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LOW ENERGY COMPONENTS FROM CHARGE TRANSFER IN NEUTRAL BEAMS FOR FUSION

O. A. Anderson

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O. A. Anderson

Lawrence Livermore Laboratory, University of California

Livermore, California 94550

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O. A. ANDERSON

I. Introduction

Charge transfer in ion beam accelerating structures is a matter of concern in MFE applications because it reduces beam efficiency and also leads to plasma confinement problems. For example, in the MFTF injector, a low energy neutral beam component causes loss of high energy mirror-confined particles.

The problem occurs when the accelerator is adjacent to the ion source and the excess D_2 gas flows through the grid structure. The large cross sections σ_{+0} or σ_{-0} in D_2 at beam energies below 20 keV can neutralize 5 to 10% of the beam before it reaches full energy. Section II treats the MFTF/TFTR injector system and shows that the LBL source gas efficiency will probably need improvement.

In the LLL double charge exchange system (section III), pumping sections eliminate the charge transfer problem in the main accelerator. But in the 1 keV D^+ accel-decel system, about half the input energy goes by charge exchange into a narrow beam of D^0 at around 10 keV. An energy spectrum is calculated which agrees well with observations.

Section IV discusses the stripping problem in surface-production negative ion systems producing beam energies up to 1000 keV. In the case of the Dimov type source, gas efficiency is low but some of the gas can be pumped from behind if the units are sufficiently spaced. The proposed surface conversion of a supersonic jet design allows back pumping without

additional spacing. The total accelerated D^+ current over a large area is thus the same as for a standard LBL D^+ source of the same energy. The charge transfer problem is actually smaller because of the back pumping.

II. MFTF/TFTR Grid Systems

MFTF, TFTR and Doublet III will use essentially the same grid systems, suitably scaled for different beam energies, and they will all be treated together in this section, using Cooper's scaling principle.¹ 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. Dushman's method², along with a little guesswork, gives the gas impedance, defined as

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

n_1 and n_0 are the input and output densities, and dN/dt is the flow rate of molecules. Adding up the partial Z 's for each section, along with appropriate entrance impedances, gives the total Z . 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 Clausing and others give corrections of a few percent, but a more important correction is needed here: Dushman's Z_0 applies to a distribution function which is isotropic in semi-infinite velocity space, roughly valid for the first grid but invalid for the others. In the present paper, a correction factor ϵ is introduced:

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

The straight sections have impedances

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

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

Finally, the tapered section has impedance

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

where the subscripts 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, some guesswork is needed on the factor ϵ in Eq. (2). Another author, treating a similar problem³, 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, only the first entrance impedance applies. In the present paper, one additional Z_0 is distributed among the remaining grids, i.e., ϵ is chosen as 1/3 for TFTR.

The density profile through the grid system varies in a complicated way. Reference 3 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

$$n(\ell) = n_0 + (1 - \frac{\ell}{L}) \frac{1}{v_a} \frac{3}{2A} \left(\frac{8}{3} + 1.75 \right) \frac{dN}{dt} \quad (5)$$

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. (The LBL source emits a small fraction of diatomic and triatomic ions, but these will be averaged in with the main D^+ component.) Gas flowing through the grids is assumed molecular (see section III). Then

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

and, with the usual $T = 1000^\circ K$ assumption,

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

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 scaling¹ gives $J = 3.4 W^{-1/2}$, with final beam energy in keV.

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

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

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.

Charge-Exchange Cross Section

Berkner, Pyle and Stearns⁴ have summarized the available pertinent data. Only the cross section for D^+ ions is needed here; the small molecular ion components are simply averaged in with the total beam, giving accuracy compatible with section II. All the data points in Ref. 4 (10 keV - 1000 keV) can be fit within experimental accuracy by the model (V in keV)

$$\begin{aligned}\sigma_{+0} &= 1.38 \times 10^{-16} \gamma, & 0 < \gamma < 6.0 \\ &8.29 \times 10^{-16}, & 6.0 < \gamma < 35.7 \\ &1.076 \times 10^{-14} e^{-.429\sqrt{\gamma}}, & 35.7 < \gamma < 1000\end{aligned}\quad (8)$$

Values below 10 keV are a reasonably good fit to data of Ref. 5. (Another low-energy model is presented in section III). Eq. (8) in the range between 120 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

Fig. 2 shows the energy spectrum,

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

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 33% 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 lost to charge-exchange within the grids, for final energy W , is

$$F(W) = \int_0^L n \sigma_{+0} d\ell = \frac{L}{W} \int_0^W n(Y) \sigma_{+0}(Y) dY \quad (10)$$

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

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

for $W \ll 35.7$ keV. Including n_0 would give an expression of similar form. 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

$$F(W) = \frac{1-n}{n} \frac{0.26}{a^3} \left[(2a^2 + 6a + 6)e^{-a} + 0.506422a^2 - 5.28758 \right] \quad (11)$$

The length L in Eq. (10) has been replaced by $W/60$, according to the Cooper scaling.¹ Fig. 3a displays $F(W)$ for various n . A gas efficiency of 15% applies to the standard LBL operation: 8 torr-ℓ/sec for the 10 cm x 10 cm 15A TFTR prototype, or 8.5 torr-liter/sec for the old "10A" 20 keV sources.⁶

According to Fig. 3a, η needs improvement for systems operating around 120 keV, where $F(W)$ is largest; increasing gas efficiency to 30% would reduce F from 9.5% to about 4%.

$F(W)$ is useful for evaluating the performance of accelerators of various energies W . The overall efficiency involves the ratio G of the grid-neutralized beam to the total D^0 beam: for a thick neutralizer,

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

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

Besides affecting the system power efficiency, the grid-neutralized beam degrades hot plasma confinement at the target. The low energy neutral fraction arriving at the target, $H(W)$, is smaller than $G(W)$ because of the difference in beam angles.

The WOLF code gives the rms beam angle $\theta(V)$ within the accelerator; the result is not a smooth curve because of the grid structure, but a good empirical fit over most of the energy range is

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

The low energy neutral fraction 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.

III. Double Charge Exchange D⁺ System

Stripping in the High Voltage Accelerator

The pumping space preceding the 100 keV (eventually 200 keV) grid system at LLL keeps the D₂ density too low for appreciable stripping within the accelerator. Cesium vapor streaming from the double charge exchange cell also has negligible effect in the accelerator region.

Charge Exchange in the 1 keV Source Grid System

The Cooper Grid system at LLL produces a remarkable D⁺ current density (0.4 A/cm² at 1 keV) 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 σ_{+0} is at its worst. The form of σ_{+0} , combined with the grid potential profile, peaks the neutralized energy sharply around 10 keV, with power comparable with the desired 1 keV beam even though the current fraction is only 5-10%. The 10 keV beam is sharply focussed and totally dominates the power density (e.g. calorimeter signals) on axis.

Grid Gas Density

Fig. 4 shows the Cooper Grid configuration and its approximation by rectangles. In the notation of section II, $\Sigma(\ell/b) \approx 1.35$ so that $Z_{\text{total}} = \frac{1}{v_a} \frac{3}{2A} \left(\frac{8}{3} + 1.35 \right)$. Since the source is not run as hard as the LBL sources, $T \approx 500^\circ\text{K}$ here. Then Eq. (6) becomes

$$n(\ell) = n_0 + 11.6 \times 10^{13} \frac{1-n}{n} \left(1 - \frac{\ell}{.6} \right) \quad (12)$$

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 Cooper Grid system. For 14 kV applied between first and second grids, geometric effects and space charge reduce the maximum beam energy to 9.7 keV. A simple model representing the WOLF result for beam energy along the axis is

$$V = 9.7 \left(1 - \left| \frac{x}{.3} - 1 \right|^m \right)$$

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,

$$\frac{x}{.3} - 1 = \pm \left(1 - \frac{V}{9.7} \right)^{1/2} \quad (13)$$

which will be used with Eq. (12), and

$$\left| \frac{dV}{dx} \right| = 64.7 \left(1 - \frac{V}{9.7} \right)^{1/2} \quad (14)$$

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)):

$$\sigma_{+0} = 8.3 \times 10^{-16} \left[\left(1 - \frac{V}{9.7} \right)^2 \right] \quad (15)$$

This fits the available data within experimental error (Fig. 6).

Energy Spectrum

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

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

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

$$\frac{dF}{dV} = (2n_0 + 11.6 \times 10^{13} \frac{1-n}{n}) 1.3 \times 10^{-17} \frac{1-(1-V/V_0)^2}{(1-V/V_0)^{1/2}} \quad (16)$$

This is singular at $V = V_0 \equiv 9.7$ keV because the beam potential gradient vanishes there. Taking the finite detector resolution $2\Delta V$ into account,

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

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

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

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

The energy spectrum measured at LLL was additionally smoothed by the 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 $\Delta V'$. Fig. 7b shows the doubly smoothed

$\langle\langle dF/dV \rangle\rangle$ for $\Delta V/V_0 = 4\%$ and $\Delta V'/V_0 = 2\%$. The shape is nearly that of the experimental result⁷, Fig. 8.

Integrated Beam Loss

Integrating Eq. (16) gives the total beam fraction F converted to 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 completely dominates the result. Then, still using the small F approximation,

$$F = \int_0^{V_0} \frac{dF}{dV} dV = \frac{8}{5} V_0 \frac{dF}{dV}(0) \quad (19)$$

or

$$F = 2.3 \times 10^{-2} J \frac{1-n}{n} \quad (20)$$

with $V_0 \equiv 9.7$ keV; n_0 in Eq. (16) is negligible here because there is no neutralizer. For $J = 0.4$ A/cm² and $n = 0.15$ (corresponding to 6 torr- μ /sec of excess gas flowing through the 30 cm² open grid space), $F = 5.2\%$.

This figure agrees with measurements at LLL⁸ within experimental error. In the high gas flow mode³, F becomes about 12%.

The power ratio between the grid-exchanged beam and the 1 keV desired beam is

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

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

$$\frac{P_x}{P_1} = \frac{F}{1-F} \frac{V_0}{W} \frac{19}{21} = 8.8 \frac{F}{1-F} \quad (22)$$

so the power ratio is 0.48 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

Fig. 5 shows the beam trajectory within the grids, as calculated by WOLF for the LLL parameters. The 1 keV beam exit angle in this figure is 15° (horizontal plane). Space charge determines the vertical beam angle, measured as 2.3° , (Fig. 9). WOLF shows parallel flow in the high energy region, giving a smaller horizontal angle (4.2°) in Fig. (9). Absence of space charge force gives a vertical angle of only 0.35° , so that the 10 keV solid angle is 23 times smaller.

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

$$\frac{J_x}{J_1} = 23 \frac{F}{1-F} = 1.26$$

including both neutral and ionized components. Reference 8 discusses the ionized fractions in the two beams.

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

$$23 \times 8.8 \frac{F}{1-F} = 11$$

Thus, 92% of the calorimetric signals on axis come from the parasitic beam. In the old higher gas flow mode this figure becomes 97%, which applies, for example, to the F^- measurements reported at St. Petersburg.

Fortunately, the 10 keV beam, being quite thin vertically, can be excluded by tilting the source slightly. This technique has given sensible results for F^- . 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 and Stearns^{9a} at LBL.

The D^- beam intensity problem is being attacked in several ways. The D^+ beam width will be improved by modifying the grid system, and the height by controlling the downstream plasma potential profile.

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 low energies, σ_{+0} in atomic deuterium becomes large enough to be troublesome. 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.

An upper limit for the D/D_2 fraction could be established but this has not yet been done.

IV. Surface-Conversion D^- Systems with Direct Acceleration

Two types of surface conversion D^- sources are under investigation. The first type, which originated with Dimov¹⁰, produces negative ions by direct interaction of a magnetron arc with a cesiated cathode. Fig. 10 shows (for hydrogen) the H^- yield increasing sharply as the arc drop is lowered. The lowest stable operating point, 100 V, gives about 25% H^+ to H^- conversion.¹¹ Prelec and Sluyters^{11a} at Brookhaven have extended the pulse length of the magnetron source and have accelerated the D^- beam to 100 keV. Gas efficiency is low; the Brookhaven group is also using a Penning discharge, looking for better gas efficiency.¹²

The second type of D^- source¹³ suitable for direct acceleration, inspired by the surface conversion calculations of Hiskes¹⁴, separates the cesiated cathode from the deuterium bombardment apparatus. This separation gives independent control of Cs coverage and bombardment energy and allows

running at optimum conversion efficiency (perhaps 50%). Also, the gas loading in the grid system is low because excess gas from the bombardment jet is separately pumped. Another advantage is that pumping can be provided behind the cathode strips (Fig. 11) without increasing the overall acceleration area. This feature of the supersonic jet surface conversion scheme gives it an advantage over the conventional LBL D^+ systems for the same beam energies. Even though σ_{+0} falls off faster than σ_{-0} at high energies, the extra pumping feature in the D^- system gives somewhat smaller charge conversion loss.

Grid Gas Density

The Brookhaven group has not yet designed a focussed grid system for direct acceleration, but the gas density characteristics presumably would be similar to the model of Eq. (6). Recent measurements^{14a} with both magnetron and Penning discharges have shown gas efficiencies of a few percent or less. Back pumping is clearly mandatory. To get a total D^- beam of, say, 50A might require a rather large array if sufficiently large pumping spaces are interposed between the units. In any case, the present analysis should be useful in arriving at a final design.

The jet surface-conversion grid system¹³ includes (without affecting the overall dimensions) pumping spaces between the cathode strips. The width of these spaces (Fig. 11) is 40% of the average grid opening b , Eq. (3). From section 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

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

where η is now the Cs-W cathode efficiency for converting D^0 atoms from the jet^{13,15} to extracted D^- ions.

Stripped Beam Energy Spectrum

The stripping cross section σ_{-0} from Ref. 4 may be represented within experimental accuracy by the model

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

Then Eq. (9) give the spectrum, which is plotted in Fig. 12 for an 80 keV case (MFTF) and a 500 keV case (TMX). Fig. 13 compares the spectra for the TFTR D^+ system and the jet surface conversion D^- system at the same 120 keV energy. Conversion is higher for D^- above 65 keV but at lower energies the back pumping gives the D^- system an advantage. The area under the $D^- - D^0$ curve is about 60% of the $D^+ - D^0$ area.

Integrated Beam Loss

Eq. (11) again applies, except that the constants have different values taken from the model Eq. (24). Fig. 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 $D^0 - D^-$ 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 fast pumping, affects the overall gas efficiency but not the density within the grids. The η 's as

defined might be expected to remain about equal for the two systems as their development progresses. The surface conversion η , expected theoretically to reach an optimum 50%, might be 15% in initial experiments, corresponding to the present LBL gas efficiency.

Fig. 14a illustrates an intermediate development stage at 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%.

Fig. 14b compares the fraction $G(W)$, defined in section 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. 16). The advantage of using negative ions is clearly shown for all energies.

Low Energy Beam Fraction at the Target

The low energy fraction at the target due to grid neutralization, $H(W)$, is shown in Fig. 14c. Again, the D^- system is better. 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. 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. 17.

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- Fig. 1 Standard LBL grid configuration for TFTR, MFTF, and Doublet III. (a) WOLF computation, showing self-consistent equipotentials and beam trajectory. (b) Grid representation for gas impedance calculation.
- Fig. 2 Energy spectrum of beam charge-exchange within the grids for two different final energies; $\eta = 0.15$.
- Fig. 3 Total fraction of beam lost to charge exchange within the grids as a function of final energy. (a) $F(W)$, based on total accelerated beam. (b) $G(W)$, based on total neutralized beam. (c) $H(W)$, the grid-neutralized fraction at the target. $\eta = 15\%$ in all cases.
- Fig. 4 Cooper Grid configuration and representation for gas impedance calculation.
- Fig. 5 WOLF calculation for Cooper Grid, showing potential distribution and beam trajectory.
- Fig. 6 σ_{+0} in range 1-10 keV; experimental points from Ref. 5 and curve from model, Eq. (15).
- Fig. 7 Energy spectrum calculated for Cooper grid: (a) with 4% smoothing; (b) with 4% and 2% double smoothing. Gas efficiency $\eta = 15\%$.
- Fig. 8 Energy spectrum measured with Cooper Grid: $V_2 - V_1 = 14$ keV, high gas flow mode.
- Fig. 9 Angular profiles of 1 keV and 10 keV beams from Cooper Grid, low gas flow mode.
- Fig. 10 Surface conversion for cesiated molybdenum cathode; K^- is fraction of H^- ions produced per energetic bombarding particle, (assumed to be H^+).
- Fig. 11 Grid and cathode arrangement for surface conversion of D^- from a supersonic jet of D^0 . Potentials and trajectories taken from TFTR

calculation for illustration. Actual values would be slightly different.

Fig. 12 Energy spectra of beam stripped within the grids at final energies 80 keV and 500 keV; $\eta = 0.15$.

Fig. 13 Comparison of spectra for TFTR system and Surface Conversion system, at 120 keV; $\eta = 0.15$.

Fig. 14 Comparison of total fraction of beam lost within the grids, for D^+ and D^- systems. (a) $F(W)$, (b) $G(W)$, and (c) $H(W)$, as defined under Fig. 3; $\eta = 25\%$ in all cases.

(a)

(b)

0.3%

0.2%

0.1%

0

 $W = 40 \text{ keV}$ $W = 200 \text{ keV}$ $V, \text{ keV}$ 550-110
10 X 10 TO THE 7 INCH
KODAK SAFETY FILM
KODAK SAFETY FILM
KODAK SAFETY FILM

Fig. 3

Fig. 5

10X10 TO THE CM. 2 359T-14G
KEUPTON & ESSEN, INC. MADE IN U.S.A.
+0.05mm

Fig 6

Energy spectrum,
relative scale

(c) Smoothed $\pm 4\%$
(b) ~~Smoothed~~ $\pm 4\%$, $\pm 4\%$

Fig. 7a, b

JAN 22 1976

V_1 measured with freshly calibrated scope

00418

Note new cutoff the signal is measured near beginning of beam time. Therefore we should use 300 V rather than 290 or 280 for calibration. Then we multiply deflection voltages by $\frac{1050}{300} = 3.5$

Fig 9

Discharge Voltage, Volts

Fig 14 b

Fig 14c

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