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Demonstration of a high-intensity neutron source based on a liquid-lithium target for Accelerator based Boron Neutron Capture Therapy

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HIGHLIGHTS

- A liquid lithium target (LiLiT) is bombarded with a 1.91 MeV, 1.5 mA CW 10 mm-wide proton beam.
- The target dissipates >3 kW/cm^2, >0.5 MW/cm^3 and generates $\sim 3\times 10^{10}$ n/s in stable conditions.
- We estimate that $\sim$15 mA near threshold proton current would deliver therapeutic doses in $\sim$1 h.
- The liquid lithium target makes in-hospital accelerator-based BNCT within reach.

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ABSTRACT

A free surface liquid-lithium jet target is operating routinely at Soreq Applied Research Accelerator Facility (SARAF), bombarded with a $\sim$1.91 MeV, $\sim$1.2 mA continuous-wave narrow proton beam. The experiments demonstrate the liquid lithium target (LiLiT) capability to constitute an intense source of epithermal neutrons, for Accelerator based Boron Neutron Capture Therapy (BNCT). The target dissipates extremely high ion beam power densities (>3 kW/cm^2, >0.5 MW/cm^3) for long periods of time, while maintaining stable conditions and localized residual activity. LiLiT generates $\sim 3\times 10^{10}$ n/s, which is more than one order of magnitude larger than conventional ^{7}Li(p,n)-based near threshold neutron sources. A shield and moderator assembly for BNCT, with LiLiT irradiated with protons at 1.91 MeV, was designed based on Monte Carlo (MCNP) simulations of BNCT-doses produced in a phantom. According to these simulations it was found that a $\sim$15 mA near threshold proton current will apply the therapeutic doses in $\sim$1 h treatment duration. According to our present results, such high current beams can be dissipated in a liquid-lithium target, hence the target design is readily applicable for accelerator-based BNCT.

1. Introduction

In the last decade, the availability of compact light-ion accelerators of sufficient intensity opened the possibility to use accelerator-based neutrons for Accelerator-based BNCT (ABNCT) (Blue and Yanch, 2003), which is at the forefront of research on neutron radiotherapy today, holding a great promise for available and efficient cancer radiotherapy (Sauerwein et al., 2012). However, the application of particle accelerators to BNCT is not a simple task, in order to allow for reasonable patient treatment time, the accelerator particle current has to be of the order of mA's. Such a high current, usually low-energy, beam will deposit kilowatts of heat in a short range within the neutron producing target, generating high power densities that require very challenging target cooling.

The ^{7}Li(p,n)^{7}Be reaction at proton energies of 1.9–2.8 MeV has been widely studied as a prime candidate for production of accelerator-based neutrons for BNCT (Halfon et al., 2014a; Lee and Zhou, 1999; Aleyinik et al., 2011; Burlon et al., 2004; Willis et al., 2008). The emitted neutrons with average neutrons energy in the range 25–200 keV is much closer to that optimally required for therapy of deep-seated tumors ($E_n = 0.5$ eV–10 keV) than that obtained from reactor-produced neutrons (Sauerwein et al., 2012) or from other common neutron producing nuclear reactions. One important example is ^{9}Be(p,n)^{9}B, which is usually used with proton energies above 4 MeV in order to get applicable yield, and

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produces neutron mean energies above 1 MeV.

The use of near threshold proton energy, several tens of keV above the ^{7}Li(p,n)^{7}Be reaction threshold (E_{thr}=1.8804 MeV), is of special interest for BNCT. Working close to the threshold reduces the total neutron yield, compared to higher beam energies, but the maximum and mean neutron energies are much lower as well, requiring less moderation, which leads to less neutron attenuation. A further advantage of proton energies near the threshold is the forward direction kinematics of the emitted neutrons, increasing the usable yield for therapy. Moreover, a lower energy accelerator is needed (~2 MeV protons), sharply reducing the self-activation of accelerator material, which is of great concern in a high current machine. For example, the threshold for the ^{65}Cu(p,n)^{65}Zn reaction is ~2.167 MeV, working below this threshold reduces activation problems of copper components like a Radio Frequency Quadrupole (RFQ) accelerator (usually built with copper electrodes) and copper beam dumps (Weissman et al., 2011). These advantages of a BNCT assembly based on a lithium target irradiated at ^{7}Li(p,n) near threshold energies would enable its relatively easy installation in hospital settings.

However, a practical lithium target would need to operate under beam power levels considered for therapy purposes (several kW) and large volume power densities (> 1 MW/cm^3) which are required for the desired epithermal neutron flux density. Such conditions prove very difficult to achieve because of the mechanical, chemical and thermal properties of lithium (low melting point of 180.5 °C and low thermal conductivity of 85 W/(m K) at 300 K). The major problem lies in removing the thermal power generated by the required high-intensity proton beam. In addition, high current protons irradiation of solid targets causes blistering that might corrupt the target. Few research groups around the world are attempting to design solid lithium targets for high intensity particle beams and high power densities (Willis et al., 2008; Green et al., 2014 and others), but no operational target suitable for practical treatment yet exists.

In the first section of this paper we present an advanced high-power Liquid-Lithium free-surface jet Target (LiLiT) (Halfon et al., 2013) as a prototype of a neutron source for BNCT. In the second section we describe experiments of high-power (~3 kW) and power densities (> 2.5 kW/cm^2, > 0.5 MW/cm^3) irradiations of LiLiT with a proton beam (Halfon et al., 2014b) from the Soreq Applied Research Accelerator Facility (SARAF, Kreisel et al., 2014). In Section three the BNCT doses in a water phantom are calculated in order to evaluate the proton charge needed for a BNCT treatment. These results allow us to formulate an established estimation for the feasibility of accelerator based BNCT using a liquid lithium target.

1.1. LiLiT target

The physical principle of the LiLiT system, schematically illustrated in Fig. 1, consists of a film of liquid lithium (at ~200 °C, above the lithium melting temperature of 180.5 °C) forced-flown at high velocity (up to 7 m/s) onto a concave-curvature thin stainless-steel wall. The target is bombarded by a high-intensity proton beam impinging directly on the Li-vacuum interface (windowless) at an energy above and close to the ^{7}Li(p,n) reaction threshold. A rectangular-shaped nozzle just before the curved wall determines the film width and thickness (18 mm and 1.5 mm, respectively). The liquid-lithium jet acts both as a neutron-producing target and as a beam dump, by removing with fast transport the thermal power generated by high-intensity proton beams. Of specific concern is the power densities created by the protons in the Bragg peak area, of the order of 1 MW/cm^3 (volume power density), about 150 μm deep inside the lithium. The target was designed based on a thermal model, accompanied by a detailed calculation of the ^{7}Li(p,n) neutron yield, energy distribution and angular distribution (Halfon et al., 2013).

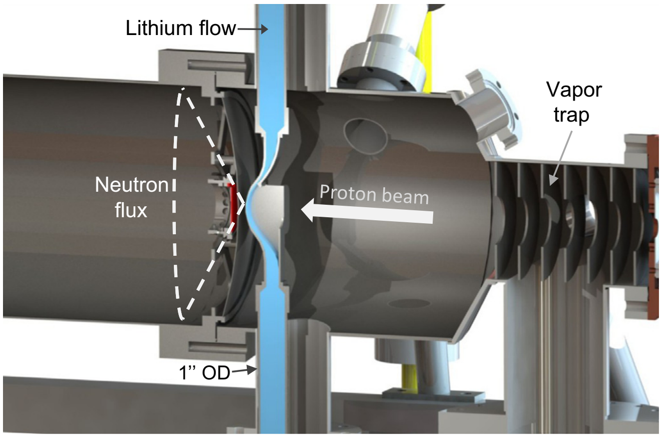

Fig. 1. LiLiT vacuum chamber cross section.

Fig. 2 illustrates the LiLiT general assembly. The liquid lithium, maintained above liquefaction temperature by external and internal heating elements, is circulated, driven by an electromagnetic (EM) induction pump (the pump loop is marked by F in Fig. 2) from the reservoir (E) through the pipes and the vacuum chamber (B, cross section seen in Fig. 1) that hosts the nozzle (D). The lithium is returned into the reservoir where a heat exchanger removes the beam power to a secondary oil loop (seen in Fig. 3), which in turn is connected to an oil-air heat exchanger. The vacuum in the system is maintained in the range of 10^{-7} mbar using a custom-built arc-pump and an adjoined ion-pump. More details on the target components and design can be found in (Halfon et al., 2014a).

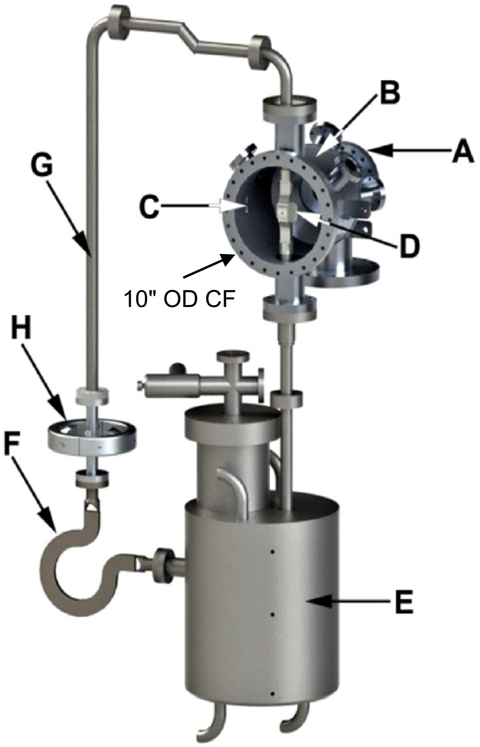

Fig. 2. Schematic drawing of the LiLiT assembly viewed from the neutron exit port: (A) proton beam inlet port, (B) target chamber (cross section seen in Fig. 1), (C) neutron port (shown open); (D) lithium nozzle, (E) lithium containment tank (including heat exchanger and ^{7}Be cold trap), (F) electromagnetic (EM) pump (only the circulation loop is shown), (G) loop line, (H) electromagnetic flow-meter.