

RPC-based Muon Identification System for the neutrino detector of the SHiP experiment

R. Albanese,^{b,j} A. Alexandrov,^b S. Buontempo,^b K.-Y. Choi,^g L. Congedo,^{a,i,*}
R. de Asmundis,^b G. De Lellis,^{b,j} M. de Magistris,^{b,m} G. De Robertis,^a M. De Serio,^{a,i,*}
F. Debernardis,^{a,i} A. Di Crescenzo,^{b,h,j} R.A. Fini,^a R. Fresa,^{b,l} G. Galati,^{a,i} A. Golovatiuk,^{b,j}
E. van Herwijnen,^h G. Iaselli,^{a,i} A. Iuliano,^{b,j} Y. Jo,^f M. Kang,^f Y.G. Kim,^d S.H. Kim,^c
J.-W. Ko,^c A. Lauria,^{b,j} K.S. Lee,^f K.Y. Lee,^c V.P. Loschiavo,^{b,k} A. Miano,^{b,j} M.C. Montesi,^{b,j}
B.D. Park,^c A. Pastore,^a A. Prota,^{b,j} A. Quercia,^{b,j} T. Ruf,^h S. Simone,^{a,i} J.Y. Sohn,^c
V. Tioukov,^b C. Visone,^{b,j} J.-K. Woo^e and C.S. Yoon^c

^aSezione INFN di Bari, Bari, Italy

^bSezione INFN di Napoli, Napoli, Italy

^cPhysics Education Department & RINS, Gyeongsang National University, Jinju, Korea

^dGwangju National University of Education, Gwangju, Korea

^eJeju National University, Jeju, Korea

^fKorea University, Seoul, Korea

^gSungkyunkwan University, Suwon-si, Gyeong Gi-do, Korea

^hEuropean Organization for Nuclear Research (CERN), Geneva, Switzerland

ⁱUniversità di Bari, Bari, Italy

^jUniversità di Napoli "Federico II", Napoli, Italy

^kConsorzio CREATE, Napoli, Italy

^lUniversità della Basilicata, Potenza, Italy

^mUniversità di Napoli Parthenope, Napoli, Italy

E-mail: liliana.congedo@ba.infn.it, Marilisa.Deserio@ba.infn.it

ABSTRACT: The SHiP experiment has been proposed at CERN to shed light on phenomena still unexplained in the framework of the Standard Model, such as the nature of dark matter, the baryonic asymmetry of the Universe and the neutrino oscillations, searching for hints of New Physics. A section of the detector will be dedicated to the study of neutrino physics with special emphasis on tau neutrino properties, still very poorly measured. A system to identify the muons produced in neutrino interactions, based on RPC technology, has been proposed and it is presented in detail in this paper.

KEYWORDS: Particle tracking detectors (Gaseous detectors); Resistive-plate chambers; Front-end electronics for detector readout

*Corresponding author.

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1 Introduction

The Search for Hidden Particles (SHiP) experiment [1–3] at CERN has been proposed to investigate the existence of light, very weakly interacting (*hidden*) particles [4], postulated by several theoretical models in the framework of searches for Physics beyond the Standard Model. The experiment has been conceived to operate in beam-dump mode at the Beam Dump Facility (BDF [5]) under study in the CERN SPS North Area. The experimental setup is shown in figure 1. A beam of 400 GeV/c protons with a slow extraction of 1s spills impinges on a compact, dense target, followed by a hadron absorber and a magnetised muon shield [6], deflecting in the horizontal direction the muons produced at the beam dump in order to reduce their flux [7] in the detector acceptance.

The layout includes two complementary detectors: the upstream Scattering and Neutrino Detector (SND) and the downstream Hidden Sector Decay Spectrometer (HSDS).

The SND has been designed to study neutrino physics and neutrino-induced charm production with unprecedented statistics [8] as well as to search for light dark matter candidates [9]. It consists of a 7 m-long hybrid detector located in a magnetic field, followed by a Muon Identification System, based on Resistive Plate Chamber (RPC) technology. The magnetic field of about 1.2 T is provided by a dipole magnet [10] with a characteristic hourglass shape specifically designed to reduce the residual muon flux halo impinging on the magnet structure.

The hybrid detector consists of a target region and a downstream tracker. The target region has a modular structure. Walls of Emulsion Cloud Chambers, that allow reconstructing neutrino interactions and short-lived particle decays with sub-micrometric resolution, are alternated with SciFi Tracker planes that assign a time stamp to the interactions occurring in the target in the spill window of 1s. The downstream tracker, consisting of three SciFi tracker planes separated by air, contributes to the measurement of the charge and momentum of particles exiting from the target region and to connect the tracks reconstructed inside the neutrino target with those crossing the Muon Identification System.

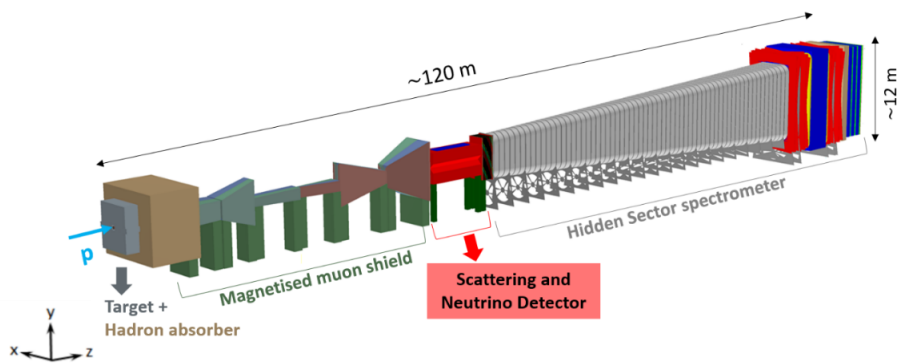


Figure 1. Layout of the BDF and the SHiP detector.

The SND Muon Identification System has the crucial task to detect and reconstruct with high efficiency the muons produced in neutrino interactions and in short-lived particle decays occurred in the emulsion target. Three additional multi-gap RPC planes act as an upstream veto for the HSDS. Their time resolution of the order of 100ps helps rejecting the combinatorial background due to neutrino interactions and muon inelastic scattering producing tracks not correlated in time to the hidden particles.

The HSDS is designed to detect hidden sector particles with masses $O(\text{GeV}/c^2)$, such as Heavy Neutral Leptons and dark photons, which would be copiously produced in the decays of charmed and beauty hadrons. Visible decays of such feebly interacting particles occurring in a 50 m long vessel kept under vacuum, located immediately downstream of the SND, are reconstructed by a large spectrometer, composed of a Straw Tracker, a Timing Detector providing a resolution of about 100 ps and a PID system. In order to keep the background below 0.1 events at 90% C.L. in five years of operation at nominal intensity, corresponding to 2×10^{20} protons on target, the entire decay volume is surrounded by a Background Tagger.

In this paper the SND Muon Identification System is presented and studied in detail: its design is described in section 2; the tests and performance of RPC prototypes operated with standard gas mixture are shown in section 3; results of the current R&D activity on new eco-friendly gas mixtures for SHiP RPCs are summarised in section 4.

2 The SND Muon Identification System

2.1 Muon system layout

The layout of the SND Muon Identification System is shown in figure 2. It is 4.3 m high (y), 2.9 m wide (x) and 1.6 m long (z) and consists of eight tracking planes based on single-gap RPCs interleaved with iron walls, acting as hadron filters. The dimensions of the Muon System and the hourglass shape of each iron wall, similar to that of the upstream dipole magnet, are studied to minimize the area exposed to the residual muon flux from the beam dump; as shown in figure 3, the distribution of such residual muons impinging on the most upstream detector plane is mainly concentrated in two lateral regions.

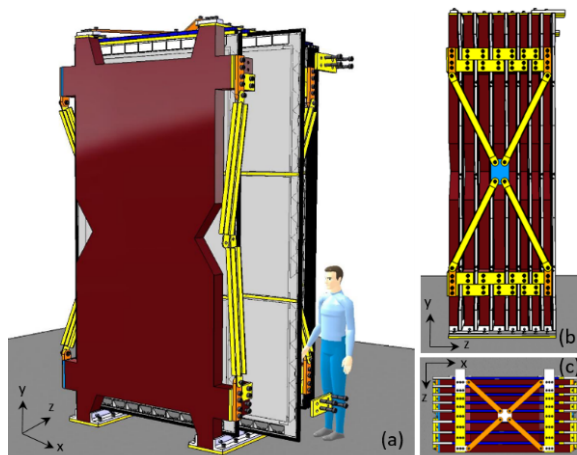


Figure 2. Layout of the SND Muon Identification System and its support structure: tridimensional view (a), lateral view (b) and top view (c).

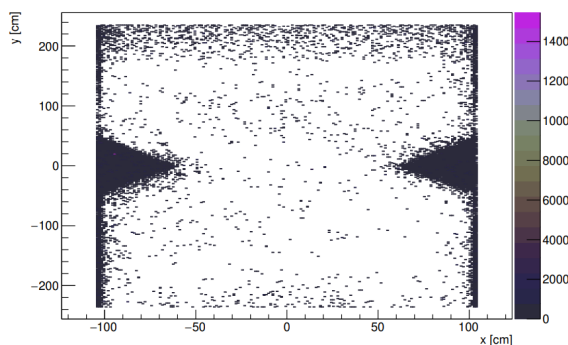


Figure 3. Expected number of charged particles impinging on the most upstream RPC plane in one spill.

The thickness of the iron planes (15 cm for the four most upstream walls, 10 cm for the others) has been optimized by means of Monte Carlo simulation studies in order to minimize the amount of material and thus the possible background for Hidden Sector searches due to interactions occurring in the iron slabs.

The detailed simulation [11] used a specific neutrino event generator, GENIE [12], along with GEANT4 [13]. Neutrino interactions are generated according to the momentum distribution of neutrinos produced at the beam dump and set in SND according to material density along the neutrino flight direction; finally, the produced particles are propagated in the whole detector.

The distributions of momentum and polar angle of the muons coming from the neutrino interactions in the SND target are shown in figure 4. The muons with low momentum and large angle are deviated from the SND magnet, thus they do not reach the Muon system.

Several criteria have been studied in order to optimize the muon identification. In the current analysis (figure 4), muons are required to be detected by at least three RPC planes with at most one station without hits between them. A detection efficiency as high as 97% is obtained normalizing the number of detected muons to those impinging on the first active plane assuming fully efficient RPC planes.

The RPC planes and the iron walls are supported by a custom mechanical structure. In order to withstand gravity and seismic loads, the iron walls are tied in the top and in the bottom of the structure (x - z plane) as well as on the sides (y - z plane) through a system of braces, transmitting seismic actions to the ground. Each system consists of U-shaped coupled steel profiles, interlocked to the structure both at the center of each section and on its sides. The brace system on the y - z section of the structure can be unmounted, allowing for the lateral extraction of the RPC planes.

In order to keep detector planes vertical and avoid bending problems, the tracking planes are hanging from the top of the support structure.

Figure 5 shows the layout of one tracking plane. The Faraday cage enclosing the detector is 4290 mm long, 2844 mm wide and 50 mm thick and is made of 30 mm-thick honeycomb panels fixed to aluminum frames and interlocked with lateral squared-section profiles providing the required mechanical rigidity to the chamber.

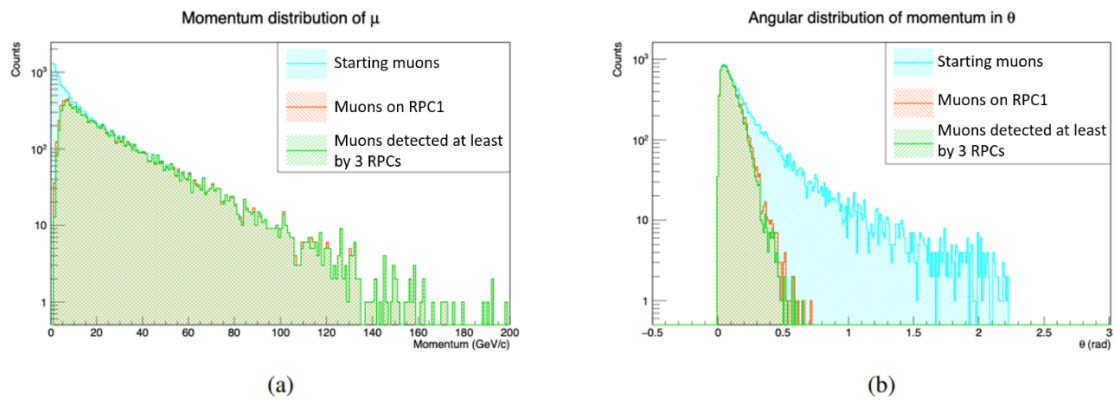


Figure 4. Momentum (a) and angular (b) distributions of the muons produced in the CC interactions (*Starting muons*), the muons impinging on the first RPC and those detected by at least three RPCs with at most one station without hits between them.

The mechanical structure of each plane has been designed in order to include all services, namely high voltage and low voltage distribution, front-end electronics and gas distribution system.

In order to minimize dead spaces, each tracking plane consists of three large gaps, with active area of (1900×1200) mm² each and a thickness of 2 mm. Since the maximum expected particle rate, computed in the two lateral region of the most upstream RPC plane (figure 3), is about 400 Hz/cm², RPCs will be operated in avalanche mode.

The electrodes of each gap consist of 2 mm-thick phenolic high-pressure laminate (HPL) panels, with a bulk resistivity of about 10^{11} $\Omega \cdot$ cm. A regular pattern of 2 mm-thick polycarbonate spacers with a pitch of 10 cm ensures a uniform gap width. Two gas inlet and two gas outlet nozzles are glued at the four corners of each gap.

In order to measure the 2D position of particles impinging on detector planes, each RPC is readout by two panels of perpendicular strips with a maximum length of 2 m and a pitch of about 1 cm placed on either side of the gas gap. Each strip panel is manufactured by gluing two 30 μ m copper foils on each side of a 5 mm-thick polyethylene foam panel.

The strip pattern is machined on one of the copper foils, while the other acts as a ground plane. The strip impedance is approximately 50 Ω . The ground plane is in direct contact with the Faraday cage.

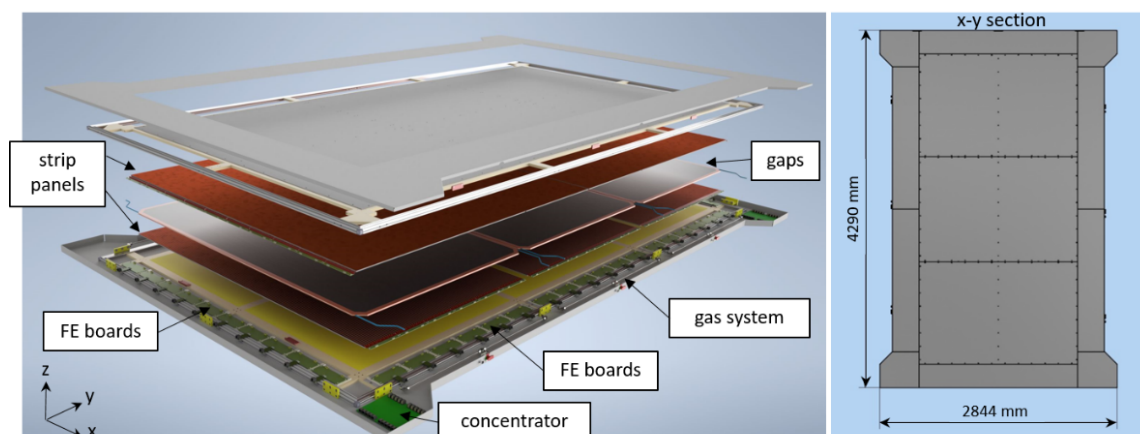


Figure 5. Layout of one RPC tracking plane for the SND Muon Identification System (left). Frontal view of its mechanical structure (right).

In order to compensate for the acceptance loss due to two inactive areas of $(6 \times 190) \text{ cm}^2$ between adjacent gaps, tracking planes are staggered by $\pm 10 \text{ cm}$ in the vertical direction.

2.2 Readout electronics

A common trigger-less readout scheme has been designed for all SHiP sub-detectors. The read-out electronics for the Muon System will collect data from about 4800 channels. The design strategy is based on the serial transmission of data from the front-end (FE) boards, where a custom FE FPGA controls the serialization process, to concentrator boards sending data at high speed through optical links to a host computer in the SHiP central event filter farm.

The whole electronic system for SHiP RPCs [14] is shown in figure 6. The front-end electronics is composed of 38 boards for each RPC plane, each equipped with two Front-End Electronics Rapid Integrated Circuit (FEERIC) ASICs [15], developed by the ALICE Collaboration, and an FPGA (Xilinx Spartan-6 XC6SLX9 TQG144). The two FEERIC ASICs with a total of 16 input channels amplify signals through a trans-impedance amplifier and digitize them through a zero-crossing discriminator. An LVDS driver transmits FEERIC output data to the FPGA on-board for data timestamping at a frequency of 120 MHz, zero-suppression and serialization. The FE FPGA, controlled and configured by the user through the DAQ system, transmits serialized data at a maximum speed of 400 Mbps to a concentrator board through the 8b/10b protocol via RJ45 CAT7 cables.

Each concentrator board, serving up to 20 FE boards, hosts a read-out FPGA (Xilinx Kintex-7) for data concentration and transmission via optical link (10 Gb Ethernet) to the FE host computer. The FE boards configuration parameters are transmitted by the host PC to the concentrator as slow control (SC) commands and then distributed to the FE system. The SHiP global fast commands (FC), e.g. the synchronization signal, are instead transmitted to the concentrator by the experiment timing and fast control (TFC) system. Pulse and trigger FC for test functionalities are managed by a custom auxiliary board, with the same hardware of concentrator boards, and transmitted to the concentration system.

The main blocks of the FE FPGA are shown in figure 7. RPC signals are synchronized, zero suppressed, formed according to the user configuration, timestamped, and then handled by the Data

Block. Data Transmission (TX) is managed by a custom block: it assigns packets priorities, encodes words using the 8b/10b code and serializes data embedding a cyclic redundancy check (CRC) code to control the correct transmission of data.

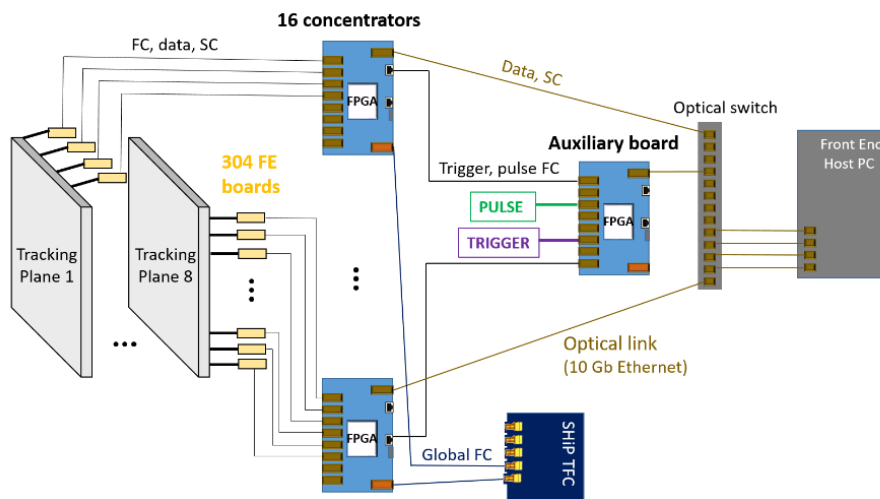


Figure 6. Overview of the electronics for SHiP RPCs.

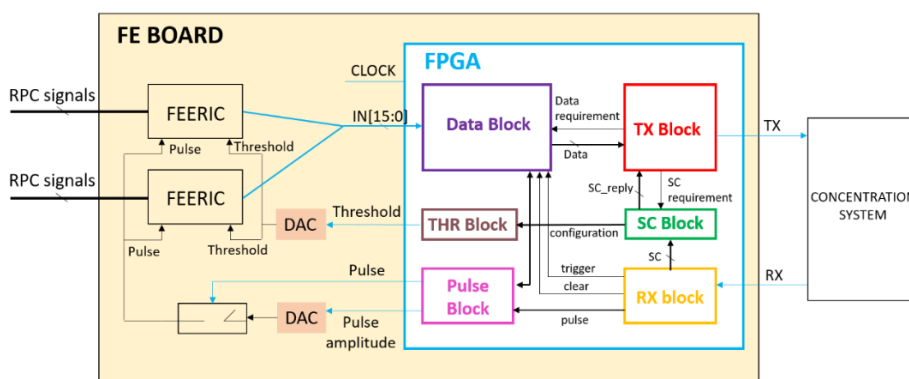


Figure 7. Block diagram of the front-end board for SHiP RPCs.

The receiver (RX) Block decodes received data and executes fast commands. The TX/RX systems are optimized in order to guarantee a fixed latency between the FC transmission by the concentrator board and the FC execution performed by the FE FPGA. Received slow control (SC) packets are managed by a dedicated block (SC Block). The FE thresholds, set by the user and transmitted as SC commands to the FPGA, are handled by the THR Block. For test purposes, a pulse mode of operation with variable pulse amplitude set by the user has been also implemented (Pulse Block).

The front-end board for SHiP RPCs as well as the concentration board have been designed and fully simulated with the Synopsys FPGA based-design software. Prototypes of the FE boards and concentrators have been produced and are currently under test.

3 Test of RPC prototypes for SND tracking planes

As a pilot production, five single-gap¹ RPCs with the same dimensions as the gaps foreseen for the tracking planes described in section 2 have been produced.

Each detector is readout by orthogonal strips with a pitch of 10.6 mm connected to 20 front-end FEERIC boards (figure 8 left) developed for the ALICE experiment. FE boards provide LVDS output signals sent to custom FPGA-based readout boards for data timestamping and transmission via Ethernet to the DAQ system.

A test-campaign to study the performance of SHiP RPCs was undertaken in Bari using cosmic rays. One prototype operated in avalanche mode with *standard* gas mixture (95.2% C₂H₂F₄, 4.5% iC₄H₁₀, 0.3% SF₆) was placed in a vertical telescope equipped with four additional streamer RPCs used for trigger and tracking. The streamer RPCs have a 2D readout with 3 cm-pitch strips. The trigger was defined as the coincidence of the four streamer RPCs. For each trigger, the track with the best χ^2 was selected. The distribution of the residuals between the expected position and the closest cluster, detected within a time window of 50ns by the RPC under test, has a width $\sigma \approx 0.7$ cm in each direction. The efficiency was thus computed as the number of tracks with a cluster detected within a pre-defined search window of 3σ around the predicted position normalized to the total number of tracks. An efficiency as high as 96% was measured in both directions (figure 8 right).

Despite the large dimensions of each RPC gap, the detector response showed a good uniformity (figure 9 left). The decrease in efficiency observed at the leftmost side (blue area) is due to the two leftmost strips overlapping the gap frame non-active zone. These results were obtained with a FE threshold of 100 mV, corresponding to a charge of about 200 fC [16], required to keep the noise rate of about 1 Hz/cm².

A current of about 500 nA and an average cluster size of 2.2 were measured at the effective operating voltage (H_{Ve}ff), about 9700 V, corrected for temperature and pressure [17] w.r.t. the reference values of 293.5 K and 1013.5 hPa respectively.

In order to measure the spatial resolution, further measurements were performed at CERN with a similar setup using the other four SHiP RPC prototypes as tracking detectors, thus profiting of the reduced strip pitch of 1 cm. A spatial resolution as high as 3 mm was measured in both directions (figure 9 right).

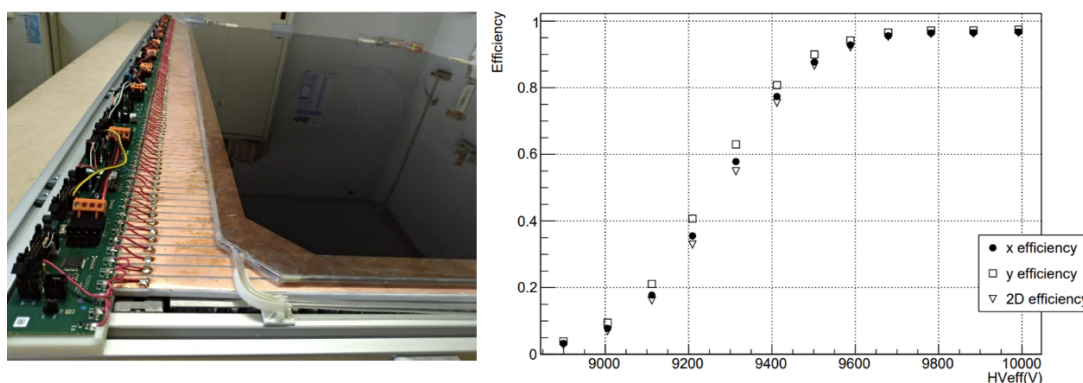


Figure 8. Detail of an RPC prototype for SHiP (left). Efficiency vs effective high voltage measured with standard gas mixture (right).

¹RPC gaps have been produced in KODEL, Korea University.

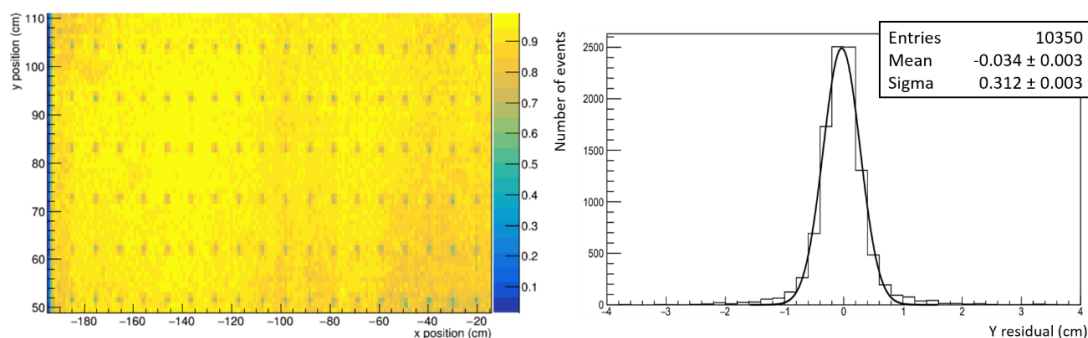


Figure 9. Efficiency map for a SHiP RPC tested with cosmic rays (left). Result of the spatial resolution measurement in one direction (right).

The five RPC prototypes were also successfully operated in the muon flux measurement [18] performed by the SHiP Collaboration at the SPS-H4 beam line at CERN, where they were used to instrument a prototype of the SND Muon System. The RPCs were operated in avalanche mode with standard gas mixture and FE thresholds set to 70 mV, corresponding to a charge of about 130 fC [16], reaching an efficiency of 98% with a noise rate of about 1 Hz/cm².

4 Test of new eco-friendly gas mixtures for SHiP RPCs

In 2014, the European Parliament, following a recommendation of the Intergovernmental Panel on Climate Change of the United Nations [19], agreed to severely limit the use of hydrofluorocarbons (HFCs) [20], a family of fluorinated gases, commonly used in a wide variety of applications, such as refrigeration and air-conditioning. HFCs are classified as greenhouse gases due to their high Global Warming Potential, a parameter quantifying the contribution of a gas to the greenhouse effect normalized to the effect of CO₂.

Since the main component of RPC standard gas mixture is R134a (chemical formula C₂H₂F₄), a HFC with GWP equal to 1430, the search for new eco-friendly gas mixtures for RPCs is crucial for future experiments to be installed at CERN.

First tests [21, 22] were performed by replacing a large amount of R134a with HFO-1234ze (chemical formula C₃H₂F₄), a Hydrofluoroolefin compound with GWP as low as 6, low toxicity and non-flammable, used in industrial applications. It was observed that the use of a high percentage of such gas results in a significant increase of the detector operating voltage (above 13 kV for 2 mm gaps).

Several eco-friendly gas mixtures were tested in Bari. Figure 10 shows the efficiency as a function of the effective applied voltage for two mixtures based on HFO-CO₂, in the following referred to as mix A (35% HFO, 60% CO₂, 4.5% iC₄H₁₀, 0.5% SF₆) and mix B (25% HFO, 69.5% CO₂, 5% iC₄H₁₀, 0.5% SF₆), both with GWP ~ 120. Fitted curves computed using a sigmoid function [23] are superimposed. The detector working point (WP) for each mixture is defined as the voltage where the efficiency reaches 99% of the asymptotic value approached by the fit function.

The efficiency values are only about 1.5% below the standard case at the WP, resulting to be about 1.8 kV and 700 V above the standard WP of 9700 V, for mix A and B respectively. The operating

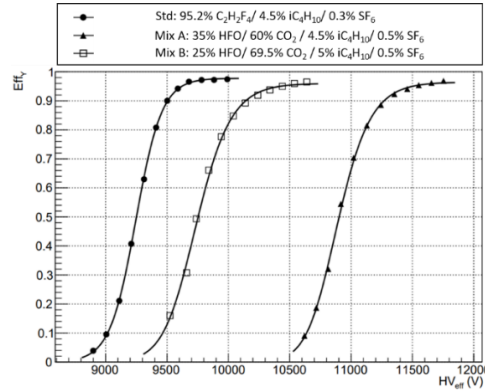


Figure 10. Efficiency measured for a 2 mm-gap SHiP RPC with two eco-friendly gas mixtures and with the standard gas mixture.

currents are comparable (about 500 nA). A slight increase in the average cluster size (about 2.5) at the WP is observed (figure 11 left). The measured noise rate is at the level of a few Hz/cm².

Figure 11 right shows the fraction of events with cluster size larger than 4, $P(C_s > 4)$. The performance as well as the longevity of RPCs operated in avalanche mode can indeed be limited by the appearance of events with “*large charge content*”, indicating the transition towards the discharge (streamer) mode. For mix B, $P(C_s > 4)$ is above 10% at the WP (10.4 kV), moreover it increases very rapidly with the applied voltage. For mix A, the fraction of large cluster size events at the WP (11.5 kV) is comparable to the standard case (a few percent).

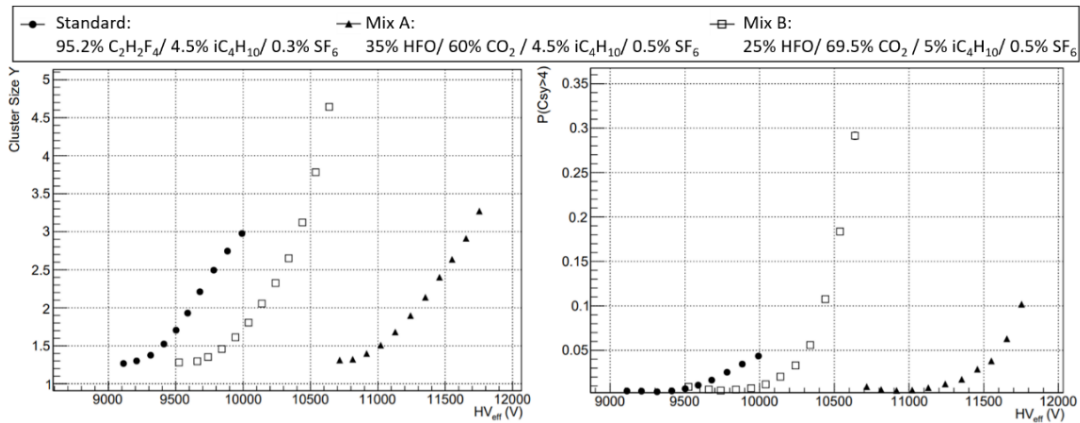


Figure 11. Performance of a 2 mm-gap SHiP RPCs with two eco-friendly gas mixtures and with the standard gas mixture. Y cluster size (left) and percentage of events with Y cluster size larger than 4 (right).

In order to decrease further the detector operating voltage, gaps with reduced thickness of 1.6 mm were tested and operated with several mixtures. Figures 12 and 13 show the performance obtained with the standard mixture, mix B and an additional mixture, referred to as mix C (35% HFO, 60% CO₂, 4% iC₄H₁₀, 1% SF₆). No efficiency reduction is observed for standard mixture and mix B at the WP w.r.t. 2 mm gap. A fast increase of large cluster size events with the applied voltage is observed for mix B also with 1.6 mm gap. Mix C, containing the same fraction of HFO

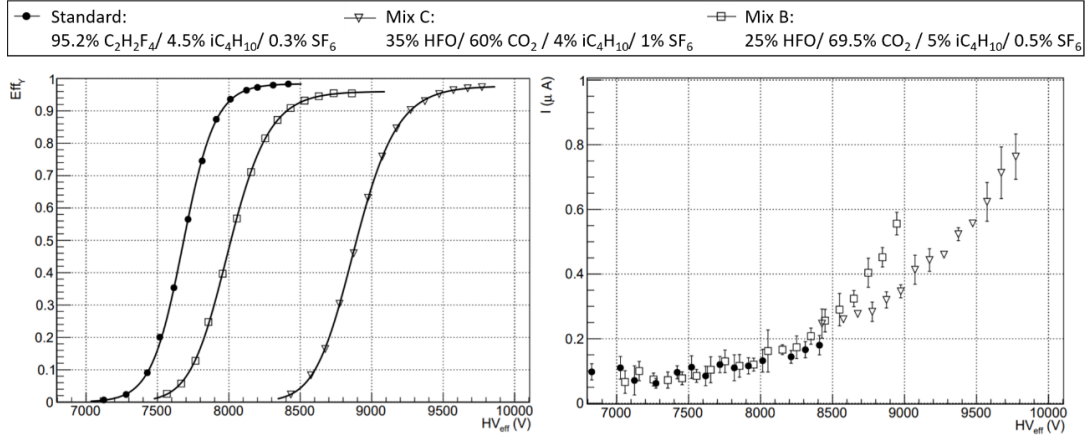


Figure 12. Efficiency (left) and currents (right) measured for a 1.6 mm RPC gap with two eco-friendly gas mixtures and with the standard gas mixture.

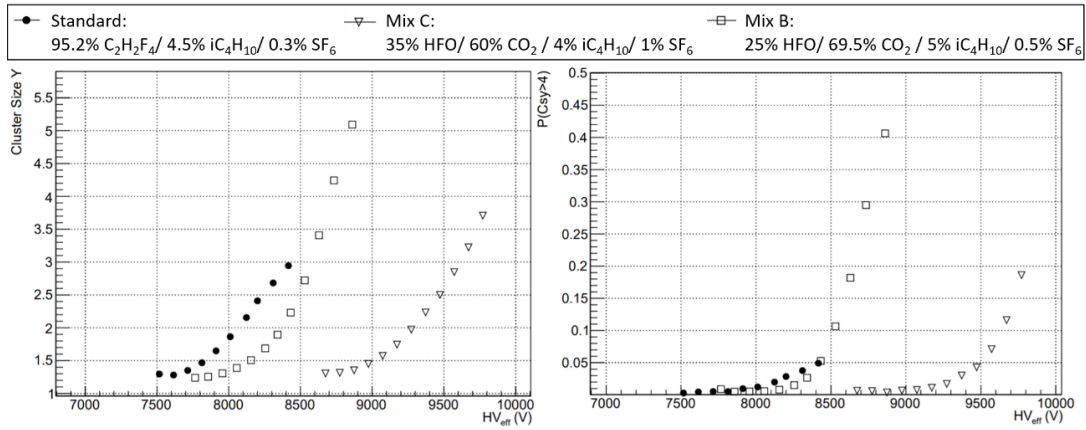


Figure 13. Performance of a 1.6 mm RPC gap with two eco-friendly gas mixtures and with the standard gas mixture. Y cluster size (left) and percentage of events with Y cluster size larger than 4 (right).

and CO_2 as mix A, shows comparable performance to the standard mixture in terms of efficiency (95% at WP), current, cluster size and $P(Cs > 4)$ with a GWP ~ 237 , significantly reduced w.r.t. the standard gas (GWP ~ 1430). Moreover, the use of such mixture in combination with 1.6 mm thick gaps results in a WP of about 9.5 kV, similar to the operating voltage of standard gaps.

Mix C can be thus regarded as a promising candidate for SHiP RPCs. A further study of the RPC performance with mix C in different irradiation conditions is currently ongoing at CERN GIF++[24] within the RPC EcoGas@GIF++ Collaboration, a joint effort between communities from LHCb-SHiP, ALICE, ATLAS, CERN EPDT and CMS.

5 Conclusion

The Scattering and Neutrino Detector (SND) of the proposed SHiP experiment aims at studying neutrino physics, with special emphasis on tau neutrino properties. It is equipped with a Muon System based on large gap RPCs identifying muons coming from neutrino interactions. Each detector

plane, composed of three gaps, is designed to provide a uniform, highly efficient spatial response with a resolution of a few millimeters in both x and y directions. The electronics for SHiP RPCs is designed for the serial transmission of data with high speed through optical link from detector planes to the data acquisition system.

Prototypes for SHiP RPCs have been tested with standard gas mixture and exposed at CERN H4 beam line showing an efficiency at the level of 98%.

Since the standard gas mixture contains a large fraction of R134a, a greenhouse gas recently banned by the European Union, new eco-friendly gas mixtures based on HFO/CO₂ have been tested for SHiP RPCs. The significant increase in the RPC operating voltage, due to the HFO component, suggested to use HFO-based gas mixtures in combination with 1.6 mm-thick gaps. No performance degradation is observed as a result of the gap thickness reduction. Among various eco-friendly alternatives tested with 1.6 mm gaps, the low GWP mixture composed of HFO/CO₂/iC₄H₁₀/SF₆ in the mole fraction 35%/60%/4%/1% is currently the most promising, leading to RPC performance similar to the typical *standard* one. At the working point (about 9.5 kV), thin SHiP RPCs show an average cluster size of about 2.5 and a low probability of larger clusters. The detection efficiency is as high as 95% in both x and y directions. In order to validate the new eco-gas mixture for SHiP RPCs, aging studies are currently ongoing within the RPC EcoGas@GIF++ Collaboration.

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