200
11-1-74

DR 1044

UCRL-51650

POWER EFFICIENCIES OF NEUTRAL BEAM SYSTEMS

J. H. Fink

September 11, 1974

Prepared for U.S. Atomic Energy Commission under contract No. W-7405-Eng-48

**LAWRENCE
LIVERMORE
LABORATORY**

University of California/Livermore

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

NOTICE

"This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, 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."

Printed in the United States of America
Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy \$ *; Microfiche \$1.45

<u>*Pages</u>	<u>NTIS Selling Price</u>
1-50	\$4.00
51-150	\$5.45
151-325	\$7.60
326-500	\$10.60
501-1000	\$13.60

**TID-4500, UC-20
Controlled Thermonuclear Processes
and Plasma Physics**

LAWRENCE LIVERMORE LABORATORY
University of California, Livermore, California 94550

UCRL-51650

POWER EFFICIENCIES OF NEUTRAL BEAM SYSTEMS

J. H. Fink

MS. date: September 11, 1974

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, 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.

MASTER

List of Symbols

No. 1

D^0	D^0 : neutral atomic deuterium current
D_2^0	$(D_2^0 + D_3^0)$: neutral molecular deuterium current
D^+	D^+ : positive atomic deuterium ion current
	$(D_2^+ + D_3^+)$: positive molecular deuterium ion current
D^-	D^- : negative atomic deuterium ion current
D_2^-	$(D_2^- + D_3^-)$: negative molecular deuterium ion current
F_A	F_A : the fraction of a positive atomic deuterium ion beam that can be neutralized by repeated passes through an ideal neutralizer.
$F_{\bar{A}}$	$F_{\bar{A}}$: the fraction of a negative atomic deuterium ion beam that can be neutralized by repeated passes through an ideal neutralizer
F_{0+}	F_{0+} : the fraction of a positive atomic deuterium ion beam that can be neutralized in a single pass through an ideal neutralizer
F_{0-}	F_{0-} : the fraction of a negative atomic deuterium ion beam that can be neutralized in a single pass through an ideal neutralizer
I^+	I^+ : the total positive deuterium ion current extracted from an ion source
N	N : the number of times the ion beam is recycled through the neutralizer cell
P_A	P_A : the arc power required for the ion source; incorrectly assumed to be on only during the beam pulse
P_H	P_H : the neutral atomic deuterium beam power
P_{HT}	P_{HT} : the neutral atomic plus molecular deuterium beam power
P_f	P_f : the filament power required for the ion source; incorrectly assumed to be on only during the beam pulse
P_{IN}	P_{IN} : the total power input to the system including the arc power, the filament power, and the power required to accelerate the beam
P_{L1}	P_{L1} : the power lost at the first magnetic separator
P_{L2}	P_{L2} : the power lost at the second magnetic separator
P_R	P_R : the unused beam power that is recovered
eV	eV : the energy of the final beam
eV_P	eV_P : the beam energy coming from the source
eV_{PA}	eV_{PA} : the beam energy added by post acceleration
η_1	η_1 : the fraction of positive atomic deuterium ions in the beam, as extracted from the source

- η_- = the fraction of a positive atomic deuterium ion beam that becomes negative through double charge exchange in a cesium or sodium vapor cell
- ϵ_1 = the fraction of beam energy, lost at the first separator, which is recovered
- ϵ_2 = the fraction of beam energy, lost at the second separator, which is recovered
- ϵ_L = the fraction of an ion beam that is effectively retained through a single pass around an ion beam recycling unit

POWER EFFICIENCIES OF NEUTRAL BEAM SYSTEMS

Abstract

The power efficiencies of several neutral beam systems are presented as functions of beam energy. Direct injection systems are found to be most efficient at

low beam energies while negative ion systems are best at high energies. In the intermediate range, post acceleration is best.

Introduction

Although there are many ways to evaluate a neutral beam system, an elementary comparison of the power efficiencies of three concepts of neutral beam generation (i.e., direct injection, Figs. 1, 2, and 3; post acceleration, Figs. 4, 5, and 6; and negative ion conversion, Figs. 7, 8, and

and 9) is presented, along with two methods of enhancing their efficiencies (i.e., unused beam power recovery and ion beam recycling. For each of these schemes, as well as for several combinations of them, efficiencies were calculated over a range of beam energies from 20 to 240 keV.

Assumptions

Since most of these systems have never been tried, certain assumptions had to be made to evaluate their performance. These assumptions are:

- First, an ion source of the Berkeley type¹ was considered typical. It consists of 86 filaments, each requiring 25 A at 12 V, and is operated with a 3000-A arc at 50 V to deliver a 70-A ion beam that is roughly 75% atomic deuterium. Thus,

$$\eta_1 = 0.75.$$

Although the operating period of the filament and arc is longer than that of the beam, the following approximation was used:

$$\frac{P_f + P_A}{I^+} = 2.5 \text{ kW A}^{-1}.$$

This simplifies the analysis while it does not make much difference at the beam energies of interest.

- To obtain negative ions via a process of double charge exchange, in a cesium cell,² it was assumed that the incident ion beam is extracted from the source at

$$V_E = 1.75 \text{ kV},$$

resulting in a fraction of negative ions such that

$$\eta_- = 0.2.$$

Schematic Diagram

Ion source

ηI

Neutralizer cell

$F_{0\infty}$

Ion beam loss

Magnetic separator

Target

Pertinent Relationships

	Current (A)	Power (kW)
Target	$D^0 = \eta_1 F_{0\infty} I^+$ $(D_2^0 + D_3^0) = (1 - \eta_1) F_{0\infty} I^+$	$P_B = D^0 V$ $(P_{BT} - P_B) = (D_2^0 + D_3^0) V$
Ion beam loss	$D^+ = \eta_1 (1 - F_{0\infty}) I^+$ $(D_2^+ + D_3^+) = (1 - \eta_1)(1 - F_{0\infty}) I^+$	$P_L = (1 - F_{0\infty}) I^+ V$
Power input		$P_{IN} = P_f + P_A + I^+ V$

Performance

Fig. 1. Direct injection.

Schematic Diagram

Pertinent Relationships

	Current (A)	Power (kW)
Target	$\begin{cases} D^0 = \eta_1 F_{o\infty} I^+ \\ (D_2^0 + D_3^0) = (1 - \eta_1) F_{o\infty} I^+ \end{cases}$	$\begin{aligned} P_B &= D^0 V \\ (P_{BT} - P_B) &= (D_2^0 + D_3^0) V \end{aligned}$
Ion beam loss	$\begin{cases} D^+ = \eta_1 (1 - F_{o\infty}) I^+ \\ (D_2^+ + D_3^+) = (1 - \eta_1) (1 - F_{o\infty}) I^+ \end{cases}$	$P_L = (1 - F_{o\infty}) I^+ V$
Power input		$P_{IN} = P_f + P_A + I^+ V$
Power recovery		$P_R = \epsilon (1 - F_{o\infty}) I^+ V$

Performance

Fig. 2. Direct injection with unused beam power recovery.

Schematic Diagram

Pertinent Relationships

	Current (A)	Power (kW)
Target	$D^0 = \eta_1 F_A I^+$ $(D_2^0 + D_3^0) = (1 - \eta_1) F_{\infty} I^+$	$P_B = D^0 V$ $P_{BT} = (D^0 + D_2^0 + D_3^0) V$
Ion beam loss	$D^+ = \eta_1 (1 - F_A) I^+$ $(D_2^+ + D_3^+) = (1 - \eta_1)(1 - F_{\infty}) I^+$	$P_L = [(1 - \eta_1)(1 - F_{\infty}) + \eta_1 (1 - F_A)] I^+ V$
Power input		$P_{IN} = P_f + P_A + I^+ V$

$$F_A = (F_{\infty}) \left[\frac{1 - [\epsilon_L (1 - F_{\infty})]^N}{1 - \epsilon_L (1 - F_{\infty})} \right]$$

Performance

Fig. 3. Direct injection with ion beam recycling.

Schematic Diagram

Pertinent Relationships

	Current (A)	Power (kW)
Target	$D^0 = \eta_1 F_{0\infty} I^+$	$P_B = \eta_1 F_{0\infty} I^+ V$
First separator loss	$(D_2^+ + D_3^+) = (1 - \eta_1) I^+$	$P_{L1} = (1 - \eta_1) I^+ V_E$
Second separator loss	$D^+ = \eta_1 (1 - F_{0\infty}) I^+$	$P_{L2} = \eta_1 (1 - F_{0\infty}) I^+ V$
Power input		$P_{IN} = P_f + P_A + I^+ V_E + \eta_1 I^+ V_{PA}$

$$(V_{PA} = V - V_E)$$

Performance

Fig. 4. Post acceleration system.

Schematic Diagram

Pertinent Relationships

	Current (A)	Power (kW)
Target	$D^0 = \eta_1 F_A I^+$	$P_B = \eta_1 F_A I^+ V$
First separator loss	$(D_2^+ + D_3^+) = (1 - \eta_1) I^+$	$P_{L1} = (1 - \eta_1) I^+ V_E$
Second separator loss	$D^+ = \eta_1 (1 - F_A) I^+$	$P_{L2} = \eta_1 (1 - F_A) I^+ V$
Power input		$F_{IN} = P_f + P_A + I^+ V_E + \eta_1 I^+ V_{PA}$
Power recovery		$P_R = \epsilon_1 (1 - \eta_1) I^+ V_E$

Performance

Fig. 5. Post acceleration system with ion beam recycling.

Schematic Diagram

Pertinent Relationships

	Current (A)	Power (kW)
Target	$D^0 = \eta_1 F_{0.00} I^+$	$P_B = \eta_1 F_{0.00} I^+ V$
First separator loss	$(D_2^+ + D_3^+) = (1 - \eta_1) I^+$	$P_{L1} = (1 - \eta_1) I^+ V_E$
Second separator loss	$D^+ = \eta_1 (1 - F_{0.00}) I^+$	$P_{L2} = \eta_1 (1 - F_{0.00}) I^+ V$
Power input		$P_{IN} = P_f + P_A + I^+ V_E + \eta_1 I^+ V_{PA}$
Power recovery		$P_R = \epsilon_1 P_{L1} + \epsilon_2 P_{L2}$

Performance

Fig. 6. Post acceleration system with unused beam power recovery.

Schematic Diagram

Pertinent Relationships

	Current (A)	Power (kW)
Target	$D^0 = \eta_1 \eta_- F_{Q\infty} I^+$	$P_B = \eta_1 \eta_- F_{Q\infty} I^+ V$
First separator loss	$D^+ = \eta_1 (1 - \eta_-) I^+$ $(D_2^+ + D_3^+) = (1 - \eta_1)(1 - \eta_-) I^+$ $(D_2^- + D_3^-) = (1 - \eta_1) \eta_- I^+$	$P_{L1} = (1 - \eta_1 \eta_-) I^+ V_E$
Second separator loss	$D^- = \eta_1 \eta_- (1 - F_{Q\infty}) I^+$	$P_{L2} = \eta_1 \eta_- (1 - F_{Q\infty}) I^+ V$
Power input		$P_{IN} = P_B + P_A + I^+ V_E + \eta_1 \eta_- I^+ V_{PA}$

Performance

Fig. 7. Negative ion system.

Schematic Diagram

Pertinent Relationships

	Current (A)	Power (kW)
Target	$D^0 = \eta_1 \eta_- F_A I^+$	$P_B = \eta_1 \eta_- F_A I^+ V$
First separator loss	$D^+ = \eta_1 (1 - \eta_-) I^+$ $(D_2^+ + D_3^+) = (1 - \eta_1) (1 - \eta_-) I^+$ $(D_2^- + D_3^-) = (1 - \eta_1) \eta_- I^+$	$P_{L1} = (1 - \eta_1 \eta_-) I^+ V_E$
Second separator loss	$D^- = \eta_1 \eta_- (1 - F_A) I^+$	$P_{L2} = \eta_1 \eta_- (1 - F_A) I^+ V$
Power input		$P_{IN} = P_f + P_A + I^+ V_E + \eta_1 \eta_- I^+ V_{PA}$
Power recovery		$P_R = \epsilon_1 P_{L1}$

Performance

Fig. 8. Negative ion system with ion beam recycling.

Schematic Diagram

Pertinent Relationships

	Current (A)	Power (kW)
Target	$D^0 = \eta_1 \eta_- F_{\infty} I^+$	$P_B = \eta_1 \eta_- F_{\infty} I^+ V$
First separator loss	$D^+ = \eta_1 (1 - \eta_-) I^+$ $(D_2^+ + D_3^+) = (1 - \eta_1)(1 - \eta_-) I^+$ $(D_2^- + D_3^-) = (1 - \eta_1) \eta_- I^+$	$P_{L1} = (1 - \eta_1 \eta_-) I^+ V_E$
Second separator loss	$D^- = \eta_1 \eta_- (1 - F_{\infty}) I^+$	$P_{L2} = \eta_1 \eta_- (1 - F_{\infty}) I^+ V$
Power input		$P_{IN} = P_f + P_A + I^+ V_E$ $+ \eta_1 \eta_- I^+ V_{PA}$
Power recovery		$P_R = \epsilon_1 P_{L1} + \epsilon_2 P_{L2}$

Performance

Fig. 9. Negative ion system with unused beam power recovery.

Similarly for a sodium cell,

$$V_E = 10 \text{ kV}$$

whereby

$$\eta_- = 0.1.$$

- The neutralizer cells were considered to operate at their maximum efficiency at values of $F_{0\infty}$ and $F_{0\infty}$, which approach those shown in Fig. 3 of Ref. 3.

Meanwhile, the fraction of a positive ion beam that could be neutralized by continuously circulating through a neutralizer cell was determined by recognizing that the ion current available for the second pass would be $[\epsilon_L (1 - F_{0\infty})]$ times the current in the first pass.

Thus for N passes

$$I_N = [\epsilon_L (1 - F_{0\infty})]^{N-1} I_1 \text{ ampere,}$$

and the total current passing through the neutralizer, is

$$I_{\text{total}} = \sum_{N=1}^N I_N = \left\{ \frac{1 - [\epsilon_L (1 - F_{0\infty})]^N}{1 - \epsilon_L (1 - F_{0\infty})} \right\} I_1 \text{ A.}$$

By definition

$$F_A = \left(\frac{I_{\text{total}}}{I_1} \right) F_{0\infty} = \left\{ \frac{1 - [\epsilon_L (1 - F_{0\infty})]^N}{1 - \epsilon_L (1 - F_{0\infty})} \right\} F_{0\infty}.$$

If we let

$$1 - [\epsilon_L (1 - F_{0\infty})]^N = 0.99,$$

the required passes through the neutralizer becomes

$$N = \frac{-3.9}{\log [\epsilon_L (1 - F_{0\infty})]}.$$

By direct analogy, by substituting $F_{0\infty}$ for $F_{0\infty}$ and F_A for F_A , these relationships become applicable for negative ions.

- Because of the relatively low energy and the possibility of an unwanted molecular neutral beam component, the unused beam energy at the first magnetic separator is recovered thermodynamically at an efficiency of

$$\epsilon_1 = 40\%.$$

However, at the second magnetic separator direct electrical recovery is anticipated at a much better efficiency, i.e.,

$$\epsilon_2 = 85\%.$$

- Finally, the ultimate beam energy equals that which it initially obtained upon extraction from the ion source, plus whatever energy was derived from post acceleration. Thus

$$|V| = |V_E| + |V_{PA}| \text{ kV.}$$

Conclusion

The results of these calculations are shown in Figs. 1 through 9. The same curves are redrawn several times, Figs. 10 through 13, to provide a more vivid comparison of these various approaches. Although these graphs need little explanation, it must be emphasized that some of the assumptions used to generate these curves are questionable, at least quantitatively. Therefore, only the most general conclusions can be drawn from this work.

Also, there are factors other than power utilization that should be reviewed. These include gas efficiency, development risk and cost, capital costs, maximum

realizable power density and beam uniformity at the target, reliability, and any other consideration that may be pertinent to a particular situation.

It is clear from Figs. 10 through 13 that if the molecular component of the neutral beam makes a useful contribution, the direct injection system without enhancement is reasonably efficient at beam energies less than 80 keV. If the molecular component is undesirable the post acceleration system should be considered, except at energies greater than 100 keV where the negative ion system is best, irrespective of the method of efficiency enhancement.

Fig. 10. Comparison of neutral beam systems without efficiency enhancement.

Fig. 11. Comparison of neutral beam systems with unused beam power recovery.

Fig. 12. Comparison of neutral beam systems with ion beam recycling.

Fig. 13. Comparison of efficiency enhancement on a cesium negative ion system.

References

1. W. R. Baker, K. H. Berkner, W. S. Cooper, K. W. Ehlers, W. F. Kunkel, R. V. Pyle, and J. W. Stearns, "Neutral Beam Research and Development at LBL Berkeley," in 5th Symp. on Eng. Probl. of Fusion Res. (Princeton, New Jersey, 1973).
2. J. E. Osher, F. J. Gordon, and G. W. Hamilton, "Production of Intense Negative Ion Beams," in Proc. of the 2nd Inter. Conf. on Ion Sources, (Vienna, Austria, 1972).
3. K. H. Berkner, R. V. Pyle and J. W. Stearns, "Mixed Species in Intense Neutral Beams," in Proc. of the 1st Topical Meeting on the Technol. of Contr. Nucl. Fusion, (San Diego, California, 1974).