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A HIGH ENERGY NEUTRAL BEAM SYSTEM FOR REACTORS

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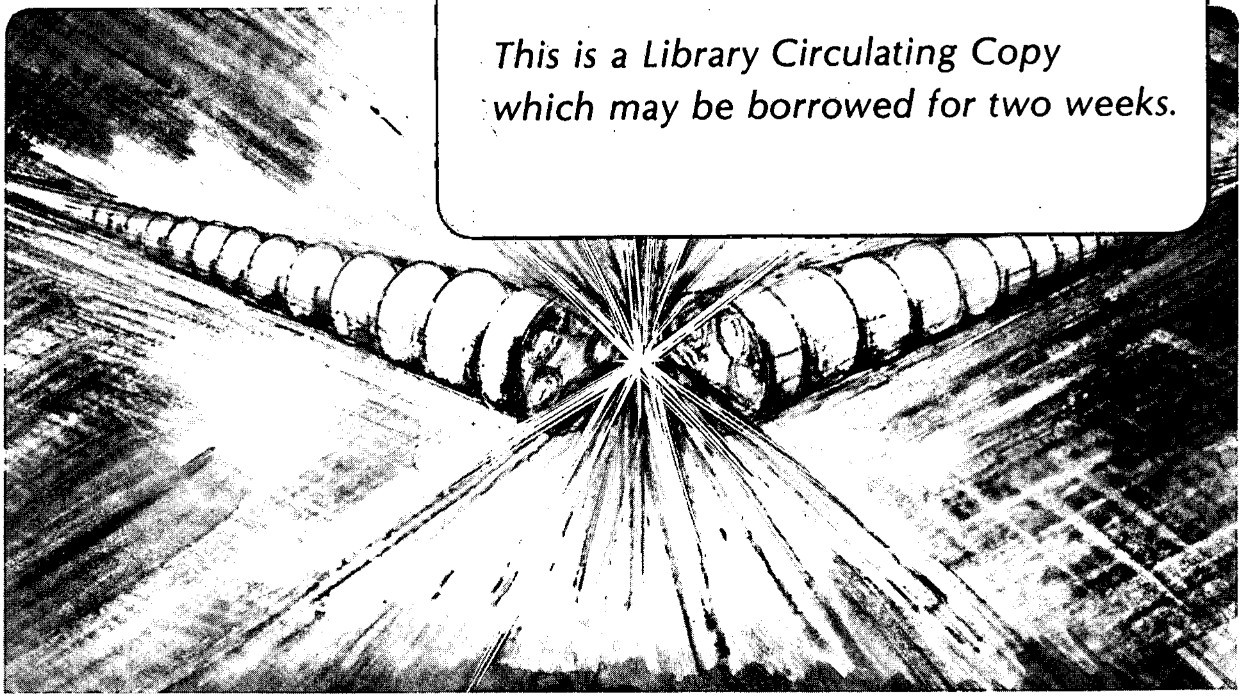

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A HIGH ENERGY NEUTRAL BEAM SYSTEM FOR REACTORS

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High energy neutral beams provide a promising method of heating and driving current in steady-state tokamak fusion reactors. As an example, we have made a conceptual design of a neutral beam system for current drive on the International Thermonuclear Experimental Reactor (ITER). The system, based on electrostatic acceleration of D^- ions, can deliver up to 100 MW of 1.6 MeV D^0 neutrals through three ports. Radiation protection is provided by locating sensitive beamline components 35 to 50 m from the reactor. In an application to a 3300 MW power reactor, a system delivering 120 MW of 2-2.4 MeV deuterium beams assisted by 21 MW of lower hybrid wave power drives 25 MA and provides an adequate plasma power gain (Q = 24) for a commercial fusion power plant.

1. INTRODUCTION

As an example of a typical neutral beam system for current drive on tokamak reactors, we present a conceptual design of the neutral beam system that we propose for ITER. We have chosen a conservative approach, one that requires the least extrapolation from existing technology. The design is modular and flexible, so that upgrades can be accommodated as the technology progresses. Three beamlines are clustered to inject into a single port; the layout is shown in Figure 1. Three or four ports, depending on the choice of neutralizer, will be needed for injection of the required power of approximately 80 MW. The specifications of a single beamline are given in Table 1.

2. BEAMLINE DESCRIPTION

2.1. Ion source and preaccelerator

The D^- sources are modular volume-production sources.[1] Each source feeds a linear array of 17 accelerator channels spaced about 5 cm apart; each channel carries 0.1 A. Each beamlet is accelerated to 100 keV by a conventional electrostatic preaccelerator, and is then matched into a dc multichannel accelerator.

Table 1: Specifications for a single ITER Beamline

Beam energy	1.6 MeV
Accelerated D^- current	10 A
Neutral D^0 power (plasma neutralizer)	12 MW
Neutral D^0 power (gas neutralizer)	7.5 MW
D^- current density at the source	15 mA/cm^2
Current per beamlet	0.1 A
Energy variation at constant current	2 : 1
Beam divergence	$\leq$ 3 mradians

The development of a suitable D^- ion source probably represents the greatest challenge in developing ITER neutral beam systems. The sources needed for the ITER beamline require an improvement by roughly a factor of 2 or 3 over current state-of-the-art source technology, especially in gas and power efficiency.

2.2 High voltage accelerator

We have chosen for our system a strong focusing Electrostatic Quadrupole (ESQ) high

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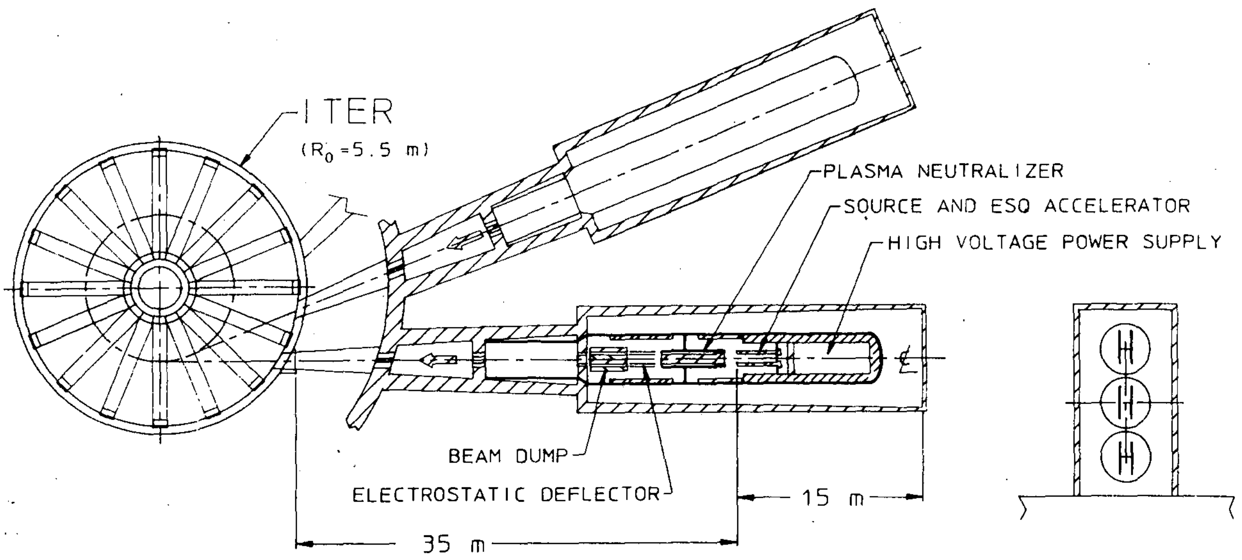

FIGURE 1
Neutral Beam System for Current Drive on ITER

voltage dc accelerator.[2] This approach offers a) the ability to stretch the accelerator column to reduce the average voltage gradient with no reduction in current, b) the ability to vary the beam energy from 0.8 to 1.6 MeV at constant current (to be able to match varying plasma conditions), c) the presence of transverse electrostatic fields in most of the volume of the channel, which should substantially reduce the likelihood of breakdown of the whole column, and d) the potential of higher power efficiency than rf acceleration schemes. The average gradient along the column is only 5 kV/cm; the largest local electric field is approximately 40 kV/cm. The design is modular, with a voltage increment of 100 kV per module. For the ITER beamline design we assume a current of 0.1 A per channel, but the same accelerator can also accommodate 0.2 A per channel; this provides an option to upgrade the design as source performance improves. A 200 kV version of this accelerator is now being tested at LBL.

A similar accelerator, but pulsed and without the capability to vary the energy at constant current, has been tested by E. A. Abramyan et al at Novosibirsk; this accelerator produced an H^+ beam of 0.08 A at 1.2 MeV.[3]

2.3. Neutralizer

Our beamline concept uses a plasma neutralizer, which provides a 60% increase in neutralization efficiency over that of a gas neutralizer, which is our back-up choice. In plasma neutralizer experiments carried out at JAYCOR, 60 kW of 1.4 MHz (pulsed) rf power produced an argon plasma in a volume of 0.15 x 0.35 x 0.39 m^3 with a peak ion density of 2.5 x 10^{13} cm^{-3}; the degree of ionization exceeded 30%.[4] A similar plasma one to two meters long and with an adequate cross section would give the correct target thickness for an ITER plasma neutralizer; scaling studies are continuing at JAYCOR.

2.4. Residual-ion removal system

We use electrostatic deflection, rather than magnetic; such a system is simple, and will operate with electric fields of less than 1 kV/cm. We have already tested an electrostatic deflector with an 0.8 A, 80 keV H$^-$ beam.[5] The deflected beams strike dumps which use conventional cooling technology. The power densities on the dumps do not exceed the capability of existing, tested cooling panels.

2.5 High voltage power supply

Each beamline is driven by a single 10 A, 1.6 MV dc power supply. To avoid a megavolt transmission line, the power supply is located in close proximity to the ion sources. We do not yet have a conceptual design for this supply, which would probably be gas insulated, have low capcitance, and might operate at high frequency. We propose eliminating the usual series high voltage switch; the ion source itself would serve as a switch.

2.6. Vacuum system

Pumping will be provided by cryopumps operating at ground potential. The high voltage insulation of the ESQ accelerator is of large diameter (2.5 m) in order to provide adequate conductance from the ion sources to the pumps. The cryopumps must be capable of continuous operation; such pumps have been demonstrated by LLNL and Grumman Corp.[6]

2.7. Radiation shielding

Basic radiation protection is provided by locating the sensitive components (ion source, accelerator, and power supply) 35 m or more from the tokamak, with the beam passing through apertures in several layers of neutron shielding between the beamline and the tokamak. A first look at the activation problem indicates that the materials that we propose to use would survive undamaged for the lifetime of ITER--the total dose will be less than 10^{10} rads. This analytic calculation will be followed by Monte Carlo neutronics calculations. The shield configuration shown in Fig. 1 should limit the dose to less than 2.5 mrem/hr outside the shield one day after shutdown. A final step will be to optimize the shielding for maximum effect and minimum cost.

3. NEUTRAL BEAMS FOR REACTOR APPLICATIONS

We have also examined the suitability of using neutral beams for current drive on a full scale steady state power reactor with a major radius of 7.5 m, and the results are very encouraging. Steady state current drive is achieved with a combination of neutral beams in the plasma core, lower hybrid slow wave current drive in the other regions, and bootstrap current. A beam energy of 2 to 2.4 MeV (D^0) is required for adequate penetration.

Suitable neutral beams could be produced by reasonable extensions of the same technology used for ITER. For instance, if better neutron shielding were required, one could either move the beamlines even farther from the reactor or electrostatically bend the ion beam[7] to remove the sources and accelerators from direct neutron irradiation. The performance parameters for one possible reactor operating point are given in Table 2.

The power balance calculations for this reactor are similar to those done for ITER, but with a Z_{eff} of 1.5 and with the energy confinement of the core plasma assumed to be 1.5 times Goldston scaling.[8] The density profile was assumed to be parabolic. The figures of merit $n_e R_0 I/P$ for neutral beams and lower hybrid are 0.58 and 0.56 x 10^{20} A/Wm^2, respectively. The plasma power gain of 24 is quite adequate for an economical fusion power reactor.

Table 2: Performance Parameters for a steady state beam-driven power reactor

Fusion power	3300 MW
Q	24
Neutral beam power	120 MW
Lower hybrid power	21 MW
Average neutron wall loading	2 MW/m^2
Plasma current	25 MA
Bootstrap current	7.5 MA
Neutral beam driven current	15 MA
Lower hybrid driven current	2.5 MA

4. CONCLUSIONS

Neutral beams based on negative ions provide an attractive option for current drive and heating of ITER as well as a representative steady state power reactor. The neutral beam technology required is based on reasonable extrapolations from existing demonstrated technologies.

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