OBSERVATION OF COHERENT SYNCHRO-BETATRON BEAM-BEAM MODES AT VEPP-2M

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Abstract

An experimental evidence is presented of the coherent synchro-betatron beam-beam modes in the spectrum of coherent dipole oscillations observed at the VEPP-2M collider. The measured current-dependent behavior of the mode spectrum is in good agreement with predictions of our theoretical models, taking full account of the finite length of colliding bunches. Potential effect of the synchro-betatron modes on the beam-beam blowup is discussed.

1 INTRODUCTION

Among the beam-beam phenomena there is a large group of effects concerning the coherent motion of colliding bunches [1]-[4]. It has been recently proposed that a finite length of colliding bunches can lead to the coupling of synchro-betatron modes in the beam-beam system (Fig. 1) and affect the beam stability [5]. However, there was no experimental evidence of existence of such modes at the present colliders. This paper gives an outline of the theory and presents the experimental investigation of the synchro-betatron beam-beam modes at the VEPP-2M collider, comparing the measured data with theoretical predictions.

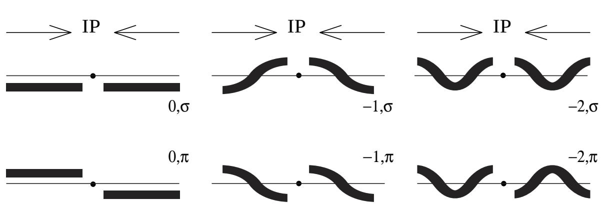

Figure 1: Naming convention for the synchro-betatron beam-beam modes.

2 THEORY: MODE SPECTRUM

The dipole motion of bunches, coupled via the beam-beam force can be expressed in terms of coherent synchro-betatron modes. Usually the betatron coupling between the transverse degrees of freedom is small, and therefore a separate treatment of horizontal and vertical synchro-betatron oscillations is a good approximation. Since the rise time of the head-tail instability is much shorter than the radiation damping time in e^+e^- machines, we can drop the radiative effects in what follows.

For the case of small betatron oscillation amplitudes it is often allowable to linearize the transverse force exerted by the beams on each other. This linearized beam-beam interaction is considered here.

We study the dipole moments as functions of the longitudinal position in the bunch. Discrete approximation of the appropriate eigen-functions allows to reduce the task to linear algebra.

We use the so-called “hollow beam” model. It assumes that all particles of the bunch have equal synchrotron amplitudes and are evenly spread over the synchrotron phase, forming a circle in the synchrotron phase space. This circle is divided into N mesh elements, each characterized by its transverse dipole moment (2 variables) and its number corresponding to its synchrotron phase. In the arcs synchro-betatron oscillations of the elements forming a bunch are represented by the $2N \times 2N$ matrix $M = C \otimes B$, where $\otimes$ denotes the outer product, B is the betatron oscillation matrix of dimension 2×2, C is the $N \times N$ circulant matrix [6], which transports the dipole moment around the circle formed by the mesh elements with fixed synchrotron phases and thus performs a synchro-betatron mapping of $2N$ variables for each of the colliding bunches.

The linearized beam-beam interaction is described by a $4N \times 4N$ matrix M_{bb} consisting of consecutive short kicks and drifts between interactions of macroparticles sitting in each mesh, and assumed to be transversely-rigid Gaussian disks [2].

The complete one-turn matrix is the product of the arc matrix M and the beam-beam matrix M_{bb}. Its ξ-dependent eigenvalues and eigenvectors completely characterize the synchro-betatron modes of the beam-beam system and can be obtained numerically using a computer algebra system [7], see an example in Fig. 2.

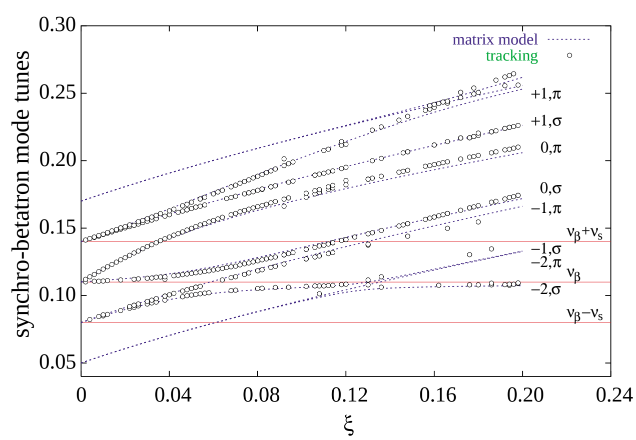

Figure 2: Synchro-betatron mode tunes vs. the beam-beam parameter ξ. Comparison of the circulant matrix model and tracking. Equal bunch intensities, $\nu_\beta = 0.11$, $\nu_s = 0.03$, and the bunch length is $0.7\beta^*$.

3 OBSERVATION TECHNIQUES

Vertical coherent oscillations of the bunches were observed using the beam synchrotron radiation from the dipoles. The optical image of the beam was focused into the movable screen plane (Fig. 3). The screen was cutting off a portion of the light in the beam image plane. For a fixed edge position, a displacement of the beam centroid resulted in modulation of the light flux.

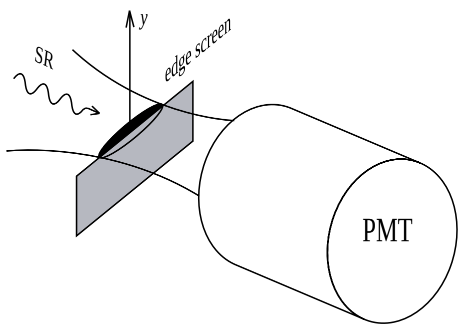

Figure 3: Edge detector scheme.

The light which passed through the optical system then fell on the PMT (Fig. 4). The PMT signal, with modulation proportional to the beam displacement, was fed to the fast ADC input. In our system we used the CAMAC-standard 8-bit ADC with the 8k read buffer and minimum transform time of 10 ns. The PMT bandwidth was adjusted to observe separate turns of the bunch in the storage ring. The ADC clock rate was exactly equal to the beam revolution frequency and the phase was locked to the RF phase of the bunch. Timing of the ADC start with the high voltage beam excitation pulse was performed using the multichannel time interval generator (TIG in Fig. 4): the TIG trigger signals were passed to both the ADC and the HV generator.

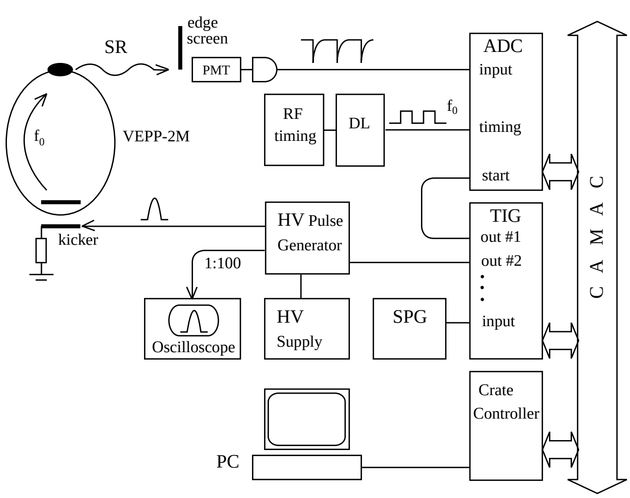

Figure 4: Block diagram of the experimental setup.

The similar observation channel was implemented for the positron beam. For synchronization of the electron and positron channels the clock pulse splitter was used with the delay correction tuned by means of the additional cable in the positron channel.

The HV pulse generator gave a one-turn kick to the bunch, with an adjustable amplitude of the excited oscillations. A minimum amplitude was equal to 0.2σ, σ being the Gaussian vertical beam size. The kicker plate terminated in a matched load, to kick only the electron bunch.

4 EXPERIMENTAL RESULTS

The center of mass positions of the colliding bunches were sampled turn-by-turn. The Fourier transform of the collected data gave the coherent mode spectrum, where the proposed synchro-betatron modes of the beam-beam system were experimentally detected, and their spectrum was measured as a function of the beam-beam parameter at different synchrotron tunes.

The complete results of the coherent beam-beam mode spectra calculation with the account of the finite bunch length are presented in [5, 7]. Since VEPP-2M had a negligible transverse impedance, we compare these experimental data with the simulation results for the case where the collective interaction is completely due to beam-beam. Fig. 5 shows the dependence of the measured and calculated synchro-betatron mode tunes on the beam current for equal electron and positron bunch intensities.

In perfect agreement with the theoretical model, the measurement has shown that besides the leading σ and π modes a number of synchro-betatron modes coupled via the beam-beam force exist in the dipole mode spectrum. These modes show up and disappear with the beam current change due to ξ-dependence of the beam-beam mode eigen-states. For the ξ value less than the synchrotron tune ν_s, the state excited with the kick consists of only two beam-beam modes, σ and π, with the synchrotron wavenumber $m = 0$. In the range $\nu_s < \xi < 2\nu_s$ the initial condition is the combination of four eigenmodes: -1σ, 0σ, 0π, $+1\pi$. Here the first index labels the synchrotron wavenumber, the second labels the coherent beam-beam eigenmodes with even and odd symmetry between the two colliding bunches, respectively. With larger ξ the dipole moment passes on to -2σ, $+2\pi$ and later to -3σ, $+3\pi$ σ modes. Because of small coupling of modes with large synchrotron wavenumber these transitions do not show an apparent tune split.

An important parameter in the coherent beam-beam effect is the ratio Y between the coherent beam-beam σ and π modes tune split $\Delta\nu$ and ξ. The rigid Gaussian beam model [2] predicts the ratio $\Delta\nu/\xi = 1.0$. With non-rigid beams, solution of the Vlasov equation [4] gives for our case of flat beam and vertical oscillations $\Delta\nu/\xi = 1.21$.

In our experiment $\Delta\nu(I)$ was evaluated by fitting the theoretical mode spectrum to the whole dataset of the measured spectrum, using a *single fitting parameter*, $Y\xi$. Then

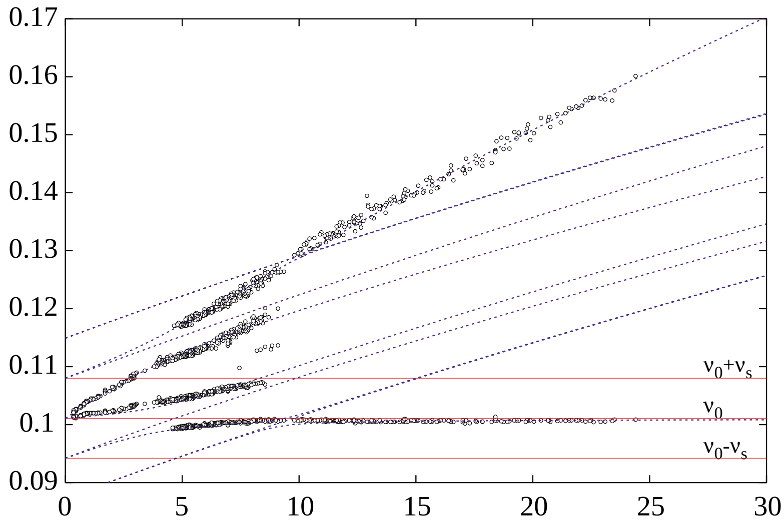

Figure 5: Measured (circles) and calculated (lines) synchro-betatron mode tunes vs beam current I (mA). VEPP-2M was operated with one e$^+$ and one e$^-$ bunches colliding at two IPs, $\nu_\beta = 0.101$, $\nu_s = 0.0069$, $\beta^* = 6$ cm, and the bunch length was 3.5 cm.

$\xi(I)$ was evaluated from the luminosity measurement:

$$\xi_y = \frac{2er_e\beta_y}{\gamma I}L\ .$$

The main inaccuracy in ξ thus evaluated is due to statistical straggling of on-line L data and equals to $\sim 10\%$. A good linearity of L vs $\sqrt{I}$ evidenced for current-independent beam sizes at the IP, i.e. we had $\xi \propto I$ without saturation, in the whole range of currents used. From our experiment we have found $Y = \Delta\nu/\xi = 1.05$.

This result can be related to our experimental procedure. Indeed, after the kick the transverse beam density distribution does not change during the measurement period of 8192 turns (or effectively less, limited by decoherence). This is much less than the radiation damping time. For this reason the situation appears to be equivalent to interaction of two transversely-rigid Gaussian bunches.

5 CONCLUSION

The observation system allowed to discover the synchro-betatron modes in the spectrum of coherent oscillations of colliding bunches at the VEPP-2M collider. The measured spectra dependence on the beam current is in excellent agreement with analytical and numerical models [5, 7]. The measured coherent beam-beam mode tune split is 1.05ξ. This is close to the value expected from the rigid Gaussian model which seems to be adequate to the used experimental technique.

The above presented experimental evidence of the synchro-betatron beam-beam modes adds confidence to the conclusions of their theory. One of them is that for the negligible transverse impedance the mode system remains stable unless some of the mode tunes reach a half-integer resonance.

On the other hand, calculations involving the machine impedance predict a coherent beam-beam *instability* without a threshold. Some, though not all, of the synchro-betatron modes can be damped by optimizing the betatron tune chromaticity. Since the theoretical models [5, 7] used the linearized beam-beam interaction, their prediction of instability is not as conclusive as the above prediction of stability. In a realistic nonlinear beam-beam system one can expect saturation of such an instability at amplitudes of the order of the vertical beam size. However, this mechanism can cause a vertical emittance blowup detrimental to the high performance of the flat-beam colliders.

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