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ABSTRACT - Two types of direct converters, one for beams and one for plasma, are under development with voltages and power densities approaching reactor-like conditions. Beam direct conversion raises the efficiency of producing neutral beams, can save millions of dollars when applied to next-generation experiments, and can improve the power balance of driven reactors. Direct conversion allows positive ion beams to be made into neutrals efficiently up to 150 keV for D^0 , 2.5 keV for T^0 and 300 keV for $^3He^0$. Above these energies, the efficiency is less than 50% and falling rapidly, requiring negative ions to be used for neutral beam formation, which even they can benefit from direct conversion because the conversion fraction from negatives to neutrals is less than 100% (~80% plasma cell, ~60% gas cell). The in-line beam direct conversion concept uses either electrostatic or magnetic fields for electron suppression. At low powers (~1 kW continuous) and low voltage (10-15 keV), both have operated at an efficiency better than 70%. Experiments now underway using an LBL 102 keV 50 kW He^+ beam and cryopumping have achieved voltages over 75 kV and efficiencies of about 25% initially, decaying to less than 10% by the end of the 0.5 s pulse, due to outgassing related effects. This converter, designed for 0.8 MW power, could be modified to handle over 3 MW continuously. Plasma direct converters for recovering end leakage power from mirror reactors use immersed grids, and come in one-stage versions resembling a radio triode, and in two- and three-stage versions called Venetian Blind direct converters. Low power experiments at 1 keV gave 65% efficiency for two stages. Experiments are now underway at over 80 keV with power densities $\sim 100 \text{ W cm}^{-2}$ continuous.

Beam Direct Energy Conversion - A neutral beam injector system based on positive ions with an in-line direct converter (Barr [1], Barr [2], Moir [3]) is shown in Figure 1. The elements of this injector are listed below:

a. Plasma source. A source of plasma is required from which positive ions such as D^+ may be extracted with the required characteristics of beam density, uniformity, and stability.

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b. Extraction System. The ions are extracted from the plasma by focussed electric fields applied by high-voltage grids. A substantial quantity of electrical power is invested in the production of the fast ion beam.

c. Neutralizing Cell. Normally this is a duct filled with gas of sufficient thickness such that the fast beam attains a state of equilibrium. In an equilibrium neutralizing cell, the rate of fast atom production by charge exchange collisions with gas molecules is equal to the rate of fast atom loss by re-ionization. The maximum neutralization efficiency is therefore determined by the ratio of charge exchange and ionization cross sections. The efficiency becomes low at D^+ energies above 100 keV because of the small charge exchange cross-section at high speeds.

d. Direct Energy Converter. The converter improves the overall efficiency and also disposes of the residual charged beam by deceleration of the charged beam and collection of the ions at a potential close to the potential of the plasma source.

e. Gas Pumping System. High-speed pumps are required to remove the gas flowing from the neutralizer and produced at the beam targets. The pressure must be reduced to the 10^{-5} Torr range to avoid beam loss by re-ionization and to avoid secondary products in the Direct Converter.

Shown in Fig. 1 is a long, narrow beam cross section to facilitate the suppression of electrons. A pumping space of about 0.5 meter between the neutralizer and the converter (longer than is shown) is required for the pumping system, and also to reduce the density of gas streaming from the neutralizer collisionlessly into the converter. Cryogenic panels are probably the only available technique to attain the high-pumping speed required.

A side view of the converter showing ion trajectories is shown in Fig. 2. Electrostatic electron suppression is employed.

In this version, the neutralizing gas cell is at ground potential, the collection electrode is at positive high voltage V^+ (100 to 110 kV), and the electrons produced in the neutralizing cell are repelled by negative voltages V^- (20 kV) applied by electron repellers before and after the positive collector.

The charged beam begins to diverge (blow up) because of its own space charge when the electrons are suppressed. The beam blowup becomes more

pronounced as the beam is decelerated because of the increase in space-charge density. Under optimized conditions, 90% or more of the charged beam is collected at positive high voltage. Trajectory computations (Barr [1]) indicate that a small fraction of the charged beam is lost either by transmission through the collector or by reflection from the collector entrance. This fraction depends upon the collector potential and the beam density.

The use of magnetic electron suppression (discussed more fully in reference 2 and shown in Fig. 6) allows handling larger and denser beams measured by the parameter nd^2 . Magnetic electron suppression is also being worked on by the ORNL group, and follows an idea by O. B. Morgan (Schilling [4]).

Beam direct conversion can have three distinct benefits: improved beam dump, save power supply cost, save power.

Improved Beam Dump - Disposal of the high-power charged beam may be possible by direct conversion under conditions not possible by other techniques. Designs indicate that beam power densities of 10 to 20 kW/cm^2 may be handled by a direct converter, although these densities exceed the heat-transfer limitations for steady-state beam targets. This is because most of the beam energy is removed by deceleration before the ions strike the collector, and because the charged beam is spread over a large area by electro-static blow-up. This possibility is interesting, aside from other advantages, because the converter occupies less volume than the large sweep magnets and beam dumps otherwise required to dispose of the charged beam. Our layouts indicate more compact assemblies and more ion sources in a single beam line than the alternatives.

Save Power Supply Costs - A substantial saving in the capital cost of injector power supplies will be possible in large experiments by using the converter to supplement the accel power supplies. This saving may amount to several million dollars for a large experiment.

Save Power - The reduction in power requirement will significantly reduce the cost of electricity, and will also affect the feasibility of large experiments limited by power availability.

Electrical Circuit and Grounded Neutralizer vs. Grounded Source -

Fig. 3 shows one possible circuit for recirculating the recovered power back to the injector. A low-voltage supply is needed to maintain a potential difference between the ion source and the collector. Several

options are available in the choice of where to define the ground potential.

It is conventional in most systems to ground the neutralizer at Point A and to operate the ion source at positive high voltage. However, another option (preferred at Fontenay-aux-Roses) is to ground the collector (Point B) and to operate the neutralizer at negative high voltage. In principle, the direct converter and the ion source operate equally well in either ground condition, although there are some practical differences:

a. If the neutralizer is operated at negative-high voltage (ground condition B), it is necessary to prevent the electrons produced within the neutralizer from escaping. Therefore the converter is almost mandatory for condition B, but is optional for condition A.

b. Ion source electronics will be simplified under ground condition B, since the arc and filament circuits are operated near ground potential. Voltage-holding conditions will be different since the energy stored by the capacitance of the neutralizer is not the same as the energy stored in the plasma source and isolation transformers.

Neutral Injection Efficiency - The injection efficiency is defined as the ratio of neutral beam power to electrical power used to produce the beam. Assuming 80% energy recovery efficiency of full energy ions, and a number of usual assumptions discussed in reference 3, the injection efficiency is plotted versus energy in Fig. 4 for D^0 and $^3He^0$.

Neutral Injection Systems Operating on Helium - Several advantages may be obtained by operating neutral injection systems on helium rather than on hydrogen isotopes. Some of the arguments for and against the use of energetic helium atoms for heating toroidal systems have been presented by Ernie Thompson in his letter in Nuclear Fusion 15, 347 (1975). In the list below, Ernie's arguments are identified by asterisks. The new development of cryogenic pumping for helium, by T. Batzer, has removed the most important liability that existed at the time of Ernie's Letter. In addition to Ernie's arguments, we will include some additional thinking on this subject.

(1) Arguments in favor of injection of fast helium atoms:

*a. Deeper penetration of He^0 and D^0 at equal energies up to 60-100 keV.

*b. Almost constant trapping cross section of He^0 in the energy range from 10 to 500 keV. Therefore the injection energy can be selected for other reasons.

*c. More efficient production of fast neutrals because of the larger electron capture cross section for He^+ . This improvement is shown by Fig. 3, showing the overall efficiency for the understood assumption for D and for ^3He injectors.

d. A helium ion source normally produces only one ion species, He^+ , in comparison with the three species H^+ , H_2^+ , H_3^+ produced by sources of hydrogenic ions. This avoids the production of half-energy or third-energy neutrals derived from molecular ions, and avoids several disadvantages:

(1) Optimum heating of toroidal plasma requires an injection energy above a certain value. Injection of half-energy or third-energy particles tends to heat electrons (undesirably) rather than ions.

(2) The half-energy or third-energy injection enhances the charge-exchange at the outer portion of the plasma, causing wall bombardment, gas loading, and other undesirable effects.

(3) Penetration of a mixed-species beam is non-uniform.

(4) Beam Direct Conversion is more complicated and less efficient if a mixture of energies is present in the charged beam emerging from the neutralizer.

e. Injection of He^0 rather than D^0 avoids the need for neutron shielding in plasma experiments and in neutral-beam test stands.

f. An He injection system involves a smaller gas load than an equivalent H or D system because of the higher neutralization efficiency.

g. The design of certain types of D- ^3He reactors would become possible if ^3He neutral injectors are available.

h. Field reversal in steady-state mirror devices probably will require the injection of at least two ion components with different charge numbers and different speeds. This is required as shown by Ohkawa so the electrons dragged along with the circulating ions do not completely neutralize the circulating current. The logical species to inject for this reason are D^+ and He^{++} .

(2) The arguments against the injection of fast He atoms are:

*a. The impurity buildup of trapped He^{++} ions is tolerable only up to a certain level.

*b. A new type of gas pumping is required for helium gas. (This requirement now appears to be satisfied.)

Experimental Results - A steady-state MATS-III ion source was masked to produce a slab beam 15-mm thick and 60-mm wide. The energy was 12 keV with 20% of the particle at one-half energy due to molecular breakup. The total power was 1450 W. The collector configuration was approximately as shown in Fig. 2. The current voltage characteristics are shown in Fig. 5. The peak recovered power occurs at a voltage 0.98 times the beam voltage, and the efficiency was measured to be $70 \pm 2\%$. The power supplied to the electron suppressor electrode is included, and the reduced efficiency due to the half energy ions is included.

Experiments on the LBL 1/4 Scale TFTR Beam - The experimental setup is shown in Fig. 6. A resistive load is connected to the collector which self-biases. The experimental results are shown in Figs. 7 and 8. The beam is $^4\text{He}^+$ at 102 keV, and is 0.51 A for 0.5 sec. In times short compared to 10^{-4} sec, the voltage and current collected rise to fixed values and then slowly decay in time, as shown. The collected current of 0.2A is near the value calculated with the computer code DART. The current decay is apparently due to a buildup of gas evolved from the electrodes during the pulse. The current voltage traces typically have an interrupt of 20 msec long at a random time, as shown. The current and voltage at zero time are plotted for different load resistance values in Fig. 8. The striking feature is the voltage limit at low currents (open circuit voltage) of 76 kV, rather than the expected beam voltage of 102 kV. Further experiments will be needed to determine the proper design parameters for successful, highly efficient beam direct converters.

There are several other beam direct conversion concepts being pursued. The Fontenay group is developing a converter that uses grids and is apparently working well for pulsed beams. A concept similar to the in-line concept, but scaled down to each beamlet, is being pursued by Thompson at Culham and Cooper at Berkeley. The in-line concept with magnetic electron suppression is being pursued at ORNL, as well as LLL.

Plasma Direct Conversion - Direct energy conversion of the power carried out the ends of mirror reactors will be needed to make mirror reactors economical with non-negligible recirculating power fractions. We have designed such direct converters and tested several types at low powers and voltages (Barr [1]). One concept, due to Post, had 22 collector

stages, and was tested with a wide energy spread at 87% efficiency. Engineering studies, however, showed the simpler 1-stage gridded and 2,3-stage Venetian Blind converters were both more practical and lower cost.

The 1-stage concept shown in Fig. 9 resembles a triode radio tube. Efficiencies with energy distributions expected from mirror reactors are approximately 50%, as has been borne out in low power tests. To get higher efficiency, we employ the Venetian Blind concept which can have several stages. We tested a 2-stage unit and achieved 65% efficiency. The 2-stage unit is shown in Fig. 10. The 2-stage unit can be very effective when used on the tandem mirror, with one collector set to catch the central cell ions with their narrow energy spread and the second collector can catch the plug leakage ions. The energy distribution of the collected current is shown in Fig. 11.

Now that plasma direct converters have been proven at low voltages and low powers, and studies (Barr [5], Barr [6], Barr [7]) have shown that they are practical and workable in the reactor context, high power tests are called for. Accordingly, we are testing a 1-stage (2-stage tests will follow) converter at reactor-like conditions. The converter is shown in Fig. 12. A 100 keV, 100 mA continuous ion source simulates the leakage plasma. Operation at 80 keV has been successful. The tests will determine voltage-holding and power density limits, and explore the effects of cold plasma near the grids, as well as gas effects.

The objective of this development is to prove end loss direct conversion to be practical. Suppression of electron emission from the electrodes is a necessary part of plasma direct conversion, which interestingly is also necessary to minimize axial electron heat conduction in open-ended confinement concepts. Grid for electron suppression will be tried in TMX.

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100 keV 10A NEUTRAL INJECTOR SYSTEM

Fig. 1. Conceptual design of an ion source-converter combination for a 120-keV neutral-beam source. The ion source, left, generates a slab beam of 120-keV deuterium ions. In the neutralizer cell, about 40% of the ions turn back into atoms, still at 120 keV. The converter traps the remaining ions, converting most of their energy into electricity to help run the ion source. The 120-keV deuterium atom beam passes unimpeded into the reactor.

Fig. 2. Space-charge-controlled beam direct converter. In this version, the neutralizing cell is at ground potential, and the potentials of the positive and negative electrodes are $+V^+$ and $-V^-$, respectively. Full energy ions are collected, and half energy ions are reflected as shown.

Fig. 3. A circuit for recirculating the power recovered by a Beam Converter to supplement the accel power supply.

Fig. 4. Efficiency of producing neutrals versus beam energy for D^0 and $^3He^0$ with and without direct conversion.

Fig. 5. Current voltage characteristics of the 12 kV, 1.5 kW beam direct conversion tests. Efficiency was 70%.

Cross
Beam

Source

Beam
dump

Analyzer

13 - a

Fig. 6(a). Beam direct beam line arrangement for the LBL 120 keV,
1/4 scale 1/4 scale.

Fig. 6(b). Cross section of converter electrodes.

Fig. 7. Time-dependent current-voltage characteristics for the arrangement shown in Fig. 6, with a 0.5 sec beam pulse.

Fig. 8. I-V characteristics for different load impedances at zero time.

Fig. 9(a). One-stage Collector - (a) An isometric view of a module designed for the hybrid reactor, where the collector is louvered to allow for gas pumping.

Fig. 9(b) One-stage collector - (b) The grid arrangement designed for the tandem mirror reactor.

Fig. 10. Two-stage collector and grid array for the venetian blind direct converter. The pair of wire grids at the left reflect the electrons and allow ions to pass on through the venetian blind collector. The venetian blind appears transparent to the incoming ions but opaque to the ions reflected by the second collector.

Fig. 11. The distribution in ion energy at the direct converter for the tandem mirror reactor. For He^{++} , the energy per unit charge is plotted.

Fig. 12(a). 100 keV test apparatus for plasma direct conversion;
(a) photograph of apparatus showing location of
ion collector.

Fig. 12(b). 100 keV test apparatus for plasma direct conversion;
(b) cross section of collector.