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DIAGNOSTICS FOR NEUTRAL-BEAM-HEATED TOKAMAKS

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R.J. Goldston

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PRINCETON UNIVERSITY
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DIAGNOSTICS FOR NEUTRAL-BEAM-HEATED TOKAMAKS

Dr. Robert J. Goldston

Princeton Plasma Physics Laboratory

Princeton, New Jersey

ABSTRACT

Diagnostic techniques for neutral-beam-heated tokamak plasmas fall into three categories: 1) magnetic diagnostics for measurements of gross stored energy, 2) profile diagnostics for measurements of stored thermal and beam energy, impurity content and plasma rotation, and 3) fast time resolution diagnostics to study MHD fluctuations and micro-turbulence.

Diamagnetic and equilibrium poloidal field measurements of total stored energy lend themselves to rapid analysis and immediate feedback to machine operations. Detailed profile measurements of n_e , T_e , and T_i are required to substantiate the magnetic measurements and to provide direct information on plasma confinement. Typical diagnostic techniques for "kinetic" stored energy profiles include microwave and FIR interferometry, Thomson scattering, electron cyclotron emission, charge exchange, X-ray Doppler broadening, and neutron emission (with $H^0 \rightarrow D^+$ injection). Impurity content and radiative power loss are monitored with bolometry, and UV and X-ray spectroscopy; plasma rotation is measured by UV and X-ray Doppler shift techniques, and by frequency shifts in Mirnov oscillations. Beam ion thermalization is studied with scanning charge exchange analysis and, for D^0 injection, with neutron emission measurements.

The primary diagnostic techniques for MHD fluctuation measurements have been soft X-ray diode arrays and arrays of Mirnov coils. In high- β

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discharges, however, fast time-resolution charge exchange and neutron measurements have also provided insight into the effects of the observed fluctuations on energetic ions. CO_2 and microwave scattering techniques give information on MHD activity and especially on micro-turbulence during beam injection. This extensive array of diagnostics for neutral-beam-heated tokamaks is required in order to allow consistency checks between different diagnostic techniques. In addition, the new phenomena encountered with auxiliary heating, especially at low q and high β , are sufficiently complex that a high degree of time and space resolution will be required if the new processes are to be understood.

INTRODUCTION

The earliest tokamak diagnostic systems were electro-technical in nature: plasma current measured with a Rogowski coil, loop voltage measured across a ceramic break, B_θ loops for plasma position shift within a conducting shell, a diamagnetic loop for total stored energy. Soon these were supplemented by the simplest profile measurements: microwave interferometry for plasma density, single point Thomson scattering for electron temperature and density profiles, neutral particle analysis for ion temperature, elementary ultra-violet spectroscopy. As tokamak experiments have grown in size and complexity, their diagnostic systems have undergone a similar development. Single channel instruments have developed into multi-channel devices, time and space resolution has been improved, entirely new diagnostic techniques have been implemented. In this lecture we will concentrate both on the new techniques which are especially important for neutral beam heated tokamaks, and on older measurement techniques, such as magnetic diagnostics, which have found new importance in this context.

MAGNETIC DIAGNOSTICS

1. Equilibrium Field

Figure 1(e) shows the location of the field coils which provide the vertical equilibrium magnetic field in a modern tokamak. This field is required because the inductance of the plasma and the stored kinetic energy give rise to an outward directed hoop force, tending to make the major radius of the plasma column expand. In early tokamaks this tendency was countered by using a thick toroidal copper shell around the plasma column. Image currents were generated in the shell by any plasma motion, repelling the plasma and

thus counteracting the radial force for times shorter than the L/R time of the conducting shell. In modern devices, where equilibrium is required for periods of up to 5-10 seconds, an externally applied vertical equilibrium field, controlled by a feedback amplifier, is used to maintain plasma position. For a circular cross-section plasma, in the limit of high aspect ratio, the required vertical field is given by /1/

$$B_v = \frac{I_p}{R} \left[\ln \left(\frac{8R}{a} \right) + \frac{1}{2} (\ell_i + \beta_{p\parallel} + \beta_{p\perp}) - \frac{3}{2} \right], \quad (1)$$

where

$$\beta_{p\perp} \equiv \frac{8\pi \int d^3r u_{\perp}}{B_p^2(a) \int d^3r}, \quad u_{\perp} = \frac{1}{2} m_i \int f_i v_{\perp}^2 d^3v + \frac{1}{2} m_e \int f_e v_{\perp}^2 d^3v \quad (2)$$

and

$$\beta_{p\parallel} \equiv \frac{16\pi \int d^3r u_{\parallel}}{B_p^2(a) \int d^3r}, \quad u_{\parallel} = \frac{1}{2} m_i \int f_i v_{\parallel}^2 d^3v + \frac{1}{2} m_e \int f_e v_{\parallel}^2 d^3v.$$

(3)

and

$$\ell_i \equiv \frac{2}{a^2 B_p^2(a)} \int_0^a B_p^2(r) r dr.$$

(Note that some authors use a definition of β_{pl} that is one-half of what is given here. This arises from an "energy" rather than a "pressure" definition of β_p . The definitions given here are more consistent with the original Russian literature, more generally employed, and more convenient.) The equilibrium field which is automatically supplied by the feedback amplifier measures a combination of the plasma inductance (both external and internal) and the stored thermal energy. Note that the parallel stored energy $u_{||}$ is given twice as much weight in this expression as the perpendicular stored energy $u_{\perp}$. This ratio can be understood by considering the total radial hoop force exerted by the plasma expressed as dU/dR , where R is the plasma major radius and U is the total stored energy in the plasma. By conservation of the magnetic moment, $\mu = W_{\perp}/B$, for all the plasma particles $dW_{\perp}/dR = dW_{\perp}/dB \times dB/dR = -W_{\perp}/R$. Since the total particle number is conserved, this implies $dU_{\perp}/dR = -U_{\perp}/R$, which is thus the total radial expansion force due to the perpendicular stored energy. On the other hand, by conservation of angular momentum, for all the particles $dW_{||}/dR = v_{||} d(mv_{||})/dR = -2W_{||}/R$, and so $dU_{||}/dR = -2U_{||}/R$. Thus, per unit energy, the parallel stored energy exerts twice the radial force as the perpendicular and so requires twice the applied vertical field for equilibrium. For an isotropic thermal plasma $\beta_{pl} = \beta_{p\perp}$, and the use of $(\beta_{p||} + \beta_{p\perp})/2$ in Eq. (1), rather than simply β_p , has no effect. With neutral beam injection, however, the beam distribution is typically quite anisotropic and can contribute significantly to the total stored energy in the plasma. Based on Monte Carlo beam slowing down calculations for PLT and PDX, it is reasonable to estimate for tangential injection that the beam $\beta_{p||}$ is 2 - 3 times the beam $\beta_{p\perp}$, while for perpendicular injection the beam $\beta_{p||}$ is 2 - 3

times the beam β_{pl} . Thus if one uses the equilibrium field to estimate the total stored energy, with no correction for anisotropy, the beam contribution will be overestimated by 12.5 - 20% for tangential injection, and underestimated by 10 - 14% for perpendicular injection. In either case, of course, the total β_p measured from the equilibrium field can be compared with calculations based on summing the kinetically measured plasma stored energy and performing a proper evaluation of the beam parallel and perpendicular pressure. A problem which remains, however, in making a measurement of β_p from the equilibrium field is how to estimate the magnitude of $l_i/2$. In non-circular tokamaks the vertical field required for equilibrium must be determined from 2-D numerical calculations of MHD equilibrium. The resulting vertical field is a function, again, of both stored plasma energy and internal inductance. However in elongated plasmas, the degree of vertical "stretching" achieved for a given amount of "pulling" at the top and bottom is largely only a function of internal inductance. Thus by measuring the "stretching" with diagnostic flux loops or field probes, it is possible in a tokamak with $> 1.4:1$ elongation to measure both β_p and $l_i/2$ independently /2/. In circular cross-section devices, however, this is not possible. In experimental situations with relatively little I_p , and relatively little change in electron temperature profile shape with injection, one can assume that $l_i/2$ changes little with neutral beam injection. Under these circumstances one typically plots $\Delta(\beta_p + l_i/2)$ as the measured quantity /3/. In situations with significant I_p , but non-pathological profiles, various techniques can be used to estimate $l_i/2$, including solving the magnetic diffusion equation with the measured $T_e(r,t)$ as an input. Moderate success can be achieved by assuming

$$j \propto [1 - (r/a)^2] [q(a)/q(0) - 1]$$

and then calculating $l_1/2$ numerically. $q(0)$ can be estimated perhaps as 0.8 for discharges with sawteeth. Figure 2a shows the results from a measurement of β_t^{eq} in PDX, using this technique /4,5/. For the scan shown here the beam power was varied by injecting 1 to 4 beams into discharges with 4 different plasma currents. Toroidal field and plasma density were held fixed at 12 kG and $4 \times 10^{13} \text{ cm}^{-3}$, respectively.

2. Diamagnetic Effect

The dia- or para-magnetism of a current-carrying plasma column can be used to determine its average perpendicular pressure. Magnetohydrodynamic equilibrium in an axisymmetric system with magnetic surfaces requires

$$\frac{1}{c} (\vec{j} \times \vec{B}) = \nabla p_{\perp} . \quad (4)$$

In the limit of large aspect ratio (R/a) and circular cross section this reduces to

$$\frac{1}{c} (J_{\theta} B_{\phi} - J_{\phi} B_{\theta}) = \frac{dp_{\perp}}{dr} . \quad (5)$$

Integrating over the plasma cross section and assuming $\delta B_{\phi} \ll B_{\phi}$, one obtains

$$\Delta\Phi = \frac{\pi a^2 B_p^2(a)}{2B_\phi} (1 - \beta_{pl}), \quad (6)$$

where $\Delta\Phi$ is the change in the toroidal flux due to the presence of the plasma. Note that in this equilibrium one may allow $p_\perp$ to be unequal to $p_\parallel$, and it is only $p_\perp$ that enters into the result. Because the diamagnetic loop is completely insensitive to β_{pl} , it is more strongly affected by the anisotropy of the beam distribution than is the equilibrium measurement. Making the same assumptions about beam anisotropy given above, we find that the diamagnetic measurement tends to underestimate the beam stored energy by 25 - 40% with tangential injection, and tends to overestimate it by 20 - 29% with perpendicular injection.

It is interesting to note that in the large aspect ratio calculation presented here the current profile and internal inductance play no role in the measured diamagnetic effect. Calculations taking into account toroidal effects /6/ show relatively little perturbation due to finite aspect ratio, and so only a small uncertainty is introduced.

Figure 2b shows the diamagnetic measurement of β_t^{dia} on PDX for the same current and power scan as Fig. 2a /7,5/. In this case the voltage induced in the toroidal field coil system by the changing diamagnetic flux of the plasma was used to measure β_t^{dia} . A separate diamagnetic loop was not required.

KINETIC DIAGNOSTICS

1. Electron Diagnostics

Magnetic measurements of total stored energy are extremely useful for rapid multi-dimensional parameter scans, and for fast feedback to machine operators during normal discharge tuning. On the other hand, in order to understand the transport processes going on within a plasma it is necessary to have profiles of electron and ion temperature and density, as well as some information on the power and particle inputs from the neutral beams. Electron temperature and density profiles are most reliably obtained from Thomson scattering measurements. Modern instruments measure at a number of radial points simultaneously, allowing efficient data collection. Systems using detector arrays which image the scattered photons both in wavelength and in spatial location give up to 56 point profiles of n_e and T_e (Fig. 3) /8,5/. In general Thomson scattering systems are not sufficiently stable in absolute calibration that they can be used for absolute density measurements. Rather the density profiles obtained from the scattering measurements must be normalized to a line average density obtained from microwave or FIR interferometry.

At high β_p the magnetic axis of a tokamak plasma shifts outwards in major radius, relative to the center of the outermost flux surface. This means that a vertically scanning Thomson scattering system cannot view the plasma center on both high- and low- β_p plasma shots, without physical displacement. For a circular cross-section plasma, with $\beta_p \ll R/a$, Shafranov has calculated the magnetic axis shift /9/:

$$\Delta = \int_0^a \frac{r}{R_0} \left[\frac{8\pi (\overline{p(r)} - p(r))}{B_p^2(r)} + \frac{\overline{B^2(r)}}{2B_p^2(r)} \right] dr \quad (7)$$

where

$$\overline{x(r)} \equiv \frac{2}{r^2} \int_0^r x(r') r' dr'.$$

Alternatively, a quick estimate of the magnetic axis shift can be made by considering the position of a line current that is required to produce the same external poloidal flux as the plasma /1/:

$$\Delta_{1c} = \frac{a^2}{2R_0} \left(\beta_p + \ell_i/2 - \frac{1}{2} \right). \quad (8)$$

This formula tends to slightly underestimate the more accurate calculation of Eq. (7) /10/, but it can be seen that at $\beta_p + \ell_i/2$ of order 1.5, a relative shift of $\Delta/a \sim a/(2R)$ can be expected. For a typical tokamak aspect ratio of 3, this corresponds to a 17% shift. Thus even at fairly modest values of β_p , it is desirable to scan across the horizontal midplane with Thomson scattering, rather than along a vertical chord. For single shot profile measurements this means that the laser beam must fire across the midplane, while the viewing system looks from top or bottom. Similarly the

interferometer used for density normalization must view across the midplane. This arrangement presents difficulties with the laser dump, which has to be very efficient at absorbing light, without using up valuable territory on the inboard major radius side of the plasma. A horizontally viewing interferometer has similar problems with placing a stable reflector on the tokamak inner wall. On the other hand, a horizontal Thomson scattering system can directly measure the magnetic axis shift, from the shift of $T_e(R)$, if one assumes that rapid parallel electron thermal conduction equalizes T_e around a flux surface. This provides an indirect check on β_p determined from other measurements. Furthermore in/out asymmetries in the density profile, relative to the electron temperature profile (Fig. 3, /11/), may reflect beam ion density asymmetries, plasma rotation effects, or transport in/out asymmetries.

Thomson scattering techniques, while capable of providing good time and space resolution, are in general relatively poor for measuring the time evolution of plasma parameters. With the exception of multi-pulse or continuous mode laser systems, which are still developmental, Thomson scattering systems must take data at different times in successive plasma shots. Concatenating data from a series of nominally identical shots to form a time evolution risks introducing spurious "breathing" in profile shape due, for example, to sawtooth oscillations that occur at random times with respect to the laser firing time. Because of this limitation of the Thomson scattering technique, it is desirable to find a method to measure $T_e(r,t)$ during a single discharge. Theoretical considerations /12/ indicate that even at modest densities tokamak plasmas should emit extraordinary mode radiation at twice the electron cyclotron frequency essentially at the blackbody level, so long as the electron drift parameter, ξ ($= v_{de}/v_{te}$), is sufficiently low. In the FT tokamak significant deviation from thermal emission was observed for

$\xi > 0.025$ /13/. A further limitation is that the plasma density must not be so high that ω_{pe} approaches $2\omega_{ce}$, where significant refraction and even cut-off can occur /14/. Within these constraints spectrally resolved measurements of the natural plasma emission in the millimeter microwave region, or in the very far infrared, constitute time and space resolved measurements of electron temperature. Combined with a multi-chord interferometer to measure the electron density profile as a function of time, this forms a very powerful system for single-shot time and space resolved electron measurements.

In order to measure $T_e(R)$ with electron cyclotron emission (ECE), one must view the plasma along a major radius, and cover a spectral range of width $\Delta\omega/\omega \sim 2a/R$. Heterodyne microwave detection can be used in moderate field devices, while quasi-optical far-infrared techniques must be used at higher fields. Here one uses either a grating polychromator, to measure T_e at specified locations with excellent time resolution (Fig. 4) /15/ or a scanning Michelson interferometer to measure across the full radial profile, but with significant integration time or at least a few milliseconds. Most ECE systems must be calibrated in situ against another, absolutely calibrated measurement technique. While these systems do not have the spatial resolution of the laser scattering measurements, due to finite spectral resolution and viewing angle, nor the absolute calibration, ECE diagnostics have proved to be especially useful for neutral beam heating experiments. With injection heating, where in addition to the complex tokamak system one also has a sometimes temperamental beam system to contend with, diagnostics which require a minimum number of nominally identical plasma shots to complete a scan are desirable. Furthermore, at low powers it is often a relatively small $\Delta T_e/T_e$ which is the subject of study, and ECE diagnostics, which may have significant systematic errors but can be designed to have very low random errors, are

especially well suited to the job. One problem that occurs at high β , of course, in addition to the axis shift, is the fact that B_T no longer varies precisely as $1/R$. Under these circumstances a more complex unfolding will be needed to find $T_e(R)$.

A final standard electron temperature diagnostic technique for tokamaks, soft X-ray spectroscopy, has not found extensive application in neutral beam heated tokamaks. This is perhaps because it strikes an uncomfortable balance between the strengths and weaknesses of the Thomson scattering and ECE techniques. Multi-chord soft X-ray spectroscopy, while it can give the full time evolution of $T_e(r,t)$, like ECE, generally can only obtain rather coarse time and space resolution ($\Delta t \gtrsim 25$ msec, $\Delta r/a \sim 1/5$) even with averaging over a number of shots. Although soft X-ray spectroscopy does not require absolute calibration against other diagnostics, it shares the problem with the ECE diagnostic that a supra-thermal electron tail can affect the measurement significantly. Soft X-ray spectroscopy shares with passive charge exchange the problem that chord-integral measurements are made. Therefore, careful judgment must be used in choosing which range of the energy spectrum is to be used. The best technique is to use Abel inversion to determine local emission spectra, but then this introduces uncertainties associated with the inversion process. Finally, the Si(Li) detectors used for pulse height analysis measurement of the soft X-ray spectrum are sensitive to photons from (n,γ) reactions. In cases of D^0 neutral beam injection copious γ -rays are produced due to reactions between neutrons generated in the plasma and materials in the vicinity of the detector. This produces a spurious high energy tail on the spectrum which can eventually swamp the measurement itself at high enough neutron flux.

2. Ion Diagnostics

The traditional basic technique for measuring the central ion temperature in tokamak plasmas has been by neutral particle analysis. Hot ions within the plasma core suffer charge exchange with ambient neutrals and then have some probability of subsequently escaping the plasma and being detected. By measuring the energy spectrum of escaping neutrals along a chord viewing through the plasma minor axis, one can obtain information about the ion distribution function in the central region of the discharge. The neutral density profile in a tokamak, however, is sharply peaked towards the edge of the plasma, and so the greatest charge exchange reaction rate occurs near the surface. To avoid measurements dominated by particles produced in the edge region, one typically measures the neutral particle energy spectrum in the range of $\sim 3 - 10 T_i(0)$. Because the edge plasma is much cooler than $T_i(0)$, there are in general exponentially few ions in this energy range near the plasma surface. Thus the measurement tends to concentrate on the high energy tail of the ion distribution function near the plasma center. To measure the $T_i(r)$ profile one simply scans the analyzer (typically vertically on a tokamak) such that the point of closest approach of the analyzer sight-line to the plasma minor axis is at the desired radius.

The technique described here has been successfully employed on Ohmically heated tokamak plasmas at moderate line integral densities, where neutrals from the plasma center have a reasonable probability of escaping to be detected. With neutral beam injection charge exchange measurements have proven very useful, but additional complications are introduced by the presence of a large population of supra-thermal ions in the plasma. First of all, it is clear that to measure ion temperature on tokamaks with injection

heating one must have a neutral particle analyzer capable of discriminating mass as well as energy. This is because the slowing down distribution of beam ions dominates the high energy portion of the ion distribution function in the energy range typically used for ion temperature measurement. To distinguish unthermalized beam-injected particles from the bulk thermal ion population, it is convenient to inject one species of neutrals (for example hydrogen) into a plasma composed dominantly of a second species (in this case deuterium). A mass discriminating analyzer is then used to measure the distribution function of the second species, since these particles are believed to be unambiguously members of the bulk thermal ion population. It is easy to show that a purely electrostatic ion energy analyzer, such as was used in the first tokamak neutral particle detectors, is incapable of distinguishing two particles of identical charge and energy, but differing mass. On the other hand energy analyzers based solely on magnetic fields cannot distinguish particles of identical charge and momentum, but differing mass. In order to provide mass-sensitive charge exchange analysis it is necessary to make a combined magnetic and electrostatic system. Typically in these systems the ions are momentum analyzed in a magnetic field, and subsequently they are energy analyzed (which at this point is equivalent to being mass analyzed) using an electrostatic field /16,17/. In some cases the two fields are superimposed /18/. Only very crude mass resolution is required in this sort of system, since it is generally only necessary to distinguish between different hydrogenic species. On the other hand, the rejection ratio for cross-talk between masses must be very high ($\sim 1000:1$) to measure the tail of the bulk ion distribution function in cases of high beam injection power, and relatively low $T_i(0)$.

If one solves the mass discrimination problem, there are still further difficulties with charge exchange analysis during high power neutral beam injection. The Maxwellian nature of the thermal ion distribution function at high energies is set up by a delicate balance of velocity diffusion and drag. If the plasma is heated to high temperature, and the energy confinement time stays roughly constant, then the particles at $3 - 10 T_1(0)$ may have collision times comparable to the ion energy confinement time. This implies that significant distortions of the ion energy distribution can occur. Neutral beam injection itself does not preferentially heat the high energy portion of the ion distribution, but an ion energy loss mechanism with even a moderate velocity dependence can cause a significant change in df_1/dv at high energies /19/.

If the ion distribution function is no longer Maxwellian, then the use of standard charge exchange techniques, which depend on measuring f_1 well above the thermal range, becomes questionable. In this case it is necessary to use a modulated neutral beam to dope the plasma with neutrals in a chosen region along the analyzer sight-line /20/. Modulated flux observed at the analyzer corresponds to neutrals generated in the region where the beam and analyzer sight-lines cross. With this "active" technique it is no longer necessary to use only the high energy portion of the ion distribution function to measure T_1 , and any distortions from a Maxwellian can be ascertained directly. On PLT and PDX, using this technique, it was found that the central ion energy distribution function was indeed close to Maxwellian. Detailed profile measurements on PDX, however, show that a substantial non-Maxwellian tail is present on f_1 outside of the central plasma region (Fig. 5) /21/. One possible explanation for this observation is that the radial transport time

for hot particles in the plasma core is comparable to their thermalization time. As a result, while they are being transported radially, they must be observable in the outer region of the plasma with energies comparable to the energies present in the high energy ion tail located in the plasma core. A second, more mundane possibility, which is currently being investigated, is the presence of a small proportion ($\sim 1\%$) of hydrogen contamination in the nominally deuterium neutral beams on PDX.

An alternative technique for determining ion temperature in a tokamak plasma is to rely on Doppler broadening of impurity line radiation due to thermal motion of the impurity ions. This technique depends on the use of high resolution spectroscopy, either in the ultra-violet or in the soft X-ray region. Two recent developments in plasma spectroscopy have facilitated the development of these techniques. First, forbidden (magnetic dipole) line radiation has been identified in the near ultra-violet from highly stripped metallic impurity ions, whose dominant resonant line radiation is in the extreme ultra-violet /22/. These highly stripped ions reside in the plasma core, and yet emit detectable radiation at long wavelengths. Thus they provide a unique measurement opportunity, since high throughput optics can be employed and Doppler broadening measurements are relatively easy. This makes Doppler broadening techniques applicable all across the radial profile. Previously they had been relegated to measuring ion temperature in the edge region of the plasma, where ionization potentials are low, and consequently resonant line radiation is at long wavelengths. The second recent development in plasma spectroscopy is the application of very high resolution ($1/15000$) curved crystal X-ray spectrometers to measuring Doppler broadening of metallic impurity ion $K\alpha$ lines /22/. By choosing the $K\alpha$ line of the helium-like charge

state, one has a relatively simple spectrum to analyze /24/, and one studies an ionization state which dominates the charge distribution of the impurity ion over a wide range in electron temperature.

An interesting problem arises in applying any form of impurity line radiation Doppler broadening technique to measuring ion temperature in a neutral beam heated tokamak. The energy transfer rate from the circulating beam ion population to any particular thermal ion in the plasma scales as

$$\left. \frac{dE}{dt} \right|_b \propto \frac{Z^2}{m} . \quad (9)$$

Where Z is the charge of the thermal ion, and m its mass. Thus the beam ions couple energy proportionally more rapidly to impurity ions than to the bulk hydrogenic species. The total energy loss rate for the beam ions is generally insensitive to the impurity ion fractional concentration (particularly in the case of a deuterium bulk plasma) because, for fixed electron density, a single impurity ion "replaces" Z hydrogenic ions by quasi-neutrality. It is still true, however, that the impurity ion population is being heated at a rate $\sim Z$ times faster than the hydrogenic ions. The dominant mechanisms which nonetheless maintain the impurity ion temperature close to the bulk ion temperature are impurity ion - bulk ion energy coupling, and, to a lesser extent, impurity ion - electron coupling. Direct transport loss from the impurity ions may play a role as well. At high ion temperatures and low densities (both serving to reduce v_{ii}), the difference between the impurity and hydrogenic ion temperatures can become substantial. This effect can be calculated by setting up a system of temperature equilibration equations for the heating of each of the impurity species, and for their coupling to each

other and to the bulk plasma. In general however, because of the low impurity ion velocities and high charge states, one finds that the impurity ions are well coupled to each other, even in cases where the impurity temperature (T_x) differs significantly from the hydrogenic ion temperature (T_h). Under these circumstances one can lump all of the impurities together and treat them in an average sense, and thus set up a rather simple temperature equilibration equation:

$$\frac{dT_x}{dt} = \frac{T_h - T_x}{\tau_{xh}} + \frac{T_e - T_x}{\tau_{xe}} - \frac{T_x}{\tau_{Ex}} + \frac{2}{3} \left. \frac{dE}{dt} \right|_b \quad (10)$$

where τ_{xh} and τ_{xe} are the energy equilibration times /25/ between the impurities and the hydrogenic species, and between the impurities and the electrons, respectively. τ_{Ex} is an estimated energy containment time for the impurity ions. For the most extreme cases of low density ($n_e(0) \sim 5 \times 10^{13} \text{ cm}^{-3}$) and high temperature ($T_i(0) \sim 6.5 \text{ keV}$) analyzed for PLT /26/ the impurity ion temperature was found experimentally to lie $\sim 1.5 \text{ keV}$ above the bulk hydrogenic ion temperature, in rough agreement with Eq. (10).

Another technique which is useful for measuring central ion temperature in the case of H^0 injection into a D^+ plasma is neutron emission. In general the neutron emission is high enough during neutral beam injection that non-thermonuclear neutron production by photo-nuclear processes and by electro-disintegration of deuterium is negligible. A significant problem can arise, however, due to deuterium contamination of the hydrogen neutral beam. At low ion temperatures even the natural concentration of deuterium can create a problem, and with continuous tokamak operation in deuterium some contamination of the beam-lines is inevitable. Furthermore, if the ion sources are switched

between hydrogen and deuterium operation, some modest wall retention and subsequent desorption of the incorrect species is to be expected. The only way to discriminate with certainty against neutrons produced by D^0 contamination of the neutral beams is to measure the energy spectrum of the neutrons emitted from the plasma. Along (against) the direction of injection there will be a significant up-(down-) shift in neutron energy, given by

$$E_n = 2.45 \text{ MeV} + \frac{1}{2} E_b \pm \left[\left(2.45 \text{ MeV} + \frac{3}{8} E_b \right) (E_b/2) \right]^{1/2} \quad (11)$$

where E_b is the beam deuteron energy. While the second term in this equation is negligibly small, the third term shifts the neutron peak up or down by an energy of order $\sqrt{E_b E_n}$, which can be measured with standard neutron spectroscopic techniques /27/.

In the temperature range around 1 keV the D-D fusion rate coefficient for a Maxwellian plasma varies about as T_i^4 , so problems of absolute calibration have relatively modest impact on the determination of T_i . Again of course, as with charge exchange, if the deuterium ion distribution function is distorted from Maxwellian this measurement, which is a "tail" measurement in effect, will give an incorrect result. The most vexing problem, however, with H^0 injection into D^+ plasmas is contamination of the plasma with non-reacting hydrogen. The gas flow into the torus during beam conditioning can result in a significant buildup of hydrogen on the torus walls, and the injection pulse itself introduces cold hydrogen gas into the torus, as well as energetic neutrals into the core of the plasma. This problem can at least be monitored, however, using active charge exchange to measure n_h/n_d in the plasma core. Some information can be gained by observing the ratio of the $H\alpha$ to $D\alpha$ radiation due to recycling gas /28/.

With all of these caveats, neutron emission has nonetheless proved to be a reasonably reliable and robust ion temperature measurement technique, especially for high density plasmas with relatively little gas flow out of the beam lines. Figure 6 shows a comparison of neutron emission, charge exchange, X-ray Doppler and UV Doppler measurements of $T_i(0)$ in PLT with 1.6 MW H^0 injection into a D^+ plasma /15/. The agreement between the different techniques gives one confidence that a true $T_i(0)$ is measured.

Another parameter which is important to measure during neutral beam injection is the plasma rotation speed. Especially with unbalanced tangential injection, there is some theoretical concern that instabilities and enhanced ion thermal transport can be caused by toroidal rotation speeds which become comparable to the ion sound speed. One of the first techniques employed to assess plasma rotation was to measure the change in frequency of the $m=1/n=1$ sawtooth precursor oscillations /29,15/. If one interprets this as being due to bulk plasma toroidal rotation carrying the mode past the soft X-ray detector, much like a truck carrying a horizontal barber pole, then the rotation speed is easy to estimate. On the other hand, one must be concerned that changes in the plasma pressure and current profiles associated with neutral injection may change the mode frequency independent of any rotation. In addition it has been observed on a number of experiments that the rotation of MHD modes can be stopped by the introduction of modest non-axisymmetry into the system, suggesting that the mode rotation is only weakly coupled to the plasma motion. On PLT at first good correlation was found between the toroidal rotation velocity measured with this technique and by other methods /15/. However when a toroidal field coil was damaged such as to create 0.5% toroidal field ripple on axis, the correlation was lost /30/.

Both X-ray and UV Doppler techniques can be applied to the measurement of plasma rotation, simply by addressing one's attention to the measured Doppler shift, rather than to the broadening. For toroidal rotation measurements the instrument must be aligned to face at least somewhat in the direction around the torus, while for poloidal rotation the viewing sight-line must scan across the plasma cross section. It is important in practice to measure both of these quantities, since the radial electric field, which may be important in determining at least impurity particle confinement, if not other aspects of transport as well, is correlated with the velocity perpendicular to the field lines, rather than with either toroidal or poloidal rotation independently. For these applications, near UV techniques employing rotating mirrors to scan in viewing angle, coupled with vibrating plates to scan in wavelength, are the most flexible. If at the same time one takes advantage of the range of different forbidden lines now identified, it is possible to make quite detailed measurements of the radial profile and time evolution of plasma rotation /31/. Because momentum transfer rates between impurity and bulk ions are very rapid, one anticipates no significant difference between the impurity and bulk ion rotation speeds analogous to the temperature difference discussed above.

3. Impurity Diagnostics

The techniques employed to assess plasma impurity levels and radiation losses during neutral beam injection are little different from those used in ohmically heated plasmas. One is dealing, typically, with much higher radiation levels due to the greater energy throughput, but the basic techniques of X-ray and ultra-violet spectroscopy and bolometry developed for

ohmically heated tokamaks remain largely unchanged. One difficulty introduced by neutral beam injection is the presence of a high toroidally averaged density of energetic hydrogen neutrals in the core of the plasma ($\sim 10^8 \text{ cm}^{-3}$). A fraction of these primary beam neutrals suffer charge exchange collisions with impurity ions within the plasma, lowering the charge state of the impacted impurity ions by 1. For high injection powers this can lead to a reduction in the average charge state of the impurity ions, because charge exchange begins to compete with the normal ionization and recombination processes. This results in a net increase in the radiation level, for a fixed concentration of impurity ions, with the amount of the increase depending on the ionization balance prior to injection and the radiative efficiency of the different charge states involved /32,33,34/. The assessment of the total impurity ion radiation level, based on the measurement of a few selected lines, then depends on the profile of the beam neutral density and on the value of a number of charge exchange cross sections which are somewhat uncertain.

Ultra-violet and X-ray spectrometers suffer from the fact that they can only measure a limited region of the electromagnetic spectrum. With bolometric techniques one attempts to overcome this problem by directly measuring the total radiative power emitted by the plasma, which is the actual quantity of interest for electron power balance calculations with neutral injection. The usual experimental technique involves exposing to the plasma an array of thin metal foils with thermistors attached to their backs. The total radiated power deposited on each foil is found by measuring the rate of increase in temperature of the foil as a function of time. By arranging the foils to view the plasma along a number of sight-lines, through a single

collimator, one can obtain the full chord integrated radiation pattern using a single, relatively simple detector. Abel inversion techniques are then used to find the volume radiation emission rate. Poloidal and toroidal asymmetries in the radiative power, however, introduce some uncertainty into these measurements, since the Abel inversion assumes these symmetries. The principle difficulty with present bolometric techniques for neutral beam injected plasmas is that it is not now possible to separate radiation impinging on the detector from neutral particle flux due to charge exchange loss of either thermal or beam ions. In particular it has been calculated for PDX with near perpendicular injection, and a perpendicularly viewing bolometer array, that a substantial part of the power flux measured by the bolometer should be due to beam ion charge exchange. The bolometrically measured flux cannot simply be taken to be the sum of both radiative and beam charge exchange losses, however, because the beam losses are known to be both poloidally and toroidally asymmetric, as well as strongly anisotropic. In principle, with an absolutely calibrated neutral particle analyzer located near a bolometer, it should be possible to evaluate the total power carried by neutral particles along their common sight-lines. In practice, however, typical uncertainties in the absolute calibration of neutral particle analyzers (perhaps a factor of 2) make this technique somewhat unsatisfactory.

4. Beam Ion Thermalization

Perhaps the first question that was asked about neutral beam injection heating in tokamaks was whether the beam ion thermalization process was proceeding in agreement with classical theory. The primary diagnostic technique used to answer this question was to aim a neutral particle analyzer

into the plasma at about the same angle as the neutral beam, and to measure the charge exchange energy spectrum of the beam ions as a function of time. In general the results from a number of such experiments have shown agreement with theory, within experimental uncertainties, /35,36,37/. The next level of sophistication involves using a number of analyzers aimed at different angles, or a single analyzer with multi-sight-line capability. For this application mass analysis is not critical, since thermal species ions are not likely to be found in the energy range of greatest importance for these measurements. This simplifies the construction of the analyzer, and indeed makes multi-sight-line instruments possible /38/. For the multiple viewing chords one has a choice of a vertically scanning near-perpendicular system, or a horizontally scanning system which views from near perpendicular to parallel in the tokamak midplane. The vertically scanning system gives information related to the radial profile of the beam ion density, $n_b(r)$ but since charge exchange analyzers do not integrate over pitch angle, the strong anisotropy of the beam distribution makes this measurement very indirect. The uncertain neutral density profile shape creates further difficulty in determining $n_b(r)$ with this technique. A horizontally scanning system gives information about the competition between slowing down and pitch angle scattering of the beam ions, since off-angle channels will have significant flux only insofar as some particles are able to scatter in angle as they slow down. With either kind of system the beam ion loss rate can be assessed by comparing the slowing down spectrum with theory. If the spectrum is substantially depleted at energies below E_{inj} , relative to the theoretical calculation, then this can be interpreted to mean that beam ions are being lost from the discharge before they are able to thermalize and transfer their energy to the plasma.

Figures 7a and 7b show a comparison of experiment and theory for a PDX case of 2.5 MW injection into a divertor plasma. This work is characteristic of the more sophisticated studies of beam ion thermalization being performed now /39,40/. The charge exchange spectra were measured with a single instrument which viewed the plasma simultaneously along 5 horizontal chords, whose tangency radii varied from -15 to -63 cm. The tangency radius denotes the minimum distance from the detector sight-line to the symmetry axis of the machine. The detector in this case viewed counter moving ions (ions moving in the toroidal direction opposite to the plasma current), which is indicated by the negative sign of R_{tan} . The value of v_i/v to which an analyzer with tangency radius R_{tan} is sensitive, at a given major radius within the plasma, R_{det} , is given by $v_i/v = R_{\text{tan}}/R_{\text{det}}$. The spectra in Fig. 7a were taken by sweeping the voltage on the electrostatic energy analyzer in time, such that an energy range of 10 keV was covered in 7.5 msec. Thus the entire spectrum was obtained in ~ 40 msec. The center-lines of the PDX neutral beam injectors have tangency radii of + 35 cm, injecting co-moving ions. It is interesting that the maximum in the signal viewed with the counter-facing detector does not correspond to $R_{\text{tan}} = - 35$ cm. This is because co-injected particles, when they execute their initial banana orbits, move inwards in major radius. Thus their inner half-banana's, on which the particles are moving in the counter direction, are located in a higher magnetic field region than the initial deposition point. By μ conservation the particles must then become more perpendicular in pitch angle, and so are viewed at a smaller absolute value of R_{tan} . With counter-injection, the orbits move outwards in major radius, and the outboard co half-banana is more nearly parallel than the initially injected counter half-banana. This is seen in the charge exchange spectra on

PDX in the case of counter injection, and co detection. In this case the signal is greatest, with the analyzer viewing from $R_{tan} = + 14$ to $+ 63$ cm, at $R_{tan} = + 63$ cm, and the signal at $R_{tan} = + 14$ cm is undetectable at high energies.

Based on the above discussion, it is clear that theoretical calculations which do not take into account finite banana width effects will not give good agreement with the fast ion charge exchange spectra observed on PDX. However a bounce averaged Fokker-Planck calculation, which takes into account finite orbit width only in injection and detection, does give fairly reasonable results. In that code /41/ newly ionized particles are tracked to their banana tips, then deposited at that radius, and assumed to slow down and pitch angle scatter without further radial transport. For detection, at each point along the detector sight-line an orbit is again tracked to the flux surface where its banana tip is located, and Liouville's theorem is invoked to determine that f_b (the beam ion distribution function) must be constant along the orbit, and so f_b at the location of the banana tip is used to evaluate the charge exchange production rate at the relevant point along the sight-line. If the orbit tracking parts of this code are turned off, the reasonable agreement with experiment is lost, and the results give completely incorrect relative amplitudes of the signals at different values of R_{tan} . This indicates that the orbit physics of injection and detection determine much of the structure of the observed data. What is shown in Fig. 7b, however, is a different calculation. The Monte Carlo beam treatment /42/ in the transport analysis code, TRANSP, now includes a calculation of the charge exchange spectra observed by any array of specified neutral particle analyzers. To do this a beam ion distribution function is accumulated during the Monte Carlo

calculation, and then it is folded together with a calculation of the detector sensitivity along the trajectory of the detector's sightline through phase space. For these calculations f_D is binned into 121 spatial zones (both in minor radius and in major radius, or effectively in minor radius and poloidal angle), 50 energy zones, and 50 zones in $v_{||}/v$. The resulting calculation clearly shows excellent agreement with experiment for this PDX divertor case. Interestingly, in non-divertor PDX cases the agreement is somewhat less good, with the experiment showing about as much range in signal over five channels as the calculation shows over four. This is interpreted as being due to the presence of a top rail limiter located close to the analyzer, which gives rise to a neutral density profile that is not strongly peaked at the edge, when viewed across the horizontal midplane. This sort of problem, associated with a non-symmetry in the neutral density profile, is, of course, common to all kinds of charge exchange diagnostics. A very similar problem makes it difficult to use the curvature of a typical thermal charge exchange spectrum to determine $T_i(r)$. The relative contribution from different radii depends strongly on the (unknown) neutral density profile along the detector sightline. In this case as well, the relative contribution from the center and edge is critical to the fine detail of the results, although not to the overall picture.

In addition to charge exchange, the other main technique employed to study beam ion thermalization is to use neutron flux measurements with D^0 injection into D^+ plasmas. In this case the neutron emission is due both to beam-target and beam-beam reactions. With good electron temperature and density profiles it is possible to calculate the theoretically predicted neutron emission, and this can be compared with experiment. (For

perpendicular injection, however, one must take into account the poloidal localization of the beam ions in evaluating the beam-beam reaction rate. This effect has generally been neglected.) By varying the various plasma and beam parameters, the theoretically predicted neutron production can be made to vary by a factor of 100. Results from a study of this sort on PLT /41/ are shown in Fig. 8. The level of agreement here as well tends to support the idea that the beam slowing down and energy transfer are in reasonable agreement with theory.

FLUCTUATION MEASUREMENTS

The primary diagnostics used to measure MHD fluctuations in Ohmically heated tokamaks are soft X-ray detector arrays, and arrays of $\vec{B}_0$ coils located around the plasma in both the toroidal and poloidal directions. In neutral beam injected plasmas these diagnostics maintain the same function, although the signals they observe become more complex. Instead of the usual $m=2$ oscillations or sawtooth oscillations observed in almost all Ohmically heated tokamaks, a host of variations on these themes are seen in neutral beam heated devices, especially at high β . Progress is being made in classifying the kinds of oscillations observed, and delineating their evolution with increasing β . A great deal of work on this subject has been done by the ORNL group; very pretty correlations have been made between observed X-ray signals and theoretical predictions of high β_p distortions or the $m=1/n=1$ resistive tearing mode /43/.

Microwave and CO_2 laser scattering techniques are used to study small scale fluctuations in both Ohmically heated and beam heated devices. Here again the change is not so much in diagnostic technique as in the complexity

of what is observed. In general some increase in amplitude and frequency width of small scale fluctuations is observed with injection heating /44,45/, but the interpretation of these changes is uncertain. In conditions where strong MHD activity is induced, the scattering techniques can provide information on the fluctuating density perturbations, but again the complexity of the observed phenomena has as yet resisted simple interpretation.

Recently on PDX neutron and charge exchange measurements have also been used to study MHD activity. Previously small ($\sim 4\%$) sawtooth oscillations had been observed on the neutron emission on PLT with D^0 injection into D^+ plasmas, correlating with the sawteeth observed on the soft X-ray array system /41/. These "neutron sawteeth," with fall times of 2 - 3 msec, could be explained in terms of the changes in the background plasma parameters, without invoking any significant radial losses of the fast ions. On PDX at high beam powers and low B_T , however, much stronger (20 - 40 %) sawtooth oscillations are observed on the neutron flux, with fall times of the order of 300 microseconds and repetition times of typically 2 - 6 msec /5/. These rapid drops in neutron emission correlate with bursts of Mirnov oscillations and internal oscillations seen on the soft X-ray detector array (Fig. 9). At the same time bursts of strongly enhanced perpendicular neutral particle flux are seen, carrying oscillations which are frequency and phase correlated to the Mirnov and X-ray oscillations. This instability pattern has been dubbed "fishbones" because of the characteristic pattern observed on the Mirnov signals. Fig. 10 shows the effects of these oscillations on the slowing down spectrum of beam ions. Superposed here are the most perpendicular ($R_{tan} = -14$ cm) data channel from the 2.5 MW PDX divertor case shown in Fig. 7a, and the equivalent data channel from a similar plasma with 5 MW of neutral beam injection and strong

fishbone oscillations. These data are somewhat confusing because the fishbones, which are actually mostly time dependent phenomena, develop an apparent energy dependence caused by the sweeping of the energy analyzer voltage in time. However if we take the time between the particle bursts to represent the slowing down spectrum in the quiescent plasma, it is clear that below $E_{inj}/2$ there is little effect due to fishbones, and the expected increase of the beam distribution by a factor of 2, with increased injection current, is observed. Just near E_{inj} the expected increase occurs as well, but in the range $E_{inj}/2 < E < E_{inj}$ there is a clear depletion of the slowing down spectrum, indicating that the fishbone oscillations are giving rise to substantial beam particle losses. These new fluctuations observed at high β with perpendicular injection clearly give added impetus to the development of fast time response neutron and charge exchange diagnostics.

CONCLUSIONS

A rather large array of diagnostic apparatus is required to understand--or even just to evaluate--the results of neutral beam injection experiments on tokamaks. Magnetic diagnostics play the role of providing fast feedback on plasma conditions. Kinetic or profile diagnostics give the detailed back-up for the magnetic measurements that allows power balance calculations to be made, and the transport processes going on within the plasma to be estimated. Finally fluctuation measurements may hold a key to understanding the basic physics of transport, or at least, in the case of strongly enhanced MHD oscillations at high β , to helping understand the physical mechanisms which limit β in tokamaks.

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FIGURE CAPTIONS

- Fig. 1 Schematic diagram of the essential components of a modern tokamak with an air-core transformer. Diagram (e) shows the location of the equilibrium field windings which provide the vertical magnetic field required for in/out position equilibrium of the plasma.
- Fig. 2 (a) Equilibrium field measurements of β_t in PDX with neutral beam injection. Both plasma current and the injected power were varied in this scan. (b) Diamagnetic measurements of β_t from the same current and power scan as in (a).
- Fig. 3 Single shot multi-point Thomson scattering data from PDX, comparing density and temperature profiles with and without neutral beam injection. Data taken across the horizontal midplane.
- Fig. 4 Electron temperature vs time at $r = 0, 10$, and 20 cm in PLT, measured using a grating polychromator which views radiation at $2 \omega_{ce}$. In this case 1.2 MW of H^0 beams was injected into a D^+ plasma. For the same shot and radial positions, the temperatures obtained at $t = 500$ msec from Thomson scattering are shown for comparison.
- Fig. 5 Ion distribution function measured with "active" charge exchange in PDX. The hydrogen ion distribution function away from the plasma center has a significant high energy tail. This is a case of high power, nominally deuterium neutral beam injection into a hydrogen background plasma.

Fig. 6 Central ion temperature vs time in PLT with 1.6 MW H^0 injection into a D^+ plasma. Measurements by neutron emission, charge exchange, UV Doppler forbidden line, and X-ray Doppler K_α measurements show good agreement.

Fig. 7 (a) Experimental slowing down spectra measured with a multi-sight-line charge exchange analyzer. The five angular channels are swept in energy simultaneously. (b) Theoretical calculation of the slowing down spectra for the plasma conditions of Fig. 7a. Calculation performed using a Monte Carlo beam-orbit code.

Fig. 8 Comparison of theory and experiment for neutron production during $D^0 \rightarrow D^+$ neutral beam injection in PLT.

Fig. 9 Observations of "fishbone" activity on PDX using X-ray, H_β , charge exchange, and neutron emission diagnostics.

Fig. 10 Comparison of near perpendicular ($R_{tan} = -15$ cm) slowing down spectra for two and four beam injection into the same PDX target plasma. The four beam case had strong "fishbones" and showed only a very modest increase in β_t over the two beam case. Note that the data are taken by sweeping the analyzer energy in time, so that the repetitive "fishbones" appear (incorrectly) to be localized in energy.

Fig. 1

82X0746

Fig. 2a

82 X 0813

Fig. 2b

82 x 0764

Fig. 3

Fig. 4

Fig. 5

Fig. 6

#82X0811

Fig. 7a

Fig. 7b

Fig. 8

Fig. 9

Fig. 10