УДК 539.1.07

TRACKING PERFORMANCE OF THE HERA-B OUTER TRACKER PC CHAMBERS

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The track-finding efficiency in the OTR PC chambers has been estimated from the real data by using external reference tracks provided by VDS, RICH, and ECAL reconstruction. A method of reducing the ghost fraction in the reference track sample has been developed. The experimental data taken during the 2000 run have been analyzed. A set of routines have been developed to provide a tool to estimate the track efficiency of the OTR. The limitations of the considered method are discussed in the conclusion.

Разработан метод оценки трековой эффективности PC-камер внешнего трекера (OTR) из анализа реальных данных с использованием опорного трека, полученного с помощью реконструкции в вершинном детекторе (VDS), детекторе черенковских колец (RICH) и электромагнитном детекторе (ECAL). Рассмотрен новый метод подавления доли ложных треков в наборе выделяемых опорных треков. Для анализа были использованы экспериментальные данные, набранные в сеансе облучения установки в 2000 г. В заключение обсуждаются ограничения на применимость рассмотренного метода.

INTRODUCTION

The Outer Tracker (OTR) consists of honeycomb drift chamber superlayers PC1–PC4, TC1–TC2 and also MC chambers in the magnet (see the general view of the HERA-B setup in Fig. 1). The complicated modular geometry of the OTR is described in [1]. The track-finding efficiency (track efficiency) in the PC chambers of the OTR has been studied with respect to reference tracks reconstructed in other subdetectors.

In a reference track approach, one should perform matching of the PC track segments with the track given by the external subdetectors placed before and after superlayers PC1–PC4. In the present study, information about segments of reconstructed track in the Vertex Detector System (VDS), Ring Imaging Cherenkov Counter (RICH) and Electromagnetic Calorimeter (ECAL) has been used to develop the reference VDS+RICH+ECAL track. Such reference tracks can be obtained either by matching a VDS segment with RICH and ECAL or from the full ARTE [2] reconstruction providing the VDS+ECAL track with the RICH ring assigned. A crucial point is a ghost fraction in the sample of reference tracks. Special selection criteria have been considered, and are detailed in the present paper, to reduce the ghost rate in the sample of reference tracks. Version ARTE-03-08-r7 was used for data analysis. Reconstruction of tracks in PC and TC areas was made by Ranger package [3].

We shall use the ARTE coordinate system: the Z axis goes along the proton beam starting near the target (the center of the magnet is given at 450 cm), the X axis is directed horizontally to the left when looking towards increasing Z, and the Y axis completes the orthogonal system, pointing upwards.

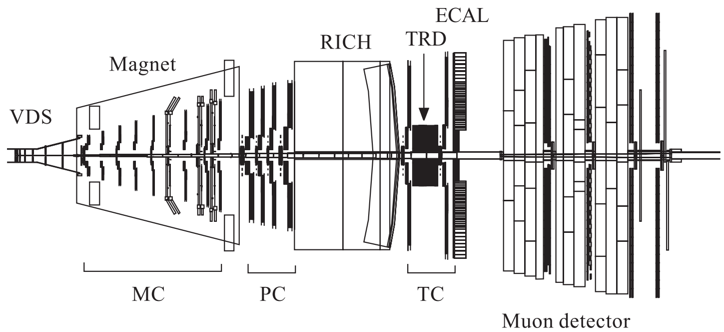

Fig. 1. General view of the HERA-B detector

1. METHODS FOR THE TRACK EFFICIENCY STUDY

The track efficiency in the PC chambers of the OTR is defined as the ratio

$$\varepsilon_{\rm tr} = N_{\rm tr}^{\rm OTR}/N_{\rm tr}\,, \tag{1}$$

where $N_{\rm tr}$ presents the total number of the external reference VDS+RICH+ECAL tracks, and $N_{\rm tr}^{\rm OTR}$ corresponds to the number of segments in the PC chambers of the OTR matched with reference tracks. Three methods were applied to study the OTR track efficiency from real data. These methods used different approaches to match VDS, RICH and ECAL segments in a reference track, to evaluate reference track parameters in PC chambers and to check the correspondence between the reference track and PC segment:

Method 1. The full VDS+RICH+ECAL reconstruction by ARTE is used without including the information from the OTR. After this we pick up a track having track segments in the VDS, RICH and a cluster in the ECAL. To get the reference track parameters at the PC chamber region after the magnet, the VDS segment is propagated through an inhomogeneous magnetic field (from $z_{\rm in} = 200$ cm to $z_{\rm out} = 680$ cm) using the value of momentum taken from this track. The estimates of track parameters at the position $z_{\rm out}$ of the outlet from the magnet are $t_x^{\rm ref}$, $t_y^{\rm ref}$, and in the ECAL are $x_{\rm ECAL}^{\rm ref}$, $y_{\rm ECAL}^{\rm ref}$.

We find an ECAL cluster with coordinates $x^{\rm ECAL}$, $y^{\rm ECAL}$, which are the nearest to $x_{\rm ECAL}^{\rm ref}$, $y_{\rm ECAL}^{\rm ref}$ and fulfill the requirements

$$|x_{\rm ECAL}^{\rm ref} - x^{\rm ECAL}| < x^{\rm cut}\,, \quad |y_{\rm ECAL}^{\rm ref} - y^{\rm ECAL}| < y^{\rm cut}\,. \tag{2}$$

A RICH segment with slopes $t_x^{\rm RICH}$, $t_y^{\rm RICH}$ is searched which fulfills the matching conditions with the track slopes $t_x^{\rm ref}$, $t_y^{\rm ref}$:

$$|t_x^{\rm ref} - t_x^{\rm RICH}| < t_x^{\rm cut}\,, \quad |t_y^{\rm ref} - t_y^{\rm RICH}| < t_y^{\rm cut}\,. \tag{3}$$

Here, $x^{\rm cut}$, $y^{\rm cut}$, $t_x^{\rm cut}$ and $t_y^{\rm cut}$ are the cutoff constants which can be fixed according to the widths of the correlated peaks in the distributions of track parameter differences. The typical histograms for track parameter differences are shown in Fig. 2 of Ref. [4], and the cutoff constants have been fixed as follows:

$$x_x^{\rm cut} = 0.6 \text{ cm}, \quad y_x^{\rm cut} = 3 \text{ cm},$$
$$t_x^{\rm cut} = 0.005, \quad t_y^{\rm cut} = 0.01.$$

It is supposed that the PC chambers have registered the segment related to the reference VDS+RICH+ECAL track if a PC segment was found which fits the matching conditions

$$\begin{aligned} |\Delta x_f| < x_f^{\rm cut}, \quad |\Delta x_e| < x_e^{\rm cut}, \\ |\Delta y_f| < y_f^{\rm cut}, \quad |\Delta y_e| < y_e^{\rm cut}. \end{aligned} \tag{4}$$

Here,

$$\Delta x_{f/e} = x_{f/e}^{\rm ref} - x_{f/e}^{\rm OTR}, \quad \Delta y_{f/e} = y_{f/e}^{\rm ref} - y_{f/e}^{\rm OTR},$$

where $x_{f/e}^{\rm ref}$ and $y_{f/e}^{\rm ref}$ are the coordinates of the VDS+RICH+ECAL track extrapolated downstream from the position $z_{\rm out}$ to the position $z_{f/e}^{\rm OTR}$ where the coordinates $x_{f/e}^{\rm OTR}$, $y_{f/e}^{\rm OTR}$ of the beginning/end of the PC segment have been determined. The values of the cutoff constants $x_{f/e}^{\rm cut}$ and $y_{f/e}^{\rm cut}$ can be fixed from the correlations of track parameters using distributions of the differences $\Delta x_{f/e}$ and $\Delta y_{f/e}$. The typical histograms are shown in Fig. 3 of Ref. [4], and the corresponding matching cutoff constants have been fixed as

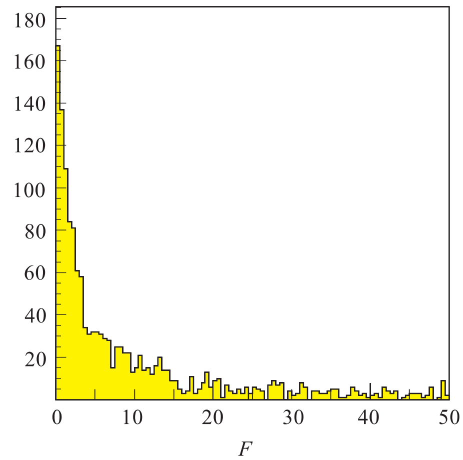

Fig. 2. The distribution of the value of the estimator F evaluated according to (5)

$$x_f^{\rm cut} = 3.3 \text{ cm}\,, \quad x_e^{\rm cut} = 3.3 \text{ cm}\,, \quad y_f^{\rm cut} = 2.7 \text{ cm}\,, \quad y_e^{\rm cut} = 2.6 \text{ cm}\,.$$

Method 2. The full VDS+RICH+ECAL reconstruction by ARTE is used without including the information from the OTR. The coordinates of the reconstructed VDS+RICH+ECAL track in the ECAL and its slopes in the RICH are used to define parameters $x_{f/e}^{\rm ref}$, $y_{f/e}^{\rm ref}$. Then track segments in the PC chambers are searched for matches, as defined by (4). The distributions of the differences $\Delta x_{f/e}$ and $\Delta y_{f/e}$ are shown in Fig. 4 of Ref. [4], and the corresponding cutoff constants have been fixed as

$$x_f^{\rm cut} = 5.4 \text{ cm}\,, \quad x_e^{\rm cut} = 5.2 \text{ cm}\,, \quad y_f^{\rm cut} = 5.3 \text{ cm}\,, \quad y_e^{\rm cut} = 5.1 \text{ cm}\,.$$

Method 3. In this case the full VDS+RICH+ECAL reconstruction is also used in the same way as in method 2. The difference is that instead of matching condition (4), a selection criterion based on the estimator of matching quality

$$F = \left(\frac{\Delta x_f}{\sigma_f^x}\right)^2 + \left(\frac{\Delta x_e}{\sigma_e^x}\right)^2 + \left(\frac{\Delta y_f}{\sigma_f^y}\right)^2 + \left(\frac{\Delta y_e}{\sigma_e^y}\right)^2 \tag{5}$$

is applied. The values of the constants $\sigma_{f/e}^x$ and $\sigma_{f/e}^y$ can be fixed from correlations of the parameters of tracks and segments. The track segment found in the PC chambers with the minimum value of F, and with $F < F^{\rm cut}$, where $F^{\rm cut}$ is a threshold constant, is selected at

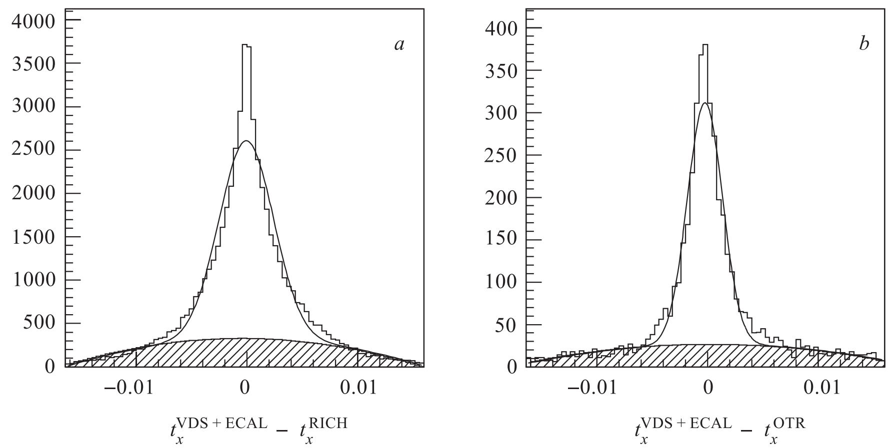

Fig. 3. Distributions of the slope differences used to estimate the ghost rates for the VDS+RICH+ECAL track reconstruction (*a*) and for matching PC segment with the VDS+RICH+ECAL track (*b*). The dashed area is considered as the ghost contribution

the best match. The typical histograms of track parameter differences are shown in Fig. 5 of Ref. [4], and the corresponding values of the constants $\sigma^x_{f/e}$ and $\sigma^y_{f/e}$ have been fixed as

$$\sigma^x_f = 2.0\ \mathrm{cm}\,, \quad \sigma^x_e = 1.9\ \mathrm{cm}\,, \quad \sigma^y_f = 1.8\ \mathrm{cm}\,, \quad \sigma^y_e = 1.6\ \mathrm{cm}\,.$$

The value of the threshold constant $F^{\mathrm{cut}} = 20$ was fixed by the distribution of F plotted for matched PC segments in Fig. 2.

2. STUDY OF THE GHOST RATE IN THE REFERENCE TRACK SAMPLE

A study has been performed to observe from the experimental data the ghosts for reconstruction of external reference tracks and their matching with the PC segment. For this purpose we used the VDS+ECAL tracks having a RICH ring assigned and corresponding to a momentum $p^{\mathrm{VDS+ECAL}} > 5$ GeV/c. Only events with the number of hits $900 < N_{\mathrm{hits}} < 10000$ in the PC chambers have been considered.

The distribution of the difference $(t_x^{\mathrm{VDS+ECAL}} - t_x^{\mathrm{RICH}})$ has been plotted, where $t_x^{\mathrm{VDS+ECAL}}$ is the slope of the VDS+ECAL track at the outlet from the magnet and t_x^{RICH} is the slope of the best candidate in the RICH. Then, the obtained slope difference plot (see Fig. 3) has been fitted with the sum of a Gaussian function (signal) and a quadratic polynomial function (ghosts) to estimate the ghost rate in case of VDS+RICH+ECAL track reconstruction. In an analogous way, using the PC segments to plot the slope differences $(t_x^{\mathrm{VDS+ECAL}} - t_x^{\mathrm{OTR}})$ (see Fig. 3) with the additional selection requirement $|t_x^{\mathrm{VDS+ECAL}} - t_x^{\mathrm{RICH}}| < 0.012$, we tried to estimate the ghost rate for PC segment matching. In both cases we observed a substantial background.

These results demonstrate the importance of taking into account the ghost rate corrections or reduction of ghosts by using additional selection criteria for reference tracks.

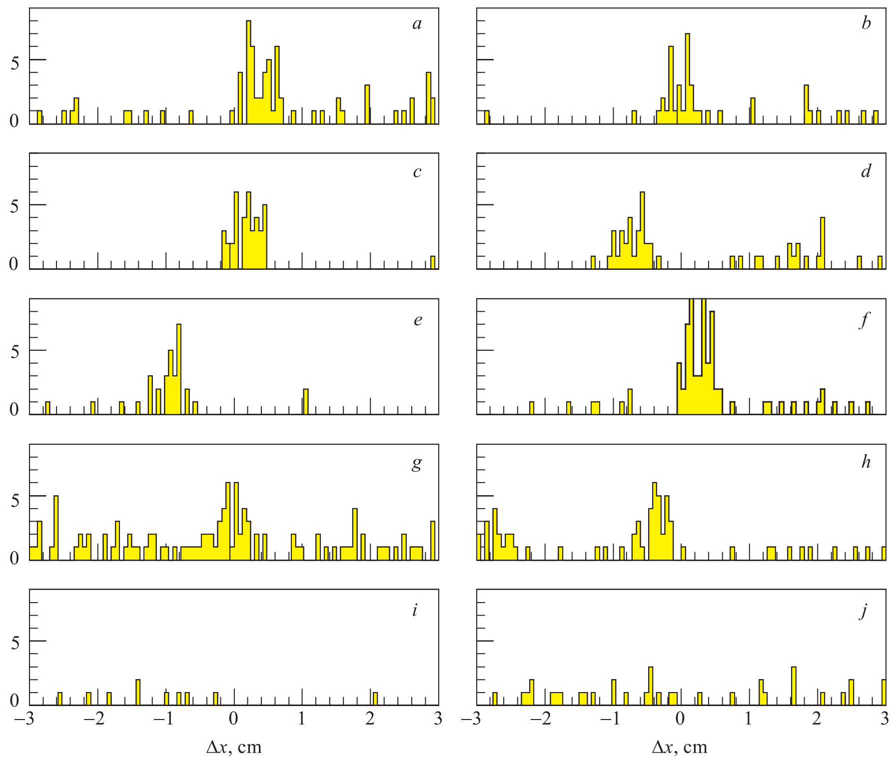

Fig. 4. Examples of histograms for the residual $\Delta x = x^{\rm tr} - x^{\rm hit}$ for individual events in run 14577: *a–h*) correspond to the case of found PC segment; *i, j*) correspond to the events where no track in PC was observed

3. REDUCTION OF REFERENCE TRACK GHOSTS

An idea for reducing the number of ghosts in the available sample of external VDS+RICH+ECAL tracks is to use the information on hits of the OTR detector itself. If we apply soft cuts, this will not lead to a large bias in the estimate of track efficiency. Figure 4 shows examples of histograms for the difference $\Delta x = x^{\rm tr} - x^{\rm hit}$, plotted for some of the typical events in run 14577. Here, $x^{\rm hit}$ is a hit coordinate, and $x^{\rm tr}$ is the coordinate of the VDS+RICH+ECAL track extrapolated into the PC chambers at the z position of the hit. One can see from Fig. 4 that there is usually a characteristic cluster of hits corresponding to an OTR segment. However, such clusters are absent for some events, or have a small size (see Fig. 4, *i, j*). This corresponds to the fact that for these external tracks there are no OTR hits, and most probably such an external VDS+RICH+ECAL track is a ghost.

To reduce the number of ghosts in the reference track sample VDS+RICH+ECAL used for the OTR track efficiency study in methods 1, 2 and 3, we developed the selection criteria based on the additional analysis of hits in the PC chambers as follows:

- A given VDS+RICH+ECAL track is extrapolated into PC chambers as a straight line. Then, the hit distribution of the coordinate difference Δx is plotted for all hits in the

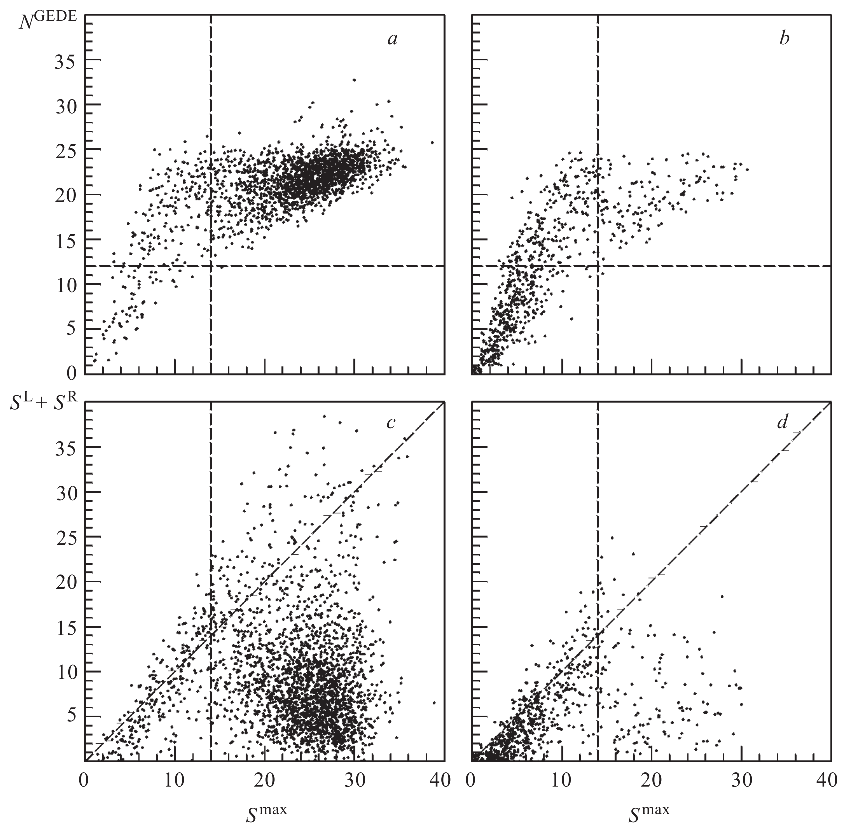

Fig. 5. Two-dimensional distribution of $S^{\max}$ and N^{GEDE} plotted for VDS+RICH+ECAL tracks with (*a*) and without (*b*) track registered in the PC chambers. The dashed straight lines correspond to the equations $N^{\mathrm{GEDE}} = 12$ and $S^{\max} = 14$. Two-dimensional distribution of $S^{\max}$ and $S^{\mathrm{L}} + S^{\mathrm{R}}$ plotted for VDS+RICH+ECAL tracks with (*c*) and without (*d*) track registered in the PC chambers. The dashed straight lines correspond to the equations $S^{\max} = S^{\mathrm{L}} + S^{\mathrm{R}}$ and $S^{\max} = 14$

PC chambers within the window $|\Delta x| < 3$ cm around this straight line. The size of the histogram channel in Δx was chosen to be equal to 1 mm.

- For each group of five neighbouring channels in Δx, the sum

$$S = \sum_{i=1}^{5} N_i(\Delta x) \tag{6}$$

is calculated, where $N_i(\Delta x)$ is the number of hits in the i-th channel of the histogram. If a cluster of five neighbouring channels with a maximal value of (6), $S^{\max}$, is found, then analogous sums, S^{L} and S^{R}, are calculated for five neighbouring channels of the histogram both on the left- and right-hand sides from this cluster, respectively.

- The VDS+RICH+ECAL track is used as the reference track for matching with the OTR segments in methods 1, 2 or 3 only if the following three conditions are fulfilled simultaneously:
    - ◇ $N^{\rm GEDE} \geq N^{\rm GEDE}_{\rm cut}$, where $N^{\rm GEDE}$ is the number of sensitive volumes («GEDE» volumes in ARTE's terminology [2]) with hits within the window $|\Delta x| < 3$ cm around the straight line extrapolating the VDS+RICH+ECAL track into the PC chambers, and $N^{\rm GEDE}_{\rm cut}$ is some cutoff;
    - ◇ $S^{\rm max} \geq S^{\rm max}_{\rm cut}$, where $S^{\rm max}_{\rm cut}$ is some cutoff;
    - ◇ $S^{\rm max} \geq S^{\rm L} + S^{\rm R}$.

  Otherwise, the VDS+RICH+ECAL track is considered as a ghost.

To choose the values of the cutoff parameters $N^{\rm GEDE}_{\rm cut}$ and $S^{\rm max}_{\rm cut}$, the two-dimensional distribution of $S^{\rm max}$ and $N^{\rm GEDE}$ is plotted for only VDS+RICH+ECAL tracks confirmed by observation of track in the PC chambers. From such a histogram, shown in Fig. 5, *a*, the values of $N^{\rm GEDE}_{\rm cut} = 12$ and $S^{\rm max}_{\rm cut} = 14$ have been fixed. For comparison, in Fig. 5, *b* we show the two-dimensional distribution of $S^{\rm max}$ and $N^{\rm GEDE}$ plotted for VDS+RICH+ECAL tracks without observation of track in the PC chambers. In addition, the two-dimensional distributions of $S^{\rm max}$ and $S^{\rm L} + S^{\rm R}$ plotted for VDS+RICH+ECAL tracks are also shown in Fig. 5, *c, d*. It is easy to see from Fig. 5 that VDS+RICH+ECAL tracks confirmed by observation of track in the PC chambers are concentrated in the regions corresponding to the selection criteria

$$N^{\rm GEDE} \geq 12\,, \qquad S^{\rm max} \geq 14\,, \qquad S^{\rm max} \geq S^{\rm L} + S^{\rm R}\,.$$

4. TRACK EFFICIENCY STUDY

All the methods discussed in section 1 have been applied for the analysis of two runs, 14577 (minimum bias events) and 16371 (triggered events, First Level Trigger $\mu + e$). The following selection criteria have been used:

- Only events with the total number of hits $900 < N_{\rm hits} < 10000$ in the PC chambers have been used (see the distribution of $N_{\rm hits}$ for all events in Fig. 6). A requirement was made also for the mean TDC count value per event $157 < \bar{t} < 180$ and its RMS value $\sigma_t < 50$. These criteria partially discard the events produced by the coasting beam.
- When using method 1, only those VDS segments which are longer than 50 cm and correspond to momentum $p > 5$ GeV/c have been selected.
- In all the three methods only those VDS+RICH+ECAL tracks which passed through more than 20 sensitive GEDE volumes in the PC chambers of the OTR have been considered.

The average numbers of hits in the PC chambers within the range $900 < N_{\rm hits} < 10000$ were found to be about 4760 for run 14577, and 5860 for run 16371. Table 1 shows the final

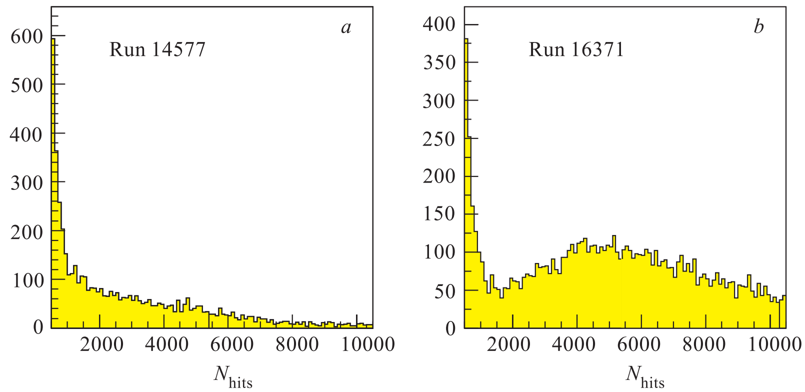

Fig. 6. Event distributions of the number of hits in the PC chambers of the OTR

Table 1. **Track efficiency in the PC chambers of the OTR (in %) for events with** $900 < N_{\rm hits} < 10000$ **after reduction of reference track ghosts**

Run	Method 1			Method 2	Method 3	$N_{\rm tr}$
	Matching in XZ	Matching in YZ	Full			
14577	94.4	95.7	91.4	92.9	93.7	2300
16371	86.7	93.0	82.9	78.4	80.5	1250
14577 ($x < 0$)	96.2	96.3	93.5	94.6	95.6	1200
14577 ($x > 0$)	91.8	94.2	88.7	89.3	91.1	1100

results of track efficiency in the PC chambers obtained by different methods after applying to VDS+RICH+ECAL tracks the additional selection criteria described in the previous section. These criteria reduce the numbers of ghost tracks in the reference track sample.

For run 14577, with method 1, the fraction of discarded reference tracks is about 30 %, while with method 2 or 3 about 33 %. The track efficiency for run 14577 (method 3) defined with respect to the initial reference sample is 78.1 %. It increases up to 93.7 % after applying the procedure of reduction of reference track ghosts. This change of efficiency by about 15 % indicates a real ghost level in the initial reference sample rather than a fraction of discarded reference tracks, which is about 30 %. For run 16371, the fraction of discarded reference tracks is, on average, at the level of $38 \div 40$ %.

In the present study we call the reference tracks discarded according to the described procedure «ghosts». This is only a jargon. More exactly, we clean up sample of reference tracks from ghosts, but probably not all of the discarded reference tracks are ghosts.

In method 1, the track efficiency obtained in the case that only XZ projections are matched is lower when compared to YZ projection matching. This observation can be explained by the influence of the following factors:

- Because of the lower precision of track reconstruction in the YZ projection, we should take larger values of $t_y^{\rm cut}$ as compared to $t_x^{\rm cut}$.

- The spread of the PC segment distribution of t_y is less than that of t_x since the magnetic field deflects tracks only in the XZ plane. Therefore, there is a larger probability to have a match in the YZ plane than in the XZ plane.

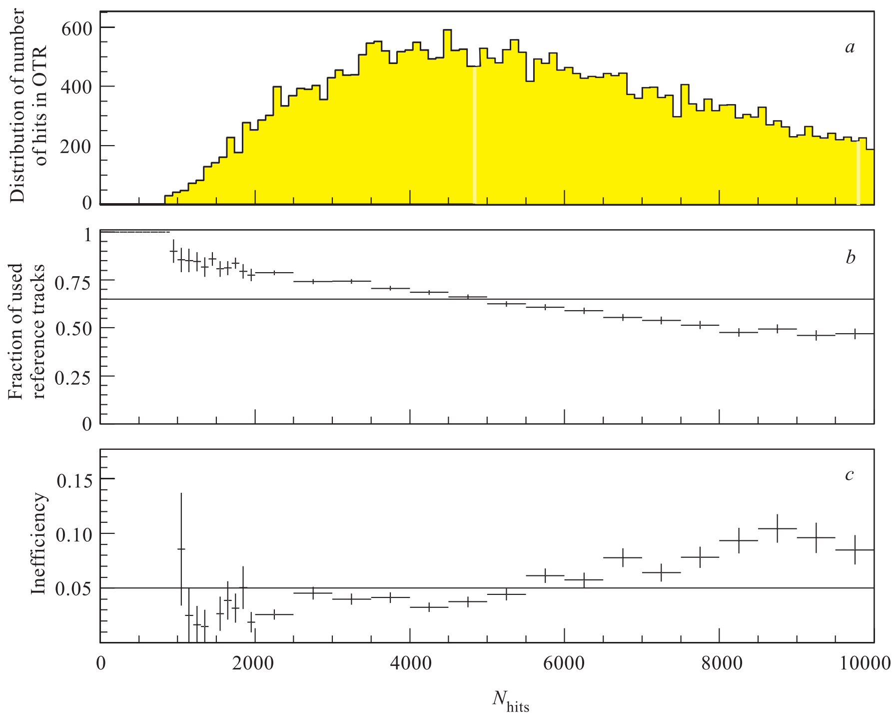

Fig. 7. Dependence of the PC chambers track-finding inefficiency on the number of hits

Different methods give similar results (within errors of a few percent) for each run. No large asymmetry between the $+x$ and $-x$ sides of the PC superlayers has been observed, but lower track efficiency in $+x$ is evident. It is in agreement with lower cell efficiency in this side of the PC superlayers. Here, a segment is considered to be on the $x < 0$ ($x > 0$) side if the x coordinates of both its beginning and end are negative (positive).

Several next figures (Figs. 7–9) have been done for method 3, which was enhanced by using a full refit of VDS and RICH segments and ECAL clusters to define a reference track. Such a procedure gives a more accurate prediction of the x coordinate of the reference track in the PC chambers region. The dependence of the PC chambers track-finding inefficiency on the number of hits is shown in Fig. 7. The fraction of used reference tracks decreases with growth of N_{hits} while the track efficiency is rather stable with respect to occupancy and falls for very busy events when $N_{\text{hits}} > 7000$ because of the large number of possible hit combinations under high occupancy of the PC chambers. The value $N_{\text{hits}} \approx 7000$ corresponds to about 5 inelastic interactions. Nevertheless, the track efficiency for runs 14577 and 16371

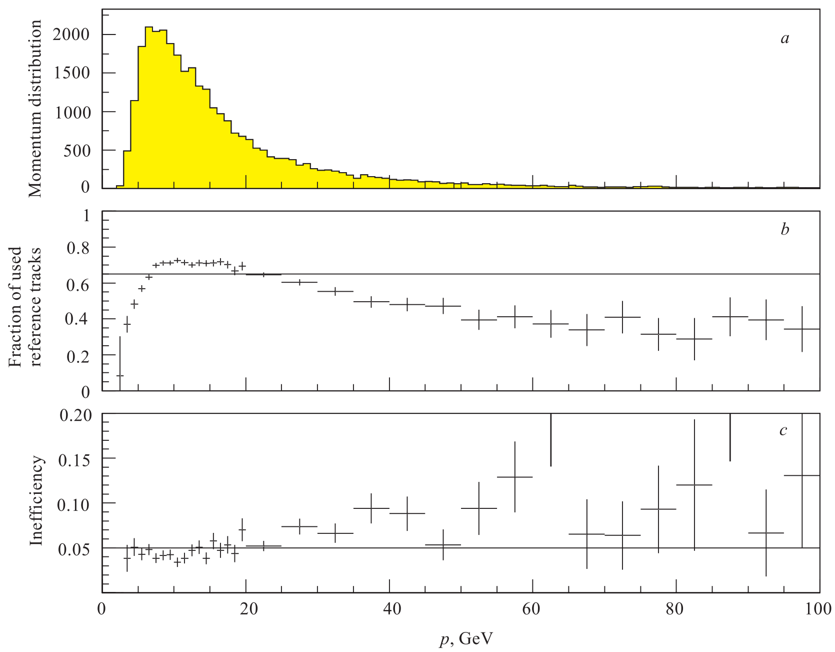

Fig. 8. Dependence of the PC chambers track-finding inefficiency on the momentum of the track

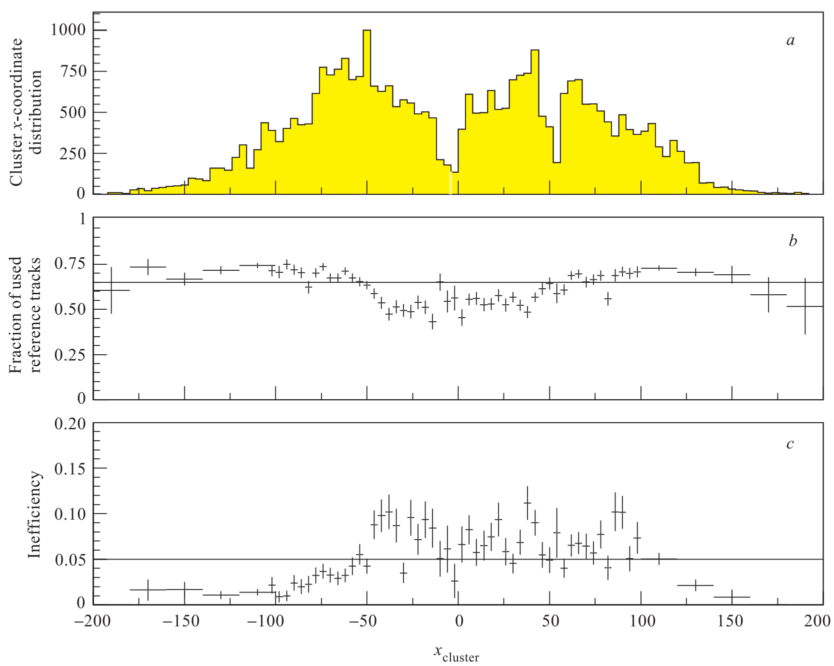

Fig. 9. Dependence of the PC chambers track-finding inefficiency on the x coordinate of ECAL cluster

Table 2. **Fraction of various particles, corresponding track efficiency and fraction of used reference tracks**

Particle	Fraction, %	$\varepsilon_{\rm tr}$, %	$f_{\rm used}$, %
e	23	95.0	59
μ	23	95.8	72
π	46	95.3	77
K	6	92.2	45
p	2	90.3	29

(with different trigger conditions) differs significantly (see Table 1). Figure 8 shows that the fraction of used reference tracks decreases with momentum, but there is no significant momentum dependence of track efficiency. In Fig. 9 we plot the dependence of the fraction of used reference tracks and inefficiency on the x coordinate of the cluster in the ECAL which has

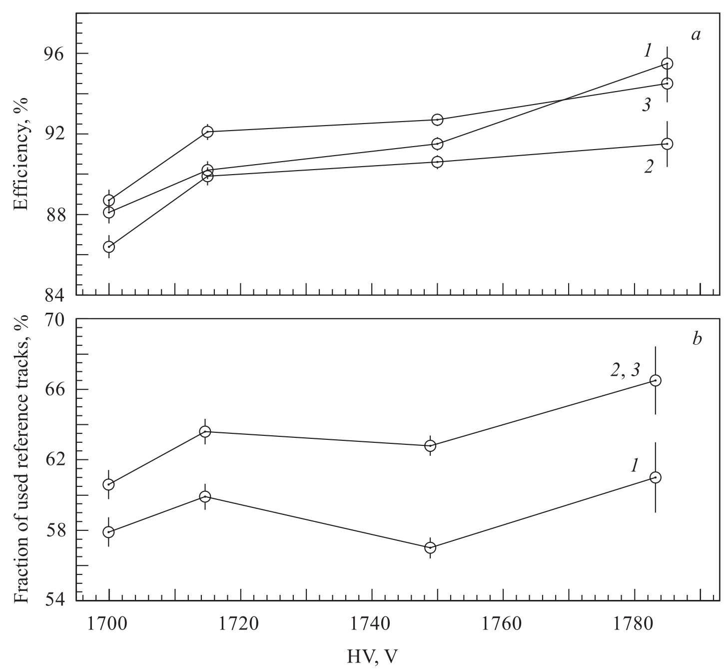

Fig. 10. High voltage scan results: *a*) dependence of the track efficiency in PC chambers on high voltage at 5-mm chambers; *b*) dependence of the fraction of used reference VDS+RICH+ECAL tracks on high voltage. The lines are labelled with the number of the method used

been used to define the reference track. One can see that inefficiency drops significantly for $x_{\rm cluster} < -50$ cm. This can possibly be attributed to a non-uniform picture of the ECAL cluster distribution on the XY plane. If we take only the tracks having $x_{\rm cluster} < -50$ cm, the PC track efficiency is $97.3 \pm 0.2\,\%$, and the fraction of used reference tracks is estimated to be 70 %. It is also interesting to compare track efficiency for various particle species. We have obtained estimates with an additional requirement that the Cherenkov ring radius measured by the RICH is compatible with the various particle species hypothesis using the momentum estimate from the external track (see Table 2) [5].

Figure 10 shows the dependences of the track efficiency and fraction of used reference tracks on high voltage for runs from HV scan. The systematic uncertainties can be studied if one considers the variation of the cut F^{cut}. Figure 11 shows the corresponding variation of the inefficiency.

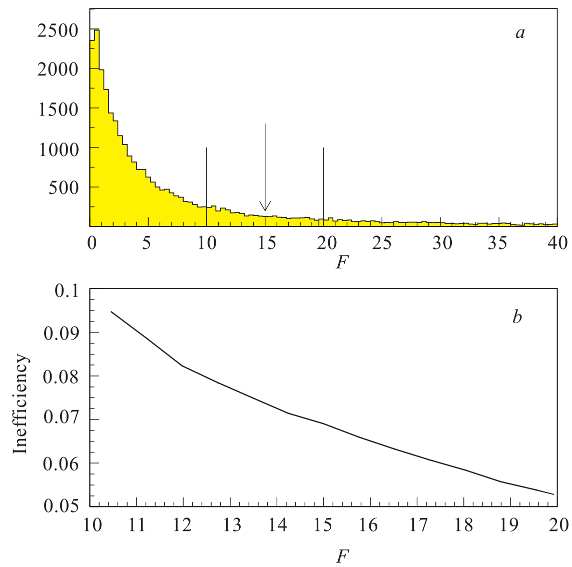

Fig. 11. Systematic uncertainties due to the choice of F^{cut}: *a*) distribution of F and the chosen cut; *b*) variation of the inefficiency according to the F^{cut} value

CONCLUSION

In the paper we have presented the results of a systematic study of an approach to estimate the track-finding efficiency of the OTR PC chambers. The approach uses the tracks defined by VDS, RICH and ECAL subdetectors as the reference ones. Three methods were applied to study the OTR track efficiency. These methods used different approaches to matching VDS, RICH segments and ECAL clusters, evaluation of the reference track parameters in the PC chamber and checking the correspondence of the reference tracks and PC segments.

The study has shown that it is difficult to obtain an absolute value of the track efficiency because of two reasons: (i) the ghost fraction in the sample of VDS+RICH+ECAL tracks is too high; (ii) the criteria to select the reference track and match them with the PC segment have some degree of freedom. This can introduce a systematic bias in efficiency. We have estimated it at least as large as a few percent.

Nevertheless, this approach can be used to estimate the track-finding efficiency in the PC chambers and to study relative changes of efficiency. The study has shown rather stable behaviour of efficiency with respect to the occupancy and momentum of reconstructed particles. The method can also be used for monitoring the detector performance and reconstruction procedure.

A set of routines have been developed to provide a tool to estimate track efficiency in the OTR. The routines are described in the paper [4].

Acknowledgements. We would like to thank D. Dujmič, P. Moissenz, O. Igonkina, K. Reeves, B. Schmidt and U. Uwer for useful and helpful discussions. The major part of the study was made when the authors visited DESY. We would like to thank DESY for the kind hospitality extended to us during these visits.

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Received on January 15, 2002.