eRD102 – dRICH

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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 $\sim$ 3 GeV/c to $\sim$ 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 identification in the hadron endcap during the Yellow Report initiative.

The milestones of the FY23 proposal have been: (1) initial characterization of realistic mirror and aerogel components (April 23), achieved with the characterization of aerogel samples from Aerogel Factory (Japan) initiated in collaboration with ALICE; (2) projected performance of the baseline detector as integrated into EPIC (June 23), achieved with the general revision of the dRICH simulation framework performed in preparation of the ePIC PID review (and presented at the beginning of July); (3) assessment of the dRICH prototype performance with the EIC-driven detection plane (October 23), for which a new test-beam campaign has been organized in Fall '23, with the primary scope to operate the new EIC-driven readout plane (SiPM sensors and ALCOR digitalization), see below.

R&D plan for FY24 and FY25 preview: The main technical goals of FY24 R&D are the realization of a real-scale prototype to validate the mechanical elements in conjunction with a realistic off-axis optics, study the thermal aspects, mount a complete readout plane with the design readout boards, operate demonstrators of the optical components as results of the ongoing developments. This step will be instrumental to the consolidation of the technical specifications to meet EPIC requirements in preparation of the TDR. FY25 is taken as a contingency time for further optimization of the components towards performance enhancement, cost reduction and risk mitigation.

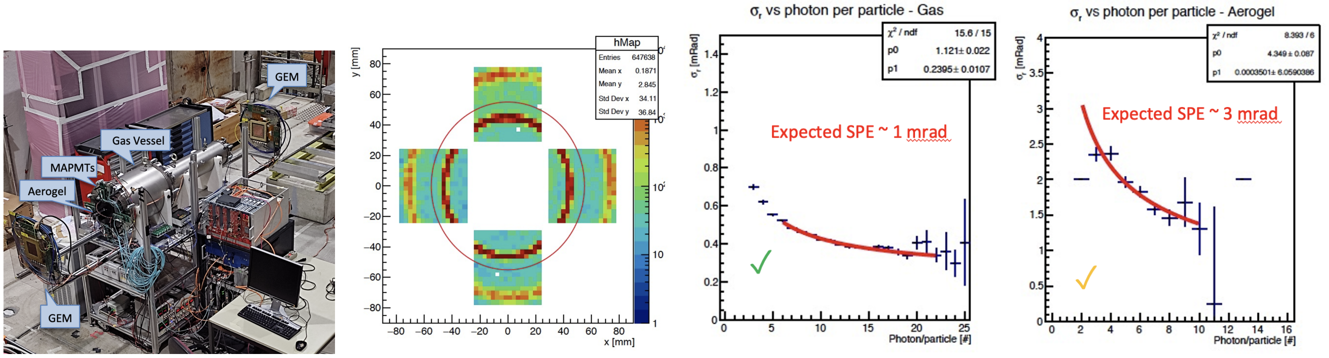

Figure 1: dRICH baseline prototype at the SPS beam line in October '23, complemented with a GEM tracking system (left). Imaging of the two radiators with the reference photon-detector based on MA-PMTs and MAROC3 chip (center). Measured angular resolution as a function of the detected photon number for each of the two radiators (right). The fit parameter p_0 can be compared to the single photo-electron (SPE) resolution expectation.

Prototype: The first version of the prototype and the 2021 test-beam campaign concentrated on the proof-of-principle of the dual radiator imaging. The baseline dRICH prototype has been subsequently upgraded with a global and mirror alignment system, gas recovery system, a DAQ chain to achieve 1 ns time resolution, an acquisition system to tag the incoming particle type with beam instrumentation (Cherenkov-gas detectors). A second campaign in Fall '22 focused on the first assessment of the photon yield and angular resolution of the two radiators. The results indicate the photon yield (for both radiators) and the angular resolution for gas are in line with expectations, while the aerogel resolution is about 50% worse than expectations, see Fig. 1. This is not surprising, as the measurements are based on the first samples of aerogel at n=1.02 from Aerogel Factory, a material that did not underwent any optimization. These results were obtained with the reference photon-detection plane derived from CLAS12 RICH, and based on the H13700 multi-anode photomultiplier (MA-PMT) readout by MAROC3 chips. The prototype is now being upgraded with a new detector-box to mount the EIC-driven detector units based on H13361-3050 silicon photomultiplier arrays in conjunction with the ALCOR (version 2) chip. The imaging capability of these readout units will be measured during the Fall '23 test-beam at CERN (FY23 milestone 3). The new detector box will allow a preliminary study of the thermal gradients and possible effects on the gas performance. The present dRICH prototype structure is not compatible with EPIC, as uses standard massive stainless steel components, thick glass mirrors, and has a simplified geometry centered on the mirror optical axis. In FY24 a real-scale prototype will be realized with composite materials and a realistic geometry (part of a dRICH sector). This will serve to study the assembling details (e.g. of transparent septa), the mechanical stability, the gas tightness, but also to reproduce the final working conditions with realistic components. The prototype will be realized in order to mount the detector box in few relevant locations, and image the complete gas ring (or partial aerogel ring) off-axis, mimicking specific EPIC configurations, i.e. maximum, central or minimum rapidity, see Fig. 2. Funds are requested to support these upgrades (**20 k$**). Financial support from INFN is expected to cover part of the modifications but a contribution from EIC project is essential for the prototype evolution and test-beam organization.

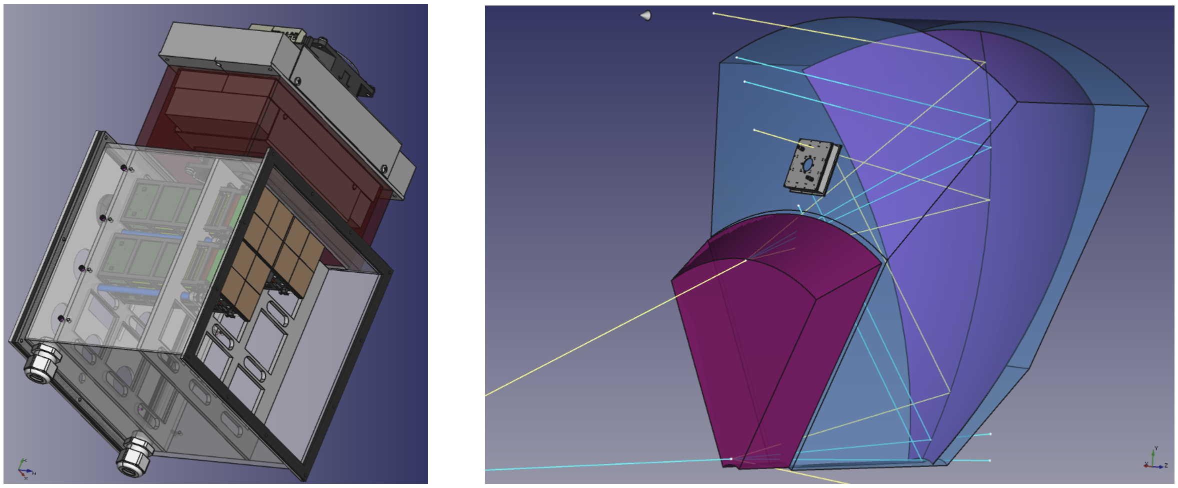

Figure 2: New detector box with EIC-driven readout units and cooling station (left). Concept of the real-scale dRICH prototype with outlined the charged particle and photon trajectories at the extreme $\eta = 1.5$ and $\eta = 3.5$ rapidity values (right).

Radiators: Aerogel Very few manufacturers of optical quality aerogel and even less offering large production capability are currently available. Russian aerogel, a basically handcrafted product, was widely used in the past as customization towards world-leading performance in transparency and size was possible, but is not accessible nowadays. In USA, ASPEN company has pursued SBIR development programs for optical aerogel reaching promising transparencies at low refractive index, but has lately dismissed this activity. An interesting development has been initiated at the Tsinghua University in China, that could offer future alternate production sites, but is still at an early stage. 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. Small samples were acquired from Aerogel Factory in collaboration with ALICE. The light transmission at the dRICH design refractive index (n=1.02) were preliminary measured at INFN, and compared with analogous measurement done at CERN at various refractive indexes (from n=1.005 to n=1.05). The planned laboratory characterization includes among others: defects (cracks, chips, clarity, cleanliness) by optical inspection, density ad refractive index by precise weighting, shape and planarity by coordinate measuring machines (CMM), transmittance and tranflencance by spectro-photometers, forward scattering by laser beam broadening, see Fig. 3. To this end, the existing laboratories at INFN are being refurnished and contacts have been activated to develop quality assurance test stations in US via the ePIC RICH Consortium. Promising preliminary results have been obtained with the dRICH prototype, despite the measured resolution appears to be about 50% worse than expectations. Dedicated R&D is required to optimize the optical performance, reach large dimensions (i.e. 20×20 cm^2) and limit the detrimental edge effects. The quality and mass production capability needs to be validated with laboratory characterization. Aerogel refractive index needs optimisation for photon yield, resolution and momentum coverage in conjunction with the gas radiator. It is assumed that the the EIC Project will continue to support a synergistic effort within ePIC, to pursue a customization program toward needs and performance optimization of the RICH detectors. INFN will contribute to the procurement of samples for the dRICH prototype and provide expertise and laboratory instrumentation for the optical characterization.

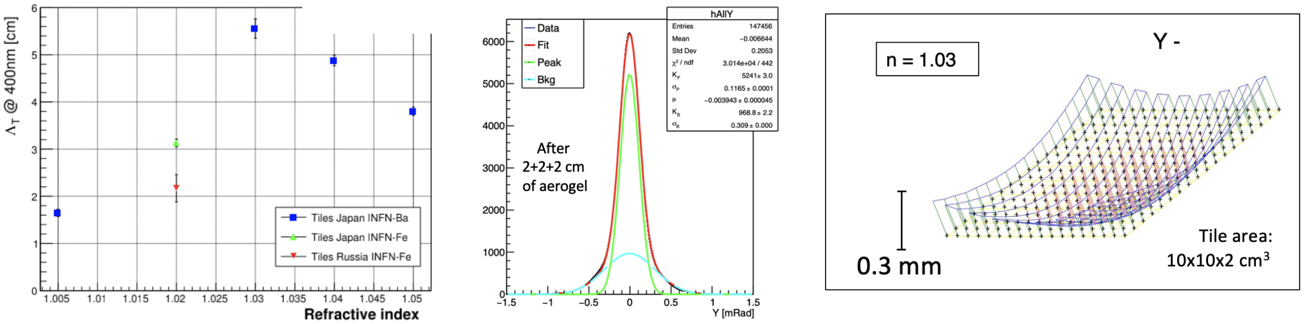

Figure 3: Transparency of Aerogel Factory samples as a function of the refractive index (left). Broadening of a collimated laser beam passing through the aerogel (secondary gaussian distribution), indicating possible inhomogenities (center). Planarity of the aerogel surfaces as measured by a CMM machine (right).

Radiators: Gas The C_2F_6 gas nominally features a refractive index that match well with the dRICH momentum range, and a superior chromaticity. However, the use of C_2F_6 in Cherenkov applications is less common than other fluorocarbon gases (like C_4F_{10}). Dedicated measurements of the absorption length (connected also to the impurity contamination level) of commercially available C_2F_6 are planned with existing instrumentation at CERN. The C_2F_6 is a greenhouse gas with high warming power. Alternative gas mixture are being studied (i.e. at CERN) to mitigate the environmental impact while preserving the optical quality. Funds are requested (**10 k\$**) to support the use and characterization of C_2F_6 and alternative gas mixtures, 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 window is 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 has been used to study the prototype optical performance. The septum material requires validation in term of light transmission, material budget and radiation tolerance. Small samples will be acquired in FY23 to support these initial studies. FY24 funds are requested (**5 k\$**) to realize the demonstrators (with the choosen material) to be used with the real-scale dRICH prototype and detector box. INFN will support the activity at CERN, but EIC funds will be instrumental to supply material and operate the prototype.

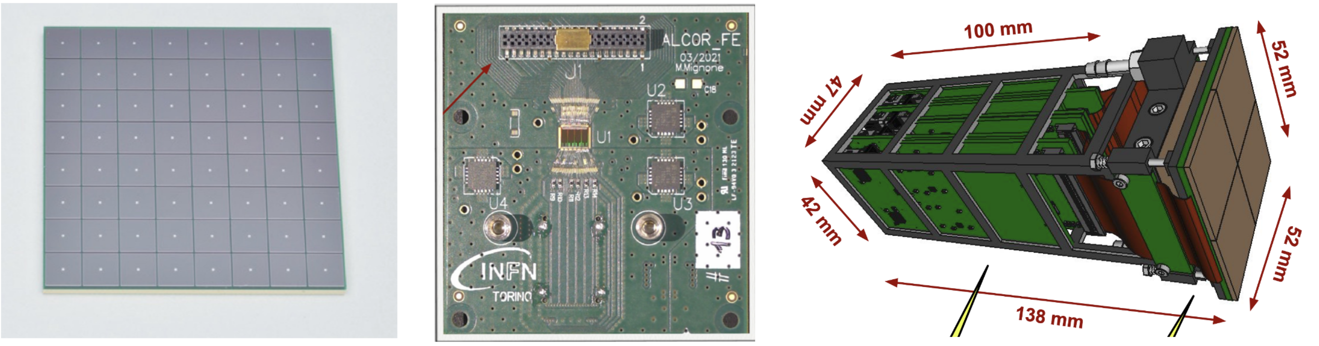

Figure 4: Baseline H13361 SiPM array (left). ALCOR chip (center). New EIC-driven photon detector unit under realization.

Photosensor and Electronics: The dRICH photosensor should preserve single-photon detection capability inside a strong and not-uniform magnetic field. The dRICH focusing system is designed to keep the detector in the shadow of the barrel calorimeter, in a volume with reduced requests in terms of material budget and with moderate radiation levels, making possible the usage of magnetic-field tolerant silicon photomultipliers (SiPMs). A milestone of the eRD102 activities has been the realisation of a prototype readout plane (with a medium-size area of 10 × 10 cm^2) driven by EIC-requirements. The plane should feature 3 mm pixelization, sub-nanosecond time resolution, high rate capability (up to 0.5 MHz per channel) and support streaming readout tests. The photosensor and radiation-hard SiPM programs (eRD110) in conjunction with the electronics/ASIC program (eRD109) have identified a baseline solution based on the Hamamatsu H13361-3050HS sensor array and the ALCORv2 (a ToT discriminating architecture) readout chip. Photon detection units, collecting 256 pixels in a 52 × 52 mm^2 area, are being developed for the FY23 test-beam campaign, see Fig. 4. The unit comprises a cool plate (with liquid cooling circuit to reach at least -30 Celsius) and circuitry for on-site annealing via Joule effect. The DAQ is still based on a custom developing kit. Beam tests utilising this new optical readout plane will be performed in October '23. It has to be noted that, while such instrumented surface allows one to record photons from a large fraction of the Cherenkov rings, it does not provide full coverage of the dRICH prototype emitted Cherenkov photons. We plan to complete the photosensor surface in FY24 to serve the real-scale prototype with full gas ring coverage, and implement the prototype RDO boards and the preliminary 64-channel version of ALCOR. Recent results indicate that a potential significant optimisation of the dRICH phototedector performance might come from the choice of SiPM with larger pixel pitch (75 μm) with respect to the sensors that equip the present detector prototype (50 μm). Such improvements impact the timing performance of the sensors coupled with the front-end electronics as well as the photon detection efficiency. Support is requested to purchase SiPM matrices to equip a further 10 × 10 cm^2 readout area (**20 k$**). The corresponding extension of the readout electronics and ASIC chips will be provided in-kind with INFN funds.

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 (CMA), in Tucson (AZ, USA), that offers wide experience (HERMES, AMS, LHCb, CLAS12) and continuous improvements. 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. CMA mirrors are made by two thin layers and a honeycomb core of carbon fiber reinforced polymer (CFRP), achieve an areal density lower than 5 kg/m^2 and a shaping accuracy better than 0.2 mrad. The mirror surface roughness depends on the quality of the mandrel and stringent specifications have to be imposed to obtain the

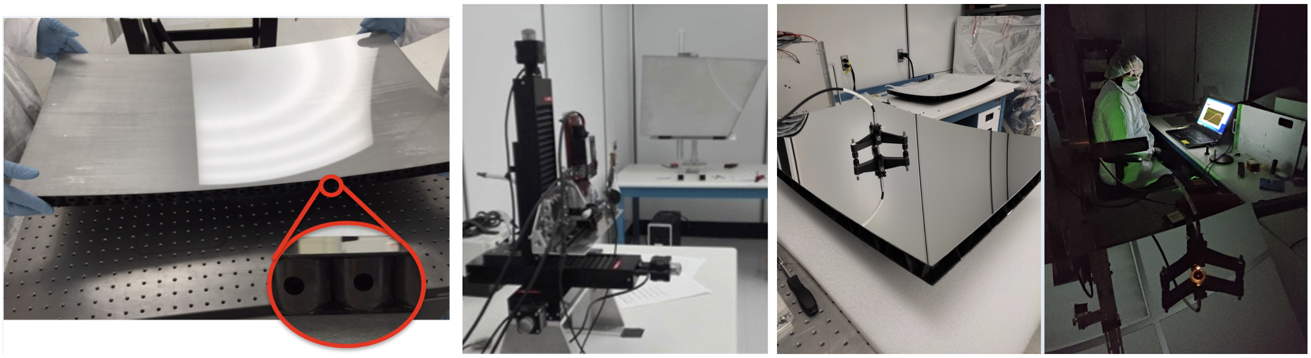

Figure 5: Carbon-fiber mirror with highlighted the core structure (left). Characterization station with Shack-Hartmann sensor and point-like image kit (center). Reflectivity measurement station with a portable spectrometer (left).

needed roughness of 1-2 nm r.m.s and the sub-mrad surface accuracy. CMA has recently developed innovative technology solutions for the mandrel and mirror core structure to reduce cost and increase flexibility (e.g. on dimensions). These need validation for EIC needs in comparison with more traditional approaches. 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. Evaporated Coating Inc (ECI), in Philadelphia (PA, USA), has demonstrated good capability in dealing with carbon fiber substrate. The potential use of a custom evaporating station, originally developed at INFN and now at Stony Brook University, is under evaluation. Most likely, a process of iterations with feedback from the dRICH team to the manufactures will be necessary to optimize the mirror and coating parameters. Contacts have been initiated with CMA to negotiate the production of mirror demonstrators. A characterization laboratory is being refurnished at Jefferson Lab in collaboration with Duke University, see Fig. 5. After training during R&D phase, it is planned to transfer part of the instrumentation to a Duke University laboratory for creating a long-term mirror quality assurance facility. The planned characterization includes among others: defects (voids, scratches, chips) by visual inspection, shape and dimensions by coordinate measuring machines, optical aberrations by Shack-Hartmann sensor, surface accuracy by point-like source image, reflectivity by portable spectrometer. To pursue these targeted R&D on mirrors, and the realisation of a demonstrator for the real-scale prototype (with a minimal support structure), dedicated funds are required (**25 k$**). INFN will contribute to part of the costs and with the expertise and instrumentation (already present at Jefferson Lab and movable to Duke) for the optical characterization.

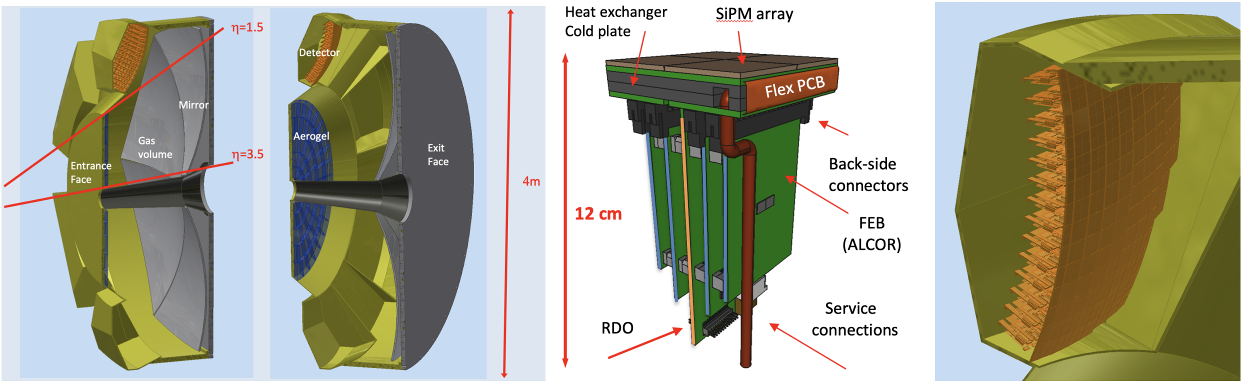

Figure 6: dRICH 3D mechanical model (left). Details of the dRICH photon detection unit (center). dRICH readout plane shaped to best match the mirror focalization surface (right).

Mechanics: The dRICH structure is divided in three main pieces. The aerogel volume, the gas volume and the photosensor boxes. Composite materials allow to develop large structures with excellent properties of lightness and stiffness. While working at atmospheric pressure, the dRICH vessel could be realized by a skeleton of light carbon fiber (CFRP) ribs connected by laminated planes. To minimize the material budget in the ePIC forward acceptance, it is assumed to use skin-core-skin sandwiches for the entrance and exit faces (order of 1% of radiation length), and a possible bulk structure for the inner tube and external cylindrical shell (order of 4% of radiation length), see Fig. 6. All these structures are being designed to comply with ePIC detectors requirements. Aerogel requires a minimal support structure, assumed to mimic the BELLE-II solution, and an insulation window. Mirrors require a support with an integrated alignment system. The detector boxes, being outside acceptance, could be relatively massive to provide support for sensor, electronics, integrate services and cooling. A transparent window is required to separate the gas volume from the sensor and electronics volume. A conceptual compact readout unit has been outlined to support the curved detection surface, and fit the limited available space at ePIC.

Fluorocarbon gases are ideal radiators because of the high refractive index and low chromatic dispersion in the visible range, resulting in high accuracy. The quantity of C_2F_6 estimated for a 10 years service of dRICH is nowadays available at more than one gas distributor. 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 gases 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. An engineering study of a possible over-pressurized vessel has been initiated at INFN that foreseen a first prototype of simple geometry (cylinder) to test promising materials, like CRFP or Al composites, and to verify corresponding FEM analyses. In case of promising indications, a second prototype with realistic geometry is foreseen in FY24.

The design activity requires a close collaboration between INFN with BNL and JLab engineers to comply with the safety regulations and EPIC installation and integration aspects. Related hardware costs are outlined in the previous sections. INFN technical workforce is an in-kind contribution but US technical support is requested from the EIC project.

Simulation and Integration: The dRICH optics should be adapted to the limited space available at EPIC, compromising on the need of long charge particle paths in the gas (for photon yield), and proper focalization. Motivated by the PID review, a general revision of the dRICH simulation package have been pursued. A baseline optimization of the dRICH geometry within ePIC has been completed taking into account the minimization of mechanical interference with other subsystems. Realistic models of the components have been implemented, see Fig. 7 taking into account the measurements done during laboratory characterization and beam-test campaigns. Simplified models of the passive elements have been introduced to mimic the material budget. It should be noted that new developments are not immediately available for users and official ePIC production campaigns, because they need to be reviewed and formally approved by the software group to ensure ePIC standards. In the next months the dRICH team will cooperate with the ePIC software group to release these updates. The simulations will necessarily evolve following the developments of the dRICH mechanics and the prototype results. New developments will be required to implement the transparent septa, to segment the mirror and re-tune the relative focalization, to study the interplay with EPIC tracking, timing and PID integrated systems. This effort is possible thanks to dedicated manpower at Duke and INFN which will require continued co-funded support to ensure further refinements and updates of the simulation could be completed.

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

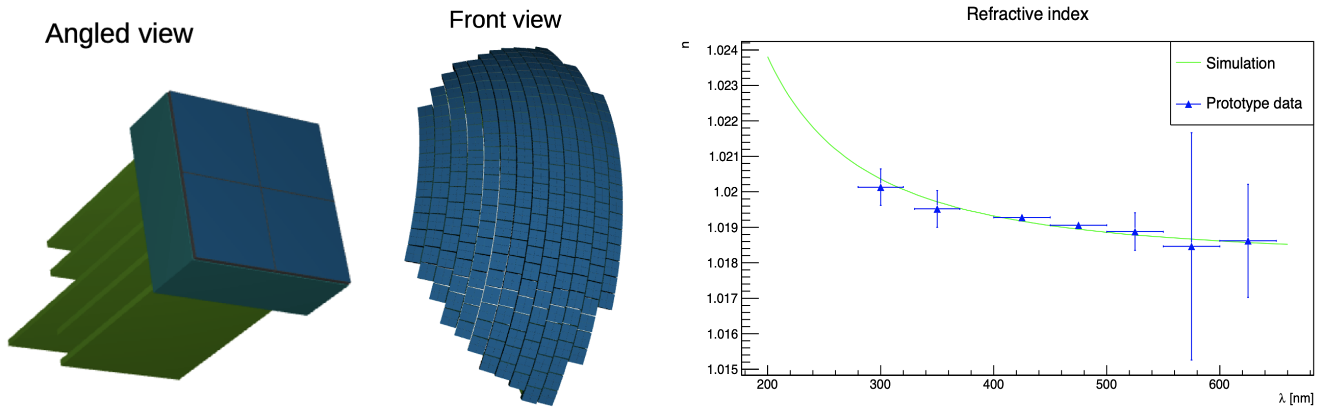

Figure 7: Details of the photon detection unit and readout plane implemented in the dRICH simulations (left). Chromatic dependence in input to the dRICH simulation (green curve) compared to measurements (blu points) done with the dRICH prototype on aerogel samples from Aerogel Factory (right).

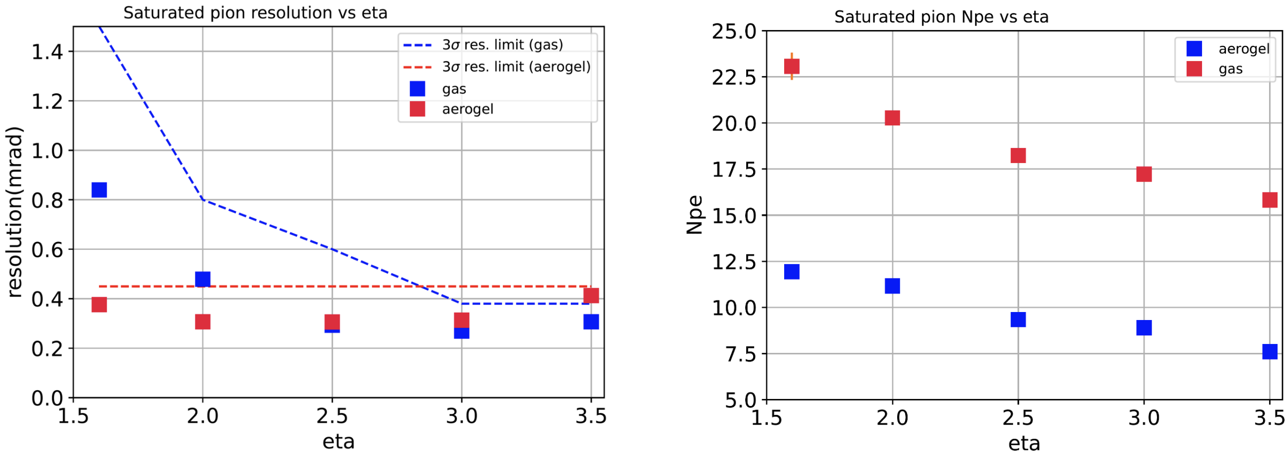

Figure 8: Preliminary simulation results for dRICH as configured within EPIC: angular resolution resulting better than the 3σ separation limit (left), and number of expected photons (right) as a function of rapidity, for each of the two radiators.

manpower direclty involved into 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 (pfRICH), in particular the simulations, the aerogel and mirror characterization and developments, the structural analysis. 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 one half technologist position are requested in FY24 for a total of (**105 k$**).

Milestones: Preliminary definition of the technical specifications of all the dRICH components (April '24); Complete mechanical design of the dRICH structure (June '24); Integration of the readout and optical component developments in a real-scale prototype (October '24). The estimated timeline is assumed to concatenate with the FY23 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 with DARKSIDE and aerogel with ALICE), tehcnical and scientific manpower plus about a 80 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. Continued financial support from the EIC project R&D program of the dRICH post-doc and their work on software as well as on hardware is crucial. The proposed funding profile is outlined in Table 1. FY25 is indicated as contingency, as it is anticipated that the engineering activity on radiators, mirrors and readout with integrated cooling, may continue beyond FY24 for further optimization and risk mitigation. The proposed FY24 funding per Institution is listed in Table 2.

The Duke request corresponds to 0.5 FTE for a PD which will be split between the simulation effort and the development of the mirror testing protocol. On the simulation side, this is to address some open tasks as well as to refine the simulations and adapt to demands from the detector integration. Examples of open tasks are the evaluation of performance for given physics channels and the implementation of advanced reconstruction algorithms. The mirror testing protocol to be developed at Duke University will be based on the experiences from the mirror test of the CLAS12 RICH, but would need to take into account the unique requirements of the ePIC dRICH. It is planned to reuse a large part of the instrumentation available at JLab and other institutions, and leverage synergies with the pfRICH as well as SoLID activities. Additional funds are requested for travel and to cover the cost of shipping and of minor materials to build up the mirror test stand. As currently programmatic funding for US universities are very limited, a substantial support from R&D funds is necessary to realise the program above.

The INFN request corresponds to 0.5 FTE for a post-doc and 0.5 FTE for a technologist, to continue the hardware developments ongoing in EU as described above, and their integration in a real-scale prototype. Dedicated manpower will be crucial for the laboratory characterization of components, the analysis of the test-beam data, and the update of the dRICH and prototype simulation model. Technical manpower will be essential in all of the hardware activities, in particular in the development of the dRICH prototype and preparation of the test-beam campaigns. Travel funds are requested to support the beam-tests at the CERN facility and collaboration with Duke on the mirror activity.

It is planned to redirect efforts of locally co-funded personnel, such that the employment of the early career scientist is not necessarily dependent on the future continuation of the R&D funds.

	prototype	aerogel	gas	mirror	photodetector	personnel	travel	total
FY24	20		15	25	20	105	10	195
FY25*			10		20	80	10	120

Table 1: Proposed EIC project funding profile in k$. The anticipated 80 k$/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	aerogel	gas	mirror	photodetector	personnel	travel	total
INFN	20		15	20	20	60	5	140
DUKE				5		45	5	55

Table 2: Proposed FY24 project funding per Institution in k\$. The anticipated 80 k\$ budget from INFN and personnel co-funding in-kind contribution is in addition.