LBL-35540
UC-419

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

Presented at the Accelerator-Based Neutron Sources for Boron Neutron Capture Therapy Conference, Jackson, WY, September 11–14, 1994, and to be published in the Proceedings

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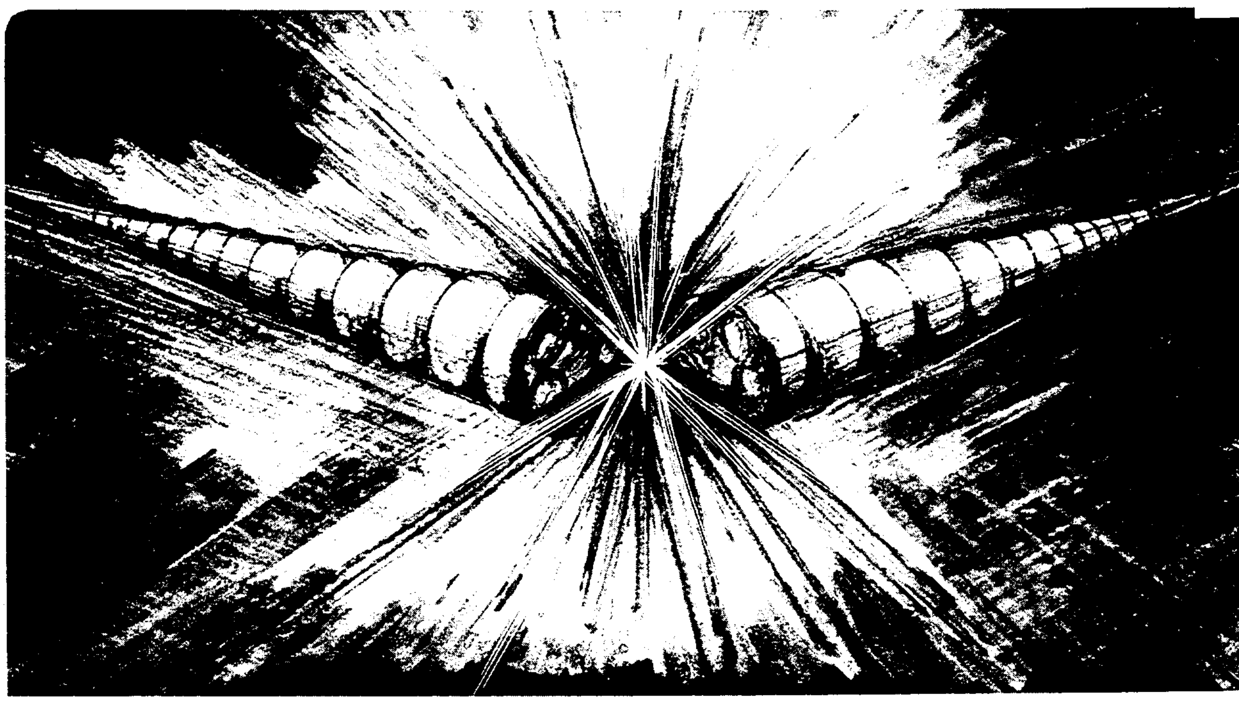
April 1994



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

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This work was supported in part by the Director, Office of Energy Research, Office of Fusion Energy, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

LBL #35540

ELECTROSTATIC QUADRUPOLE DC ACCELERATORS FOR BNCT APPLICATIONS

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KEYWORDS: BNCT, ESQ, DC Accelerator

ABSTRACT

A DC electrostatic quadrupole (ESQ) accelerator is capable of producing a 2.5 MeV, 100 mA proton beam for the purpose of generating neutrons for Boron Neutron Capture Therapy. The ESQ accelerator is better than the conventional aperture column in high beam current application due to the presence of stronger transverse field for beam focusing and for suppressing secondary electrons. The major challenge in this type of accelerator is in developing the proper power supply system.

INTRODUCTION

In an accelerator-based neutron source for Boron Neutron Capture Therapy (BNCT) application, the accelerator must be a high current one in order to achieve a reasonable dose time, e.g. within a couple of hours. In a recent paper, O.A. Anderson et. al. proposed to use a dc electrostatic quadrupole (ESQ) accelerator to deliver more than 100 mA (time-averaged) of proton beam with 2.5 MeV energy onto a lithium target.[1] In addition to minimizing the dose time, high beam current has the advantage of allowing the use of a refractory lithium target which has lower lithium concentration but a much higher melting point.

Beam energies much higher than 2.5 MeV are routinely produced in today's electrostatic accelerators powered by Van de Graaff generators or shunt multipliers. However, these accelerators are typically low current devices which have a modest demand on beam focusing and power supply current. We have been developing high-current ESQ accelerators for injecting neutral particle beams into tokamak fusion reactors, and as injectors for a heavy ion induction linac driver for inertial fusion reactors. For neutral beams, the goal is to produce neutralized deuterium

*This work was supported in part by the Director, Office of Energy Research, Office of Fusion Energy, of the US Dept. of Energy under contract No. DE-AC03-76SF00098.

beams at higher than 1 MeV energy and 2 A dc current per channel.[2] For inertial fusion, beam energy > 2 MeV with current > 0.8 A of K^+ ions for a 1 μs pulse has already been achieved as an injector for the induction linac.[3]

While the beam physics in dc ESQ accelerators has been demonstrated, the remaining challenge is to develop a compact power supply system tailored to an ESQ accelerator.

DC ELECTROSTATIC ACCELERATORS

In a dc electrostatic accelerator, charged particles are accelerated by the dc potential drop in an accelerator column. The column is typically linear in geometry and is composed of a series of electrodes separated by insulators (see Fig. 1). The electrodes are built to meet the following requirements: (i) providing an aperture large enough for beam transport, (ii) providing beam focusing to prevent beam loss, (iii) shielding the insulators from stray particles, (iv) electrically grading the insulating column to accelerate the beam and regulate field stress.

Since high voltage is applied to the column continuously, the electrode spacing must prevent electrical arc-down. To alleviate the size problem, the accelerator column is often kept under high pressure insulating gas such as SF_6 enclosed by a steel pressure tank. The metal tank is also useful for providing an electrical ground as well as x-ray shielding. Since arc-down is a cascade phenomenon which has a rise-time depending on the particles' flight time and ionization time, the arc-down limit is much lower for dc operations than for short-pulse (e.g. < 1 μs) ones. In addition, a breakdown can be induced by stray particles in the column (on the vacuum side), therefore it is more difficult to hold voltage in a high current device.

Dielectric strength is defined as the voltage gradient at which breakdown may occur. Typical values are 32 kV/cm across a gap in 1 atm. of air and 86 kV/cm in 1 atm. of sulfur hexafluoride gas (SF_6). At 7 atm. of SF_6, the dielectric strength can be as high as 200 kV/cm. Vacuum gaps have a dielectric strength of about 100 kV/cm.[4] However, the most likely place for an arc-down is along the surface of an insulator. As a design rule, the insulator should not be subjected to more than 20 kV/cm on the vacuum side and 10 kV/cm on the air side. Since the air-side number can be raised to 58 kV/cm when air is replaced by 3 atm. of SF_6, the minimum length of a dc accelerator column is determined by the vacuum/insulator interface which allows a maximum accelerating gradient of 20 kV/cm, or 2 MV/m.

At the same potential difference, an insulator has greater immunity to arc-down if it is separated into a number of short sections (this is also true for vacuum gaps). This phenomenon is due to charge multiplication along the acceleration path. Thus, accelerator columns are typically constructed by joining a series of grading rings between insulator sections. The grading rings also provide a convenient way to supply voltages to the electrodes.

The schematic diagram in Fig. 1 shows a dc accelerator powered by a cascade ladder circuit. The circuit was first invented by Greinacher[5] in 1920 and later improved by Cockcroft and Walton[6] in 1932 to produce high energy positive ions. This type of voltage multiplier offers many advantages over the straight forward 60 Hz high voltage transformer and rectifier system. The size of a 2.5 MV, 60 Hz power supply would be impractical. The size reduction achieved with a high frequency voltage multiplier system can be 100 fold. The power supply can be nested along side the acceleration electrodes thus making the voltage distribution and insulation much simpler. The energy storage in voltage multiplier system is also much lower and so is the potential for damage in an arc-down. A variation of the often referred to Cockcroft-Walton (or series multiplier circuit) is the shunt-fed multiplier. In the shunt-fed multiplier, the high frequency source is fed in parallel with the multiplier circuit and offers the same size advantages with higher current capability. Multiplier circuits have provided voltages to several megavolts at many tens of milliamperes.[7]

Another common method to obtain dc high voltage is the Van de Graaff generator (invented in 1929).[8] In this device, electrical charge is deposited on a motor-driven insulating belt and is transported into a smooth metal sphere at high voltage. The device is reliable, has good voltage regulation, and has been successfully demonstrated to operate up to 25 MV. The main disadvantage of Van de Graaff generator is the limit in output current, which is typically less than a milliampere. Figure 2 shows a tandem Van de Graaff accelerator. In the tandem geometry, negative ions are first accelerated from ground to high positive potential, then doubly stripped to become positive ions and continue to be accelerated from the positive potential back to ground. The accelerated particles have an energy of $2qV$, where q is the particle charge and V the power supply voltage.

In earlier days, dc electrostatic accelerators were frequently used as injectors at the front end of a high-energy rf accelerator. Since rf accelerators accelerate beam particles in short bunches, it is not necessary to have an injector that can operate in dc mode. So lately, many dc injectors have been replaced by RF quadrupole (RFQ) linacs, because the RFQs are more compact and are capable of delivering higher beam current in short pulses. Nevertheless, for high average current applications such as neutral beam injectors in magnetic fusion reactors, dc electrostatic accelerators are still the best choice.

BEAM FOCUSING

Although particles are accelerated by the longitudinal electric field, the transverse field is also important because it provides the necessary focusing force. Without focusing, charged particles in a beam will drift apart under their own electrostatic repulsion resulting in beam loss and severely limiting the beam's capability to travel over a long distance. Two focusing systems are discussed here: (A) thick apertures and (B) electrostatic quadrupoles (ESQ).

A. THICK APERTURES (PIERCE TYPE) FOCUSING

In an array of thick apertures, the equipotential lines are periodically compressed and expanded, creating a series of alternating converging and diverging lenses (see Fig. 3). The combined effect of a converging lens and a diverging lens of equal strength is net focusing. According to the paraxial approximation for systems with cylindrical symmetry, and neglecting any space charge force from the beam particles, the radial field depends entirely on the gradient of the longitudinal field on axis[9]:

$$E_r(r,z) \cong -(r/2)\left[\partial E_z(0,z)/\partial z\right]$$

This coupling of the radial field with the longitudinal field implies that in order to obtain sufficient focusing for a high current beam, the longitudinal field gradient can become very large. Therefore a large potential difference between thick aperture plates is required.

As an example, a recent design for a 1 MeV, 4 A multiple-channel dc accelerator has a 0.6 m long column.[10] This corresponds to an average potential gradient of 1.7 MV/m (the peak field on the insulator is higher because of finite grading flange thickness) which is strong enough to be concerned about arc-down along the insulators.

B. ELECTROSTATIC QUADRUPOLE (ESQ) FOCUSING

In an ESQ system, the transverse electric field is derived from the potentials applied to two pairs of electrodes as shown in Fig. 4. Instead of being cylindrically symmetric, the particles have transverse motions that are x, y independent. Ideally, the electrodes have hyperbolic surfaces and the transverse field components are given as[9]:

$$E_x(x) = +E_o(x/a) \quad \text{and}$$

$$E_y(y) = -E_o(y/a)$$

where a is the distance from the axis to the electrode tip and E_o is the electric field at the tip. E_o is determined by the ESQ voltages and electrode dimensions but is not directly related to the longitudinal acceleration field. ESQs are similar to the magnetic quadrupoles frequently used in high energy accelerators. Due to the velocity dependence of the magnetic force, magnetic quadrupoles are more effective when the particle is already moving at high speed (the high energy section of the accelerator), whereas ESQs are more useful in the low energy sections.

In order to do focusing in both x-z and y-z planes, the ESQ reverses polarity for each subsequent unit (a scheme often known as alternating gradient). Similar to that discussed in the last section, a combination of converging and diverging lenses produces a net focusing effect to the beam. The key advantage of an ESQ system is that the transverse focusing function can be separated from acceleration. Application of a strong focusing field to a high current beam can be done without incurring a longitudinal field near or exceeding the breakdown limit.

Another advantage in applying a strong transverse field is that the secondary electrons (or ions) generated within the accelerator column are quickly removed by the ESQ electrodes instead of being allowed to multiply to develop into a column arc-down. High energy stray electrons are most undesirable in a vacuum chamber because they produce unwanted x-rays.

In a recent ESQ design for a 1.3 MeV, 1.0 A dc accelerator,[11] the average accelerating field is about 0.65 MV/m or 6.5 kV/cm. The lower field makes the accelerator slightly longer, but with the gain in safety and reliability.

ESQ ACCELERATOR DEVELOPMENT AT LBL

In 1970, Abramyan et. al.[12] reported the achievement of a 1.2 MeV hydrogen beam (50% H_1^+, 30% H_2^+ and 20% H_3^+) using an ESQ accelerator. The machine operated in pulsed-mode; with a peak current of 80 mA and an average power of 10 kW. The recent development of ESQ accelerators has been driven by two separate needs in the fusion program.

In the magnetic fusion program, where high power neutral beams (deuterium atoms) are required to inject power into a tokamak reactor, dc ESQ accelerators are most suitable to produce high current beams in the energy range of 1-2 MeV. Earlier tokamak reactors used high power (several MW) neutral beam injectors with particle energy up to 120 keV. Conventional electrostatic aperture column accelerators are used in these machines. In the next generation reactors (e.g. the International Thermonuclear Experimental Reactor), which are larger and have a hotter and more dense plasma, the required beam energy can be as high as 1.3 MeV in order to obtain sufficient beam penetration. This combination of high energy and high current calls for a different approach than the existing aperture column type accelerator. At LBL we proposed to build the neutral beam lines using several modules of ESQ accelerator that can carry 2 A of deuterium beam per channel.

Figure 5 is a schematic diagram of a 1.3 MeV, 1.0 A D^- dc ESQ accelerator. The accelerator was designed to be modular for low cost and easy construction.[11] The average accelerating gradient is about 0.65 MV/m. A special feature of this design is the use of acceleration gap between each set of quadrupoles thus providing a greater flexibility in separately controlling beam focusing and beam acceleration. Consequently, the accelerator is capable of varying the beam energy without changing the beam current. We have built a smaller prototype which contains five quadrupoles designed to accelerate 100 mA of He^+ to 200 keV. The pole tip has an electric field strength of 14 kV/cm. In testing, almost no beam loss and very little degradation of beam optics were found.[13] The prototype was also tested with H^- beams, although the performance was limited by that of the H^- sources. Nevertheless we have achieved more than 100 mA of H^- beam and have clearly demonstrated the suitability of ESQ accelerators for neutral beam application.

In the inertial fusion program, heavy ion beams are being considered as drivers for pellet implosion. Here, the main acceleration will be done by a pulsed induction linac to reach beam energy as high as 10 GeV, but a MeV-ranged ESQ accelerator is needed as an injector. At LBL, we have successful developed a 2.0 MeV ESQ injector which is capable of delivering 800 mA of 1μs K^+ beam. The accelerator is powered by a Marx generator and operates at 1 Hz. Details of measured beam optics are in very good agreement with 3-D simulations. Again, the experiment has shown no beam loss or aberrations. The injector, including the K+ surface ionization source, the extraction diode and the ESQ accelerator, is shown in Fig. 6. The apparatus is enclosed by a 5-ft diameter steel tank. During operation, the tank is filled with 80 psig of SF_6.

A CONCEPTUAL ESQ ACCELERATOR FOR BNCT APPLICATION

If we assume an acceleration gradient of 0.65 MV/m, a 2.5 MeV proton beam will have a column approximately 4 m long, operable in air. The ion source and extractor at the front end will take up another 0.5 m. Additional space ≈2 meters or more must be allowed to prevent electrical arc-down to the walls. The system is more compact if we enclose the column in a steel tank filled with SF_6. In this case, we can raise the gradient to 1.5 MV/m (still below the 2 MV/m vacuum/insulator limit), so that a 2.5 MeV column is 1.7 m long. Again after adding space for the ion source and the surrounding, the enclosure tank is approximately 3 m long. To save space, the power supply can be custom built along side or wrap-around the accelerator column. The enclosure tank will therefore have a diameter of 2-3 m wide.

The power supply system must provide dc power to the high voltage dome, where the ion source is located, as well as to all the ESQ electrodes along the accelerator column. Typical voltage tolerance is 1% or less. We have considered three options: (1) mechanical coupling by a series of rotating insulated shafts or by hydraulic or compressed-air motors; (2) high frequency cascade transformer coupling; and (3) ladder network.

During our test of the 200 kV prototype, typical drain current for the ESQ electrodes in the first few quadruple units was found to be about 10% of the He^+ beam current and became much smaller farther from the ion source (where gas was flowing out from the aperture). With a good vacuum, the ESQ electrode may draw very little current. In that case, the ladder network is ideal for providing the many voltage "taps" to the ESQ accelerator. However, if the drain currents at the

ESQ electrodes are substantial, the mechanical coupling or transformer coupling methods would be more suitable because the currents are drawn from floating power supplies which can regulate the ESQ voltages and transfer power more efficiently. At present, it is not clear whether the mechanical coupling is better than transformer coupling or vise versa. The mechanical coupling may be less reliable due to too many moving parts whereas the transformer coupling requires efficient transformer cores and careful electrical insulation. More R&D work is needed in order to address these issues.

Aside from providing the necessary power, the system must be protected against arc-down. This is generally done by minimizing the storage energy and adding surge blockers (such as series resistor or inductor) to limit the current flowing to the electrodes. Additionally, one would like to either turn off the power supply quickly or use a shunt switch to momentarily divert the power supply current from the accelerator.

The idea of using a tandem ESQ accelerator is worth considering because it reduces the high voltage requirement to 1.25 MV. Furthermore, the ion source is now conveniently located at ground potential. The main disadvantage of this approach is that the H^- ion source is not as well developed as the H^+ ion source.[14] In general, the H^- ion source has a lower current density and operates with a higher source pressure. H^- ions are less stable than H^+ ions therefore there is a higher beam loss which results in more stray electrons. Nevertheless, these problems are solvable (by using the ESQ focusing) and it is reasonable to conclude that the technology of building a dc accelerator for BNCT application is within reach.

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ACKNOWLEDGMENT

This work was supported in part by the Director, Office of Energy Research, Office of Fusion Energy, of the US Dept. of Energy under contract No. DE-AC03-76SF00098.