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# TRIDENT: a new concept for particle identification in the upgrade

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**Abstract**

A solution for particle identification in the LHCb upgrade is proposed. It involves the removal of RICH-1, and the replacement of RICH-2 with a full-acceptance RICH detector with twin radiator gases. This provides improved performance compared to the existing layout, while requiring fewer photodetectors. Since the photodetectors and their associated readout electronics dominate the cost of such detectors, this is a cost-effective way to provide outstanding particle identification for the upgrade.

# 1 Introduction

One of the key features of LHCb is its excellent particle identification system. In particular, the separation of charged hadron species is crucial for much of the flavour physics that the experiment is studying. This is currently provided by a RICH system of two detectors, the first (RICH-1) combining aerogel and $C_4F_{10}$ gas radiators, and the second (RICH-2) with $CF_4$ gas radiator. They are instrumented with HPDs (Hybrid Photo-Detectors), that provide high efficiency for single photon detection with very low noise [1]. LHCb is running at a levelled luminosity of $4 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, so after a few years of operation at the full LHC energy the data doubling time will become long. It is therefore planned to upgrade the experiment in the second long shutdown of the LHC starting in 2018, to profit from the higher luminosity available from the LHC, with a target of 1–2 $\times\, 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ [2, 3]. The main feature of the upgrade is the readout of the full detector at the beam crossing rate of 40 MHz, with the trigger performed in software in a large CPU farm. A consequence of this strategy is that the RICH photodetectors have to be replaced, as the HPD readout chip (currently adapted for readout at 1 MHz) is encapsulated within the detector.

The current baseline assumption for particle identification in the upgrade is to maintain the existing RICH vessels, but replace the HPDs with commercially available Multi-anode Photo-Multiplier Tubes (MaPMTs), with new (external) readout electronics. Since the use of aerogel has been found not to be viable at the higher occupancies of the upgrade, it will be removed [2]. It has been proposed to replace the low-momentum particle identification (that the aerogel was originally designed to provide) with a time-of-flight based system named TORCH [4]. The TORCH design pushes the state of the art, and has been awarded a grant from the EU for R&D over the next four years [5], but is not expected to be ready for installation at the start of the LHCb upgrade. Assuming that the R&D is successful it would be proposed for later installation [3].

There are some outstanding issues with the current baseline plan, that motivate a search for an alternative solution. The main of these is the high cost, driven by the large number of MaPMTs that are needed to equip the photodetector planes of the existing devices. This has been estimated as 3712 units: 1152 for RICH-1 (gas radiator only), and 2560 for RICH-2 [3]. The MaPMTs chosen are 64-channel devices, giving a total channel count of 240k. A second concern is the high occupancy that is seen in RICH-1, for a few central photodetectors. At the baseline upgrade luminosity of $1\times10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ this may be acceptable, but it is proposed that detectors should be able to handle $2 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, to provide flexibility in operating the experiment, and at that luminosity the RICH-1 occupancy reaches a value of over 30% in the hottest region, which is uncomfortably high. The current design for RICH-1 has severe access restrictions for the photodetectors, as the optics is arranged such that the photodetector planes are sited above and below the beam pipe, with access only possible during an extended stop of the machine. So, if RICH-1 were to be redesigned to reduce the peak occupancy, one would also profit of the occasion to rearrange the optics and provide improved access. However, such changes would only tend to *increase* the number of photodetectors required (in fact a further 1152 MaPMTs have been considered as a reserve for such a change). Another issue is the sensitivity of the latest MaPMT to magnetic field, which is expected to be greater than previous versions, and in the RICH-1 location right next to the spectrometer magnet the fringe field is high. The photodetectors are also rather close to the interaction point and to the beam line there, so the radiation dose is higher than at the downstream RICH-2 location, which may be an issue for the readout electronics. Finally, RICH-1 lies right in the middle of the tracking volume, between precision silicon devices (VELO and TT), and multiple scattering in its material can disturb the tracking of low-momentum particles.

For these reasons, it would be advantageous to remove RICH-1. The problem is that RICH-2 is designed for high-momentum coverage, so has only a limited acceptance, $< 120$ mrad. The possibility of a full-acceptance RICH-2 has therefore been studied, previously referred to as Super-RICH, but in those studies a significantly larger footprint along the beam axis and a larger photodetector plane were assumed. I have now revisited those studies, but in the current climate of financial prudence have aimed to limit the cost. The idea is to combine two radiator gases in a single device. The gases should not be mixed, as then one would get their average properties as a single radiator (e.g. the resulting Cherenkov threshold would lie between those of the component gases). Instead two distinct gas volumes are required, separated by a window, but sharing a common photodetector plane. The existing gases, $C_4F_{10}$ and $CF_4$, are retained: $C_4F_{10}$ provides the lowest Cherenkov threshold of an unpressurised gas at room temperature, good for extending the coverage towards low momentum; $CF_4$ is needed for high-momentum coverage, due to its lower refractive index and low chromatic distortion. The $CF_4$ is only really needed in the low-angle region ($< 120$ mrad) as that is where the high-momentum tracks are found, which is why RICH-2 was designed to only cover this range. But $C_4F_{10}$ is also needed in that region as well as for larger angles, since the low-momentum particles populate the full angular range.

I was astonished to discover a solution that fits into the available space, and uses *fewer* photodetectors than the current baseline. This concept is described below.

# 2 New detector concept

The conceptual layout of the new detector is shown in Fig. 1. Its footprint along the beam axis starts at $z = 950$ cm, as for the current RICH-2, but extends to $z = 1240$ cm, using the space behind RICH-2 that will be vacated by the first muon station, M1, which will be removed for the upgrade. Most probably the Preshower detectors (PRS/SPD) that follow M1 will also be removed; the next detector (ECAL) starts at $z = 1250$ cm [1]. Using the space that will be liberated behind RICH-2 will entail rearranging the beam-pipe supports that are sited there, but since the upstream support structure is being completely revised for the upgrade, this will hopefully not be too serious an inconvenience. The space taken along $z$ could be adjusted if the PRS/SPD are retained, but the extra $\sim 30$ cm liberated by M1 is essential for the concept, which is unlikely to be feasible if it is forced to stay within existing RICH-2 limits. It would anyway be a pity not to make full use of the

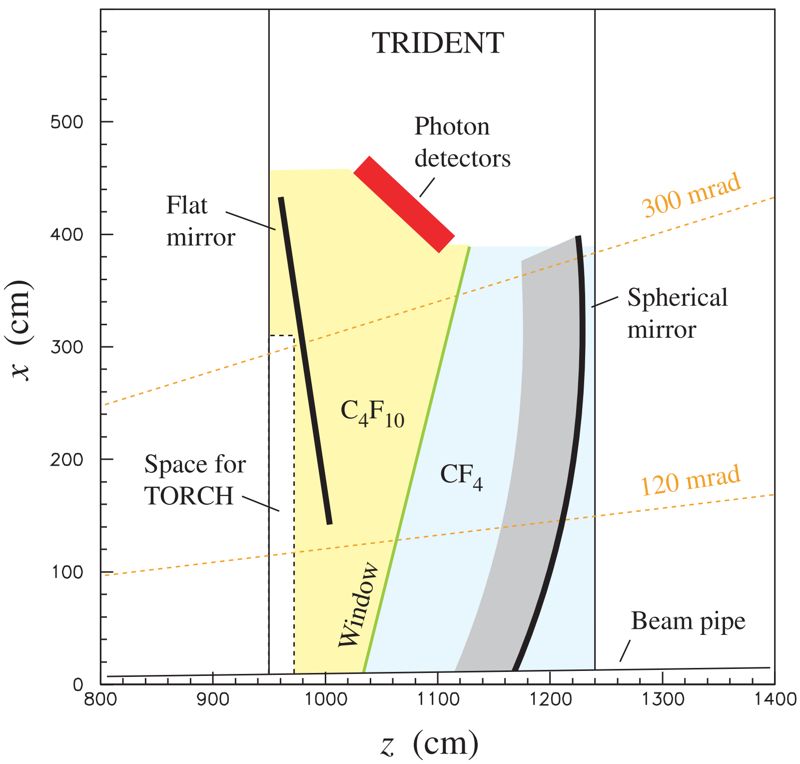


Figure 1: Layout of the TRIDENT concept, viewed from the top. Only one side of the detector is shown, the other side of the beam axis ($x < 0$) is a reflection of this side. The grey shading in front of the spherical mirror indicates the impact points of photons across its full surface, when viewed in this projection.

space available. The proposed optical system is similar to that of RICH-2, with a tilted spherical focussing mirror, and a flat mirror to limit the device's extension along $z$. The photodetectors are required to be situated outside the 300 mrad spectrometer acceptance.

The two gas radiators, $C_4F_{10}$ and $CF_4$, are separated by a window. This window is an element of the design that will need R&D. Ideally it would be a thin transparent plastic foil, e.g. of Mylar. It only needs to separate the gas volumes, and some distortion due to their different densities is acceptable, as long as the final shape is stable. The nominal shape of the window is an inclined plane on each side of the beam pipe, as shown in Fig. 1 (it is vertical in the other projection). As a back-up solution, the window could be engineered out of a few mm of glass. Note that baseline photodetector (described in next section) has a borosilicate glass window, so there is no need for transmission at lower wavelengths. With a thin glass window, though, a supporting frame would presumably be required, that would reduce the effective transmission when averaged over the acceptance, so a single plastic sheet on each side looks preferable. For now, a 95% transmission of photons through the window has been assumed. Note that for photons from the $C_4F_{10}$ the window is traversed twice, so for them this transmission factor is squared.

Rather than referring to this concept as RICH-3, a new name is proposed: TRID (Twin

Ring Imaging Detector), by extension from the CRID acronym used for RICH detectors in the US. Of course, RICH-1 (and the HERMES RICH) is already a twin radiator RICH detector, but due to the large and sparse rings from the aerogel this feature is not very apparent. In contrast, the twin gas radiator layout of the TRID should give striking twin ring signatures, as illustrated below. A kaon (for example) will provide no, one or two concentric rings depending on whether its momentum is below or above the Cherenkov threshold values of 9 GeV/$c$ and 15 GeV/$c$ for the $C_4F_{10}$ and $CF_4$ radiators respectively. This feature may be useful to enhance the pattern recognition.

Such a layout could not have been used in the current phase of LHCb, due to the requirement of incorporating aerogel for positive identification of kaons below 9 GeV/$c$. Without the aerogel, one can only distinguish pions from kaons below this threshold in "veto" mode—relying on the fact that a pion should give light, while the kaon does not. This works well for isolated tracks, but is not obvious in the busy environment of upgrade events. It would not be feasible to equip a downstream device with aerogel due to the large area that would be required to cover with aerogel tiles, and the enormous photodetector area that would result from its large Cherenkov angle. However, as mentioned above, TORCH has been proposed as a replacement for the low-momentum capability, based on time of flight, and it only requires a small space for installation in the downstream region (i.e. after the tracking volume). TORCH consists of a thin plate of quartz in the acceptance, about 1 cm thick, so little space is required. It is advantageous to site it at $z = 950$ cm rather than later, since this will minimize the scattering of the low-momentum particles, and also minimize the area to be instrumented. The TRID layout provides space for TORCH, making use of the otherwise dead area upstream of the flat mirror, as illustrated in Fig. 1. A space of 20 cm has been reserved along $z$, to provide room for the optics and detection system which will be attached to the upper and lower edges of the quartz plate (i.e. at $y = \pm 250$ cm). When TORCH is included, the complete system is named TRIDENT, standing for TRID ENclosing Torch, or (perhaps more elegantly) Triple Radiator IDENTification system.[1] TORCH, as the third prong of the TRIDENT, will not be considered further here, as its implementation will depend on the successful outcome of its R&D programme; it is important that it is kept in mind, though, during the engineering design of the TRID.

If this proposed solution is adopted, then RICH-1 can be honourably retired when the upgraded experiment is installed. This will remove material from the middle of the tracking volume, which should help the performance of the upgraded tracker. (On the other hand, it should noted that every effort was made to limit the material budget of RICH-1, and about half of its material is in the aerogel which is already planned to be removed.) The space liberated might also be used for the reoptimisation of TT, or to provide an enhanced magnetic field in the region between VELO and TT, which could be used to speed up the software trigger. With the photodetectors all now sited downstream of the magnet and further from the beam line, they will be in a lower fringe field, and lower radiation environment. The only potential disadvantage of this change that I can

[1] No relation to the nuclear weapon system of the same name.

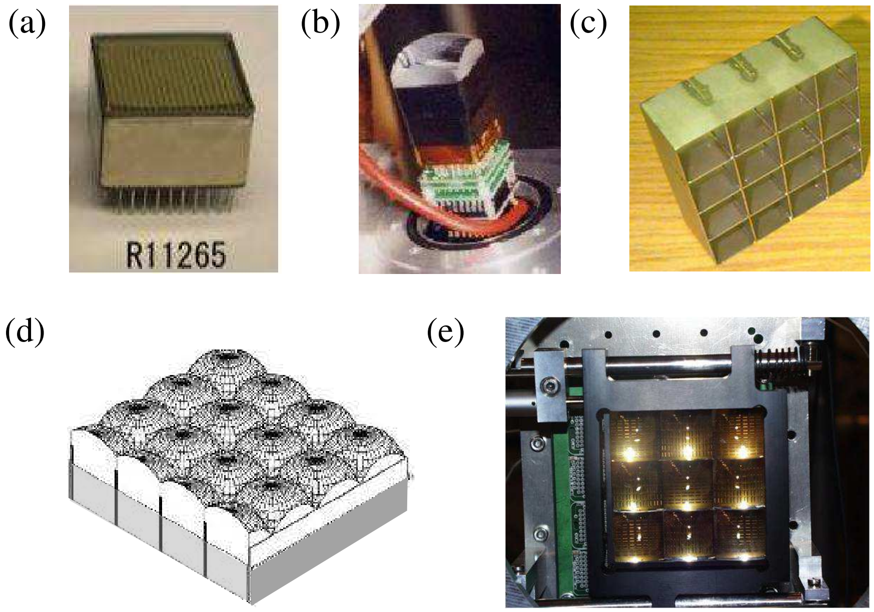


Figure 2: Compilation of pictures related to the MaPMT photodetector: (a) photograph of the baseline 64-channel version, R11265 from Hamamatsu; (b) a single lens attached to the entrance window of an earlier version of the MaPMT, with readout electronics; (c) a "wine-crate" of Mu-metal magnetic shielding plates, arranged to fit around a $4 \times 4$ array of MaPMTs; (d) schematic of such a module, with lenses attached; (e) photograph of a $3 \times 3$ module equipped with lenses, used in test-beam studies [9].

think of is that upstream tracks (i.e. those composed of VELO + TT hits alone, that do not reach the TRID) will not be identified. However, as far as I am aware such tracks are not currently being used, since they are typically of very low momentum and as a result have poorly defined track parameters.

The low-angle coverage of RICH-2 currently extends down to 15 mrad, not down to the nominal LHCb acceptance of 10 mrad, due to a heating jacket installed around the beam pipe for bake-out purposes. It would be worth investigating whether this is feature is still needed, in light of experience, or whether it might be reduced in size. Anyway, the $C_4F_{10}$ inner acceptance of the TRID will be substantially improved compared to RICH-1, which is limited to the 25 mrad of the beryllium beam pipe in the upstream region.

# 3 Photodetector assumptions

This concept could in principle be adapted to any suitable photodetector. However, to be concrete a baseline layout has been established taking the existing assumption for the upgrade: the 64-channel MaPMT. The latest version R11265 from Hamamatsu is assumed, shown in Fig. 2 (a), which features an improved active-area fraction compared to earlier versions. The default type of this tube that has been assumed in the RICH upgrade is the SBA (Super Bi-Alkali) photocathode, with borosilicate glass window [6]. There are other types available, CBA with lower quantum efficiency (QE) at a lower cost, and UBA with higher QE at higher cost, but the SBA appears to be a good compromise between photon yield and expense. The borosilicate window transmits less signal from the blue end of the spectrum, compared to the more expensive UV glass or quartz windows, so the photon yield is reduced. But the visible photons give lower chromatic distortion than those in the UV, so this also looks like a good compromise. In case the photon yield is lower than expected, this choice leaves room for reaction (at higher cost). The assumed QE vs. wavelength is shown in Fig. 3.

The nominal dimensions of the face of a bare MaPMT is 26.2 mm square, with an active area of 23 mm square divided into an $8 \times 8$ array of pixels, each separated by an insensitive region of $\sim 0.1$ mm. Hence the effective pixel size is about 2.8 mm square. This is, however, too small for a RICH detector in the the downstream region of LHCb, since the contribution of the pixel size $d$ to the uncertainty on the Cherenkov angle is given by

$$\sigma_{\text{pixel}} = d/\sqrt{3}\,R \quad , \tag{1}$$

where $R$ is the radius of curvature of the focussing mirror. In this region the radius of curvature needs to be of order 8 m to bring the image out of the spectrometer acceptance, and to obtain a pixel error of about 0.3 mrad one therefore needs a pixel size of $\sim 4$ mm. Any less and the pixel error will be much smaller than the other limitations to the resolution from chromatic and emission-point effects. Note that RICH-2 was significantly over-designed in this respect, with a negligible pixel error, but this was due to the simplicity of using the same photodetector in both RICH-1 and RICH-2, and the relatively small pixel size was needed for RICH-1. Now that constraint has been removed, the pixel size should be increased.

There is a very convenient way to achieve this, using a hemispherical lens attached to the entrance window of each MaPMT, as shown in Fig. 2 (b). Such a lens can provide an extremely high active area, by enlarging the pixel size by a factor of 3/2 [7], which corresponds to 4.2 mm, ideal for our purpose. The resulting image of the active area of the MaPMT then has a size of 34.5 mm square, and within this area the effective active-area fraction is 94%. Again to give a concrete design, it is assumed that a $4 \times 4$ array of MaPMTs equipped with such lenses is assembled to form a module. The space between the individual tubes can be used for mechanical support and magnetic shielding, as illustrated in Figs. 2 (c, d). Note that the pitch assumed here of 34.5 mm is somewhat larger than the minimum of 29 mm that has been recommended in studies so far [8], allowing for relaxed tolerances or more shielding if required. The resulting larger coverage per MaPMT is obviously important to minimize the total number of photodetector units required, and associated electronics channels. Similar modules were already tested in the beam, during the preparation for the choice of photodetector for the current RICH system, as shown in Fig. 2 (e). In that case the lenses were machined from quartz [9], but given the limited bandwidth of the borosilicate MaPMT entrance window, a moulded plastic lens might also be feasible, or glass. If the lens is optically coupled to the MaPMT entrance window, for example with optical grease or gel, there will be no additional transmission loss, a

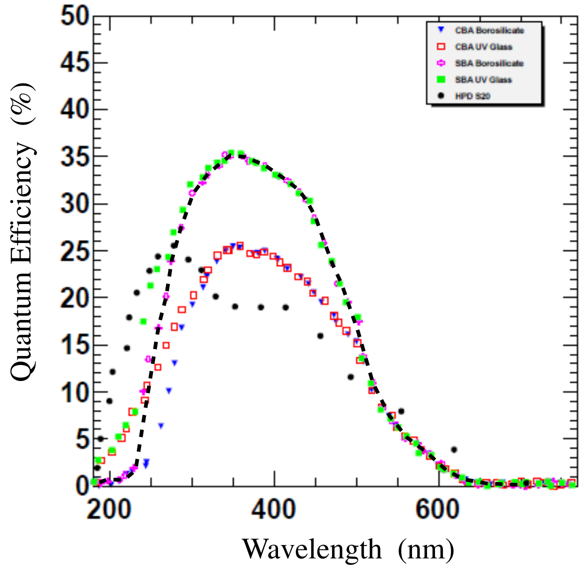


Figure 3: Quantum efficiency as a function of wavelength for various photodetectors [6]. The response assumed for the simulation is indicated by the dashed line (MaPMT with SBA photocathode and borosilicate window).

significant advantage over other possible lens systems that have been proposed. Ideally the lens array could also act as the interface to the radiator gas volume, replacing the large quartz windows that are used in the current RICH detectors. This would further reduce transmission losses, at the cost of some inconvenience when accessing the photodetectors (though not everyone shares my enthusiasm for this idea).

Two types of modules are assumed: fully and half-instrumented. The half-instrumented ones are the same dimension as the fully instrumented, but just have 8 rather than 16 MaPMTs installed, for use in regions of the detector plane where the photon yield is not the limiting factor. This could be achieved by inserting the MaPMTs in a checker-board pattern, or any other arrangement that is convenient, depending on the modularity of the electronics.

The detection efficiency for the photoelectrons produced at the photocathode of the MaPMT is taken to be 90% [6].

# 4 Optical layout

The layout of the elements shown in Fig. 1 has been optimised using a simple ray-tracing programme. High-momentum tracks are simulated, uniformly distributed across the entrance window of the device, in straight lines from the interaction point. For each track photons are thrown off randomly as they pass through the radiator, according to the Cherenkov angle, taking into account the dispersion in the radiator gas and the bandwidth of the photodetector. They are traced through the optical system until they reach the photodetector plane. The Cherenkov angle is then reconstructed using the standard

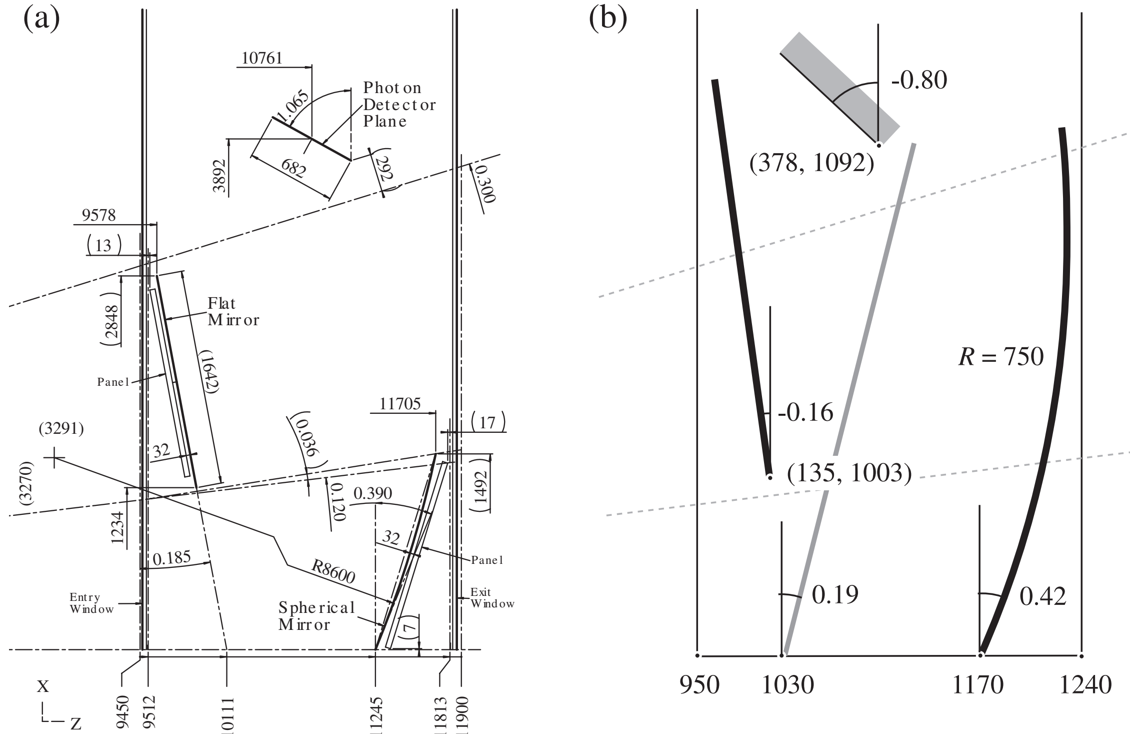


Figure 4: Comparison of the plan views of (a) the existing RICH-2 detector [10], and (b) the new TRID, on roughly the same scale. Units are mm in (a) and cm in (b), with angles in radians; see Fig. 1 for labelling of the TRID components.

technique [11], from the photodetector hit and assuming the photon emission point to be at the middle of the radiator. This allows the smearing due to emission-point and chromatic effects to be determined, along with the overall size of the image on the photodetector plane. The various components are then moved around to find the optimal layout. This does not correspond to ideal focussing, as one can live with a certain level of aberration, in the quest for a compact detector plane and large photon yield.

A selection of the various aspects that are kept in mind during this process are as follows: the radius of curvature of the spherical mirror should be reduced to limit the photodetector area, but needs to be sufficiently large to keep the image plane outside the acceptance. The angle of the photodetector plane influences the quality of focussing and hence the emission-point error, with the ideal focussing achieved for a roughly vertical plane; however, this also affects the size of the image, and it is important for the incoming photon angle of incidence not to be too large. The solution preferred here is to provide roughly normal incidence, to avoid the need to stagger the photodetector modules, which would give problems of shadowing or dead area—they lie on a single plane in the solution proposed. The position and angle of the window separating the two gas radiators can be adjusted to vary the photon yield from each of the radiators, while also affecting the emission-point error. The dimensions of the best working point that has been found to date are given in Fig. 4, where the layout is compared to the existing RICH-2 detector.

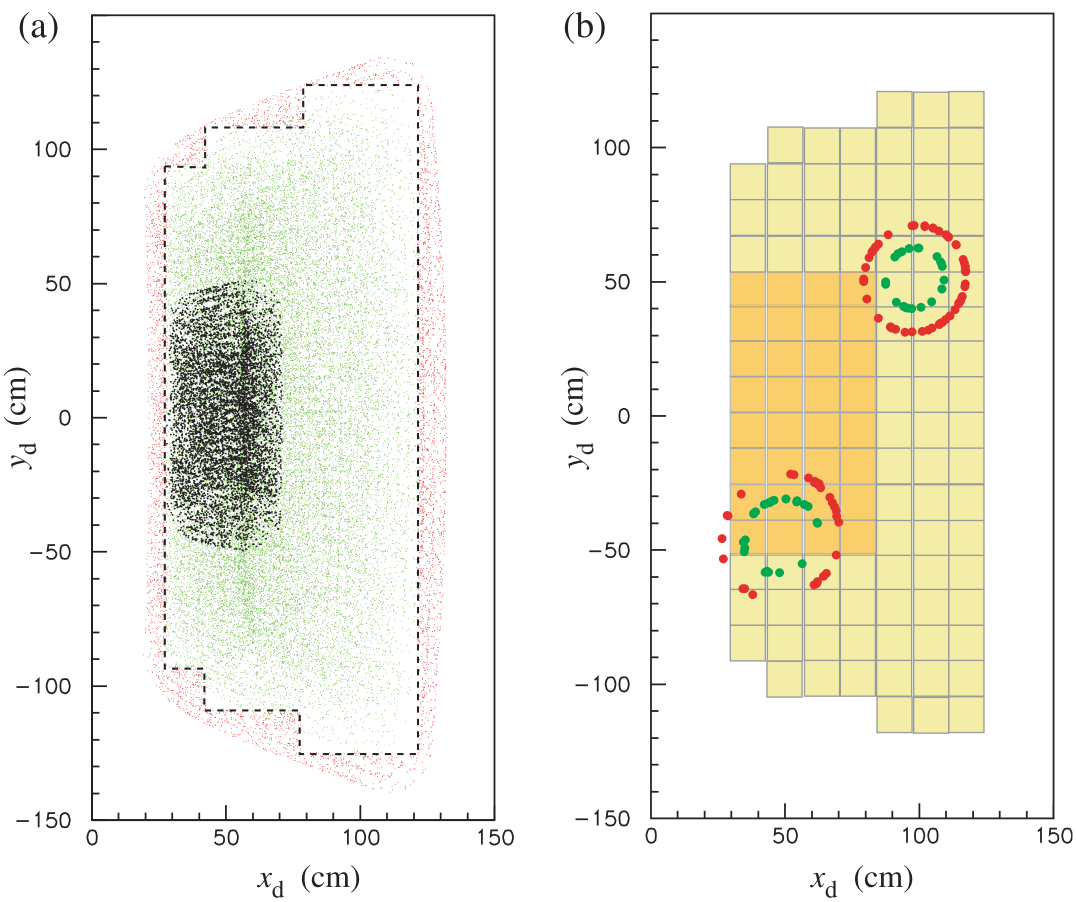


Figure 5: One of the two photodetector planes of the TRID (a) showing the impact points of photons from the simulation of tracks over the full acceptance in the $C_4F_{10}$ radiator (red points) and $CF_4$ (green points), as well as in the $CF_4$ for the limited acceptance of RICH-2 (black points). The dashed line indicates the limit of the instrumented region, which includes most of the $CF_4$ photons; the $C_4F_{10}$ photons are only drawn if they fall outside this region, for clarity. (b) For the same plane, the tiling of photodetector modules is illustrated, with each square corresponding to a $4 \times 4$ MaPMT module; the darker-shaded (orange) modules are fully instrumented, the lighter-shaded (yellow) ones are half-instrumented. The photons from two randomly selected tracks are superimposed to illustrate the signals from a saturated track, with the outer ring from the $C_4F_{10}$ (red points) and the inner ring from the $CF_4$ (green points).

This procedure is the same as was used in the original optimisation of the RICH-1 and RICH-2 optics, and reproduces the resolution contributions for those devices that are listed in Table 1. Although the procedure sounds rather rudimentary, very good agreement was found for the resolution in the real data, for both detectors. Their expected photon yields are also listed in the table—here the simulation has been slightly less successful, over-estimating the yields by about 10–20% compared to the real data. Nevertheless it should be safe to make a relative comparison of the TRID performance and the current RICH system, as the same procedure is used.

The resulting images on the photodetector plane are shown in Fig. 5, along with the

Table 1: Performance parameters for the TRID, compared to the existing RICH detectors [1]: the average number of detected photoelectrons (for the $CF_4$ in TRID this is quoted within the angular acceptance of RICH-2); the contributions to the Cherenkov angle resolution, the total uncertainty per photon (given by the sum in quadrature of the contributions) and the estimated momentum limit for $3\,\sigma$ $K$–$\pi$ separation. Note that the pixel error for RICH-1 and RICH-2 includes a contribution from the point-spread function of the HPD focussing, which does not affect the MaPMT used in the TRID.

| | RICH-1 | RICH-2 | TRID | | |
|---|---|---|---|---|---|
| Radiator | $C_4F_{10}$ | $CF_4$ | $C_4F_{10}$ | $CF_4$ | |
| $\langle N_{pe} \rangle$ | 30 | 22 | 27 | 25 | |
| $\sigma_{emission}$ | 0.8 | 0.2 | 0.39 | 0.42 | mrad |
| $\sigma_{chromatic}$ | 0.9 | 0.5 | 0.43 | 0.22 | mrad |
| $\sigma_{pixel}$ | 0.6 | 0.2 | 0.33 | 0.33 | mrad |
| $\sigma_{track}$ | 0.4 | 0.4 | 0.40 | 0.40 | mrad |
| $\sigma_{total}$ | 1.5 | 0.7 | 0.78 | 0.70 | mrad |
| $p_{3\sigma}(K\text{–}\pi)$ | 51 | 92 | 69 | 95 | GeV/$c$ |

proposed instrumentation with MaPMT modules. 116 modules are required to cover the image on each side of the detector, 32 of them fully instrumented to catch the photons from the $CF_4$ at low angles, while the remainder need only be half-instrumented, due to the profuse yield of photons from the $C_4F_{10}$ in the outer region.

# 5 Expected performance

The performance parameters that have been determined using this simulation of the TRID are listed in Table 1, where they are compared to the corresponding parameters from the existing RICH detectors. As can be seen the photon yield from the $CF_4$ is slightly higher than in RICH-2, while maintaining the same resolution: the increased pixel error is compensated by reduced chromatic (due to the borosilicate window of the MaPMT). For the $C_4F_{10}$ this reduction in chromatic contribution is even more striking, while the number of detected photoelectrons is maintained at roughly the same level as in RICH-1. Of course that number could be easily increased by replacing half-instrumented modules with fully-instrumented ones, but given the dramatic improvement (by a factor of two) in overall resolution, that does not seem necessary to me.

The contribution to the resolution due to uncertainty on the track parameters is taken to be unchanged at 0.4 mrad, to be conservative. The resolution would clearly benefit from some reduction of this, in the upgraded tracker design. Nevertheless, all contributions to the uncertainty are now reasonably well matched, for both radiators. Their impact can be illustrated by calculating a figure of merit, the momentum limit for $3\,\sigma$ $K$–$\pi$ separation,

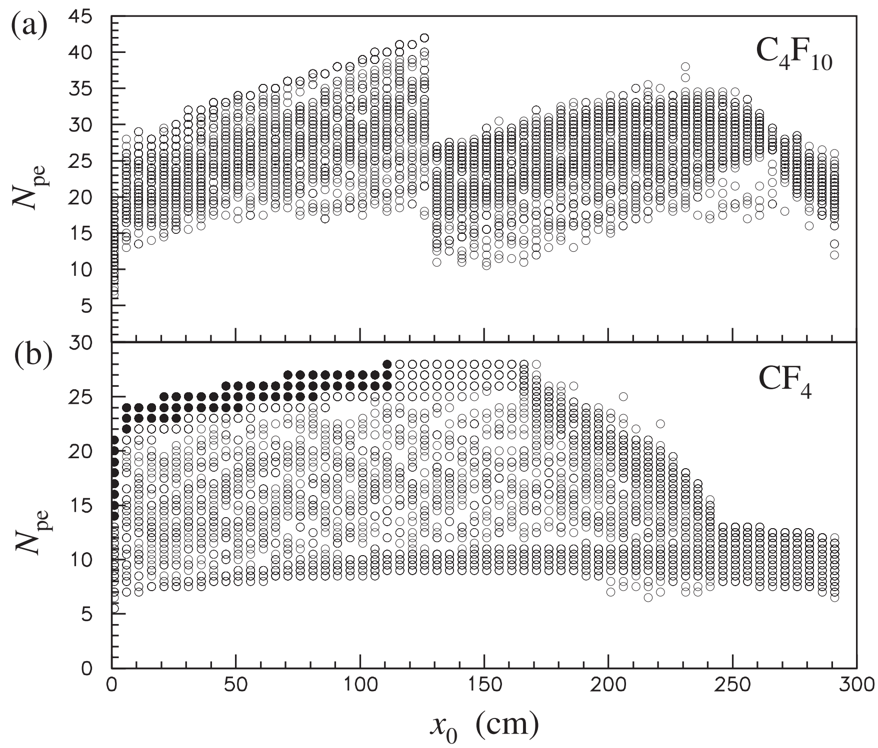


Figure 6: Number of detected photoelectrons per saturated track, as a function of the entrance point $x_0$ of the track, for tracks simulated over the full entrance window of the TRID: (a) for the $C_4F_{10}$ radiator and (b) for $CF_4$. In (a) the discontinuity at around $x_0 = 130$ cm is due to the edge of the flat mirror, which sits in the $C_4F_{10}$ volume; in (b) the tracks within the acceptance of the current RICH-2 are indicated with solid points.

which is given by

$$p_{3\sigma} = \sqrt{\frac{(m_K^2 - m_\pi^2)\,\sqrt{N_{\rm pe}}}{\sigma_{\rm total}\,\sqrt{72\,(n-1)}}} \quad , \tag{2}$$

where $n$ is the refractive index of the gas, $n = 1.0014$ (1.00045) for $C_4F_{10}$ ($CF_4$). These values are also listed in the table. Significant improvement is seen for the $C_4F_{10}$ radiator compared to RICH-1, and a small improvement for the $CF_4$ compared to RICH-2, due to the slightly increased number of detected photons. Note that this is calculated for the $CF_4$ over the angular acceptance of RICH-2, i.e. up to 120 mrad in the $(x, z)$ projection and 100 mrad in the $(y, z)$ projection. As shown in Fig. 6, the $CF_4$ radiator in TRID also gives detected photons over the full acceptance of the experiment (i.e. out to 300 mrad horizontally and 250 mrad vertically). Averaged over the full acceptance, the number of detected photoelectrons is 17 per saturated track. The wide-angle high-momentum coverage is just a bonus from the TRID arrangement: of course, most high-momentum tracks are at small angle, so this will not be a major benefit. The main point is that the full acceptance is covered with somewhat better overall performance, compared to the previous baseline, but using significantly fewer photodetectors.

Full simulation will be required for the final word on the occupancy for this set-up. But the occupancy in RICH-2 is currently an order of magnitude lower than that of RICH-1, so even with pixels that are roughly double the size, and approximately doubling the number of hits due to the twin gas images, I expect that it should be fine. The major problem with RICH-1 is the peak rather than average occupancy, and the image is more uniformly spread in the RICH-2 location.

# 6 Conclusions

A conceptual design for a particle identification system named TRIDENT has been presented. It consists of a twin gas radiator device (TRID), eventually to be combined with the TORCH to enhance the low-momentum coverage. As shown above, the TRID performance surpasses that of the existing RICH system, while requiring fewer photodetectors. The total count is 116 modules each side, 32 of them fully instrumented with $4 \times 4$ MaPMTs while the remainder are only half-instrumented, giving a total of 2368 MaPMTs in the complete detector, and 150k channels. This can be compared to the 3712 MaPMTs that are currently assumed for the baseline costing of the RICH upgrade, i.e. it corresponds to 64% of that number. Given that the photodetectors and their readout electronics dominate the total cost estimate of 9.4 MCHF [3], this represents a saving of about 3.4 MCHF. Unlike for the current baseline, no extra reserve will be required for adapting to a luminosity of $2 \times 10^{33}\,\mathrm{cm^{-2}s^{-1}}$, as this is expected to be handled by the proposed system—but that should be verified with full simulation.

Of course, additional work will be required to construct the new detector. But adapting the existing RICH detectors to the new photodetector would anyway have been challenging. The technology used for RICH-2 can be essentially copied. The reduction in material budget from the removal of M1 will more than compensate for the extra few mm of glass from the larger mirror areas in TRID. Some part of the RICH-2 superstructure or mirror support structure might be re-usable. But even if not, then using the same technical solutions for the somewhat larger detector should simplify and accelerate the construction. The cost estimated for the mechanics and optics of RICH-2 was 1.2 MCHF [12], so there should still be an overall saving. I would suggest that any resources liberated are reserved for the eventual addition of TORCH. The only R&D that is required, apart from the characterisation of the photodetector and its readout electronics which is already in progress, is for the choice of materials for the window that separates the two gas volumes, and the lens array in front of the MaPMTs.

I hope that my enthusiasm for this concept is shared, so that it can be adopted for the LHCb upgrade.

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