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By

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ABSTRACT

The effect on neutral-beam design and reactor performance of using high-energy (~ 3-10 MeV) tritium neutral beams to drive steady-state tokamak reactors is considered. The lower current of such beams leads to several advantages over lower-energy neutral beams. The major disadvantage is the reduction of the reactor output caused by the lower current-drive efficiency of the high-energy beams.

I. INTRODUCTION

Steady-state tokamak reactors based on neutral beam current drive will be commercially attractive only if the neutral beam system has both high electrical efficiency and high current-drive efficiency.[1] Neutral beams using electrostatic accelerators have the potential for high electrical efficiency, and new designs[2] may permit the use of acceleration voltages high enough ($\sim$ 1 MV) to produce a respectable current-drive efficiency. On the other hand, existing types of rf accelerators[3-5] could be used to produce beam energies of 1-2 MeV/amu which maximize the current-drive efficiency, but the electrical efficiency of these accelerators is relatively low. With even higher beam energies, the current-drive efficiency changes very little; thus the required beam current drops, thereby alleviating several beam system design problems. In the present work, we discuss the major beam technology issues and the reduction in reactor performance caused by raising the beam energy. These estimates provide a guide for beam designers in determining whether the beam system advantages (which are design dependent) are sufficient to offset the reactor performance disadvantages.

We have found that using tritium, rather than deuterium, neutral beams minimizes the disadvantages of raising the beam energy and maintains the advantages of reducing the beam current. This result occurs because replacing deuterium with tritium at a given beam *speed* raises the current-drive efficiency slightly while reducing the current (at fixed power) by a third. We have, therefore, considered only high-energy tritium neutral beams, although tritium causes some problems in beam system design.[6]

II. NEUTRAL BEAM ISSUES

A. Hydrogen isotope choice

Once one has chosen beam energies that are sufficiently high then rf acceleration is required, and the criterion for beam penetration is inverted with respect to the situation that customarily prevails when using electrostatic acceleration. The difficulty associated with electrostatic acceleration is a strongly increasing function of beam energy. Hence deuterium rather than tritium is used for the beam isotope, since the particle energy, and thus the voltage, required for a given degree of plasma penetration is 50% greater for tritium than for deuterium. With an rf accelerator, increasing the beam particle energy is less difficult; the accelerator simply becomes longer if the other parameters are kept about the same. With an rf accelerator, it is desirable to minimize the current, which simplifies the design of both the accelerator resonator and the negative ion sources. Just as deuterium is the logical choice with an electrostatic accelerator, it appears that the different constraints associated with an rf accelerator make tritium the most desirable hydrogen isotope. For a permitted value of shinethrough, each tritium atom can carry 50% more energy than deuterium. Consequently, the current required to deliver a given power can be reduced by one third, which is the principal benefit of using tritium.

B. Advantages and disadvantages

By simply lengthening an rf accelerator one can increase the beam particle energy, and thereby reap several benefits. For a fixed beam power, increasing the beam energy reduces the required negative ion current. A good low energy (~ 200 keV to 1-2 MeV) accelerator, the radio-frequency quadrupole (RFQ),[3] could be followed by a higher efficiency rf accelerator to raise the overall electrical efficiency. Finally, the stripping and ionization cross sections are lower at higher energy, so higher pressure in the post-acceleration drift ducts and neutralizer can be tolerated.

Lowering the negative ion current has several benefits. Fewer ion sources are needed and there is less total gas flow, hence, less high-vacuum beam-system pumping needed. If the current per beamline is maintained, the neutralizer efficiency is increased, while the number of beamlines and tokamak shielding penetrations and the amount of neutral beam shielding may be reduced.

The lower vapor pressure of T_2 relative to D_2 is a potential benefit of tritium. With cryocondensation pumps at 4.2° K, the vapor pressure of both deuterium (4×10^{-11} Torr) and tritium ($\sim 2 \times 10^{-13}$ Torr) is very low.[7] However, with higher temperature pumps (e.g., cryosorption pumps), the difference in vapor pressure may be a real advantage.

Kim and Stewart[6] have discussed several disadvantages of tritium neutral beams at energies of 150 keV with an electrostatic accelerator. Cryocondensation pumps might need to be regenerated more frequently to reduce the β-decay heat load, but with continuously regenerating pumps[8] beam operation need not be interrupted. They found that tritium inventory might be a problem with high-current beamlines.[6] However, we are considering currents roughly 100 times lower and tritium inventory is likely to be a minor consideration. Neutral beams in a reactor environment will be radioactively contaminated and must be remotely maintained whether or not tritium is used.

As an upper limit, if all of the energy resulting from the β decay of tritium were deposited in the cryopanel and its frost, the additional heat load would be 0.997 W/mole of accumulated tritium.[7] For example, if one had a 3 A T^- source with a 20% gas efficiency, which appears to be an obtainable figure,[9] then the β-decay heat load would increase at a rate of 0.6×10^{-4} W/sec of beam operating time. This appears to be satisfactory for any pulsed beam applications, and would very probably be tolerable for steady-state applications, because even with deuterium beams the cryopanels would have to be purged periodically.

For a given energy, tritium has a lower speed than deuterium by a factor of $(2/3)^{1/2}$, and will take a longer time to move out of the beam path and reach the cyropumps. For a fixed current and ion-source gas efficiency (see below), the gas density in the beamline will be raised by a factor of $(3/2)^{1/2}$, which does not pose a large problem.

The D^- sources now being developed[10-12] could be used as T^- sources. If there is a mass dependence[10] in the negative ion yield, the brightness of the source may be $(3/2)^{1/2}$ less for T^- than for D^-. Since the gas flow from the ion source is reduced by the same factor, the gas efficiency would be unchanged. As a consequence of the reduction in source brightness, the source emittance per unit of beam current will be proportionately larger. Even if this occurs, the change in the total beam emittance will be a smaller factor because the emittance growth in the rf accelerator should be little changed. Moreover, the source brightness might not decrease as the isotope mass increases. To the extent that negative ion production processes depend on ion velocities (which seems likely, although momentum could play a role in surface-plasma sources), it should be possible to remove the mass dependence of source brightness and emittance by increasing the appropriate accelerating potential by 50%. In a surface plasma source, for instance, the potential between the converter plate and the plasma could be increased, which would increase the flux of positive ions to the plate. The practicality of raising this potential would depend on whether the additional power loading on the converter could be tolerated, and on whether the increased potential could be held without breakdowns.

The rf accelerators being considered for producing high-energy beams of deuterium or light impurities[4,5] could be used to produce high-energy tritium beams. The RFQ accelerator[3] is being developed at Los Alamos Scientific Laboratory for a variety of possible applications. A Multiple Electrostatic Quadrupole Linac, MEQALAC,[5] has been designed at Brookhaven National Laboratory. Either of these accelerators could be used, after an electrostatic pre-accelerator, to bring the beam up to multi-MeV energies. After acceleration to 1-2 MeV/amu by an RFQ, a drift tube linac would be able to handle the high current, and it could probably be made more power efficient than the RFQ.[13]

On the whole, it appears that using tritium, rather than deuterium, is a very simple and cost-effective way of improving the feasibility and attractiveness of radio-frequency-accelerated hydrogen-isotope beams.

III. REACTOR PERFORMANCE

We use a simple reactor model[1] to evaluate the use of high-energy neutral beams in beam-driven steady-state tokamak reactors. As a preliminary, we estimate the maximum allowable impurity contamination of the plasma. Then the reactor model is described and the reduction in reactor output caused by increasing the beam energy is calculated. This result is then used to estimate the level of beam cost reduction and beam efficiency increase which would be required to offset the reactor output reduction.

A. Impurity limits

As the beam energy is raised above 1-2 MeV/amu, the resulting decrease in current-drive efficiency is due primarily to increasing beam shinethrough. The plasma could be made more "opaque" by raising the density, but with β fixed the current-drive efficiency is reduced drastically. It is less harmful to increase the plasma opacity by adding impurities to raise the effective ionization cross section, σ_{eff} (See Ref. 1 for references concerning cross sections).

The two major deleterious side effects of adding impurities are: they radiate strongly (thereby cooling the plasma), and they reduce the fusion power by "diluting" the reacting fuel species. Using low Z impurities minimizes the impurity radiation power loss, while using high Z impurities minimizes the fusion power loss. The impurity limits due to radiative power loss in a 0-d plasma[14] are expressed as Z_{eff} limits in Table I for T_e = 10 and 15 keV. These limits are for strongly heated Q = 10 plasmas and are *consequently higher than the limits for ignited plasmas.*

We have used the BALDUR[15] plasma transport code to include the effect of temperature profiles on the Z_{eff} limits. Impurities were slowly added to an INTOR plasma with $\langle n_e \rangle = 1.5 \times 10^{14} cm^{-3}$ and $\langle T_e \rangle_n \sim 15$ keV heated by 100 MW of 10 MeV T^o beams. Although the impurity density was a constant function of radius, the strong temperature dependence of the radiative power loss[16] causes the radiation power density to peak near the edge. The Z_{eff} limit was determined by the onset of thermal collapse in the edge plasma (Table I).

It appears that $Z_{eff} \sim 2$-5 may be sustainable for impurities in the range of iron to tungsten. The 1-d limits depend sensitively on the size of the low temperature edge plasma and the impurity concentration there. The limits in the hotter bulk of the plasma, which is where the neutral beam ionization cross section must be increased, are certainly high enough for our purposes.

B. Reactor model

In the evaluation of high-energy tritium beams there are a number of issues that must be considered. By using tritium instead of deuterium the pitch angle scattering is reduced and, at the optimal beam speed, the current-drive efficiency is increased by ~ 5%. By raising the tritium beam energy above the optimal energy of ~ 3-5 MeV, the current-drive efficiency is reduced and the shinethrough is increased. By adding impurities to reduce the shinethrough and raise the current-drive efficiency, the fusion power is reduced by fuel dilution. The reduced current-drive efficiency raises the required beam power, which combines with the reduced fusion power to lower the net electrical output of the reactor.

To account for these effects quantitatively and to determine the optimized plasma conditions, we have used a numerical reactor model which includes plasma power balance, electrical power accounting, and cost estimates.[1] The 0-d plasma power balance calculation includes transport losses, beam and alpha heating, and ion-electron temperature equilibration. The electrical power needed to run the beams and other systems is subtracted from gross electrical production to obtain the net electrical output. To introduce a degree of economic realism into the model, we estimate the cost of total plant and the figure of merit that is optimized is the cost per unit of net electrical output. Our original reactor model[1] has been extended to include a finite upper limit on the ion-energy confinement time of five times the electron-energy confinement time. We have applied the model to INTOR (see Ref. 1, for INTOR parameters) and STARFIRE[17] (see Table II for STARFIRE parameters).

The improvements in beam cost and efficiency that may be possible with higher-energy tritium beams cannot be quantitatively estimated at this time. Therefore, the reactor optimization calculations were done with constant beam cost (per MW) and beam efficiency. These results are interpreted in the next section to derive estimates of the cost and efficiency improvements necessary to offset the reactor output reduction described above. Current estimates of rf-based beam cost and efficiency are unattractive;[1] we have used a cost of $C_b = 3\ W^{-1}$ and efficiency of $\eta_b = 0.6$ on the grounds that they would be minimum requirements for commercial reactor applications.

IV. RESULTS

For INTOR and STARFIRE, with $\beta = 6.7\%$ and 10%, the plasma density, temperatures, and Z_{eff} were varied to find the optimal reactor output for tritium beams with $3\ \mathrm{MeV} \leq E_b \leq 15\ \mathrm{MeV}$ (Fig. 1). The results for each trial value of Z_{eff} are shown for INTOR with $\beta = 6.7\%$. Despite the use of tungsten as the impurity, the effects of fuel dilution are quite evident in the Z_{eff} dependence of C_W for $E_b \sim 3$ MeV. As expected, higher Z_{eff} is beneficial for higher beam energies, and raising the beam energy (with constant C_b and η_b) increases C_W.

Only the results for the best choice of Z_{eff} are shown in the other three cases, where the higher densities and larger plasma reduce the shinethrough losses (and, hence, reduce the Z_{eff} dependence) and increase the gross electrical power, thereby reducing the recirculated power fraction and the dependence on E_b. The optimal Z_{eff} is modest and appears attainable.

The asterisks in Fig. 1 mark the optimized results for the 800 keV D^0 electrostatic beam system designed for FED-A,[18] with $C_b = 2.6\ W^{-1}$ and $\eta_b = 0.7$. These results are competitive in spite of the lower current-drive efficiency of 800 keV D^o; this illustrates the need for high electrical efficiency in rf accelerator-based beams.

The effect of beam improvements on C_W can be easily estimated from the fractional beam cost (f_c = beam cost/total reactor cost) and the fractional beam power consumption (f_e = beam electrical consumption/net electrical power) (Table III). If, for example, the beam system cost at 9 MeV is lowered by 10% and the efficiency is raised by 5%, then the reduction in C_W for INTOR with β = 6.7% would be ΔC_W = 10% × 0.20 + 5% × 0.58 ≈ 5%, which is half of what is needed to reduce C_W at 9 MeV to C_W at 3 MeV. The same beam improvements are sufficient to reduce C_W at 9 MeV below the optimal C_W for the other three cases shown in Table III. Improvements in beam cost are increasingly effective for higher β and larger tokamaks, while improvements in efficiency are very important for low β INTOR and become less important with higher β and larger tokamaks.

V. CONCLUSIONS

Using 3 MeV T beams in place of 2 MeV D beams raises the current-drive efficiency by about 5% with no increase in beam shinethrough. If the consequent reduction in beam current permits improvements in beam design that offset the disadvantages associated with tritium's radioactivity, then the tritium beams would be preferred.

Raising the beam energy above the optimum for current drive (~ 3-5 MeV tritium) reduces the reactor output. With sufficient improvements in beam cost (~ 10-20%) and efficiency (~ 5%), higher energy (~ 10 MeV) tritium beams would be preferred.

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TABLE I. Maximum permissible Z_{eff}.

Impurity (Z)	Z_{eff} Limit		
	0-d (Q = 10)		1-d
	T_e=10 keV	T_e=15 keV	
Fe (26)	3.1	6.2	3.0
Kr (36)			2.9
Mo (42)	3.8	7.9	2.7
Xe (54)			2.3
W (74)	2.0	5.3	1.9

TABLE II. STARFIRE reactor parameters.

V_E	5150 m^3
A_W	740 m^2
R_o	7.0 m
a	1.94 m
b/a	1.6
I_p	10.1 MA
B_o	5.8 T
Q^*_{ie}	[a]59 MW
τ^*_{INTOR}	[b]4.4 sec

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[a] Scaled by $R_o ab$ from INTOR, see Ref. 1.

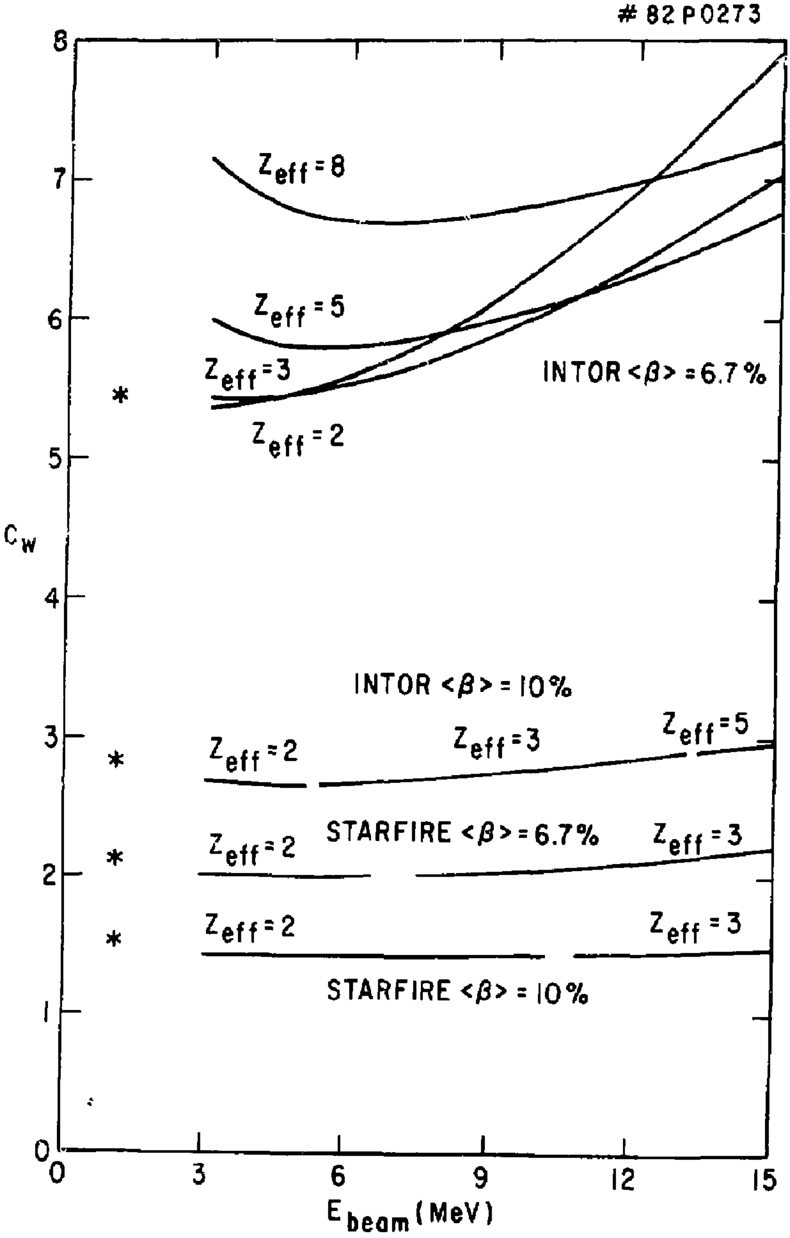
[b] Scaled by a^2 from INTOR, see Ref. 1.

TABLE III. Fractional beam cost and power consumption.

	$\langle\beta\rangle$	f_c	f_e	E_{opt}	$\frac{C_W(9\ \text{MeV})}{C_W(E_{opt})}$
		(9 MeV)		(MeV)	
INTOR	6.7%	0.20	0.58	3	1.10
	10%	0.21	0.25	4	1.04
STARFIRE	6.7%	0.21	0.19	4.5	1.04
	10%	0.18	0.10	5	1.01

FIGURE CAPTION

FIG. 1. The optimized cost per unit of electrical output, C_W, versus tritium beam energy for INTOR and STARFIRE with plasma β of 6.7% and 10%. The asterisks denote the optimized C_W if 800 keV deuterium beams are used (see text for details).



82 P0273
C_W
E_{beam} (MeV)
0
3
6
9
12
15
0
1
2
3
4
5
6
7
8
Z_{eff} = 8
Z_{eff} = 5
Z_{eff} = 3
Z_{eff} = 2
INTOR <β> = 6.7 %
INTOR <β> = 10%
Z_{eff} = 2
Z_{eff} = 3
Z_{eff} = 5
STARFIRE <β> = 6.7%
Z_{eff} = 2
Z_{eff} = 3
Z_{eff} = 2
Z_{eff} = 3
STARFIRE <β> = 10%

FIG. 1

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