PROGRESS ON IMPLEMENTATION OF A VARIABLE WEDGE FOR FRIB ARIS*

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Abstract

A variable wedge system is being developed for the Facility for Rare Isotope Beams (FRIB)-Advanced Rare Isotope Separator (ARIS) facility to provide flexible control of beam energy loss through independently adjustable wedge angle and center thickness. This research evaluates two parallel strategies: a multi-material six-piece solid wedge system and a liquid-filled wedge system. For the solid wedge, the control model and optimization algorithms have been developed and verified, with systematic testing confirming automated control across a 1–20 mrad range. Current efforts focus on exploring sub-mrad regimes (<1 mrad). To address fabrication limitations associated with very thin wedges, a multi-material method was developed in which materials with different densities are selected while maintaining constant areal density. This approach scales the effective thickness range by the density ratio, improving achievable thickness resolution and reducing deviations between calculated and experimentally achievable equivalent wedge configurations. Computational efficiency was further improved by using an L_∞-based trajectory solver to minimize the maximum coordinated actuator displacement. This framework is currently being integrated into the fragment separator simulation code LISE++. In parallel, a liquid-filled wedge model was developed, utilizing bellows-integrated cylindrical housing to enable continuous density tuning alongside adjustable wedge geometry. Together, these developments provide a robust basis for enhancing rare isotope beam delivery at FRIB.

INTRODUCTION

The Advanced Rare Isotope Separator (ARIS) at FRIB utilizes wedge-shaped degraders to provide momentum-dependent energy loss for beam purification [1]. Modern experiments increasingly demand real-time adjustments of wedge angle and thickness [2]. The core design challenge lies in achieving a target areal density (ρ·t) that depends on beam transverse position, where ρ is the material density and t is the path length.

A major limitation of conventional single-material wedge systems appears in the small-angle regime, where fabrication and positioning constraints reduce achievable thickness resolution. Another consideration is that each experiment requires a different central thickness and angle. Currently, each wedge set is fabricated separately, leading to discrete jumps in beam parameters rather than continuous tuning.

To address these limitations, this work investigates two parallel strategies:

Multi-material Six-piece Solid Wedge: A multi-material approach is explored to improve achievable thickness resolution in the small-angle regime while maintaining the required areal density.

Liquid-filled Wedge: A bellows-integrated liquid wedge concept is investigated as a continuously tunable alternative to conventional solid wedge systems.

Both systems incorporate L_∞ trajectory optimization to manage vacuum thermal loads. The corresponding control framework is being integrated into the LISE++ framework [3] to provide a standardized utility for the global research community.

MULTI-MATERIAL SIX-PIECE SOLID WEDGE

Mechanical Architecture and Material Strategy

The six-piece variable wedge consists of three independently movable wedge pairs that combine to generate an effective linear thickness gradient along the beam axis [4]. Two quadratic-profile wedge pairs (200 mm long) are used for angle generation, while a complementary linear-profile pair (300 mm long) provides independent center-thickness compensation.

To improve achievable resolution in the small-angle regime, a multi-material strategy is employed. The quadratic wedge pairs are fabricated from materials with distinct densities, typically Al6061 (UNS A96061) and epoxy, allowing the system to optimize angular resolution for different experimental conditions.

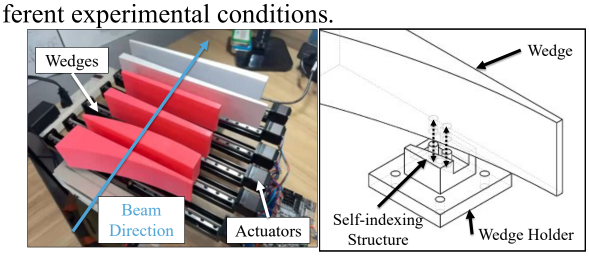

Figure 1: (a) 3D-printed prototype of the six-piece variable wedge system and (b) SolidWorks model of the self-indexing wedge-holder interface.

The mechanical design incorporates a simplified self-indexing interface between the wedge holders and wedge

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elements using circular alignment features to improve assembly repeatability while minimizing additional structural material. A 3D-printed prototype and SolidWorks model are shown in Fig. 1.

Advanced Control Logic and Path Optimization

The control framework was extended to provide automated high-precision wedge positioning under mechanical motion constraints. Building upon previous simulation studies [5], the system converts target wedge angle and thickness parameters into coordinated multi-axis actuator motion commands.

A key refinement is the implementation of an L_∞-norm trajectory optimization solver. For each targeted operating point, multiple candidate actuator configurations are evaluated for the six coordinated axes (XYZABC). By minimizing the maximum actuator displacement,

$$min\|\Delta x\|_\infty = min(max|\Delta x_i|)\ . \qquad (1)$$

The solver reduces coordinated actuator travel and distributes motion more evenly across the system, reducing concentrated actuator wear and limiting thermal loading during vacuum operation.

Key Features

The major operational features of the control framework are summarized below:

- Dual Operating Modes: **Batch Mode**: Automated execution of predefined experimental sequences using uploaded datasets. **Single-Point Mode**: Real-time parameter input for interactive beam tuning.
- Manual Fine-tuning: Incremental actuator adjustment capability is provided for experimental correction and compensation of beam-condition variations
- Simulation Mode: A virtual operating mode enables feasibility evaluation and trajectory computation without physical actuator motion.
- L_∞ Optimization: The trajectory solver evaluates all valid actuator configurations and selects the solution that minimizes the maximum coordinated actuator displacement.

THE LIQUID-FILLED VARIABLE WEDGE SYSTEM

Conceptual Design Principle

The Liquid-filled Variable Wedge System is being investigated as a continuously tunable alternative to conventional solid wedge systems. The design utilizes a sealed cylindrical chamber filled with liquid, where the effective wedge geometry is defined by thin entrance and exit windows. Unlike solid wedges, the liquid-filled approach introduces fluid density as an additional tuning parameter for beam energy loss.

Mechanical Layout and Control Strategy

The current conceptual design incorporates a bellows-integrated chamber with a dual-actuator mechanism that independently controls wedge angle and center thickness through coordinated motion of the movable window. A SolidWorks model of the assembly is shown in Fig. 2.

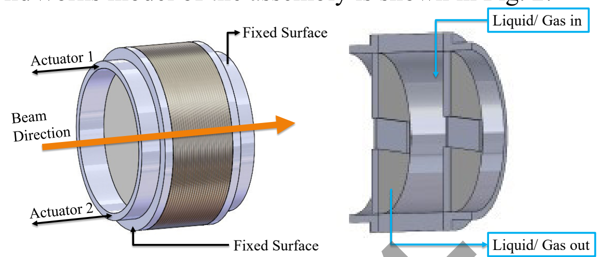

Figure 2: SolidWorks model of the liquid wedge assembly: (a) external view and (b) cross-sectional view. The bellows enables adjustable angle and thickness.

Window Integrity and Structural Challenges

A major engineering challenge is minimizing window-induced beam interference while maintaining structural integrity under pressure loading. Preliminary ANSYS FEA studies showed that thicker windows (~1.4 mm) provide mechanically stable operation. However, such thicknesses introduce excessive beam interaction and reduce the intended dominance of the liquid energy-loss medium. Current efforts therefore focus on micron-scale (~10 µm) window designs to minimize solid-material effects on the beam.

Volume Compensation and Pressure Stability

Internal volume fluctuations caused by wedge thickness adjustments are mitigated by a secondary bellows-based side tank. This compliant buffer stabilizes internal pressure, preventing mechanical deformation of the windows. The main chamber and reservoir are linked via dedicated ports with high-vacuum valves; when closed, these establish a static, sealed environment. This closed-loop configuration maintains the precise liquid volume required for a stable energy-loss profile during operation.

Pressure Compensation and Current Development

To avoid excessive window deflection, the operational strategy aims to maintain near-zero differential pressure across the windows by simultaneously evacuating both the wedge chamber and the accelerator vacuum environment. Candidate liquids are being evaluated based on vacuum compatibility, density requirements, and boiling stability under reduced-pressure conditions. Experimental validation of the pressure-balancing concept is currently under development.

RESULT DISCUSSION AND FUTURE TASKS

Six-Piece Variable Wedge System Performance and Operational Constraints

The six-piece variable wedge system has progressed to full-scale physical benchmarking. Experimental results show that the L_∞-optimized control logic effectively reduces positioning error across the operational range.

A key observation is that Al6061 and epoxy wedges exhibit different performance characteristics in different angular regimes. For the epoxy case, target angles were scaled by the material density ratio relative to the Al6061 reference configuration to preserve equivalent areal-density conditions. Although the plotted angular ranges differ numerically, the two datasets correspond to equivalent effective wedge conditions (see Fig. 3).

Aluminum provides sufficient energy loss over the primary 1–20 mrad operating range but exhibits increased deviation in the low-angle regime due to its higher density and actuator resolution limits. In contrast, the lower-density epoxy wedges improve achievable tuning resolution in equivalent sub-mrad operating conditions (see Fig. 4).

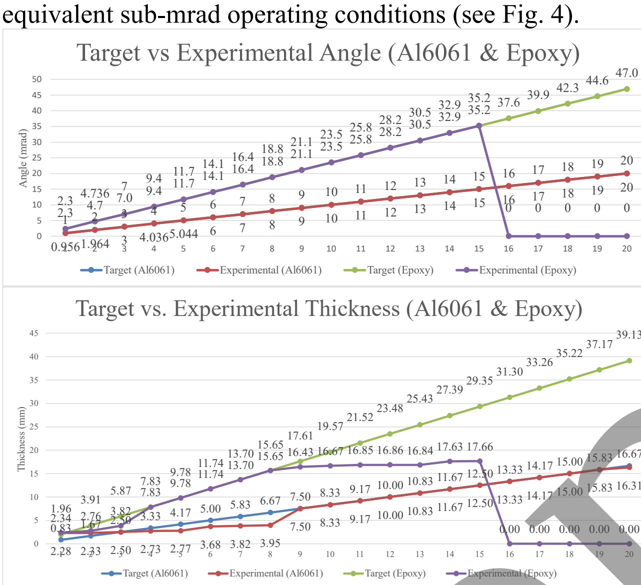

Figure 3: Target vs. experimental angle and thickness for (a) Al6061 and (b) epoxy over the equivalent 1–20 mrad operating range. The epoxy case was density-scaled relative to the Al6061 reference configuration.

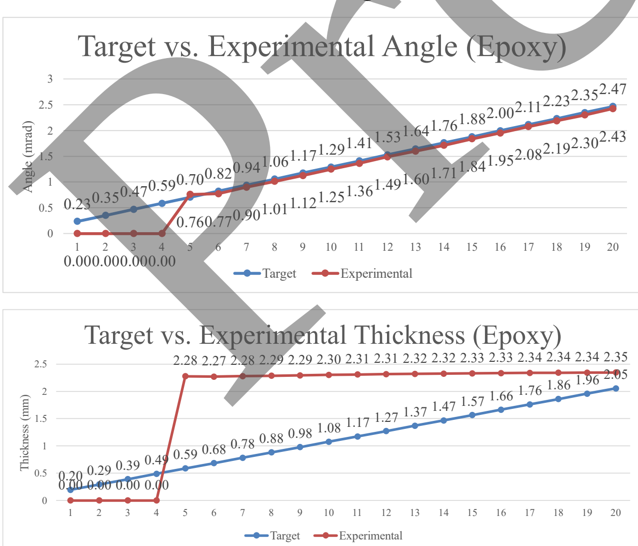

Figure 4: Target vs. experimental (a) angle & (b) thickness for epoxy for < 1 mrad.

While angular precision meets design targets, measured center-thickness deviations remain slightly above expectations due to machining tolerances and discrete actuator motion. Current efforts focus on developing a compensation algorithm that independently accounts for material density and angular range to improve achievable thickness precision. The resulting correction framework is planned for future integration into LISE++.

Liquid-filled System: Integration and Installation Challenges

The primary challenge for practical implementation of the liquid-filled wedge system is maintaining the integrity of the ultra-thin windows. To minimize beam interaction, the current design targets micron-scale window thicknesses; however, such thin foils cannot safely withstand atmospheric pressure differentials during conventional installation or liquid filling procedures (see Fig. 5).

To address this limitation, a pressure-balanced installation strategy is being developed. Instead of filling the wedge under atmospheric conditions, the wedge assembly and DB2 vacuum chamber are evacuated simultaneously to maintain near-zero differential pressure across the windows during pump-down. After reaching the target vacuum condition, degassed liquid is introduced into the pre-evacuated wedge chamber through a controlled filling interface.

A bellows-based compensation structure is incorporated to accommodate internal volume variation during liquid transfer while minimizing pressure loading on the windows. Current efforts focus on validating pressure-equalization strategies for stable micron-scale window operation under vacuum conditions.

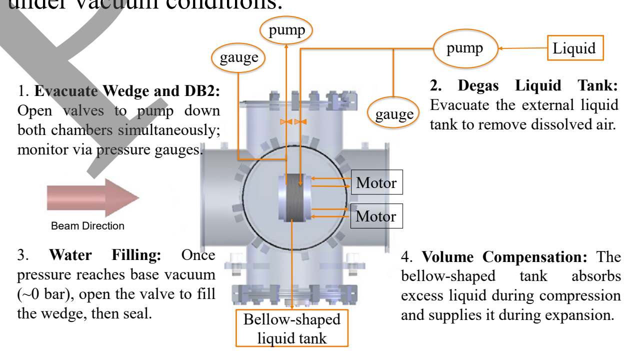

Figure 5: Schematic of the pressure-balanced filling system for the liquid wedge.

SUMMARY

The multi-material six-piece wedge system demonstrated automated control over the 1–20 mrad operating range, with ongoing efforts focused on improving sub-mrad tuning precision and thickness compensation. In parallel, the liquid-filled wedge concept established a preliminary framework for pressure-balanced operation of micron-scale window structures under vacuum conditions. Future work will focus on experimental validation and LISE++ integration.

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