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Development of a higher power cooling system for lithium targets

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HIGHLIGHTS

- Our submerged jet high power lithium target cooling system is described.
- Results for the effect of changing pumping power are presented.
- A binary ice, phase change coolant was tested. No advantage was found over water.

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ABSTRACT

The accelerator based Boron Neutron Capture Therapy beam at the University of Birmingham is based around a solid thick lithium target cooled by heavy water. Significant upgrades to Birmingham's Dynamitron accelerator are planned prior to commencing a clinical trial. These upgrades will result in an increase in maximum achievable beam current to at least 3 mA. Various upgrades to the target cooling system to cope with this increased power have been investigated. Tests of a phase change coolant known as “binary ice” have been carried out using an induction heater to provide a comparable power input to the Dynamitron beam. The experimental data shows no improvement over chilled water in the submerged jet system, with both systems exhibiting the same heat input to target temperature relation for a given flow rate. The relationship between the cooling circuit pumping rate and the target temperature in the submerged jet system has also been tested.

1. Introduction

The Dynamitron accelerator at the University of Birmingham has been in service for more than 40 years. For the last decade it has been used primarily as a neutron source for research work related to Boron Neutron Capture Therapy (BNCT). The accelerator is routinely used at proton currents of 1 mA at 2.8 MeV, producing a neutron source intensity of 1.37×10^{12} n/s (Campbell and Scott, 1976), although currents of up to 1.5 mA have been achieved.

Historically clinical BNCT trials worldwide have relied on fission reactor based neutron sources (Busse et al., 2003; Chadha et al., 1998; Sauerwein et al., 1999; Yamamoto et al., 2011; Hatanaka and Yoshinobu, 1994). However there are two factors which make them unattractive for widespread hospital use. One is their cost and relative inflexibility and the other is the public perception of the dangers of nuclear reactors. As a result, the use of accelerators for neutron production has been widely investigated, a summary of accelerator based BNCT worldwide has recently been published by Kreiner et al. (2014).

2. Target and cooling system design

Neutrons are produced at the Birmingham facility via the lithium-7 (p,n) reaction, with a thick natural lithium target and typically a 2.8 MV accelerating voltage. The choice of the thickness of the lithium layer is a trade off between a number of factors including cooling performance, mechanical properties and gamma ray production.

In the target design described in this paper, all protons stop in the lithium layer. This has the significant advantage of avoiding concerns over blistering of the backing layer, which is a serious problem in some materials and can lead to lithium separating from the backing (Astrelin et al., 2010). Experience of running these thick lithium targets has demonstrated that proton implantation in, and blistering of, the lithium itself has a negligible impact on target performance even over many months of running.

The Li(p,n) reaction has a threshold of 1.882 MeV. Protons

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below this energy are therefore not producing neutrons but can still produce gamma rays via inelastic scatter from the lithium nuclei. Targets thinner than the proton range reduce this additional undesirable dose to the patient by ensuring the protons only slow to the threshold energy in the lithium, doing the remaining slowing down in the heavy backing layer. Birmingham's design reduces this additional photon dose by incorporating a 20 mm thick layer of antimony-free lead into the beam shaping assembly immediately surrounding the target (Brown and Scott, 2000). This layer reduces the photon dose due to scattering in the lithium by 97%.

Lithium is a poor thermal conductor, with a thermal conductivity of 84.8 W m^{-1} K^{-1}. It also has poor mechanical properties and degrades rapidly in contact with air or water. These properties make target construction more of a challenge than with some other candidate materials. Birmingham's target consists of a 0.8 mm thick layer of lithium metal on an oxygen free copper backing. Within the copper backing thermocouple channels are used to monitor the target temperatures; these are 1 mm diameter holes spark etched into the 2 mm thick copper backing which extend into the area underneath the lithium. In routine operation 0.5 mm diameter, insulated, k-type thermocouples (RS part number 444-1247) are inserted in these channels and data is read using a National Instruments NI 9213 module. This temperature data is used both to aid in beam positioning and profiling, and as an input into the safety monitoring system, which controls the beam interlocks.

The mechanical and thermal bond between the copper and the lithium layer is critical for good target performance, and a method has been developed which forms a lithium–copper intermetallic layer with negligible thermal resistance (Brown and Scott, 2000). To produce this, a mechanical pressing and heating regime is used, noting that the final target quality is very sensitive to the parameters in both of these processes. The target preparation methodology has been extremely successful at current Dynamitron powers despite the detailed composition of the lithium–copper intermediate layer not being known. It is possible that this layer is an alloy or solid solution with significantly different thermal properties to lithium. Experimental work investigating the physical properties of this layer in more detail is currently ongoing.

Cooling of the target is provided by a submerged jet of heavy water impinging directly on to the copper backing, as shown in Fig. 1. Simulations and associated experimental verifications which lead to this design have been previously described in the literature (Brown and Scott, 2000). The cooling set-up has proved to be capable of maintaining a solid lithium target with heat loads of up to 4.2 kW, equating to a heat flux of over 3 MW/m^2. In order to have a clinical facility capable of irradiating patients in a reasonable time, upgrading the Birmingham system was considered necessary, with the aim of having a target capable of remaining solid up to at least 3 mA and, ideally, 5 mA.

The current system is extremely robust, requires minimal maintenance and has relatively low cost. A desire to preserve these characteristics has lead to an investigation of a number of relatively minor upgrades rather than a radical redesign of the whole cooling system.

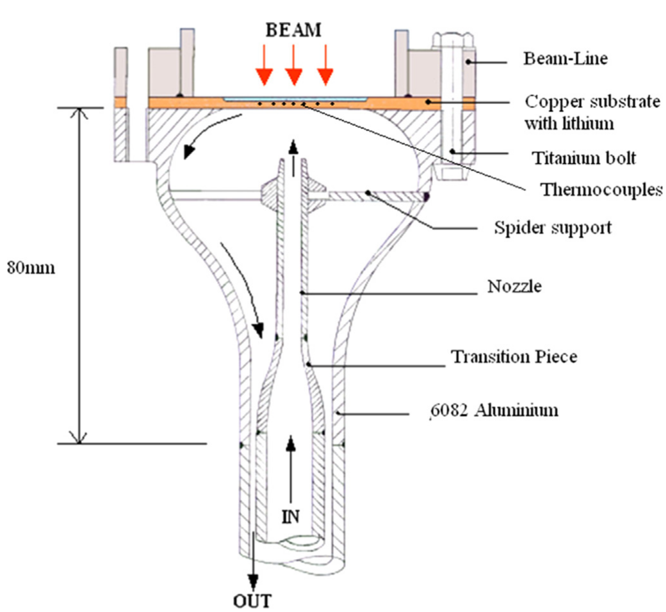

Fig. 1. The existing submerged jet cooling system.

3. Cooling tests

3.1. Heating methodology

Representative tests of cooling system upgrades require a heat source capable of reproducing both the power density and the power input of the Dynamitron. Initial tests were made with a resistive heater; a gold plated silicon chip soldered directly to a copper target blank. It was found that temperature gradients across the heating element under load caused thermal stresses leading to rapid mechanical failure of the heating element.

Inductive heating was then tried using a large commercial induction heater capable of supplying a nominal 50 kW (Minac 25 supplied by EFD). Initial attempts were made to couple the power directly into the copper target but this proved impractical as the heating unit was optimised for steel. A 5 mm steel plate was then silver brazed to a copper boss, which was then vacuum brazed to a copper target blank (Fig. 2). Heat flow down the copper boss was calculated from several thermocouple readings down the axis of the bar, and heat variation across the target region was monitored by thermocouples in the same configuration as used with the normal, lithium, target. This arrangement comprises a central thermocouple surrounded by six equally evenly spaced thermocouples at a radial distance of 20 mm. Tests showed that a maximum heat input of approximately 8 kW was possible before the surface of the steel layer began to melt.

Several approaches to gas flame heating have also been employed. First a solid copper boss brazed to the back of the target was used, the boss being heated with multiple oxyacetylene torches. However, the required power input could not be achieved. The most recent tests have been done using a small (2 mm diameter) pinpoint gas flame and a jig which allowed repeatable positioning anywhere on the target surface (Fig. 3). This has proved very successful indeed allowing rapid and reproducible

Fig. 2. Target blank prepared for induction heating.