Update on the performance of the HERA-B Vertex Detector System

I. Abt\textsuperscript{a, *}, T. Perschke\textsuperscript{a}, S. Schaller\textsuperscript{a}, S. Masciocchi\textsuperscript{b}, C. Bauer\textsuperscript{c}, M. Bräuer\textsuperscript{c}, W. Hofmann\textsuperscript{c}, T. Jagla\textsuperscript{c}, K.T. Knöpfle\textsuperscript{c}, M.A. Pleier\textsuperscript{c}, K. Reeves\textsuperscript{c}, M. Schmelling\textsuperscript{c}, B. Schwingenheuer\textsuperscript{c}, F. Sciacc\textsuperscript{a}

\textsuperscript{a}Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 München, Germany
\textsuperscript{b}Deutsches Elektronen Synchrotron, Notkestr. 85, 22607 Hamburg, Germany
\textsuperscript{c}Max-Planck-Institut für Kernphysik, Postf. 103980, 69029 Heidelberg, Germany

Abstract

The HERA-B Vertex Detector System (VDS) is a Roman Pot system integrated into the proton ring of the HERA accelerator at DESY and serves as an independent part of the tracking system of the HERA-B forward spectrometer. The performance of the VDS meets the design specification. It is based on double-sided silicon micro-strip detectors which are operated as close as 1 cm to the beam and are thus exposed to extremely high and inhomogeneous radiation levels. At the design luminosity the peak irradiation is around $3 \times 10^{14}$ minimum ionizing particles per cm$^2$ per year. Test measurements have shown adequate radiation tolerance on the required time scale of 1 year. New long-term studies presented here indicate that on periods longer than 1 year charge collection efficiencies might drop.

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Keywords: HERA-B; Vertex detector; Roman pot; Vertex resolution; Silicon strip detector; Radiation damage

1. Introduction

HERA-B \cite{1} is a forward spectrometer operating at the proton storage ring HERA at DESY, Hamburg. Protons with an energy of 920 GeV interact with a fixed target consisting of wires arranged around the beam. HERA-B was originally designed to study CP violation using $B \rightarrow J/\Psi K^0$ decays and is now used for a wide variety of studies of proton nucleon interactions focusing on the prompt production of $J/\Psi$ mesons.

The Vertex Detector System (VDS), covering an acceptance from 10 to 250 mrad vertically and horizontally, is based on double-sided silicon strip detectors integrated in a Roman pot system. It has been described in detail in Ref. \cite{2} and Ref. \cite{2–5} therein. The silicon strip detectors \cite{3} are mounted perpendicular to the beam and are arranged in eight super-layers and four quadrants. Each quadrant of a super-layer contains two silicon micro-strip detectors. In total this amounts to 64 detectors. The double-sided option was chosen in order to minimize material. Each detector has an

*Corresponding author.
E-mail address: isa@mppmu.mpg.de (I. Abt).
active area of $50 \times 70 \text{ mm}^2$. The read-out pitch is $\approx 50 \text{ m}$m. The strips are tilted by $2.5^\circ$ with respect to the edge of the detector. This yields a stereo angle of $5.0^\circ$ when mounting two detectors back to back. Detectors from two sources, SINTEF and the semiconductor laboratory HLL of the MPI, are in use.

The minimum design specification for the decay length resolution for secondary $J/\Psi$ vertices was to be less than 10% of the mean decay length of $B_d$-mesons in HERA-B which is $\approx 10 \text{ mm}$. However, the aim was to have a significantly better resolution.

In Ref. [2] also the VDS auxiliary systems, i.e. vacuum, RF-shield and cooling, are described. In addition the performance of the system as achieved in the commissioning run in 2000 is given. This paper can be considered as an update of Ref. [2]. It is organized as follows: First results of an irradiation test of detectors produced by SINTEF which come from a batch also used in the experiment are presented. This is followed by results from a complimentary study of the damage to detectors inside the HERA-B setup which were produced by the semiconductor laboratory HLL. The paper closes by presenting the initial performance of the HERA-B silicon tracker in 2002.

2. Radiation tolerance

In Ref. [2] we reported that the radiation damage constant observed during the initial commissioning of HERA-B in 2000 agrees well with the expectation [4]. We also reported that dedicated tests [5,6] have shown that the silicon detectors should be operational within the HERA-B setup for 1 year where at design luminosity a fluence of $3 \times 10^{14}$ minimum ionizing pions per cm$^2$ at the detector edge is expected.

For the irradiation tests it was not possible to recreate the particle spectrum from the experiment. The irradiation test facility at the MPI Heidelberg is described in detail in Ref. [8]. It uses 21 MeV protons scattered off a 50 m$m$m thick Au-target to produce inhomogeneous irradiation of approximately the same shape as observed in HERA-B. The fluence varies by a factor of 250 between the innermost and outermost detector areas. During irradiation the detectors were biased with 140 V and cooled to $10^\circ$C. The readout chips were shielded to avoid any damage to them. Both detectors were irradiated individually with a peak fluence of about $1 \times 10^{14}$ protons/cm$^2$. This should result in approximately the same damage as expected in the HERA-B setup. We estimate that the absolute fluence determination for the test setup is better than 20%

In a long-term follow up of the original publication [6] two detectors which were irradiated in September 2000 in a comparative test of an oxygenated and a standard detector were studied. Both detectors were produced by SINTEF with individual atoll “p-stop” isolation on the n-side. One detector was oxygenated [7] to a level of $2 \times 10^{17}$ cm$^3$, the other one remained at the “normal” level of $10^{16}$ cm$^3$. Both detectors were integrated in fully assembled standard HERA-B VDS modules with HELIX readout chips which have a rise time of the pulse shaping of 50 ns.

The characterization of the detectors was done with a laser test-stand and the determination of the signal to noise ratios with a $^{106}$Ru source. Three weeks after irradiation in regions of low radiation dose, signal over noise ratios of 22 and 16 were measured for n- and p-side, respectively. In the region of maximum fluence, $S/N$ values of $17$ and $15$ were obtained at a bias voltage of 450 V for n- and p-strips, respectively. The dependence of $S/N$ on the bias voltage is described in detail in Ref. [6]. On the n-side the full signal is observed already at lower bias voltages, around 300 V. This is due to the higher mobility of the electrons. The effect is seen because the pre-amplifier has a short, 50 ns, shaping time. The noise level does not change significantly with the bias voltage. The fact that the signal to noise ratios in general are better on the n-side is caused by the geometry of the detectors and modules which results in input capacitances of $8 \text{ pF}$ on the n-side and $10 \text{–} 20 \text{ pF}$ on the p-side. The standard and the oxygenated detectors did not show any significant difference. This could be due to the relative high concentration of oxygen in the normal detector which is due to the SINTEF production process.

The laser test-stand used to study charge collection and division is described in detail in
Ref. [9]. For the tests described here the laser was tuned to 950 or 1050 nm corresponding to penetration depths of about 100 and 400 μm, which has to be compared to the wafer thickness of 300 μm. The beam always hits the detectors from the n-side. There is no precise absolute calibration of the laser pulse. A charge equivalent to the deposit of approximately two minimum ionizing particles was injected. The core [1 sigma] width of the beam on impact was around three strips and 20 strips were summed up for the analysis.

After 8 months at room temperature the charge collection dependence on the bias voltage was measured in all regions of the detector, i.e. “area of highest irradiation” (H) where type inversion is completed, “transition area” (T) where type inversion is in progress and “area of low irradiation” (L) where the crystal is basically undamaged. Like before the irradiation we did not observe any abnormal behavior. Plots are shown in Ref. [6]. At temperatures below 10°C all regions could be operated simultaneously using a bias voltage of about 400 V. However, at higher temperatures and high voltages (above 400 V for the oxygenated and above 500 V for the normal detector) some localized areas in region H did show large noise and no signal.

Depletion voltages were deduced from the charge collection versus. voltage behavior on the p-side, where full depletion was assumed at the 90% level of the maximum signal. That takes the further increase in signal after full depletion due to the faster movement of holes in higher fields into account. Fig. 1 shows the depletion voltage versus the n-side strip number after 8 months for both detectors. The measurements were taken in the middle of the detectors with respect to the other dimension. The region up to about strip 375 is type inverted on both detectors.

The studies were continued after an additional 6 months of storage at 8°C. After 14 months no signal could be reproducibly found in the ≈50 strips of highest irradiation in region H of the oxygenated detector while the corresponding strips of the normal detector still worked well. It has been pointed out [10] that for strongly oxygenated detectors the radiation induced increase of oxide charge can lead to locally enhanced electric field strengths and, as a consequence, to electric breakdown and micro-discharges. This could be a possible explanation for the observed behavior. The setup did not allow further investigation.

After 14 months we also observed that the charge collection of both detectors showed severe degradation on the n-side and some on the p-side. Fig. 2 shows the charge collection versus bias voltage at various positions for a wavelength of 1050 nm for the normal detector. The top left picture depicts the response for a strip in region H with highest irradiation. The strip used in the top right picture is still in the type inverted area of the detector. The two plots in the middle depict strips that are in the dip, i.e. in the area T of type inversion. The bottom 2 pictures show strips from region L which basically did not see any irradiation. In regions T and L the charge collection...
Fig. 2. Relative signal size versus biasing voltage for the normal detector after 14 months at different spots, see also Fig. 1, probed with 1050 nm wavelength. The top left picture represents the area of highest irradiation, the top right depicts the situation in the type inverted region at a full depletion voltage of ≈150 V. The two pictures in the middle represent different strips in the area of type inversion, region T in Fig. 1, and the two bottom pictures depict results from the area of low irradiation, region L in Fig. 1. Each curve is normalized to 1 for the highest value. As a guidance to the eye two dashed lines corresponding to 1% and to 90% of the average of the last 5 points for the n-side are drawn.
efficiency drops dramatically when the detector is over-biased. Additional tests performed at 950 nm wave-length, i.e. lower penetration, showed identical results. The behavior of the oxygenated detector was, as before, very similar. While we have no model to explain this behavior quantitatively, it was pointed out [11] that the p-isolation in the n-side connects all areas of the detector. Its potential adjusts to the area of the highest fields, i.e. highest irradiation. This might create strong mismatches in the other areas. More studies after 18 months of storage revealed additional operational problems including oscillations.

In the experiment in Hamburg the detectors were so far not exposed to as much radiation as the detectors in the test studies. However, we investigated a module that was exchanged in 2000 after 2 years of operation during the commissioning and had a radiation load of \( \approx 10\% \) of a nominal HERA-B year [4]. In the HERA-B geometry some n-side strips were exposed to \( 1.1 \pm 0.2 \times 10^{13} \) pions per cm\(^2\) at one end and effectively no radiation at the other. Type inversion did not occur at any location on the detector. The detector was produced at the silicon facility of the Max-Planck-Institut in Munich. The n-side strip isolation technology used was “p-spray”. Table 1 lists the values for signal to noise versus the bias voltage as obtained with the Ru source for both ends of the affected n-side strips. The absolute level of the noise did not change significantly for the different bias voltages.

The laser test-stand was again used to determine the depletion voltage using the charge collection on the p-side. In the area of highest irradiation a drop of depletion voltage from \( \approx 85 \) to \( \approx 70 \) V was observed. Fig. 3 shows the normalized charge collection versus bias voltage for the affected strips at both ends. On the n-side we see an anomaly above the depletion voltage which is not observed for n-side strips which were not exposed to significant irradiation in any section. We did not observe any anomaly for p-side strips. It should be noted that degradations of the levels observed in this module are insignificant for the overall operation of the HERA-B VDS.

### Table 1
Signal to noise ratio for both ends of inhomogeneously irradiated n-side strips

<table>
<thead>
<tr>
<th>Bias voltage (V)</th>
<th>40</th>
<th>80</th>
<th>120</th>
<th>160</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S/N ) irradiated end</td>
<td>7</td>
<td>15</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>( S/N ) unirradiated end</td>
<td>7</td>
<td>9</td>
<td>14</td>
<td>16</td>
</tr>
</tbody>
</table>

Fig. 3. Normalized charge collection versus bias voltage for the irradiated (top) and unirradiated (bottom) end of inhomogeneously irradiated n-side strips. Also depicted are the responses of the p-side strips at the same location. Each curve is normalized to 1 for the highest response. As a guidance to the eye two dashed lines corresponding to 1% and to 90% of the average of the last 5 points for the n-side are drawn. The bars on each point indicate the r.m.s. widths of the charge distribution for 100 events.

3. Performance

As pointed out in Ref. [2], the HERA-B VDS reached its design specifications during the commissioning run in 2000. The VDS can provide independent tracking and vertexing. In general it is
advantageous to have the tracking based on space-points in order to avoid ambiguities. However, the construction of space-points from hits is only reliable in a low noise environment. The noise level in the HERA-B VDS is typically well below 0.05% and thus allows this procedure. Pattern recognition is performed using a cellular automaton. The complete procedure is described in Ref. [12] and yields a tracking efficiency of $\geq 95\%$ for tracks with momenta larger than 1 GeV, even for high density, multiple interaction events.

The procedure to reconstruct primary vertices consists of wire constrained track clustering and an extended Kalman estimator [13]. It should be noted, that the track momenta are not used in the purely geometrical vertex fit itself, but taken into account in the error calculation. In order to allow rigorous error calculation no wire constraint is used in the final vertex fit.

Aside of the VDS the HERA-B tracking system includes a large number of honeycomb drift chambers and micro-strip gas chambers. Both components were significantly improved between the commissioning run in 2000 and the restart of data taking in 2002. Tracks are independently reconstructed in the VDS and the rest of the system and then matched, if possible. As by design the VDS has a larger acceptance than the rest of the system, even with perfect efficiencies not all tracks can be matched and not all tracks can be assigned a momentum. Extensive Monte Carlo studies [14] were performed to determine the optimal selection of tracks for the vertexing procedure. Several selection criteria like length of track, reconstruction in all detector components and momentum were investigated to optimize the resolution. However, the determining factor proved to be the track multiplicity in the vertex. Any improvement that could be achieved due to quality cuts in the tracks is over-compensated by the reduction of number of tracks. Therefore it proved to be best to use all reconstructed tracks seen in the VDS. About $\approx 30\%$ of them are only reconstructed in the VDS and have thus, by construction, no momentum assigned. Fig. 4 shows the primary vertex resolution versus the number of tracks. The minimum number of tracks in a vertex accepted is three.

HERA-B has two target stations approximately 4 cm in $z$ apart with four wires (inner, outer, above, below) of different materials each. The primary vertex resolution is affected by the target material, as high $Z$ materials produce events with higher track multiplicity. The $z$ position is important as it changes the angular acceptance for tracks and in addition the distance to the first measured hit. The first plane of the VDS is located at approximately $z = 9.6$ cm. During 2002 mostly three wires were used. Table 2 gives their position in $z$, material and overall primary vertex resolution.

The resolutions given in Table 2 were determined using the area weighted widths from double Gaussian fits. If these resolutions together with the geometry of the wires are used to predict the longitudinal widths of the primary vertex distributions in the simple frame-work of Gaussian errors, the results differ up to 30 $\mu$m from the direct Monte Carlo determination of the widths. This is
Table 2
Primary vertex resolution for different wires as determined in Monte Carlo studies for minimum bias, i.e. proton nucleon events without heavy quark production

<table>
<thead>
<tr>
<th>Station</th>
<th>Wire</th>
<th>Material</th>
<th>Geometry</th>
<th>Position (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Inner</td>
<td>C</td>
<td>ribbon</td>
<td>$z = -4.59$</td>
</tr>
<tr>
<td>1</td>
<td>Below</td>
<td>C</td>
<td>ribbon</td>
<td>$z = -1.12$</td>
</tr>
<tr>
<td>1</td>
<td>Inner</td>
<td>W</td>
<td>circ. $d = 500 \mu m \times 100 \mu m$</td>
<td>$z = -0.55$</td>
</tr>
</tbody>
</table>

Average number of reconstructed tracks/vertex

<table>
<thead>
<tr>
<th>Resolution</th>
<th>8.2</th>
<th>8.4</th>
<th>13.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x (\mu m)$</td>
<td>40</td>
<td>41</td>
<td>31</td>
</tr>
<tr>
<td>$y (\mu m)$</td>
<td>42</td>
<td>40</td>
<td>32</td>
</tr>
<tr>
<td>$z (\mu m)$</td>
<td>430</td>
<td>350</td>
<td>260</td>
</tr>
</tbody>
</table>

The wires with the ribbon geometry have a rectangular cross-section with the larger dimension aligned in $z$, i.e. with the proton beam axis.

an estimate of the systematic error of the longitudinal resolutions as quoted here. In $x$ and $y$ we estimate an error of about 3 $\mu m$.

There is no significant difference in the resolution in $x$ and $y$, i.e. parallel or perpendicular to the wire. The transverse resolution is not affected by the larger distance of station 2 to the VDS. The longitudinal resolution, however, shows a very clear effect. It is extremely sensitive to the steep tracks measured in the very first planes of the VDS. The comparison between the carbon and the tungsten wire in station 1 clearly shows the importance of track multiplicity.

Because HERA-B routinely runs with multiple interactions, the ability to separate primary vertices in space is important. Monte Carlo studies [14] show that two vertices 250 $\mu m$ apart are separately identified with a probability of $\approx 50\%$. At a distance of 750 $\mu m$ we reach $\approx 90\%$. These numbers mainly depend on the track clustering procedure.

Data taken in 2002 was reconstructed online and was compared with the Monte Carlo predictions. The micro-strip gas chambers were not yet included and the online reconstruction used a very preliminary alignment. The resolution is not directly observable in the data and therefore Table 3 lists the longitudinal width of the primary vertex distribution for randomly triggered events, i.e. proton–nucleon interactions, in Monte Carlo and data. The discrepancies of around 200 $\mu m$ are within the range of a contribution expected from a preliminary alignment. The individual modules of the VDS have to be moved by $\approx 2$ cm during the injection and thus for optimal performance at least one alignment per fill is needed. This was not done for the online reconstruction so far. In Ref. [15] it was shown that this can cause extra contributions to the longitudinal vertexing resolutions of up to 400 $\mu m$. However, we should note that the wire geometry as quoted is an ideal geometry, especially for the carbon ribbons. In addition the Monte Carlo used for proton–nucleon interaction does not take heavy quark production into account. In the data there is charm production at the $10^{-3}$ level which adds tracks from decays which also can affect the distribution.

The resolution for prompt $J/\Psi$ mesons, i.e. $J/\Psi$s produced in the primary interaction, was studied for the wire inner 2 which is our “worst case scenario”. The longitudinal resolution in Monte Carlo was found to be 460 $\mu m$ without using a mass constraint. Observable in data is the longitudinal width of the vertex distribution for prompt $J/\Psi$ mesons, i.e. $J/\Psi$s produced in the primary vertex. The width of this distribution is predicted to be 510 $\mu m$ and observed to be 560 $\mu m$. The discrepancy is compatible with what is observed for primary vertices. The predicted decay length resolution for $J/\Psi$ mesons is 690 $\mu m$. The data as given in Fig. 5 show a width of 750 $\mu m$. Again that is compatible with an extra contribution of about 200 $\mu m$ the primary and $J/\Psi$ vertex resolution. The decay length is calculated after the lepton tracks from the $J/\Psi$ are removed from the primary vertex and it is refit. In the data we expect a small contribution to the decay length distribution from misidentified

Table 3
Longitudinal width of the primary vertex distribution for minimum bias events as seen in Monte Carlo and data in $\mu m$

<table>
<thead>
<tr>
<th>Station</th>
<th>Wire</th>
<th>MC ($\mu m$)</th>
<th>Data ($\mu m$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>Inner</td>
<td>450</td>
<td>500</td>
</tr>
<tr>
<td>1</td>
<td>Below</td>
<td>380</td>
<td>410</td>
</tr>
<tr>
<td>1</td>
<td>Inner</td>
<td>290</td>
<td>340</td>
</tr>
</tbody>
</table>

The discrepancy is compatible with what is observed for primary vertices. The predicted decay length resolution for $J/\Psi$ mesons is 690 $\mu m$. The data as given in Fig. 5 show a width of 750 $\mu m$. Again that is compatible with an extra contribution of about 200 $\mu m$ the primary and $J/\Psi$ vertex resolution. The decay length is calculated after the lepton tracks from the $J/\Psi$ are removed from the primary vertex and it is refit. In the data we expect a small contribution to the decay length distribution from misidentified
double semileptonic charm decays and B meson decays. The observed decay length resolution clearly fulfills the design specifications even with a preliminary alignment. We expect the distributions in data to become compatible with the Monte Carlo after the alignment will be performed on a fill by fill basis.

4. Conclusions

The HERA-B Vertex Detector System has been operated in its final configuration since 1999. It proved to be very stable and reliable and needed little maintenance. The radiation tolerance of the system was shown to be adequate for inhomogeneous fluences of up to $3 \times 10^{14}$ minimum ionizing particles per cm$^2$ over the duration of 1 year. Special long-term studies revealed problems on time scales longer than 1 year that should be investigated further. The performance of the system as a tracker and vertex detector easily met the design specifications.

References

[13] I. Kisel, et al., Test of vertex reconstruction and fitting algorithms on $J/\psi \to \mu^+\mu^-$ data. HERA-B Note 00-182 Physics; S. Masciocchi, et al., Primary vertex reconstruction by ROVER. HERA-B Note 00-139 VDET.
[14] S. Masciocchi, Primary vertex reconstruction Studies. HERA-B Note 02-123 VDET.

Fig. 5. Decay length distribution in cm as seen in data for the carbon wire Inner 2.