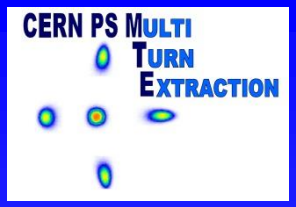


Using Resonance Islands for Optimum Performance and Advanced Commissioning Techniques

M. Giovannozzi - CERN

Summary:

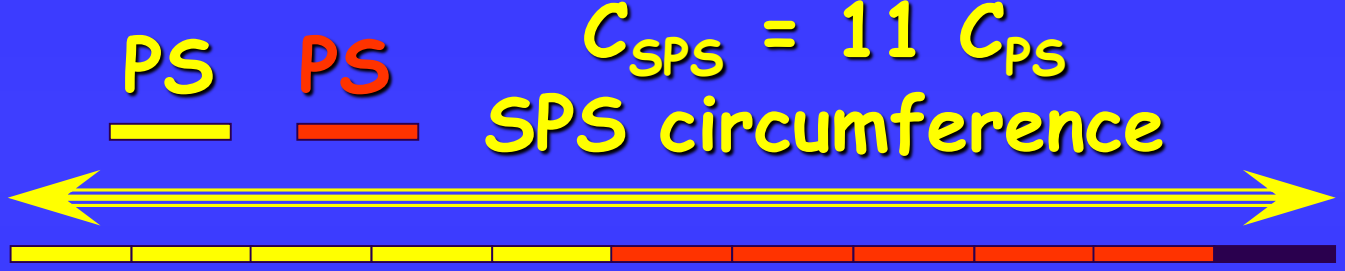
- Introduction
- Stable islands: static case
- Stable islands: dynamic case
- Outlook

Acknowledgements: A. Bazzani, A. Franchi, C. Frye, S. Gilardoni, C. Hernalsteens, A. Huschauer, G. Sterbini, G. Turchetti.

CERN PS MULTI TURN EXTRACTION

Introduction - I

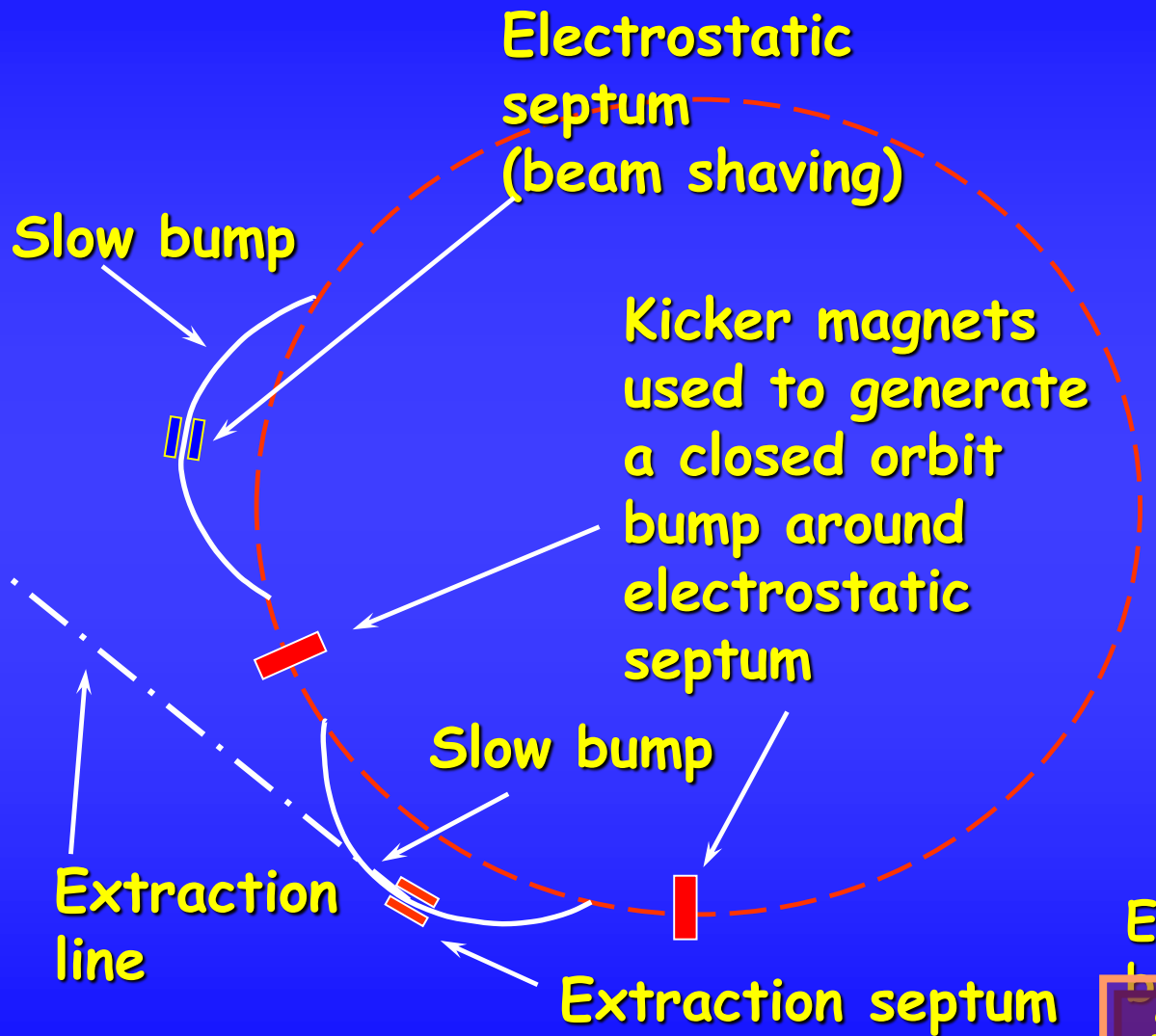
- Application of stable islands in CERN machines started with PS, aiming at replacing the Continuous Transfer (CT) from PS to SPS

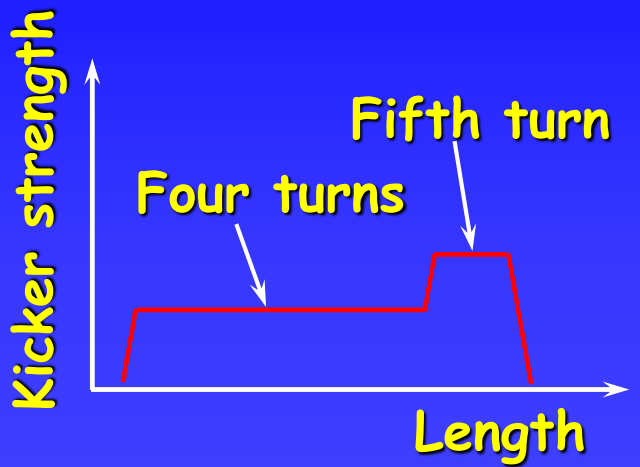


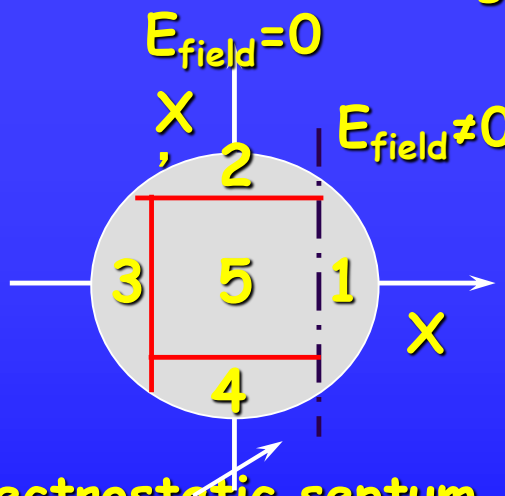
First PS batch Second PS batch Gap for kicker

CERN PS MULTI TURN EXTRACTION

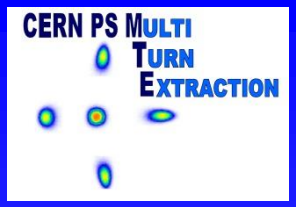
Introduction - II







Slicing is performed during extraction



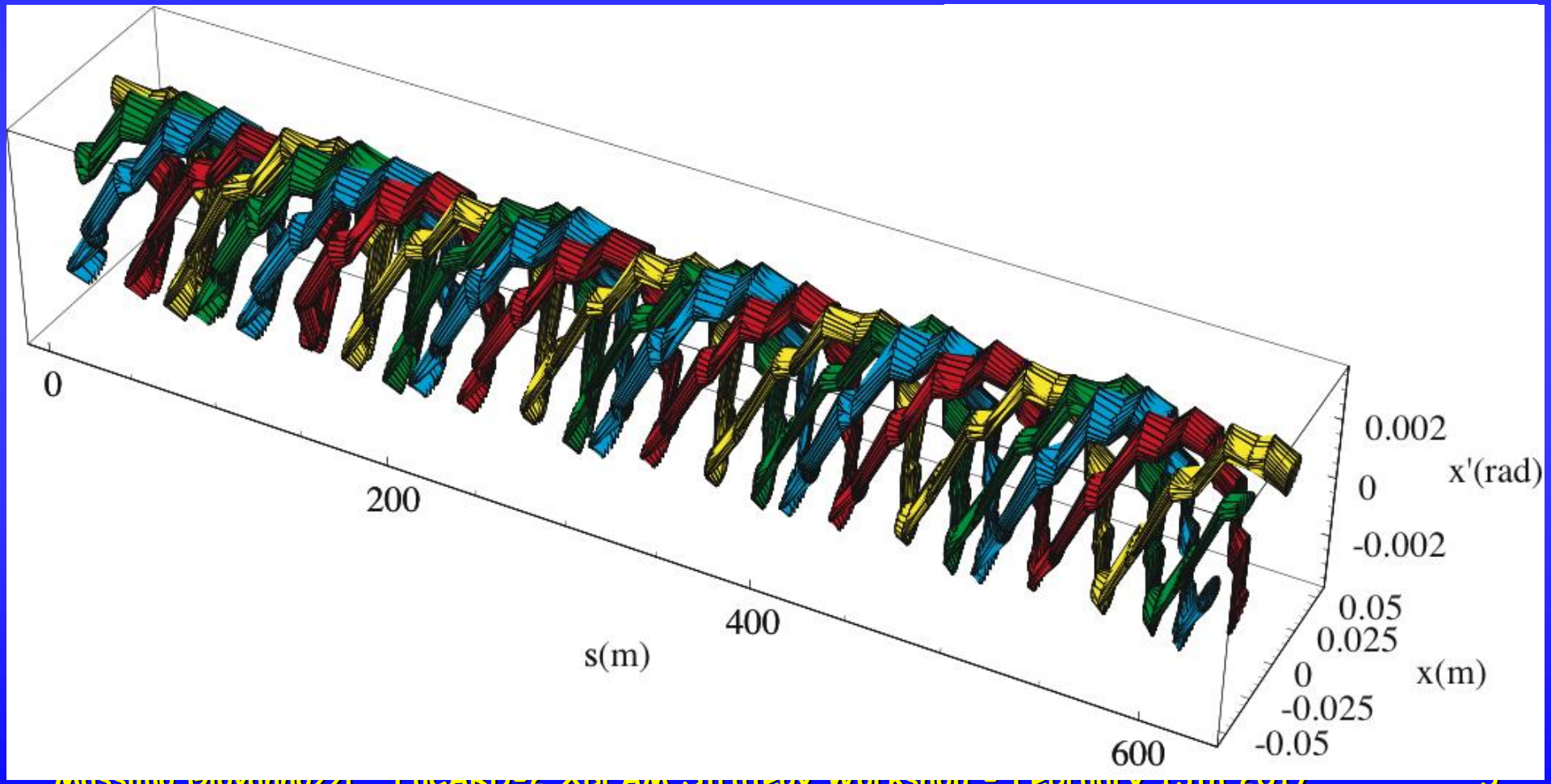
Introduction - III

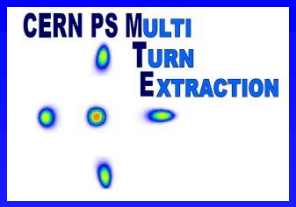
- Stable islands provided a more efficient way of extracting beams over few turns from a circular machine.
- Starting from the original application, several others can be envisaged, well beyond the original goal.
- Two scenarios can be considered
  - Static use of stable islands
  - Dynamic use of stable islands

CERN PS MULTI TURN EXTRACTION

Static stable islands - I

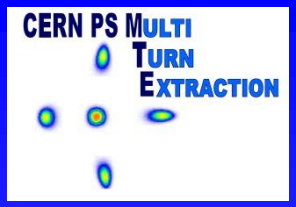
- Sextupoles and octupoles can be used to generate stable islands in phase space





Static stable islands - I

- Some observations
  - Two closed orbits are simultaneously available: the standard one and that related with the fixed points.
  - The length of the closed orbit related to the fixed points is longer than the ring circumference.
  - The orbit related to the fixed points is sensitive to non-linear fields: possibility of independent control of the two closed orbits.

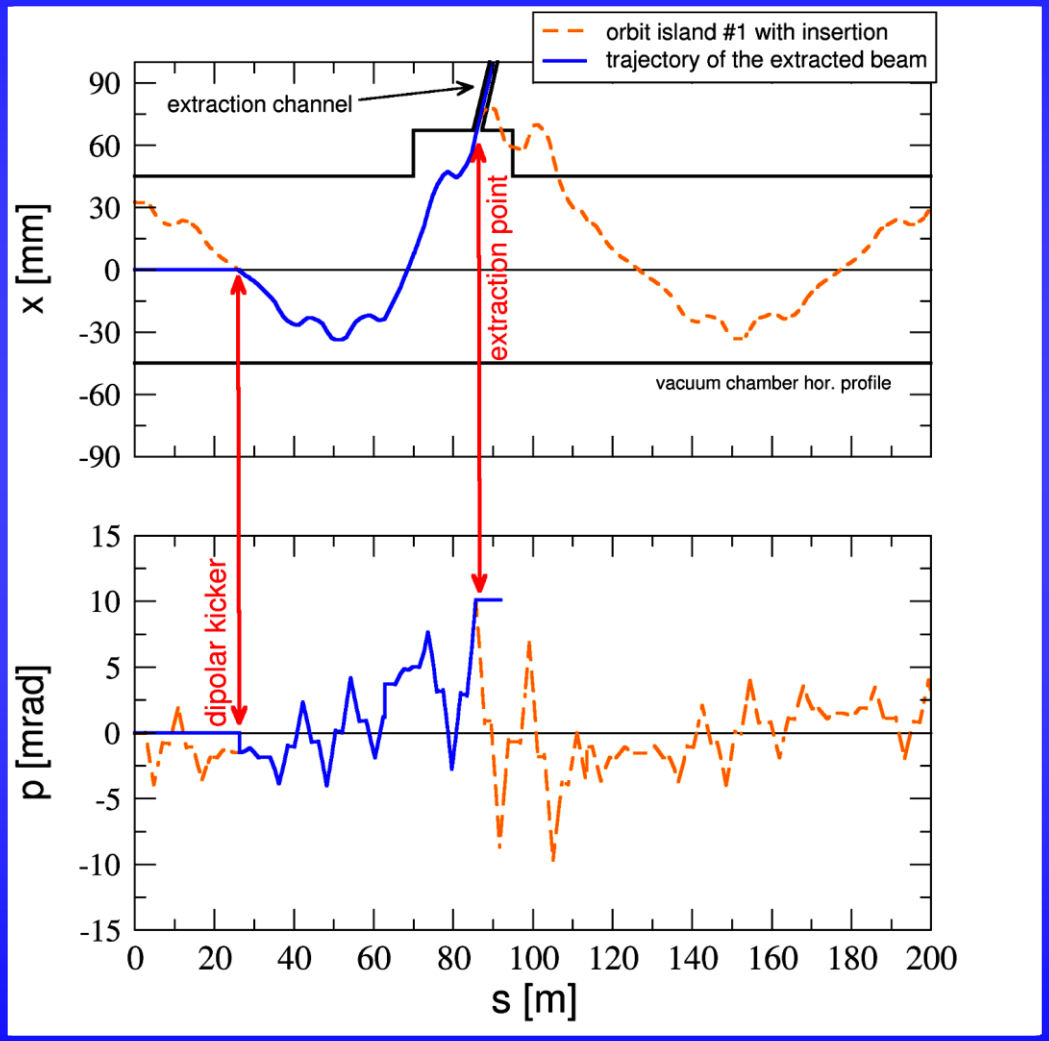


Static stable islands - II

- Some observations
  - The linear optics around the two closed orbits is different.
  - The optical parameters related to the fixed points is sensitive to non-linear fields: possibility of independent control of the two sets of optical parameters.
- Implications
  - Possibility to design septum-less injection/extraction
  - Possibility to propose alternative schemes to perform transition jump.

CERN PS MULTI TURN EXTRACTION

Septum-less extraction or injection



to avoid insertion optics (unpopulated) islands may be displaced by moving Q_x only

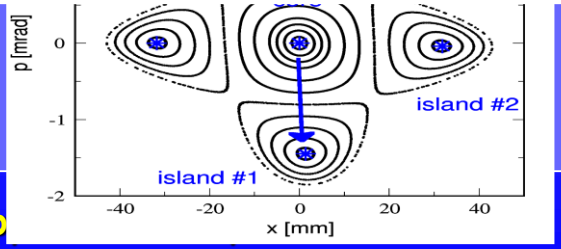
o not populate) four islands. the beam remain on axis

step 2: introduce the insertion optics via quadrupole bumpers, not kickers (actually not needed)

$$x^*(\Delta,\Omega_2,s) \propto \sqrt{\beta_x(s)\,\rho^*(\Delta,\Omega_2)}$$

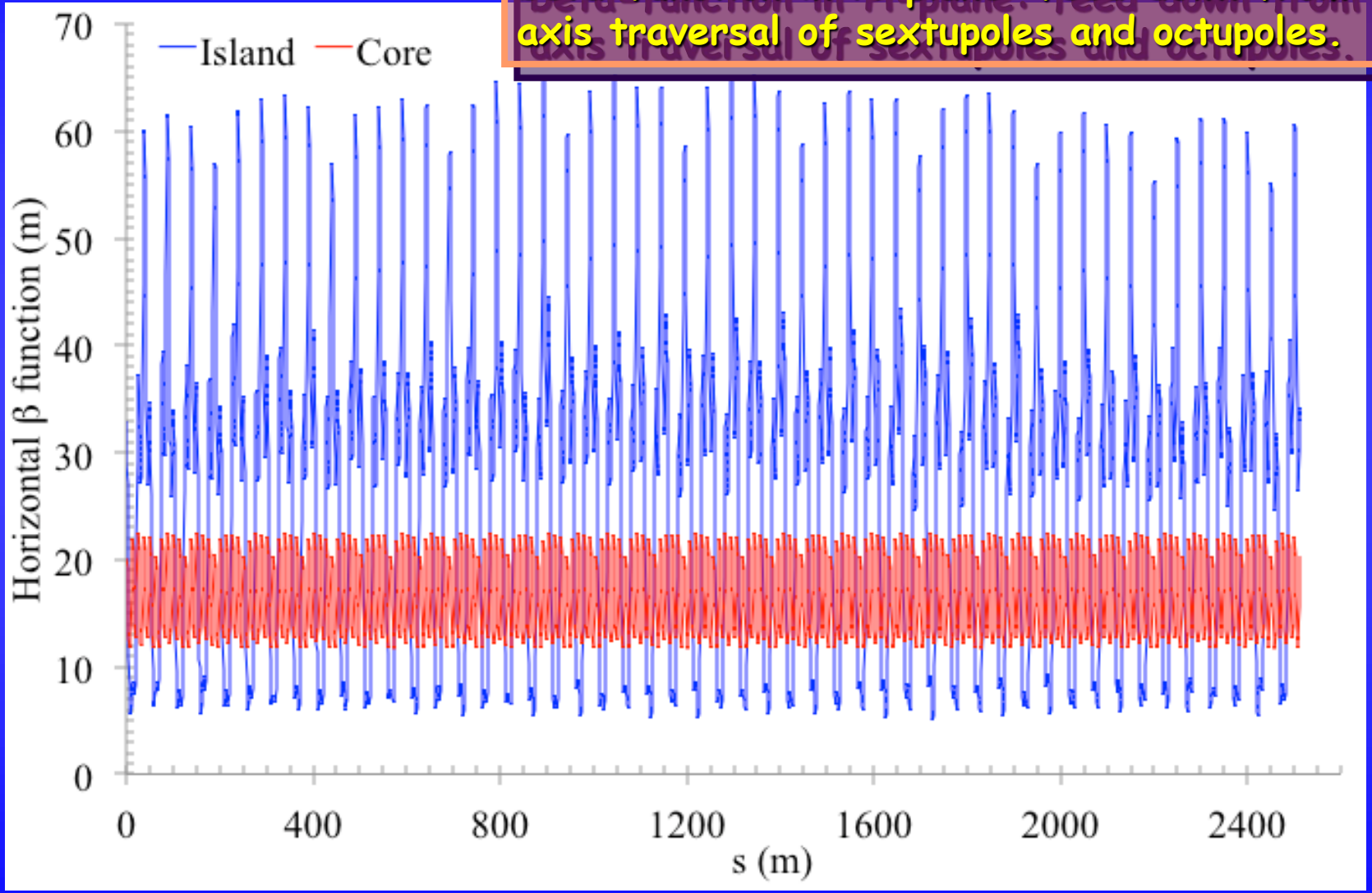
$$p^*(\Delta,\Omega_2,s) \propto -\sqrt{\frac{\rho^*(\Delta,\Omega_2)}{\beta_x(s)}}$$

$$\rho^*(\Delta,\Omega_2) \simeq -\frac{2\pi\Delta}{\Omega_2} \quad \begin{cases} \Delta = Q_x - \overline{Q}_x \\ \Omega_2 = \text{detuning coefficient} \end{cases}$$

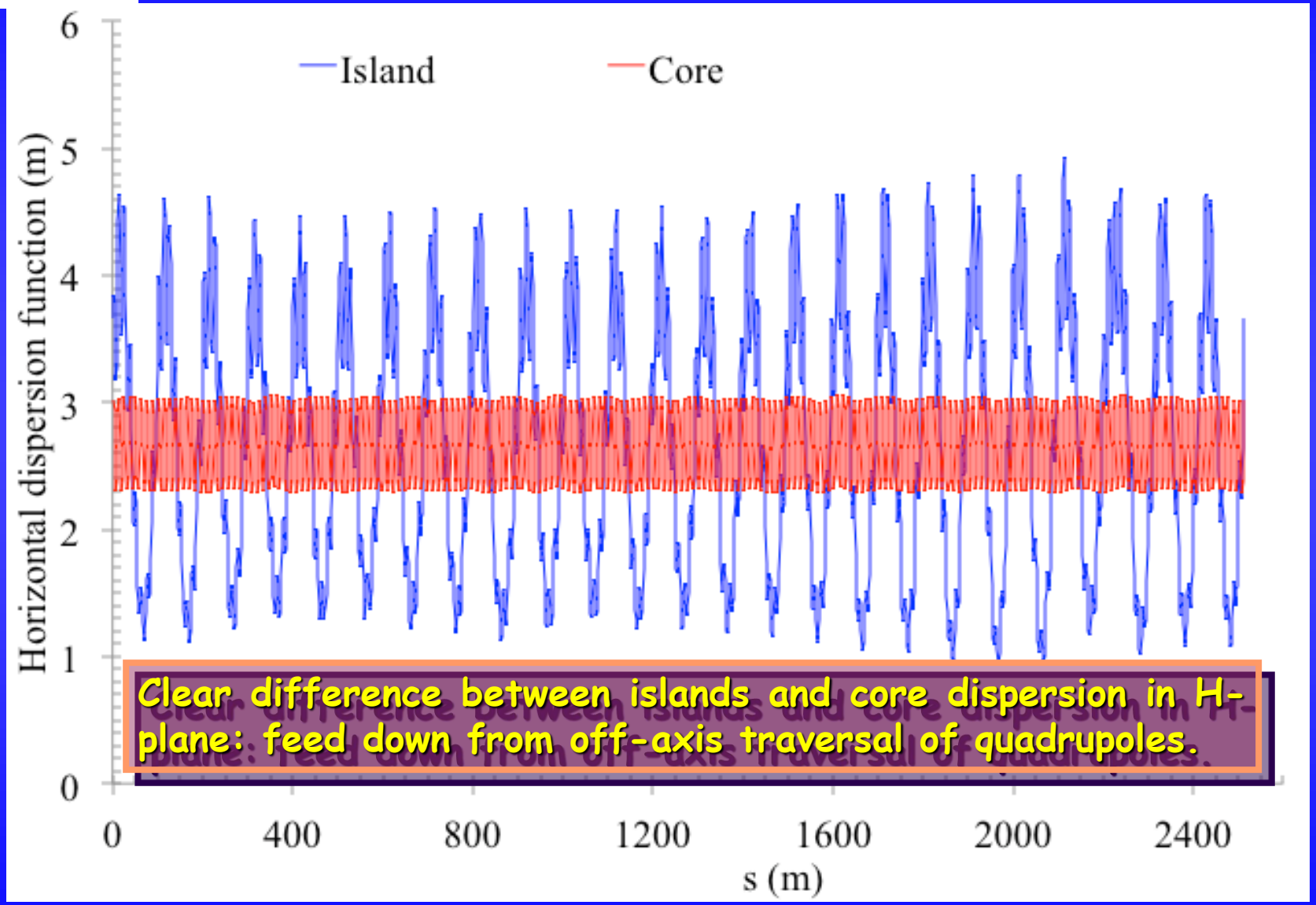


Examples based on PS ring - I

Clear difference between islands and core beta-function in H-plane: feed down from off-axis traversal of sextupoles and octupoles.



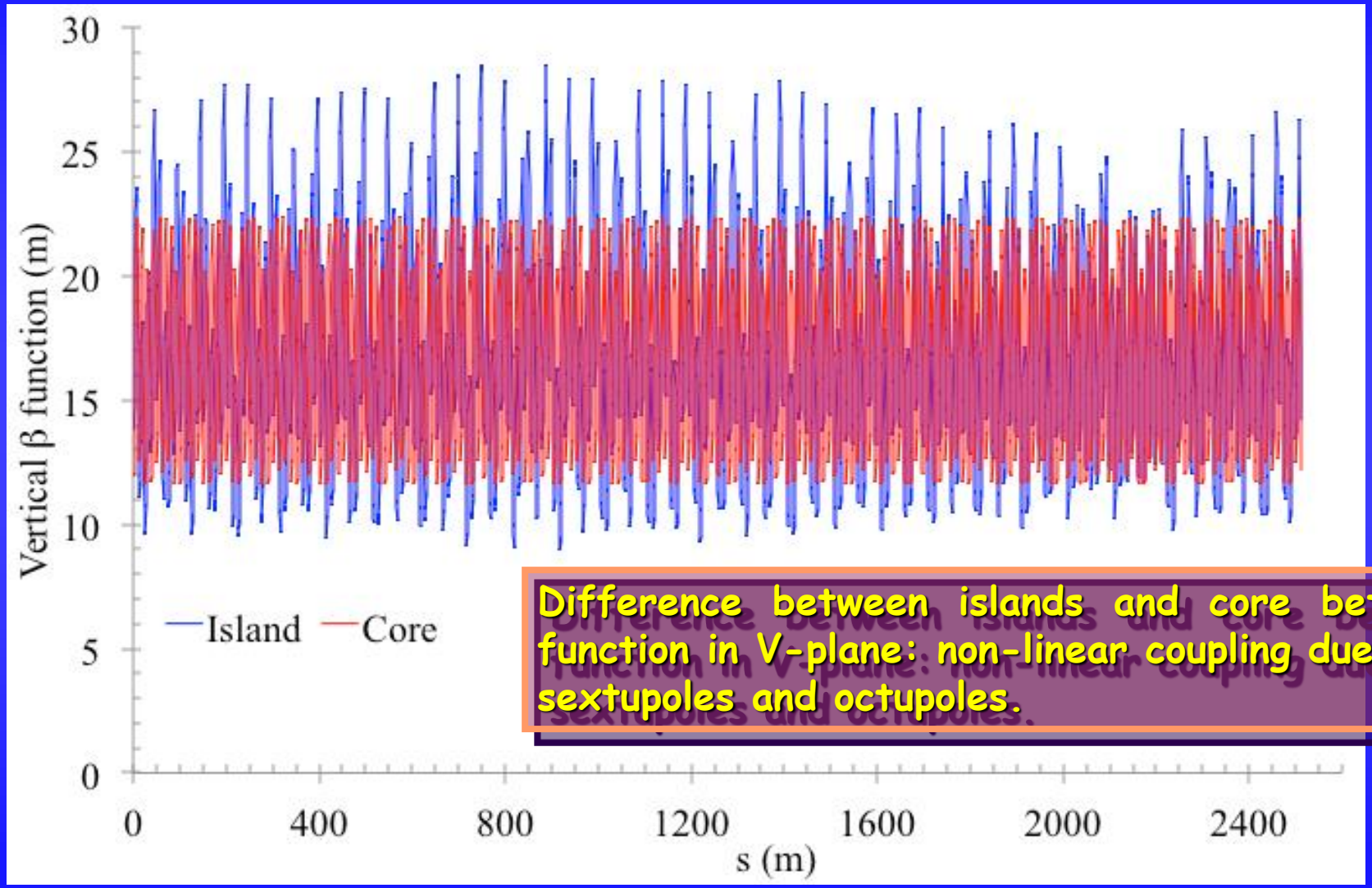
Examples based on PS ring - II



Clear difference between islands and core dispersion in H-plane: feed down from off-axis traversal of quadrupoles.

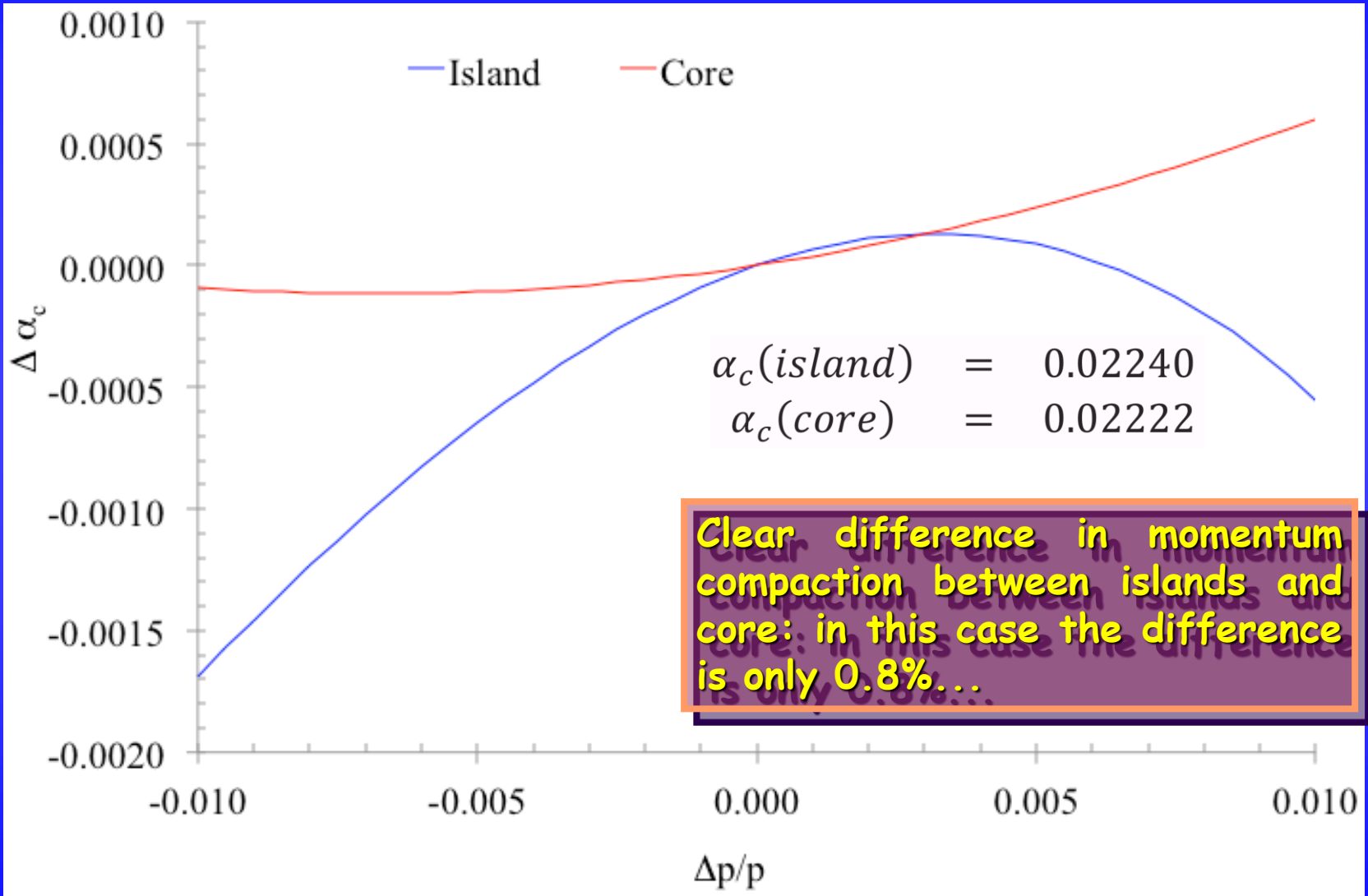
CERN PS MULTI TURN EXTRACTION

Examples based on PS ring - III



Difference between islands and core beta-function in V-plane: non-linear coupling due to sextupoles and octupoles.

Examples based on PS ring - IV

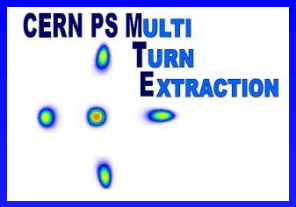


Clear difference in momentum compaction between islands and core: in this case the difference is only 0.8%...

Alternative gamma-jump scheme

- The optics around the fixed points can be designed to enhance the difference of gamma jump between the two closed orbits.
- The transition can be jumped by kicking the beam from the central closed orbit to the fixed points (and back).

Simulations are on-going to assess the performance of such a technique.



Dynamic stable islands

- The transverse position of the stable islands is controlled by: transverse tune, strength of sextupoles, octupoles etc.
- By adiabatically changing any of these parameters it is possible to perform
  - Splitting of a standard beam into several beamlets. This is the heart of the Multi-Turn Extraction (MTE) in use at CERN
  - Merging several beamlets into a single one. This could be an option for Multi-Turn Injection (MTI).

CERN PS MULTI TURN EXTRACTION

CT vs. MTE

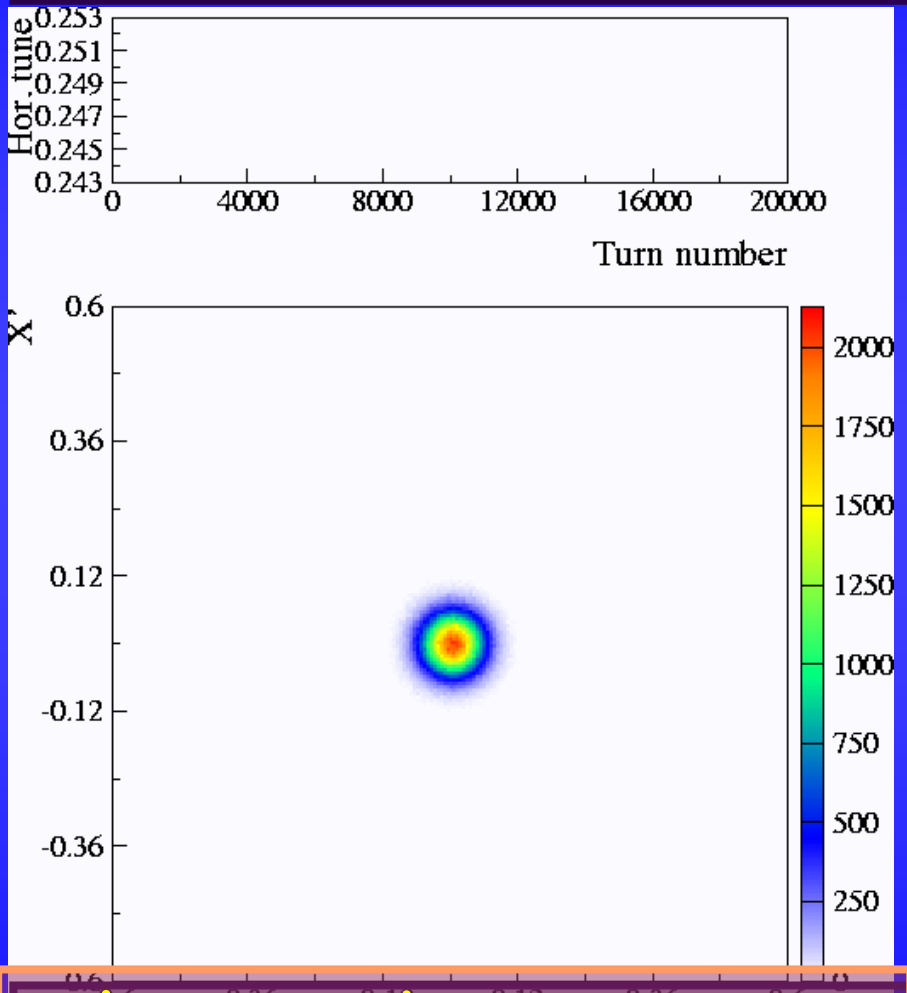
CT

- Losses are unavoidable due to electrostatic septum used for beam slicing.
- Slices feature different emittances and optical parameters.

MTE

- Nonlinear magnets to create stable islands
- Slow tune variation to cross a resonance
- Extraction losses are reduced (virtually to zero).
- Beamlets have same emittance and optical parameters.

Example of transverse beam splitting using a simple dynamical model

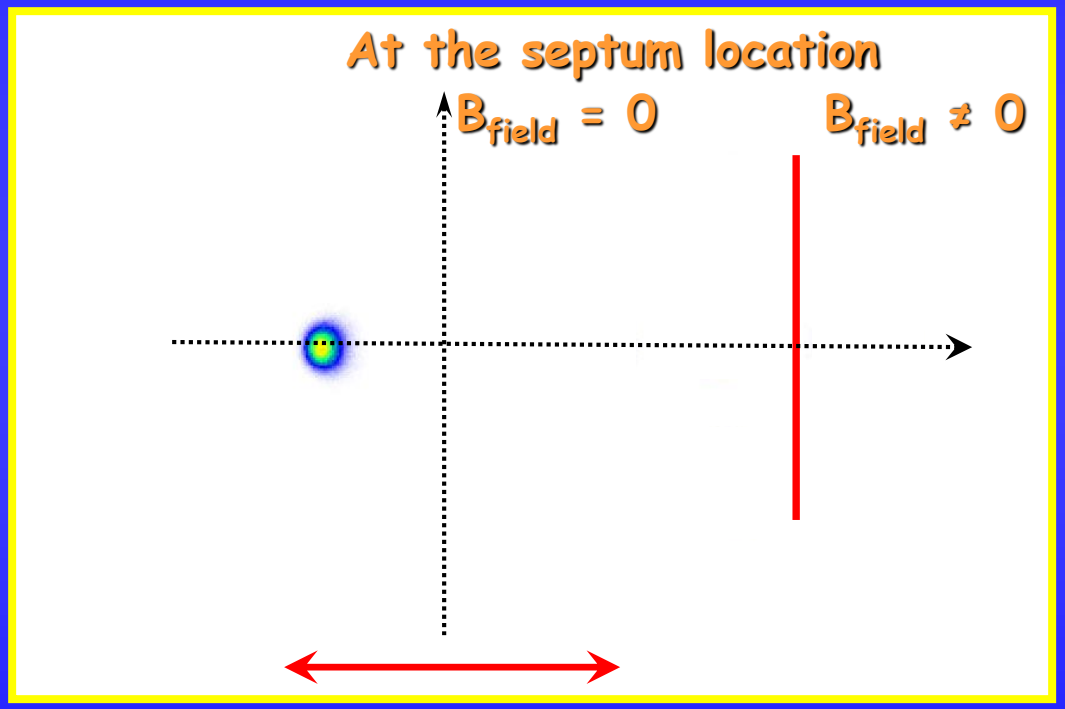


Splitting and extraction are well-separated processes

CERN PS MULTI TURN EXTRACTION

MTE: extraction process

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



About 6 cm in physical space

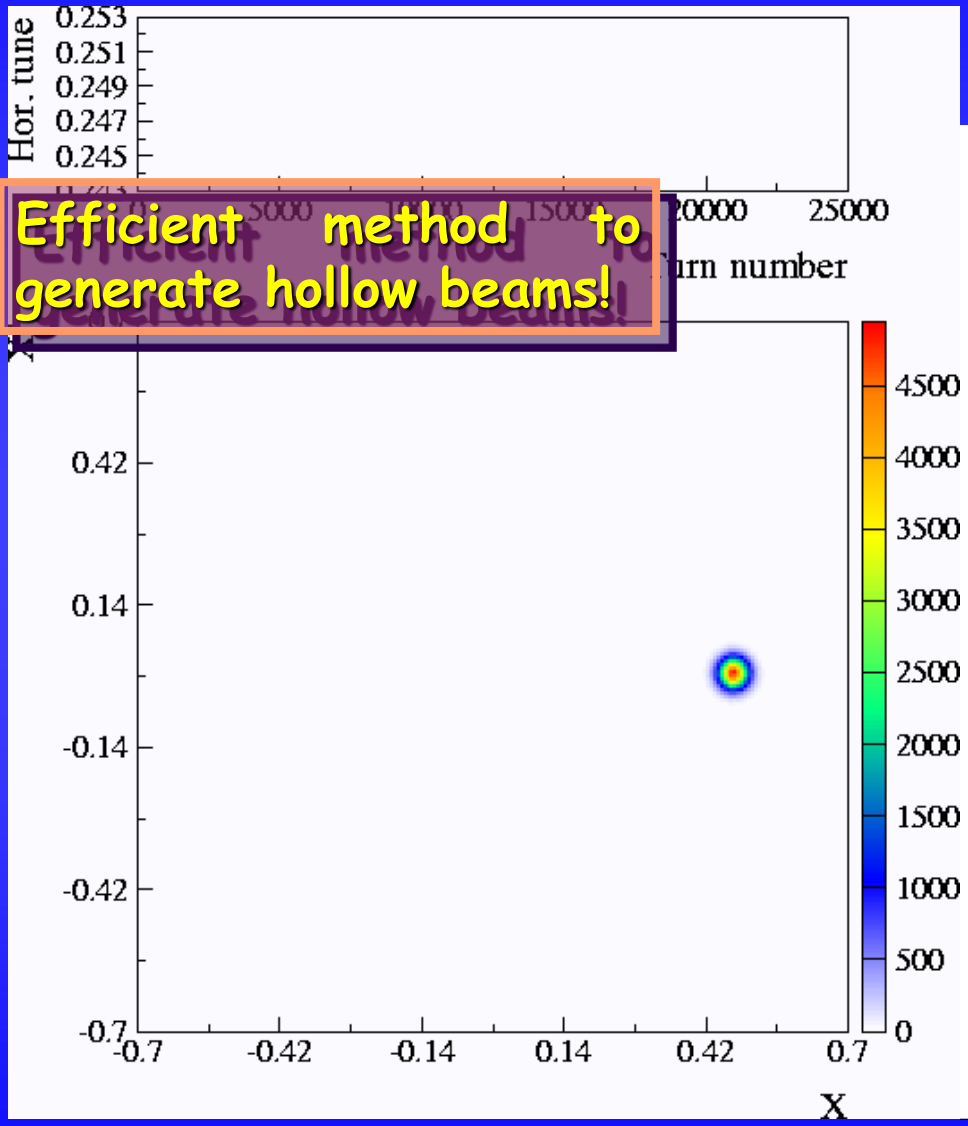
Slow (few thousand turns) bump first (closed distortion of the periodic orbit)

Fast (less than one turn) bump afterwards (closed distortion of periodic orbit)

CERN PS Multi Turn Extraction

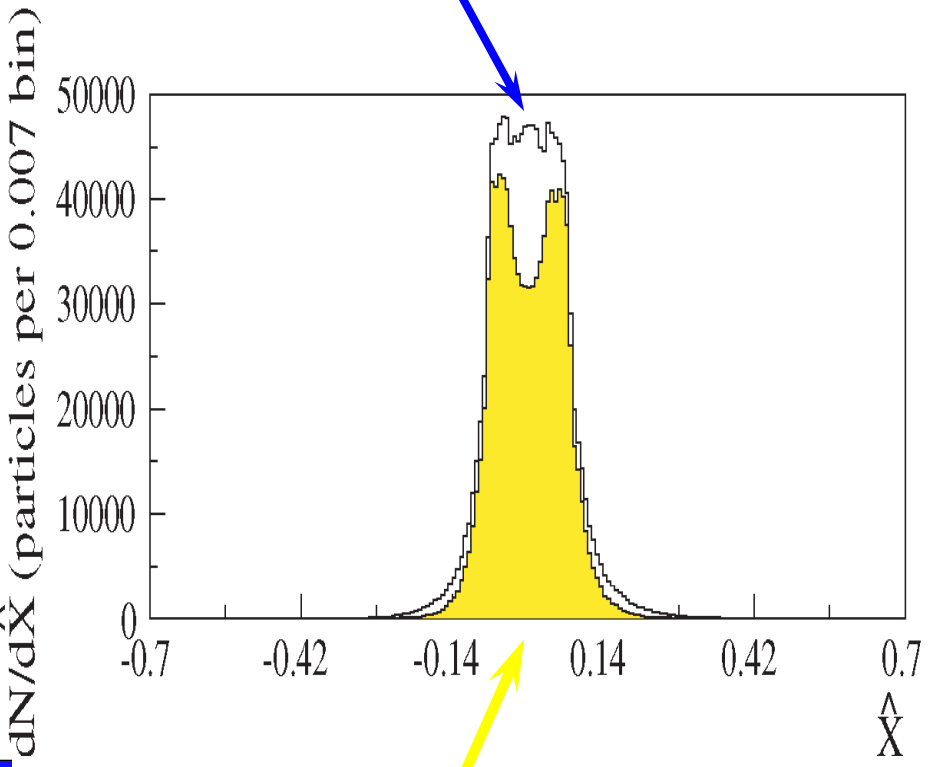
Multi-Turn Injection

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



Efficient method to generate hollow beams!

Flat beam distribution obtained by injecting a fifth turn in the centre.

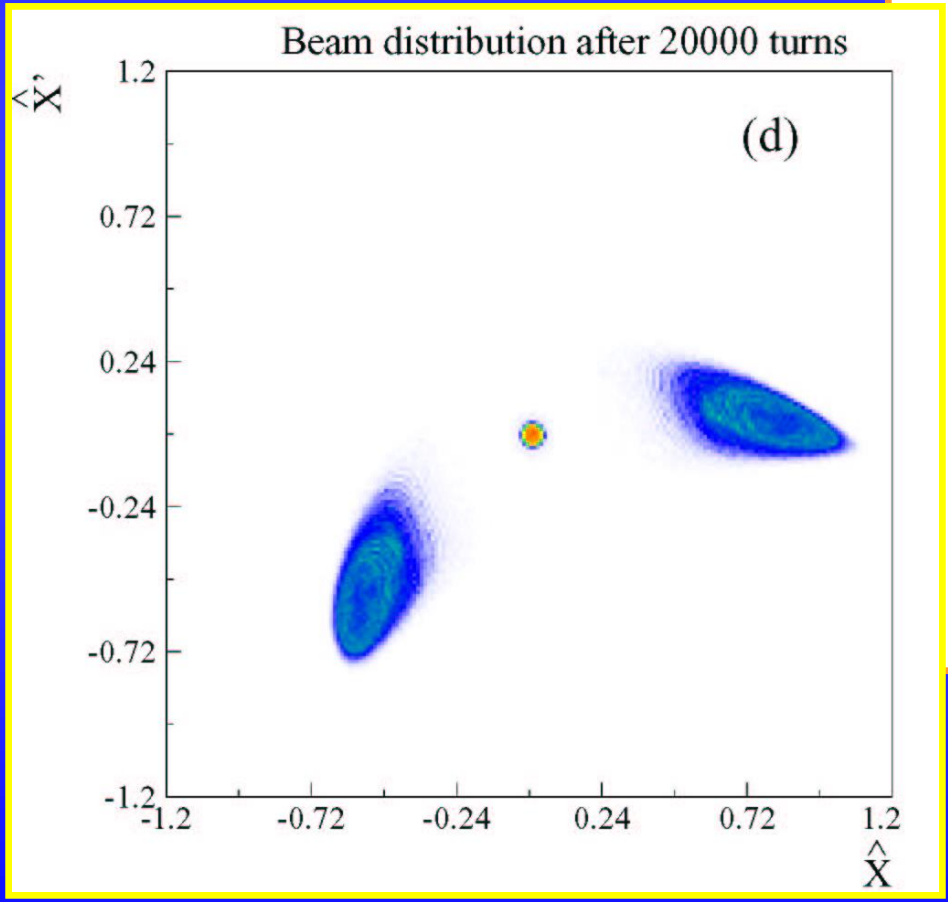


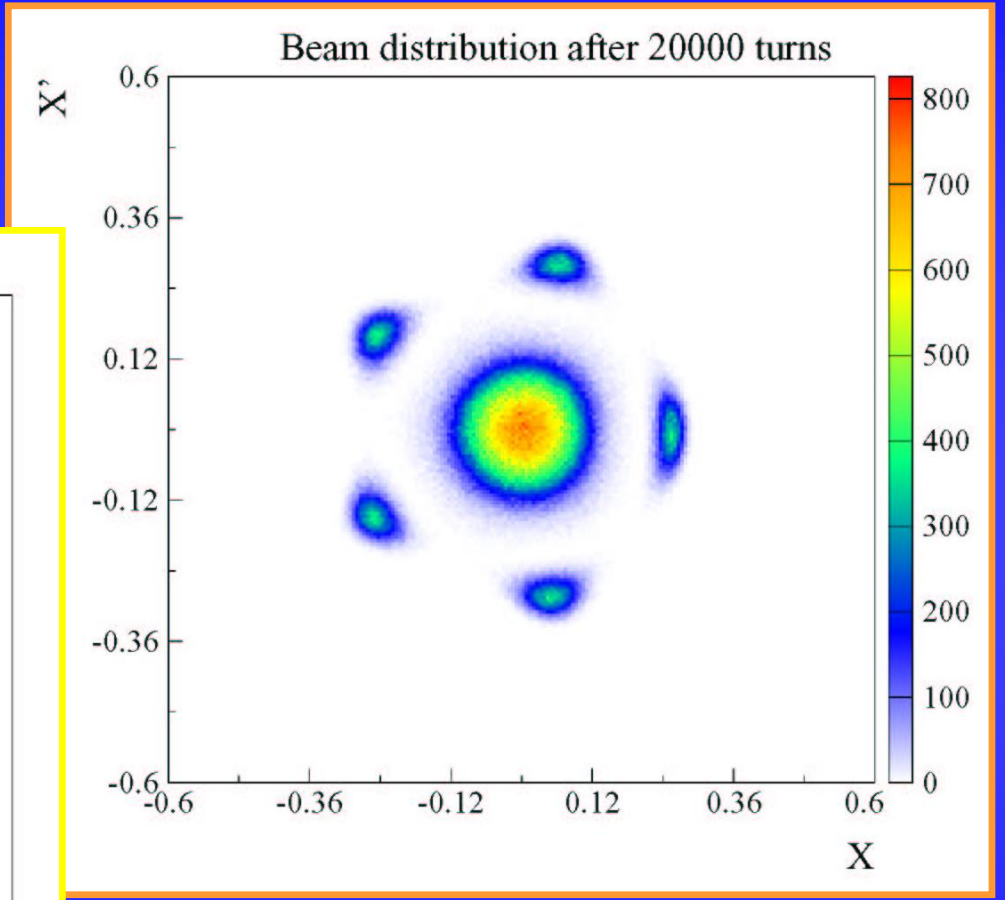
Hollow beam distribution

CERN PS MULTI TURN EXTRACTION

Multi-Turn Extraction with other resonances

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

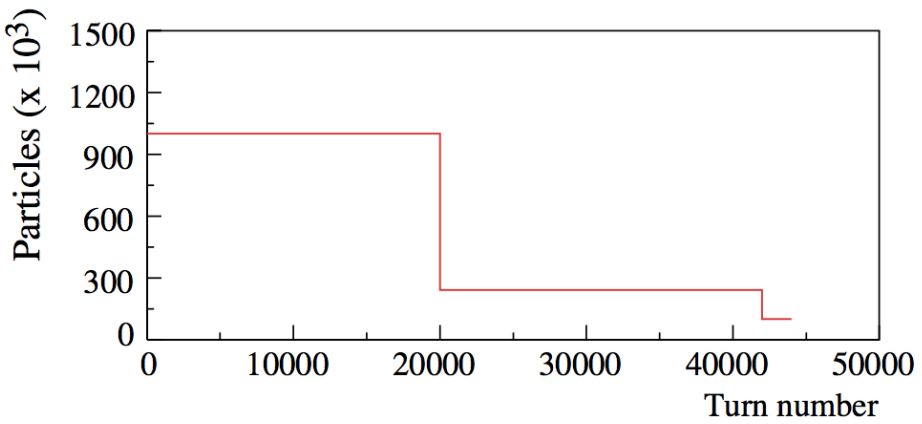


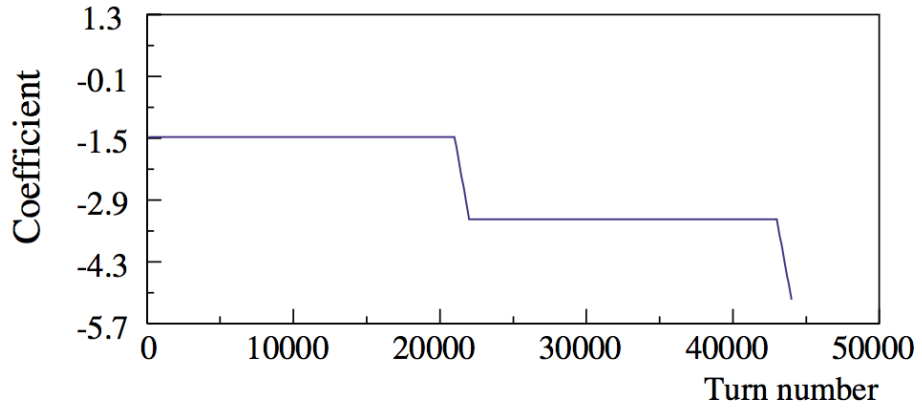


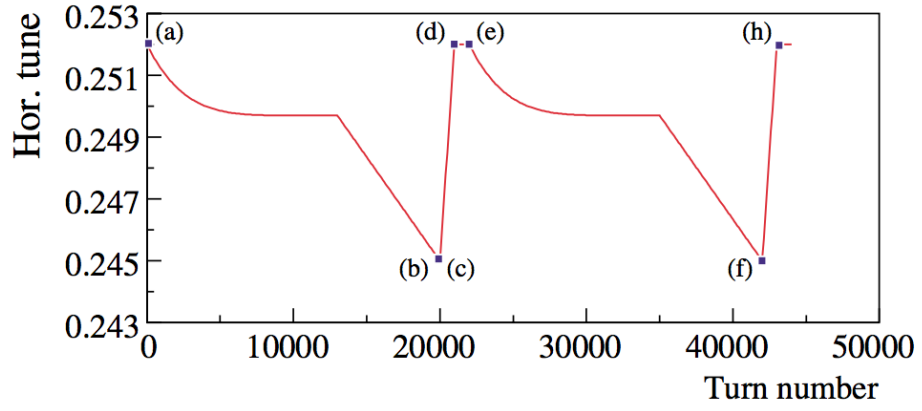
The fifth-order resonance is used, thus giving a six-turn extraction

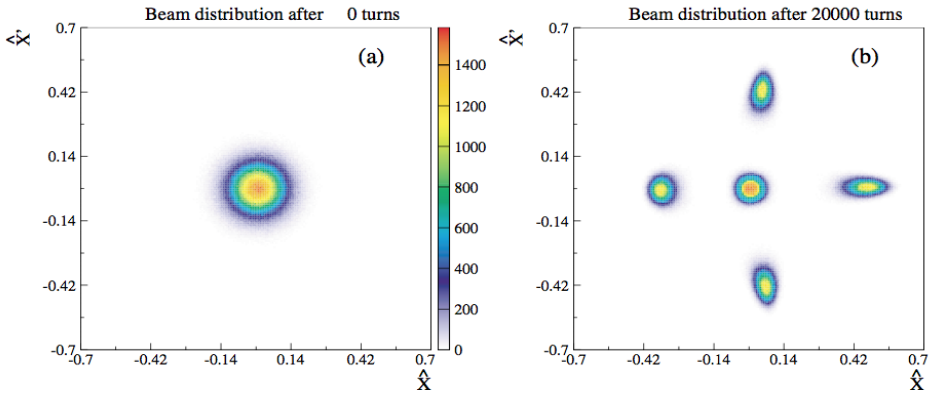
CERN PS MULTI TURN EXTRACTION

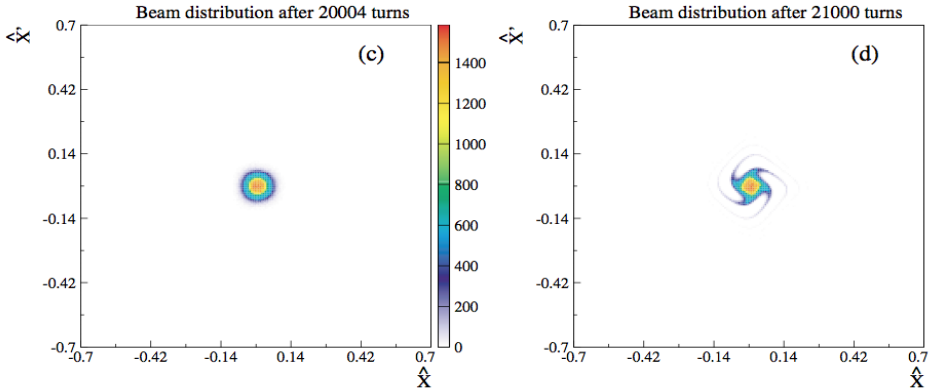
Multiple Multi-Turn Extraction

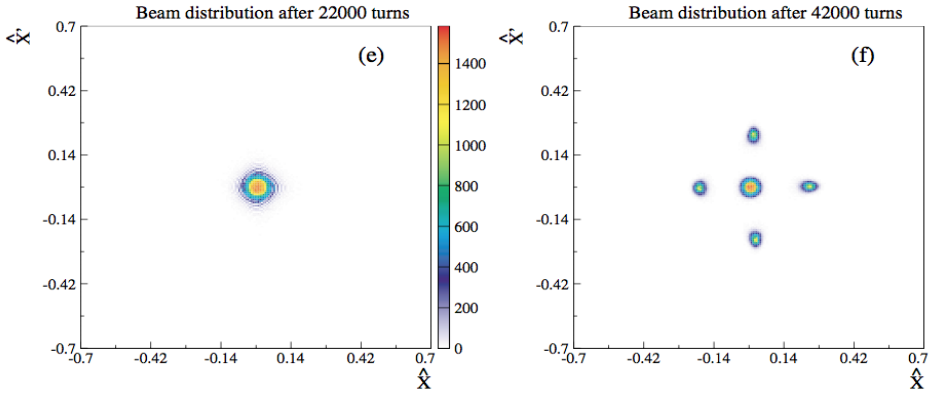


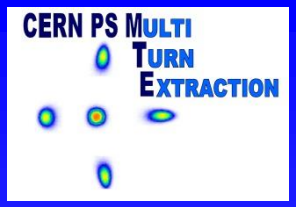






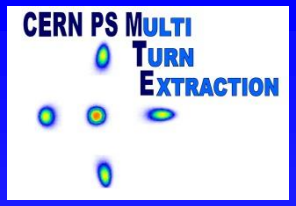






Outlook

- Several applications of stable islands to circular accelerators have been proposed.
- Till now, the main domain of applicability is hadron machines.
- Beam splitting has been proven in operation.
- The next step is to extend some of the proposals to lepton machines.

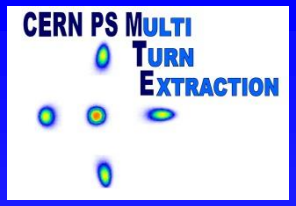


Thank you!

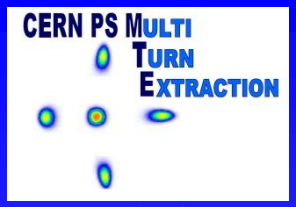
CERN PS MULTI TURN EXTRACTION

Selected references

- S. Abernethy at al., Phys Rev. Accel. Beams 20, 014001 (2017).
- J. Borburgh et al., EPL 113 34001 (2016).
- A. Franchi, M. Giovannozzi, Phys. Rev. ST Accel. Beams 18, 074001 (2015).
- A. Bazzani et al., Phys. Rev. E 89, 042915 (2014).
- S. Gilardoni, M. Giovannozzi, C. Hernalsteens, Phys. Rev. ST Accel. Beams 16 051001 (2013).
- M. Giovannozzi, D. Quatraro, G. Turchetti, Phys. Rev. ST Accel. Beams 12 024003 (2009).
- A. Franchi, S. Gilardoni, M. Giovannozzi, Phys. Rev. ST Accel. Beams 12 014001 (2009).
- M. Giovannozzi and J. Morel, Phys. Rev. ST Accel. Beams 10 034001 (2007).
- S. Gilardoni at al., Phys. Rev. ST Accel. Beams 9 104001 (2006).
- R. Cappi, M. Giovannozzi, Phys. Rev. ST Accel. Beams 7 024001 (2003),
- R. Cappi, M. Giovannozzi, Phys. Rev. Lett. 88 104801 (2002).



Reserve slides



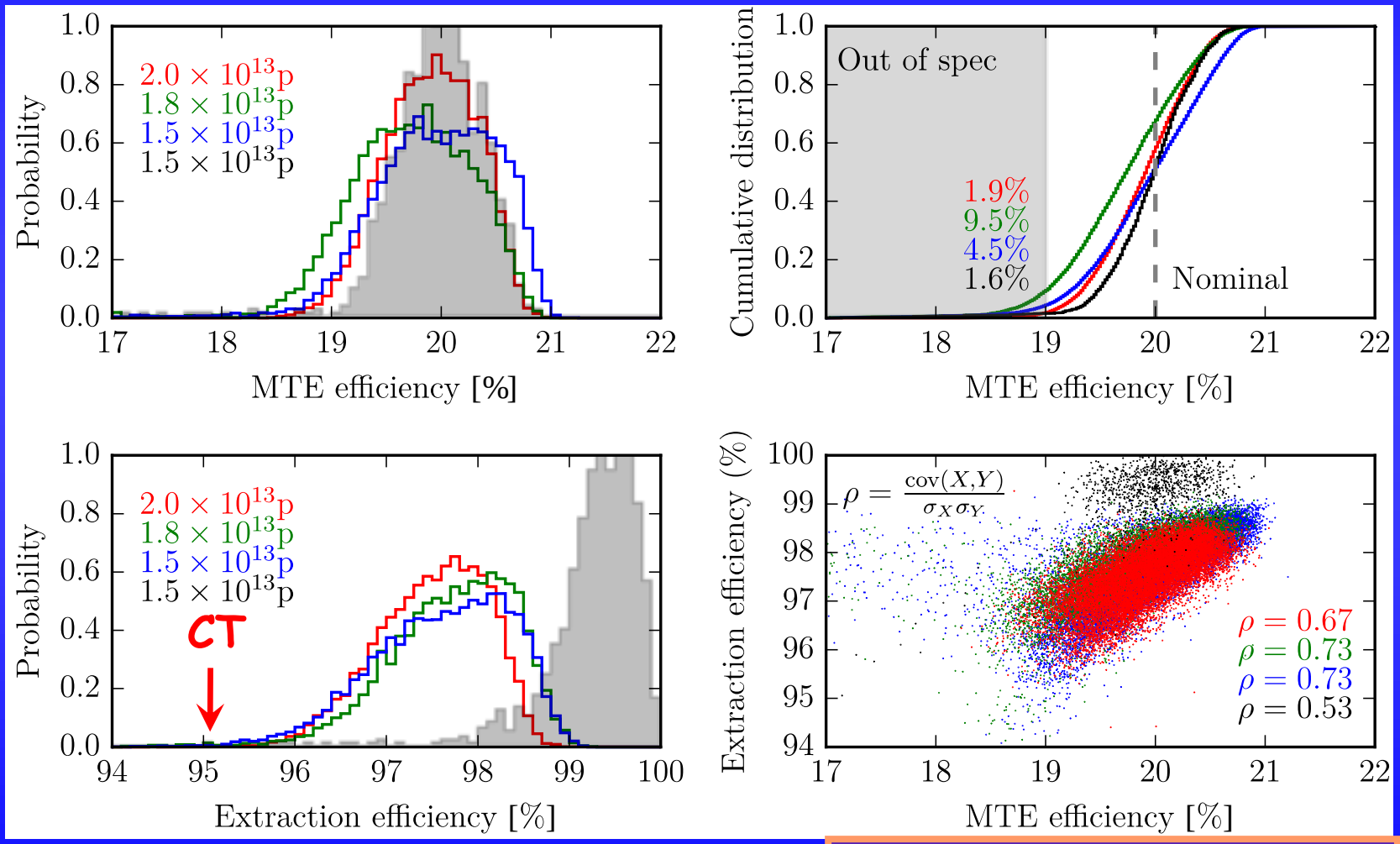
A brief history of MTE - II

- 2008-9: Initial beam commissioning. Bunched beams used and occasionally sent to SPS.
- 2010: Short operational period. Observed:
  - Increase of irradiation of the extraction region. This is due to the longitudinal beam structure (continuous).
  - Poor reproducibility of the trapping efficiency
  - Poor reproducibility of extraction trajectories
- 2010-12: Reproducibility studies. Looking for physical observable(s) correlated with the trapping.
- 2013-14: Installation of dummy septum and beam commissioning. This is the solution to the increased irradiation in the extraction region.
- 2015: Successful beam commissioning and operation.

CERN PS MULTI TURN EXTRACTION

2015 beam commissioning and operation - VII

History of the 2015 MTE run



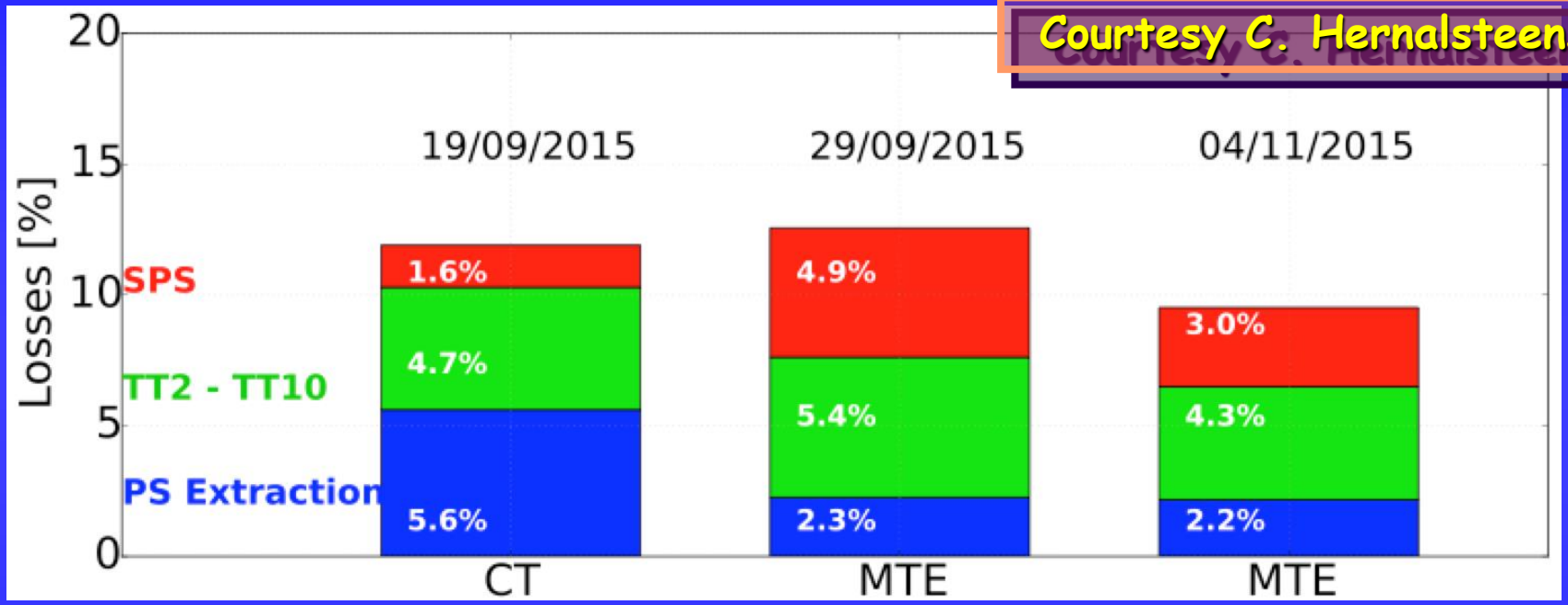
Courtesy C. Hernalsteens

CERN PS MULTI TURN EXTRACTION

2015 beam commissioning and operation - VIII

History of the 2015 MTE run

Courtesy C. Hernalsteens



Losses from PS flattop to SPS flattop. Three configurations are shown: CT operation early 2015 (left), initial MTE operation (centre) and improved MTE operation (right).