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A 120-keV BEAM DIRECT CONVERSION SYSTEM FOR TFTR INJECTORS

G. W. Hamilton

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MASTER

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A 120-keV BEAM DIRECT CONVERSION SYSTEM FOR TFTR INJECTORS

Abstract

Several practical motivations exist for the development of beam direct conversion systems that are compatible with the injection systems of large experiments such as the Tokamak Fusion Test Reactor (TFTR). We present a preliminary design in which we analyze the most acute problems involved in scaling up existing designs and apparatus to fulfill TFTR requirements. Some of the questions addressed are the requirements for electron suppression, gas pumping, compactness, and power densities. A new idea is presented that allows for the handling of higher beam power. The gross savings in the capital cost of injector power supplies for the TFTR will be about \$7.2 million, but the net savings will be somewhat less than this. This preliminary design has not yet revealed fundamental limitations with respect to the development of beam energy-recovery systems operating at high levels of current, voltage, and power densities.

Introduction

Several practical motivations exist for the development of beam direct conversion systems¹ that are compatible with the high-energy injection systems of large experiments such as the Tokamak Fusion Test Reactor (TFTR):²

- Savings in capital cost. Designs of large experiments such as TFTR and MX³ are normally limited by the capital cost, of which a significant fraction is the cost of power supplies for the high-voltage injector. A substantial saving in capital cost is possible if the power can be reduced by 30 to 70% by recovering the energy of the residual charged beam rather than deflecting it to a beam dump.

- Simplification. The high-power beam dump may be simplified if the charged beam is decelerated in the recovery system before it is collected.

- Size reduction. It may be possible to shorten the overall length of the injection system by eliminating the large sweep magnet and replacing the high-power, charged-beam dump with the direct energy converter.

For these reasons, we are designing a beam direct converter system suitable for the TFTR injection system. This development is the logical step after the 120-keV experiments we are now beginning in the LBL neutral-beam test stand.^{4,5}

Ion Source Designs

Ion sources for the TFTR will be developed at both the Lawrence Livermore and Lawrence Berkeley Laboratories (LLL and LBL) and at the Oak Ridge National Laboratory (ORNL). In each instance, the ion sources will be optimized to emit a 50- to 80-A total beam (mostly D_1^+) at energies of 120 keV or higher. The efficiency of neutralization by electron capture will be a maximum of 44% for 120-keV D_1^+ or 14% for 120-keV H_1^+ . Because of the higher neutralization fraction of the slower particles and because the beams will be optimized for D_1^+ , the half- and third-energy fractions of the residual, charged beams will be only 10 to 20%.

The LBL/LLL TFTR ion source will consist of a rectangular emission area of maximum size 10×40 cm from which ions will be extracted and accelerated in a slab-shaped beam; the ions will then be partially converted to neutral atoms by electron capture in a neutralizing duct up to 2 m long. If the beam density at the plasma source is 250 mA/cm^2 , the grid transparency is 60%, and the neutralization fraction is 40%, the density of the residual charged beam will be approximately 90 mA/cm^2 . These source characteristics represent a two-fold change in our previous design parameters for direct conversion systems: the larger charged-beam current per unit width (0.9 A/cm or 11 MW/m), and the higher beam space-charge potential in the regions not neutralized by electrons.

The ORNL TFTR ion beams differ from the LBL/LLL beams because of their circular shape. A beam of about 50 A will be produced in a 25-cm-diam cross section. This implies an average residual charged-beam current density of 61 mA/cm^2 , again assuming 40% neutralization. For purposes of direct conversion, the important difference is in the shape of the beam cross section.

Direct Conversion System

A side view of an in-line, beam direct converter^{1,4} is shown in Fig. 1. To be compatible with TFTR injectors, the neutralizing cell must be at ground potential; the collection electrode must be at positive high voltage $+V^+$ (about +100 to +110 kV); and the electrons produced in the neutralizing cell must be repelled by a negative high voltage $-V^-$ applied by negative electrodes before and after the positive collection electrode.

The most acute problem arising from the requirements presented by the TFTR ion sources is the suppression of electrons produced within the neutralizing chamber so that they are not collected at positive high voltage by the collection electrode. The potential profiles applied by these collection electrodes, including the effect of beam space charge, are shown in Fig. 2 for the LBL/LLL design. Figure 2(a) shows the longitudinal profile $\phi(z)$; Fig. 2(b) shows the traverse profile $\phi(x)$ near the first negative electrode, at the position indicated in Fig. 1 as Section A-A. Figure 2(b) shows a slab-shaped beam of thickness $a = 10$ cm passing between two electrodes to which the negative high voltage V^- is being applied. To avoid bombardment of the negative electrodes by the beam, the spacing b between the negative electrodes must be larger than thickness a .

Fig. 1. Space-charge-controlled direct converter. The dimensions a , b , and L are defined in the text. Section A-A indicates the location of the transverse potential profile $\phi(x)$ shown by Fig. 2(b). In this version, the neutralizing cell is at ground potential, and the potentials of the positive and negative electrodes are $+V^+$ and $-V^-$, respectively.

If the beam dimensions are assumed infinite in the y and z directions, and if the beam density j is uniform, the potential profile can be computed from Gauss's Law:

$$d^2\phi/dx^2 = -j/\epsilon_0 v. \quad (1)$$

For a boundary condition $\phi = -V^-$ at $x = \pm b/2$, the potential profile within the beam ($|x| \leq a/2$) is

$$\phi(x) = ja^2/8\epsilon_0 v (2b/a - 1 - 4x^2/a^2) - V^-.$$

Outside the beam ($a/2 \leq |x| \leq b/2$),

$$\phi(x) = ja/4\epsilon_0 v (b - 2x) - V^-. \quad (2)$$

Suppression of electrons originating at the potential $\phi = 0$ requires that $\phi(x) < 0$ for all values of x. That is, for a slab-shaped beam,

$$V^- > ja^2/8\epsilon_0 v (2b/a - 1). \quad (3)$$

> 75 kV for LBL TFTR conditions.

Fig. 2. Longitudinal and transverse potential profiles in a beam direct energy converter. (a) Longitudinal potential profile $\phi(x)$, including the negative potentials required to prevent electrons from being collected at positive high voltage. (b) Transverse potential profile $\phi(x)$ at Section A-A (see Fig. 1), where $\phi = -V^-$ at $x = \pm b/2$. The effect of beam space charge reduces the negative potential barrier as shown.

For a cylindrical beam of equal current, electron suppression is an even more severe problem. If the beam radius is a and the electrode radius is b , the negative voltage required to suppress the electrons for a circular beam is

$$V^- > j a^2 / 4 \epsilon_0 v (1 + 2 \ln b/a). \quad (4)$$

For ORNL TFTR conditions,

$$V^- > 150 \text{ kV.}$$

Because of voltage-holding problems and power consumption by the negative electrode, such large negative voltages are not desirable. The negative electrode draws current via two agencies: the collection of positive ions produced in the background gas; and the secondary electrons emitted by the interception of some fraction of the half-energy beam component. We must therefore consider several means of reducing the negative voltage required to suppress the electrons produced within the neutralizing chamber:

- A portion of the power consumption is proportional to the background gas pressure; therefore, if the gas pressure is sufficiently low, this portion of the power consumption will be negligible.

- The negative voltage may be reduced by reducing the product $j a^2$ (if this reduction is compatible with TFTR specifications).

- The negative voltage may be reduced by substituting a long, transparent grid for the solid electrode shown in Fig. 1.⁶

- Bombardment of the negative electrodes by the ion beam must be avoided. The suppressor electrode must be shaped to avoid interception of a large fraction of the half-energy component. The electrode shape should be designed so that the secondary electrons will be collected at ground potential and not at positive high voltage. The ion source could be designed to leave shadows in the beam where nonintercepting electrodes could be located.

In the following sections of this paper, we shall discuss each of these possibilities.

Gas Pressure Requirements for Efficient Direct Conversion

The most critical gas-pressure requirement placed on a direct conversion system is imposed by the power load resulting from the acceleration and collection of the slow ions and electrons produced by ionization and charge exchange of the background gas. The resulting emission of secondary electrons at negative high voltage must also be considered. Other gas-pressure considerations such as voltage-holding requirements are less critical than the power load.

The power load due to the above effects must be negligible compared to the power of the charged beam, $I^+ V^+$, where the energy of the charged beam is almost equal to the positive electrode voltage V^+ . If an ion-electron pair produced by ionization of a gas molecule is accelerated to a total energy of $(V^+ + V^-)$, the power load will be

$$\left[I^+ n_{\text{gas}} L (\sigma_{10} + \sigma_{\text{ion},+}) + I^0 n_{\text{gas}} L \sigma_{\text{ion},0} \right] (V^+ + V^-)(1 + \epsilon) \ll I^+ V^+, \quad (5)$$

where n_{gas} is the background gas density, and L is the effective length of the direct conversion system (see Fig. 1). The cross sections for slow-ion production by charge exchange and by ionization by fast ions and fast neutrals are, respectively, σ_{01} , $\sigma_{\text{ion},+}$, and $\sigma_{\text{ion},0}$. The coefficient for secondary electron emission ϵ may be about 1.

The inequality (5) is slightly conservative with respect to the power load due to charge exchange because no free electrons are involved in charge exchange.

For an equilibrium beam emerging from the neutralizer, $I^0 \sigma_{01} = I^+ \sigma_{10}$, where σ_{10} is the cross section for re-ionization of fast neutrals. Therefore, I^+ and I^0 cancel from the inequality. The gas pressure can be computed as follows:

$$n_{\text{gas}} L \left(\sigma_{10} + \sigma_{\text{ion},+} + \frac{\sigma_{10}}{\sigma_{01}} \sigma_{\text{ion},0} \right) \ll \frac{V^+}{(V^+ + V^-)(1 + \epsilon)}. \quad (6)$$

The relevant cross sections⁷ for 120-keV D⁺ ions are the following:

$$\begin{aligned}\sigma_{10} &= 0.9 \times 10^{-16} \text{ cm}^2 \\ \sigma_{01} &= 1.5 \times 10^{-16} \text{ cm}^2 \\ \sigma_{\text{ion},+} &= 2.6 \times 10^{-16} \text{ cm}^2 \\ \sigma_{\text{ion},0} &= 0.4 \times 10^{-16} \text{ cm}^2\end{aligned}$$

Thus,

$$\left(\sigma_{10} + \sigma_{\text{ion},+} + \frac{\sigma_{10}}{\sigma_{01}} \sigma_{\text{ion},0} \right) = 3.74 \times 10^{-16} \text{ cm}^2.$$

If $V^+ = 120$ kV, V^- is a maximum of 100 kV, and the coefficient ϵ is the maximum of 1.0, the right side of inequality (6) has a minimum value of 0.273. Therefore, $n_{\text{gas}} L \ll 7.3 \times 10^{14}$ molecules/cm². If the effective length of the direct conversion system is about 100 cm, the gas density is $n_{\text{gas}} \ll 7.3 \times 10^{12}$ molecules/cm³, or $p \ll 2 \times 10^{-4}$ Torr.

This density is satisfied by the gas pressures computed for either the TFTR beam line (about 4×10^{-6} Torr)² or the system on the LBL high-voltage test stand⁵ (a maximum of 3.5×10^{-5} Torr). In both designs, a differential pumping stage will be installed between the high-pressure neutralizing cell and the low-pressure, direct conversion system. If the systems operate as designed, it will be possible to use negative electrode voltages as large as -100 kV without excessive power loss and without voltage breakdown. This statement implies the assumption that the half-energy beam component will be collected separately and that it will not cause an additional power loss.

Using the appropriate cross sections, we have experimentally verified this computation using a 12-keV H⁺ beam. In the test, we increased the background gas pressure up to 5×10^{-4} Torr while measuring the power loading of the negative electrodes. The increase in power load was consistent with inequality (5).

Methods for Reducing the Voltage Required for Electron Suppression

Although it may be possible to apply a negative voltage of 75 kV or more to suppress electrons, we prefer to reduce this voltage. This can be done by reducing the beam thickness, by using a grid to suppress only those

electrons in an outer sheath, or by subdividing the beam while protecting the negative electrode from being bombarded by the beam.

REDUCTION OF PRODUCT ja^2

Inequality (3) shows that the V^- can be reduced by reducing the value of either j or a . Because the voltage is proportional to ja^2 , it is more profitable to reduce a than to reduce j .

In a slab-shaped beam system, the most straightforward solution is to restrict the beam thickness a to a value compatible with energy recovery and to increase the length of the source module to provide sufficient extraction area. It has been proposed that the thickness of the LBL/LLL beam be reduced from 10 cm to 8 cm for a different reason. This would reduce the V^- requirement from 75 kV to 48 kV, assuming the ratio b/a is maintained at 1.5.

Another way to reduce the beam thickness is to subdivide the beam by immersing a nonintercepting negative electrode within the beam. This option is shown by Fig. 3, which also shows the shielding required to protect the negative electrode from beam bombardment. By subdivision, the beam thickness a can be reduced by a factor of 2, thereby reducing the required V^- from 75 kV to 19 kV if the ratio b/a is not changed. This appears to be practical if the negative electrode can be shielded from beam bombardment (see next section).

Fig. 3. Subdivision of a beam to reduce the thickness a (not to scale). (a) End view of a 10-40-cm emission area, subdivided to reduce the effective beam thickness a . (b) Side view of a subdivided beam, showing partitions in (1) the plasma source, (2) the neutralizing duct, (3) the ground-potential electrode, and (4) the negative electrode. High-power beam bombardment is avoided by this series of partitions. Also shown are the plenum (5) for differential pumping and the collector electrode (6).

USE OF ELECTRON SUPPRESSION GRID

Raimbault⁶ has computed that the negative voltage requirement can be greatly reduced by a long, cylindrical suppressor grid designed to suppress the electrons only in an outer boundary layer. By doing this, the beam can be made to expand and pass through the grid layer by layer as it propagates within the long grid. In principle, this system will work for any beam current or beam dimensions if the suppressor grid is long enough. For a cylindrical system similar to that of the ORNL TFTR system, Raimbault has computed that the electrons will be suppressed by a 1-m-long grid at a potential of only -16 kV. However, power loading on the grid must be kept below the level (100 W/cm^2 for steady state) at which thermionic emission begins. Although this may be a severe limitation, the system deserves further study for TFTR application.

PROTECTION OF NEGATIVE ELECTRODE FROM BEAM BOMBARDMENT

Subdivision of the beam into thinner sections requires a negative electrode immersed in the beam. To avoid emission of secondary and/or thermionic electrons at negative high voltage, it is essential that the negative electrode be protected from beam bombardment. It is possible to install a series of partitions to ensure that the immersed negative electrode is shielded from the beam. Figure 3(a) shows how the ion beam may be so partitioned to shield the immersed negative electrode.

Bombardment of surfaces at ground potential or above may be tolerable because the resulting secondary electrons are not serious unless they are accelerated. However, it is not possible to install a shield directly in the high-power beam, which has an average power density (18 kW/cm^2) that exceeds the heat-transfer limitations for a water-cooled surface. To shield the negative electrode, the beam must be partitioned at the source and a series of partitions must be installed in the neutralizer and pumping plenum.

Figure 3 shows how the extraction grid can be partitioned within the plasma source before the beam is extracted. The 1/e beam divergence in the direction parallel to the slit grids is only $\pm 0.5^\circ$ in the LBL 20-keV sources; therefore, we expect the divergence to be only $\pm 0.2^\circ$ when such a beam is accelerated to 120 keV. The beam will thus spread out by only about $\pm 3.5 \text{ mm}$ as it travels 1 m through the neutralizer. The density of the beam power

deposited on the walls of the partition will be small because of the grazing incidence. The power density deposited on the side wall will be approximately equal to the beam power density (18 kW/cm^2) multiplied by the tangent of 0.2° (i.e., 63 W/cm^2).

Because the partition in the neutralizing duct will also impede the flow of gas through the duct, it will be possible to increase the average gas pressure in the duct and to shorten the neutralizer.

Preliminary Layout for a Beam Direct Converter for TFTR Injectors

Figures 4, 5, and 6 show a preliminary layout for a beam direct conversion system compatible with the LBL/LLI TFTR injectors. Figure 4 shows

Fig. 4. Trajectories (a) and potential contours (b) for a subdivided energy recovery system consistent with TFTR requirements, as computed by the DART code.

Fig. 5. A layout of the subdivided system shown schematically by Fig. 3, drawn to scale to fit the dimensions of the TFTR beam lines and consistent with the trajectory computation of Fig. 4. This system occupies the space intended for a large sweep magnet and charged beam dump, both of which will be replaced by the direct conversion system.

the trajectories and potential contours computed by the DART code⁸ for a system in which the slab-shaped beam is subdivided by an immersed negative electrode at a voltage of -25 kV. The system collects 95% of the full-energy beam at a potential of +105 kV, which implies a power efficiency of 83% for recovery of this component. Raising the collector voltage does not improve the efficiency because the immersed negative electrode perturbs the beam

Fig. 6. Two examples of circuits to recirculate the recovered energy to supplement the acceleration power supply of the ion source. In both designs, the total power supply requirement is 4.15 MW, assuming 40% neutralization efficiency for 120-kV D^+ . Compared to the total beam requirement of 60 A at 120 kV, the gross saving in acceleration power supplies is 3.05 MW (assuming 70% overall efficiency of beam direct conversion).

optics. The net efficiency is actually somewhat lower than 83% because of the power consumed by electrons, half-energy ions, and the negative electrodes.

Figure 5 shows how such a system could be installed in the beam line now being designed for TFTR injectors.² The direct converter system would occupy the space now required for the large sweep magnet and the charged-beam dumps. At this position, after one stage of differential pumping, the gas pressure is predicted to be only 4×10^{-6} Torr. The direct converter systems are sufficiently compact that adjacent beams can be installed at 35-cm intervals, a spacing that is consistent with the existing TFTR design.

Figure 6 shows two examples of power supply systems that could feed back the recovered energy to supplement the high-voltage power supplies for the ion source. These power supplies, which may be the most expensive components of the injection system, could thereby be upgraded to extract a total beam perhaps twice as large as the current capacity of the rectifiers without direct conversion. Beam-energy recovery could therefore be used either to economize on the capital cost of power supplies or to increase the total beam using existing power supplies.

If we assume that the overall efficiency of charged beam energy recovery is 70% and the neutralization efficiency is 40%, the total power supply requirement in each of the examples of Fig. 6 is 4.15 MW. Because of its higher neutralization efficiency, the half-energy charged beam will be not more than 10 to 20%. This effect is included in the 70% overall efficiency of direct conversion, and is not otherwise indicated in the simplified diagrams of Fig. 6. In comparison with the total beam power of 7.2 MW, these examples represent a saving of 3.05 MW for each injector, each of which supplies 2.9 MW of neutral-beam power.

Twelve such injectors will be required to furnish 34 MW of neutral-beam power for the TFTR. If the capital cost of power supplies is \$200/kW, the savings provided by the use of beam direct conversion will be \$7.2 million. The savings will be somewhat reduced by the cost of installing the recovery systems and will be increased by eliminating the large sweep magnets and beam dumps for the charged beams.

Conclusions

We find that the requirements for direct conversion of the residual charged beam of injectors programmed for large experiments such as TFTR represent an advance over present designs and that these requirements can probably be fulfilled by any of several techniques. One solution is to reduce the beam thickness from 10 cm to 8 cm or less. Another possibility is to employ the new idea presented in this paper, namely, the addition of an extra negative electrode to suppress electrons. Our preliminary designs indicate feasibility with respect to the increased beam densities and beam areas projected for TFTR. Some of the questions addressed are the requirements for electron suppression, gas pumping, compactness, and power densities. The motivations for development of beam direct conversion systems for such applications are the economies in capital cost, disposal of the charged beam at a very high power density, and the savings in space by elimination of the large sweep magnets and charged-beam dumps.

This preliminary design has not yet revealed fundamental limitations with respect to development of conversion systems operating at even higher levels of current, voltage, and power densities.

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