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PARASITIC COMPONENTS FROM CHARGE TRANSFER IN NEUTRAL BEAMS FOR FUSION

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ABSTRACT

Charge exchange within accelerating grids in neutral beam systems produces parasitic beam components which degrade the performance of the systems. These components also change the plasma confinement properties at the target. This note discusses parasitic beams produced in three types of grid systems: (1) TFTR/MFTF sources, (2) accel-decel grids for low energy beams, and (3) the JSC negative ion system.

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I. Introduction

In analyzing various MFE neutral beam systems, it is important to take account of charge transfer within the ion accelerating structure, because this process may degrade the beam system performance in several ways. Previous studies have shown that some of the low-energy ions formed within the grids contribute to heating problems there.¹ The present report concentrates on the emerging low energy neutral beam produced by charge transfer. This beam diverges more than the main beam and part of it sprays the duct leading to the plasma chamber. The rest reaches the target and affects the plasma confinement. In the case of MFTF, the parasitic neutral beam (peaking around 10 keV) may improve the confinement (by producing a more stable density profile)² even though it allows some of the high-energy mirror-confined particles to be lost by charge exchange. In TFTR, however, the parasitic beam appears to be entirely detrimental, for reasons cited by Jassby in discussing the effect of half- and third-energy components in the injected beam.³ These latter components will become less important with improved species mixes and will be eliminated in systems using D^- , but the parasitic beams discussed here will need to be taken into account, both in the beam line and at the plasma target.

The charge transfer problem occurs when the accelerator is adjacent to the ion source and excess D_2 gas from the source flows through the grid structure. This gas converts part of the ion beam to neutral atoms. Both the gas density and the charge-changing cross section are greatest in the low-energy region of the accelerator, so that most of the parasitic beam is concentrated in the region below 20 keV or so.

Section II treats positive ion systems, in particular the type being developed at LBL for MFTF and TFTR.⁴ The calculations show that for moderately large gas flow (in the range favored by some users) the parasitic beam fraction may be 10% or more. However, this beam is rather divergent and its flux density at the target is shown to be relatively low.

Section III discusses the accel-decel type of grid system used for low-energy beams. In this case the parasitic beam has higher energy than the main beam. For example, in the 1 keV beam produced at LLL for

injection into a cesium cell,⁵ the parasitic beam peaks at around 10.5 keV. Thus, although its current is only 5% to 10% of the main current, the total powers are comparable. Conversely to the case in Sec. II, it is the parasitic beam which is better focussed, so well-focussed in fact that it carries almost all of the power density on axis. The energy spectrum of this beam as calculated in Sec. III agrees well with observations.

Section IV discusses the problem of charge loss in direct-production negative ion acceleration, for final beam energies up to 1000 keV. In the alternative cesium cell approach being developed at LLL,⁶ excess gas may be pumped away before reaching the main accelerator, and very little stripping occurs there. On the other hand, with direct-production negative ion systems the problem is similar to the one discussed in Sec. II. For the proposed jet surface conversion system,⁷ with reasonable gas efficiency and good pumping around the exit grids, the parasitic stripping fraction can be kept below 6%. For the ion magnetron system at BNL,⁸ with low gas utilization efficiency, it appears necessary to provide a pumping space before final acceleration.

II. MFTF/TFTR Grid Systems

MFTF, TFTR and Doublet III will use similar grid systems, suitably scaled for different beam energies, and they will all be treated together in this section, using Cooper's scaling principle.⁹ They will all be simply referred to by the prototypical name "TFTR grids" (Fig. 1a).

Grid Gas Density

The system of rectangles and trapezoids shown in Fig. 1b represents the TFTR grid system in this molecular flow problem. The total gas impedance is

$$Z = \frac{n_1 - n_0}{dN/dt} ; \quad (1)$$

n_1 and n_0 are the input and output densities, and dN/dt is the flow rate of molecules. Dushman's method calculates and adds up the partial Z 's for each section, along with appropriate entrance impedances.^{10,11}

Dushman originally introduced the entrance impedance Z_0 as equivalent to Z for a thin orifice, with the well-known value $4/v_a A$; v_a is the average molecular thermal velocity, and A is the orifice area. Improved calculations by Clausen¹² and DeMarcus¹³ give corrections of a few percent, but a more important correction is needed here:^{14,15} Dushman's Z_0 applies to a distribution function which is isotropic in semi-infinite velocity space. This is roughly valid for the first grid but invalid for the others because of shadowing. Therefore, in the present paper, a correction factor ϵ is introduced which is less than unity except for the first grid:

$$Z_0 = \frac{\epsilon}{v_a} \frac{4}{A} \quad (2)$$

The straight sections have impedances¹¹

$$Z_s = \frac{1}{v_a} \frac{3}{2A} \frac{a}{b} \quad (3)$$

(a)

(b)

Fig. 1. Standard LBL grid configuration for TFTR, MFTF, and Doublet III. (a) WOLF computation, showing self-consistent equipotentials and beam trajectory, from Ref. 4. (b) Grid representation for gas impedance calculation.

where b is the grid opening (assumed small compared to transverse length), and z is measured in the direction of gas flow.

Finally, the tapered section has impedance¹¹

$$\begin{aligned} Z_t &= \frac{1}{v_a} \frac{3}{4} \int_0^l \frac{\text{Perimeter}}{A^2} dz \\ &= \frac{1}{v_a} \frac{3}{2A_0} \frac{l}{b_1} \end{aligned} \quad (4)$$

where the subscripts 0 and 1 refer to the two ends of the tapered section; note that $A_0 b_1 = \bar{A} \bar{b}$ using geometric mean values.

Before adding up to find the total impedance, a judicious choice is needed for the factors ϵ [Eq. (2)]. D. S. Prono, treating a similar problem,¹⁶ used the full Z_0 for each grid, and obtained a very large total Z which disagreed with experiment.

Clearly, in the limit of very short gaps between channels of equal width, only the first entrance impedance would have any meaning. In the present paper, one additional Z_0 is distributed among the remaining grids, i.e., the last three ϵ 's are assumed to have average values of 1/3 for TFTR.

The density profile through the grid system varies in a complicated way. Reference 16 used the easy-to-integrate step function approximation. A linear model is probably more realistic and is adopted here. Then Eqs. (1 - 4) give for the geometry of Fig. 1b

$$n(z) = n_0 + \left(1 - \frac{z}{L}\right) \frac{1}{v_a} \frac{3}{2A} \left(\frac{8}{3} + 0.75 + 1.0\right) \frac{dN}{dt} \quad (5)$$

The first entrance impedance is not included because it primarily affects the pressure in the arc chamber. dN/dt depends on the efficiency η for converting neutral gas molecules into pairs of D^+ ions. (Diatomic and triatomic ions are also emitted. Their fractions were small in the

original LBL sources¹⁷ and should be small again when the TFTR source is fully developed. These ions are simply averaged in with the main D^+ component in the present treatment.) Excess gas flowing out through the grids is assumed mainly molecular(cf. Sec. III). Then

$$\frac{1}{A} \frac{dN}{dt} = 6.24 \times 10^{18} \frac{J}{2} \frac{1-\eta}{n}$$

and, using the D_2 temperature measured in the arc chamber,¹⁸ roughly 1000°K,

$$n(x) = n_0 + 9 \times 10^{13} J \frac{1-\eta}{n} \left(1 - \frac{x}{L}\right) \quad (6)$$

The entrance density depends on grid shape but not directly on grid size; the ion current density J , of course, scales with grid size or beam energy. Cooper's scaling⁹ gives $J = 3.4 W^{-1/2}$, with final beam energy W in keV.

Although the potential variation along the beam axis is usually approximated by the plane diode $x^{4/3}$ law, a simple linear model is used here (having accuracy compatible with the above density model). Then

$$n(V) = n_0 + 3 \times 10^{14} W^{-1/2} \frac{1-\eta}{n} \left(1 - \frac{V}{W}\right) \quad (7)$$

Scaled down to 40 keV, this predicts $n(0) - n_0 = 2.7 \times 10^{14} \text{ cm}^{-3}$ at $\eta = 0.15$, or $4.8 \times 10^{13} \text{ cm}^{-3}$ at $\eta = 0.5$. These values are consistent with experience on the comparable LBL 40 keV grid structure.¹⁹

Charge-Exchange Cross Section

Berkner, Pyle and Stearns²⁰ and Stearns²¹ have summarized the data (up to 1975) for deuterium ion charge-changing cross sections in D_2 gas. For the case of D^+ electron capture, σ_{+0} , the following model fits all the data points in Ref. 20 (10 keV-1000 keV) within experimental accuracy:

$$\begin{aligned}\sigma_{+0} &= 1.4 \times 10^{-16} V, & 0 < V < 6.0 \\ &8.3 \times 10^{-16}, & 6.0 < V < 35.7 \\ &1.08 \times 10^{-14} e^{-.429\sqrt{V}}, & 35.7 < V < 1000\end{aligned}\quad (8)$$

Values below 10 keV are a reasonably good fit to data of Ref. 21 . (Another low-energy model is presented in Sec. III). Equation (8) in the range between 200 and 1000 keV is not needed here but may be useful elsewhere.

When the beam energy reaches 120 keV, as in TFTR, the stripping cross section σ_{0+} competes with σ_{+0} . But Fig. 2 (next paragraph) shows most of the charge conversion occurring below 40 keV, where σ_{0+} may be safely neglected.

Grid-Neutralized Beam Spectrum

Figure 2 shows the energy spectrum of the charge-exchanged beam current,

$$\frac{dF}{dV} = \frac{n\sigma}{dV/dx} \quad (9)$$

obtained from Eqs. (7) and (8). For the 200 keV case, the grid-neutralized beam peaks at about 11.5 keV (about 6% of full energy); with a 40 keV source on this model the beam peaks at about 20% of full energy.

The high energy part of the 200 keV spectrum would be somewhat smaller than shown if σ_{0+} were included, but the integrated beam loss would be essentially unaffected.

Integrated Beam Loss

The total fraction of beam current lost to charge-exchange within the grids, for final energy W , is (with the above linear potential model)

$$F(W) = \int_0^L n\sigma_{+0} dx = \frac{L}{W} \int_0^W n(V)\sigma_{+0}(V) dV \quad (10)$$

Fig. 2 Energy spectrum of beam flux neutralized within the grids for two different final energies. Scaled for the high gas-flow case, $\eta = 0.15$; see p. 10 for scaling to other cases.

assuming $n_0 L \ll 1$, as in the present applications. In systems with pumping space between grids and neutralizer, n_0 in Eq. (7) can be neglected, and integration gives

$$F(W) = \frac{1-n}{n} \frac{0.26}{a^3} \left[\left(2a^2 + 6a + 6 \right) e^{-a} + a^2 \left(\frac{d^2}{2} - d - \frac{f^2}{4} + 1 \right) e^{-d} - \left(\frac{d^4}{4} - \frac{f^4}{12} + d^3 + 3d^2 + 6d + 6 e^{-d} \right) \right]$$

for $W > 35.7$ keV. Including n_0 would give an expression of similar form but would not change the result very much. The function $a(W)$ and the constants d and f depend on the numerical factors appearing in the models (7) and (8): $a \equiv .429 \sqrt{W}$, $d \equiv .429 \sqrt{35.7}$ and $f \equiv .429 \sqrt{6.0}$. Evaluating the constant factors for this case gives

$$F(W) = \frac{1-n}{n} \frac{0.26}{a^3} \left[\left(2a^2 + 6a + 6 \right) e^{-a} + 0.51 a^2 - 5.3 \right] \quad (11)$$

The length L in Eq. (10) has been replaced by $W/60$, according to the Cooper scaling.⁹ $F(W)$ has a maximum value at $W = 125$ keV, and scales as shown with the gas utilization efficiency n . The LBL sources have been run with a wide range of gas flow rates depending on the needs of various users,^{22,23,24} with the corresponding gas utilization efficiencies ranging from 15% to 45%. High flow rates have been used to compensate for short neutralizers²³ and during developmental operation.²⁴ Figure 3a shows $F(W)$ for a high-flow case where $n = 15\%$. Figure 3 is easily scaled for other efficiencies: e.g., divide by 2 for $n = 26\%$ and by 4 for 41%.

$F(W)$, the fraction of charged beam lost, is useful for evaluating the performance of accelerators of various energies W . Another significant quantity is the ratio G of the total grid-neutralized beam to the total D^0 beam: for a thick neutralizer (optimizing the main neutral beam),

$$G(W) = \left(1 + \sigma_{0+}(W)/\sigma_{+0}(W) \right) F(W)$$

to first order in F . $G(W)$ is plotted (for D_2 gas) in Fig. 3b.

Besides affecting the system efficiency, the grid-neutralized beam creates problems in the beam duct and affects hot plasma confinement at the target. Fig. 1 shows that the beam angle is larger at low energies, where most of the parasitic beam is formed. Therefore the parasitic beam diverges more than the main beam and sprays the walls of the beam duct, tending to evolve gas there. This could be troublesome in the region between the neutralizer and the plasma target.

The central part of the parasitic beam continues all the way into the plasma chamber, and contributes a low-energy component to the main beam, along with any half- and third-energy components. (As discussed in the introduction, these latter components should have less relative importance in the future.) References 2 and 3 describe the ways in which plasma confinement is affected.

It is useful to define the parasitic beam flux density fraction arriving at the target, $H(W)$. The parasitic beam diverges more than the main beam, so that the ratio of flux densities downstream, $H(W)$, is smaller than $G(W)$. The WOLF code gives the rms beam angle $\theta(V)$ within the accelerator; the result is not a simple curve because of the grid structure, but a good empirical fit over most of the energy range is

$$\frac{\theta(W)}{\theta(V)} = \frac{1}{13} \left(1 + 12 \frac{V}{W} \right).$$

The low energy neutral flux density fraction on axis at the target due to grid neutralization is then

$$H(W) = \left[1 + \frac{\sigma_{0+}(W)}{\sigma_{+0}(W)} \right] \frac{L}{W} \int_0^W \frac{1 + 12 \frac{V}{W}}{13} n(V) \sigma_{+0}(V) dV$$

which can be integrated similarly to Eq. (10), with the result shown in Fig. 3c.

Fig. 3. Fraction of beam flux neutralized within the grids as a function of the final energy W .

- (a) $F(W)$, based on total accelerated beam.
- (b) $G(W)$, based on total neutralized beam.
- (c) $H(W)$, the flux-density ratio at the target.

These curves illustrate the high gas-flow case, $\eta = 0.15$. For other efficiencies, multiply curves by $3(1 - \eta)/17\eta$. As discussed on p. 10, this multiplying factor equals 0.5 for $\eta = 0.26$ and 0.25 for $\eta = 0.41$.

III. Double Charge Exchange D^- System

One of the D^- beam production methods being developed at LLL⁶ starts with a ≈ 1 keV D^+ beam, converts this to D^- in a cesium cell, and then accelerates it to around 60 keV (eventually 200 keV or higher). There is pumping preceding the high-voltage accelerator which keeps the D_2 density too low for appreciable stripping. The small amount of vapor streaming from the cesium cell also has a negligible effect in the accelerator region. However, there is an intense parasitic beam associated with the 1 keV D^+ beam.

Charge Exchange in the 1 keV Source Grid System

The Cooper Grid system⁵ at LLL produces a remarkable D^+ current density at 1 keV (0.4 A/cm^2) by accelerating the beam to about 10 keV before decelerating to the final energy, but much of the beam path is in the energy range where charge exchange ν_{+0} is at its worst. The form of ν_{+0} , combined with the grid potential profile, peaks the parasitic beam around 10 keV, with power comparable with the desired 1 keV beam even though the current fraction is only 4-10%. The 10 keV beam is sharply focussed and totally dominates the power density (e.g. calorimeter signals) on axis.

Grid Gas Density

Figure 4 shows the Cooper Grid configuration and its approximation by rectangles. In the notation of Sec. II, $\pi(a/b) \approx 1.35$ so that $Z_{\text{total}} = \frac{1}{v_a} \frac{3}{2A} \left(\frac{8}{3} + 1.35 \right)$. Then Eq. (6) becomes

$$n(z) = n_0 + 8.2 \times 10^{13} \frac{1-z}{1} \left(1 - \frac{z}{0.6} \right) \quad (12)$$

again using the linear approximation. As before, the molecular ion components are assumed small and are merely averaged in with the total current.

Potential Gradient

Figure 5 shows results of the WOLF calculation of the beam dynamics and potential in the original Cooper Grid system as run at LLL, derated from the design current density. For 14 kV applied between first and

Fig. 4. Cooper Grid configuration and representation for gas impedance calculation.

Fig. 5. WOLF calculation for Cooper Grid (1976 version), showing potential distribution and beam trajectory.

second grids, geometric effects and space charge reduce the maximum beam energy to 10.7 keV. A simple model representing the WOLF result for beam energy along the axis is

$$V = 10.7 \left(1 - \left| \frac{z}{.3} - 1 \right|^m \right)$$

where $m = 4/3$ gives the best fit over the whole range, but $m = 2$ is better in the important region where σ_{+0} is large. In the latter case,

$$\frac{z}{.3} - 1 = \pm \left(1 - \frac{V}{10.7} \right)^{1/2} \quad (13)$$

$$\frac{dV}{dz} = 71 \left(1 - \frac{V}{10.7} \right)^{1/2} \quad (14)$$

These equations are symmetrical about the midplane, in the spirit of the Cooper Grid design. The slight asymmetry in Fig. 5 is negligible in the interesting central region.

Charge Exchange Cross Section

The σ_{+0} data in the range 1-10 keV is conveniently modeled here by an analytic function similar to Eq. (14) (rather than the piece-wise form of Eq. (8)):

$$\sigma_{+0} = 8.5 \times 10^{-16} \left[1 - \left(1 - \frac{V}{10.7} \right)^2 \right] \quad (15)$$

This fits the available data^{21,25,26} within experimental error (Fig. 6).

Energy Spectrum

In Eqs. (12) and (13), $v(V)$ is double valued giving left and right branches n_1 and n_2 :

$$\frac{dF}{dV} = \frac{n_1 + n_2}{|dV/dz|} \sigma_{+0}$$

Fig. 6. Charge-exchange cross section σ_{+0} for D^+ energies in the range encountered in Fig. 5.

and from Eqs. (12) through (15),

$$\frac{dF}{dV} = \left(2n_0 + 8.2 \times 10^{13} J \frac{1-n}{n} \right) 1.2 \times 10^{-17} \left[\frac{1-(1-V/V_0)^2}{(1-V/V_0)^{1/2}} \right] \quad (16)$$

This is singular at $V = V_0 = 10.7$ keV because the beam potential gradient vanishes there. Taking the finite detector resolution ΔV into account,

$$\langle \frac{dF}{dV} \rangle = \frac{1}{2\Delta V} \int_{V-\Delta V}^{V+\Delta V} (dF/dV) dV \quad (17)$$

and the spectrum is finite everywhere. Smoothing by Eq. (17) is only needed near $V \approx V_0$, where the numerator in Eq. (16) is essentially constant, i.e.,

$$\frac{dF}{dV} \approx \frac{C}{(V_0 - V)^{1/2}}$$

giving

$$\langle \frac{dF}{dV} \rangle = \begin{cases} \frac{C}{\Delta V} \left[\sqrt{V_0 + \Delta V - V} - \sqrt{V_0 - \Delta V - V} \right], & V \leq V_0 - \Delta V \\ \frac{C}{\Delta V} \sqrt{V_0 + \Delta V - V}, & V_0 - \Delta V \leq V \leq V_0 + \Delta V \end{cases} \quad (18)$$

Figure 7a shows the results from (16) and (18) for the case $\Delta V/V_0 = 4\%$.

The energy spectrum measured at LLL was further smoothed by the effects of finite beam angle and by space charge in the detector apparatus. These effects can be approximated by another application of Eq. (17), using an appropriately different width $\Delta V'$. Figure 7b shows the doubly smoothed $\langle\langle dF/dV \rangle\rangle$ for $\Delta V/V_0 = 4\%$ and $\Delta V'/V_0 = 2\%$. The spectrum is nearly the same as the experimental result,²⁷ Fig. 8.

Fig. 7. Calculated charge-exchanged energy spectrum for Cooper grid (Fig. 5): (a) [dashed curve] with 4% smoothing; (b) [solid curve] with 4% and 2% double smoothing.

Fig. 8. Experimental charge-exchanged energy spectrum for Cooper grid, measured with electrostatic energy analyzer.

The parasitic beam is peaked near 10 keV (actually, nearly 11) and is referred to below and on pp. 20,21 as the "10 keV beam".

Integrated Beam Loss

Integrating Eq. (16) gives the total beam fraction F converted to parasitic neutrals within the grids. The integration can be started from 0 keV for the reason already mentioned in connection with the symmetry of Eq. (13): the high energy region dominates the result. Then, still using the small F approximation,

$$F = \int_0^{V_0} \frac{dF}{dV} dV \quad (19)$$

with $V_0 = 10.7$ keV. Integrating the quantity in square brackets in Eq. (16) gives $8V_0/5$; then neglecting n_0 (because there is no neutralizer),

$$F = 1.7 \times 10^{-2} J \frac{1-\eta}{\eta} \quad (20)$$

For $J = 0.4$ A/cm² and $\eta = 0.15$ (corresponding to 6 Torr-2/sec of excess gas flowing through the 30 cm² open grid space), $F = 4\%$.

This figure agrees with measurements at LLL²⁸ within experimental error. In the high gas flow mode,¹⁶ F becomes about 10%.

The power ratio between the approximately 10 keV parasitic beam and the 1 keV desired beam is

$$\frac{P_{10}}{P_1} = \frac{1}{1-F} \frac{1}{W} \int_0^{V_0} V \frac{dF}{dV} dV \quad (21)$$

where $W = 1$ keV is the main beam energy. From the form of Eq. (16), and comparing Eq. (19),

$$\frac{P_{10}}{P_1} = \frac{F}{1-F} \frac{V_0}{W} \frac{19}{21} = 9.7 \frac{F}{1-F} \quad (22)$$

so the power ratio is 0.4 for normal operation and 1.2 for high gas flow. (The electrical input power ratio is several times larger because of secondary emission at the middle grid.)

Angular Profile of 1 keV and 10 keV Beams

Figure 5 shows the beam trajectory within the grids, as calculated by WOLF for the LIL parameters. The 1 keV beam exit angle in this figure is 15° (horizontal plane). Space charge and transverse ion temperature determine the vertical beam angle, measured as 2.3° (Fig. 9).²⁹ WOLF shows nearly parallel flow in the high energy region, giving a smaller horizontal angle (4.2°) in Fig. 9. Absence of space charge force helps reduce the vertical angle to only 0.35° , so that the 10 keV solid angle is 23 times smaller.²⁹

The flux density ratio at the target axis (normal gas feed) is

$$\frac{J_{10}}{J_1} = 23 \frac{F}{1-F} = 1.0$$

including both neutral and ionized components. Reference 28 discusses the ionized fractions in the two beams.

The power density ratio is, from Eq. (22),

$$23 \times 9.7 \frac{F}{1-F} = 10.$$

Thus, 91% of the calorimetric signals on axis come from the parasitic beam. In the old higher gas flow mode this figure becomes 96%, which applies, for example, to the F^- measurements reported at St. Petersburg.³⁰ (F^- is the fraction of D^- ions in the 1 keV beam emerging from the cesium cell.)

In later experiments the 10 keV beam was excluded by tilting the source slightly. This technique gave sensible results for F^- .³¹ Without correction for molecular ions in the primary beam, $F^-(\infty) \approx 18\%$; estimated corrections would give a value between 20% and 25%, consistent with the more accurate measurements of Schlachter, Stalder and Stearns³² at LBL.

Fig. 9. Angular profiles of 1 keV main beam and 10 keV parasitic beam from Cooper grid, low gas flow mode. The dashed curve for 1 keV beyond 5° was not measured; it is based on the WOLF calculation (Fig. 5).

The current density of the 1 keV beam can be increased by narrowing the beam divergence angle (Fig. 9). This may be done in part by improving the source operating characteristics and in part by improving the space charge neutralization of the beam just beyond the grids. One way to get more electrons in the latter region is to place a hot emitting wire beyond each set of grids; this scheme will be investigated soon at LLL.

Low-Energy Components in the High-Energy Neutral Beam

In the neutral beam system being developed at LLL, the 1 keV D^- ions emerging from the Cs cell will be accelerated (eventually) to 200 keV and then converted to D^0 in a stripping cell. Although the gas pressure in the D^- accelerator can be kept low enough to avoid appreciable charge transfer, one must remember that 80% of the 1 keV beam emerges as D^0 from the Cs cell. These 1 keV neutrals pass through the accelerator as a low energy parasitic component of very large flux density. In a close-coupled system, this parasitic flux could exceed the D^- beam flux entering the stripper. J. H. Fink is studying the problems which could arise in various types of strippers.

Further downstream, the 10 keV beam (because of its narrower angle) will become the dominant low-energy component, and ways to control it may need to be considered.

Evidence for Diatomic Gas in Grids

It has been assumed in the present report and by other authors that the excess deuterium flowing through the grids is essentially molecular. This is an important point because at D^+ energies below 20 keV, σ_{+0} is larger in atomic deuterium than in D_2 . The data of Fig. 8, however, agree with the calculated curve based on D_2 and would disagree with a curve for D where σ_{+0} rises at energies below 10 keV instead of falling off.

A quantitative value for the D/D_2 fraction could be obtained by extending the measurements (Fig. 8) to lower energies, but this has not yet been done.

IV. Surface-Conversion D^- Systems

There are two types of D^- sources employing cesiated tungsten or molybdenum cathodes. The first type, which originated at Novosibirsk,^{33,34} produces negative ions by direct interaction with a magnetron arc or a Penning discharge. This type is called a surface-plasma (S P) source. Figure 10 shows the negative ion yield at the cathode increasing sharply as the arc drop is lowered.³⁵ The lowest stable operating point, 100 V, gives about 25% conversion to negative ions (using hydrogen in this case). The negative ion group at Brookhaven has developed an S P source with a one-ampere beam accelerated to 120 keV,⁸ and they are extending the pulse length to 50 msec.³⁶ Low gas efficiency may necessitate a pumping space between the extractor and main accelerator; the density profile assumed in Sec. II would not apply to this problem.

The second type of D^- source, called the jet surface conversion (JSC) system,^{7,37,38} separates the cesiated cathode from the deuterium bombardment energy and allows running at optimum conversion efficiency (perhaps 50%).³⁹ Also, the gas loading in the grid system is low because excess gas from the bombardment jet³⁸ is separately pumped.⁷ Another advantage is that pumping can be provided behind the cathode strips (Fig. 11) without increasing the overall acceleration area.⁷ This feature of the supersonic jet surface conversion scheme makes it competitive with the conventional LBL D^+ systems for the same beam energies. Even though σ_{-0} falls off less rapidly than σ_{+0} at high energies, the extra pumping feature in the D^- system compensates for this.

The favorable gas conversion efficiency of the JSC system makes a pumping space unnecessary between the D^- cathode and the high voltage accelerator. This means that the high-quality grid design already developed for TFTR⁴ can be adapted, as shown in Fig. 11, for the JSC system. Because the analysis developed in Sec. II is also easily adapted, the JSC system is chosen for illustration here.

Fig. 10. Surface conversion for cesiated molybdenum cathode; K^- is the fraction of H^- ions produced per energetic bombarding particle (assumed to be H^+). From Ref. 35.

Fig. 11. Grid and cathode arrangement for surface conversion of D^- from a supersonic jet of D^0 . Equipotentials and trajectories are taken from TFTR WOLF calculation (Ref. 4) for illustration. Some of the electrodes have been modified, and the actual trajectories would be slightly different.

Grid Gas Density

The jet surface conversion grid system⁷ includes back-pumping spaces between the cathode strips. The width of these spaces (Fig. 11) is 40% of the average grid opening b , Eq. (3). From Sec. II, the total impedance is given by

$$\begin{aligned} Z^{-1} &= Z_{\text{slot}}^{-1} + Z_{\text{grids}}^{-1} \\ &= \frac{v_a}{4} A (.40) + \frac{2}{3} v_a A \left(\frac{8}{3} + 1.38 \right)^{-1} \end{aligned}$$

or

$$Z = \frac{1}{v_a} \frac{3}{2A} \quad (2.52) .$$

Comparing this with Eqs. (1) and (5) shows that Z here is 57% of Z_{TFTR} , so that Eq. (7) becomes

$$n(V) = n_0 + 1.7 \times 10^{14} W^{-1/2} \frac{1-\eta}{\eta} (1 - \frac{V}{W}) \quad (23)$$

where η is now the Cs-W cathode efficiency for converting D^0 (in monomer or dimer form) from the jet^{7,38} to extracted D^+ ions. Unconverted atoms from the jet entering the grids are assumed to recombine into D_2 , with a temperature arbitrarily taken as 1000°K.

Stripped Beam Energy Spectrum

According to Refs. 20 and 21, the cross sections for D^+ electron loss and D^+ electron capture in D_2 agree within $\pm 15\%$ in the range from 3 to 30 keV, so that low-energy spectra are nearly alike. Although $\sigma_{-10} \gg \sigma_{10}$ near the final stages of acceleration, the low gas pressure in that region prevents excessive stripping at high energies.

The stripping cross section σ_{-0} from Refs. 20 and 21 may be represented within experimental accuracy by the model

$$\begin{aligned} \sigma_{-0} &= 1.0 \times 10^{-16} V, & 0 < V < 10 \\ &= 1.0 \times 10^{-15}, & 10 < V < 20 \\ &= 1.40 \times 10^{-15} e^{-.07515 V}, & 20 < V < 1000 \text{ keV} \end{aligned} \quad (24)$$

Then (taking the density profile into account) Eq. (9) gives the spectrum, which is plotted in Fig. 12 for an 80 keV case (MFTF) and a 500 keV case (TMX). Figure 13 compares the spectra for the TFTR D^+ system and the jet surface conversion D^- system at the same 120 keV energy. Charge transfer is larger for D^- above 65 keV but at lower energies the back pumping gives the D^- system an advantage. The area under the D^- curve is about 60% of the D^+ area.

Integrated Beam Loss

Equation (11) again applies, except that the constants have different values taken from the model, Eq. (24). Figure 14 compares $F(W)$ for the D^- and D^+ systems at the same η . Note that η for D^+ means overall gas efficiency and η for D^- means cathode conversion ratio. In the latter case, part of the impinging D^0 jet strikes the outside grid (or misses the D^- system altogether): this part, which is handled by outside pumping, affects the overall gas efficiency but not the density within the grids. The η 's as defined might be expected to be about 50% for each system under ideal conditions.

Figure 14a illustrates a somewhat pessimistic case in which both the D^+ and D^- systems have η 's of 25%. The worst F for D^+ , 5%, occurs at 120 keV, where F for D^- is around 4%. The D^- beam loss only rises to 5% at ~200 keV. At 1000 keV, on this model, an η of 0.4 will keep the loss below 5%.

Figure 14b compares the neutral beam fraction $G(W)$, defined in Sec. II, for the two cases. The D^+ case assumes a D_2 neutralizer; the D^- case assumes a plasma stripping cell with neutralizing efficiency of 85% (Ref.40). The advantage of using negative ions is clearly shown for all energies.

Low Energy Beam Fraction at the Target

The flux density fraction at the target due to grid neutralization, $H(W)$, is shown in Fig. 14c. Again, the D^- system appears superior. In the case of the D^+ system, there are additional D^0 components at the target, of energy $W/2$ and $W/3$, from breakup of molecular ions in the neutralizer.

Fig. 12. Energy spectra of D^- beam current stripped within the grids at final energies 80 keV and 500 keV; $\eta = 0.25$.

Fig. 13. Comparison of parasitic beam spectra for TFTR system and Jet Surface Conversion (JSC) system at 120 keV; $\eta = 0.25$.

Fig. 14. Comparison of fraction of beam neutralized within the grids for D^+ and D^- systems, as a function of the final energy W ; $n = 0.25$ in all cases. (a) $F(W)$, based on total accelerated beam. (b) $G(W)$, based on total neutralized beam. (c) $H(W)$, the flux-density ratio at the target.

These fractions may be much larger than the grid-neutralized fraction shown in Fig. 14c, and are entirely absent in the D^- system. This additional advantage of the D^- approach for all energies is discussed in Ref. 41.

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NOTICE

"This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Department of Energy, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights."

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For energies 10 keV - 1000 keV, this paper tabulates the attachment cross section σ_{+0} modeled by Eq. (8), Sec. II, and the stripping cross section σ_{-0} modeled by Eq. (24), Sec. IV.

21. J. W. Stearns (Lawrence Berkeley Laboratory, 1975, unpublished). This reference gives the data of Ref. 20 in graphical form and extends it down to 2 keV (for deuterium).

Note. After the original version of the present report was written, the new Oak Ridge tables appeared: C. F. Barnett, J. A. Ray, E. Ricci, M. I. Wilker, E. W. McDaniel, E. W. Thomas, and H. B. Gilbody, "Atomic Data for Controlled Fusion Research," Oak Ridge National Laboratory report ORNL-5206, Feb. 1977. The up-to-date cross sections in Vol. I agree well with those used for the present report for energies down to 10 or 20 keV. At lower energies, the newer values become systematically larger than the old ones. At 2 keV, the discrepancy reaches a factor of 2 for σ_{+0} and a factor of 3.5 for σ_{-0} . Making the corresponding corrections would noticeably change the energy spectra (e.g. Fig. 2) at the lowest energies but would have very little effect on the integrated values (e.g. Fig. 3).

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This report describes operation of both the 7 X 7-cm and the 7 X 35-cm sources. The 7 X 7-cm source produced a beam of almost 16 A, consisting of 75% D^+ , 15% D_2^+ , and 10% D_3^+ . The D_2 gas flow was 8 Torr-cm/sec. Using these figures, one finds that 22% of the deuterium nuclei fed into the source are accelerated, as D^+ , D_2^+ , or D_3^+ . This "nuclear gas efficiency" is relevant for applications such as mirror injection, where low-energy

22. (continued)

beam components may be desirable (Ref. 2). For tokamaks, where such components are probably undesirable (Ref. 3), it may be better to introduce the "full-energy-beam gas efficiency," i.e., the fraction of deuterium nuclei accelerated to full energy (neglecting charge exchange in the grids). This gas efficiency turns out to be 13%. A third efficiency (used in the text in anticipation of improved D^+ fractions) is based on the total accelerated current (16 A in the reference under discussion). This "accelerated-current efficiency" is then 17% for the 7 X 7-cm source.

The data given in this reference for the 7 X 35-cm source implies an accelerated-current η of 31% and a nuclear η of 38%. It is stated that nuclear η 's of up to 49% can be reached.

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A Developmental 8 X 10-cm 120 keV source for TFTR is described. Using 7 Torr- ℓ /sec of D_2 , a 10 A beam is produced with minimum divergence. The species mix is not specified, but the accelerated-current η (defined above in Footnote 22) is 12.5%.

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