THE LONGITUDINAL DISTRIBUTION AND BUNCH LENGTH MEASUREMENTS AT VEPP-2000 COLLIDER*

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Abstract

The paper describes the bunch length measurement system for VEPP-2000 collider, equipped with optical analysers based on LI-602 dissector, which provides permanent measurements of the longitudinal beam profile. Potential well distortion lengthening was measured at different bunch currents for the energies below 500 MeV. First measurements reveals the presence of microwave instability with turbulent emittance growth. The thresholds of these processes was used to estimate the values of reactive part of the longitudinal impedance. Measured energy loss factors was compared with computer simulations for the RF cavity. All results will be discussed and further estimations will be given.

VEPP-2000 OVERVIEW

The VEPP-2000 collider [1] exploits the round beam concept (RBC) [2]. This approach, in addition to the geometrical factor gain, should yield the significant beam–beam limit enhancement.

Collider itself hosts two particle detectors [3], Spherical Neutral Detector (SND) and Cryogenic Magnetic Detector (CMD-3), placed into dispersion-free low-beta straights. The density of magnet system and detectors components is so high that it is impossible to arrange a beam separation in the arcs. As a result, only a one-by-one bunch collision mode is allowed at VEPP-2000.

Table 1: VEPP-2000 Main Parameters @ E = 1 GeV

Parameter	Value
Circumference (C)	24.3883 m
Energy range (E)	150÷1000 MeV
Number of bunches	1 × 1
Number of particles per bunch (N)	1×10^{11}
Betatron functions at IP ($\beta^*_{x,y}$)	8.5 cm
Betatron tunes ($\nu_{x,y}$)	4.1, 2.1
Beam emittance ($\varepsilon_{x,y}$)	1.36×10^{-7} m rad
Beam–beam parameters ($\xi_{x,y}$)	0.1
Luminosity (L)	1×10^{32} cm^{-2} s^{-1}

The layout of the VEPP-2000 collider as it worked until 2013 is presented in Figure 1. The main design collider parameters are listed in Table 1.

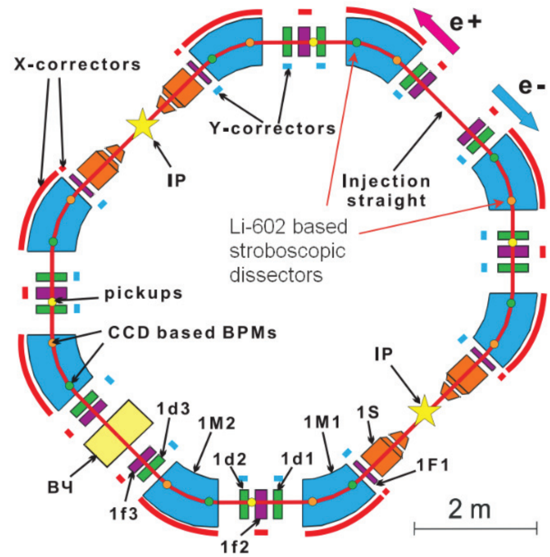

Figure 1: VEPP-2000 collider layout.

BEAM DIAGNOSTICS

Diagnostics is based on 16 optical CCD cameras that register the visible part of synchrotron light from either end of the bending magnets and give full information about beam positions, intensities and profiles. In addition to optical beam position monitors (BPM) there are also four electrostatic pickups installed in the technical straight sections, two photomultipliers for beam current measurements via the synchrotron light intensity, and one beam current transformer as an absolute current monitor.

In 2013 VEPP-2000 was equipped with two phi-dissectors [4] – stroboscopic image dissector with electrostatic focusing and deflection, that gives information about e+/e− longitudinal distribution of particles and bunch length.

In general, the instrumental temporal resolution of the dissector is determined by a set of different factors. The most important ones: energy and angular distribution of the photoelectrons emitted by a photocathode; quality of the electron image in the plane of the slit aperture; light image size at the photocathode; amplitude and frequency of sinusoidal sweep voltage; slit aperture size.

The contribution to the instrumental temporal resolution of the first factor is estimated as equal (or less) to 1.0 ps. value and contribution of other factors can be measured. For this purpose a point-like image of the continuous light source is projected onto photocathode and the signal

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duration with the switched on and off RF sweeping voltage is determined [4].

The width of the technical instrumental function for first prototype of the dissector is close to 30-40 ps. FWHM. The typical longitudinal bunch distribution measured during routine operations with a single beam at VEPP-2000 collider is shown on Figure 2, where dashed blue curve is a Gaussian fit of the raw data.

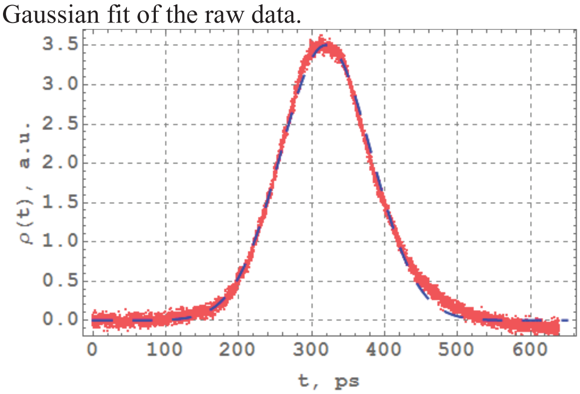

Figure 2: The longitudinal bunch distribution at low bunch intensity (~1 mA).

The control system of the VEPP-2000 collider allow us to measure and even store (for offline analysis) almost all parameters of magnetic system, RF system, timings and measured beam parameters. The most of these parameters can be measured with frequency 1-5 Hz. The resolution of beam current measurement is equal to 0.1 mA and of the RF cavity voltage – 0.2 kV.

BUNCH LENGTHENING

The length of an electron bunch in a storage ring depends on the peak current of the bunch. The two effects that alter the length are potential well distortion and microwave instability. For potential well distortion bunch length varies due to the electro-magnetic fields induced by the electrons, that modify the RF voltage seen by the bunch. This effect is present even at very low currents. The second effect, microwave instability, is only observed after a certain threshold current has been reached. Above this threshold energy spread of the beam increases until the peak current of the bunch reduces to equal the threshold current again.

Direct observation of the onset of microwave instability in the VEPP-2000 was possible at an intermediate energy. Measurements have been carried out for electrons, with intensities up to 50 mA at energy equal to 478 MeV with different values of RF voltages, in presence of positrons with infinitesimal intensity. In these experiments all beam dimensions were recorded as a function of bunch current. A subsequent experiment for positrons shows the same dependencies of lengthening behaviour and threshold values as for electrons.

Throughout the experiment σ_x remained constant below certain threshold (see Figure 3, where blue dots show bunch size below threshold, red ones – above), confirming that the beam was indeed below the threshold of microwave instability. The variation of the bunch length with the beam current is given in Figure 4. One can clearly see that the microwave instability threshold appears at around 24.5 mA and 32 mA for RF voltages equal 9.2 kV and 18.5 kV respectively.

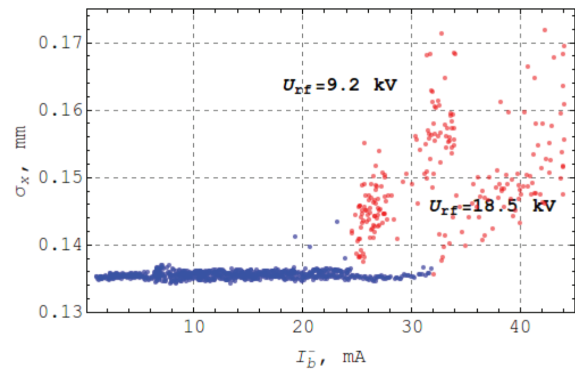

Figure 3: Horizontal beam size on 4M1L CCD (in place with non-zero dispersion) as a function of beam current at energy E=480 MeV.

The bunch length data below threshold has been fitted to the model [5] described by equation:

$$\sigma_z^3 - \sigma_{z0}^2 \sigma_z = \frac{\alpha_p \left| Z/n \right|_{eff} R^3}{\sqrt{2\pi}(E/e)\nu_s^2} I_b,$$

where I_b is the average beam current, e is the electron's charge, R is the ring average radius, E is the beam energy and ν_s is the synchrotron tune. The magnitude of the effect depends on the reactive part of the effective longitudinal coupling impedance |Z/n|. The dashed lines on the figure is a curve derived using equation above for |Z/n| = 2.32 Ohm.

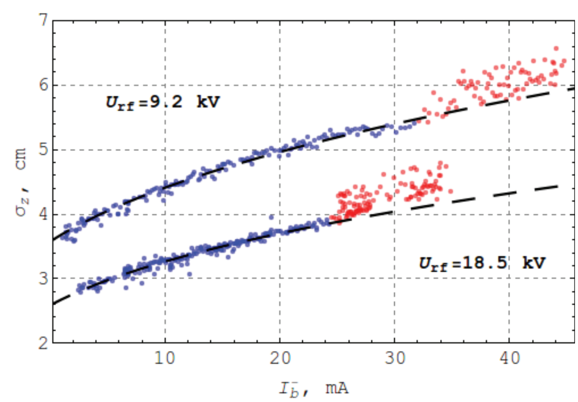

Figure 4: Bunch length as a function of beam current at energy E=480 MeV.

Our capabilities do not allow to measure the energy spread directly, but estimation can be done by methods developed [6] during VEPP-2000 operations. These methods based on measurements of beam transverse sizes along the ring with further fitting the emittances end effective beta functions to known optical model of the ring assuming that there is no focusing perturbations other than those caused by collisions. In Figure 5, one can find beam energy spread is estimated in such a way.

Longitudinal Loss Factor

The energy loss in accelerator rings due to impedance is proportional to the longitudinal loss factor as an integral over the real (or resistive) part of longitudinal impedance

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times the bunch spectrum. Vacuum chamber itself and RF cavity [7], were considered as the major contributors to the impedance in VEPP-2000.

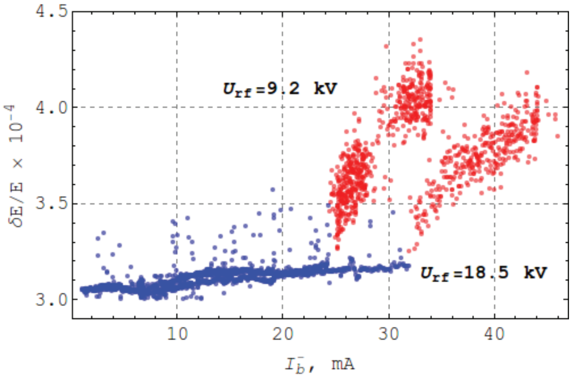

Figure 5: Beam energy spread as a function of beam current at energy E=480 MeV.

The synchronous phase shift is being determined as a difference between phase of beam longitudinal distribution centre of mass and phase of RF system reference signal. Dependence of synchronous phase on beam current allow to determinate a value of a bunch coherent energy loss.

$$k_l = f_0 \cdot U_{rf} \cdot Cos(\varphi_s) \cdot {}^{d\varphi_s}/_{dI_b} \text{ and } \Delta E = -k_l \cdot q^2,$$

where f_0 – revolution frequency, φ_s – synchrotron phase, U_{rf} – RF voltage and I_b – beam current.

The coherent energy losses of the beam is caused by the interaction with the RF cavity – the beam itself excite the electromagnetic field on frequencies proportional f_0 – was calculated (SLANS и CLANS2 code at BINP) [8].

Results are shown in Figure 6, where dashed line corresponds to coherent energy loss caused only by RF cavity HOM frequencies. As one can see from the pictures the contribution of the RF cavity is comparable (or slightly less) with the contribution of the net vacuum chamber in the ring (k_l = 0.15÷0.7 V/pC for U_{rf} = 10÷30 kV, while σ_z = 2.5÷6 cm, what corresponds to I_b = 0÷50 mA).

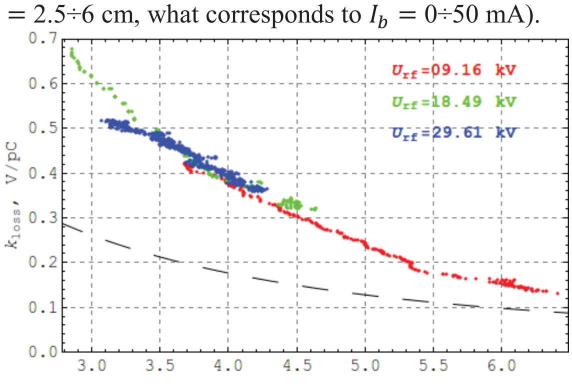

Figure 6: Longitudinal loss factor at energy E=480 MeV.

FUTHER ESTIMATIONS

If the values of effective longitudinal impedance obtained, then one can estimate the behaviour of the bunch length with beam current variance, for the case |Z/n| has no frequency dependence (pure inductance). The results of such naïve estimation is shown on Figure 7. Different lines corresponds to energies: 480 MeV – black, 500 MeV – red, 700 MeV – brown, 990 MeV – blue.

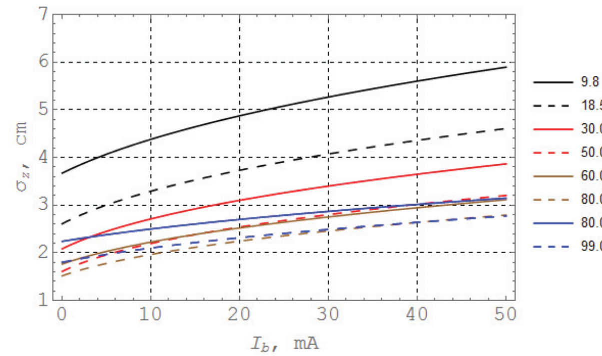

Figure 7: Bunch length as a function of beam current at different energies and RF voltages.

CONCLUSION

The current dependence of bunch length was measured at beam energy level E = 400-500 MeV. This dependence is in a good agreement with that obtained from the solution of balance equation. Estimated longitudinal impedance is |Z/n| = 2.32 Ohm and |Z/n| = 5.2 Ohm below and above the threshold accordingly. Measured dependence of the bunch length on bunch current on the threshold of microwave instability is linear.

The longitudinal loss factor integrated over the ring is a twice bigger than value predicted by the interaction with single mode RF cavity only. We strongly believe that this difference partially caused by interaction of the beam with dipole HOM in RF (1 mm transverse beam shift in RF cavity gives 20% gain in energy losses). Moreover, the net vacuum system also gives its influence on the common longitudinal impedance at the same level as RF cavity.

At high bunch current the longitudinal shape changes from Gaussian to parabolic profile. Besides an asymmetry of bunch shape takes place. It is believed this asymmetry provided by the contribution of real part of impedance.

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