Focusing studies at Cincinnati

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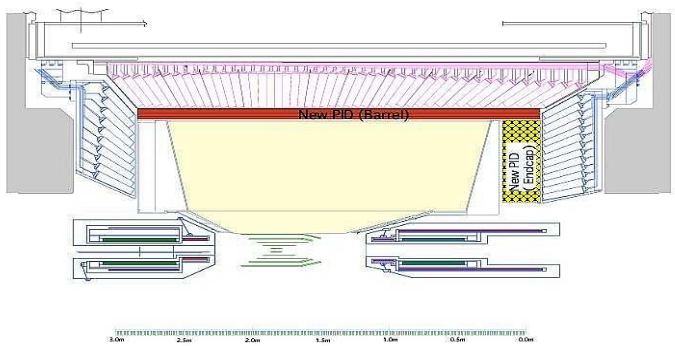
Outline:

- *Three issues: space, spherical aberrations, astigmatism*
- *Mathematica method: SLAC fDIRC prototype geometry*
- *Cincinnati fDIRC geometry (A. Drutskoy)*
- *(Older) results on performance*
- *Astigmatic effect*
- *Finding optimal focusing surface for a single track direction (fixed DIP angle and track azimuthal angle)*
- *Future directions*

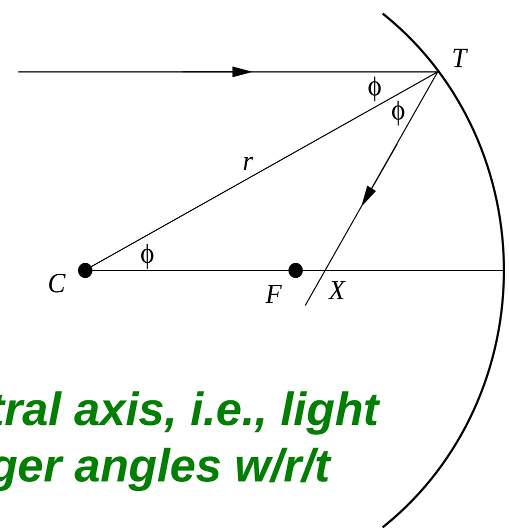
Challenges

- **Space:** *very little for focusing optics, i.e., parabolic mirror and photodetectors at focal surface*



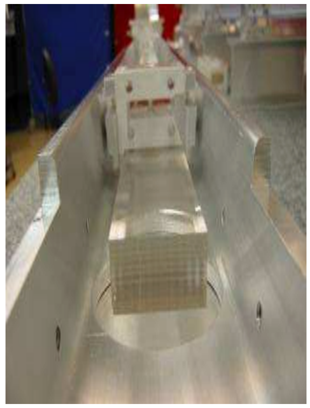
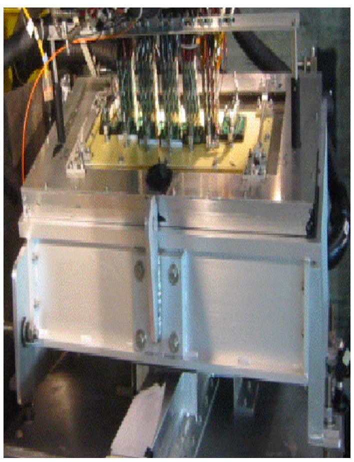
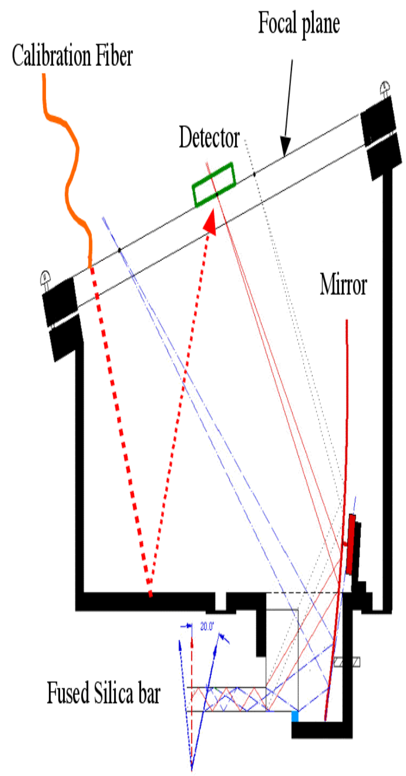
- **Spherical aberration:** *when photons strike spherical mirror away from optical (central) axis*

$$
\begin{aligned}
CT &< CX + XT \\
CT &< 2CX \\
2CF &< 2CX \\
CF &< CX
\end{aligned}
$$



- **Astigmatism:** *when object position is off central axis, i.e., light rays incident on mirror are not paraxial, make larger angles w/r/t optical axis*

Focusing DIRC Prototype Optics

- Radiator:
  - 1.7 cm thick, 3.5 cm wide, 3.7 m long fused silica bar (spares from BABAR DIRC).
- Optical expansion region:
  - filled with a mineral oil to match the fused silica refraction index (KamLand oil).
  - include optical fiber for the electronics calibration (PiLas laser diode).
- Focusing optics:
  - a spherical mirror with 49cm focal length focuses photons onto a detector plane.

Simulate SLAC focusing DIRC prototype

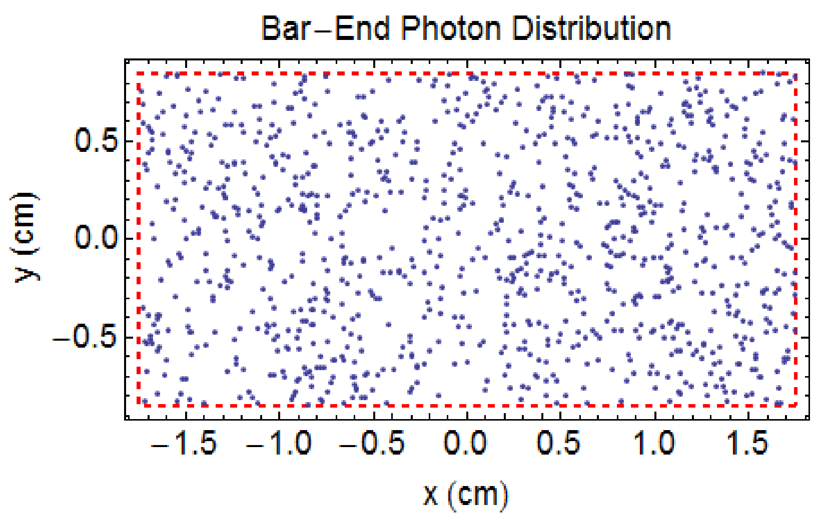
- *Use Mathematica to simulate focusing optics of SLAC focusing DIRC prototype. Spherical mirror parameterized as:*

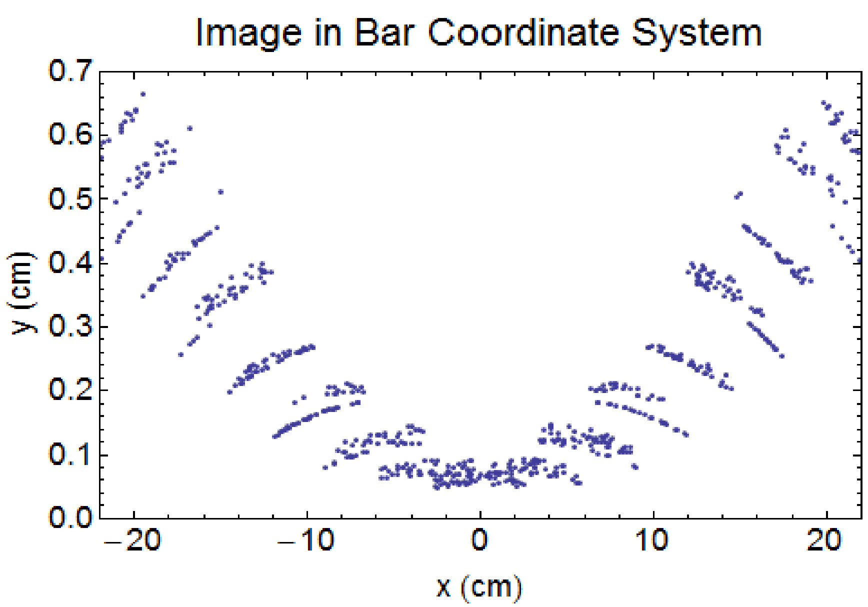
a11*x² + a22*y² + a33*z² + 2*a12*x*y + 2*a13*x*z + 2*a23*y*z + 2*a14*x + 2*a24*y + 2*a34*z+a44 = 0

$$a11 x^2 + a22 y^2 + a33 z^2 + 2 a12 x y + 2 a13 x z + 2 a23 y z + 2 a14 x + 2 a24 y + 2 a34 z + a44 = 0$$

a11=1, a22=1, a33=1, a12=0, a13=0, a23=0, a14=0, a24=-23, a34=86.6, a44=23^2+86.6^2-(2*49.5)^2

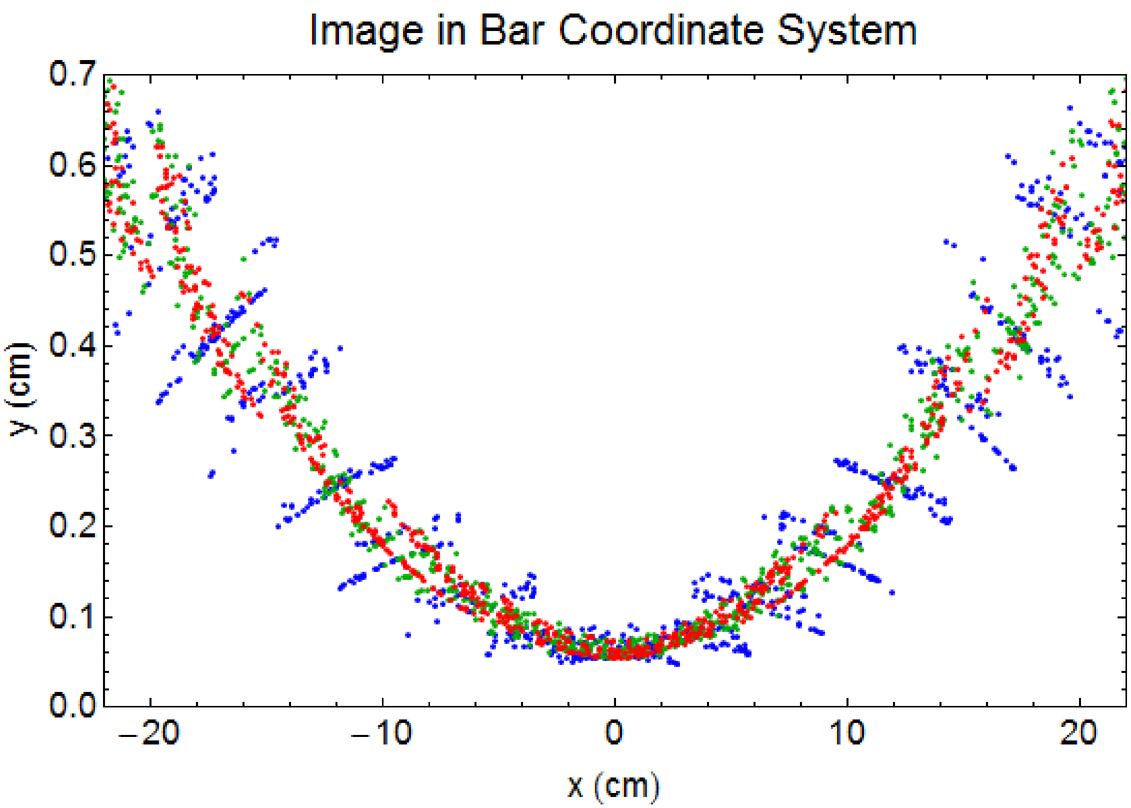
- *simulation **does not** include reflections off back of bar nor photons incident to bar surface at angles < Critical Angle.*
- *photons originate from* x0=0, y0= `Random[Real,{-BarH/2,BarH/2}]`, z0 = –35
- *photons random in Cerenkov azimuthal angle, produced by a track with* $\beta = 0.95$





Periodic Pattern Due to Bar

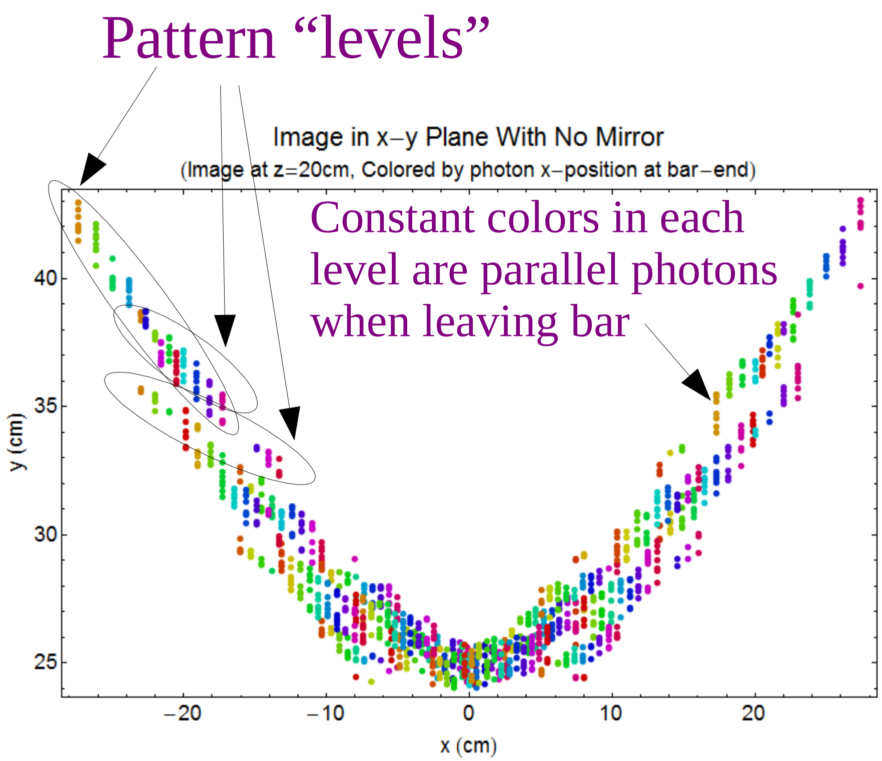
- Pattern is exaggerated by not simulating bar rear reflection.
- Clearly due to bar dimensions, but affected by mirror (see next slide)
- Smaller bar width reduces effect.
- Smaller width → more bars

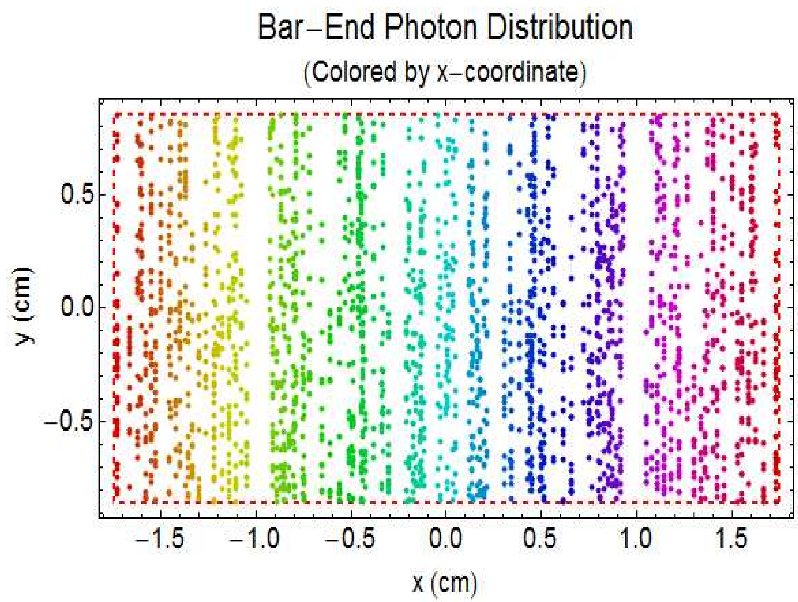


- **blue:** produced by Babar quartz bar (35 mm wide)
- **green:** produced by radiator of width = 8 mm
- **red:** produced by radiator of width = 0.7 mm

Periodic Pattern Due to Bar

- *in the absence of a mirror, effect is still visible*
- *these photons are produced by a "vertical" track (as per slide 2) and are colored by bar end x-coordinate.*
- *several Azimuthal Cerenkov Angles (ACAs) produce photons that exit the bar at the same x coordinate. Each set of photons with same unique ACA that exit bar at the same bar-end x-position reside in a specific level of the pattern.*

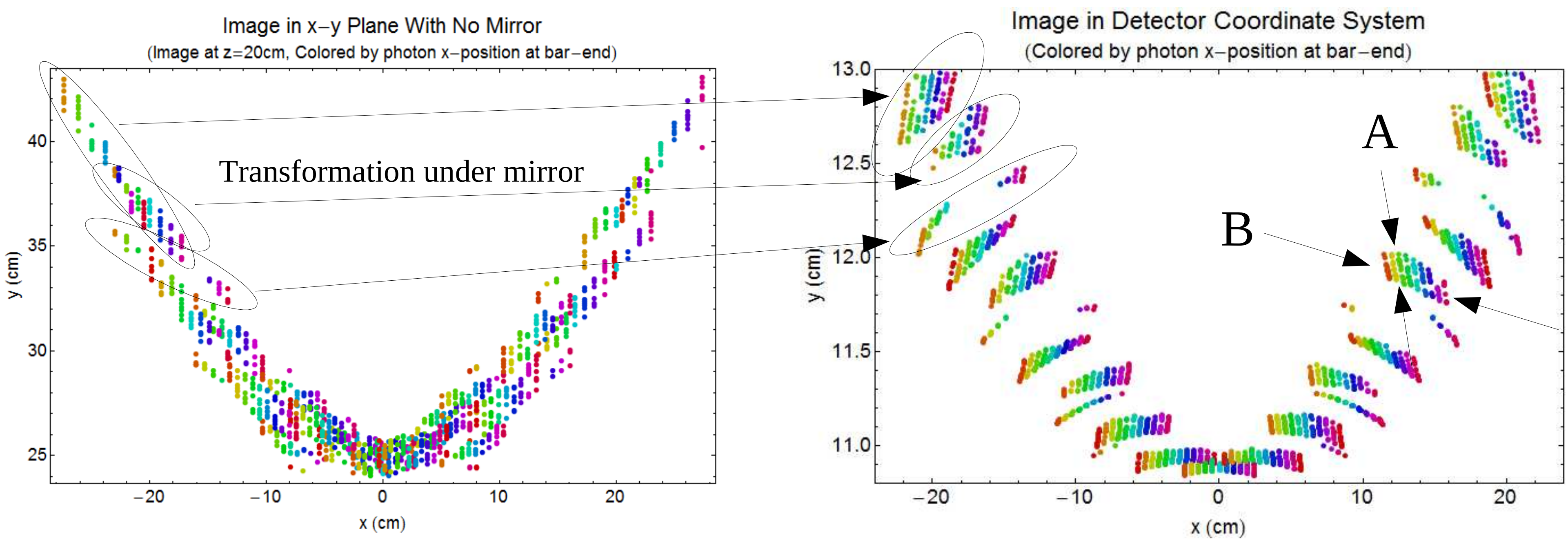




Periodic Pattern Due to Bar

- *spherical mirror brings parallel (same color within pattern level) photons to focus.*
- *the different ACAs are not brought to focus.*

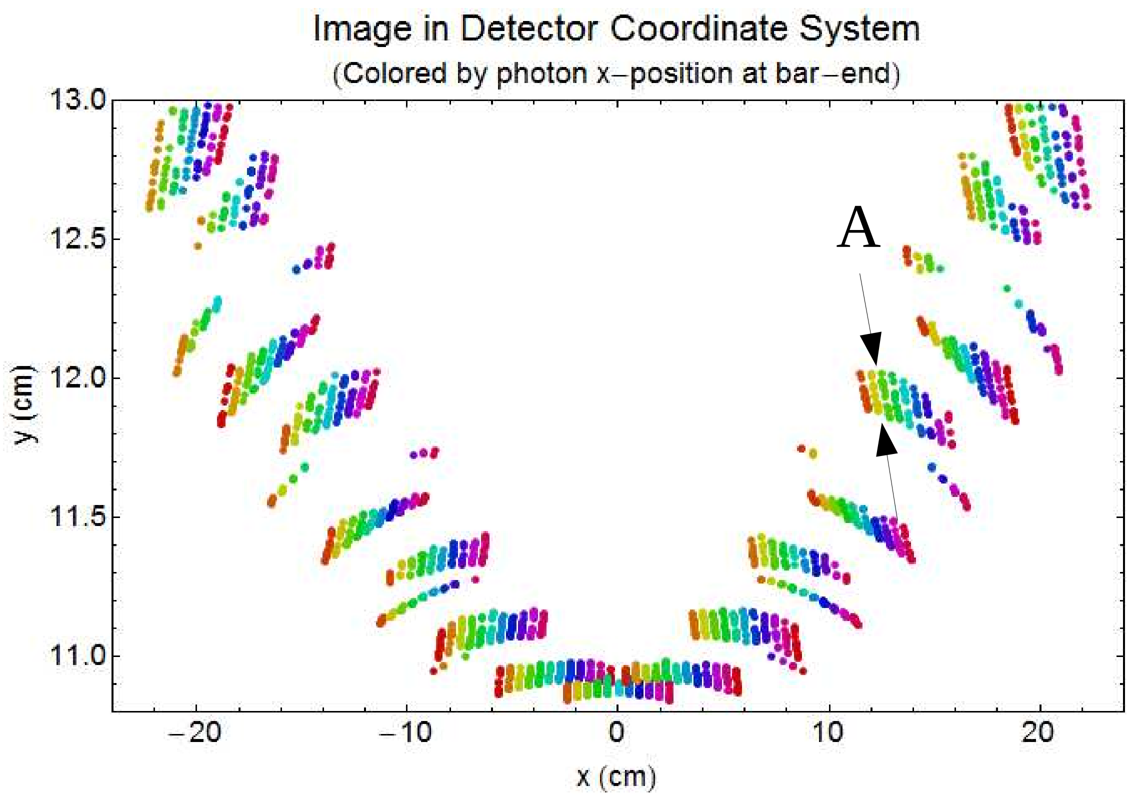
- *better focusing along A (parallel photons)*
- *spread along B (non-parallel photons) associated with astigmatic effect (reduces for narrower bar)*



Spherical mirror used in slide 2

Focusing goals

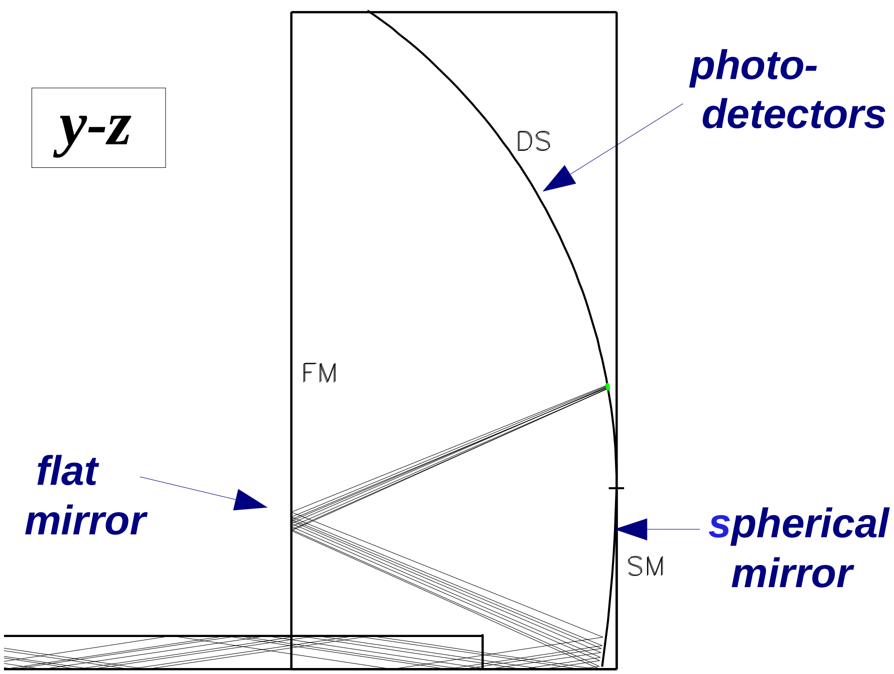
- ***width of each color along (A) due to spherical aberration (rays are not paraxial), non-ideal focal plane***
- ***our goal is to find a better focal plane and understand how significant aberrations are***

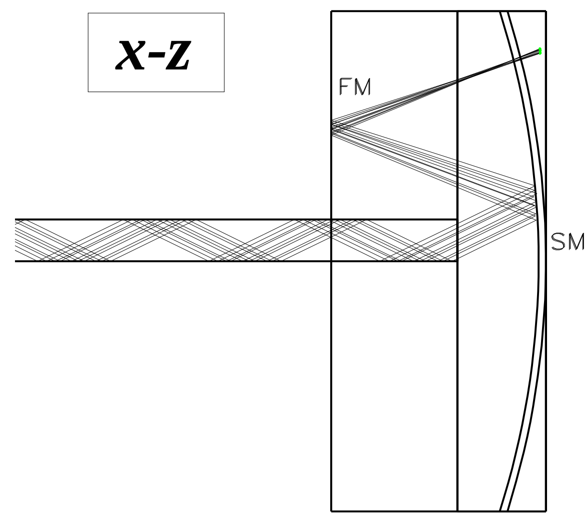


Spherical mirror used in slide 2

A. Drutskoy: A 2-mirror design

- synthetic quartz bars (n=1.46), 17.2 x 35 mm^2 (Babar-like) 12 per box
- spherical mirror, 10 x 42 cm^2 , one per box
- flat mirror to halve depth of box, one per box (located at z=-7 cm)
- flat mirror to redirect -y component of photon directions (replaces Babar wedge)
- box, 16 x 34 x 42 cm^2, filled with purified water (n=1.33). 12 boxes in j
- wall of PMTs, pixel size 6 x 6 mm^2, 3000 per box





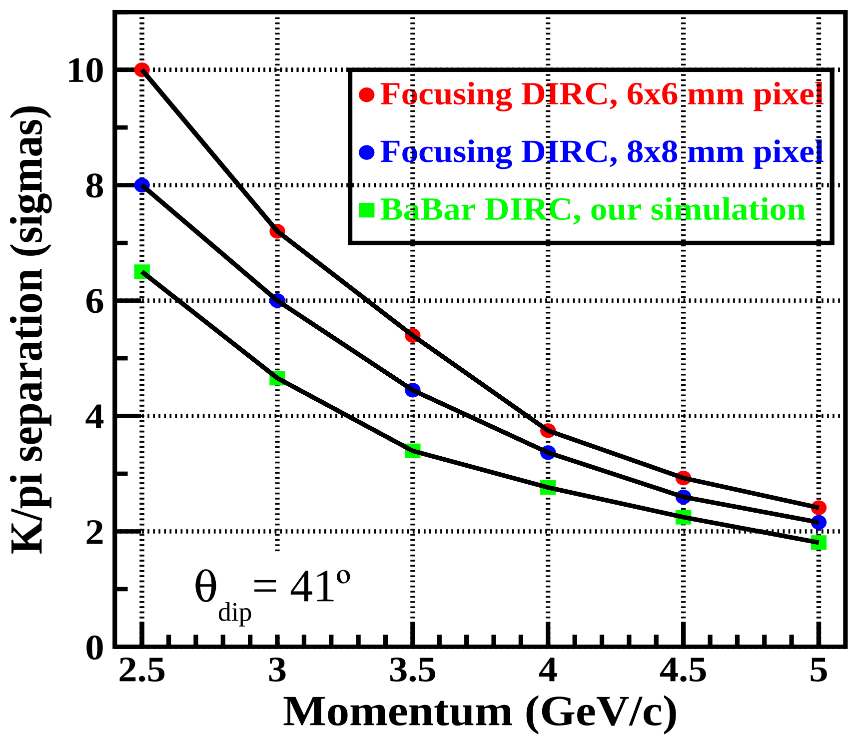
mirror equation:

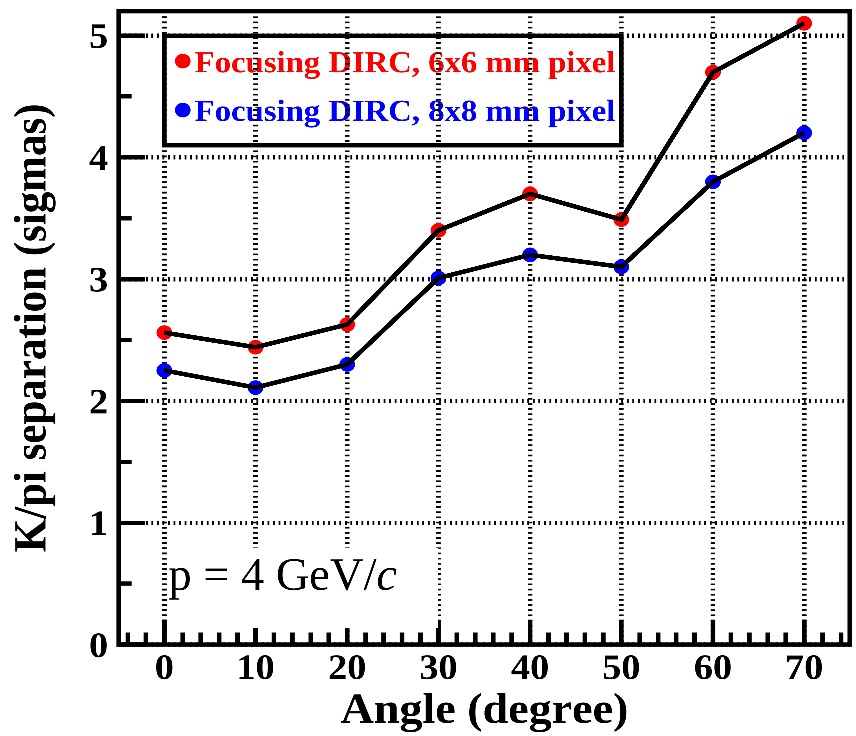
$$(x-0)^2+(y-10.65)^2+(z+60)^2=70^2$$

A 2-mirror design: performance

For a track (fixed p and θ_{dip}):

- run 1000 π tracks, obtain pdf for PMTs
- run 1000 K tracks, obtain pdf for PMTs
- run a π or K track, calculate π & K likelihoods
- calculate likelihood ratio $L_K/(L_\pi+L_K)$ and N_σ



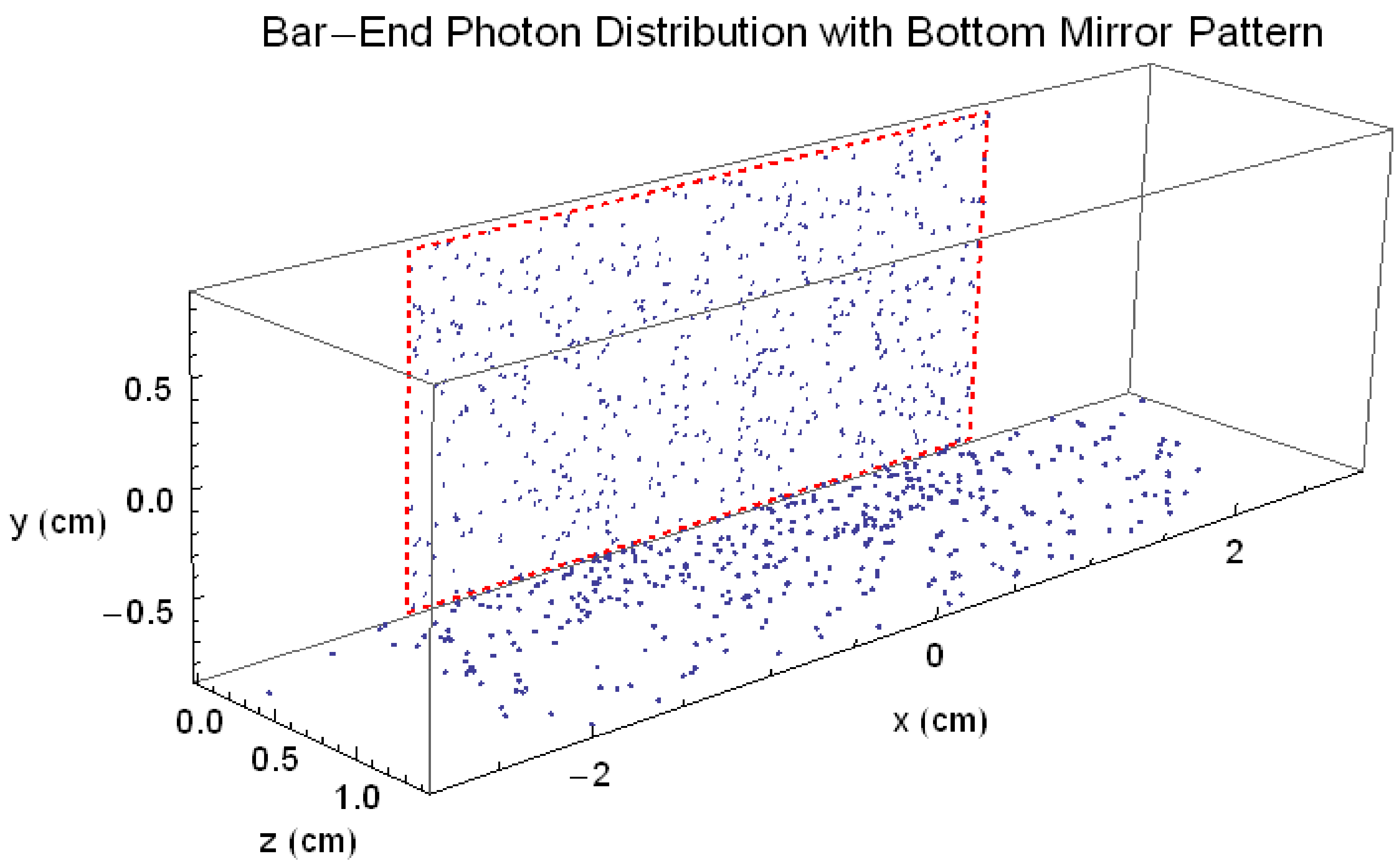


- Focusing DIRC give ≥ 3σ separation up to 4 GeV/c
- 1-2σ performance difference between 6x6 mm^2 and 8x8 mm^2

Bar-End Photon Distribution

- *1000 photons*
- *Photons originate from*

  x0=0, y0= `Random[Real,{-BarH/2,BarH/2}]`, z0 = -35
- *Including points where photons intersect bottom flat mirror*



Ring Images in Bar Coordinate Sys.

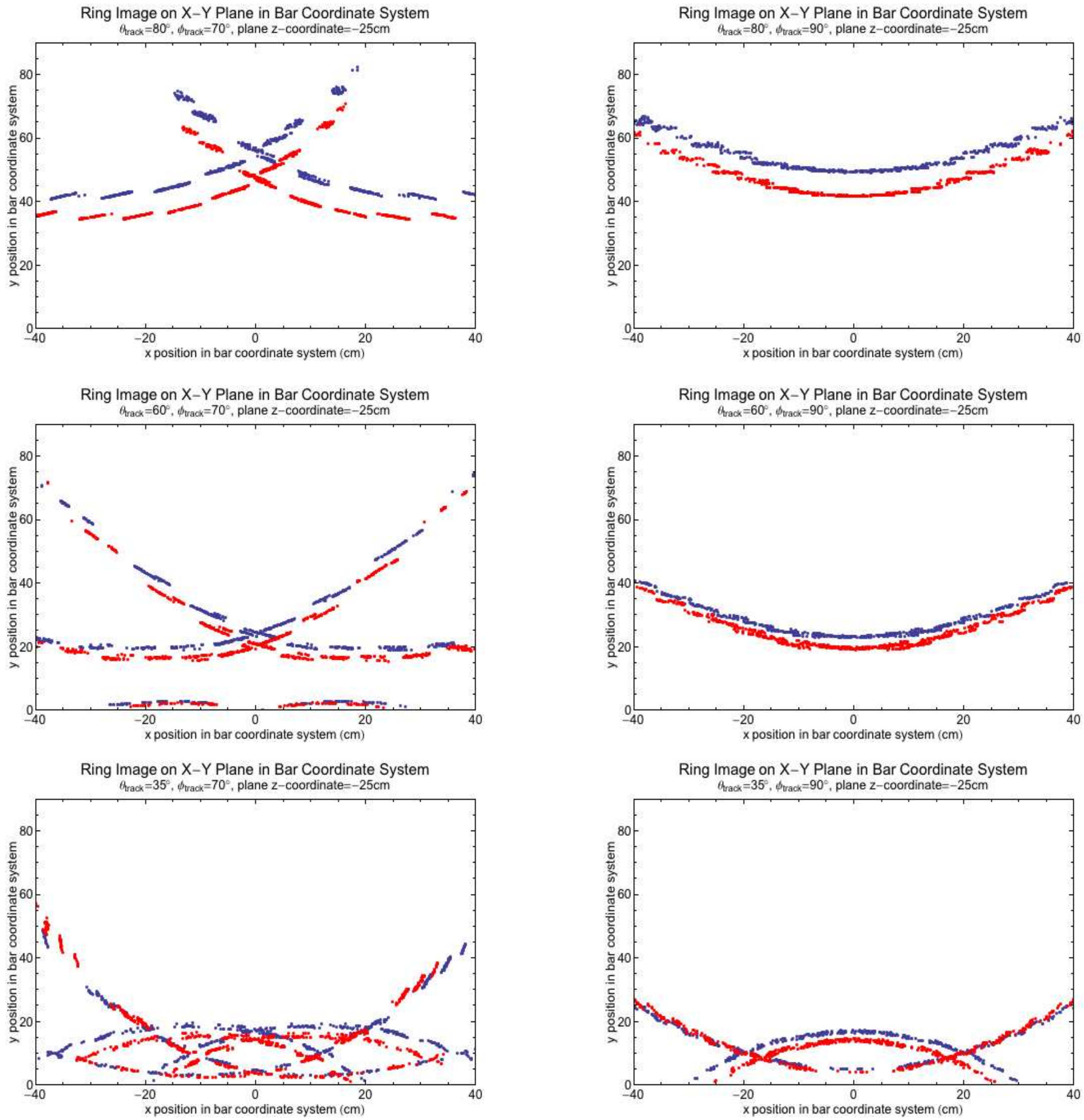


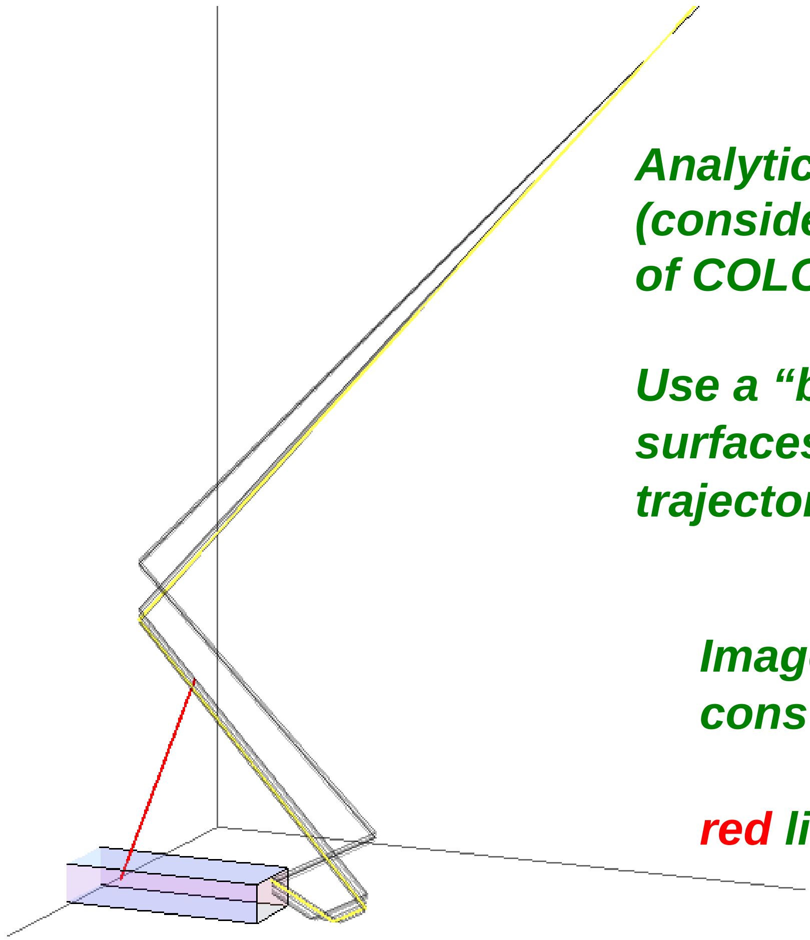
Image of rings produced by tracks (β = 0.95) with various trajectories through bar.

Tracks enter bar at x=0, y=0, z=-35 cm.

The blue image is produced on a screen in the bar x-y plane located at z=-25 cm (our mirror's paraxial focus). The red image is produced on a screen at z=-20 cm.

An x-y plane at the paraxial focus may not be the best focal plane.

Finding a Better Focal Surface



Analytical Approach difficult, possibly intractable (considering spherical aberration, astigmatism, location of COLC for oblique rays)

Use a "brute-force" method of finding ideal focal surfaces for slices of constant $\phi_{cerenkov}$ for specific track trajectories (defined by a forward and a lateral dip angle)

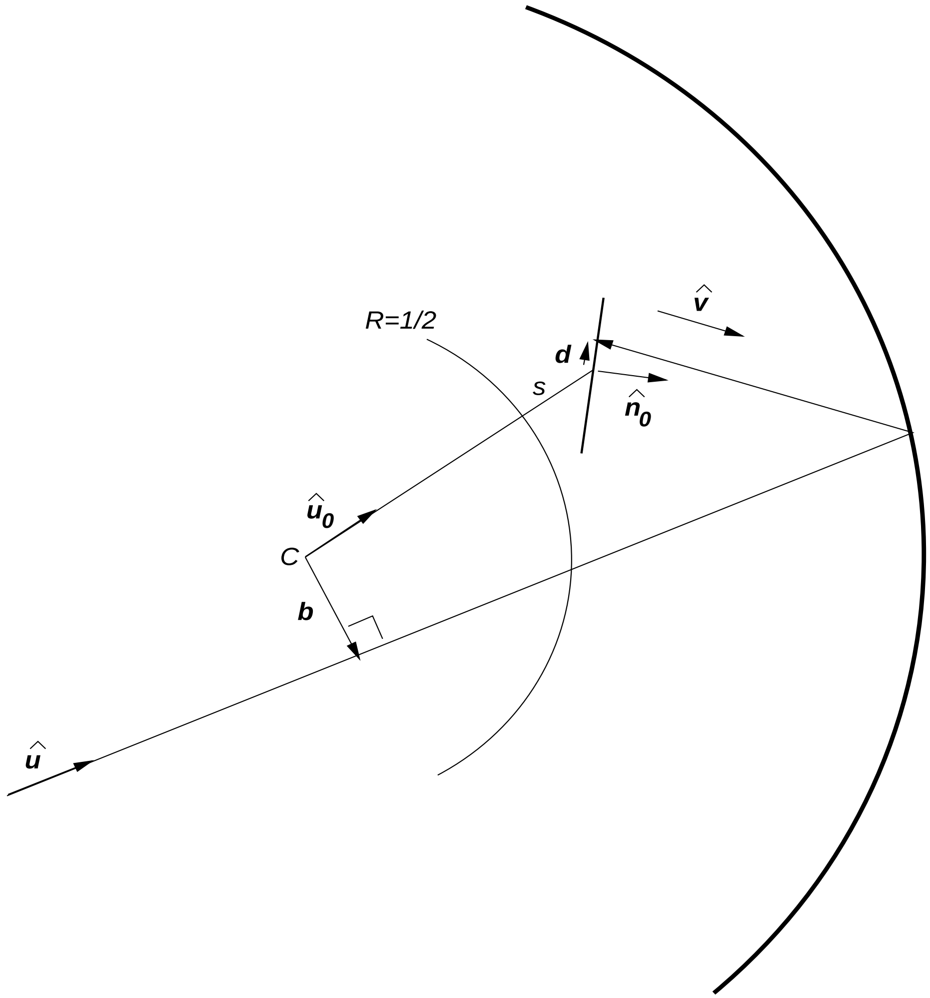
Image of arbitrary track producing rays at constant $\phi_{cerenkov}$.

red line indicates track (β = 0.95) trajectory.

Analytic approach

$$\boldsymbol{d} \;=\; \frac{1}{(\hat{\boldsymbol{n}}_0 \cdot \hat{\boldsymbol{v}})}\,\hat{\boldsymbol{n}}_0 \times \left[\frac{1}{2}(1+2s)(\hat{\boldsymbol{u}}-\hat{\boldsymbol{u}}_0)\times\hat{\boldsymbol{v}} \;+\; \left(\frac{b^2}{1+\sqrt{1-b^2}} - 2s\sqrt{1-b^2}\right)\hat{\boldsymbol{u}}\times\boldsymbol{b}\right]$$

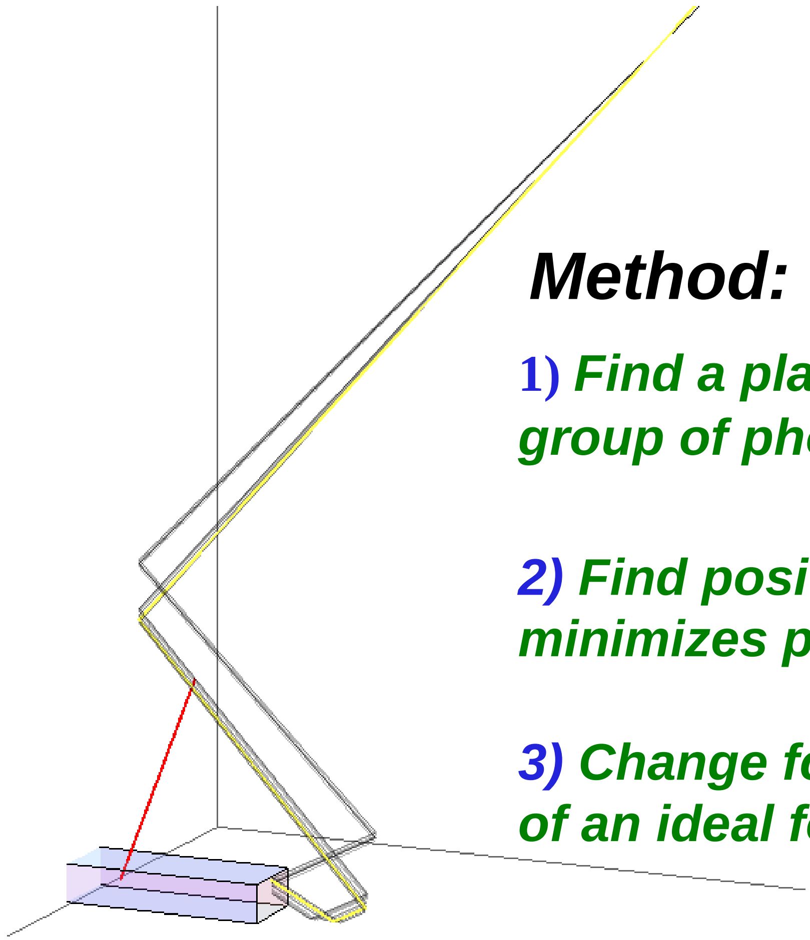
$$\hat{\boldsymbol{v}} \;=\; (1-2b^2)\hat{\boldsymbol{u}} \;+\; 2\sqrt{1-b^2}\,\boldsymbol{b}$$



Note: R_M=1, and *d* depends on *b* (the magnitude of ***b***)

Ref: Krizan & Staric, NIM A 379, 124 (1996)

Finding a Better Focal Surface (cont'd)



Method:

1) ***Find a plane normal to average direction of a group of photons with constant $\phi_{cerenkov}$***

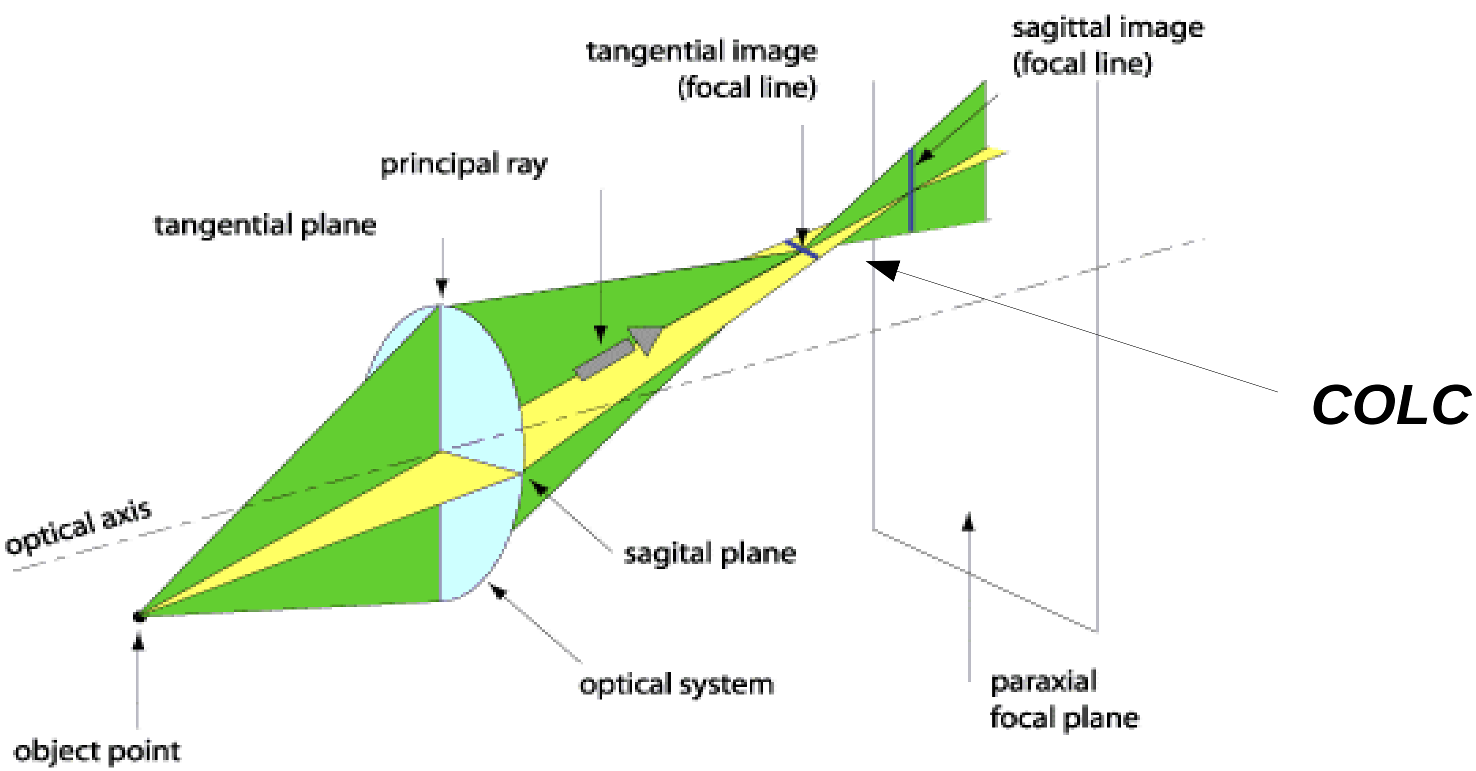
2) ***Find position of plane with above normal that minimizes photon image separations in the plane***

3) ***Change fcerenkov and repeat. This yields a slice of an ideal focal surface for a particular trajectory***

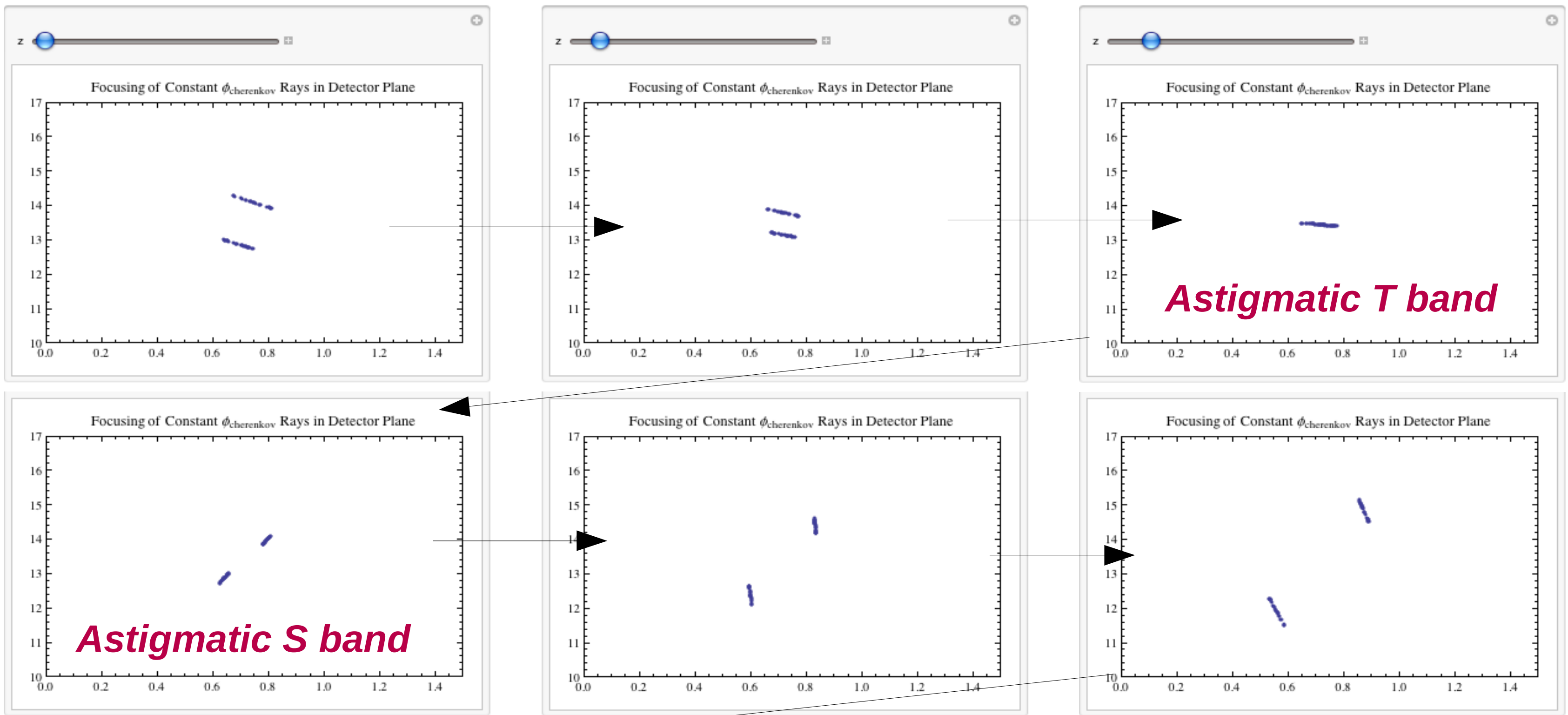
Astigmatism

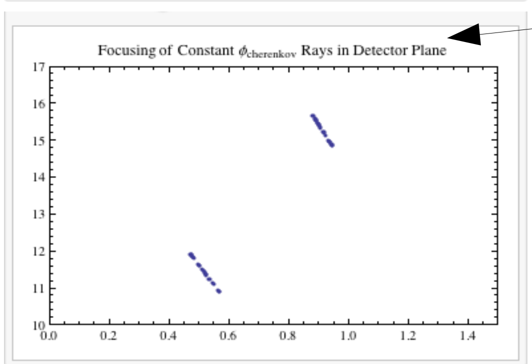
- *Rays passing through a spherical optical system at oblique angles form sharply focused orthogonal bands corresponding to separate focusing of rays in Sagittal and Tangential planes.*

- *Good focusing occurs between the bands in the "Circle of Least Confusion" (COC)*



Astigmatism in Focal Planes

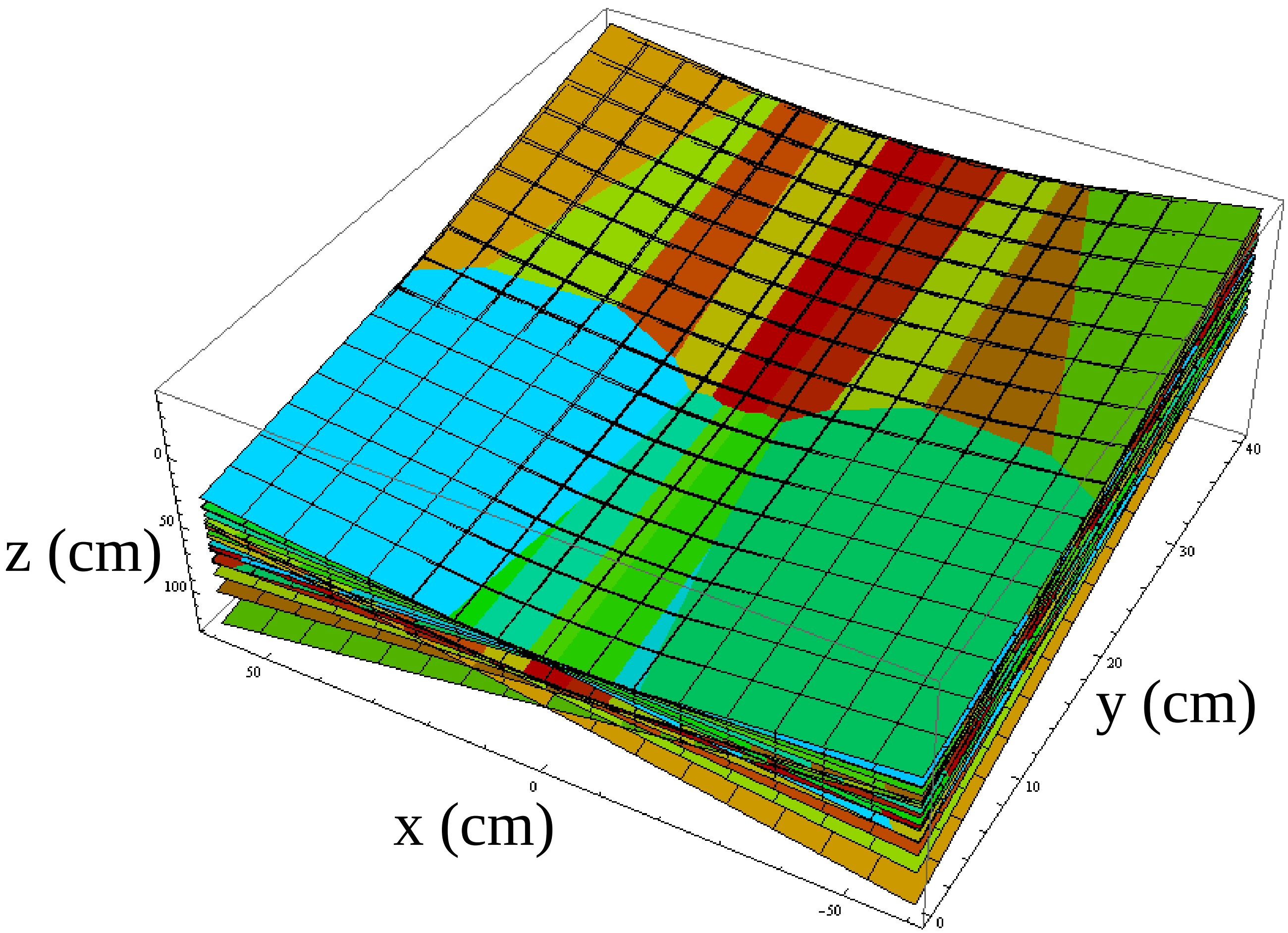




These are images formed on a focal plane that is moved out along the average photon direction (for fixed $\phi_{cerenkov}$). Frames 3 & 4 show the S and T bands of astigmatic focusing ***(see e.g. Jenkins & White (p. 112)***

Optimum focusing is in COLC between frames 3 & 4.

A Preliminary Focal Surface



The envelope of focusing planes for 27 $\phi_{cerenkov}$ angles for a track of $\pi/2$ forward dip angle and $\pi/2$ lateral dip angle (a vertical track)

This process would nominally be repeated for many track angles.

A weighted average of ideal focal planes can then be constructed.

Summary

- ***Mathematica simulation code relatively well developed, provides a useful tool.***

- ***For SLAC focusing DIRC prototype geometry, have obtained results consistent with SLAC beam-test results***

- ***Are trying to better understand and minimize the astigmatism***

- ***There is no focal surface that eliminates the astigmatism for all azimuthal angles. However, some azimuthal angles are more important (have greater acceptance) than others; the mirror can be optimized for such an azimuthal range.***

- ***An 'optimized' focal surface for different track angles will require some sort of weighted averaging. We are starting to study this now.***