DIRECT ENERGY CONVERSION FOR D-^{3}He REACTOR

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ABSTRACT

Results of particle simulation indicate that $E \times B$ drift is available for the purpose of ion energy selection, which is necessary for direct energy conversion. High energy conversion rate of the traveling wave direct energy converter up to 0.8 is obtained both from orbit calculation and from computer simulation as a result of improvement of proton beam modulation. Computer simulation using a particle-circuit code demonstrates stabilization of the excited wave by the external electric load and stable response of the wave to variation of the load. A very preliminary design of electric circuits of the traveling wave direct energy converter is also presented.

I. INTRODUCTION

A scheme of the direct energy conversion is essential for purposes of rising plant efficiency of a D-^{3}He fusion reactor, because the majority of the fusion power is carried by charged particles, i.e., 14.7- MeV fusion protons and thermal ion components. Development of high-efficiency direct energy converter (DEC) is indispendably needed to realize the favorable characteristics of D-^{3}He fuels.

An electrostatic DEC is applicable for the thermal ions,[1-3] however, the kinetic energy of 14.7- MeV protons is too high to control by an electrostatic potential. A novel DEC using a traveling wave, i. e., a traveling wave direct energy converter (TWDEC), was presented for fusion protons in a recent design study of the D-^{3}He-fueled field-reversed configuration (FRC) reactor Artemis,[4] and a concept of the TWDEC was developed based on the principle of a backward wave oscillator.[5-7] Installation of different two types of DEC's needs effective separation of the protons from thermal components. Furthermore, effective energy selection of the thermal ions is necessary for achieving higher energy conversion efficiencies. In order to respond to this demand, we proposed a new type DEC in which separation of the fusion protons and energy selection of the thermal ions are simultaneously accomplished by using $E \times B$ ion drifts.[8]

Purpose of this paper are to demonstrate effective energy selection using $E \times B$ drift, to achieve high energy conversion efficiency of the TWDEC, and to display performance characteristics of the TWDEC. Particle simulation is carried out to examine ion drift across magnetic field lines at a constant speed in the $E \times B$ drift section. High energy conversion rate of the TWDEC are obtained from particle trajectory calculation. Stabilization of the excited wave by external electric load and stable response of the wave to variation of the load are demonstrated by computer simulation using a particle-circuit code. A very preliminary design of electric circuits of the TWDEC is also presented.

II. $E \times B$ DRIFT TYPE DEC

A new type DEC system was proposed for a D-^{3}He fusion reactor.[8] Separation of 14.7 MeV fusion protons and energy sellection of thermal ions are accomplished by using $E \times B$ drift of ions. This energy conversion system has advantages as compared with the traditional DEC. Since a collector system becomes simple in construction, it is possible to solve the cooling problem of ion collectors by employing a direct cooling method. Fusion protons are separated from thermal ions so that protons can be guided to a pair of TWDEC's. Higher direct energy conversion effciencies can be achieved by dividing a collector system of the electrostatic DEC into a number of small sections biased at suitable voltages.

A. Energy Selection of Ions Using $E \times B$ Drift

All changed practices drift across magnetic field at constant speed E/B in the $E \times B$ section where strong transverse DC electric field is generated between a pair of plane electrodes biased at DC voltages. Since parallel velocity of particle is proportional to the square root of their parallel kinetic energy, particle trajectories have angular dependence on parallel kinetic energies. Using this angular dependence, we can simultaneously accomplish energy selection of thermal ions and separation of fusion protons.

B. Particle Simulation

In order to examine generation of the uniform DC electric field in a plasma and particle drift across magnetic field lines at constant speed, simulation of a plasma at the $E \times B$ drift section is carried out using a particle code, which is one dimensional in real space and three dimensional in velocity space. Figure 1 show the profile of DC electric field strength in the direction perpendicular to magnetic field lines. In the simulation, particle density profile of a deuterium plasma is chosen to be parabolic and its maximum density is 7.5×10^{15} m^{-3}. The broken line is the value calculated using the dielectric constant of a plasma perpendicular to magnetic field lines

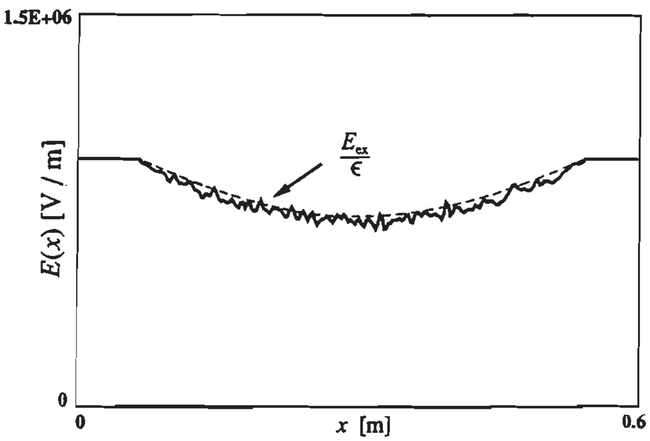

Fig. 1 The profile of DC electric field strength in the direction perpendicular to magnetic field lines. The broken line is a result calculated using the perpendicular dielectric constant.

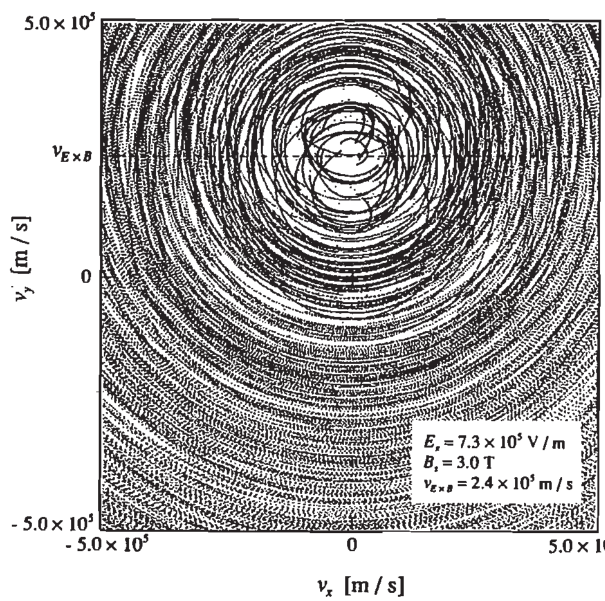

Fig.2 Ion trajectories in the v_x-v_y velocity space, where electric field is chosen in the x direction and the magnetic field is in the z direction.

$$\epsilon = 1 + \frac{\omega_{pi}^2}{\omega_{ci}^2} + \frac{\omega_{pe}^2}{\omega_{ce}^2}.$$

Figure 2 shows ion trajectories in the v_x-v_y velocity space. All ions drift across magnetic field at a nearly constant speed. These results indicate that the effective energy selection of ions can be accomplished by DC biasing for such a strongly magnetized plasma that $\omega_{ci} > \omega_{pi}$.

III. TWDEC

A. Improvement of Beam Modulation

The TWDEC consists of two parts. One part is the modulator where the 14.7 MeV proton beam is bunched by electrostatic traveling wave or standing wave with wavelength λ_0. Another part is the decelerator where a set of electrodes provides a traveling electrostatic wave whose phase velocity spatially decreases in the direction of the beam. The bunched protons are trapped and decelerated by the traveling wave so as to lower their kinetic energy to a range suitable for electrostatic direct energy conversion at the end of the TWDEC. Since the proton beam has energy speed about 2 MeV due to thermal motion of fuel ions, the amplitude of the traveling wave about 1 MV is required for trapping and deceleration of the beam.[5]

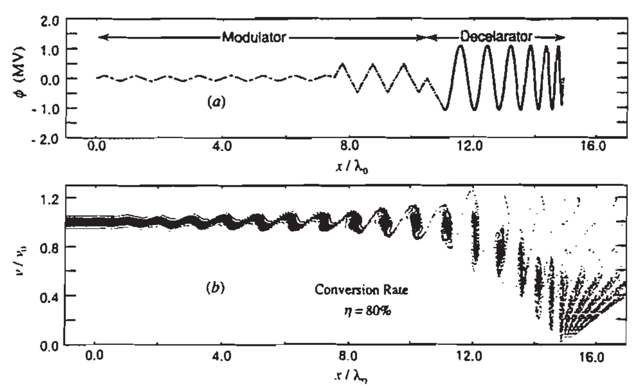

Fig.3 (a) Spatial potential profile of the standing wave (chain lines) with ϕ_m=0.04 MV and 0.2 MV, and the traveling wave (solid line) with ϕ_m=1.1 MV in the TWDEC. (b) Phase space plots of fusion protons obtained from the particle trajectory calculation. Energy spread of the proton beam is given to be 2 MeV.

Trapping rate of the beam at the decelerator strongly depend on beam bunching, then the way to modulate the beam is essential for increasing the energy conversion rate of the TWDEC. In this paper, we apply serial standing waves at the modulator in order to improve beam bunching. Figure 3 shows potential profile of the waves and phase space plots of fusion protons obtained from particle trajectory calculation, where the chain lines are the standing waves and the solid line is the traveling wave. Nearly perfect beam bunching is realized by applying serial waves at the modulator and almost all ions are trapped by the traveling wave at the decelerator. High energy conversion rate of the TWDEC up to 0.8 is obtained. More than 90% of the total kinetic energy of fusion protons can be converted to electricity if the electrostatic DEC having conversion rate higher than 0.5 is installed at the end of the TWDEC for recovering the remaining kinetic energy of protons.

B. Electric Circuit of TWDEC

Since the proton speed $v_0=5.7\times10^7$m/s is much smaller than the light speed, electric circuits are designed using lumped elements. Electric circuit for excitation of standing waves at the modulator consists of serial L-C resonant circuits. A transmission-line loop for the traveling wave at the decelerator is made up of high pass, low pass and L-C resonant circuits. Capacitor between electrodes and inductance connected to electrodes in a series make up resonant or high pass circuits. Low pass circuits at the decelerator are used to make of transmission-line loop, and L-C resonant circuits play a role to fix the frequency of the excited wave at $\omega_0 = 2\pi v_0 / \lambda_0$. The electric power required at the modulator is supplied from the decelerator, and amplitude of standing waves is controlled by serial capacitors in low pass circuits. Equivalent resistors R are introduced to model external electric load applied to the transmission-line loop. Each circuits in the transmission-line loop is matched (reflection-less) at the frequency ω_0.

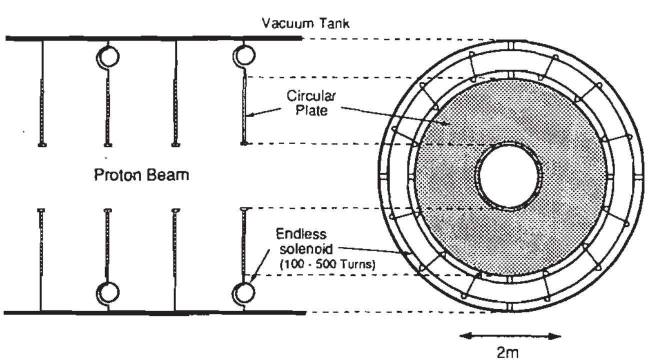

Fig. 4 Drawing of electrode structure at the modulator.

A very preliminary design of electrodes at the modulator is installed in Fig. 4. Resonant and high pass circuits are composed of the capacitor between circular plates and the endless solenoid with a few hundred turns. The electrode structure both at the modulator and at the decelerator becomes very simple. We can avoid ion collisions with electrodes by using the circular plate, and can diminish power loss due to eddy current by using the endless solenoid.

C. Particle-Circuit Simulation

One-dimensional particle-circuit code is developed in order to display performance characteristics of the TWDEC.[7] Variables in the code are position of all particles in the phase space, potential at electrodes, electric field between them, voltage, charge and current in the curcuit. Equation of motion for protons and node and branch equations of the circuit for the wave are transformed to finite-difference equations so that they can be solved with leap-frog time-stepping. The electrostatic coupling between the beam and the circuit is treated by solving Poisson's equation. The circuit field and the space-charge field between electrodes are determined from Poisson's equation under boundary condisions at grouded electordes.

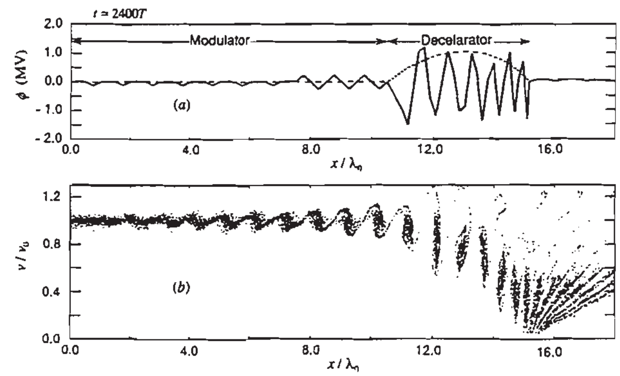

Fig. 5 (a) Potential profile of the wave and (b) phase space plots of fusion protons at t=2400T in rising phase under no load condition.

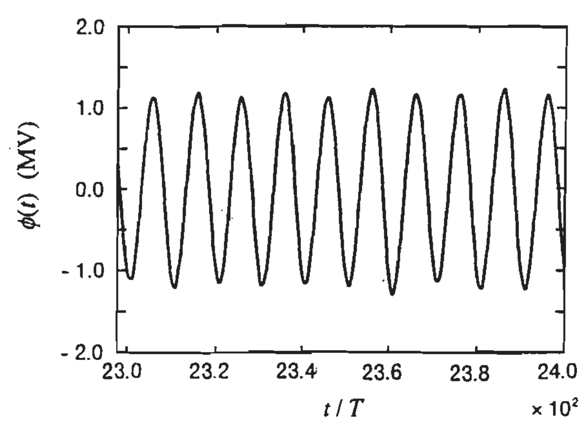

Fig. 6 Wave form of the excited wave.

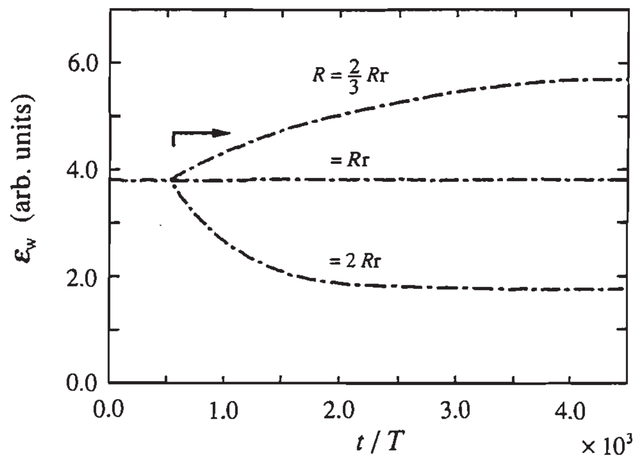

Fig. 7 Response of the wave energy ε_w to sudden variation of the load from the rated resister Rr to 2/3Rr and 2Rr.

The traveling wave is spontaneously excited without power supply from any electric power source, gaining the energy from the beam at the decelerator. The wave energy circulates along the transmission-line loop. The TWDEC becomes a backwave oscillator when the loop gain exceeds unity. The potential profile of the excited wave and phase space plots of fusion protons at an instance in rising phase are shown in Figs. 5 (a) and 5 (b) respectively, where T is a period of the wave with the frequency ω_0. Results of the simulation and those of the particle trajectory calculation in Fig. 3 resemble each other very well. The excited wave has a sinusoidal wave form with the frequency ω_0 as shown in Fig. 6.

The wave amplitude becomes large with time in rising phase, but it saturates under loading, *i.e.* $R \neq 0$. Response of the wave to load variation is simulated in order to examine stability of the wave under loading. Results shown in Fig. 7 indicate that the wave gradually reaches another stable equilibrium state without observation of any kind of instability after a sudden charge of the resistor R.

IV. CONCLUSIONS

Direct energy conversion for a FRC/D-^{3}He reactor was studied by numerical calculations and computer simulations. One dimensional particle simulation was carried out to demonstrate ion drift across magnetic field lines between biased electrodes. Simulation results indicate that $E\times B$ drift is available for the purpose of ion energy selection.

Orbit calculation was carried out to evaluate energy conversion rate from the proton kinetic energy to electricity. High conversion rate up to 0.8 is obtained as a result of realization of nearly perfect beam modulation by applying a series of standing potential waves at the modulator. The total conversion rate higher than 0.9 can be achieved if the $E\times B$ drift type DEC is installed at the downstream of the TWDEC. A computer simulation confirmed high energy conversion rate obtained from orbit calculation. The simulation also displayed desiable performance characteristics; the excited traveling wave is kept its equilibrium state under loading and the wave is stable to variation of the load.

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