A METHOD FOR MEASUREMENT OF TRANSVERSE IMPEDANCE DISTRIBUTION ALONG STORAGE RING

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Abstract

A new method for measurement of transverse couple impedance distribution along storage ring is described. The method is based on measuring of a closed orbit deviation caused by local impedance. Transverse impedance acts on the beam as a defocusing quadrupole, strength of which depends on the beam current. If a local bump of closed orbit has been created at the impedance location, then the orbit deviation occurs while varying the beam current. The local impedance can be evaluated using the orbit deviation measured. Measurement technique is described, the method accuracy is evaluated. The method described was successfully used for measurement of the impedance distribution along the VEPP-4M storage ring.

1 INTRODUCTION

The impedance approach is widely used to describe interaction of bunch particles with induced wake fields. In this case, vacuum chamber is considered as set of sections with frequency dependent impedance.

Knowledge of impedance allows qualitative estimates and predictions of the beam stability, and evaluation of the instability thresholds and increments. Calculation of impedance for complex vacuum chamber is quite a cumbersome problem, which should be solved at the initial stage of accelerator design. Since the accelerator was already built, measurement of the impedance and its distribution along the ring makes possible an explanation of various collective effects observed.

There are precise methods to measure some integral characteristics of the impedance.

So, by measuring energy loss factor and current dependence of bunch length one can evaluate integral values for both resistive and reactive components of longitudinal impedance. The resistive component of transverse impedance can be found from measurements of decrement of fast damping of coherent betatron oscillations. The reactive component of transverse impedance can be found by measuring current dependence of coherent betatron frequency shift [1,2].

Methods for measurement of local impedance using beam orbit measurement system are developed and successfully used in CERN [1]. So, distribution along the ring of the resistive component of longitudinal impedance one can obtain by calculation of the difference of two radial orbits measured with different current values. Measurement of betatron phase advance on pickups gives distribution of the reactive component of impedance. These methods yield impressive results if the total effects measured are rather big and much greater than pickup coordinate resolution and accuracy of betatron phase measurement. There are 300 μm of the orbit deviation and 30º of the phase advance for LEP. Terminal number of sections having impedance simplifies matters. For LEP, as for the most of modern accelerators, major part of total impedance is determined by high order modes (HOM) of RF cavities, placed in one or two straight sections.

Our attempts to use these methods at the VEPP-4M had failed, firstly because of the effect predicted is an order less than at LEP, secondly because the impedance structure differs essentially from the LEP one.

The main contribution into the total impedance of the VEPP-4M [2] is made by about 50 places of violation of vacuum chamber homogeneity like sharp change of cross section or ceramic insert, and 16 vertical electrostatic separators and 3 radial ones. All of them are mainly placed in the technical and experimental straight sections and in the half-ring inserts, and results in TMC-instability of vertical motion. The radial aperture is more than twice larger than the vertical one, and collective effects are 5 times weaker.

To solve the problem a new method for impedance measurement was developed.

2 BASIS OF THE METHOD

A possibility to measure impedance of an individual section is based on the following assumptions.

By comparing the expression for coherent shift of betatron frequency [2]:

$$\Delta Q = -\frac{1}{8\pi} \cdot \frac{I_a \cdot \langle Z_\perp \beta \rangle}{E/e}$$

with the formula for small detuning of betatron frequency by an additional defocusing force:

$$\Delta Q = -\frac{1}{4\pi} \cdot \frac{\Delta Gl}{H\rho} \cdot \beta$$

one can conclude that the product of an amplitude value of bunch current I_a by the transverse impedance $Z_\perp$ is the defocusing lens strength ΔGl. Current dependence of this strength indicates a possibility of its switching on/off. If at the lens location we induce the local distortion of closed orbit (bump) and then compare two orbits measured with the lens switched on (large current) and switched off (small current), we obtain the orbit deviation in the form of a wave propagating from the lens location.

Amplitude of the wave:

$$\Delta y(s) = \frac{\Delta I_a \cdot Z_\perp}{4 \cdot (E/e) \cdot \sin \pi Q} \cdot \sqrt{\beta \cdot \beta(s)} \cdot y$$

where ΔI_a is the amplitude current difference, β is the beta function at the bump location, gives information about the transverse impedance value $Z_\perp$ of the section where the bump y is located.

Note, that a limitation of the bump length exists. It is desirable that betatron phase advance $\Delta\psi$ for the bump length will not exceed π. Otherwise if there are two sections with equal values of impedance at the bump and phase advance between the sections is $\Delta\psi = \pi$, then the wave amplitude outside the bump will be $\Delta y(s) = 0$, and all the orbit deviation will be at the section of bump. Because of small number of pickups at this section the measurement accuracy will be poor.

Let's estimate a value of the effect. If the whole impedance of a ring would be located in one place, the wave amplitude could easy be found from the expression for coherent tune shift value ($\sin \pi Q \cong 1$):

$$\Delta y_{max} \cong 2\pi \Delta Q \cdot y$$

For the VEPP-4M, if $\Delta Q = 0.03$ and $y = 5$ mm, then $\Delta y = 1$ mm. Thus, the effect is notable enough even considering the fact that the impedance is distributed among the 50 places.

In reality, typical value of coherent tune shift is $\Delta Q \cong 0.8\nu_s$, where $\nu_s \cong 0.02$ is synchrotron frequency of the VEPP-4M. Therefore, to increase the effect, all the measurements have been performed with a feedback [3] switched on, the tune shift was $\Delta Q = 0.035$.

Frequency dependence of the impedance was not measured in these experiments, all the measurements have been done with the bunch length fixed, $\sigma_s \cong 8$ cm.

The question now arises of correct interpretation of the results measured by the method. Some results of theoretical study and numerical simulation can be used here.

For rotationally symmetric structure [4] like RF cavity, electromagnetic field can be expanded in the series of azimuthal harmonics, proportional to $\cos m\varphi$ and $\sin m\varphi$. The transverse impedance is proportional to:

$$Z_\perp \sim r_0^m \cdot r_1^{m-1}$$

The strongest impedance is determined by the dipole field harmonic ($m = 1$), and is proportional to the transverse position r_0 of the leading particle, but independent of the position r_1 of the test one.

For particles near the axis, higher harmonics can usually be neglected.

Thus, for measurement of impedance of axial symmetric structure, if the bump value is specified by 1/3 of the aperture, when the beam current is under threshold ($r_0 = r_1$), the orbit wave amplitude is determined only by dipole component of transverse impedance.

For rotationally non-symmetric structure but symmetric about coordinate plane, such as elliptic or rectangular vacuum chamber, separator plates, etc, the crossing terms in the field expansion arise, and notable part of transverse impedance is determined by quadrupole harmonic [5]. While the dipole harmonic always defocus the beam, the influence of the quadrupole harmonic is defocusing in one direction, but it is focusing in the orthogonal one. By this is meant that conclusion about impedance value can not be reached from single measurement in one direction, there is a need to measure dependence $Z_x = F(x, y)$.

For structure lacking any symmetry like pin SR collector, scraper, etc, conclusion about impedance can be made only if the field topography is measured detailed enough.

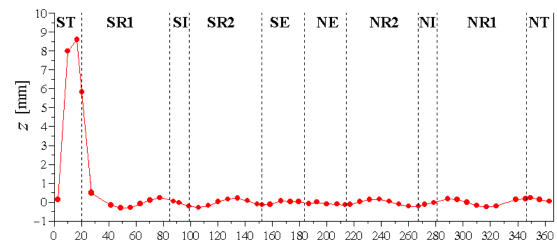

Figure 1: Vertical orbit bump.

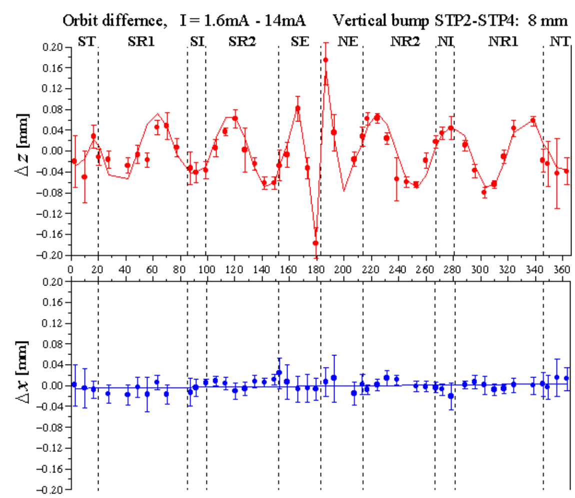

Figure 2: Orbit deviation: measurement and simulation.

3 MEASUREMENT TECHNIQUE

The impedance measurement procedure for some section of a ring consisted in the following. Prior to measurements the vertical and radial orbits were corrected to zero so that r.m.s. deviation would not exceed 0.5 mm. The orbit is measured and memorized at two current values: the maximum (15÷20 mA) and the minimum (of the order 1 mA). Then, the local vertical orbit distortion was produced on the measuring section (Fig.1) and orbit measurement were performed at two different current values close to those given above.

A difference of two vertical orbits measured with and without a bump at the ST section is shown in Fig.1. There are pickup data versus the VEPP-4M azimuth. The VEPP-4M is a mirror-symmetrical racetrack storage ring with the 366 m circumference. The ring consists of: the technical straight section NT-ST; the half-rings SR, NR with the inserts SI, NI; and the experimental straight section SE-NE with mini-beta insert in the centre. The azimuth zero is in the centre of the technical straight section NT-ST.

The bump shown in Fig.1 is in the section included 3 vertical electrostatic separators, 3 of 5 RF cavities, and 5 sections with the vacuum chamber inhomogeneity.

The difference of the four orbits measured as described above enables us to eliminate errors caused by non-linear characteristics of pickups and their current dependencies. This orbit difference is pure effect determined by an integral value of beta-weighted transverse impedance of the section of bump location.

Fig. 2 shows such the differences of vertical and radial orbit measured by pickups when the 8.5 mm vertical bump (Fig.1) was induced. There are error bars in Fig.2, which sizes correspond to measured values of pickup resolution [6]. R.m.s measurement error is about 20 µm. The results of numerical simulation are also shown in Fig.2 (solid line). This provides possibility to determine the beta-weighted impedance value $<Z_{\perp}\beta_z>$ on the bump length. In this case it is $<Z_{\perp}\beta_z>\cong 2.1$ MΩ.

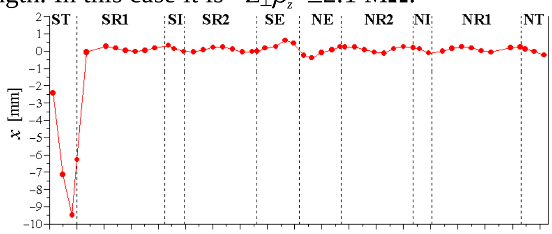

Figure 3: Radial orbit bump.

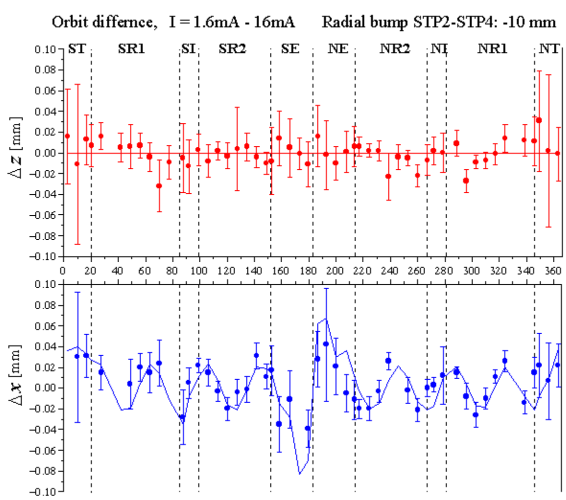

Figure 4: Orbit deviation: measurement and simulation.

To evaluate the contribution of HOM of RF cavities into the impedance value, a radial bump (Fig.3) was induced and the orbit differences were measured (Fig.4).

Unlike Fig.2 the vertical orbit deviation do not give a significant information, but the radial one is a wave, amplitude of which corresponds to the impedance value of HOM of the 3 RF cavities: $<Z_{\perp}\beta_z>\cong 0.7$ MΩ.

If a radial bump was induced in other places of the ring, there was not a considerable effect, unlike a vertical bump.

4 EXPERIMENTAL RESULTS

Since the orbit bump has a finite length, it is convenient to introduce the notion of specific beta-weighted impedance per unit length: $\Delta<Z_{\perp}\beta_z>/\Delta s$. Figure 3 shows the $\Delta<Z_{\perp}\beta_z>/\Delta s$ distribution along the VEPP-4M storage ring measured by the method described above.

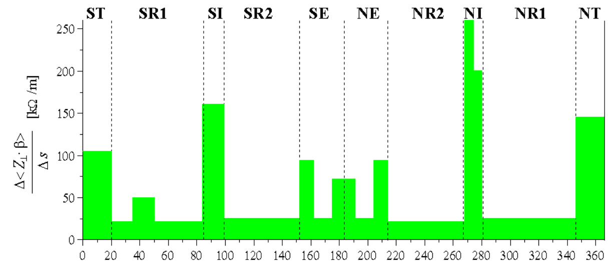

Figure 5: Distribution of the VEPP-4M impedance.

As is expected, the main contribution into the total impedance of the VEPP-4M is made by the vacuum chamber inhomogeneities in inserts (SI, NI) technical section (NT-ST) and experimental section (SE-NE). The half-rings are rather smooth except for the section on azimuth s = 40 m where the local limitation of vertical aperture is observed.

5 CONCLUSION

The method described is rather universal, it provides beam-based measurements of two-dimensional topology of wake field which acts on a bunch at the orbit bump location. The data measured can be used to obtain a harmonic set of local transverse impedance. Frequency dependence of the impedance can also be measured if bunch length is varied.

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