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REQUIREMENTS FOR NEGATIVE ION BASED SYSTEMS
FROM USERS' POINT OF VIEW

By

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REQUIREMENTS FOR NEGATIVE ION BASED SYSTEMS
FROM USERS' POINT OF VIEW*

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ABSTRACT

This paper reviews the projected requirements of tokamak and mirror confinement devices for negative ion based neutral beam systems. The physics bases for the requirements are reviewed; the stated requirements are summarized for various mirror and tokamak devices, including MFTF- α +T, MARS, FED-A, and FED-R; and changes in those stated requirements, based on improved calculations of beam-stopping cross sections, are estimated.

A. INTRODUCTION

The high beam energies required if neutral beams are used to heat, drive current in, or fuel reactor plasmas dictate negative ion based systems. Next generation confinement devices, now being designed and intended to lead us to reactors, in most cases are already suitable for high energy negative ion based systems. Thus, these devices could be used as intermediate applications for the beam technology, as well as intermediate steps in reactor confinement technology, if projected beam requirements match with projected available beam technology.

This paper summarizes present projections of future mirror and tokamak requirements for neutral beams in the energy range suitable for negative ions. The physics bases for the requirements are reviewed, the stated requirements are summarized for various mirror and tokamak devices, and changes in those requirements, based on recent, improved calculations of beam-stopping cross sections are estimated.

E. MIRROR USES^{1,2}

1. Center-Cell Heating and Fueling

In many tandem mirror design studies, neutral beams are used to maintain the center-cell temperatures and density against energy and particle losses. In recent design studies however, there has been a tendency to use other technologies for this

*Presented at the Third International Symposium on the Production and Neutralization of Negative Ions and Beams, Brookhaven National Laboratory, November 14-18, 1983.

function. For example, as the recent Mirror Advanced Reactor Study (MARS) effort progressed, the 200 keV heating and fueling beams were replaced by ICRF for heating and by cold passing ions for fueling, principally because sufficient duct space could not be maintained in the design.^{3,4}

2. Transition Pumping³

Center-cell ions passing through the transition region scatter in pitch angle and become trapped. Unless some of these ions are removed, the density will increase, leading to an undesirable increase of the potential in the transition region. Many of the trapped ions have turning points in the anchor, and these will increase the density and potential at the thermal barrier. The net effect is a decreased thermal insulation between the center-cell and the warm electrons, a cooling of these electrons, and a lowering of the confining potential of the center-cell ions.

A pump beam can be used to counter this effect. The beam energy and direction are chosen so that ions, resulting from charge-exchange of the beam atoms, pass into the central cell. The neutrals formed from the trapped ions pass radially out of the plasma.

Although the energy required of pump beams is generally low enough such that positive ion beams could be considered, very high energy purity is needed (because lower energy ions will fill the velocity space which is being pumped), and negative ion based systems satisfy this requirement.

As the MARS study evolved, the 94 keV pump beams were replaced by Drift Pumping.^{3,4} However, it should be noted that the physics basis for this drift pumping concept is still relatively speculative.

3. Anchor Sloshing Ion Beams⁵

A related function of neutral beams which is essential in the present tandem mirror concept is to help form the thermal barriers by maintaining the sloshing ions. High energy ions are generated using neutral beams aimed slightly off the midplane of the end plugs. These ions are trapped in the magnetic well formed by the end plug magnets. The ions slosh back and forth, thus forming a potential minimum at the center of the magnetic well. The potential minimum separates the cold electrons in the central cell from the hot electrons in the end plugs. At the same time, low energy ions collect and fill out the ion distribution function, damping oscillations that cause microinstabilities. The potential minimum must be large enough to hold back the hot electrons while sustaining an adequate density of low energy ions.

The present design parameters for the Mirror Fusion Test

Facility upgrade, MFTF- α +T,⁶ and for MARS⁴ include sloshing ion beams at energies in the negative ion range.

C. TOKAMAK USES^{1,2}

1. Bulk Heating and Fueling

Neutral beams can be used to heat tokamak plasmas from temperatures characteristic of ohmically heated plasmas (~ 1 keV) to those required for ignition and/or sustained burn (~ 10 keV). This application is analogous to center-cell heating and fueling in tandem mirrors. The physics is well understood both experimentally and theoretically.

Although energetic neutral beams can provide local fueling, it is not possible to use high energy beams to totally fuel a reactor while still maintaining net power production: too much power is required for the beams. Therefore, reactors must be primarily fueled by a nonenergy intensive method, such as gas puffs or high velocity frozen pellets. Beams might still be used to provide local fueling in the plasma center if it is found to be advantageous.

The beam energy required for tokamak reactor heating is generally agreed to be in the range of 150 to 500 keV. Most of the recent design studies for future large tokamaks, including the near-term Tokamak Fusion Core Experiment (TFEX), use ICRF heating and pellet fueling in place of neutral beams. The perceived advantages of RF heating techniques are less complexity, smaller size (adjacent to the tokamak), lower cost, less of a neutron-streaming problem, and nearer-term technology.

2. Current Drive

Neutral beams might be used to drive the toroidal plasma current that provides the confining poloidal field in a tokamak reactor, thus enabling a reduced dependence on the ohmic heating transformer, or possibly enabling steady-state operation. In tokamak design studies, a reduction in the performance requirements for the ohmic heating system leads to simplification, enhanced performance, and/or cost reduction. A tokamak reactor which can operate continuously may have reliability and cost advantages.

A disadvantage of neutral beam current drive is that it results in net toroidal momentum for the plasma. Experimentally, however, no deleterious effects have yet been observed, even with strongly unbalanced toroidal beam power input.⁷ It should also be noted that the calculated neutral beam power requirements for current drive at full operating densities and temperatures lead to projections of high circulating power in reactors. However, theoretical and experimental current drive efficiencies for other candidate drivers, at these temperatures and densities, are no

more promising.

Beam energies required for tokamak reactor current drive are in the range of 500 keV to 1 MeV. Most recent design studies of future large tokamaks, including the near-term TFCX, use lower hybrid current drive systems rather than neutral beams.

One advantage that neutral beams may have in tokamak applications is that it appears that a single system, 500 keV-1 MeV neutral beams, could be used to both heat and drive the current in a tokamak reactor. In contrast, the presently preferred auxiliary heating technology, ICRF, probably will not efficiently drive current. The presently preferred current drive technology, lower hybrid frequency waves, is found experimentally and theoretically to be ineffective in heating the higher density and temperature tokamak plasmas characteristic of a reactor. Having one system do both the heating and the current drive may lead to simplification, and therefore improved reliability and reduced cost in a tokamak reactor.

D. ENHANCEMENT OF THE BEAM-STOPPING CROSS SECTION

Recent work by Boley *et al.*^{8,9} indicates that the beam-stopping cross sections, applied to calculations of energetic neutral beams of hydrogen isotopes incident on a plasma, should be increased to account for multistep processes involving excited atomic states.¹⁰ Calculations of beam penetration have generally assumed this effect was small, and use only cross sections for ionization of ground-state neutrals.

For typical plasma and beam parameters of present large tokamak experiments, this enhancement is expected to be from 25% to 50%. The enhancement is predicted to increase with plasma density and with energy, and can be much larger for tokamak and mirror reactors.

In many tokamak designs, the beam energy is determined by the penetration requirements. Thus, in these cases, the enhancement of the stopping cross section will lead to specification of higher beam energies and, therefore, to more of a demand on beam technology.

For mirrors, the beam energy is generally fixed by requirements other than penetration, and, in fact, shine-through is usually a problem. Thus, in the mirror case, the enhancement of the stopping cross section may lead to lowered demands on the beam dump and the beam injector power capability, including source current capability, beam mechanical hardware, power supplies, and pumping, and may mean an improved mirror system power balance.

Specific examples of the changes in perceived user requirements, as a result of application of this recent work, are given below.

E. USER REQUIREMENTS

Machine designs or machine design studies which are current and which include requirements for negative ion based neutral beam systems are MFTF- α +T (tandem mirror), MARS (tandem mirror), FED-A (tokamak), and FED-R (tokamak). The parameters for these beam systems are presented and discussed below. The most serious next-device study now ongoing, the TFCX tokamak, presently considers negative ion based neutral beams as a backup to ICRH for plasma heating and has not established beam requirements.

1. MFTF- α +T Requirements^{5,6}

The presently favored upgrade of MFTF-B, called MFTF- α +T, includes 200 keV beams to generate sloshing ions in the end plugs. A current of 8.4 A of 200 keV deuterium atoms is specified to be delivered to the plasma: one-half to each end plug. Additional requirements are the capability for running continuously for periods of 100 hours, compatibility with a radiation environment, and optics suitable for a relatively narrow, 14.7 cm, plasma target. MFTF- α +T is proposed for start-up in 1992.

Applying the enhanced beam-stopping cross sections described above, to an MFTF- α +T end plug plasma with $\bar{n} = 5 \times 10^{12} \text{ cm}^{-3}$ and $Z_{\text{eff}} = 1$, yields an estimate of an increase in the trapping cross section of about 30%. When the previous trapping fraction (0.15) is combined with the enhanced trapping, the incident current required is reduced to 6.6 A and the beam dump power is reduced by 0.36 MW. The required source current may be reduced more than linearly, because the source width could be reduced and the beam system is expected to be optics limited.

2. MARS Requirements¹¹

The recently completed MARS tandem mirror reactor study invokes 475 keV neutral beams to provide sloshing ions for each of two anchors. A total of 5.7 MW is to be absorbed by the plasma, and 8.9 MW is calculated as the required incident power. Additional requirements are steady-state operation, compatibility with a radiation environment, and very high availability: >97% for the total heating system, including beams, ECRH, ICRH, and all of the associated power supplies, pumps, controls, etc. In the design study, such high availability was considered reasonable because MARS is specified as a tenth-of-a-kind reactor.

Enhanced beam-stopping cross sections for the MARS anchors, with $\bar{n} = 5 \times 10^{13} \text{ cm}^{-3}$ and $Z_{\text{eff}} = 1$, yield an estimated 40% increase in the trapping cross section. If it is assumed that deposition profiles are unaffected, and thus 5.7 MW is still the

required absorbed power, only 7.5 MW of incident power is needed, and the beam dump requirement drops from 3.2 MW to 1.8 MW.

3. FED-A Requirements¹²⁻¹⁴

The FED-A tokamak study is a recent extension of the Fusion Engineering Device (FED) studies which is aimed at possible improvements in the original concept allowed by more aggressive physics assumptions. A key physics assumption for FED-A is noninductive current drive. The baseline current drive technology for the study is lower hybrid waves, while two alternative technologies considered are based on negative ion beam systems: 400 keV beams to provide a cyclic, "internal transformer" mode of current drive, and 800 keV beams to provide steady-state current drive.

For the 400 keV, internal transformer case, the required power is 44 MW, and the beams are pulsed for 4 sec every 33 sec (plasma cycle time). For the 800 keV case, 50 MW of steady-state beam power are specified to drive the 4 MA of plasma current. High availability and radiation compatibility are requirements in both cases, although in the cyclic case, the possibility exists for closing off the beam duct during most of the plasma burn phase.

The effect of the enhanced beam-stopping cross is quite dramatic for the 400 keV cyclic case. The Z_{eff} is purposely raised to 6 during the drive phase, and for the mean density $\bar{n} = 1 \times 10^{13} \text{ cm}^{-3}$, the stopping cross section would be enhanced by a factor of about 2.25. However, it is beam shine-through which determines the lower limit on the plasma density during the drive phase, and with an enhanced stopping cross section, this density can be lowered and the current drive efficiency will be raised.¹⁵ The result is that the required beam power drops from 44 MW to 20 MW.

In the 800 keV steady-state case, the beam energy is determined by current drive considerations rather than penetration, so even though the stopping cross section is estimated to increase by about 75%, it is expected that penetration will still be sufficient and the beam requirements will be unchanged.¹⁶

4. FED-R Requirements¹⁷

The FED-R is a recently studied variation of FED utilizing resistive magnets, rather than superconducting, and aimed at providing a substantial fluence of fusion neutrons to irradiate a large test area in order to do blanket testing. A Stage II of this device, to be operable in the late 1990s, specifies 100 MW of incident neutral beams to both heat the plasma and drive the plasma current (4 MA). Half of the power is required to be 250 keV deuterium and half is to be 250 keV tritium. The blanket

testing objective necessarily means that the beam systems must be radiation compatible and steady state with high availability.

The beam energies were determined from penetration considerations, so enhanced beam-stopping cross sections will mean higher energy beams are required for proper penetration. For a mean density $\bar{n} = 8 \times 10^{13} \text{ cm}^{-3}$ and $Z_{\text{eff}} = 1.5$, equivalent penetration will be provided with approximately 400 keV beams. It should be noted, however, that the FED-R design philosophy was to use near-term technology, so that some of this increment in beam energy might be absorbed in overall machine parameter and goal changes.

SUMMARY

User requirements are summarized in the Table. Listed are the approximate device start-up date, the isotope, and the beam energy, current, and power incident on the plasma as dictated by the user. The modifications to the energy, current, and power, estimated to arise from recent recalculations of beam-stopping cross sections, are also listed. Additional requirements for all of the listed systems are high availability and radiation compatibility. The FED-R 400 keV system requires 4 sec pulses every 33 sec, while the remaining systems are steady state.

A dominant recent trend is a shift by all users to various RF techniques to replace beams. Tandem mirrors are more firmly committed to beams, with the principal application being sloshing ion beams, requiring 200 keV for the near-term and ~ 500 keV for reactors. The trend in tokamaks is towards specifying beams only as a technological backup to RF.

In general, the effect of the enhanced stopping cross section appears to be less ambitious beam systems for tandem mirrors while for tokamaks it depends on the particular case: more attractive systems in some cases and somewhat less attractive systems in other cases.

ACKNOWLEDGMENT

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TABLE USER REQUIREMENTS

	PUBLISHED REQUIREMENTS					REQUIREMENTS AS MODIFIED BY ENHANCED STOPPING		
	YEAR	ATOM	keV	A*	MW*	keV	A*	MW*
MFTF- q+T	1992	D	200	8.4	1.7	200	6.6	1.3
MARS	2020	D	475	19	8.9	475	16	7.5
FED-A [†]	~1995	D	400	110	44	400	50	20
FED-A [†]	~1995	D	800	63	50	800	63	50
FED-R	1998	D	250	200	50	400	125	50
		T	250	200	50	400	125	50

*Incident on the plasma
†Alternative approaches for FED-A

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