Accelerator Target Slider – A Temperature Controlled Multi-sample Irradiation System

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REACTOR MATERIALS TESTING LAB
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Introduction

The Queen's Reactor Materials Testing Laboratory (RMTL) houses an 8MeV tandem accelerator, used to study the irradiation damage in materials caused by the neutron flux of a nuclear reactor. Since material microscopy often requires multiple samples and pumping ultra-high vacuum can take up to a day, the existing irradiation procedure proved inefficient. This demand led to the development of an Accelerator Target Slider (ATS), allowing up to 10 samples to be irradiated without compounding vacuum time. The ATS was designed to functionally replicate the current Proton Irradiation Sample Holder (PISH II) and be mechanically interchangeable with the Energy Degrader. This ensures universal experimental compatibility, and a proven multi-sample actuation system with seamless integration to the target chamber.

PISH II

- Heating & cooling up to 450°C.
- Current pickups & ceramic isolation to calculate Displacement Per Atom (DPA).
- Tantalum aperture for sample mounting.
- **Can only mount 1 sample.**

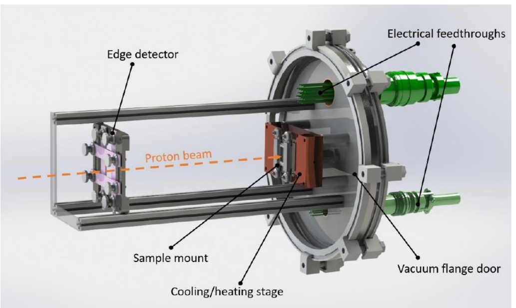

Figure 1: SolidWorks model of PISH II irradiation assembly.

Energy Degrader

- Twin actuated frames with closed loop control for automated beam alignment.
- Cooling lines to dissipate beam heat.
- **Not modular & high friction.**

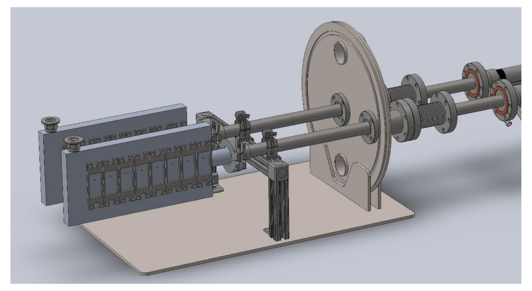

Figure 2: SolidWorks model of the Energy Degrader.

Methodology

The greatest challenge in replicating the performance of the PISH II with multiple samples is mitigating transverse heating to avoid recovery from annealing. The proposed solution is individually heated compact sample stages that mount to a water-cooled aluminum frame. This allows high temperature gradients to be held between samples and provides electrical isolation for current measurement. The stages can be optimized for different temperature ranges by changing the thickness, cross sectional area, and thermal conductivity.

$$Q = kA\left(\frac{\Delta T}{\Delta X}\right)$$

The mechanical design modelled after the Energy Degrader replaces all welded piping connections with Swagelok and Quick Clamp fittings to be readily disassembled. The previous brass bushing was replaced with a low friction Teflon sleeve bearing for smoother actuation. The flange mounted system is compatible with the existing linear actuators for seamless integration.

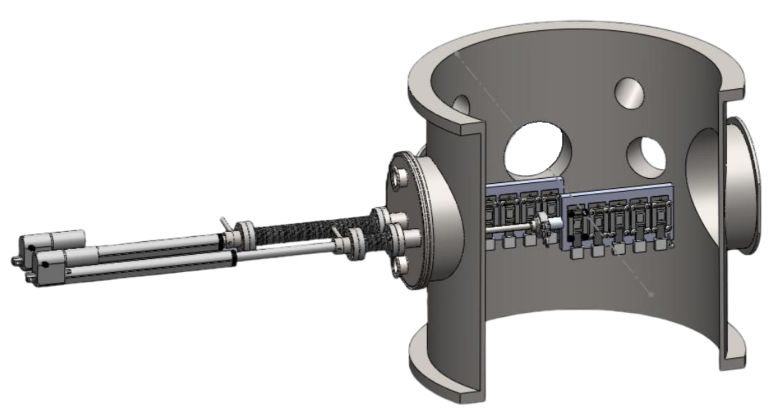

Figure 3: SolidWorks model of Accelerator Target Slider mounted to the target chamber.

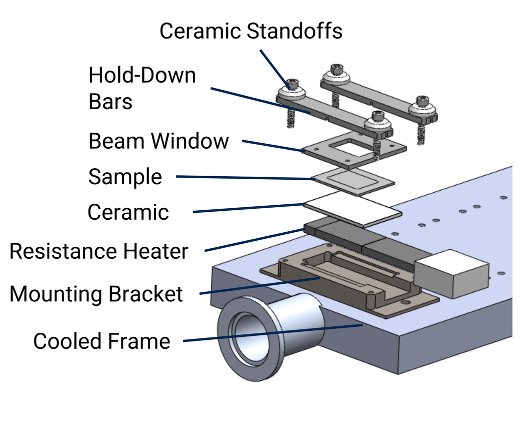

Figure 4: Exploded SolidWorks model of new sample stage design.

Thermal Simulation

The thermal performance of sample holder designs were assessed with SolidWorks CFD and FEA simulations, requiring the convection coefficient of the cooling water through the frames. This was approximated using the Dittus-Boelter equation for the Nusselt number as shown.

$$N_u = 0.023{R_{eD}}^{0.8}{P_r}^{0.4}, \qquad h_c = \frac{N_u k}{D}$$

This simulation also requires the thermal contact conductance between all interfacing surfaces. Since the ATS operates in high vacuum below 600°C, only constriction conductance is considered. For interfaces without standard accepted values, the Cooper-Mikic-Yovanovich correlation with an empirical approximation for asperity was used as shown.

$$h_c = 1.25k_c\left(\frac{m}{\sigma}\right)\left(\frac{P}{H_c}\right)^{0.95}, m \approx 0.125\sigma^{0.402}$$

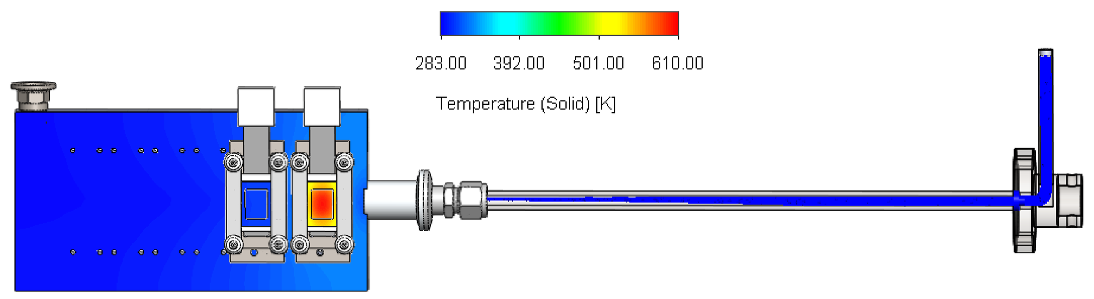

Figure 5: Steady state SolidWorks CFD Flow Simulation for SS304 sample stages with 15°C cooling water at 30psi and 130W of heating power. Primary sample $T_{mean} \approx 330$°C and Adjacent sample $T_{mean} \approx 19$°C.

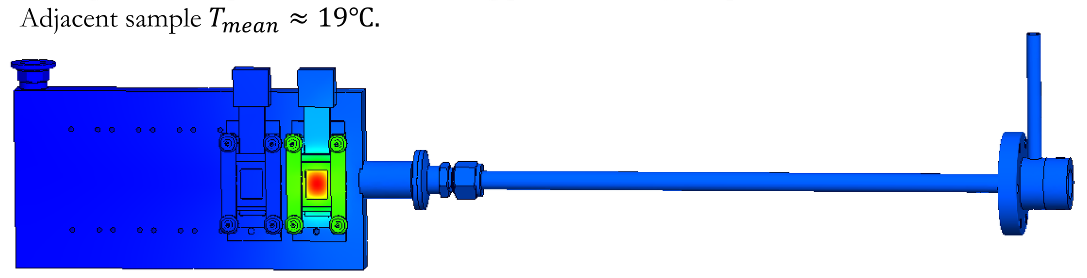

Figure 6: Steady state SolidWorks FEA Thermal Analysis for SS304 sample stages with a cooling water convection coefficient $h_c = 4500\ W/mK$ and 130W of heating power. Primary sample $T_{mean} \approx 310$°C and adjacent sample $T_{mean} \approx 22$°C.

Results

Thermal Performance

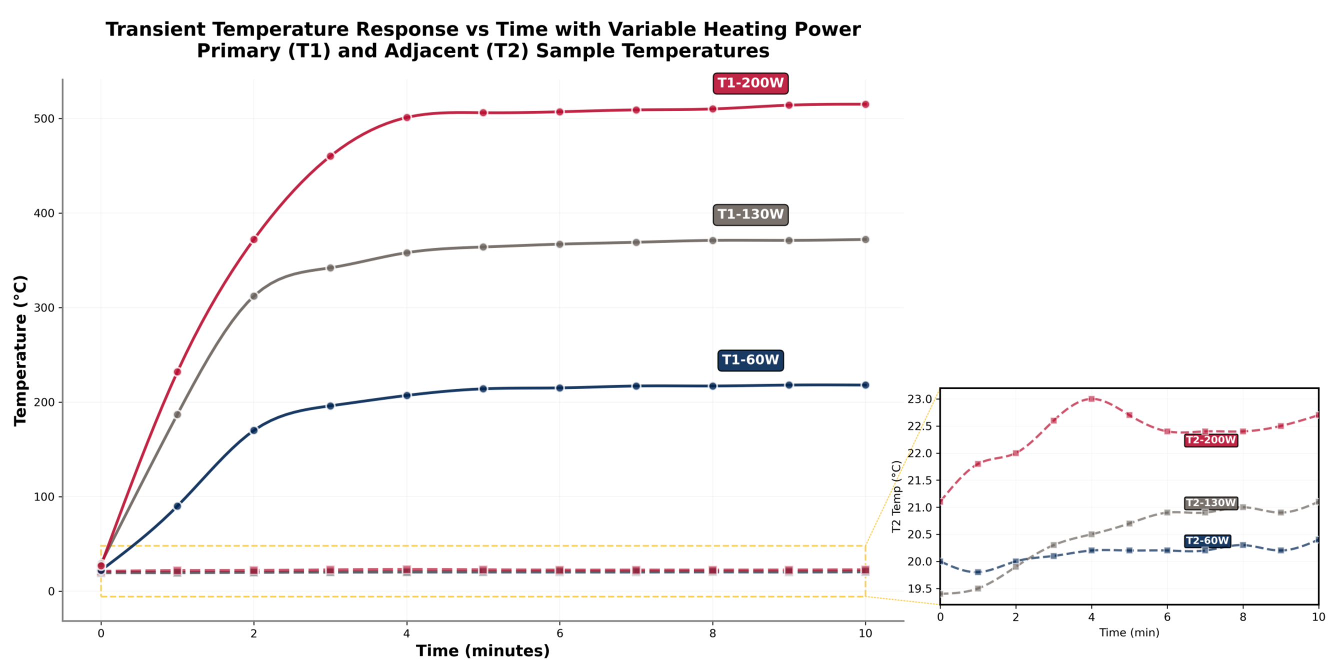

Figure 7: Transient primary and adjacent sample heating curves over a 10-minute period in vacuum. 60W, 130W, and 200W of heating power were applied to the primary sample stack. The adjacent temperature curves are zoomed in to better illustrate relationship with the primary sample temperature.

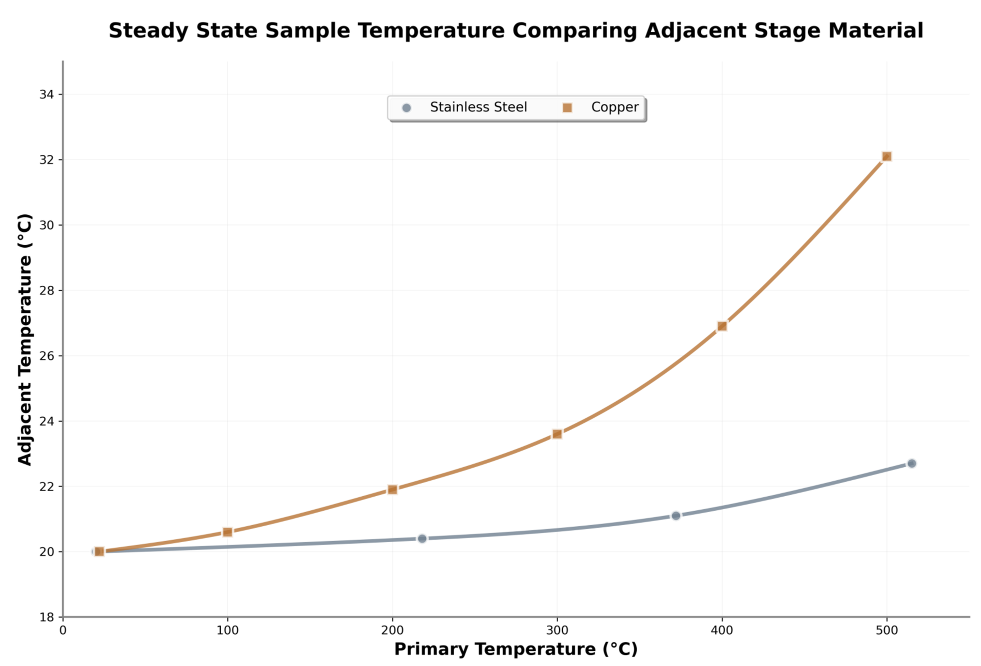

Figure 8: Steady state relationship between primary sample temperature and adjacent sample temperature up to 500°C in vacuum. Copper and stainless-steel stages were tested to compare their effectiveness in mitigating transverse heating.

Electrical Performance

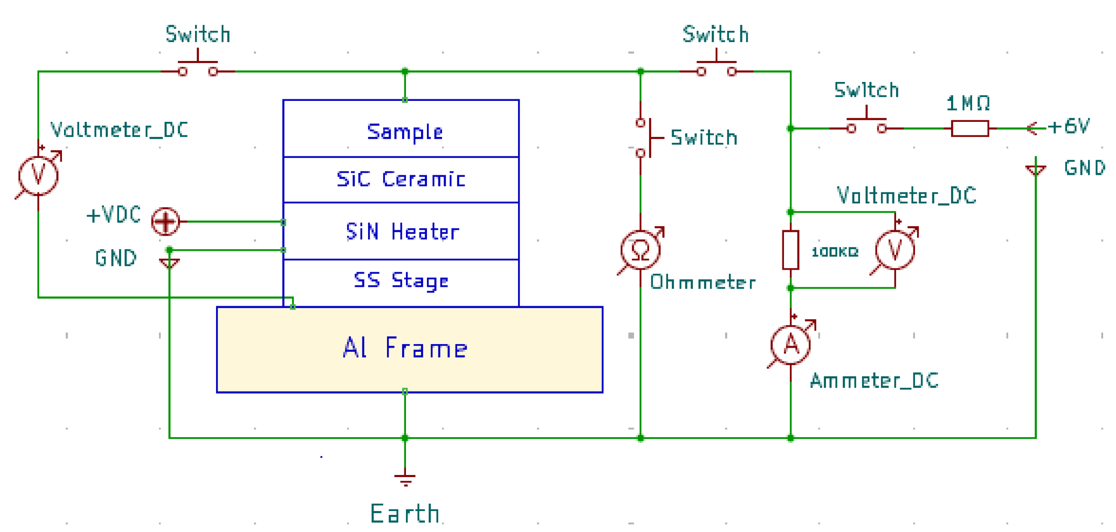

Figure 9: Electrical circuit schematic used to measure the leakage current with and without a 5uA source introduced. The ceramic's resistance was measured to determine the resistivity as a function of temperature and correct current measurements.

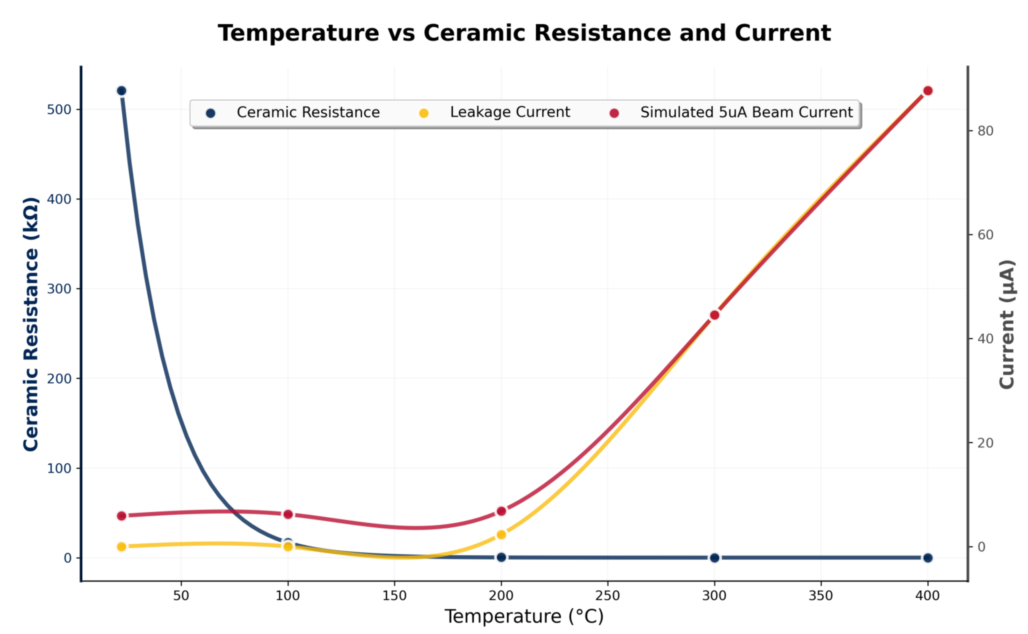

Figure 10: Ceramic resistance and measured sample current with and without a 5uA source modelling the beam plotted as a function of temperature. For operation, the leakage current from the heater is required to stay below 1uA.

Conclusion

- Thermal testing proved the simulations to be accurate within an acceptable temperature range, proving the sample stage design successful at mitigating transverse heating.
- The copper stage increases adjacent sample temperature, yet still within an acceptable range up to 500°C. This stage should be favoured for experiments requiring a high energy beam or lower sample temperatures.
- Electrical testing proved the sintered silicon carbide layer to be the root cause for excessive leakage current due to it's poor resistivity-temperature curve. It should be replaced with aluminum nitride for future usage.
- The Swagelok and Quick Clamp fittings were proven successful by pulling vacuum down to $5x10^{-6}$ mbar with 30 psi water flow.
- The Teflon sleeve bearing performed successfully, providing smoother actuation compared to the previous brass bushing. The sleeves longevity is unknown and should be monitored for routine maintenance.

Future Work

- The thermal performance should be tested under varying beam energies to compare different stage designs with the beam as an added heat source.
- Different sample types (C-shape tubes, thin foils) should be tested for thermal compatibility.
- A future design should consider adding additional ports to use the energy degrader and beam profile monitors alongside sample mounting to form a permanent fully capable irradiation system.

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