ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-THPMK094

THERMAL DESIGN OF A 100 KW ELECTRON TO GAMMA CONVERTER AT TRIUMF

B. G. Cade†, L. Egoriti, and A. Gottberg, TRIUMF, V6T 2A3 Vancouver, Canada
D. Priessl, University of Victoria, Dept. of Physics and Astronomy, V8P 5C2 Victoria, Canada

Abstract

The electron target station of the TRIUMF-ARIEL Facility will employ an electron "driver" beam to irradiate Isotope Separator On-Line (ISOL) targets for the production of radioactive isotopes via photofission [1]. 35 MeV electrons will be converted to gamma spectrum Bremsstrahlung photons via an electron to gamma (e-γ) converter located upstream of the ISOL target. The e-γ concept uses a composite metal with two layers: One high-Z material to stop and convert electrons to photons, and one low-Z material to provide structural support, thermal dissipation, and maximal transparency to the produced gamma photons as well as to provide attenuation of remaining primary electrons.. Several material combinations and bonding processes are currently being evaluated and tested using TRIUMF's e-linac. Water-cooling and thermal design are being optimized for 100 kW electron beam power operation and have thus far been experimentally validated up to 10 kW driver beam power equivalent. The latest test results and future prospects are summarized.

BACKGROUND

Producing isotopes via photofission [2] has the potential to improve the purity of ion beams available in neutron-rich regions of the chart of nuclides, which is desirable for several of the experiments at TRIUMF-ISAC [3]. Additionally, a photofission target station can be driven by an e-linac, allowing a second source of isotope production for TRIUMF's ISAC facility independent of the primary 500 MeV proton cyclotron.

The e-γ converter sits immediately upstream of the photofission target within a hermetic target vessel. The converter is a solid-state concept which consists of a high-Z material layer bonded to low-Z material layer . 35 MeV electrons strike the high-Z layer of the converter, producing gamma spectrum Bremsstrahlung photons that then irradiate the photofission target. Worldwide, there is little precedence in such systems. A similar radioisotope production mechanism is used at ALTO-IPNO [4], but at significantly lower electron beam power (500 W), allowing for direct irradiation of the target with electrons without prior conversion to X-rays. Similar converter concepts with lower electron energies and electron beam power were studied in [5]. The conceptual layout of the TRIUMF-ARIEL e-γ converter is shown in Figure 1.

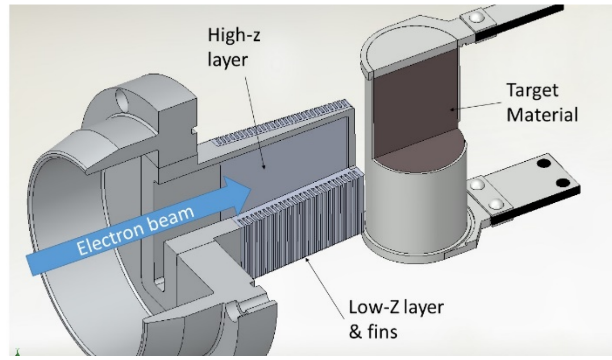

Figure 1: Layout of the converter and photofission target.

THERMAL DESIGN CONCEPT

The electron irradiation produces a very large heat load. At 100kW of beam power the converter sees 6.0×10^6 W/m^2 of heat flux on the High-Z surface. To dissipate this heat, the Low-Z layer is made of thermally conductive material (aluminum) machined into a fin array. Various fin geometries were investigated, however a simple vertical fin array was determined to be advantageous due to manufacturability and pressure drop requirements.

Cooling Fins

Cooling water approaches the converter perpendicularly to the beam axis, and flows over the fin arrays on both sides of the converter wedge.

The fins are optimized to maintain the Low-Z material at the lowest possible temperature. ANSYS CFX CFD [6] software and ANSYS Design Explorer Response Surface Optimization is used to optimize the flow rate, fin height, fin thickness, and channel thickness to minimize temperature and pressure drop.

Flow is delivered by a half-inch National Pipe Standard pipe to a diffuser shape that distributes the flow evenly across the converter fins. This diffuser is shown in cross-section in Figure 2 and the resultant flow distribution in Figure 3.

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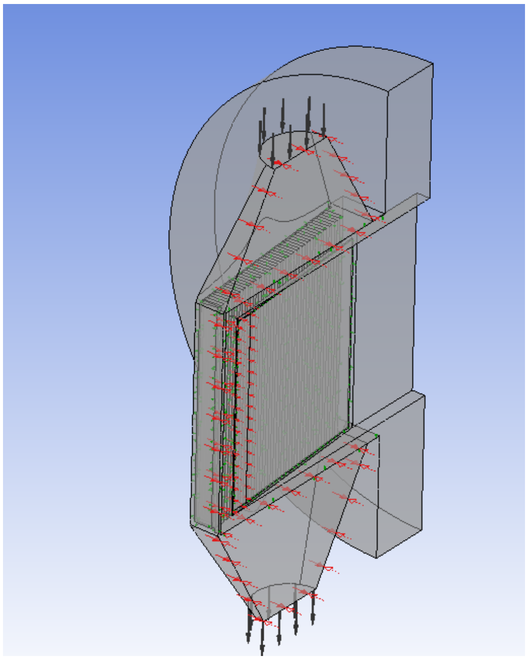

Figure 2: Cross-section through the vertical plane along the beam axis of the converter weldment with diffuser shape designed to evenly distribute flow across all fins. Arrows indicate flow direction.

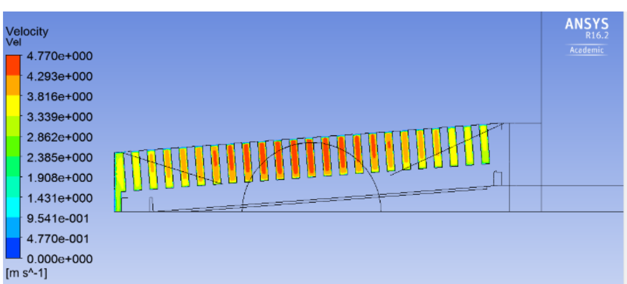

Figure 3: Cross-section through the horizontal plane along the beam axis showing flow balance in water between all fins.

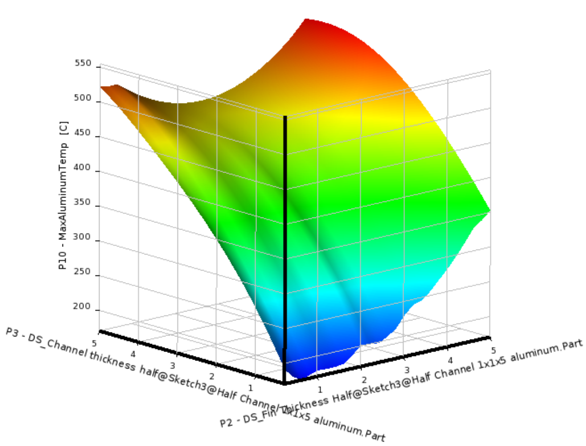

Figure 4: Response Surface of fin optimization showing temperature as a function of fin thickness and channel thickness.

Optimal Fin Geometry

The selected optimized fin geometry is 4 mm tall fins, 1.2 mm thick, with 1.2 mm thick channels between them. At 100 kW of beam power and 50 liters per minute (LPM)of water flow the resultant performance is summarized in Table 1. An average effective convective heat transfer coefficient of 58,000 W/m^{2}K is achieved, within the range of water nucleate boiling.

Table 1: Optimal Fin Performance

Parameter	Value	Units
Effective Heat Transfer Coefficient	58,000	W/m^{2}K
Maximum Aluminum Temperature	350	℃
Pressure Drop	1	kPa
Fin Efficiency	16	%

Fin efficiency is typically a desirable parameter to maximize in fin array designs, as a more efficient fin typically will remove more heat from the cooled body, however a low fin efficiency must be accepted to avoid film boiling of the water in the bottom of the fin channels.

ANSYS CFX Validation

As the converter is operating within the range of possible nucleate boiling effects it is important to consider this in the CFD simulations. The RPI boiling model used for nucleate boiling simulation in ANSYS CFX is developed and validated for large surface areas such as in boilers and pressure vessels [7], however the very small areas present in the e-γ converter concept may introduce boiling model inaccuracies and therefore are validated via experiment.

A test bench was built to replicate the power density of 10 kW electron beam power on a scaled down prototype converter, shown in Figure 5.

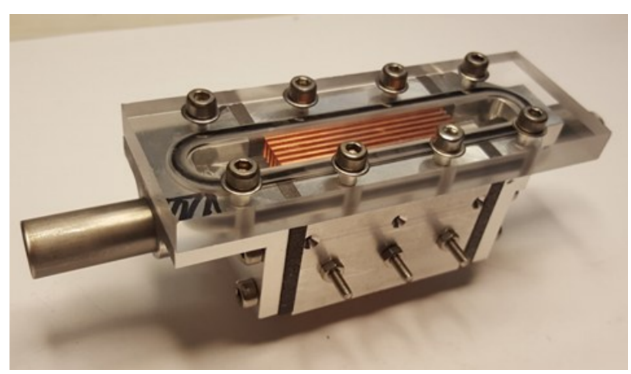

Figure 5: Prototype converter in housing; converter fins are copper surrounded by aluminum housing and a clear polycarbonate lid. Graphite thermally isolates the converter. Heat is applied to the bottom (not visible).

A TIG welder is applied to a copper block which diffuses the heat before it reaches the aluminium converter prototype. Temperature measurements were taken in the body of the converter at three locations and several flow rates. This test bench is shown in Figure 6.

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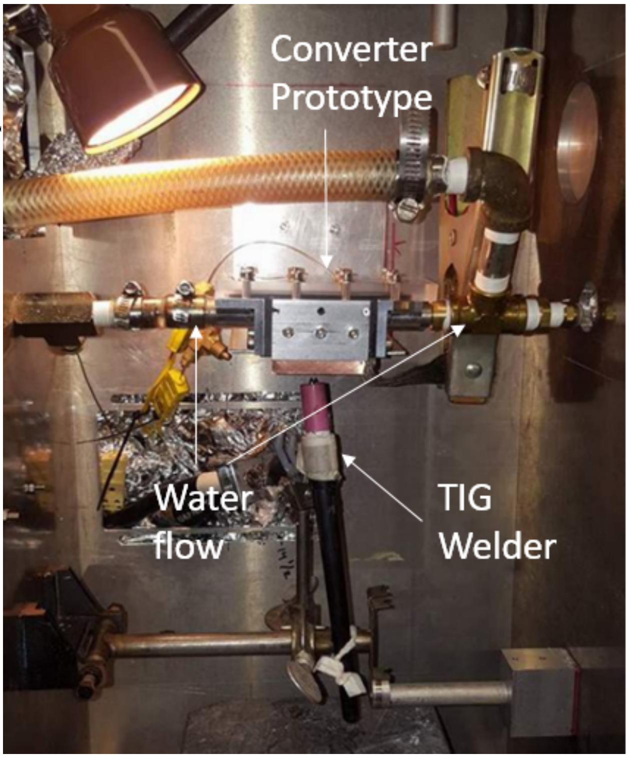

Figure 6: Validation testing apparatus.

The test bench was recreated in ANSYS CFX (shown in Figure 7) and analysed with RPI boiling on or off for each flow rate case conducted previously.

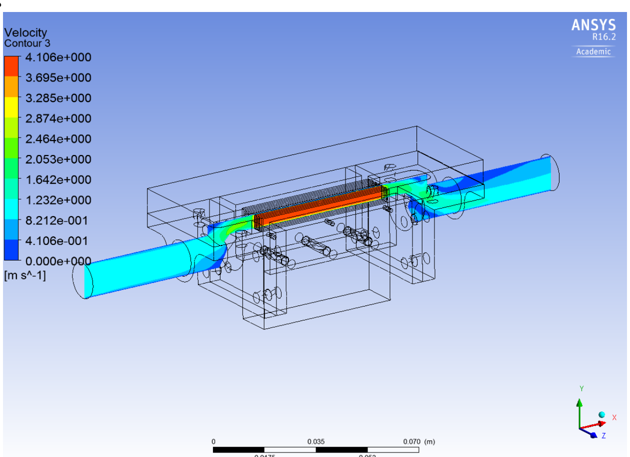

Figure 7: ANSYS CFX Converter Prototype showing flow velocity through the vertical mid plane.

Temperature measurements were compared between the three thermocouple measurements on the prototype and three point measurements in the ANSYS CFX model. The relative percentage difference between the experimental temperature measurements and the CFX results is calculated as the flow rate is varied and RPI boiling model is turned on or off. shown in Figure 8.

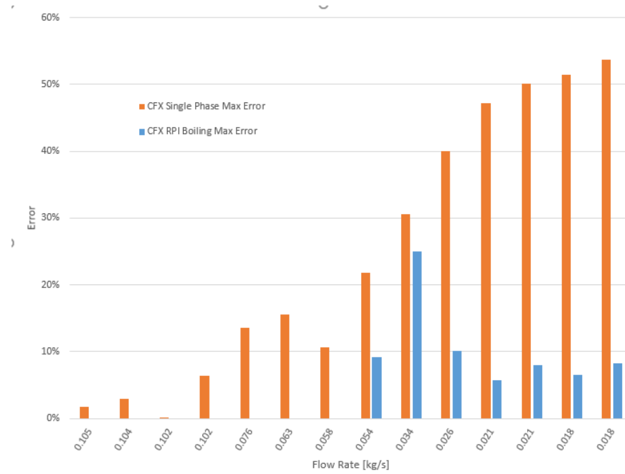

Figure 8: Maximum % difference found between CFX simulations and experimental validation of converter fins with RPI boiling model off and on.

CFX validation has shown that as long as nucleate boiling is properly accounted for via the RPI model, this approach to thermal design of the converter will have an average error less than 10%.

Future Prospects

The high flow rates deemed necessary for thermal design cause concern for the corrosion-erosion performance of the aluminium fins. Long term high-velocity flow tests are ongoing to examine the effect of sustained corrosion-erosion on the converter, which could lead to investigations of hardening or coating the fins.

CONCLUSION

Numerical thermal design, development, and benchtop validation tests of the TRIUMF-ARIEL electron-to-gamma converter have produced a feasible concept to withstand irradiation with 100 kW of 35 MeV electrons.

ACKNOWLEDGEMENTS

ARIEL is funded by the Canada Foundation for Innovation (CFI), the Provinces of AB, BC, MA, ON, QC, and TRIUMF. TRIUMF receives federal funding via a contribution agreement with the National Research Council of Canada.

The authors acknowledge additional support from D. Karlen and P. Poffenberger (Department of Physics and Astronomy, University of Victoria).

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