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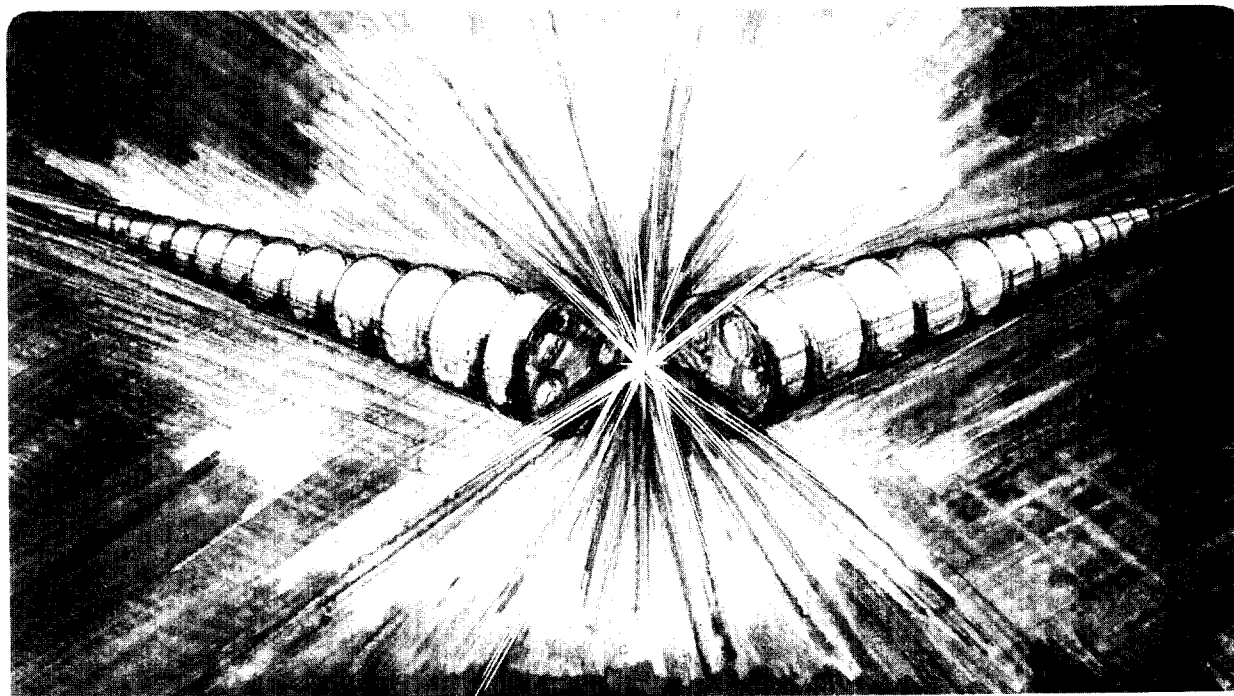
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A 2.5 MEV ELECTROSTATIC QUADRUPOLE DC ACCELERATOR FOR BNCT APPLICATION*

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A DC electrostatic quadrupole (ESQ) accelerator is capable of producing a 2.5 MeV, 100 mA proton beam for the purpose of generating epithermal neutrons for Boron Neutron Capture Therapy. The ESQ accelerator has a strong transverse field for beam focusing and for suppressing secondary electrons and is therefore suitable for high current use. The ESQ physics is well understood and the remaining challenge ahead is in developing the proper power supply system.

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1. Introduction

In a recent paper, O.A. Anderson et al. [1] proposed to use a dc electrostatic quadrupole (ESQ) accelerator to deliver more than 100 mA of 2.5 MeV proton beam onto a lithium target for Boron Neutron Capture Therapy (BNCT). A high beam current has the advantage of minimizing treatment time (less than one hour) and allowing the use of a refractory lithium target material to withstand the power load.

Beam current ≥ 100 mA can only be achieved by electrostatic accelerators. We have been developing high-current ESQ accelerators as neutral particle beam injectors into tokamak fusion reactors, and as injectors for heavy ion induction linac drivers for inertial fusion reactors. While the beam dynamics in dc ESQ accelerators has been demonstrated in previous experiments, the remaining challenge is to develop a compact power supply system tailored to the accelerator.

2. Beam focusing using thick apertures vs. ESQ's

In an array of thick apertures, the equipotential lines are periodically compressed and expanded, creating a series of immersion lenses. 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:

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

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.

In an ESQ system, the particles have transverse motions that are x, y independent. Ideally, the quadrupole electrodes have hyperbolic surfaces and the transverse field component is given as:

$$E_x(x) = +E_o(x/a)$$

where a is the distance from the axis to the electrode tip and E_o is the transverse electric field at the tip. The ESQ reverses polarity for each subsequent unit (alternating gradient) to achieve focusing in both planes. The key advantage of an ESQ system is that the transverse focusing can be very strong (useful for a high current beam) without incurring a longitudinal field near or exceeding the breakdown limit [2].

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 into a column arc-down. High energy stray electrons are detrimental in a vacuum chamber because they produce unwanted x-rays.

3. ESQ accelerator development

In 1970, Abramyan et al. [3] reported the achievement of a 1.2 MeV hydrogen beam (50% H_1^+ , 30% H_2^+ and 20% H_3^+) using an ESQ accelerator (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 US fusion program. 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 is ≈ 1.3 MeV. Figure 1 depicts a 1.3 MeV, 1.0 A D^- dc ESQ accelerator channel which was designed to be modular

for low cost and easy construction [4]. The average accelerating gradient is about 0.5 MV/m. The lower field makes the accelerator slightly longer, but with the gain in safety and reliability. A special feature of this design is the use of an acceleration gap between each set of quadrupoles thus providing a greater flexibility in varying the beam energy without changing the beam current. A smaller prototype which contains five quadrupoles to match and accelerate 100 mA of He^+ to 200 keV was built and tested at LBL. In testing, almost no beam loss and very little degradation of beam optics were found [5]. 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 validity of considering 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, a 2.0 MeV ESQ injector was successfully tested to deliver 800 mA of $1\mu\text{s}$ K^+ beam [6]. The accelerator is powered by a Marx generator. Details of measured beam optics were reported to be in 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. 2. The apparatus is enclosed by a 5-ft diameter steel tank. During operation, the tank is filled with 80 psig of SF_6 .

4. A conceptual ESQ accelerator design for BNCT application

First, let us examine the required size of a 2.5 MeV ESQ accelerator. The most likely place for an arc-down is along the surface of an insulator. As a general 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 SF₆, 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.

If we assume a very conservative acceleration gradient of 0.5 MV/m, a 2.5 MeV proton beam will have a column approximately 5 m long, operable in air. The ion source and extractor at the front end will take up another 0.5 m. Additional space (\approx 2 meters) must be allowed to prevent electrical arc-down to the surroundings. The system is more compact if the column is enclosed in a steel tank filled with SF₆. 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 alongside 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 multiplier.

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 will draw very little current. In that case, the Dynamitron or Cockcroft-Walton type 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. 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. Aside from providing the necessary power, the system must be protected against arc-down by minimizing the storage energy, and adding series resistors or inductors to limit the damages. More R&D work is needed in order to address these issues. The concept of using a tandem ESQ accelerator is noteworthy because it reduces the high voltage requirement to 1.25 MV and also places the ion source at ground potential. The main disadvantage of this approach is that the H^- ion source has a lower current density and operates with a higher source pressure [7]. H^- ions are less stable than H^+ ions therefore there is a higher beam loss which results in more stray electrons. Nonetheless, these problems can be tackled by using fast pumping near the ion source along with the electron suppression provided by the ESQ's. In conclusion, a dc ESQ accelerator is capable of providing a proton beam of 2.5 MeV and 100 mA for BNCT application.

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Figure Captions

Figure 1. Schematic diagram of a proof-of-principle 1.3 MeV, 1.0 A D^- dc ESQ accelerator proposed for neutral beam injector for ITER.

Figure 2. Schematic diagram of a 2.0 MeV, 800 mA, $1\mu s$ K^+ beam ESQ injector developed for heavy ion fusion accelerator driver.

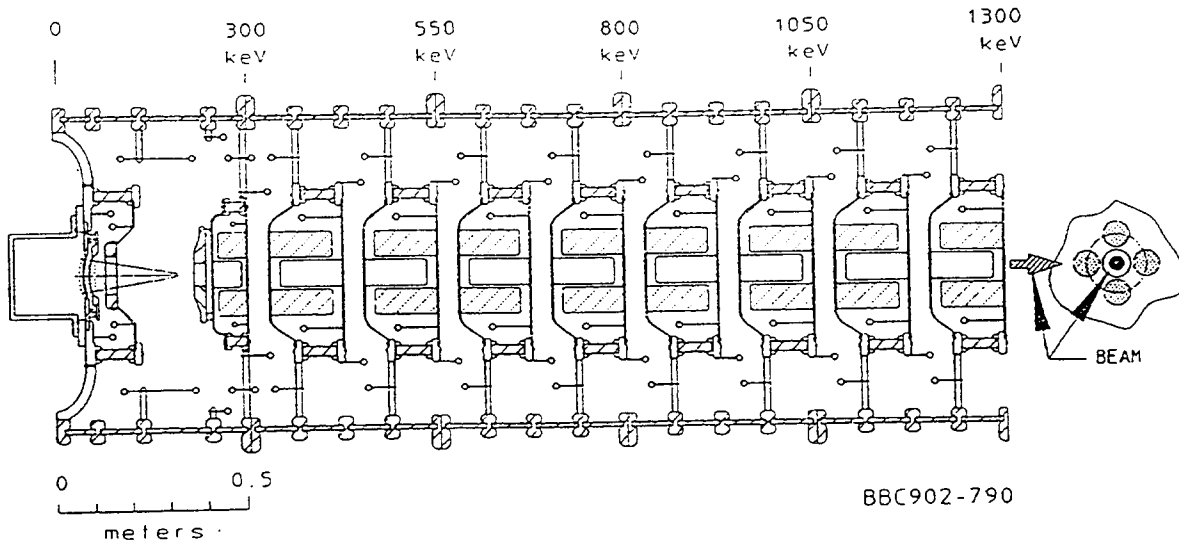


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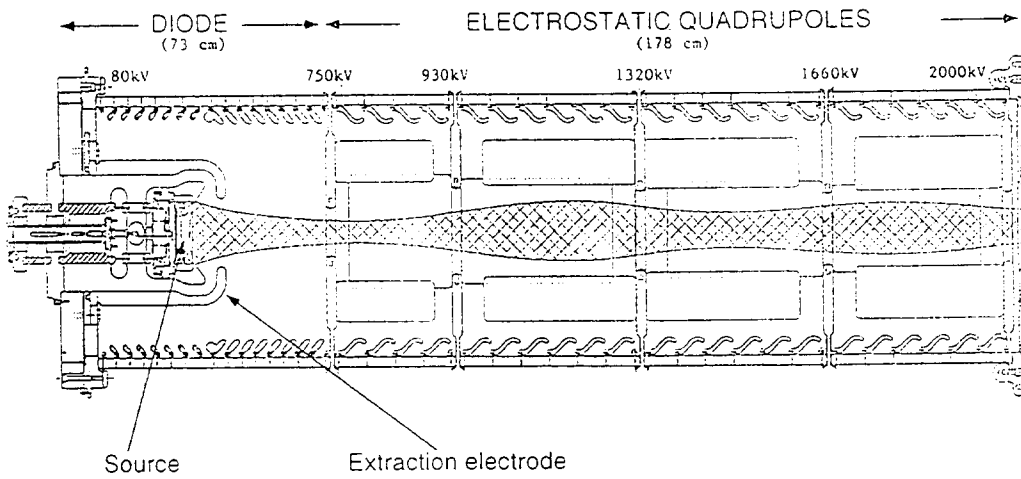


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