Resonant multi-turn extraction project: principle and experiments at the CERN Proton Synchrotron

M. Giovannozzi

For

PS Multi-Turn Extraction Project

Summary:

Introduction

Present multi-turn extraction

New multi-turn extraction (MTE)

Measurement results

Implementation of MTE

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.

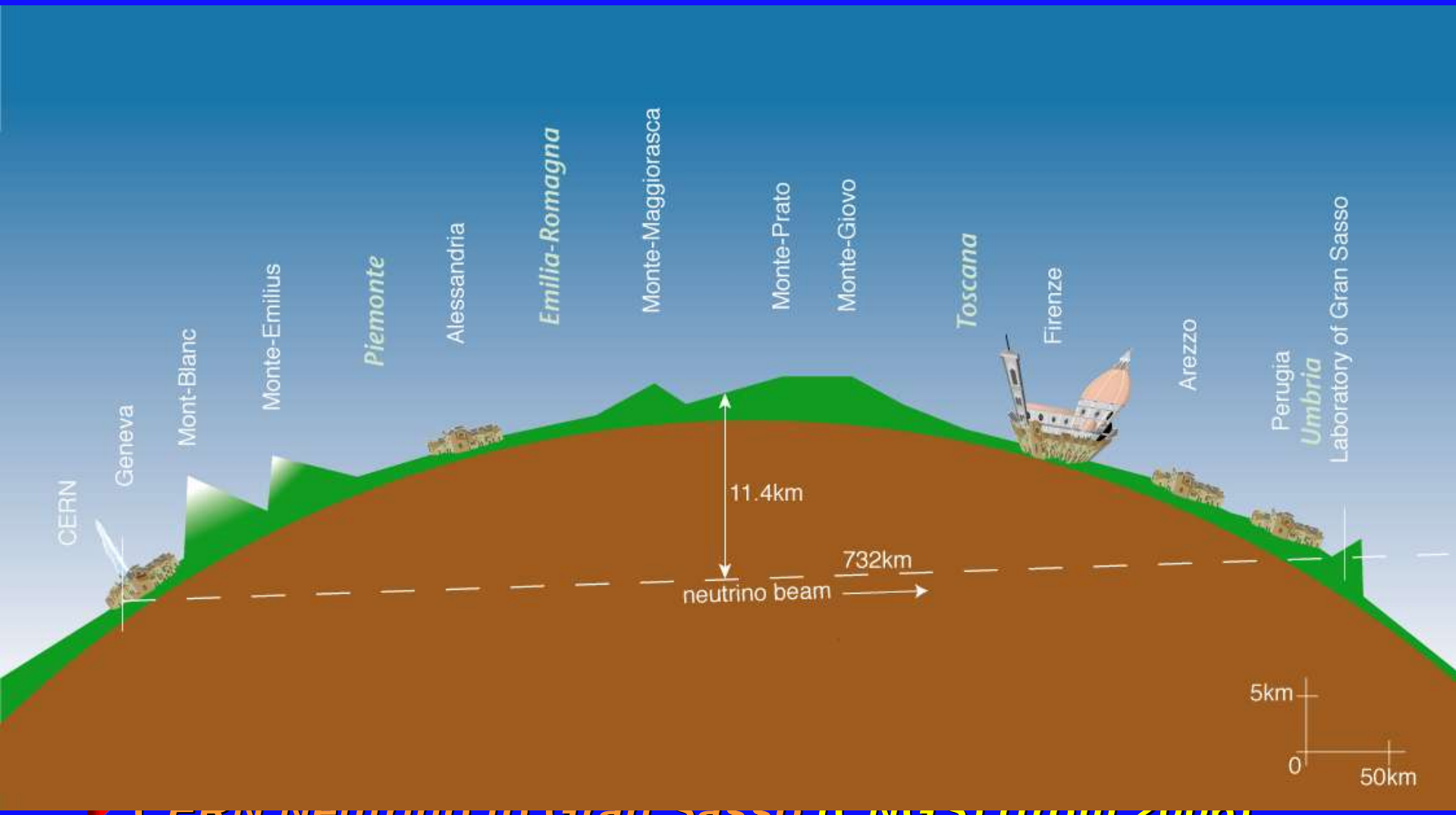
Multi-turn!

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

What is in between?

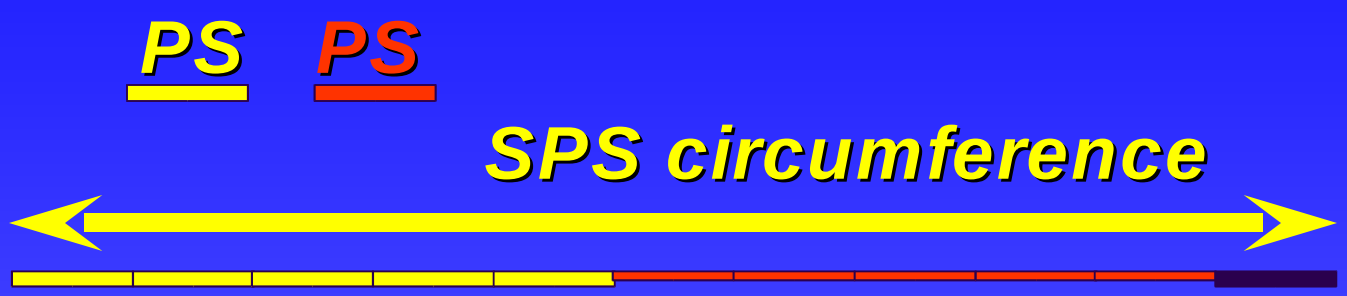
Introduction - II

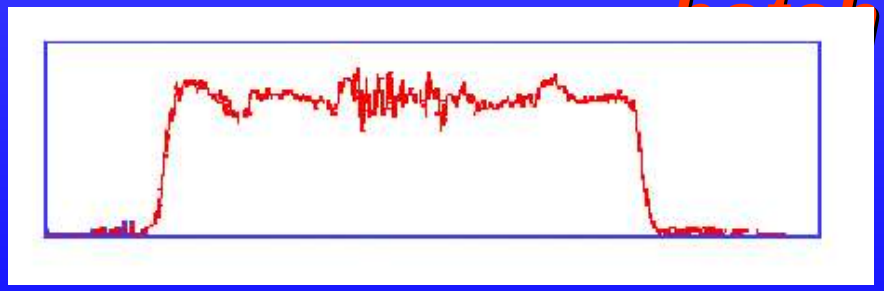


- CERN Neutrino to Gran Sasso (CNGS) (from 2006)
- These beams are high-intensity (about 3×10^{13} p in the

Present multi-turn extraction – I

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

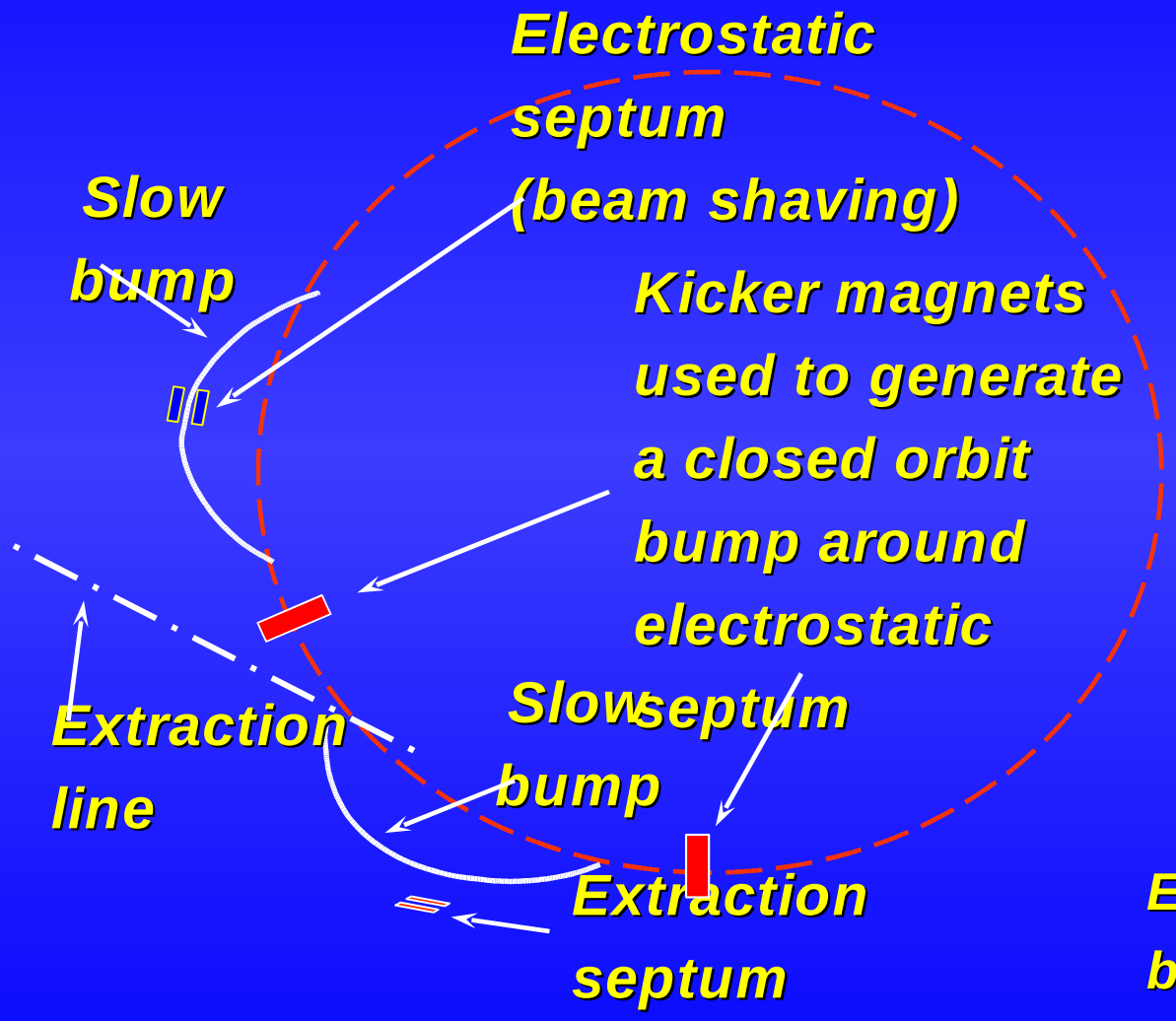


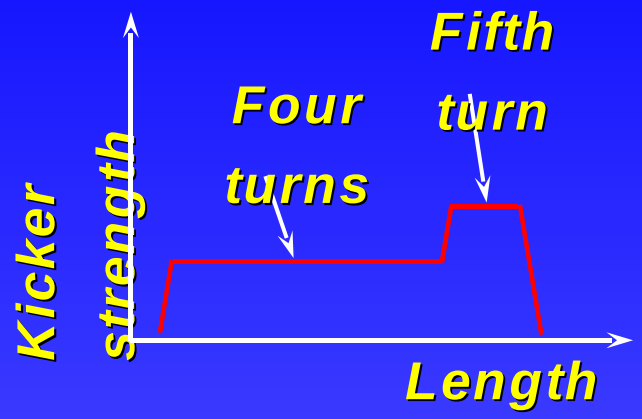


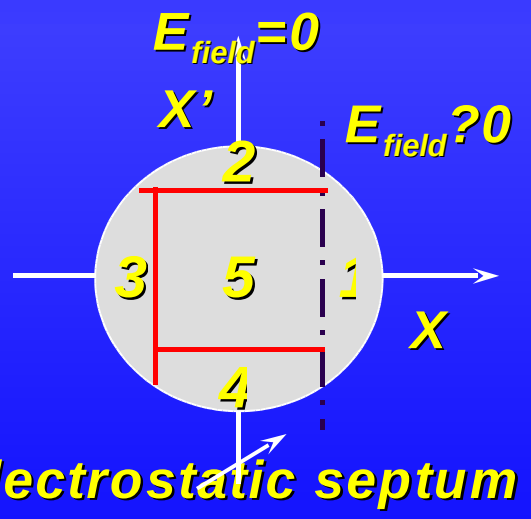
Beam current transformer in the PS/SPS transfer line

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

Present multi-turn extraction – II







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**

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

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

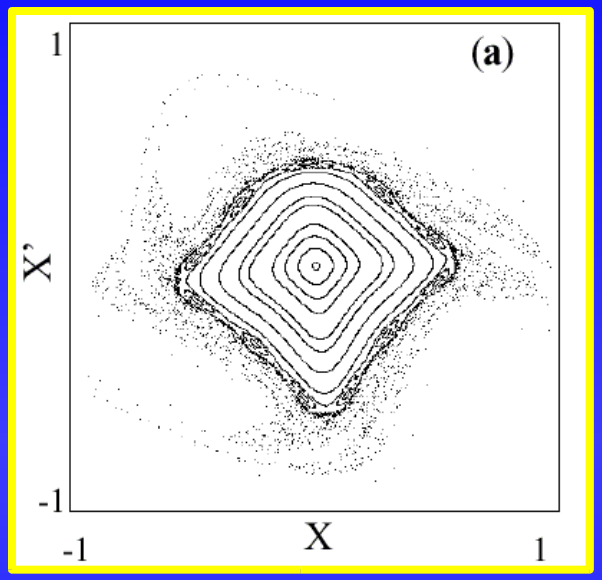
$$\begin{vmatrix} \hat{X} \\ \hat{X}' \end{vmatrix}_{n+1} = \mathbf{R}(\omega) \begin{vmatrix} \hat{X} \\ \hat{X}' + \hat{X}^2 + \kappa \hat{X}^3 \end{vmatrix}_n \qquad \kappa = \frac{2}{3} \frac{K_3}{K_2^2 \beta_x}$$

Quadrupoles

Sextupole

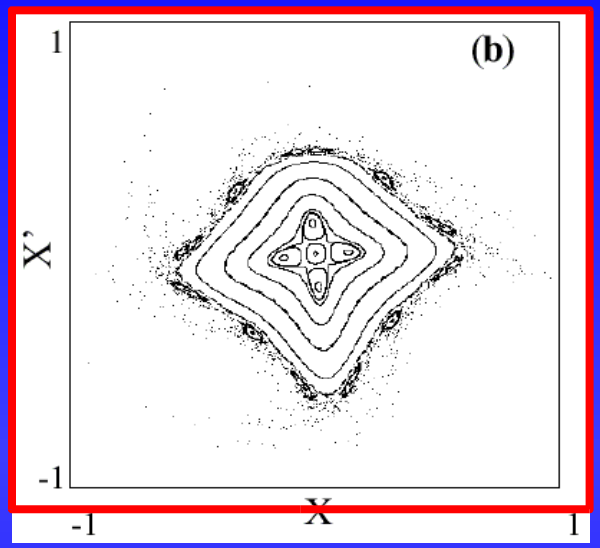
Octupole

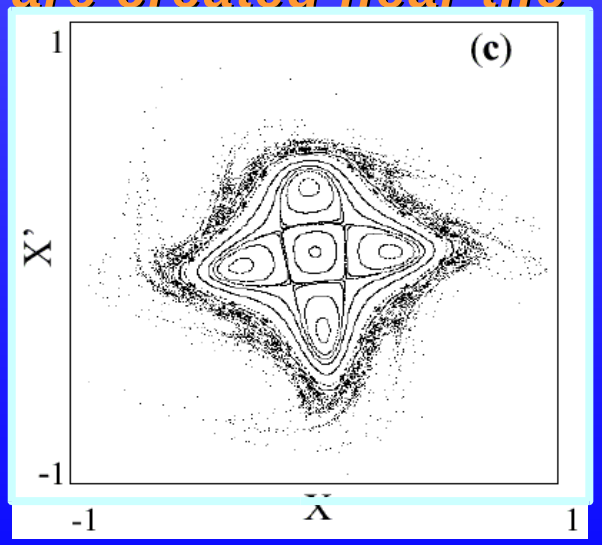
Novel multi-turn extraction – II



Left: initial phase space topology. No islands.

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



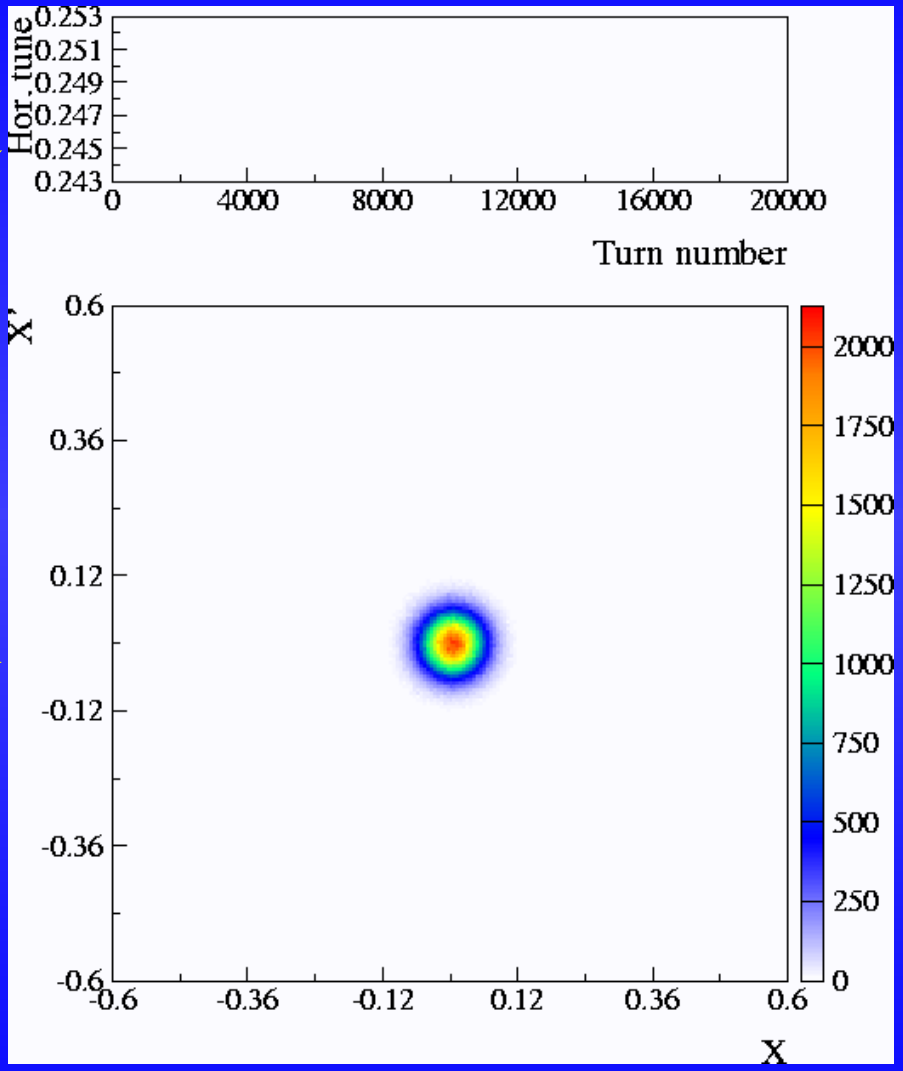


Bottom: final phase space topology. Islands are separated to allow extraction.

Novel multi-turn extraction - III

Tune variation

Phase space portrait

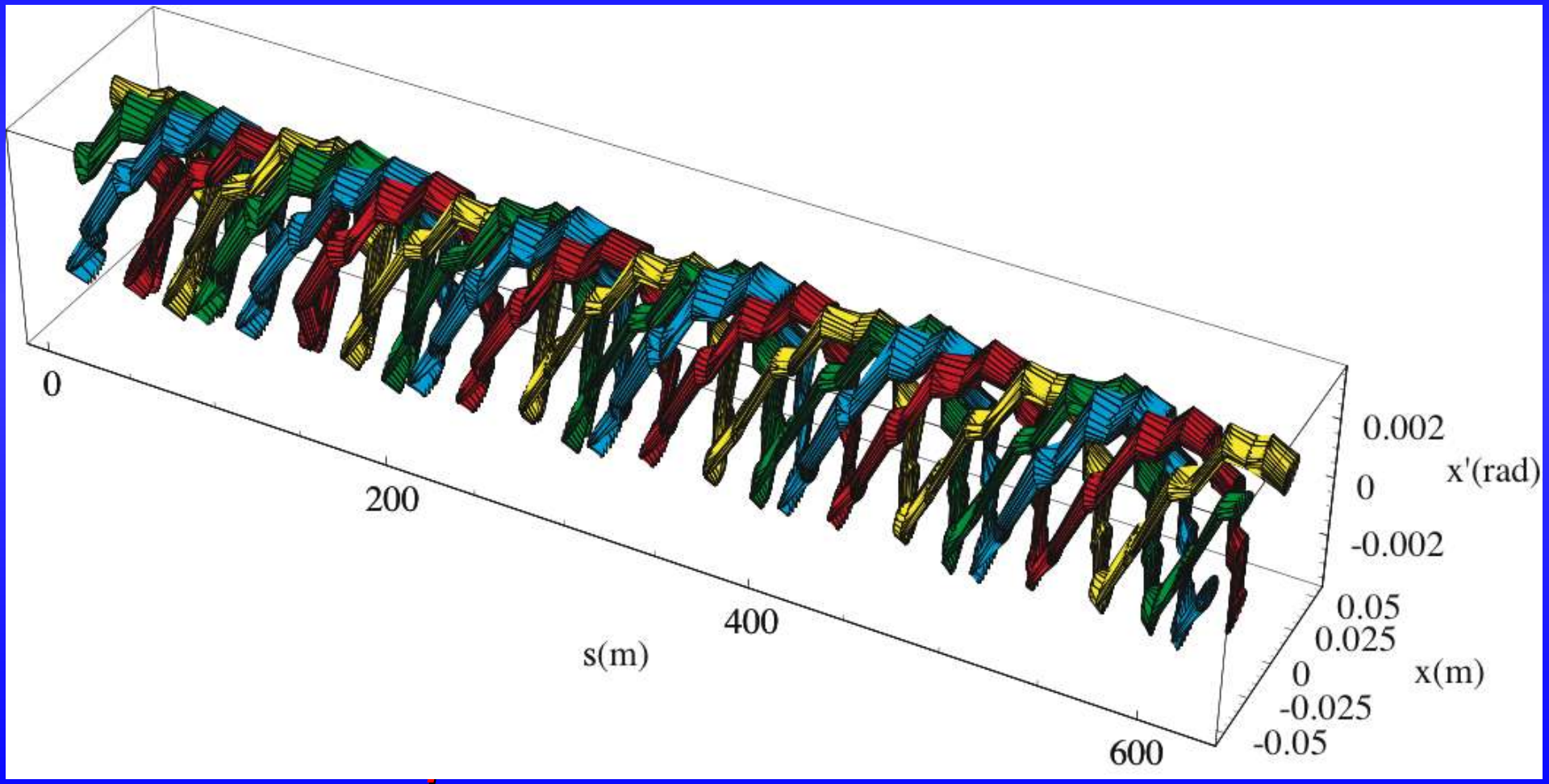


Simulation parameters:

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

Novel multi-turn extraction – IV

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



The capture process - I

Initial gaussian distribution

Particles in island 2

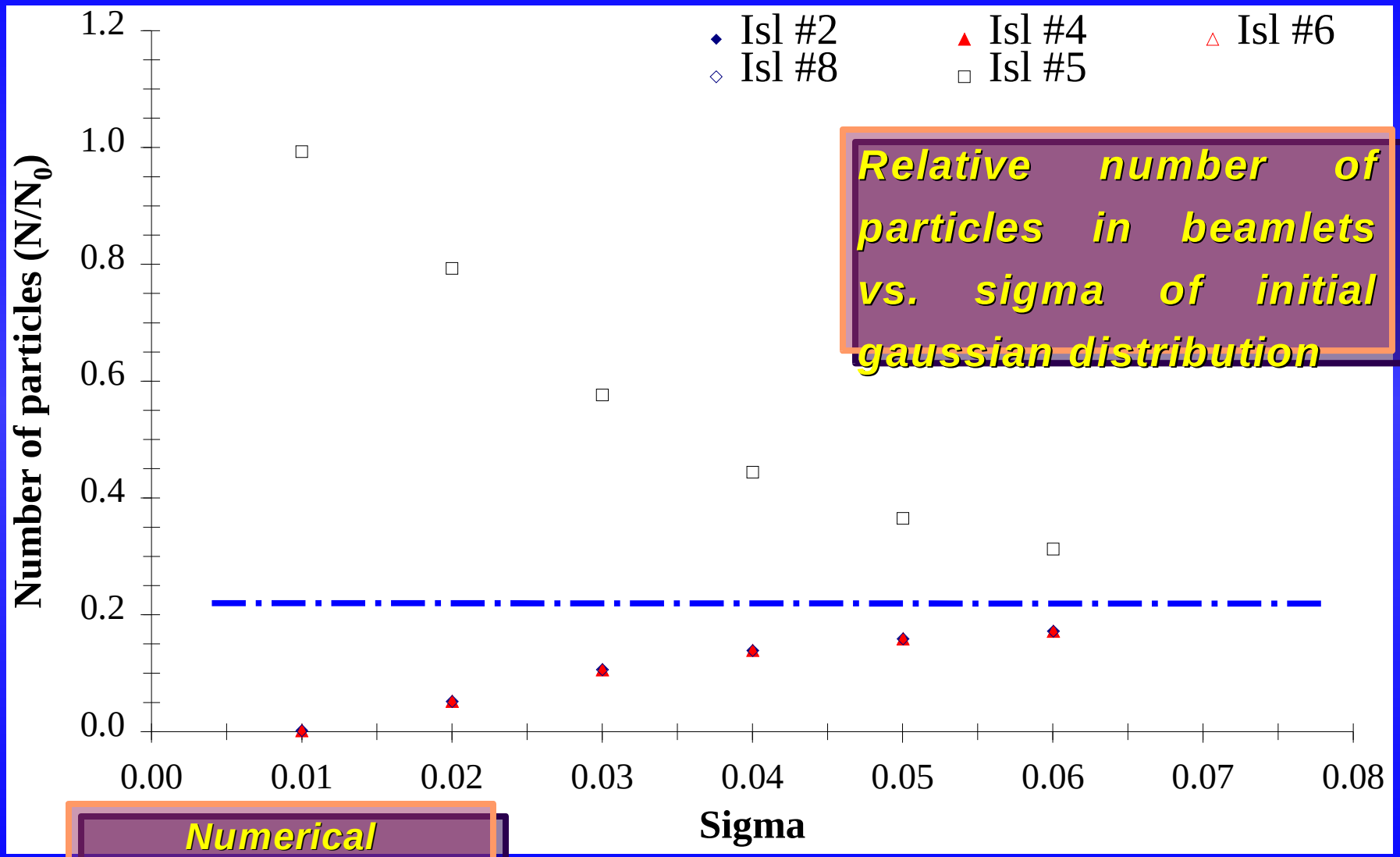
Particles in island 4

Particles in island 6

Particles in island 8

Particles in beam core

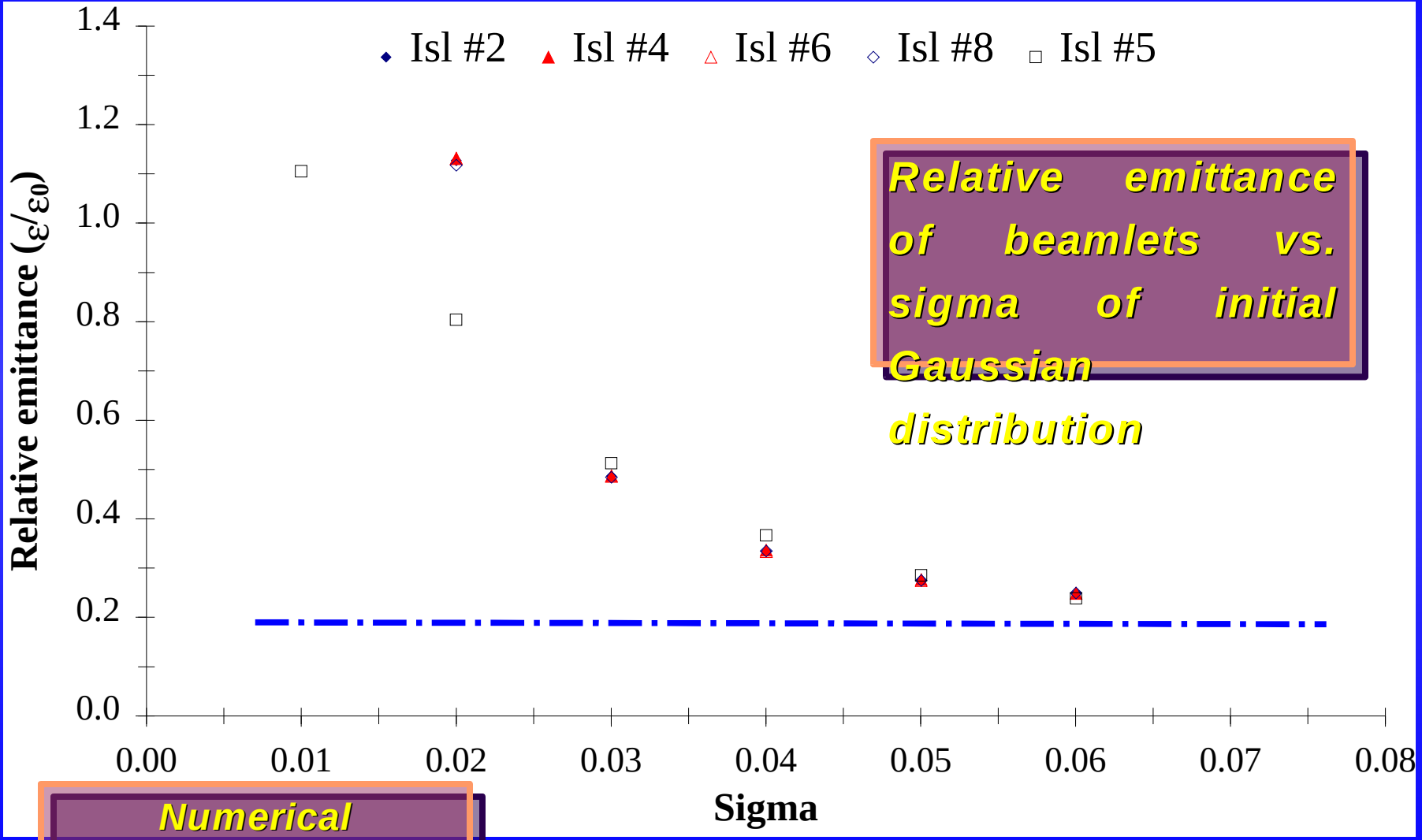
The capture process - II



Relative number of particles in beamlets vs. sigma of initial gaussian distribution

Numerical simulations

The capture process - III



Relative emittance of beamlets vs. sigma of initial Gaussian distribution

Numerical simulations

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

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

Secondary frequency

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

Distance of fixed points from origin of phase space

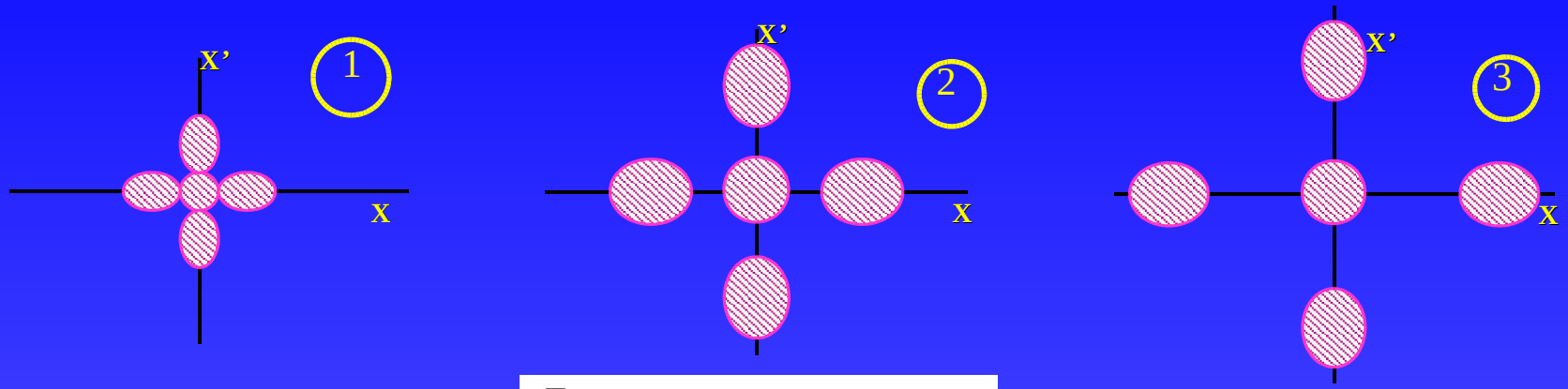
$$\Sigma = 16\sqrt{\left|\frac{\varepsilon}{\Omega_2}\right| \left|u_{0,3}\right| \rho_+^2}$$

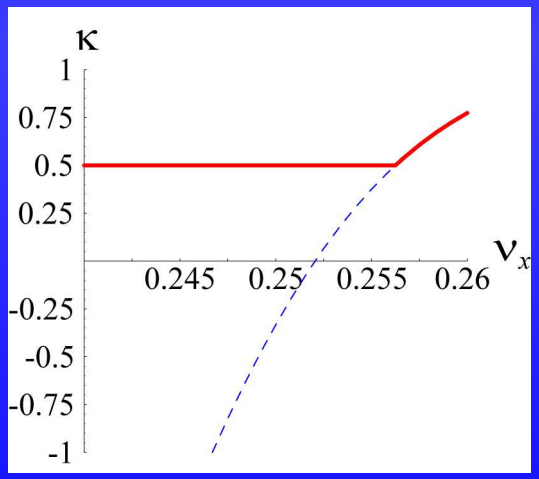
Island's surface

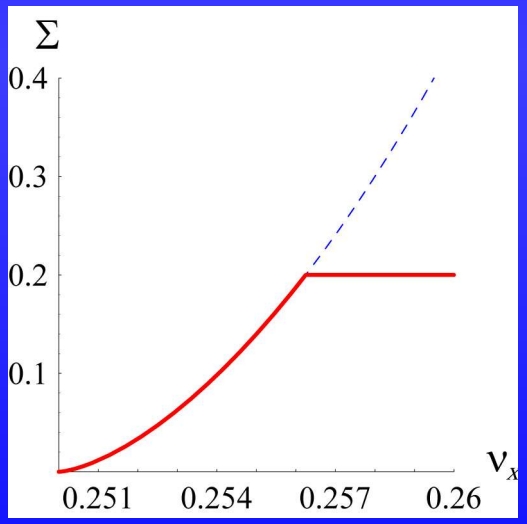
$$\Delta = 4\sqrt{\left|\frac{\varepsilon}{\Omega_2}\right| \left|u_{0,3}\right| \rho_+^2}$$

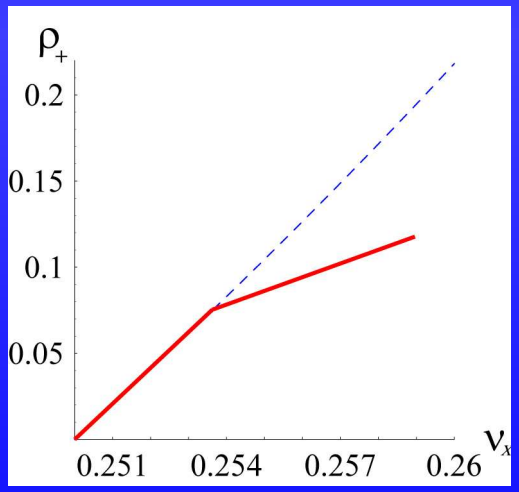
Distance between separatices

Example: how to keep island's surface constant









To be tested with numerical simulations…

Novel multi-turn extraction - V

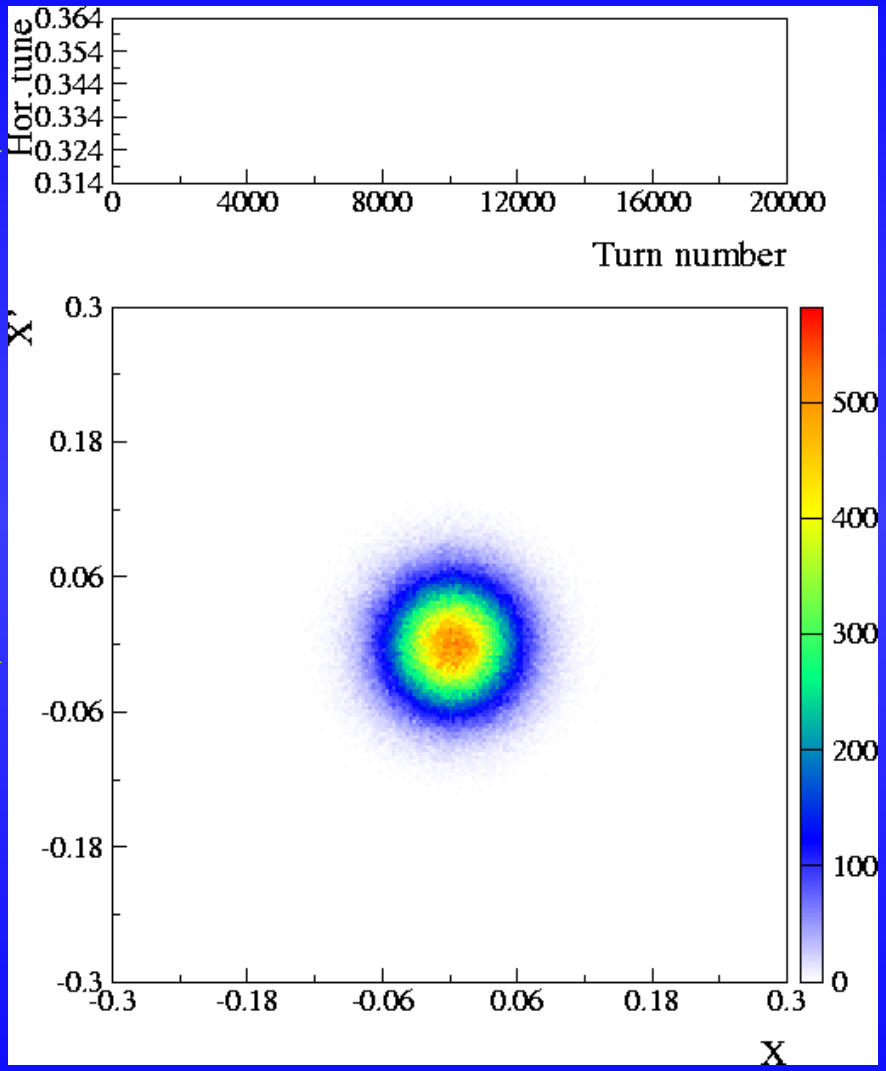
The original goal of this study was to find a replacement to the present Continuous Transfer used at CERN for the high-intensity proton beams. However the novel technique proved to be useful also in different context, e.g.

- 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

Novel multi-turn extraction with other resonances - I

Tune variation

Phase space portrait



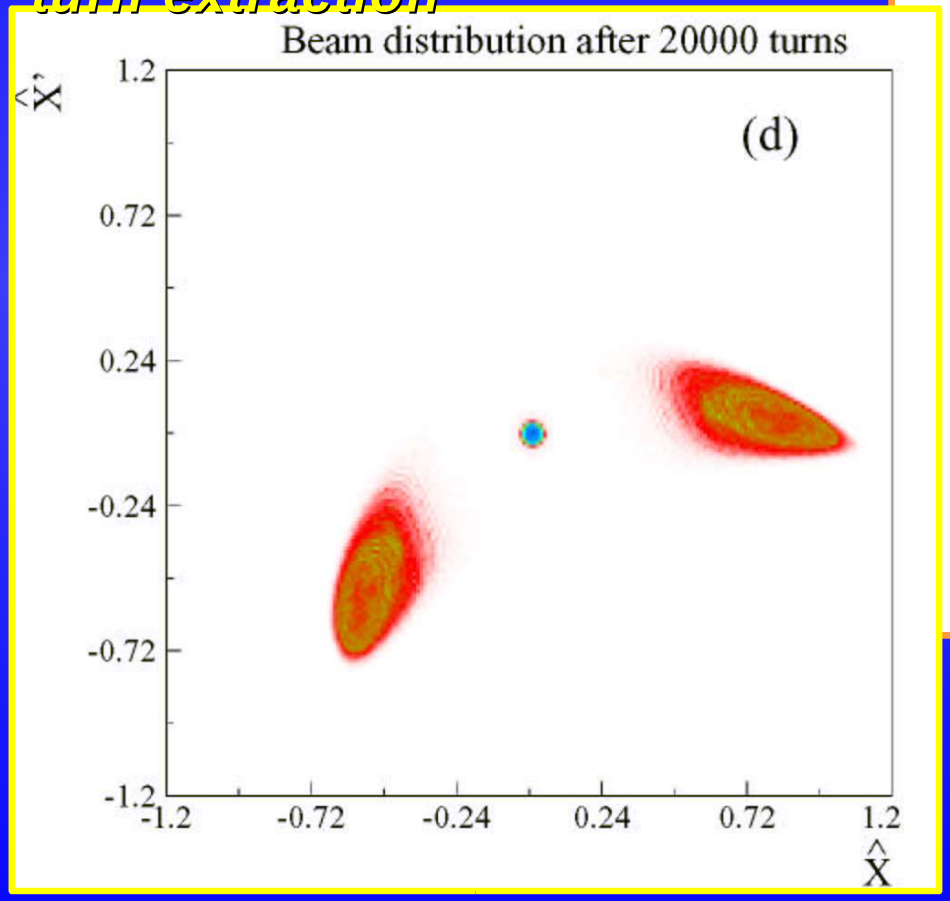
Simulation parameters:

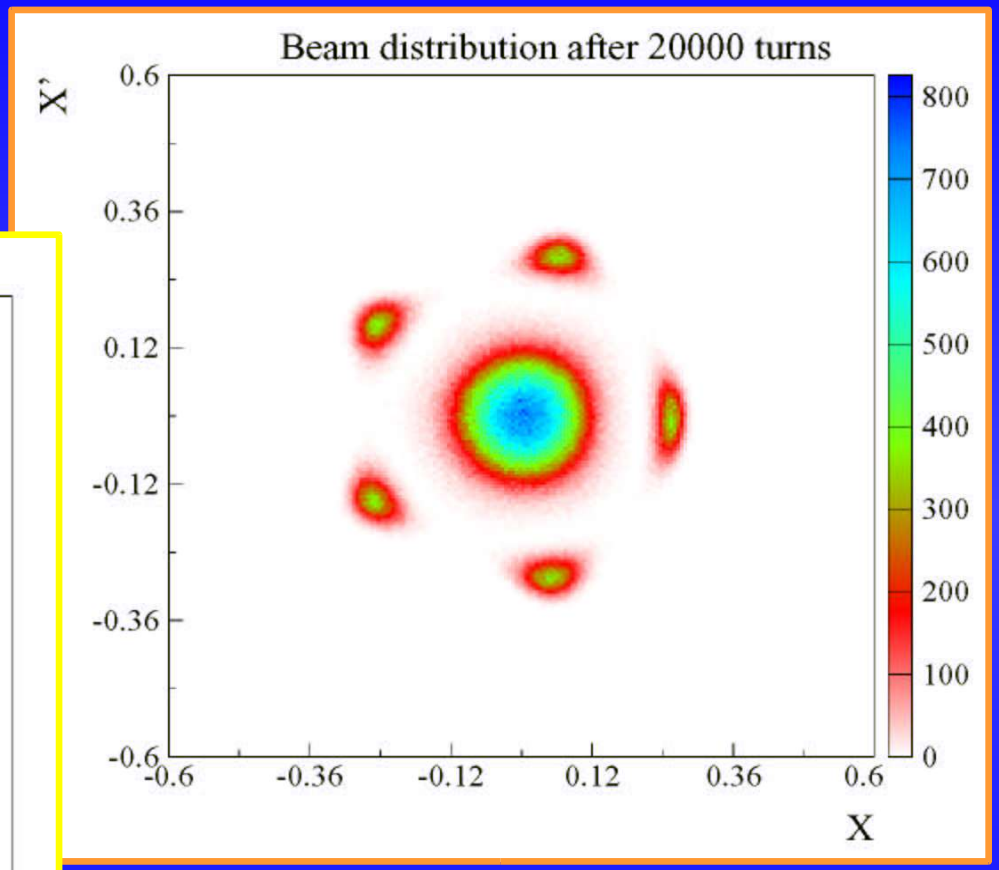
Hénon-like map with sextupole and octupole

The third-order resonance is used, thus giving

Novel multi-turn extraction with other resonances - II

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





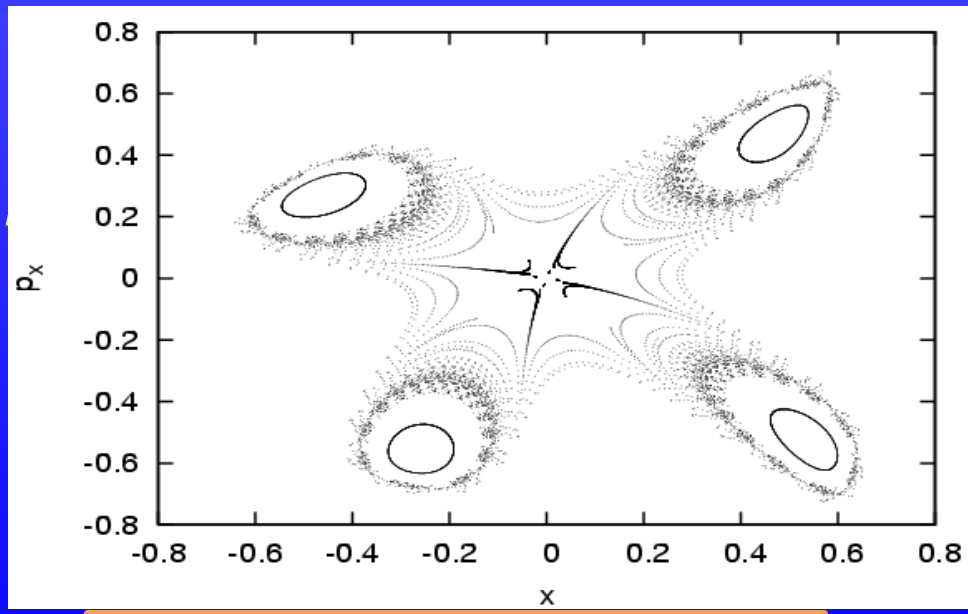
The fifth-order resonance is used, thus giving a six-turn extraction

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.

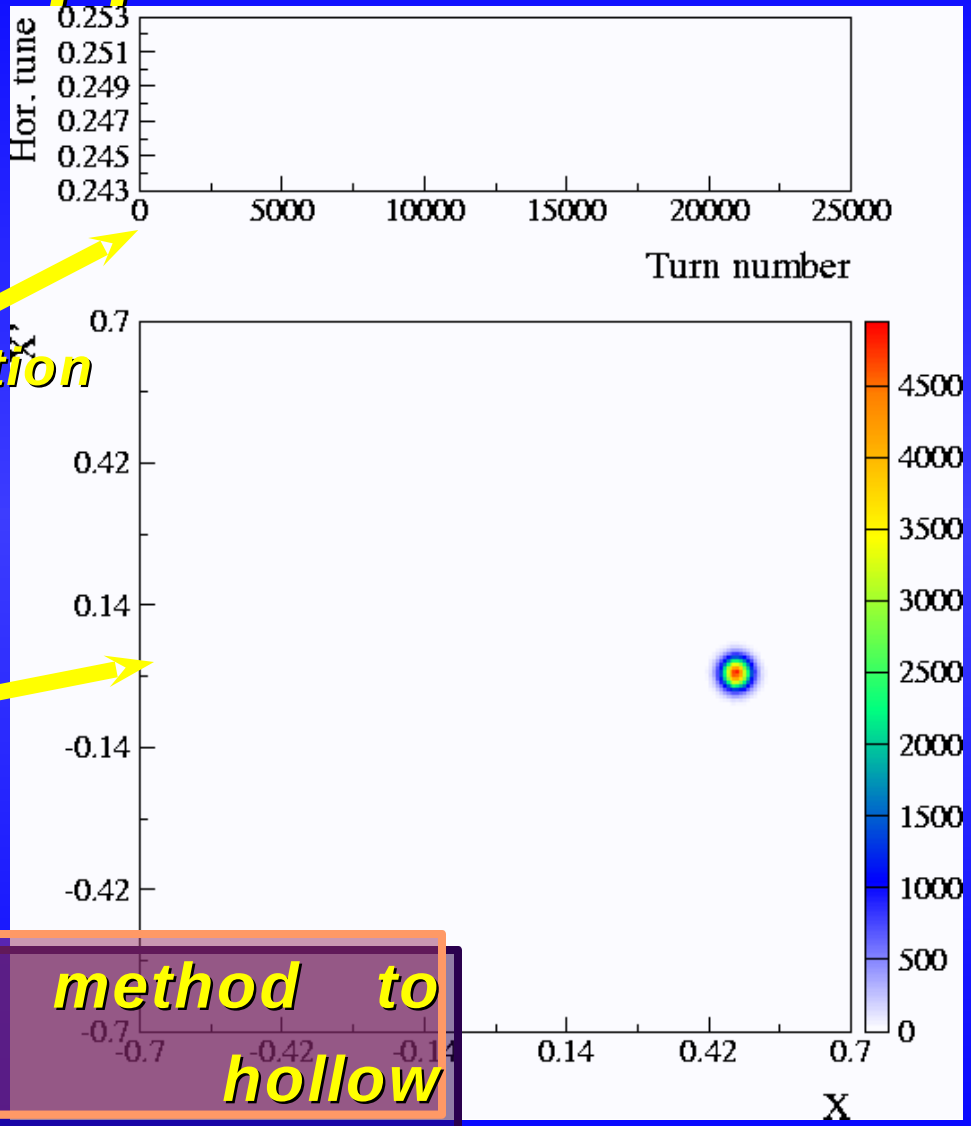
$$\nu_x = \nu_{x,0} + \Omega_2 A_x \quad \rightarrow \quad \Omega_2 = 0$$

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



Master thesis Diego Quatraro

Novel multi-turn injection: new application!



Tune variation

Phase space portrait

Simulation parameters:

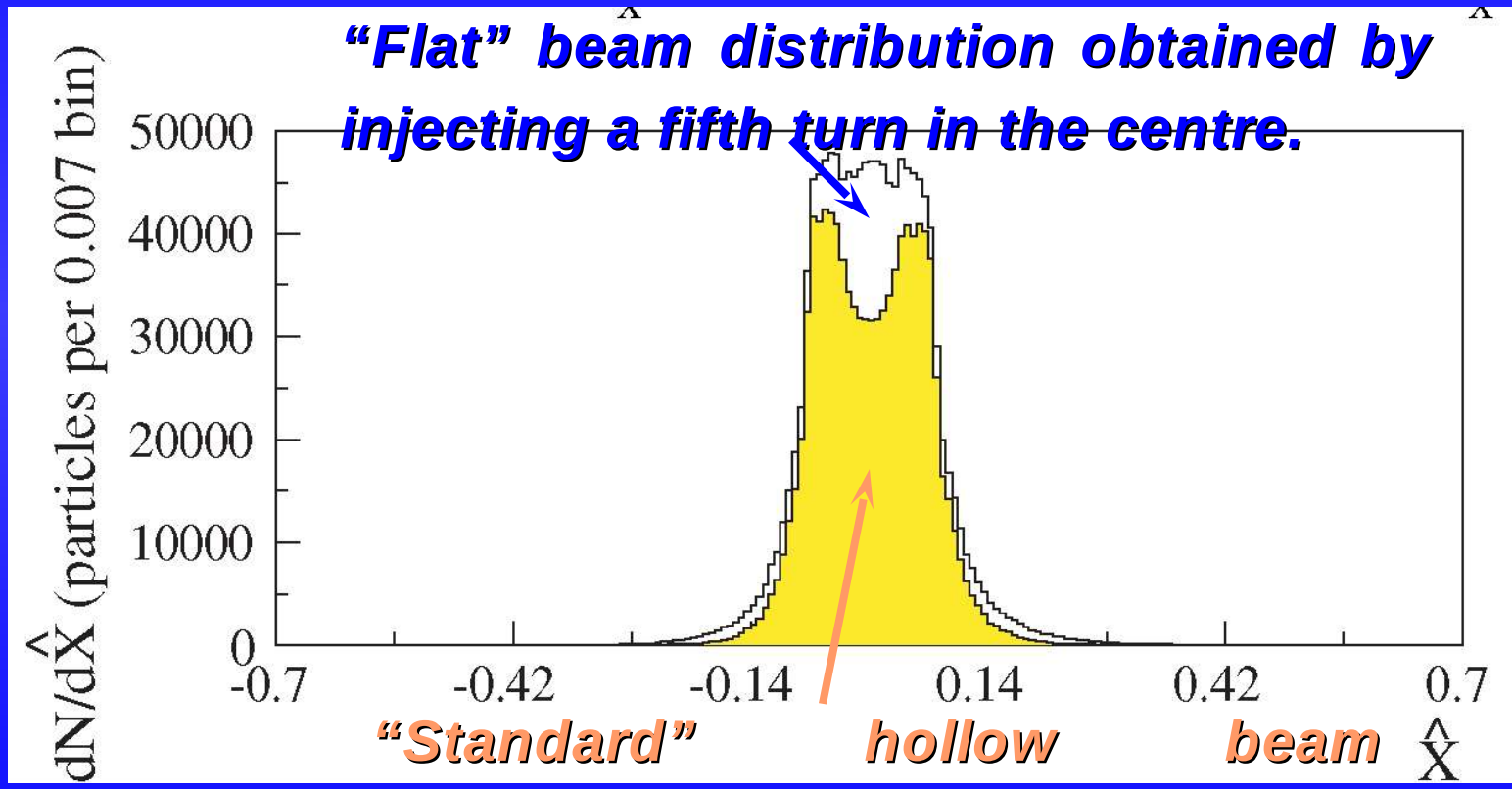
Third-order polynomial map representing a FODO cell with sextupole and octupole

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

Efficient method to generate hollow beams!

Novel multi-turn injection: new application!

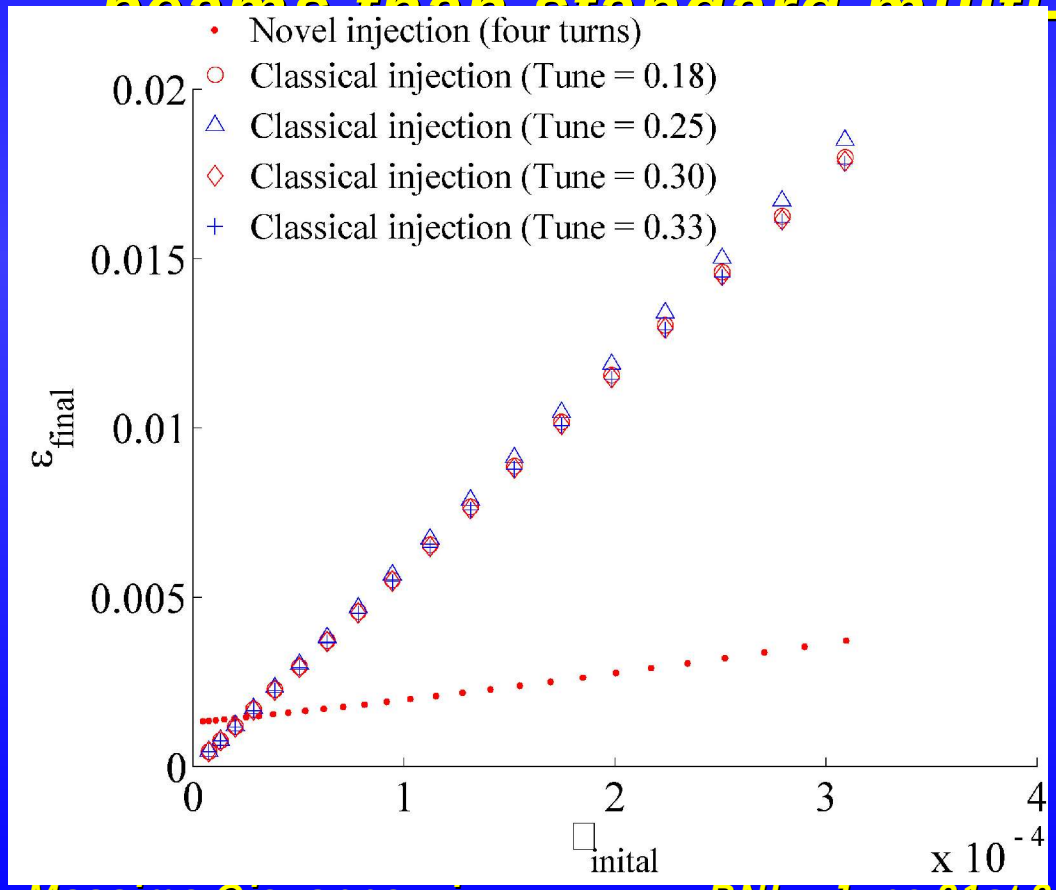
- Possible applications: transverse shaping of beam distribution.

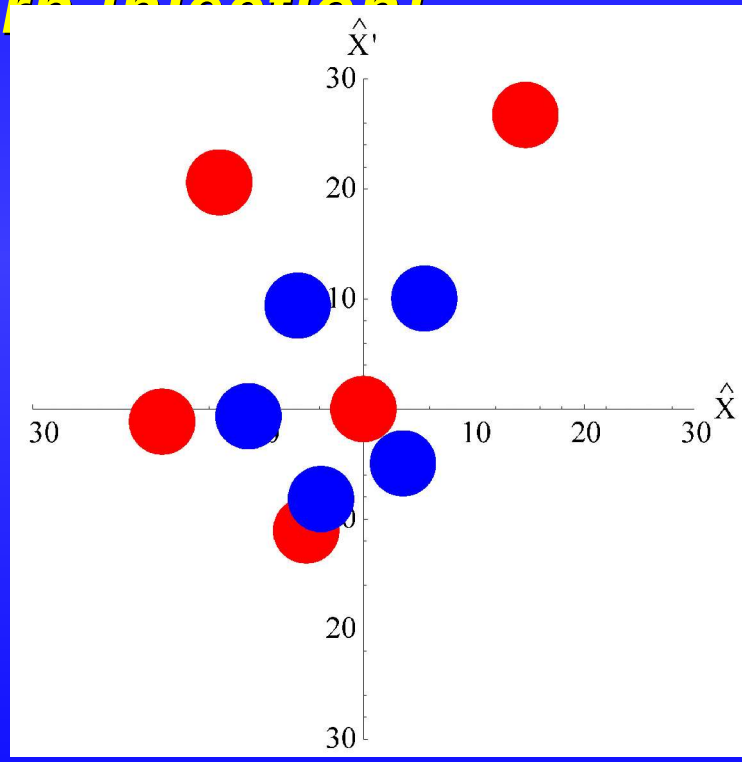


M. Giovannozzi, J. Morel, PRST-AB, 10, 034001 (2007)

Novel multi-turn injection: new application!

- 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)

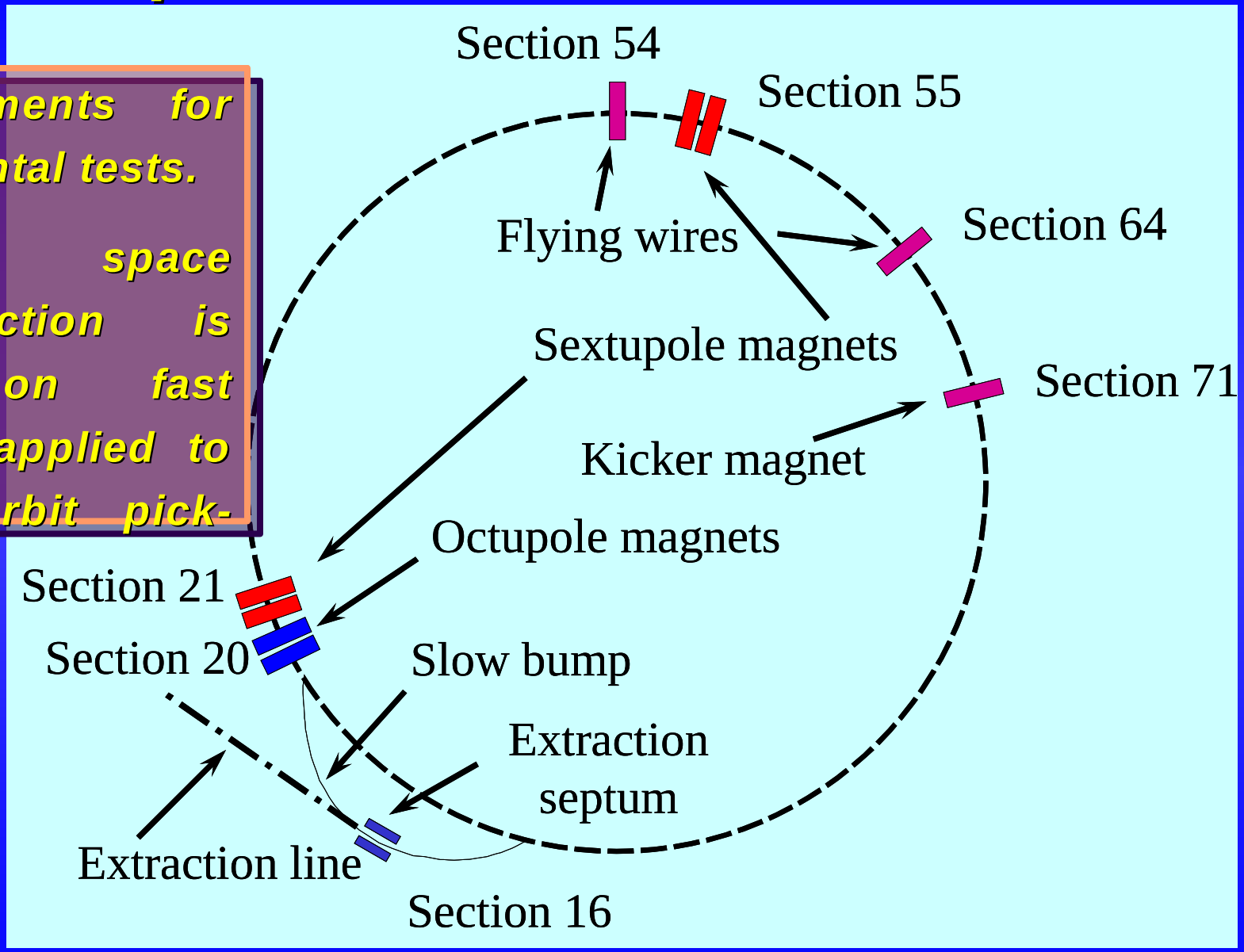
Experimental results - I

- Experimental tests were undertaken since 2002.
  - 2002 run: proof-of-principle of the capture process using a low intensity beam.
  - 2003 run: detailed study of capture process with low-intensity beam and first tests with high-intensity proton beam.
  - 2004 run: main focus on high-intensity beam to solve problems observed in 2003.
  - 2006 run: improve intensity sharing.
- Overall strategy:
  - Phase space reconstruction using low-intensity, pencil beam.
  - Capture with low-intensity, large horizontal emittance beam.

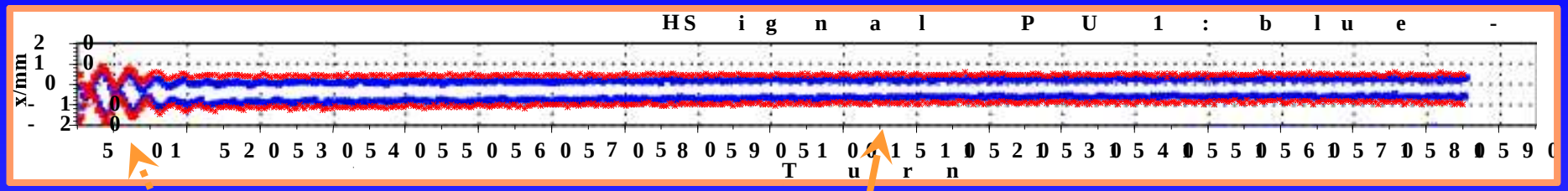
Experimental results - II

Key elements for experimental tests.

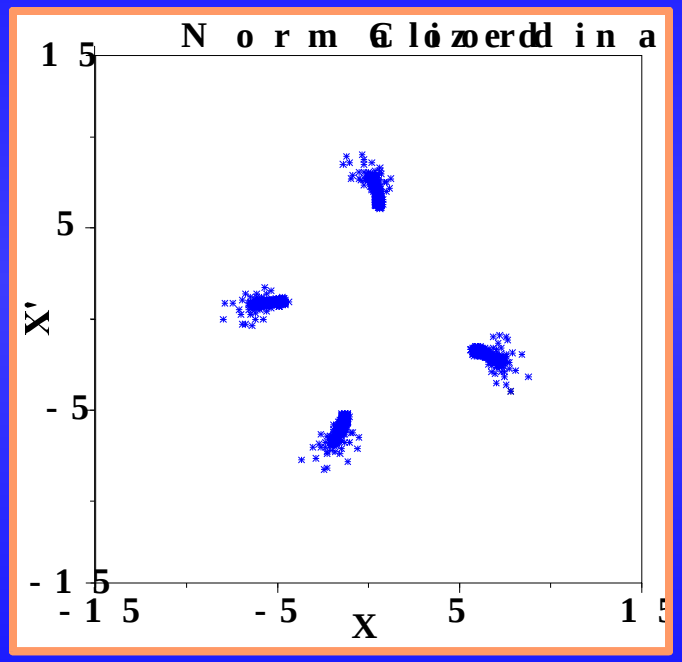
Phase space reconstruction is based on fast digitiser applied to closed orbit pick-ups.

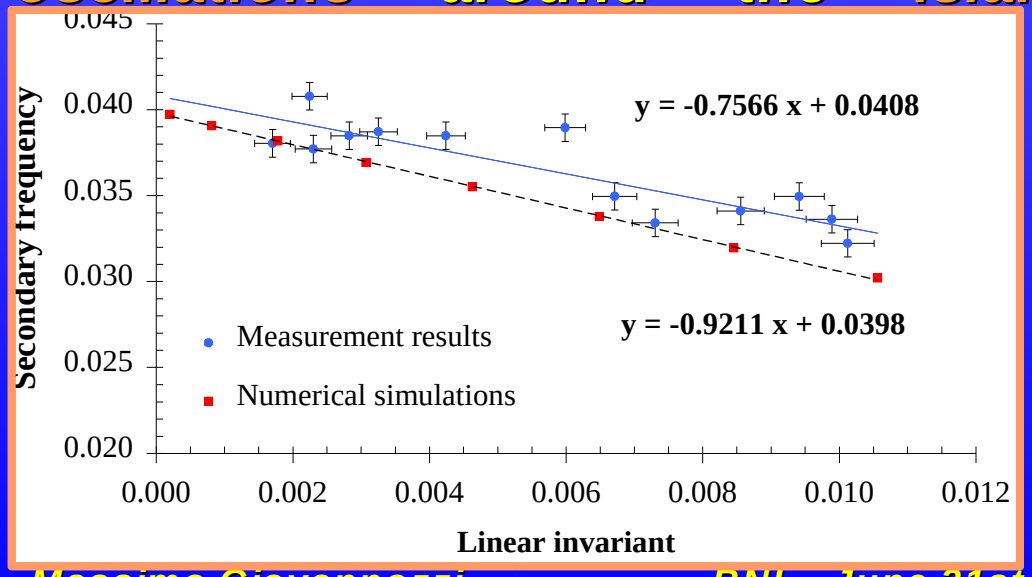


Experimental results - III



The pencil beam is kicked into the islands producing a strong coherent signal (filamentation is suppressed). Initial wiggles represent beam oscillations around the islands'

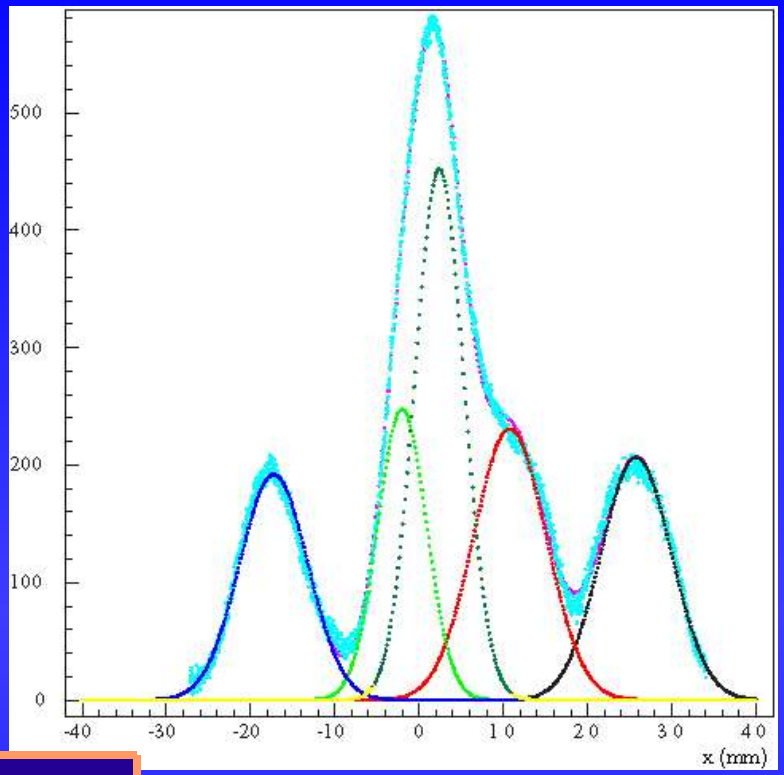




Measured detuning inside an island compared to numerical simulations.

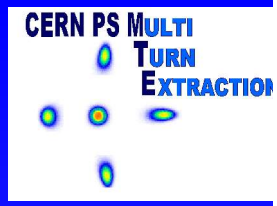
Data analysis and beam parameters

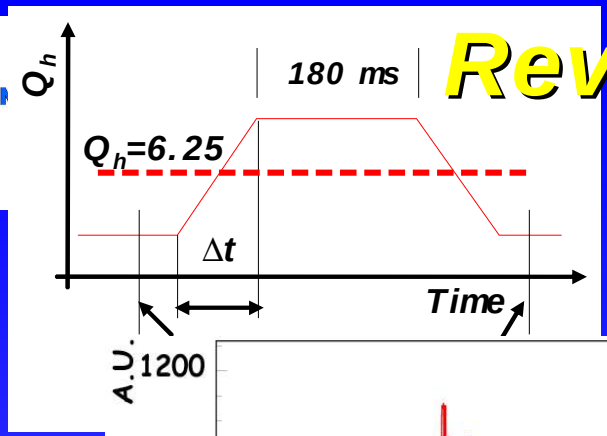
- The wire scanner is the key instrument for these studies.
- Raw data are stored for off-line analysis.
- Five Gaussians are fitted to the measured profiles to estimate beam parameters of five beamlets



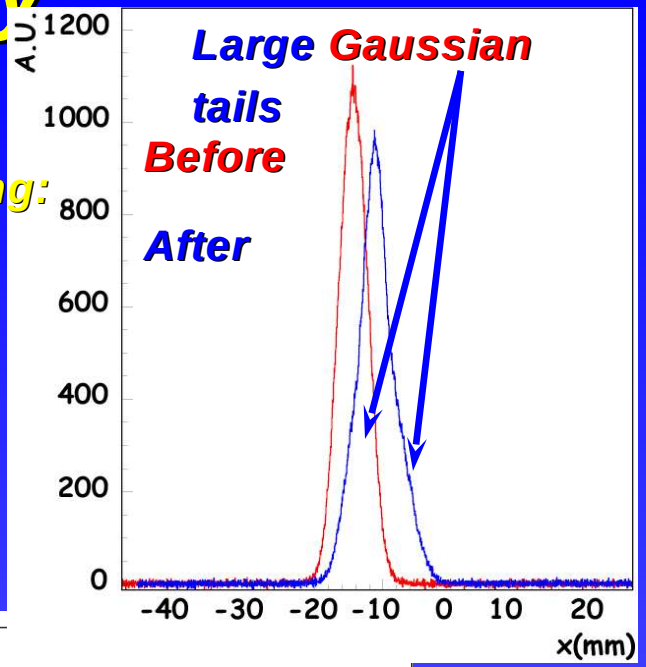
	Intensity	$\varepsilon^*_H(\sigma)/\varepsilon^*_V(\sigma)$
Low-intensity pencil beam	5×10^{11}	2.3/ 1.3
Low-intensity large H emittance	5×10^{11}	6.2/ 1.6
High intensity beam	6×10^{12}	9.4/ 6.4

Reversibility

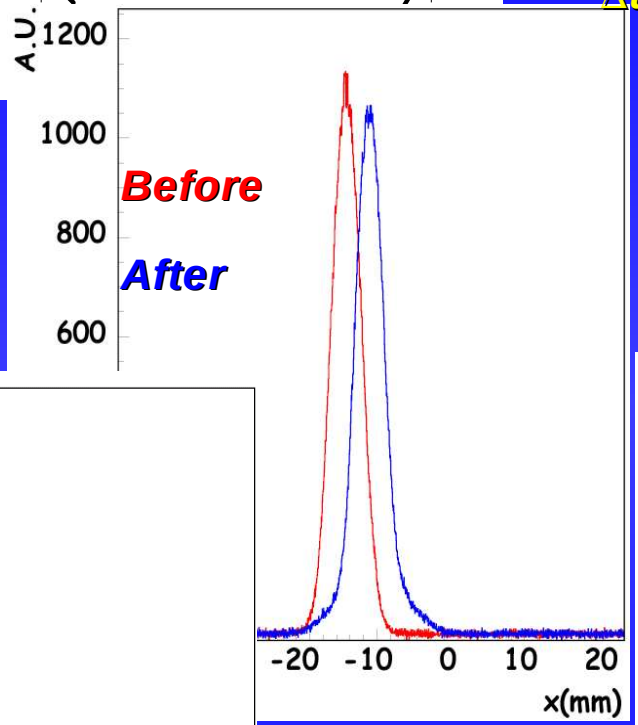


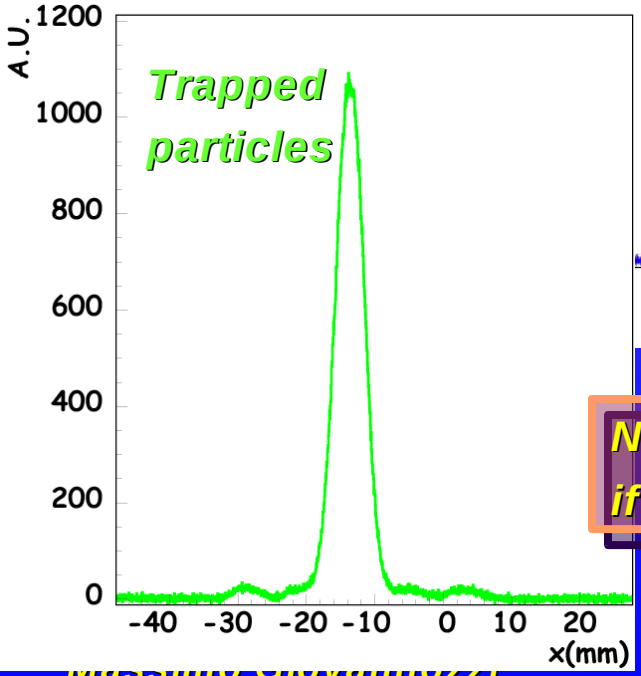


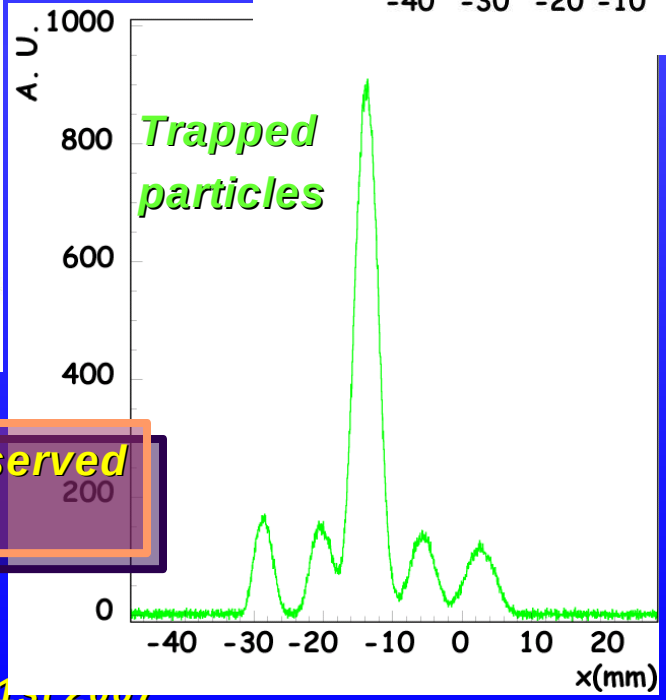
Slow crossing:
Δt 90 ms.



Fast crossing:
Δt 5 ms.





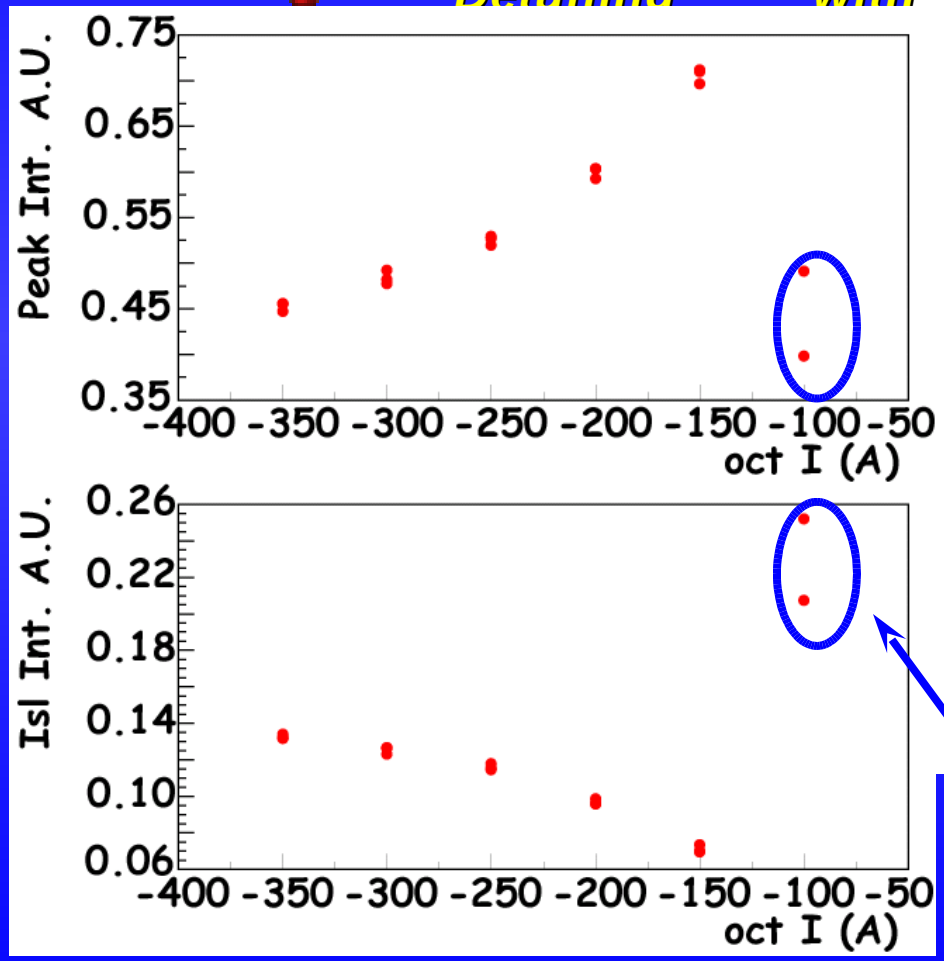


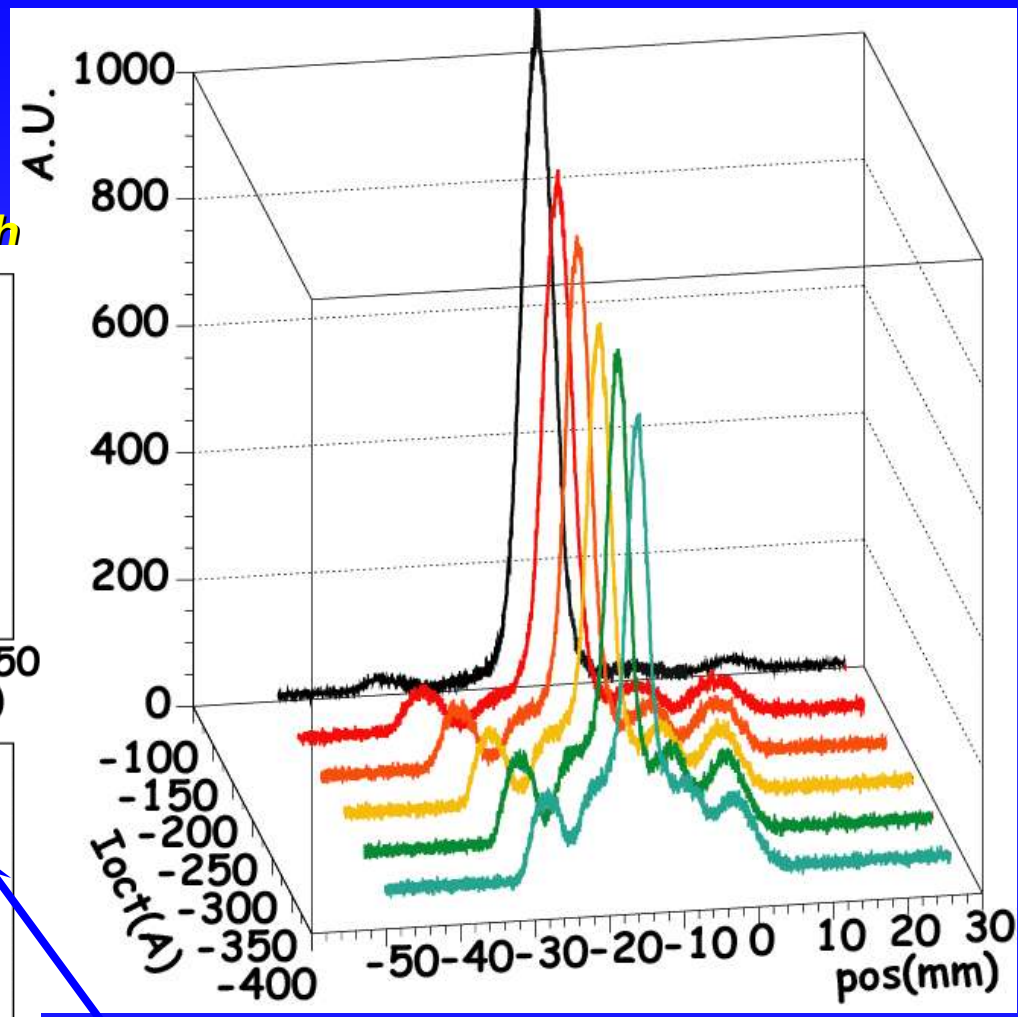
No difference observed
if Δt > 20-40 ms.

Influence of octupole strength

Octupole action

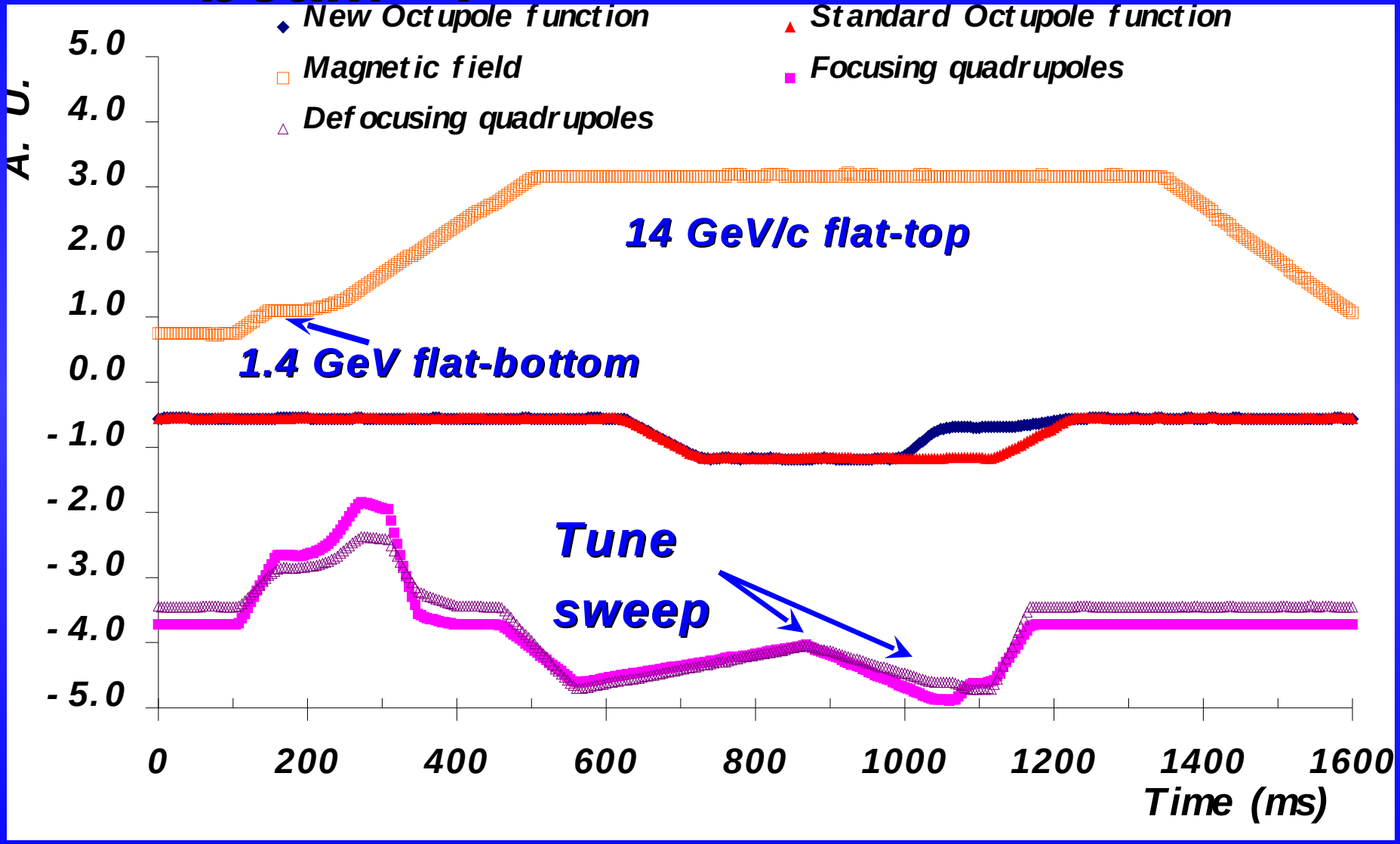
- Island size.
- Detuning with



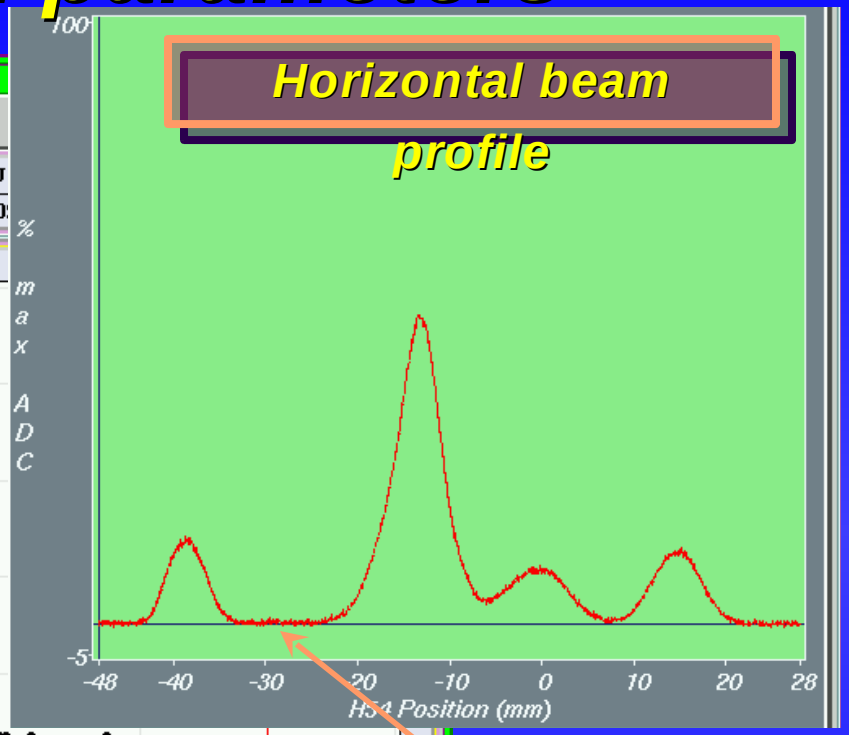


Problems with the fit

Crucial part: high-intensity beam - I



After optimisation of transverse and longitudinal parameters



Capture losses are reduced to zero…

Depleted region: extraction septum blade will not intercept any particle

A movie to show the evolution of beam distribution

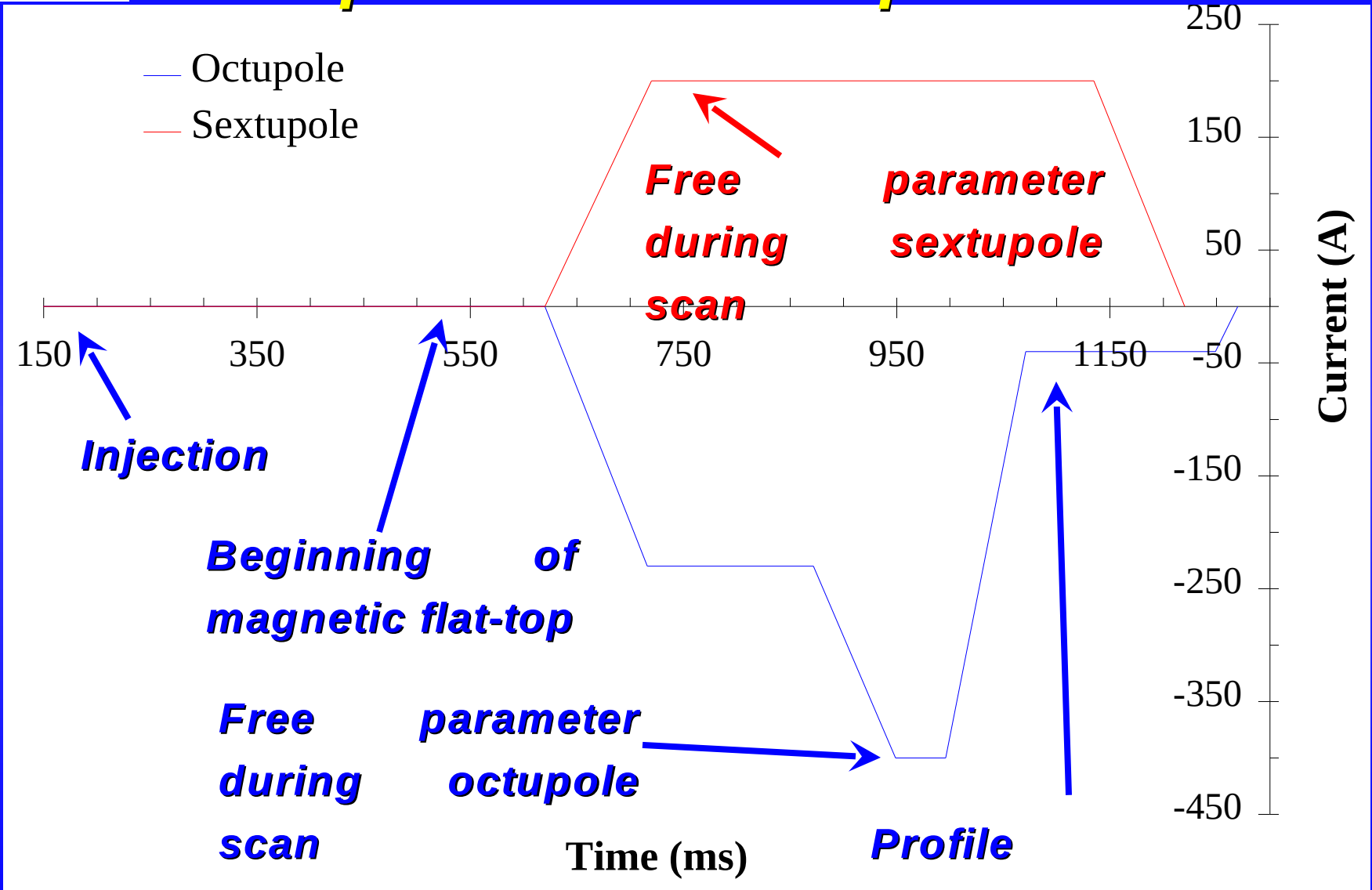
A series of horizontal beam profiles in section 54 have been taken during the capture process.

The beam is the high-intensity one.

Other studies with high-intensity beams: how to increase the fraction of trapped particles

- The horizontal emittance delivered by the PS-Booster was increased at its maximum value.
- The strength of the octupole was varied to change the island size
- The strength of the sextupoles was changed too (more difficult as this has an impact on chromaticity).
- Summary of results (detailed data analysis is in progress)
  - The fraction of trapped particles reached about 18% (NB: the limit set by SPS on the turn-by-turn intensity variation is (20±1)% for the last beamlet).

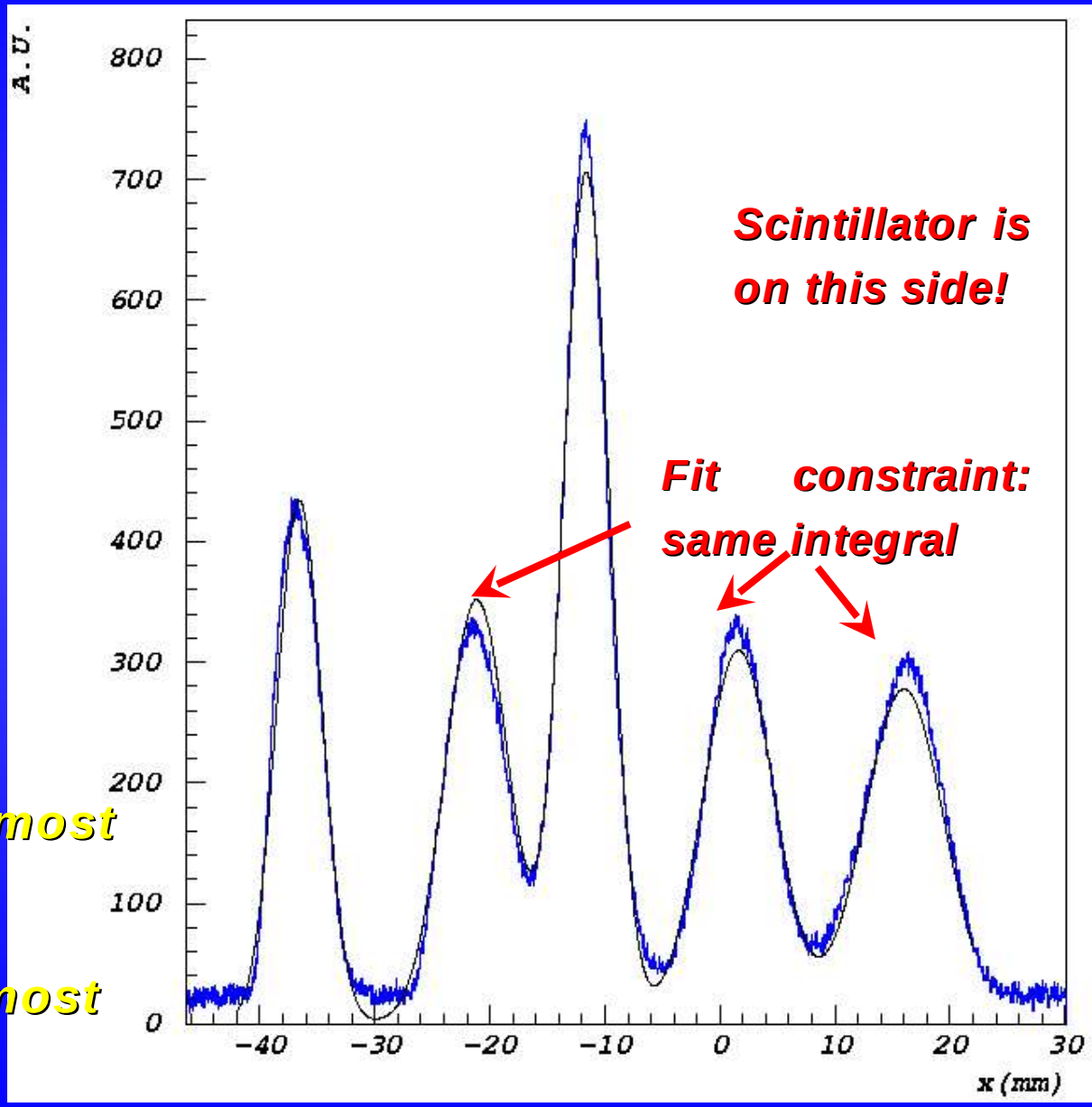
Experimental conditions sextupoles and octupole scan



Best result (2004) in terms of capture

Assuming that:

- Beamlets are affected by a different solid angle
- Beamlets are fitted using five gaussians. Instead of imposing the same integral for the four beamlets (physical arguments), only three have such a constraint (solid angle consideration)



Capture

- 18% three rightmost beamlets
- 16% single leftmost beamlet

Best result (2006) in terms of capture

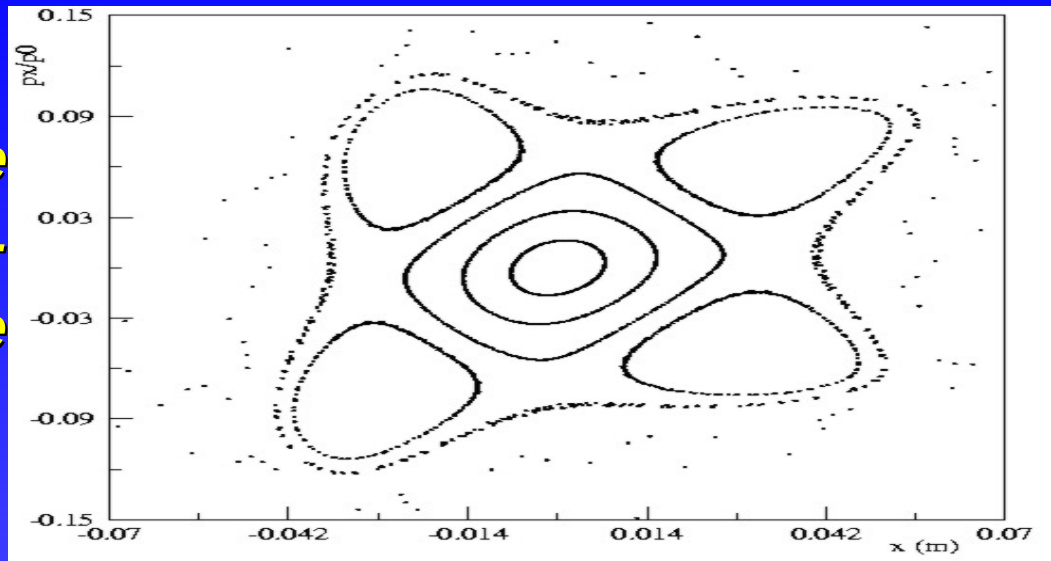
Using a setting based on the reduction of the amplitude-dependent detuning, the fraction of trapped particles:

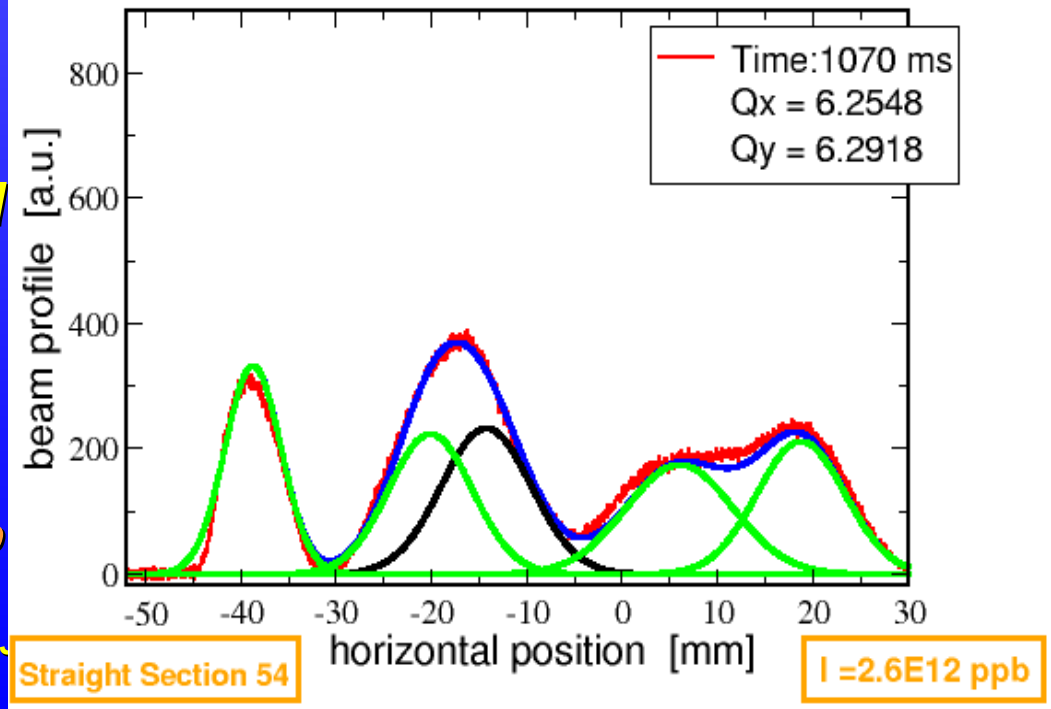
- Core: 22%
- Beamlets: 19.5%

increases to the required (20±1)%.

Total intensity: 2.5× 10^{12} p

Losses at capture: about 1% (without optimization).





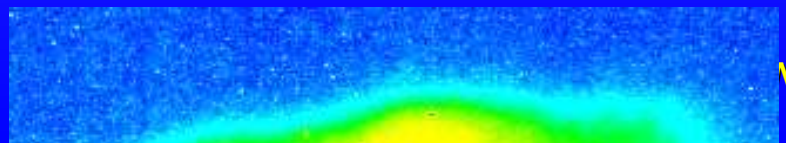
Fast-extraction tests in TT2

The high-intensity beam is fast extracted towards the dump D3.

Prior to extraction beamlets are partially merged back with central core.

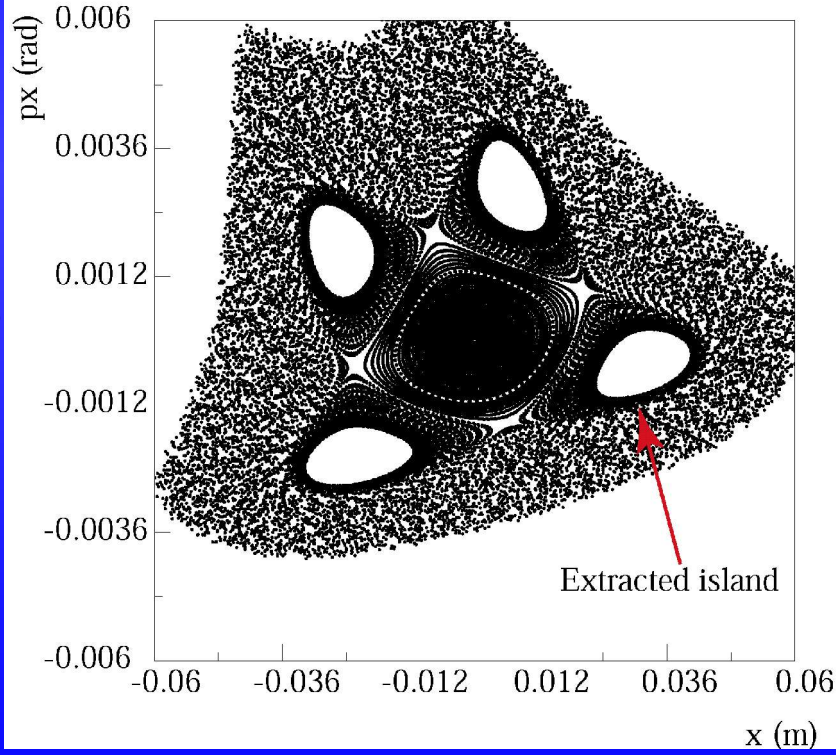
Beamlets projected onto x-axis

The OTR in TT2 allows visualising the 2D beam distribution (pixel size is 225 μm).



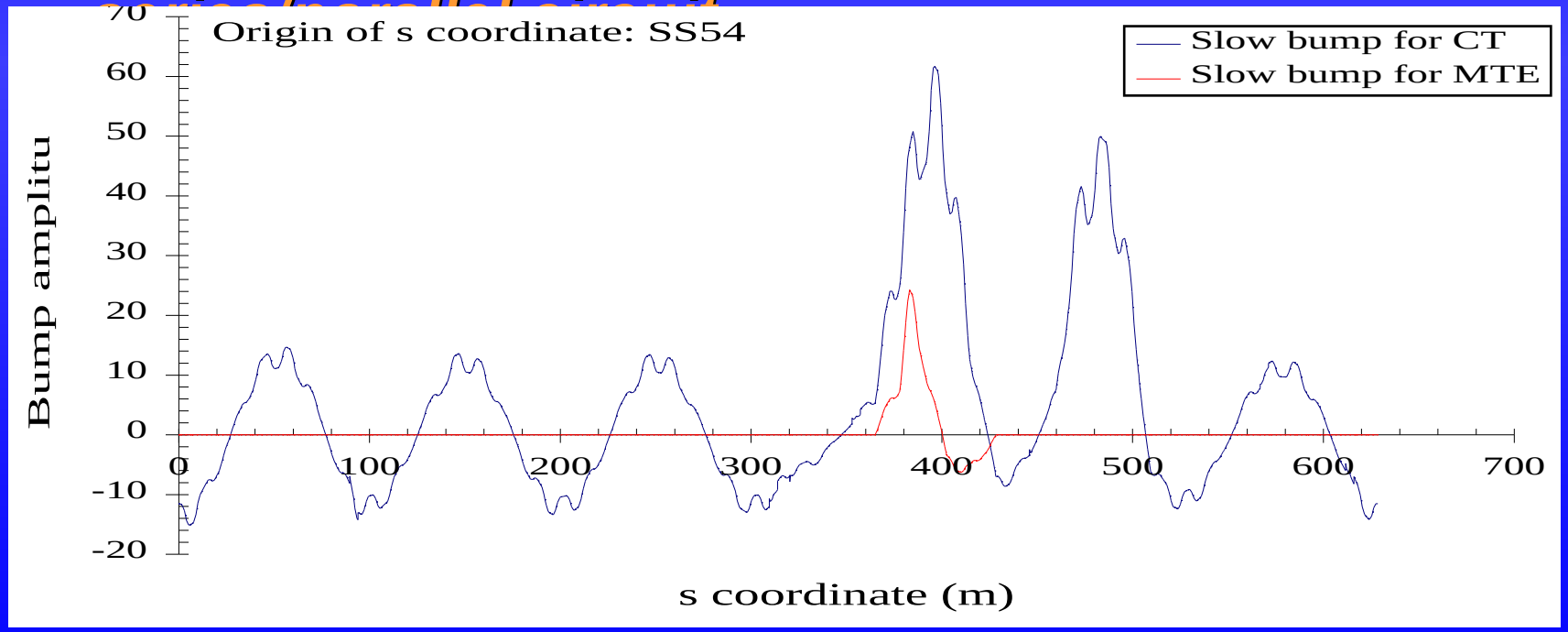
Implementation of MTE - I

- Three main items:
  - Generation of stable islands
  - Extraction proper:
    - Slow bump to approach the septum
    - Fast bump to jump septum
- Generation of stable islands
  - two pairs (spaced by 2π) of
    - two sextupoles
    - one octupole
    - will be used



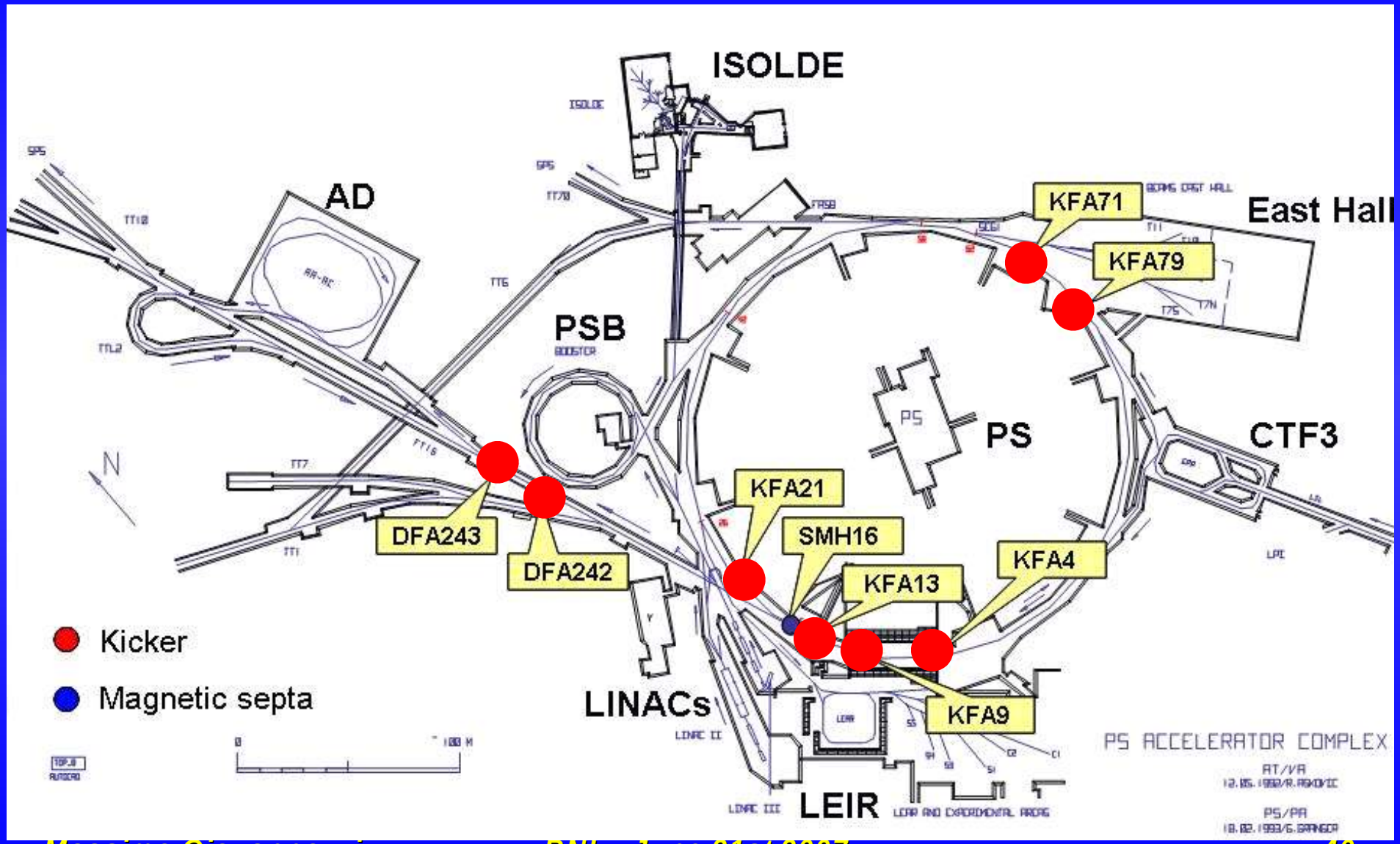
Implementation of MTE - II

- **Extraction proper: slow bump**
  - Six dipoles, independently powered, are foreseen.
  - Large number of magnets -> optimal bump shape.
  - Present slow bump: four dipoles powered with a series/parallel circuit

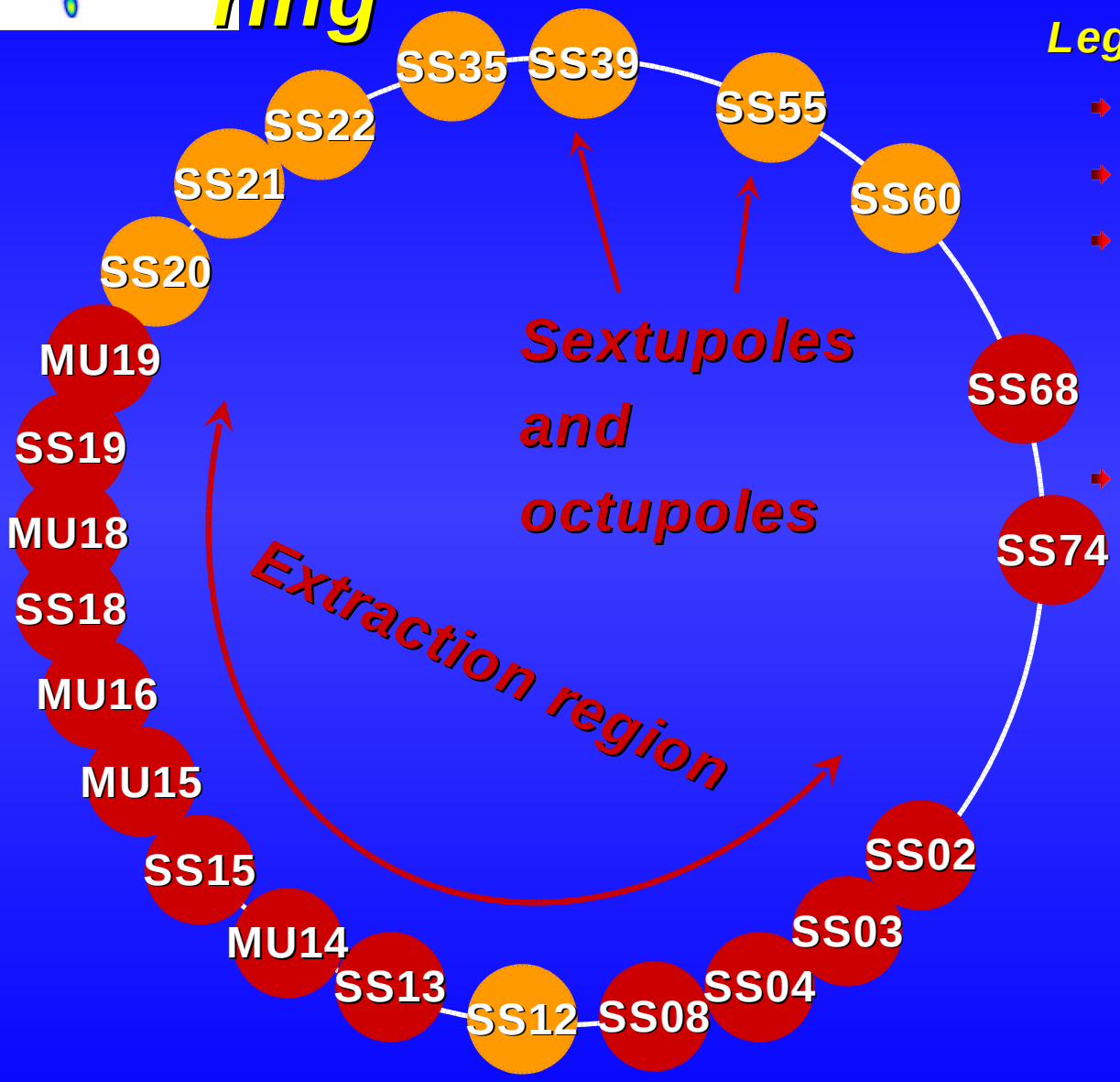


CERN PS MULTI TURN EXTRACTION

Implementation of MTE - III



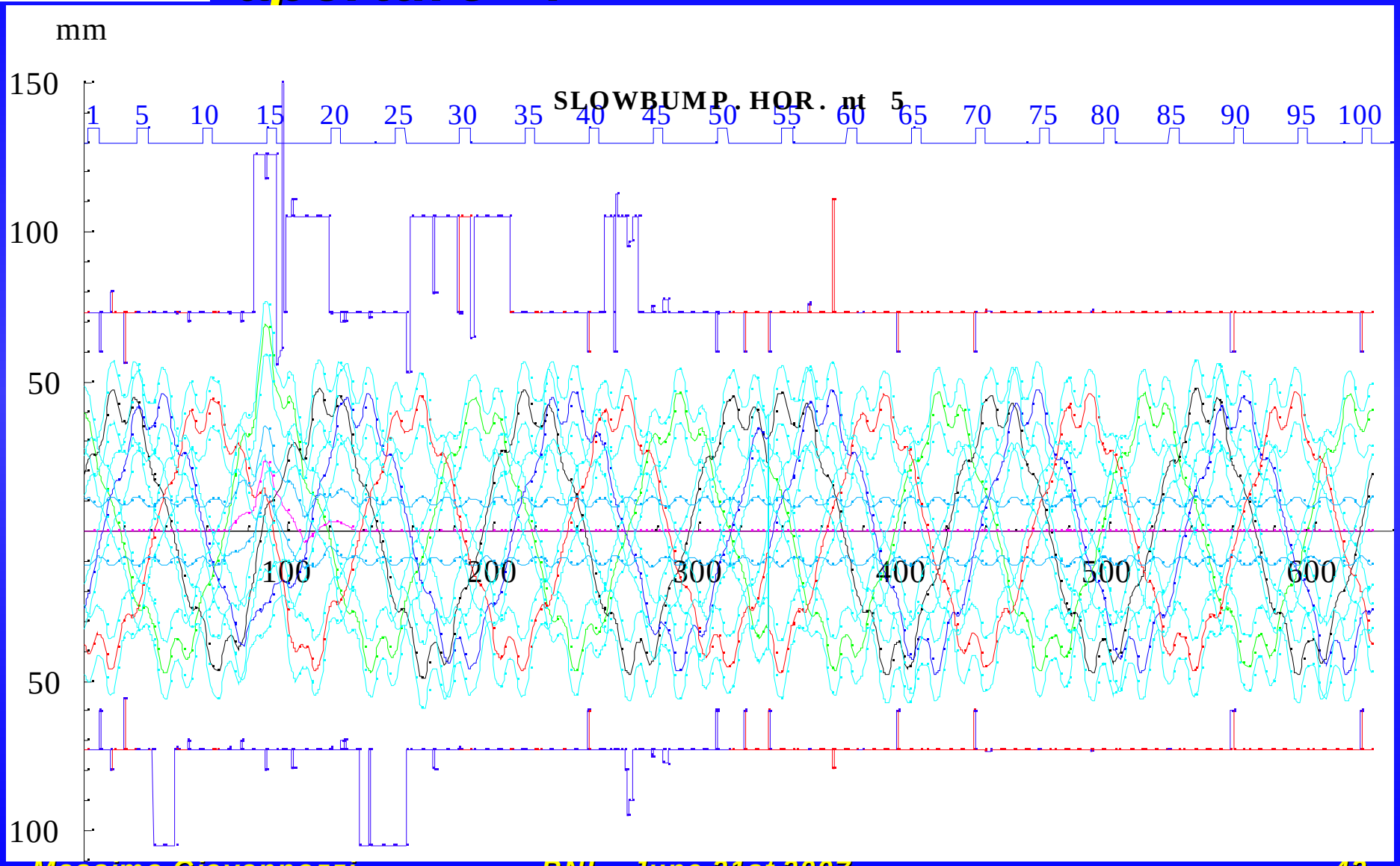
Summary of changes in the PS ring



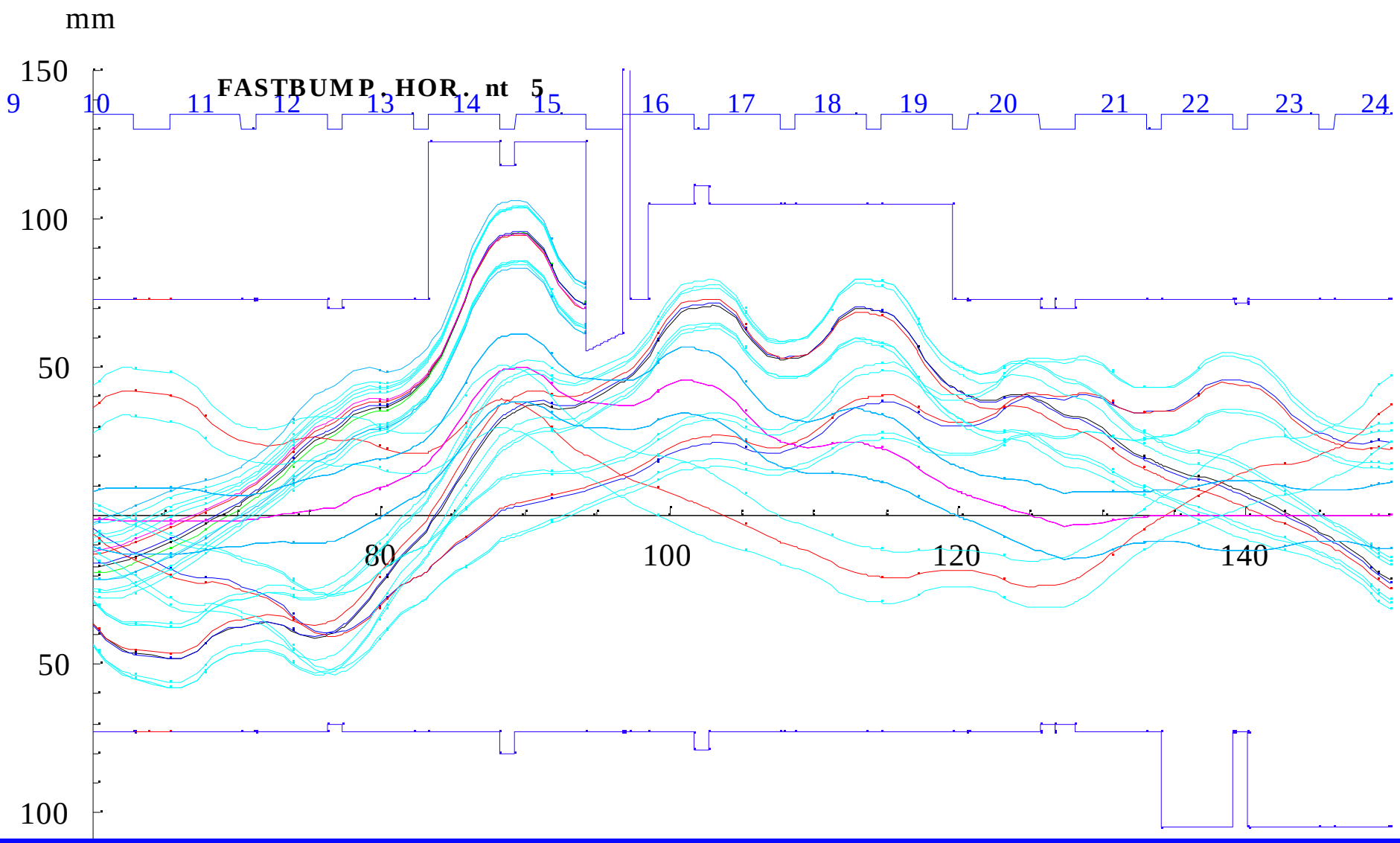
Legend:

- SS -> Straight Section.
- MU -> Magnet Unit.
- Red circle -> "heavy" intervention: mechanical design, vacuum intervention.
- Orange circle -> "light" intervention: auxiliary magnet exchange.

Critical issues: available mechanical aperture - I



Critical issues: available mechanical aperture - II



Time scale of changes

- Install slow extraction sextupoles in SS03, keeping those in SS19.
- Replace magnets of slow bump 16 with type 205 magnets.

05/06

- Remove slow extraction sextupoles in SS19.
- Move cavity.

06/07

- Enlarge vacuum chambers.
- Install kickers.
- Install modified vacuum chambers (straight sections and magnets).

07/08

- Build and install sextupoles and new octupoles.

Summary and Outlook - I

- A novel multi-turn extraction is studied since a few years
- This approach allows manipulating the transverse emittance in a synchrotron!
- Numerical simulations on a simple model confirmed the validity of the principle.
- Experimental tests showed that:
  - Capture into stable islands: successfully* obtained with both low- and high-intensity, single-bunch beam.
  - Beamlets separation: successfully* obtained with both low- and high-intensity, single-bunch beam.
  - multi-turn extraction proper: attempted. Hardware limitations might prevent realistic tests.
  - Increased trapping fraction: latest tests showed that more than 19 % can be trapped inside islands. Some beam losses at resonance crossing where observed (about 1 %),

Summary and Outlook - II

- The same principle can be used for injection.
- Transverse shaping is possible, i.e. generation of hollow bunches.
- Since late 2006, a project was set-up to implement the novel multi-turn extraction at the CERN PS:
  - The implementation will be staged (two steps).
  - The crucial part will be the installation during the 2006/7 (very successful) and 2007/8 (very challenging) shutdowns.
  - First stage should be commissioned by mid-2008.
  - Complete extraction will be commissioned by mid-2009.

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