DEVELOPMENT OF A LOW COST PICOAMMETER FOR BEAM CURRENT MEASUREMENT WITH SEGMENTED COLLIMATORS

Alexandru-Gabriel STOICA[1,*2], Cătalin NEACŞU[3]

In preparation of the experiments at particle accelerators, the beam transport must be optimized in order to reach the experimental setup with the required parameters. In the IDS-ISOLDE case, the optimization process proved to be time-consuming. To solve this problem, a low-power, low-cost, four-channel picoammeter was designed. It can measure the beam currents collected by a PCB divided into four sections attached to a collimator. The measured input currents are in the range of +/-1 nA with a resolution of 0.5 pA. The picoammeter has been validated and is used at IDS in the optimization process to determine when the particle beam is misaligned. In addition, a four-segment collimator with a guard structure was built to eliminate the error due to the secondary electron current.

Keywords: particle beams, collimator, picoammeter, low-cost, CERN-ISOLDE

1. Introduction

During the preparation of nuclear physics experiments at particle accelerators it is necessary to optimize the particle transport from the ion source to the experimental setup. This cannot be done without beam diagnostic instrumentation that provides information such as beam current intensity, beam position relative to the optical axis, and transverse intensity profile. Several solutions have been developed in this regard [1].

At the CERN-ISOLDE facility [2], experiments are carried out with radioactive beams obtained by bombarding thick targets with proton pulses at GeV energies. The products obtained from these interactions are accelerated, separated and transported to the experimental setups. IDS (Isolde Decay Station) is one of the permanent experimental setups that studies the decay of radionuclides, which are implanted on an aluminized-mylar tape [3]. Here the beam optimization process is performed by using a collimator made of a metalic plate with holes of different

[1]*Nuclear Physiscs Department, Horia Hulubei National Institute of Physics and Nuclear Engineering – IFIN-HH, R-077125 Bucharest, Romania, e-mail: alexandru.stoica@nipne.ro (corresponding author)
[2]Physics Department, National University of Science and Technology POLITEHNICA Bucharest, Bucharest, Romania
[3]Nuclear Physiscs Department, Horia Hulubei National Institute of Physics and Nuclear Engineering – IFIN-HH, R-077125 Bucharest, Romania

sizes, a Faraday cup, and a picoammeter. After steering the beam to the collimator, we attempt to pass it through and measure the current in the Faraday cup. However, this process has proven time-consuming when the beam is misaligned and steering is determined by trial and error. A collimator with four current-collecting surfaces is needed to indicate the beam's position relative to the optical axis. Commercially available picoammeters have high performance and many features but at a high cost. Depending on the application, those features may not be necessary. As a compromise between performance and cost, there is a trend for "in-house" manufacturing of low-cost picoammeters with specific features for the intended application, such as those presented in Table 1. Another circuit topology not mentioned in Table 1 is the charge integrator, which can be implemented entirely on a single chip or built with discrete components. Ref. [4] describes such a picoammeter for ion chambers, with an input current range from 0.1 pA to 100 nA.

Table 1

Comparison of different in-house picoammeters

Paper	Circuit topology	Multi scale	Bandwidth	Imax	Resolution on the smallest scale	Usage/Additional information
Ref. [5]	Feedback resistor	yes	~2.5kHz	2 nA	10 fA	Build for general purpose with <10 % accuracy
Ref. [6]	Feedback resistor	no	0.48Hz	1.5 nA	1-5 pA	Design for biosensor chip signal reading
Ref. [7]	Shunt resistor	yes	Not mentioned	1 uA	Not mentioned	Dielectric nanomaterial/film characterization
Ref. [8]	Shunt resistor	no	0.08 or 0.16 Hz	Not mentioned	Better than 5 fA	Beam particle profile monitor The acquisition is done using the card PCI-6224
Ref. [9]	Feedback resistor	no	4.82 Hz	10 pA	Not mentioned	Aerosol charge measurements It uses a hermetically sealed resistor in glass.
Ref. [10]	Feedback resistor	no	1 kHz	~11.36 pA	Not mentioned	Heavy ion beam current monitor and has a linearity error of less than 0.12%.

Compared to the previously mentioned devices, the commercial Keithley 6485 picoammeter has a resolution of 10 fA for the 2 nA scale, with an accuracy of 0.4% and an offset of 0.4 pA according to Ref. [11].

This work aims to design and build a low-cost system consisting of a four-channel picoammeter and a segmented collimator. It is also necessary that the device be flexible in data transmission and in integration with various particle-beam diagnostic systems. Starting from the current experience, the design parameters are:

scale of +/-1 nA with a resolution of 0.5 pA, a minimum sampling rate of 5 samples/s per channel, Wi-Fi and USB connection.

2. Method

The developed system consists of a collimator and a picoammeter. One design constraint was to minimize changes to the IDS collimator. To achieve this, a small square printed circuit board (PCB) divided into four segments was mounted on the existing collimator. As shown in Fig. 1, the segments area is small and sometimes allows the beam to pass by. As a result, no information about the beam position is obtained. Another problem with this collimator is the absence of a negative biased guard ring, which leads to the loss of secondary electrons.

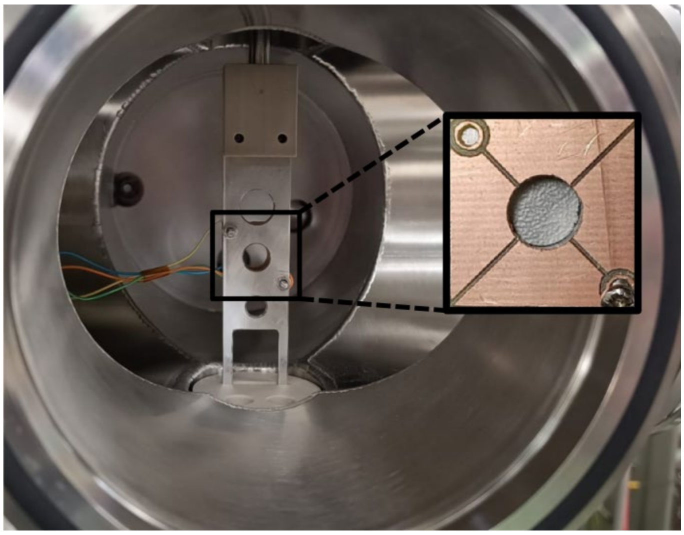

Fig. 1. The IDS collimator with a segmented PCB for beam-current pick-up

Given the limitations mentioned above, a second prototype of the segmented collimator was developed and is shown in Fig. 2. It is equipped with a guard structure, a mounting support, and improved electrical insulation for the segments. The collimator consists of a PCB base and four 3D-printed mechanical legs that push outward and facilitate positioning in the beam line. The guard structure around the segments was made of copper foil. The segments that collect the beam current are made of PCB and are supported on the base by insulated elements. This design ensures that conductive material deposits that accumulate over time, do not cause to current leakage between different segments or between segments and the guard structure.

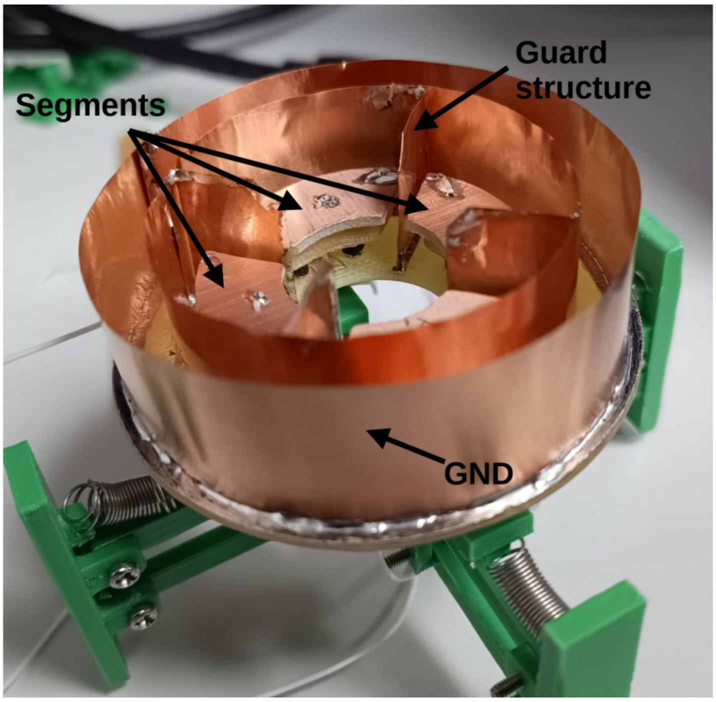

Fig. 2. Collimator with segments, a guard structure, and mounting supports

The main part of a picoammeter is the front-end, which must be carefully designed. According to Ref. [12], there are two basic circuits for measuring current: shunt ammeters and feedback ammeters. The second, shown in Fig. 3, offers advantages over the first such as low burden voltage and fast response time. For this reason, feedback ammeters are most commonly used for currents of the order of picoamperes.

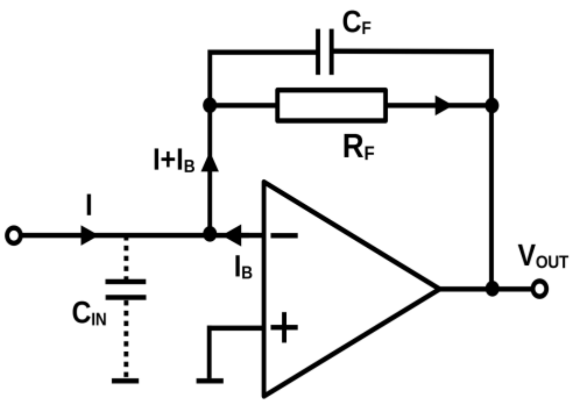

Fig. 3. Basic feedback ammeter circuit

For this amplifier the output voltage V_{OUT} is given by the eq. (1)

$$V_{\mathrm{OUT}} = -\mathrm{IR}_F - I_B R_F - V_{\mathrm{OS}} \tag{1}$$

where I is the measured current, I_B is the bias current of the inverting input and V_{OS} is the offset voltage of the operational amplifier (op-amp). Although errors are undesirable, as long as V_{OUT} does not reach the op-amp's saturation voltage, the last two terms can be corrected later, either digitally or by analog means. A problem encountered with this circuit is the instability caused by the input capacitance, which can be fixed by adding the C_F capacitor to the feedback network. If the input capacitance C_{IN} is known, then C_F can be calculated as a function of C_{IN}, R_F and the op-amp bandwidth as described in Ref. [13]. When C_{IN} is not known or cannot be approximated, C_F can be found by trial and error until the amplifier becomes stable.

The circuit shown in Fig. 3 is used as the front end for our system. Considering the very high impedance and susceptibility to noise, the system has been divided into three separate circuits: the front-end circuit, the filtering and acquisition circuit, and the processing and communications circuit. The system structure is shown in Fig. 4.

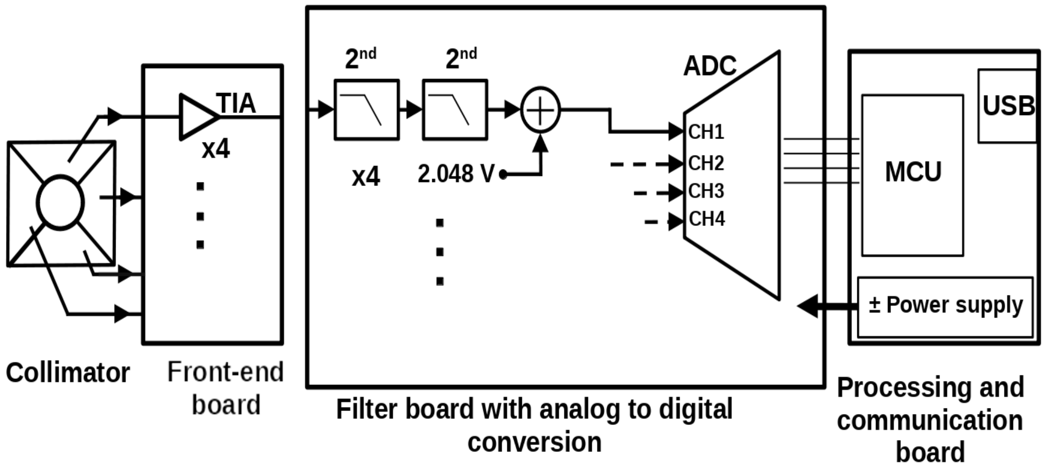

Fig. 4. Block diagram of the system

For the front-end circuit, an op amp with an input bias current on the order of picoamperes and an offset voltage as low as 1 mV is required. Ref. [9] uses hermetically sealed resistors and places silica gel nearby to reduce amplification error due to environmental humidity. In our case, we decided to place the circuit in a vacuum near the collimator. This approach also reduces pickup noise. The primary means of cooling a circuit in vacuum is conduction. Therefore, it is essential to use a low-power operational amplifier. Several op-amps were evaluated, including the ADA4530-1, AD549 and LMC6464. The LMC6464 was selected because it is a quad op amp, low-cost, low-power, it has 150 fA bias current, 0.25 mV offset voltage. R_F has a value of 2 GΩ and C_F has a value of 1 pF. An 1 GΩ resistor and a multi-turn potentiometer were placed on the board to form a current source used to determine the gain differences between the channels. Gain errors can be compensated digitally if significant. The measured current paths were raised above the board. Teflon insulated terminals were used as recommended in Ref. [12] to reduce current leakage and parasitic capacitances. A shield was placed over the amplifier and feedback network components to prevent possible mechanical damage.

The signals from the front-end circuit are fed into the filtering and analog-to-digital conversion stage. Since the front-end is located at the end of the beamline, it is electrostatically shielded, resulting in low 50 Hz noise. To further reduce noise, the signal passes through two second-order active filters in series using the Sallen–Key topology described in Ref. [14], build with NCS21911 precision op-amps and have a cutoff frequency of 6.5 Hz. An op-amp shifts the baseline from 0 V to 2.048 V so that a unipolar analog-to-digital converter (ADC) can measure negative signals from the front-end circuit. In this case, the MCP3204 was used because it is a SAR ADC with 12-bit resolution, four single-ended channels, ±1 LSB maximum DNL and INL, an SPI communication interface, and low power consumption (≤ 2 mW) [15]. For this ADC, the time between SPI transfers determines the conversion rate. The voltage reference is formed by two shunt precision references, ADR5040, connected in series.

The final stage of the picoammeter is driven by an ESP32-C3-MINI module, a low-power, low-cost RISC-V microcontroller (MCU) with Wi-Fi and Bluetooth. The MCU communicate with the ADC via SPI and reads the voltages on the four channels sequentially. Three software solutions have been implemented for transmitting data to the end user. The first option is to transmit data using IP/UDP packets over Wi-Fi, but this requires the user to run a dedicated server to receive the data. The second option is to transmit data via HTTP requests to an InfluxDB database, which Grafana application then imports and displays. The third option is to send the data directly to a serial port via USB and display it in a graphical interface application. The circuit incorporates the LM27762, which is a positive voltage regulator, a charge-pump inverter, and a negative voltage regulator. It supplies the analog components of the system.

The entire picoammeter is powered via a USB Type-C connector, though batteries can also be used. The three circuits comprising the picoammeter are shown in Fig. 5.

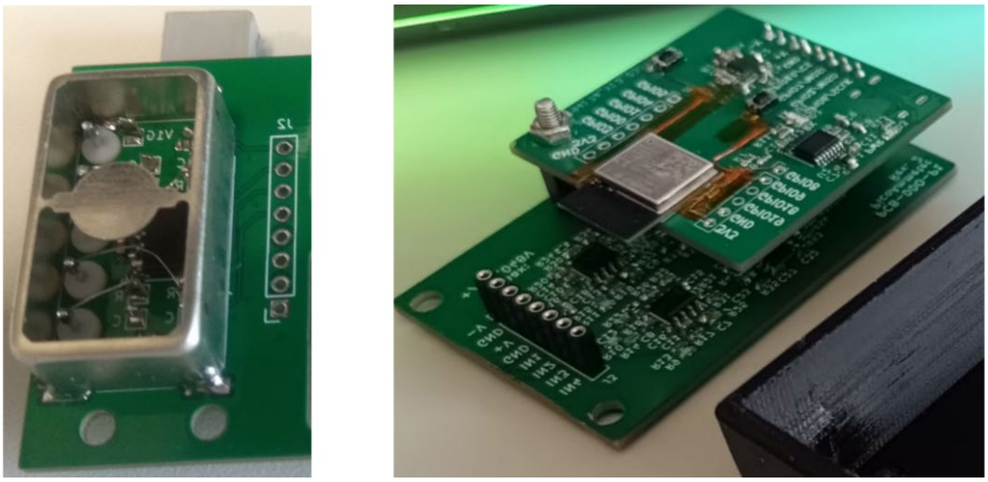

Fig. 5. The final device: the front-end on the left and the filtering and acquisition circuit connected to the MCU on the right.

3. Results

To testing the circuit, a voltage source and a 1 GΩ resistor were connected in series with the picoammeter, and currents up to 1 nA were measured. The same measurement was performed using a commercial Keithley 6485 picoammeter. Fig. 6 shows the results, where V_{R1G} is the voltage across the 1 GΩ resistor, I_D are the measurements from channel 1 of our picoammeter, and $I_{Keithley}$ are those obtained with the commercial picoammeter. The offsets of both devices were corrected. If the Keithley is taken as the reference, the slope difference is about 1.7%, which arises mainly from the feedback resistor value, known to have a 1% tolerance. The maximum current variation indicated by our device was approximately ±1 pA, with no nonlinear trend observed. Measurement stability was verified for over four hours with no observable drift. This period is sufficient for beam optimization when using our system.

Two measurements were performed with the old collimator and the segmented PCB from Fig. 1. The first concerns the noise on each picoammeter channel in the absence of the beam and has the following RMS values: 0.92 pA, 0.51 pA, 0.37pA and 0.55 pA. Fig. 7 shows the waveform of channel 1, recorded continuously at a sampling rate of 200 samples/s.

For the second measurement, the currents were recorded during the beam optimization process at a sampling rate of 5 samples/s per channel. Fig. 8 shows a segment of the recording, which indicates the relative position of the beam. This system was used during preparation of the experiment at IDS-ISOLDE and helped determine when the beam was misaligned.

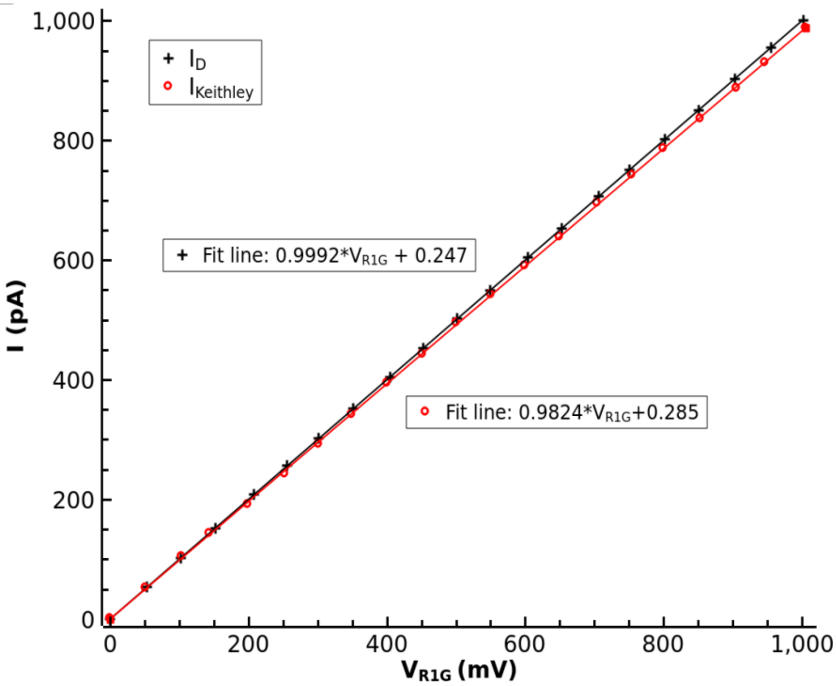

Fig. 6. Comparison of currents measured by our picoammeter and a Keithley picoammeter

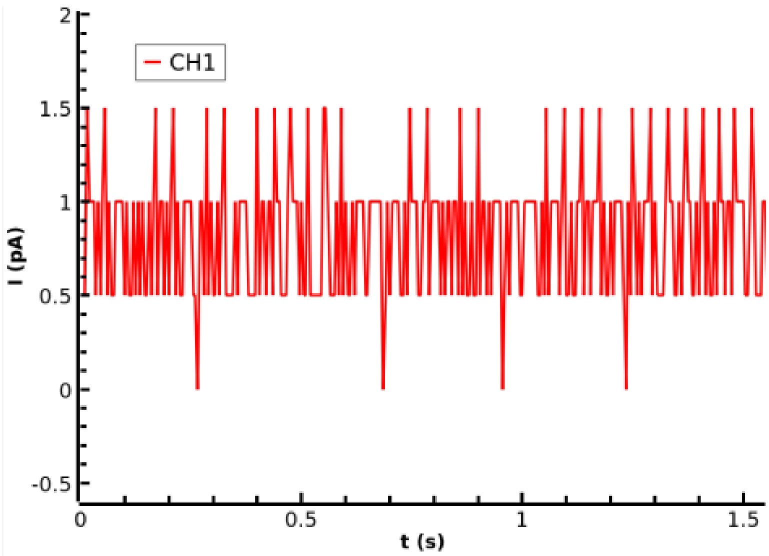

Fig. 7. The noise recorded by the picoammeter

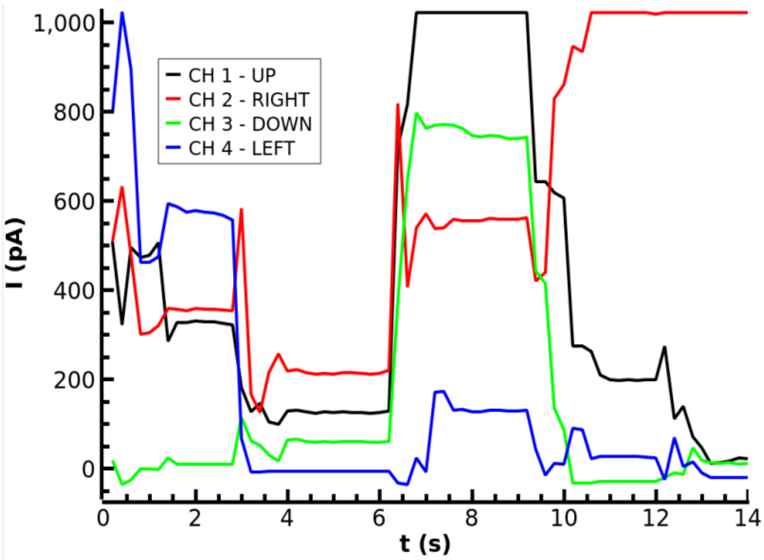

Fig. 8. Currents measured during transport optimization

The new optimization procedure is more efficient than the previous one. Using readings from our system, the beam is steered toward the collimator center until it passes through it.

The collimator shown in Fig. 2 was tested in-beam with currents of a few μA for approximately two hours at the TANDEM-FN 9 MV accelerator of IFIN-HH. After beam exposure, the collimator was inspected, and the deposited material did not increase leakage current between the segments and the guard structure. Secondary electron losses can be reduced by applying a negative voltage to the guard structure. This collimator will be used in future experiments preparation at IDS-ISOLDE and the TANDEM-FN 9 MV.

4. Conclusions

A low-cost system was developed to indicate when the beam is misaligned at the CERN IDS-ISOLDE setup. It has been validated and used during experiments preparation, reducing the time required for beam transport optimization. The picoammeter measures currents up to ±1 nA with 0.5 pA resolution and provides more than 5 samples/s per channel. The device can be easily integrated into beam-monitoring systems via USB and Wi-Fi. In addition, a segmented collimator with a guard structure was built and tested for future use at IDS-ISOLDE and the TANDEM-FN 9 MV accelerator from IFIN-HH. Future improvements aim for a smaller form factor and a 24-bit ADC to extend the input range.

Acknowledgements

I acknowledge support for this work by the Romanian IFA Grant CERN/ISOLDE and Nucleu Project No. PN 23 21 01 02.

REFERENCES

[1] *M. Gasior, R. Jones, T. Lefevre, H. Schmickler, K. Wittenburg*. Introduction to beam instrumentation and diagnostics. CERN, 2014. No. arXiv: 1601.04907, DOI: 10.5170/CERN-2014-009.23

[2] ***, The ISOLDE Radioactive Ion Beam facility website: https://isolde.cern/

[3] *R. Lica*. Development of the ISOLDE Decay Station and γ spectroscopic studies of exotic nuclei near the N= 20 "Island of Inversion". PhD Thesis, University "Politehnica" of Bucharest 2017, CDS Reference CERN-THESIS-2017-232

[4] *W. Burkhardt, M. Iacopini, P. Maranesi*, Picoammeter for Ion Chamber Spans Six Decades without Range Switching. *IEEE Transactions on Nuclear Science*, vol. **30**, no. 1, pp. 311-313, Feb. 1983, DOI: 10.1109/TNS.1983.4332276

[5] *M. Stagg.* "Design and Development of a Low-Cost Handheld Picoammeter" (2013). Honors Theses. 1432. https://repository.lsu.edu/honors_etd/1432

[6] *MN. Kamalmaz.* Picoampere Streaming Current Measuring Unit for a Microchip Biosensor. Uppsala University (2024). DiVA id: diva2:1872463

[7] *S. Epure, R. Belea, L. Frangu*. Low-cost picoammeter for dielectrics, 2013 IEEE 19th International Symposium for Design and Technology in Electronic Packaging (SIITME), Galati, Romania, 2013, pp. 95-98, DOI: 10.1109/SIITME.2013.6743651.

[8] *Deyang Yu, Junliang Liu, Yingli Xue, Mingwu Zhang, Xiaohong Cai, Jianjun Hu, Jinmei Dong, Xin Li.* A 128-channel picoammeter system and its application on charged particle beam current distribution measurements. *Rev. Sci. Instrum.* 1 November 2015; **86** (11): 115102. DOI: 10.1063/1.4934849

[9] *P. Intra, N. Tippayawong*. Development and Evaluation of a Faraday Cup Electrometer for Measuring and Sampling Atmospheric Ions and Charged Aerosols. *Particulate Science and Technology*, 2015, **33**(3), 257–263. DOI: 10.1080/02726351.2014.952392

[10] *Chao-Yang Zhou, Hong Su, Rui-Shi Mao, Cheng-Fu Dong, Yi Qian, Jie Kong*. An accurate low current measurement circuit for heavy iron beam current monitor. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 2012, **280**, 84-87, DOI: 10.1016/j.nimb.2012.01.033

[11] *Keithley*, Model 6485 Picoammeter Specifications Rev. B, download 20 Oct. 2025 https://download.tek.com/document/6485RevB_DocSpec.pdf

[12] *A. Al Mortuza*, et al. Pico-current measurement challenges and remedies: A review. Univers. J. Eng. Sci, 2017,Vol **5**, No: 57-63. DOI: 10.13189/ujes.2017.050401

[13] *P. Horowitz, W. Hill.* The Art of Electronics : The X-Chapters. Cambridge, United Kingdom , Cambridge University Press, 2020. Print. P289-230, ISBN: 9781108499941, DOI: 10.1017/9781108753029

[14] *J. Karki*. Active low-pass filter design. Texas Instruments, Application report SLOA049D july 2000 – revised february 2023, https://www.ti.com/lit/an/sloa049d/sloa049d.pdf

[15] *Microchip Technology Inc*. MCP3204/3208 – Datasheet Revision E (September 2008), https://ww1.microchip.com/downloads/en/devicedoc/21298e.pdf