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Simulation of the Focusing DIRC Optics with Mathematica

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***Abstract*–The Focusing DIRC is considered for the Barrel PID at a possible Super-B factory. To reduce sensitivity to background, it would be desirable to reduce a size of the present BaBar photon detector. One way to do it is to replace it with a focusing optics and use smaller photon detector pixels. We have simulated the focusing optics with simulation software based on a 3D calculation performed with the Mathematica program. The software does not use Optica package, instead, it uses its own 3D algorithm. The advantage of the presented method is that it is transparent, fast and that it uses a full backing of the Mathematica graphics, and it does not require expertise to run Geat4 MC software.**

I. Introduction

The DIRC detector at the BaBar experiment provides excellent particle identification performance [1], [2]. Based on this success, our group has been following an R&D program to develop an appropriate photon detector for future particle identification systems. One such idea, a focusing DIRC (or FDIRC) [3]-[7], would be capable not only of measuring an (x,y) coordinate for each photon with an angular resolution similar to the present BaBar DIRC, but, in addition, measuring each photon's time-of-propagation (TOP[1]) along the Fused Silica bar with ~150 ps single-photoelectron timing resolution (the present BaBar DIRC has a timing resolution of only $\sigma \approx 1.6$ ns). Small pixel size would allow a design of a photon detector expansion volume up a factor 10 smaller than the existing BaBar DIRC. Smaller geometrical size together with better timing would allow the suppression of the background by more than one order of magnitude; in addition, better timing will allow correction of the chromatic error and thus improve the angle measurement substantially. The focusing element also removes the bar thickness as a term that contributes to resolution smearing. Such a device could be important for a future Super B-factory.

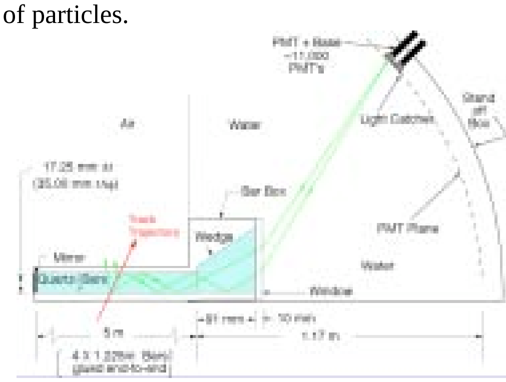
We have built the first prototype of a focusing DIRC and had two successful test beam runs with it. In these runs, we established that (a) the new photon detectors work as expected, based on our bench tests; (b) we can achieve similar Cherenkov angle resolution as the BaBar DIRC with much more compact and faster detectors; (c) we can achieve single-photon timing resolution at a level of 100-200 ps; (d) we can clearly observe the expected chromatic dispersion on a photon by photon basis; and finally, (e), we can correct the chromatic error through this timing measurement [5]-[7]. At the end, after the prototype was built, we have also developed a Geant 4 Monte Carlo simulation of the prototype.

The FDIRC prototype optics was originally designed by author using a ray tracing with a mechanical drawing package called Vellum. This proved to be rather cumbersome and there was a clear need to develop something a bit more elegant. In this paper we present a small-scale optics simulation of FDIRC detector using the Mathematica program. The simulation considers a track entry, the Cherenkov photon production and propagation along the square Fused silica bar (geometry as in BaBar DIRC), wedge at the end of the bar (geometry as in BaBar), and it adds a spherical or cylindrical or parabolic focusing mirror, from which the photons are reflected to a focal plane with detectors.

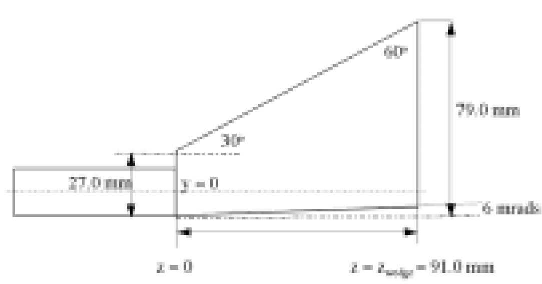
II. Principle of BaBar DIRC

Fig. 1a shows a principle of Ring Imaging with DIRC at BaBar, and Fig. 1b shows typical images one simulates for various types of particles.

(a)



(b)



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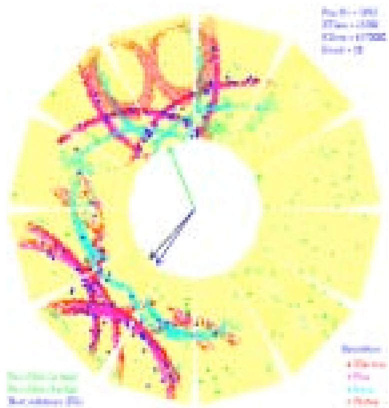
[1] Definition: TOP(Φ, θ_c, l) = [L/$v_g(\lambda)$] $q_z(\Phi,\theta_c)$, θ_c - Cherenkov angle, L - distance of light travels in the bar, $v_g(\lambda)$ - group velocity of light, λ - photon wavelength, and $q_z(\Phi,\theta_c)$ – z-component of the unit velocity vector.

(c)



(d)

Fig. 1. (a) Principle of BaBar DIRC, (wedge at the end of each bar direct light into a photon detector, (c) Cherenkov ring images as obtained from Monte Carlo simulation, and (d) real DIRC bars in clean room. [1].

III. Example of a Mathematica Code

Fig. 2 shows how laser beam reflects in a DIRC bar through internal reflection.

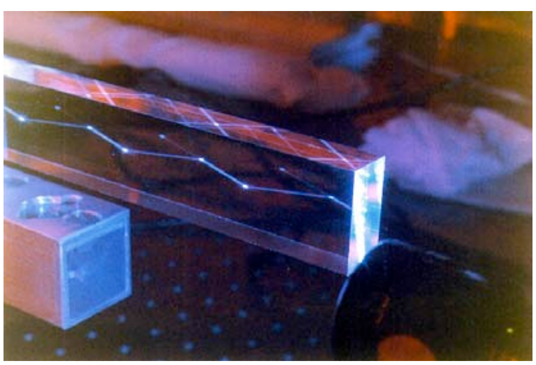


Fig. 2. Laser propagation via an internal reflection in a DIRC bar [1].

Table I shows an example of a Mathematica code describing such photon propagation in a rectangular bar. A similar code is used for photon reflection of the mirror and intersection with focal plane, etc.

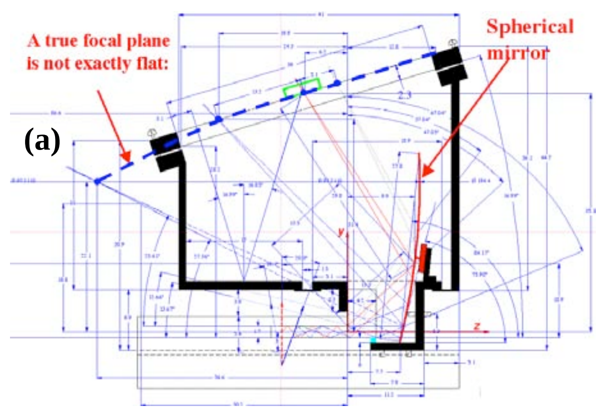
Table I – example of a code in the Mathematica

IV. Cherenkov Ring Image with Focusing DIRC, with Spherical Mirror and with No Wedge at Bar's End

A. Shape of Focal plane surface

Fig. 3a shows the FDIRC prototype as built [3]-[7]. The picture also shows that a flat focal plane is a reasonable approximation of a true calculated shape. Fig.3b shows a spherical mirror located at the end of the bar.

(a)



(b)

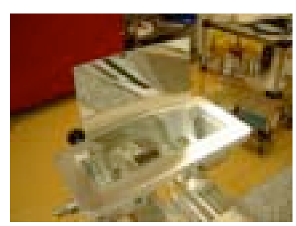


Fig. 3. (a) FDIRC prototype with a spherical mirror and bar. A calculated focal plane is not exactly flat, but not far from flat approximation for shown range of dip angles. The picture also shows the bar coordinate system. (b) A real picture of the mirror in the prototype.

To find a focal plane we would throw pairs of parallel lines for a given particle dip angle and find their intersect. This is shown in Fig.4. One can see that for the range of z the prototype was built a flat focal plane is a good approximation. In the following text we assume a flat detector surface.

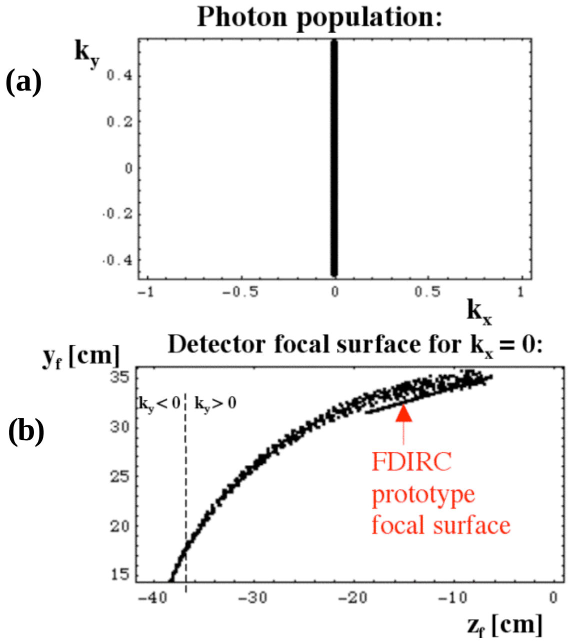
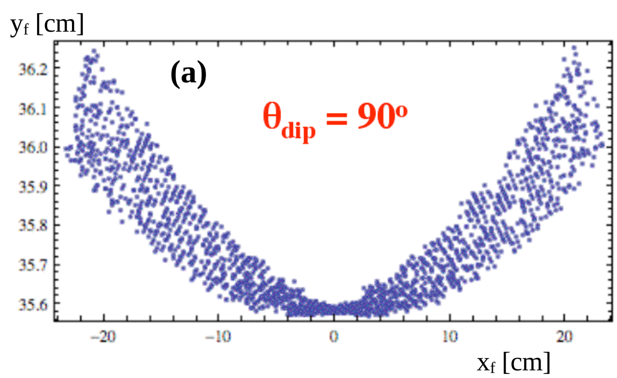


Fig. 3. Find a focal plane in 2D by throwing pairs of parallel photons for each particle dip angle and find their intersect after their reflection from a spherical mirror. k_x, k_y, and k_z are direction cosines, z is along the bar axis

B. *Cherenkov ring image for θ_{dip} ~ 90^0*

Fig. 4a shows details of the Cherenkov ring image for θ_{dip} ~ 90^0. One can see that the ring has a kaleidoscopic image, which is a result of rectangular bar. This pattern limits the resolution at large ϕ angles, which corresponds to ring's wings. The kaleidoscopic pattern can actually be observed if one looks directly into the bar – see Fig. 4b.



(b)

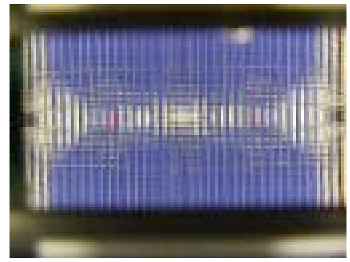


Fig. 4. (a) A kaleidoscopic image of the Cherenkov ring for a dip angle of 90^0 in the bar coordinate system, as simulated by the Mathematica program. (b) A real kaleidoscopic image when viewing the bar's end.

C. *Cherenkov ring images for various θ_{dip} angles*

Fig. 5 shows the ring images for various dip angles for a flat detector plane. As one changes a dip angle the image moves in y about ~2.3 cm for every 10^0 of dip angle.

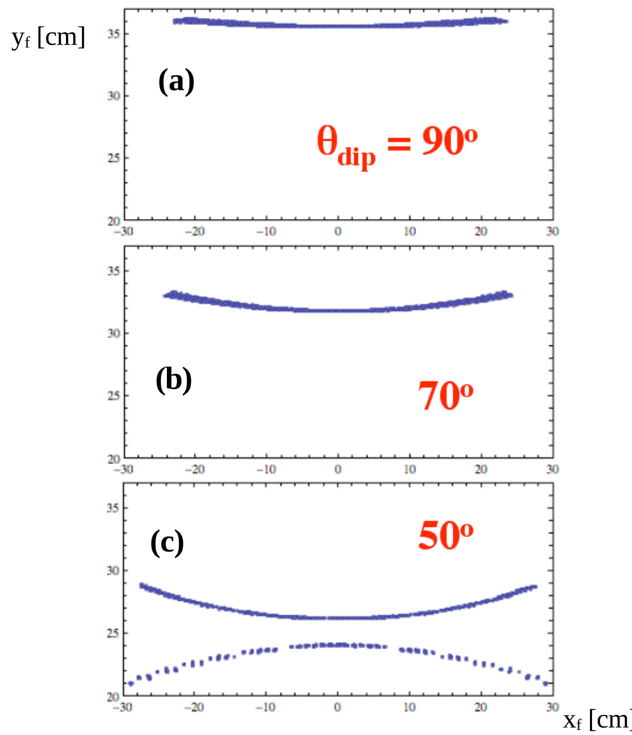


Fig. 5. Cherenkov ring images in the focal plane for various dip angles for FDIRC with spherical mirror and no wedge.

V. Cherenkov Ring Image with Non-Focusing DIRC, with no Mirror, and no Wedge at Bar's End

Fig. 6 shows a comparison between a DIRC with no mirror and focusing DIRC with a spherical mirror of Fig. 3a, both for a dip angle of θ_{dip} ~ 90^0, and for the same size of the detector canvas. It is apparent that FDIRC image is sharper, even in the ringtails where we have the effect described on Fig. 4a. One does not see the kaleidoscopic pattern in these particular images, but it is there in both cases.

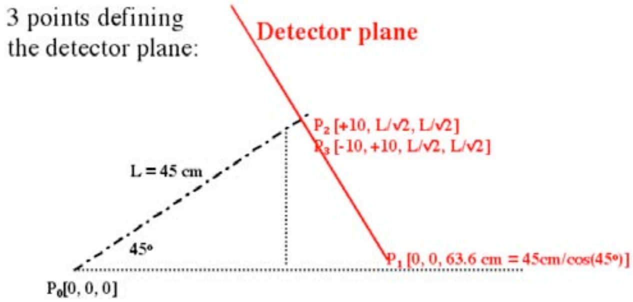


Fig. 6. Geometry of the detector plane for the non-focusing DIRC

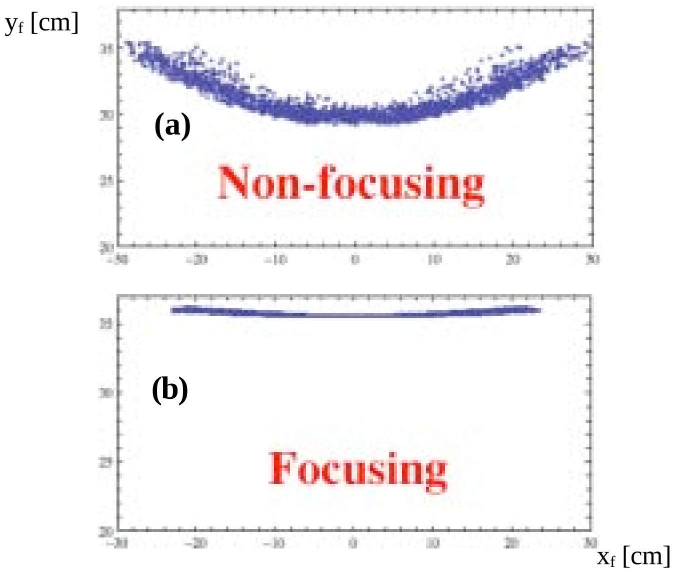


Fig. 7. (a) Cherenkov ring image for the non-focusing DIRC (Fig. 6). (b) Ring image for the FDIRC (Fig.3a) for the same detector canvas size.

The overall size of the detector size, when one integrates over all dip angles is about two times larger in the non-focusing DIRC compared to the focusing DIRC. This is the most important argument in favor of building FDIRC.

VI. Cherenkov Ring Image with Focusing DIRC, with Cylinrical Mirror and with the Wedge at Bar's End

The wedge (see Fig. 3b) is part of the present BaBar Fused Silica bars and it would be very difficult to remove them. Therefore, we have to investigate their impact on any future optics modification. Fig.8 shows a wedge "simply added" into a Fig.3, in order to investigate its effect on the optics. For simplicity, we assume that an internal reflection from its inclined surfaces works as if those surfaces are in air.

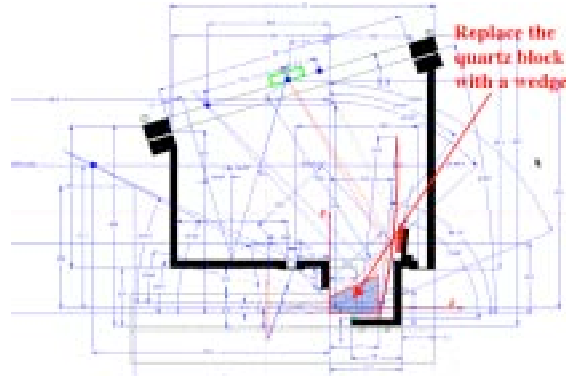


Fig. 8. Geometry of the focusing DIRC with a cylindrical mirror and the wedge (see Fig. 3b) added to see the effect of its inclined surfaces.

Figs.9 and 10 show that adding the wedge to the optics simulation indeed does contribute to increased complexity of the Cherenkov ring image detail, however, its effect on the ring resolution is smaller that the kaleidoscopic effect seen in Cherenkov ring wings.

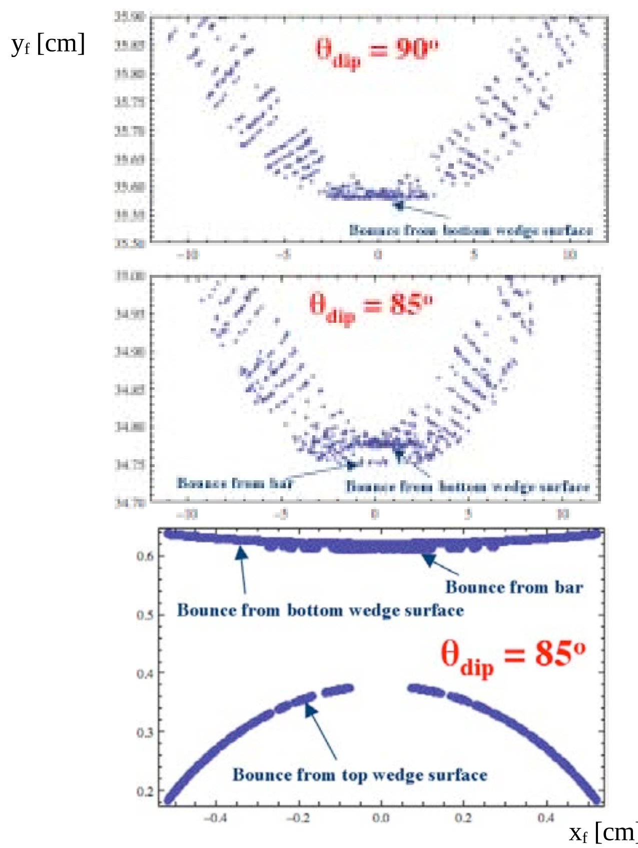


Fig. 9. Cherenkov ring images for the focusing DIRC with a cylindrical mirror and with the wedge at the bar's end. Adding the wedge to the bar's end, as shown on Fig 8, adds to the complexity of the Cherenkov ring image..

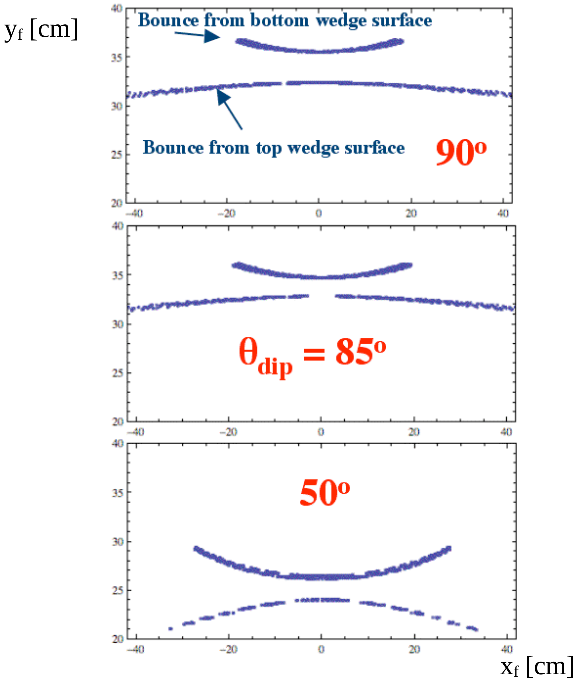
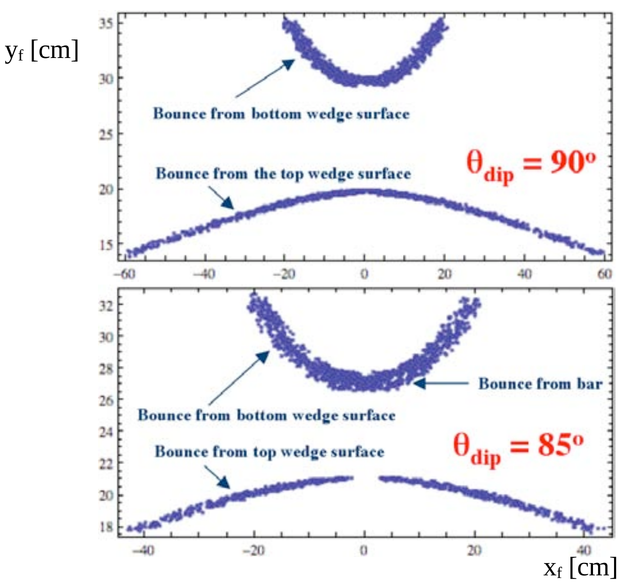


Fig. 10. Cherenkov ring images for several particle dip angles for the focusing DIRC with cylindrical mirror and the wedge at bar's end.

VII. Cherenkov Ring Image with Non-focusing DIRC, and with the Wedge at Bar's End

In this case, we use detector geometry of Fig.6, but the bar has the wedge. Fig.11 shows the Cherenkov ring images. One can conclude that the complexity of imaging with a wedge is similar in both cases, the non-focusing and focusing DIRC options.



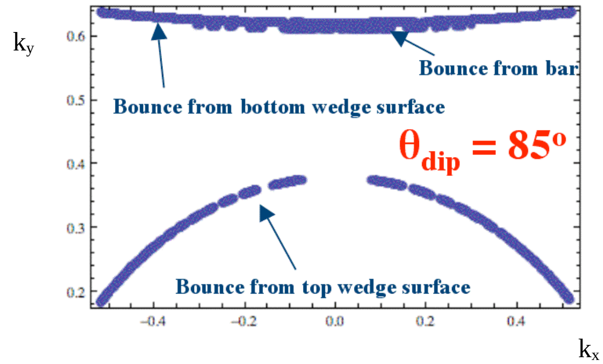


Fig. 11. Cherenkov ring images for the non-focusing DIRC with the wedge at the bar's end. One can see that the complexity of imaging due to wedge is similar to that shown on Fig.9.

VIII. Conclusion

The focusing DIRC's focal surface is slightly curved, although a flat surface is acceptable approximation. One major advantage of the focusing DIRC compared to the non-focusing DIRC is that the detector canvas size is about a factor of two smaller requiring smaller number of detectors. Another important conclusion is that one can reuse the BaBar DIRC bar boxes even for FDIRC. The wedge, as expected, does add to the complexity of the image, but this is similar in both cases, the focusing or non-focusing geometry.

Acknowledgment

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References

[1] I. Adam et al., "Particle Identification System for the BaBar experiment," Nucl. Instr.&Meth., A538(2005)281-357.

[2] B.N. Ratcliff, Nucl. Instr.&Meth., A502(2003)211.

[3] C. Field, T. Hadig, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff, J. Schwiening, J. Uher and J. Va'vra, "Development of photon detectors for a fast focusing DIRC," Nucl. Instr.&Meth., A553(2005)96-106.

[4] C. Field, T. Hadig, M. Jain, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff, J. Schwiening, and J. Va'vra, "Novel photon detectors for focusing DIRC prototype," Nucl. Instr.&Meth., A518(2004)565-568.

[5] J.F. Benitez, I. Bedajanek, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff. K. Suzuki, J. Schwiening, J. Uher and J. Va'vra, "Development of a Focusing DIRC," IEEE Nucl.Sci, Conference records, October 29, 2006, and SLAC-PUB-12236, 2006.

[6] J. Va'vra , J.F. Benitez, I. Bedajanek, D.W.G.S. Leith, G. Mazaheri, B. Ratcliff. K. Suzuki, J. Schwiening, and J. Uher, "The Focusing DIRC – the first RICH detector to correct the chromatic error by timing," presented at Vienna conference on Instrumentation, Feb. 2007, and SLAC-PUB-12803, 2007.

[7] J.F. Benitez, I. Bedajanek, D.W.G.S. Leith, G. Mazaheri, L.L.Ruckman, B. Ratcliff. K. Suzuki, J. Schwiening, J. Uher, G.S. Varner, and J. Va'vra, "Status of the Fast Focusing DIRC (FDIRC)," presented at Trieste RICH conference, Oct. 2007, to be published in Nucl. Instr.&Meth. A595(2008)104-107.