PREFACE

SPECIAL SECTION ON BEAM DIRECT CONVERSION

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With the recent remarkable progress toward the feasibility of nuclear fusion in large tokamaks, fusion energy has become a more viable and realistic energy alternative. The most important advantage of fusion energy is the potential that it could be the ideal large-scale energy alternative for the future, satisfying all public acceptance criteria, such as safety, environmental, economic, and technological issues. To achieve such an advantageous energy option, however, it is necessary to develop innovative and aggressive methods to utilize the unique characteristics of fusion energy as effectively as possible.

One development that comes to mind is high-efficiency direct energy recovery from the charged particles associated with fusion energy production by using decelerating electric fields, which cannot yet be attained through conventional methods.

In fusion, there are two possible direct energy conversion methods: (a) plasma direct energy conversion (PDC), which recovers the plasma energy leaking out of the confined region, and (b) beam direct energy conversion (BDC), which recovers the unneutralized energetic ion energy in a neutral beam injection (NBI) system used for plasma heating and to sustain current. Since the fundamental principles and techniques are the same for both methods, successful achievement of high-efficiency energy recovery with the BDC could reasonably support the technological aspects of the PDC scheme as well. Thus, high-efficiency fusion reactors are viable, particularly the D-^{3}He reactor where an appreciable fraction of the fusion energy is carried out by the charged particles with the least neutron energy production.

In the very powerful near-term NBI systems in fusion devices such as the International Thermonuclear Experiment Reactor (ITER), Next European Torus (NET), or Fusion Experimental Reactor (FER), on the other hand, the innovative BDC will be very efficient, even essential, in recovering huge amounts of energy from unneutralized energetic ions, although the BDC technique and energy recovery structure are quite simple.

Energetic NBI is a major method for plasma heating that has been successfully applied through a positive-ion-based system. Ions are produced by discharges in the ion source, are accelerated by electric grids to enter the neutralizer, undergo charge-exchanges with gases so that they are partially neutralized, and are finally injected to the plasma without being affected by the confining magnetic fields. If the ion beams are not neutralized, they cannot enter the plasma because of the strong surrounding magnetic fields that confine the plasma.

With an increase in the injection energy, however, the efficiency of the conversion from ion beam to neutral beam (the neutralization efficiency) decreases rapidly in the gas neutralizer due to the decreasing probability of charge transfer of electrons from the gas molecules to the beam ions. As is seen in Fig. 1, the neutralized fraction of the positive ion beams is reduced to as low as 20% for 200-keV D^+ ions, leaving a balance of 80% as unneutralized ion beams, for example.

This could be improved by the use of newly developed negative ions (D^- in Fig. 1) up to, for example, 60% by the gas neutralizer, with 40% of the ion beams remaining unneutralized. A plasma or photodetachment neutralizer could also greatly improve the efficiency of negative ions (Fig. 1), but unfortunately, neither an appropriate plasma nor a powerful laser neutralizer is yet within reach.

Thus, the useless unneutralized energetic ion beams must be removed after the gas neutralizer and disposed of as efficiently as possible. In current NBI systems, actively water-cooled high heat flux beam dumps are used to dispose of pulse beam energy as heat by allowing bombardment of the ion beam onto metal surfaces at full energy. In the more energetic near-term, long-

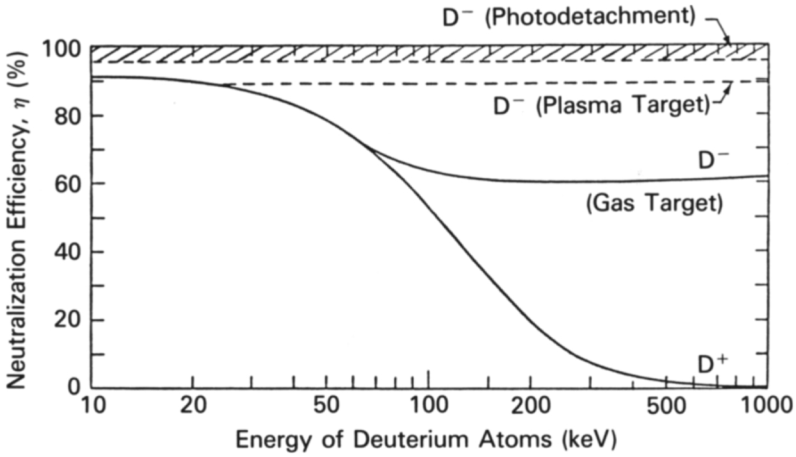

Fig. 1. Neutralization efficiency versus deuteron beam energy.

pulse or continuous wave (CW) deuterium NBI systems, however, there are several limitations to such an NBI system with a conventional beam dump:

1. degradation of NBI system efficiency, since most of the energetic beam energy is discarded as heat
2. the size of the beam dumps since the surface area needs to be large enough to reduce the extremely high CW heat flux to the level of several kilowatts per square centimetre at most, which can be handled continuously
3. neutron production due to the deuterium-deuterium reaction on the beam dump surfaces, resulting in the activation of neighboring materials and heat load to the cryogenic system
4. damage of the beam dump surfaces by energetic beam bombardment.

These problems are inherent in NBI systems using a gas neutralizer, regardless of whether they are positive or negative ion based. To resolve these issues, direct energy recovery from the unneutralized portion of the ion beam is essential, and several types of electrostatic BDCs have been proposed.

The BDC principle is to recover kinetic energy of ion beams into potential energy through decelerating electric fields and to allow all incident ion beams to land softly on the collector surfaces without damage, then evacuate them as gases, with virtually no influence on the transport of energetic neutral beams.

To successfully recover energy by this scheme, it is first necessary to separate (or suppress) accompanying electrons from the ion and neutral beams flowing out of the neutralizer before ion collection, as is shown in Fig. 2. The ions must then be separated from straight-moving neutrals to decelerate them (recover energy) and eventually make them land softly on the collectors at relatively high potential.

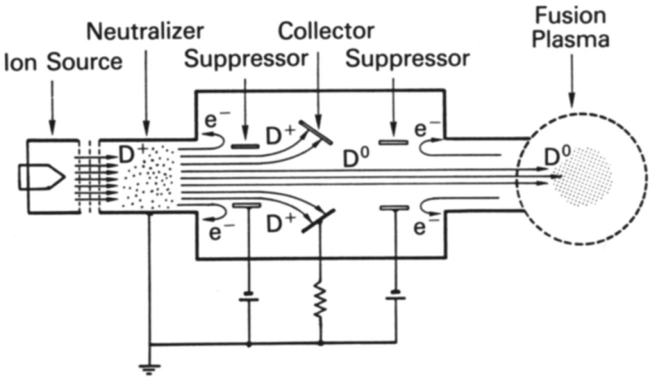

Fig. 2. Schematic of beam direct energy recovery in an LLNL-type electrostatically electron-suppressed BDC.

There are two methods for suppressing such accompanying electrons. One is electrostatic suppression,[1,2] i.e., placing a high negative-potential (with respect to the neutralizer potential) electron suppressor between the exit of the neutralizer and the high positive-potential collectors of the BDC to repel the electrons, as is shown in Fig. 2 for a Lawrence Livermore National Laboratory (LLNL)-type BDC. The other method is magnetic suppression,[3] which uses the appreciable difference in Larmor radii between the electrons and the energetic ion beams.

Electrostatic suppression has the advantage of compactness over magnetic suppression, which needs a relatively large magnet. However, electrostatic suppression is predicted to be considerably sensitive to the beam perveance, as well as the background gas pressure.[4] This is because the ion beam tends to blow up too rapidly to be effectively recovered by the collectors when the beam perveance is too high, and the maximum permissible operation pressure is limited mainly by the atomic-process-induced power losses that are generally proportional to the gas pressure.

Most of the LLNL-type BDC studies have been devoted to ways to successfully suppress and control secondary electrons in order to reduce subsequent power losses. Since these are emitted from the low-potential parts of the BDC through bombardment of ions produced by the ionization and charge-exchange processes between the beams and background gases (with secondary emission coefficients usually in excess of unity), their acceleration tends to enhance the acceleration loss due to slow-energy ions.

There are also two methods to separate the ion beams from the neutral beams: use of the blowup of ion beams by ion space-charge-induced self-electric fields perpendicular to the beam axis when the neutralizing electrons are suppressed[1,2] (see Fig. 2) and conventional magnetic deflection.[3]

The electric deceleration scheme is commonly adopted for ion beam energy recovery, i.e., converting ion kinetic energies into potential energies, opposite to the ion beam acceleration process. Depending on the potential profiles in the NBI system, this is done, for example, by applying high positive potential (but slightly lower than the potential corresponding to the beam energy) to the collector on which the ion beams land softly (see Fig. 2).

In a very high energy, near-term, negative-ion-based NBI system using a gas neutralizer, unneutralized positive and negative ion beam components compose ~40% of the total beam current extracted from the ion source. It is, therefore, necessary to have a substantial understanding of direct energy recovery to design a new BDC applicable to such systems in the near future, in order to dispose of both species at the same time by efficiently recovering their energies.

Based on the above schemes, LLNL performed BDC experiments using an electrostatically electron-suppressed converter designed by the two-dimensional DART code[5] and a reduced-area version of an NBI for the Tokamak Fusion Test Reactor (TFTR) developed at Lawrence Berkeley Laboratory (typically 100-keV/1.6-A, 600-ms hydrogen ion beams at the BDC entrance at an operation pressure of 2.6×10^{-3} Pa). A beam direct energy recovery efficiency of 65 ± 7% was achieved at the beginning of the pulse when the pressure was low.[4] This relatively low efficiency has been attributed to the atomic processes between the incident (ion and neutral) beams and the background gases.

At Fontenay-aux-Roses, a peripheral full beam energy recovery system was developed.[2] The ion source was held at grounded potential, and the neutralizer at high negative potential. By using a long, gridded electron suppressor at the neutralizer exit, the BDC recovered 45% of the energy of the full-energy ions, with a limited pulse length due to excess heating of the grids by ion beam interception.

At Toshiba, they proposed a magnetically guarded electron suppressor[6] (MGS) BDC in a basically LLNL-type BDC, which is a BDC with an MGS to trap the secondary electrons emitted from the electron suppressor at high negative potential by local magnetic fields generated by the solenoidal coils surrounding the suppressor. It is reported that the MGS concept was proved efficient in energy recovery experiments, and the recovery efficiency could be improved by almost 30% (Ref. 6).

In the LLNL-type BDC experiments at Japan Atomic Energy Research Institute (JAERI) using an electrostatic electron suppressor and a flat plate collector with an aperture in the center, an energy recovery efficiency of 55 ± 3% was achieved for a 50-keV/44 ± 3-mA helium ion beam at a pressure of 8×10^{-4} Pa (Ref. 7).

At Kyoto University, by adapting negatively biased secondary electron suppressor grids to the LLNL-type BDC, a net energy recovery efficiency of 87 ± 6% has been achieved in experiments for the theoretically predicted maximum recovery efficiency of 93%, with successful suppression of secondary electrons even at relatively high pressures of 10^{-2} Pa using a 15.4-keV/90-mA, 100-ms helium ion beam.[8] The experimental results have also shown excellent agreement with numerical results by the two-dimensional code KUAD, including evaluation of atomic processes.[9]

At Oak Ridge National Laboratory, a perpendicular kilogauss magnetic field was used to suppress accompanying electrons using local electric fields and to deflect ion beams from the beamline for energy recovery. According to preliminary experiments at up to 35 keV, the results indicated an efficiency of 80 ± 20% for energy recovery from full-energy unneutralized ions.[3]

Five papers in this special section describe the results of BDC proof-of-principle experiments or advanced BDC concepts: two papers related to BDC experiments in small-scale positive-ion-based NBI systems and one in an NBI system of practical size, as well as two three-dimensional conceptual design studies of advanced BDC concepts for a 500-keV negative-ion-based NBI system in the near-term FER fusion reactor being developed at JAERI, where both negative and positive ions need to be effectively recovered.

Although recent demands of NBI energies >1 MeV seem to make application of electrostatic deceleration schemes to such systems somewhat difficult, readers will find that the adoption of the BDC in near-term NBI systems using negative ions is well worthwhile as an advanced technology that will be required in future advanced fusion reactors.

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