ESQ-Focused 2.5 MeV DC Accelerator for BNCT

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Abstract

The recent development of dc ESQ accelerators has been driven by magnetic fusion energy applications, which require many amperes of D^- at typically 1.3 MeV. We discuss designs for a new application, Boron-Neutron Capture Therapy (BNCT) for cancer treatment. In this application, 2.5 MeV H^+ beams produce neutrons in a target containing lithium. For reasonable dose times, the required current is around 100 mA. Because of the high voltage, ESQ focusing has an important advantage: transverse fields sweep out stray charges generated along the channel, thus inhibiting voltage breakdown. (This inhibition has been verified experimentally at LBL.) The particular ESQ configuration discussed here has additional advantages: (a) acceleration and focusing are independent, so that the average longitudinal voltage gradient can be lowered for reliability; and (b) the design uses a series of identical acceleration modules, so that the production cost is minimized. We present a conceptual design for a system that includes a 2.5 MeV dc accelerator, integrated modular power supply, and target.

1. Introduction

Boron neutron capture therapy is a treatment proposed for deep, inoperable brain tumors [1]. Recently, a number of factors have emerged that greatly improve its chances of success.

The principle of BNCT is to selectively destroy cancer cells by loading them with boron compounds and then introducing neutrons to convert the boron nuclei into pairs of short-range ions which deliver their energy within the cancer cell. The recent developments are: (1) New boron compounds have been developed which are much more likely to concentrate in the cancer cells than in the blood stream or in normal tissues; (2) There is improved understanding of the optimum energy spectrum for the neutrons to minimize damage of healthy tissue; (3) New filters are being designed to efficiently produce the required spectrum; (4) A practical accelerator-based neutron generator scheme has been identified which avoids the need for a nuclear reactor and which should be suitable for a hospital environment.

The accelerator-based neutron generator scheme discussed in this paper incorporates an efficient 100 mA, 2.5 MeV dc proton accelerator and a newly devised refractory target which produces neutrons through the $^7Li(p,n)^7Be$ reaction.

Section 2 describes the H^+ accelerator, which uses the modular Constant-Current Variable-Voltage (CCVV) type of ESQ focusing originally developed for the U.S. magnetic fusion energy program [2] and proposed for the ITER program [3]. We show that ESQ focusing supports about 9 times the current of a Pierce column for the same peak fields. Sections 3 and 4 discuss the compact integrated power supply and the new refractory target. Remaining issues are summarized in section 5.

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2. The ESQ-Focused Accelerator

The CCVV accelerator described here answers the particular needs of the BNCT application because it offers high current, reliable operation, efficiency, and relatively low construction cost.

It differs from other ESQ accelerators [4] in simultaneously offering easily stackable modules and dc operation. Each pair of ESQ electrodes has a separate electrical connection, allowing independent control of focusing and acceleration voltages; this facilitates modularity and flexibility in choice of overall length. The average gradient of the channel can be made uniform and adjusted to match the length of the graded insulating column, as illustrated in references [2] and [5]. The ESQ focusing forces remove most secondary ions and electrons generated within the ESQ sections. A prototype of this system has been built and tested at LBL [6].

2.1 Comparison of DC Pierce Column with ESQ Accelerator

High-current accelerators need focusing to prevent space-charge blowup of the beam. The CCVV type of focusing has several advantages over the conventional Pierce column, which utilizes a gradient in the longitudinal field E_Z. In a Pierce column with a given cold-beam current density J, E_Z follows Child's law for a planar diode,

$$E_Z^2 = 4 \left(\frac{m}{2|q|}\right)^{\frac{1}{2}} \frac{1}{\varepsilon_0} J|V|^{\frac{1}{2}}, \quad (1)$$

with V the beam potential along the column (referred to the ion source). In a high-current high-voltage column, E_Z becomes so large that it is difficult to prevent voltage breakdown, especially since there is no inhibiting transverse field as there is with the ESQ.

For the ESQ case, assuming that emittance pressure and E_Z' focusing are negligible, we have [7]

$$E_Q^2 = \frac{1}{g(\eta)} \frac{a_Q^2}{L^2} \left(\frac{m}{2|q|}\right)^{\frac{1}{2}} \frac{1}{\varepsilon_0} J|V|^{\frac{1}{2}}, \quad (2)$$

where E_Q is the focusing field at the quadrupole pole tip, a_Q is the pole tip radius and L is the half-cell length. Approximate numbers used in the LBL prototype [6] were: $a_Q/L = 1/6$ and occupancy factor $\eta = 2/3$, giving hard-edge form factor $g(\eta) = \eta^2(3-2\eta)/12 = 5/81$. These numbers give the coefficient 9/20 in Eq. (2) vs. the coefficient 4 in Eq. (1); for a given J, the peak longitudinal focusing field required in a Pierce column is three times larger than the transverse pole tip field required for the ESQ:

$$\frac{E_Z}{E_Q} = \frac{2}{3}\sqrt{20} = 3.0 .$$

The CCVV prototype at LBL [6] needs a pole tip field of only 14 kV/cm.

For the same peak fields, this ESQ geometry supports 8.9 times the current density of a Pierce column.

Because of the independence of the transverse focusing field and the longitudinal acceleration field, the average longitudinal field along the external insulator can be uniform instead of increasing nonlinearly as it does in the Pierce column [Eq. (1)]. In our proposed accelerator for BNCT, we can choose a reasonable external gradient, such as 5 or 10 kV/cm, and set the ESQ voltages according to Eq. (2).

2.2 *Influence of BNCT Requirements on ESQ Parameters*

With relatively low current required for BNCT compared to magnetic fusion, a very conservative 2.5 MeV design is possible: Eq. (2) shows that if the current density is decreased by a factor of two relative to the previous CCVV designs [2,5], the beam energy can be increased by a factor of four with no change in the cell size or in the focusing voltage at the exit. However, the overall length of the accelerator would exceed 4 meters, as in the example of section 2.3.

A more compact design retains the previous current density of about 80 mA/cm^2 [2,5] but reduces the beam radius and the quadrupole apertures. The overall CCVV length would be about 3 meters. (With higher current density, it could be reduced to 2 meters—see section 3.) The diameter of the evacuated column enclosing the quadrupoles depends on the pumping requirements; in any case it is much smaller than the 80-cm size used for the magnetic fusion accelerator [2,5], because the gas load for H^+ production is relatively low.

Previous CCVV designs for H^- and D^- [2,3,5] were complicated by the high source pressure needed to create these ions and by their fragility. Those designs not only required high gas-pumping speeds, but also high-current power supplies for the early stages of ESQ focusing and water cooling passages in the initial focusing electrodes. All these complications are avoided in the BNCT application. Furthermore, the required current (100 mA) is less than 10% of the current per channel contemplated for the fusion experiments [5]. The operating voltage of 2.5 MV needed for BNCT thus appears to be a reasonable goal.

2.3 *Simulation*

A beam envelope simulation for a conservatively designed 23-module, 2.5-MeV CCVV accelerator is shown in Fig. 1. The ESQ voltages for this structure are determined by the beam current (100 mA), the emittance (assumed low), and assumptions about the acceleration voltage gradient (assumed uniform in this case) and the average beam radius (assumed constant). With this model, Eq. (2) applies, and was used to calculate the quadrupole voltages; note these are proportional to the fourth root of the beam energy.

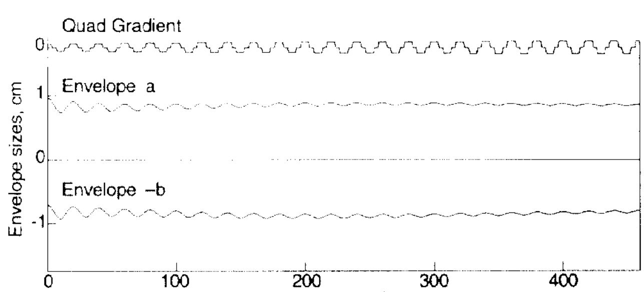

Fig. 1. Envelopes for CCVV acceleration from 200 keV to 2.5 MeV.

3. Modular Power Supply

Although the design of a 100 mA, 2.5 MeV ESQ accelerating column is straightforward, the power supply design is challenging because of space limitations and cost constraints. We are investigating simple modular designs using a series of compact inexpensive components stacked in parallel with the ESQ accelerator modules. This arrangement is easy to connect to the individual ESQ modules and should mimimize stored-energy damage and give good reliability.

We have considered several methods for transferring power from the ground plane up through the stack: (1) transformer coupling using a frequency of about 50 kHz; (2) mechanical transfer to small generators through a series of rotating insulated shafts or by hydraulic or compressed-air motors; (3) Cockcroft-Walton electrostatic coupling using modern compact capacitors.

The accelerating column and the power supply can be configured in several ways. In one scenario, large gradient rings surround the column and the power supply stack. The exterior of the acceleration column is housed in a medium pressure SF_6-air mixture, with the 2.5 MV potential held between the pressure stack and the cylindrical shell formed by the gradient rings. A spacing of 60 cm or more between the shell and the stack gives a reasonable stored electrostatic energy. A safety factor of at least 2 is chosen between the breakdown and operating voltages. Metal-oxide varistors may be used to dissipate stored energy in case of a fault, eliminating the need for protective spark gaps along the accelerating and power supply columns. These columns would be 2 to 4 meters long, the smaller length requiring higher SF_6 pressure to prevent breakdown along the columns. For a vertical orientation the overall height would be 3 to 5 m, allowing 1 m for the source dome.

Another scenario is shown in Fig. 2, where the large gradient rings are eliminated and potential grading is accomplished by the gradient rings on the accelerator modules and on the matched-potential power supply modules. Operated at low current density and low voltage gradient, this design would not need a pressurized tank, and would lend itself to proof-of-principle testing at minimum cost.

To further reduce the cost, such testing could employ long-pulse rather than dc power supplies. A study for H^- applications recently funded by DOE and conducted by Universal Voltronics considered several options such as storage batteries and flywheels. At the relatively low currents required for BNCT, such schemes may or may not prove economical.

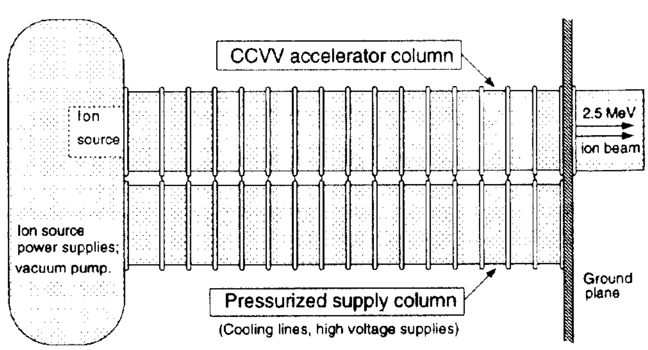

Fig. 2. Schematic of modular accelerator and modular power supply.

4. Refractory Lithium Target

Previous efforts to develop a cost-effective accelerator for BNCT applications [8,9] have centered around the use of relatively low current devices such as the RFQ or tandem cascade accelerators which, at the present state of development, typically provide average proton currents of only a few mA; thus, in those studies, every effort was made to maximize the target efficiency. The $^7Li(p,n)^7Be$ reaction is clearly the reaction of choice to produce a neutron beam of appropriate energy for further moderation to the necessary epithermal energies required for BNCT. The only target seriously considered by previous workers has been metallic lithium, since this would provide the highest yield per incident proton. Metallic lithium has serious drawbacks as a target material because of its low melting point and high chemical reactivity. Complicated schemes have been discussed for the dissipation of up to 100 kW in a lithium target, but none has been shown to be adequate to the task.

The ESQ accelerator allows one to consider average proton currents in excess of 100 mA, so that alternative target materials can be seriously considered. We have examined the use of lithium oxide and lithium fluoride for this purpose. We discuss the former first.

Lithium oxide (Li_2O) has a melting point above 1700°C and does not undergo chemical degradation at such temperatures. The relative yield from the p,n reaction from Li_2O compared to metallic lithium can be estimated by noting that Li_2O and Li contain 0.415×10^{23} and 0.893×10^{23} atoms of Li per gram, respectively. The relative proton capture ratio per gram of material for Li_2O is thus 0.464. Independent calculations using the TRIM code provided to us by D. Nigg (private communication) and using the values of Wang [10] for the thick target yield from the p,n reaction on metallic lithium give a capture ratio of 0.48 per gram of Li_2O, in good agreement with the simpler calculations. Shefer [8] also has calculated these relative yields and found approximately the same ratio.

An important consideration in the use of an oxide target is a possible competing nuclear reaction in oxygen that would degrade the yield. A careful review of the literature by us has not led to the discovery of any significant oxygen reactions in the proton energy range below 2.5 MeV. The largest cross sections for oxygen in this energy domain are around 100 times smaller than for lithium.

Using the proton range and stopping power tables either of Zeigler or Janni, we find the effective range of 2.5 MeV protons in Li_2O to be around 40-50 μm, compared with 200 μm range in metallic lithium.

Calculations of neutron yield from the $^7Li(p,n)^7Be$ reaction on Li_2O lead to an estimate of 5×10^{12} n/ster at 0° from a 100 mA beam of 2.5 MeV protons. This value is well in excess of the minimum neutron flux needed for effective boron neutron capture therapy.

Possible drawbacks for Li_2O are that it is hygroscopic and that it may be difficult to form a well-bonded layer with good mechanical properties for a high-power target. Therefore we are also investigating the suitability of lithium fluoride (LiF) which is known to form stable crystals. It has a smaller proton capture ratio than Li_2O; however, it would not be difficult to make the necessary adjustment of the ESQ current.

Still another possibility is to look for a refractory metallic alloy which contains lithium in high concentration, at least near the surface.

The Idaho Nuclear Engineering Laboratory (INEL) is planning to measure the neutron yield from some of these refractory targets in order to check our calculations.

We conclude that a refractory lithium target in combination with the ESQ accelerator will make a very promising device for realistic treatment of tumors by this modality.

5. Remaining Issues

As discussed, the BNCT accelerator design is simplified because negative ions are not employed. However, to prevent electrons in the downstream plasma from backstreaming, a trap is needed, as was used in positive-ion testing of the CCVV prototype [6]. A more efficient trap might be required for a 2.5 MV system. Also, baffles may need to be designed to prevent long-path breakdown along the pumping column that surrounds the ESQ array. And, of course, beam diagnostics and control systems will be needed, especially for startup and initial testing.

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