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W. L. Barr and R. W. Moir

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A REVIEW OF DIRECT ENERGY CONVERSION FOR FUSION REACTORS*

W. L. Barr and R. W. Moir

LAWRENCE LIVERMORE LABORATORY, LIVERMORE, CALIFORNIA

The direct conversion to electrical energy of the energy carried by the leakage plasma from a fusion reactor and by the ions that are not converted to neutrals in a neutral beam injector is discussed. The conversion process is electrostatic deceleration and direct particle collection as distinct from plasma expansion against a time-varying magnetic field or conversion in an EXB duct (both MHD). Relatively simple 1-stage plasma direct converters are discussed which can have efficiencies of about 50%. More complex and costly (measured in $/kW) 2-, 3-, 4-, and 22-stage concepts have been tested at efficiencies approaching 90%. Beam direct converters have been tested at 15 keV and 2 kW of power at 70 ± 2% efficiency, and a test of a 120-keV, 1-MW version is being prepared. Designs for a 120-keV, 4-MW unit are presented. The beam direct converter, besides saving on power supplies and on beam dumps, should raise the efficiency of creating a neutral beam from 40% without direct conversion to 70% with direct conversion for a 120-keV deuterium beam. The technological limits determining power handling and lifetime such as space-charge effects, heat removal, electrode material, sputtering, blistering, voltage holding, and insulation design, are discussed. The application of plasma direct converters to toroidal plasma confinement concepts is also discussed.

INTRODUCTION

The first significant fusion reactor application of electrostatic direct energy conversion was a concept put forth by Post to apply the idea of a linear periodic focused accelerator in reverse.(1) The exhaust or leakage plasma from a mirror reactor was magnetically guided, expanded, and transformed into a thin fan shape (see Fig. 12). This process both reduced the plasma to a thickness of order one debye length and converted random motion to directed motion. Next, the electrons were separated from the ions by a transverse magnetic field with the help of a negative electrical barrier (which is possible because the fan thickness is of order a Debye length). Next, the ions were decelerated and collected on various electrodes (22 electrodes) at potentials near the kinetic energy of the ions. The electrons were collected at low (ground) potential and formed the return current from the ion collector stage. This concept has been successfully tested at over 90% efficiency with a steady-state plasma source. Simpler concepts based on

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triode, tetrode, etc. vacuum tubes have resulted in 1-, 2-, etc. stage concepts, called Venetian blind direct converters,(2) which have lower efficiency but also much lower costs ($/kW). A 4-stage concept(3) seems to have many of the advantages of the previous two.

More recently, attention is turning to the application of direct conversion to neutral-beam injectors to increase their efficiency (i.e. to reduce power consumed), to reduce the power supply requirements, and to ease the design of the *charged particle beam dump*. We have developed and tested a so-called in-line beam direct converter concept(4) where the neutrals created from accelerated ions in a charge-exchanged cell continue through the "in-line" direct converter electrodes. The ions which are not converted to neutrals however are decelerated and caught on these in-line electrodes.

In this paper, we discuss the beam direct converters, the plasma direct converters, technological problems, and application of plasma direct converters to toroidal reactors (tokamak and reversed-field mirror reactors).

BEAM DIRECT CONVERSION

To efficiently produce neutral beams for fusion reactors, the energy carried by the unneutralized portion of the ion beam may have to be recovered in a direct converter. Neutral beams are produced by passing an accelerated ion beam through a gas cell where a fraction is neutralized by charge exchange, but a significant fraction is not. When a beam of 100-keV D^+ is passed through the optimum thickness of D_2 gas, about half of the beam power remains unneutralized. At higher energies, the unneutralized fraction becomes even greater. It is therefore necessary to recover this power if the injector is to be efficient. The ions can be magnetically deflected into a beam dump from which power can be recovered thermally, but the direct recovery of electrical power is more efficient and can allow a more compact design.

The first beam direct converter concept involved magnetic deflection and then recovery in an immersed-grid direct converter.(5) This converter type was tested steady state at 20 keV and 200 W/cm^2 in a series of experiments in 1970.(4) The problem with the magnet was that the packing of a large array would be difficult. A concept of immersed grids in an in-line direct converter was developed by Fumelli.(6) This in-line concept solved the packing problem and resulted in a compact beam line, but beam interception on the grids severely limited the beam power density times pulse time, and for steady state the power was extremely limited (few hundred W/cm^2). In 1974, an in-line, nonintercepting electrode converter was proposed.(4) Designs and computer simulations using the DART code were then done(7) and a comparative analysis of the immersed-grid concept of Fumelli's and the nonintercepting concept was made.(8) Analytical and computer studies of both the immersed-grid and nonintercepting-electrode concept were reported on in 1975 by Raimbault.(9) The nonintercepting converter can handle much higher power densities than the immersed-grid concept, but the product of beam thickness and current density is somewhat restricted as discussed below. To overcome this limitation, we propose to divide the beam into two blankets. Raimbault has recently(10) proposed an interesting concept employing aspects of both immersed-grids and nonintercepting electrodes that promises to raise the beam thickness and power density both.

Principle of the Nonintercepting Concept

The nonintercepting beam direct converter(4) makes use of the fact that the space charge of an unneutralized ion beam will cause the beam to diverge. By stopping the neutralizing electrons with an applied negative potential, most of the ions can be caused to leave the fast-atom part of the beam and be collected on appropriate electrodes. The neutral (atom) component of the beam is not affected. Figure 1 shows a cutaway view of an injector system(11) with this type of direct converter. Ions are extracted from the source, accelerated to 120 keV, and passed through a gas cell where 41% of the D^+ ions are converted to D^0 atoms at 120 keV. (The neutralization would be 43% efficient if the cell were very long). The gas cell is cooled to reduce the flow of gas into the direct converter region where the gas pressure is kept below 10^{-2} Pa (8×10^{-5} Torr) by baffled cryopumps. Higher pressure than this would result in an unacceptably high density of cold ions which would be accelerated into the negative electrode.

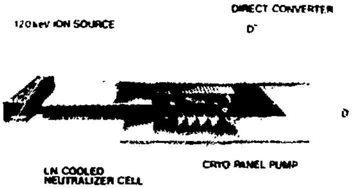

Fig. 1 A 120-keV neutral injector with a beam direct converter to recover power from unneutralized ions.

The negative electrode is water-cooled and is held sufficiently negative (-15 kV) to prevent the electrons produced in the neutralizer cell from reaching the positive electrodes. The positive electrodes are also water cooled and are oriented so that they intercept as much of the diverging ion beam as possible. They are held at high positive potential (about +110 kV here) that is adjusted to maximize the recovered electrical power. Another water-cooled negative electrode prevents backstreaming electrons from reaching the ion collectors.

There is a complication due to the fact that existing ion sources produce not only the desired ions (usually D^+), but also several other species (such as D_2^+, D_3^+) that break up in the neutralizer. The result is that at 120 keV, about 20% of the ion current at the direct converter (10% of the ion beam power) is in half-energy ions, and about 8% of the ion current (3% of the ion power) is in one-third energy ions. These fractional energy ions are turned back by the high positive potential in the collector region and are caught on the curved collector which is at ground potential. The purpose of the curved collector is to prevent the fractional energy ions from striking and heating the LN-cooled baffles near the cryopanels.

Calculated ion trajectories are shown in Fig. 2 for both full-energy (120-keV) ions and half-energy ions. The collector in this case was held at 110 kV. The calculations were done in two dimensions

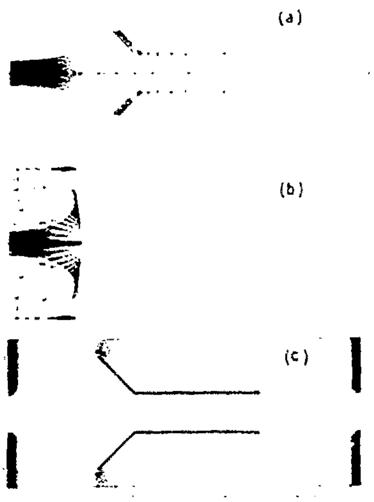

Fig. 2 Computer simulation of a beam direct converter at 17 A/m of 120-keV D^+. Total length is 1.0 m: (a) full energy, (b) half energy, and (c) equipotentials.

with the DART(12) computer code, which calculates ion trajectories in the applied potential plus the self-consistent space-charge potential of the ions and electrons. Vacuum potential due to the specified electrode geometry and voltages is first calculated using an over-relaxation technique. Ion trajectories are then calculated for that potential in order to get a first approximation to the space charge of the ions. Two groups of electrons are then added, each with a Maxwell-Boltzmann (M-B) density distribution. The primary electrons that neutralize the incoming ions are included only on the entrance side of the first minimum in potential with a M-B referenced to ground potential. Secondary electrons produced at the positive ion collector are included everywhere with a M-B referenced to the collector potential. The combined potential, vacuum plus space-charge, is recalculated and the electron density is recalculated. This process is repeated until there is no further change, and then the entire process is repeated until there is no further change.

In Fig. 2, the current density profile is Gaussian (e^{-r^2/a^2}, a [illegible].3 cm), and both groups of electrons have a temperature kT_e 3[illegible] eV. Both groups of electrons have important effects. Primary electrons prevent the blowup of the ion beam until the electron density is reduced by the negative potential. Secondary electrons limit the buildup of the potential maximum inside the collector to a few kT_e above collector voltage. For this reason, secondary electrons allow the collection at high potential of a much higher density ion beam than would be possible otherwise.

Secondary electrons are also produced at the negative electrodes. The space charge of these energetic electrons is negligible, but their current and power may not be. Their trajectories are calculated to determine the loss in direct converter efficiency.

Although a finite amount of space charge is necessary for efficient recovery, too much space-charge produces unacceptable losses. To stop the electrons, the negative electrode must be able to produce a negative potential even in the presence of the positive space charge. An increase in beam density requires an increase in the applied negative voltage, and simultaneously produces greater divergence of the beam once the electrons are turned back. The power loss at the negative electrode thus increases with increased beam density, and the efficiency of the direct converter decreases. An approximate scaling law for the efficiency can be derived by assuming that the ions are collected when the outermost part of the beam is deflected through a 45° angle. The analysis shows that, for a parabolic density profile, the direct converter efficiency η scales with ion density and energy as:

$$\eta = \eta_0 - k(\omega_p \tau)^2 (d/L).$$

Here, $\omega_p^2 = nq^2/\epsilon_0 M$ is the square of the ion plasma frequency, d is the thickness of the beam, and τ is the time required for an ion to go a distance L. The scale length L is defined by $W_0 = qEL$, where W_0 is the ion energy, and E is the applied retarding electric field between the collector and the negative electrode. When n, the central beam density in a parabolic profile, is expressed in terms of beam current I, the scaling displays the expected $I \propto W_0^{3/2}$ at constant η:

$$\eta = \eta_0 - k\left(\frac{3}{4\epsilon_0}\right)\sqrt{\frac{M}{2q}}\;\frac{(I/h)L}{(W_0/q)^{3/2}},$$

where h is the width of the beam and M is the ion mass. The constants k and η_0 are determined by trajectory calculations. The best fit to results at high current were $\eta_0 = 1.0$ and $k = 0.11$ for a flat-topped beam profile. Calculations have also been done for a Gaussian profile. In that case, η_0 is smaller than in the flat-topped case because more of the beam power is concentrated in the center of the beam where recovery is poor. For the Gaussian profile, $\eta_0 = 0.9$ and we assume $k = 0.11$ as before, although k has not been studied in this case.

In practice, the efficiency is not as good as this simple scaling predicts. The fraction of the beam that is made up of fractional-energy ions is lost in the present designs. Part of these fractional-energy ions strike the negative electrode and produce secondary electrons, some of which reach the collector. These effects are peculiar to the particular ion source that is used since both the relative currents and the current profile are different for different sources.

We have experimentally tested a beam direct converter of this type.(13) A steady-state MATS-III ion source was masked to produce a slab beam 15-mm thick and 60-mm wide consisting mostly of H^+ ions. The ion energy was varied over the range from 10 keV to 15 keV, and the full-energy ion current varied from about 50 mA to 130 mA. Since the ion current from the source varies as $W_C^{3/2}$, we expected and found the same efficiency at all beam energies.

A photograph of the direct converter is shown in Fig. 3. The device was constructed from molybdenum and was cooled by radiation only. When the voltages

Fig. 3 Photograph of a scaled direct converter tested at 2 kW of 15-keV H^+. Efficiency is 70%.

are varied, the various electrodes range from warm up to white hot. At the optimum setting, the collector is only dull red since most of the power is recovered electrically.

The efficiency was determined by measuring the currents and voltages at all electrodes and by measuring the ion beam power with a calorimeter. The calorimeter can be seen in its retracted position in the photo. By recording the total beam power transmitted through the direct converter with no applied voltages and also with voltages set to stop all ions, the neutral component of the beam could be subtracted out to give a measure of the total incident ion beam. The currents to the different electrodes were measured as the voltage at the collector electrode was varied from zero up to above the source voltage. Maximum recovered power, and hence maximum efficiency, occurred at about 0.98 of source voltage. Measured efficiency was typically $\eta = 0.70 + 0.02$ for the total ion beam, including the ~20% of beam current in half-energy protons.

Figure 4 shows a plot of the measured currents to the positive collector and to both negative electrodes versus the voltage applied to the collector. The negative electrodes were both held at -3 kV, the source voltage was 12 kV, and the total ion beam power was 1450 W as measured with the calorimeter. At 11.8 kV, the collected power reached a maximum of 1050 W, and the drain on the negative power supply was 48 W. Therefore, in this case the efficiency was

$$\eta = \frac{1050 - 48}{1450} = 0.69.$$

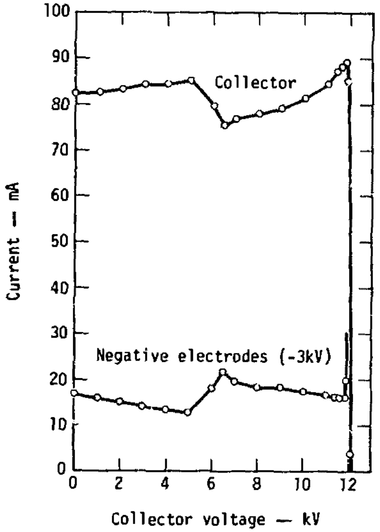

Fig. 4 Data taken on the device shown in Fig. 3 with 12-keV H^+. The effect of half-energy ions can be seen.

The 1450 W includes the half-energy ions whose effect can be seen at about 6 kV in Fig. 4.

A larger version of this direct converter is being constructed and will be tested on the Lawrence Berkeley Laboratory's 120-keV test stand. The direct converter is designed to recover the 800-kW (6.75-A), 1/2-s pulse of full-energy D^+ ions. The direct converter will be located about 5 m from the 10-cm-square source, where the beam profile is Gaussian with an elliptical cross section. The computer calculations indicate that the highest heat load on the collector will occur when the collector is at ground potential and the negative electrodes are at their -15 kV operating potential. Then, most of the ions diverge and strike the collector with their full kinetic energy. The ion power will be distributed rather uniformly over the collector surface, so that the power density is calculated to be less than 200 W/cm^2 everywhere on the collector. The collector structure is shown in Fig. 5. The electrodes are all made of water-cooled copper and are nickel plated to reduce sputtering.

All electrodes and apertures have elliptical cross sections to follow the contour of the beam power density. The first aperture is the smallest, with major and minor diameters of 36 cm and 9 cm, respectively. At maximum power and best focus, the beam power density striking the aperture will be 500 W/cm^2. The aperture has a tungsten insert to allow for less than optimum focus and alignment. Total power density (neutrals plus ions) at the center of the beam will be 37 kW/cm^2.

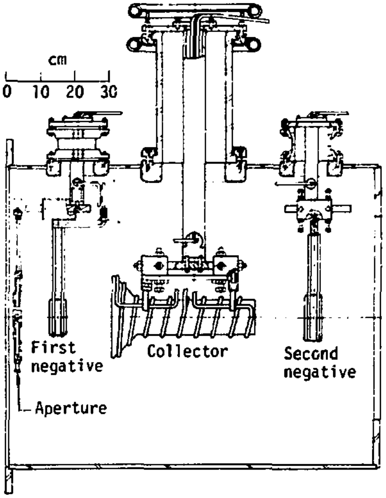

Fig. 5 A direct converter being built to recover 800 kW of 120-keV D^+.

The recovered power will not be used, but will be dissipated in a variable resistor that will be adjusted to give the desired voltage at the collector. All high-voltage cables will be kept short to reduce the stored energy that could be dissipated in a spark. Diagnostics will be electrical and also calorimetric. Testing is expected to begin in November of this year.

In anticipation of favorable results from these tests, a preliminary design is being developed for a direct converter to be used on the injectors for the TFTR (*Tokamak Fusion Test Reactor*). *We* are assuming that the ion sources will be 10-cm x 40-cm versions of the 10-cm square source being developed in Berkeley. The power density at the direct converter will be higher on TFTR than in Berkeley because of the larger source. However, the more important difference is due to the shorter distance between the direct converter and the source on TFTR. There, the 4-MW beam of unneutralized ions will have nearly a flat-topped profile and will be the full 10-cm thick. The space charge potential at the center of the beam after the electrons are removed will *be more than* 50 kV, requiring about 80-kV negative voltage on the negative electrode to penetrate in order to stop the electrons.

Such a high negative potential is not practical because of the power loss and because of the danger from sparking. One possible solution is to reduce the beam height to 5 cm, which would reduce the required negative potential to about -20 kV. This, unfortunately, would reduce the output of each beam by a factor of 2, which could be made up by doubling the number of beams. Another possible solution to the problem is to modify the source to produce a shadow down the center of the beam. The negative electrode in the direct converter could then have a web in the shadow. This effectively halves the beam thickness and reduces the space charge potential to one fourth of what it was. Figure 6 shows some trajectories run in this geometry. Those ions, especially the fractional-energy ions, that pass close to the web are strongly deflected and appear to be the most serious problem with this scheme.

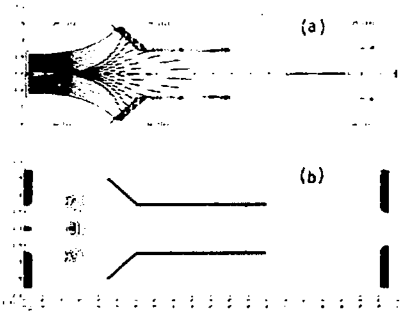

Fig. 6 Calculated trajectories (a) and equipotentials (b) for 90 A/m of 120-keV D^+ with central shadow.

Principle of the Immersed-Grid Beam Direct Converter

The idea is to direct the ion beam through a rugged but still tenuous grounded grid (cathode). To reflect electrons with a similar grid which is held at a potential about 3 kT_e/e negative (central grid) and to then decelerate the ions with a positive collector (plate) at a potential approaching but somewhat below the beam energy. The grid set can either be in-line or the ions can be magnetically deflected into the beam recovery unit. This concept has been discussed at some length in Ref. 4, where experiments done in 1970 at 20 keV and 200 W/cm^2 were reported. Further analysis was presented in Ref. 8. In this reference, is developed a fairly fundamental power limit. For example, with the in-line immersed grid concept being pursued by Fumelli and Coworkers,$^{(6)}$ the grids are sufficiently small that for pulse durations of interest (~1 ms) the temperature is uniform across the grid diameter. In that case, for ribbons 0.1-mm by 1.0-mm made of molybdenum, a power density times pulse length of 500 W·s/cm^2 will raise the grid from 300 K to 2200 K, where thermionic emission losses will exceed the recovered power. This value of 500 W·s/cm^2 corresponds to a power density of 1 kW/cm^2 for 0.5-s pulses, whereas the 120-keV converter at 4 MW discussed above is designed to operate at 10 kW/cm^2 for 0.5 s, and quite possibly would go to steady-state operation. At steady state the power density is either limited by thermionic emission from immersed grids to about 50 W/cm^2 or by the convective cooling limit of possibly as high as 2 kW/cm^2. The low limits on power densities and pulse lengths for immersed grids are the effects which led us towards the nonintercepting-grid beam direct converter concepts.

PLASMA DIRECT CONVERSION

Another type of direct converter is required to recover the power from the ions that leak out from a magnetically confined plasma. In a mirror fusion reactor, only a small fraction of the injected beam power results in fusion before it escapes out the mirrors. It is therefore important to the overall efficiency to recover this power, just as it is important to recover the unneutralized ion power in the injectors.

The functions of the direct conversion process can be seen by following a typical particle. A fuel ion will move back and forth between mirror points in the reactor until the particle diffuses by Coulomb collisions into the loss cone. Then it passes over the maximum field (~15 T), where its energy is essentially transverse to $\vec{B}$. As it moves outwardly in the expander, whose field may drop to a few hundred gauss, the perpendicular energy will drop linearly with B according to the principle of adiabaticity $(W_\perp/B) = \text{const}$, so that, by the conservation of total energy, the velocity, which started out perpendicular to $\vec{B}$ is now nearly parallel to $\vec{B}$. Therefore, the expander serves two purposes: it produces a directed beam of ions, and it reduces the current and power densities in the beam.

Plasma direct converters can be divided into two general types according to whether the electrons are separated out magnetically or electrostatically. For magnetic separation, the plasma is guided and expanded magnetically into a thin slab from which the magnetic field, and hence the electrons, can be abruptly diverted. The ions continue on with only a slight deflection if the expansion resulted in a sufficiently weak field. For electrostatic separation, the plasma stream is expanded in two dimensions to produce directed motion and to reduce the power flux to a level (~100 W/cm^2) where immersed grids can be used to reflect the electrons. The fate of the electrons is different in the two types of separation. With magnetic separation, the electrons are removed from the beam and can be collected, while an immersed negative grid simply reflects the electrons without disposing of them. The sink for the electrons in this case is provided by a grounded grid which precedes the negative grid in the beam line and establishes ground potential.

Immersed-grid plasma direct converter

The average energy of the electrons hitting the grounded grid is slightly less than kT_e. A numerical method using a random-walk technique is being developed and can be used to calculate the electron energy more precisely. The loss of the electron power is small if kT_e is much less than the mean energy of the escaping ions.

The simplest direct converter of the immersed-grid type has only one collector stage. Figure 7 shows a 1 stage direct converter module. The first grid is grounded, and the second one is held at a negative potential equal to about $-3\ kT_e/e$ to stop nearly all $(1-e^{-3} \approx 95\ )$ primary electrons. High-pressure helium at about 1000 K is used to cool the grounded grid so that the electron and the intercepted ion power can be recovered in a thermal cycle. The negative grid is water cooled to prevent thermionic emission and to keep the tube size small for a minimum interception of ions. The ion collector is also helium cooled and louvered so that it is opaque to the directed ions but rather transparent for gas pumping. It is held at the positive potential determined from the ion energy distribution to give the maximum recovered power. For mirror machines, this potential is just equal to the parallel component of the minimum energy per unit of charge, so that all ions can reach the collector and none are reflected. This potential is given by

$$V_{coll} = R\phi_0 \cos^2\theta/(R-1),$$

where θ is the maximum angle between the velocity vectors and the magnetic field lines, ϕ_0 is the ambipolar potential, and R is the mirror ratio in the confining magnetic field. In mirror machines, $\phi_0 \approx 5\ kT_e/e$.

The design shown in Fig 7 is for a mirror reactor$^{(14)}$ for which the minimum energy of the escaping ions is 96 keV, the average energy is 146 keV, and θ = 0.20 radians. After allowing for the 8% of the incident power that is carried by electrons, the efficiency of the direct converter is 52 .

Behind the ion collector is a cryopump with a water-cooled and an LN-cooled baffle. The pressure in the expander must be kept below about 10^{-3} Pa (8×10^{-6} Torr) to reduce the losses caused by charge exchange between ions and gas molecules. Economics determine the optimum operating pressure for a reactor.

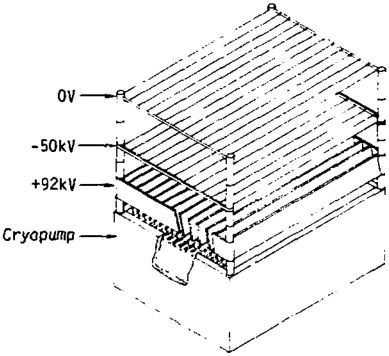

Fig. 7 A single-stage direct converter module designed to handle 1.75 MW/m^2. Mean energy is 96 keV. Efficiency is 52%.

Any number of intermediate stages can be added to this basic structure by using the concept of the Venetian blind direct converter. For that, the direct converter is tilted at a slight angle relative to the incoming beam so that the ions follow parabolic trajectories. Intermediate stages, each similar to a Venetian blind and each held at successively higher potential, are added with the slope of the individual plates adjusted for maximum transmission of the incoming ions. If an ion has insufficient energy to reach the next higher potential, it will be turned back, but with the wrong slope to get through the plates. Consequently, the ions tend to be caught on the collector that is at the highest potential that the ion can reach. Since the ions are collected on the backs of the collectors, an electron suppressor grid is located directly behind each intermediate collector stage to control secondary electrons.

Figure 8 shows a three-stage direct converter module designed for a mirror fusion reactor$^{(14)}$ for which the leakage ions have a mean energy of 178 keV and a minimum of 100 keV. With that energy distribution, the efficiency of the direct converter is 60 after allowing for the 8 of the incident power which was carried by electrons. The module is 2.6-m square and the interelectrode spacings are each 1.0 m. The 1.0-m spacings are slightly less than the maximum allowed by space charge for the given power flux and energy distribution. Since the average power flux into the direct converter is only 45 W/cm^2, the

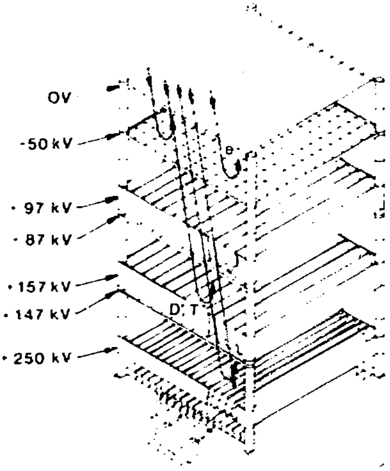

Fig. 8 A three-stage module of a Venetian blind direct converter. At 0.5 MW/m^2, the efficiency is 60%.

negative grid and the two intermediate electrodes with their suppressor grids are made of carbon fiber and are cooled by radiation. The third stage is made up of a chevron pattern to allow gas pumping without transmitting either ions or radiation. It and the walls are cooled by 1000 K helium to allow thermal recovery of the excess ion energy and the radiated heat. A water-cooled baffle, a liquid-nitrogen cooled baffle, and then the cryopump follow the third stage. The support posts are water cooled in order to keep the high-voltage insulators cool. This design can handle up to 100 W/cm^2 of incident ions, and more intermediate stages could be added. There is little to be gained by adding more than about five stages, however, because of the increased interception on early stages.

Figure 9 shows possible locations of the two direct converters discussed above on a mirror fusion reactor.$^{(14)}$ The single-stage direct converter at the bottom in the figure was kept small so that the lower half of the reactor can be lowered to allow access to the blanket. Only 20% of the power was allowed to go to the 1-stage unit, while 80% goes upward to the 3-stage converter. One of the 3-stage modules is shown being replaced.

We have experimentally tested a 2-stage version of the Venetian blind direct converter$^{(15)}$ using an ion source and later using a plasma source, at the end of a magnetic expander. The measured efficiency varied with the energy of the incident ions in good agreement with the calculated efficiency. The measured efficiency of 65% was only slightly less than the calculated 69%.

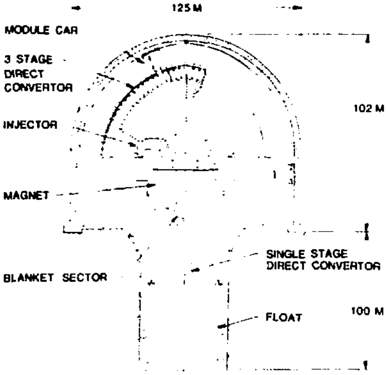

Fig. 9 Showing possible locations of the two direct converters on a mirror fusion reactor, with one module being replaced.

Slab-Geometry Plasma Direct Converter

We have studied two different direct converters of the slab-geometry type. Both depend on a magnetic expander to form the plasma stream into a slab of well directed ions. The magnetic field deviates abruptly at the entrance to the direct converter. Electrons, behaving adiabatically, are guided away, while energetic ions cross the field lines and enter the direct converter.

The simplest of the two direct converters is the space-charge dominated, 4-stage device(3) shown in Fig. 10. It is similar to the beam direct converter discussed above. The first electrode is an electron repeller to stop any electrons that are not magnetically diverted. Without the electrons to neutralize their space charge, the ions repel one another and the beam diverges. Low-energy ions diverge more rapidly than high-energy ions, thus providing some sorting of the ions according to energy. The four electrodes are each at successively higher positive potential, and the resulting electric field enhances the sorting. The voltages applied to the four collectors are adjusted to maximize the power recovered. Their values depend on the ion energy distribution.

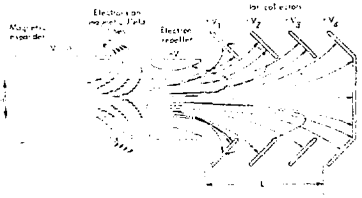

Fig. 10 Four-stage, space-charge dominated, plasma direct converter requiring slab geometry.

Optimization was done using the DART computer code to calculate ion trajectories in the applied electric field plus the self-consistent space-charge field. The efficiency depends on the energy distribution and on the amount of space charge. Lower space charge allows higher applied voltages, and hence greater recovered power. An analysis shows that for a given energy distribution, the efficiency scales by the same expression as for the beam direct converter, but with different coefficients. For a triangular-shaped distribution (to approximate the efflux from a mirror reactor) and for a 300-to-1 expansion into a thin slab, we find

$$\eta = 0.80 - 0.10\ (\omega_p \tau)^2 (d/L).$$

For example, we expect $\eta \approx 0.65$ if the linear power density around the periphery of the fan-shaped expander is 3 MW/m of 200-keV D^+ with a beam height of 0.73 m.

No allowance was made here for the power carried by the electrons, but it seems reasonable that the electron power might also be partially recovered since the electrons are magnetically deflected out of the ion beam.

The other slab-type direct converter used periodic electrostatic focusing and was proposed by Post(1) in 1969. Because of the large number of stages, this device is capable of high efficiency even with a broad energy distribution. However, its sensitivity to space charge makes this concept most useful for ion energies above 400 keV.

Immediately following the region of electron separation is the first stage of the direct converter. This stage is held at a negative potential to ensure the stopping of all electrons. In the collector region, the ion beam is electrostatically decelerated and kept from spreading out by the focusing effect of periodic electrostatic lenses. When the ion loses most of its energy, this focusing becomes unstable (overfocused), and the ion is driven into a collector cup, where it is caught on a high-voltage electrode. The dc current from these high-voltage electrodes provides an output of electrical power.

We have analyzed(16) one particular kind of deceleration and focusing field given by,

$$\frac{V}{V_0} = \frac{x}{L} + \frac{A}{2\pi} \sin\left(\frac{2\pi x}{L}\right) \cosh\left(\frac{2\pi Z}{L}\right) +$$

$$\frac{C}{2\pi} \sin\left(\frac{2\pi X}{L}\right) \sinh\left(\frac{2\pi Z}{L}\right) .$$

The cosh term gives weak focusing, whereas the sinh term gives strong focusing, which allows higher densities to be handled in the presence of space-charge blowup. Other potential functions could be investigated in order to optimize the collection process. However, we take the same form but with $A = 0$. In this case, there are three parameters (V_0, L, and C) whose values can be adjusted in searching for the most efficient collection compatible with practical dimensions and electric field values. In Fig. 11, a collector is located every $L/2$, whereas for the cosh term a collector is located every L; thus, the direct converter overall length is effectively halved by the use of strong focusing for the same number of collectors.

In Fig. 11, the curved electrodes and the plane parallel electrodes lie on equipotential surfaces as defined by the above equation. On the collection side, the electrode is made of a grid of wires to allow the ions to pass through and be caught on collectors at potentials that are higher than those of the grids.

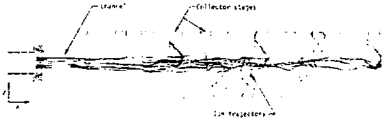

Fig. 11 A 22-stage plasma direct converter using periodic electrostatic focusing in slab geometry.

The DART computer code was used to optimize the efficiency by varying the parameters.(17) Individual trajectories were followed in ion beams with a specified energy distribution and current density. Certain qualitative features emerge from this parameter search. For C greater than optimum, efficiency declines because of particles being collected too soon (at too low a potential). On the other hand, for C less than optimum, efficiency loss is mainly caused by so-called "retrograde" particles, those particles that turn around and escape without being collected.

In this type of direct converter, space charge has a deleterious effect. The electric field due to space charge in the beam tends to defocus the beam. Increasing C partially counteracts this effect since the focusing field is proportional to C. The condition that the applied perpendicular field, $E_\perp = \partial V/\partial Z$, be stronger than the field due to space charge everywhere in the beam reduces to

$$(\omega_p \tau)^2 < C,$$

where ω_p is the ion plasma frequency and $\tau = L/\bar{v}$ as before, but now L is the spacial period in the periodic structure. Thus, as the power density is increased C must also be increased, with the penalty described above.

By optimizing the parameters in our numerical simulation studies of beams with different densities, we find$^{(16,17)}$ that the efficiency, η, varies as

$$\eta = \eta_0 - k(\omega_p\tau)^2(d/L)^2.$$

This relation was also predicted by Marcus and Watson.$^{(18)}$ When restated in terms of the linear power density. P_ℓ (watts per metre of periphery around the expander), the efficiency becomes

$$\eta = \eta_0 - k' P_\ell W^{-2},$$

where W is the mean ion energy. Beam thickness, d, is assumed to be proportional to $W^{1/2}$ here. For a flat-topped energy distribution with W = 600-keV O^+ and P_ℓ = 3 MW/m, we find numerically that $\eta = 0.65$ if $\eta_0 = 0.85$. We have included all non-space-charge-related losses in η_0.

In the design of a reactor, a compromise must be made between a large expander giving a low P_ℓ and hence a high η, and a small expander that is less expensive. Figure 12 shows a drawing of a conceptual design of a reactor$^{(19)}$ equipped with a fan-shaped expander and a periodic-focusing direct converter. The overall diameter is 275 m, and the output from the direct converter is 1 GW in this design.

The periodic focusing concept was tested in a series of scaled experiments.$^{(16,20)}$ Physical size scales with orbit size in the expander, and space-charge effects scale according to the expressions discussed above. The experimental results agree with those from numerical simulation.

Fig. 12 A mirror fusion reactor with a fan-shaped expander and periodic focusing direct converter.

Alternate Concepts for Plasma Direct Energy Conversion

Several other concepts have been proposed.

Parabolic Trajectory Concept: The idea is to form the plasma stream into a narrow, well directed slab and remove the electrons by electric and/or magnetic fields. Then the ions enter a region of uniform electric field whose direction is nearly but not quite directed against the ion flow direction. The ion will slow down and bend following a parabolic trajectory. Since different energy ions have different trajectories, the slowing down progress leads to spacial separation of the different energy groups and allows collection on many electrodes whose voltages nearly match the initial ion energy. The concept was independently conceived by a Soviet group$^{(21)}$ and by Barr.$^{(22)}$ The idea was analyzed and shown to be very efficient (98%). However, the concept has been shown$^{(22)}$ to be sensitive to space-charge effects;

hence, the concept seems uninteresting from a cost per unit of power standpoint.

E×B Concepts: The idea is to use the different $\vec{E} \times \vec{B}/B^2$ drifts of different energy particles to produce energy separation. Two different concepts were proposed,(5,23) but neither seemed very promising and were not pursued.

Cyclotron Resonance: The concept due to Forrester(24) is to form a slab beam as in the case of the 22-stage concept but have a magnetic field continue through the deceleration region. A periodic transverse electric or magnetic field is superimposed so that spatial cyclotron resonance occurs for particles as they slow down. Once near resonance, the particle energy transverse to the guide field increases rapidly with a corresponding increase in gyroradius. Collectors are arranged to catch these slowed down ions. A detailed evaluation of this concept has not been made nor has a comparison to the 22-stage periodic focusing concept been made.

Traveling Wave: An electrostatic wave is imposed with electrodes such that the amplitude increases with distance and the wave velocity slows down. The idea(25) is to trap ions in the wave and then slow these trapped ions down. The concept is space-charge limited to about the same power as the 22-stage concept and appears to be limited to about 50% efficiency. Good coupling or loading of the electrical circuit by the beam may be a problem.

Electric Field Deflection: This concept, due to Hamilton,(26) is based on the idea that an electrostatic deflection of a beam results in a larger-angle deflection for lower-energy (momentum) ions than for higher-energy ions. Once energy separation occurs, then deceleration by immersed grids can be done. This concept has not been studied sufficiently to determine its limitations, but it is expected to be about 70% efficient and to handle about as much power as the 22-stage concept.

Cost Analysis and Comparison

The choice of a particular type of plasma direct converter will depend on the economics of the particular application. For a fusion power reactor, the parameter to be minimized will probably be the total cost per unit of net electrical power output (\$/kWe). Other considerations, such as the effect of waste heat on the environment, may however, require high efficiency even if that means an increased cost. In the case of a D-T fueled mirror reactor, the output from the direct converter accounts for roughly half of the gross electrical output. Therefore, the efficiency of the direct converter has a strong effect on the net electrical output. An expensive direct converter may produce the lowest \$/kWe even if it is only slightly more efficient than any less-expensive one. This situation also exists in an advanced fuel reactor, since the direct converter will handle most of the power. On D-T fueled tokamaks and on fusion-fission hybrids, the direct converter handles only a small fraction of the total power, and its choice will be dictated by other considerations such as magnetic field geometry and pumping requirements.

Cost estimates can be scaled from the various conceptual designs that have been published on different direct converters. In comparing the costs, it must be kept in mind that the assumptions that were used in making the different cost estimates were not all the same. However, the following examples demonstrate the main differences:

Venetian Blind: In Ref. 14, a 3-stage Venetian blind direct converter for ions with 170-keV mean energy (See Figs. 8 and 9) was estimated to cost $260 per kilowatt handled. Of this, $90/kW was due to the cryopump. Since the efficiency was about 60%, the cost amounts to $430/kWe. It appears that a minimum of about $290/kWe would be obtained (but the efficiency would drop to 53%) if the number of stages were reduced to two and if the area of the cryopump was reduced. The decrease in efficiency is due mostly to the loss of ions by charge exchange because of the reduced pumping. Pumping costs dominate at lower ion energy. At 80 keV, the minimum cost would be about $460/kWe, and 15% of the ions would charge exchange before reaching the direct converter.

Periodic Electrostatic Focusing: In Ref. 19, an estimate of $280 per kilowatt handled (1976 dollars) was obtained for a 22-stage direct converter and a large fan-shaped expander (Fig. 12). That design was for ions with a mean energy of 600 keV and for a power density of 3 MW/m. Since the efficiency was about 73%, the net cost was $380/kWe. At lower energy, the cost would be much higher, varying roughly in proportion to the inverse fourth power of the energy. This is because of the planar expansion and the sensitivity of the efficiency to the power per linear metre, while the cost varies approximately as the surface area.

Space-charge Dominated Four-Stage: No cost estimate has been made for this type of direct converter, but the cost at 200 keV must be roughly the same as for the periodic focus device at 600 keV and the same power density because the expander would be nearly the same in both cases. However, at 200 keV the cost of the cryopump is significantly greater than at 600 keV. At 200 keV and at 6 MW/m the net cost would be approximately $280/kWe for a 55 efficient direct converter. The cost would increase rapidly as the energy is decreased because of the planar expansion and because of the greater pumping area that would be needed.

Technology

The design of a direct converter must offer solutions to the technological problems associated with heat removal and voltage holding in the presence of 1 MW/m^2 of incident energetic ions and electrons.

Heat Removal: Because direct converters are not 100% efficient, a significant fraction of the incident power is converted to heat. This heat must be removed to limit the temperature of the various surfaces, yet it must be removed at as high a temperature as possible to allow its use in a thermal bottoming cycle. In the case of immersed-grid direct converters, the problem is complicated by the fact that most of the structure must be kept highly transparent to the incident ions. For this reason, both conceptual designs of Venetian blind direct converters that have been done used radiatively cooled intermediate stages. The walls and the last stage receive the radiated heat and are convectively cooled with high-temperature (1000 K) helium.

The grids can be radiatively cooled if the total incident power flux is less than about 1 MW/m^2. At higher power flux, the grids become hot enough to emit thermionic electrons that seriously degrade the efficiency. Up to about 5 MW/m^2, convectively cooled tubes can be used if the loss due to interception on the tubes and the manifolds can be tolerated.

Convective cooling at higher temperature and hence high pressure is complicated by the different high voltages. Either heat exchangers designed to stand off high voltage, or insulators designed to confine high pressures at high temperature, may be used.

Choice of Materials: Those structures that are cooled by radiation must be made of conducting materials that can withstand high temperatures (up to 1800 K). The choices are the refractory metals or carbon. Either woven or monolithic structures made of carbon have interesting possibilities. One objection to the use of carbon is that the sputtered carbon could cause the embrittlement of nearby hot, refractory metals.

Convectively cooled grids require materials that have high tensile strength to withstand the hoop stress and the thermal stress in small, thin-walled tubes. The alloy Ta-10 W was chosen as a superior material under similar conditions in the first wall of the Fusion Engineering Research Facility (FERF) design.(27)

Electrode Damage and Voltage Holding: Electrodes will be bombarded by ions causing both short-term and long-term problems. The short-term problem is expected to be a degradation of voltage holding due to roughening of the surface due to blistering produced primarily by He^{++} bombardment. This problem is discussed in Ref. 28. For typical power levels (~100 W/cm^2), the dose of 10^{18} cm^{-2} is reached in 8 hours. Voltage-holding tests on tungsten and niobium electrodes that were blistered with a 300-keV He$^+$ beam showed a significant voltage-holding degradation, but proper conditioning such as high-temperature operation allowed voltage to be held as high as with unbombarded electrodes.(29) Sputtering may also lead to roughening of the surfaces, but again at elevated temperatures the voltage-holding properties may not be degraded.

The long-term damage problem will be the erosion of electrodes due to sputtering and build up of sputtered material. This process will set replacement times for electrodes and will be most severe for the thin radiation-cooled grids of the immersed-grid concept. Present estimates give an erosion rate of 0.02 mm/yr for tungsten wires and a considerably faster rate for carbon fibers.

Chemical Compatibility: One material under consideration for electrode material is graphite due to its good high-temperature properties and low cost. One potential problem is chemical sputtering due to formation of methane. Another potential problem is the tritium holdup that is not possible to predict because of the lack of experimental data.

Another problem(30) is the chemical reaction with metals at high temperatures. For example, one concept called for graphite platelets strung on tensioned tungsten wires. The tungsten wires will quickly form a carbide layer which is so brittle as to be unusable. Present concepts that use graphite electrodes use metals only at relatively low temperatures (~1000 K).

Insulators: Insulators used in direct converters will have to be very well designed to stand up to the harsh environment. γ radiation will have to be kept down to a certain level to prevent the insulator from becoming a semiconductor with a catastrophic breakdown. Replacement will be set by neutron-induced damage and possibly surface deteriortion due to neutron and charged particle sputtering. The insulators will have to be well shielded from sputtering. Special cooling will be required to prevent the insulator properties from being seriously degraded by high temperatures. The whole question of insulator requirements and an assessment of the technology of insulators for mirror fusion reactors has recently been reviewed.(31)

Application of Plasma Direct Converters to Toroidal Reactors

A number of problems arise when applying plasma direct converters to toroidal reactors. A divertor must be designed which will lead or guide plasma leakage ions and electrons out of the toroidal confinement region to the magnetic expander before cross-field diffusion to the walls can cause plasma cooling due to wall reflux. In the reversed-field mirror reactor, an axial diverter is part of the equilibrium configuration itself and is not expected to be a problem. In the case of the tokamak, poloidal and toroidal (bundle) diverters are being investigated, and difficult technological problems are in evidence. Once the plasma is diverted and guided past the toroidal coils, magnetic expansion is not difficult.

The next problem appears to be the conflict between the direct converter operating efficiently at higher energies (50 keV) and the plasma wanting to operate at lower energies (50 keV) due to power-density related costs. The reason the direct converter wants to operate at relatively high energies is that the ions can be lost due to charge exchange in the flight path from the divertor to the collector, i.e., in the magnetic expander. The probability of charge exchange drops rapidly as the energy is increased. For example, we find the direct converter efficiency is halved if the mean energy drops from above 100 keV to 50 keV in one particular case.(17) We find a very encouraging effect that tends to alleviate this problem: the edge (separatrix) of the toroidal plasma is at a fairly high positive potential due to ambipolar plasma flow to the grounded wall (first direct converter electrode). The plasma ions have a mean energy of order $3/2\ kT_i$ when they leave the toroidal region, but gain an energy $e\phi$ where ϕ is some as yet undetermined multiple of T_e. A deleterious effect is that the temperature of the leaking ions will tend to be lower than the bulk of the contained ions because of a number of effects such as radiation cooling of the outer layers, and cooling due to wall reflux.

The technological and economic aspects of the converter design are not expected to be different for toroidal application than for mirror application except as noted above.

CONCLUSION

A number of different concepts for direct energy converting plasma end losses and ion beams in neutral-beam injectors have been proposed and experimentally verified. Theoretical analysis aided by computer simulation has resulted in design scaling laws that have been tested at relatively low voltages and low powers; now we are in the process of going from the scientific feasibility stage to the development stage. We are preparing tests at over 100 keV and powers exceeding 1 MW (0.5 MW/m^2 for the plasma direct converter). Past accomplishments include a 22-stage plasma converter tested at 91% ± 2% efficiency with a steady plasma, a 2-stage Venetian blind plasma converter at 65% ± 2% with a plasma source, and a 15-keV, 2-kW ion beam at 70 ± 2% efficiency. We are preparing a 120-keV 1-MW ion beam recovery test and a 100-keV, 0.5-MW/m^2 Venetian blind plasma converter test. For the future, we plan to integrate the beam direct converter into the neutral-beam injector for the TFTR.

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