DIRC-based PID for the EIC Central Detector

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An essential requirement for the central detector of an Electron-Ion Collider (EIC) is to provide radially compact particle identification (PID) over a wide momentum range. To this end, the electromagnetic calorimeter (EC) needs to be complemented by one or more Cherenkov detectors, primarily for hadron identification. With a radial size of only a few cm, a Detector of Internally Reflected Cherenkov light (DIRC) provides a very attractive option. However, the requirements of the BaBar detector, where the first DIRC was used, differ somewhat from the needs of an EIC, in particular in terms of the momenta of the produced particles and the impact of the readout of the DIRC bars on the required detector acceptance. Currently, R&D is being undertaken for several DIRC projects around the world (PANDA, SuperB, Belle-II). A future EIC DIRC can benefit from many aspects of this R&D, but also provides its own unique set of challenges and priorities.

The proposed R&D has three major goals. The first is to demonstrate the feasibility of using a DIRC as part of a full-acceptance EIC detector. The key question in this regard is how to build a suitable readout, which is both reasonably compact, and can operate inside of the strong magnetic field (2-4 T) of the central detector solenoid. The second goal is to investigate the possibility of pushing the state-of-the-art of DIRC performance in terms of momentum coverage. This would be required if a DIRC would be the only means of π/K separation in the central detector. The third goal is to determine the optimal configuration for using a DIRC together with a supplementary gas Cherenkov detector, which would extend the e/π and the π/K coverage. The integration of the DIRC into the EIC detector, and the study of the overall detector performance are, however, important with or without the supplementary gas Cherenkov.

1. Physics Requirements for Large-Angle PID

While an EIC will support multiple interaction regions, the primary detector will have a general purpose character. This means that it should be able to offer satisfactory performance for a wide range of processes and kinematics. In practice, however, the PID requirements for the central detector tend to be driven by semi-inclusive reactions, and exclusive reactions at moderate values of Q^2 (typically around 10 GeV^2 for light meson production, required to ensure that factorization applies). Kinematically there are two factors to consider. One is the asymmetry of the collisions between the electrons and ions, which tends to boost the produced hadrons to high lab momenta and small angles. This poses a challenge for the forward detection, but as shown in Fig. 1, most particles produced at mid rapidities have relatively low momenta for most collision kinematics.

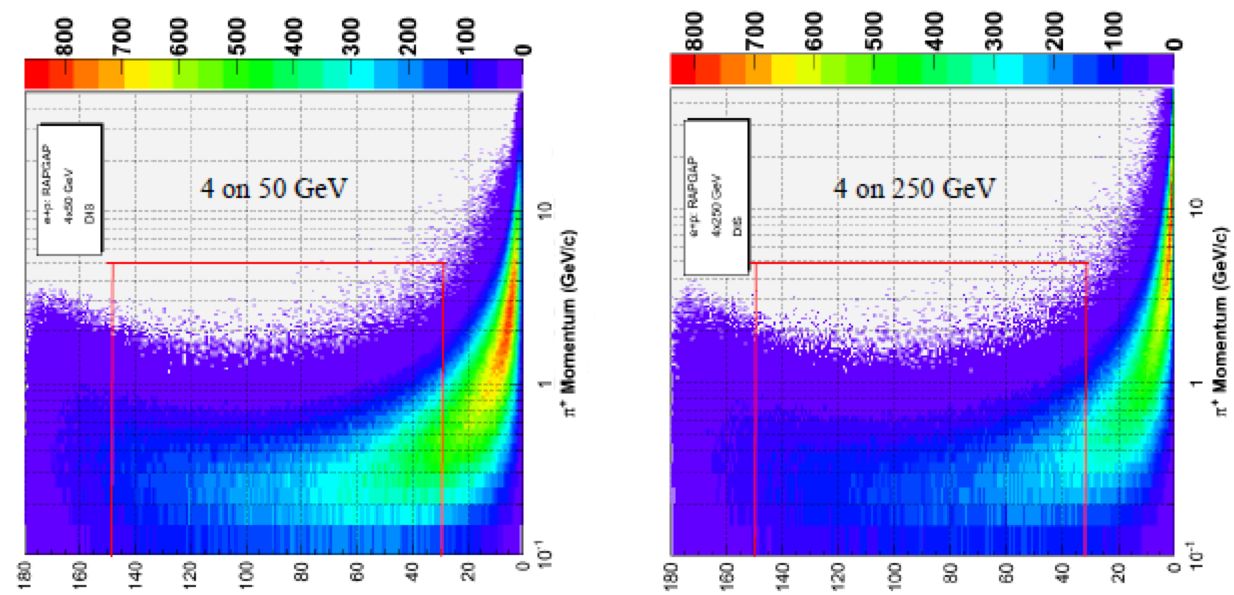

Fig. 1: DIS pions produced in collisions of 4 GeV electrons on 50 and 250 GeV protons, respectively. The vertical red lines placed at 30° and 150° indicate the approximate transition from the central detector to the endcaps. The horizontal line at 4 GeV/c shows the limit of 3σ π/K separation for current DIRC detectors. No cuts on Q^2 have been applied in the plots. Note that in the HERA convention the electron beam is moving towards 180° (left) and the ions beam is moving towards 0° (right).

The second factor is that the more exclusive the process, the more momentum tends to be picked up by the produced (leading) hadron, and hence the momentum vs angle distribution looks a little different than the inclusive one shown in Fig .1. In the case of Semi-Inclusive DIS (SIDIS) kinematics, one also needs to keep in mind that the transverse momentum component, p_T, of the leading hadron is defined in the target rest frame with respect to the virtual photon direction rather than that of the ion beam. The p_T in the lab frame may thus differ from that in the rest frame, but the lab momentum p is almost always larger than the p_T at rest. The lab angles and momenta as function of p_T are shown in Fig 2 for the SIDIS leading hadron at intermediate collision energies.

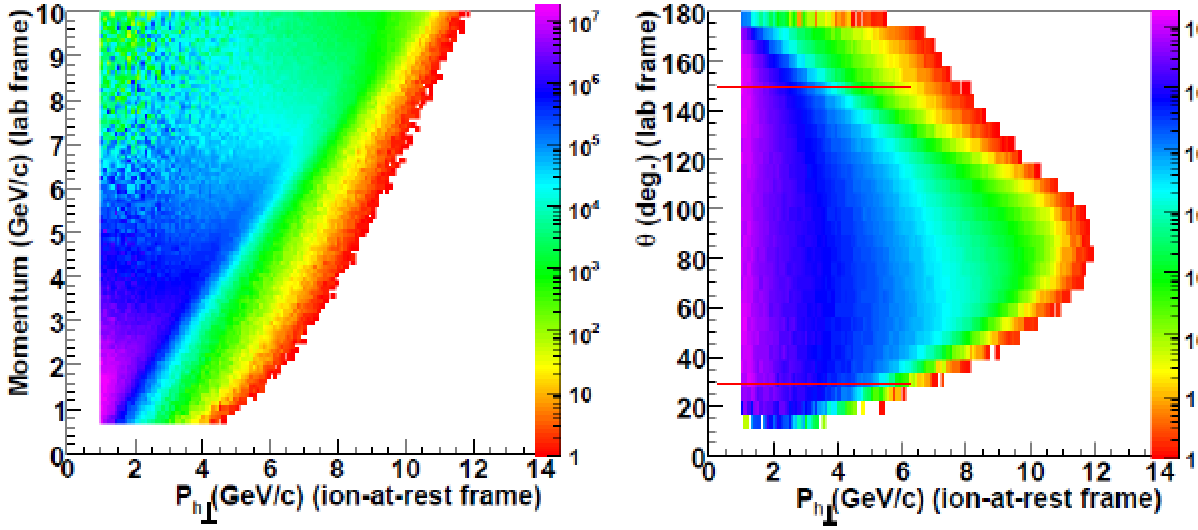

Fig. 2: Leading SIDIS pions for 11 electrons on 60 GeV protons, with cuts on $0.2 < z < 0.8$, $Q^2 > 1$ GeV^2, $M_x > 1.6$ GeV, $W > 2.3$ GeV, $0.05 < y < 0.8$, and $p < 10$ GeV, as function of p_T. The horizontal red lines indicate the approximate transition from the central detector to the endcaps.

The SIDIS lab momenta as function of angle are shown in Fig. 3. The left panel focuses on the central detector, showing the range that can covered by a DIRC. The right panel shows the distribution of forward-going particles, the momenta of which are driven by the ion beam energy. Due to the lower electron energy in the right panel, the momenta of backward going mesons are lower. To take full advantage of the p_T accessible at higher c.m. energies, one would want to extend the range of π/K identification beyond the 4 GeV/c offered by a BaBar-type DIRC. On the other hand, the higher momenta also pose a greater challenge for other detector components with which the PID competes for radial space. A supplementary low-threshold gas Cherenkov detector could extend this to 9 GeV/c, but would increase the radius of the detector by at least 60-70 cm beyond the few cm needed for the DIRC.

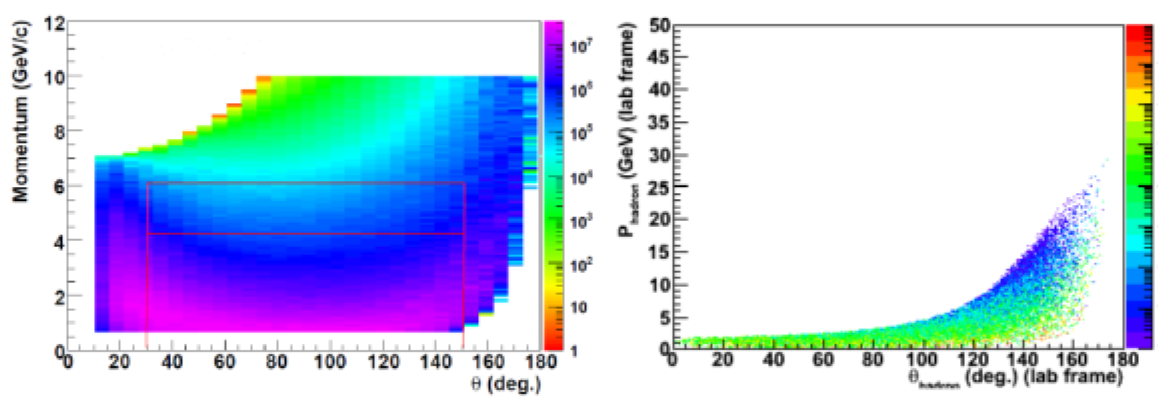

Fig. 3: Leading SIDIS pions for 11 GeV electrons on 60 GeV protons (left panel) and 4 GeV electrons on 50 GeV protons (right panel). In the left panel the same cuts have been applied as in Fig 2, while on the right, $0.4 < z < 0.6$ and $1 < Q^2 < 10$ GeV^2. The horizontal red lines at 4 and 6 GeV/c indicate the state-of-the-art and possible "super" DIRC 3σ π/K separation and the maximum that can be achieved using fused silica, respectively. Note that these and subsequent plots use the standard electron scattering

convention where the electron beam moves towards 0°. The left/right directions of the electron/ion beams are, however, the same as in Fig. 1.

Most demanding are exclusive reactions at moderate and high Q^2, where the produced meson carries a significant momentum and ends up in the central detector. As shown in Fig. 4, the meson momentum rises quickly with the collision energy. A momentum coverage up to 4 GeV/c is only adequate for the very lowest values of s. On the other hand, increasing this value to 6 GeV/c would provide almost complete coverage up to s = 2000 GeV^2, if the collision kinematics are reasonably symmetric, and partial coverage for higher energies. This could, in particular, provide an attractive way of balancing cost and performance for a medium-energy EIC (or "EIC stage I").

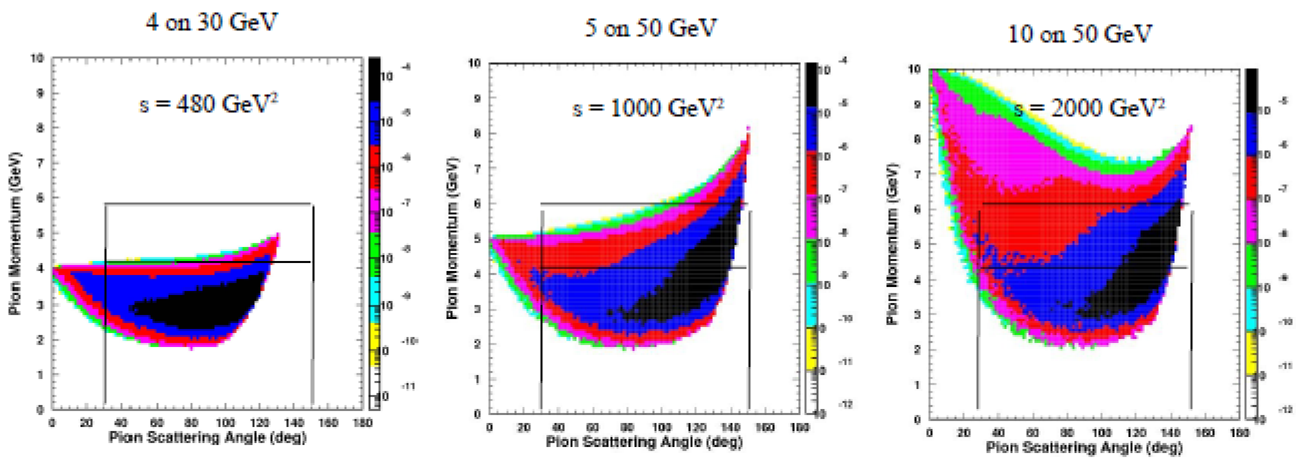

Fig. 4: Exclusive pion production at Q^2 > 10 GeV^2 for three kinematics: 4 on 30, 5 on 50, and 10 on 50 GeV. As indicated by the horizontal lines, π/K identification up to 4 GeV/c is sufficient at the lowest c.m. energies, but quickly becomes inadequate as the energy increases.

While this section has primarily focused on π/K identification, both e/π and to some extent p/K capabilities are also important for the EIC central detector. The former is essential for reliably detecting and identifying high-Q^2 electrons when the electron beam energy is low, and the energy of the scattered electrons is even lower. Detection issues aside, Fig. 1 indicates that the pion background may not be negligible at energies up to about 1 GeV. At these energies, a DIRC and / or a gas Cherenkov detector constitute an important supplement for the electromagnetic calorimeter. A low-threshold gas Cherenkov can perform e/π separation up to about 3 GeV/c, and a BaBar-type DIRC up towards 1 GeV/c. As in the case of the π/K separation, the latter could be extended somewhat in a "super DIRC". Since the pion background drops off rapidly in the 1-3 GeV/c range, the precise requirements for such supplementary coverage need to be determined.

A gas Cherenkov would offer limited p/K identification capabilities. A BaBar-type DIRC can do the job up to about 6 GeV/c, while a "super DIRC" would extend the range even further. High-p_T protons are expected to be rare, as most baryons originating from the fragmentation of the target are produced at small angles and end up in the endcap detectors on the outgoing ion side. The capability to detect high-p_T protons can nevertheless be valuable.

2. Proposed R&D

2.1 Development of a Compact DIRC readout for high magnetic fields

Hermeticity is a key design goal of the EIC detector, and as such there are limited possibilities to accommodate a large inactive volume inside the detector, or give up significant angular coverage in the endcaps. While the radius of the central tracker is important for the momentum resolution in the central detector, a good tracking resolution at forward rapidities primarily requires a strong solenoidal field. The readout for a DIRC should thus be able to operate in magnetic fields in the 2-4 T range, and be reasonably compact. Fig. 5 show the baseline layout for the EIC detector.

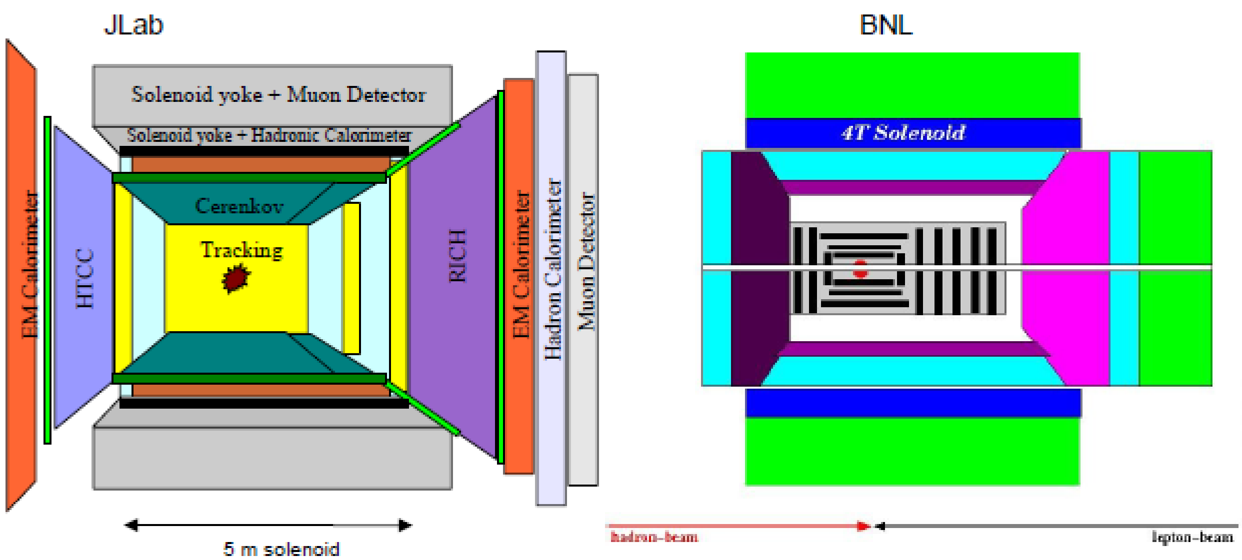

Fig. 5: Baseline EIC central detector cartoon as showed at INT-10-3. The JLab version on the left has the DIRC and TOF in the barrel colored dark green, while the BNL version uses magenta. The readout will replace the last 20-30 cm of the DIRC bar so as not to interfere with the electron tracking. The BNL version on the right is generally similar, but does not explicitly show any gas Cherenkov in the barrel.

The expected PID performance of the DIRC is determined by the resolution in θ_c, the Cherenkov polar opening angle of the particle. The angle θ_c is defined as $\cos\theta_c = 1/n(\lambda)\beta$, where $\beta = v/c$, v is the particle velocity, $n(\lambda)$ is the index of refraction of the material, which, in a dispersive medium, is a function of λ, the wavelength of the Cherenkov photon.

The error σ_c^{track} on the track Cherenkov angle behaves as

$$(\sigma_c^{track})^2 = (\sigma_c^{photon} / \sqrt{N_{p.e.}})^2 + (\sigma^{track})^2,$$

where $N_{p.e.}$ is the number of detected photoelectrons and σ_c^{photon} is the single photon Cherenkov angle resolution. The last term, σ^{track}, is the uncertainty of the track direction in the DIRC, dominated by multiple scattering and the resolution of the tracking detectors.

The single-photon Cherenkov angle resolution σ_c^{photon} can be calculated as

$$\sigma_c^{photon} = \sqrt{\sigma_c^{pixel} + \sigma_c^{bar} + \sigma_c^{imperfections} + \sigma_c^{chromatic}}$$

where σ_c^{pixel} is the contribution from the detector pixel size, σ_c^{bar} is the error due to optical aberration and imaging errors, $\sigma_c^{imperfections}$ is the error due to bar imperfections, such as non-squareness, and $\sigma_c^{chromatic}$ is the uncertainty in the photon production angle due to the dispersion n(λ) of the fused silica material.

The readout consists of an expansion volume (EV) with sensors. The purpose of the expansion volume is to project a spatial image of the Cherenkov light from the DIRC bar. Reading out the image using sensors with a smaller pixel size makes it possible to reduce the size of the expansion volume, or to improve the resolution. The size of the expansion volume can also be reduced by introducing active focusing elements (lenses), although careful design and testing is required to ensure that photons are not lost at certain angles.

The size of the expansion volume used for the PANDA barrel DIRC is 30 cm both radially and along the axis, while SuperB plans to have one that is 56 cm radially and 22 cm long. The former size could be acceptable, but the latter would be challenging to integrate with the EIC detector. Since an important goal of the R&D is to improve the DIRC performance beyond state-of-the-art, and there is a tradeoff between size and resolution, we do not expect the expansion volume to be much smaller than the one planned for PANDA.

The next generation of sensors that will be used in the EIC DIRC need to have small pixels and a high tolerance to magnetic fields. However, for the proposed R&D it is cheaper and more effective to use two sets of sensors. One will provide sufficiently many pixels for use with the expansion volume prototype to optimize the reconstruction of the projected image, and one will be tested in strong magnetic fields.

2.1.1 Compact expansion volume

The required depth of the expansion volume is given by the size of the detector pixels, the size of the bar image after focusing, and the desired Cherenkov angle (θ_c) resolution. To simplify operation the water used in BaBar is replaced with oil (PANDA) or fused silica (SuperB). In the EIC design we will try to further improve performance while maintaining a compact size by introducing an active focusing element, such as a lens doublet. Note that a compact design along the lines of Belle II, relying primarily on timing while sacrificing spatial imaging, would be unlikely to fulfill the requirements of the EIC in terms of momentum coverage and the length of the DIRC bars.

2.1.2 Small-pixel readout

A small pixel size is essential for reaching the desired spatial resolution. To test this performance in our prototype, a sufficient number of channels is required. The most economical way of achieving this is to use multi-pixel PMTs such as the Hamamatsu H9500-03 (256 pixels, 3.0 mm pixel pitch) or Photonis XP85022 (1024 pixels, 1.6 mm pixel pitch). An important performance consideration is optical and electrical cross-talk between pixels. A prototype of the Photonis 85022 tested at SLAC in 2005/2006 did not perform as well as a prototype of the Hamamatsu H9500.

2.1.3 Readout in a high magnetic field

Tests will be performed using an MCP-PMT with small-diameter MCPs, such as the 6 micron MCP-PMT produced by BINP, Novosibirsk, and Philips digital SiPMs. While SiPMs potentially could be less sensitive to magnetic fields, their high dark count rate at the level of 1 MHz/cm^2 at room temperature will require cooling to reach the desired performance.

2.2 Initial Development of a High-Performance DIRC

The primary goal of developing a "super DIRC" that would push the performance beyond the state-of-the-art, would be to eliminate the need for a supplementary gas Cherenkov for π/K identification, reducing the radial space required for PID by at least 60-70 cm. The freed space can be used for a larger central tracker, improving the momentum resolution, or to reduce the radius of the solenoid magnet. A smaller overall radius would not only reduce the cost of the solenoid and the electromagnetic calorimeter, but also that of the endcap detectors (which goes as the radius squared). A cartoon of a configuration using only a "super DIRC" is shown in Fig. 6.

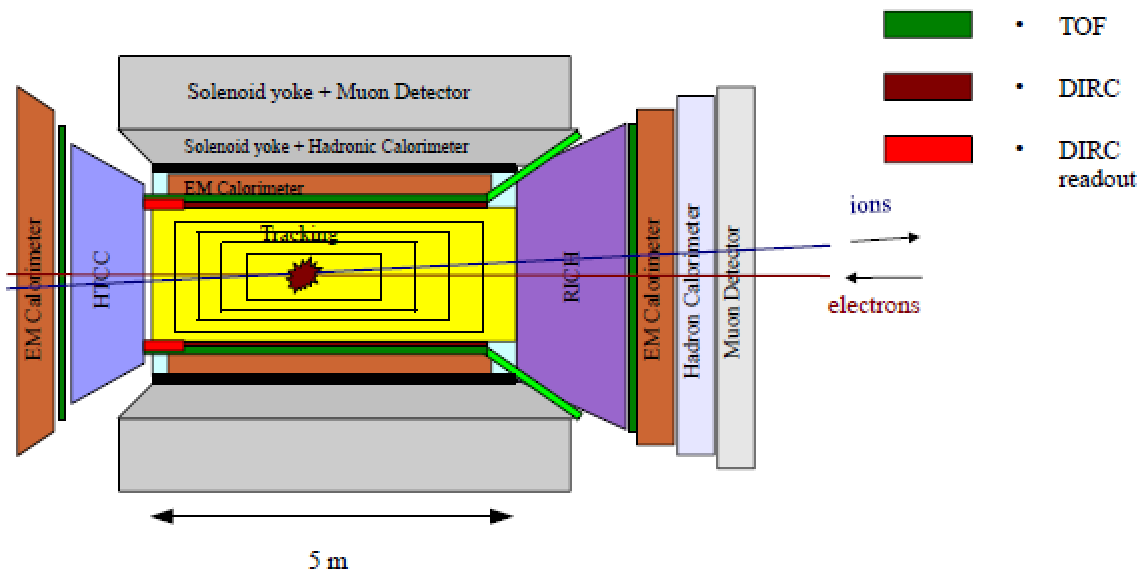

Fig. 6: EIC central detector cartoon showing a DIRC-only configuration.

As the particle momentum increases, so do the demands on the Cherenkov angle resolution. Fig. 7 shows how the π/K difference in Cherenkov angle for drops from 6.5 to 2.9 mrad between 4 and 6 GeV/c. Achieving 3σ separation would require a Cherenkov angle resolution of 1.3 mrad at 5 GeV/c and 1.0 mrad at 6 GeV/c. In addition to the design of the DIRC itself, achieving this performance also assumes that the central tracker will be able to provide an angular resolution comparable to the CLAS12 forward detector.

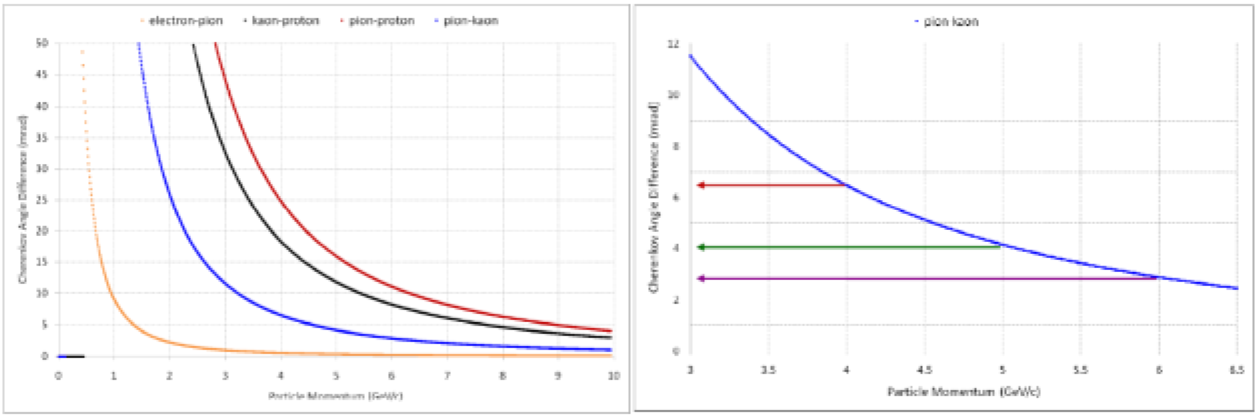

Fig. 7: Cherenkov angle difference in fused silica as function of momentum for e/π, π/K, K/p, and π/p (left panel), and a close-up of the π/K curve (right panel). Extending the π/K separation from 4 to 6 GeV/c requires more than a factor-of-two improvement in the resolution.

As shown in the equation above, there are four ways of improving the Cherenkov angle resolution:

1. Reduce the size of the image from the DIRC bar using focusing optics.
2. Reducing the pixel size of the readout to better resolve the image.
3. Improving the photon yield and collection (various methods).
4. Reducing the effect of chromaticity ($n = n(\lambda)$) through precise timing or wavelength filters.

The first two items are addressed in section 2.1 above as part of the readout optimization process, while section 2.2.2 below lists the proposed R&D associated with the last two.

2.2.1 Simulations

An important consideration for the feasibility of a DIRC-only Cherenkov configuration is whether the electromagnetic calorimeter will be sufficient for dealing with the pion background outside the e/π identification range of the DIRC, or a sufficiently high threshold can be imposed on the detected electron without limiting the accessible kinematics. Electron identification is not only important for event reconstruction, but also for the asynchronous trigger, for which the scattered electron provides an excellent time stamp. A detailed knowledge of the pion backgrounds in the central detector is thus essential for the choice of PID strategy.

2.2.2 Hardware

The separation power of the DIRC can be calculated from the Cherenkov angle (θ_c) resolution per particle, which is a function of the number of detected photons and the single photon Cherenkov angle resolution.

2.2.2.1 Increasing the photon yield

The most straightforward way to improve the photon yield is to increase the bar thickness. This does not impose any additional manufacturing complications, but simulations are needed to study the impact of having 0.2 r.l. or more of bar material in front of the electromagnetic calorimeter and other subsystems. We will also investigate the possibility of reducing photon losses by using either MCP-PMT or MaMPT with an improved, UV-optimized photocathode, or large-cell SiPMs (due to their intrinsically high PDE). The same SiPMs could be used for this purpose as for the magnetic field tests in section 2.1.3. Another way, falling outside the scope of the proposed R&D, would be to apply anti-reflective coatings to the optics in the focusing system to prevent losses in the glass/air boundary.

2.2.2.2 Precision timing

When the DIRC bars are relatively long and the readout uses small pixels, the chromatic dispersion may no longer give a negligible contribution to the single-photon θ_c resolution. The focusing DIRC prototype at SLAC has shown that dispersion effects can be corrected by using fast timing at the 100 ps level, and this proposal thus aims to provide timing close to that level. Should this prove not to be sufficient, more stringent timing requirements may be needed for the EIC DIRC, or wavelength filters can be applied to improve the single-photon resolution. The loss of photons due to the latter may, however, make the overall θ_c resolution for the track worse.

2.3 Investigation of PID based on a DIRC / gas Cherenkov combination

If the final EIC detector will be required to cover a wider momentum range than can be achieved with a DIRC alone, one can augment it with a gas threshold Cherenkov, or replace it with a dual radiator (aerogel + gas) barrel RICH, which would be a slightly larger and offer slightly lower performance. The former alternative can have two configurations. Option 1, shown in Fig. 5, involves placing the DIRC outside of the gas Cherenkov, close to the time-of-flight (TOF) detectors. Option 2, shown in Fig. 8, places the DIRC inside of the gas Cherenkov close to the central tracker.

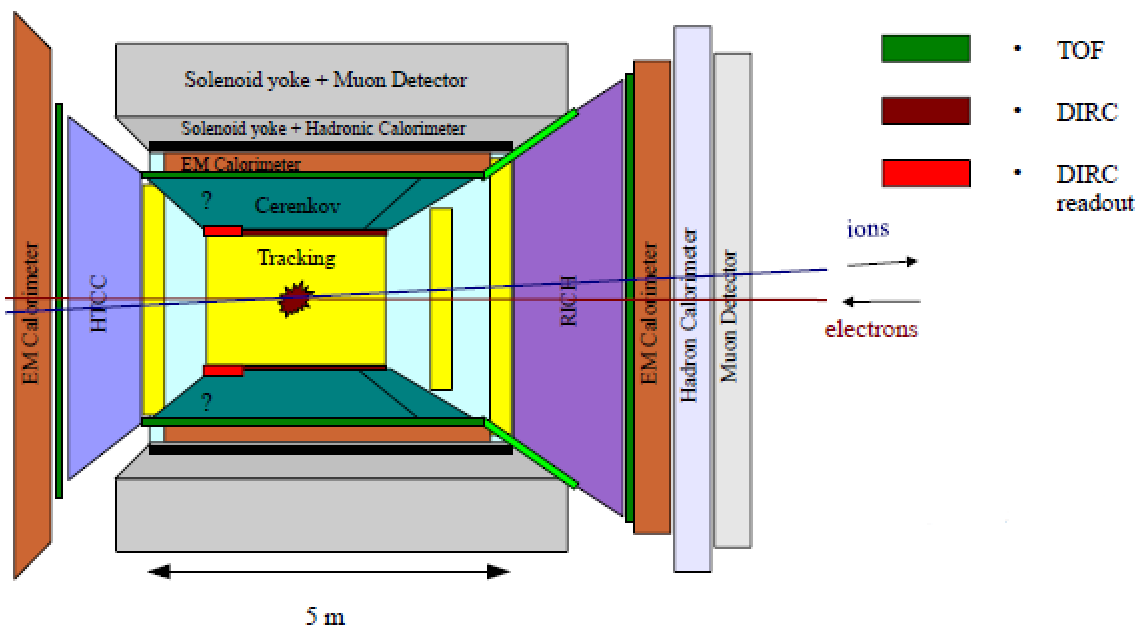

Fig. 8: Detector cartoon showing the DIRC inside of the supplementary gas Cherenkov (Option 2).

Compared with Option 1, Option 2 has three main advantages:

1. Reducing the radius (and length) of the DIRC makes it significantly cheaper.
2. The proximity to the central tracker gives a better angular resolution for the incident track.
3. The shorter DIRC bar will suffer from less chromatic dispersion and offer better timing.

There are, however, also three disadvantages:

1. Adding 0.15-0.20 r.l. of material in front of the gas Cherenkov will expose it to δ-electrons.
2. The proximity to the collision point will increase the solid angle covered by the readout.
3. The distance to the TOF will reduce the timing benefits.

Option 1 seems to be the more conservative choice, but to determine the feasibility of Option 2, a quantitative study is needed.
We thus propose to make a GEANT-based simulation of the central detector to compare the options above, understand the interdependence of the PID detectors, and optimize the parameters for various components, such as the thickness of the DIRC bars.

2.4 Synergies with Ongoing DIRC R&D

The hardware R&D makes substantial use of synergies with the PANDA DIRC detector development.

An example is the use of radiator bars made from synthetic fused silica. The production of a bar with optical quality sufficient for the EIC DIRC prototype would require a minimum of 4-8 bars to be produced at a cost of approximately $25-30k per bar. However, a number of prototype bars were produced for the PANDA Barrel DIRC R&D at GSI. The EIC DIRC R&D will have access to one of the bars for a possible test beam run.

Another example is the test of photon sensors. The GSI group owns a $10k electronic pulser and a $15k fast laser pulser system (PiLas) with a FWHM timing jitter below 25 ps, required for measurements of the fast single photon timing for the EIC DIRC. The test of SiPM will require the sensors to be cooled to between -10° and -25° C. For simple tests a Peltier-cooled setup will be constructed at modest cost. For more detailed studies the R&D will make use of a $10k large cooling box owned by the GSI group.

3. R&D Timeline

3.1 Year 1

3.1.1 Design and Simulation

Simulation of pion backgrounds in the EIC central detector will determine the need for supplementary e/π discrimination capabilities (beyond the DIRC and EC) in the central detector.
Studies will be carried out of the performance of different expansion volume (EV) sizes, shapes, focusing designs, and radiator shapes, in terms of single photon resolution and light yield. The work will comprise:

1. Implementation of initial prototype in Geant, including:
    a. Polished fused silica bar/plate
    b. Small 30-cm depth expansion volume (EV)
    c. Focusing lens
    d. Multi-pixel readout
2. Development of reconstruction algorithm for the bar/plate geometry.

3.1.2 Hardware

Early results of design/simulation will be used to design the expansion volume prototype. The work will include:

1. Construction of a prototype compact EV with multi-pixel readout.
2. Set up DAQ system for readout.
3. Test of EV imaging and sensors using fast laser pulser.

3.1.3 Deliverables

1. Initial e/π identification requirements for the central EIC detector.
2. Simulation and reconstruction framework for DIRC prototype.
3. DIRC resolution studies and design of prototype.
4. Compact expansion volume prototype with multi-pixel readout.
5. DAQ system tested using laser pulser.

3.2 Year 2

3.2.1 Design and Simulation

1. Implementation of initial version of EIC DIRC in EIC detector.
2. Interaction between DIRC and other detector components.
    a. material budget
    b. optimize location
3. Initial EIC DIRC performance from physics channels.
    a. establish required performance for "Super-DIRC"
    b. identify areas for performance improvement R&D
4. Design of final EV prototype.

3.2.2 Hardware

1. Study magnetic field tolerance of SiPM and MCP-PMT.
2. Test focusing options.
3. Test of EV with particle beam, if available.

3.2.3 Deliverables

1. Integration of a DIRC into the EIC detector.
2. Performance plots for EIC DIRC.
3. Design for final prototype EV.
4. Test of sensor response at 2-4 T magnetic field.
5. Cherenkov ring resolution in test beam (if available).

3.3 Year 3

3.3.1 Design and Simulation

Final EIC DIRC performance from physics channels

3.3.2 Hardware

1. Build final EV prototype based on simulation and year 1-2 results.
2. Test performance with particle beam, if available.

3.3.3 Deliverables

1. Performance parameters of DIRC in the EIC detector.
2. In-beam test of compact EV (if available)
3. Comparison of photon yield for different multi-pixel sensors
4. Determination of Cherenkov angle resolution of final prototype EV.

4. Management Plan

4.1 Funding Request and Budget

We request a total of $329k over a three year period, as indicated in the table below.

Budget

	Year 1	Year 2	Year 3	Total
Postdoc (50%)	$45k	$46k	$47k	$138k
Undergrad	$8.3k	$8.3k	$8.3k	$24.9k
Hardware	$47k	$37k	$30k	$114k
Travel	$14.7k	$17.7k	$19.7k	$52.1k
Total	*$115k*	*$109k*	*$105k*	*$329k*

Comments

The salaries for the postdoc and undergraduate students include university overhead. Matching funds are available for the postdoc. The travel and hardare (except item 1 in year 1) include JLab overhead.

4.2 Procurement

Year 1:

1. Materials for CUA undergrad student (computer, etc): 1.5k
2. Prototype EV: $2k
3. Dark box for prototype: $2k
4. One multi-pixel PMT: $11k
    a. option A: Hamamatsu H9500-03 (256 pixels)
    b. option B: Photonis XP85022 (1024 pixels)

5. Two digital SiPMs, Philips: $4k
6. One 6 micron MCP-PMT, round, single anode, BINP, Novosibirsk: $2k
7. Readout electronics: $5k
    a. option A: HADES TRBv2 with TOF-addON, 128 channels with fast TDC (100ps/count) and time-over-threshold
    b. option B: new, faster version (TRBv3) expected in late 2011 (~10ps/count, more channels per board), similar cost per channel
8. Cabling: $1k
9. Temperature-controlled cool box for SiPM tests: $2k
10. Focusing optics (lenses, small mirror): $3k

Total: $33.5k

Year 2:

1. MCP-PMT or MaMPT with improved photocathode: $14k
2. add 256 more readout channels: $10k
3. cabling: $2k

Total: $26k

Year 3:

1. Construct very compact EV from solid fused silica: 10k$
2. If solid fused silica EV is not required we should add one more multi-pixel readout module to the setup (PMT or SiPM): 11k$

Total: $21k

Comment

Most costs are in Euro. A conversion rate of 1.4 USD per 1 Euro is assumed. Listed costs are direct.

4.3 Responsibilities

Following the outline in section 3 above, the main responsibility of the US part of the collaboration (JLab, CUA, ODU) will be simulations, design, and integration of the DIRC into the EIC detector. To carry out these tasks, a postdoc will be hired at ODU and undergraduate students at CUA, the latter focusing on the overall detector optimization and performance.

The primary responsibility of the German part of the collaboration (GSI) will be to guide the design of the hardware, prototype construction, and carrying out a range of tests. However, an important part of the proposal is also to provide travel support, creating opportunities for the US partners (including the postdoc) to take part in the development of the hardware, and for the German partners to present their results to and participate in the activities of the EIC collaboration.