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"PLASMA DIAGNOSTIC TECHNIQUES USING
PARTICLE BEAM PROBES"

BY

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MASTER

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USING

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BY

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PLASMA DIAGNOSTICS USING PARTICLE BEAM PROBES

I. INTRODUCTION

The remarkable development of plasma diagnostic techniques in the past decade has played an extremely important role in the steady advancement of the controlled thermonuclear fusion program. The new devices and concepts that have been investigated as potential fusion reactors have led to an ever-increasing need for measurements of important parameters in high energy density plasmas. This has been, and continues to be, met by the development of new, usually sophisticated measurement techniques. The promise of substantial improvements in the spatial resolution and time continuity of measurements, coupled with the availability and continued development of accelerator technology, has placed particular emphasis on particle beam probing techniques. These techniques all involve injecting a beam of neutral or charged particles into the plasma and observing the results of the interaction between beam particles and the plasma.

Figure 1 shows one possible classification of plasma diagnostic techniques. This scheme classifies all available techniques as being either Passive or Active. Passive diagnostic techniques are based upon inferring the parameters of the plasma from measurements of what naturally emanates from the plasma region, whether it be in the form of magnetic fields, particles, or electromagnetic radiation. These techniques have the advantage of being completely non-perturbing to the plasma, but usually

FIGURE 1 CLASSIFICATION OF PLASMA DIAGNOSTIC TECHNIQUES

do not provide as much spatial resolution as desired. Active diagnostic techniques are based on determining the parameters of the plasma by measurements of the results of deliberately caused interactions between the plasma and a "probe". These techniques generally provide better spatial resolution than passive techniques, but have the potential for perturbing the plasma under investigation. Particle beam probing is thus seen as a sub-set of active (or probing) techniques, along with Mechanical Probes such as the classic Langmuir probe, and Radiation Probes such as microwave interferometry and Thomson scattering.

Section II presents a brief overview of particle beam probing. The fundamental concepts common to all techniques are discussed as well as the design considerations for choosing a particular diagnostic technique. The capabilities of existing and proposed techniques, and the present status of the techniques in major magnetic confinement geometries is also presented.

Section III is devoted to those techniques which involve the injection of a beam of neutral particles into the plasma. The techniques of beam attenuation, beam scattering, and active charge exchange using a beam of "light" particles such as Hydrogen or Helium are first presented. Optical measurements of the Zeeman splitting of the radiation from a neutral Lithium beam is then discussed, including a new proposal for significantly improving this technique through the addition of a dye laser. Two techniques involving the injection of "heavy" neutral particles are then presented, and the section concludes with two proposed techniques for measuring the properties of the alpha particles produced from actual fusion reactions.

For each technique the discussion includes a review of the basic principles, the plasma parameters which can be determined, the typical (or expected) space and time resolution, and the applicability of the technique to future generations of fusion-oriented devices.

Section IV discusses the diagnostic techniques which are based upon the injection of a beam of charged particles into the plasma. The advantages and limitations of these techniques in comparison with the neutral techniques are discussed, followed by a description of specific techniques. The capabilities of electron beams are first presented. Techniques involving the use of both "light" and "heavy" ion beams are then presented, including techniques which involve optical measurements of a Barium ion beam and the use of a negative Gold ion beam.

Section V briefly presents the conclusions that can be drawn concerning the importance and potential of particle beam diagnostic techniques, as well as mentioning areas which need specific development. The major references and key personnel working on the techniques presented are also provided.

II. PARTICLE BEAM PROBING

A. Fundamental Concepts

Particle beam probing is based upon injecting a beam of particles into a plasma, and observing the results of either collisional interactions between the beam and plasma particles, or in some cases the direct effect on the beam particles of the electric and magnetic fields associated with the plasma. The fundamental relationships are thus the reaction rate equations which determine the number of collisional "events" which take place, and the trajectory equations which describe the path of the beam through the plasma.

Figure 2 shows a typical particle beam injected into a plasma. For simplicity, we will assume the injected beam to have a constant, uniform cross-sectional area A_b , a uniform density of initially n_{b0} particles per unit volume, and be monoenergetic at energy E_b . In addition, we will assume the energy is low enough to ignore relativistic effects so that the beam speed is constant at $v_b = \sqrt{\frac{2E_b}{m_b}}$ where m_b is the mass of the beam particles. These assumptions are not strictly valid in practice, of course, which may have a very important effect on the sensitivity of a particular diagnostic technique. The actual trajectory followed by the beam can be determined by solving the Lorentz force equation:

$$\vec{F} = q_b (\vec{E} + \vec{v}_b \times \vec{B}) \quad (1)$$

FIGURE 2 PARTICLE PROBING BEAM

for the position and velocity of the beam particles at each point along the trajectory where q_b is the charge of the particles. The solution is trivial for an uncharged neutral beam, of course, but can become quite complex for charged particle beams travelling through complicated electric and magnetic field structures.

For each type of collisional interaction between beam particles and plasma particles, the reaction rate equation which describes the average number of interactions per unit volume per unit time may be expressed as:

$$R = \frac{\text{number of interactions}}{\text{unit volume-unit time}} = n_b n_p \langle \sigma v_r \rangle \quad (2)$$

n_b is the density of the beam particles at the point of interaction, n_p is the density of the plasma particles at this point with which the beam particles collide, σ is the relevant cross-section for the interaction, v_r is the relative speed between the colliding particles, and the brackets indicate the averaging over the velocity distribution function of the plasma particles. The dependence on plasma density is evident, and any additional sensitivity to plasma parameters must result from either the details of the cross-section or the effect of electric and magnetic fields on the by-products of the collision.

Equation (2) allows the calculation of the expected number of collisional interactions in terms of the plasma parameters as long as the beam density at the point of collision is known and accurate cross-section information is available. Of course, as the beam travels through the plasma and suffers more and more interactions, the original density of beam particles becomes "depleted". This is best described by defining an equivalent current

for the beam:

$$I_b = (n_b v_b q_b) A_b \quad (3)$$

where in this case q_b is either the actual charge of the particles in an ion or electron beam, or taken as $+e$ for a neutral beam. The beam current thus changes along the trajectory of the beam. Noting that in time dt the beam will travel a distance $d\ell = v_b dt$ leads to the usual beam attenuation relation:

$$I_b = I_{b0} \exp [-\sigma_{\text{eff}} \overline{n_p \ell}] \quad (4)$$

$\sigma_{\text{eff}} = \langle \sigma v_r \rangle / v_b$ is referred to as the effective cross section for the interaction, and $\overline{n_p \ell}$ is the average plasma line density (# particles/unit area) along the path length ℓ .

The essence of most particle beam probing techniques is to choose the injected beam parameters such that the major collisional interactions are due to processes for which the cross-sections are reasonably well-known, and are sensitive functions of important plasma parameters. In addition the beam must be chosen such that it penetrates to the point where measurements are desired with sufficient density to produce a measurable signal, and such that the beam does not seriously perturb the plasma under diagnosis. Equation (4) shows that penetration can, at least in principle, be obtained by using high energy beams to control the magnitude of σ_{eff} .

Using a beam such that $n_b \ll n_p$ will usually insure that the diagnostic is non-perturbing. In practice, however, the range of beam energies and currents are determined by the available accelerator technology for each particular type of beam. The increasing size and energy density of fusion-oriented plasmas requires a continuing program of high-energy beam development for diagnostic applications.

The principal advantage of probing techniques over passive techniques is substantially improved spatial resolution. For particle beam probes this results from observing by-products of plasma interactions which follow trajectories out of the plasma which differ from the trajectory of the probing beam. The "sample volume" is then determined by the intersection of the injected beam trajectory and the "viewing aperture" of a detector located outside the plasma. This change in trajectory might be the result of a change in charge to mass ratio of probing particles due to a collision with plasma particles. In this case nearly all the by-products from the sample volume arrive at the detector. Another example would be observing radiation emitted from the sample volume as a result of the beam interacting with plasma particles or fields. In this case the emission would most likely be distributed over a full 4π of solid angle so that a finite detector would collect only a small portion of the total number of by-products. Spatial profiles of plasma parameters can be obtained by either scanning the beam across the plasma and using a fixed detector, or by leaving the beam fixed and using an array of detectors (movable detectors are usually not practical). The limits of spatial resolution are in general determined by the size of the probing beam, the details of the trajectories, and the size and location of whatever type of detector is employed.

B. Capabilities and Status of Particle Beam Probes

Before the details of various diagnostic techniques are presented, it is instructive to take a look at the capabilities of existing particle probing diagnostic techniques and to show the status of these techniques in terms of measurements on major types of plasma devices. The objective is to illustrate the reason why particle probes are beginning to receive more attention and development as the controlled thermonuclear fusion program advances.

Figure 3 presents a listing of the major parameters of magnetically confined plasmas and shows whether particle probing techniques have been developed which are sensitive to each parameter, whether actual measurements have been demonstrated on the three major types of confinement devices or on other devices, and whether or not competitive, non-particle probing techniques are available. The footnotes provide additional information where appropriate.

The overall record for particle beam probing techniques is impressive, especially since the area has not received the attention and funding of other probing techniques. For example, particle beam techniques (primarily heavy ion beam probing) for providing spatially resolved measurements of plasma space potential, $\phi(r)$, have been developed, measurements have been demonstrated in all three major confinement geometries as well as on other devices, and there are no competitive techniques available. The same is true for electron density measurements, where several particle probing techniques have been developed, except that competitive techniques such as

CAPABILITIES AND STATUS OF PARTICLE BEAM PROBES

Plasma Parameter	Are Particle Beams Sensitive?	Present Status of Diagnostic Technique				Are Other Techniques Available?
		TOKAMAK	EBT	MIRROR	OTHER	
$\phi(r)$	Yes	Yes ¹	Yes	Yes ^{2,3}	Yes	No
$n_e(r)$	Yes	Yes ¹	Yes ¹	Yes ^{2,3}	Yes ¹	Yes ⁴
$T_i(r)$	Yes	Yes	No	No	No	Yes ⁵
$T_e(r)$	Yes	No	No ³	No	Yes	Yes ³
$J(r)$	Yes	Yes ⁶	--	--	No	Yes ⁷
$\beta(r)$	Yes	No	No	No	No	No
$\tilde{\phi}$	Yes	No ³	No ³	No ³	Yes	No
$\tilde{n}_e$	Yes	Yes ¹	No	No	Yes	Yes ⁴
$\tilde{T}_i$	?	No	No	No	No	No
Z_{eff}	Yes ⁶	Yes ⁶	No	No	No	Yes ⁴
Fluctuation Correlations	Yes	No	No	No	Yes	No

¹Refinement of technique in progress.

²Demonstrated on central cell of TMX, but not in minimum B geometry.

³Development of technique in progress.

⁴No continuous spatially resolved technique.

⁵Passive charge exchange techniques are available, but a particle beam is necessary to obtain space resolution.

⁶Light emission from Li neutral beam-PULSATOR; to obtain Z_{eff} have to assume Spitzer conductivity

⁷Modulated Thomson Scattering has been demonstrated on DITE

Figure 3

multi-channel microwave interferometry are available. Ion temperature profiles using active charge exchange have been demonstrated on tokamaks, but passive charge exchange techniques are being used on other types of devices at the present time. Electron temperature measurements have been demonstrated on an arc plasma using a heavy ion beam probe and are being developed presently on EBT-S, but have not been demonstrated on tokamaks or mirror-confined plasmas. The principle competition is Thomson scattering and microwave radiometry. Current density profiles, $J(r)$, applicable only to tokamaks, have been demonstrated on PULSATOR. Particle probing techniques which are sensitive to plasma β have been proposed, but have yet to be demonstrated. Potential and density fluctuations have been observed with particle probes and development work is currently in progress, but it is not certain that particle probes will be sensitive to fluctuations in ion temperature. The effect of impurities has been demonstrated on tokamaks, and correlations of fluctuating parameters have been demonstrated on a small arc plasma with a heavy ion beam probe. In summary particle beam probing techniques have been developed which are sensitive to nearly all the important parameters of fusion-oriented plasmas. However, much more development work needs to be done to fully realize the potential of these techniques.

III. NEUTRAL BEAM PROBING TECHNIQUES

A. Advantages and Limitations

The principal advantage of using a neutral particle beam for plasma diagnostics is that the electric and magnetic fields usually associated with high energy density, fusion-oriented plasmas have essentially no effect on the trajectory of the neutral beam. The injected beam will follow a straight trajectory determined by the injection angles and, except for the effects caused by beam divergence, will maintain a constant cross-section through the plasma. Beam penetration is determined only by the collisional processes which deplete the beam. An additional advantage in modern devices is that high energy neutral beams of Hydrogen or Deuterium are often used for auxiliary heating. Hence the technology for beam production is available, and often a "heating" beam can also be used as a diagnostic beam.

The disadvantages are principally the loss of maneuverability of the probing beam and the high total cross-section for collisions between neutral particles and plasma particles. The neutral beam injection angle must usually be controlled mechanically since the neutral particles cannot be electrostatically "swept" across the plasma the way charged particles can. Hence most neutral beam techniques rely on a fixed probing beam and must use multiple detectors to get suitable spatial resolution. The beam penetration problem becomes quite severe for fusion-oriented plasmas due mainly to electron impact ionization and charge exchange collisions with plasma ions. Penetration to the core of reactor-type plasmas will require beam energies of several MeV.

B. Specific Diagnostic Techniques

1. Beam Attenuation

The transmission characteristics of a neutral probing beam (which might well be a heating beam) can be used to measure the average line density, $n_p \bar{\ell}$, of the plasma along the beam trajectory. The total amount of equivalent beam current is measured before and after traversing the plasma and $n_p \bar{\ell}$ is determined using Equation (4). This is shown schematically in Figure 4.

The application of the beam attenuation relation, Equation (4), requires knowledge of the total cross-section for collisions which attenuate the neutral beam. Four types of collisions are the major contributors and will be briefly reviewed since they will provide the basis for discussing additional diagnostic techniques. For simplicity, we will assume the plasma consists only of electrons and protons:

- Charge Exchange-----The interaction is described by

where R^0 denotes a neutral beam particle, and H^+ a proton. The neutral particle becomes singly ionized and hence is no longer part of the neutral beam (it may well be confined by the magnetic field, producing a "hot" ion). The neutral Hydrogen atom formed usually has a thermal velocity which is much smaller than the

FIGURE 4 BEAM ATTENUATION

velocity of the injected probing beam and hence does not contribute to the neutral beam. In fact, since $v_b \gg v_i$ (proton velocity) in most cases, $\sigma_{\text{eff}} \approx \sigma_c$, the resonant charge exchange cross-section, and increasing the beam energy does not lead to a reduction in σ_{eff} .

- Electron Impact Ionization-----This is described by

Since $m_e \ll m_b$, the electron thermal velocity, v_e , is usually much greater than v_b . This means that $\sigma_{\text{eff}} \approx \langle \sigma_I v_e \rangle / v_b$, where σ_I is the electron impact ionization cross-section and the averaging must be performed over the distribution of electron velocities. For a Maxwellian distribution therefore, σ_{eff} is a function of T_e . Note that as long as $v_b < v_e$, σ_{eff} will decrease by increasing the beam energy.

- Proton Scattering-----This interaction is described by

In this case the beam particle remains neutral, but has its momentum scattered sufficiently that it is lost from the original beam. Again we expect $v_b \gg v_i$, implying that $\sigma_{\text{eff}} \approx \sigma_s$, the momentum scattering cross-section.

- Proton Ionization----This interaction is described by

The neutral particle is ionized, but the proton remains a proton, but with a different energy. We expect $\sigma_{\text{eff}} \sim \sigma_p$, the cross-section for ionization by proton impact.

A quasi-neutral plasma will have $n_i \approx n_e \approx n_p$. Thus combining these four processes results in a general beam attenuation relation:

$$I_b = I_{b0} \exp \left[-\left[n_p \bar{\ell} (\sigma_c + \sigma_s + \sigma_p + \frac{\langle \sigma_i v_e \rangle}{v_b}) \right] \right] \quad (8)$$

The line density $n_p \bar{\ell}$ is determined by the ratio I_b/I_{b0} as long as all the appropriate cross-sections are known. It must be pointed out, however, that Equation (8) neglects the affects of any impurities in the plasma, which can be particularly important in the case of charge exchange interactions with highly charged impurity ions. This process is usually approximated by using the term $n_p \bar{\ell} Z_{\text{eff}} \sigma_c$ for the charge exchange contribution, where Z_{eff} is the effective charge state of the plasma ions.

The electron impact ionization contribution, which often predominates, is a function of T_e as noted above. Hence an independent measure of T_e along the beam trajectory is necessary as well as knowledge of Z_{eff} in order to determine the average line density. This, however, also provides the potential for an additional diagnostic. $n_p \bar{\ell}$ is often available from microwave interferometry and $T_e(r)$ from Thomson scattering. If this is the case, the beam attenuation measurement can be used to determine Z_{eff} .

Any neutral beam can be used as long as the appropriate cross-section information is available. Usually "light" beams such as Hydrogen, Deuterium, Helium, or Lithium are employed in order to ensure adequate penetration at practical accelerating voltages. Measurements averaged along the beam trajectory are obtained, but with excellent time continuity. Time resolution is determined by appropriate neutral particle detectors, and is typically $\sim 10 \mu\text{sec}$, so that fluctuations in line density can also be obtained.

Beam attenuation measurements of line density have been made on such devices as TM-3¹, 2XIIB², and are routinely made using heating beams on TMX³ since all that is required is a suitable detection system. Continued development of low divergence neutral beams for diagnostic purposes is necessary to improve spatial resolution.

2. Beam Scattering

Two techniques have been proposed⁴ for providing information concerning the energy and mass of plasma ions based on the simple scattering of light neutral beam particles such as Hydrogen or Helium. Development work is progressing in the USSR, and will be actively pursued on the ISX-B device at ORNL.

The first technique involves measuring the broadening of the neutral beam energy at a fixed scattering angle (Figure 5). The energy distribution of the scattered atoms is a function of the initial beam energy, the scattering angle, the mass ratio of beam particles to plasma ions, and the local ion temperature. Specifically,⁵

$$\Delta E \approx 4\theta \left[E_b kT_i \frac{m_b}{m_i} \ln 2 \right]^{1/2} \quad (9)$$

FIGURE 5 BEAM SCATTERING

The scattering cross section is a strong function of both the scattering angle and the mass of the beam particles. Hence measurements must be made at relatively small angles using light neutral particles to ensure adequate signals. Also a low divergence, monoenergetic neutral beam is required. For $\theta = 5^\circ$, $E_b = 10$ keV, $m_b = m_i$, and $T_i = 100$ eV, an energy spread $\Delta E \sim 300$ eV should result, which is measurable with standard charge exchange neutral analyzers.⁶ The necessary beam intensity, however, is ~ 0.1 Amps/cm², which is very difficult to obtain in a beam suitable for diagnostics. Note also that the energy spread depends on the mass of the plasma ions which is not necessarily known. However, measurements could be made at various angles and beam energies to provide information concerning both T_i and Z_{eff} .

The second technique involves measuring the intensity of scattered particles at different scattering angles. If the target ions were at rest, the maximum angle at which scattering would occur would be given by

$$\theta_{max} = \arcsin \frac{m_i}{m_b}, \quad m_b > m_i \quad (10)$$

If the plasma ions have thermal velocities, scattering can occur for $\theta > \theta_{max}$. The cross section for scattering at $\theta > \theta_{max}$ increases rapidly with ion temperature, but scattering at $\theta < \theta_{max}$ changes only slightly.⁷ Thus the ratio of scattering at angles greater than θ_{max} to that for angles less than θ_{max} is a function of both T_i and m_i , but independent of ion density. Measurements at different angles and beam energies should again, in principle, provide information concerning both T_i and Z_{eff} . This technique has the advantage that a beam intensity $\sim .01$ Amps/cm² is required for application to present day devices.

The spatial resolution of either technique depends on the beam size and scattering angle and becomes quite poor for low angles. Time resolution would be determined by the detection electronics. Increased sensitivity could be obtained by modulating the beam and using phase sensitive detection.

3. Active Charge Exchange

The most common technique for determining ion temperature in present confinement devices is to measure the energy distribution of neutral particles escaping from the plasma as a result of charge exchange collisions with plasma ions.⁴ This is a passive technique which has been shown to provide a reasonably accurate measure of the highest value of T_i along a chord through the plasma viewed by the detection system.⁶ The principles of this technique will be briefly reviewed to demonstrate the advantage of using an active version of this technique in both "small" and "large" devices.

High temperature plasmas, when initially formed, are almost completely ionized. The source of the neutrals for the charge exchange interactions is the molecular Hydrogen trapped in the walls of the vacuum vessel. Molecular Hydrogen is first desorbed from the surface as a result of the charged particle flux and electromagnetic radiation coming from the plasma. It is quickly dissociated into Hydrogen atoms upon contact with the edge of the plasma (Figure 6a). This results in a sheath of relatively cold ($\approx 1-3$ eV) neutral atoms surrounding the plasma, which cannot penetrate because their mean free path for electron impact ionization is quite small ($\lambda_{mfp}^c \approx 1$ cm). However, some cold neutrals charge exchange with warm plasma ions at the edge of the plasma, resulting in the formation of warm neutrals. These warm neutrals have a longer mean free path $\lambda_{mfp}^w \approx 10$ cm, and can penetrate to the core of most plasma devices, resulting in a equilibrium neutral density profile similar to that shown in Figure 6b. These warm neutrals can then, in turn, charge exchange with hot plasma ions, giving rise to hot neutrals

FIGURE 6 PASSIVE CHARGE EXCHANGE

which can readily escape from the plasma, and are detected by means of a stripping cell followed by electrostatic (or a combination of magnetic and electrostatic) energy analysis.⁶

The spatial resolution of the measurement can be considerably enhanced in "small" devices by the addition of an energetic neutral beam. ("Small" is used to denote those devices where the mean free path of the hot neutrals $\lambda_{mfp}^h \geq L_p$, where L_p is the characteristic dimension of the plasma). As shown in Figure 7, the same detection system collects the usual charge exchange neutrals from all along a chord through the plasma, plus the neutrals formed by the charge exchange interactions between plasma ions and the injected beam. As long as the detection signal is predominately due to the beam induced neutrals, a localized measure of T_i is obtained from the energy analyzer. One would typically want the beam size, ℓ to be $\leq 0.1 L_p$ for good spatial resolution, and the induced signal to be ≥ 10 times the natural neutral flux. This requires the neutral beam density to be $\approx 10^2$ times the natural neutral density, which is not always easy to do without seriously perturbing the plasma. However, the problem can be solved by modulating the injected beam and using phase sensitive detection. Profiles of T_i can best be obtained by using multiple detection systems which collect neutrals from different points along the injected beam trajectory.

The use of this active charge exchange technique is much more attractive in large machines where $\lambda_{mfp}^h \approx L_p$. In these machines very few warm neutrals formed at the edge of the plasma can penetrate to the plasma core to serve as targets for charge exchange with hot plasma ions. Furthermore, the few hot neutrals which are produced in the core have a

FIGURE 7 ACTIVE CHARGE EXCHANGE

high probability of charge exchanging back into ions before they can escape from the plasma. The total neutral flux arriving at the detector is seriously attenuated, and what is measured by the detection system is not necessarily representative of the central region of the plasma. Both problems are alleviated by injecting an auxiliary, modulated neutral beam (typically 15-20keV at a few amps of equivalent current), and using phase sensitive detection.

The frequency response (ultimately determined by time-of-flight through the detection system) is in practice, limited by the detection electronics to the low KHz range. Active development of this technique has been pursued by Eubank and colleagues at PPPL,⁸ and in the USSR by Afrosimov et al.⁹

4. Zeeman Splitting of Neutral Lithium

The first three techniques have all involved the injection of neutral particles, and the subsequent detection of neutral particles. An important variation is to monitor radiation emitted from injected beam particles as they pass through the plasma. The beam particles can either be injected in an excited state so that they emit radiation continuously as they pass through the plasma, or they can be injected at the ground state and subsequently "pumped" to an excited level due to collisions with plasma particles. In either case the characteristics of the emitted radiation will provide localized information concerning the plasma. Furthermore, both neutral and ion beams may be employed for this type of diagnostic. The neutral beam techniques developed so far have primarily centered around the

use of Lithium, and have provided the most detailed measurements of the poloidal field profile in tokamaks. Localized electron density measurements are also possible.

Neutral Lithium has a strong 2p-2s resonance line at $6708\text{\AA}$. The cross section for exciting this transition by means of collisions with electrons in most fusion-oriented plasmas is high enough to provide a measureable flux of photons using relatively modest neutral beams ($E_b \sim 50\text{keV}$, $I_b \sim 100\mu\text{A}$). Direct measurements of the intensity of the emitted photon flux provides localized plasma density information. (See Figure 8). However, as in most techniques which use electron impact collisions, an independent measurement of T_e is required since the excitation cross-section depends on the electron temperature. The major advantage is the large bandwidth capabilities using high gain visible photomultiplier tubes. A rotating mirror can also be used to sequentially focus a different portion of the beam-plasma intersection on a fixed detector to generate radial profiles. The major effort in developing this technique has been by Fujita and his colleagues at Nagoya University.^{10,11}

A more important application is to monitor the polarization of the emitted $6708\text{\AA}$ radiation in tokamak geometry. The arrangement is shown schematically in Figure 9. The Lithium neutral beam is injected into the plasma perpendicular to the toroidal magnetic field. The optical detection system is located at 90° to the injected beam, in the same plane. For toroidal field strengths in excess of $\approx 10\text{kG}$, the $6708\text{\AA}$ line is split into a well-defined Zeeman triplet. (At lower magnetic fields the fine structure of the line is much more complicated and the technique to be described is no longer valid). The σ components of this triplet will be polarized

$$\lambda = 6708 \text{ \AA}$$

FIGURE 8 DENSITY MEASUREMENT

FIGURE 9. POLOIDAL FIELD MEASUREMENT

perpendicular to the total magnetic field in the region where the light is radiated. These components will also be slightly shifted to either side of $6708\text{\AA}$. ($\Delta\lambda \approx 1.1\text{\AA}$ at $B = 25\text{kG}$). The unshifted π component of the triplet is polarized parallel to the local magnetic field. Hence the angle which the polarization of the π component makes with respect to the horizontal plane provides a localized measure of the ratio of poloidal to toroidal field, $\theta = B_p/B_T$. The π component can be separated from the shifted σ components by using a Fabry-Perot etalon ($\Delta\lambda \approx 0.5\text{\AA}$).

The technique developed by McCormick, et. al.^{12,13,14} at the Max-Planck Institut for Plasmaphysik in Garching uses a regular (ground-state) Lithium neutral beam with the $6708\text{\AA}$ line being excited by electron impact. The polarization angle of the emitted π radiation is measured by a polarimeter consisting of a Faraday rotator, a Wollaston prism, two photomultiplier tubes, a differential amplifier, and a servo amplifier. The Wollaston prism separates the incident light into two polarization components which are then measured by the photomultipliers. The difference signal from the PMT's is then amplified and used to drive a current in the windings of the Faraday rotator until a null condition is reached. The current in the windings of the rotator is proportional to the angle through which the incident light has been rotated, and is thus a direct measure of the pitch angle, θ . Alignment of the optical system is performed by injecting the Lithium beam into a back-filled vacuum chamber and pulsing only the toroidal field. The $6708\text{\AA}$ line is excited by collisions with background gas molecules, and the polarization of the π component is parallel to the toroidal field. The Wollaston prism is then adjusted until no current is needed in the Faraday rotator for a null condition.

A measurement sensitivity of a few tenths of a degree has been demonstrated which could be considerably improved with increased beam intensity. The spatial resolution is determined by the beam size and the collection optics and is typically $\sim 1\text{cm}$. Time resolution of the system is limited by the response time of the Faraday rotator and is presently $\sim$ several milliseconds.

The technique has provided the first definitive measurement of the poloidal field profile in tokamaks. However, there are some serious obstacles for its application to large fusion-oriented devices. McCormick¹⁴ has performed detailed calculations of the expected attenuation of a Lithium neutral beam due to charge exchange on protons, electron impact ionization, and ionization by protons. The effective cross-section for electron impact ionization peaks for $T_e \sim 50\text{ eV}$. Also the use of higher energy Lithium beams will reduce the effective cross-section due to the $1/v_b$ dependence. However for ion temperatures above $\sim 1\text{ keV}$, charge exchange becomes the dominant attenuation mechanism, and does not decrease much with increasing beam energy, as we noted earlier. Thus the technique suffers from the most important problem common to all neutral beam techniques; the difficulty of penetrating to the central core of large, fusion-oriented plasma devices.

A method to combat the penetration problem has recently been proposed by Baur, West, and Ensberg at General Atomic.¹⁵ A co-linear configuration of the Lithium beam and a CW dye laser is the focal point of their proposal. The dye laser can be used to "saturate" the $6708\text{\AA}$ transition before the neutral beam is injected into the plasma; i.e. a high percentage of the Lithium atoms are placed in the appropriate excited state. The subsequent level of emission as the beam passes thru the plasma is considerably higher

than what would be possible if electron impact collisions were providing the excitation. The neutral beam will still be attenuated as it traverses the plasma, but increased sensitivity should result from the generally higher intensity levels. Still further advantage can be gained by using a piezoelectric crystal in the laser beam path to electro-optically modulate the polarization of the laser light. When the laser is used to "pump" the Lithium line, the resultant $6708\text{\AA}$ emission will also be modulated. Thus, not only is the resulting radiation increased in intensity over electron impact excitation, but phase sensitive detection techniques can now be employed to "find" the weak signal coming from the central region of large machines. This is an impressive improvement over the present technique and represents one of the first "hybrid" probing techniques which combine the capabilities of particle beams and lasers. It is proposed to test the technique in the research tokamak facility, TEXT, at the University of Texas. The hybrid diagnostic approach is one of the exciting new entries in the plasma diagnostic field and more hybrid-type systems can be anticipated in the near future.

5. Heavy Neutral Beam Probing

There are serious disadvantages in using a neutral beam of "heavy" atoms for the techniques discussed so far. Heavy neutral beams will in general have smaller scattering cross-sections, and higher cross-sections for ionization and charge exchange reactions than corresponding "light" neutral beams. In addition, their spectroscopy tends to be more complicated. However, the possibility of simultaneously measuring several important plasma parameters, at a savings of at least a factor of two in beam energy

over a heavy ion beam probe (to be discussed later), and with increased spatial resolution, makes a heavy neutral beam probe quite attractive.

The standard heavy neutral beam technique is basically identical to heavy ion beam probing. The technical details will hence be left to the following paper on heavy ion beam probing, and we will be concerned here only with the basic principles and proposed variations. Figure 10 shows a beam of heavy neutral particles injected into a plasma in a direction perpendicular to the confining magnetic field. The beam energy is chosen so that the radius of curvature of singly charged ions formed by electron impact collisions is large enough to allow the ions to escape from the plasma where they can be detected. The magnetic field structure, the injection parameters of the neutral beam, and the size and location of the detector will determine the sample volume in the plasma. Measurements of the current of singly ionized particles arriving at the detector will provide information concerning the electron density and temperature in the sample volume. The energy of the detected ions provides a direct, spatially resolved measurement of the plasma space potential, and the displacement of the ions out of the injection plane may provide information concerning local magnetic field structure, and hence plasma beta.

Heavy ion beam probing uses a $1^+ - 2^+$ transition rather than the $0 - 1^+$ transition described here. Hence at least a factor of two is saved in beam energy by using a neutral beam. Additional advantages are possible in devices which use strongly three-dimensional magnetic field structures such as minimum-B mirrors. The injected neutral beam does not respond to the magnetic field and hence will arrive at the center of the device with about the same cross-sectional area as when it was injected. An ion beam,

FIGURE 10 HEAVY NEUTRAL BEAM PROBE

however, may be seriously defocused and distorted by the magnetic field gradients as it traverses the plasma.¹⁶ Development work for a heavy neutral beam for application to a "baseball" geometry is presently being pursued using the ALEX facility at Rensselaer,¹⁷ and a Thallium neutral beam probe system was installed on the PLT tokamak at Princeton in an attempt to measure space potential at the edge of the plasma.^{18,19} Penetration of the plasma, and the inability to readily move the injected neutral beam remain serious obstacles to this technique, but it may well be the only possible technique for measuring the potential well developed in the end plugs or barrier regions of tandem mirror devices.

A variation of the heavy neutral beam technique has been proposed by Hershcovitch and Hickok.²⁰ A high energy beam of noble gas neutrals, such as Krypton, is injected into the plasma. The probing neutrals charge exchange with plasma protons producing a noble gas ion and a Hydrogen atom. In certain energy ranges there is a high probability of leaving the Hydrogen atom in an excited state such that it will emit Lyman α radiation. Many plasma parameters are thus obtainable by measuring the various by-products of the interaction. The heavy ions escaping provide the same parameters as the usual heavy beam probe technique. The escaping Hydrogen neutrals can be measured using the usual charge exchange technique described earlier to provide localized information concerning the ion temperature. This, in turn, can be verified by measuring the Doppler shift of the emitted Lyman α radiation. Finally, Zeeman splitting of heavy neutral radiation pumped by electron impact may provide information concerning localized magnetic fields similar to the Lithium technique. The technique has a lot of potential and preliminary calculations appear favorable. However, the technique has not yet been attempted in the laboratory.

6. High Energy Probes for Alpha Particle Measurements

A key indicator of the recent progress in the controlled thermonuclear fusion program is that diagnostic techniques for measuring the products of actual fusion reactions are now being developed. This section on neutral particle probing techniques concludes with a brief description of two recently proposed techniques^{21,22} to monitor the alpha particles produced from D-T fusion reactions.

The first technique involves single charge exchange reactions between an injected "light" neutral beam and the doubly ionized alpha particles (He^{++}). The scheme proposed by Post et.al^{21,22} is to inject a high energy neutral beam (880 keV/amu) which will transfer one electron to the alpha particle, leaving a singly ionized Helium ion in an excited state. If a neutral Hydrogen beam is used, the subsequent radiation is primarily Lyman α at $304\text{\AA}$. The Doppler shift due to the beam velocity ($\approx 10\text{\AA}$) allows the determination of the alpha particle distribution. A variation proposed by West, et. al²³ employs a neutral Lithium beam and monitors the resulting Balmer α radiation from He^+ at $1640\text{\AA}$ to yield the density of the alpha particles.

The second technique^{21,22} employs injecting several mA of $^3\text{He}^0$ at 2.6 MeV to undergo double charge exchange reactions with the alpha particles. The double charge exchange reactions leave the alpha particles in a neutral state where they can now escape from the plasma and be analyzed using the standard charge exchange neutral technique to yield the alpha particle distribution. Practical diagnostic beams appear feasible using 2.6 MeV $^3\text{He}^-$ beams that have already been developed and a condensible gas neutralizer.²⁴

Beam development work is actively being pursued for both single and double charge exchange techniques and initial tests of the diagnostic will be attempted in TFTR.

IV. CHARGED PARTICLE BEAM PROBING TECHNIQUES

A. Advantages and Limitations

There are two principle advantages of probing a plasma with a beam of charged particles rather than neutral particles. The most important is that the attenuation problem which is the bane of all neutral beam probing techniques is significantly reduced. The total cross-section for collisions between charged beam particles and plasma particles is considerably smaller, implying that it is generally much easier to penetrate to the core of a plasma. The second advantage is the drastic improvement in the ability to maneuver the probing beam. Electrostatic sweep plates may be placed anywhere along the injection path to sweep or steer the beam to any desired location of the plasma. Thus a charged particle beam presents the opportunity for obtaining information from an entire cross-section of the plasma, even during a relatively short pulsed experiment.

The major disadvantage of charged particle beams is that they are obviously affected by the magnetic fields used to confine the plasma. This actually helps the spatial resolution of some measurements, but in general results in a higher beam energy than a corresponding neutral beam, and may cause serious defocusing or distortion of the injected probing beam.¹⁶ The momentum of the probing beam must be sufficient to allow the beam to cross the field lines and penetrate the plasma. Hence "penetration" remains a problem, but the cause is completely different from the attenuation problems of neutral beams. For this reason there are very few diagnostic

techniques using electron beams to probe magnetically confined plasmas, and most ion beam techniques involve the use of "heavy" ions.

B. Specific Diagnostic Techniques

1. Electron Beam Probing

The extremely small radius of curvature for even very energetic electrons usually precludes their use as diagnostic probes. However, electron beams have been used for determining the maximum potential in a plasma by injecting the electron beam along a magnetic line of force. An excellent example was the use of an electron beam probe on a biconical gun-injected cusp experiment at LASL by Karr and Osher.²⁵ The plasma under study developed a negative potential well of ~ 1 kV. A low energy, .5 - 5keV, electron beam was injected along a field line connecting adjacent cusps in the magnetic field. The beam energy was varied until no trace of the beam (modulated at 500kHz) could be observed at the next cusp. The beam energy at cut-off is thus a measure of the depth of the potential well.

A slight variation of this technique, which will work on both positive and negative potential wells, is to measure the time-of-flight of the injected electron beam. The flight time will be shorter or longer depending on whether the beam was initially accelerated or decelerated by the potential distribution. This requires extreme precision in the timing measurements which is best overcome by using an ion beam which travels much more slowly. Even using low energy ion beams this technique is, at best, difficult, but may have applicability to open-ended confinement systems.

2. Light Ion Beam Probing

Charged particle beams composed of relatively "light" ions (H^+ , He^+ , Li^+) suffer from essentially the same problem as electron beams; it is difficult to penetrate strong magnetic fields. However, the successful development²⁶ of a 20 keV, 30 mA He^+ beam which can be focused to a spot size less than 1 centimeter and has a relatively small energy spread has prompted research to uncover an application. Two have been proposed to date, and hopefully more will follow.

The first technique is to use the "light" ion beam to measure the axial potential along a tandem mirror device.²⁷ The arrangement is shown schematically in Figure 11. The He^+ beam is directed along the axis of the tandem mirror, which is composed of two minimum-B magnetic mirrors separated by a long solenoidal region. Electron impact collisions create He^{++} ions at all points along the trajectory, but the doubly ionized particles continue to travel axially since negligible momentum is transferred as a result of the collision. The He^{++} ions arriving at the detector placed outside the second "end plug" will have an energy which differs from the injection energy by an amount equal to $e\phi$, where ϕ is the space potential at the point at which the doubly ionized particle was created. He^+ ions (lots of them) also arrive at the detector, but at the same energy and charge state as when they were injected. Passing the detected ions through a swept electrostatic energy analyzer should produce an energy spectrum of the arriving He^{++} ions. Using independent measurements of density and electron temperature at various radial locations

FIGURE 11 LIGHT ION BEAM PROBING

along the device should then allow the determination of the axial potential profile.

The advantages of using a "light" ion beam for this measurement are that the time of flight of the beam is held to a minimum, and that considerably more beam current is possible with this He^+ source than with conventional alkali metal ion beams. A system has been constructed to measure the axial potential on TMX,²⁷ but has yet to produce results. Alignment of the beam over the entire length of the TMX device has proved to be quite difficult.

A second technique using this source has been proposed by the originator of the source itself, John Osher.²⁶ It is proposed to inject the beam into an open-ended mirror device with a selected and relatively high velocity perpendicular to the field lines. The beam will then encircle the magnetic axis many times as it traverses the plasma. The precise value of $v_{\perp}$ at each axial position would vary as the axial field strength changed due to the assumed adiabatic invariance of $\mu = \frac{1/2 m v_{\perp}^2}{B}$. Observation of the Doppler shift of the electron impact excited He^+ line at $4686\text{\AA}$ as a function of axial position should then yield localized information concerning how the magnetic field is changing. Signal to noise could be enhanced by pumping the $4686\text{\AA}$ line with a CW dye laser before injection, similar to the hybrid Zeeman splitting technique described earlier. Some initial calculations have been done which indicate the technique may be feasible, but it has not been tested.

3. Heavy Ion Beam Probing

The only charged particle beam probing technique presently in use on fusion-oriented devices is heavy ion beam probing. Heavy ion beam

probe systems are presently operating on EBT-S at ORNL, TMX at LLL, and RENTOR at Rensselaer. The principles of the standard technique are the same as heavy neutral beam probing except that a singly ionized beam is injected, and doubly (or triply) ionized particles created by electron impact are detected. The arrangement is shown in Figure 12. Typically beam energies of less than 100 keV are used at beam currents of 10-100 μ A. Ions are chosen from the alkali metal group (Na, K, Rb, Cs) or Thallium, which can all be produced from thermionic sources. The details of heavy ion beam probing will be subject of the following papers by the originator of the technique, R. L. Hickok. In this section we will examine two proposed variations of the same basic principle.

The first variation is to combine the usual charged particle detection techniques with optical measurements. This has been described by Cobble and Glowienka^{28,29} and would provide spatially resolved measurements of electron density fluctuations and magnetic field information. They are specifically concerned with learning more about the plasma beta and the dimensions of the hot electron annuli in EBT-S, but the technique is much more general.

A singly ionized Barium beam (~ 40 keV for EBT-S) would be injected into the plasma. (See Figure 13). This energy range is chosen to allow for relative ease in ion beam production and some curvature of the beam as it passes through the plasma. Optical measurements, using a rotating mirror, would be made of the strong Ba II resonance line at $4554\text{\AA}$, which is pumped by electron impact excitation. As in the Lithium technique, the optical intensity is a measure of the local electron density if the electron temperature is known from an independent measurement. Again, the

FIGURE 12 HEAVY ION BEAM PROBING

FIGURE 13 BARIUM ION BEAM DIAGNOSTIC

main advantage would be the ability to observe local density fluctuations at relatively high frequencies.

Magnetic field measurements would be based on polarization measurements of Zeeman-split components, exactly as in the neutral Lithium technique of McCormick. However, the $4554\text{\AA}$ line does not appear to be a reasonable candidate due to a complex Zeeman pattern, and attention has centered on another Ba II resonance line at $4934\text{\AA}$. This line is only half as intense, but has a much simpler Zeeman pattern. However, the splitting between the π and σ components will be $\leq .1\text{\AA}$ for $B \sim 8$ kgauss. This is within the limits of a Fabry-Perot, but puts fairly stringent requirements on the divergence and energy spread of the ion beam. The technique does appear, however, to be feasible.²⁹ It should also be possible to use the hybrid technique of Baur, et.al¹⁵ to "saturate" the Ba II lines with a dye laser and electro-optically modulate the polarization. It should also be pointed out that EBT-S is a DC experiment so that CW dye lasers and phase sensitive detection techniques become ideal.

The second variation of the standard heavy ion beam probe technique has been proposed by Ishii, et.al at the University of Tsukuba.³⁰ This technique makes use of available technology to produce negative Gold ion beams and is shown schematically in Figure 14. An Au^- ion beam is injected similar to the usual positive ion technique. Two interactions with plasma particles are of interest. The first is double detachment whereby an Au^+ ion is formed. This can be detected outside the plasma in the usual fashion. However, since the change in charge state is $2e$, the energy of the Au^+ ion will differ from that of the injected Au^- beam by $2e\phi$, where ϕ is the space potential at the collision point. Hence increased sensitivity

FIGURE 14 NEGATIVE GOLD BEAM

to the space potential is obtained with the same beam energy requirements as for a heavy neutral beam probe, since only a 1^+ ion must escape from the plasma. The standard heavy ion beam technique can achieve the same sensitivity by using the $1^+ - 3^+$ transition, but signal levels are way down due to a reduced cross-section, and beam energies must be sufficient to allow a 3^+ ion to escape from the plasma.

The second process of interest is photo-detachment whereby the injected Au^- beam is used in conjunction with a laser beam. The Au^- ion becomes a neutral, which then escapes from the plasma where it can be detected. (See Figure 15). Sensitivity to space potential is only $e\phi$ since there is a change in charge of e , but improved spatial resolution is obtained by controlling the size of the laser beam. Both techniques are extremely interesting, but have yet to be tested on fusion-oriented devices.

V. CONCLUSION

Particle beam probes are just beginning to attract the attention they deserve. There is a long list of proven techniques for providing measurements of important plasma parameters, and additions to the list are rapidly developing. Of particular interest are the hybrid techniques which combine particle and radiation probing capabilities. Most importantly, the number of scientists working with particle beam probes has grown from a scant few a decade ago to a viable, world-wide community. Hopefully, the "critical mass" of people in this area has, or soon will be, reached so that the:

FIGURE 15 NEGATIVE GOLD BEAM WITH LASER

full potential of particle beam probing techniques can be realized.

Most of the techniques developed so far have resulted not only from the need for the measurement, but from the availability of the technology to produce the necessary probing beam. The two continue to go hand in hand. As larger devices are built, and as new ideas for measurements develop, there must be a continuing program of beam development for diagnostic applications. Most critical is the development of MeV beam capabilities which are necessary to extend existing techniques to the next generation of devices, and to demonstrate the diagnostic techniques proposed for actual fusion-producing plasmas.

It is also important to emphasize that plasma diagnostic techniques are continually becoming more sophisticated. The field has progressed from hand-made I-V plots of a Langmuir probe to complete computer control of complex diagnostic systems (for example the heavy ion beam probe on TMX or the TV Thomson scattering system on PLT). Particle beam probing is by nature a sophisticated diagnostic that requires careful attention to both physics and engineering in order to make a system operational. Particle beam probing should play a vital role in the future controlled thermonuclear fusion program and appears to be on the threshold of an important new era.

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