ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-WEP14

BEAM DIAGNOSTICS IN ARIS TO INVESTIGATE WEDGE DEFECT AT FRIB*

D. Kahl†, E. Choi, M. Cortesi, S. Di Carlo, A. C. Dombos, K. Fukushima, M. Hausmann, D. Jacobson, E. Kwan, P. Manwiller, M. Portillo, L. Privatte, X. Rao, S. Rodriguez, B. M. Sherrill, M. K. Smith, M. Steiner, O. B. Tarasov, E. Wakai

Facility for Rare Isotope Beams, Michigan State University, East Lansing, MI, USA

Abstract

The Facility for Rare Isotope Beams (FRIB), operating at Michigan State University since 2022, produces a variety of nuclear species via projectile fragmentation or fission. Heavy ions are accelerated by the FRIB LINAC to energies of 110–290 MeV/u which impinge on mm-thick graphite targets to make the RIs inflight. The resulting cocktail of ions are separated and purified with the Advanced Rare Isotope Separator (ARIS). Magnetic separation of individual isotopes is accomplished with a wedge-shaped degrader that preserves achromaticity. As the first stage of ARIS involves a momentum compression of $k \approx 3$, the preseparator wedge geometric cross section is more complex than a simple isosceles triangle, having a parabolic shape to reduce aberrations. Here we report a comparison of different wedge materials using standard beam diagnostics from viewers and position-sensitive detectors. Particular attention is paid to the calibration procedure for parallel plate avalanche counters (PPACs).

INTRODUCTION

The Facility for Rare Isotope Beams (FRIB) is a DOE Office of Science User Facility that uses a variety of means to produce beams of rare isotopes (RIs) for experimental users. Using one of several ion sources coupled to a linear accelerator, we produce heavy-ion beams that impinge on a rotating carbon target, producing large cocktails of RIs inflight either by projectile fragmentation [1,2] or fission [3,4]. The cocktail beam is guided and purified by the Advanced Rare Isotope Separator (ARIS) [5] using momentum compression of $k \approx 3$ [6] to the users' specifications. Employing achromatic optics with a curved degrader at a dispersive focal plane, one can achieve significant purification of the fragment of interest (FOI) and nearby isotones [7,8], which for higher-energy beams is a wedge-shaped degrader (now simply called a 'wedge'). Wedge inhomogeneities from imperfect machining or within the material itself (e.g., bubbles, density variations) can adversely affect the beam's phase space, resulting in a larger beam spot size and lower transmission.

The locations of the preseparator wedge (PSw) and the diagnostics box 2 wedge (DB2w) in ARIS, along with locations of beam diagnostics equipment, are shown elsewhere in these proceedings (Fig. 2 of Ref. [9]). Wedges are commonly made out of aluminum for their low proton number (Z), abundance, thermal conductivity, and machinability; we have considered other materials, but here we focus on wedges made from aluminum alloys. At FRIB, we make the wedges in house [10], where we have used the alloys AL6061 and AL7075 in the present study. We report on the findings with beam diagnostics that AL6061 is more consistent for minimizing inhomogeneities of the two materials.

METHODS

Beam Diagnostics

When the beam is reasonably intense ($\gtrsim 10^4$ Hz) with a high purity, viewers (which stop the beam) and cameras are employed to directly look at the phosphorescence. The scintillator coating is made from rare earth (red) phosphor (Y_2O_2S:Eu). Because the cameras cannot be on the beam axis, a software transformation is performed to emulate the beam's view and to make quantitative measurements of the beam spot using the Viola package [11], developed at FRIB. Before each experiment, users confirm the fiducials used to make the transformation on each camera/viewer (*e.g.*, a camera's position might change by touching it during maintainence).

For cases with lower intensity or where the phase space may be significantly different for the FOI than the beam as a whole, ARIS has parallel plate avalanche counters (PPACs) installed at a number of focal points along the beam path. These delay-line PPACs [12,13] can be used for tuning and/or during experiments to track each ion event-by-event to assist in determining the particle identification (PID) by the ΔE-Bρ-ToF method (for details, see the Appendix of [14]). Here we layout a simple calibration scheme for each PPAC using a mask and an alpha source holder (ASH) mounted to the mask, which is easily able to provide the conversion from time to distance (including parallax), the central position (0,0), and orientation of each detector, shown in Fig. 1.

Beam Model

The quality of the wedges is evaluated using beam diagnostic equipment in conjunction with the $\mathrm{LISE}^{++}_{cute}$ code [15,16]. $\mathrm{LISE}^{++}_{cute}$ predicts the beam's phase space under ideal conditions and quantifies deviations caused by user-defined inhomogeneities, specified either as absolute values or percentages.

* 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.
† kahl@frib.msu.edu

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-WEP14

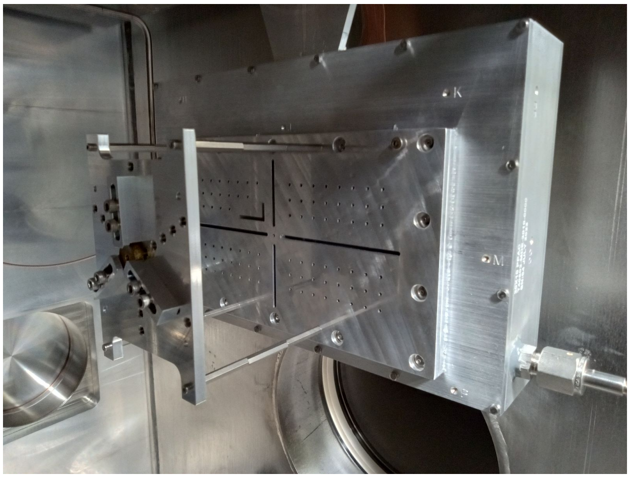

Figure 1: Photograph of a 20 × 10 cm^2 PPAC in ARIS with a mask, spacers, and ASH during calibration (see text for details). Here the spacer length (93 mm) is around half of what we have used (173 mm to minimize parallax) to clearly visualize the setup. The mask makes a crosshair centered at (0,0), an 'L' shape to determine orientation, and holes at regular intervals to check for any irrelgularities. The ASH is a collimator and ensures the radiation is centered on the PPAC, and the PPAC and specific positions on the mask are independently checked against the beamline position by surveying.

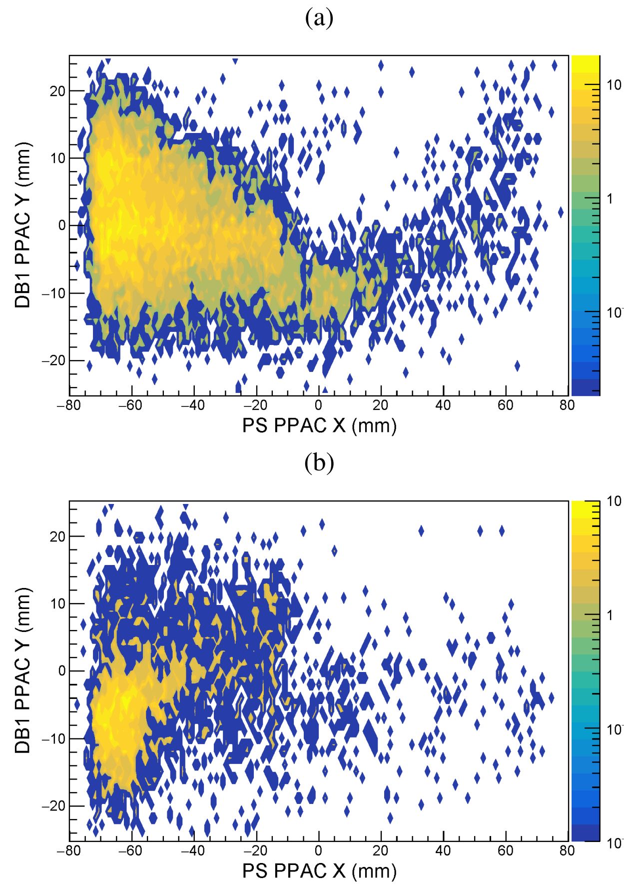

Figure 2: Tracks shown in PS PPAC$_{0,1}$ X (dispersive) vs. DB1 PPAC$_{0,1}$ Y (achromatic) for (a) a linear wedge and (b) for an HO, parabolic-shaped wedge. Software gates are applied in other detectors for the FOI, ^{44}S. Color depth is logarithmic. We can see that the HO wedge shows less systematic deviation from achromaticity.

RESULTS

Due to momentum compression, the PSw design for each rare isotope (RI) production is typically unique in thickness, angle, and shape—especially when higher-order (HO) effects are considered. As a result, the PSw often needs to be replaced for each experiment, and in some cases, multiple PSws are required within a single experiment to accommodate different RI beams. Here we show the effect of a linear wedge compared to an HO wedge at the PSw position in Fig. 2. The effort of changing the PSw in a high radiation zone is justified based on the excellent phase space produced with an HO wedge.

Until recently, we had been using AL7075 since it was determined AL5083 has large density variations [10]. We began noticing wedge uniformity issues with AL7075 as well, shown in Fig. 3. Fitting both the DB2 wedges with a gaussian function, LISE$^{++}_{cute}$ predicted the 'good' wedge had <10 µm nonuniformity, while the 'bad' wedge had greater than 13 µm nonuniformity. It was hypothesized that density non-uniformity due to inclusions in AL7075 from the constituents, including of iron group elements like Mn, Cu, Zn in the alloy, could be one source of the problem.

We subsequently switched to the AL6061 alloy, which avoids the presence of higher-Z elements and is expected to have a more uniform density throughout the material. During a production test of ^{29}Mg, we were able to use both AL7075 and AL6061 alloys at PSw and DB2w positions; it is shown in Table 1 that AL6061 at both PSw and DB2w gives a higher RI yield. A comparison of two DB2 wedges made from the AL6061 alloy with a ^{48}Ca beam during another experiment is shown in Fig. 4. A quick glance suggests Fig. 4(b) has significantly more non-uniformity than Fig. 4(a); however, the distance over the stopping range (d/R), which should be $0.5 < d/R$, was significant in both cases, and we observed no difference in these two batches in ARIS.

Table 1: ^{29}Mg Rates in ARIS with Different Wedge Combinations

PSw alloy	DB2w alloy	Rate (pps/pnA)
AL6061	AL6061	1.90 × 10^4
AL6061	AL7075	1.58 × 10^4
AL7075	AL6061	1.45 × 10^4
AL7075	AL7075	1.45 × 10^4

CONCLUSIONS

At FRIB, we are continuously updating the quality of our RI beams in terms of intensity, purity, and phase space de-

16th International Conference on Heavy Ion Accelerator Technology, East Lansing, MI, USA JACoW Publishing
ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-WEP14

(a)

(b)

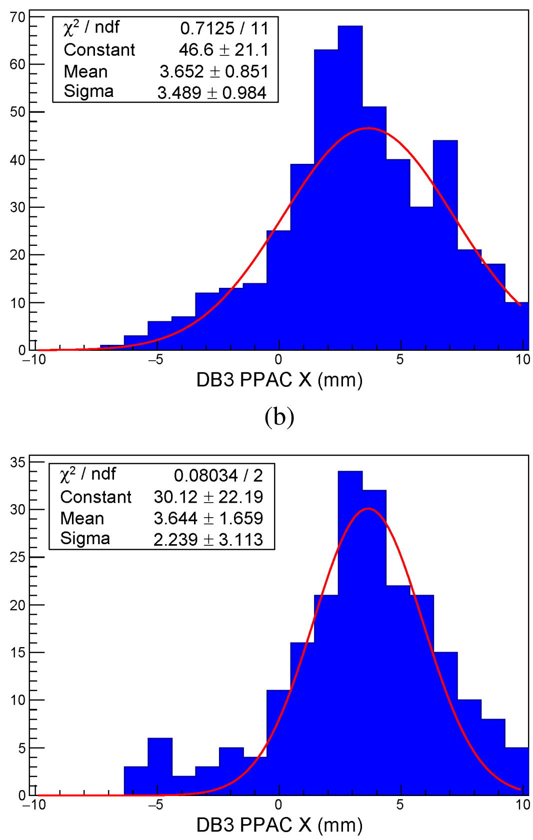

Figure 3: Tracks shown in DB3 $PPAC_{0,1}$ X projected backwards to an upstream 20 mm slit, where the beam was focused. The FOI was off-center by ~ 3.5 mm in the measurements. The FOI is ^{104}Sn (purity 0.3 ~ 0.4%) for RI beams in the neutron-deficient tin region [17] and statistics in ARIS are limited. Both the wedges are made from AL7075, but the one shown in (a) had more inhomogeneities than (b).

(a)

(b)

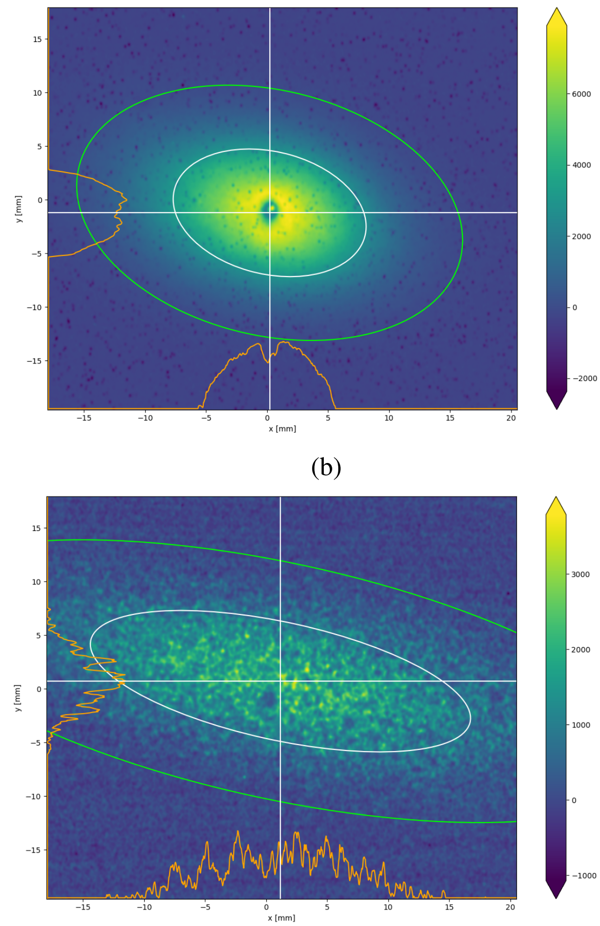

Figure 4: Comparison of beam spots by Viola for AL6061 wedges nominally (a) 5.0 mm with $\sigma = 2.7$ and (b) 6.069 mm with $\sigma = 5.2$ on the same axis scale. The white line is a 3σ ellipse. The wedge materials were made in different batches, and optical inspection after the experiment showed more surface flaws on the (b) side wedge; however, the thickness differences over the surface were all good to 1 µm. The distance over range (d/R) in LISE$^{++}_{cute}$ is (a) $d/R = 0.742$ and (b) $d/R = 0.903$; therefore, even with energy straggling turned off and perfectly homogeneous wedges results in $\sigma = 5.3$ mm for (b).

livered to users. The material and manufacturing quality of wedges used at dispersive focal planes is critically important, even when the same alloy is used. We are able to determine a given wedge's quality with beam diagnostics in ARIS, but it is not the most feasible option for characterizing wedges owing to the manpower and cost. In the future, we will continue to make improvements in wedge selection material and ways to test their uniformity.

ACKNOWLEDGMENTS

D.K. thanks Seiya Hayakawa for insightful discussions on PPAC calibration.

REFERENCES

[1] I. Tanihata *et al.*, "Measurements of interaction cross sections and nuclear radii in the light p-shell region", *Phys. Rev. Lett.*, vol. 55, pp. 2676–2679, 1985. `doi:10.1103/PhysRevLett.55.2676`

[2] O. B. Tarasov *et al.*, "Observation of New Isotopes in the Fragmentation of ^{198}Pt at FRIB", *Phys. Rev. Lett.*, vol. 132, no. 7, p. 072 501, 2024. `doi:10.1103/PhysRevLett.132.072501`

[3] M. Bernas *et al.*, "Discovery and cross-section measurement of 58 new fission products in projectile-fission of 750·A MeV ^{238}U", *Phys. Lett. B*, vol. 415, no. 2, pp. 111–116, 1997. `doi:10.1016/S0370-2693(97)01216-1`

[4] P. N. Ostroumov *et al.*, "Acceleration of uranium beam to record power of 10.4 kW and observation of new isotopes at Facility for Rare Isotope Beams", *Phys. Rev. Accel. Beams*, vol. 27, no. 6, p. 060 101, 2024. `doi:10.1103/PhysRevAccelBeams.27.060101`

ISBN: 978-3-95450-260-8 ISSN: 2673-5547 doi: 10.18429/JACoW-HIAT2025-WEP14

[5] M. Hausmann *et al.*, "Design of the Advanced Rare Isotope Separator ARIS at FRIB", *Nucl. Instrum. Methods Phys. Res. Sect. B*, vol. 317, pp. 349–353, 2013. doi:10.1016/j.nimb.2013.06.042

[6] L. Bandura *et al.*, "Fragment separator momentum compression schemes", *Nucl. Instrum. Methods Phys. Res. Sect. A*, vol. 645, no. 1, pp. 182–186, 2011. doi:10.1016/j.nima.2010.12.015

[7] J. P. Dufour *et al.*, "Projectile fragments isotopic separation: Application to the lise spectrometer at GANIL", *Nucl. Instrum. Methods Phys. Res. Sect. A*, vol. 248, pp. 267–281, 1986. doi:10.1016/0168-9002(86)91008-9

[8] R. Anne, D. Bazin, A. C. Mueller, J. C. Jacmart, and M. Langevin, "The achromatic spectrometer LISE at GANIL", *Nucl. Instrum. Methods Phys. Res. Sect. A*, vol. 257, no. 2, pp. 215–232, 1987. doi:10.1016/0168-9002(87)90741-8

[9] M. Portillo *et al.*, "Rare-isotope production optics of ARIS preseparator", presented at HIAT'25, East Lansing, MI, USA, Jun. 2025, paper FRA02, this conference.

[10] X. Rao *et al.*, "Operation status of frib wedge systems and plan for power ramp up", in *Proc. 15th International Particle Accelerator Conference (IPAC'24)*, Nashville, TN, USA, pp. 3545–3548, 2024. doi:10.18429/JACoW-IPAC2024-THPR24

[11] K. Fukushima, "Viola (online viewer application)", https://github.com/kryv/viola/.

[12] H. Kumagai, A. Ozawa, N. Fukuda, K. Sümmerer, and I. Tanihata, "Delay-line PPAC for high-energy light ions", *Nucl. Instrum. Methods Phys. Res. Sect. A*, vol. 470, pp. 562–570, 2001. doi:10.1016/S0168-9002(01)00804-X

[13] S. Di Carlo and M. Cortesi, "Parallel-plate avalanche counters for heavy-ion beam tracking: History and mysteries", *Phys. Rev. Accel. Beams*, vol. 27, no. 4, p. 044 801, 2024. doi:10.1103/PhysRevAccelBeams.27.044801

[14] O. B. Tarasov *et al.*, "Production of very neutron-rich nuclei with a ^{76}Ge beam", *Phys. Rev. C*, vol. 80, no. 3, p. 034 609, 2009. doi:10.1103/PhysRevC.80.034609

[15] O. B. Tarasov and D. Bazin, "LISE++: Radioactive beam production with in-flight separators", *Nucl. Instrum. Methods Phys. Res. Sect. B*, vol. 266, pp. 4657–4664, 2008. doi:10.1016/j.nimb.2008.05.110

[16] O. B. Tarasov *et al.*, "$\text{LISE}_{cute}{}^{++}$, the latest generation of the LISE+$^{+}$ package, to simulate rare isotope production with fragment-separators", *Nucl. Instrum. Methods Phys. Res. Sect. B*, vol. 541, pp. 4–7, 2023. doi:10.1016/j.nimb.2023.04.039

[17] C. M. Ireland *et al.*, "High-precision mass measurement of ^{103}Sn restores smoothness of the mass surface", *Phys. Rev. C*, vol. 111, no. 1, p. 014 314, 2025. doi:10.1103/PhysRevC.111.014314