eRD102 – dRICH

Contact Persons: Evaristo Cisbani, Marco Contalbrigo, Anselm Vossen

Project Members: EIC dRICH Group

DUKE University
INFN Bari and University of Bari
INFN Bologna and University of Bologna
INFN Cosenza and University of Cosenza
INFN Catania and University of Catania
INFN Ferrara and University of Ferrara
INFN Genova and University of Genova
INFN Laboratori di Frascati
INFN Laboratori del Sud
INFN Roma1
INFN Salerno and University of Salerno
INFN Torino and University of Torino
INFN Trieste and University of Trieste
NISER

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The dual-radiator Ring Imaging Cherenkov (dRICH) detector is designed to provide continuous full hadron identification ($\pi/K/p$ separation better than 3σ apart) from ~ 3 GeV/c to ~ 50 GeV/c in the ion-side end cap of the EIC detector. It also offers a remarkable electron and positron identification from a few hundred MeV/c up to about 15 GeV/c. dRICH has been identified as reference detector for particle ID in the hadron endcap during the Yellow Report initiative.

The main technical goals for the FY22 proposal have been: initial assessment of the dRICH prototype performance based on the first test-beams (milestone 12/22), implementation of a realistic dRICH model inside the EIC simulation framework (milestone 02/23), realization of a suitable EIC-driven detection plane (milestone 03/23). The baseline version of the dRICH prototype has been realized last year and commissioned in the first test-beam campaign in Fall '21 when the functionality of all the ancillary systems (tracking, trigger and timing, cooling, gas and vacuum, readout) was validated, see Fig. 1. Despite the complicated conditions (sharing of the readout with simultaneous mRICH test-beam at JLab, renovated CERN beam line still under commissioning, mostly parassitic data-taking time) some Cherenkov data were collected useful to define what has had to be improved to reach the design performance, see Fig. 2 and Fig. 3. Preliminary results were presented at national (INFN 2022, LNGS, Italy) and international (RICH2022, Edinburgh, UK) conferences.

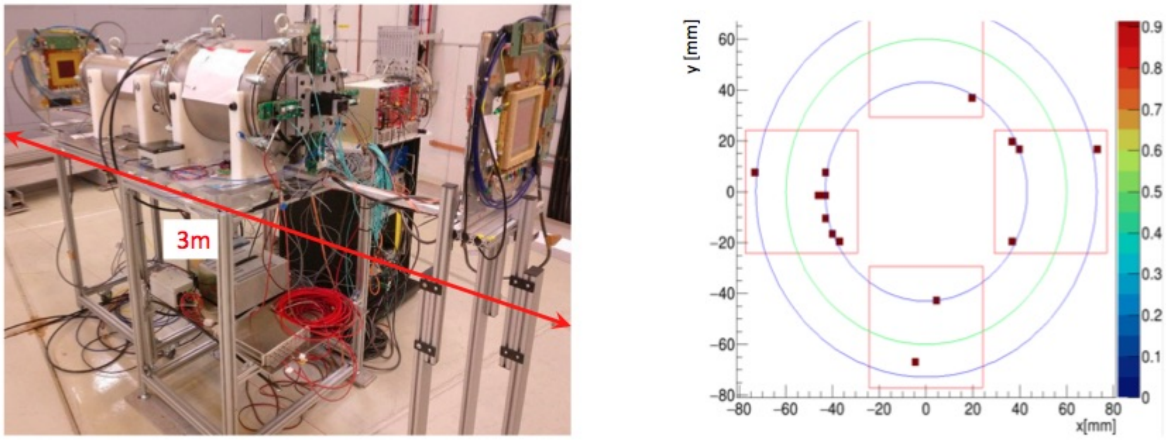

Figure 1: (Left) The dRICH prototype at T10 beam line of CERN PS. The detector box housing the sensors, readout electronics and aerogel is mounted on the entrace widow of the gas vessel. The system is complemented by two GEM tracking stations located downstream and upstream. (Right) Online event display: the sensor surface is indicated by red squares, the green circle subdivides the nominal detection areas of gas and aerogel photons: The ring with small radius originates from gas, the one at large radius from aerogel.

The prototype has been upgraded following the indications of the initial test-beams and what was anticipated in the FY22 dRICH R&D proposal, and a second test-beam campaign is now ongoing. A first test-beam (September '22) at the T4-H8 beam line of the SPS has used hadron beams with momenta between 15 GeV/c and 180 GeV/c to cover the high-momentum spectrum of the EIC hadron end-cap, and study basic imaging performance with saturated rings (maximum Cherenkov cone aperture and photon yield). A second test-beam (October '22) at the T10 beam line of the PS will use hadron beams with momenta below 15 GeV/c to investigate the transient region between the two radiator working regimes. The goal of these test-beams is to obtain detailed information on the performance of the prototype, to study the interplay of the two radiators, and to investigate various contributions to the Cherenkov angle resolution. These information will be used in input to the simulations to refine the dRICH detector model. The study of the single-photon response of SiPM coupled to the ALCOR readout electronics, a complementary target of the test, will be synergistic with eRD109 and instrumental in preparation of the EIC-driven detector plane design and realization.

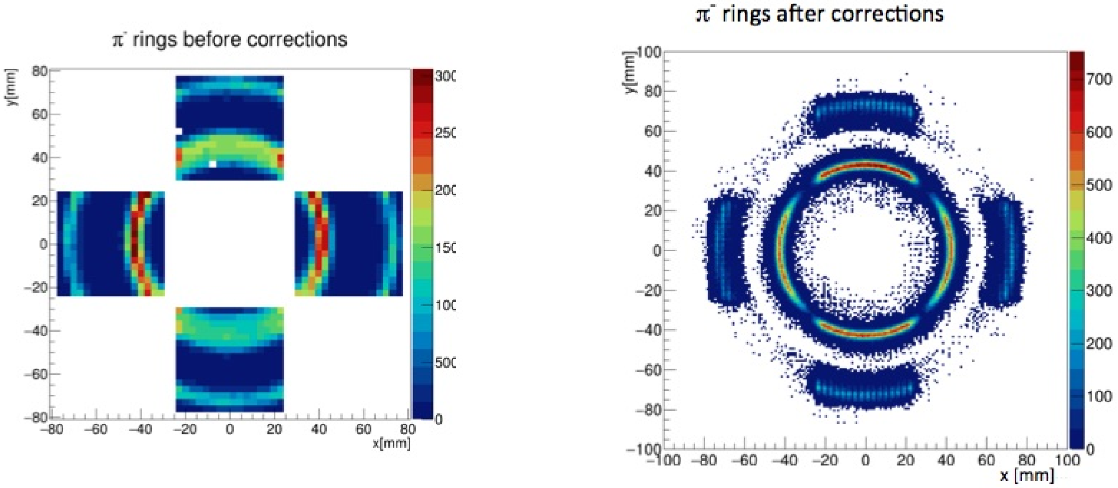

Figure 2: Cumulative distribution recorded with a 12 GeV/c mixed hadron beam and two radiators, before (left) and after (right) the correction for beam particle trajectory tracked by GEMs.

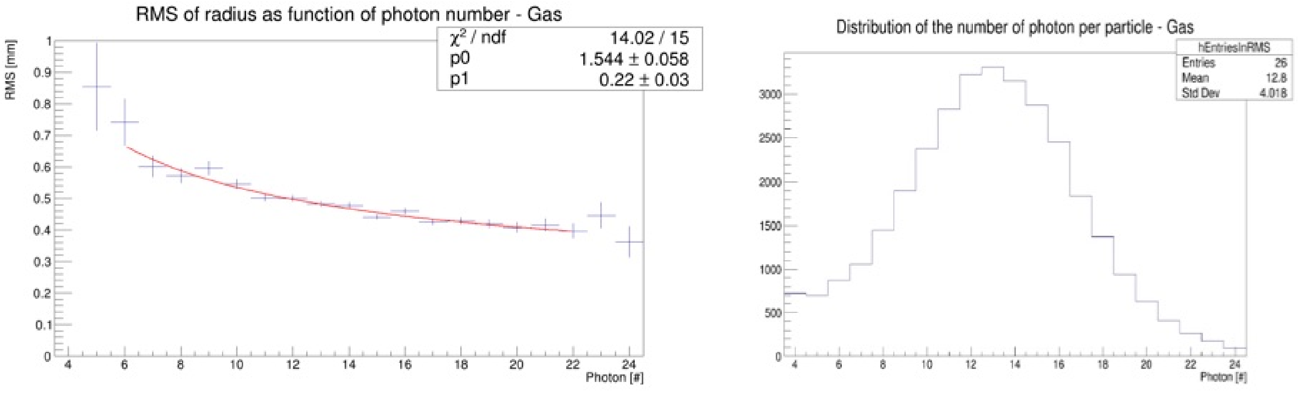

Figure 3: Preliminary analysis of the Cherenkov signal from C_2F_6 gas. Resolution as a function of the number of photons (left). Number of photons detected per particle (right). The measured values of single photon resolution (p_0 parameter on the left) and photon yield (mean on the right) are consistent with the values expected from simulations: $p_0 = 1.1$ mrad and $N_{pho} = 11.5$, respectively.

R&D plan for FY23 and FY24-25 preview: The main technical goals of FY23 R&D are the validation of the EIC-driven detector plane under realization, the study of realistic solutions for the dRICH components (vessel, radiators, mirrors) targeted to the definition of the technical specifications to meet EIC requirements, and the definition of the layout and projected performance of the baseline detector as integrated into EPIC. FY24 and FY25 will be targeted to the optimization of the EIC-driven specifications, the matching with photosensors and readout electronics (developed by other EIC R&D) with integrated cooling, the validation of cost-effective component technologies to mitigate the construction risk, and to the preparation of the technical design report.

Prototype: During FY23 and following years the prototype will be upgraded to reach the full functionality. The first version of the prototype and the 2021 test-beam campaign concentrated on the proof-of-principle of the dual radiator imaging. The initial realization of the prototype, tracking and gas system, was not sufficient to fully characterize the performance of all the components and reach complete optimization. To reach these goals, the dRICH prototype has been upgraded with: a renovated support system to facilitate the alignment, a remote controlled step-motor system to allow mirror alignment while the prototype is in operation and taking beam, a DAQ chain to tag the time of the incoming particle and improve the time resolution, a DAQ chain to acquire beam instrumentation like Cherenkov-gas detectors to tag the incoming particle type, a greenhouse gas recovery system to allow safe operations and relax restrictions due to environmental regulations. A continued adaptation of the prototype to different components will be required to validate alternate qualified producers, optimize performance and pursue cost reduction, study technical specification and risk mitigation (30 k$ the first year, decreasing the next years). Examples are the EIC-driven detector plane, gas and aerogel radiators and their UV filtering septa, light mirrors, realistic mechanics and vessel. Financial support from INFN is expected to cover part of these upgrades but a contribution from EIC project is essential for the prototype evolution and test-beam organization.

Radiators: Very few manufacturers of optical quality aerogel and even less with large production capability are currently available. Russian aerogel, basically an handcrafted product, was widely used in the past as customization towards world-leading performance in transparency and size was possible, but is not accessible anymore. Chiba University developed aerogel of excellent quality for the BELLE-II experiment and is now organizing a production facility called Aerogel Factory as spin-off. Few aerogel samples of n=1.02 were acquired and used with the dRICH prototype, with promising results, see Fig. 4. Dedicated R&D is required to reach large dimensions (i.e. 20×20 cm^2) and limit the detrimental edge effects. The quality and mass production capability need to be validated with laboratory characterization. In USA, ASPEN company has pursued SBIR development programs for optical aerogel reaching promising transparencies at low refractive index. Initial contacts have been pursued with CUA and INFN to obtain samples compatible with the dRICH goals and prototype. Funds are required (20 k$/yr) to acquire samples from these companies, to assess the current status-of-the-art and initiate a customization program toward dRICH needs. Aerogel and gas refractive indexes need optimisation for photon yield, resolution and momentum coverage. Funds are requested (20 k$ in three years) to support the use of fluorocarbon gases C_2F_6, and alternatives, in conjunction with properly associated aerogel. Given the LHCb experience that reported a long-term degradation of the aerogel when immersed in fluorocarbon gas, a septum between aerogel and gas radiator is recommended. Such a window could act as a wavelength filter to suppress the unwanted UV light component that mainly undergoes Rayleigh scattering in aerogel. A similar window may be needed to separate the gas volume from the active area (sensor and electronics) and reduce temperature gradients in the gas radiator. For the initial dRICH beam-tests a commercial 3 mm acrylic sheet will be used to study the prototype optical performance. The septum material requires validation in term of wavelength range, material budget and radiation tolerance. Funds are requested (10 k$ in three years) to acquire the relevant samples (acrylic and quartz) and perform the study. INFN will contribute to the procurement and provide expertise and laboratory instrumentation (like the photo-spectrometer in Fig. 4) for the optical characterization, but EIC funds will be essential to organize an adequate R&D.

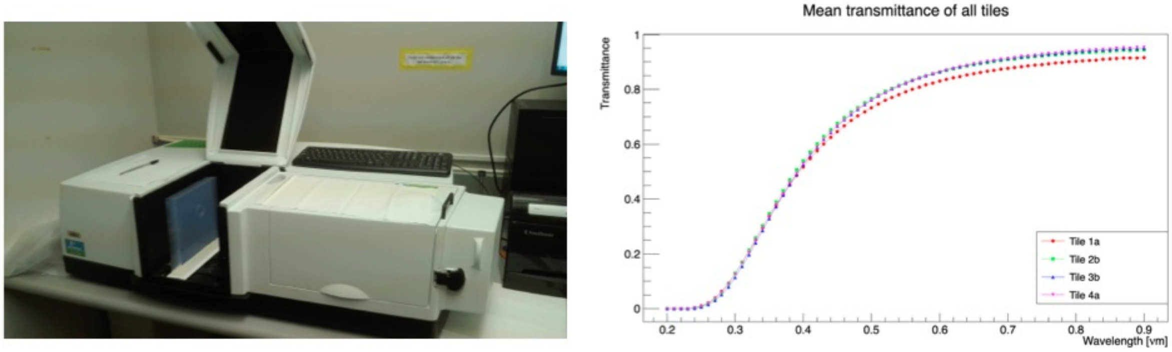

Figure 4: Photo-spectrometer available at the INFN optical laboratory, suitable for large aerogel samples, e.g. 20x20 cm^2 (left). Example of transmittance measurements done on Aerogel Factory samples (right).

Photosensor and Electronics: In order to meet the EIC specifications a critical element, common to other EIC PID detectors, is a proper choice of the photosensor, that should preserve single-photon detection capability inside a strong magnetic field. The dRICH focusing system is designed to keep the detector outside the EIC spectrometer acceptance, in a volume with reduced requests in terms of material budget and radiation levels. This feature makes dRICH a natural candidate for the exploitation of magnetic-field tolerant SiPMs. It is expected that the optimized solution will be developed by the end of FY23 within the photosensor and radiation-hard SiPM programs (eRD110) in conjunction with the electronics/ASIC program (eRD109). Nevertheless, any realistic study of the dRICH performance relies on the availability of a suitable instrumented area: at least $10 \times 10\,\mathrm{cm}^2$ with less than 3 mm pixelization and sub-nanosecond time resolution. To be compatible with SiPM and support streaming readout tests, such electronics should also cope with high rates, up to 0.5 MHz per channel and be integrated with a cooling and annealing circuit. The reference sensors (Hamamatsu H13700) and readout electronics (MAROC3) derived from the generic R&D program could still be used as reference, but can not probe such EIC-driven performance. A realistic SiPM active plane and readout to meet the above EIC basic specifications is under design and realization (FY22 milestone). The SiPM choice will be based on the initial survey and irradiation campaign performed in the past months. The readout will be based on the ALCOR chip (a ToT discriminating architecture) and ARCADIA DAQ, two INFN developments. Their initial adaptation to the dRICH needs is assumed to be an INFN in-kind contribution. Funds are requested (20 k$/yr) for complementing the front-end boards with a baseline cooling and annealing integrated system, for optimization of the layout and services (power and DAQ lines), and for implementing the new developments expected within eRD110 and eRD109 programs.

Mirror: Being inside the EIC detector forward acceptance, the dRICH spherical mirrors should be light. Large area mirrors of optical quality compatible with RICH applications can be reliably produced at Composite Mirror Applications in Tucson, AZ, USA. CMA mirrors are made by two thin layers and a honeycomb core of carbon fiber reinforced polymer (CFRP), and achieve an areal density lower than 5 kg/m^2 and a shaping accuracy better than 0.2 mrad. This company offers wide experience (HERMES, AMS, LHCb, CLAS12) and continuous improvements, but is the only one validated so far. Alternatives like the composite mirror R&D program ongoing in Chile (connected with ATLAS) and the glass-skin technology developed in Italy (for terrestrial telescopes) can only be pursued on a longer time scale. In mirrors made of composite substrate, the surface roughness depends on the quality of the mold and stringent characteristics have to be imposed to obtain the needed roughness of 1-2 nm r.m.s and the sub-mrad surface accuracy. The innovative mold technology that CMA has developed is cost-effective for large mirror sizes but need validation for EIC needs. Quality, homogeneity and wavelength range of the reflective layer deposition are critical in large surface mirrors and their optimization requires the production and characterization of real-size mirror demonstrators. Most likely, a process of iterations with feedback from the dRICH team to the manufactures will be necessary. In parallel, a study of the support and alignment structure is foreseen. To pursue these targeted R&D dedicated funds would be required (30 k\$/yr). INFN will contribute to part of the costs and with the expertise and instrumentation for the optical characterization, see Fig. 5.

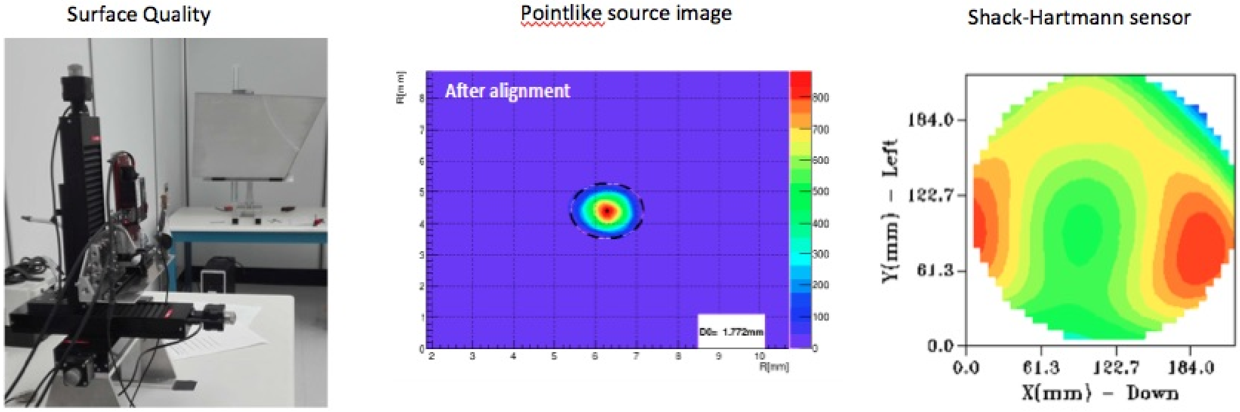

Figure 5: Characterization station (left). Example of shape accuracy measurements: point-like source image providing a global quality estimator (center) and Shack-Hartmann analysis providing a detailed mapping of surface aberrations(right).

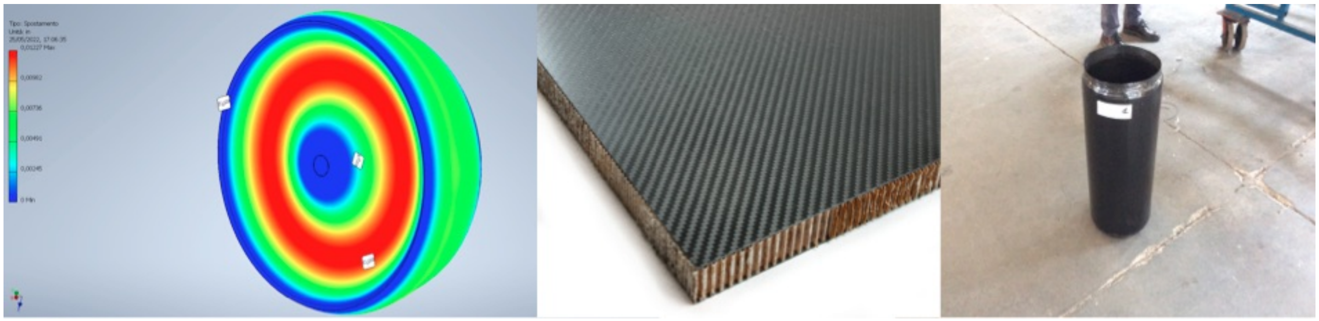

Figure 6: Example of FEM calculations for a over-pressure dRICH vessel (left). Example of composite material under study (center). Simple demonstrator designed to allow over-pressure material stress and deformation study (right).

Engineering: The dRICH structure is divided in three main pieces. The aerogel volume, the gas volume and the photosensor boxes. The detector boxes, being outside acceptance, could be relatively massive to provide support for sensor, electronics, integrate services and cooling. Aerogel requires a support layer and an insulation window. Mirrors require a support with an integrated alignment system. While working at atmospheric pressure, the gas volume and supports could be realized by a skeleton of light CFRP ribs connected by tedlar foils. All these structures should be designed to comply with EIC detectors needs. Fluorocarbon gases are ideal radiators because at atmospheric pressure and room temperature they exhibit high density, corresponding to high refractive index, and low chromatic dispersion in the visible range, resulting in high accuracy. However, for such greenhouse gases, the market availability is subject to environmental regulations and a significant future price increase or shortage can not be excluded. When pressurized, noble gas density increases and they can mimic fluorocarbons very accurately: Argon at 2-2.5 bar absolute pressure can match EIC needs and might eliminate the need of a septum between radiators. Provided that mirrors and aerogel are fixed to a rigid internal structure, some deformation of the entrance and exit window are compatible with the dRICH operations and the material budget is essentially driven by safety regulations. An engineering study has been initiated at INFN that foreseen a first demonstrator of simple geometry (cylinder) to test promising materials, like CRFP or Al composites, and verify corresponding FEM analyses, see Fig. 6, and a second prototype with realistic geometry, to be realized in FY23. This activity requires a collaboration with BNL and JLab engineers to comply with the anticipated safety regulations and a joint study has been initiated. Hardware costs are accounted for in the prototype section. Funds to cover the US technical support is therefore requested (10 k$/yr).

Simulation and Integration: The dRICH concept can be adapted to different detector geometry and optimized in conjunction with other PID detectors. This can be primarily done with Monte Carlo simulations and CAD models, properly evolved following the prototype outcomes. A dRICH model exists and has been used to support ATHENA and ECCE PID studies, see Fig. 7, and has now been implemented in the EPIC framework. An essential study is ongoing to correlate the performance with a realistic description of the optical component and geometry, accounting for the global constraints and the volume required by the services (power supply, cooling, DAQ). Dedicated manpower is already working at DUKE and INFN but requires support to be able to continue the study.

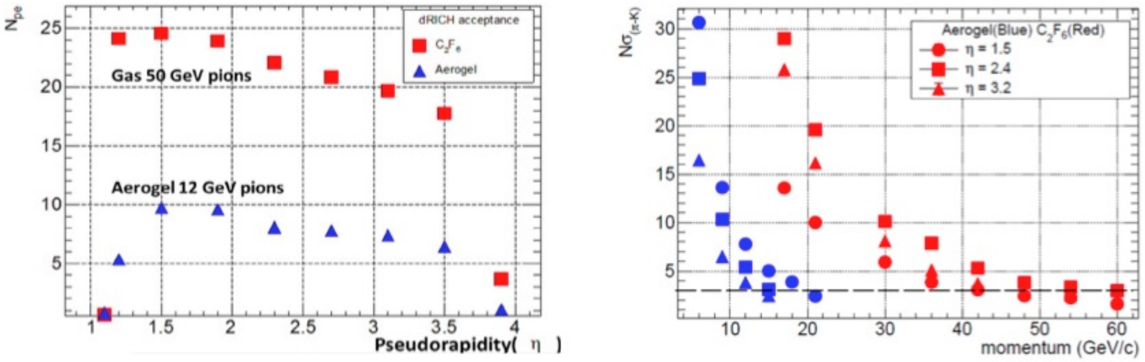

Figure 7: Example of dRICH simulation results: number of expected photons (left) and hadron separation as a function of momentum (right).

Manpower: Within the EIC R&D program, various INFN activities are targeted to possible application at the dRICH (eRD102). INFN therefore contributes at large to eRD102, and groups involved in other R&D targeted programs support this application with integration and beam tests of their diverse sub-systems under development. High-level expertise is available among the collaborating units covering all the aspects described above. INFN can count on 8 researchers (about 0.1 FTE each) as dedicated manpower to eRD102. DUKE can count on 2 researchers (about 0.1 FTE each). It is important to note that many of the proposed R&D activity will be synergistic and instrumental also for the Cherenkov detector in the electron end-cap (eRD101), in particular the EIC-driven detection plane, the aerogel and mirror characterization and developments, the structural analysis (standard pressure option). EIC funds would be crucial to co-fund young researcher positions and ensure dedicated manpower with long-term perspective. Two half post-doc positions and a half technologist position are requested in FY23 for a total of 100 k$/yr.

Milestones: Initial characterization of realistic mirror and aerogel components (April 23); Projected performance of the baseline detector as integrated into EPIC (June 23); Assessment of the dRICH prototype performance with the EIC-driven detection plane (October 23). The estimated timeline is assumed to concatenate with the updated FY22 activity plan and milestones approved within the SOWs, and is subject to funds availability.

Funding profile: The dRICH project could count on a significant INFN in-kind contribution in infrastructures, expertise and sinergetic developments (i.e. ALCOR and ARCADIA), plus about a 40 k$/yr budget covering the basic development, but relies on EIC project funds to mitigate the technological risk. Dedicated personnel can only be co-funded at this stage of the project. Minimum two-year long post-docs contracts are now mandatory by Italian law, with a total cost of approximately 80 k$. Continued financial support from the EIC project R&D program of the dRICH post-doc and their work on software as well as the dRICH prototype is crucial. The proposed funding profile is outlined in Table 1. It is anticipated that the R&D activity on radiators, mirrors and readout with integrated cooling may continue beyond FY24 for further optimization. The proposed FY23 funding per Institution is listed in Table 2.

	prototype	radiators	mirror	detector	personnel	technical	travel	total
FY23	10	20	20	20	100	10	10	190
FY24*	10	20	20	10	80	10	10	160
FY25*		20	20	10	60	10	10	130

Table 1: Proposed EIC project funding profile in k$. The anticipated 40 k$/yr of INFN in-kind contribution is in addition and covers part of the costs described in the text. Personnel funds request takes into account hardware and software needs and assume co-funding. * Projected costs.

	prototype	radiators	mirror	detector	personnel	technical	travel	total
INFN	10	20	30	10	60		5	135
DUKE					40		5	45
DOE						10		10

Table 2: Proposed FY23 project funding per Institution in k$. The anticipated 40 k$ budget from INFN and personnel co-funding in-kind contribution is in addition.