The ARC compact RICH detector: reconstruction and performance

Serena Pezzulo

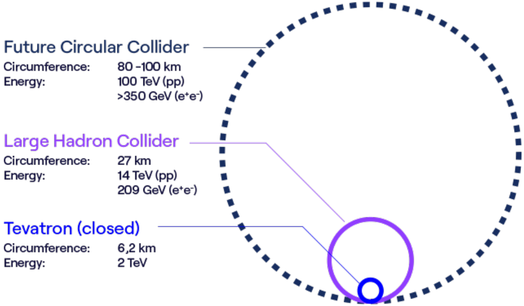
University and INFN Genova

Roberta Cardinale
Roger Forty
Alvaro Tolosa Delgado

October 9, 2024

Motivation

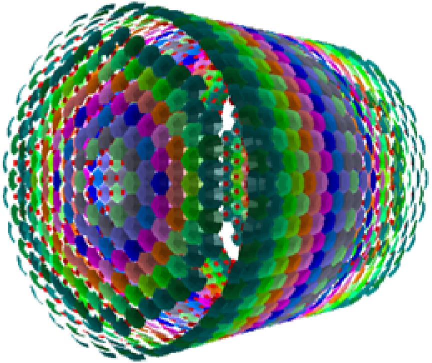
- FCC-ee will produce copious heavy flavour hadrons
- World class flavour physics programme is possible if one can have excellent **particle identification** (PID) and in particular hadron separation
- PID is crucial for B decay children (1-40 GeV), τ decays, and jet tagging in Higgs, top and W physics.



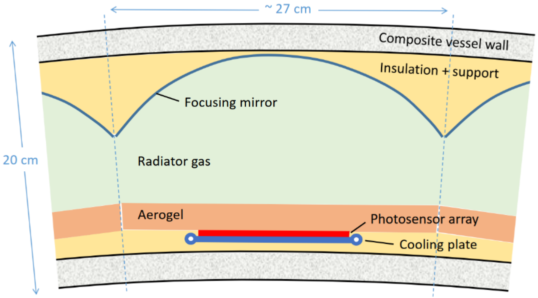
The ARC concept

ARC (**A**rray of **R**ich **C**ells) is a proposed RICH detector for the FCC (or another Higgs factory)

- First presented by R. Forty at FCC week 2021
- Lightweight and compact solution for PID
- Specifically adapted for the CLD experiment, occupying 10% of the tracker volume:
    - Dimensions: 20 cm radial depth, 2.1 m radius, 4.4 m length
    - Material budget targeted below $0.1X_0$
- Cellular in design, with each cell functioning as an independent RICH detector cell



ARC single cell geometry



- Two radiators: $\mathbf{C_4F_{10}}$ (or a more eco-friendly alternative) + **Aerogel** (for low **p** tracks)
- Spherical focusing mirror
- Photosensor array: most suitable candidates are Silicon Photomultipliers (SiPMs) arrays with cooling plates
- Aerogel also as thermal insulator between SiPM array and gas radiator

Goal: Construct prototype of single cell in 3 years (fostered by DRD4 Collaboration)

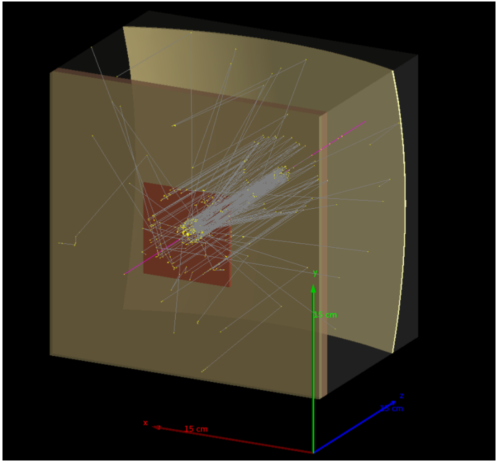
Simulation Framework

ARC Simulations performed inside **Key4Hep** framework. The tools used for a full simulation include:

- **DD4hep**: Defines the detector geometry and material properties
- **Geant4**: Simulates interactions with the detector, including optical photon interactions
- **Monte Carlo Generators / Particle Gun**: Used for generating events

Simulation of a single cell

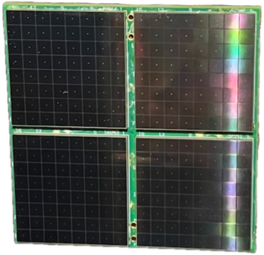
- Cherenkov photons are emitted in the two radiators and focused with a spherical mirror onto a photosensor plane (red volume)
- Each radiator produces a distinct pattern of Cherenkov light, resulting in **two separate rings**



Silicon Photomultipliers

SiPMs: compact, highly sensitive light detectors capable of detecting single photons. Array of microcells that operate in Geiger mode → high photon detection efficiency and fast response times

- SiPM array with 0.5 mm × 0.5 mm pixel
- PDE from FBK curve (at Overvoltage=10V) is considered



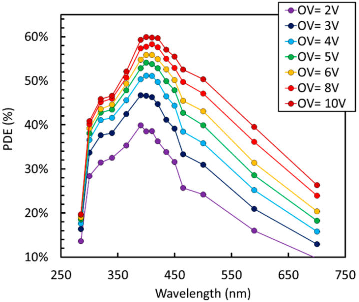


Figure: PDE vs Wavelength for FBK SiPMs doi.org/10.3390/s19020308

Cherenkov angle reconstruction

The local pattern recognition method, originally described by R. Forty and O. Schneider [LHCB/98-040] is implemented in a Gaudi algorithm

- The reconstruction of Cherenkov angle for each photon is based on track information (given by the tracking system, external to ARC)
- At the moment we are working with just **a single cell**, but we aim to apply the algorithm to the whole detector
- We also removed the aerogel to evaluate the performance of C_4F_{10} alone and optimize the reconstruction process

Performance parameters

Estimated the photon yield and the Cherenkov angle resolution separating the main different contributions

- **Emission point error**: All photons are assumed to originate from a single point along the particle's track in the middle of the radiator
- **"Pixel" error**: Due to the photodetector pixel size, the exact photon hit position on the photodetector is unknown, so all the photon detection points are assumed to be at the center of the pixel
- **Chromatic error**: Taken as the σ of the Cherenkov reconstructed angle using the "true" emission and "true" detection point

π/K/p particle separation

Estimated the number of standard deviation of separation between π and K (also p/K and p/π)

- **Number of standard deviations (estimated from simulations)** of separation between two different particle types:

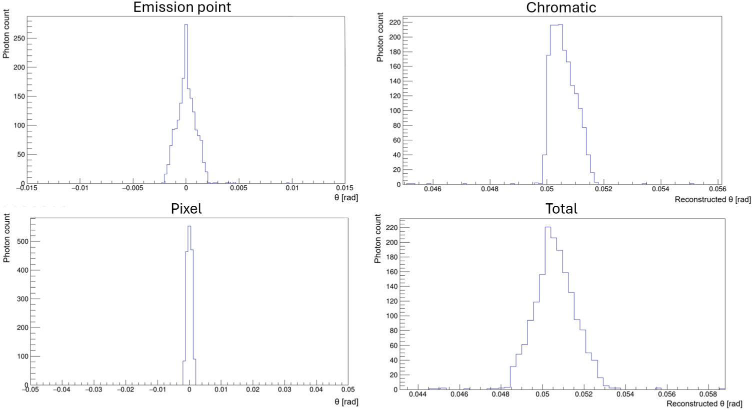
$$N_\sigma = \frac{|\theta_1 - \theta_2|}{\sqrt{\left(\frac{\sigma_1}{\sqrt{N_1}}\right)^2 + \left(\frac{\sigma_2}{\sqrt{N_2}}\right)^2}}$$

  where σ_1 and σ_2 are the total errors relative to the Cherenkov reconstructed angles while N_1 and N_2 are the average number of detected photons per track

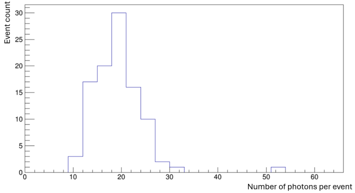
- **Number of standard deviations (expected)**:

$$N_\sigma \approx \frac{m_1^2 - m_2^2}{2p^2\sigma_{\theta_c}\sqrt{n^2 - 1}}$$

Results – C_4F_{10}



Contribution	Error [mrad]
Emission point	0.9
Chromatic	0.4
”Pixel”	0.8
Total	1.2

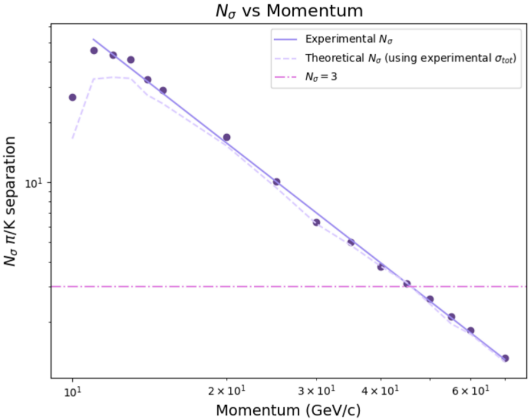


Kaon particle gun @ 45 GeV

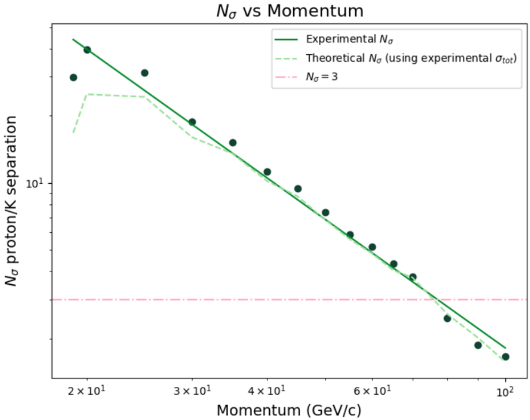
Photon yield: 19

π/K/p particle separation - C_4F_{10}

π/K



p/K



Separation above the threshold ($N_\sigma = 3$) up to 45 GeV/c for π-K and 80 GeV for p-K

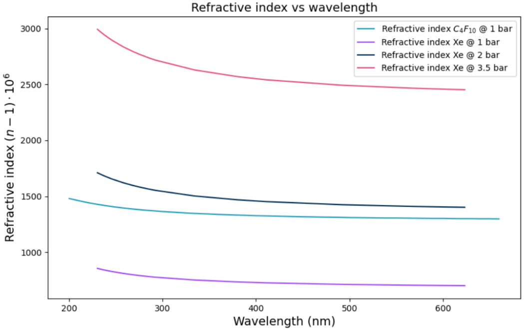
Alternative Radiator gas

With HFCs set to be banned by 2050, it is crucial to explore more environmentally friendly alternatives

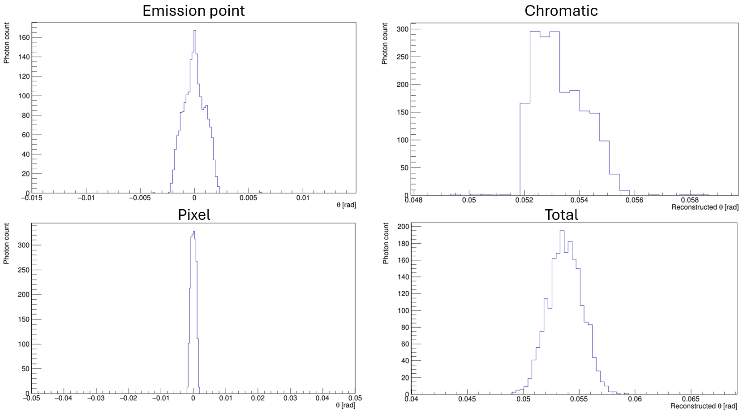
- Xenon could be suitable, but must be pressurized to achieve sufficient photon yield $\rightarrow$ higher total error, the vessel needs to be reinforced

Radiator	Photon yield	Total error [mrad][a]
C_4F_{10} @ 1 bar	19	1.2
Xe @ 1 bar	10	1.2
Xe @ 2 bar	20	1.5
Xe @ 3.5 bar	35	1.9

[a] considering 0.5 mm $\times$ 0.5 mm pixels

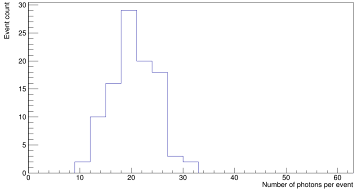


Results - Xe @ 2 bar



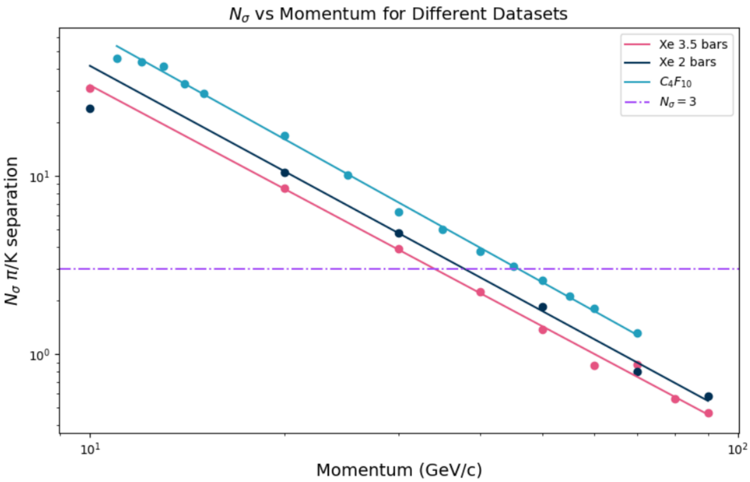
Kaon particle gun @ 70 GeV

Contribution	Error [mrad]
Emission point	1
Chromatic	0.9
”Pixel”	0.8
Total	1.5



Photon yield: 20

π/K separation - Xe



Radiator	Max p [GeV/c]
C_4F_{10} @ 1 bar	45
Xe @ 2 bar	38
Xe @ 3.5 bar	33

Conclusions

- **ARC** is a low mass and compact cellular RICH detector for PID
- **SiPMs** have been chosen as the photodetectors for their high sensitivity and compact design
- Particle separation power was investigated for:
  - C_4F_{10} gas at 1 bar, showing good performance up to 45 GeV/c
  - Pressurized **Xenon** (up to 3.5 bar) as an alternative
- **Next Steps**:
  - Extend simulations to the entire ARC detector
  - Incorporate **aerogel** as an additional radiator in the simulation
  - Include the **magnetic field** to study its effect on particle tracks
  - Investigate other **environmentally friendly** radiator gas alternatives

Thank you for the attention!

Serena Pezzulo

University and INFN Genova

Roberta Cardinale
Roger Forty
Alvaro Tolosa Delgado

October 9, 2024

Cherenkov angle reconstruction

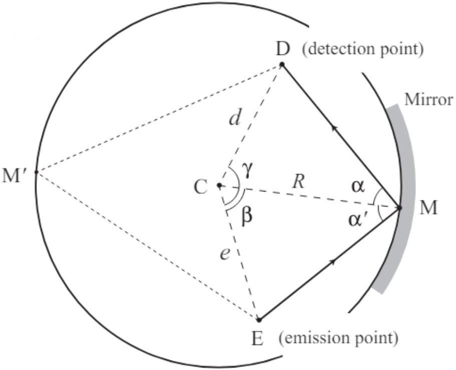


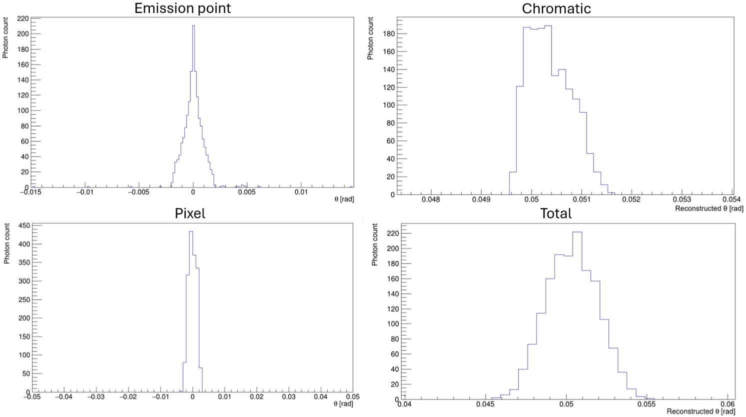
Figure: RICH pattern recognition - Forty, R W ; Schneider, O

$$4e^2d^2\sin^4\beta - 4e^2d_yR\sin^3\beta +$$
$$+ (d_y^2R^2 + (e+d_x)^2R^2 - 4e^2d^2)\sin^2\beta +$$
$$+ 2ed_y(e-d_x)R\sin\beta + (e^2 - R^2)d_y^2 = 0$$

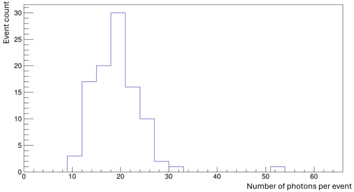
- Emission point **E** is taken to be at the midpoint of its passage through the radiator
- The eq. has two real solutions corresponding to **M** and **M'**

$\rightarrow \mathbf{p} = EM/|EM|$, $\cos\theta_c = \mathbf{p}\cdot\mathbf{t}$

Results – 0.8 mm $\times$ 0.8 mm pixels, C_4F_{10}



Contribution	Error [mrad]
"Pixel"	1.2
Chromatic	0.4
Emission point	1
Total	1.6



Kaon @ 45 GeV with θ varying in [0,3] deg and ϕ in $[0, 2\pi]$

Photon yield: 19