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The simulation of DIRC detector at the Electron-ion collider in China

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Abstract: The Electron-ion collider in China (EicC) is a proposed future electron-ion collider with a high luminosity above 2.0 × 10^{33} $cm^{-2}\cdot s^{-1}$ and center-of-mass energy ranging from 15 to 20 GeV. Excellent particle identification (PID) is essential for the study of exclusive and semi-inclusive processes and 3D imaging of the nucleon structure in the EicC experiment. To meet its PID requirement, a focusing DIRC detector is proposed, which consists of fused silica radiators, optical focus lens, and MCP-PMT photosensor array. In order to study and optimize its performance, we conducted a GEANT4 simulation involving various optical transmission and image reconstruction algorithms. The simulation results demonstrate a high angular resolution of ~ 1mrad, achieving the 3σ Pion/Kaon separation in the momentum up to 6GeV/c.

Keywords: Electron-ion collider in China (EicC), Particle identification (PID), Focusing DIRC(FDIRC), GEANT4 simulation, Reconstruction algorithm

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1. Introduction

As a future high energy nuclear physics project, the Electron-ion collider in China (EicC) has been proposed based on the High Intensity heavy-ion Accelerator Facility (HIAF), a heavy-ion accelerator currently under construction located in Huizhou, Guangdong Province in China. Figure 1 shows a layout of the EicC accelerator facility. The proposed collider will provide highly polarized electrons (with a polarization of ∼80%) and protons (with a polarization of ∼70%) with invariable center-of-mass energies from 15 to 20 GeV and a high luminosity of (2–3) × 1033 cm−2·s−1. The main focus of the EicC will be precise measurements of the nucleon structure in the sea quark region, including 3D tomography of nucleon; the partonic structure of nuclei and the parton interaction with the nuclear environment; the exotic states, especially those with heavy flavor quark contents; and the origin of mass by measurements of heavy quarkonia [1].

To meet these physics goals, the spectrometer of EicC requires precise and fast tracking in high luminosity, electromagnetic and hadronic calorimetry with large momentum coverage, and accurate PID to separate π, K, p in large momentum range. Fig. 2 shows the basic design specifications of the EicC spectrometer. A solenoidal superconducting magnet (B=1.5T) is installed at the periphery of the tracking detector for charged particle momentum measurements. The momentum resolution is <1%@1 GeV in the barrel region (-1<η<1.6) and <2% in the endcap region (-1<η<-3, 1.6<η<3). The momentum coverage of 3σ PID requirement is [2]:

≤ 15 GeV/c in the forward zone (ion endcap region);
≤ 6 GeV/c in the center (barrel region);
≤ 4 GeV/c in the backward zone (electron endcap region).

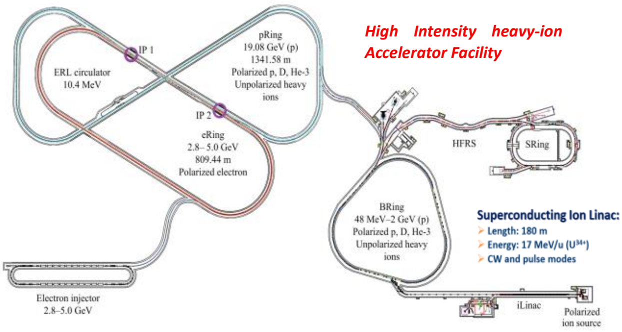


Figure. 1: The layout of EicC accelerator facility

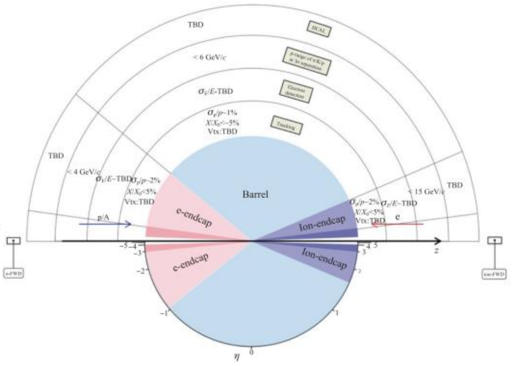


Figure. 2: EicC Detector Design Specifications

To identify charged hadrons from different reaction channels within such a large range of transverse momentum and rapidity, it requires various PID detectors with compact structures, fast response, large momentum coverage, and ultra-high detection resolution, together with high-precision tracking reconstruction and Time-Of-Flight (TOF) measurements. Synthesizing the requirements above, the EicC Collaboration proposed a conceptual design of the spectrometer (as shown in Fig. 3). The PID detectors differ in each section according to their PID kinematic coverages (as shown in Fig. 4), including:

- Barrel PID: Detector of Internal Reflection Cherenkov lights (DIRC）;
- Endcap PID: Ring Imaging Cherenkov (RICH) detectors: dual-radiator RICH (dRICH) for the ion-endcap, modular RICH (mRICH) for the e-endcap;

- Low Momentum PID (< 2GeV/c): Time-of-flight (TOF) detectors including LGAD and MRPC.

The following will focus on the barrel DIRC detector.

Compared to conventional Cherenkov detectors (such as early BABAR experiment [3]) with complex and bulky optical imaging systems, the FDIRC(Focusing DIRC) has a compact structure. It has fast response, high radiation resistance, and high momentum PID which is difficult for TOF [4]. This not only saves valuable space (especially in the spectrometer barrel), effectively reduces the cost of the spectrometer, but also meets the high momentum PID requirement in high luminosity and radiation experimental environments, making FDIRC a preferred solution for the new generation heavy flavor physics experiments such as (FAIR- PANDA [5]) and (EIC-ECCE) [6]).

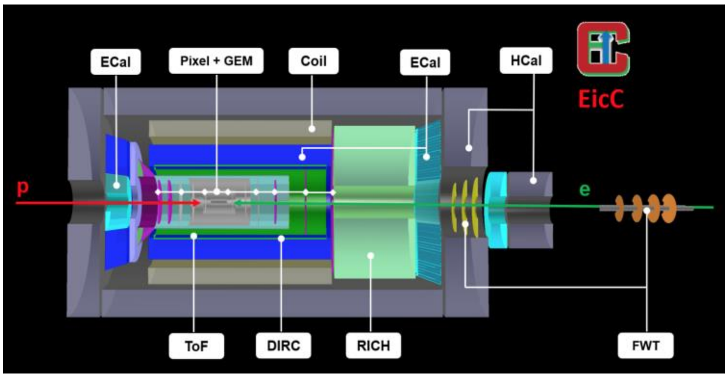


Figure. 3: Concept design of EicC spectrometer

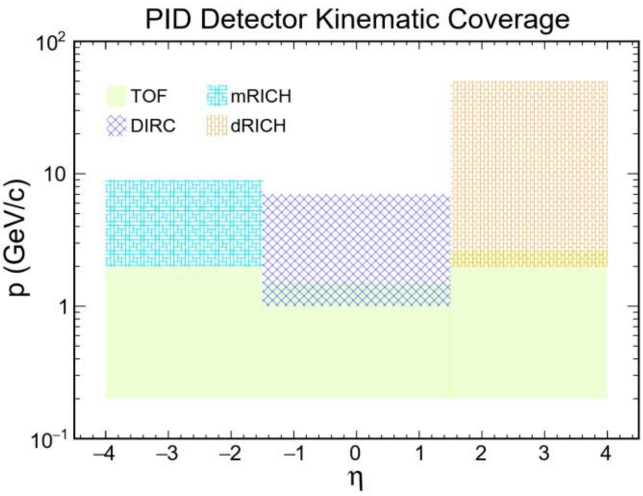


Figure. 4: Kinematic coverages for different PID detectors in EicC

2. Design of the FDIRC modules

According to the EicC detector design specifications and requirements of the PID detector mentioned above [4,5], an FDIRC module is designed as shown in Fig. 5, it consists of:

Cherenkov radiator bar (fused silica, n=1.47): 15mm×31mm×2800mm;

Expansion volume (EV): (20mm + 168mm) ×315mm×336mm;

Focusing: spherical 3-layer lens (Fused silica + N-LAK33B) [5], curvature radius: 30cm, Thickness: 10mm;

MCP-PMT: Hamamatsu R10754 (pixel size: 5.2mm×5.2mm) or Photonis XP85122 (pixel size: 3mm×3mm);

Tray box size: 50mm×320mm×4000mm with 6 bar+EV.

12 trays form a barrel detector with a minimum radius R = 630mm.

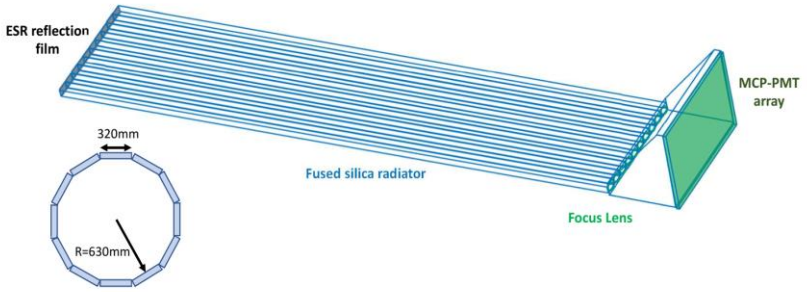


Figure. 5: FDIRC module design

According to the definition of the angle resolution of a Cherenkov imaging detector [7], the correlation between the charged particles' momentum and reconstructed angular resolution is estimated ideally without considering the dispersion and radiation background effects, as shown in Fig. 6. To achieve the 3σ π/K up to 6GeV/c, the single photon angular resolution needs to reach at least 3mrad (the green dashed line in Fig. 6). Considering the influence of particle multiplicity (including radiation background) in high luminosity experiments, the angular resolution needs to be improved to 1mrad.

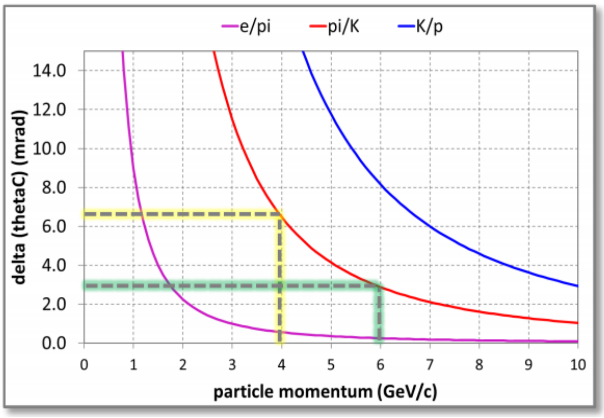


Figure. 6: The angular resolution of Cherenkov imaging as the function of the particle momentum (Calculation)

1. GEANT4 Simulation of FDIRC

The GEANT4 simulation is conducted to study the performance of FDIRC. To meet the actual measurement, the angular resolution σ_{θ_c}, and simulated parameters are defined as follows:

$$\sigma_{\theta_c}(\text{photo}) = \sqrt{\sigma_{chrom}^2 + \sigma_{foc}^2 + \sigma_{bar}^2 + \sigma_{trans}^2 + \sigma_{rec}^2}$$

Where,

σ_{chrom}: the dispersion contribution of the quartz radiator (wavelength: 300-700 nm);

σ_{foc}: error from the optical focusing lens and the pixel size of the photosensors

σ_{bar}: the influence of radiator thickness (flatness) on photon yield and transmission efficiency;

σ_{trans}: surface smoothness of the radiator

σ_{rec}: error from incidence particle tracking and image reconstruction.

The performance of FDIRC module is simulated step by step: the Cherenkov radiation induced by incident particles, photon transmission in the quartz radiator, light focus in the EV, and finally hit in the MCP-PMT array, involving various physics processes like the chromatic dispersion, reflection, and refraction at the boundary of different mediums, and light attenuation. The surface roughness of the radiator is simulated by randomizing the normal direction of the facet by $\sigma = 0.1^\circ$ (corresponding to an average reflection factor of $\sim 98\%$). The refractive index of MCP-PMT's photocathode, and its quantum efficiency varying with the wavelength [8] are also included in the simulation. To increase the photon collection efficiency of FDIRC module, the ESR reflection film is attached at the end of the radiator. The forward & backward photons are separated by the transit time cut for FDIRC's timing resolution estimation and angular reconstruction.

Fig. 7 illustrates the angular reconstruction procedure [9]. For each incident charged particle with a certain hit pattern (Fig. 8a), each detected photon yields several solutions for the initial photon direction in the simulated look-up table(Fig. 8b). Together with the track direction, each gives one hypothesis for the reconstructed Cherenkov angle of the photon (Fig. 8c). Among these solutions there is always the correct one entering the signal peak in the distribution. Collecting all tracks' reconstructed Cherenkov angles in a histogram gives a distribution peaking at the expected value of the Cherenkov angle. When the expectation, calculated based on the charged particle momentum and the mean refractive index of fused silica, is subtracted the expectation, the resulting distribution peaks at zero (see Fig. 8d). The width of the obtained distribution represents the single photon Cherenkov angle resolution (SPR) [10].

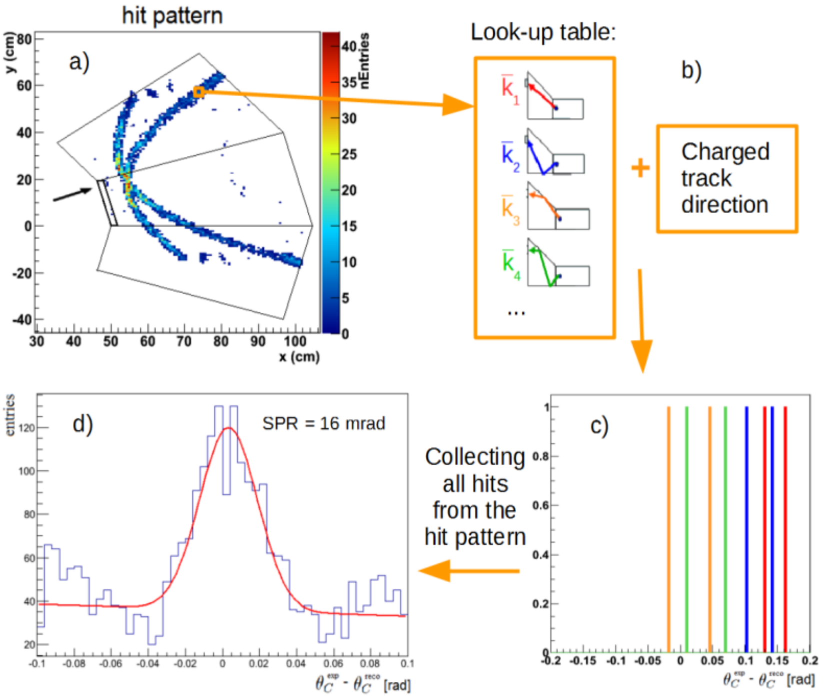
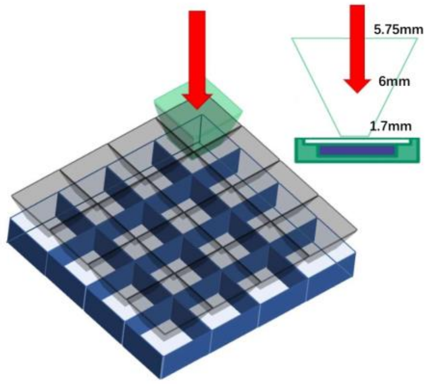


Figure. 7: Schematic of the Cherenkov angle reconstruction procedures

2. Simulated FDIRC's performance

To optimize photon collection and reduce dispersion effects, various sizes of the radiator, EV, and focus lens are simulated. For instance, there is a dead area caused by the MCP-PMT frame, which can lead to ~10% statistics loss of photon collection. A specially designed miniature optical guide is installed between the MCP-PMT and EV to eliminate this dead area, as shown in Fig. 9. It focuses the photons to the center of each pixel unit of the MCPPMT array, which can also reduce the crosstalk effect when the photons hit near the boundary of adjacent pixel units.



Optical Connector	Photon number	SPE Angle resolution (mrad)
None	14 ~ 62	9 ~ 12
6mm	16 ~ 68	6 ~ 10
8mm	16 ~ 66	7 ~ 11

Figure. 8: The miniature optical guide installed between the MCP-PMT and EV to eliminate this dead area (left); the number of photons collected per track and single photoelectron's angle resolution w/o the connector (right)

Fig. 9 shows the simulated FDIRC's performance: the angular resolution dependent on the incident polar angle of 6GeV/c pion with different MCP-PMT pixel sizes (3mm/5mm). To achieve angular resolution < 1mrad, the pixel size of MCP-PMT should be ~3mm.

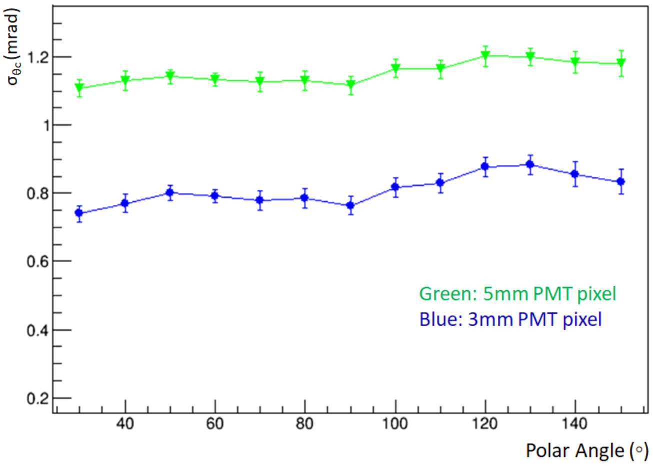


Figure. 9: Simulated FDIRC angular resolution for MCP-PMTs with different pixel sizes

The PID power of FDIRC is estimated as shown in Fig. 10. With the angular resolution ~1mrad and the average number of collected photons > 40, FDIRC's PID performance can meet the 3σ (s.d.) separation required by EicC. Within the measurable polar angle range, the 3σ separation coverage of π/K can reach the momentum up to 6 GeV/c, while e/π separation can reach as low as 1.4 GeV/c. The expected angular error contributions of the barrel DIRC are also estimated based on the simulation and PANDA TDR [5], as shown in Table 1.

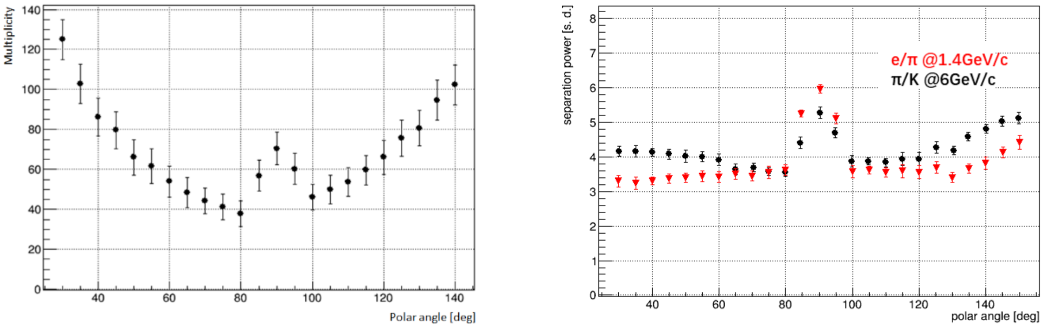


Figure. 10: The average number of collected photons (left) and the PID power (right) versus the charged track's incidence angle

Table 1: Expected indicators of the FDIRC module.

Chromatic dispersion of quartz radiator	Optical focusing lens and MCP-PMT pixel size	Thickness & width of quartz radiator	Surface properties of quartz radiator	The angle of the incident particles and image reconstruction
σ_{chrom}=5.4mrad	σ_{foc}<10mrad	$\sigma_{bar}\leq$2mrad	$\sigma_{trans}\leq$3mrad	$\sigma_{rec}\leq$1mrad

3. Conclusion

The preliminary simulation results show that FDIRC can achieve the 3σ π/K separation power up to 6GeV/c with the angular resolution ~ 1mrad. There is still potential for further improvement in FDIRC's optical design, MCP-PMT's performance, and image reconstruction methods. It is worth noting that the simulation analysis did not include the effect of the magnetic field on charged particle tracks and the impact of multiple hitting events on image reconstruction. On the other hand, the reconstruction algorithm does not utilize the information from external tracker layers to reduce the impact of multiple scattering, especially for lower momentum particles. These will be done in further sophisticated simulations.

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