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LARGE TOKAMAKS

BY

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ABSTRACT

The increase in scale of Tokamaks, together with the very large power input from auxiliary heating, lead to a requirement for new diagnostic techniques. The reference plasma parameters used in establishing this requirement for this review paper are those predicted for the operation of TFTR. The physics aspects of the diagnostic methods are described with particular inference on areas of interest to atomic physicists.

DIAGNOSTIC PROBLEMS OF LARGE TOKAMAKS

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I.. INTRODUCTION

The experimental study of high temperature plasmas in tokamaks has recently gained momentum with the occurrence of the first discharges in the two rather similar American PLT (Princeton Large Torus) and Russian T-10 Tokamaks towards the end of last year. Furthermore, the final design stage of the TFTR (Toroidal Fusion Test Reactor) was begun in March this year; the TFTR is roughly twice as large as the other two. Because of its size, the expected high electron temperatures, the very large neutral beam system to provide auxiliary heating and the intention to use tritium as a filling gas as target for deuterium beams with the resultant fusion product particles, TFTR poses some clear problems for diagnostics of the plasma behavior.

The aims behind the construction of TFTR can be summarized:¹

- i) The attainment of ion and electron temperatures of 5-10 keV ($\sim 10^8$ °K) in substantially pure hydrogenic plasmas.
- ii) The maximization of plasma density within the constraint of retaining gross stable plasma confinement.
- iii) The attaining of the product of density, n , and energy containment time, τ_E , $n\tau_E \sim 10^{14} \text{ cm}^{-3} \text{ sec}$ under favorable circumstances.
- iv) The generation of reactor-like fusion power densities under conditions of approximate break-even in plasma energy in operation with deuterium and tritium (D-T).

The high temperatures are well within the levels computed for plasmas where auxiliary heating has been applied and where the

impurity level remains low ($n_{Fe} \leq 0.1\% n_e$). A central density as high as $1 \times 10^{14} \text{ cm}^{-3}$ is an achievable goal but it is intended to raise the density by injection of gas during the discharge (and lower the relative impurity level) following the successful experiments in Alcator² and Pulsator³ Tokamaks. High density operation ab initio for the discharges has always led to bad disruptive behavior. The energy containment requirement $n\tau_E \sim 10^{14} \text{ cm}^{-3} \text{ sec}$ is of interest as this represents the break-even value for D-T fusion in a 10 keV thermal plasma (known as the Lawson criterion⁴). It is a somewhat uncertain prediction in that the extrapolation involves theoretically predicted diffusion mechanisms which have not been met experimentally in the more collisional plasmas so far measured in tokamaks. However, the criterion for break-even is relaxed for neutral beam injection, or two-component plasmas, so that the value of the experiment is maintained.

The final intention of reactor-like fusion power densities means that the gas filling for the Ohmically heated plasma in the toroid will be tritium and the injected beams will be deuterium atoms, after successful operation of the device has been achieved and the plasma reasonable understood. The major purpose of the device will be to study the fusion aspects, particularly to look at the heating. The maximum flux of virgin 14.1 MeV neutrons is expected to be $6 \times 10^{12} \text{ n cm}^{-2} \text{ sec}^{-1}$. This flux places extreme requirements on radiation shielding but although it leads to activation of the vacuum vessel it is insufficient to produce significant sputtering of impurities off the walls. However, diagnostic systems will have to operate in a hostile environment and will have to be shielded and located appropriately.

Section II provides a brief description of the operation of a Tokamak with the inference on the large TFTR device and discusses the role impurities play in the shaping and heating of the plasma. Section III describes some recent results with the inference on information obtained about impurity behavior. Section IV will discuss the problems associated with the extrapolation in scale and energy of the large future tokamaks. These problems are not related to the radiation and damage effects of the high neutron flux mentioned above though this is a severe problem.

II. OPERATION OF A TOKAMAK

II.1 Description of the Tokamak and Its Auxiliary Heating

There have been two recent comprehensive review articles about Tokamaks.^{5,6} For this paper, a much simplified description will be given to remind readers of the tokamak principles.

The simplest tokamak confinement system consists of nested toroidal surfaces of helical magnetic field lines. These are created by an Ohmic current driven in a plasma in a strong toroidal field. Figure 1 is a trimetric drawing of the TFTR which serves to show the necessary field coil arrangement. The toroidal primary windings of the, in this instance air-cored, transformer to drive the Ohmic current are placed outside the toroidal field coils.

Since the toroid of plasma tends to expand in major radius because of the plasma thermal pressure and the poloidal field pressure, an additional transverse field is necessary to hold the plasma in equilibrium. In early Tokamaks where the duration of the current pulse was short, this equilibrium could be provided by image currents in copper shells outside the vacuum vessel. The plasma is produced inside a stainless steel vacuum vessel by the Ohmic current after a preliminary production of electrons by some means such as an rf oscillator. The plasma is normally kept clear of the vacuum vessel wall by an aperture limiter made of a refractory metal occupying most of the poloidal circumference but only a minute fraction of the toroidal circumference. Charged plasma particles diffusing out from the plasma, both thermal particles and high energy runaway electrons, collide with this limiter. Radiation from the plasma and fast neutral atoms, created by charge-exchange between atoms moving into the plasma and high energy plasma ions, carry energy onto the vacuum vessel walls. Between one quarter and half the energy lost goes to the limiter under standard operating conditions in the ST⁷ and T-3⁸ Tokamaks.

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Fig. 1. Trimetric drawing of the TFTR Tokamak: 1. Stainless steel vacuum vessel containing the plasma; 2. toroidal field coil; 3. Ohmic heating field coil; 4. equilibrium field coil; 5. device substructure; 6. radiation shielding; 7. water header for cooling of field coils; 8. vacuum pump; 9. neutral injection duct.

The tokamak is called a low- β device because β , the ratio of the plasma pressure to the magnetic field pressure, is limited by loss of stability. Roughly

$$\beta \leq 0.1(a/R)$$

where a is the minor and R is the major radius of the plasma toroid. Thus to obtain high plasma temperatures, high toroidal magnetic fields and as tight a toroid as possible are desirable.

Table 1 provides a comparison of three well-documented tokamaks with PLT whose early results are given and with TFTR for which predictions are made. The ST Tokamak⁹ was a thoroughly diagnosed device while the relatively high density achieved in Alcator², and relatively low impurity level have encouraged a trend to high current densities and high toroidal fields. The TFR Tokamak¹⁰ had produced the best quality plasma parameters before the end of last year. The PLT results¹¹ are preliminary in that no detailed optimizing of conditions has yet been made. The TFTR predictions¹ are produced from sophisticated computer code studies¹² involving transport models based on diffusion and instability theories, influx of neutral gas and impurities whose reliability can only be checked by more experimental data from PLT and T-10. The dominant feature of the TFTR will be the neutral beam auxiliary heating which will provide about an order of magnitude more power than the Ohmic heating.

A high energy neutral beam entering a plasma in a magnetic field rapidly becomes ionized by electron bombardment and by charge-exchange with plasma ions. Provided the mean free path is short enough, the energy is effectively absorbed into the plasma. Experiments on the ORMAK¹³ and ATC¹⁴ Tokamaks have shown effective trapping and ion heating at low power levels. In addition, one can make use of the beams to benefit the fusion power output of a Tokamak since the peak of the fusion cross section for Deuterium-Tritium reactions is at 120 keV whereas the thermal energy of the plasma is only a few keV. Hence by injecting beams of higher energy one can enhance the fusion output considerably. Figure 2 shows a calculation for the slowing down of a 180 keV deuterium beam in a 5 keV tritium plasma.¹ Initially the energy is mostly transferred to the electrons but as it slows down the energy is transferred to the tritons by elastic collisions. The figure also shows the fusion probability and the energy multiplication factor Q .

$$Q \equiv \text{Integrated fusion probability} \times 17.6 \text{ MeV}/W_0$$

where 17.6 MeV is the fusion energy yield and W_0 is the initial beam energy.

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Fig. 2. The classical slowing down of an energetic deuteron beam in a 5 keV tritium plasma.¹ The curves show the transfer of energy to the electrons and tritons, the instantaneous fusion probability and the energy multiplication factor Q .

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Fig. 3. Computed radial profiles of electron density for four possible operational modes of TFTR.¹ a) Weakly compressed mode. b) Strongly compressed mode. c) Low-current quasi-static mode. d) High-current quasi-static mode. These are optimal results after neutral beam injection and compression (in cases a and b).

TABLE I Plasma Parameters of Some Tokamaks

	ST	TFR	ALCATOR	PLT (prelimi- nary data)	TFTR (predicted)
Major Radius R(m)	1.09	0.98	0.54	1.3	2.5
Plasma Minor Radius a(m)	0.14	0.20	0.12	0.45	0.85
Toroidal Field Strength B_T (W/m ²)	5.0	0.60	7.0	3.5	5.2
Plasma Current I(MA)	0.12	0.20	0.15	0.6	2.5
Electron Tempera- ture T_e (keV)	~2.0	~2.0	~1.0	~2.0	5-10
Ion Temperature T_i (keV)	~0.5	1.1	~0.5	1.5 estimate	5-10
Electron Density n_e (cm ⁻³)	5×10^{13}	6×10^{13}	5×10^{14}	3×10^{13}	$> 10^{14}$
Neutral Beam Power (MW)	-	~0.6	-	(1.5) not yet installed	20.0
Length OH Pulse (sec)	0.05	0.4	0.1-0.6	1.0	>1.0

Other forms of auxiliary heating have been used on Tokamaks. Heating by rf power and by adiabatic compression have shown promise and the capability for the latter is being incorporated for the TFTR device. The simplest compressional heating makes use of the fact that the toroidal field is inversely proportional to major radius, $B_T \propto 1/R$. The plasma is first formed at large R. It is then forced inwards to smaller R by increasing the vertical field. The maximum compression achievable in TFTR is about 1.5 raising the density by over 100% and the bulk plasma temperature by over 70%. If the neutral beam heating is applied before compression, there is an enhanced heating effect. Figure 3 shows computer derived radial temperature and density profiles for different modes of

operation. The plasma parameters from these figures establish the parameters for the provision of diagnostic apparatus although it is probable that the recent good high density results from Alcator² will lead to operation at densities up to $5 \times 10^{14} \text{ cm}^{-3}$ by injection of additional neutral gas. The impurity concentration is also raised by compression.

II.2 Effect of Impurities on the Plasma

The importance of atomic physics in the fusion program lies in enabling understanding of the effects impurities have on the plasma by determining the ionization states and spatial distribution of the ions. For the very high temperature discharges, $T_e \geq 5 \text{ keV}$, most of the impurities at the center of the plasma will be fully stripped except for relatively heavy atoms such as molybdenum or tungsten. These materials will probably be used in limiters or in protection plates against accidental neutral beam bombardment of the wall.

The dominant effects of impurity ions coming from evaporation or sputtering of the vacuum vessel walls or from the limiter can be summarized as follows. For relatively low power tokamaks, the impurity effect has probably been beneficial in that the plasma resistance is higher, and hence the Ohmic power input is higher, than for pure hydrogenic plasmas. ($\bar{Z}_{\text{eff}} \equiv \sum n_i Z_i^2 / \sum n_i Z_i$ has been typically 3-5 and is the relative enhancement factor.) However, there are significant detrimental effects which become more serious for larger high temperature plasmas. By cooling the outer edges of the plasma they cause the current density to shrink toward the center, which can lead to a disruptive instability. They make the plasma transport properties predominantly collisional when the ions of a pure hydrogenic plasma should be essentially collision-free. Classical theory, and more sophisticated theories including toroidal effects, particle-mirroring along field surfaces and instability driven transport, predict peaking of the impurity ions at the axis.⁶ These impurities will cool the center by the enhanced bremsstrahlung and, if they are not fully stripped, by line radiation. The peaking of the impurity concentration was observed on the T-4 Tokamak¹⁵ but not on the ST Tokamak.¹⁶ This difference may be caused by a strong mixing effect inside the unstable $q=1$ surface in the ST Tokamak for which the diffusion theories are not applicable. An experiment by Cohen et al.¹⁷, injecting small laser-produced bursts of aluminum into the ATC Tokamak discharge agreed well with the predicted theoretical penetration to the center.

An example of the effects can be seen in Fig. 4 which shows a set of computer derived radial profiles of density and temperature for plasmas with different peak densities at the same plasma

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Fig. 4. Computed radial profiles of electron density and temperature for high current operation in TFTR.¹ The central density has been varied. The lower pair of pictures are at different times in the same discharge.

current ($I_p = 2.5$ MA) in TFTR.¹ An initial oxygen concentration of 1.5% and an iron concentration of 0.1% was assumed. At the lowest central electron density of $5 \times 10^{13} \text{ cm}^{-3}$, the electron temperature profile is roughly parabolic but as the density increases and hence the radiation loss increases, relative to the power input, the profile changes to a hollow profile with a rather cool peak temperature. The lower pair of curves show two times in the same discharge and reveals the development of this radiation-caused thermal instability. It is this type of result which causes the interest in experiments with magnetic divertors which essentially retract the limiter into a separate pumping chamber and can also decrease the probability of heavy sputtered atoms from the walls getting into the hot plasma.^{18,19,20}

The radiative power loss due to iron at high levels of ionization has only recently been calculated by Merts et al.²¹ The results can be summarized in Fig. 5²² which is based on a coronal equilibrium model for which the ion transport times are assumed to be long. (Coronal equilibrium can be applied if $n\tau \geq 10^{11} \text{ cm}^{-3} \text{ sec}$ where τ is the ion containment time.) At low temperature the loss is dominated by line radiation and dielectric recombination while at the higher temperatures predicted for future Tokamaks, radiative recombination and bremsstrahlung dominate. The presence of impurities can also lead to defects in heating by high energy neutral beams. The beams themselves will tend to sputter impurities off

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Fig. 5. Radiation power loss of iron impurities calculated by Merts et al.²¹ ($n_e = 10^{14} \text{ cm}^{-3}$, $n_{\text{Fe}} = 10^{12} \text{ cm}^{-3}$). (From Ref. 22.)

BEAM-DEPOSITION INSTABILITY

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Fig. 6. Schematic representation of effect of plasma impurities on neutral beam deposition. The upper figure shows profiles of beam-deposited energetic ion density for various values of $\bar{Z}$. The lower figure shows the growth of the outer impurity layer.

the walls of the vacuum vessel to some extent. With injection tangential to the major circumference, only a small fraction, of order 10^{-4} , of the injected neutrals will hit the wall. However, another effect is possible which is shown schematically in Fig. 6.¹ As the beam enters the plasma, there is local ion heating at the edge which enhances the charge-exchange in the edge region. The product neutrals can reach the walls locally to cause sputtering with the release of iron or other impurity into the edge region. This enhanced impurity level at the edge increases the impact ionization of the beam so that there is a growing beam deposition instability curtailing the usefulness of the injection. The upper figure shows that with $\bar{Z}=5$, the deposition is strongest in the plasma edge region.

The impurities will have a significant effect on the fusion yield since the number of fusing particles is necessarily depleted by their presence. For the TFTR, the fusion yield may be reduced to make the attainment of $Q=1$ impossible.

From the point of view of diagnostics, the impurities are interesting in themselves and offer the possibility of measuring ion temperatures fairly deep into the plasma by Doppler broadening of spectral lines of highly ionized ions (e.g., Fe^{23+} , Mo^{30+}). They provide an enhancement of the continuum radiation in the x-ray region over the pure hydrogenic bremsstrahlung which should enable electron temperature measurements by x-rays to be made in the presence of the high prompt flux of γ -photons caused by the fusion neutrons colliding with the nuclei in the vacuum vessel wall and the radiation shielding surrounding the device. The impurities also strongly affect the scattering of far infrared laser light which may be used in techniques for measuring the ion temperature and the current density distribution. Evans and Yeoman²³ have shown that there is a large enhancement at the center of the ion feature due to the impurities, this distortion being as much as a factor 2 for a fractional impurity level as low as 10^{-4} of fully ionized molybdenum.

III. SOME RECENT RESULTS

Extensive studies have been made of the radiation from the plasma in the ST Tokamak in both the vacuum ultraviolet²⁴ and the x-ray²² regions of the spectrum. Amongst the most important work have been studies of the iron spectra and the interpretation of the enhancement of the continuum x-ray radiation over the pure hydrogenic levels. The x-ray signals could also be used for looking at plasma fluctuations near the center of the plasma and for measuring the radial electron temperature distribution. Recent results show that fluctuations correlated with the x-ray fluctuations can also

be seen on highly ionized molybdenum lines in TFR (Mo XXXI) at an electron temperature of about 2 keV.²⁵

As an example of the ultraviolet spectroscopy, iron has been selected although the larger radiation loss is due to oxygen. Figure 7 shows the time behavior of various iron impurity lines in the ST Tokamak integrated along a line of sight.²⁴ The average density and three electron temperature points at about 1.8 keV are also shown. The limiter radius was opened to $a = 13$ cm to let the plasma be closer to the stainless steel wall; all the iron impurity comes from that source. The Fe XV line behavior is an indication of iron influx during the pulse. Both highly ionized lines have been identified in solar flare operation so that the identification is fairly certain. From the approximate rate coefficients for excitation at 1.8 keV for these lines an increase of about a factor 3 in iron concentration is found to occur between 8 msec and 70 msec. However, spatial distributions of the lines are essential for conclusions on the ion accumulation rate in future tokamaks.

The group working on TFR have also been working on the impurity problem, and in particular on oxygen, iron, and molybdenum.²⁶ Figure 8 shows calculated curves for the fractional abundance of highly ionized states of iron as a function of temperature. The upper curve includes dielectronic recombination relative to the lower curve which only assumes radiative recombination. Dielectronic recombination has the effect of raising the temperature at which any

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Fig. 7. Time behavior of iron resonance lines in an ST Tokamak discharge.²⁴ The average density and the MoXIII resonance line are also shown. The circles indicate measurement of the peak electron temperature.

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Fig. 8. Calculated curves of the fractional abundance of ionization states of iron.²⁶ The upper curve includes dielectronic recombination and radiative recombination, the lower curve only includes radiative recombination.

ionization state is most abundant to higher values. These curves show that, while Fe 23^+ is the dominant impurity level at the center of TFR, the helium-like and hydrogen-like states will dominate in TFTR. By producing a radial scan of a number of lines of different iron ionization states, a quantitative picture of the iron influx and its effect could be built up.

The presence of iron should also be identifiable from a spectrum taken in the x-ray region. In the ST Tokamak, a spectrum was taken with a low resolution pulse-height analysis system and is shown in Fig. 9.²² The observed spectrum (a) is compared with a calculated spectrum by Merts et al. (b), for electron temperatures $T_e = 1.0$ and 1.2 keV and which accounts for the instrumental resolution.²¹ The assumption of coronal equilibrium may not apply and this may explain the rather better agreement of the theory at $T_e = 1.0$ keV with the experiment at $T_e = 1.2$ keV, this temperature having been obtained by Thomson scattering.

The impurities also affect the quantitative emission of x-rays from the plasma. Since the bremsstrahlung and recombination

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Fig. 9. Comparison of the K_{α} -line structure of iron a) measured in the ST Tokamak for central electron temperature 1.2 keV²² with b) computations of the K_{α} -line by Merts et al.²¹ for $n_e = 10^{14} \text{ cm}^{-3}$, $n_{Fe} = 10^{12} \text{ cm}^{-3}$ for two values of temperature 1.0 and 1.2 keV. The contribution of direct-collisional excitation at 1.0 keV only is also shown. (From Ref. 22).

radiation have almost the same functional dependence on the electron temperature¹⁶ and are proportional to $\sum n_i Z_i^2$ the x-ray continuum shows a considerable enhancement over a pure hydrogenic plasma. For conditions in the ST Tokamak, where the Thomson scattering system indicates a temperature of 1.45 keV, the x-ray continuum enhancement over hydrogenic bremsstrahlung was 18 with iron the dominant impurity. The pulse height analysis curve is shown in Fig. 10.¹⁶ K_{α} lines of some other impurities in the plasma can also be seen. Full analysis using the computed iron and oxygen enhancement factor produced good agreement for the average impurity $\bar{Z}$ with that obtained from the resistance measurement.

Detailed studies of x-ray fluxtuations which produced considerable insight into the stability behavior of the plasma near the hot center have been made in the ST,²² ATC,²⁷ and TFR¹⁰ Tokamaks. These results will not be discussed here, but because of their importance in understanding the magnetohydrodynamic stability of the central core of the plasma and the inferences that can be drawn from them about the current density distribution, their measurement is considered essential for large tokamaks.

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Fig. 10. The observed pulse height analysis x-ray spectrum for an ST Tokamak discharge. It is compared to the computed hydrogenic bremsstrahlung for the measured electron temperature and density profiles.

IV. PROBLEMS ASSOCIATED WITH EXTRAPOLATION TO LARGE TOKAMAKS

In considering larger tokamaks, and specifically TFTR, many technical problems appear. Diagnostics have to be capable of producing useful information from plasmas with large minor radius ($a \leq 85$ cm), high peak density ($n_e(0) > 10^{14} \text{ cm}^{-3}$) and high peak temperature ($T_e(0) \approx T_i(0) \leq 10$ keV). They must be capable of following a compression of the plasma and must share space around the tokamak with neutral beam lines, vacuum pumps and radiation shielding. Because of pulsing rate limitations due to the high magnetic field energies involved and total pulse limitations set by the permissible radiation levels, the diagnostics must collect large amounts of data in each pulse. It will be desirable to obtain spatial and temporal behavior of most plasma parameters concurrently during a single discharge. Rough estimates made to evaluate a computer data handling system suggest that about ten million words of data will be collected for each discharge at full power.

Another requirement for the TFTR is that some measure of feedback control of the plasma will be necessary. The high energy densities of the plasma and the poloidal flux require that the energy be released in as gentle a fashion as possible for protection of the vacuum vessel and the coil systems. In particular, the rapid disruption of the current common to all tokamaks at certain plasma conditions should be prevented. The diagnostic techniques for measurement of plasma current, electron density, plasma position, and large scale magnetic fluctuations for providing data for the feedback system will be quite conventional. The development problem lies in determining the precursor identifying symptoms of the disruption, determining how to integrate them into a control system, and determining the proper response.

Some of the plasma parameters for which measurement is necessary to ensure the usefulness of the large TFTR as an experimental device are summarized in Table II. Specifically the problems of measuring the power input directly from the measured voltage and current, the electron temperature by forward scattering of ruby laser light rather than 90° scattering, the plasma density distribution by interferometer and analysis of wall surfaces have been excluded as these are largely technological problems. The most used technique for measuring the ion temperature has been energy analysis of charge-exchanged neutral atoms emerging from the plasma. Figure 11 shows the penetration length (e-folding length) as a function of the emergent neutral hydrogen atom's energy using the cross

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Fig. 11. The penetration length for neutral hydrogen atoms emerging from inside the plasma as a function of energy. Electron ionization collisions have been ignored.

TABLE II Diagnostic Development Required

Parameter To Be Measured	Problem with Present Techniques	Proposed New Techniques	Research and Development Required
Ion Temperature	Mean free path limits charge-exchange neutrals.	Enhance neutral density by modulated 20 keV beam.	Check feasibility on PLT.
		Doppler broadening of impurity lines in UV.	Identify suitable forbidden lines. Develop scanning UV spectrograph.
		Doppler broadening of impurity lines in x-ray region.	Develop curved crystal spectrometer. Identify highly ionized Mo, W spectra.
		CH ₃ F laser scattering (496 μ m)	Develop laser, detector, optics system.
		CO ₂ laser scattering (10 μ m)	Develop detector, optics system.
		Neutron yield and line width.	Develop collimator system, adapt spectrometer systems. Measure TT cross section.
Quantitative Impurity Measurement	Low mass impurities fully ionized for most of plasma cross section.	Bremsstrahlung enhancement (x-ray).	Ionization rates, cross section measurement. Develop curved crystal spectrometer.
		Intensities of high Z lines in UV and x-ray.	See ion temperature.

TABLE II Diagnostic Development Required (cont.)

Parameter To Be Measured	Problem with Present Techniques	Proposed New Techniques	Research and Development Required
Neutral Hydrogen Density	Mean free path limits charge-exchange neutrals.	Lyman α fluorescence	Develop light source at 1216 $\text{\AA}$. Prove feasibility in presence of plasma light.
Current Density Distribution	No satisfactory measurement.	Heavy neutral particle probe.	Develop 2 MeV source of neutral Thallium. Establish detector system. Prove sensitivity.
		Modulation of CO_2 laser at ω_{ce} .	Set up laser-detector system. Prove feasibility on PLT.
		Polarization of Zeeman split Li impurity line.	Develop Li beam source, optics. Prove feasibility on Pulsator.
		Faraday rotation of HCN laser light.	Develop complete measurement system. Prove feasibility.

section measurements of Stebbing et al.,²⁸ the three lines being for different proton densities. For the projected discharges in TFTR the range of a neutral atom emerging from the axis is about 10 cm so that there may be as many as eight mean free paths in its trajectory outwards. Since the neutral atom density will be less than 10^8 atoms cm^{-3} (or charge-exchange will dominate the ion energy loss at the axis) measurement becomes impossible without an artificial enhancement such as that proposed by Eubank et al.²⁸ for PLT where a modulated atom beam will be injected into the plasma. The measurement of neutral hydrogen density will have to be done independently and a resonance fluorescence scheme has been proposed by Koopman et al.²⁹ This group is currently developing a laser system involving a dye laser followed by a frequency doubler and a tripling stage to produce radiation at $1216 \text{ \AA}$.

Other techniques for measuring the ion temperature have been proposed. If sufficient suitable forbidden lines in the ultraviolet spectrum can be found, then Doppler broadening measurements will be made. Doppler shift measurements can also identify gross plasma motions. Lines of Fe XX, XXI, and XXII have so far been identified and Hinnov³⁰ plans to attempt measurement of the ion temperature distribution by this technique on PLT. It may be necessary to seed the plasma with test impurities to find lines relevant to the higher temperatures of TFTR. Von Goeler et al.,³¹ are studying the possibility of a curved crystal spectrometer for looking at Doppler broadening of iron impurity lines in the x-ray region in PLT. To extend this measurement, it is essential for measurements of cross sections and spectra of other relevant highly ionized atoms to be determined.

It is also possible to obtain the temperature from collective scattering of laser radiation with $\lambda > \lambda_D$. λ is the incoming far infrared wavelength and λ_D is the plasma Debye length, typically of order $50 \text{ }\mu\text{m}$. Methyl fluoride (CH_3F)³² and carbon dioxide (CO_2)³³ laser systems have been proposed but neither has been tried on a tokamak plasma. Trials on Alcator, Dite, and PLT are expected within the next two years.

Studies of the neutrons will obviously play a major role in determining the success of the heating of TFTR. The large flux ($\sim 6 \times 10^{12}$ neutrons $\text{cm}^{-2} \text{ sec}^{-1}$) of virgin neutrons predicted for the operation with tritium and smaller flux ($\sim 6 \times 10^{10}$ neutrons $\text{cm}^{-2} \text{ sec}^{-1}$) predicted for operation with deuterium¹ must be used for detailed measurements of the ion temperature and slowing down of the beam particles. The developments required are predominantly adaptations of current nuclear physics methods with, however, an extended intense source, long times of operation and very high background fluxes of scattered neutrons slightly degraded in energy.

The ultraviolet spectral and x-ray spectral measurements for identifying impurity ions have very largely the same requirements as for the ion temperature measurement. To obtain a measurement of the average impurity level, or $\bar{Z}$, it is desirable to measure the bremsstrahlung enhancement γ factor discussed earlier. However, the interpretation is clearly very difficult and a much greater knowledge of the radiation from heavy non-ferrous impurities is necessary. The actual measurement of the continuum will be difficult during operation with tritium because of the high photon fluxes from the shielding materials and from the vacuum vessel wall facing the detector. Instead of using a pulse height analysis system with direct line-of-sight viewing of the plasma by the detectors, a low resolution crystal spectrometer might be considered. Figure 12 shows a possible arrangement of the connection of a multi-position spectrometer to the vacuum vessel where the spectrometer would be underneath six feet of shielding under the tokamak and the top tubes are placed to provide a considerably reduced promptly flux from the vacuum vessel in the line of sight. The scattered γ photon flux at the spectrometer is estimated to be of order 10^8 photons $\text{cm}^{-2} \text{sec}^{-1}$; the bremsstrahlung signal is of order 10^9 photons $\text{cm}^{-2} \text{sec}^{-1}$. To allow reasonable counting rates and dynamic range additional shielding will have to be incorporated in the spectrometer design.

For laser scattering from an impurity contaminated plasma, the ion feature can be dominated by an impurity peak at the center of the scattered line. The line shape is dependent on the average impurity concentration, $\bar{Z}$, and α , the ratio of the scattering scale length to the Debye length. By using two scattering angles to produce different values of α , $\bar{Z}$ can be determined.²³ The most probable choice of laser wavelength is 496 μm . A trial is expected shortly.

The measurement of current density distribution gains importance for TFTR because of the high power neutral beam auxiliary heating which will modify the poloidal flux and because of the difficulty of measuring the power input using a measurement of voltage around the toroid. No universally satisfactory technique has been achieved though a heavy ion beam was used on the ST Tokamak³⁴ and its development will be extended on PLT. In this technique, the singly ionized thallium ions are ionized by collision to Tl^{2+} . They then move parallel to the toroidal minor axis because of the poloidal field. In practice, the measurement was better at determining the radial electric field in the plasma by the change in energy of the Tl^{2+} ions.³⁵ For TFTR, the energy of the thallium beam must be increased and the penetration can only be achieved by means of a neutral thallium beam. The technique of looking at the Thomson scattering of 10 μm radiation from a CO_2 laser is being developed but has not been proven feasible in tokamaks.^{36,37} In a magnetic field there is a qualitative change

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Fig. 12. A view of a section of the TFTR Tokamak showing a speculative arrangement of a multichannel x-ray spectrometer at the TFTR vacuum vessel. The lower set of tubes passes through the coils and six feet of shielding material to the spectrometer in a basement. The upper set of tubes passes beyond the radiation shielding to cut γ -photon flux from the line-of-sight to a minimum.

in the spectrum of Thomson scattered light when the difference between the incident and scattered wave vectors is perpendicular to that field. In this case the Gaussian spectrum becomes a series of sharp lines separated by the electron gyrofrequency. Sufficient accuracy in determination of the line separation allows measurement of the poloidal field. McCormick³⁸ is developing a system for use on Pulsator using an injected lithium beam and looking at the polarization of the components of the Zeeman triplet. The polarization is dictated by the local magnetic field direction, from which the strength of the poloidal field can be found. The feasibility of this technique awaits trial and it is doubtful whether the high density expected in TFTR will allow its use. Faraday rotation of submillimeter laser light in the poloidal field (rotation $\propto \int n_e B_z dl$ where B_z is the magnetic field in the direction of propagation and the integration is over the path length in the

plasma) has been studied theoretically³⁹ but has not been used in a tokamak.

It is unlikely that more than one of the above techniques for measuring any one of the plasma parameters listed in Table II will be installed on the TFTR device but this is a measure of the difficulty of the diagnostic problem that so many varied techniques are considered worthy of study. It is certainly probable that other techniques will be proposed and tested by 1981, the projected start-up date for TFTR.

V. CONCLUSIONS AND ACKNOWLEDGMENTS

In a paper addressing the problems of plasma diagnostics in large tokamaks it is inevitable that many topics receive short shrift. In this paper the problems most relevant to atomic physicists have been given most weight. Some results from recently operating tokamaks have been given to show the current state of the art in ultraviolet spectroscopy and x-ray spectroscopy.

The TFTR Tokamak is expected to start operation by mid-1981. By that time, many of the diagnostic problems should have been solved. This will require some research in the area of atomic physics. Specifically for the heavier metals in highly ionized states there is very little relevant atomic data.

The list of references in this paper is far from comprehensive and much comparable work is being done by other people. I apologize for not referring to all the available literature. My special thanks go to S. von Goeler and E. Hinnov for discussions relevant to this paper. This work was supported by the U. S. Energy Research and Development Administration Contract E(11-1)-3073.

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