STUDY OF BEAM DYNAMICS DURING THE CROSSING OF RESONANCE IN THE VEPP-4M STORAGE RING

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Motivation

Beam emittance degradation and intensity loss may occur during the resonance crossing

Meanwhile, as it was recognized recently, this process can be important for the electron-positron machines with an extremely low emittance and high damping rate (linear collider damping ring, crab-waist colliders, light sources, etc)

For instance, for the CLIC damping ring, the vertical tune (due to the space charge and strong nonlinearity) during the damping varies by ~0.2 (!) crossing many nonlinear resonances.

VEPP-4M

VEPP-4M is an electron-positron collider operating now at the 1.8 GeV energy in the region of ψ-meson family

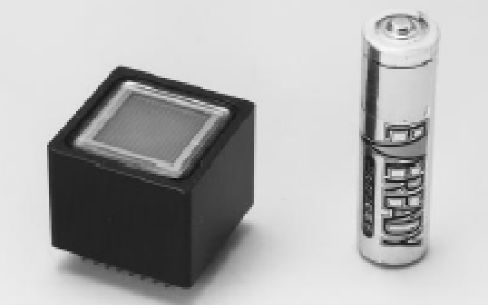
VEPP-4M is equipped with different modern diagnostics for different accelerator physics experiments

Experimental setup

The following beam diagnostic systems were used for the experimental study of the resonance crossing:

- Turn-by-turn BPMs to study the phase space trajectories (4098 turns with the resolution <50 μm) by the excitation of the beam coherent motion with the help of the fast kicker

- The beam loss monitor (scintillator counter) inserted in the vacuum chamber vertically. A position of the counter can be varied by a step motor with the accuracy of 0.1 mm



MAPMT R5900U-00-L16 HAMAMATSU

- Unique device based on the multi-anode photomultiplier R5900U-00-L16 HAMAMATSU, which is capable of recording a transversal profile of a beam at 16 points at one turn during 2^{17} turns of a beam.

Theory overview (very briefly)

A standard isolated resonance Hamiltonian in the action-angle variable is

$$H = \delta(\theta) \cdot I + \alpha_0 \cdot I^2 + A_n \cdot I^{n/2} \cos m\varphi$$

with the oscillation frequency depending on time (azimuthal angle θ).

If the particle amplitude change is much faster than the resonance island motion due to the frequency change, the particles with amplitudes

$$I_a > \left(\frac{\nu'}{2m\alpha_0 A_n} \right)^{1/n}$$

will be captured in the resonance island and travel with the island (adiabatic limit).

Otherwise (non adiabatic limit) the particle amplitude will grow insignificantly as

$$\Delta I / I_0 \approx A_n I_0^{n/2-1} \sqrt{2\pi m / |\nu'|}$$

Measurement procedure

- The vertical third-order resonance $3\nu_z = 23$ is carefully tuned by the skew-sextupole magnet (driving term strength) and the octupole magnets (nonlinear detuning)

- Phase space trajectories are measured by the turn-by-turn diagnostic system

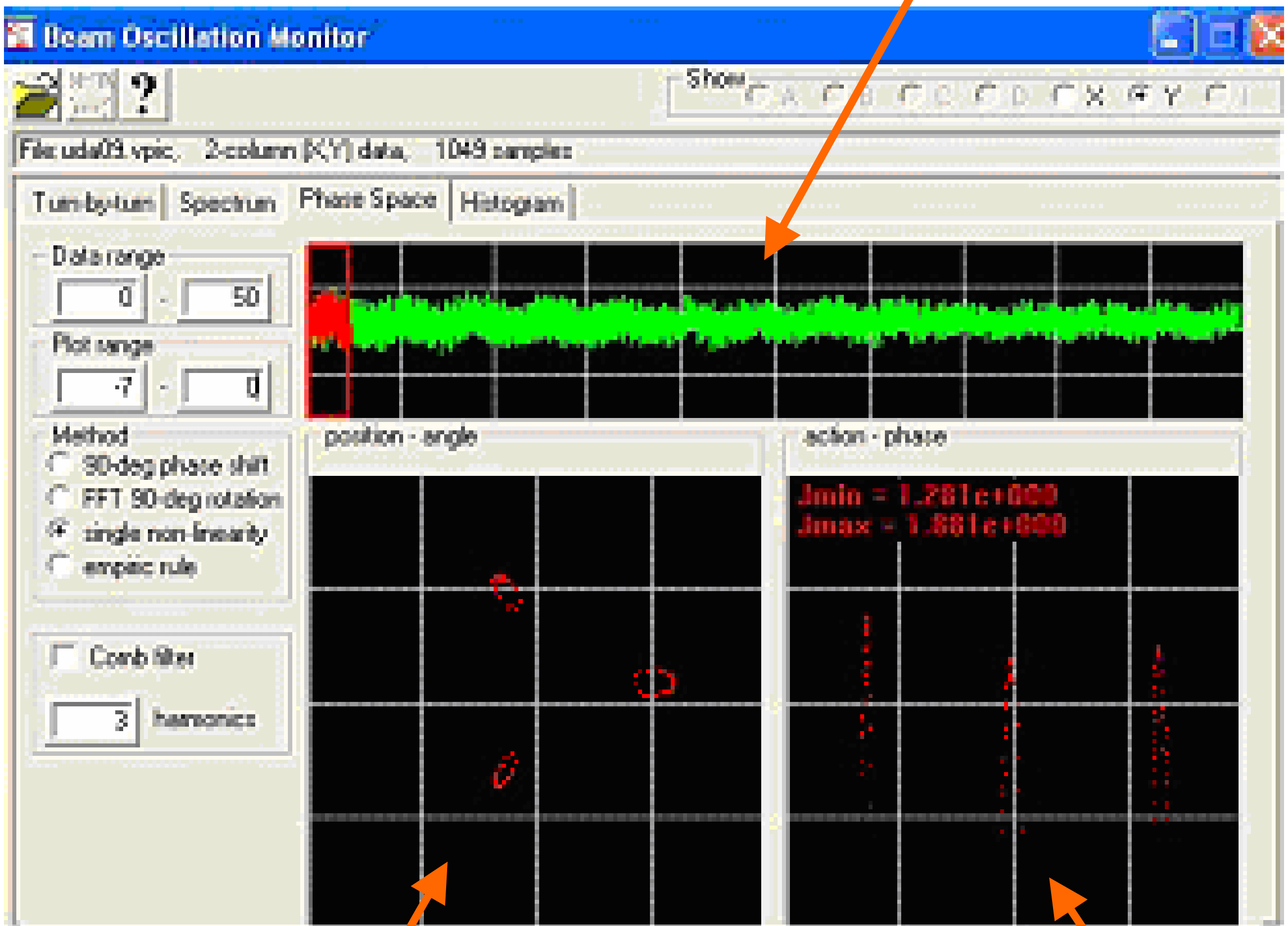
- The vertical betatron tune is changed by the quadrupole magnets (the minimal rate is dQ_z = 0.01 in 30 ms) and the resonance is crossed

- The particles loss rate and the vertical beam profile are measured during the resonance crossing as a function of the turn number

- System parameters (crossing rate, nonlinear detuning, etc.) vary and the measurement is repeated

Phase trajectories-I

Beam oscillation vs the revolution number

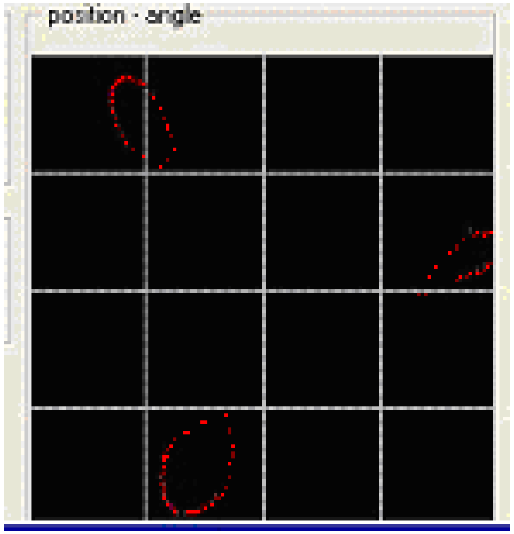


(Z, Z') phase trajectories

(J, φ) phase trajectories

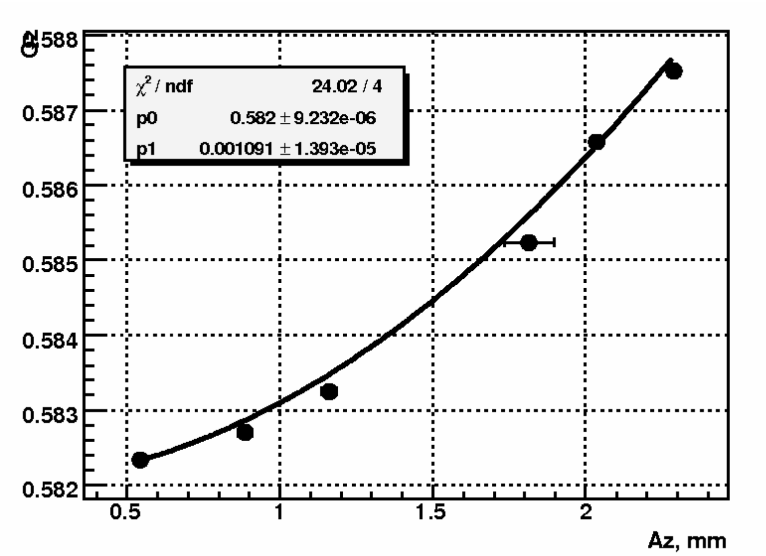
Phase trajectories-II

Adjusting the system parameters (tune, driving term and nonlinearity) we have managed to tune the resonance trajectories just before, after and on the resonance



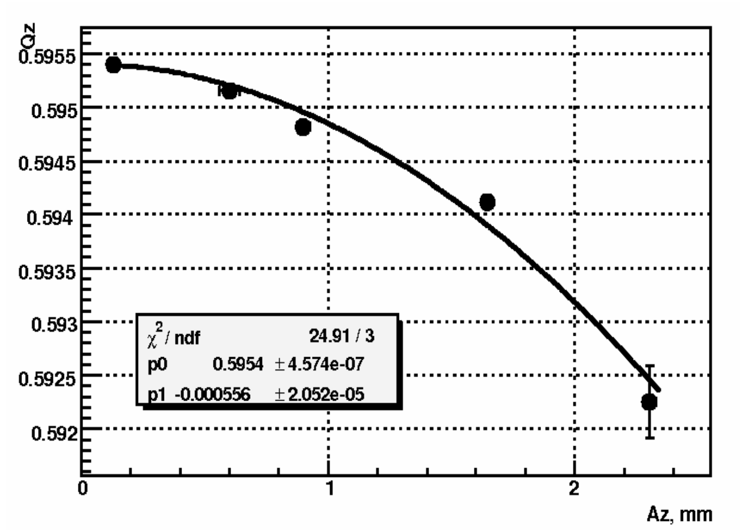
Nonlinear detuning

Octupole magnets allow the change of the value and even the sign of the nonlinear tune shift. The vertical tune as a function of the vertical amplitude:



Octupole current =-23 A

$$\alpha_0 = 1\times10^{-3} \text{ mm}^{-2}$$

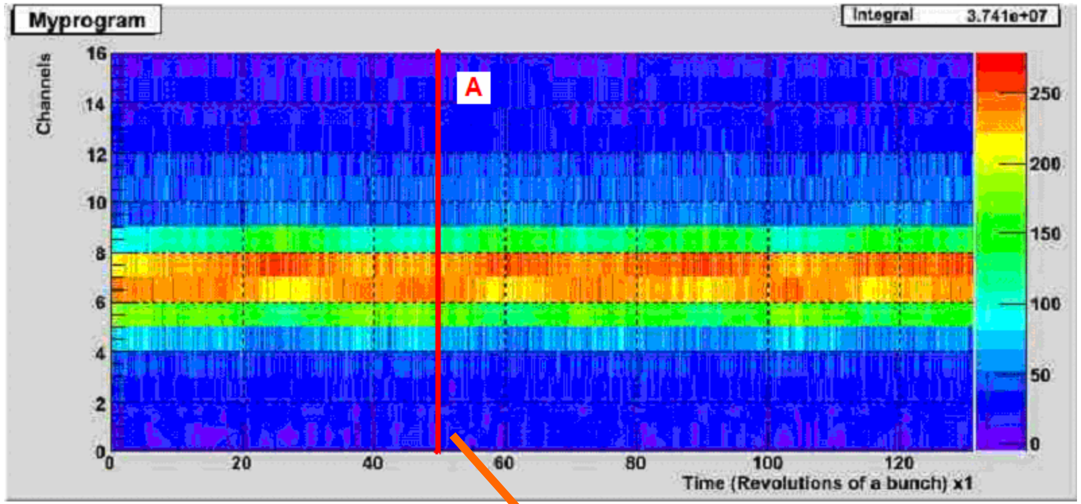


Octupole current =+23 A

$$\alpha_0 = -0.5\times10^{-3} \text{ mm}^{-2}$$

Resonance crossing at high speed

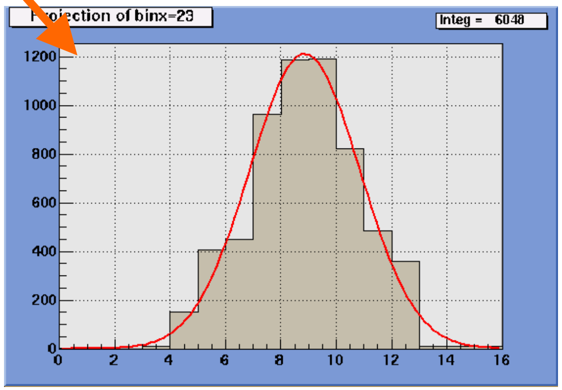
At high rate of the resonance crossing neither change of the beam vertical profile nor particle loss is observed



← Beam profile vs. the turn number. Colours indicate the particles intensity

$$\nu_z = 0.661 \rightarrow 0.672$$

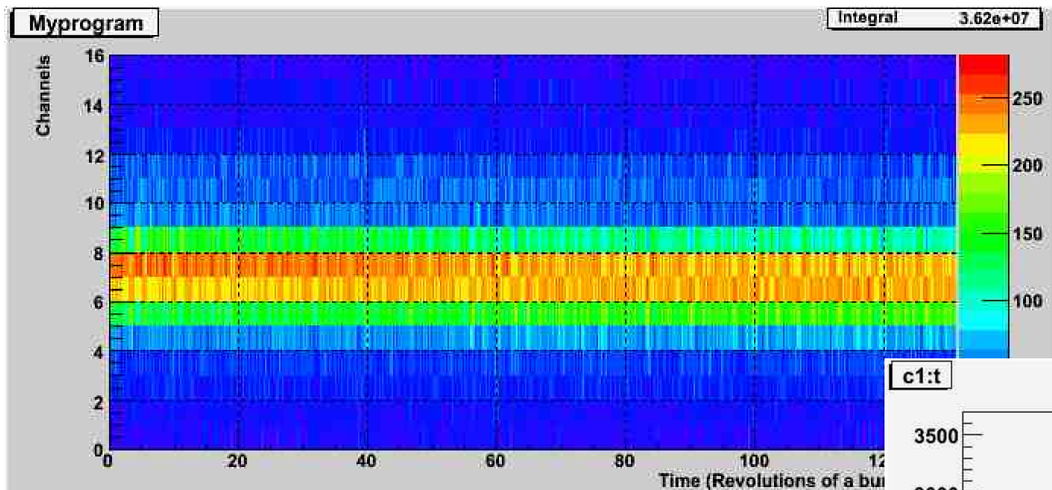
$$\Delta t = 30 \text{ ms}$$



← Beam profile cross-section with Gaussian fit

Resonance crossing at low speed

At low rate of the resonance crossing and zero nonlinearity the beam profile is not changed but particles loss is observed

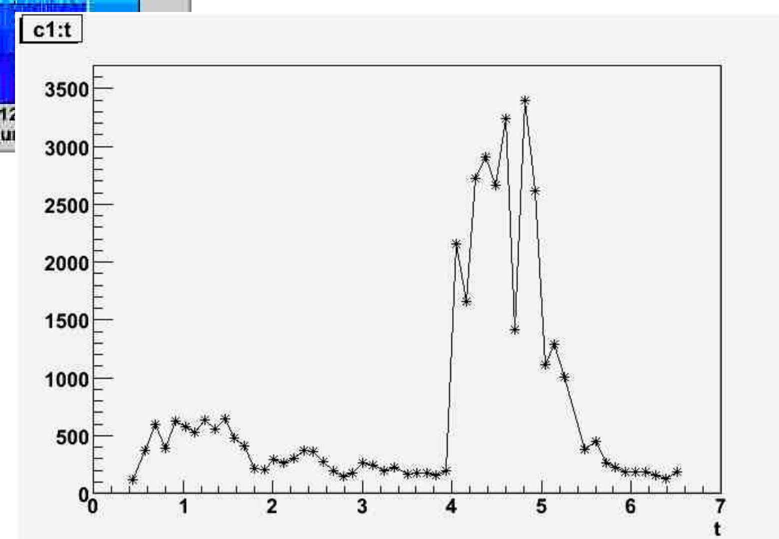


← Beam profile vs. the turn number

$$\nu_z = 0.661 \rightarrow 0.672$$

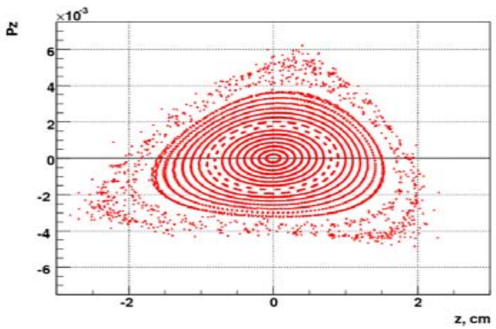
$\Delta t = 300$ ms

Loss monitor signal →

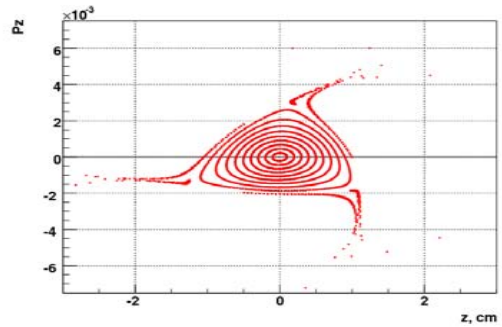


Resonance crossing with zero nonlinearity (simulation)

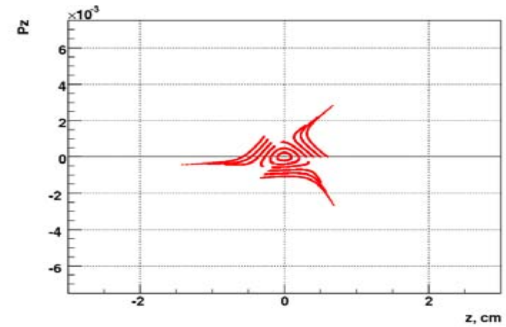
With zero nonlinearity the resonance is unstable and particles loss occurs at the low crossing rate.



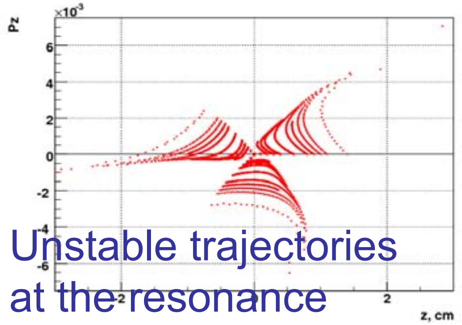
Qz = 0.654



Qz = 0.664

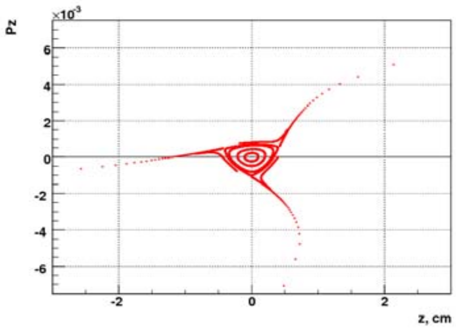


Qz = 0.665

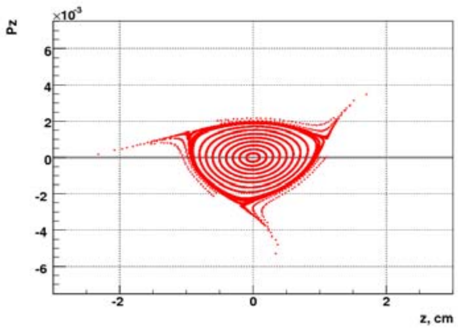


Unstable trajectories at the resonance

Qz = 0.666



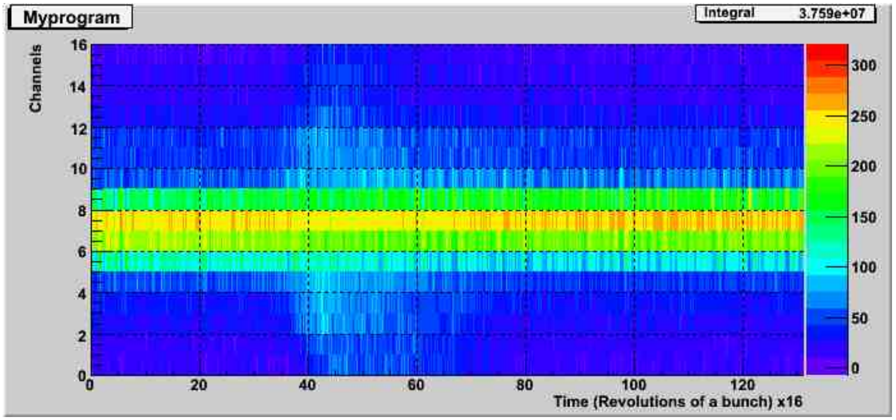
Qz = 0.667



Qz = 0.670

Resonance crossing at low speed: beam blow up

At low rate of the resonance crossing and large negative nonlinearity the beam blows-up but no particles loss or trapping into the island is observed

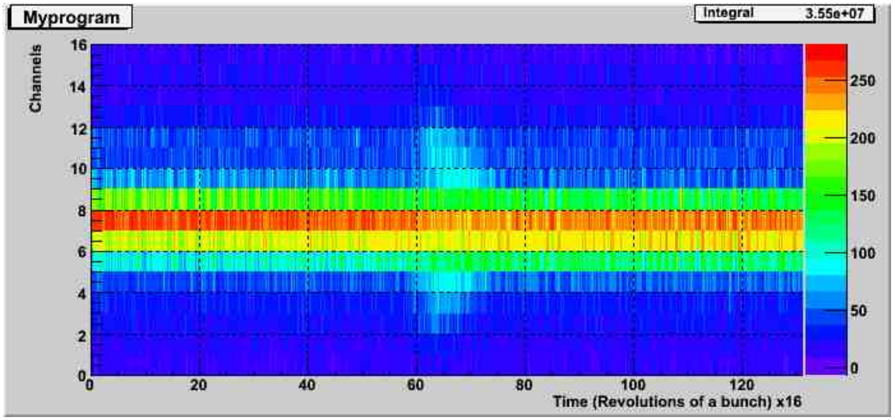


← Vertical tune increases

$Qz = 0.6736 \leftrightarrow 0.6625$ $\Delta Qz = 0.0111$

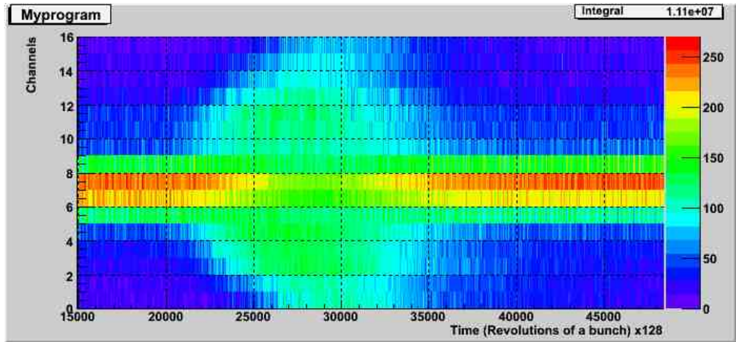
Oct + 23 A

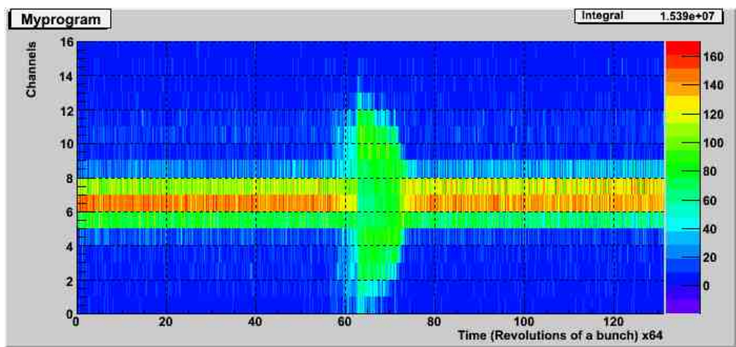
Vertical tune decreases →

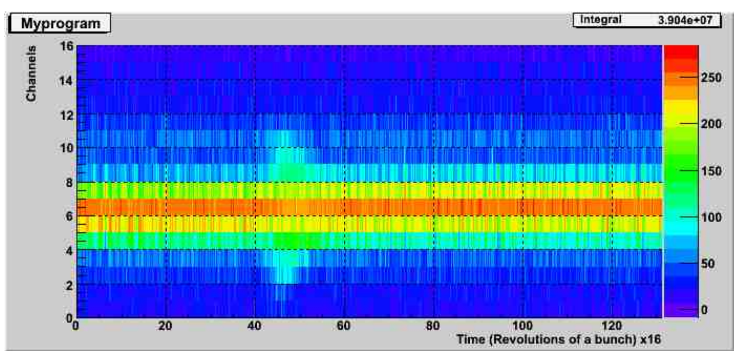


Beam blow up examples

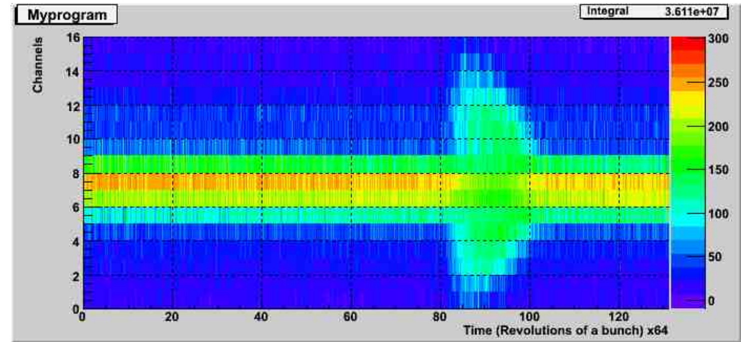
Tune increases

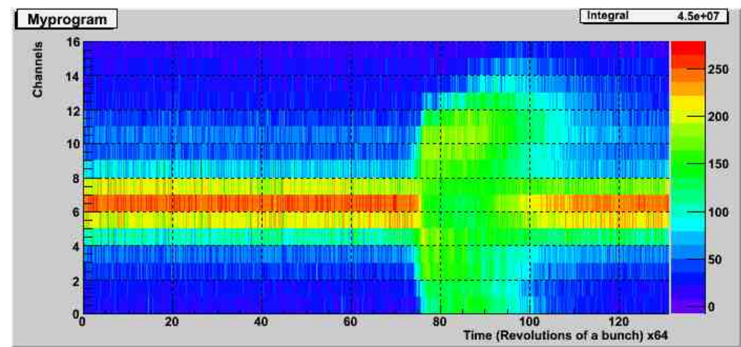


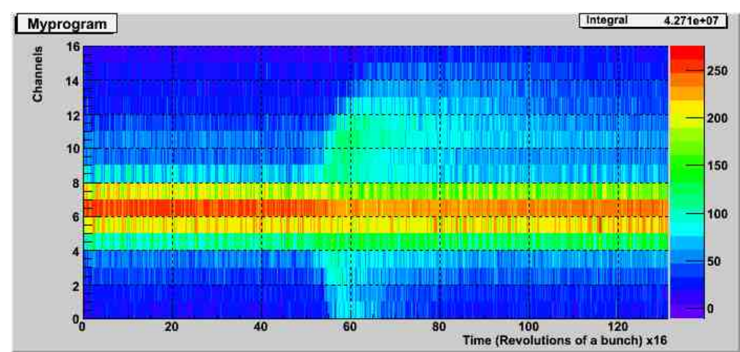




Tune decreases

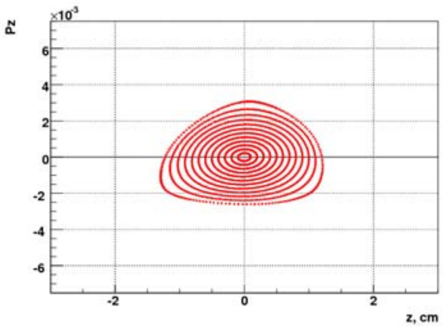




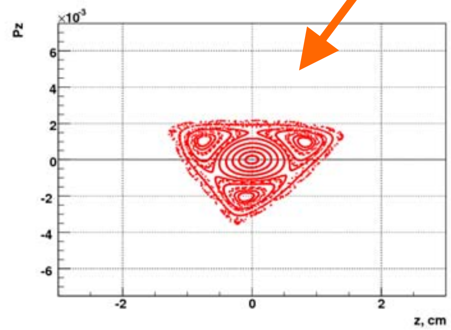


Beam blow up examples

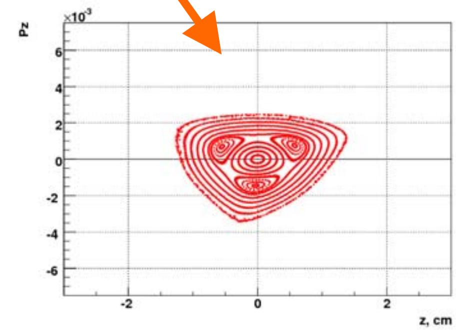
Small islands give the beam blow-up (?)



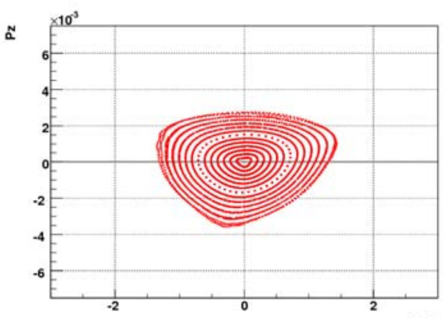
Qz = 0.650



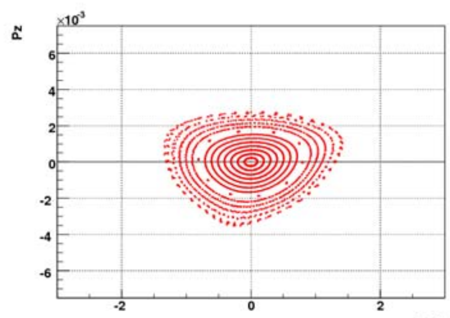
Qz = 0.664



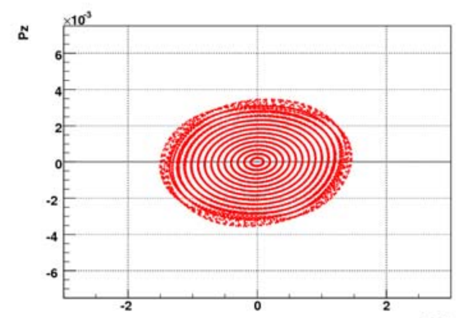
Qz = 0.665



Qz = 0.666



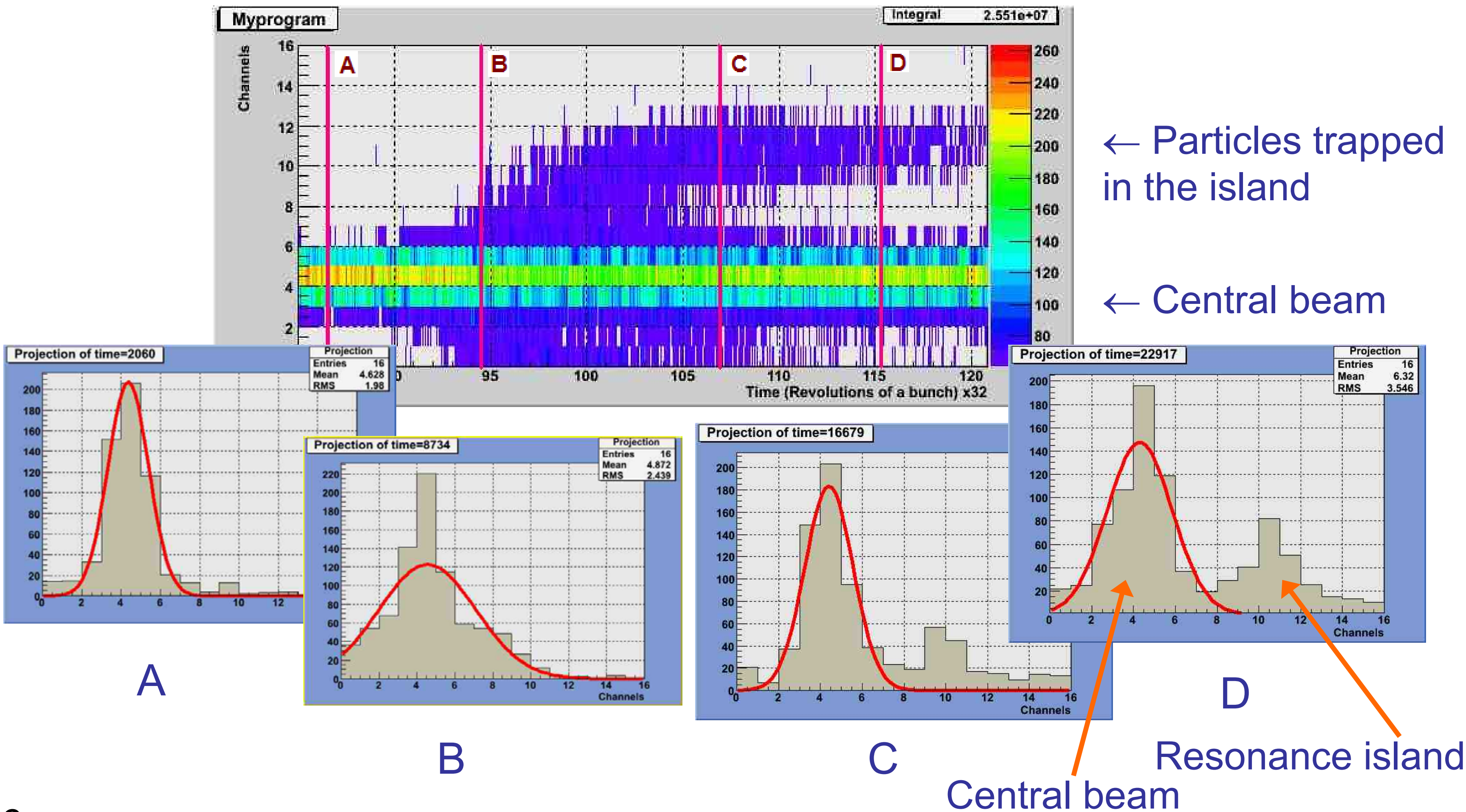
Qz = 0.667



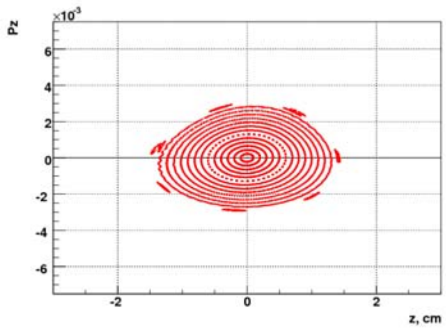
Qz = 0.675

Resonance crossing at low speed: particles trapping

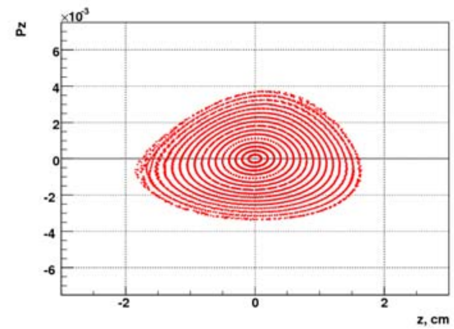
At low rate of the resonance crossing and large positive nonlinearity the particles are captured in the resonance island:



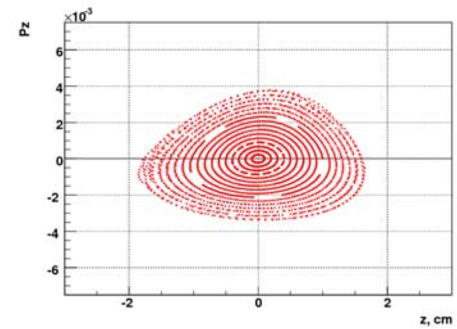
Particles trapping simulation



Qz = 0.653

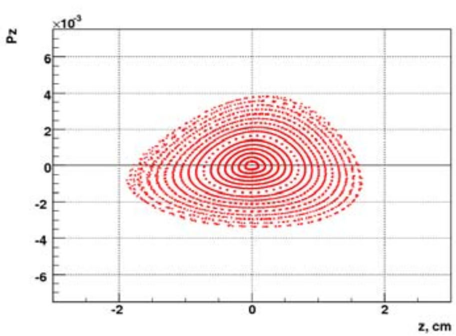


Qz = 0.664

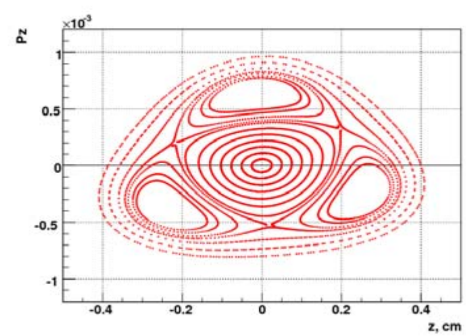


Qz = 0.665

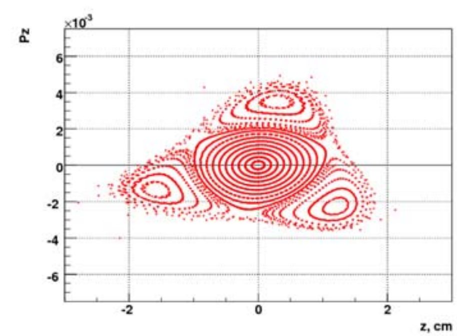
Large islands give the particles trapping and transportation outside the beam



Qz = 0.666



Qz = 0.667



Qz = 0.675

Conclusion

Turn-by-turn beam profilometer is a powerful tool to observe fast processes in circular accelerators. With the help of this diagnostic we have studied systematically the nonlinear resonance crossing under the wide range of parameters changing. The process of the resonance island creation and particles trapping was demonstrated as a function of time experimentally. Now we are planning to simulate the experimental conditions in details numerically to cross check the measurement results.