Preventivi EIC-NET/FE-RM1-LNF-CT

Since 2015, INFN researchers, are members of the EIC eRD14 consortium, devoted to the research and development of the particle identification systems for EIC.

Roma1 group, active since 2015, is responsible of the R&D of the hadron identification detector on the outgoing ion end-cup of the JLEIC spectrometer, the JLab version of the EIC spectrometer. In order to satisfy the physics requirements (essentially whole momentum range hadron identification), the Roma1 group has defined and proposed a dual-radiator Ring Imaging Cherenkov (dRICH).

Ferrara group, active since 2016, is co-responsible of the modular RICH (mRICH) designed for the electron ion-cap of the JLEIC spectrometer but flexible enough to be compatible with other detector layouts, and the development of a readout electronics common to the consortium applications.

Frascati group joined in preparation of the mRICH test-beam at Fermilab of the second prototype, done between June and July 2018.

Catania group joined the dRICH hardware activity for the realization of a prototype.

Within the EIC-NET, the INFN groups intend to continue the R&D on the dRICH, mRICH and electronics in a collaborative and synergic effort. The common priority is the realization of a dRICH prototype to validate the proposed design, to join the test-beam campaign of the mRICH project sharing experience and instrumentation, and allowing a parallel development of the sensors and electronics.

The dual-radiator RICH

The dRICH detector has been designed to provide continuous full hadron identification ($\pi/K/p$, better than 3 sigma apart) from ~3 GeV/c to ~60 GeV/c and, electron identification (e/π) up to about 15 GeV/c, on the (outgoing) ion-side endcap of the EIC detector, covering angles up to 25°. Achieving this momentum coverage on the ion-side is a key requirement for the EIC physics program. The dRICH has the unique ability to provide continuous PID coverage (in RICH mode) over this full momentum range.

After the evaluation of various alternative designs, the group has defined a “realistic” baseline configuration for this detector that consists of two radiators (aerogel and gas) that share the same outward focusing mirror and, of highly segmented (~3 mm^2 pixel size) photosensors. In such configuration the focal plane sits away from the beam and ensures that the UV photons radiated in the gas go directly to the photosensors. In order to reduce the effect of aberrations caused by the spherical mirror, the photosensor surface has been optimized and designed to be a curved surface as shown in Fig. 1.

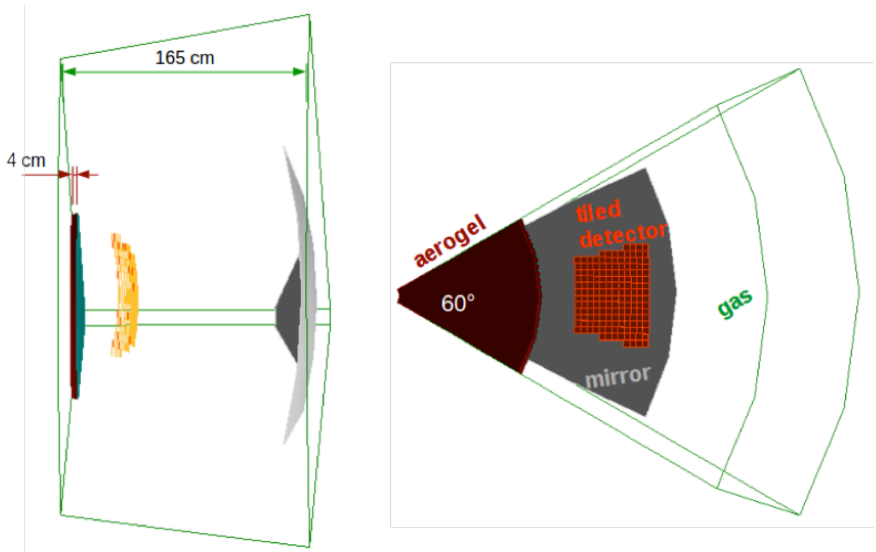

Figure 1: A single dRICH sector with slightly curved optical sensor detector surface. **Left:** side view of aerogel (dark red), mirror (light grey) and sensors (yellow); indicated are the aerogel thickness and the gas gap. **Right:** front view of aerogel (dark red), mirror (light grey) and sensors (light red).

The baseline design performance has been investigated and optimized with a realistic Geant4/GEMC model and related simulation, tuned with the up-to-date data from literature or recent measurements. Simulations have been analyzed by ad-hoc tools, including a track-based algorithm, which was extended more recently to an event-based Cherenkov-angle reconstruction to properly handle events with multiplicity larger than one.

Every detector consists of a significant number of components, and questions like how much space to allocate for each, what kind of detector to use, and which configuration allows the best PID/reconstruction, are often real dilemmas that need to be resolved without increasing costs. Learning algorithms (e.g., AI-based) can be extremely useful in making faster and more efficient decisions. Bayesian Optimizers (BO) [Jon18, Sno12] are particularly suitable for optimizing the EIC detector design and can be deployed for a variety of critical R&D efforts over the next years.

We have explored BO in the optimization of the design of the dual-RICH. In a preliminary work six main parameters were considered to model the design (radial and longitudinal positions of mirror center, mirror radius, along with vertical and longitudinal positions and rotation of detector tiles withrespect to the mirror center), see Fig. 2.

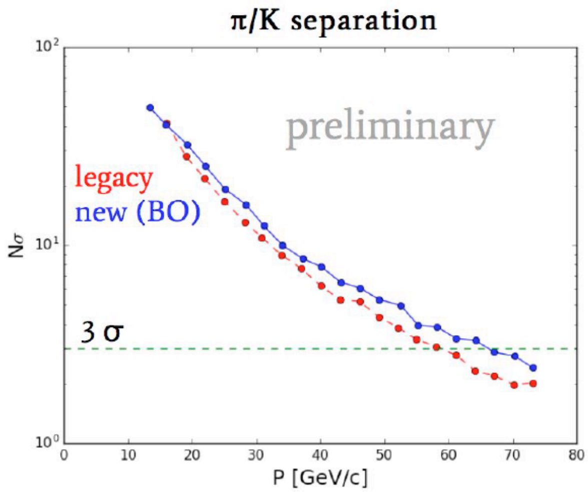

Figure 2: Comparison between the baseline and a new design for the dRICH based on bayesian optimization. The new design shows (in the gas region) an improved separation between pions and kaons of at least 3σ up to large momenta (~60 GeV/ c).

A new event-based Cherenkov angle reconstruction method was introduced in 2018 to properly treat events with multiplicity larger than 1. The method essentially consists of two main steps: a single hit (detected photon) association followed by a global hypothesis (particle-types/tracks-radiators) selection based on the previous association. Each step is based on the optimization of a specific likelihood function that accounts for the angular correlation (the angle is estimated by the Inverse Ray-Tracing method) and the number of detected photons. The performances have been evaluated using deep-inelastic PYTHIA generated physics events, about 40% of which have multiple tracks and 50% of those have overlapping rings in dRICH at EIC energies. The method has been refined and critically analyzed in the second half of 2018 and first half of 2019, especially in terms of the first-step likelihood function composition see Fig. 3.

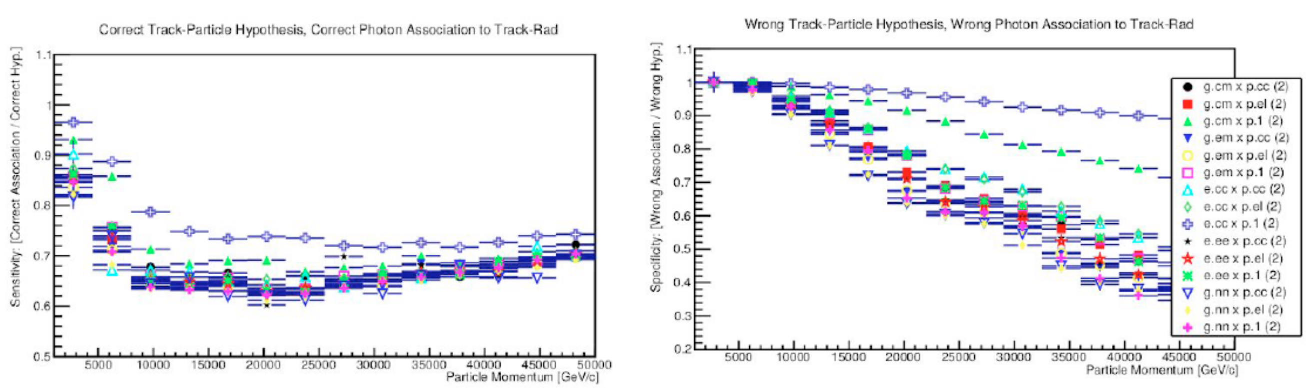

Figure 3: Analysis of the likelihood function composition used for hit association. The different points correspond to different likelihood compositions (shown in the legend). All plots show the success or failure rates as a function of particle momentum. The left and right plots show the rate of success and failure respectively for the correct and wrong particle hypotheses: they should be as large as possible.

Detector prototype

The design of the dRICH has several critical aspects that need to be experimentally investigated: in fact, the performances of the dRICH largely depend on the effective number of Cherenkov photons produced in both radiators, as well as on the quality of the aerogel in terms of chromatic dependence of the refractive index; moreover, the impact of scintillation photons in "Freon" gases needs to be evaluated. All these aspects can only be addressed in a realistic prototype. For this reason a small scale prototype is under development. The design of the prototype is driven by the following main requirements.

1. Reasonable number (order of 10) of photoelectrons for the gas ring per particle; this number depends almost linearly on the thickness (length) of the gas and therefore of the vessel.

2. Catch both the aerogel ring (with a cone aperture of 11^o) and the gas ring (with a cone aperture of 2.2^o) in order to be able to estimate the angular resolution; this constraints the minimum transverse and longitudinal sizes of the vessel.

3. Compatibility with different photosensor solutions, starting with the ones already available within the eRD14 Consortium (EIC R&D), e.g., four H13700 multianode PMTs (5x5 cm^2 each) or three S12642-1616PA matrices of 3x3 mm^2 area SiPMs, and related electronics.

4. Isolation of aerogel and optical sensors from "Freon" gases.

6. Possibility to reuse a 1-m long cylinder from the Stony Brook RICH (Klaus Dehmelt).

7. Minimization of the vessel volume (to minimize the consumption of the expensive gas).

A consolidated design of the dRICH prototype is shown in Fig. 4.

The dRICH prototype design is being developed taking into account the following goals: mimic the properties and performance of the proposed dRICH components, and/or permit to derive them in a direct way; be cost effective (trade-off of small scale, flexibility and measurable quantities); be flexible enough to allow the use and test of different detector and components solutions.

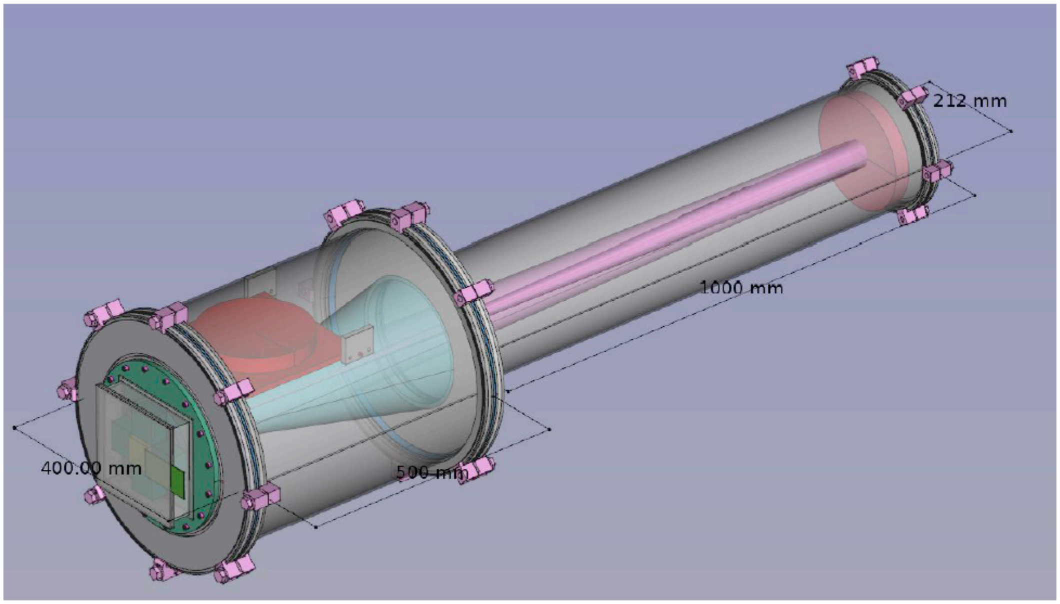

Figure 4: Consolidated 3D drawing of the dRICH prototype: the sensors (cyan) and aerogel (yellow) radiator are on the left, mounted onto the entrance flange (green) inside a dark box. The small gas mirror (red) is on the far right end. An insertable aerogel mirror (red) may intercept the aerogel photons and reflect them back to the PMTs.

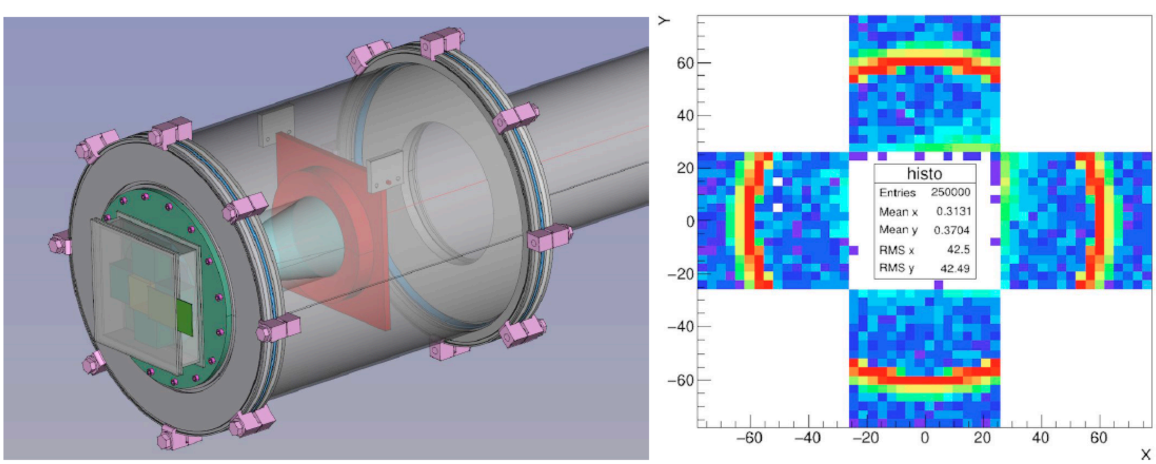

Figure 5: (Left) Detail of the dRICH prototype in the aerogel ring configuration. (Right) Simulated Cherenkov ring generated by the aerogel (on a log scale). The prototype is designed to image either the aerogel or gas Cherenkov ring at the center of the sensor array.

The prototype vessel is divided into two sections to minimize the dimensions while accommodating the different Cherenkov paths. The entrance flange houses a UV-transparent lucite foil (or quartz window) to isolate the inner gas volume while allowing the passage of the Cherenkov light. On its outer face, screw holes allow the insertion of a dark box with various sensors and an aerogel tile with possible additional UV filters. The focal planes of the mirrors coincide with the sensor entrance surface (a radius of 3 m and 0.6 m is adopted for gas and aerogel, respectively). Either the aerogel or gas Cherenkov photons are imaged at the center of the sensor array, depending on the position of the central rotatable mirror. The performance of each single radiator can be studied in detail and without interference, thus, optimizing the usage of the limited instrumented area. The elements of the vessel are made of vacuum standards, to contain the cost and allow an efficient and safe gas exchange. A cap can be mounted on the entrance face with a bypass connecting the inner volume, to prevent pressure stress on the lucite foil during gas exhaust and exchange.

The sensor dark box and covered area follows the mRICH design and accounts for the available 5x5 cm^2 sensors already successfully employed at test beams, but can also support other detector choices. The present configuration of the sensors guarantees the best coverage of the gas ring (radius of approx. 6 cm). The photo-sensor pixel size of 3 mm will keep the angular digitization (or pixel) error comparable to the other errors, allowing for the assessment of the intrinsic sources of uncertainties of the various radiators, and will reduce multiple photoelectrons in a single pixel for the gas ring (which will help to more accurately estimate the number of Cherenkov photons).

The proposed prototype configuration has been modeled and simulated in GEMC/Geant4. An example of a simulated configuration is shown in Fig. 5. The prototype allows the study of the Cherenkov resolution as a function of the optical properties of the components. The prototype shall confirm and validate the dual radiator approach to cover the momentum range of few GeV/ c – multi tens of GeV/ c. Moreover, the radiator performance will be studied in terms of number of photons as well as angular uncertainties, possibly for different aerogel thicknesses, gas types, and wavelength filters between solid and gas radiators (depending on aerogel availability). The chromatic dispersion of the aerogel, the expected dominant error in EIC configuration, can be studied with the insertion of optical filters, a method successfully employed in the past [Per16]. Of particular interest is the study with a meson beam at momenta intermediate between the two radiators working ranges.

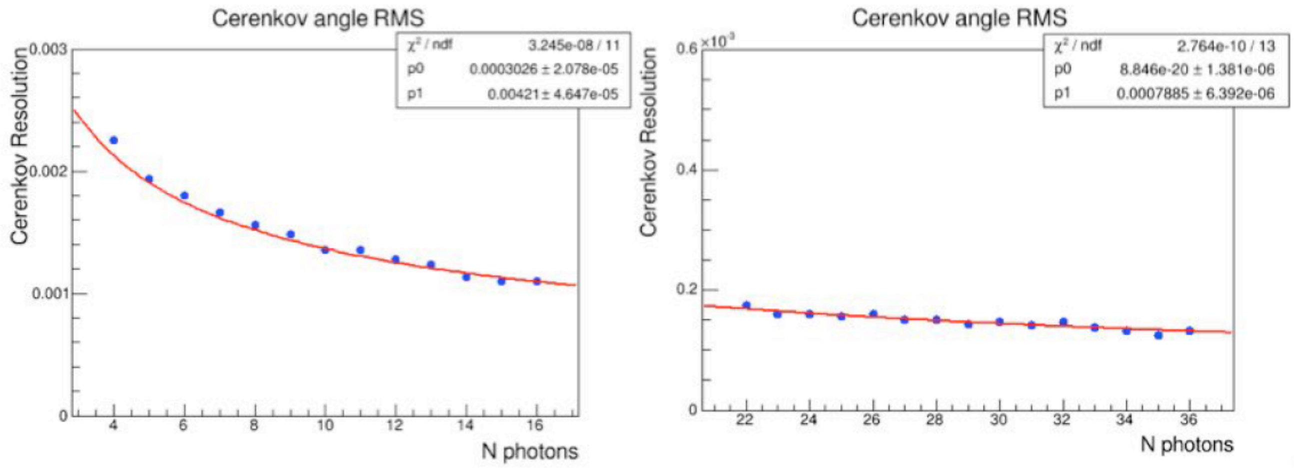

Figure 6: The expected performance of the dRICH prototype: Cherenkov angle resolution as a function of the number of detected photons for aerogel (left) and $C_2 F_6$ gas (right) for UV sensitive H13700.

The expected number of detected photons is 9.4 for the aerogel and 27.9 for the gas. The resolutions are summarized in Table 1. The uncertainties are similar to the ones expected in the EIC configuration, except for the pixel error with the aerogel radiator that, despite being larger due to the adapted imaging (reduced path of photons), is still smaller than the chromatic error and can be safely controlled by simulations.

1 p.e. Error (mrad)	Aerogel	C_2F_6 Gas
Chromatic error	3.2	0.51
Emission	0.5	0.5
Pixel	2.5	0.42

Table 1: Main sources of uncertainty of the single-photon Cherenkov angle measurement with the dRICH prototype.

Proposed activities

Recently a proposal, within the eRD14 Consortium for particle ID at EIC, has been submitted to the DOE funding program for Fiscal Year 2020 to carry on the prototyping activity. The goal is the development of a small scale, flexible, prototype that can host: aerogel, gas, mirror and either a matrix of SiPM or possibly other photon detector candidates (included the ones suitable for the only gas option like GEM).

The eRD14 founding request basically concern manpower that should be complemented be the INFN funding of essential material and people mobility.

Thanks to the synergies with external initiatives (such as CLAS12) or other eRD14 activities (mRICH and electronics) and the consequent possibility to borrow necessary materials (*i.e.*, front-end electronics and DAQ), the dRICH prototyping activity can test key concepts and components at a reasonable cost.

The modular RICH

The mRICH concept uses Fresnel lens to focalize the ring and limit the gas gap to about 20 cm. The modular design allows to reduce the active area and cover complicated geometries.

It is designed to provide hadron identification up to 10 GeV/c at JLEIC. A proof-of-principle has been obtained with a photo-sensor with 6 mm pixel. A second test beam in 2018 tested sensors with the design pixel size of 3 mm, to initiate a realistic study of the resolution.

The readout was derived from the CLAS12 RICH system, based on the VSX/SSP protocol and optical fiber connections.

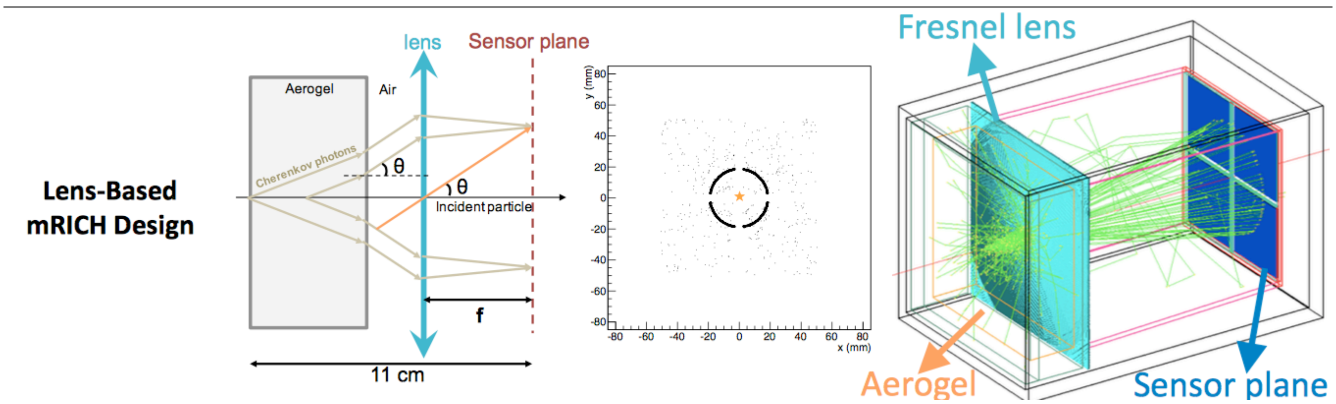

Figure 7: The mRICH concept is based on the Fresnel lens focalization of the Cherenkvo light on the detector plane.

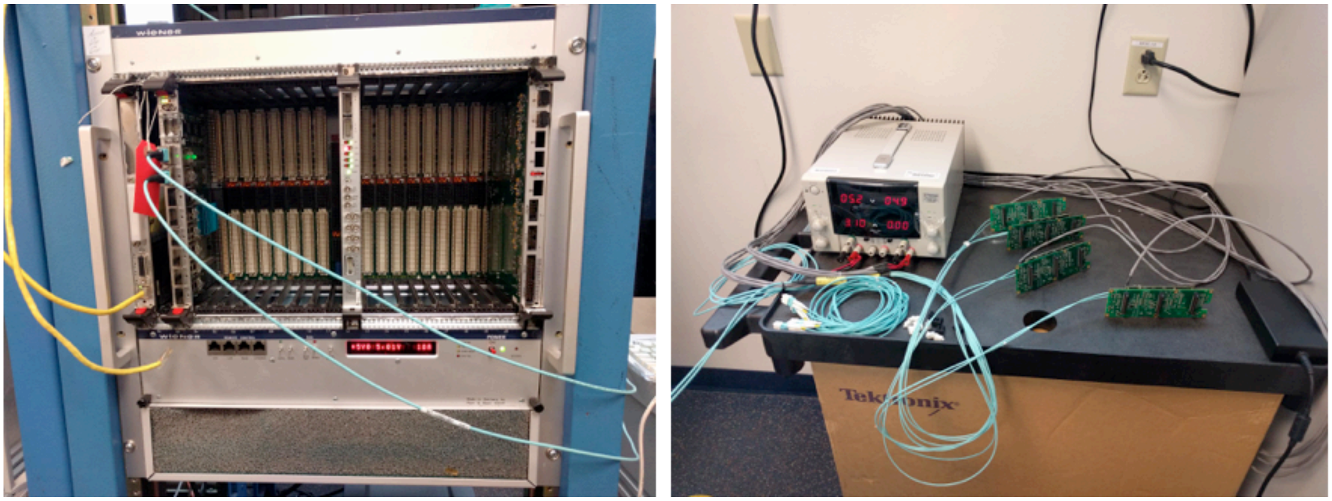

Figure 8: The readout system based on the VSX crate + SSP board (back-end) and the FPGA + MAROC3 boards (front-end) borrowed from CALS12 used for mRICH.

Funding request

The requests concentrate on the realization of a dRICH prorotype, able to exploit the development of new sensor and electronics solutions in parallel with the other consortium projects and to validate the dual radiator concept. The requests are centralized to try to maximize the efficiency and synergy of the dRICH, mRICH and electronics developments within the INFN EIC-NET program.

The 2020 funds are supposed to complete the needs for the realization of the dRICH prototype in conjunction with the funds obtained in 2019.

Roma-1: gas and aerogel for the dRICH prorotype (2 keuro). Freon gas resulted more expensive than expected due to the minimal quantity requirement. A bottle costs around 3000 euro.

Catania: mechanics of the dRICH prototype (4 keuro). In addition to the basic vessel partially funded last year, enclosing flanges have to be machined to house the feed-throughs and a separation window between gas and aerogel. A dark box should be realized to house the sensors and allow cooling.

Ferrara: SiPM readout electronics (2 keuro). The existing readout electronics should be adapted to the dRICH sensor layout.

Frascati: mirrors and supports (4 keuro) Commercial glass mirror cost scales with the diameter and is around 1000 euro each. The supports should allow a mirror alignment system.

References

[Jon18] D.R. Jones et al.,. "Efficient global optimization of expensive black-box functions." J Global Optim 13.4 (1998), 455-492.

[Sno12] J. Snoek et al., R. P. (2012). “Practical bayesian optimization of machine learning algorithms”. In NeurIPS (pp. 2951-2959).

[Per16] S.A. Pereira et al, Eur. Phys. J. A (2016) 52: 23.