RPCs: the choreography of precise timing


Abstract

We present a comprehensive overview of all steps to be taken in order to achieve precise timing of the HARP RPCs. After briefly recalling the salient features of the RPC mechanics and electronics, we discuss the results from the dedicated calibration scan in a -12 GeV/c beam which gave valuable first information on efficiency and uniformity of response, charge attenuation, the global time slewing correction, effective strip transit time, relative delays between strips of a pad, and intrinsic time resolution. The latter was determined to be \( \sim 140 \) ps which sets the scale for the control of systematic effects, so as not to deteriorate significantly the overall time-of-flight resolution of the RPCs. From physics data, primarily from ‘neutral’ and ‘charged’ hits in RPC overlap regions, further refinements are derived, in particular padring-specific modifications of the global time slewing correction, and manifestations of the ‘knock-on’ and ‘noise’ effects. With a view to a bias-free determination of pad-specific \( t_0 \) constants which transform RPC time stamps together with the time of arrival of the beam particle at the target into a time-of-flight measurement, time spectra of ‘neutral’ hits are analyzed in conjunction with an analytic simulation of the RPC electronics response. After all corrections and including the beam particle timing, the overall RPC time-of-flight resolution is \( \sim 180 \) ps.
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The results presented in this HARP Memo can be freely used by the HARP Collaboration at large, if correctly referenced.

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1 Introduction

Resistive Plate Chambers (RPCs) were chosen as time-of-flight system for particle identification in HARP's large- and medium-angle acceptance region, in particular for momenta at which the dE/dx measurement in the TPC cannot distinguish by principle between electrons and pions ($\sim 180$ MeV/c), electrons and kaons ($\sim 600$ MeV/c), and electrons and protons ($\sim 1.2$ GeV/c).

In this memo, we give a comprehensive overview of all steps to be taken in order to ascertain the highest performance for time-of-flight measurement in the HARP RPCs.

In two NIM publications [1, 2], the design and layout of the HARP RPC system has been described already, together with early results on performance. Therefore, we recall only selected features of the RPC mechanics and electronics that are needed for the topics discussed below.

After revisiting briefly the mechanics and electronics layout in Sections 2 and 3, we recall in Section 4 the salient results of the dedicated calibration scan in a $12$ GeV/c beam which provided useful input and guidance for the study of the RPC performance with physics data.

In Section 5 we review the pro's and con's of the analysis of 'neutral' and 'charged' hits for calibration purposes, and motivate our preference of 'neutral' hits.

In Section 6 we present the rich information which is obtained from the study of hits in RPC overlaps, and which proved decisive for achieving the highest timing performance of the RPCs. Section 7 summarizes our understanding of the RPC response in terms of an analytical simulation of the RPC electronics response.

Section 8 is devoted to the determination of the pad-specific $t_0$ calibration constants which are needed to convert the RPC time stamp into a time-of-flight measurement. Finally, Section 9 presents the overall performance of the RPCs for physics tracks.

In a forthcoming memo, we shall quantify the efficiency for physics tracks as well as the performance for $p/\pi^{\pm}/e$ identification of the RPCs, which obviously depends on an unbiased momentum measurement, and hence inter alia on adequate static and dynamic TPC track distortion corrections.

2 Synopsis of RPC mechanics

The RPC system consists of 46 identical chambers, 10 mm thick, 150 mm wide, and 2 m long.

Thirty of them are arranged as barrel around the TPC, providing for full coverage in azimuthal angle and covering polar angles from $17^\circ$ to $142^\circ$ w.r.t. the beam axis (seen from the HARP coordinate origin). Chamber dimensions and shape were chosen such that two layers of partially overlapping RPCs fit into the free 25 mm radial space between the TPC and the coils of the solenoidal magnet (see Fig. 1).
The other 16 RPCs are installed downstream of the TPC, perpendicular to the beam. They are arranged in four groups of four RPCs each (see Fig. 2) and cover polar angles from 6° to 16° w.r.t. the beam axis (seen from the HARP coordinate origin).

![Diagram](image)

**Figure 1**: Layout of the barrel RPCs around the TPC in upstream(!) view.

The active element of the RPC is a glass stack with four 0.3 mm thick gas gaps. It consists of two sets of three glass plates each, arranged symmetrically on both sides of the central readout electrode. The glass plates are 0.7 mm thick. A transverse cross section of the RPC structure is shown in Fig. 3.

The readout electrodes were segmented in 64 ‘strips’ of dimensions 29 mm×104 mm with 1 mm distance between them, and connected on one side to the front-end electronics. The signals of eight adjacent strips are summed to the signal of a ‘pad’ which therefore has a length of 239 mm. The geometrical configuration of strips and pads including the location of the on-chamber preamplifier printed boards, is shown in Fig. 4.

We stress the asymmetry of the signal readout stemming from the physical location of the front-end electronics on one side only. That is important for correctly taking into account the signal transit time from the impact point to the preamplifier.

Table 1 lists the mean geometrical position of the sensitive volumes of the barrel\textsuperscript{1} and forward RPCs, including the location of the preamplifiers.

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\textsuperscript{1}We note that a precision determination of the position of the barrel RPCs is genuinely connected with the adequate correction of TPC track distortions since only the overall effect can be measured; the geometrical position of the barrel RPCs is assured by the mechanical fixation to within 1 mm in the $r\cdot\phi$ coordinate; in the absence of evidence of a problem in the mechanical position of the RPCs, we adopted the strategy to take the RPCs at their nominal positions and to determine the TPC track distortions with respect to these.
Figure 2: Layout of the forward RPCs in upstream(!) view.

Figure 3: Transverse cross section of the RPC structure; beware of the different horizontal and vertical scales.

Figure 4: Layout and dimensions of strips and pads (eight adjacent strips form one pad), and location of the on-chamber preamplifier printed boards.
Table 1: Geometrical positions of the HARP barrel and forward RPCs, in the HARP coordinate system; all orientations refer to looking downstream.

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3  Synopsis of RPC electronics

The front-end electronics consists of on-chamber preamplifiers and discriminator/splitter units in a rack located at about 5 m distance from the RPCs (hence fully exposed to fluctuations of the ambient temperature).

The preamplifiers were constructed as on-chamber plug-in modules. Their main active element is a fast summing amplifier which combines the signals of eight adjacent strips into the signal of one pad. With a view to matching the strip impedance and enabling high-impedance summing of signals from adjacent strips, thus decoupling the strips from each other, each strip was first connected to a low-noise fast transistor. The transistor outputs were connected through printed-board delay lines of equal geometric length to the input of the fast summing amplifier. The delay lines were designed to render the timing of all eight strips equal within one pad (however, this goal was \textit{de facto} only met within $\sim 100$ ps, see Sections 4 and 7.3).

The output pulses of the fast summing amplifier had a rise time of $\sim 1.1$ ns and a FWHM of $\sim 15$ ns.

Each RPC had eight preamplifiers, leading to 368 readout channels for the full system.

The signals from the preamplifiers were transmitted through mini-coaxial cables over a distance of 0.8–2.5 m to a passive connector board and from there through 5 m long 50 $\Omega$ cables to a discriminator and splitter module. In the latter, the signals were once more amplified and split into two signal paths. Signals in the first path, the fast-timing path, were discriminated just above the white noise level, and the discriminator output was sent via 80 m of twisted pair cable to a TDC \footnote{CAEN V775 with $\sim 35$ ps per channel}. The transmission of the preamplifier signal through the coaxial cables and the further amplification caused a slight deterioration of the preamplifier pulse, in that the rise time increased from $\sim 1.1$ ns to $\sim 1.8$ ns. Signals in the other path, the charge path, were sent as analogue signals over a 80 m long twisted pair cable and an impedance adapter to a QDC \footnote{CAEN V792 with $\sim 0.1$ pC per channel}.

We use for the conversion of the TDC channels into picoseconds the calibration results which were obtained by Ch. Wiebusch. He had shown that on the average, the time delay per channel was with $\sim 36.5$ ps slightly larger than the 35 ps specified in the manufacturer's data sheet. The conversion constants for the 240 TDCs of the barrel RPCs are shown in Fig. 5.

After conversion of the raw TDC count to picoseconds, its difference to the time of arrival of the beam particle at the target becomes the ‘measured RPC time’.

The measured RPC time marks the time when the RPC signal exceeds a fixed threshold. Because of the finite rise time of the RPC signal the time stamp comes the later the smaller the signal amplitude is. By measuring at the same time the signal charge, an empirical relation between the delay of the time stamp as a function of the signal charge can be established and used for the calculation of a correction of an individual time stamp. This relation is referred to as ‘time slewing correction’.

\footnotesize
\begin{itemize}
  \item \textit{\textsuperscript{2}}CAEN V775 with $\sim 35$ ps per channel
  \item \textit{\textsuperscript{3}}CAEN V792 with $\sim 0.1$ pC per channel.
\end{itemize}
Figure 5: Conversion constants [ps/channel] of the 240 TDCs of the barrel RPCs.

As for the charge measured in the QDCs, no calibration was performed since there was no evidence for a substantial variation between readout channels of the conversion factor from QDC channel to picoCoulomb (a common overall deviation from the specified conversion factor would not matter).

The combined timing signal from the beam particle detectors and the RPCs has been shown to exhibit a strong dependence on the ambient temperature in the experimental area, so that an adequate normalization to the standard ambient temperature of 25°C is indispensable. This temperature dependence and its correction has been described in detail in an earlier memo [3]. In the present memo, all timing measurements are already corrected for drift with temperature and refer to the standard ambient temperature.

For completeness, we show in Fig. 6 the dependence on run number of the average QDC charges in padrings 3–8. The range of runs covers about two days of data taking. Unlike the timing response, no strong variation with time and related day-night temperature variations is exhibited.

4 Results from the dedicated calibration scan

Toward the end of the HARP physics data taking, a dedicated calibration scan was performed with four spare RPCs exposed directly to the -12 GeV/c momentum beam. The goal was to study the RPC response to particles of known type ($\pi^-$), momentum and impact point.
Figure 6: Dependence on run number of the average QDC charges in pad rings 3–8.

An important feature is that in this study of the RPC response to charged particles there is no interference with effects which stem from the neglect or from inadequate corrections of static and dynamic track distortions in the TPC.

The four RPCs were placed horizontally in front of the plane of forward RPCs, perpendicular to the beam, one behind the other. The RPCs were mounted on a moveable table which allowed for movements both in the horizontal and vertical direction.

The RPC efficiency has been determined using two RPCs as ‘trigger’ and then checking for the presence of a hit in a third RPC. Typical efficiencies of 97–98% were measured, with no dependence on position within the gap except near the physical boundaries at the chamber edges (see Fig. 7).

Note that during physics data taking the efficiency should be even better since particle intensities in the dedicated calibration scan were 3 kHz/cm² in the centre of the beam, compared to rates below 1 Hz/cm² in normal data taking.

No drop in efficiency was observed at the transition from one pad to the neighbour pad, as shown in Fig. 8.

From the dedicated calibration scan, the functional form of an average time-slewing correction, henceforth referred to as ‘global time slewing correction’, was determined. Its dependence on the charge $Q$ is shown in Fig. 9 and reads as follows:

$$
\Delta t = a + b/Q + c/Q^2 + d/Q^3
$$
Figure 7: RPC efficiency as measured in the dedicated calibration scan, as a function of the impact position; the left plot shows the scan along the gap across its eight strips (indicated by dotted lines); the right plot shows the scan along one strip.

\[
b = 1.5565 \times 10^6 \\
c = -2.8511 \times 10^8 \\
d = 7.6798 \times 10^{10},
\]

where \( \Delta t \) is the time slewing correction in picoseconds, and \( Q \) is the charge in units of QDC channels \(^4\). The additive constant \( a \) is at this stage arbitrary. The time slewing correction \( \Delta t \) is subtracted from the ‘measured RPC time’.

The application of the global time slewing correction is important since it takes out the gross effects of time slewing and thus permits a more refined study of detailed effects that are not adequately covered by the global correction. Yet an important conclusion is already in order: since the global time slewing correction spans \( \sim 3 \) ns which is very large on the scale of the intrinsic time resolution of \( \sim 140 \) ps, maximum attention must be paid to the correct charge assignment and the correct functional form of time slewing.

Since the strips are connected on one side only to the preamplifier one expects different timing for particles hitting the strip at different distances from the preamplifier. These timing differences will depend on the one hand on the signal speed along the strip, the reflection coefficient at the ‘open’ end, and the charge attenuation in the transmission line (that is what the RPC strip represents from the point of view of signal propagation), but on the other hand also on the signal shaping characteristics of the preamplifier.

\(^4\)To be precise, \( Q \) is actually the QDC channel number, minus the QDC pedestal which was typically between channels 150 and 250, plus 158.29; the latter constant was introduced to avoid a singularity at \( Q = 0 \) when fitting the data.
Figure 8: RPC efficiency as a function of impact points across a boundary from one pad to the neighbour pad; the vertical line marks the pad boundary.

Figure 10 shows the ‘measured RPC times’ as a function of the impact position across a single strip, for eight different charge bins. The preamplifiers are located at the positive end of the horizontal axis (at +75 mm). While for low charges there is hardly any time difference for positions along the strip, there is a time difference of \(\sim 200\) ps from one end to the other for large charges.

The surprising independence of position for small charges is explained in a model where half of the signal charge propagates toward the preamplifier, whereas the other half propagates first toward the strip’s open end, is same-sign reflected and then propagates back to the preamplifier. For large charges, half of the charge still crosses easily the threshold of the timing discriminator, by contrast to small charges where the other, delayed, half of the charge must ‘help’ to cross the threshold, which blurs the timing dependence on the position. This finding anticipates the later conclusion (see Sections 6 and 7) that the global time slewing correction which does not distinguish between near and far from the preamplifier, must undergo appropriate small position- and charge-dependent modifications.

Another scan across the eight strips of a pad was made, at constant distance from the preamplifier, with a view to testing the design feature that the time delays from the strips are equalized. Figure 11 shows that this expectation is not warranted in reality: in the two outer strips longer delays are evident while the four inner strips appear to have equal delays. We conjecture that the cause of this phenomenon are different capacitive couplings of the delay lines on the preamplifier board. A later test of the preamplifier electronics [4] confirmed qualitatively this hypothesis.

An estimate of the intrinsic time resolution of the RPCs has been obtained by studying tracks passing through successive RPCs. This measurement is particularly interesting since uncertainties from the beam particle timing, particle momentum, and the dependence of the
Figure 9: Functional form of the global time slewing correction; the step at large charge reflects the correction applied for QDC overflow charges.

time on the position within the strip cancel. Of course, remaining are residual effects from the use of the global time slewing correction. Figure 12 shows a typical spectrum of the time difference between two measurements of the same track in two successive RPCs. The width of the distribution corresponds to the convoluted time resolutions of the two RPCs, leading here to an intrinsic resolution of $\sigma = 146$ ps if both pads are assumed to contribute equally.
Figure 10: ‘Measured RPC times’ [ps] as a function of the impact position [mm] across a single strip, for eight different charge bins; the lowest charge bin (0–200 QDC channels) is top left, the overflow charge bin (greater than 4095 QDC channels) is bottom right.
Figure 11: Time delays of the eight strips of three different pads; the time delays have been arbitrarily equalized to be the same in the 4th strip of every pad.

Figure 12: Difference of the RPC times (after application of the global time slewing correction) of tracks passing through two successive RPCs; the sigma of the Gaussian fit gives the convoluted intrinsic resolution of the two contributing pads.
5 Physics data: ‘neutral’ versus ‘charged’ hits

While the data from the dedicated calibration scan serve well to understand systematic effects related to the detector geometry, they cannot give pad-specific properties such as the absolute time scale of every RPC channel. Hence also physics data must be analyzed for calibration purposes. We used the data obtained in the $+8.9$ GeV/c with a 5% $\lambda$ Be target.

In physics data, we distinguish between ‘neutral’ and ‘charged’ hits. Neutral hits are hits to which no reconstructed TPC track points while at least one reconstructed TPC track is required which comes from the target and points elsewhere. Charged hits are hits which are consistent with the extrapolation from a reconstructed TPC track.

The advantage of neutral hits are that their timing is generally the one of a photon from $\pi^0$ decay in the target, moving along a straight trajectory with speed of light. The disadvantage of ‘neutral’ hits lies in the fact that their impact point on the pad is not known, and that their origin from photons from $\pi^0$ decays in the target is a good approximation but not certain. This poses a problem in case of a bad reconstruction efficiency of the TPC for charged tracks because charged hits may then be misinterpreted as neutral hits.

The advantage of a charged hit is that its origin from a charged track coming from the target is beyond doubt. The disadvantages are that the RPC impact point is affected by inadequate corrections for static and dynamic TPC distortions, and by imperfect track reconstruction; furthermore, the charged particle velocity is smaller than the speed of light.

Motivated by the advantages of neutral hits, we settled long ago to use them for the timing calibration of the RPCs. Nevertheless, whenever TPC track distortions or imperfect TPC reconstruction have no impact on results, we also use charged hits.

Particles coming from the target traverse the RPCs with different polar angles. Each padring corresponds to a specific range of polar angles, with padring 8 being the most forward one.

Figure 13 shows the abundance of charged and neutral hits for padrings 1–8, for Monte Carlo data (the simulation used the GEANT4-based HARP Monte Carlo framework with a realistic detector geometry, a thin Be target and a $+9$ GeV/c proton beam setting) and for data in the $+8.9$ GeV/c beam. The qualitative agreement of the data with the Monte Carlo simulation demonstrates that the bulk of the selected neutral hits in the data is consistent with originating from photons from $\pi^0$ decays in the target.

Figure 14 shows the QDC charge spectra of neutral and charged hits for padrings 1–8. They are quite different but have in common that the average charge varies with the padring number and thus with the angle under which the particle traverses the RPC, as shown in Figure 15. We note that the data support a variation with the projection onto the $z$ axis of the pathlength through the RPCs, rather than a variation with the pathlength proper.

Neutral hits have a large background from penetrating $\sim 1$ MeV photons which are the remnants of electromagnetic showers which emanate from the upstream iron flux return of the solenoidal magnet, or are Compton-backscattered from material downstream of the TPC. That is demonstrated in Fig. 16 which shows the time spectra of neutral hits in RPC channels 145 (which is in the first padring) and 150 (which is in the sixth padring), before and after background-removing cuts. It is evident from Fig. 16 that the abundance of background
photons especially at ‘too early’ time is much higher at the upstream end of the RPCs, compared to the downstream end.

The selection which has been found effective for the removal of background from neutral hits, is the requirement of at least one reconstructed TPC track which comes from the target and points elsewhere, in conjunction with a minimum charge of the neutral hit.

The fact that charged particles move more slowly than photons, is exhibited in Fig. 17 which shows the systematic timing shift between neutral and charged hits in an RPC channel in padring 7. Since the leading edge of the time distribution is relevant for the RPC calibration, it is evident that the charged-hit distribution will lead to a biased result, confirming our preference for the neutral-hit time distribution for calibration purposes.
Figure 14: Charge spectra of ‘neutral’ hits (grey area) and ‘charged’ hits (full line) for pads 1–8, in units of QDC channels; the QDC overflows at channel 4095.
Figure 15: Comparison of the average charge per padring for charged hits (dark points) with the pathlength through the RPCs (curved line) and with the projection onto the z axis of the pathlength (straight lines).
Figure 16: Time spectra of ‘neutral’ hits before cuts (points), after requiring at least one reconstructed track from the target (full line), and after further requiring a minimum charge of more than half of the mean charge of the pertinent padring (dark area); for RPC channels 145 (top) and 150 (bottom; the insert is a blown-up view of the region before the leading edge of the time spectrum.)
Figure 17: Timing shift between neutral (crosses) and charged (full line) hits.
6 Results from hits in RPC overlaps

Hits in the ~ 15 mm wide overlap region of the barrel RPCs \(^5\) provide information on a number of issues which are important for a precise timing calibration of the RPCs. Both neutral and charged RPC overlap hits can be exploited.

The essential point is that in the RPC overlap region the time of particle passage is measured independently twice, in one pad near the preamplifier, in the other pad far from the preamplifier \(^6\). Below, we refer to the distance of a hit in an overlap region to the preamplifier in terms of ‘near’ and ‘far’.

Naively, one would expect that the two RPC times, after correction for global time slewing and after adjustment of the time scales by means of the t0 constant (see Section 8), would only differ by the transit time along a strip. Figure 18 shows the measured time difference (‘near’ minus ‘far’) of charged hits in the overlap region of two adjacent RPC pads. A narrow distribution on top of a broad distribution is apparent \(^7\). What is the origin of the large time differences beyond, say, one nanosecond?

---

\(^5\)The sensitivity of the RPCs extends well beyond the physical size of the readout pads, up to the physical size of the glass stack.

\(^6\)We are grateful for the wisdom at system design level to foresee the overlap between adjacent RPCs, small but immensely useful.

\(^7\)A correction for transit time differences has been applied.

---

Figure 18: Time difference ‘near’ minus ‘far’ of charged hits in the overlap region of two adjacent RPC pads in padring 5.
Figure 19 shows the signal charges for time differences smaller than ±400 ps (representing the ‘narrow’ distribution) and for time differences ‘near’ minus ‘far’ larger than ±400 ps (representing the ‘broad’ distribution). In order to emphasize the differences in shape, the two distributions are normalized to each other with the number of events between the dotted lines. One observes that the distributions are distinctly different: the distribution for large time differences exhibits both a shift toward larger charges and an enhancement at small charges. The former stems from the ‘knock-on’ effect, the latter from the ‘noise’ effect.

![Pad Ring 4](image)

Figure 19: Charge distributions for time differences smaller than ±400 ps (full line) and for time differences ‘near’ minus ‘far’ larger than ±400 ps (points); the two distributions are normalized to each other with the number of events between the dotted lines.

6.1 ‘Knock-on’ effect

The shifts toward larger charges in Fig. 19 suggest that for one of the two hits the charge is too large, hence the global time slewing correction is too small, hence the resulting RPC time is too large.

We came to refer to this as the ‘knock-on’ effect: when the charged track passes the RPC glass stack, delta-ray emission and/or nuclear backscattering and nuclear fragmentation take place; delta-rays will lead to slowly moving micro-spirals in the magnetic field, also remnants from nuclear backscattering and nuclear fragmentation will move slowly. Both effects lead to
a RPC time response which is in principle correct, but to larger than normal charge deposit in the RPC. Hence the time slewing correction will distort the timing toward larger times.

The knock-on effect takes place with a probability of a few percent. It is a detector physics effect which cannot be corrected. The consequence will be that the time-of-flight distribution of physics tracks will exhibit a tail toward longer time-of-flights which will have to be dealt with in physics analysis.

Although the additional charge from the knock-on effect is independent of the primary charge, the visibility of the effect will be largest when the primary charge is small. That expectation is confirmed by Fig. 20 which shows the average time difference of charged hits in the overlap region of two adjacent RPC pads, as a function of the charge of the ‘near’ pad. The correlation of the ‘wrong’ timing with small charge, which is an unavoidable artefact caused by the characteristics of the time slewing correction, is apparent.

![Graph](image)

Figure 20: Average time difference of charged hits in the overlap region of two adjacent RPC pads, as a function of the charge of the ‘near’ pad; the data show the average over all RPC overlaps in padring 8; fat points refer to time differences larger than ±500 ps, crosses refer to time differences smaller than ±400 ps.

### 6.2 ‘Noise’ effect

The second feature of the charge distributions in Fig. 19 is the enhancement at low charges.

The triggering threshold of the timing discriminator is set as closely as possible above the white noise level. For small signal pulseheights, the addition of a noise signal may succeed to pass the threshold at an earlier time than would be the case without noise: the ‘noise’ effect.
The noise effect is demonstrated in Fig. 21, which shows the RPC time (after the global
time slewing correction and the t0 correction) as a function of the charges in the ‘near’ pad
and ‘far’ pads, both for neutral and charged hits in RPC overlaps. It is apparent that for
small charges, both ‘near’ and ‘far’ hits arrive on the average considerably earlier. We note
that there is no difference between neutral and charged hits, as expected. When applying
the cut $|\Delta t| < 400$ ps on the time difference between ‘near’ and ‘far’, i.e. limiting on self to
the ‘narrow’ distribution of time differences, the early arrival times are strongly reduced.

Pad Ring 8

Figure 21: RPC time after the global time slewing correction and the t0 correction, as a
function of the charges in the ‘near’ (dark points) and in the ‘far’ (open circles) pads, for
neutral (left) and charged hits (right) in the overlap regions in pad ring 8; the lower plots
refer to the situation when requiring $|\Delta t| < 400$ ps for the ‘near’ and ‘far’ RPC times which
largely eliminates the ‘knock-on and the ‘noise’ effects.

The noise effect is also a detector effect which cannot be corrected. The consequence
will be that the time-of-flight distribution of physics tracks whose RPC charge
is smaller than $\sim 300$ QDC channels, will exhibit a tail toward shorter time-of-flights which will have to be dealt with in physics analysis.

The resolution functions which are to be used in physics analysis, in particular the tails toward short and long times, must be experimentally determined from a study of the resolution seen in RPC overlaps. For example, Fig. 22 shows the RPC times of one charged hit in the overlap regions of padring 6, on condition that the other hit has ‘normal’ time, as a function of the signal charge (‘normal’ time means that the time is less than 450 ps away from the 50% point at the leading edge of the other hit’s time distribution). In the lowest charge bins, the ‘knock-on’ and ‘noise’ effects are clearly discernible.

**Pad Ring 6**

![Graphs showing RPC times of first charged hit in overlap regions of padring 6.](image)

**Figure 22:** RPC times of the first charged hit in the overlap regions of padring 6, on condition that the other hit has ‘normal’ time, as a function of the signal charge.
6.3 Signal attenuation along the strip

Since the hits in RPC overlaps involve one hit ‘near’ the preamplifier, and the other hit ‘far’ from the preamplifier, the signal attenuation along the strip can be measured from a comparison of the two charge spectra.

Figure 23 shows the charge spectra from charged hits in RPC overlaps ‘near’ and ‘far’ from the preamplifier, for every padding. The plots demonstrate that there is no evidence for appreciable signal attenuation and signal loss at the reflection at the strip’s open end. That is an important information which is needed as input to the analytic simulation of the RPC electronics response (see Section 7.2).

However, it is to be noted that the data shown in Fig. 23 do neither exclude nor support a small signal attenuation of e.g. 20%, since the resulting net amplitude difference would be 2.5% only.

6.4 Effective signal transit time along the strip

From the comparison of the ‘near’ and ‘far’ time spectra of hits in RPC overlaps, the effective signal transit time along the strip can be determined.

Figure 24 shows the time difference for neutral hits in RPC overlaps ‘near’ and ‘far’ from the preamplifier, after the global time slewing and the z0 corrections. It appears that the typical time difference between ‘near’ and ‘far’ hits is 100–200 ps.

6.5 Padding-specific modifications of the global time slewing

The global time slewing correction is not the best that can be done to correct for time slewing. That follows from the following simple consideration. Consider first a particle impact ‘near’ the preamplifier. Half of the charge will propagate straight to the preamplifier and trigger the timing signal; the other half will propagate along the strip to the opposite open end, will be same-sign reflected and propagate back. The net effect is that the timing is the one of half of the charge, however the slewing correction will work with the full charge. However, if the charge is large to start with, even half of the charge will lead to an (almost) correct timing. Hence position-dependent and charge-dependent modifications of the global time slewing correction are expected which take such effects into account.

Hits in RPC overlaps permit to determine the necessary modifications of the global time slewing correction at the two outer ends of a strip.

We refer again to Figure 21 which showed the times of ‘near’ and ‘far’ hits both for neutral and charged hits in padding 8, as a function of the signal charge. The lower plots show the situation after the (almost complete) removal of ‘knock-on’ and ‘noise’ backgrounds.

In case the global time slewing correction world work ideally, the times both of ‘near’ and

\[\text{\textsuperscript{8}}\text{We make a difference between the ‘signal transit time’ and the ‘effective signal transit time’, as will be detailed in Section 7.2.}\]
‘far’ hits would be independent of the charge, and therefore also their difference. The data shown in Figure 21 demonstrate that this is not the case. We note that (i) there is no difference between neutral and charged hits, and (ii) there is no strong dependence on the presence or absence of the knock-on effect.

In this situation, we adopted the strategy to use the time distributions measured at the ‘near’ and ‘far’ ends of a pad, as a function of the ‘near’ and ‘far’ charges, as padring-specific modifications of the global time slewing correction.

From hits in overlap regions, only the modifications of the global time slewing correction at the outer ends of a strip are accessible. What happens in between will be determined by the results of an analytical model of the RPC electronics response (see Section 7.2).

In this way, the finally adopted time slewing correction is position-dependent and thus incorporates the signal’s effective transit time along the strip.

Figure 25 illustrates that procedure. It shows the most probable RPC time differences ‘near’ minus ‘far’ of charged hits in RPC overlaps, after the global time slewing and \( t_0 \) corrections, as a function of the charge in the ‘near’ and in the ‘far’ pads. We use the most probable RPC times rather than the average RPC times in order to be independent of the ‘knock-on’ and ‘noise’ effects.

The reason why we plot RPC time differences rather than the RPC times themselves, lies in the relatively large size of the pads which introduces an unwelcome time spread which can be eliminated by considering RPC time differences. Note that the second, subtracted, time is always integrated over all charges and therefore represents on the average a constant; hence we plot \emph{de facto} the RPC time itself.

From these data, a charge-dependent modification (which is different for ‘near’ and ‘far’) is determined which is designed to make the ‘near’ and ‘far’ RPC times equal and independent of the charges. The result of the operation (which is done in an iterative way to achieve the best accuracy) is shown in Fig. 26. A satisfactory agreement with zero is achieved for the full range of charges.

In order to give a feeling on the size of the such determined modifications of the global time slewing correction, Fig. 27 shows the functional form of the modifications for all padrings (such as shown as straight-line sections in Fig. 25), as a function of the signal charge.

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\(^9\)The analytical simulation of the RPC electronics response shows that this is only an approximation, see Section 7.2 for details.

\(^10\)Also a correction for different time delays in the strips within a pad is applied, see Section 7.3.
Figure 23: Charge spectra from charged hits in RPC overlaps ‘near’ (full line) and ‘far’ (points) from the preamplifier, for pad rings 1–8.
Figure 24: Time difference for neutral hits in RPC overlaps ‘near’ (points) and ‘far’ (shaded area) from the preamplifier, after the global time slewing and t0 corrections.
Figure 25: Most probable RPC time differences between ‘near’ and ‘far’ for charged hits in RPC overlaps in padring 6 after the global time slewing and t0 corrections, as a function of the signal charge, for the ‘near’ and ‘far’ pads; the plots show the necessary modifications of the global time slewing correction for the ‘near’ and ‘far’ positions.
Figure 26: Most probable RPC time differences between ‘near’ and ‘far’ for charged hits in RPC overlaps in padring 6 after the global time slewing and f0 corrections, as a function of the signal charge, for the ‘near’ and ‘far’ pads; the plots show the result after the modifications of the global time slewing correction for the ‘near’ and ‘far’ positions.
Additional time slewing correction

Figure 27: Functional form of the modifications for all paddings, for the ‘near’ (full lines) and ‘far’ (broken lines) positions, as a function of the signal charge.
7 Understanding the RPC timing response

7.1 From raw data to absolute time-of-flight

To begin with, we summarize the seven steps to be taken from raw TDC and QDC readings to a particle time-of-flight:

1. Conversion of TDC channels into picoseconds;

2. Subtraction of the time of arrival of the beam particle according to the procedure laid down in our earlier memo [5];

3. Correction of drifts with temperature according to the procedure laid down in our earlier memo [3]; we recall that in this correction the drift of the beam timing counters (which provide the time of arrival of the beam particle at the nominal target position $z = 0$) and of the RPC timing signals are lumped together;

4. Subtraction of the pad-specific $t_0$ constant;

5. Global time slewing correction;

6. Pad-specific and impact-position dependent modifications of the global time slewing correction;

7. Strip-specific correction for different signal delays of the strips within a pad.

Unavoidably, every step adds some systematic uncertainty to the RPC time-of-flight, the estimation of which will be detailed in Section 9.

7.2 Analytical model of the RPC electronics response

The RPC electronics response has been simulated with an analytical model. The pulse shape at the input of the timing discriminator was modelled with the functional form

$$t^2 \exp\left(-t/\tau\right)$$

with two different parameters $\tau$: one, taken as 1.8 ns, determines the rise time, the other, taken as 6.0 ns, determines the fall time. The FWHM of the pulse is $\sim 15$ ns. Figure 28 shows the resulting pulse shapes of the RPC timing pulses, at impact points ‘near’ and ‘far’ from the preamplifier. The figure makes clear how subtle the effects are which must be controlled.

In the model, half of the charge signal which is generated at the impact point, propagates toward the preamplifier. The other half propagates toward the other side, is same-sign reflected at the open end of the strip, and propagates back toward the preamplifier where the two signals are superimposed. The reflection factor is unity.
Figure 28: Pulse shapes of the RPC timing pulses as used in analytic simulations of the RPC electronics, at impact points ‘near’ the preamplifier (full line) and ‘far’ from the preamplifier (broken line); the right plot shows the leading edges on an expanded scale.

Important parameters are the signal attenuation which was found compatible with zero from the data from RPC overlaps (see Section 6.3). The other parameter is the signal transit time along the strip which was determined to be 500 ps in order to fit the data (the RPC strip has the same inductance/capacitance ratio as a normal 50 Ω coaxial cable).

As a result, the model predicts the time slewing for any point along the strip. In particular, it can be calculated for the average along the strip (which is supposed to emulate the global time slewing correction) and for the near and far ends of the strip, where it can be compared with the findings from data.

Figure 29 shows the simulated time slewing correction averaged over the strip, for impact points ‘near’ and ‘far’ from the preamplifier. The strip-averaged time slewing correction agrees well with the global time slewing correction determined from the data (see Fig. 9).

The time difference between ‘near’ and ‘far’ is for large charges ~ 200 ps, which is modelled after the data. The interesting feature is that a signal transit time of 500 ps transforms into an ‘effective signal transit time’ of about 200 ps. Furthermore, the model predicts that the time difference between ‘near’ and ‘far’ becomes smaller for small charges, and even changes sign for very small charges.

The analytical model merely serves to determine the dependence of the time slewing correction on the position within the strip, since it predicts how to interpolate between the ‘near’ and ‘far’ positions, while the time slewing corrections at the ‘near’ and ‘far’ positions are those determined by the data.
Figure 29: Analytical simulation of the time slewing correction, averaged over the strip (dark points), for impact points ‘near’ (open circles) and ‘far’ (open squares) from the preamplifier.

7.3 Relative time delays between the strips of a pad

Figure 30 shows the time spectrum of neutral hits in strips 1 and strip 4 of one selected RPC pad. No time slewing correction was applied, only more than 1000 QDC channels of charge were required to be above noise. It is evident that the relative time delays from different strips within a pad are not zero.

Figure 31 shows the average position of the time spectrum for all eight strips of a pad, averaged over all pads (we neglect here a 5–10 ps variation of the relative delays between padrings). Table 2 summarizes the relative delays of the strips within a pad w.r.t. the centre strips as used in all our data analysis and simulations.
Figure 30: Time spectrum of charged hits in strip 1 (shaded area) and strip 4 (dark points) of the RPC pad 005.

Table 2: Relative delays of time signals from strips w.r.t. the central strips 4 and 5 of a pad.

<table>
<thead>
<tr>
<th>Strip number</th>
<th>Relative delay [ps]</th>
</tr>
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<tbody>
<tr>
<td>1 and 8</td>
<td>92 ± 4</td>
</tr>
<tr>
<td>2 and 7</td>
<td>27 ± 2</td>
</tr>
<tr>
<td>3 and 6</td>
<td>5 ± 2</td>
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</table>

Figure 31: Average position of the time spectrum for all eight strips of a pad, averaged over all pads.
8 Determination of pad-specific $t_0$ constants

In order to convert the RPC time into a time-of-flight, the time of arrival of the beam particle at the target ($t \leq 0$) and a pad-specific constant ($t_0$) must be subtracted such that the time obtained after the subtraction is the real time-of-flight of the particle (no matter which type of particle, no matter where the particle hits the RPCs):

$$ t_{\text{TOF}} = t_{\text{RPC}} - t \leq 0 - t_0 , $$

where $t_{\text{RPC}}$ is the time measured by the RPCs after all corrections discussed above.

The rationale of the procedure to determine the $t_0$ constants is as follows, in increasing approximation to reality.

1. For a pad with infinitely small size and with no timing fluctuation, the time of one single RPC hit of a photon from the target is sufficient to determine the wanted $t_0$ constant, the subtraction of which (besides the subtraction of $t \leq 0$) renders the ‘measured time’ of a particle the time-of-flight of the particle according to

$$ t_{\text{RPC}} - t \leq 0 - t_0 = t_{\text{TOF}}^{\text{phot}} . $$

2. We ‘switch on’ the stochastic timing fluctuation; the only change is that we would have to take for $t_{\text{RPC}}$ the average of a sufficiently large number of photon hits in order not to lose precision. For a stochastic resolution of 140 ps, 100 events would ensure a precision of $t_0$ of $\pm 14$ ps which is good enough. Notice that in the considered simplification, averaging permits a bias-free estimate of $t_0$.

Alternatively (in anticipation of the realistic case, see below) we could consider determining a ‘specific time’ $t_{\text{spec}}$ from the timing distribution of the ensemble of calibration events, e.g. the time of half-maximum at the leading edge of the pad’s timing distribution, and relate this specific time via a correction $t_{\text{corr}}$ to $t_0$. The correction is expected to be of the order of the overall RPC time-of-flight resolution.

Thus the $t_0$ constant is determined in each pad from

$$ t_{\text{spec}} + t_{\text{corr}} - t \leq 0 - t_0 = t_{\text{TOF}}^{\text{phot}} , $$

where $t_{\text{TOF}}^{\text{phot}}$ refers to the same photons which serve as reference for $t_{\text{corr}}$. While in principle any photon impact point within the pad can be chosen, we chose for reasons of convenience the geometrical centre of the pad.

3. Next, we consider a real-size pad which entails

(i) differences in the time-of-flight from the target,
(ii) differences in the particle density across the pad,
(iii) differences in internal transit times within strips, and
(iv) differences in time delays between strips of a pad.

Since averaging is not appropriate under these circumstances, the only possible solution is a simulation of all effects, which relates a specific time $t_{\text{spec}}$, such as the time of half-maximum at the leading edge of the pad’s timing distribution, to $t_{\text{TOF}}^{\text{phot}}$ and thus determines the numerical value of $t_0$. 

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In Fig. 32 we show for the 240 barrel RPC pads the calculated time difference \( t_{\text{corr}} \) between the \( \Delta t_{\text{TOF}} \) and the 50% point at the leading edge of the time distribution of neutral hits, the \textbf{calculated} time difference between 20% and 80% of the leading edge of their time distributions, and the \textbf{measured} time difference between 20% and 80% of the leading edge of the time distributions of neutral hits. While the former stems from an analytic simulation and must be trusted, the latter can also be determined from data and thus permits to lend credibility to the calculation. The calculated time difference \( t_{\text{corr}} \) is \( \sim 240 \) ps and thus can under no circumstances be ignored. The calculated and measured time differences between 20% and 80% of the leading edge of their time distributions agree satisfactorily.

While the agreement between calculation and measurement is satisfactory, we nevertheless look forward to the ultimate test: the time-of-flight of electrons from photon conversion in the inner TPC field cage and the material at even smaller radius, must be the time at speed of light. A minor overall adjustment of the \( t_0 \) constant may result from this ultimate test.

9 Overall performance for physics tracks

The time of a track traversing the RPC overlap region has its time measured twice. No matter what kind of particle and of which momentum:

(i) the difference between the two time measurements must vanish on the average and
(ii) the observed resolution will be pretty much the overall time resolution of physics tracks, multiplied by \( \sqrt{2} \).

The vanishing of the average differences of the two time measurements is assured by construction, i.e. by the way the modifications of the global timeslewing corrections are determined, as demonstrated e.g. in Fig. 26.

The average and the resolution of the time differences constitute a test of the internal consistency and the validity of

(i) the correction algorithms for time slewing,
(ii) the correction for the strip transit time, and
(iii) the \( t_0 \) constants.

By contrast, not tested are the corrections for drifts with ambient temperature, and of all effects stemming from wrong TPC track reconstruction.

Figure 33 shows the resolutions (divided by \( \sqrt{2} \)) of the time differences for the RPC overlaps in padings 1–8, plotted as a function of the signal charge. It appears that the resolution is best for medium charges while both for small and for large charges the resolution worsens slightly.

Figure 34 shows the final result for the resolution of the narrow Gaussians (divided by \( \sqrt{2} \)) of the time differences in \textbf{all 240 overlap regions of the barrel RPCs}. A narrow Gaussian with tails which originate from the knock-on and noise effects, is apparent. Our quoted time resolution refers to the resolution of the narrow Gaussian divided by \( \sqrt{2} \). This resolution is with 145 ps pretty good. We note that this resolution comprises remanent inadequacies of the modifications of the time slewing correction and of the \( t_0 \) corrections, hence the intrinsic RPC resolution is even smaller and estimated at \( \sim 140 \) ps.
Figure 35 shows the resolution of the narrow Gaussians (divided by $\sqrt{2}$) of the time differences in all 30 overlap regions of pad rings 6 of the barrel RPCs which exhibits the best time resolution of all eight pad rings. In this plot which selects only half of the statistics, the range of signal charges was restricted. While this selection is obviously not permissible for physics analysis, we show it because it demonstrates that we achieved in the large-scale set-up of the HARP experiment essentially the same good resolution as we achieved during the design and testing work with small-scale prototypes in the test beam of the East Hall, which had small-size and hence low-capacitance pads.

Figure 36 shows the resolution of the narrow Gaussians (divided by $\sqrt{2}$) of the time differences in the eight pad rings of the barrel RPCs, with essentially no restriction on signal charges.

Table 3 summarizes the estimated contributions to the overall time-of-flight resolution of the barrel RPCs. While the intrinsic time resolution and the resolution of the beam particle arrival are of stochastic nature, all other contributions stem from estimates of the residual imperfection of systematic corrections.

Table 3: Contributions [ps] to the overall time-of-flight resolution of the barrel RPCs.

<table>
<thead>
<tr>
<th>Contribution</th>
<th>Contributions [ps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intrinsic</td>
<td>140</td>
</tr>
<tr>
<td>Beam particle arrival [5]</td>
<td>77</td>
</tr>
<tr>
<td>Spread of beam spot</td>
<td>10</td>
</tr>
<tr>
<td>Remanent temperature dependence [3]</td>
<td>20</td>
</tr>
<tr>
<td>Time slewing correction</td>
<td>30</td>
</tr>
<tr>
<td>Drift of charge measurement</td>
<td>50</td>
</tr>
<tr>
<td>Different strip delays</td>
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</tr>
<tr>
<td>Strip transit time</td>
<td>20</td>
</tr>
<tr>
<td>$t_0$ constant</td>
<td>30</td>
</tr>
<tr>
<td>Overall</td>
<td>180</td>
</tr>
</tbody>
</table>
Figure 32: Calculated time difference $t_{\text{corr}}$ [ns] between $t_{\text{TOP}}$ and the 50% point at the leading edge of the time distribution of neutral hits, for the 240 barrel RPC pads (top left); calculated time difference [ns] between 20% and 80% of the leading edge of their time distributions (top right); measured time difference [ns] between 20% and 80% of the leading edge of the time distributions of neutral hits (bottom left); comparison of the measured (dark points) and calculated (open circles) time difference [ns] between 20% and 80% of the leading edge of the time distributions of neutral hits (bottom right), for pad rings 1–8.
Figure 33: Resolutions of the narrow Gaussians (divided by $\sqrt{2}$) of the time differences in the overlap regions of the eight pads of the barrel RPCs.
Figure 34: Resolution of the narrow Gaussians of the time differences in all 240 overlap regions of the barrel RPCs; the Gaussian standard deviation divided by $\sqrt{2}$ is 145 ps.

Figure 35: Best resolution of the narrow Gaussians of the time differences in all 30 overlap regions of padring 6 of the barrel RPCs, after selection of a range of signal charges that provide the best resolution; the resulting Gaussian standard deviation divided by $\sqrt{2}$ is 120 ps.
Figure 36: Resolution of the narrow Gaussians (divided by \( \sqrt{2} \)) of the time differences in the eight padrings of the barrel RPCs; the cut in the signal charge refers to QDC channels after pedestal subtraction.
References


[4] We thank E. Oussenko for a careful measurement of the strip delays.