RF Measurements and Control of Higher Order Modes in Accelerating Cavities

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Abstract

In RF cavities, built at BINP for electron–positron storage rings, special tuners are provided for higher order modes (HOMs). The HOM tuners effect on different modes in different ways. Electrical characteristics and tuning curves of cavity modes are measured. Using these experimental data, the beam–cavity interaction at higher order modes is analyzed for different HOM tuner positions. There are combinations of HOM tuner positions, at which the cavity caused beam instabilities may occur, and there are combinations, at which they may not. The last ones are recommended for routine cavity operation.

INTRODUCTION

Beam–cavity interaction on higher order modes may cause beam instabilities, coherent energy losses and other phenomena. Different ways are possible for minimizing negative effects of that interaction for the beam.

In one way the cavity geometry may be chosen so that the frequencies of higher order modes are far from harmonics of beam revolution frequency and beam–cavity interaction is rather weak. This way is especially good when the accelerator or the storage ring is small and therefore, the beam revolution frequency is high, i. e. the distance between harmonics is large.

The other approach is the damping of the *Q* of higher order modes. If the HOM bandwidths become greater than the repetition rate of the particle bunches, coherent beam instabilities cannot be excited by cavity HOMs. This approach is good for large machines for the necessary *Q* damping is not strong in that case.

The third way is the evolution of the first one. It is the correction of HOM frequencies of the cavity by special tuners in order to avoid beam instabilities. The smaller the machine is, the easier it is to solve the problem.

At Novosibirsk we have used the last approach to different RF cavities for years [1]. We can do that because our machines are not very large. The largest machine is VEPP–4 electron-positron collider with its revolution frequency of 0.82 MHz. An accelerator of that size is probably the largest machine for which the HOM frequency correction approach can be applied.

HOM TUNERS

We use HOM tuners of different types. In one case it is a barrel that can be plunged into the cavity. In other case it is a plate of an ∞-like shape the bigger axis of which is parallel to the beam axis. It may also have a shape of a fork or a rod. If the beam revolution frequency is high, only one HOM tuner can be used. Its position is chosen so that it affects the most dangerous higher order mode. So, the RF cavity of VEPP–3 storage ring (beam revolution frequency is 4 MHz, RF frequency is 72 MHz) has one HOM tuner.

If the beam revolution frequency is low or the bunch size is very small, several HOM tuners are needed for proper correction of the HOM frequencies. Each tuner acts on different modes in different ways. E. g., there are three HOM tuners in each of six cavities of VEPP–4 collider (revolution frequency 0.82 MHz, RF frequency 181 MHz) [2]. Two of them are shown in Figure 1.

Figure 1: *HOM tuners of VEPP-4 cavities.*

RF MEASUREMENTS OF HIGHER ORDER MODES IN RF CAVITIES

We have built a specialised automated setup for study of the higher order modes in RF cavities. At the setup characteristics of the fundamental and higher order modes can be measured including *Q* and *R/Q* values, shunt impedances, resonance frequencies of the modes, and the effects of tuners on them.

Figure 2 presents experimental frequencies and impedances of the fundamental mode and the higher order

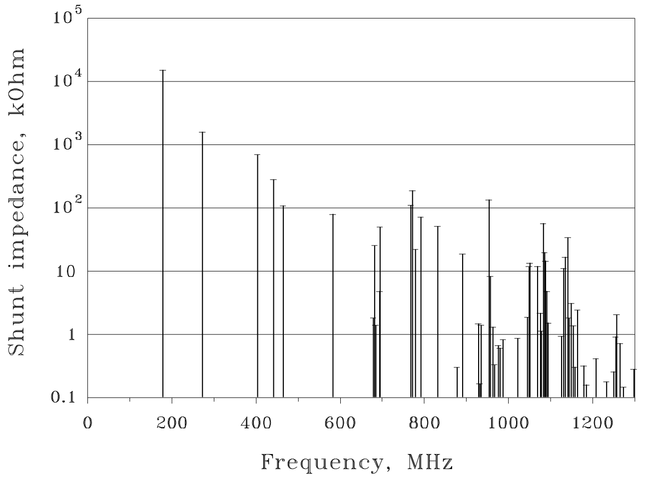

Figure 2: *Modes of a VEPP-4 cavity.*

modes of a VEPP–4 cavity that have longitudinal electrical field on the beam axis.

The dependence of the frequencies of some higher order modes on HOM tuner positions is shown in Figure 3. The numbers of curves correspond to the numbers of HOM tuners. Thin solid horizontal lines at the plots correspond to harmonics of the beam revolution frequency of the VEPP–4.

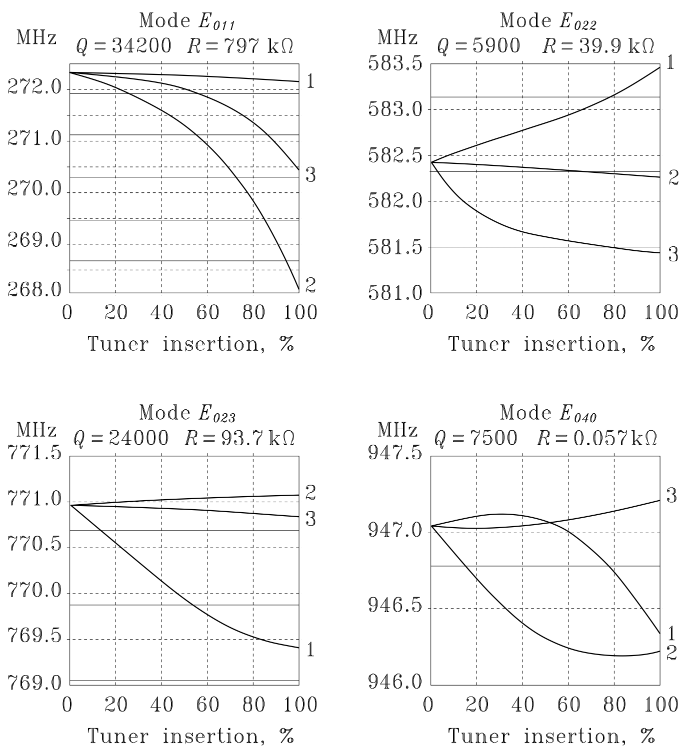

Figure 3: *Tuning curves of some higher order modes.*

APPLICATION TO BEAM DYNAMICS

Experimental data allow to compute the integral influence of the higher order modes of the cavity on longitudinal beam dynamics. The results of the analysis for the single bunch mode of operation of the VEPP–4 are presented in Figure 4. 25 higher order modes of one cavity with greater impedances in the frequency range up to 1200 MHz were taken into account. The coordinates X_n at the diagrams are the positions of the cavity tuners of number n.

For each point of the diagram, the value of

$$S = \sum_{n=1}^{N} \sum_{k=M_n-2}^{M_n+2} R_n(kf_o + f_s) - R_n(kf_o - f_s)$$

is computed. Here $R_n(f)$ is the value of the real part of the impedance of the n-th higher order mode at the frequency f, f_o is the revolution frequency of the beam in the storage ring, $M_n f_o$ (M_n is an integer) is the harmonic of the revolution frequency which is the nearest to the n-th mode, f_s is the frequency of synchrotron oscillations. N is the number of the higher order modes taken into account.

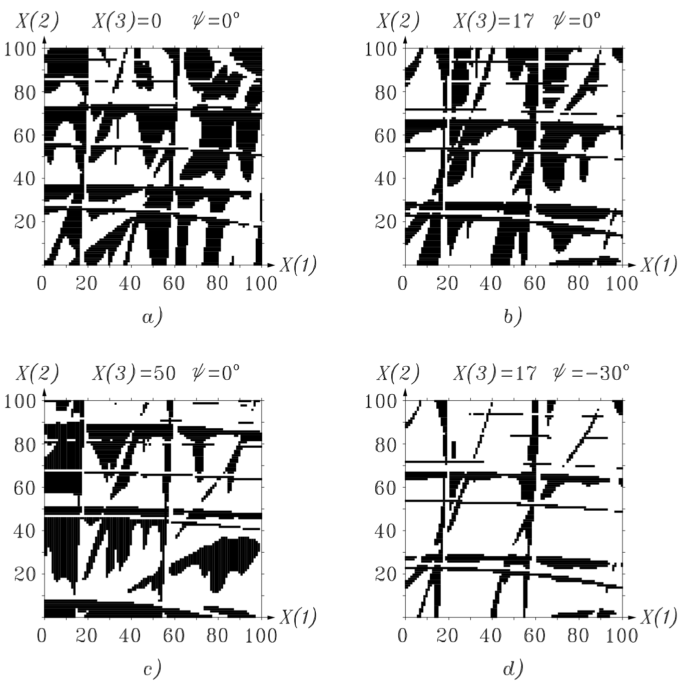

Figure 4: *Areas of longitudinal instability as functions of HOM tuner positions and tune ψ of the fundamental mode.*

As it is known [3], if the sum $S > 0$ then beam–cavity interaction at the higher order modes may produce a positive increment of the phase oscillations of the bunch that will cause longitudinal beam instability. If $S < 0$, then beam–cavity interaction at the higher order modes produces a negative increment (i. e. a positive decrement) of the phase oscillations of the bunch and the longitudinal bunch motion would be stable. The black areas at the diagrams correspond to conditions when the increment of the phase oscillations of the bunch due to beam–cavity interaction may be positive. Therefore, one should set tuners at positions corresponding to white areas.

For three HOM tuners the whole diagram is three-dimensional. The diagrams in the Fig. 4 are two-dimensional sections of this three-dimensional picture. They are plotted in coordinates of HOM tuners #1 and #2, for fixed positions of the tuner #3.

The fundamental mode of the cavity plays an important role in the longitudinal beam dynamics due to its great impedance. The effect depends on the tune of the fundamental mode. Figure 4 illustrates it. The first three diagrams are plotted for zero tune of the fundamental mode (i. e. it is tuned exactly to the resonance). The fourth diagram is plotted for the fundamental mode tuned 30^{o} off the resonance to the lower frequency. The positions of the tuner #3 are equal for plots *b)* and *d)*. One can see that the forbidden areas become much more narrow with the fundamental mode detuned.

The recommendations obtained in this analysis are to be considered as preliminary ones. During operation of the cavity in the machine the actual frequencies of the higher order modes differ from the values measured at low level. A reason is the deformation of the cavity due to RF heating. This deformation is complex and differs from an ideal model taken into account in our analysis. Another source of error is the impedance of the RF power amplifier connected to the main cavity coupler through the transmission line. Both of these factors cause perturbations of frequencies of the higher order modes. Therefore, the right positions of the HOM tuners are elucidated by beam tests in the machine.

For the multibunch mode of operation of the storage ring a new analysis [4] of HOM tuner positions is required. This analysis should take into account the number of bunches, the distance between them, the numbers of particles in each bunch, and the positions of RF cavities in the storage ring.

A single bunch approach to the beam–cavity interaction can be applied to the multy-bunch mode of operation, if the frequencies of synchrotron oscillations of the bunches are different enough and they may be considered independent from each other.

CONCLUSION

Right tuning of high order modes of RF cavities is an effective way to avoid beam phase instability for small and medium electron-positron storage rings operating in a single bunch mode. This way is applied to RF cavities of different storage rings built at Novosibirsk. This technique can be applied to the multibunch mode of operation as well. To this end splitting of synchrotron frequencies of bunches is to be done. It can be achieved by an additional RF system which frequency is not multiple of the main RF.

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