# MEASUREMENT OF THE ENERGY DEPENDENCE OF TOUSCHEK ELECTRON COUNTING RATE

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*Abstract*

We have measured a dependence of the intra-beam scattering rate on the VEPP-4M beam energy and compared it with our theoretical estimates. Measurements have been performed at several energy points in a wide range: from 1.85 up to 4.0 GeV.

## INTRODUCTION

The resonance depolarization technique (RD) with the Touschek polarimeter [1] was successfully applied for the beam energy calibration at the VEPP-4M [2] collider in the high precision measurements of the $J/\psi$, $\psi'$ [3], $D$ [4] mesons and $\tau$-lepton [5] masses with the KEDR [6] detector. After completion the activities at low energies we plan to start the experiments in the region of the $\Upsilon$-mesons with the aim to define more precisely their masses using RD. At the $1.5 - 1.85$ GeV range we measure the beam energy with an accuracy of $10^{-6}$ by a fast change in Touschek particle counting rate while scanning the depolarizer frequency. Estimation of the Touschek polarimeter efficiency at higher energies requires the measurement and calculation of the energy dependence of Touschek electron counting rate. The calculation must take into account relativistic effects in the center of mass (c.m.s.) of scattering particles. This work presents the measurement of Touschek electron counting rate energy dependence in comparison with the numerical calculations.

## CALCULATION

Relativistic calculations of the intra-beam scattering rate $\nu$ for the 2D collision model in the Born approximation were done in [7]:

$$\nu(\eta) = \frac{\pi r_e^2 c N^2 k}{\gamma^2 V_b \sigma_q^3} \int\limits_{\chi_0}^{\infty} \frac{(2\chi\sigma_q^2+1)^2}{\chi^{3/2}\sqrt{\chi\sigma_q^2+1}} S_k(\chi) d\chi \times$$
$$\times \left[ \frac{\chi/\chi_0}{\chi\sigma_q^2+1} - 1 + \ln\sqrt{\frac{\chi\sigma_q^2+1}{\chi/\chi_0}} - \frac{\chi^2\sigma_q^4}{(2\chi\sigma_q^2+1)^2} \times \right.$$
$$\left. \times \left( \sqrt{\frac{\chi\sigma_q^2+1}{\chi/\chi_0}} - 1 + 2\ln\frac{\chi\sigma_q^2+1}{\chi/\chi_0} \right) \right], \quad (1)$$

with $r_e$, the electron classical radius; $c$, the speed of light; $N$, the beam population; $V_b$, the effective beam volume; $\gamma$, the Lorentz factor in the lab system; $\sigma_q$, the radial momentum spread in electron mass units; $\chi_0 = (\eta/\sigma_q)^2$; $\chi = (q/\sigma_q)^2$; $q$, the momentum of scattered particles in the c.m.s.; $\eta = \Delta p/p$, the lower limit for the relative momentum perturbation of a registered particle; $S_k(\chi) = \exp\left[-\frac{\chi}{2}(1+k^2)\right]; I_0\left[\frac{\chi}{2}|1-k^2|\right]$ describes momentum distribution of scattered particles in the c.m.s.; $k = \sigma_q/\sigma_z$; $\sigma_z$, the vertical and momentum spread; $I_0$, the modified Bessel function. Another formula accounting the Coulomb corrections is presented in the work [8]:

$$\nu_\zeta(\eta) = \frac{2\pi r_e^2 c N^2 k}{\gamma^2 V_b \eta^2 \sigma_q^2} \int\limits_{\eta}^{1} d\beta\, g(\beta) \left\{ \left(\frac{1+\beta^2}{1-\beta^2}\right)^2 - \right.$$
$$\left. - \frac{\eta^2}{\beta^2}\left[ \left(\frac{1+\beta^2}{1-\beta^2}\right)^2 + (1+\zeta^2)\ln\frac{\beta}{\eta}(1+F_c) \right] \right\}, \quad (2)$$

with $\beta$, the velocity of scattered particles in c.m.s.; $F_c$, the Coulomb correction function [8]; $\zeta$, the beam polarization degree; $g(\beta) = S_k(\beta^2/(1-\beta^2)/\sigma_q^2)$. This formula is written in approximation $\eta \ll 1$ and works for any values of transversal momentum spread of the beam. Counting rate doesn't depend on the polarization direction respect to momenta of scattered particles. The Coulomb correction $F_c$ at $\beta \gg \alpha$ is close to zero ($|F_c| < 10^{-2}$, for $\beta > \alpha$) [8] and might be neglected in accordance with the earlier work [9]. We call the Equation (2) as Bayer-Katkov-Strakhovenko (BKS) model. For $\eta \ll 1$ the polarization contribution is of the order of $\eta$ and negligible. For high momentum spreads $\sigma_{q,z} \gg 1$ the intra-beam scattering rate and depolarization effect could be approximated by the formulas:

$$\nu(\eta) \approx \frac{4\pi r_e^2 c N^2}{\gamma^2 V_b \eta^2}, \qquad \frac{\nu_\zeta(\eta) - \nu_0(\eta)}{\nu_0(\eta)} \approx \frac{1}{2}\frac{\eta}{\sigma_q\sigma_z}. \quad (3)$$

One could expect the energy the dependence $\nu \sim E^{-2}/V_b$ but for 1.85 GeV VEPP-4M ($\sigma_q = 0.4$, $\sigma_z = 0.08$) this approximation doesn't work well. Correction is about 90 % (Figure. 1). For 4 GeV VEPP-4M ($\sigma_q \approx 2$) correction is $-10$ %.

### *Registration Conditions*

Condition for scattered particles to hit the counter defines the lower ($\eta_1$) and upper ($\eta_2$) limits of relative energy deviation. Counting rate is $\nu(\eta_1) - \nu(\eta_2)$. Limits depend on the amplitude of betatron oscillations, an azimuth of scattering, the aperture limits and the counter location in the storage ring. The calculation results of lower limit $\eta_1$ for

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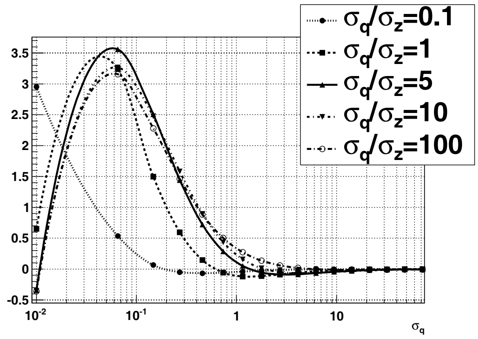


Figure 1: Correction to asymptotic Formula 3 calculated for different transversal momentum spread ratio versus radial momentum spread.

multi-turn and single-turn approximation are shown on Figure 2. Upper limit $\eta_2 = 1.12\%$ depends on the geometrical aperture. There are dead zones from which particles never hit the counter in the single-turn approach. It is taken into account by a special factor which depends on the counter position.

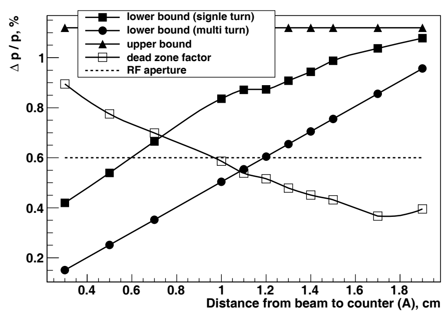


Figure 2: Upper and lower bounds of scattered electron momentum deviation vs $A$, the distance from counter to beam orbit. Dead zone factor and the energy aperture defined by the RF bucket size are shown too.

### *Calculation Results*

The results of calculation are shown on Figure 3. The calculations "2D relativity" from (1) and BKS from (2) are consistent to each other and show energy dependence $\propto E^{-3.0}$ for the counting rate normalized by the beam current squared and the beam volume $V_b$. Energy behaviors for the relativistic (1D relativity) and non-relativistic (1D non-relativity) cases for one dimension approaches are presented in the figure too. One can see that relativistic effects are sufficient for the energy more then 3 GeV. Non-relativistic approximation gives the energy dependence of the normalized counting rate $\propto E^{-3.5}$.

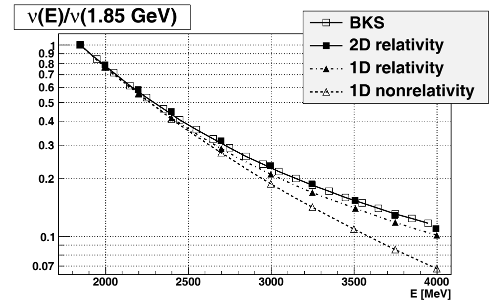


Figure 3: The results of normalized counting rate calculations for different theoretical model.

## EXPERIMENT

The measurements of scattered electron counting rate were done at the 10 points in the energy range from 1.85 to 4.0 GeV. We made two series of measurement at 2008 (Run 1) [10] and 2010 (Run 2). Three pairs of scintillation counters located in three different places of storage ring are used to register Touschek events. Internal and external counters in each pair are located inside and outside the beam orbit respectively. The longitudinal beam size was kept constant due to a proper tune of the RF voltage. Beam orbit was corrected to the orbit at 1.85 GeV. Counter position was adjusted to make equal loads of the internal and external counters while keeping constant distance between them. Several distances from 32 mm to 46 mm were used for the measurement. The beam current, vertical, radial and longitudinal beam sizes were measured. The load and the coincidence rate of signal of the external and internal counters were registered.

### *Data Analysis*

In order to reject the background events of the inelastic scattering on the residual gas the special procedure was applied. Touschek scattering produces a pair of electrons which can give correlated signals on the internal and external counters. The inelastic scattering result in an uncorrelated coincidence. By measuring the load and the coincidence rate one can extract the number of correlated events. The measured load $N_{i,e}$ consists of correlated events $C$ and uncorrelated ones $R_{i,e}$ subtracted with their cross-coincidence $CR_{i,e}/f_0$, where $i$ and $e$ mark the internal and external counters respectively; $f_0 = 818.924$ kHz, the VEPP-4M revolution frequency. The coincidence rate $N_{ie}$ includes the correlated events $C$ and the random coincidence of the uncorrelated events $R_iR_e/f_0$ subtracted with their cross-coincidence $CR_eR_i/f_0^2$:

$$N_{i,e} = C + R_{i,e} - CR_{i,e}/f_0 \qquad (4)$$
$$N_{ie} = C + R_iR_e/f_0 - CR_iR_e/f_0^2$$

Solving this one can receive the rate of correlated events:

$$C = \frac{N_{ie} - N_iN_e/f_0}{1 + (N_{ie} - N_i - N_e)/f_0} \qquad (5)$$

There are some correlated background events produced by the electromagnetic shower when the inelastic scattered electrons hit the vacuum chamber. But we have not studied this background problem yet.

### *Measurement Results*

The results of the measurement are shown on Figure 4. The extracted correlated events are normalized by the

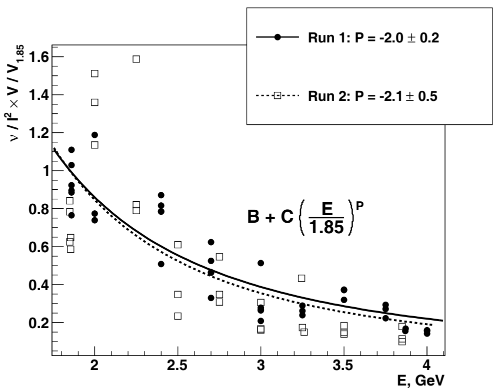


Figure 4: The correlated counting rate normalized by square of the beam current $I$ and the beam volume $V_b$ versus the beam energy. The method of least square is used to fit the data.

square of beam current $I$ and by the beam volume $V_b$. The statistical errors of each measurement are much smaller then the systematical effects due to instabilities of counting rate therefore the data were fitted by the method of least square with a function $B + C(E[\text{GeV}]/1.85)^P$ with $B$, $C$, $P$ as the free parameters. The $B$ parameter describes the inelastic scattering on the residual gas; $C$ is the Touschek contribution to the correlated events and $P$ is the power of energy dependence of the intra-beam scattering rate. For each pair of counters and for each distances between them the data were fitted. Then all data were normalized on the expected values at 1.85 GeV and combined for the final fit. The result of the final fit is $E^{-2.0\pm0.2}$ for the Run 1 and $E^{-2.1\pm0.5}$ for the Run 2. The results are statistically consistent but there is the discrepancy with the numerical calculation ($E^{-3.0}$). Background $B$ is close to zero in both runs.

## DISCUSSION

The discrepancy between the numerical calculations and the experiment could be explained by following factors:

- High background. Despite a zero fit value of the parameter $B$ a real contribution of the inelastic scattering could be higher. Proper measurements of energy dependence must include a background control based on the measurement of counting rate dependence on the beam current and pressure of the residual gas in VEPP-4M vacuum chamber.
- Energy aperture. Rise of energy while keeping the beam length constant leads to the energy aperture growth. It increases a contribution of multi-turn events. We didn't take into account this effect of energy aperture changing in our calculations.
- Magnet wiggler. In order to enlarge the beam in sizes for energy below 2.8 GeV the magnet wiggler was turned on. This increases the transverse momentum spread that leads to decrease the intra-beam scattering rate according to Figure 1.

## CONCLUSION

The measurements of energy dependence of scattering electron counting rate were done for the first time in the wide energy range from 1.85 to 4.0 GeV at the same facility. Normalized energy dependence is $\propto E^{-2.0\pm0.2}$. This contradicts to the numerical calculation ($\propto E^{-3.0}$). The discrepancy could be explained by the high background, the energy aperture growth and the magnet wiggler influence. More accurate measurement of the energy dependence must include the control of background conditions. The numerical calculations for the different theoretical models were done. The relativistic effect is sufficient for the beam energy more then 3 GeV. Asymptotic behavior of counting rate for the ultra-relativistic case is $E^{-2}V^{-1}$.

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