SLIDE 1

Coherent beam-beam effects study.

Experimental investigation of the coherent motion of colliding beams at VEPP-2M was initiated by theoretical works by Perevedentsev. He has shown that a finite length (in other words equal to β^*) of colliding bunches can lead to the coupling of synchro-betatron modes in the beam-beam system, and thus a head-tail type instability of colliding bunches may arise.

The rigid beam model for two beams of equal intensities predicts the existence of two coherent beam-beam modes: the σ mode with the tune equal to the betatron tune ν_β, and the π mode with the tune shifted by $Y\xi$, where ξ is the beam-beam parameter and Y is a factor approximately equal to 1. These modes have been observed in different machines.

Our work was devoted to detection of the synchro-betatron beam-beam modes, arising from the fact that the beams are not rigid in longitudinal direction.

I shall say a few words about calculation of the mode parameters, describe the experimental technique and show the experimental results in comparison with simulations.

SLIDE 2

This slide presents the schematic view and notation of the coherent synchro-betatron beam-beam modes. The first index in the notation labels the synchrotron wavenumber that is the number of dipole moment variations over the synchrotron phase. The second index, σ or π, is borrowed from the rigid beam model and labels the coherent beam-beam eigenmodes with even and odd symmetry between the two colliding bunches, respectively.

The mode spectrum has been calculated using two methods: direct tracking of particles with consideration of their longitudinal position and of the interaction order; and with matrix method which is based on a circulant matrix approach which performs synchro-betatron transformation of the mesh elements dipole moments conserving their longitudinal position. This considerably simplifies coding of the interaction process.

The second diagram on the slide shows the first stage of collision of two beams, each consisting of three macroparticles. First, particles 1,3,4 and 6 interaction is represented with a short kick, then follows a free drift and collision of particles number 2,4,6 and 1,3,5 and so on. The turn is closed with the synchro-betatron transformation.

SLIDE 3

The beams are considered rigid in transverse direction and the oscillation amplitudes are small. This allows to linearize the interaction. Usually the betatron coupling between two transverse degrees of freedom is small, and therefore a separate treatment of horizontal and vertical synchro-betatron oscillations is a good approximation. Thus we address only vertical oscillations.

Number of particles in tracking was limited only by computing power and in this picture was equal to 1000. Distribution of particles in the synchrotron phase space was Gaussian. The matrix model here used only 5 mesh elements per beam, and the distribution was hollow - the particles had equal synchrotron amplitudes and were evenly spread over the synchrotron phase.

We see that instead of the two σ and π modes the spectrum contains a number of synchro-betatron modes which couple via the beam-beam interaction. The measure of their coupling is the interaction region length. There is no coherent instability in the whole range of ξ when the tune of neither mode reaches 0 or 0.5. Interaction in this system is symmetrical, and the system is closed. Oscillations in such systems are stable.

In this calculation we did not take into consideration the machine impedance. The VEPP-2M collider also had a negligible transverse impedance, we had an opportunity to compare these simulation results with experimental data.

SLIDE 4

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. 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.

The light which passed through the optical system then fell on the PMT. 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: the TIG trigger signals were passed to both the ADC and the HV generator.

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.

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.

SLIDE 5

Figure 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.

COLCLUSION

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.