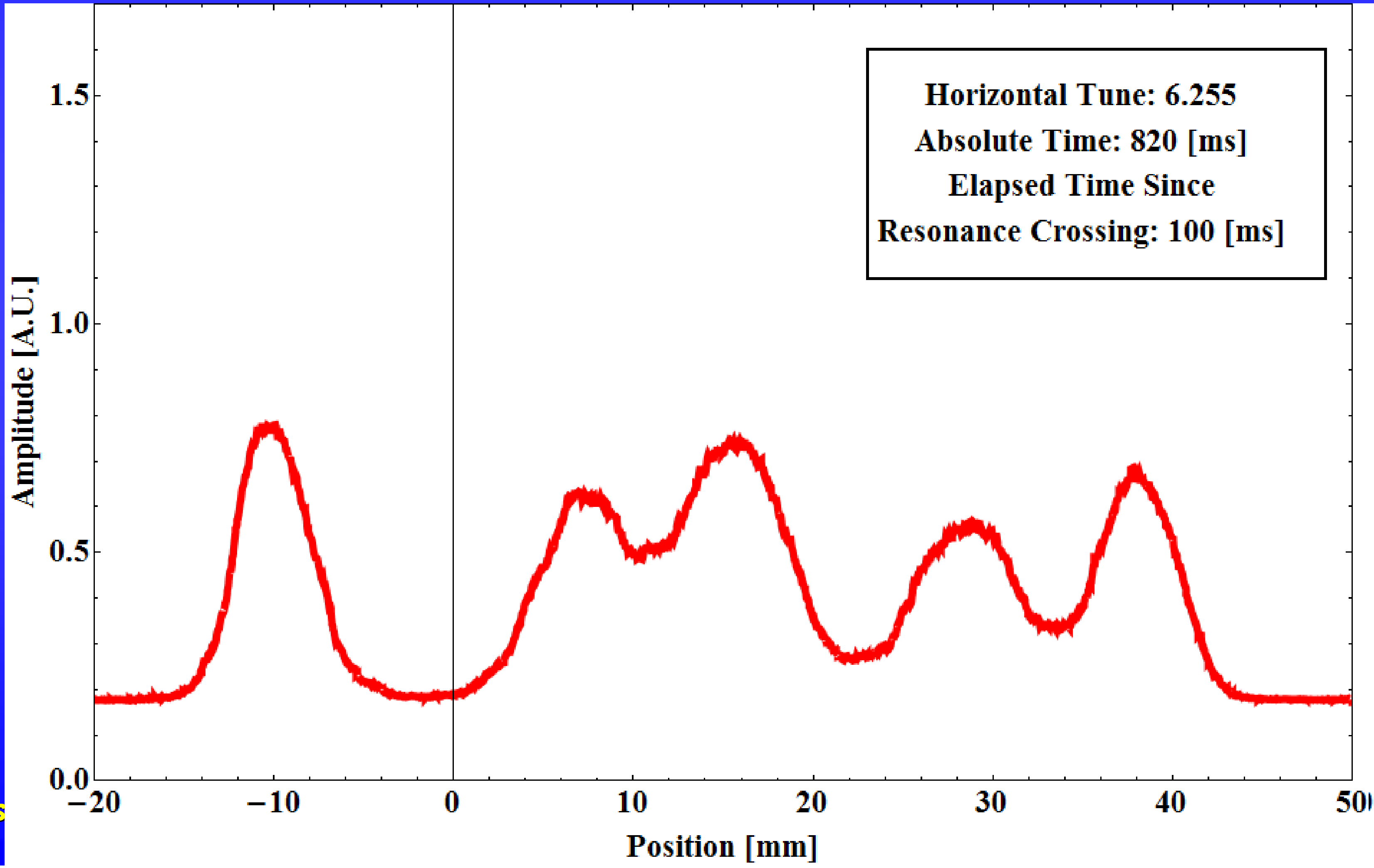


Transverse dynamics - III



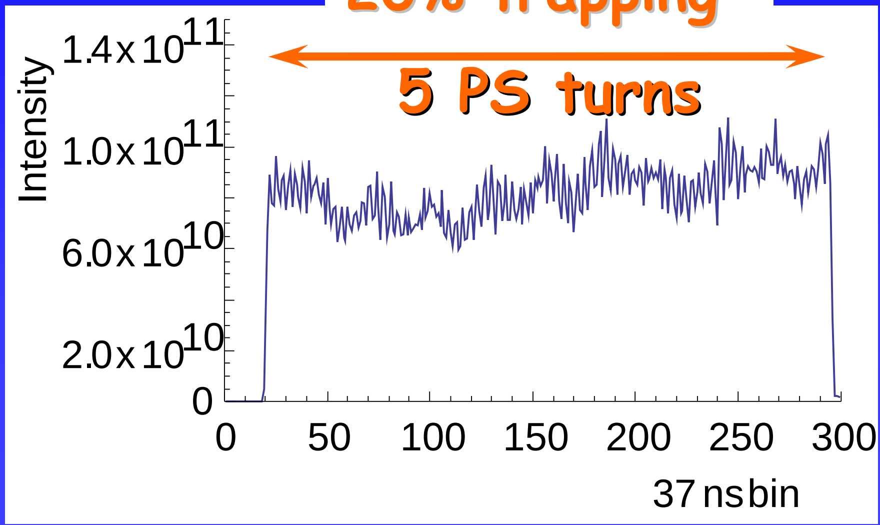
Evolution of beam distribution

Horizontal beam profiles in section 54 have been taken during the capture process (total intensity ~2.1×10^{13}).

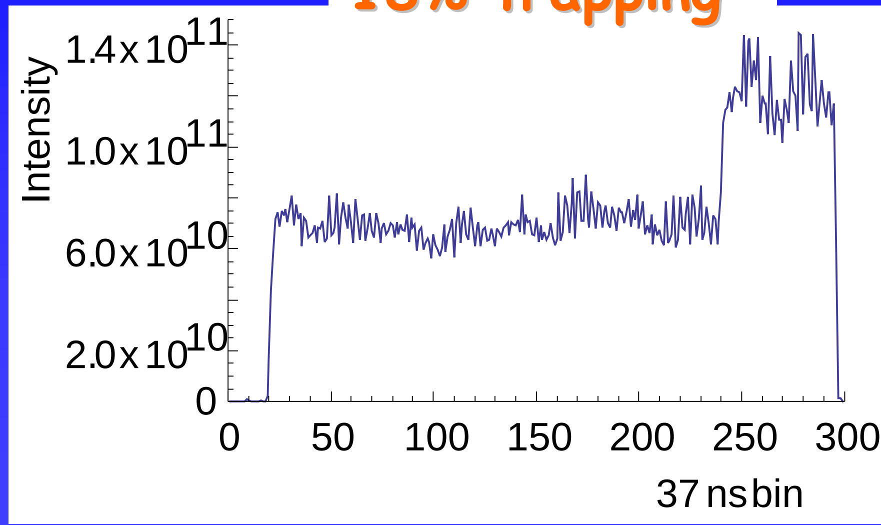


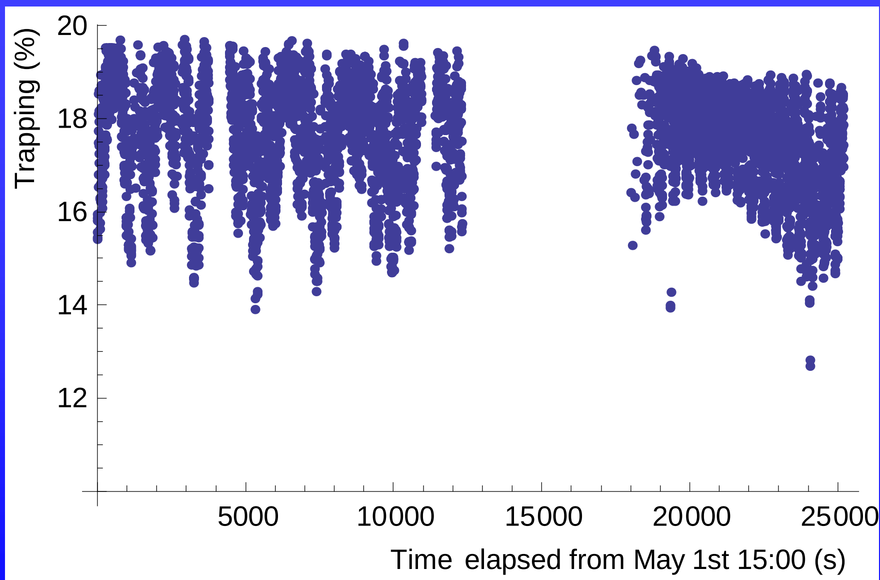
Trapping performance

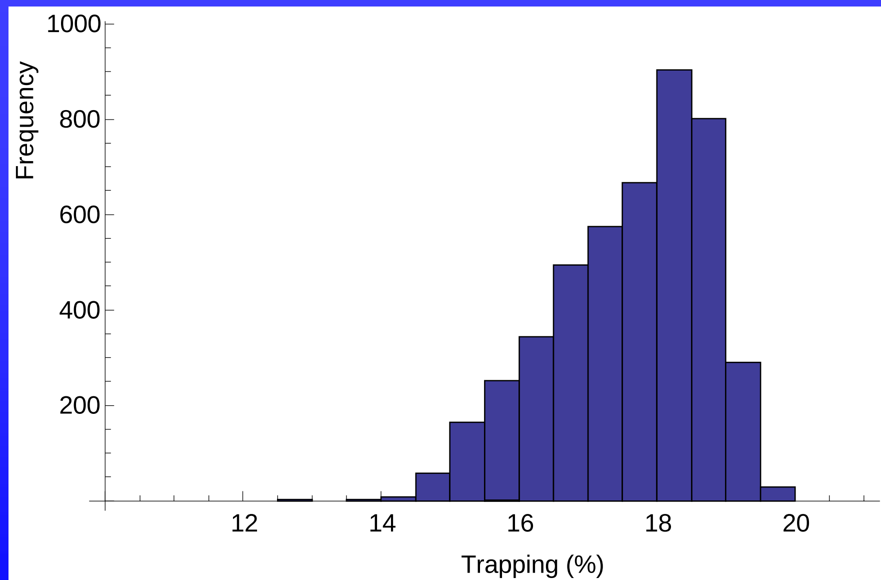
20% trapping



18% trapping







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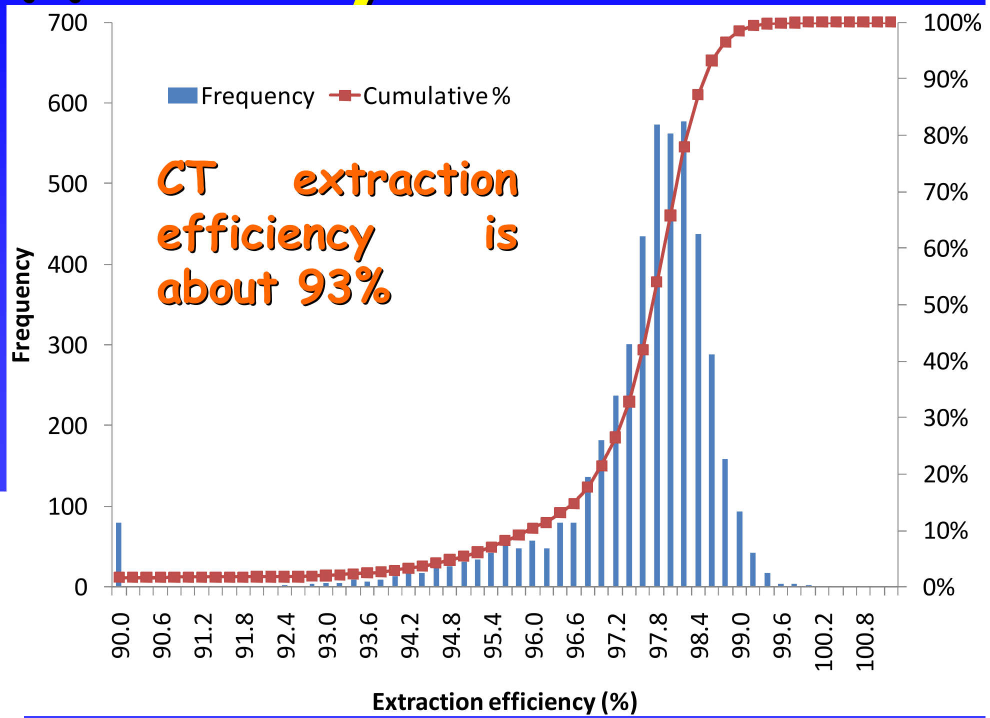
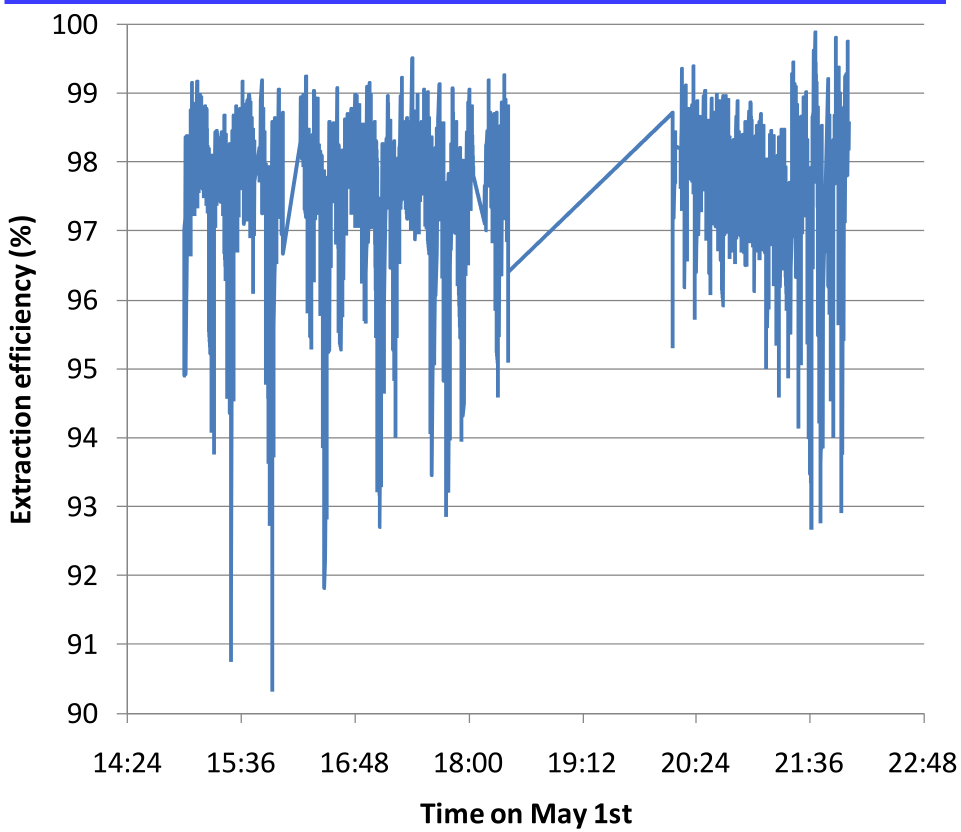
Extraction efficiency

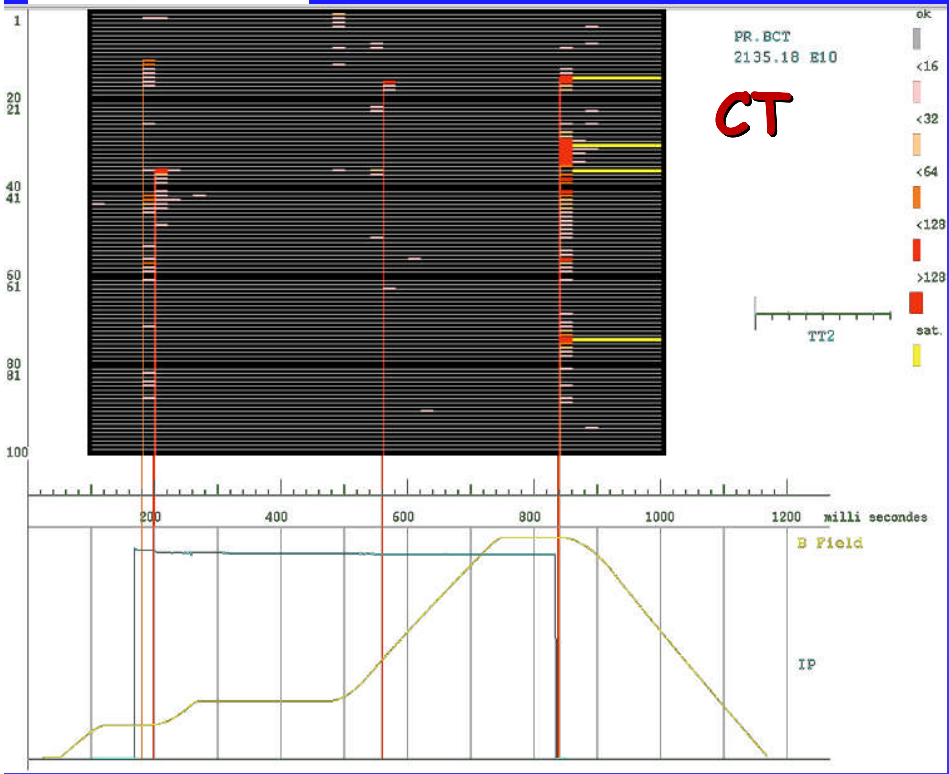
Regular fluctuations in the extraction efficiency are also observed and seem well correlated to spill fluctuations.

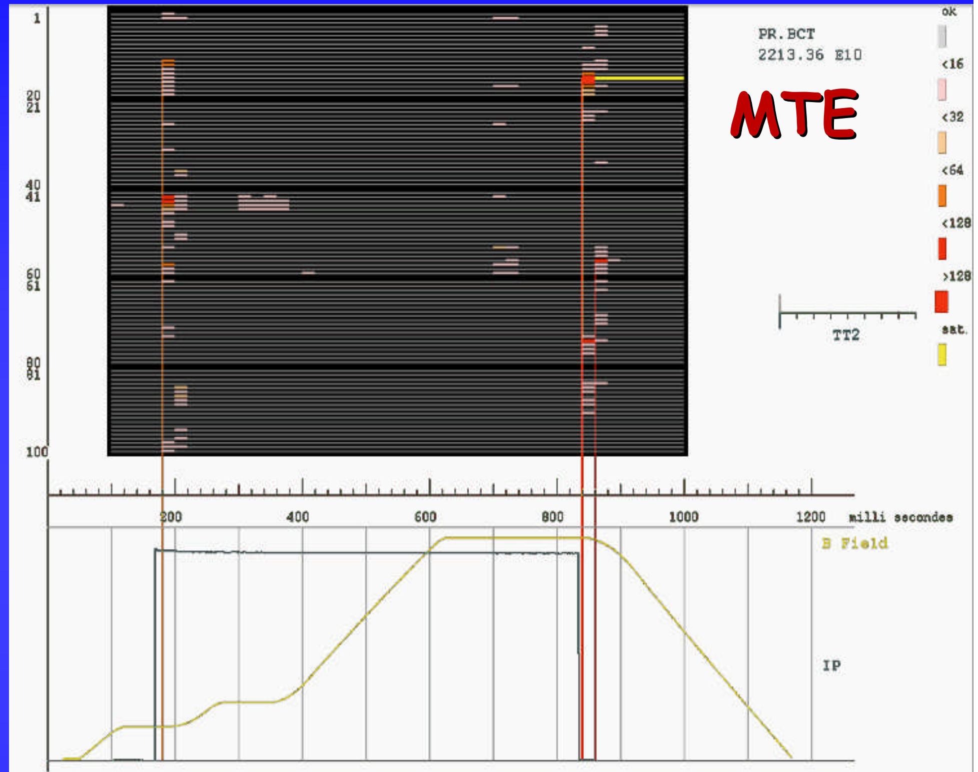




Distribution of extraction efficiency is peaked at about 98% (NB: the beam is debunched at extraction! Unavoidable beam losses are estimated at about 1-2%)

CT vs. MTE: extraction losses

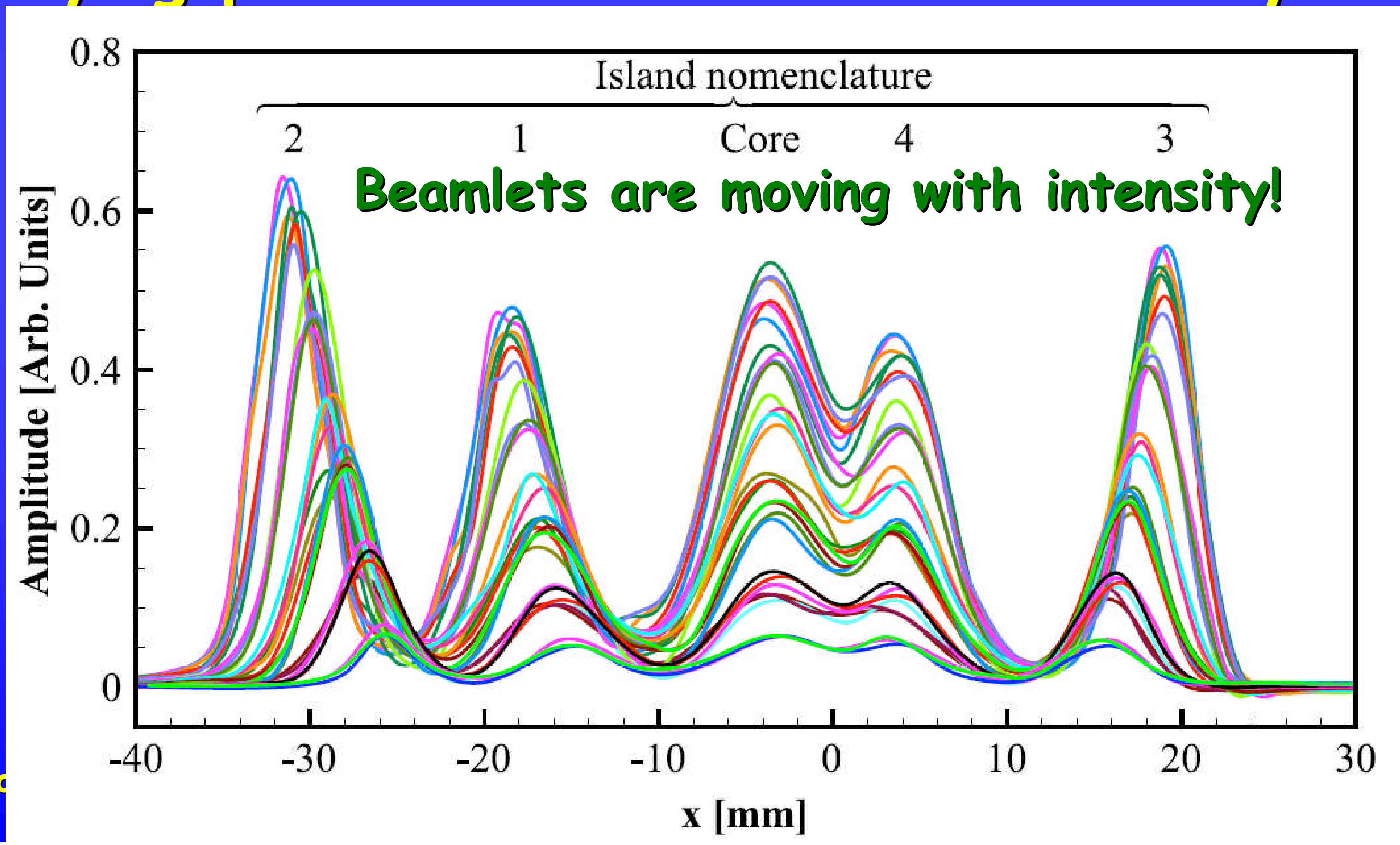




- For the same extracted intensity, the CT features more losses, about the double, compared to MTE.
- The CT losses are spread around the ring whereas for MTE the losses are more concentrated on the extraction septum as anticipated in the MTE Design Report.

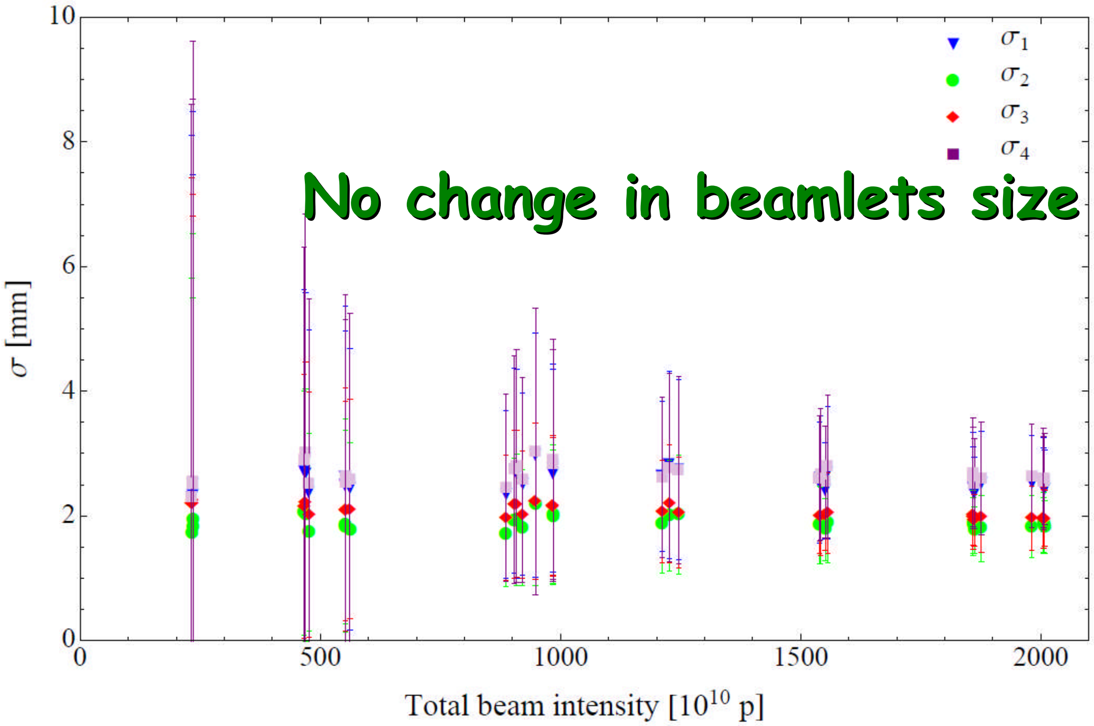
First observations of intensity-dependent effects - I

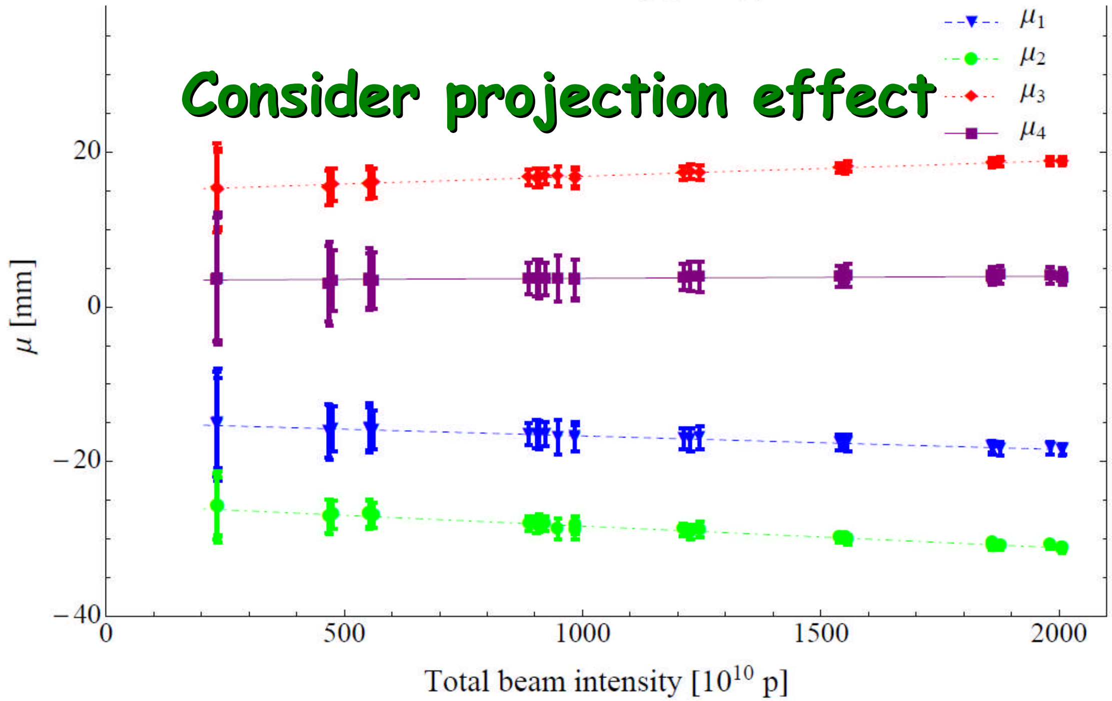
- Usual process for trapping the beam into stable islands.
- Varying parameter: total beam intensity.



First obs… depender…

- The observed effect can be explained with an intensity-dependent shift of the single particle tune.
- Possible sources:
  - Image currents.
  - Direct effects (interaction between beamlets).





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Summary and Outlook - I

- A novel multi-turn extraction is studied since a few years: it allows manipulating transverse emittances in a synchrotron!
- First MTE beam delivered to the SPS by mid-September 2009 (about 1.5×10^{13} p/extraction).
- Equal sharing for islands/core achieved by the end of 2009.
- In February 2010 the commissioning was resumed.
- High intensity beam was extracted (about 2.1×10^{13} p/extraction) with record intensity 2.6×10^{13} p/extraction.
- 2010 physics run at SPS was started using MTE beam.
- Open issues:
  - Variation of the fraction of particles trapped in islands.
  - Activation of extraction septum due to the longitudinal structure of the beam (de-bunched as needed by the SPS).
- New optimised extraction scheme to avoid losses on extraction septum -> beam commissioning in 2014.

Summary and Outlook - II

- The same principle can be used for injection.
- Transverse shaping is possible, i.e. generation of hollow bunches.
- Lines of research:
  - Complete study of splitting process in 2D and extend to 4D.
  - Study trapping in 4D, i.e., manipulations in x-y plane.
  - Study intensity-dependent effects.

And many more!

Selected references

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