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**TITLE: INTENSE DIAGNOSTIC NEUTRAL BEAM
DEVELOPMENT FOR ITER**

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**SUBMITTED TO: Ninth APS Topical Conference on High-Temperature
Plasma Diagnostics
Santa Fe, NM
March 15-19, 1992**

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Intense Diagnostic Neutral Beam Development for ITER

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ABSTRACT

For the next-generation, burning tokamak plasmas such as *ITER*, diagnostic neutral beams and beam spectroscopy will continue to be used to determine a variety of plasma parameters such as ion temperature, rotation, fluctuations, impurity content, current density profile, and confined alpha particle density and energy distribution. Present-day low-current, long-pulse beam technology will be unable to provide the required signal intensities because of higher beam attenuation and background bremsstrahlung radiation in these larger, higher-density plasmas. To address this problem, we are developing a short-pulse, intense diagnostic neutral beam. Protons or deuterons are accelerated using magnetic-insulated ion-diode technology, and neutralized in a transient gas cell. A prototype 25-kA, 100-kV, 1- μ s accelerator is under construction at Los Alamos. Initial experiments will focus on *ITER*-related issues of beam energy distribution, current density, pulse length, divergence, propagation, impurity content, reproducibility, and maintenance.

I. INTRODUCTION:

Over the last decade, diagnostic neutral beam (DNB) spectroscopy has emerged as a powerful diagnostic techniques for tokamak plasmas.¹ Applications include local measurement of: (1) ion temperatures and plasma rotation profiles by charge-exchange recombination spectroscopy (CHERS); (2) density fluctuations; (3) fully-stripped impurity densities in the plasma core; and (4) current density profiles by motional Stark or Zeeman polarimetry. Furthermore, DNB spectroscopy will be needed to measure the confined alpha particle densities and energy distributions in upcoming large burning plasma experiments such as *ITER*.

While DNB spectroscopy is desirable in large tokamaks, it is becoming evident that present-day low-current, long-pulse neutral-beam technology will be insufficient in providing the required intensities.² Specifically, large-radius, high-density plasmas pose two basic problems: (1) they prevent beam penetration; and (2) they reduce the signal-to-noise ratio S/N since the signal intensity rises linear with n while the background bremsstrahlung increases as n^2a . These problems are illustrated in Fig. 1 by simulations with the *CHERSB* code³ for a 1-MW, 100-keV neutral hydrogen beam into a typical *ITER* plasma ($R = 5.8$ m, $a = 2.2$ m, $n = 1.1 \times 10^{20} [1-(r/a)^2]^{1/2} \text{ m}^{-3}$, $T = 10 [1-(r/a)^2] \text{ keV}$, $Z_{\text{eff}} = 2$). A beam area of 0.05 m^2 and divergence of 35 mrad are assumed. Significant beam attenuation occurs, while the anticipated charge-exchange-recombination emission from the hydrogen-like carbon 529.2 nm line (from the $N = 8 \rightarrow 7$ transition), drops several orders of magnitude below the background Bremsstrahlung level over the first meter from the plasma edge. An improved deposition profile may be obtained at higher beam energies, as evidenced by the calculation in Fig. 2 for a 600-keV hydrogen beam. Indeed, high-energy (1.3 MeV) neutral beams will be needed for heating in *ITER*;⁴ however, high-energy beams lead to unacceptable S/N for *CHERS* diagnostics because of the charge-exchange reaction rates which decrease significantly with beam energy.¹ To provide adequate signals at energies matched to the charge-exchange reaction

cross sections, relatively low-energy (about 100 keV/amu), high-current-density beams with short signal integration times are needed.

To obtain sufficient intensities and S/N in *ITER*, we are developing an intense diagnostic neutral beam (IDNB) which may offer improvements in beam current density of up to three orders of magnitude over conventional technologies. In the prototype IDNB device under construction, protons or deuterons will be accelerated to energies of up to 120 keV using high-power, magnetically-insulated ion diode technology. Ions are extracted and propagated through a gas cell where they are converted to neutrals.

II. ION SOURCE:

The computer simulations indicate that the optimum diagnostic neutral beam for *ITER* will require high-power and relatively low particle energies, consistent with the use of positive ion sources. The required power, however, is well beyond the realm of conventional neutral beam technologies. On the other hand, short-pulse (10 ns to 1 μ s) light ion beams at the Gigawatt to Terawatt level have been developed over the past two decades in support of DOE magnetic and inertial confinement fusion programs.⁵

The magnetically-insulated ion diode is an intrinsically high-power-density device, capable of operating with ion current density enhancement factors α of up to 100-times the Child-Langmuir space-charge limit for the vacuum condition.⁶ The magnetic field is applied to confine electrons inside an anode-cathode (A-K) gap. The electrons provide a virtual cathode, which, if controlled, will decrease the gap dimensions and reduce the space potential of the accelerating ions, thereby allowing the magnetically-insulated diode to operate at much higher powers than conventional long-pulse, low-current beams presently used on tokamaks.

For applications in which intense beams are injected into an adjacent chamber, a popular diode configuration is the extraction geometry shown in schematically in

Figure 3. An annular ion beam is accelerated by applying a pulsed high voltage across an axial A-K gap. A radial magnetic field B is applied in the gap by energizing two or more concentric coils usually located inside vacuum. For optimum performance, B is usually set to about 1.5 times the critical field needed to confine high-energy electrons in the A-K gap. The extraction geometry is optimum since electron $E \times B$ drift trajectories remain confined in the gap, resulting in a configuration which minimizes electron losses and enhances ion current densities.

An anode ion source of order 0.1 mC/cm^2 is required for the operation of an IDNB. A common proton source used in magnetically-insulated ion diodes involves the flashover of a dielectric attached to a metallic anode. The anode plasma is created by the bombardment of the dielectric material by energetic electrons which are accelerated from the cathode and diffuse across the insulating magnetic field. While easy to implement, the flashover anode is undesirable for tokamak applications because of impurity generation and degradation of the anode surface with each pulse. Pure proton and deuteron sources have been produced in magnetically-insulated diodes using cryogenic⁷ and gas-loaded metallic foil anodes.⁸ A more-appealing ion source which is reproducible, pure, and capable thousands of pulses has been developed at Cornell, utilizing a plasma anode.⁹ A high-density, annular sheet of gas is injected supersonically in front of a fast pancake magnet coil. This magnet is pulsed to inductively break down the gas (with full ionization and dissociation), and to propel the plasma into the anode plane of the diode.⁹

For neutral beam production, positive ion sources are only useful at low energies, typically $E < 100 \text{ keV/amu}$, because of the rapid decrease of the neutral conversion efficiency with E . This decrease, however, is offset by the $\alpha E^{3/2}$ dependence of the enhanced space-charge-limited ion current density. A reasonably-wide operating window is possible, as illustrated by the calculation shown in Figure 4 for a proton ion source, a 1-cm A-K gap with $\alpha = 100$, and a thick H_2 neutralizer cell.

III. PROTOTYPE BEAM

A prototype IDNB beam is under construction at Los Alamos. A low-inductance, 120-kV, 125-kJ capacitor bank is configured to power a 300-cm² area, applied-B_r extraction ion diode. Ion currents up to 100-kA are expected. Both dielectric and plasma-anode ion sources will be studied. The beam may be focussed ballistically, by conically configuring the diode. Ions are converted into neutrals in a puff gas charge-exchange cell located downstream.

The technical issues to be addressed in upcoming proof-of-principal experiments are identical to those needed for *ITER*:² the beam energy distribution, current density, pulse length, divergence, propagation, reproducibility, maintenance, and impurity content. An overall assessment of the technology's suitability for beam spectroscopic measurements on tokamaks will be made.

Following proof-of-principal IDNB extraction experiments, a prototype beam will be installed on an existing moderate-sized tokamak as a *CHERS* T_i(r) diagnostic. In addition to the *ITER*-related issues, the high-power prototype IDNB will be a unique tool that may be utilized in present-day tokamaks for a variety of new applications, such as two-dimensional turbulence imaging, and as a rapid energy and density perturbation source to measure transport coefficients. Future accelerator development will include design of multiple-pulse prototype devices for eventual use on the *ITER*. Ultimately, a full-scale beam will be developed, compatible with the high-density, large burning plasma environment with substantial radiation exposure.

ACKNOWLEDGMENTS:

The authors are grateful to Prof. H. H. Fleischmann and Dr. J. B. Greenly (Cornell Univ.) for useful discussions on IDNB physics, and to Dr. K. M. Young (Princeton Plasma Physics Laboratory) who first informed us of the *ITER* DNB requirements. This research is funded by the U.S.D.O.E. Office of Fusion Energy.

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Figure Captions:

1. Calculations of (a) beam penetration and (b) CHERS and bremsstrahlung background signals for a 1-MW, 100-keV neutral H° beam injected into ITER.
2. Calculations of (a) beam penetration and (b) CHERS and bremsstrahlung background signals for a 1-MW, 600-keV neutral H° beam injected into ITER.
3. Schematic diagram of an intense ion diode with extraction geometry.
4. Proton and neutral hydrogen current densities in an IDNB.