Received by OSTI

FEB 05 1990

CONF-891055--8

GA-A19889

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JANUARY 1990

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GA-A--19889

DE90 006298

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This is a preprint of a paper to be printed in the Proceedings
of the Fifth International Symposium on the Production &
Neutralization of Negative Ions & Beams (October 30th
through November 3, 1989), Long Island, N.Y.

Work supported by
Department of Energy
Contract DE-AC03-89ER51114

**GENERAL ATOMICS PROJECTS 4913 & 3466
JANUARY 1990**

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NEGATIVE ION-BASED NEUTRAL INJECTION ON DIII-D*

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ABSTRACT

High energy negative ion-based neutral beam injection is a strong candidate for heating and non-inductive current drive in tokamaks. Many of the questions related to the physics and engineering of this technique remain unanswered. In this paper, we consider the possibility of negative ion-based neutral beam injection on DIII-D. We establish the desired parameter space by examining physics trades. This is combined with potential design constraints and a survey of component technology options to establish an injector concept. Injector performance is estimated assuming particular component technologies, and concept flexibility with respect to incorporating alternate technologies is described.

INTRODUCTION

Neutral beam injection (NBI) is a principal candidate for plasma heating and for noninductive current drive in tokamaks. However, there are many important NBI physics and engineering issues which still need resolution in order to lay the groundwork for the planning, design and execution of NBI in future applications such as ITER.

The DIII-D tokamak at GA has been suggested as a test-bed on which high energy NBI physics issues might be explored. We have considered the possibility of negative ion-based NBI on DIII-D. To establish the desired parameter space, we have examined the impact of beam energy on potential DIII-D NBI heating and current drive physics experiments. We have looked at potential design constraints and have surveyed component technology options to establish an injector concept. We have estimated injector performance parameters by assuming particular component technologies. Finally, because the actual injector configuration will depend on future development program direction, we have explored concept flexibility with respect to incorporating alternate technologies.

PHYSICS TRADES

The existing experimental data base for neutral beam injection into tokamaks extends to beam energies of ~ 100 keV: an order-of-magnitude lower than needed for ITER. A study of physics processes, while applying ~ 0.5 MeV injection into DIII-D, would increase confidence in theoretical predictions and in the choices for ITER design parameters.

*Work sponsored in part by the Department of Energy under Contract No. DE-AC03-89ER51114.

Table I lists four physics processes relating to neutral beam injection into a tokamak plasma, and indicates programmatic importance and key DIII-D experiments for each. The two bottom-line physics processes are heating and current drive, and two primary physics processes which directly affect heating and current drive efficiency are multistep ionization and shear-Alfven instability. The programmatic importance in all cases derives from the choice of neutral beams as the primary current drive engine for ITER.

Table I Physics processes

Process	Importance	Key Experiment
Heating	Determines ITER mix of beam and rf heating	Inject high E_b beams, ECH and ICH into same target
Current drive	Determines ITER power needs	Amps/watt versus E_b
Multistep ionization	Determines ITER shine-through and orbit losses	Shine-through and penetration versus E_b
Shear-Alfven instability	Establishes ITER I-drive efficiency	Search for onset in DIII-D operating space

Data on basic heating efficiency and current drive efficiency would allow some confidence in the ITER choices of beam energy, beam power, and supplemental rf type and power. A key set of experiments on plasma heating would be the injection of neutral beams, ECH, and ICH into essentially identical plasmas. Recognizing that the method of heating is a primary factor in determining plasma parameters, the approach would be to generate ITER-relevant plasmas in DIII-D using 10 to 20 MW of 80 keV neutral beams, then to apply a megawatt of ~ 0.5 MeV beams, ECH, or ICH.

Physics processes which influence heating and current drive effectiveness are multistep ionization and possibly the shear-Alfven instability. Many predictions of neutral beam effectiveness neglect multistep ionization and thereby underestimate beam attenuation. With a representation of the true cross section as $\sigma_{gs} (1 + \delta)$, where σ_{gs} is the ground state cross section, the predicted correction factor δ is shown in Fig. 1.¹ The dotted vertical lines on Fig. 1 and on the following figures show beam energies of 80 keV, representing the existing DIII-D injectors, and 400 keV, representing a future negative ion-based injector.

Fig. 1. Excitation-enhancement of the beam stopping cross section.

The predicted δ is ~ 1 for plasma conditions and beam energies of interest on DIII-D, so the real ionization cross section is predicted to be about twice that for the ground state. Because of the strong influence of δ on penetration and power deposition, particularly for ITER, there is a high premium on experimental verification. The observables on DIII-D will be Balmer alpha emission distribution and shine-through power. Figure 2 shows predicted DIII-D shine-through and orbit losses for quasi-tangential injection and for relevant plasma conditions.²

Fig. 2. NBI shine-through and orbit losses.

The theory of the shear-Alfvén³ mode predicts that it should appear in ITER with high energy NBI.⁴ What is needed now is data for benchmarking the theory and for establishing the effect of the shear-Alfvén mode on the confined plasma. Neutral beams are predicted to drive the shear-Alfvén mode when the ion thermal velocity (v_i), the electron thermal velocity (v_e), the beam ion velocity (v_b)

and the Alfvén speed (v_a) are ordered as $v_i < v_a < v_b < v_e$. The conditions on v_i and v_e are met in tokamak plasmas.

However, in DIII-D with 80 keV NBI, the condition $v_a < v_b$ is attained only marginally. Because v_a scales as $B/\sqrt{n_e}$, lowering v_a entails low field-high density operation, a disruption-prone and somewhat atypical regime. Injection with ~ 400 keV beams, on the other hand, allows DIII-D operation in the normal, broader, and more stable operating regime. This is illustrated in Fig. 3, a density-field plot which compares the DIII-D Murakami scaling with the regimes of $v_b > 2 v_a$ for 80 and 400 keV injection.

Fig. 3. DIII-D Murakami scaling and regimes of $v_b > 2 v_a$ for 80 and 400 keV H^0 injection.

Calculated neutral beam current drive efficiency as a function of energy for representative DIII-D plasma conditions is shown in Fig. 4.² The curve labeled η_G is for gross efficiency, the driven current divided by the total neutral power incident on the plasma, and the curve labeled η_N is for net efficiency, where the neutral power has been corrected for orbit and shine-through losses. Because of their uncertainty, shear-Alfvén effects have not been incorporated. The efficiencies show a broad maximum at about 400 keV for either H^0 or D^0 injection.

Because the initial DIII-D negative ion-based NBI system would be limited in current to that produced by one (or possibly two) sources, a more relevant consideration may be the amount of driven current for a fixed amount of beam current. This is shown in Fig. 5 to level off at about 1 MeV, with a knee at ~ 500 to 700 keV. So although somewhat more beam-driven current could be obtained with 1 MeV injection, there is diminishing return above about 600 keV.

INJECTOR DESIGN CONSTRAINTS

Table II lists principal constraints, their origin and their impact on the design of a negative ion-based neutral beam system for

Fig. 4. NBI current drive efficiency.

Fig. 5. NBI current drive effectiveness:
driven current ÷ beam current.

Table II Constraints on injector design

Constraint	Origin	Impact
Minimize overall perturbation	DIII-D operations; total cost	Convert one or two beams initially
Try to use present cryopump	Cost	Basic beamline geometry fixed; source and stripper gas loads ~ present
Length	Building walls	Little impact on design
Shine-through	Heat dissipation in DIII-D wall armor	E_b can be at least 1 MeV
Neutrons	Deuterium beam onto dumps, calorimeter	E_b can be at least 1 MeV

DIII-D. As an overall constraint, the size of this proposed undertaking is bounded by realism on budgets and by the need to avoid interference with DIII-D experimental operations. The scale for initial modification of beamline, power and cooling systems must not be large. As a consequence, at most one beamline, and more likely one beam, is considered for conversion. For the same reasons, it is desirable to use the existing beamline cryopump. This means the beamline geometry, as well as the gas loading due to the ion source and neutralizer, should be basically similar to the existing positive ion-based injectors.

Three other potential constraints were evaluated. Building walls either are not in the way or can be moved. If care is taken to avoid very low plasma density operation, shine-through can be tolerated up to at least 1 MeV. Most neutron generation will occur in the tokamak plasma; most plasma neutron generation will be due to the present energy inputs and not to the additional high energy neutral beam. As a result, neutron radiation is not increased significantly for beam energies at least up to 1 MeV.

INJECTOR CONCEPT

Figure 6 shows side-view layouts of the present positive ion injectors and of our concept for the injector as modified for negative ions. The existing positive ion sources produce an approximately rectangular beam of 12 x 48 cm cross section. This geometry matches the entrance ports of DIII-D, and would be maintained in converting to a negative ion system. The existing beamlines have cryopanel in the calorimeter and neutralizer regions. These cryopanel are to be left undisturbed if possible. It does not appear reasonable to adapt the existing 180 degree bending magnet and charged beam dumps. At a minimum, extensive redesign would be required to accommodate the higher beam energy as well as the significant amounts of beam power in both the negative and positive components of the neutralized beam.

In the proposed negative ion system, sizes for the various beamline components have been estimated assuming specific component technologies which accommodate either a 400 keV H^- beam or a 400 keV D^- beam. We have chosen an extraction energy of 400 keV as a compromise which maximizes physics performance while minimizing technology extrapolation and cost. A 400 keV high voltage system at the current we anticipate (5 A) is well within present design technology for stackable, modular units.

Starting at the tokamak end of the proposed beamline, the calorimeter region with its cryopanel is unchanged. Upstream from the calorimeter is an ion separator/dump unit. The unit shown has been sized such that either magnetic or electrostatic technology could be accommodated. Upstream from the separator is a stripper with gaps at each end for pumping. The 2 meter length shown for the stripper is that estimated for H_2 gas. The 0.8 meters allotted for the accelerator is sufficient for Pierce or ESQ⁵ technologies. The

Fig. 6. Side views of the existing and proposed DIII-D beamlines.

total additional length needed for the negative ion system is provided by adding a 2 meter vacuum chamber segment. The interface of this segment with existing chamber will be as open as possible to maximize conductance between the accelerator and the main cryopanel.

Table III presents performance parameters estimated for the injector concept when assuming 10% gas efficiency for the ion source, accelerator pumping constrained by a Pierce-like geometry, and an H_2 gas stripper. The estimated neutral power includes transmission losses and the power/energy degradation due to stripping in the accelerator. The impact of this stripping is indicated by the full energy and the above-two-thirds energy (>270 keV) beam fractions in the table. The neutral, positive, and negative fractions

Table III Estimate performance parameters (one beam)

Parameter	Basis	H ⁰ Value	D ⁰ Value
Extraction energy	Physics benefits, cost, technology extrapolation	400 keV	400 keV
Ion current	H ⁻ at 20 mA/cm ² x 250 cm ²	5.0 A	3.5 A
Neutral power	Combined loss estimates	1.1 MW	0.72 MW
Beam fractions:			
Neutral	Cross sections	0.60	0.60
Full energy	Estimate premature stripping	0.86	0.80
>270 keV	Estimate premature stripping	0.92	0.89
Positive	Cross sections	0.20	0.20
Negative	Cross sections	0.20	0.20
Transmission	Estimate	0.95	0.95

are essentially the same for the H⁰ and D⁰ cases because the relevant cross sections have the same scaling with nucleon energy.

COMPONENT TECHNOLOGIES

The beamline concept was formulated after surveying candidate technology options⁵⁻⁹ for the principal injector components. Although no detailed component design was attempted, component sizes were estimated and initial evaluations on possible system effects of incorporating various technologies were made. Table IV indicates the component technologies which would be allowed within the constraints of Table II and the envelope of Fig. 6.

The first option entered in each column is the technology assumed in deriving the performance estimate of Table III. Substitution of a volume source, with its significantly lower gas efficiency, would cause increased premature stripping within the accelerator, resulting in additional accelerator loading, more power in the less-than-full energy portion of the neutral beam, and less injected neutral power. A capillary stripper-separator-dump⁶ would decrease the extractor beamlet packing density such that a larger source would be needed or less power would be generated. The use of

Table IV Allowable injector component options

Source	Accelerator	Stripper	Separator/Dump
Surface*	Pierce*	Standard gas*	Magnetic*
Volume	ESQ	Cooled gas	Electrostatic
		Capillary gas	Capillary tube
		Plasma	

*Basis for performance estimate.

a plasma stripper would yield a larger neutral fraction and therefore more injected neutral power.

Of all the component technologies surveyed, only an RFQ accelerator is questionable as a candidate for application on the proposed negative ion system. There is rf power on-site at about the right frequency, but the ~4 meters required for existing high-current RFQ concepts^{7,8} would violate length constraints. Although these RFQ concepts are for considerably higher energies (several MeV), the gentle-bunching function in an RFQ prevents a straightforward decrease in length with decreasing energy. We speculate that a shorter RFQ could be designed which compromises bunching and therefore has reduced acceleration efficiency. This possibility has not been explored.

SUMMARY

A concept for a negative ion-based NBI for DIII-D has been described and has the following attributes:

- It would extend NBI physics data base on heating and current drive for more relevance to ITER.
- It would have an acceptable impact on DIII-D operations.
- With the possible exception of an RFQ, there would be no restrictions on the incorporation of the many candidate negative ion component technologies.

The authors gratefully acknowledge W. S. Cooper of LBL for discussions and ideas.

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