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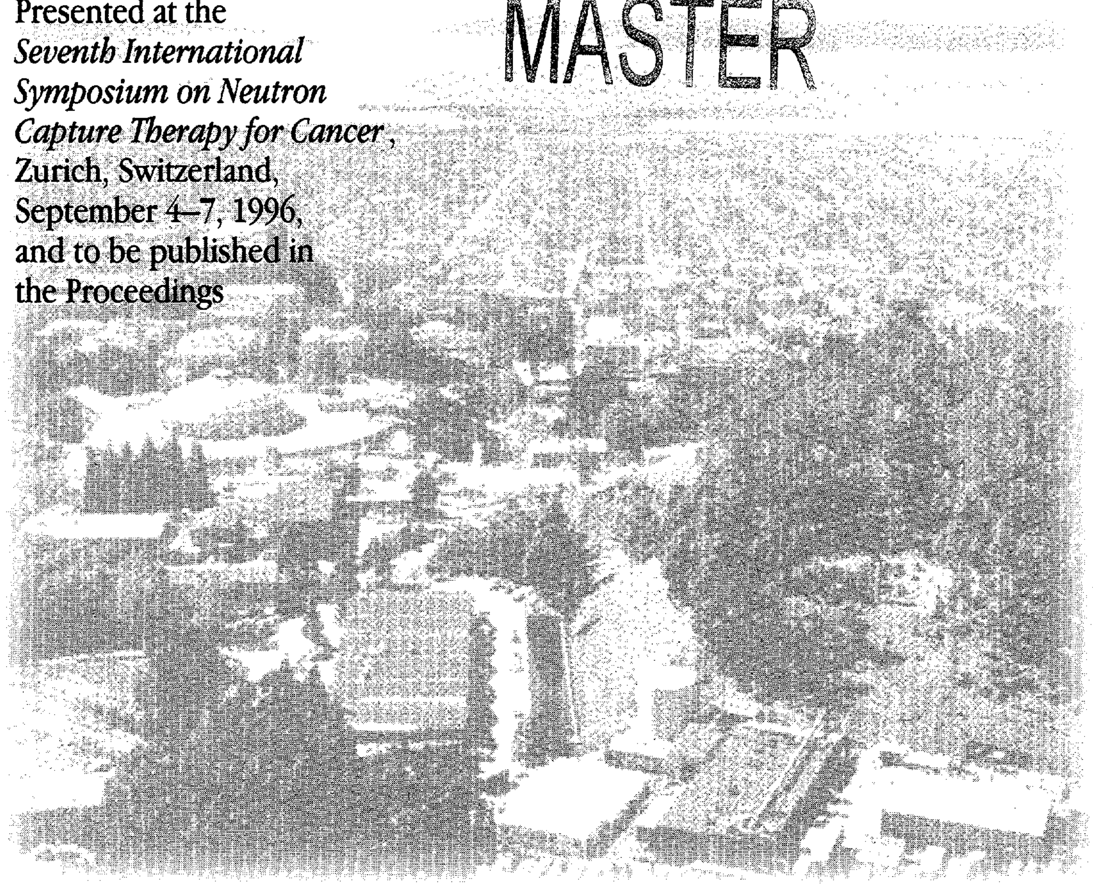

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Design of a new BNCT facility based on an ESQ accelerator

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Introduction

We plan to build a BNCT facility based on electrostatic quadrupole (ESQ) accelerator technology. It is an experimentally-proven technology capable of delivering a high proton current for producing a neutron intensity greater than what is required for BNCT clinical trials. We also present a design of a lithium neutron-production target with adequate cooling of the heat generated by the high-current proton beam.

Clinical requirements for an accelerator-based BNCT facility

Studies have identified a ^7Li target as an excellent choice for producing neutrons for BNCT via the $^7Li(p,n)^7Be$ reaction. This reaction has a 1.88 MeV proton energy threshold, and a prominent resonance at 2.3 MeV which drops sharply at 2.5 MeV. Therefore, an use of 2.5 MeV protons is generally thought to produce the highest neutron yield for BNCT.

Bleuel et al. [1] have studied the dose rate and quality of the epithermal neutron beam as function of moderator thickness and incident proton energy for three moderator materials, namely, BeO, D_2O, and Al/AlF_3. The useful (1 eV to 10 keV) neutron flux peaks at an incident proton energy around 2.3 MeV, where the epithermal neutron flux is roughly 35% higher than that at a proton energy of 2.5 MeV. The neutron energy spectrum can be varied by changing the proton beam energy and moderator thickness with the potential of optimization for different tumor depths. Therefore, the accelerated proton energy should be tunable from 2.0 to 2.5 MeV. Bleuel et al. have also shown that 2.3–2.5 MeV protons at a current of 20 mA impinging onto a Li target produce enough neutrons to achieve the same dose rate available at the Brookhaven Biomedical Research Reactor operating at 3 MW, and with appropriate moderation and filtering, provide a clinically superior neutron energy spectrum. Therefore, the accelerated proton current should exceed 20 mA d.c.

ESQ accelerator development

At LBNL, Kwan et al. [2] have been developing high-current D.C. accelerators using ESQ columns for neutral particle beam injectors for tokamak fusion reactors, and injectors for heavy ion induction linear accelerators (for inertial fusion reactors). An ESQ accelerating a 200 keV of He^+ beam to 100 mA and another 2.0 MeV ESQ injector delivering 800 mA of 1 μs K^+ beam have been successfully tested.

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Unlike straight-line electrostatic accelerators, in ESQ accelerators the transverse focusing is independent of the longitudinal accelerating electric field, and can be very strong (important for a high-current beam) without incurring a longitudinal field near or exceeding the breakdown limit. Another advantage in applying a strong transverse electric field is that the secondary electrons (or ions) generated within the accelerator column are quickly removed, instead of being allowed to multiply and eventually develop into a column arc-down. High energy stray electrons produce unwanted x-rays.

High voltage power supply development

In order to meet the requirement for future high current application, e.g., up to 100 mA, we decided to investigate the coupled-transformer technique previously considered in the neutral beam program at LBNL to generate high voltages at high currents. Both ferrite-coupled and air-core transformers were considered and small-scale prototypes were constructed and tested. Results indicated that either technique could deliver the desired 100 mA at 2.5 MV but the air-core device is more compatible with the existing steel vacuum tank of the Adam injector.

Low-voltage tests were performed on the impedance and voltage distribution along the air-core transformer, indicating that the coupled transformer technology offers an order of magnitude lower impedance than the shunt-fed capacitively coupled Dynamitron type of drive. It means that 100 mA should be achievable[3].

Ion source

An ion source has been developed to provide high brightness hydrogen ion beams with high atomic species (i.e., mostly H_1^+ and little H_2^+ or H_3^+) and long lifetime between servicing. We have demonstrated that the rf-driven multicusp source is capable of delivering a high current density beam (>1 A/cm^2) with an atomic hydrogen fraction as high as 94%. Thus the use of a bulky magnetic mass separation magnet can be avoided. The exit aperture diameter is 6 mm and the required rf input power to the source plasma generator is approximately 2.5 kW.

Beam Transport System

The extracted proton beam (~2.5 MeV) will be transported to the target area through a beam line consisting of magnetic focusing lens (which is also useful in separating the heavier molecular ions from the protons to prevent wasting heating of the target surface) and a wobbler to spread out the beam spot size.

A conceptual ESQ accelerator design for BNCT application

The main acceleration is done in 13 ESQ modules. One extra non-accelerating ESQ is placed at the end for beam matching into the transport line. The ESQ has a bore diameter of 6 cm. The column is 3.8 meter long and is made of 70 alumina rings that are 45 cm in diameter. The design is modular; each ESQ module has several alumina rings brazed together and the full assembly is held under compression by tie rods. Electrode alignment tolerance is less than 0.1 mm. All electrodes are made of copper which has good thermal, electrical and vacuum properties.

We will reuse the surplus ADAM Injector high-pressure vessel, the insulator supporting structure, and the high voltage dome. The accelerator assembly is enclosed inside a 6.1 m long 2.4 m diameter steel tank. The accelerator column will be pressurized (125 psi) with insulating gas such as sulfur hexafluoride gas (SF_6).

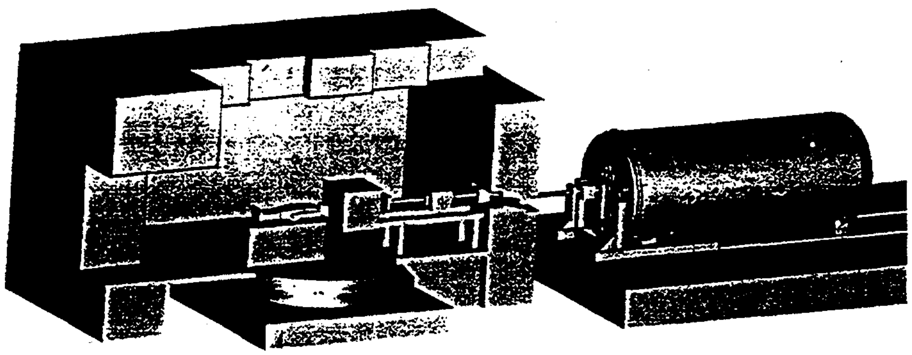

Figure 1. A schematic drawing showing the ESQ accelerator, the external beam line through the shielding wall, the moderator assembly, and a patient on the patient positioner inside the shielded treatment room.

Neutron-Production Target

A beam of 2.5 MeV protons at 20 mA presents a heat-load of 50 kW to the target. The heat generated by the proton beam must be efficiently removed in order to prevent the lithium from melting (melting point 179°C). Assuming the diameter of the proton beam of 10 cm and a target area of 100 cm^2, a uniform energy deposition would result in a heat-load of 500 W/cm^2. For a Gaussian beam profile, the peak heat-load (in the center) is 1280 W/cm^2, or by tilting the target to at a 30° incident angle the maximum heat-load can be halved to 640 W/cm^2.

Our design is based on a convectively-cooled aluminum substrate coated by a 45 μm (effective thickness is 90 μm for 30° incident protons) thick Li layer which is protected by a 1–2 μm thick aluminum coating. 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 are subject to optimization. The cooling strategy proposed for this application is an adaptation of the past experiences at LBNL of a high heat-load beam dump and an extension of the microchannel concept to a copper alloy substrate for the design of a photon absorber at the Advanced Light Source. The thermal response was calculated using the finite-element code ANSYS for the target subjected to a Gaussian heat load and cooled by 20°C water with a flow velocity of 9 m/s. The result show a maximum temperature at the cooling channels of 103°C which is about 15°C less than the boiling point of water at the elevated pressure in the channel. The maximum temperature on the heat-absorbing surface does not exceed 140°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, which is less than the yield strength of pure aluminum.

The LBNL BNCT Facility

The new BNCT treatment room will be developed in an existing shielded patient irradiation enclosure at the Bevatron, previously used as a treatment room by the heavy ion biomedical program. This room has a useful interior floor area of approximately 6.4 m x 8.5 m (55 m^2) and is surrounded by concrete shielding that varies from 1.2–3 meters in thickness (see Fig. 1). The accelerator itself will be located immediately outside the irradiation room, in a high-bay experimental hall which has a heavy-duty reinforced floor, and is serviced by a 30 ton crane. An area approximately 18 m x 18 m (324 m^2) will accommodate the accelerator, proton beam line and supporting equipment. This site is located in close proximity to the Laboratory's Nuclear Medicine Facilities, the Imaging Facilities and the Isotope Production Cyclotron.

Summary

The ESQ technology opens up the possibility of building a high-current, d.c., electrostatic accelerator that can meet the requirements of BNCT. The ESQ configuration has a clear advantage towards suppressing electrical arc-downs and is therefore capable of operating at high current. At present, the critical path is the development of a compact, high current, multi-megavolt, d.c. power supply and a lithium target that can withstand the high beam power.

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