Efficiency Calculations for the Direct Energy Conversion System of the Cadarache Neutral Beam Injectors

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Abstract

A prototype energy conversion system is presently in operation at Cadarache, France. Such a device is planned for installation on each of six neutral beam injectors for use in the Tore Supra experiment in 1989. We present calculations of beam performance that may influence design considerations. The calculations are performed with the DART charged particle beam code. We investigate the effects of cold plasma, electron suppression, electrode shape and placement with calculations of efficiency for direct energy conversion and neutral beam production.

Contents

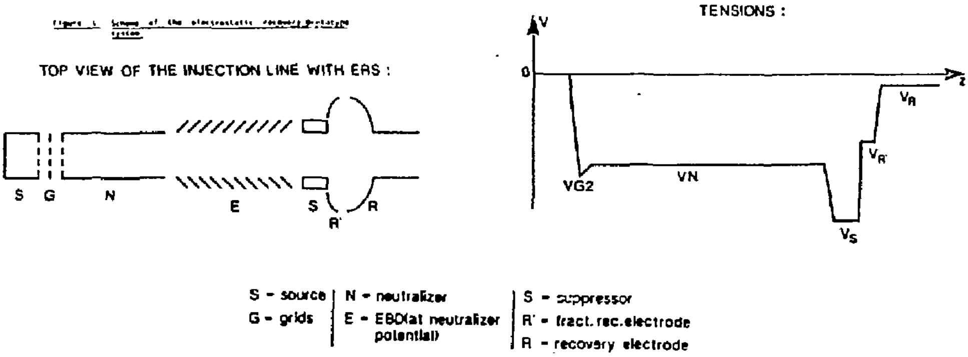

Figure 1: Schematic of the Tore Supra neutral beam injection system from Paméla.

1 Introduction

Fumelli and coworkers[2] are testing neutral beam injectors for Tore Supra incorporating an energy recovery system based on the LLNL concept[1]. Fumelli's neutral beam configuration consists of a grounded source, the neutralizer at a large negative potential, and full energy collector electrodes at a potential slightly below ground. This reduces losses due to secondary electron currents between the electron suppressor and the ion collector. Electrons which would be incident on the collector are diverted to the walls of the tank. This feature reduces the concern of secondary electron contributions to the degradation in efficiency.

Detailed studies of the energy conversion system were performed using the Livermore charged particle beam code called DART[4]. We have performed these studies to contribute to the research and development efforts for the implementation of such a system.

2 Overview of Neutral Beam Injection Line

The Tore Supra neutral beam injectors consist of a grounded source and a neutralizer at -100kV. In the prototype, an electrostatic beam dump (EBD) is placed between the neutralizer and direct converter electrodes. Although the EBD is the backup system to the energy conversion system, it is kept in line to provide gas pumping to reduce the pressure at the entrance to the direct converter. Paméla's schematic of the entire apparatus is shown in Figure 1.

The input power of each of six neutral beam lines will be 4 MW. For 100 keV D^+, the unneutralized beam power is about 1.2 MW. The objective of the direct converter system is to recover as much of this power as possible. A view of the neutral beam injection line before the direct energy conversion system is shown in Figure 2.

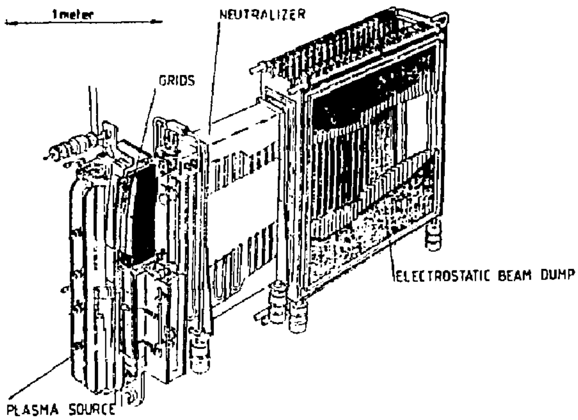

Figure 2: The neutral beam injection line including the source, neutralizer, and electrostatic beam dump (from Fumelli).

2.1 The Direct Energy Conversion System

The Cadarache energy conversion system consists of electron suppressors to hold back electrons from the neutralizer, collector electrodes to collect the decelerated ions, and an optional set of fractional recovery electrodes to collect half and third energy ions. The entrance to the direct converter is kept at -100 kilovolts and the walls are at ground potential. The total charged particle current contained in the beam after it enters the direct converter is about 16 amps. We are searching for ways to recover this current after the deceleration of the ions which carry it.

3 Reducing the Background Gas Pressure

The total efficiency of the energy conversion system can be increased by reducing the background gas density. Such a decrease results in fewer cold ions produced from charge exchange and ionization in this background gas. The reduction of cold ions also implies fewer impacts on the suppressor electrodes and fewer secondary electrons which strike the full energy collector electrodes.

The DART calculations of total efficiency with cold ions and secondary electron emission, for two different gas pressures and two different collector voltages, are shown in Table I. These calculations assume that all full energy ions strike the collector electrode. Thus, these are the best estimates for the displayed parameters. The first row are DART runs with a -10 kilovolt collector electrode. The second row is with a -5 kilovolt collector electrode, and the third is without the fractional energy recovery electrode (FRE). The third row also has the -5 kilovolt collector electrode. The FRE is discussed in Section 5.

Background Gas Pressure	2.0 $mTorr$	0.2 $mTorr$
Total Efficiency for -10 kV	72%	75%
And for -5 kV collector	77%	81%
...without frac E electrode	73.5%	78.5%

Table I: DART Direct Converter Efficiency for Corresponding Background Gas Pressures. All full energy ions were collected to get these values. This provides the best case efficiency estimates since losses are neglected.

4 Electron Modelling to Reduce Collector Electrode Potential

We began our studies on variation of the collector electrode potential with a reference value of −10 kilovolts (Paméla's choice).[3] This potential could be reduced to −5 kilovolts before space charge effects reflect the full energy ions.

The potential can be reduced even further by including an electron population in the region just before the collector electrode. We model the electrons with a Boltzmann distribution at a temperature of 10 eV and a potential referenced to the collector voltage. To be able to realistically achieve such an electron population in an experiment, one must add a second electron suppressor between the collector and the exit of the direct converter system. Such a system is depicted in Figure3. The potential for the second suppressor was set at -15 kilovolts to depress the potential completely across the beam.

Only half of the geometry is used from symmetry as was the case in Paméla's studies with the SLAC code[3]. The currents used are the same as Paméla's of 13.6, 1.44, 0.64 for the full(100 keV), half(50 keV), and third(33 keV) energy constituents respectively. These are the final ion currents that actually enter the direct converter. We model them with discrete trajectories, each carrying a fraction of the total current weighted to give a Gaussian profile.

Electrons, on the other hand, are modeled with a Boltzmann distribution given by

$$q_e = A\, exp\left[(\phi - V_g)\frac{1}{T_e}\right], \qquad (1)$$

where V_g is the reference potential, $T_e = 10$ eV is the electron temperature, and A is given by

$$A = \mu\, \bar{q}_i\ . \qquad (2)$$

$\bar{q}_i$ is the average ion charge density taken over a reference area. The reference area is an area in the (x, z) plane which contains enough ion trajectories to match with electrons for quasineutrality. In this case, the reference area is intercepted by ion trajectories just beneath the collector electrode in Figure 3. μ is e^{-3}, and represents the sheath region around an electrode by dropping the potential by a factor of $3T_e$. The second suppressor electrode voltage is -15 kilovolts.

The present version of the DART code allows electrons to be modelled in up to three different regions, each with its own reference potential, V_g. Electrons at the entrance aperature form one region, those at the exit form another, and if the second suppressor exists, a third group can be trapped at the ion collector electrode. The second suppressor electrode is necessary to keep electrons from escaping out the back of the energy conversion

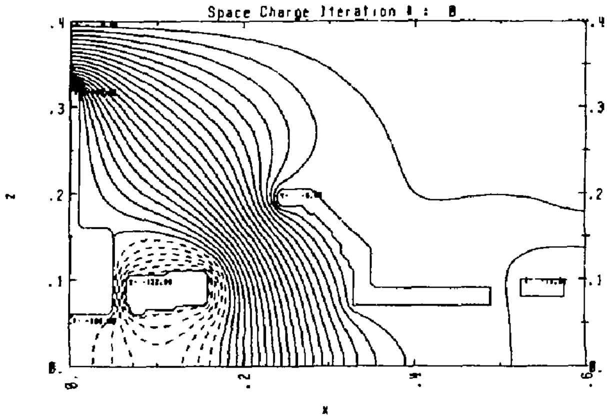

Figure 3: DART model of energy conversion system with second suppressor shown to the far right. The potential on the collector electrode is −5 kilovolts and the potential on the second suppressor is −15 kilovolts. These are the vacuum potential contours.

system. This allows a Maxwellian distribution to accumulate around and just before the the collector electrode.

The efficiency increase should come from the reduced potential difference that this allows between the full energy collector electrodes and ground. The electrons do neutralize space charge build up below the collector in the figures. This allows ions to pass through the now zero electric field region and not be divertd to the collector as they were before. Since a significant fraction of the charged particle beam current is carried by these ions, it has a significant effect on the direct converter efficiency calculations. This is observable in the tables. Table 1 shows higher efficiencies than the later tables for the −5 kilovolt collector potential. This true because the later data includes the electron population. This is the price we pay for attempting to lower the collector voltage to a less negative value. If the ions close to the midplane can be collected, then the second suppressor set provides an advantage. Otherwise, it may not be worth the trouble. We discuss this problem further in Section 9. One solution to this problem may be to increase the potential of the source to around 5 kilovolts. This possibility is discussed further in Section 10.

5 The Proposed Fractional Energy Electrode.

When the half and third energy ions impact a surface, they can generate a large amount of heat. One of Paméla's solutions to the power deposition problem is to install an additional electrode called a fractional energy electrode (FRE). It is set at − 70 kilovolts and is located directly outside of the suppressor. With or without the FRE, the direct converter efficiency would be about the same if cold ions and secondary electrons are neglected.

The geometry used in this study with the FRE included is shown in Figures 4 and 5. The two full energy trajectories that miss the collector in Figure 4 are counted at collected for the calculations in Table I. We will assume that they are NOT collected for the rest of this paper. A discussion of this treatment will appear in Section 9.

Secondary electrons do not appear to make as much of a difference as first anticipated. The cold ions and their secondaries supply the difference in efficiencies for the direct converter design. The path-lengths of the fractional energy ions are shortened which gives rise to fewer cold ions, and consequently, fewer of the cold ion stimulated secondary electrons.

The local electric fields produced by the combination of the FRE and the suppressor tend to hold electrons to the FRE. This can be observed in Figure 4. We should also be concerned about voltage breakdown between the FRE and the suppressor when they are close to one another. The cold ion trajectories and their secondary electrons are shown in Figure 5.

The DART efficiency increase when the FRE is included is about 3-4%, which appears not to be significant enough to warrant including this electrode in the geometry. This translates to a less than 1% contribution to the efficiency of the overall system (see Appendix A).

6 A Flattened Collector Electrode

We may be able to benefit from changing the shape of the full energy collector electrode. A trajectory which intersects this electrode at normal incidence is less likely to be reflected due to space charge build up or due to the collector voltage being moved closer to ground. From trajectory observations, it might be feasible to use a flattened recovery surface to increase the surface area of normal incidence (See Figure 6). Such an electrode would also be easier to manufacture.

The DART simulations show that when the second suppressor set is added and the Boltzmann electrons are present, the flat electrode may capture more of the trajectories closer to the midplane. The electrons must be effectively trapped by the second suppressor for the space charge to be neutralized as it is in this test case. The trajectories and potential contours for a -3 kilovolt collector potential are displayed in Figure 6. The figure shows no difference in the number of trajectories intercepted by the collector electrode, indicating that the DART efficiencies are the same. The angle of incidence for the trajectories closest to the midplane does, however, seem to be improved. Perhaps further electrode shape studies should be carried out.

7 Secondary Electron Scaling

In DART, when we vary the secondary electron emission coefficient for the electrodes, we study the affect on the efficiency of the neutral beams with direct conversion. We present the results from this study in Table II. The secondary electron coefficient (γ) is calculated by

$$\gamma_{DART} = \epsilon\ (0.3)\ \sqrt{E(keV)}\ , \qquad (5)$$

for $E < 100keV$. ϵ is a DART input parameter. ϵ represents the effectiveness of any scheme to reduce the secondary emmission. E is the impacting ion energy. For the Cadarache scheme, we assume $\epsilon = 0.3$.

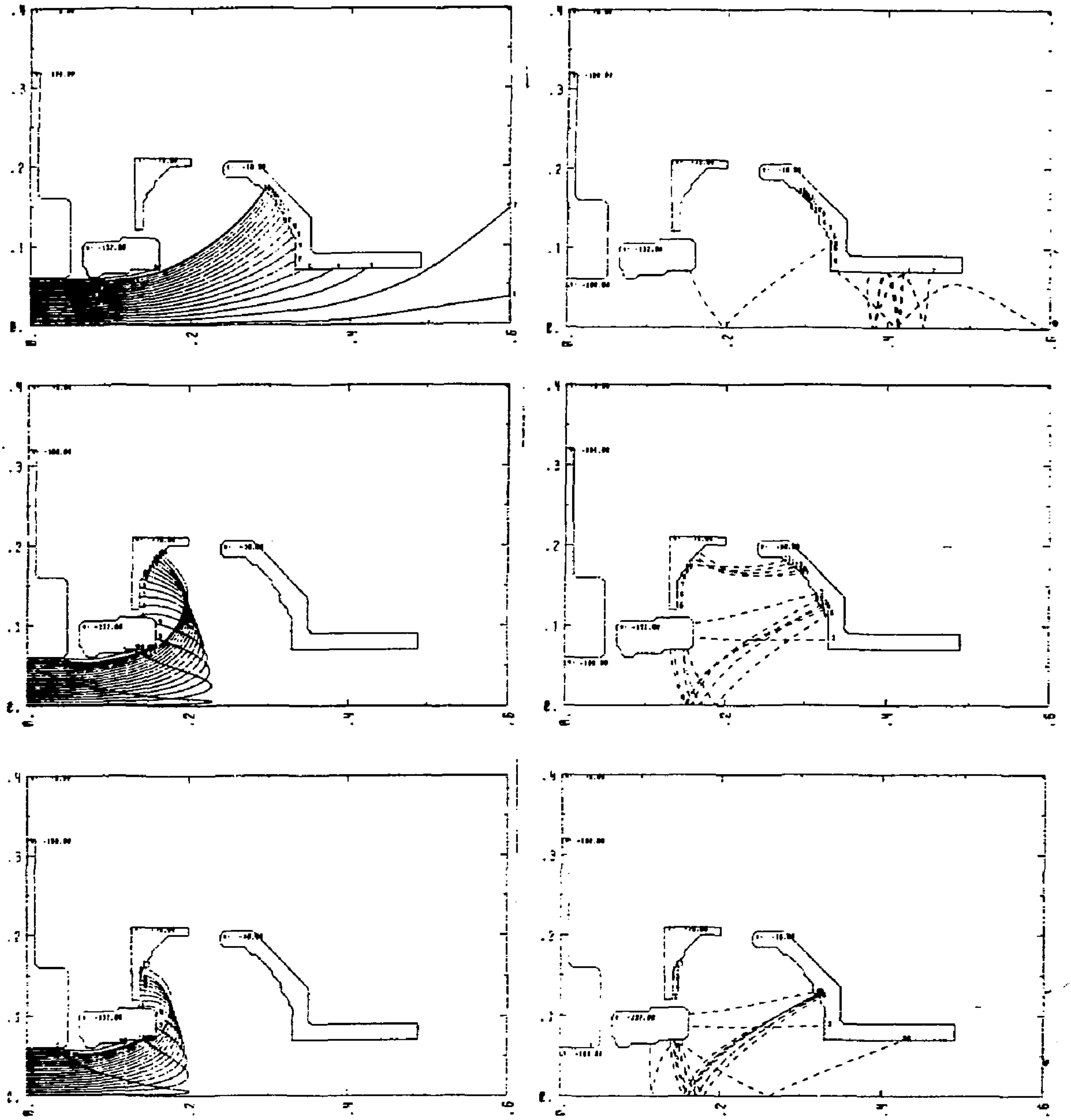

Figure 4: Fractional energy ion trajectories and secondary electrons with the fractional recovery electrode (FRE) present.

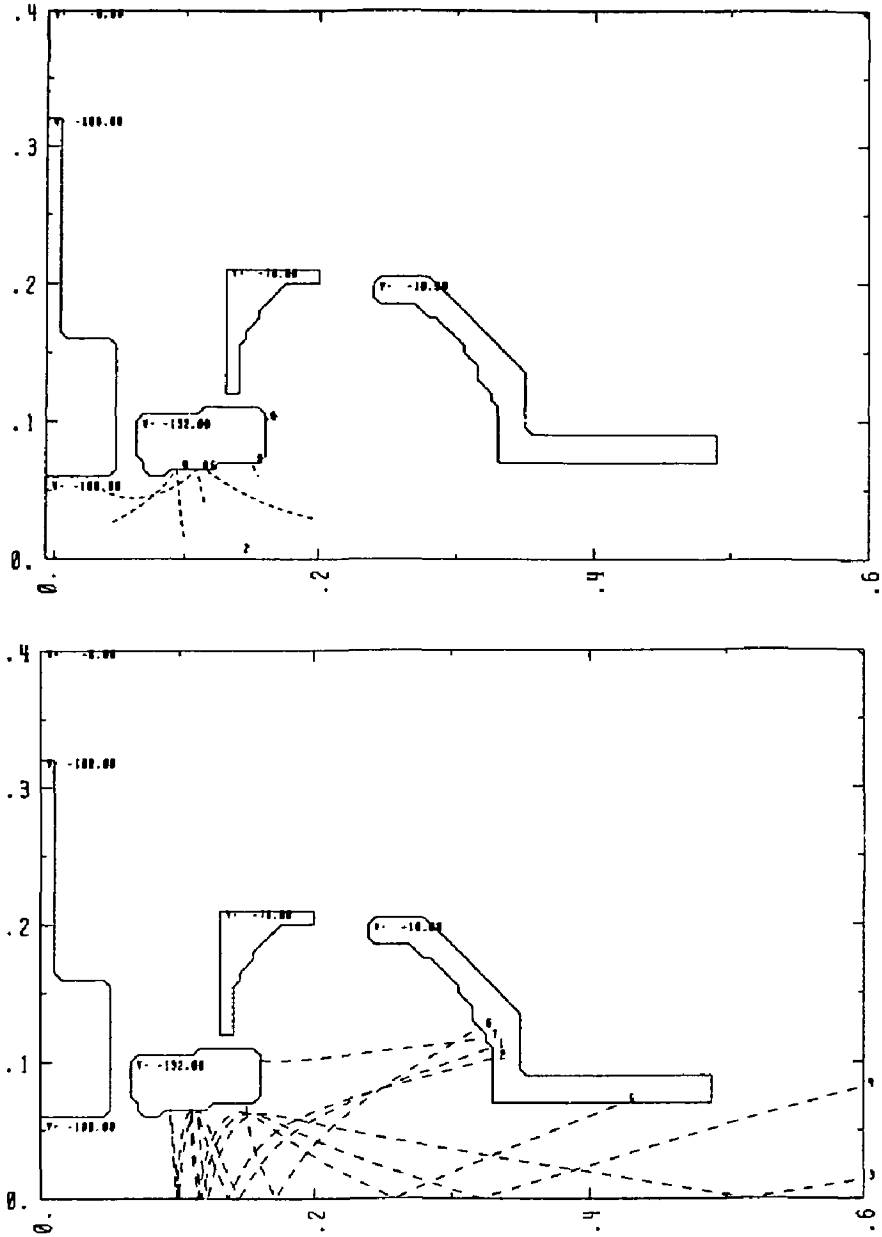

Figure 5: Trajectories of cold ions and their secondary electrons produced by the trajectories in the previous figure.

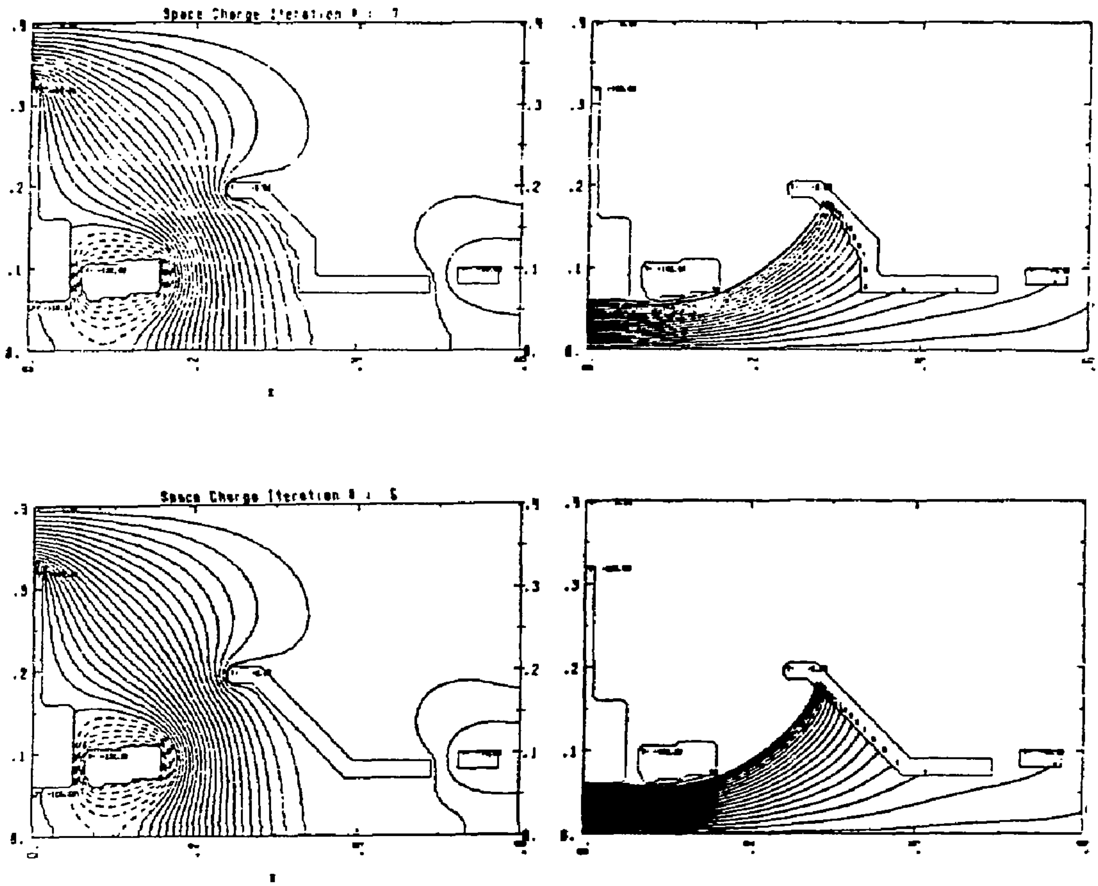

Figure 6: Full energy trajectories and potential contours with curved and flat collector electrodes.

Secondary Electron Coefficient Multiplier ϵ:	0.3	0.5	0.7	0.9
DART direct converter efficiency:	69%	66%	62%	56%
Total neutral beam efficiency:	55%	55%	54%	52%

Table II: DART Direct Converter Efficiency for Different Secondary Electron Yields. Boltzmann electrons and second suppressor present with collector voltage at −5 kilovolts.

Energy Ratio (full:half:third)	D.C. Efficiency	Beam Efficiency
(65:15:20)	46%	50%
(85:10:5)	69%	55%
(90:6:4)	75%	57%

Table III: DART Direct Converter Efficiencies for the Ratios of (full:half:third) Energy Ions. Background gas pressure is 2×10^{-4} Torr. $\epsilon = 0.3$ Collector voltage is -5 kilvolts with a Boltzman electron distribution and second collector set.

η table	Collector at -5 kV :	with FRE :	Full E at 90% :
Initial beam	75%	75%	77%
With cold ions and sec e's...			
$P = 2 \times 10^{-4}$Torr:	69%	72%	75%
Overall Beam η_{NBI}:	55%	56%	57%
$P = 2 \times 10^{-3}$Torr:	64%	67%	71%
Overall Beam η_{NBI}:	54%	55%	56%

Table IV: DART Direct Converter Efficiency and Overall Neutral Beam Efficiency (See Appendix A). Collector voltage is -5 kilvolts with a Boltzman electron distribution and second collect-- set.

8 Partial Energy Fraction (Source) Considerations

Paméla's results were based on extracted fractions of (85:10:5) and (65:15:20) for (full:half:third) energy ions. Although simulations thus far use the former ratio, the latter could be used to simulate poor beam quality and to get an idea how much the efficiency is effected by such. We calculate DART direct converter efficiencies for both of these cases and for a (90:6:4) ratio. These ratios are translated to currents for input to DART assuming a 40 amp beam, 80% transmission, and neutralization fractions of (0.5,0.55,0.6) respectively. The formula used for the current calculation is:

$$I_j = 40\,(.80)(1 - \zeta_i)(f_i)\,, \qquad (4)$$

with ζ_i as the neutralization fraction, and f_i as the fraction of the ith species (i.e. $\zeta_1 = 0.5$ and $f_1 = .85$ give $I_1 = 13.6$ amps for the current input for the full energy ion species).

The efficiency results are shown in Table III. These calculations were done with a collector voltage of -5 kilovolts, a background gas pressure of 2×10^{-4} Torr, and with the second suppressor installed. The secondary electron coefficient multiplier, $\epsilon = 0.3$.

The overall beam efficiency calculations are based on Paméla's estimates, and details are in Appendix A.

8.1 A Worst Case Example

If we gather together all of the negative effects to get a "worst case", we could see how bad the efficiency is affected. When we ran DART with a cold ion background pressure of

2×10^{-3} Torr, a secondary electron coefficient multiplier of $\epsilon = 0.9$, and a (full:half:third) energy ratio of (65:15:20), we got a direct converter efficiency of $\eta_{dc} = -44\%$, which indicates an overall neutral beam injector efficiency of $\eta_{NBI} = 56\%$. The secondary electrons from the third energy ion impacts on the suppressor are largely responsible for the poor performance.

9 Discussion of Lost Trajectories

In an effort to model the neutral beam system, we left the wall on the right-hand side open to permit the neutral beam to exit. This gave rise to the question: how do we measure efficiency when charged ions exit through this hole? The efficiency calculations rely on the answer to this question.

DART does not record current from trajectories which are not collected. This has the effect of assuming that these ions return to the neutralizer (100 kilovolts in the Cadarache system). True ion trajectories are likely either to be reflected around the collector electrode and impact the left-hand wall (at -100 kV), or to be reflected along the axis to the accelerator. In these cases, the efficiencies do not need to be changed. If however the ions are collected at near ground potential, they will improve the efficiency estimate. This is an important factor due to the Gaussian profile assumed for the beam current. Those trajectories close to the midplane (bottom of the figures) carry the greatest amount of current per trajectory. When 20 trajectories are used to represent half of the full energy beam, each trajectory which escapes degrades the DART direct conversion efficiency by 3.5%.

10 The Source at a Higher Potential

The losses due the to noncollected ions, and the consequential degradation in efficiency, may be offset by an alternative acceleration setup. If the source was maintained at 5 kilovolts above ground, the ions that pass by the collector can be collected downstream in the grounded recovery region. We now consider the netralizer at -95 kilovolts, the suppressor electrode at -127 kilovolts, and the collector at ground. Since the losses described in Section 9 do not occur, the increase in efficiency proposed by the addition of a second suppressor in Section 4 may be realized.

With the electrode potentials described above, a background gas pressure of 2×10^{-4} Torr, a secondary electron coefficient multiplication factor of $\epsilon = 0.3$, and an energy distribution ratio of (85:10:5), the direct conversion efficiency is $\eta_{dc} = 82\%$ which equates to an overall neutral beam injection efficiency of $\eta_{NBI} = 59\%$.

11 Summary

Minimizing background gas density, secondary electron yield, and fractional energy ions are all important in improving the direct converter efficiency. Modifications to the collector electrode could also be useful. These modifications did not result in a substantial improvement in the overall neutral beam efficiency, but this reflects the good choice in starting parameters made by Paméla et al. These studies may still provide useful information, and should be used in further design considerations.

Some of the DART calculations are is displayed in Table IV. These calculations were done with -5 kilovolts on the collector electrode and a Boltzmann distribution of electrons referenced to −5 kilovolts. The potential on the second suppressor was −15 kilovolts. They include loss of full energy ions which were not collected as described in Section 9. Putting the source at 5 kilovolts above ground helps to insure collection of all or most of the full energy ions, and may be worhwhile to consider.

Acknowledgments:

I would like to thank Ralph Moir and Bill Barr for their continuing discussions and education on direct converters. Also, I thank Jerome Paméla and Michel Fumelli for their conversations.

References

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A Calculation of Beam Efficiency from DART Results.

The total efficiency of the neutral beam prototype can be inferred from the direct conversion efficiency calculated by the DART code. An analysis of the overall system will involve this total efficiency. Since the power required to accelerate the initial beam is 4 megawatts, and other power to needed to operate the source and accelerator system (i.e. arc, filament, magnets) is roughly 160 kilowatts, the total power required is about 4.16 megawatts. Thus, with the direct converter system, the total electrical power spent is

$$P_{NBI} = 4.16\ MW - P_{dc}\ , \tag{5}$$

where P_{dc} is the electrical power recovered in the direct converter. The definition of P_{dc} is:

$$P_{dc} = \sum_{i=1}^{n} I_i V_i - V_{ref}\ , \tag{6}$$

where I_i is the current collected on the ith electrode, V_i is the potential on the ith electrode, V_{ref} is the reference voltage at which ions enter the direct converter (−100 kilovolts) and n is the total number of electrodes. The efficiencies are given by:

$$\eta_{dc} = \frac{P_{dc}}{P_{elec}} \qquad \eta_{NBI} = \frac{P_n}{P_{NBI}}\ . \tag{7}$$

P_{elec} is the initial electrical (non-neutral) power in the beam, and P_n is the neutral power given by

$$Pn = Tr \, \zeta \, I_d \, V_a \, , \tag{8}$$

with

Tr : beam transmission efficiency (0.80)

ζ : neutralization efficiency (0.55)

I_d : drain current (40 A)

V_a : accelerator voltage (100 kV)

The above notation and values are taken from Paméla[3]. The beam transmission efficiency includes losses in the accelerator gap and backsteaming electrons. From the above equations, we can write

$$\eta_{NBI} = \frac{P_n}{4.16\,MW - P_{elec}\eta_{dc}} \tag{9}$$

$$\eta_{dc} = \frac{1}{P_{elec}}\left(4.16\,MW - \frac{P_n}{\eta_{NBI}}\right). \tag{10}$$

Equation 10 indicates that $\eta_{NBI} = 54\%$ (Paméla's η_{ers}) corresponds to DART's $\eta_{dc} = 63\%$. The above formulas are used to obtain the η_{NBI} values found in the tables in this report.