PID techniques: Alternatives to RICH methods

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ABSTRACT
In this review article we discuss the recent progress in PID techniques other than the RICH methods. In particular we mention the recent progress in the Transition Radiation Detector (TRD), dE/dx cluster counting, and Time of Flight (TOF) techniques.

1. Introduction

Fig. 1 shows the typical reach of various PID techniques used in present experiments. The transition radiation detector (TRD) technique is typically used to identify electrons in hadron colliders. It is a mature and well understood method, and has been proven to work well. It needs a lot of longitudinal or radial detector space, typically \(-20\) cm for every \(\pi/e\) rejection factor of 10. The TOF technique is useful in \(e^+e^-\) colliders to identify hadrons below a few GeV. The dE/dx technique has been described many times before, and therefore here we want to concentrate only on cluster counting, which may provide better performance. Although none of these methods compete with the performance of the RICH technique across such a broad energy range, they are generally less complex, may cover a lower momentum range, and, are in principle cheaper.

The radiation environment in some of the new experiments is severe. Table 1 shows typical conditions at SuperB, Belle II, LHC and ALICE heavy ion collisions. For example, the pp-diffractive scattering at LHC will have to cope with proton rates up to \(10^{-15}\) MHz/cm\(^2\) and total accumulated neutron doses up to \(10^{12}/\text{cm}^2\) after 10 years of running. All this means that designers of these experiments have very severe challenges, which will undoubtedly lead to problems and required upgrades.

2. Transition radiation detectors (TRD)

A particle passing through a dielectric boundary emits photons with some probability. The radiated power is proportional to the 
\(\gamma\) factor of the particle, but the number of emitted photons is small and proportional to \(\sim 1/137\), and the opening angle is also small and proportional to \(1/\gamma\). The emitted photon energy is typically between 2 and 15 keV. The TRD concept is used to identify electrons, as their \(\gamma\)-factor can be sufficiently high. To increase the probability of emission, one wants to use many dielectric boundaries within the detector, for example, using polypropylene foam [1]. This was used as a radiator of transition radiation in the ATLAS central tracker\(^2\) (see Fig. 2a). Fig. 2b shows a typical pulse height spectrum from the ATLAS TRD detector in the test beam, and Fig. 2c shows the first LHC results [1].

A TRD detector needs substantial detector space. Typically, an order of magnitude in rejection power against pions is gained each time the TRD detector length is increased by \(-20\) cm. Table 2 lists several experiments, which contain TRDs, with the typical \(\pi\) rejection factors achieved.

3. dE/dx cluster counting

The dE/dx particle separation in terms of the number of sigmas is
\(N_\sigma = \left| dE/dx(m_1) - dE/dx(m_2) \right| / \sigma\), where dE/dx (keV/cm) is the average energy deposit in a given sample, \(m_1\) and \(m_2\) are the masses of two particles, and \(\sigma\) is an error of the measurement. A classical dE/dx method integrates the total charge in a given drift cell track segment. The values of dE/dx and \(\sigma\) can be predicted easily semi-empirically, for example, as shown in Ref. [10]. For typical Ar-based or He-based gases, and a 1-cm-long sample at 1 bar, one obtains the resolution of FWHM/dE/dx\(~\sim\)100%. This value can be improved significantly if one determines the energy deposit instead by the cluster counting.

Cluster counting has been studied extensively in the past [2–8] both theoretically and experimentally. To resolve individual ionization clusters, two methodologies have been studied: (a) either

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time expansion chamber, where ions drift in a very low electric field, or, (b) employing low gas pressure. Neither method is very practical in the modern drift chambers considered at high luminosity colliders, such as SuperB. Instead, to resolve individual clusters, it is suggested \[9\] to use a He-based gas with no more than 5% of quencher, such as iC\(_4\)H\(_10\) gas. The He gas has 5.5 \(\pm\) 0.9 primary clusters/cm at 1 bar, and iC\(_4\)H\(_10\) gas has 70 \(\pm\) 12 primary clusters/cm. Fig. 3a shows that 95% He+5% iC\(_4\)H\(_10\) gas at 1 bar has \(\frac{N_{\text{primary clusters}}}{N_{\text{primary ions}}}\) = 15 primary ions/cm\(^2\) from 2.6 cm of drift cell \[9\]. One can see that there is a small tail due to delta rays, which will have to be dealt with by a truncated mean method. This is, however, nowhere near as large in magnitude as a typical Landau tail one observes in the classical \(dE/dx\) method, which integrates the charge from the entire track sample. Fig. 3b shows the measured and simulated pulses from clusters in the same cell \[9\]. Clearly, a challenge of this method is to fine tune the amount of iC\(_4\)H\(_10\) so that one has a large enough number of clusters but not too large to prevent reliable counting.

To illustrate the \(dE/dx\) performance improvement with the cluster counting, we take 95% He+5% iC\(_4\)H\(_10\) gas, with a 1 cm long drift sample. We obtain \(N_{\text{primary ions}}\) \(\approx\) 15 and therefore we expect FWHM/(\(dE/dx\)) \(\approx\) 2.35/\(N_{\text{primary ions}}\). The graph also shows that the \(dE/dx\) “hole” near \(\approx 1\) GeV/c could be “filled” with a TOF counter operating with \(\approx 100\) ps resolution.

4. Time-of-Flight (TOF)

The TOF particle separation in terms of number of sigmas is \(N_{p} = \left\{(L_{\text{path}}/2p^{2})(m_{1}^{2} - m_{2}^{2})\right\}/\sigma\), where \(L_{\text{path}}\) is the path length, \(c\) the
Table 2
Experiments employing TRD detectors [1].

| Experiment | Gas        | L (cm) | No of channels | σ_{rejection} |
|------------|------------|--------|----------------|---------------|
| HELIOS (NA34) | Xe-C_{2}H_{10} | 70     | 1744           | 2000          |
| H1         | Xe-He-C_{2}H_{6} | 60     | 1728           | 10            |
| NA31       | Xe-He-CH_{4}   | 96     | 384            | 70            |
| ZEUS       | Xe-He-CH_{4}   | 40     | 2112           | 100           |
| D0         | Xe-CH_{3}     | 33     | 1536           | 50            |
| NOMAD      | Xe-CO_{2}     | 150    | 1584           | 1000          |
| KTeV       | Xe-CO_{2}     | 144    | ~10k           | 250           |
| PHENIX     | Xe-CH_{4}     | 4      | 43k            | 300           |
| PAMELA     | Xe-CO_{2}     | 28     | 964            | 50            |
| AMS        | Xe-CO_{2}     | 55     | 5248           | 1000          |
| ATLAS      | Xe-CH_{4}-CO_{2} | 51-108 | 425k           | 100           |
| ALICE      | Xe-CO_{2}     | 52     | 1.2 M          | 200           |

Fig. 3. (a) Number of primary clusters in a 2.6 cm long drift cell with 95% He+5% iC_{4}H_{10} gas at 1 bar. (b) Measured and simulated numbers of primary clusters in the same gas [9].

Fig. 4. Author’s prediction of the p/K separation obtained using the “cluster counting” method in a SuperB drift chamber for tracks in the forward region for a dip angle of 45° (circles), compared to the predicted classical dE/dx performance for a dip angle 90° (diamonds). The graph also shows the predicted performance of a forward PID with a TOF detector having σ ~ 100 ps resolution (squares), which would be enough to “fill” the dE/dx hole near ~ 1 GeV/c. For comparison, we show also the predicted FDIRC RICH performance.

Fig. 5. ALICE MRPC: (a) side view showing 10 gaps, (b) top view showing a nylon line used as a spacer between glass plates, and (c) the power of combining the information from the TPC’s dE/dx and the TOF MRPC. This particular graph is based on initial preliminary TOF resolution of ~ 130 ps [18].

velocity of light, p the particle momentum, m_{1} and m_{2} are masses of two particles, and σ is the error of the time measurement. The error σ is influenced by many factors such as the detector transit time spread (σ_{TS}), electronics, photon radiator, bunch length, track length, chromatic effects, and many other detailed effects. The hardest parts to deal with, but which contribute significantly to the TOF performance, are the contribution from the detector (through
and the electronics, and that is why this paper will concentrate on its effort in these two areas.

4.1. MRPC detectors

The concept was developed from the Resistive Plate Chambers (RPCs) [11–13], and perfected further, for example, by Williams [14] and his collaborators at ALICE [15]. Other experiments used MRPC detectors (STAR3 [16]), or are planning to use them (CBM4 [17]). MRPC detectors are multi-gap glass RPC detectors, which can reach extremely good timing resolution. The gap size is only 250 μm to prevent a development of sparks. Because a large signal is developed only if an electron is produced very near the cathode, one needs many gaps to reach high enough efficiency. Fig. 5a and b shows the MRPC concept of the ALICE experiment [14,15,18]. The electrical contact is made only to the outer glass plates, while the inner ones are electrically floating. Simple fishing nylon lines maintain precise gap dimensions. The MRPC detectors are easy to build even for large area coverage. Table 3 shows the operating parameters of the ALICE MRPC design.

![Fig. 6. (a) MRPC prototype with 24 gaps (160 μm/gap), and 14% r.l./MRPC. Two identical MRPCs were used in the test beam. (b) Resolution obtained in the test beam σ = 15.8 ps/one MRPC detector [18].](image)

![Fig. 7. MCP-PMTs used in recent beam tests: (a) Hamamatsu HPK-6 (also called R3809U-50-11X), (b) Photek-210 & 240, (c) Photons Planacon, and (d) Hamamatsu SL-10. In this paper we consider only tubes with a double-MCP configuration.](image)

Table 3

| Parameter                              | Value |
|----------------------------------------|-------|
| Total number of active gaps per MRPC & total in ALICE | 10 / MRPC & 160,000 total in ALICE |
| Gap size (controlled by a fishing line) | 250 μm |
| Glass size in one MRPC & total in ALICE | 1200 x 72 mm² & 150 m² in ALICE |
| Pad geometry & number of pads/MRPC    | 25 x 36 mm² & 96 pads/MRPC |
| Gas                                   | 90% C₃F₇H₆ + 5% C₄H₁₀ + 5% CF₆ |
| Signal rise time                      | ~500 ps |
| Average total charge                  | ~2pC / MRPC |
| Typical counting rate                 | ~100 Hz/cm² (max rate: ~1kHz/cm²) |
| Total mass per MRPC with 10 gaps      | ~6% of r.l. / particle passage |
| Magnetic field in ALICE               | 16 KG |
| Pulse height correction               | Leading & trailing edge timing (TOT) |

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of ~16 ps per single MRPC is shown in Fig. 6b, where the MRPC
contribution to the final resolution is \(\sigma_{\text{MRPC}} < 10\) ps, and the
limiting factor is believed to be the electronics.\(^5\)

This shows that MRPCs are potentially excellent TOF detectors,
which are affordable for large-scale applications. The major
problem is that the maximum rate capability is only \(\sim 1\) kHz/cm\(^2\). This makes them presently unusable for applications at
SuperB, Belle II or pp-diffractive scattering at LHC. However, there
are some attempts to develop a low resistivity glass to improve
their rate capability\(^[18]\).\(^6\)

### 4.2. MCP-PMT detectors

Fig. 7 shows the typical micro-channel plate PMTs (MCP-PMTs),
which are commercially available. Table 4 summarizes their
geometry, QE, type of photocathode, their single photoelectron transit
time spread (\(\sigma_{\text{TTS}}\)), or simply TTS, and the risetime. To measure these
parameters correctly, one needs a very fast oscilloscope,\(^6\) a very fast
light source,\(^7\) and the electronics must be as fast as the MCP-PMT.\(^8\)

As this is not always available, the upper TTS or risetime limit is
mostly quoted. Other variables will influence the timing resolution,
for example, the \(S/N\) ratio or the cross-talk, which is a problem in
multi-anode devices. All these factors make the TTS measurement at
a level of 10–20 ps rather hard and make the setup expensive.

Although MCP-PMTs are very fast detectors, one must remem-
ber that there is a loss of photoelectrons at the entry to the MCP
hole, thus reducing the \(S/N\) ratio. This is demonstrated in Fig. 8,
which shows a 2D single photoelectron efficiency scan of the
Photonis-25 tube normalized to the Photonis Quatacon PMT
XP2262/B\([26]\), indicating that it is less than 50–60% as efficient,
and this includes out-of-time hits in the tail of the distribution, i.e.,
the in-time efficiency is even lower by 20–30%. This loss has to be
compensated by a longer radiator.

### 4.3. R&D test results with both MCP and radiator in the beam and
their possible applications

The Nagoya group\([27]\) was the first to demonstrate that to
achieve high-resolution timing with MCPs, one needs not only a
fast detector coupled to a fast electronics, but also a radiator
producing Cherenkov light. They used the HPK-6 tube. This was
followed by good test results in SLAC/Fermilab beam tests using
Photonis Planacon-10 and 25 tubes\([28]\) and Photek-240 tubes\([24]\).

Table 5 shows the summary of all the beam test results up to this
point. In all cases both the MCP tube and the radiator were placed
directly in the beam. The tests used two identical tubes to provide
start/stop timing. The results in the table indicate resolutions per
single tube.

The Nagoya test\([27]\) varied the radiator length\(^9\) during the
beam test, while operating at high gain of \(\times 10^6\). The advantage of
the high gain approach is that one can reduce the radiator thickness
and still obtain a very good timing resolution. To illustrate this
point, Fig. 9a compares the Nagoya results and the author’s
parameters correctly.\(^6\) The 16–18 GHz BW oscilloscope is needed to measure a risetime of \(~200\) ps.

\(^6\) For HPK-6 in Table 4, Hamamatsu\([19]\) used C5594 1.5 GHz BW amplifier and a
Nd-YAG laser with FWHM \(~5\) ps width, instead of typical laser diodes, providing a
light width of FWHM \(~30–35\) ps, which was used in most of the tests of Table 4.

\(^7\) For Photek-210 in Table 4, Ronzhin et al.\([24]\) used 1 GHz BW Ortec 9327CFD/566TAC/114ADC electronics; Brandt\([29]\) used two Minicircuit ZX60 amplifiers
(3–8 GHz BW, 10x) with a 2 GHz filter to reduce the noise, Louvain CFD and 16 GHz
BW, 80 GSa/s scope.

\(^8\) They obtained \(~20\) photoelectrons (pe) for \(L = 3\) mm, and \(~40–50\) photoelec-
trons for \(L = 10+3\) mm. The best resolution was obtained for \(L = 10\) mm, with 3 mm
window on MCP.

\(^9\) A 4-channel 10 GSa/s digital oscilloscope was used instead of TDCs.
calculation. One can see that even a 3-mm-thick window, used as a radiator, gives a very good result. On the other hand, the SLAC/Fermilab beam tests [28] with the Photonis-10 MCP-PMT were run at low gain, motivated by rate and aging problems at SuperB factory due to a large single photoelectron background. The reason for this is that in $e^+e^-$ machines most of the background is caused by gammas causing a few photoelectron deposits in the radiator. If one lowers the gain, one becomes sensitive to charged tracks only. On the other hand, one has to have the radiator thick enough to produce $N_{\text{pe}}$ photoelectrons/track to get a sufficient $S/N$ ratio for good timing. The radiator was made of the fused silica cubes with polished sides. The author’s calculation is shown in Fig. 9b. One can see that the main disadvantage of this approach is that the resolution degrades very rapidly as $N_{\text{pe}}$ (the number of photoelectrons) goes down for shorter radiator length. One can see that one needs at least 10 mm radiator length plus 2 mm window thickness to get good resolution at low gain.

Table 5 also shows rather good results with a Photonis-25 tube, operated at high gain with a 6 mm external radiator. It is equally good as the previous result with the Photonis-10 tube, operated at low gain. Table 5 also shows results with a Photonis-25 tube, operated at high gain, and a 2 mm radiator made of a MCP window [31]. The result of $\sigma \sim 37$ ps, obtained using a common “bottom MCP out” signal, was slightly worse than the above model’s prediction; however, the common signal may be affected by a cross-talk more easily. Clearly, there is a trade-off between the high and low gain operation, perhaps, the low gain operation is not the best in terms of the highest possible resolution; however, it is better for aging and rate issues.

Fig. 10 shows a possible application of the low gain operation concept proposed to SuperB for the endcap TOF detector [32]. A similar concept is being considered for the Phoenix experiment TOF wall [33].

To progress significantly further with the TOF technique based on MCP-PMT detectors, it is important to bring their cost down; here an important contribution may come from the pioneering development of MCP designs within the LAPD collaboration [34].

4.4. Application in LHC pp-diffractive scattering, where the radiator is in the beam and the MCP is out of beam

Both ATLAS and CMS experiments at LHC plan to place several sets of TOF detectors close to the beam lines, measuring timing of diffractively scattered protons in an attempt to discover the Higgs particle. Even with the long flight distances to these counters,
a timing resolution of ~ 10 ps is required to reduce the background. High rate and aging problems prevent the placement of the MCPs directly into the proton flux. The solution is either (a) short multiple-bar quartz radiators in detectors called either Quartic [29] or Qbar [24] (Fig. 11a), or (b) a C4F10 gas radiator with a mirror in a detector called Gastof (Fig. 11b). The quartz radiator gives a considerable chromatic contribution and has to be kept short. Although a single bar contributes a resolution of only $\sigma \approx 40$ ps, multiple bar measurements combined will deliver $\sigma \approx 10$ ps. On the other hand, the C4F10-based radiator has very fast light production contributing $\sigma_{\text{Radiator}} < 1$ ps, and thus this concept is limited only by the detector [30].

The first result from the Qbar detector beam tests at a Fermilab 120 GeV proton beam shows very good results. The two detectors used Photek-240 MCP-PMTs. With two detectors A and B mounted on the same side of the beam as it would be in LHC, so that the particle horizontal position cancels in the time difference, they measured $\sigma_{\text{A}} = 15.5$ ps and $\sigma_{\text{B}} = 16.3$ ps, so that the pair of counters [if considered as a single detector] had a resolution $\sigma(\text{AB}) = 11.2$ ps [24]. They plan to add more detectors in tandem to reduce the final error even further. However, to deal with very high multiplicities at the full LHC luminosity, one may have to use a segmented MCP-PMT such as what is planned for the Quartic detector [29].

These detectors have huge operational challenges at LHC due to very large background rates, close to the MCP maximum limit, and also due to the photocathode aging due to large charge doses. Novel ideas will be required to make this possible, and a lot of testing. Possibly one has to replace them often.

4.5. DIRC-like TOF detectors

As shown in Ref. [35], the DIRC concept, employing internally reflecting photons in the quartz radiator, can derive its particle separation capability not only from its measurement of the Cherenkov angle, as in imaging RICH detectors such as the BaBar DIRC, but it can also separate particles as a TOF counter. In this paper, we call these conceptually similar detectors DIRC-like TOF detectors [37, 38]. They are also called TOP [21, 36] and TORCH [39]. DIRC-like TOF detectors are devices where a quartz radiator is coupled to a string of fast MCP detectors measuring time and usually one space-coordinate only (the so-called x-dimension, which is approximately orthogonal to the typical average particle and photon propagation paths). The Cherenkov angle resolution is
generally not sufficient to achieve good particle separation, when considered as a RICH detector [35]. However, the counter can be used as a high resolution TOF detector provided that the timing resolution is adequate, the individual photon path lengths can be determined with a modest number of ambiguities, and that the quartz piece is small enough to limit the chromatic broadening. The examples of such devices are (a) the short TOP counter initially proposed for Belle II [36], which clearly demonstrated a resolution of 40–50 ps in the test beam, or (b) the recently proposed SuperB endcap TOF counter (see Fig. 12) [37, 38], which hopes to achieve a similar resolution. The beauty of this concept is that the total number of photon detectors is small. On the other hand, these devices are more sensitive to background as they do not have the redundancy of the highly pixilated RICH detectors, which may also be readout in three dimensions. This is true especially in the region below the Kaon threshold, where a large background will fake Kaons into pions, and would make such device less useful (see more discussion on this topic in Ref. [40]). The threshold region is an important region for SuperB or Belle II physics.

4.6. TOF with G-APD

Geiger mode operating APD (Avalanche Photo-diode) detectors, also known under names such as G-APD, SiPMT (Silicon Photomultiplier), MPPC (Multi-Pixel Photon Counter), etc., have generated great interest recently in regards to possible TOF applications. Although specially prepared G-APDs achieved superb $\sigma_{\text{TTS}} = 17–100 \text{ps}$ [41] or $37 \text{ps}$ [42], more typical values of commercial G-APDs are close to $\sigma_{\text{TTS}} = 80–100 \text{ps}$. Nevertheless one can get a very good TOF timing resolution even with these devices if the radiator provides enough photoelectrons. Fig. 13 shows a beam test result, performed recently at Fermilab in the 120 GeV proton beam [24]. Coupling a single 3 mm x 3 mm Hamamatsu G-APD to a 3-cm-long quartz radiator matching the G-APD’s footprint of 3 mm x 3 mm produced a timing resolution of $\sigma = 16.3 \text{ps}$ for a typical signal of ~60 photoelectrons. If one unfolds the contribution from a start counter (Photek-210 in this case), the G-APD resolution was $\sigma_{\text{G-APD}} = 14.5 \text{ps}$. Although G-APDs are very sensitive to bias voltage and temperature (6.2 ps/10 mV and 11.5 ps/0.5 °C [24]), it is possible to correct these effects by simply monitoring the pulse height.

4.7. TOF with a proximity focusing H-APD

A proximity focusing Hamamatsu H-APD (Hybrid-APD) is a combination of a vacuum tube with a uniform electric field and an avalanche photo diode (APD). These detectors are just emerging, and therefore not many parameters are known. They can operate in a large magnetic field, reach $\sigma_{\text{TTS}} = 100 \text{ps}$ [43], and obtain a gain of $10^4–10^5$. With a quartz radiator they could be used very well for a good TOF detector application.

4.8. Electronics for TOF detectors

(a) MCP-PMT tests: The Nagoya beam test [27] used the commercial electronics Becker&Hickl SPC-134 CFD/TAC/ADC providing $\sigma_{\text{Electronics}} = 4.1 \text{ps}$ and time scale calibration of 814 fs/count. SLAC/Fermilab beam tests [28] used the commercial Ortec 9327CFD/566TAC/114ADC electronics providing $\sigma_{\text{Electronics}} = 3.4 \text{ps}$ and time scale calibration of 3.17 ps/count. Brandt’s group [29] used a tandem of two Mini-Circuit ZX60 amplifiers.

Table 6

| Detector | PRO | CON |
|----------|-----|-----|
| MRPC     | - TOF detector timing resolution limit with a 24gaps/128 MRPC: ~10 ps. - Can be built in very large sizes. - Very cheap technology. | - Charged particle rate limited to ~1kHz/cm² presently - 24 gaps/128 MRPC represents ~14% of $X_g$ without the electronics |
| MCP-PMT  | - TOF detector resolution limit: ≤ 5 ps. - $\sigma_{\text{res}} \sim 10–30$ ps - Probably the fastest detector available. - “Bottom MCP electrode” is very useful. | - Very expensive technology presently. This limits this technology to small TOF detector systems at present. - Relative single photoelectron efficiency response compared to Photonis Qantoxaon XP 2272B PMT is typically less than 50-60% at 407 mm. “In time” response is even 20–30% lower due to tail. This reduces the S/N ratio. - Cross-talk between anodes for high BW amplifiers - Photonis Planacron MCP-PMT represents ~14% of $X_g$ |
| G-APD    | - $\sigma_{\text{res}} \sim 17–100$ ps - TOF timing resolution limit: ≤ 15 ps - No sensitivity to magnetic field - Relative cheap technology | - Sensitive to neutron background for a total integrated flux of >10³ neutrons/cm² - Very sensitive to bias voltage and temperature |
| H-APD    | - $\sigma_{\text{res}} \sim 100$ ps - No sensitivity to magnetic field | - Not yet available - Total gain is only 10³–10⁸. |
| Drift chamber with cluster counting | - Improvement in PID performance up to a factor of 2 compared to a classical dE/dx | - Requires sampling rate of ~1.5 GSa/s, ~500MHz amplifier BW, 8 bit ADC dynamical range - Data analysis of waveforms could be very complex - The He/C₂H₆ gas mix has to be tuned very carefully. |

14 $\sigma_{\text{res}} = \sqrt{\sigma_{\text{Electronics}}^2 + (\sigma_{\text{Chromatic}}/\sqrt{\sigma_{\text{Commercial, test}} \times N_{\text{pe}}})^2 + (\sigma_{\text{TOF}}/\sqrt{\sigma_{\text{Commercial, test}} \times N_{\text{pe}}})^2 + \sigma_{\text{Track}}^2 + \sigma_{\text{Detector coupling to bar}}^2 + \sigma_{\text{to}}^2} \sim 30–40 \text{ps, where } \sigma_{\text{Electronics}} - \text{electronics contribution } ~ 5–10 \text{ps (WaveCatcher), } \sigma_{\text{Chromatic}} - \text{chromatic term } 1/f \text{ (photon path length) } ~ 10–25 \text{ (Geant4), } \sigma_{\text{TOF}} - \text{transit time spread } ~ 35–40 \text{ ps, } \sigma_{\text{Track}} - \text{tracking error due to track length } L_{\text{path}} \sim 5–20 \text{ ps (FastSim), } \sigma_{\text{Detector coupling to bar}} - \text{coupling to the bar } ~ 1–20 \text{ ps (Fast Sim), } \sigma_{\text{to}} - \text{start time dominated by the SuperB crossing bunch length } ~ 15–20 \text{ ps.} |

15 Measured by the author using a special time calibration pulser made by Impeccable Instruments. A. Ronzhin of Fermilab measured $\sigma_{\text{Electronics}} = 2 \text{ ps}$ with the same electronics, but calibrated it using the micrometer-based delay line.
(10 × each, 8 GHz BW), followed by a 2 GHz BW filter, a Louvain CFD [30], and 16 GHz BW, 40 GAs/s scope.

(b) The latest MRPC test beam used two LeCroy four-channel 10G Sa/s oscilloscopes, believed to be contributing $\sigma_{\text{Electronics}} \sim 5$ ps [18].

(c) The question is if the new emerging waveform digitizing electronics [44,45] can start competing with the above mentioned commercial CFD electronics. The answer depends on the digitizer’s front end BW, the S/N ratio, and the sampling frequency. Recently, there was an attempt to start answering some of these questions empirically [46] using TARGET and WaveCatcher waveform sampling electronics, and a laser bench setup with two Hamamatsu C5594 1.5 GHz BW amplifiers with $63 \times$ gain. The paper [46] concluded that waveform digitizing timing results using the WaveCatcher board are consistent with the SLAC/Fermilab beam test results, which used a combination of the Ortec 9327CFD, TAC588, and 14bit ADC114 electronics (see Fig. 14). The TARGET chip results are worse due to (a) lower bandwidth, (b) worse S/N ratio, and (c) lower sampling frequency.16 Similar conclusions about the exquisite timing possible with waveform digitizing techniques was shown in Ref. [47], where the authors compared simulations with measurements using an 18 GHz BW oscilloscope operating at 40 GAs/s sampling.

5. Conclusion

The TRD technique is mature and has been tried in many hadron colliders. It needs space though about 20 cm of detector radial space for every factor of 10 in the $\pi/e$ rejection power, and this tends to make such detectors large.

Although the cluster counting technique is an old idea, it was never tried in a real physics experiment. Recently, there are efforts to revive it for the SuperB experiment using He-based gases and waveform digitizing electronics. A factor of almost 2 improvement, compared to the classical $dE/dx$ performance, is possible in principle. However, the complexity of the data analysis will be substantial.

The TOF technique is well established, but the introduction of new fast MCP-PMT and G-APD detectors creates new possibilities. It seems that resolutions below 20–30 ps may be possible at some point in the future with relatively small systems, and perhaps this could be pushed down to 10–15 ps with very small systems, assuming that one can solve many systematic issues. However, the cost, rate limitation, aging, and cross-talk in multi-anode devices at high BW are problems. There are several groups working on these issues, so progress is likely.

Table 6 summarizes the author’s opinion of pros and cons of various detectors presented in this paper based on their operational capabilities. We refer the reader to Ref. [40] for discussion on other more general limits from the PID point of view.

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