HIGH-POWER LITHIUM TARGET FOR ACCELERATOR-BASED BNCT

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Abstract

A water-cooled conical target for producing neutrons via the $^{7}Li(p,n)^{7}Be$ reaction at 2.5 MeV is under development at Linac Systems. The target is intended to accept an expanded 50-kW beam from an rf linac, and is predicted to meet the intensity requirements for practical accelerator-based boron neutron capture therapy (BNCT) in concert with Linac Systems' CW RFI linac[1]. Lithium metal targets present well-known physical and mechanical challenges at high beam power density that are addressed in our design. CFD modelling indicates that the peak lithium temperature can be held below 150°C with a water flow rate near 80 kg min^{-1} and corresponding pressure drop of 170 kPa. The target prototype has been fabricated and is undergoing thermal-hydraulic testing using an electron beam at the Plasma Materials Test Facility, Sandia National Laboratories.

INTRODUCTION

The $^{7}Li(p,n)^{7}Be$ reaction on lithium metal, at energies in the range of 1.9-3.0 MeV, has desirable properties as a potential source of neutrons for BNCT. Yield is high, typically reported in the range of 8-9 $\times$ 10^{14} n A^{-1} s^{-1} at 2.5 MeV. Neutron energy is low; at 2.5 MeV, the flux-weighted mean neutron energy is only 330 keV.

Despite nuclear advantages, lithium presents thermal challenges in a high-power-density target. The solid is preferable on account of the corrosive and mobile nature of the liquid, but its 180°C melting point necessitates careful cooling. Recent experimental attempts at using solid lithium in targets have elucidated other difficulties. Taskaev[2] operated a 10-cm-diameter planar copper-backed lithium target with a 25-kW beam, finding that blistering of the copper substrate by beam-implanted hydrogen limited target lifetime to under a day.

Linac Systems is developing a unique solid lithium target for a 2.5-MeV, 20-mA beam. In this paper we focus on the target prototype mechanical design and some results of experiment and modelling pertaining to the thermal hydraulics of the heat removal system.

TARGET DESIGN AND FABRICATION

Design Criteria and CFD Modelling

Several basic functional requirements for our target were stipulated to guide the design:

- The proton beam is an 8-cm-diameter stationary (i.e. not rastered or rotated), magnetically-expanded, “waterbag” distribution produced by an rf linac.
- Peak surface temperature must not exceed 150°C to keep lithium layer solid (including safety margin).
- Liquid water coolant will be used with inlet temperature of 20-30°C, outlet pressure of 101 kPa.
- Symmetry of target system about the beam axis is desirable to simplify neutron dosimetry and treatment planning calculations.

The concept born from these requirements consists of a 10-cm diameter conical heat exchanger with water channels on the exterior that mates with a coolant manifold. This concept is illustrated in Figure 1.

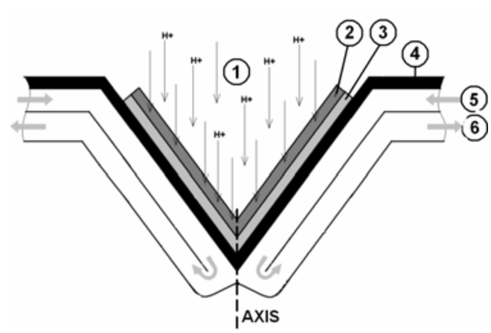

Figure 1: Protons (1) strike a 50-µm lithium metal layer (2) that is deposited on a Pd anti-blistering substrate (3), supported by a channelized conical heat exchanger (4). Coolant (5) flows through a conical-annular duct that encompasses the channels of the heat exchanger; reverses at the apex; returns via an outer conical-annular duct, and exits (6).

Design of the channelized heat exchanger was carried out with the aid of the CFD packages FLUENT, CFDesign, and COSMOS FloWorks. Simulations examined the effects of channel dimensions, number of channels, heat exchanger material, and apex-region geometry upon the coolant flow, pressure drop, and pumping power needed to meet the target surface temperature requirement. Initial studies focused on designs with straight tangential channels, but we determined that helical channels would offer superior performance (Figure 2). Copper was selected as the only viable heat exchanger material. In simulations comparing identical aluminium and copper heat exchangers, copper conferred a ~40°C target temperature improvement over aluminium for given coolant flow rates.

Modelling concluded with the acceptance of a copper heat exchanger design with 20 2-mm helical channels. According to the FloWorks models, this design will hold the target surface temperature below 150 °C by means of 80 kg min^{-1} of water flow with 170 kPa pressure drop. Such a requirement is easily met with a small centrifugal pump.

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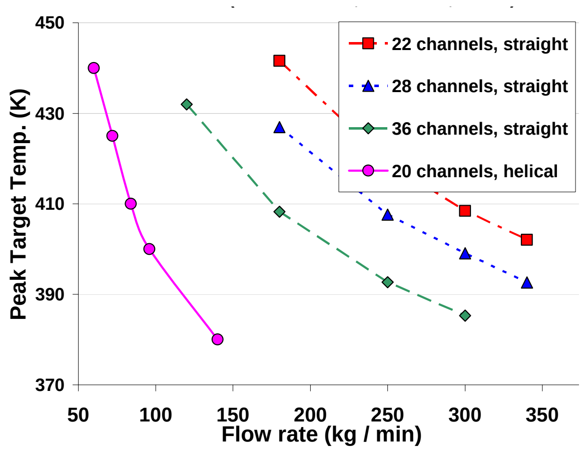

Figure 2: Predicted maximum target temperature as a function of coolant flow for various copper heat exchangers. Maximum design temperature is 420K.

Our proposed antidote to the blistering problem is a ~10-µm substrate of electroplated palladium interposed between the lithium and the heat exchanger, of sufficient thickness to encompass the Bragg peak of the beam and dissipate hydrogen either by storage or diffusion. Palladium electroplating on copper is routine. Lithium readily alloys with palladium[3], indicating that adherence is likely to be good, but raising the possibility of destructive solid phase changes.

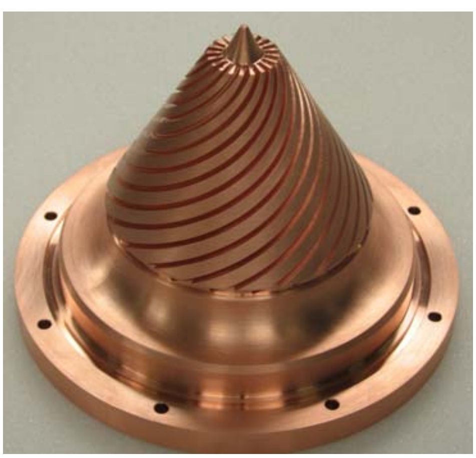

Figure 3: Channelized heat exchanger.

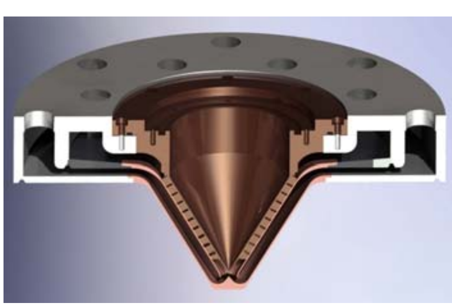

Figure 4: Manifold with target heat exchanger installed.

Prototype Fabrication

A prototype target heat exchanger (Figure 3) and manifold (Figure 4) were constructed to experimentally validate our CFD thermal-hydraulic predictions.

The conical heat exchanger is OFE copper, while the manifold is mostly aluminium that has been electroless-nickel-plated internally to prevent galvanic corrosion. Components in the apex region of the manifold, where coolant flow is rapid and potentially erosive, are solid copper joined to the plated aluminium with low-temperature silver solder. These joints have so far proven reliable. Water enters and exits the manifold through 16 3/4-inch (1.9 cm) pipe fittings in the upstream face.

EXPERIMENTS AND RESULTS

The prototype BNCT target has undergone limited electron-beam thermal testing with the 50-kW EB-60 electron gun at the Plasma Materials Test Facility, Sandia National Laboratories, Albuquerque, and further testing is planned. The capabilities of this unique user facility are described in detail by Youchison[4]. Linac Systems has used a homemade flow loop for preliminary hydraulic testing at its own laboratory.

Preliminary Hydraulic Testing

A test cooling loop at Linac Systems is based upon a small centrifugal pump (Chemflo-1, MP Pumps, Inc.), transit-time ultrasonic flow meter, pressure transducers, and data-logging computer. The target and manifold were connected to this loop to produce pressure-vs.-flow data that is in good agreement with the FloWorks predictions (Figure 5).

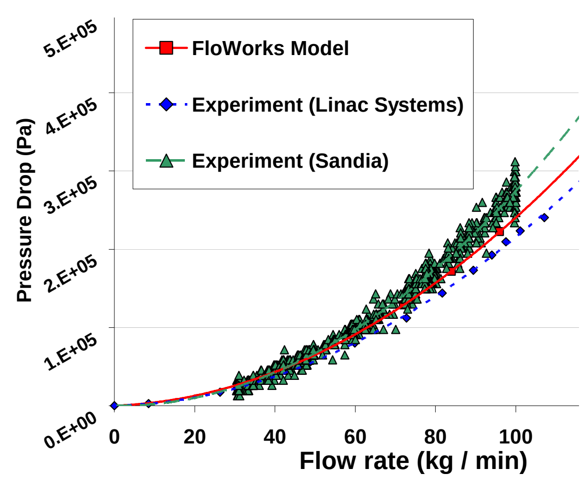

Figure 5: Pressure-flow characteristics of 20-helical-channel heat exchanger, with both CFD and experimental results. Design flow is 80 kg min^{-1}.

PMTF Experiment

Manifold, target, and associated plumbing have been placed in the PMTF EB-60 vacuum chamber for testing. In this facility, a 20-keV electron gun scans a raster pattern representing the intended “waterbag” power density distribution onto the conical target surface. According to plan, two series of data will be collected: surface temperature as a function of beam power with fixed coolant flow rate; and temperature as a function of flow rate for fixed beam power. Water from a high-purity loop is used to cool the target. Absorbed power measurements are made by calorimetry on this coolant, the inlet and outlet feedthroughs being fitted with platinum RTDs.

Target surface thermographs are collected using IR cameras observing the target through ZnSe viewports. To account for the emissivity of the surface and calibrate the cameras, thermocouples are mounted in a section of the target wall.

Thus far, results from e-beam testing have been limited by some practical difficulties: a leaky weld on the manifold, and an apparent inability to produce more than 10 kW from the EB-60 gun. Alternatively, the latter observation may suggest problems with calorimetry, since the electron gun power supplies indicated that up to 30 kW has been developed.

Figures 6 and 7 show an example thermograph and radial temperature profile, respectively, of the target surface. Conditions in that experiment were 9.3 kW absorbed power, 36.7 kg min^{-1} coolant flow.

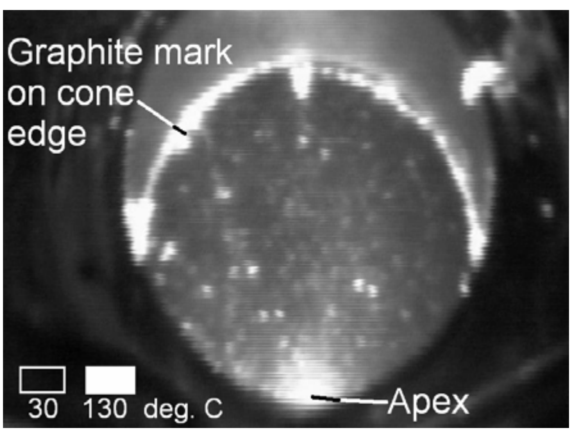

Figure 6: Thermograph of target surface.

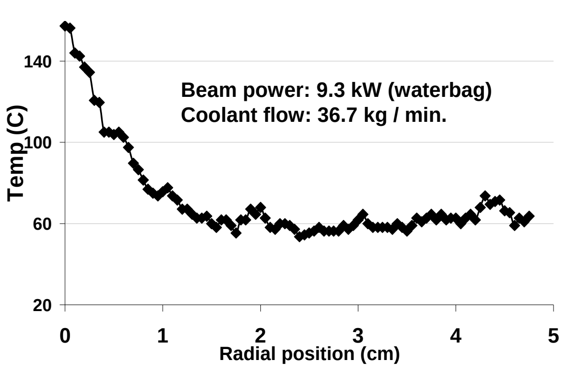

Figure 7: Target surface temperature vs. position.

CONCLUSIONS

Electron-beam heating is an attractive tool to validate CFD models of high-power accelerator targets, particularly those whose operation would be associated with significant hazards to personnel and equipment. Linac Systems' experience with e-beam heating at PMTF is only in the incipient phase and there may be limits to the utility of the technique. These include variations in surface emissivity during testing; inaccurate power-density distributions on the concave conical surface resulting from electron scattering; or simply the inability of the PMTF guns to deliver required beam power (which so far has remained below 10 kW). We are also sceptical of the calorimetry at PMTF in our tests to date. More work needs to be done to allow us to trust thermal data from e-beam heating.

Pressure-flow characteristics of the target heat exchanger match CFD predictions. We were concerned that the fast (~ 10 m s^{-1}), turning flows in the apex region would be prone to cavitation, but after an estimated 10 hours of exposure to high-flow testing—including flow rates 20% higher than the estimated requirement—the target and manifold components show no signs of erosion.

In the present work we have focused on the heat removal problem. Of course many other aspects of design must be considered before a high-power lithium target for BNCT can enter clinical service, including neutronics, shielding, and the target preparation and replacement procedures. We hope to publish detail on our work in these areas soon.

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REFERENCES

[1] D. Swenson, “An rf focused interdigital linac structure”, Proc. LINAC2002, p. 227 (2002)

[2] S. Taskaev and B. Bayanov, “Development of lithium target for accelerator based neutron capture therapy”, Proc. ICNCT-12 p. 292 (2006)

[3] T. Nohira and Y. Ito, “Thermodynamic properties of Pd-Li alloys”, J. Electrochem. Soc. 125(3) p. 785 (1998)

[4] D. Youchison and J. McDonald, “High heat flux testing capabilities at Sandia National Laboratories, New Mexico”, Proc. ASME Heat Transfer Division, HTD-Vol. 301, p. 31 (1994)