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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference ($C$)</td>
<td>24.3883 m</td>
</tr>
<tr>
<td>Energy range ($E$)</td>
<td>150±1000 MeV</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>$1 \times 1$</td>
</tr>
<tr>
<td>Number of particles per bunch ($N$)</td>
<td>$1 \times 10^{11}$</td>
</tr>
<tr>
<td>Betatron functions at IP ($\beta'_{x,y}$)</td>
<td>8.5 cm</td>
</tr>
<tr>
<td>Betatron tunes ($\nu_{x,y}$)</td>
<td>4.1, 2.1</td>
</tr>
<tr>
<td>Beam emittance ($\epsilon_{x,y}$)</td>
<td>$1.36 \times 10^{-7}$ m rad</td>
</tr>
<tr>
<td>Beam–beam parameters ($\xi_{x,y}$)</td>
<td>0.1</td>
</tr>
<tr>
<td>Luminosity ($L$)</td>
<td>$1 \times 10^{32}$ cm$^{-2}$ s$^{-1}$</td>
</tr>
</tbody>
</table>

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.

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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...
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).](image)

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 $\sigma_z$ 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.](image)

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

$$\sigma_z^3 - \sigma_0^3 - \sigma_z^2 = \frac{\alpha_p |Z/n|_{\text{eff}} R^3}{2\pi (E/e) \nu_s^2} I_b,$$

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 $\nu_s$ 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.](image)

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

**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.

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

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**Control and diagnostic systems**

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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.

\begin{equation}
\Delta E = -k_t \cdot q^2,
\end{equation}

where \( f_0 \) – revolution frequency, \( \varphi_s \) – 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 to the revolution frequency. It was calculated (SLANS and 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 (\( k_t = 0.15\pm0.7\) V/pC for \( U_{rf} = 10\pm30\) kV, while \( \sigma_z = 2.5\pm6\) cm, what corresponds to \( I_b = 0\pm50\) mA).

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

**FURTHER 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 correspond 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.

**REFERENCES**