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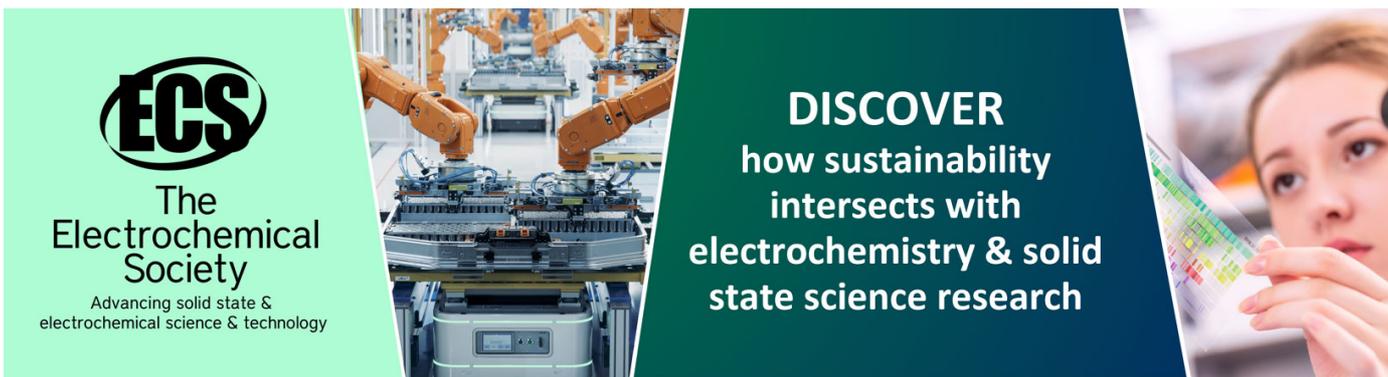
# A resistive ACHINOS multi-anode structure with DLC coating for spherical proportional counters

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## A resistive ACHINOS multi-anode structure with DLC coating for spherical proportional counters

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**ABSTRACT:** The spherical proportional counter is a gaseous detector used in a variety of applications, including direct dark matter and neutrino-less double beta decay searches. The ACHINOS multi-anode structure is a read-out technology that overcomes the limitations of single-anode read-out structures for large-size detectors and operation under high pressure. A resistive ACHINOS is presented, where the 3D printed central component is coated in a Diamond-Like Carbon (DLC) layer. The production and testing of the structure, in terms of stability and resolution, is described.

**KEYWORDS:** Dark Matter detectors (WIMPs, axions, etc.); Detector design and construction technologies and materials; Electronic detector readout concepts (gas, liquid); Gaseous detectors

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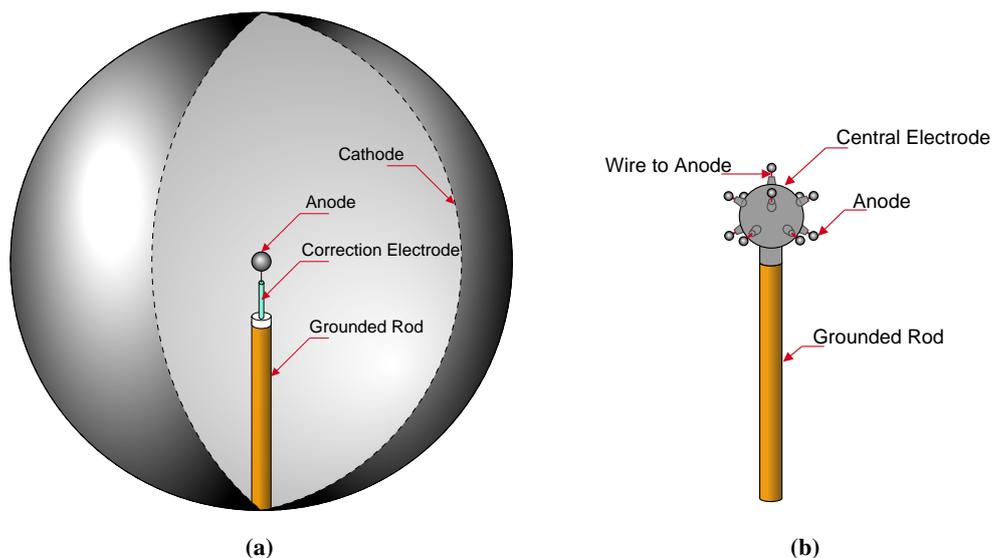
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## 1 Introduction

In its simplest form, the spherical proportional counter [1], shown in figure 1(a), consists of a grounded, spherical, metallic vessel filled with an appropriate gas mixture and a spherical anode of radius approximately 1 mm at the centre. The anode is supported by a grounded metallic rod, which also shields the wire used to apply a positive voltage to the anode and read out the signal. The electric field, which varies as  $1/r^2$  in an ideal spherical proportional counter, allows the ionisation electrons produced through particle interactions in the gas volume to drift to the anode. Within approximately 1 mm from the anode an avalanche occurs, providing signal amplification. Experiments using this detector include NEWS-G [2], searching for dark matter particles, and R2D2 [3], searching for neutrino-less double beta decay.

For large detectors, or detectors operating in high pressure, the small ratio of electric field strength to gas pressure ( $E/P$ ) increases the probability of electron attachment and recombination. In the single anode configuration, increasing the  $E/P$  ratio can be achieved by either increasing the anode voltage or the anode size, both of these options lead to an increased discharge probability.

ACHINOS, a sensor structure composed of several anodes at a radius  $r_S$  from the centre, as shown in figure 1(b), has been proposed to overcome this challenge [4]. The anodes are maintained in position by means of a central support structure. This structure needs to be constructed using resistive materials, as has been the case with previous read-out technologies [5]. With ACHINOS, the avalanche gain is determined by the anode radius  $r_A$  and voltage  $V$ , while the electric field at large radii is the collective electric field of all the anodes, determined by  $V$ ,  $r_S$ , and the number of anodes. Additionally, it is possible to read out each anode individually, allowing the three-dimensional reconstruction of the ionisation tracks.



**Figure 1.** Schematic of (a) the spherical proportional counter, showing the grounded cathode, central read-out anode, and the anode support structure, and (b) the ACHINOS structure.

## 2 ACHINOS with “resistive glue” coating

The ACHINOS central electrode is manufactured with resistive material, a choice that has been shown to reduce sparking rate and intensity [4, 5]. 3D printing provides a convenient means to produce a high-precision structure, however, currently 3D printing with insulators and conductors is more widely available. Thus, an appropriate coating needs to be applied. Initially, an Araldite adhesive mixed with copper powder was explored, with main benefits being the relatively low radioactivity of Araldite 2011 [6] and the possibility to control the resistivity of the coating by changing the relative amounts of Araldite and copper. It was found that mixtures containing 20% to 50% w/w copper powder were appropriate. An example is shown in figure 2. Despite the promising results, the coating layer was found to be susceptible to damage from discharges. Specifically, a single discharge could destroy the central electrode coating, by creating a conductive path. This behaviour was also observed repeatedly using a spark-test chamber.

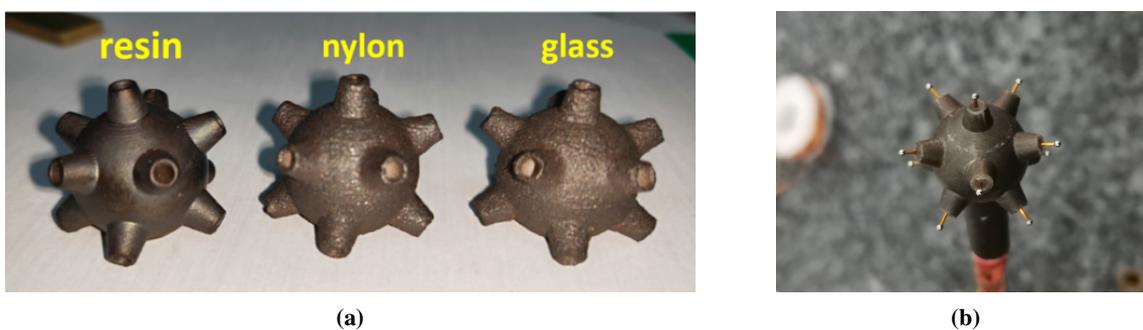


**Figure 2.** ACHINOS using an Araldite-copper layer on the 3D-printed structure to form the central electrode.

### 3 ACHINOS using DLC coating

DLC is a form of amorphous carbon containing both the diamond and the graphite crystalline phase. Thanks to its excellent surface resistivity, in addition to structural, chemical and thermal stability, DLC coating [7] offers a novel method for producing high quality resistive materials for gaseous detectors [8, 9].

The central structure was constructed using 3D printing with different substrates, including resin, nylon, and glass, as shown in figure 3(a). DLC was deposited using magnetron sputtering. Several batches of DLC-coated structures were produced, with a range of coating thickness between 360 nm and 720 nm. The measured resistance between two anti-diametric points on the surface, ranged from 0.3 to 10 G $\Omega$ . The DLC-coated resin 3D printed structure was mounted on a copper rod and electrically connected to it using a conductive Araldite copper mixture, as shown in figure 3(b).



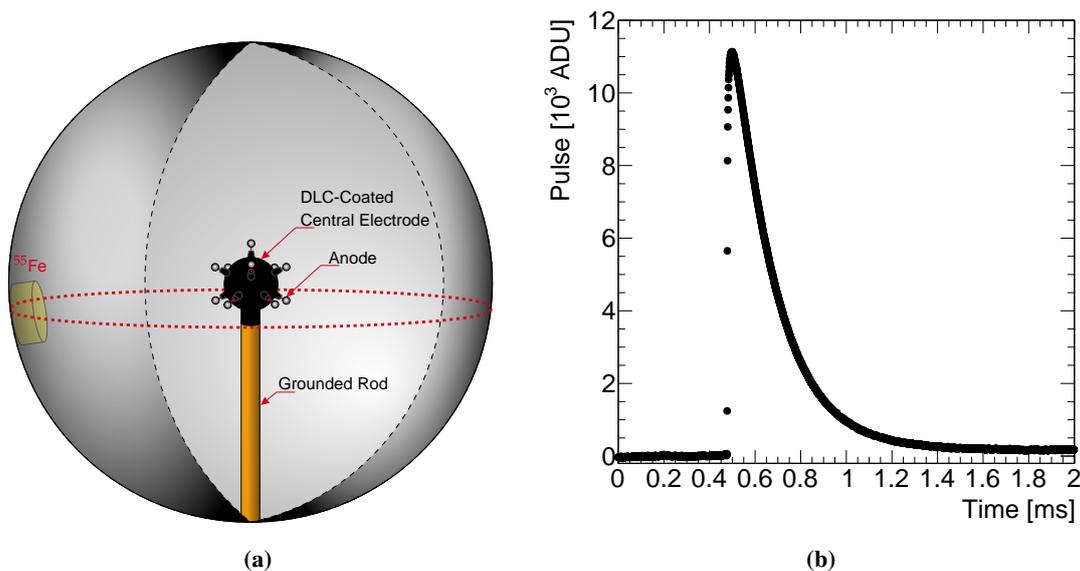
**Figure 3.** (a) Three different support materials (resin, nylon, glass) covered with a DLC layer. (b) An 11-anode ACHINOS constructed using a DLC-coated support structure.

### 4 Experimental results

The ACHINOS structure with 11-anodes, each 1 mm in diameter, shown in figure 3(b) was installed in a 30 cm diameter spherical proportional counter that operated in sealed mode. An  $^{55}\text{Fe}$  source was installed inside the detector, the position of which could be adjusted without opening the detector. The source principally emits a 5.9 keV X-ray when it decays to  $^{55}\text{Mn}$  by electron capture. The experimental set-up is shown in figure 4. An ISEG NHR 22 60r power supply was used to apply voltage to the anodes. The central electrode was, typically, grounded through the rod, but alternative configurations were also tested. Signals are read out by a CREMAT CR-110-R2 charge sensitive preamplifier. The preamplifier output is passed to a “CALI” digitiser, manufactured by CEA Saclay [10], with a dynamic range of  $\pm 1.25$  V and maximum sampling frequency of 5 MHz.

An example digitised output pulse, recorded with a sampling rate of 1 MHz, is shown in figure 4(b). The exponential falling edge is defined by the 140  $\mu\text{s}$  time constant of the preamplifier. A preamplifier output of 1 ADU,<sup>1</sup> corresponds to a charge of approximately 0.027 fC at the preamplifier input. Contamination from cosmic-ray muons interacting in the gas volume is suppressed using loose event selections on the pulse rise time, defined as the time required for the signal to increase from 10% to 90% of its amplitude, and the ratio of the pulse integral to its amplitude.

<sup>1</sup>ADU = Analogue-to-Digital Units.



**Figure 4.** (a) Schematic of the experimental set-up, with the position of the  $^{55}\text{Fe}$  source relative to the 11-anode ACHINOS. (b) Digitised output pulse recorded in a 2 ms window, with the pulse peak positioned at 25% of the window width.

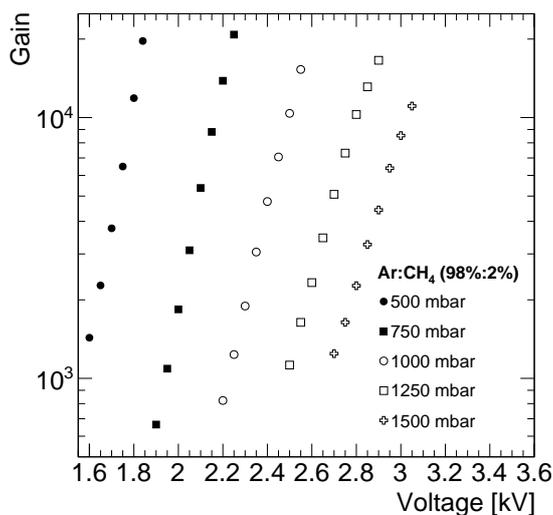
#### 4.1 Gain

The detector was filled with 500 mbar of Ar : CH<sub>4</sub> (98% : 2%) and data were collected at various anode voltages and pressures, and the amplitude of the 5.9 keV peak were recorded. These measurements, performed with the central electrode electrically floating, are presented in figure 5, where the detector is shown to operate in proportional mode over a wide pressure range. Furthermore it is demonstrated that large gas gains (avalanche electron multiplication factor) of up to  $10^4$  can be achieved with this detector configuration.

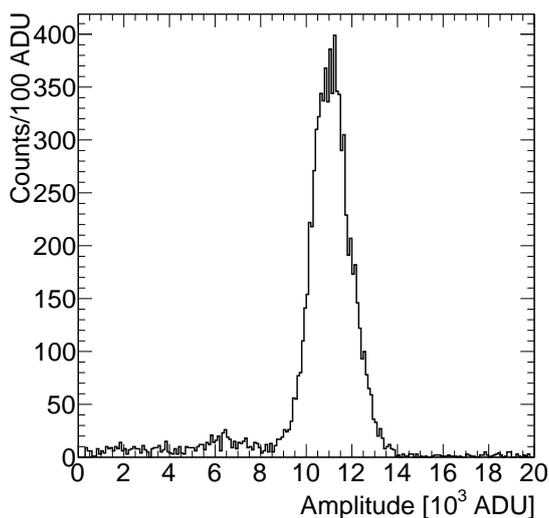
#### 4.2 Anode response uniformity

To check the uniformity of the sensor response, data were taken with the  $^{55}\text{Fe}$  source at various longitudinal positions, while at a fixed latitude of approximately  $12^\circ$  below the equator, as shown schematically in figure 4. The detector was operated with 1000 mbar of Ar : CH<sub>4</sub> (98% : 2%) and an anode voltage of 2200 V. The amplitude and local energy resolution were estimated using the 5.9 keV peak and an example spectrum is shown in figure 6. A gaussian fit of this yielded an amplitude of  $(11090 \pm 10)$  ADU, corresponding to a gas gain of  $8.3 \times 10^3$ , and a local energy resolution  $\sigma$  of  $(7.4 \pm 0.1)\%$ . The same procedure was repeated for the other measurements, with the results shown in figure 7(a) for the amplitude and figure 7(b) for the local energy resolution, which varies between 7.1% and 9.2%.

The maximum (minimum) amplitude at approximately  $320^\circ$  ( $210^\circ$ ) corresponds to a gas gain of  $8.8 \times 10^3$  ( $5.7 \times 10^3$ ). The amplitude modulation as a function of the azimuthal angle observed in figure 7(a) is intriguing. To understand its origin a dedicated framework for the simulation of spherical proportional counters was used [11], which combines the strengths of Geant4 [12] and



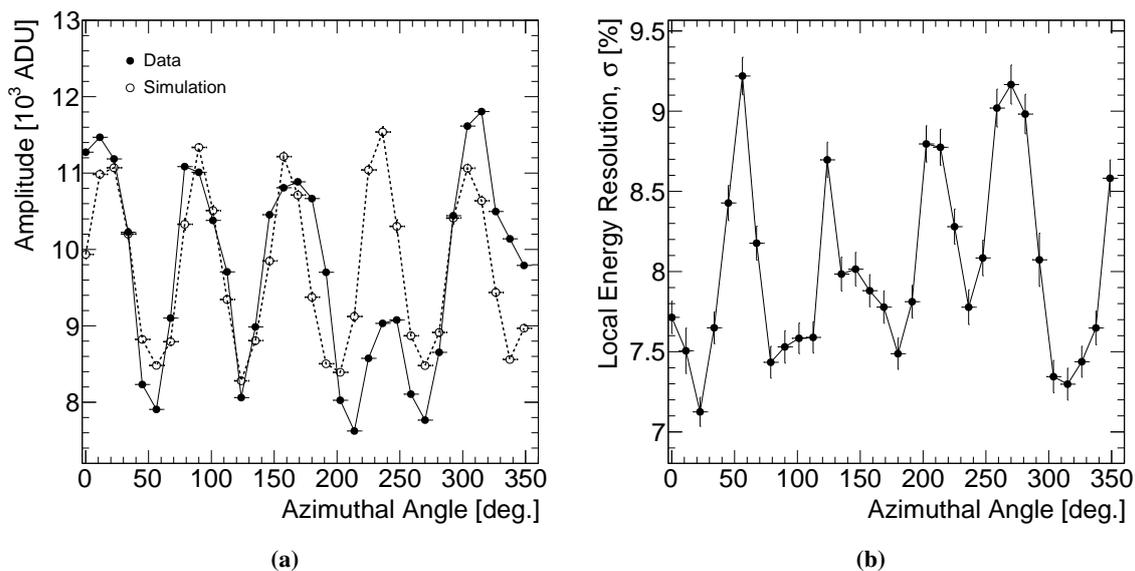
**Figure 5.** Measured amplitude versus the voltage applied to the anode for several pressures of Ar:CH<sub>4</sub> (98% : 2%) in a spherical proportional counter using an ACHINOS.



**Figure 6.** Energy spectrum from an <sup>55</sup>Fe source measured using a spherical proportional counter filled with 1000 mbar of Ar : CH<sub>4</sub> (98% : 2%) and using an ACHINOS. The primary peak has an energy resolution ( $\sigma$ ) of  $(7.4 \pm 0.1)\%$ . The second peak, to the left of the main one, is the argon escape peak.

Garfield++ [13]. In the simulation 5.9 keV photons were generated near the cathode surface and directed within a 45° cone towards the detector centre. A similar analysis to those applied to the data was implemented. The open circles in figure 7(a) correspond to the simulation results which reproduce the modulation observed in the data.

To understand the origin of the effect, the 11-anodes of the ACHINOS were split in two groups. The first group comprises the five co-planar anodes near the support rod, while the second group comprises the five co-planar anodes far from the support rod and the anode furthest away from



**Figure 7.** Measured and simulated amplitude (a) and measured local energy resolution  $\sigma$  (b) of the 5.9 keV X-ray in a spherical proportional counter with an ACHINOS as a function of azimuthal angle. The detector was operated filled with 1000 mbar of Ar : CH<sub>4</sub> (98% : 2%).

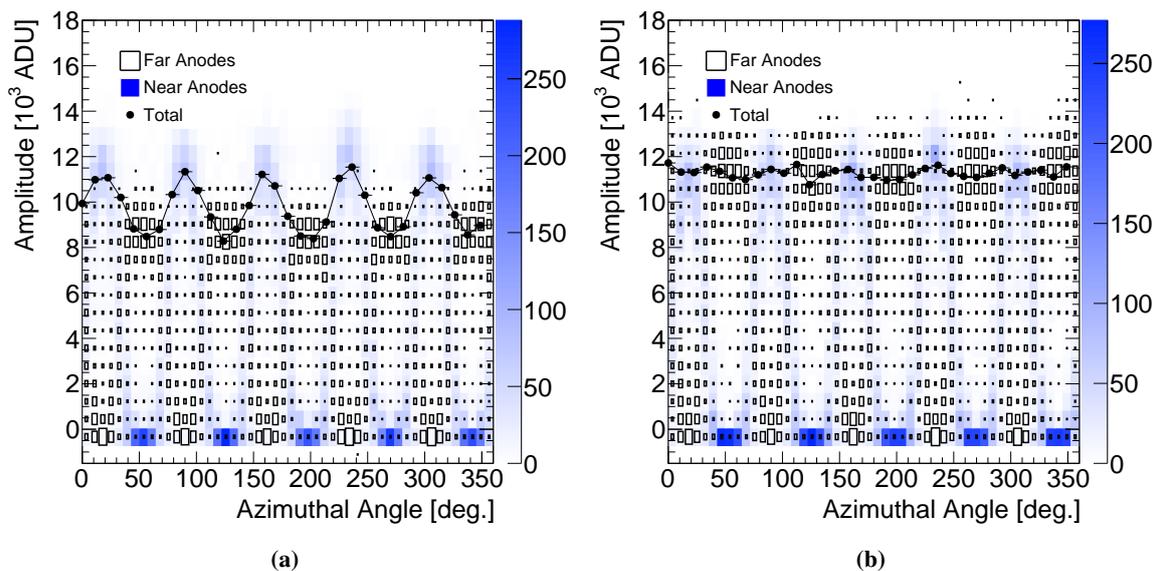
the support rod. In the following these two groups will be referred to as “Near Anodes” and “Far Anodes” respectively. In figure 8(a) the amplitudes recorded by reading out each set separately is presented. It is observed that the amplitudes are modulating in antiphase. This provides a clear explanation of the effect; as the source is moved around the sphere, the produced primary electrons are drifting towards different anodes, alternating between the Near and the Far anodes.

The relative difference in maximum amplitude between the Near and Far anodes is due to the gain difference between the two sides. The Near anodes exhibit an increased electric field due to the proximity to the grounded support rod, which results in deviations from the spherical symmetry. This effect can be readily corrected for by separately adjusting the applied voltage to the Near and Far anodes. In figure 8(b) the simulation is repeated with the voltage applied to the Far anodes increased by 30 V. In this case the azimuthal dependence of the amplitude is minimised, and could be eliminated by further tuning of the Far anodes voltage.

A potential source of additional response non-uniformity may arise from construction differences of the individual anodes. This effect is not included in the simulation, however it can be estimated from the experimental data. The difference in gain within the two sets of co-planar anodes are typically within 10%. This is shown in figure 7(a), where a single outlier is also observed in each of the sets. These differences are attributed to variations in the anode radii, the smoothness of the anode surface, and the distance to the central electrode. These non uniformities can be corrected for with an anode-by-anode calibration, when each anode is read-out individually.

### 4.3 Stability

The detector operated stably filled with 1000 mbar of Ar : CH<sub>4</sub> (98% : 2%) and the anode voltage set to 2200 V. The amplitude of the <sup>55</sup>Fe peak was monitored and no significant gain variations



**Figure 8.** (a) Simulated amplitude recorded by the Near and Far anodes as a function of azimuthal angle. The difference in relative maximum amplitude between the two is due to a higher electric field magnitude for the Near anodes, which is caused by their proximity to the rod. (b) The amplitude recorded by the Near and Far anodes in the case where 30 V more is applied to the Far anodes.

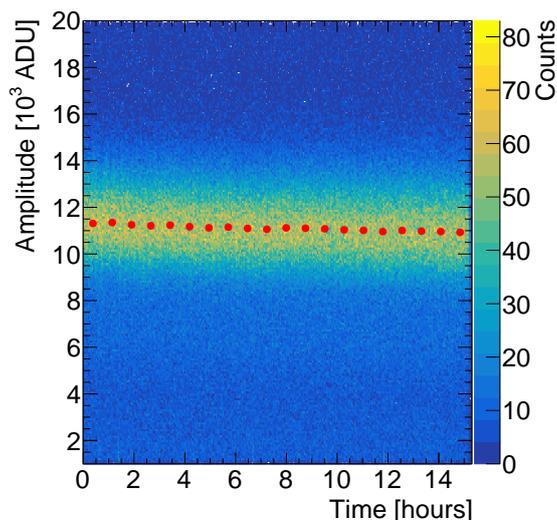
were observed over approximately 15 hours, as shown in figure 9. The gradual decrease in gain over time is attributed to the introduction of contaminants coming from outgassing and leaks in the vacuum system, a behaviour that has been observed in earlier studies [5]. In further tests, the sensor was operated without issues for a period of 30 days despite an observed average of approximately one discharge per day. Furthermore, no damage was observed following intentionally induced discharges.

## 5 Future developments

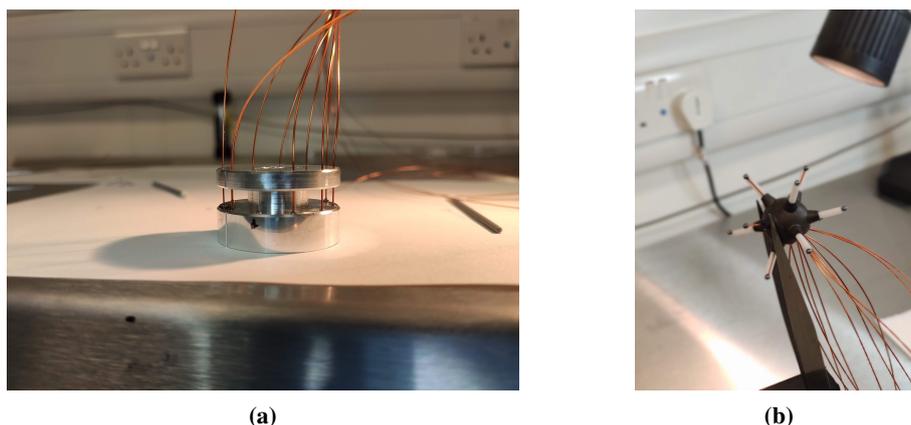
Additional R&D effort is foreseen, aiming to consolidate the construction and performance of ACHINOS. The main directions for such developments are briefly discussed in the following.

A major task is the industrialisation of the sensor manufacturing, ensuring reliable and reproducible behaviour. The use of additive manufacturing techniques, like 3D printing, for the construction of the central electrode and its DLC coating has been a significant step in this direction. Further improvements in the manufacturing are being explored, including the production of assembly tools for anode alignment and attachment of wires. As an example, an assembly tool constructed at the University of Birmingham, is shown in figure 10(a), along with the spacers used to align the anodes with during assembly, shown in figure 10(b).

To further improve the ACHINOS performance, the gain variation among different anodes needs to be reduced. A major source of this variation arises from irregularities in the shape of the individual anodes. Identifying vendors that can supply anodes with high sphericity and small surface roughness is being investigated.



**Figure 9.** Amplitude versus time for a spherical proportional counter filled with 1000 mbar of Ar:CH<sub>4</sub> (98% : 2%) and using an ACHINOS. The red points superimposed on the histogram show the mean amplitude in time slices. The slight decrease in amplitude with time is attributed to impurities leaking into the detector.



**Figure 10.** (a) Assembly tool used for simultaneously bonding several wires and anodes. (b) An ACHINOS being constructed using custom-made spacers to position and align the anodes.

A number of applications of the spherical proportional counter, such as dark matter searches [2], Supernovae [14] detection, fast neutron spectroscopy [15], and measurements of neutrino coherent scattering [16], would benefit from operation under high gas pressure. The use of ACHINOS is an important development in this aspect. To further progress in this direction, the use of anodes with small radii, of order 100  $\mu\text{m}$ , is being explored. This would facilitate achievement of higher gain by increasing the electric field near the anode surface, without further increase of the anode voltage. An important challenge towards smaller anode radii is the bonding to the read-out wire, which needs to be performed in a manner that minimises exposed contacts which may lead to discharges. Ideas to achieve this are being explored with industrial collaborators, at CERN and at CEA Saclay.

Furthermore, the number and configuration of anodes in the ACHINOS may be optimised for each specific application, depending on the size and pressure of the vessel. Such a development can

be guided by a dedicated simulation program [11]. At the same time, a further milestone would be the individual read-out and high-voltage biasing of each anode. This would allow three dimensional reconstruction of the ionisation track, and anode-by-anode calibration of the gas gain.

## 6 Summary

A multi-anode read-out structure for the spherical proportional counter has been developed. ACHINOS now incorporates a DLC layer to prevent discharges, and its operation stability has been demonstrated. It was also found that the DLC layer is robust under discharges. The gas gain in various pressures was also studied, demonstrating the ability to operate the detector in a gain of up to  $10^4$  in 1500 mbar of Ar : CH<sub>4</sub> (98% : 2%). The local energy resolution has been assessed as a function of azimuthal angle and found to be better than 10% ( $\sigma$ ). The difference in gain between different anodes was not greater than 25%, and this can be further improved by using anodes with a smaller deviation from an ideal sphere and lower surface roughness, individually calibrating each anode and the inclusion of more anodes.

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