Lawrence Berkeley National Laboratory
Recent Work

Title
An Epithermal Neutron Source for BNCT Based on an ESQ-Accelerator

Permalink
https://escholarship.org/uc/item/4xq8f961

Author
Ludewigt, B.A.

Publication Date
1997-07-01

ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY

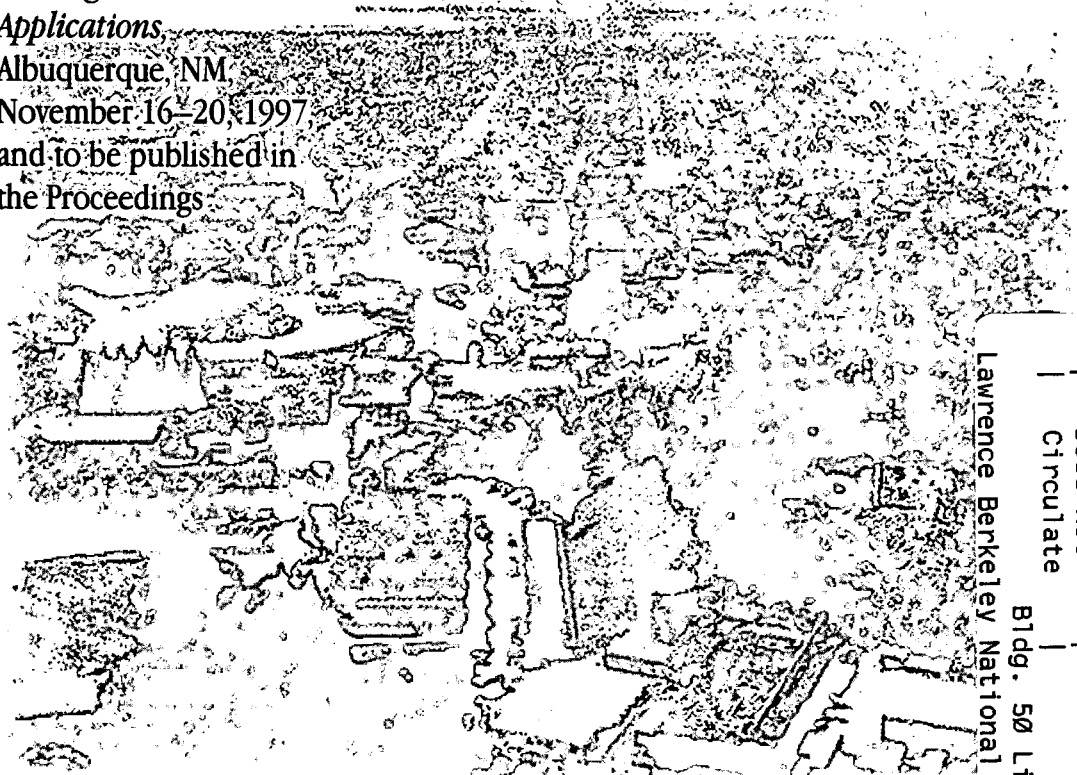# An Epithermal Neutron Source for BNCT Based on an ESQ-Accelerator

B.A. Ludewigt, W.T. Chu, R.J. Donahue, J. Kwan,
T.L. Phillips, L.L. Reginato, and R.P. Wells

Accelerator and Fusion
Research Division

July 1997

DISCLAIMER

An Epithermal Neutron Source for BNCT Based on an ESQ-Accelerator

B.A. Ludewigt, W.T. Chu, R.J. Donahue, J. Kwan, T.L. Phillips,
L.L. Reginato, and R.P. Wells

Accelerator and Fusion Research Division
Ernest Orlando Lawrence Berkeley National Laboratory
University of California
Berkeley, California 94720

July 1997

AN EPITHERMAL NEUTRON SOURCE FOR BNCT BASED ON AN ESQ-ACCELERATOR

B. A. Ludewigt, W. T. Chu, R. J. Donahue, J. Kwan, T. L. Phillips, L. L. Reginato, and R. P. Wells

Lawrence Berkeley National Laboratory, Berkeley, CA 94720

Abstract

An accelerator-based BNCT facility is under development at the Lawrence Berkeley National Laboratory. Neutrons will be produced via the $^7Li(p,n)$ reaction at proton energies of about 2.5 MeV with subsequent moderation and filtering for shaping epithermal neutron beams for BNCT. Moderator, filter, and shielding assemblies have been modeled using MCNP. Head-phantom dose distributions have been calculated using the treatment planning software BNCT_RTPE. The simulation studies have shown that a proton beam current of ~20 mA is required to deliver high quality brain treatments in about 40 minutes. The results also indicate that significantly higher doses can be delivered to deep-seated tumors in comparison to the Brookhaven Medical Research Reactor beam. An electrostatic quadrupole (ESQ) accelerator is ideally suited to provide the high beam currents desired. A novel power supply utilizing the air-coupled transformer concept is under development. It will enable the ESQ-accelerator to deliver proton beam currents exceeding 50 mA. A lithium target has been designed which consists of a thin layer of lithium on an aluminum backing. Closely spaced, narrow coolant passages cut into the aluminum allow the removal of a 50kW heat-load by convective water cooling. The system under development is suitable for hospital installation and has the potential for providing neutron beams superior to reactor sources.

I. Introduction

The first clinical BNCT trials for high-grade primary brain tumors (glioblastoma multiforme) have been started at the Brookhaven Medical Research Reactor (BMRR)[1] and at the Massachusetts Institute of Technology Research Reactor. Given the problems associated with new reactor installations accelerator-based BNCT facilities will be needed for a wider use of this modality. In addition, accelerator neutron sources offer the potential for better clinical performance in terms of improved depth-dose distributions, increased flexibility, and perhaps even higher neutron fluxes and dose rates.

Different types of accelerator-based neutron sources have been studied in the past and have shown promise for BNCT. Examples are photo-neutron sources[2] and sources based on proton and deuteron induced reactions in lithium and beryllium targets[3-7]. We have compared ^{7}Li(p,n), ^{9}Be(p,n) and ^{9}Be(d,n) reactions at energies between 2.1 and 19 MeV. Preliminary results indicated that given the available accelerator technologies and estimated beam current requirements, the ^{7}Li(p,n) reaction at a proton energy of ~2.3 MeV is the preferred choice. It was also found that the relatively low maximum neutron energy of ~600 keV from that reaction is advantageous for producing the desired energy spectra[8].

In this paper we report on the development of an accelerator-based BNCT facility. The basic components of such a neutron source are the particle accelerator, the neutron production target, and the moderator and filter assembly. Electrostatic quadrupole (ESQ) accelerators have successfully been developed at LBNL as particle injectors for nuclear fusion. This technology is very well suited for accelerating protons to the desired energy of ~2.5 MeV at very high beam currents. The ESQ-accelerator concept and its application to BNCT are discussed in Sec. III. The lithium target itself is a crucial component of a neutron source for BNCT utilizing the ^{7}Li(p,n)^{7}Be reaction since the melting point of metallic lithium is very low. The target design and first test results are presented in Sec. IV. A summary of the planned facility is given in Sec. V.

Our approach has been to first establish the clinical requirements and then derive the target and accelerator specifications. A good moderator design, which produces the desired neutron spectrum and optimizes the epithermal neutron flux, is essential for establishing the accelerator and target requirements. Clinical requirements, in-phantom dose calculations, and the simulation of the neutron and photon transport from the target through the moderator and filter assembly into the phantom are briefly described in Sec. II. In addition, the simulated beams are compared to the currently available beam at the BMRR.

II. Simulation Studies

The neutron beam modeling served two purposes: a) to study various moderator materials and designs and b) to address accelerator requirements such as energy and current of the proton beam and target specifications. A standard setup, shown in Fig. 1, was used for simulating the radiation transport through the moderator and filter assembly and a head phantom. The neutron source was modeled as uniformly distributed across the surface of a disk with a 5 cm radius, corresponding to a uniform proton beam

coverage. The cylindrically shaped moderator was surrounded by an Al_2O_3 reflector. The interface surfaces were lined with [6]Li for the filtering of thermal neutrons. Energy and angular dependencies of the neutron yield were calculated using normalized Legendre coefficients[9] for predicting cross sections for the [7]Li(p,n)[7]Be reaction.

Three moderator materials were analyzed: D_2O was chosen because it had been shown to be an effective moderator leading to high dose rates[3-5], a mixture of Al (40%) and AlF_3 (60%) has produced excellent BNCT beams at a TRIGA reactor[10], and [7]LiF has been identified as a good candidate in a previous study[11]. The Monte Carlo code MCNP[12] was used to determine the neutron and photon energy and angular distributions across a 20 cm diameter surface at the exit of the moderator. These distributions were used as input for a second Monte Carlo model. The special-purpose BNCT Radiation Treatment Planning Environment (BNCT_RTPE) software system[13,14] was used to simulate the transport of neutrons and protons through a head phantom using a CT-scan of a human head of typical size. More details about the modeling can be found in Bleuel et al.[8].
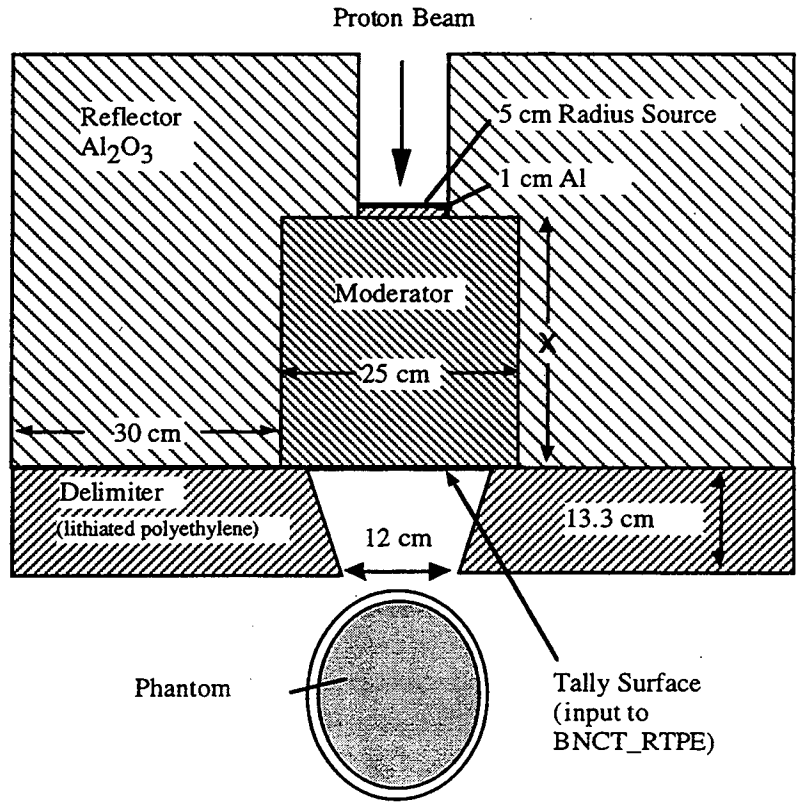

Fig. 1 Cross section of moderator and filter assembly.

We have based our evaluation of the clinical effectiveness of the simulated neutron beams on the equivalent dose distributions in a head phantom. The equivalent dose depends strongly on boron concentrations in tumor and normal brain, relative biological effectiveness (RBE) and compound factors. In our dosimetric calculations we have

followed the protocol for the clinical trial at BMRR[1,15] and assumed [10]B concentrations of 45.5 ppm and 13 ppm for tumor and normal brain tissues, respectively. Our analysis was restricted to single beam treatments although in practice two or more fields are likely to be used.

As the main clinical requirement the maximum dose to the healthy brain was set to 12.5 Gy-Eq following the BMRR clinical protocol. A second normal tissue dose requirement was introduced to limit the proton-recoil dose at the entrance. The dose as calculated for normal brain tissue at a depth of 0 cm was limited to 10 Gy-Eq. This implicitly limits the volume which receives the maximum normal brain dose of 12.5 Gy-Eq and ensures that the dose to the scalp is not excessively high. Treatment times of less than an hour were regarded as acceptable in respect to patient comfort and change in [10]B concentration as a function of time.
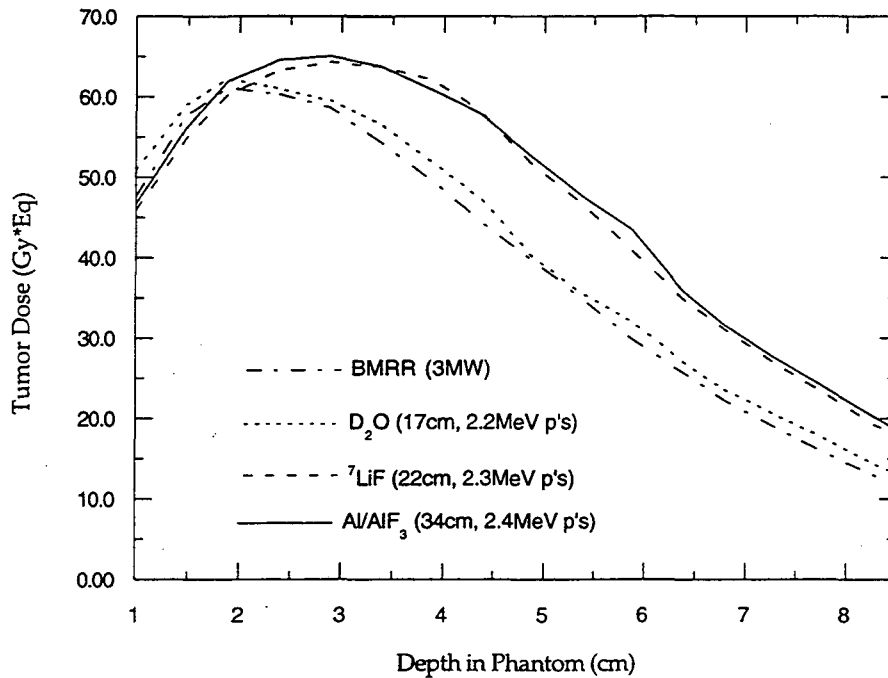
Fig. 2: Depth distributions of total equivalent tumor doses for D_2O, [7]LiF and Al/AlF[3] moderated neutron beams from a [7]Li(p,n) source and the BMRR beam.

The in-phantom dose distributions were evaluated in terms of the depth-dose profiles along the proton-beam axis and their dose rate for a given proton beam current. In particular, the equivalent dose to the tumor cells at 8 cm depth, roughly the midline of the brain, was adopted as the figure-of-merit. The most penetrating depth dose distributions were found for the [7]LiF and the Al/AlF[3] moderators at proton energies between 2.3 and 2.5 MeV. As can be seen in Fig. 2 for these moderators the equivalent dose to the tumor cells and the thermal neutron flux as a function of depth are clearly superior to the BMRR

4

beam. At 8 cm depth, near the midline of the brain, the ^{7}Li(p,n) source with the ^{7}LiF moderator delivers an almost 50% higher equivalent dose than the BMRR beam. The treatment time of ~40 min is about the same for a 20 mA proton beam and the reactor operating at 3 MW. These results indicate that the accelerator should be able to provide a proton beam with an energy of up to 2.5 MeV and a beam current of at least 20 mA.

III. ESQ Accelerator

DC electrostatic accelerators are the preferred choice for applications that require high average beam current or variable energy. DC accelerator technology based on the electrostatic quadrupole (ESQ) accelerator concept has been developed at LBNL for applications such as injectors for fusion reactors[16]. For example, a 2.0 MeV, 800 mA K$^+$ beam ESQ-accelerator has been built and tested as an injector for a heavy ion fusion driver. In a conventional accelerator column of thick apertures the radial field is coupled to the longitudinal field. This tends to make the longitudinal field gradient very large in order to obtain sufficient focusing necessary for a high beam current. Using an ESQ column with alternating polarities achieves very strong focusing without incurring a longitudinal field near the breakdown limit. As an additional advantage secondary electrons or ions are quickly removed by the transverse ESQ electrodes before they can develop into a column arc-down[17].

PRESSURE VESSEL
TRANSFORMER PRIMARY COILS
TRANSFORMER SECONDARY COILS
Power Supplies and Accessories for Ion Source
Ion Source
ESQ ACCELERATOR
HV DOME
SUPPORT STRUCTURE
3.61 METERS
OVERALL TANK LENGTH IS 6.10 METERS LONG BY 2.44 METERS IN DIAMETER
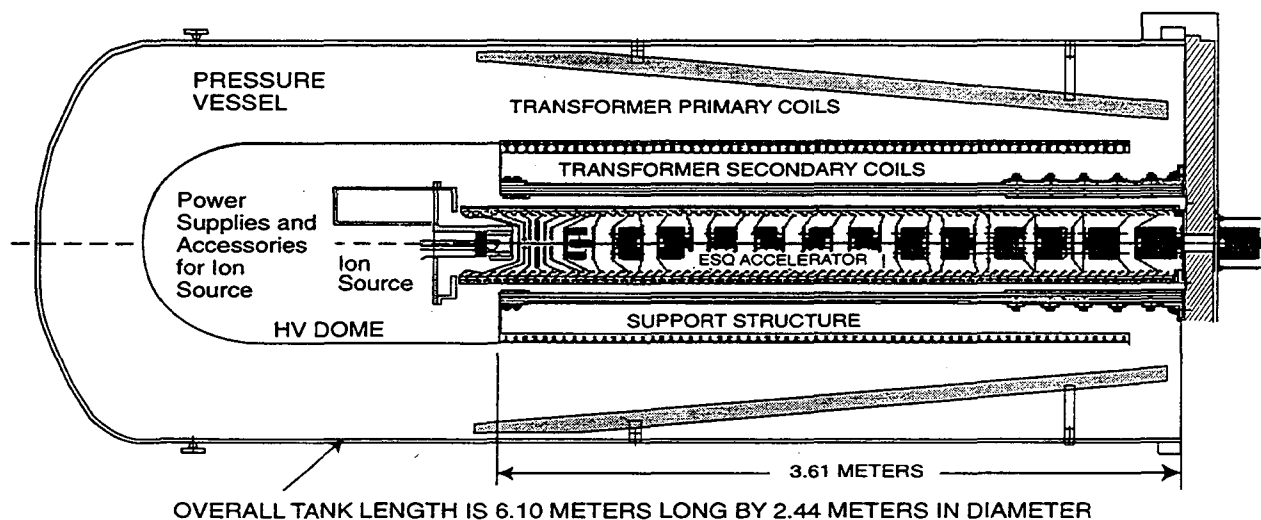
Fig. 3 Schematic cross section of the 2.5 MeV accelerator showing pressure vessel, ion source, ESQ accelerator column and air-coupled transformer coils.

At LBNL we are refurbishing a decommissioned DC accelerator for use in the BNCT facility. The old acceleration column has been removed to be replaced with a new ESQ column. An air-core multistage transformer-rectifier stack will replace the existing power supply (Dynamitron) in order to supply tens of mA beam current. The supporting structure and high pressure vessel and the existing oscillator will be reused.

5

Fig. 3 shows a schematic cross section of the ESQ-accelerator and power supply inside the refurbished pressure vessel. The ion source is mounted in the high voltage dome. It is a multicusp source which can deliver positive hydrogen ion beams with the monatomic ion fraction higher than 90%[18]. Clean, reliable, and long-life source operation is provided by radio-frequency induction discharge. The suitability of the ion source for BNCT has been demonstrated with an extractable hydrogen ion current density of 100 mA/cm^2. A low energy beam transport section (LEBT) consisting of 6 electrodes accelerates the extracted protons to 325 keV. The LEBT is then followed by 13 ESQ modules for the main acceleration up to 2.5 MeV. Cooling keeps the temperature rise of the copper electrodes below 100°C for a power deposition of 100 W per electrode. The acceleration column has been designed for accelerating a 125 mA beam. A more detailed description is found in Kwan et al.[19]. The ESQ accelerator will not only be able to deliver sufficient beam current for producing a high flux epithermal neutron beam via the ^{7}Li(p,n) reaction as discussed in Sec. II, but will also be able to provide enough beam current for exploring other neutron production targets and moderator and filter designs. Future ESQ-accelerators enclosed in a steel tank filled with SF$_6$ could be more compact, approximately 3 m long with a diameter of 2-3 m for a 2.5 MeV accelerator.

While the beam dynamics in DC ESQ-accelerators have been demonstrated previously, the greater challenge is the development of a suitable and affordable power supply. For beam currents above 10 mA a capacitively coupled Cockcroft-Walton power supply becomes increasingly inadequate. The existing power supply has been modified from capacitively coupled to inductively coupled for test measurements[20]. These tests were performed with a full scale primary coil and ten secondaries. They showed that primary to secondary coupling along the length of the acceleration column can ultimately be equalized to ±1% by adjusting the primary current density and the number of turns in the secondary coil. The low impedance of the inductively coupled system, about 5 MΩ or one order of magnitude lower than the capacitively coupled system, will allow acceleration of beam currents exceeding 50 mA.

IV. Lithium Target for Neutron Production

A 20 mA beam of 2.5 MeV protons deposits a heat-load of 50 kW in the lithium target and its support and cooling structure. Metallic lithium is a challenging material for a high power neutron production target. Its low melting point of 179°C makes very effective cooling mandatory. Our design is based on a convectively cooled aluminum substrate coated by a 45 μm thick lithium layer. The target consists of two panels mounted at a 30° angle in respect to the incident beam in order to cut the heat-load per surface area in half. The effective thickness of the Li layer is 90 μm, sufficient for 2.5 MeV protons to lose enough energy to fall below the neutron production threshold. The remainder of the proton energy is deposited in the aluminum backing.

The heat is dissipated by water flowing through closely spaced, narrow coolant passages (microchannels) cut into the back side of the heat absorbing surface. This concept relies on enhancing the surface area for heat transfer and utilizing relatively modest heat transfer coefficients. The size and spacing of these channels and the required coolant flow and pressure drop were optimized using the finite-element code ANSYS. A

cross section of the target design is shown schematically in Fig. 4. For a heat-load of 600 W/cm^2 assuming surface heating and cooling by 20°C water with a flow velocity of 9 m/s, the simulation results showed a maximum temperature at the cooling channel of ~100°C which is about 15°C less than the boiling point of water at the elevated pressure in the channel. The temperature on the heated surface was 152°C which is well below the melting point of lithium. A structural analysis based on a full 3-D finite element model showed that the maximum thermally-induced stress encountered in the cooling substrate is about 130 MPa.
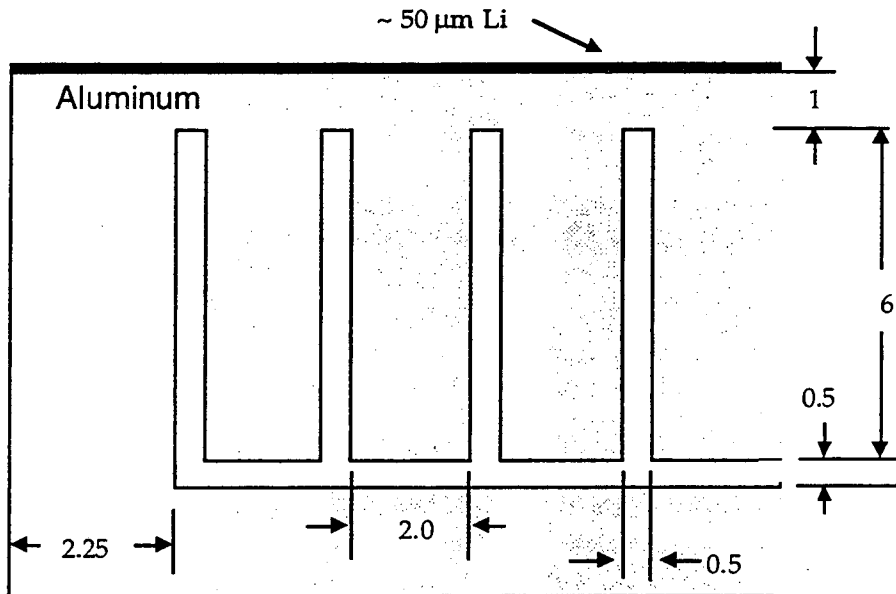

Fig. 4 Design of prototype of neutron production target (cross section, units in mm).

A prototype aluminum target panel has been fabricated. Using wire EDM, both the heated surface and the back plate were machined from a single plate of aluminum in one operation. Recently, the panel has been heat-load tested at the Plasma Materials Test Facility at Sandia National Laboratory in Albuquerque, NM. A defined heat-load profile was delivered to the target utilizing a scanned electron beam. The thermal response up to heat-loads well above the anticipated operating point, was measured. The results are displayed in Fig. 5. At heat-loads up to 500 W/cm^2 the measured surface temperature agrees well with the prediction whereas at higher heat-loads the measured curve flattens out and the experimental values stay below the predicted temperatures. For a heat-load of 600 W/cm^2 a surface temperature of ~130°C was measured. The melting point of lithium was reached at ~900 W/cm^2. Also tested was the thermal fatigue reliability of the prototype panel by subjecting it to 50,000 heat-load cycles. No indications of problems such as cracks or hot spots were detected.

For a 10 cm diameter proton beam a 600 W/cm^2 heat-load corresponds to a total heat-load of ~90 kW making it possible to handle more than 30 mA of 2.5 MeV protons. Results from our neutron transport modeling of the moderator and filter assembly indicate that even larger proton beams and target sizes up to about 15 cm in diameter

could be chosen without significantly decreasing the efficiency of the epithermal neutron production. This could extent the useful range of this design to above 50 mA of proton beam current. Thus, we believe that our target design satisfies the heat-load requirements for a BNCT facility and is well matched to the high beam current capability of an ESQ-accelerator.
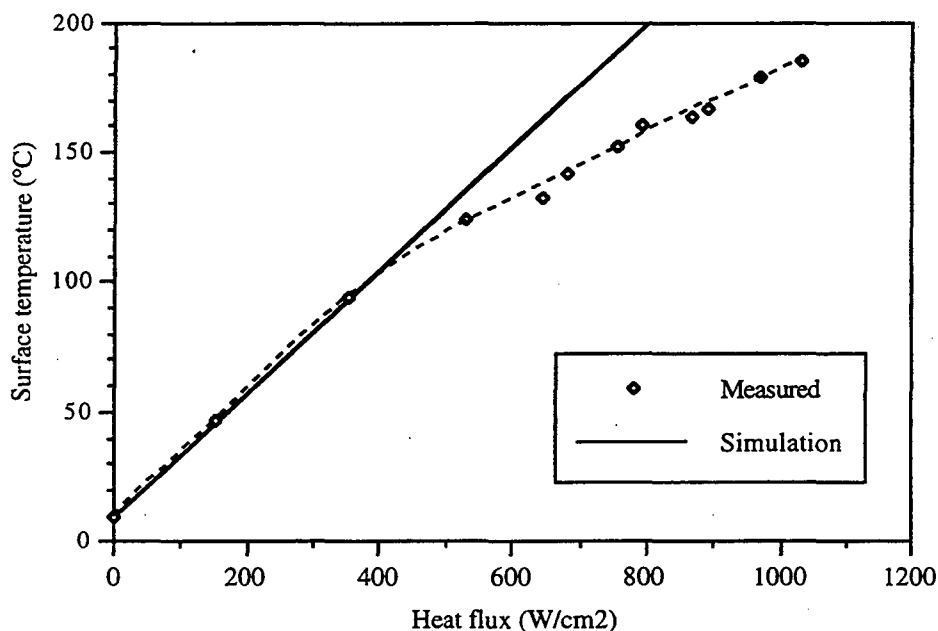

Fig. 5 Thermal response of target panel. (Dashed line to guide the eye).

V. Treatment Facility

The facility will, as a minimum, feature one shielded treatment room enclosure, which will house the target, moderator and filter assembly, the patient positioning device, and other auxiliary equipment. The accelerator will be located adjacent to the treatment room. A simple, all magnetic beam line will transport the beam onto the target in the treatment room. A pair of 7.5° dipole magnets, 1 m apart and buried in the shielding wall will separate H_2^+ and H_3^+ from the protons to avoid unnecessary target heating. The "dog-leg" introduced by the separator will also prevent neutrons from back streaming into the accelerator room. A quadrupole doublet will control the beam size at the target. The beam line will be equipped with beam and target monitoring instrumentation and fast shutters for preventing a contamination of the accelerator with ^7Li and radioactive ^7Be in case of a target failure.

The lithium target will allow for the generation of very high epithermal neutron fluxes and the delivery of optimized patient treatments. Further, the high current capability of the ESQ-accelerator will make it possible to explore the use of alternative targets and nuclear reactions for BNCT. The facility under development will demonstrate the practicality and the capabilities of an accelerator-based neutron source for BNCT.

REFERENCES

1. J.A. Coderre, E.H. Elowitz, M. Chadha, R. Bergland, J. Capala, D.D. Joel, H.B. Liu, D.N. Slatkin and A.D. Chanana, "Boron neutron capture therapy for glioblastoma multiforme using p-boronophenylalanine and epithermal neutrons: Trial design and early clinical results," J. Neuro-Oncology **33**: 141-152, 1997.

2. D. Nigg et al., "Computational and Experimental Studies of an Electron Accelerator Based Epithermal Photoneutron Source Facility for BNCT," INEL-96-0139, 1996.

3. C.-K. C. Wang, T.E. Blue, R. Gahbauer, "A neutronic study of an accelerator-based neutron irradiation facility for boron neutron capture therapy," Nucl. Technology **84**, 93-107, 1989.

4. J.C. Yanch, X.L. Zhou, R.E. Shefer, R.E. Klinkowstein, "Accelerator-based epithermal neutron beam design for neutron capture therapy," Med. Phys. **19**, 709-721, 1992.

5. D.A. Allen and T.D. Beynon, "A design study for an accelerator-based epithermal neutron beam for BNCT," Phys. Med. Biol. **40**, 807-821, 1995.

6. W.B. Howard, J.C. Yanch, S.M. Grimes, T.N. Massey, S.I. Al-Quraishi, D.K. Jacobs, and C.E. Brient, "Measurements of the ^{9}Be(p,n) thick target spectrum for use in accelerator-based Boron Neutron Capture Therapy," Med. Phys. **23**, 1233-1235, 1996.

7. F. Harmon, R. Kudchadker, J.F. Kunze, S.W. Serrano, X.L.Zhou, Y.D. Harker, R.W. Hamm, "Accelerator Neutron Sources for NCT Using Near Threshold Charged Particle Reactions," Proc. of the 14th Int. Conf. on the Applications of Accelerators in Research & Industry, Denton Texas, November, 1996, AIP Press, New York, **Vol. II**, 1285-1288, 1997.

8. D.L. Bleuel, R.J. Donahue, B.A. Ludewigt, and J. Vujic, "Designing acclerator-based neutron beams for BNCT," submitted to Med. Phys., and LBNL-40551, July 1997.

9. H. Liskien and A. Paulsen, "Neutron Production Cross Sections and Energies for the Reactions ^{7}Li(p,n)^{7}Be and ^{7}Li(p,n)^{7}Be*," Atomic Data and Nuclear Data Tables, **15**, 57-84, 1975.

10. I. Auterinen and P. Hiismaki, "Design of an epithermal neutron beam for the TRIGA Reactor in Otaniemi," in the Proc. of the CLINT BNCT Workshop, Helsinki 1993, TKK-F-A718, 14-24, 1994.

11. Y Karni, E. Greenspan, J. Vujic, and B. Ludewigt, "Optimal Beam-Shaping Asssemblies for BNCT Facilities using 2.5 MeV Protons on ^{7}Li or 19 MeV Protons on Be," Trans. of the Am. Nucl. Soc., San Francisco, CA, Oct. 29 - Nov. 2, Vol. **73**, p. 29, 1995.

12. "MCNP-A A General Monte Carlo N-Particle Transport Code, Version 4A," J.F. Briesmeister, Ed., LA-12625, Los Alamos Natl. Lab., 1993.

13. D.W. Nigg, "Methods for Radiation Dose Distribution Analysis and Treatment Planning in Boron Neutron Capture Therapy, " Int. J. of Rad. Onc. Bio. Phys. **28**, 1121-1134, 1994.

14. D.W. Nigg, F. J. Wheeler, D. E. Wessol, J. Capala, M. Chada, "Computational Dosimetry and Treatment Planning for Boron Neutron Capture Therapy," J. of Neuro-Oncology **33**, 93-104, 1997.

15. A.D. Chanana, "Boron Neutron-Capture Therapy of Glioblastoma Multiforme at the Brookhaven Medical Research Reactor, A Phase I/II Study, FDA IND # 43,317, Protocol #4," Med. Dep., Brookhaven Natl. Lab., Upton, NY 11973-5000, January, 1996.

16. J.W. Kwan, G.D. Ackerman, O.A. Anderson, C.F. Chan, W.S. Cooper, G.J. deVries, W.B. Kunkel, L. Soloka, W.F. Steele and R.P. Wells, "Testing of a High Current DC ESQ Accelerator," Conference Record of the 1991 IEEE Particle Accelerator Conference, May 1991, San Francisco, CA, Vol. 3: 1955-1957, 1991.

17. J.W. Kwan, O.A. Anderson, L.L. Reginato, M.C. Vella, S.S. Yu, "A 2.5 MeV electrostatic quadrupole DC-accelerator for BNCT applications," Nucl. Instrum. Methods **B99**, 710-712, 1995.

18. K.N. Leung, "Ion Sources for High Purity Ions," Proc. of the 14th Int. Conf. on the Applications of Accelerators in Research & Industry, Denton Texas, November, 1996, AIP Press, New York, **Vol. II**, 1203-1205, 1997.

19. J.W. Kwan , E. Henestra, C. Peters, L.L. Reginato, and S.S. Yu, "Design of a DC ESQ Accelerators for BNCT Application," Proc. of the 14th Int. Conf. on the Applications of Accelerators in Research & Industry, Denton Texas, November, 1996, AIP Press, New York, **Vol. II**, 1313-1315, 1997.

20. L.L. Reginato, J. Ayers, R. Johnson, C. Peters, R. Stevenson, "Designing Power Supplies for 2.5 MeV, 100 mA d.c. for BNCT," Proc. of the 14th Int. Conf. on the Applications of Accelerators in Research & Industry, Denton Texas, November 1996, AIP Press, New York, **Vol. II**, 1305-1308, 1997.