STUDY OF BEAM DYNAMICS DURING THE CROSSING OF THE THIRD ORDER RESONANCE AT VEPP-4M

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Motivation

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

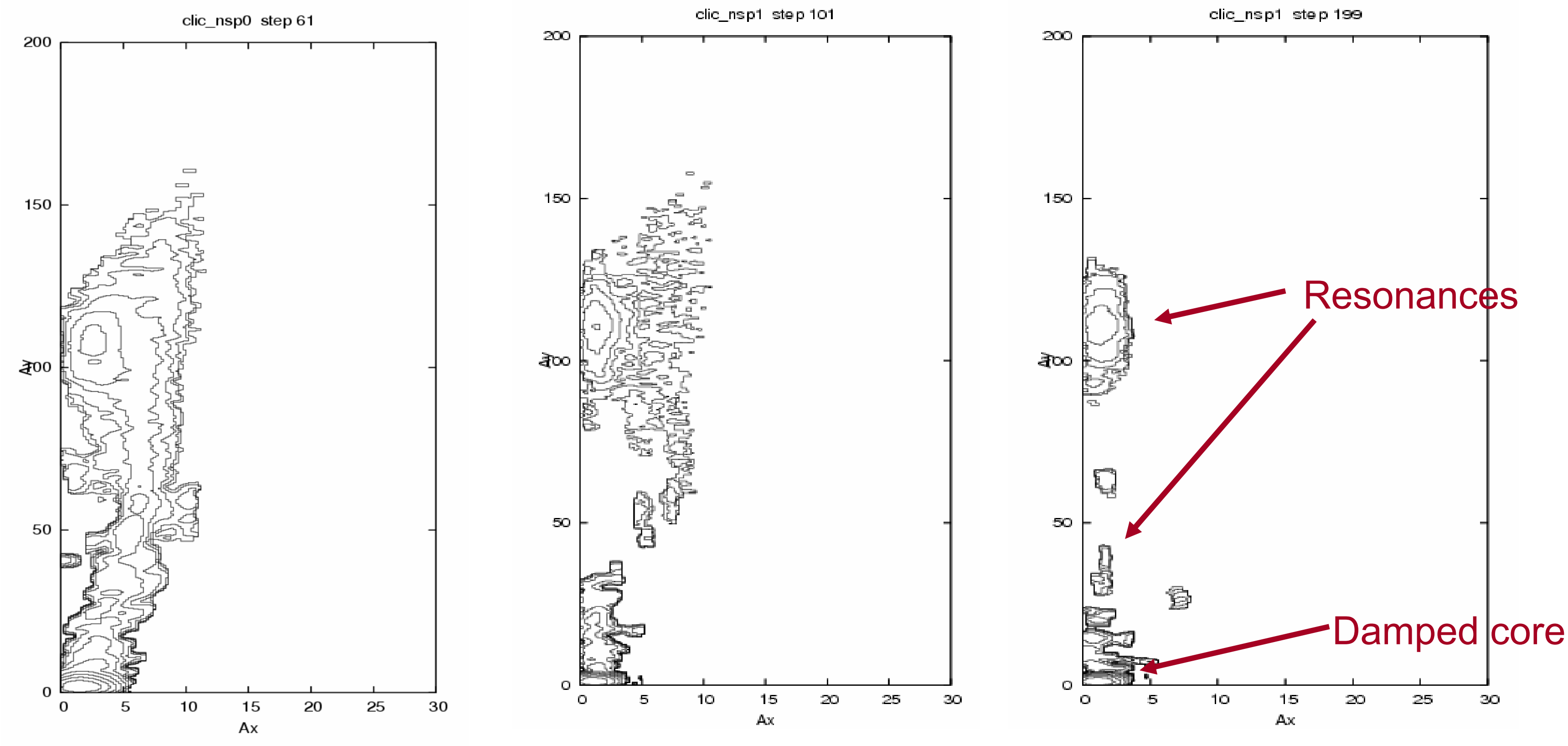
It is important for the resonance extraction from proton and ion synchrotrons, for FFAG synchrotrons development, etc.

Recently it was recognized that 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 ~0.1 – 0.2 (!) crossing many nonlinear resonances.

Example for the CLIC DR

PAC’09: TH6PFP093



4 tau 6 tau 8 tau

Simulation of the beam distribution with damping and space charge shows that the particles can be trapped during the damping in the CLIC DR in many 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

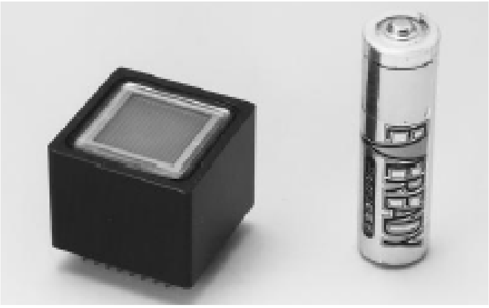
VEPP-4M is equipped with different modern diagnostics for different accelerator physics experiments

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.

Measurement procedure

- The vertical third-order resonance 3Qz = 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

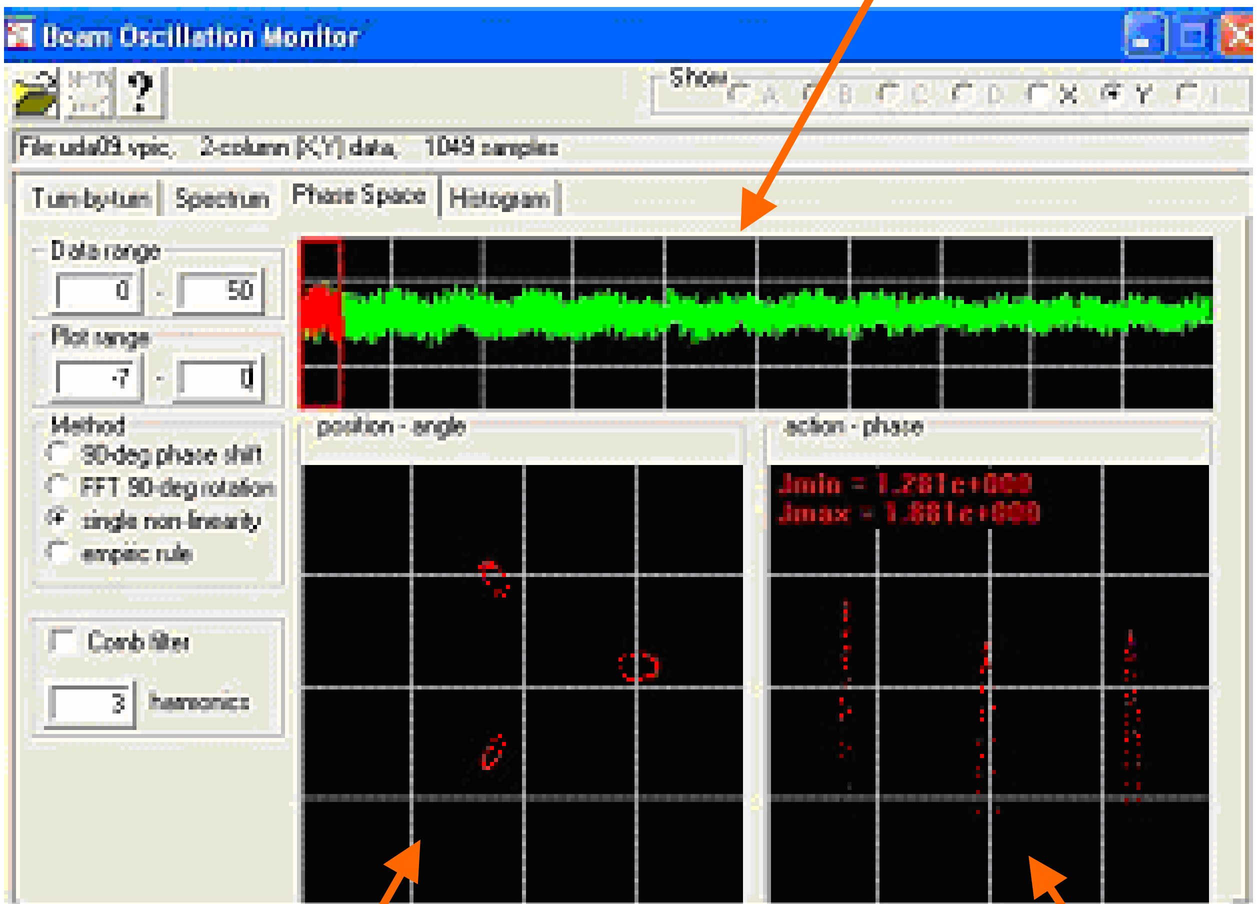
- The particles loss rate and the vertical beam profile are measured during the resonance crossing as a function of the turn number

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

Phase trajectories-I

3Qz = 23

Beam oscillation vs the revolution number

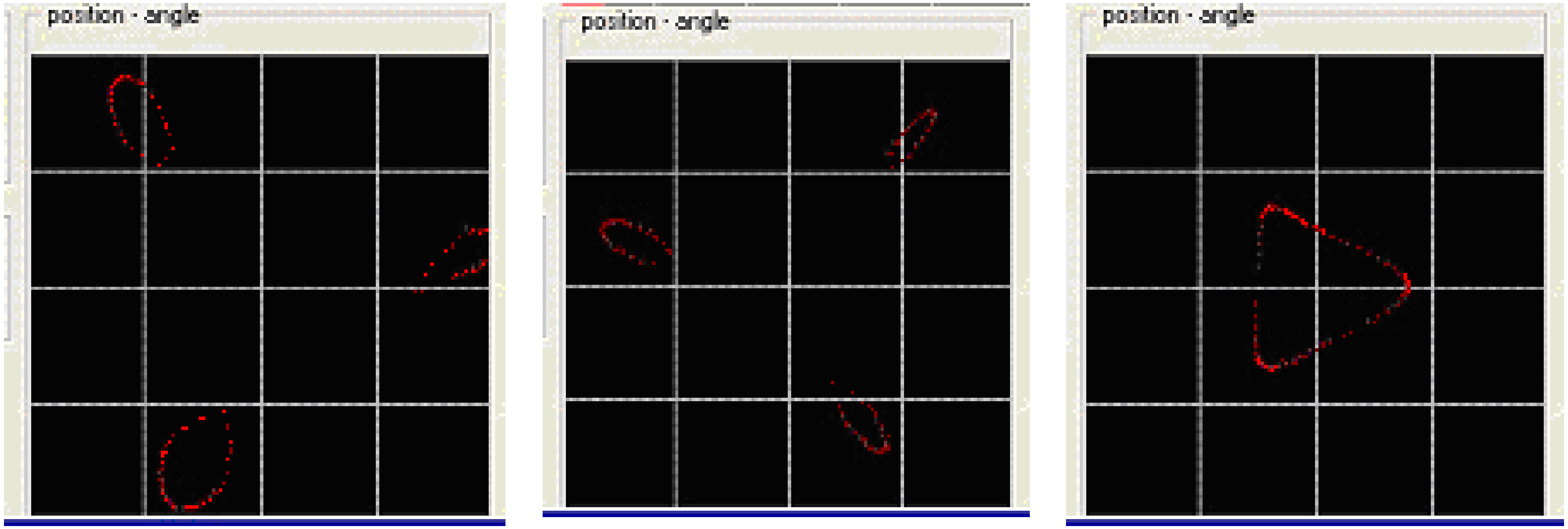


(Z, Z') phase trajectories

(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



Resonance driving term

Measurement of the phase space curve allows us to find the value of the resonance driving term from following consideration:

(a) From the phase curves distortion and knowing of the second order invariant of the motion:

$$a_{3n} \approx \frac{J_{\max} - J_{\min}}{J_{\max}^{3/2} + J_{\min}^{3/2}} \qquad a_{3n} = 3\sqrt{8}\,\frac{A_{3n}}{3\nu_z - n}$$

where *Jmax* and *Jmin* is the maximum and minimum of action variable

(b) From the boundary of the stable motion close to the resonance

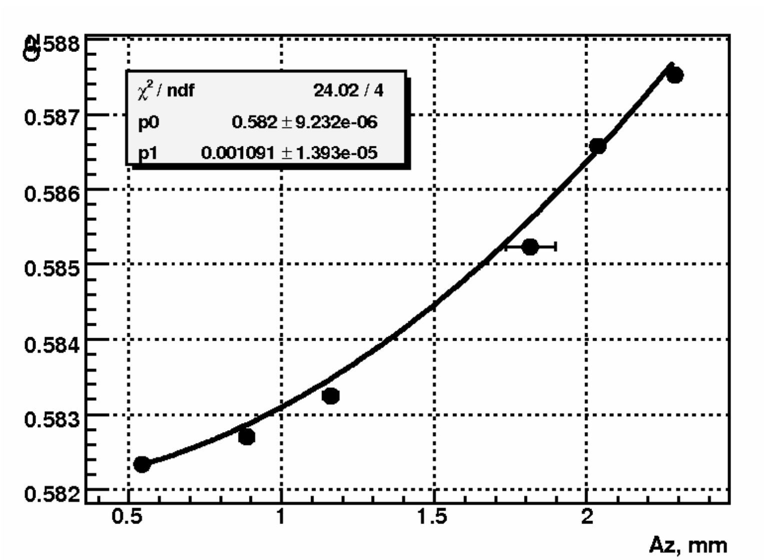
$$A_{z\max} = \sqrt{\beta_{zSRP3}}\,\frac{\delta}{3A_{3,2}}$$

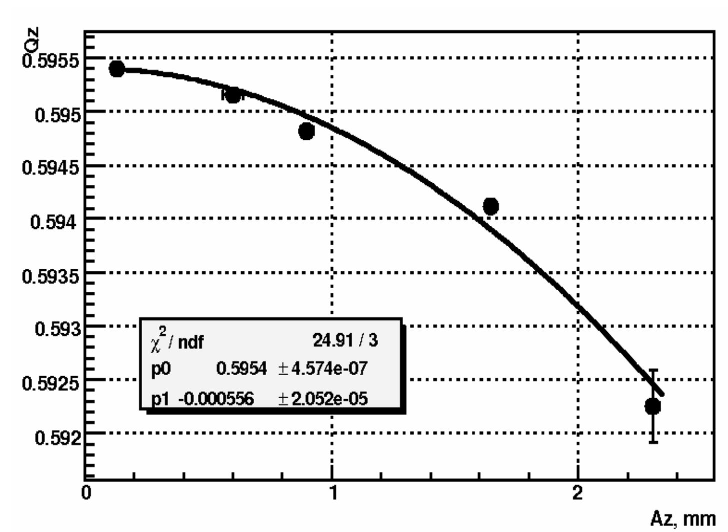
(c) From the beam lifetime in the vicinity of the resonance

All methods consistently give the value $A_3 \sim 0.02 - 0.07\ \mathrm{mm}^{-1/2}$ depending on the operation mode

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

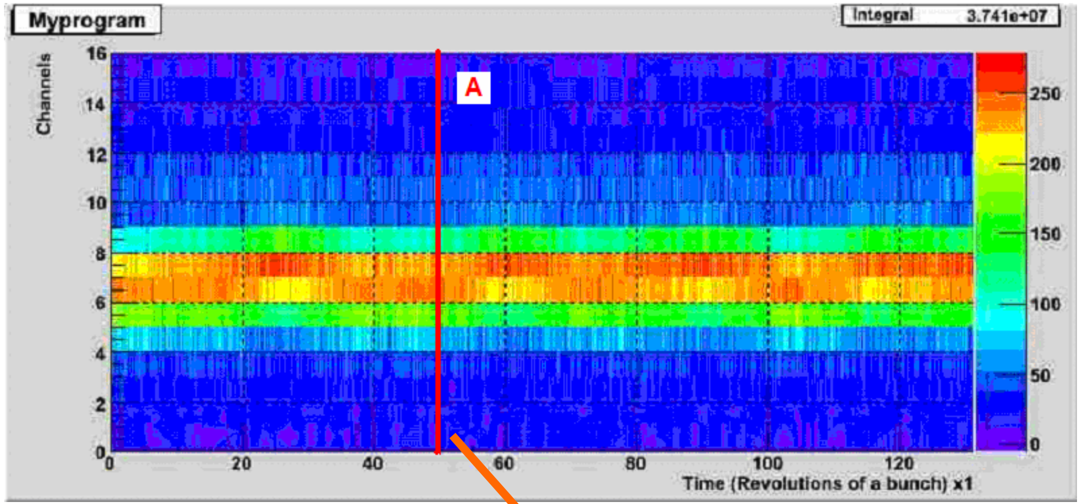
$\alpha_0 = 1\times10^{-3}$ mm^{-2}

Octupole current =+23 A

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

Resonance crossing at high speed

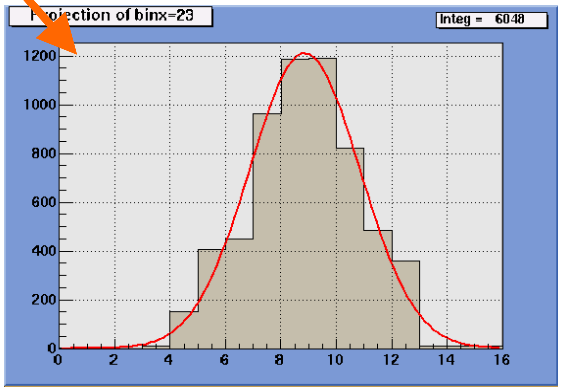
At high rate of the resonance crossing neither change of the beam vertical profile nor particle loss is observed



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

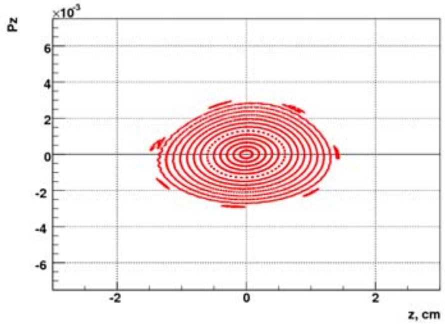
$$\nu_z = 0.661 \rightarrow 0.672$$

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

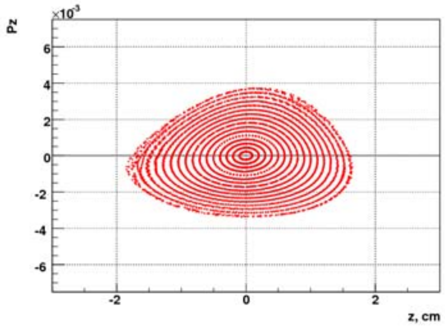


← Beam profile cross-section with Gaussian fit

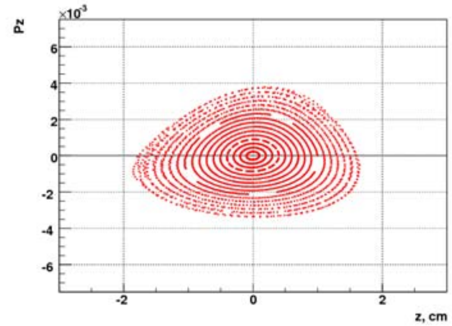
Resonance crossing with high nonlinearity



Qz = 0.653

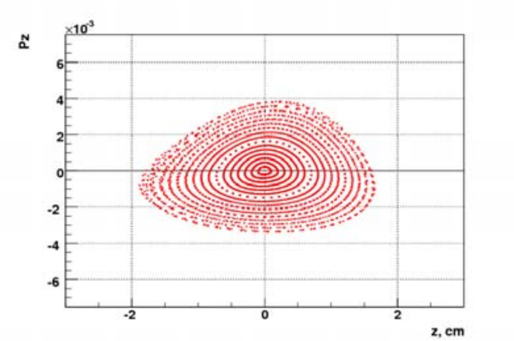


Qz = 0.664

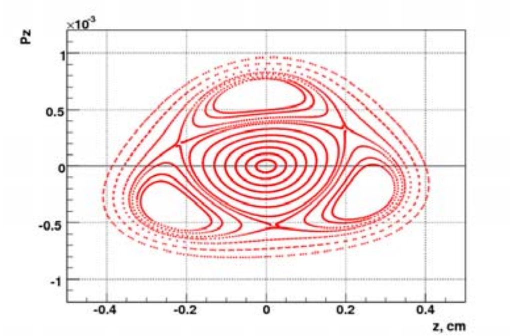


Qz = 0.665

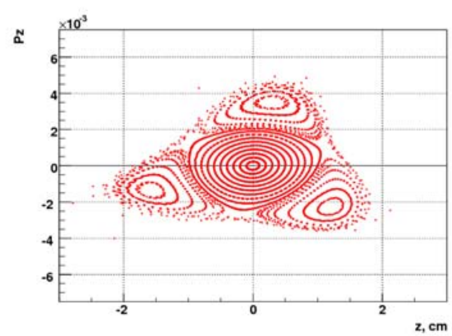
Large islands give the particles trapping and transportation outside the beam



Qz = 0.666



Qz = 0.667



Qz = 0.675

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

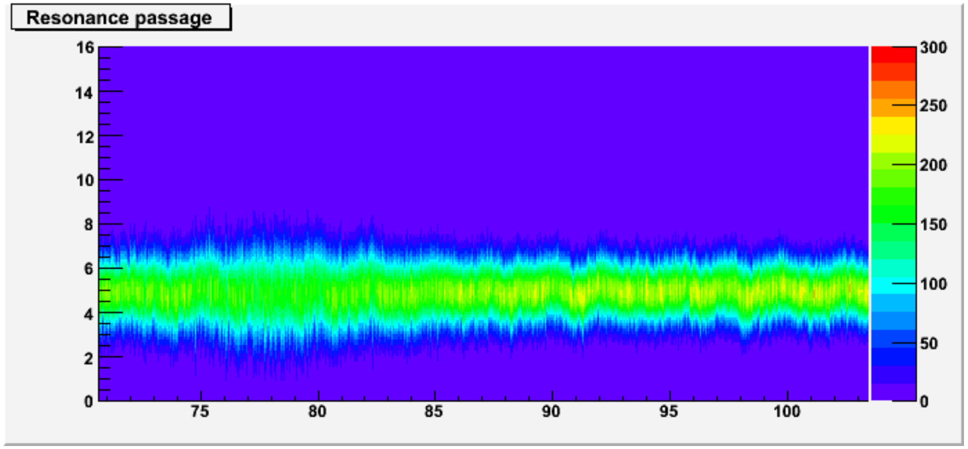
$$I_a > \left(\frac{\nu'}{2m\alpha_0 A_n} \right)^{1/n}$$

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

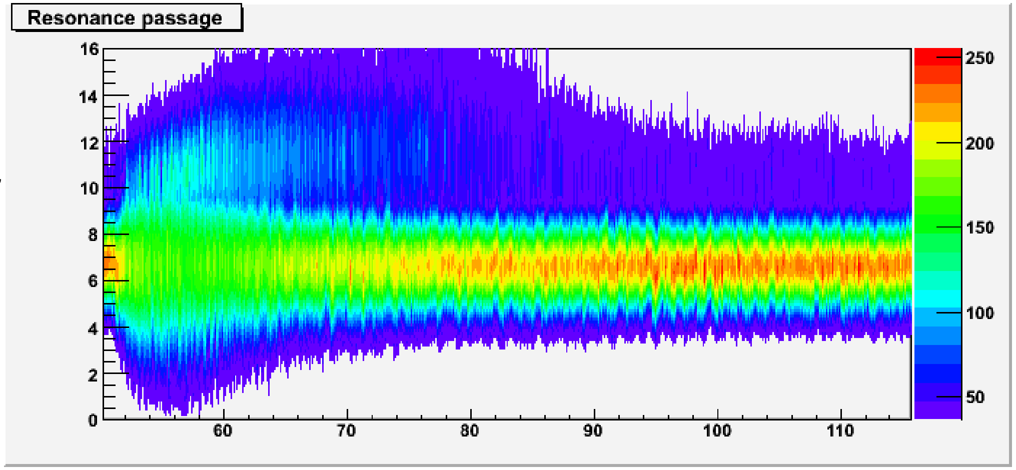
$$\Delta I / I_0 \approx A_n I_0^{n/2-1} \sqrt{2\pi m / |\nu'|}$$

Resonance crossing with high nonlinearity I

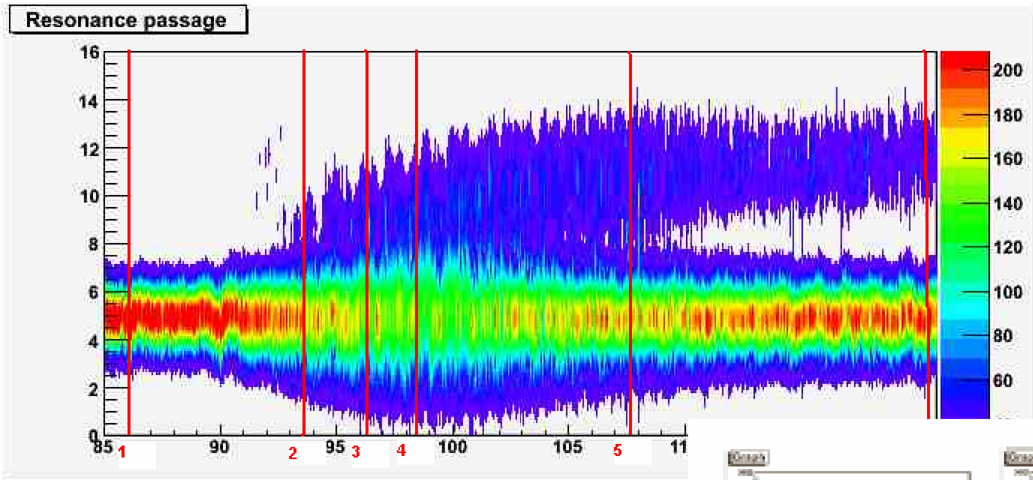


Tune range is $Qz = 0.6608 \div 0.6717$; crossing time is 40 ms. For high rate neither beam size change nor particles capture is seen.

The same but the crossing time is 0.3 s. A beam blow-up and some evidence of the particles trapping are observed.



Resonance crossing with high nonlinearity II



Time evolution of the vertical beam profile in the case of the particle trapping in the resonance island (Δt = 3s).

Beam profile (Gauss fit) measured during the resonance crossing

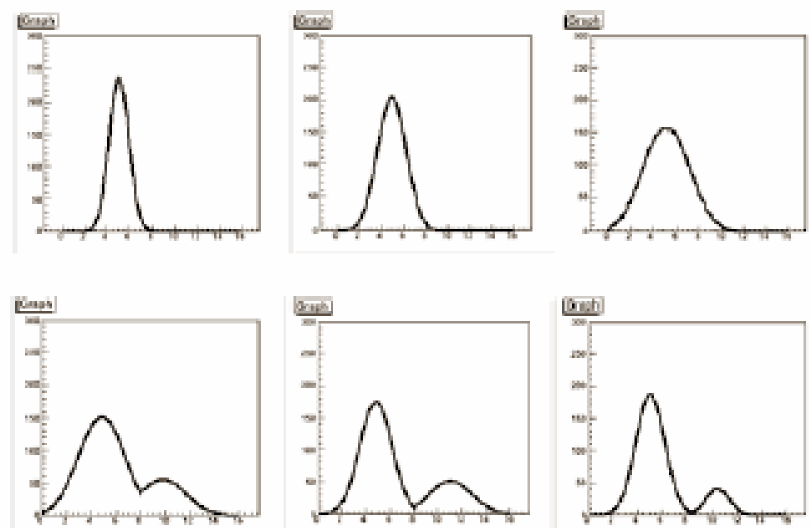
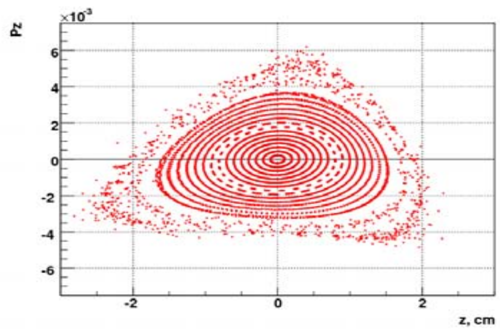


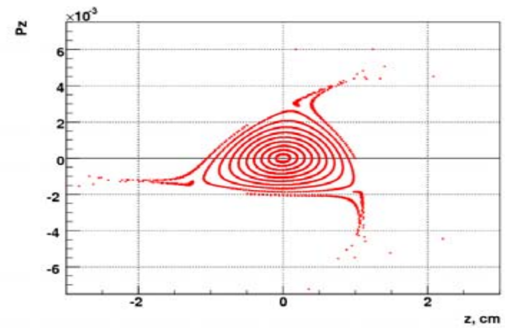
Figure 9: Transverse distribution of the beam profile (Gauss fit of the MAPMT 16 channels) corresponding to the different moments indicated by the red lines in Fig.8.

Resonance crossing with low nonlinearity I

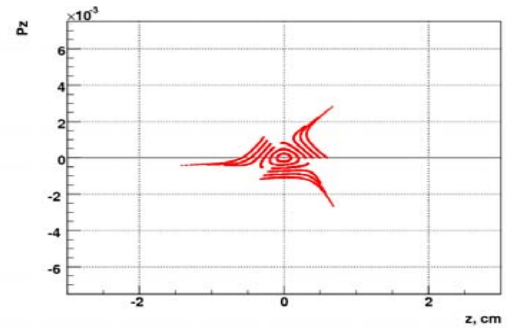
With zero nonlinearity the resonance is unstable and particles loss occurs at the low crossing rate.



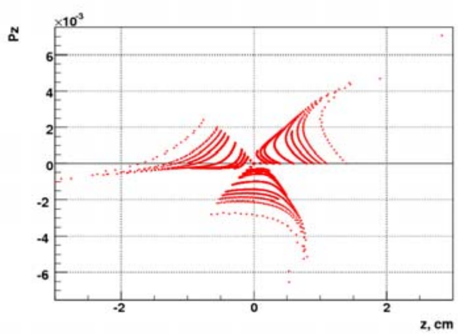
Qz = 0.654



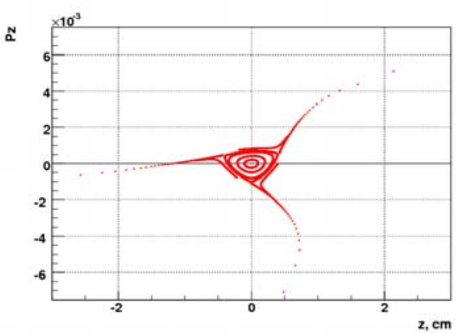
Qz = 0.664



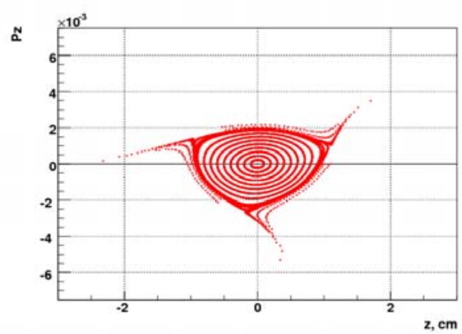
Qz = 0.665



Qz = 0.666
Unstable trajectories



Qz = 0.667



Qz = 0.670

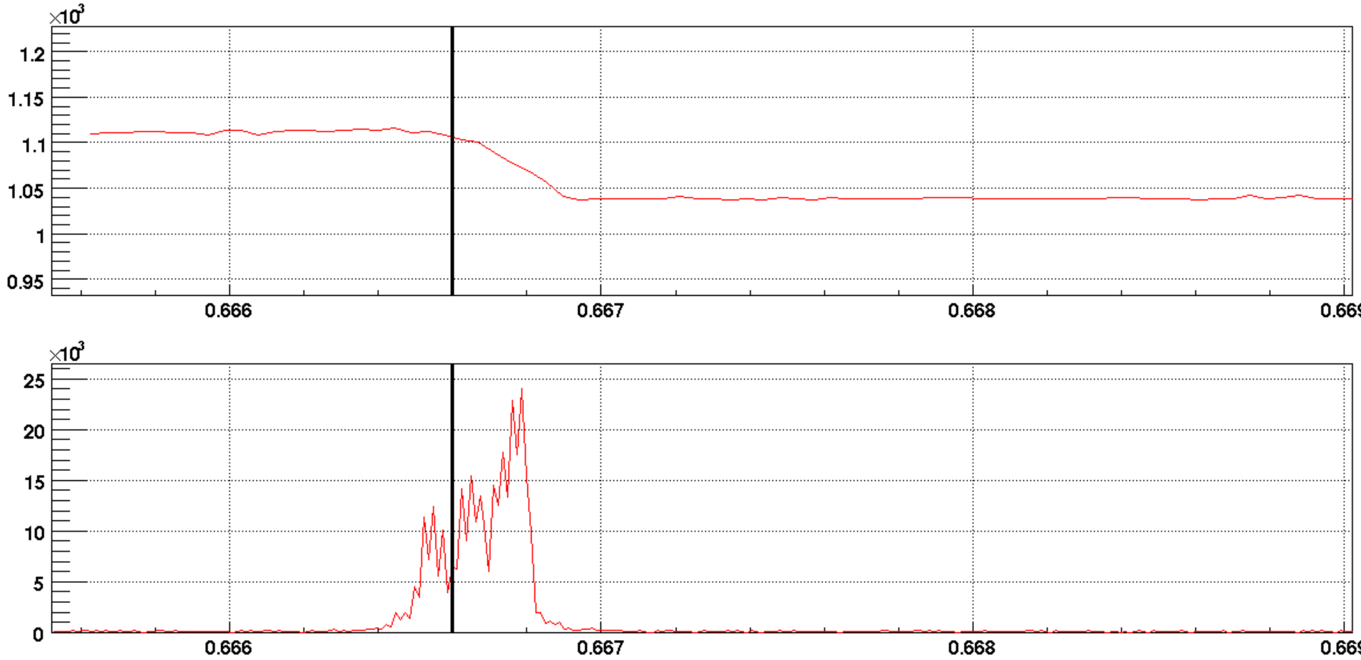
Adiabatic condition for the resonance crossing with low nonlinearity

The adiabatic criterion in this case can be formulated as follows. All the particles will be lost from the beam during the unstable resonance crossing if the crossing rate $\nu' = d\nu / d\theta$ satisfies the relation

$$\nu' << A_3^2 \cdot \varepsilon_z / 8\pi$$

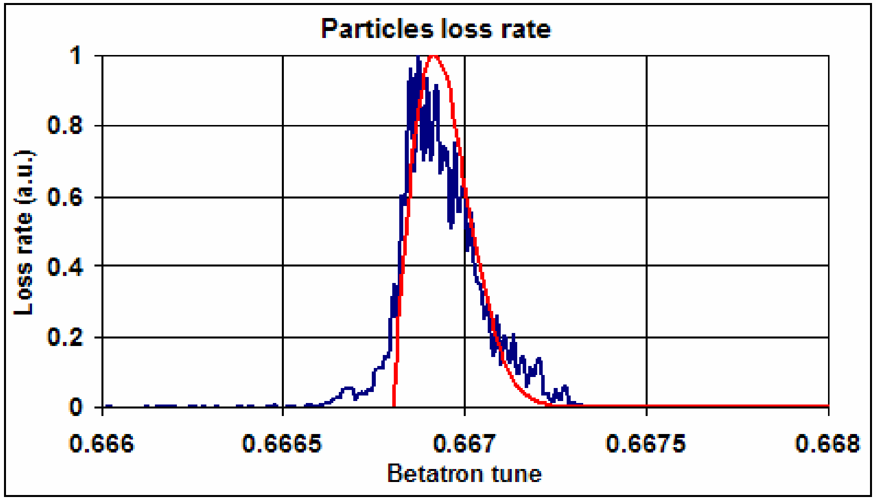
where ε_z is the beam emittance and A_3 is the resonance driving term.

Particles loss measurement during the crossing of the unstable vertical third order resonance

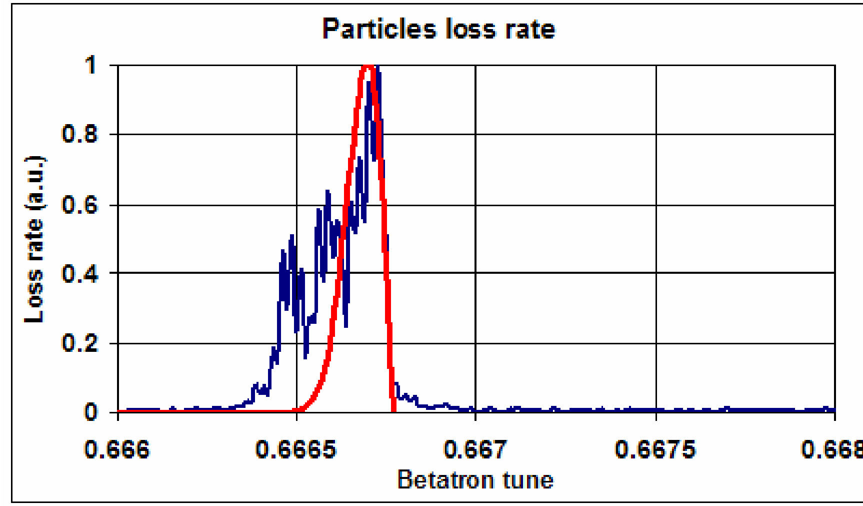


Total intensity decrease (upper plot) and particles loss rate (lower plot) during the resonance crossing. Tune change 0.6687→0.6653 for 1 s, I = 0.212 → 0.214 mA

Comparison of theory and experiment



The vertical betatron tune change
ΔQz = 0.6653→ 0.6685 for 1 s,
I = 0.183→0.181 mA

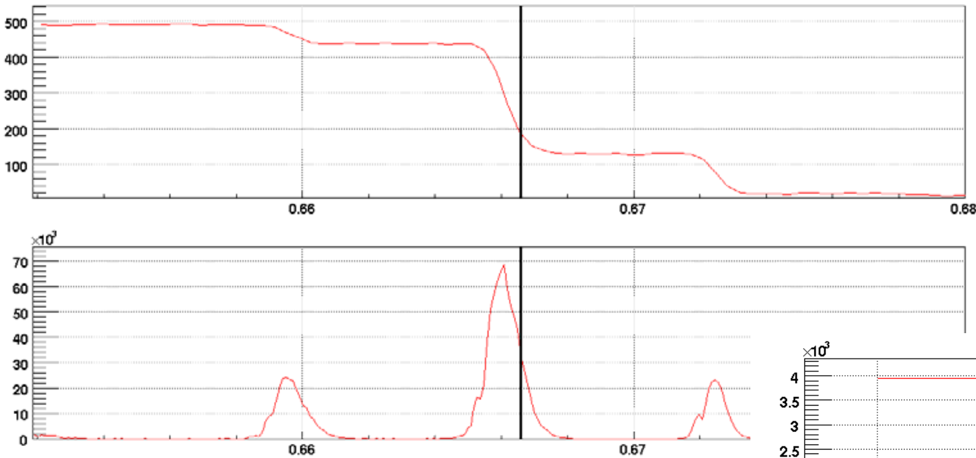


Tune shift if 0.6687→0.6653 for 1 s,
I = 0.212→0.214 mA

However, despite the relative loss rate profiles found theoretically and experimentally are rather consistent, the absolute value of the intensity loss is differs much.

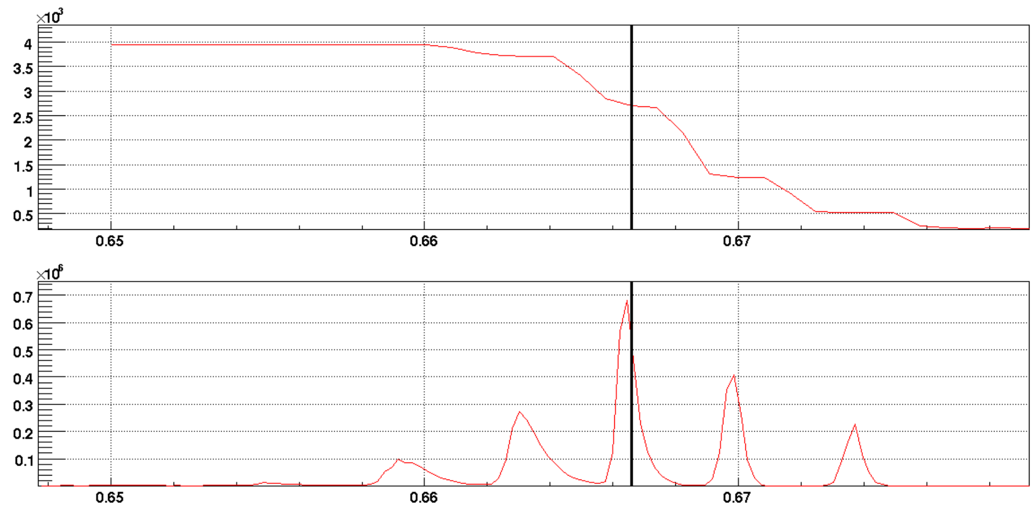
Now we are trying to explain it either by the radiation damping or the residue nonlinearity.

Synchrobetatron resonances observation



Particles loss while crossing the unstable resonance with synchrobetatron satellites

Vertical chromaticity = 9



Vertical chromaticity = 15

For high chromaticity the synchrobetatron resonances are observed.

Conclusions

♦ 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.

♦ For high value of the vertical tune-amplitude dependence it was shown that with the adiabatic crossing rate, the resonance islands can capture some fraction of particles and transport them to the high amplitudes.

♦ The trapping capability can be controlled by the octupole magnets. This fact can be useful to provide high performance of the damping rings: the nonlinear detuning coefficients should be adjusted during the damping to prevent particles captures in the nonlinear resonances.

♦ For the low value of the amplitude-dependent tune shift no resonance islands appear and significant portion of the beam intensity can be lost during the resonance passage. This case is sensitive to the beam damping and the residue nonlinearity as well as to the ripple of the power supply system.