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

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Abstract

The influence of resonances on the beam dynamics in the storage rings is of a substantial interest for the accelerator physics. For example, a fast crossing of resonances occurs in the damping rings of future linear colliders during the beam damping due to the space charge tune shift that can result in a loss of particles. We have studied experimentally the crossing of resonance nearby the working point of the VEPP-4M storage ring. The observation of the beam sizes and particle losses has been done with a single-turn time resolution.

INTRODUCTION

The passage of beam in synchrotron or storage ring through the betatron resonance and the corresponding loss of particles or the beam distribution degradation were extensively studied in the past [1-3]. Recently, this issue has again become popular mainly because of the FFAG synchrotron projects [4]. We'd like to point out that this issue could be important for electron-positron accelerators with an extremely low emittance such as linear collider damping rings or particles super-factories based on the crab-waist collision approach. In both machines the beam is injected with a relatively large emittance and then damps to the values as low as 1÷2 pm. During the damping two effects provide the resonance crossing mechanism:

- The betatron tune moves (predominantly for the vertical motion) by considerably large value ~0.1÷0.2 due to the space charge force: $\Delta\nu_{sc} \sim (\gamma\varepsilon)^{-1}$.

- As the low emittance strong focusing lattice requires strong chromatic sextupoles yielding rather large amplitude dependent tune shift, the betatron frequency of each individual particle changes with the amplitude decrease according to the nonlinear detuning. It is worth mentioning that the space charge also produces the nonlinear tune shift depending on the beam emittance and it should be taken into account together with the external (magnet) nonlinearities.

These two effects in combination can increase or decrease the resonance crossing speed providing either particle trapping (in the adiabatic limit) or the beam size growth.

In this paper we discuss the results of experimental study of the resonance passage at the VEPP-4M collider. The third-order resonance $3\nu_z = 23$ was traversed by the electron beam with the variable speed. During the experiment the resonance strength could be changed by a single skew-sextupole magnet while the nonlinear detuning was controlled by a number of the octupole lenses. Different parameters such as particles loss rate, beam size and transverse distribution, space phase trajectories, amplitude dependent tune shift, etc. were measured.

MEASUREMENT SETUP

The VEPP-4M electron-positron collider with a maximum energy of 5.5 GeV is operating now at ~1.8 GeV in the region of the ψ-meson family. The collider is equipped by a number of beam diagnostics, which allow the measurement of different parameters and the study of nonlinear motion.

The phase space trajectories are registered by the excitation of the coherent beam motion with the help of the fast electromagnet kicker with 50 ns 30 kV pulse. To measure the beam centroid motion, BPMs in the turn-by turn mode are used. The BPM resolution is ~50 μm.

Particles loss and the beam distribution tails are measured by a set of scintillator counters inserted into the vacuum chamber. The counter can be moved by a step-motor in and out of the beam with the accuracy better than 0.1 mm.

CCD-cameras are employed to measure transversal beam dimensions and position (Figure 1). Camera has an external trigger with the jitter of 100 μs.

To measure a single-turn transverse beam distribution during tens of thousands of turns of the beam we have designed a unique device [5] based on the multi-anode photomultiplier R5900U-00-L16 HAMAMATSU. This device 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

In this section we overview very briefly the main results of the resonance crossing theory. Let's start with a standard isolated resonance Hamiltonian in the action-angle variable

$$H = \delta(\theta) \cdot I + \alpha_0 \cdot I^2 + A_n \cdot I^{n/2} \cos m\varphi, \quad (1)$$

with the nonlinear tune shift coefficient α_0, the driving term strength A_n and the distance from the resonance $\delta(\theta)$ that depends on the time (azimuthal angle) θ. Two cases corresponding to the slow (adiabatic) and the fast crossing should be considered. A condition for the adiabatic crossing can be obtained by comparing the maximum rate of the amplitude (action) change

$$(I')_{max} = -(\partial H / \partial\varphi)_{\sin m\varphi=1} = mA_n \cdot I^{n/2}, \quad (2)$$

with the rate of the resonance island motion. The latter is found from the resonant action equation

$$\delta(\theta) + 2\alpha_0 \cdot I_r = 0$$

as

$$\frac{dI_r}{d\theta} = \frac{1}{2\alpha_0}\frac{d\nu}{d\theta}.$$ (3)

A particle at amplitude I is considered adiabatic if its amplitude is such as

$$I'_r < I'_{\max},$$

or

$$mA_n I^{n/2} > \frac{\nu'}{2\alpha_0}.$$ (4)

In other words, a particle with amplitude

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

will be captured by the resonance island and remained inside the island as it moves.

If the adiabatic criterion is not fulfilled, the particle is not trapped in resonance but its amplitude increases as

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

and the faster the particle passes the resonance, the smaller is the growing of its amplitude. The explanation of this fact is evident: resonance can change the particle oscillation energy by a small fraction during the fast passage.

MEASUREMENT RESULTS

At first we tuned the system parameters to observe the third-order resonance $3\nu_z = 23$ at the phase space plot by the turn-by-turn equipment (Figure 1). The tuning was performed by a single skew-sextupole magnet controlling the driving term in the Hamiltonian (1) and by a set of octupole magnets regulating the amplitude dependent tune shift.
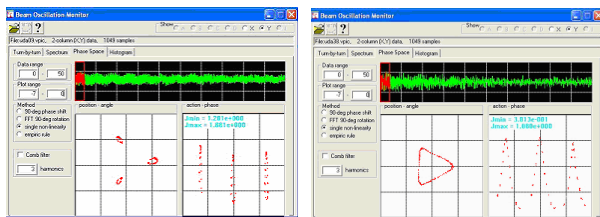

Figure 1: Phase trajectories at the resonance (left) and before the resonance creation. Each plot shows the trajectories in the variables (z, z') and (I_z, φ_z). The tune is $\nu_z = 0.6621$ and the amplitude of the island center is 0.9 mm

Turn-by-turn technique allows measuring the nonlinear behaviour of the betatron tune. Figure 2 shows the vertical tune as a function of the amplitude for different excitation currents of two octupole magnets SEOQ and NEOQ placed symmetrically to the IP at the azimuth with $\beta_z \gg \beta_x$.

After we managed to control reliably the resonance parameters, we started the main experiment on the resonsnce crossing. All measurements were performed at

low electron current ~0.5 mA to avoid coherent effects. We changed the vetical betatron tune by the increasing or decreasing of the quadrupole magnet current with the variable rate. The minimal rate is $\Delta\nu_z = 0.01$ at 30 ms.
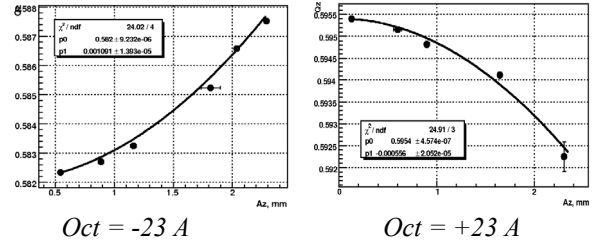

$Oct = -23\ A$ $Oct = +23\ A$

Figure 2: Vertical tune vs. amplitude for different currents in the octupole corrections. Polarity changing yields change of the tune shift term from $\alpha_0 = 1\times10^{-3}\ \text{mm}^{-2}$ to $\alpha_0 = -0.5\times10^{-3}\ \text{mm}^{-2}$

Also we varied the strength of the resonance driving term and the amplitude dependent tune shift. During the resonance passage we have registered turn-by-turn the vertical beam profile by the fast 16-channel photomultiply tube and the particle loss with the help of the scintillator counter inserted in the vacuum chamber vertically. The example of the vertical beam profile measurement as a function of the turn number during the resonance crossing with the maximum speed and the nonlinear detuning close to zero is shown in Figure 3.
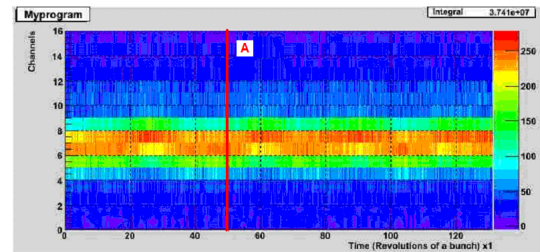

Figure 3: The vertical beam profile vs. revolution number ($Oct = 0$ A, $\nu_z = 0.661 \to 0.672$, $\Delta t = 30\ \text{ms}$). Colors indicate the beam intensity

A cross-section of the plot in Figure 3 along the line A is depicted in Figure 4.
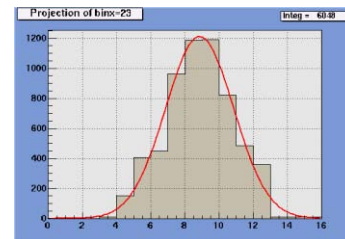

Figure 4: Single shot vertical beam profile fitted by the Gauss function

From Figure 3 one can see that at the high crossing rate and low nonlinearity neither beam distribution change nor particles loss is observed. When slowing down the

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crossing rate and still keeping the nonlinearity near zero we could see the beam loss but the transverse distribution is not changed. It means that the resonance is unstable for the low value of nonlinearity and has no island structure. But as the resonance is weak, the unstable area is very narrow, providing particles loss only at the low crossing rate.

Then we have changed the nonlinear term and repeated the resonance crossing measurements with variable speed. For the positive value of the octupole current we could clearly see the beam blow-up but there was no particle capture in the resonance islands (Figure 5).

$$\nu_z = 0.662 \rightarrow 0.674$$
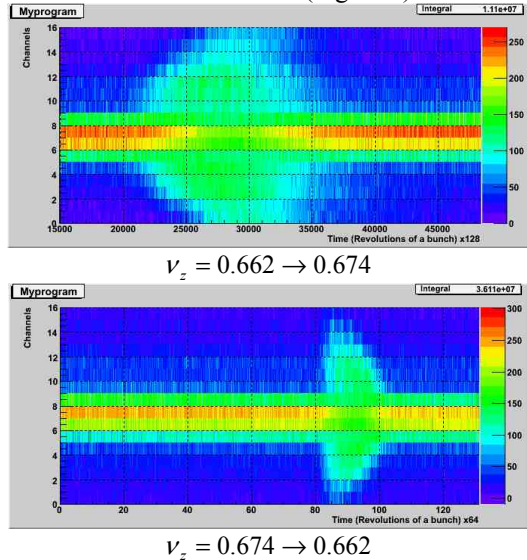

$$\nu_z = 0.674 \rightarrow 0.662$$

Figure 5: The vertical beam profile blowing up for $Oct = +23$ A and $\Delta t = 0.5$ s

The beam blowing-up depends on the crossing direction (increasing or decreasing of the tune) and enlarges with the resonance crossing speed slowing down.

For the negative octupole term ($Oct = -23$ A) and slow tune variation the island creation and particles trapping are clearly seen in Figure 6-7.
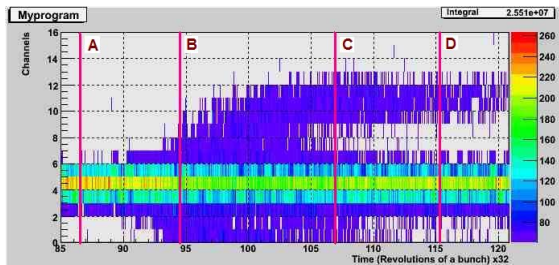

Figure 6: Time evolution of the vertical beam distribution in the case of the particle trapping in the resonance island ($Oct = -23$ A, $\nu_z = 0.679 \rightarrow 0.658$, $\Delta t = 0.5$ s).

In Figure 6 the vertical beam profile vs. the revolution number demonstrates the moment of the resonance island creation and its moving outwards. This case relates to the adiabatic resonance traversing. The vertical beam distribution corresponding to the different times (cross-sections lines A, B, C and D in Figure 6) is shown in Figure 7.
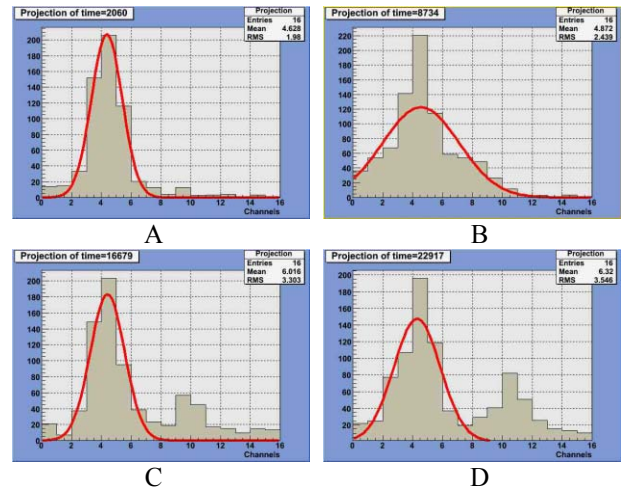

Figure 7: Creation of the resonance island and particles trapping in the adiabatic limit

It is worth mentioning that with the changing of the resonance passage direction we could see, instead of particles trapping, insignificant blow-up of the beam size. Such "hysteresis" of the nonlinear resonance behaviour is well known and was studied theoretically in the past.

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. 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 numerically to cross check the measurement results.

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