Application of Compact MeV Symmetric Neutralized Ion Beams to Magnetically Confined Fusion Plasmas

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by

Alfred Y. Wong and Nathaniel K. Hicks
University of California, Los Angeles

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The use of symmetric neutralized ion beams of MeV energies for heating, current drive, diagnosis, and phase space control of magnetically confined fusion plasmas is discussed. Symmetric neutralized ion beams are composed of positive and negative ions of equal charge-to-mass ratios (e.g. D^+ and D^-). Given sufficient density, they are capable of propagating across a transverse magnetic field and can therefore accomplish many of the tasks of a conventional neutral beam. RFQ accelerators driven at GHz frequencies yield compact beam modules (~1 m length) with beam energy > 1 MeV and beam power density > 10 MW / cm^2. The compact size allows beam modules to be placed in a variety of locations and injection angles, including on the inner wall of a toroidal vessel. 2-D and 3-D PIC simulation of the beam propagation is ongoing, as are experiments on beam production.

I. An alternative to conventional neutral beam injection

Beam injection systems are an essential part of the design of magnetic confinement fusion devices such as ITER. The beams are needed for heating and current drive of the fusion plasma. Beams composed of neutral particles have historically been used for these tasks since they may reach the center of the plasma without being deflected by magnetic fields. The ITER design specifies injection of 1 MeV beams, which necessitates negative ion based neutral beams. Based on the experimental results achieved so far, there is uncertainty as to whether conventional negative ion based neutral beams can meet the ITER requirements. Conventional systems are also very large in size, require extremely high voltages, and present gas pressure management challenges.

Due to these questions and drawbacks surrounding conventional systems, it may be appropriate to consider alternative means of accomplishing beam heating and current drive. Symmetric neutralized ion beams (SNIBs) are beams composed of positive and negative ions of equal charge-to-mass ratios (e.g. D^+ and D^-) [1]. When sufficiently dense, such beams can propagate across transverse magnetic fields, and can thus perform the functions of the conventional neutral beam. Radio frequency quadrupole (RFQ) accelerators [2] may be employed to produce SNIBs of suitable energy, density, and beam quality. This process is depicted in Fig. 1. By driving the RFQs at high frequencies (GHz range), the size of the beam system is kept small (1 – 2 m length), and the current density of the beam is increased [3]. Voltages are kept relatively low (~10 kV RF), and the bulky, high pressure gas cell of conventional systems is not needed.

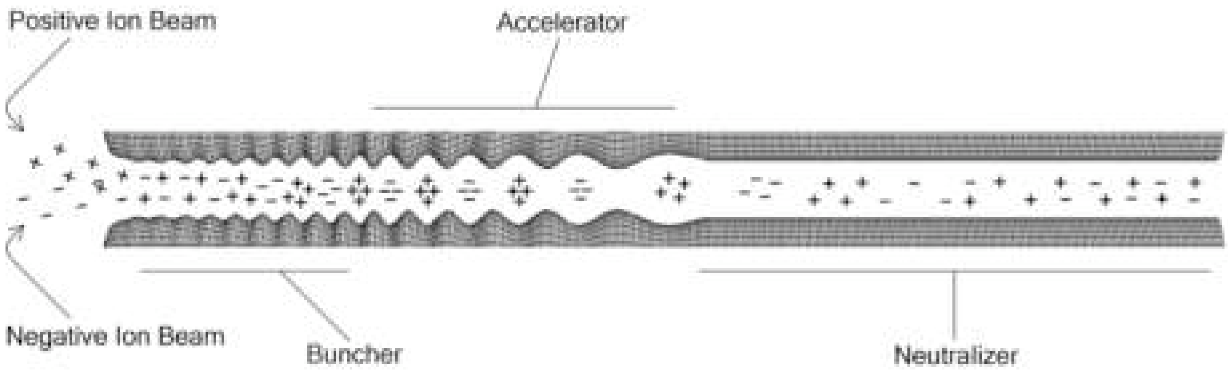

Fig. 1. Concept of production of energetic symmetric neutralized ion beam. Positive and negative ion beams are injected into an RFQ, where they are bunched and accelerated. The ions mix in the neutralizer, yielding a SNIB.

II. SNIB production simulations

Simulation of the SNIB production process has been undertaken, using a modified version of the standard RFQ code, PARMTEQ [4]. The process illustrated in Fig. 1 is simulated, as shown in Fig. 2. The successful acceptance, bunching, and acceleration of a beam of positive and negative ions are demonstrated, as well as the subsequent debunching to yield a uniform SNIB. A PARMTEQ design and simulation results for a 1 MeV D^+ / D^- SNIB accelerator are presented in Table 1.

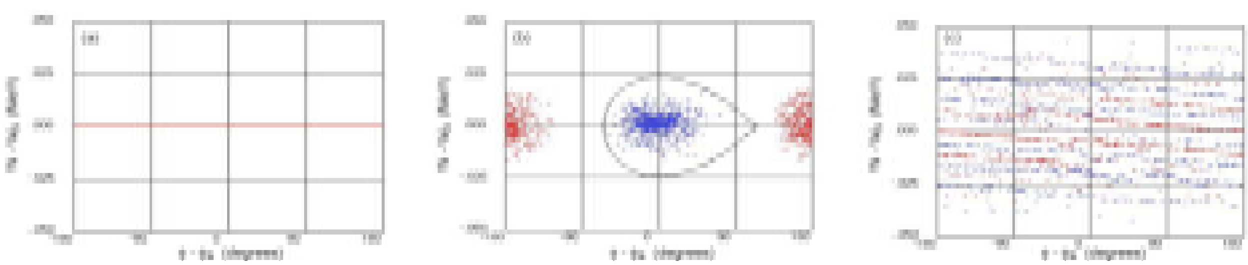

Fig. 2. PARMTEQ simulated longitudinal distribution of beam particles over one RFQ traveling wave wavelength. For each particle tracked by the simulation, $W - W_s$ (particle energy minus RFQ traveling wave synchronous energy) is plotted versus $f - f_s$ (particle phase minus RFQ traveling wave synchronous phase). (a) The initial beam is uniformly distributed in longitudinal space and all particles have $W - W_s = 0$. (b) As the longitudinal bunching/accelerating field in the RFQ is increased, the D^+ ions (blue) are bunched in the wave trough centered at 0 degrees, and the D^- ions (red) are bunched in the wave crest centered at +/- 180 degrees. (c) After acceleration, the longitudinal field is relaxed, and the ions mix freely.

<table>
<tr><th colspan="2">Design Values</th><th colspan="2">PARMTEQ Beam Results</th></tr>
<tr><td>Ion Species</td><td>D^+</td><td rowspan="2">Input Beam Current</td><td rowspan="2">3.9 mA</td></tr>
<tr><td>Frequency</td><td>2.45 GHz</td></tr>
<tr><td>Length</td><td>104 cm</td><td rowspan="2">Output Beam Current</td><td rowspan="2">2.7 mA</td></tr>
<tr><td>Voltage</td><td>8.8 kV</td></tr>
<tr><td>Aperture Radius</td><td>0.1 mm</td><td rowspan="2">Beam Transmission</td><td rowspan="2">70%</td></tr>
<tr><td>Input Energy</td><td>20 keV</td></tr>
<tr><td>Final Energy</td><td>1 MeV</td><td rowspan="2">Transmitted Beam Current Density</td><td rowspan="2">8.7 A/cm^2</td></tr>
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Table 1. 1 MeV D+ / D- accelerator—PARMTEQ design and beam simulation.

III. SNIB cross-field propagation

Unlike a single species charged particle beam, a SNIB is able to propagate across a transverse magnetic field [5]. The mechanism is shown in Fig. 3. The beam must be sufficiently dense and energetic, as may be expressed as a constraint on the plasma dielectric constant of the beam, $e = 1 + \frac{w_i^2}{W_i^2} >> 1$, where w_i and W_i are the ion plasma and cyclotron frequencies. 2-D particle-in-cell simulation of this effect has been conducted, and confirms the generation of an electric field that cancels the deflection due to the magnetic field in the bulk of the beam (Fig. 4). A 3-D code is now available to model this process, and will be used to investigate effects of background electrons and beam spreading.

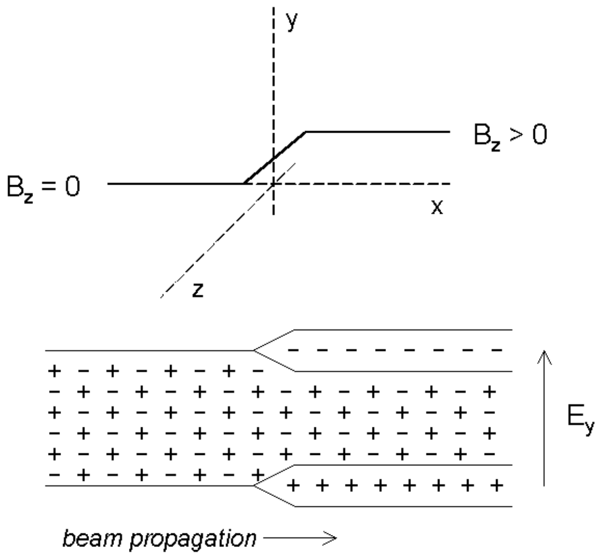

Fig. 3. Symmetric neutralized ion beam propagates across a transverse magnetic field. When the beam encounters the magnetic field, the positive and negative beam species are deflected in opposite directions. This forms charge layers, and the resulting electric field causes E x B drift of the beam across the magnetic field.

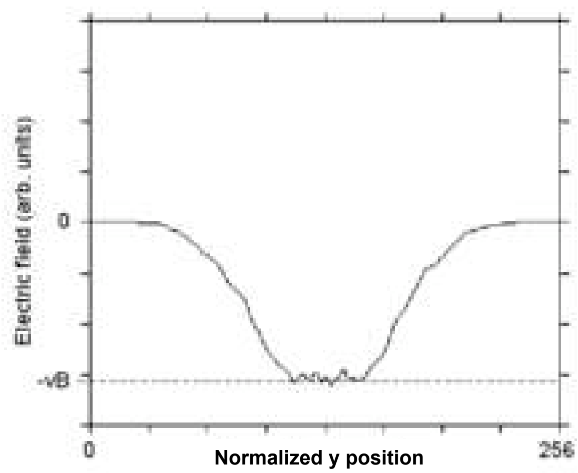

Fig. 4. Transverse electric field (E_y) is plotted vs. y position within the beam. The electric field forms when the oppositely charged beam species separate in response to the magnetic field. Where the electric force negates the magnetic force ($E_y = -vB$) the beam propagates undeflected.

IV. Compact RFQ experimental results

Ion acceleration experiments using a very small RFQ (15 cm length, 0.75 mm aperture) have been conducted. The RFQ is shown in Fig. 5. This RFQ is driven at 120 MHz, and H^+ or H^- ions are accelerated from 350 eV to 7 keV. This factor of 20 energy gain corresponds to the increase of RFQ scallop wavelength by about 4.5 times from entrance to exit. Beam energy analyzer results are shown in Fig. 6These compact RFQ results provide an encouraging basis with which to proceed to higher frequency, higher current density, SNIB experiments. Injection into a magnetic mirror device and into the UCLA Electric Tokamak are planned.

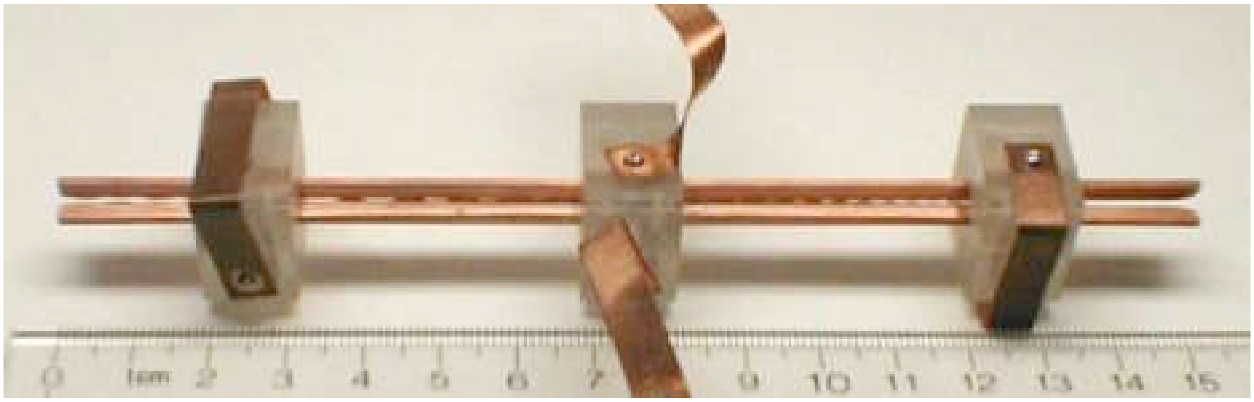

Fig. 5. 15 cm long RFQ accelerator used in experiments. Scallop wavelength increases by about 4.5 times from right to left, yielding a factor of 20 energy gain for accelerated ions.

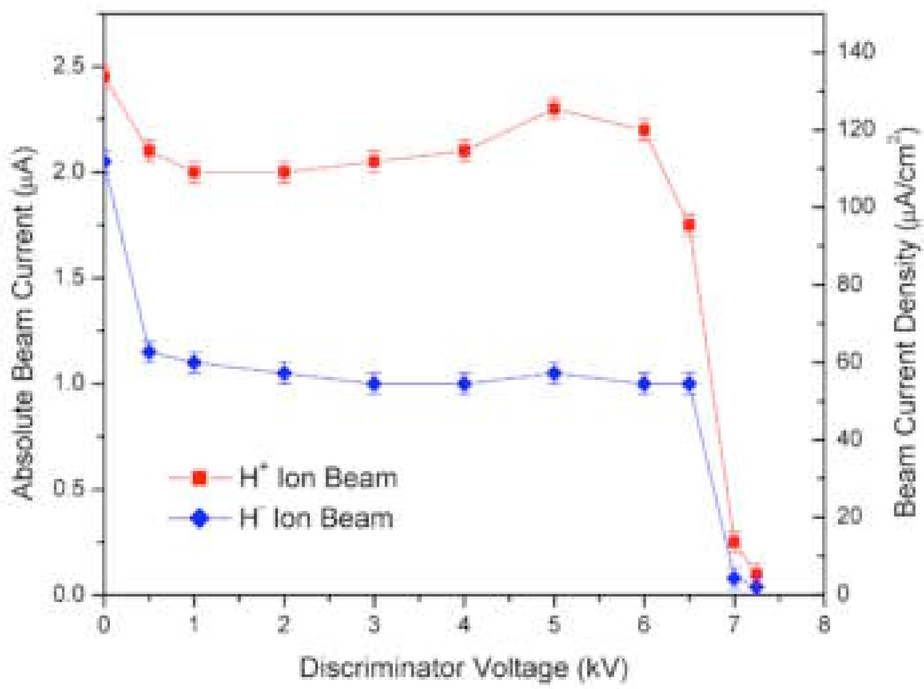

Fig. 6. Drop in current around 7 kV indicates H^+ and H^- ion beams have about 7 keV energy, and have thus been successfully accelerated by the RFQ.

References:

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