# THE LONGITUDINAL BROADBAND IMPEDANCE AND ENERGY SPREAD MEASUREMENTS AT VEPP-4M

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*Abstract*

The paper presents studies of the longitudinal broadband impedance of VEPP-4M and measurements of its bunch energy spread at different energies in range of 1.45 – 3.5 GeV. In order to measure the longitudinal bunch size at different currents we used "PS-1/S1" streak camera with picosecond temporal resolution. Considering that influence of collective effects is negligible at low currents we determined bunch energy spread from its length at low currents. Collected bunch length data demonstrate microwave instability thresholds and potential well distortion lengthening. Potential well distortion was studied at 3 GeV and 3.5 GeV. Measured potential well distortion lengthening was used to estimate a value of the reactive part of the longitudinal impedance. Observed microwave instability thresholds was used to measure the value of broadband impedance. Measured value of the VEPP-4M is 7.9 ± 1.5 Ω.

## ELECTRON BUNCH LENGTH

### *Natural Length*

A length of the electron bunch is determined by synchrotron oscillations and has no current dependence if collective effects are negligible [1]. While the energy spread is determined by the balance between quantum excitation and synchrotron damping, so longitudinal bunch size $\sigma_S$ and its relative energy spread $\sigma_E / E$ are:

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

where $\alpha$ is the momentum compaction factor, $c$ is the speed of light, $\omega_s$ is the synchrotron oscillation frequency.

### *Intrabeam Scattering*

With the increasing of electrons density in the bunch the effects of the intrabeam scattering (or multiple Touscheck effect) becomes significant. The effect is based on transferring of momentum from transverse plane of motion to the longitudinal that leads to growth of bunch energy spread and bunch lengthening [2]. Growth of energy spread can be obtained as a solution of (2-4):

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

$$\chi_m = \frac{N^{1/3} r_0 \beta_x^2 Q_s^{1/3} \left(\sigma_{ET}/E\right)^{-3}}{2\sqrt{\pi}\gamma^2 \left(\beta_x U_x + \eta^2\right)^{7/6} \left(k\beta_z U_x\right)^{1/6} \left(\alpha R\right)^{1/3}}; \qquad (3)$$

$$f(\chi_m) = \int_{\chi_m}^{\infty} \frac{1}{\chi} \ln\left(\frac{\chi}{\chi_m}\right) e^{-\chi} d\chi . \qquad (4)$$

Where $N$ is a number of particles in the bunch, $\beta x$, $\beta z$ is a horizontal and vertical beta functions, $\tau_E$ is a synchrotron damping time, $\gamma$ is the Lorentz factor, $\eta$ is a dispersion function, $k$ is a betatron coupling, $r_0$ is the classical electron radius, $Q_s$ is a synchrotron tune, $\sigma_{ET}$ is the energy spread induced by intrabeam scattering, $U_x$ is determined by (5).

$$U_x = \frac{\tau_x}{\tau_E} < \frac{1}{\beta_x}\left[\eta^2 + \left(\beta_x \eta' - \frac{1}{2}\beta_x' \eta\right)^2\right] > \qquad (5)$$

Where $\tau_x$ is horizontal betatron damping time and the averaging is made in bending magnets only. Since these effects are independent then the total bunch length is quadratic sum of lengths.

### *Wake Field Interactions*

There are two effects appearing due to interaction of the bunch with 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 synchrotron frequency shifts due to this effect also. The effect can be observed even at low bunch currents. Lengthening caused by this effect is expressed by (6).

$$\left(\frac{\sigma_s}{\sigma_{s_0}}\right)^3 - \left(\frac{\sigma_s}{\sigma_{s_0}}\right) + I_b \frac{\alpha Im\left[\left(z_{\parallel}/n\right)_{eff}\right]}{\sqrt{2\pi} E Q_{s_0}^2}\left(\frac{R}{\sigma_{s_0}}\right)^3 = 0 \qquad (6)$$

Where $I_b$ is the 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.

As bunch current increase, as we can observe a threshold of the microwave instability. The effect leads to a growth of a length and energy spread of the bunch but the synchrotron frequency of the bunch remains undisturbed [3]. Microwave instability threshold is determined by (7).

$$I_{th} = \frac{\sqrt{2\pi}\alpha E \sigma_s}{R\left|z_{\parallel}/n\right|_{BB}}\left(\frac{\sigma_E}{E}\right)^2 \qquad (7)$$

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



ISBN 978-3-95450-181-6

Above the threshold we have an influence of both effects on the bunch length and the lengthening is described by Eq. (8) [3].

$$\sigma_s^3 = \frac{R^3 \alpha I_b}{\sqrt{2\pi} E Q_{S0}^2} \left( \left| z_{\parallel} / n \right|_{BB} - Im\left[ \left( z_{\parallel} / n \right)_{eff} \right] \right) \quad (8)$$

## EXPERIMENTS

For our purposes we need to measure a bunch length and synchrotron damping time. Other parameters of the VEPP-4M are known and presented in the Table 1 and Table 2.

Table 1: VEPP-4M Parameters

| Parameter | Value |
|---|---|
| Momentum compaction factor | 0.016 |
| Circumference | 366 m |
| $U_x$ | 25 cm |
| Optical functions $\beta_x/\beta_z/\eta$ | 4.4/12.9/0.82 m |
| e | 0.04 |
| Revolution frequency | 818.924 kHz |

Table 2: Synchrotron Tune

| Energy, MeV | Synchrotron tune |
|---|---|
| 1558 | 0.0091 |
| 1865 | 0.0103 |
| 3000 | 0.0125 |
| 3500 | 0.0140 |

The "PS-1/S1" streak camera was implemented into optical diagnostics of the VEPP-4M for measurements of the longitudinal bunch size [5, 6]. The camera had a temporal resolution about 3 ps. The example of longitudinal profile of the bunch acquired by the camera is shown in Fig. 1.

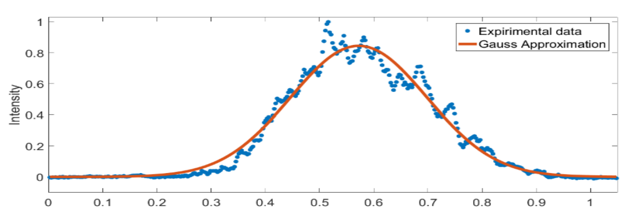


Figure 1: The longitudinal profile obtained by the streak camera.

Besides the longitudinal size we need to measure the synchrotron damping time in order to calculate the energy spread induced by intrabeam scattering.

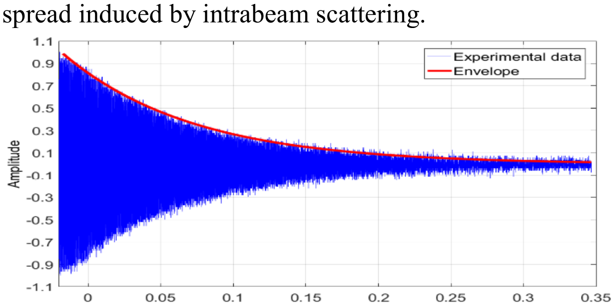


Figure 2: Synchrotron damping time measurements.

For these measurements we applied the fast phase detector which is used in the longitudinal feedback system of the VEPP-4M [4]. The acquired data are presented in Fig. 2.

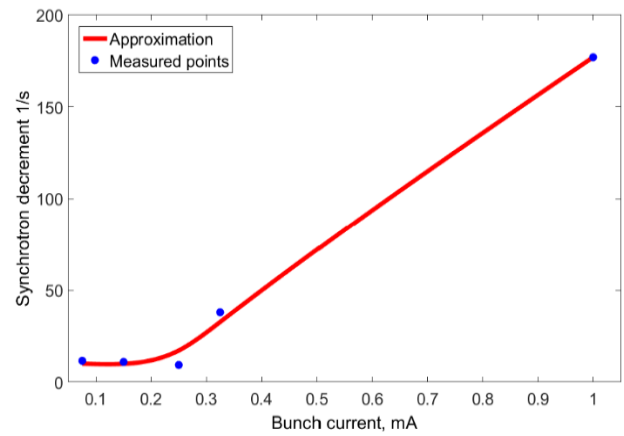


Figure 3: A dependence of the damping time vs bunch current.

We have measured the synchrotron damping time only at the energy of $E$ = 1865 MeV. The experiments revealed the current dependence of the damping time (Fig. 3). We believe that it's caused by collective effects. The measured value of the damping time is $\tau_E$ = 94±11 ms and calculated value is $\tau_E \approx$ 100 ms. We have used the beam current less than 250 μA (Fig. 3) for these calculations.

### *Longitudinal Impedance*

The next step was the measurements of the longitudinal bunch size at different currents and energies of the accelerator. At energy of 1865 MeV we can observe the thresholds of microwave instability (Fig. 4, 5).

Using measured data and Eq. (7) we measured longitudinal broadband impedance $\left| z_{\parallel} / n \right|_{BB}$ from thresholds of microwave instability at different energies (Table 3).

Table 3: Impedance Measurements

| Energy, MeV | Threshold, mA | Impedance, Ohm |
|---|---|---|
| 1558 | 0.3±0.1 | 7.7±1.4 |
| 1865 | 0.5±0.1 | 7.3±1.4 |
| 3000 | 1.7±0.3 | 8.8±1.7 |

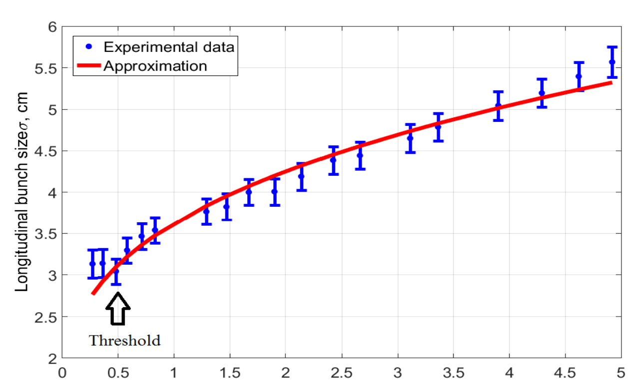


Figure 4: The bunch length at the energy $E$= 1865 MeV.

ISBN 978-3-95450-181-6

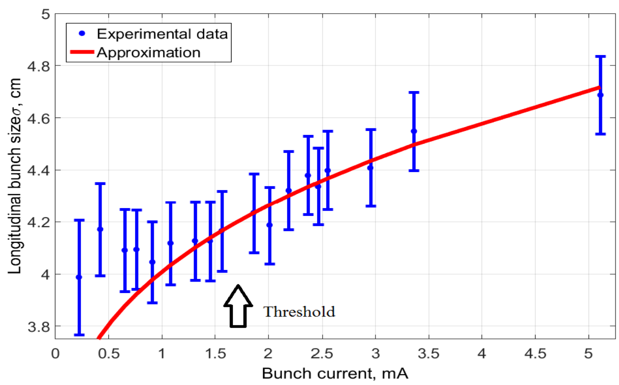


Figure 5: The bunch length at the energy $E = 3000$ MeV.

The average value of impedance is 7.9±1.5. Unfortunately we can't observe the influence of potential well distortion. We can only estimate maximum value of imaginary part of the longitudinal effective impedance which is $\mathrm{Im}(z_0/n)_{\mathrm{eff}} \approx -1$ ohm. The estimation was made using Eq. (6) with the assumption that the lengthening is smaller than the instrumental function of the streak camera. The estimation is in a good agreement with lengthening fitted by Eq. (8). The fit was performed at the bunch current superior the threshold.

### *Energy Spread*

We have measured a relative energy spread $\sigma_E / E$ using bunch length data at beam currents less than 0.3 mA applying Eq. (1). As we know a natural bunch length is proportional to the bunch energy. Thus it's expected that if we exclude energy spread induced by intrabeam scattering then the energy spread will be fitted by linear approximation. We were able to determine the intrabeam scattering effect only at the energy of 1865 MeV. The total energy spread was $\sigma_E / E = 3.2\cdot10^{-4}$ and impact of intrabeam scattering obtained as a solution of (2-4) was $0.74\cdot10^{-4}$ thus we conclude that natural energy spread is $3.1\cdot10^{-4}$. From Eq. (2) we see that intrabeam scattering effect is inversely proportional to bunch energy. Using this fact, we can expect that at the energies of 3 and 3.5 GeV this effect is negligible. Then we can assume that measured energy spread at these energies is natural energy spread. Using values of energy spread at $E = 1865$, 3000 and 3500 MeV we made linear fit of energy spread. The results are presented in Fig. 6.

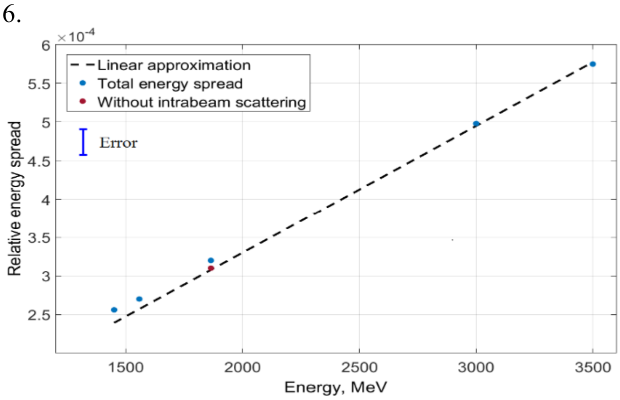


Figure 6: The measured energy spread.

Here we can see that the total energy spread is deviated from this fit. This deviation is due to the intrabeam scattering. Using the deviation, we can estimate energy spread of this effect at lower energies. The results of this estimation are presented in the Fig. 7.

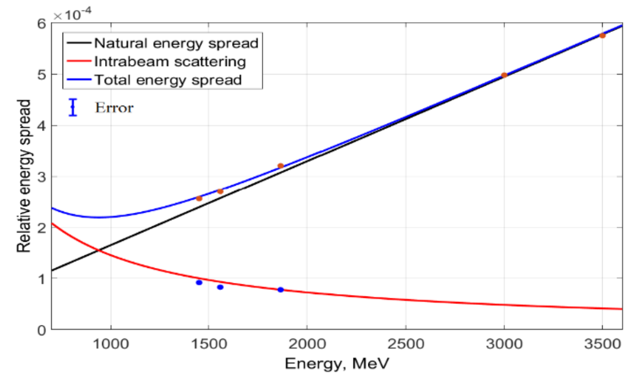


Figure 7: An expected behaviour of the energy spread.

## CONCLUSION

We have observed the effect of intrabeam scattering and the microwave instability measuring dependence of beam length on the beam current. To complete this study, we are going to measure a bunch length and synchrotron tune at lower range of energies to prove the existence of minimum of the energy spread of a beam as it is shown in Fig. 7.

## ACKNOWLEDGMENTS

The presented experimental results were implemented due to financial support of the Russian Science Foundation (Projects N 14-29-00295).

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ISBN 978-3-95450-181-6