THE LONGITUDINAL BROADBAND IMPEDANCE AND ENERGY SPREAD MEASUREMENTS AT THE VEPP-4M ELECTRON-POSITRON COLLIDER

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Abstract

The paper presents measurements of the longitudinal broadband impedance and beam energy spread of the beam at the VEPP-4M electron-positron collider in an energy range of 1.0 – 3.5 GeV. In order to measure the longitudinal bunch size at various beam currents we used “PS-1/S1” streak camera with picosecond temporal resolution. The dependence of bunch length from the bunch current at different energies demonstrates a microwave instability threshold. The bunch lengthening was caused by potential well distortion as well. Potential well distortion lengthening was used to estimate a value of the reactive part of the longitudinal impedance of the vacuum chamber of the collider. Observed microwave instability thresholds was used to measure the value of the broadband impedance. The impact of the Touschek effect in the beam energy spread is discussed.

ELECTRON BUNCH LENGTH

Natural Length

A length of an electron bunch is determined by the synchrotron oscillations and has no current dependence if collective effects are negligible [1]. In this case the energy spread (natural energy spread) is determined by the balance between quantum excitation and synchrotron damping. Natural energy spread is determined only by the accelerators lattice. The relation between the energy spread and the bunch is described by a well-known formula:

$$\sigma_S = \frac{\sigma_E}{E}\frac{\alpha c}{\omega_S}, \qquad (1)$$

where α is the momentum compaction factor, c is the speed of light, ω_s is the synchrotron oscillation frequency, σ_S is the bunch length, σ_E is the energy spread, E is the bunch energy.

Intrabeam Scattering

When the density of electrons in the bunch increases the influence of the intrabeam scattering (IBS or multiple Touscheck effect) becomes significant. The effect is based on transferring of momentum from transverse plane of motion to the longitudinal boosted by Lorentz factor. It leads to growth of bunch energy spread and its lengthening [2,3]. The lengthening is proportional to energy spread growth and determined by Eq. (1) where the overall relative energy spread is replaced by IBS induced energy spread.

Equation (2) simply describes dependence of IBS energy spread from accelerator parameters [2].

$$\left(\frac{\sigma_{ET}}{E}\right)^6 = \frac{N r_0^2 \beta_x \tau_E \omega_S f(x_m)}{2^5 \pi \gamma^3 \left(\beta_x U_x + \eta^2\right)\sqrt{k\beta_z U_x}\,\alpha}. \qquad (2)$$

Where N is a number of particles in the bunch, βx, βz are a horizontal and vertical beta functions, τE is a synchrotron damping time, γ is the Lorentz factor, η is a dispersion function, k is a betatron coupling, r0 is the classical electron radius, σET is the energy spread induced by intrabeam scattering, Ux is determined by (3).

$$U_x = \frac{\tau_x}{\tau_E} < \frac{1}{\beta_x}\left[\eta^2 + \left(\beta_x\eta' - \frac{1}{2}\beta_x'\eta\right)^2\right] > \qquad (3)$$

Where τ_x is horizontal betatron damping time and the averaging is made in bending magnets only.

The energy spread growth is not correlated with the quantum excitation. Thus the total bunch length is determined by the quadratic sum of natural length and the IBS term.

Wake Field Interactions

Two effects appearing due to interaction of the bunch with self-induced wake fields. First is the effect of potential well distortion that leads to bunch lengthening or shortening depending on the value of impedance. The effect also shifts the synchrotron frequency. The effect can be observed even at low bunch currents. Lengthening caused by this effect is expressed by (4).

$$\left(\frac{\sigma_s}{\sigma_{s_0}}\right)^3 - \left(\frac{\sigma_s}{\sigma_{s_0}}\right) + I_b\frac{\alpha Im\left[\left(z_\parallel/n\right)_{eff}\right]}{\sqrt{2\pi}EQ_{s_0}^2}\left(\frac{R}{\sigma_{s_0}}\right)^3 = 0 \qquad (4)$$

Where I_b is a bunch current, E is a bunch energy, R is an average radius of accelerator, $Im\left[\left(z_\parallel/n\right)_{eff}\right]$ is an imaginary part of the longitudinal effective impedance and subscript 0 stands for values at low currents where the effect is negligible.

Another effect is the longitudinal microwave instability. The effect is observed only after bunch current is higher than a threshold of instability. The effect leads to a growth of a length and energy spread of the bunch while the synchrotron frequency of the bunch remains undisturbed [4]. Microwave instability threshold is determined by Eq. (5).

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$$I_{th} = \frac{\sqrt{2\pi}\alpha E\sigma_s}{R\left|z_{\parallel}/n\right|_{BB}}\left(\frac{\sigma_E}{E}\right)^2 \quad (5)$$

Where I_{th} is the threshold current and $\left|z_{\parallel}/n\right|_{BB}$ is an absolute value of the longitudinal broadband impedance.

Above the threshold we have an influence of both effects on the bunch length and the total lengthening is described by Eq. (6) [3].

$$\sigma_s^3 = \frac{R^3\alpha I_b}{\sqrt{2\pi}EQ_{S0}^2}\left(\left|z_{\parallel}/n\right|_{BB} - Im\left[\left(z_{\parallel}/n\right)_{eff}\right]\right) \quad (6)$$

EXPERIMENTS

VEPP-4M Parameters

For the measurement of the energy spread and the longitudinal impedance the bunch length and the synchrotron tune need to be measured. All other necessary parameters of the VEPP-4M are known and presented in the Table 1.

Table 1: VEPP-4M Parameters

Parameter	Value
Momentum compaction factor	0.016
Circumference	366 m
Optical functions at the measurement point $\beta_x/\beta_z/\eta$	4.4/12.9/0.008 m
Coupling	0.04
Revolution frequency	818.924 kHz

The synchrotron tune was measured at the energies below 1865 MeV. For the upper energy region well-known tune dependence from the bunch energy and RF-voltage was used to scale it:

$$Q_s^2 \sim \frac{U_{RF}}{E} \quad (7)$$

Bunch Length Measurements

In order to determine current dependence of bunch length the "PS-1/S1" streak camera was implemented into optical diagnostics of the VEPP-4M [5, 6]. The camera has a temporal resolution about 3 ps. The example of longitudinal profile of the bunch acquired by the camera is shown in the Fig. 1.

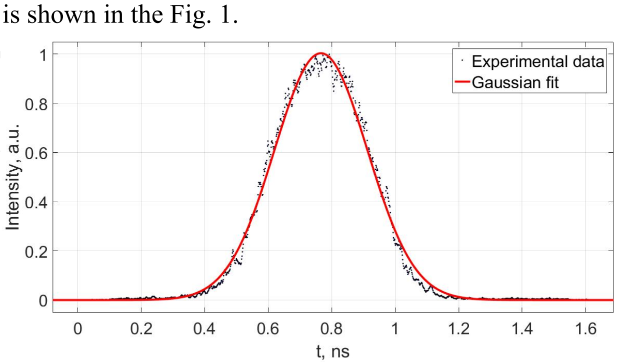

Figure 1: The longitudinal profile of the bunch obtained by the streak camera.

RESULTS

Longitudinal Impedance

Using the acquired dependences of the bunch length on the bunch current, the thresholds of microwave instability were detected. The example of the dependence is shown in the Fig. 2.

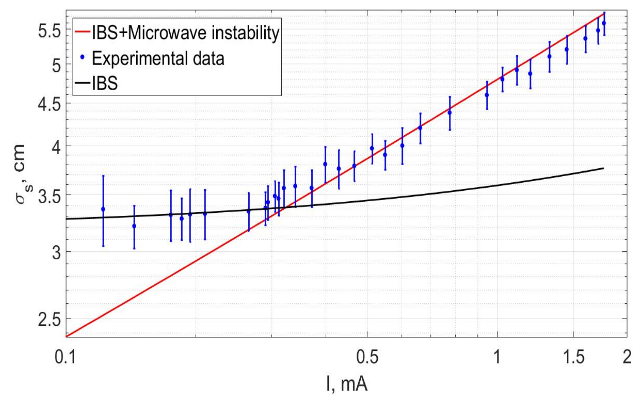

Figure 2: The dependence of the bunch length on the bunch current at E=1200 MeV. The threshold of the microwave instability is clearly seen.

The plots are presented with a double-logarithmic scale to show the change of dependence at the threshold current. The black curve presents the lengthening caused by the IBS. It is seen that this approximation is not working after the certain current. It is the threshold current of the microwave instability. After that point the sum of microwave instability and IBS is the best approximation for the experimental dependence. Using Eq. (3) for threshold currents at different energies the longitudinal broadband impedance of the VEPP-4M was calculated. Equation (4) was also used to check the measured value of the impedance. The results are presented in table 2.

Table 2: The Measured Value of the Broadband Impedance of the VEPP-4M

E, MeV	Threshold current, mA	Threshold size, cm	Impedance, Ω
1200	0.3±0.07	3.4±0.2	6±1.2
1300	0.4±0.07	3.3±0.2	5.9±1.2
1865	0.95±0.15	3.35±0.2	6.3±1.2

The average result value of the impedance is 6.1±0.7Ω.

It was not possible to register the lengthening caused by the effect of potential well distortion. Pre-threshold lengthening is negligible and explained by the IBS energy spread growth. Even at higher energies, where the influence of IBS is negligible and the threshold current of microwave instability is high it was not possible to observe the potential well distortion lengthening. Measured bunch length dependence at 3000 MeV is shown in Fig. 3. There is no trace of any sufficient lengthening of the bunch. Synchrotron frequency also remained constant within an accuracy of the measurements.

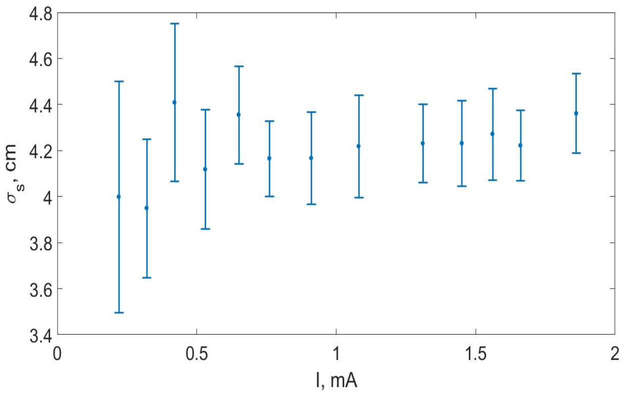

Figure 3: Bunch length at E=3000 MeV.

Energy Spread

The measurements of the energy spread of the beam were performed at the bunch currents lower than the threshold of the microwave instability. The selected current for the energy spread measurements was in the area of 0.09 - 0.15 mA. Equation (1) was used to obtain the energy spread value from the measured bunch length. The measured values of the energy spread are shown in Fig. 4.

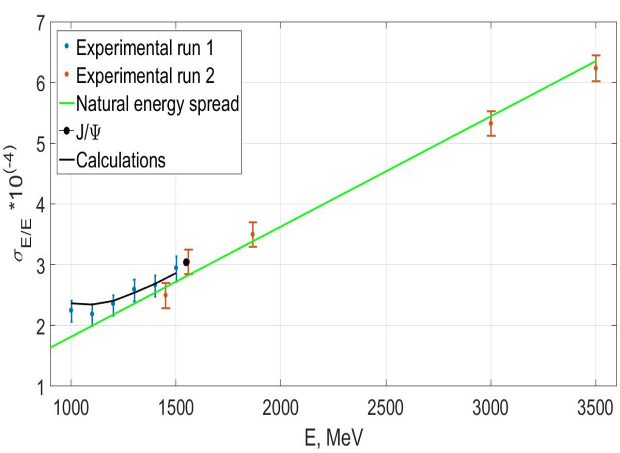

Figure 4: The results of energy spread measurements. The black point – KEDR data of the J/ψ meson width.

The influence of IBS results in non-linear dependence of the energy spread on the energy of the beam. The calculated dependence of the natural energy spread on the beam energy is presented by the green line. At the energies above 1.5 GeV the measured energy spread values are in good agreement with that dependence. The measured value of the energy spread at the region of 1.5-1.6 GeV is in a good agreement with the measured width of J/ψ meson [7] which is determined by the energy spread. The calculations of the energy spread in the presence of IBS [3] are in good agreement with the measurements.

In order to observe stronger deviation from natural energy spread another series of measurements were performed. For that purpose, the RF voltage was increased to compress the bunch Fig. 5. Figure 6 shows the difference in the measured energy spread.

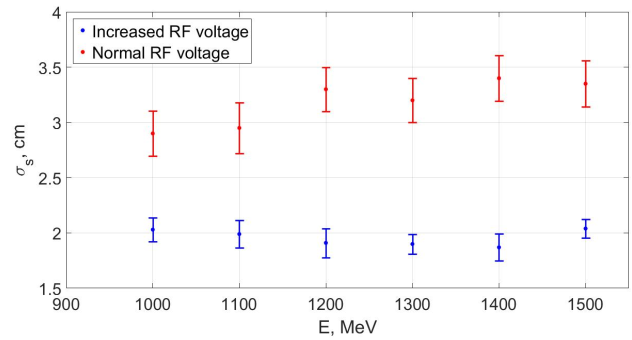

Figure 5: Comparison of measured lengths.

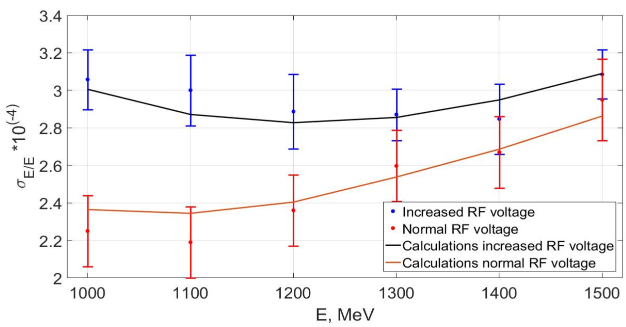

Figure 6: Comparison of measured dependencies.

The energy with the minimal energy spread is near 1.2-1.4 GeV. The calculation for the energy spread with increased IBS power is in a good agreement with the experimental results.

CONCLUSION

The measured value of the longitudinal broadband impedance is 6.1±0.7Ω. In comparison with the modern accelerator this value is giant. It is not possible to avoid significant bunch lengthening due to microwave instability. IBS influence was studied at the energies lower than 1.5 GeV. The minimum of energy spread was acquired near 1.3 GeV. Calculations of the energy spread are in a good agreement with the measurements.

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