Active Spectroscopy

Neutral Beam Diagnostics for Alcator C-Mod

Contents

William L. Rowan, Roger D. Bengtson, R. V. Bravenec, H. He, J. Jagger,
D. M. Patterson, D. W. Ross, P. M. Valanju, and A. J. Wootton
Fusion Research Center, The University of Texas at Austin,
Austin, Texas 78712
E. S. Marmar, J. H. Irby, J. A. Snipes, and J. L. Terry
Plasma Fusion Center, Massachusetts Institute of Technology,
Cambridge, Massachusetts 02139

A diagnostic neutral beam will be installed on Alcator C-Mod for measurement of $\tilde{n}_i, n_z, T_z, v_\theta, v_\phi$, and j. The beam will be used primarily for the study of thermal transport, E_r in H-mode discharges, and to provide critical profile and turbulence data for tests of theoretically based models of turbulence and transport. The beam selected for this work was used on TEXT and is rated at 50 kV and 6 A of extracted current in hydrogen. It can produce beams of deuterium or helium as well. It is currently being re configured for installation on C-Mod. Capabilities for the intended measurements are described using simulations based on measured C-Mod profiles.

INTRODUCTION

A diagnostic neutral beam will be installed on C-Mod for measurement of ion density fluctuations $\tilde{n}_i$, impurity density n_z, impurity temperature T_z, rotational velocities v_θ, v_ϕ, and current density j. The beam will be used primarily for the study of thermal transport, the radial electric field E_r in H-mode discharges, and to provide critical profile and turbulence data for tests of theoretically based models of turbulence and transport. While the first two applications will be well embedded in the C-Mod experimental program, the last continues work begun on the Texas Experimental Tokamak (TEXT), and is based on the observation that theory based models of transport due to turbulence can be successfully compared with experiment[1] and are sufficiently mature to produce detailed, testable descriptions of the underlying turbulent spectra.[2] All of these measurements will be unique because of the unique operational regime of C-Mod. Though profiles predicted by the theory-based transport model of reference 1 are being tested at lower densities and fields, there is no such comparison in the C-Mod regime of high densities and fields which in some respects is closer to the parameters of the next generation of tokamaks. Further, the turbulence spectra predicted by this turbulence-based model have not been tested at all. Since beams have not been applied to plasmas of such high density and magnetic field, this paper is mainly concerned with penetration of the beam into the plasma and with macroscopic measurements.

THE FRC DIAGNOSTIC NEUTRAL BEAM

Description

The Fusion Research Center (FRC) diagnostic neutral beam (DNB) was designed and constructed by the Culham Beam Development Group on the model of a JET injector.[3] In turn, the PBX beam was designed on the model of the FRC beam.[4] In its commissioning tests,[5] the FRC DNB produced a 50 keV beam with 6 A of extracted current in hydrogen with full, half, and third energy components in the ratio 50:20:30. The current density of the full energy component in the target plane was 70 mA/cm^2. Beams of deuterium and helium have been produced as well. The beam pulse duration is approximately 100 ms, and the beam was designed for modulation as fast as 1 kHz.

The DNB consists of five major components: plasma source, accelerator, neutralizer, deflector magnet, and vacuum system. The plasma source has cylindrical, permanent-magnet, bucket geometry with a six-filament array including two spare filaments. The accelerator is composed of four edge-cooled grids. For focusing, the grids have the form of a section of a sphere. (Ramifications of this design will be discussed in greater detail in section III.) The magnetically shielded neutralizer is rigidly mounted together with the source and the accelerator so that the assembly can be moved as a unit for directional control. There is a deflector magnet between the neutralizer and the plasma that directs residual charged particles onto a cooled titanium dump plate. The vacuum for the beam is provided by a cryopump with a pumping speed of 30,000 liter/s in hydrogen and 15,000 liter/s in helium.

Neutral Beam Penetration

First the practicality and then the design of diagnostics depend on the beam penetration. The penetration was simulated for the full energy component with experimental C-Mod profiles. In the simulation, the beam interacts with the plasma only through attenuation by ionization and charge exchange:

$$H^+ + H^0 \rightarrow H^0 + H^+$$

$$e + H^0 \rightarrow e + H^+ + e$$

$$p + H^0 \rightarrow p + H^+ + e$$

Excitation to and ionization from excited states will not affect the conclusions of this paper concerning hydrogen beam penetration and the ion temperature measurements. (Ionization from excited states is included in the comments on helium beam penetration in section III. C.) Each attenuation process is described by a rate, and the processes are assumed to be independent. The beam travels a straight line trajectory y along a plasma major radius at constant velocity $v_B = \sqrt{\frac{2E_B}{m_B}}$ from its launch at y=0 with density $n_B(y=0)$. Hence,

$$n_B(y) = \frac{n_B(y=0)}{v_B} \exp\left(-\int_0^y K dx\right)$$

where K is the sum of the rates. The penetration into two discharges is shown in Figures 1 and 2. The transmission of a 50 keV hydrogen beam is shown in Figure 1a for the L-mode discharge described in Figure 1b. Approximately 35% of the beam reaches the plasma center (r = 0); 15% reaches the far edge of the plasma. In this case, charge exchange is the major attenuation process.

In contrast, Figure 2 shows the penetration into a PEP mode discharge.[6] Here about 5 % of the beam is predicted to penetrate to the axis and less than 1% to the far edge of the plasma. It would appear unlikely that beam diagnostics would be of much use in the inner half of the plasma though information there might be inferred by invoking assumptions such as constancy on flux surfaces. To ameliorate this limitation, we are investigating an increase in the beam voltage to 80 keV. The effect of this change on penetration is shown as a dashed line in each of Figs. 1a and 2a.

DIAGNOSTICS

Profile measurements

In the interaction of beam particles with ambient impurities, emission from ambient impurities is generated via processes

$$H^0 + A^q \rightarrow H^+ + A^{(q-1)*}(n,l)$$
$$A^{(q-1)*}(n,l) \rightarrow A^{(q-1)*}(n',l') + h\nu$$

where the beam neutral is represented by H^0, $A^q(n,l)$ represents an impurity ion of charge q in a quantum state (n,l), and the emission is represented by $h\nu$. The impurity density n_Z

is inferred from the intensity of the spectral emission, impurity temperature T_Z from the width of the Doppler broadened spectral line, and the rotational velocities of the impurity v_θ and v_φ from the Doppler shifted spectral line. Radial electric field E_r may be inferred from the rotational velocities via the radial component of the impurity momentum balance equation.

The spatial resolution of this measurement will depend on the width of the beam which can be modified to a limited degree for C-Mod. The beam is composed of beamlets, each of which emanates from one of the 61 apertures in the accelerator grids. The apertures are closely spaced over a circular area of 0.16 m diameter. To reduce the plasma area illuminated by the beam and thereby improve the resolution of the diagnostics, the accelerator grids are curved so that the ballistic trajectories of the neutral beamlets intersect at some point in the plasma that is designated as the focus. The beam was designed to focus at the center of the TEXT plasma with a full Gaussian width of 0.05 m, but the accelerator grids will be located further from the plasma in the C-Mod installation. Without modification, the beam width would be approximately 0.13 m. A straightforward increase in the grid radius of curvature will reduce that to approximately 0.08 m at the plasma center. Clearly, this modification will improve spatial resolution. For the measurement of T_z, n_z, and v_θ, the poloidal component of the impurity rotation velocity, the beam will be viewed from above as shown in Figure 3. With this view, the radial resolution is limited by the optimized beam width to 0.01 m for $r/a = 0.5$ and 0.03 m at the plasma edge. A horizontal view of the beam has even better resolution in the edge, 0.01 m. Thus with refocusing of the beam, the radial resolution becomes acceptable. These numerical estimates are intended as examples of beam optimization for C-Mod and will not become final until the details of the installation are complete. Collection optics effects are omitted.

The radial range over which ion temperature measurements are possible may be limited by the penetration of the beam. A simulation of the T_z measurement will help to better understand the conditions under which measurements can be made. For this simulation, the emission of principal interest consists of bremsstrahlung and the impurity line emission (5292 Å, n = 7 - 8, C^{+5}) due to beam-impurity interaction. Continuum emission due to recombination is small compared to bremsstrahlung for this wavelength. Impurity line emission from thermal processes in the plasma is ignored. The bremsstrahlung emissivity is[7]

$$\varepsilon_B(d\lambda) = \frac{1}{4\pi}\frac{2^5\pi e^6}{3m_e c^2\lambda^2 kT_e} Z_{eff} n_e^2 \left(\frac{2\pi kT_e}{3m_e}\right)^{1/2} \exp\left(-\frac{hc}{\lambda kT_e}\right)\langle g_{ff}\rangle(d\lambda)$$

The line emissivity is[8]

$$\varepsilon_L(d\lambda) = \frac{1}{4\pi}\frac{hc}{\lambda}\sigma(\lambda) n_Z n_B(d\lambda).$$

In these representations, $\langle g_{ff}\rangle$ is the free-free Gaunt factor,[7] and $\sigma(\lambda)$ is the cross section[8] for photon emission in the beam-impurity interaction. The beam penetration is as calculated in the previous section, and the profile of the beam density transverse to the direction of propagation is Gaussian with a half width at 1/e points of 0.03 m. The Doppler broadened radiance spectrum is computed for chords such as those in Figure 3. It is then possible to estimate the radial range over which an accurate measurement of the spectral line width (T_z measurement) and the spectral line shift (v_θ measurement) are possible. Of course, this will vary with impurity concentration. For the plasma described in Figure 1, it will be possible to measure widths and shifts for carbon concentrations as low as $n_C / n_e = 0.001$. Measurements are limited for plasma with densities in excess of 3×10^{20} m^{-3}. This density range can be extended upward for T_z even without modulation of the beam as it is a less stringent measurement. The penetration depth of the beam at the higher densities can be increased by increasing the beam energy. The accompanying reduction in impurity excitation partially compensates this so that the beam current density must be increased to obtain a major increase in emission. An increase in current density would be included in a modification of the beam energy in order to keep the beam on perveance; that is, to maintain a minimum beam divergence.

Turbulence measurements

Beam neutrals are excited by interactions with thermal plasma constituents, electrons, protons, and impurity ions. Thus, plasma ion density fluctuations are transferred to the excited state density of the beam by proton impact and then to the emitted spectrum. For ions, the principal processes involved are

$$p^+ + H^0 \rightarrow p^+ + H^{0*}$$

$$H^{0*} \rightarrow H^0 + h\nu$$

Electron density and impurity density fluctuations will be impressed on the beam emission in a similar fashion. In the prototypical experiment, the beam ion and the plasma ion are the same. It would then be necessary to view the beam so that the fluctuating beam emission could be distinguished from the thermal edge emission by the Doppler shift due to some component of the beam velocity. That view would be along field lines to avoid averaging out the poloidal and radial components of the turbulence. Hence, the neutral beam trajectory would itself require a significant toroidal component. This is not practical for C-Mod. Further, the usual hydrogen emission observed in these experiments is insensitive to density fluctuations at the high densities of C-Mod; consequently, a helium beam will be used. The thermal edge emission will not contain an appreciable contribution from edge recycled helium: The amount of helium introduced by the beam is small and will not be retained in the walls between shots. The small amount of room temperature helium that escapes the beam line will appear only after the beam pulse.

The beam will be viewed toroidally. The intersections of the horizontal viewing chords with the beam are shown as the small rectangles in Figure 3. The viewed volumes are arrayed in a cruciform with poloidal turbulence data inferred from the vertically displaced volumes. The radially displaced volumes are used for radial correlations of turbulence and for beam noise compensation. The radial and poloidal separation between channels can be as small as 0.01 m, though the finite lifetime of the states used for these measurements may induce smearing on spatial scales of that order.

Helium beams have a metastable component which has a significantly larger ionization cross section than the ground state component. While penetration calculations show that the beam component in the ground state will penetrate the plasma of Figure 1, the metastable component will not. Thus, the penetration of the entire beam will be a strong function of the constituency of the beam. As demonstrated in previous work on TEXT,[9] the metastable component can be tailored to suit the experiment. In the TEXT experiment, the metastable component was deliberately increased, but reduction of that component will be advantageous in the higher density C-Mod experiments. Proper operation of the beam on C-Mod will require additional experimental study. The emission to be used in this experiment has not yet been selected although there are helium transitions that retain density sensitivity even at the high densities of C-Mod.

CONCLUSIONS

On C-Mod, a diagnostic neutral beam will contribute to our understanding of thermal transport, H-mode, and turbulence induced transport. While it will not be possible to make all possible measurements throughout the density range of C-Mod, measurements can be made over a major part of that range. The primary uncertainties are in the fluctuation measurements, but these can be overcome by using modifications of existing techniques.

ACKNOWLEDGMENT

This work was supported by the U. S. Department of Energy by Grant DE-FG03-94ER-54241 to the University of Texas Fusion Research Center and by Contract DE-AC02-78ET-51013 with the MIT Plasma Fusion Center.

REFERENCES

1 M. Kotschenreuther, W. Dorland, M. A. Beer, and G. W. Hammett, Phys. Plasmas **2,** 2381 (1995).

2 W. D. Dorland, personal communication (1996).

3 J. R. Coupland, D. P. Hammond, J. W. Mepham, and O. J. Hancock, 12th Symposium on Fusion Engineering, Monterey, CA, 1987.

4 H. W. Kugel, R. Kaita, G. M. Gammel, T. A. Kozub, D. W. Roberts, J. R. Coupland, I. L. S. Gray, and J. W. Mepham, Nuclear Instruments and Methods in Physics Research **B40/41,** 988 (1989).

5 D. P. Hammond, Culham Laboratory Report (1985).

6 Y. Takase, R. L. Boivin, F. Bombarda, P. T. Bonoli, C. L. Fiore, and D. Garnier, Plasma Fusion Center, Massachusetts Institute of Technology PFC/JA-96-9 (1996).

7 W. J. Karzas and R. Latter, The Astrophysical Journal Supplement Series **55,** 167 (1961).

8 R. J. Fonck, D. S. Darrow, and K. P. Jaehnig, Physical Review A **29,** 3288 (1984).

9 Y. Y. Karzhavin, R. D. Durst, R. D. Bengtson, R. V. Bravenec, D. L. Brower, G. Cima, R. J. Fonck, J. W. Heard, J. S. Kim, A. N. Nikitin, A. Ouroua, E. J. Powers, D. R. Roberts, C. Watts, and A. J. Wootton, 22nd European Physical Society Conference on Controlled Fusion and Plasma Physics, Bournemouth, UK, 1995.

FIGURE CAPTIONS

Figure 1. Transmission of a neutral beam (a) through a C-Mod L-mode plasma with profiles as in (b).

Figure 2. Transmission of a neutral beam (a) through a C-Mod PEP-mode plasma with profiles as in (b).

Figure 3. Example of vertical viewing chords which would be used to view the neutral beam from a top port. The small rectangles labeled "Horizontal View Intersections" represent the intersections of horizontal (toroidal) viewing chords with the beam.

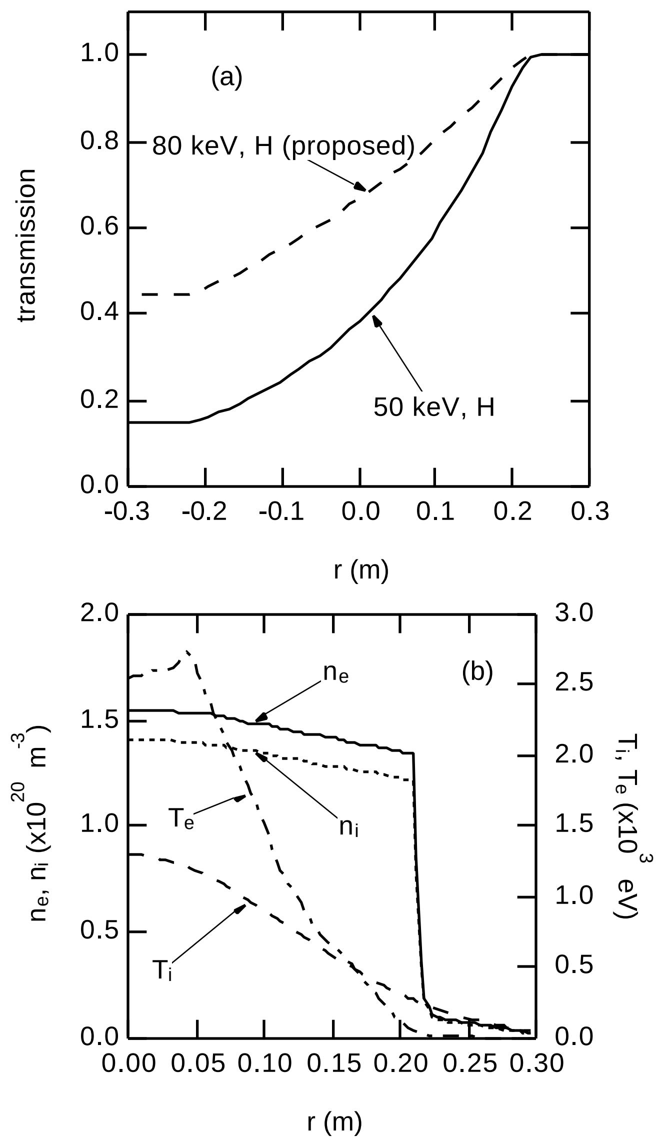

Fig. 1, Rowan, et al., RSI

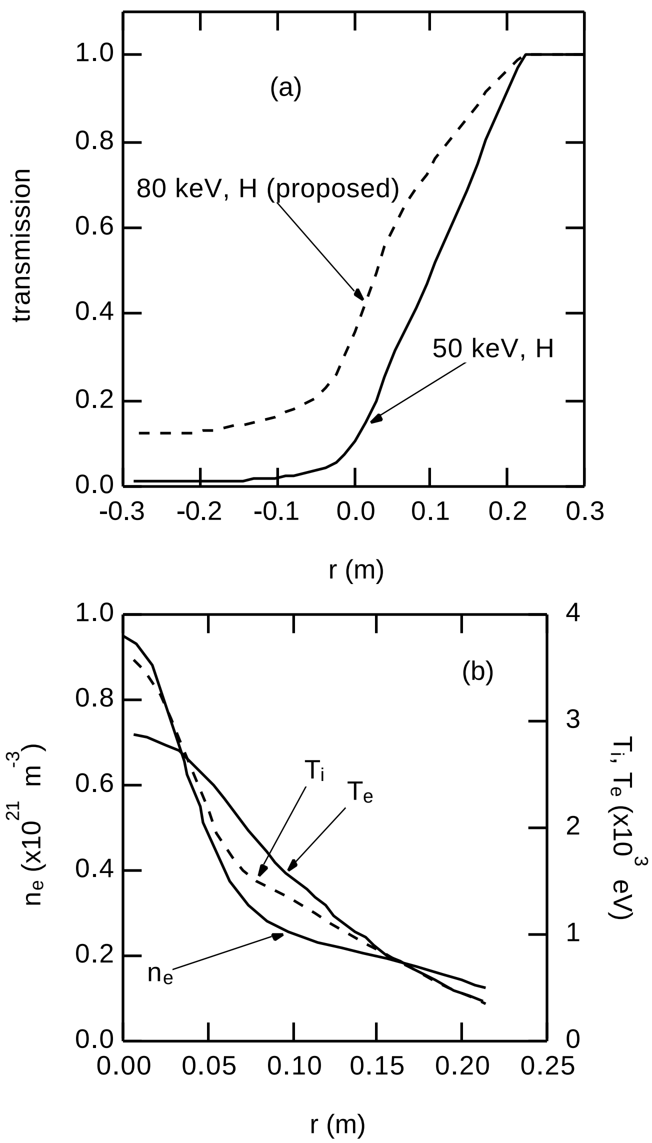

Fig. 2, Rowan, et al., RSI

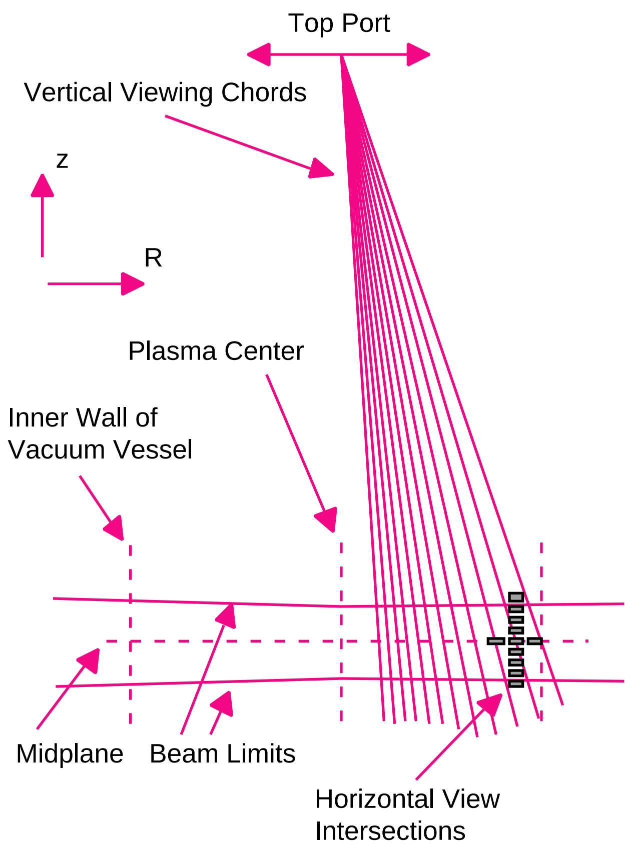

Fig. 3, Rowan, et al., RSI