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Study of the Machine Induced Background in KLOE

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1.0 Introduction

The two experiments, DEAR and KLOE, that were or are presently data taking in the DAΦNE collider, both suffered from large machine induced background hits in their detectors. These background rates are much higher than was predicted, and beam lifetimes are smaller than their expected values. A study has been performed to try to understand this situation.

The beam lifetime in DAΦNE is predicted to be dominated by Touschek losses [1]. Loss rates from elastic Coulomb scattering and inelastic beam gas Bremsstrahlung are considerably smaller. The probability of an elastic Touschek scattering of two particles in a bunch is proportional to the particle density times the number of particles in the bunch, $P_t = a\ i_b^2/V_b$. The two emerging off-momentum particles suffer the same change in momentum, one gains and the other looses. The probability for beam-gas interactions, however, is – in the case of a negligible component of dynamical pressure to the total vacuum pressure – proportional to the beam current.

Machine induced backgrounds to the experiments, that are installed in the two interaction regions (IR) of DAΦNE, consequently follow the same pattern. Simulations [2] show that background rates are mainly due to Touschek scattered particles. To protect the detectors of the experiments from these off-momentum particles, scrapers have been installed for the incoming beams on either side of each experiment. They are placed just upstream of the splitter magnets, about 7.0 m from the interaction point (IP). Two horizontal jaws per scraper, external and internal, are required to intercept the two off-energy particle families, those who gained and those who lost energy in the scattering process.

The effect of the scrapers has been simulated by tracking Touschek particles from their origin in the arcs into the IP's. When closing the scraper jaws around IP1 to $\pm 9\sigma_x$ all Touschek off-momentum particles can be intercepted, that otherwise would reach the vacuum chamber around IP1 and produce background in the KLOE detectors [3]. However, the simulations assume that all particles that reach the scraper jaws are completely stopped within the 10 radiation length of the tungsten material. As the scrapers also intercept off-momentum particles, that otherwise would not get lost around the ring, they also reduce the beam lifetimes when being closed around the beams.

In the following a study of background rates measured by the forward calorimeters in KLOE as function of scraper openings and other beam parameters are described.

2.0 Scraper scans

Scraper scans were performed with colliding beams during physics data taking as well as with single beams of electrons and positrons.

Rates of the two forward calorimeters in KLOE were taken as function of the opening of horizontal scrapers around IP1. The two rates from the calorimeters ECM2 and ECM4, that are available in the DAΦNE control room, integrate the signals over the four innermost sectors of the west and east forward calorimeters each.

In order to allow a comparison of the results from different measurements with different beam parameters, the calorimeter rates are given per bunch and for 1 mA bunch current and are scaled for a "roundness" of R=0.1, i.e. the obtained calorimeter rates are divided by the square of the beam current and multiplied by the number of bunches per beam and the measured value of the beam roundness. The roundness parameter R is the ratio of the vertical to horizontal beam size measured at the location of the synchrotron light monitor SLM. Assuming a constant size of the horizontal and longitudinal beam during each set of measurements, R is a measure of the changing bunch volume due to induced variations in the beam coupling. The measured values of R during our experiments, with standard settings of beam coupling, varied between R=0.07 and R=0.13. The indicated errors on the data points present the estimated statistical fluctuations during the measurement.

2.1 Scans with colliding beams

Scraper scans were made during two fills of physics data taking with colliding beams of 45 bunches per beam and initial beam currents of i^-=235 mA, i^+=320 mA for the scan of the external jaw, and i^-=270 mA, i^+=280 mA for the scan of the internal jaw.

The jaws of the scraper SCHEL101 on the incoming electron beam in the KLOE IP1 were closed from their "out" positions at ±43 mm from the beam axis until background rates rose to above 1000 kHz or lifetimes were reduced to less than 1500 sec. First the external jaw ($x_{scr}>0$), and thereafter the internal jaw ($x_{scr}<0$) were scanned. The amplitude and angle of the closed orbit at the scraper position was measured to be +4.8 mm and +0.6 mrad, respectively, in both fills. The roundness was about $R \approx 0.1$.

The obtained background rates in the two calorimeters and the measured beam lifetimes as function of the scraper openings are shown in Figures 1 and 2, respectively.

No or very little reduction of the background rate in the KLOE calorimeters were observed when closing in the scraper jaws. However, a strong increase of the background rate was seen when the scrapers were moved to a distance of less than about ± 23.5 mm from the closed orbit position. This distance corresponds to 8.8 standard deviations of a gaussian beam distribution with an horizontal emittance of ε_x= 0.79 mm mrad. The scraper therefore does not intercept beam particles but is cutting into the much wider horizontal distribution of off-momentum particles. It appears that the tungsten scraper, when intercepting an increasing number of these particles, is scattering or showering a large fraction of them onto the vacuum chamber around the IR, and thereby enhancing the background in the detectors. In fact, due to the scrapers interaction, off-momentum particles, that would otherwise pass the IR and not get lost, are now directed onto the beam pipe and add to the background counts. A corresponding loss of the electron beam lifetime is clearly seen in Fig. 2.

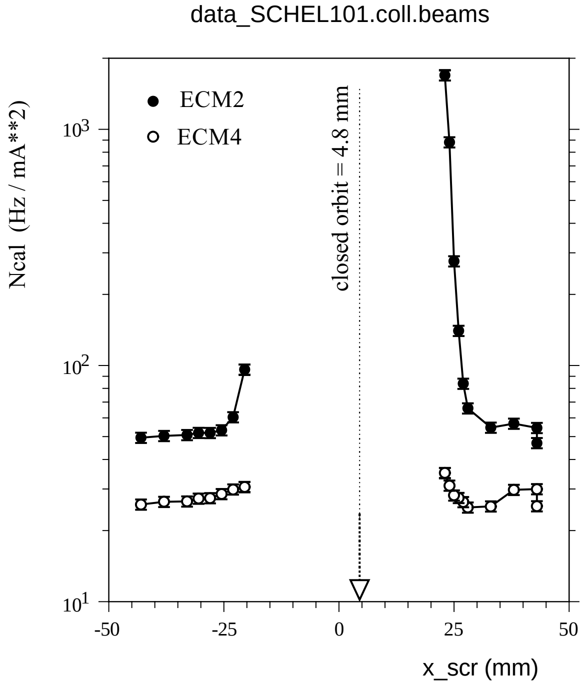

Figure 1: Scan of the background rate in the KLOE forward calorimeters ECM2 and ECM4 as function of the opening of the external and internal jaws of the electron beam scraper (SCHEL101) with **colliding beams**. The scraper openings are measured from the central beam axis.

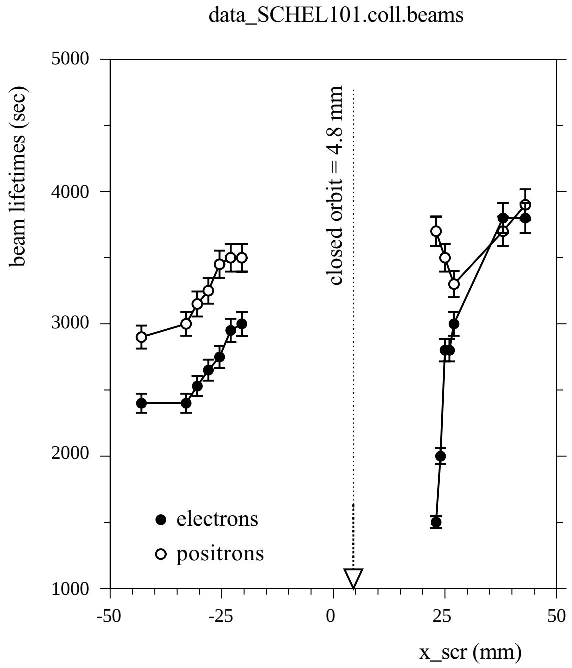

Figure 2: Beam lifetimes versus opening of the external and internal jaws of the electron beam scraper (SCHEL101) with **colliding beams**.

2.2 Scans with single beams

Scraper scans with single electron and positron beams have been performed. Beams with 20 bunches and total current of about 100 mA were used. Their roundness parameter was about $R^- \approx 0.13$ for the electron beam and $R^+ \approx 0.08$ for the positron beam. In preparation for the electron scan the closed orbit of the electron beam was carefully flattened through the IP1 around the 12.5 mrad separation angle line as well as outside the IP1 region. After this procedure the closed orbit amplitude and angle at the electron scraper SCHEL101 were –2.7 mm and 1.3 mrad, respectively. The values of the uncorrected positron orbit at the position of positron scraper SCHPL101 were +1.9 mm and 0.8 mrad.

The obtained background rates in the corresponding calorimeter ECM2 and the electron beam lifetime for the electron scan are shown in Figures 3 and 4, respectively. While the internal jaw behaves as before with colliding beams, and is increasing the background rate, the external jaw now allows to reduce the background by a factor of 2.3. However, at about the same distance from the beam centre (closed orbit), the background rate again starts rapidly to rise.

The main difference as compared to the experiment with colliding beams (Fig.1), which might be responsible for the improved protection capability of the external electron scraper jaw, is the corrected closed orbit for the electron beam.

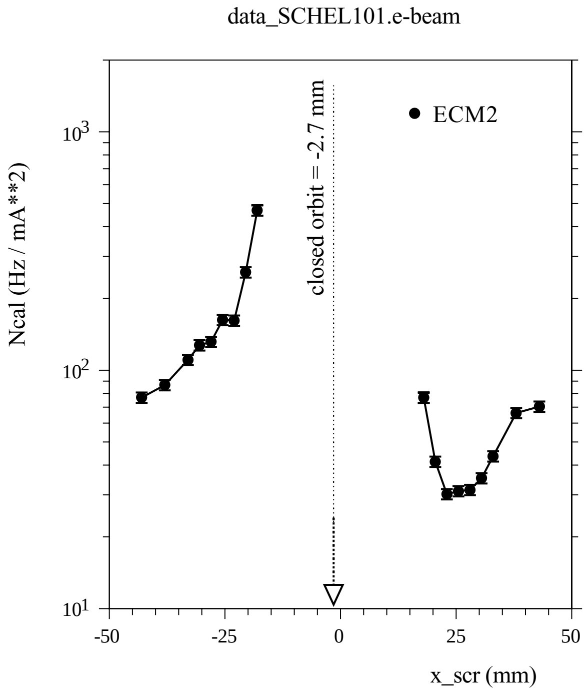

Figure 3: Scan of the background rate in the KLOE forward calorimeter ECM2 as function of the opening of the external and internal jaws of the electron beam scraper (SCHEL101) for a single **electron beam**. The scraper openings are measured from the central beam axis. (about 100 mA in 20 e^- bunches $R^- \approx 0.13$).

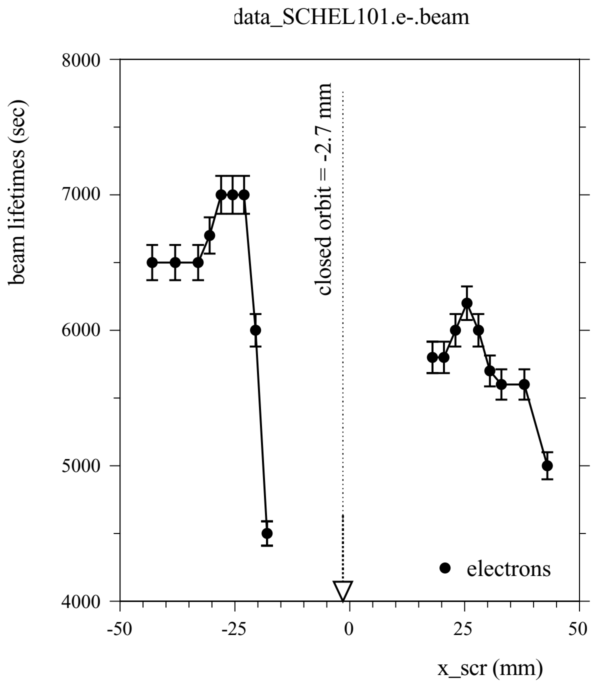

Figure 4: Beam lifetimes versus opening of the external and internal jaws of the electron beam scraper (SCHEL101) for a single **electron beam**.

The horizontal orbit position at the scraper SCHEL101 has moved by 6 mm (from +4.8 mm to –2.7 mm) away from the external and towards the internal jaw. The horizontal orbit position at the scraper SCHEL101 has moved by 6 mm (from +4.8 mm to –2.7 mm) away from the external and towards the internal jaw. The horizontal angle of the orbit at the scraper changed from +0.6 mrad to +1.3 mrad, therefore directing off-energy particles hitting the scraper near the edge of the jaws further into the block for the external and further out of the absorber block for the internal jaw. Consequently, the outer jaw is more and the inner jaw less efficient in stopping background particles, as compared to the case with the uncorrected orbit in Fig. 1.

The scraper scan for the electron beam has been repeated two days later with the same settings of the corrected orbit and similar beam parameters in order to test the reproducibility of the observed effect. Results of the two scans are shown in Fig. 5 Exactly the same background reduction curve has been obtained in the two measurements.

The result of the scraper scan for the positron beam is given in Figure 6. Again the scraper has no, or little, improving effect, but enhances the background in KLOE when approaching the beam to less than about 22 mm from the beam axis.

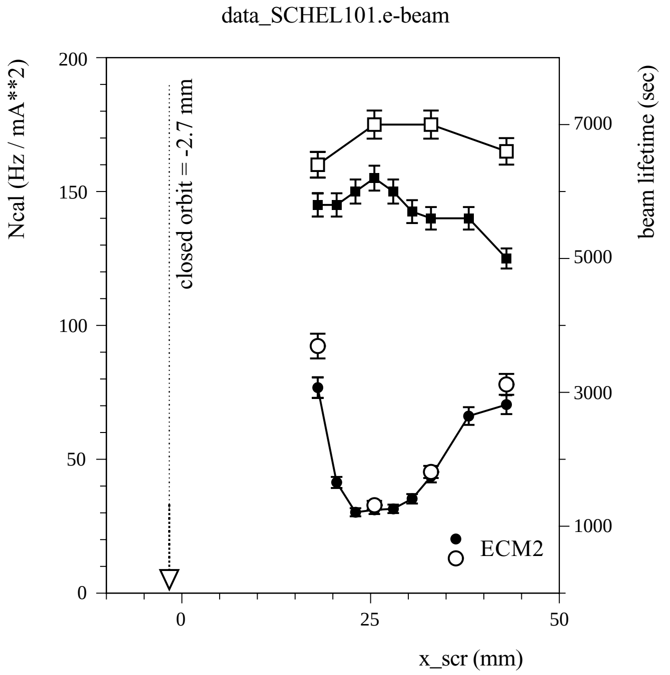

Figure 5: Repeated measurements of the background rates in the KLOE foreword calorimeter ECM2 and beam lifetimes as function of the opening of the external jaw of the electron beam scraper (SCHEL101) for a single **electron beam**. Circles are ECM2 rates, rectangles are beam lifetimes. Data with full symbols are taken on Sept. 29 (from Figs. 3 and 4) and those with open symbols two days later.

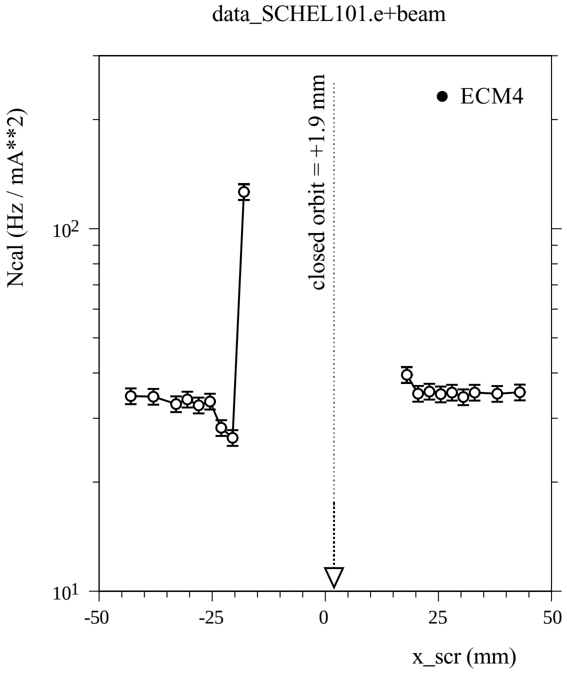

Figure 6: Scan of the background rate in the KLOE forward calorimeter ECM4 as function of the opening of the external and internal jaws of the positron beam scraper (SCHPL101) for a single **positron beam**. The scraper openings are measured from the central beam axis. (about 100 mA in 20 e^+ bunches, $R^+ \approx 0.08$).

3.0 Test of the type of background

In order to probe the possible contribution of off-momentum background from beam-gas scattering to the total measured background rate, the different current and beam size dependencies of the two components could be used.

$$N_{meas} = N_T + N_{bg} + \dots$$

$$N_{meas} = a_T * n_b * i_b \, (i_b/V_b) \ + \ a_{bg} * n_b * i_b + \dots$$

with n_b number of bunches per beam, i_b the bunch current and V_b the bunch volume. N_T and N_{bg} are the components in the measured background rate N_{meas} from Touschek scattered particles and beam-gas interactions, respectively.

If the bunch currents are changed by large amounts the bunch size will change as well due to bunch lengthening and possible increased coupling. As these effects are difficult to control, we have used instead the V_b dependence. The beam height has been varied by changing the transverse plane coupling using skew quadrupoles. Assuming that the horizontal and longitudinal beam sizes stay unchanged during this process, the change of the roundness parameter R can be used as measure of the change of the vertical beam emittance or V_b.

Figure 7 shows the variation of the background rate from ECM2 multiplied by the roundness parameter R as function of R. The calorimeter rate is normalised for one bunch and 1 mA bunch current. The three different curves are for three different settings of the electron scraper SCHEL101 from Fig. 3: at the out position of (x_scr=43 mm), at the background minimum (x_scr=25.5 mm) and at the innermost setting (x_scr=18 mm). In all three cases the beam roundness was increased from about $R^- = 0.12$ to about $R^- = 0.37$, while the electron beam current reduced by less than 10% for each collimator setting. The curves are least square fits to the measurement points.

The resulting curves are not constant, as would be expected if the dominant contribution came from Touschek scattering, but contains a strong 1/R-term as well as some contribution proportional to R. The 1/R-term could be explained by a constant off-set in the measurement of the small vertical beam size at the SLM, i.e. $R_{meas}= R+\partial R$. Assuming $\partial R/R<<1$

$$(N * R)_{meas} = b_T + b_T * (\partial R/R_{meas}) + b_{bg} * R_{meas} + \dots$$

The monitor resolution of the R-measurement was checked in a later experiment by varying the coupling strength and it was found that the vertical electron beam size could be best fitted by subtructing quadratically an off-set of $\partial R=0.09$ from the measured roundness, $R'=\sqrt{(R^2-\partial R^2)}$. When taking this correction into account, see Fig. 8, the behaviour of the background becomes much more like it is expected, if most of the background is due to Touschek scattered particles.

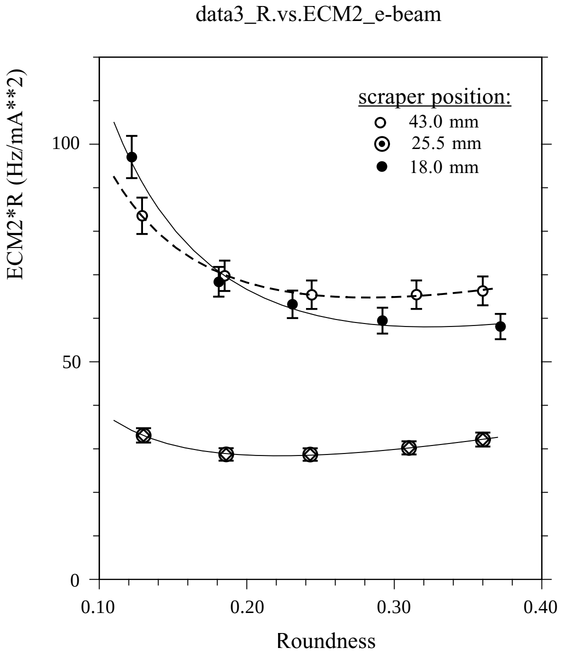

Figure 7: The normalised ECM2 calorimeter rate multiplied by the beam roundness R as function of R. The external jaw of the electron beam scraper (SCHEL101) was set to the three openings given above. A single **electron beam** was used (about 100 mA in 20 electron bunches).

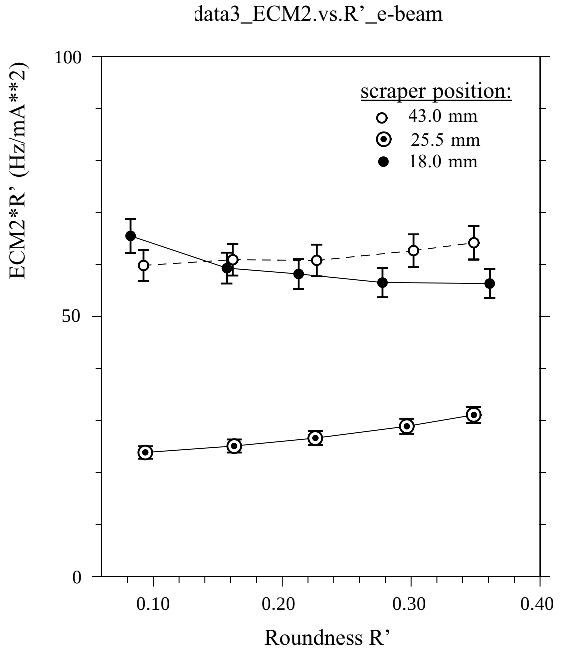

Figure 8: The same like in Fig. 7, but the measured roundness R has been corrected for a constant contribution to the detector resolution $R'=\sqrt{(R^2-\partial R^2)}$ with $\partial R=0.09$.

The remaining term proportional to R' can either be a contribution from beam-gas scattering events in the background, or partly due to a reduction of the horizontal beam emittance for large coupling values of R'. These effects have to be further studied.

4.0 Discussion and outlook

The following conclusions about of the machine induced background to KLOE can be extracted from the measurements:

1. When measured by the forward KLOE calorimeters, background events from the two beams are orthogonal with little cross talk in the two calorimeters. Background from the positron beam is dominantly seen by ECM4 and that from the electron beam by ECM2.
2. Electron and positron background rates are about the same with single or two colliding beams. This and the above statement allows to study the background to KLOE during physics runs with colliding beams.
3. Background from the positron beam is by a factor of (2±0.2) smaller than the background from the electron beam. This difference can probably be explained by the larger beam dimensions of the positron beam (see table below), although the smaller electron beam dimension in the vertical plane is only obtained, if the electron roundness measurement is corrected for a likely off-set in the synchrotron light monitor. The dispersion function H, that drives the betatron oscillations of the off-energy particles, in the corresponding nearest arc, however, is 10% larger for positrons than for electrons.

	Positron beam	Electron beam
ε_x (mm mrad)	0.95	0.79
ε_y (mm mrad)	$3.7\ 10^{-3}$	$5.2\ 10^{-3}$ $(1.7^{\circ}10^{-3})^{*)}$
$H = \gamma D^2 + 2\alpha DD' + \beta D'^2$	3.04	2.77

*) corrected for an off-set of 0.09 in the e^- roundness measurement

4. Although the dominant component of the background observed is due to Touschek scattered off-momentum particles, sizable contributions from beam-gas scattering can not yet be excluded.
5. Present scrapers have limited collimation efficiency and do not allow to protect the experiments, but seem to produce as many or more background particles as they do intercept. Only under special closed orbit conditions can scrapers reduce background rates to KLOE by a factor of about two per scraper jaw (see Fig. 3).

The collimation efficiency of tungsten collimators has been studied for 50 GeV electron beams in LEP [4]. A collimator of 30 radiation length (r.l.) was considered to be sufficient to limit the punch-through probability for E=50 GeV electrons to a level of much below 10^{-6}. As the shower length scales like $\ln(E/\varepsilon_0)$, with the critical energy $\varepsilon_0 = 7.4$ MeV for tungsten, the 30 r.l. length for 50 GeV electrons corresponds to 14.3 r.l. for 500 MeV particles. The DAΦNE scrapers have 10 r.l., which should be just sufficient.

More serious is the reduced collimation efficiency for particles that impinge the scraper block close to its edge. For 50 GeV electrons with normal incident angle onto a tungsten absorber the escape probability falls from 1 at the edge to 10^{-6} at a distance from the edge of about 10^{-2} r.l. When integrating over the total edge one finds 4×10^{-4} electrons that escape the block back into the beam with an energy loss of less than $dE/E\leq0.05$. The escape probability quickly increases if particles with larger energy loss must be considered, as is the case for DAΦNE. The escape probability also depends strongly on the impact angle. An incident angle of 0.5 mrad towards the inner face of the block increases the escape probability for 50 GeV electrons by a factor of 10. We have in fact observed a substantial increase of the collimating efficiency of the electron scraper's external jaw after the angle of the horizontal orbit was changed by 0.7 mrad towards this jaw (see Fig.3).

The width of the transparent edge is mainly due to multiple scattering and Bremsstrahlung and scales therefore with the Molière length, or as 1/E. From this one might expect that the edge effect of the scrapers in DAΦNE with 500 MeV beam energy are 100 times worse than at LEP.

This "edge" effect is most likely the source of the observed low collimation efficiency of the DAΦNE scrapers. If this turns out to be true, a two stage collimation system might be needed.

These observations stimulate the following actions to be undertaken in order to understand and improve the present very difficult background situation for the DAΦNE experiments:

Short term:

1. Optimisation of the amplitude and angle of the closed orbit at the scrapers in order to reduce the edge effect and improve the collimation efficiency. Most likely the efficiency of only one jaw per scraper can be optimised this way. Therefore a reduction factor of the KLOE background rate of four (or more) might be reachable.

2. Completing and extending the reported measurements during physics data taking and also with single beams during special machine development sessions.

3. Improved on-line background signals from KLOE to the control room will be very helpful for the above studies. In particular the spatial distribution of the background hits in the forward calorimeters around the vacuum pipe are of interest.

Medium term:

4. Tracking of Touschek scattered particles under present optics conditions should be repeated and the effects of the scrapers, including edge effects, be tested. A search for better scraper locations, or adapted optics should be envisaged.

5. Simulations of the edge effect of the scraper should be performed for the actual scraper dimensions, including its copper wake field shield. A shower program like EGS can be used and realistic distributions of incident particles obtained by the simulations of action 4 should be included.

6. Particles incident on the vacuum pipe around the IP's should be tracked into the DEAR, KLOE and FINUDA detectors in order to establish the relative importance of different background sources and their possible remedies. The input to this calculations will be provided by the simulations of action 4. The hope is, that this work can be done by the experiments using their tracking and Monte Carlo codes.

Long term:

7. The above studies might lead to the request of hardware changes like improved scrapers, possibly a two stage scraper system, or modifications of vacuum chambers.

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