Rate-induced aging effects on Parallel-Plate Avalanche Counter (PPAC) caused by heavy ion beams

Salvatore Di Carlo[a,1], Marco Cortesi[a], Iulia-Maria Harca[a]

[a] *Facility for Rare Isotope Beam, Michigan State University, 640 S Shaw Ln, East Lansing, 48824, MI, USA*

Abstract

The Facility for Rare Isotope Beams (FRIB) is one of the premier scientific user facilities for nuclear science with radioactive beams, capable of producing most (approximately 80%) of the isotopes expected to exist, from oxygen to uranium, at energies up to 200 MeV/u. With the increase in beam power from the present 10kW to the planned 400kW, FRIB experiments are about to enter a new era. An unprecedented rate capability as well as stable performance of all the planned instrumentation intended for beam diagnostics and beam tuning is required at the expected high beam intensities (>1 MHz). A summary of aging phenomena at high heavy-ion beam rates observed in the Advanced Rare Isotope Separator (ARIS) detectors for beam diagnostics, including Parallel Plate Avalanche Counters (PPAC) and plastic scintillation for time-of-flight measurements, is discussed. Current research and development project to mitigate rate-induced aging are presented.

Keywords: Parallel-plate avalanche counter, Heavy-ion detector, Heavy-ion beam tracking, Rare isotope beam physics, Low-pressure detector, Timing measurement, Aging effects.

1. Introduction

The Facility for Rare Isotope Beams (FRIB) [1] is a newly established national user facility funded by the Department of Energy (DOE), Office of Nuclear Physics (NP), that serves the scientific community by providing rare isotope beams for low-energy nuclear physics experiments.

Beam diagnostics and detectors for particle identification are used in the fragment separator (ARIS [2]) and in various beam lines at FRIB [3] to

[1] dicarlo@frib.msu.edu

assist in beam tuning before and during experiments. This enables the characterization of beam properties and transmission efficiency, provides event-by-event tracking and timing information for physics analysis, and facilitates stable long-term operation and appropriate machine protection. For instance, event-by-event particle position and angle measurements are performed using Parallel Plate Avalanche counters (PPAC) [4, 5, 6, 7].

The high beam intensities, up to 1 MHz, and the characteristics of the beam (from ^{18}O up to ^{238}U, often with tens of different isotopes simultaneously transported, with a typical energy of 200 MeV/u) pose strong demands on the performance and stability of diagnostics and detectors. Fast aging of thin electrode foils and other detector components, caused by high absorbed dose and beam rate-related secondary effects, has been observed in standard detector configurations at the present beam power of 10 kW. As a result of these effects, future plans to increase beam power to 400 kW within a few years are of concern in term of diagnostics performance [8].

This work describes a systematic study of the aging effects on different detector components caused by heavy-ion beams, mostly focusing on delay-line PPAC [9] used for tracking. Mitigation and further development projects for more robust devices in high-rate applications, radiation resistant materials, and better fabrication technologies are also presented.

2. Aging effects in PPACs

2.1. PPAC construction: material and design

Position-sensitive PPAC is a well-established and old detector technology that has been used extensively as a heavy-ion beam tracking system [9]. The design, fabrication procedure, and materials used for the construction of the present PPAC detectors at FRIB were developed during the era of the National Superconducting Cyclotron Laboratory (NSCL) [10]. The major difference between the NSCL and the FRIB PPACs is the readout scheme - the latter uses the delay-line method, which allows a rate capability two orders of magnitude larger than the resistive chain system implemented in the NSCL PPAC. The inner electrodes of the PPAC, consisting of a central cathode and two lateral anode foils, are made of stretched polypropylene (0.75μm thick). The foils are then coated with thin (150 nm) metal (gold or aluminum) layer using an electron-beam evaporator system. The external anode foils are segmented into strips characterized by a pitch of about 0.05 inch (1.27 mm) - one foil with strips along the vertical direction, and the other foil along the horizontal direction, to achieve position sensitivity. PPACs at FRIB are either operated in Isobutane (iC_4H_{10}) or Octafluoropropane (C_3F_8) at a pressure range 7-12 Torr. With the two external pressure windows made of aluminized Mylar (6 μm thick), the equivalent aluminum thickness for each PPAC is 9.0 μm.

2.2. Problems observed at high rate

Significant aging effects on the FRIB PPAC electrode foils were observed at high beam rates (>500 kHz/cm^2). As the electrodes gradually deteriorate, detection efficiency gradually declines.

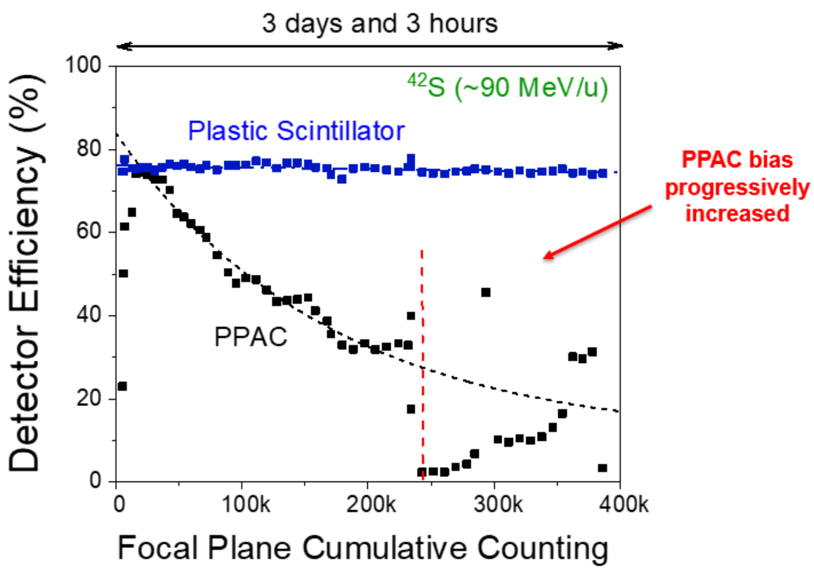

Figure 1: Comparison between detection efficiency of a thin (150 μm thick) plastic scintillator (blue graph) and a PPAC detector (black graph), irradiated with ^{42}S beam at about 90 MeV/u energy for several days. The beam rate exceeded 700 kpps and the detector.

Fig. 1 shows a comparison of detection efficiency measured on a thin (150 μm thick) plastic scintillator and a PPAC detector, both irradiated for several days with a ^{42}S beam, at an energy of about 90 MeV/u and a rate exceeding 700 kpps over a small area (about 1 cm^2). The detection efficiencies are displayed as a function of the cumulative counts of events recorded by the detectors at the focal plane of the S800 spectrometer. It should be noted that the total number of events in the S800 focal plane is only a tiny fraction of the total number of beam particles traversing the PPAC and the plastic scintillator. Partial detection efficiency was achieved by increasing the voltage bias on the PPAC anode, at the expense of a higher probability of sporadic energetic discharges that may cause rupture of the fragile electrode foils. For the above reasons, it is necessary to replace the electrode foils frequently to maintain the detector's full performance.

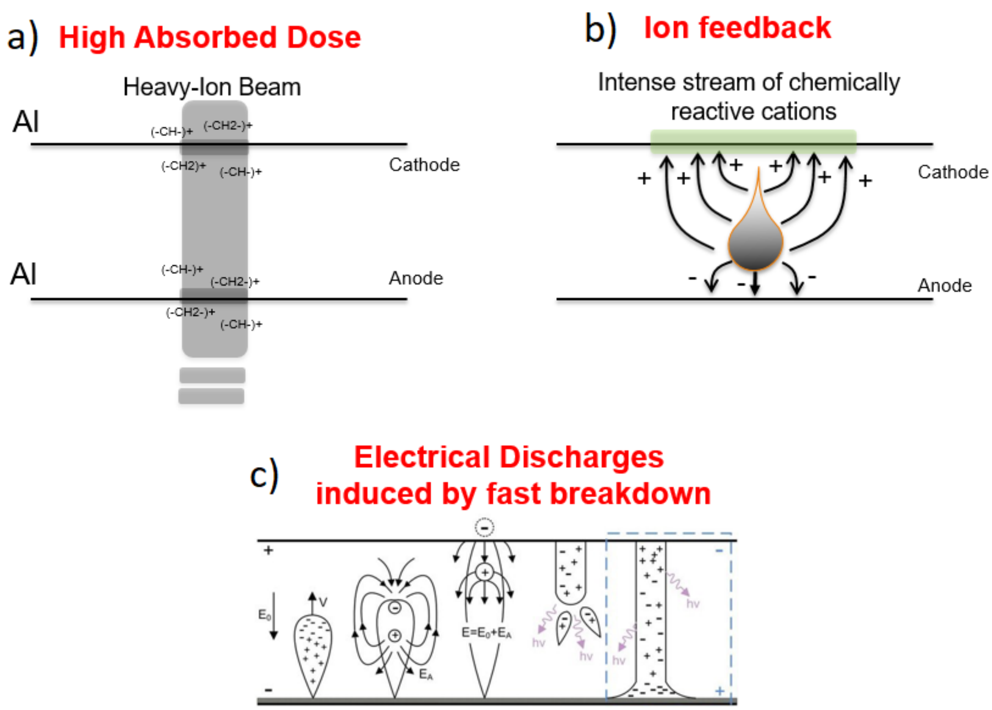

Figure 2: Schematic description of the aging effects causing PPAC performance to deteriorate over time due to: a) loss of mechanical properties in the polymer substrate, b) demetallization of the electrode due to ion back streaming, and c) violent streamer discharges.

We have identified three potential processes that might contribute to the degradation of detector components, each having its own unique impact under different operational conditions. They are schematically illustrated in Fig. 2.

The first process (Fig.2a) is responsible for the progressive degradation of the mechanical properties of the polymer (polypropylene) used as the electrode substrate. Several studies have demonstrated that in polypropylene, as well as a large variety of polymers generally, highly absorbed doses improve tensile strength while making them more brittle [11, 12] and more susceptible to rupture in case of discharges. These effects are driven by long polymer chain scissioning and free radical generation, leading to increased ultimate strength, decreasing maximum elongation and increasing Rockwell hardness [13, 14]. The loss of elasticity and the increase of brittleness make them prone to rupture when stimulated by mechanical vibrations (movement of the detector in and out of the beam) or during sporadic electric discharges.

In the second mechanism (Fig.2b), intense streams of ions are produced during the gas avalanche multiplication and flow towards the cathode electrode. The impact of ions on the electrode leads to a progressive demetallization of the foil [15, 16]. The process is essentially similar to that used in the Ion Beam Etching (IBE) technique [17]. The process of IBE involves the slow erosion of a surface caused by the bombardment of high-energy ions over time. As the process is entirely mechanical, it involves the transfer of momentum between the impinging ions and the surface atoms so that the latter gain sufficient momentum directed away from the surface to produce a net material loss, also known as sputtering. IBE can cause the etching of non-reactive metals and noble metals, including Au, Pt, Pd and others. Clearly the effects are strongly correlated to the operational condition of the PPAC detector, including beam rate and gas gain.

The third and final process (Fig.2c) that can damage the thin metal layer of the electrode, as well as the complete rupture of the electrode foil, is streamer discharges [18]. As in all gas avalanche detectors, the transition from proportional to streamer mode occurs once the accumulation of charge in the avalanche reaches a limit of 10^7-10^8 (Raether limit [19]). The consequence of a streamer discharge are twofold:

1. An ions plasma at an extreme high temperature develops towards the cathode electrode (cathode-directed streamer). The impact of the streamer on the electrode surface can cause metal layer evaporation.
2. Once the streamer is completely formed across the PPAC, the release of the energy accumulated in the detector occurs in the form of a violent electric discharge. The electric discharge can, therefore, lead to a complete rupture of the electrode foil.

Figure 3 illustrates a collection of different types of damage observed on the metal electrodes, resulted from the mechanisms described above. This includes gold-etching in the form of localized abrasion, circular or ring-shaped patterns (a); corrosion of aluminum surface (b); rupture due to discharges

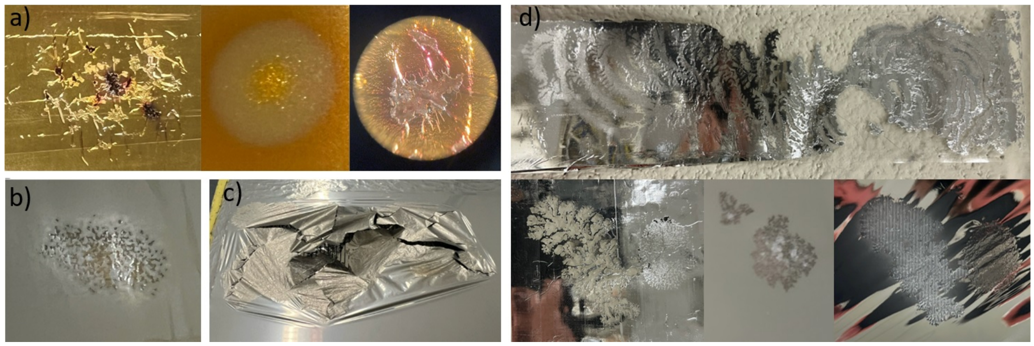

Figure 3: Photographs showing examples of different types of damages (a few cm^2 in size) observed on the metal electrodes of PPACs.

(c); electrical tree-like discharge structures, generally spreading over large surface areas (d).

3. Current projects to mitigate aging effect at high rate

To mitigate the change of the mechanical properties of the polypropylene substrate at high absorbed dose, more radiation hard polymers have been considered [20]. Kapton is an excellent alternative for its mechanical and radiation-hardening properties. However, there is no commercially available ultra thin (<1 μm) kapton film at present, so a novel technique for stretching thick kapton sheet must be developed to keep the total thickness of the detector below the acceptable value.

One of the main sources of PPAC performance loss over time is the etching/abrasion of the thin metal layer on the cathode electrode, caused by the high-temperature streamer formed during streamer discharge. Alternative metals to gold and aluminum, with higher melting points to mitigate evaporation, are likely to be tested as coatings for the cathode. These metals include chromium, silver and carbon. Further research activities involve foil conditioning (e.g., with ultraviolet (UV) light) to improve the metal-polypropylene adhesion and the use of multi-metal layers (e.g. chromium before aluminum or silver) to improve mechanical stability.

Another effective approach to reduce streamer-induced aging effects is the replacement of the uniform cathode foil with thin gold-plated tungsten wires, in a multi-wire proportional chamber configuration. Wires are generally avoided in the development of heavy-ion transmission detectors, as they induce an inhomogeneous response across the effective detector area [21]. A prototype is being developed by using a small diameter wire (12 μm) and a large pitch (1 mm), resulting in 98.8% optical transmission of the cathode wire, with minimal straggling induced on the beam. Wire-based PPAC will allow excellent timing properties and an improved long-term stability.

In parallel, the development of an Anti Discharge Unit (ADU), similar to the one proposed by ref. [22], has been carried out. The operational principle of the ADU comprises of a signal separator connected to the electrode that detects large discharge currents. Large currents, above a fixed threshold, drive a uni-vibrator to activate a power MOS-FET that functions as a switch. Subsequently, the bias voltage on the cathode is forcibly grounded and discharge is suppressed. A prototype will be available for further tests shortly.

Acknowledgments

Work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0023633, the State of Michigan, and Michigan State University. This manuscript was prepared with the support, encouragement, and suggestions provided by the FRIB members of the radiation detector lab, Beam Measurements and Instrumentation department (BIM), and the ARIS beam physicist group.

References

[1] J. Wei, et al., Accelerator commissioning and rare isotope identification at the Facility for Rare Isotope Beams, Mod. Phys. Lett. A 37 (09) (2022) 2230006.

[2] M. Hausmann, A. Aaron, A. Amthor, M. Avilov, L. Bandura, R. Bennett, G. Bollen, T. Borden, T. Burgess, S. Chouhan, V. Graves, W. Mittig, D. Morrissey, F. Pellemoine, M. Portillo, R. Ronningen, M. Schein, B. Sherrill, A. Zeller, Design of the advanced rare isotope separator aris at frib, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 317 (2013) 349–353, xVIth International Conference on ElectroMagnetic Isotope Separators and Techniques Related to their Applications, December 2–7, 2012 at Matsue, Japan.

[3] M. Portillo, B. Sherrill, Y. Choi, M. Cortesi, K. Fukushima, M. Hausmann, E. Kwan, S. Lidia, P. Ostroumov, R. Ringle, M. Smith, M. Steiner, O. Tarasov, A. Villari, T. Zhang, Commissioning of the advanced rare isotope separator aris at frib, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 540 (2023) 151–157.

[4] J. Christiansen, Self-quenching parallel-plate vapor counter at voltages below the static breakdown field strength, Z. angew. Physik 4 (1952) 326.

[5] J. Christiansen, G. Hempel, H. Ingwersen, W. Klinger, G. Schatz, W. Witthuhn, Investigation of delayed fission in 236 U, Nucl. Phys. A 239 (1975) 253–259.

[6] H. Stelzer, A Large Area Parallel Plate Avalanche Counter, Nucl. Instrum. Meth. 133 (1976) 409–413. doi:10.1016/0029-554X(76)90423-7.

[7] W. Seidel, H.-G. Ortlepp, F. Stary, H. Sodan, Double-grid avalanche counter with large dynamic range, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 273 (2) (1988) 536–540.

[8] J. Wei, C. Alleman, H. Ao, B. Arend, D. Barofsky, S. Beher, G. Bollen, N. Bultman, F. Casagrande, W. Chang, Y. Choi, S. Cogan, P. Cole, C. Compton, M. Cortesi, J. Curtin, K. Davidson, S. D. Carlo, X. Du, K. Elliott, B. Ewert, A. Facco, A. Fila, K. Fukushima, V. Ganni, A. Ganshyn, T. Ginter, T. Glasmacher, A. Gonzalez, Y. Hao, W. Hartung, N. Hasan, M. Hausmann, K. Holland, H. Hseuh, M. Ikegami, D. Jager, S. Jones, N. Joseph, T. Kanemura, S. Kim, C. Knowles, T. Konomi, B. Kortum, N. Kulkarni, E. Kwan, T. Lange, M. Larmann, T. Larter, K. Laturkar, M. LaVere, R. Laxdal, J. LeTourneau, Z.-Y. Li, S. Lidia, G. Machicoane, C. Magsig, P. Manwiller, F. Marti, T. Maruta, E. Metzgar, S. Miller, Y. Momozaki, M. Mugerian, D. Morris, I. Nesterenko, C. Nguyen, P. Ostroumov, M. Patil, A. Plastun, L. Popielarski, M. Portillo, A. Powers, J. Priller, X. Rao, M. Reaume, S. Rodriguez, S. Rogers, K. Saito, B. Sherrill, M. Smith, J. Song, M. Steiner, A. Stolz, O. Tarasov, B. Tousignant, R. Walker, X. Wang, J. Wenstrom, G. West, K. Witgen, M. Wright, T. Xu, Y. Yamazaki, T. Zhang, Q. Zhao, S. Zhao, P. Hurh,

S. Prestemon, T. Shen, Technological developments and accelerator improvements for the frib beam power ramp-up, Journal of Instrumentation 19 (05) (2024) T05011.

[9] S. Di Carlo, M. Cortesi, Parallel-plate avalanche counters for heavy-ion beam tracking: History and mysteries, Phys. Rev. Accel. Beams 27 (2024) 044801.

[10] D. Swan, J. Yurkon, D. Morrissey, A simple two-dimensional ppac, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 348 (2) (1994) 314–317.

[11] J. Cassidy, S. Nesaei, R. McTaggart, F. Delfanian, Mechanical response of high density polyethylene to gamma radiation from a cobalt-60 irradiator, Polymer Testing 52 (2016) 111–116.

[12] I. A. E. Agency, Advances in Radiation Chemistry of Polymers: Proceedings of a Technical Meeting Held in Notre Dame, Indiana, USA, 13-17 September 2003, IAEA-TECDOC, International Atomic Energy Agency, 2004.

[13] J. Polvi, K. Nordlund, Irradiation effects in high-density polyethylene, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 312 (2013) 54–59.

[14] A. A., C. M.C., C. X., D. C., D. M.S., U. P., A.-S. M., Polymerization reactions and modifications of polymers by ionizing radiation, Polymers (Basel) 12 (12) (2020) 2877.

[15] D. K. Avasthi, G. K. Mehta, Materials Engineering with Swift Heavy Ions, Springer Netherlands, Dordrecht, 2011, pp. 142–230.

[16] N. Chkhalo, M. Mikhailenko, A. Mil'kov, A. Pestov, V. Polkovnikov, N. Salashchenko, I. Strulya, M. Zorina, S. Zuev, Effect of ion beam etching on the surface roughness of bare and silicon covered beryllium films, Surface and Coatings Technology 311 (2017) 351–356.

[17] R. LEE, Chapter 11 - ion-beam etching (milling), in: N. G. Einspruch, D. M. Brown (Eds.), Plasma Processing for VLSI, Vol. 8 of VLSI Electronics Microstructure Science, Elsevier, 1984, pp. 341–364.

[18] S. Nijdam, J. Teunissen, U. Ebert, The physics of streamer discharge phenomena, Plasma Sources Science and Technology 29 (10) (2020) 103001.

[19] P. Fonte, V. Peskov, B. Ramsey, The fundamental limitations of high-rate gaseous detectors, in: 1998 IEEE Nuclear Science Symposium Conference Record. 1998 IEEE Nuclear Science Symposium and Medical Imaging Conference (Cat. No.98CH36255), Vol. 1, 1998, pp. 91–95 vol.1.

[20] L. McKeen, The Effect of Radiation on Properties of Polymers, Plastics Design Library, Elsevier Science, 2020.

[21] C. Scheidenberger, T. Stöhlker, W. Meyerhof, H. Geissel, P. Mokler, B. Blank, Charge states of relativistic heavy ions in matter, Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms 142 (4) (1998) 441–462.

[22] Y. S. et al., Status of beam line detectors for the bigrips fragment separator at riken ri beam factory: issues on high rates and resolution, JPS Conf. Proc. 6 (2015) 030124.