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INTRODUCTION TO MAGNETIC CONFINEMENT
FUSION DIAGNOSTICS

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I. Introduction

These notes present a brief survey of some of the current diagnostic techniques used in magnetic fusion plasma devices. To give an idea of the range of parameters and geometries encountered the parameters of four representative experiments - PLT, TMX, ZT-40 and EBT-I(S) - are given in Section II. The central issue of all experiments is to understand the flow of power which can be summarized by the following two volume integrated equations for the ions and electrons.

$$\frac{d}{dt} \int n_i \frac{3}{2} kT_i d^3x = P_{ei} + P_{auxi} + P_{cx} + P_{tr,i} + \dots$$

$$\frac{d}{dt} \int n_e \frac{3}{2} kT_e d^3x = -P_{ei} + P_{auxe} + P_{rad} + P_{tr,e} + \dots$$

P_{ei} is the power coupled from the electrons to the ions, P_{auxi} the auxiliary power input to the ions (neutral beam injection, ICRF,...), P_{auxe} the auxiliary power input to electrons (ohmic heating, ECRH, ...), P_{cx} is the ion energy lost by charge exchange, P_{rad} is the radiated power and $P_{tr,i}$ and $P_{tr,e}$ are transport losses. To make a beginning it is necessary to know time resolved spatial profiles of the density and ion and electron temperatures. Apparatus and methods used to obtain this information, selected from the four experiments listed above, are described in Section III; interferometry, Thomson Scattering, electron cyclotron emission and charge exchange analysis. Of course it is necessary to know a great deal more than this and a somewhat arbitrary selection of additional diagnostic examples are presented in Section IV; bolometry (radiated power), VUV spectroscopy (plasma composition), soft x-rays (plasma composition, electron temperature, MHD stability), heavy ion beam probe (plasma potential) and electrostatic end loss

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analyzer (plasma potential, and loss current in a linear machine). Because this is an introductory survey lecture only the barest outline of physical principals and techniques could be accommodated. Two recently published works that contain a great deal of valuable information and many references are;

E. Sindoni, C. Wharton, eds. "Diagnostics for Fusion Experiments,"
Pergamon Press, 1979.

TFR Group, "Tokamak Plasma Diagnostics," Nuclear Fusion, 18, 647 (1978).

II. Four Experiments

- A. PLT - Princeton Large Torus
- B. TMX - Tandem Mirror Experiment
- C. ZT-40 - Reversed Field Pinch
- D. EBT-I(S) - Elmo Bumpy Torus

11.A. PLT Tokamak

The PLT tokamak at Princeton Plasma Physics Laboratory is representative of the large tokamaks now in operation. Plasma stability is provided by a toroidal magnetic field component B_ϕ that is set up by external coils. The plasma is confined by the poloidal magnetic field component B_θ generated by a toroidal plasma current I_ϕ . The toroidal current is excited by an air core transformer with the plasma acting as the secondary. In order to be MHD stable to current driven helical instabilities the parameter q , defined by

$$q = rB_\phi / RB_\theta$$

must be greater than unity throughout the discharge. R is the major radius of the torus while r is the minor radial coordinate. Physically the requirement $q > 1$ says that each field line must make more than one turn the long way around the torus before going once around the short way. Tokamaks generally operate with $q_a \geq 2.5$ at the limiter radius $r = a$. The PLT plasma is ohmically heated by the I_ϕ current to electron and ion temperatures of the order 1 keV. Because the ohmic heating current I_ϕ is limited by the requirement $q \geq 1$ and because the plasma resistivity decreases as $T_e^{-3/2}$ ohmic heating is ineffective above the range 1 to 2 keV. For this reason it is believed that supplementary heating will be needed for tokamaks to reach reactor temperatures of the order 10 keV. The PLT device has employed 2.4 MW of neutral beam injection to reach ion temperatures of 6.5 keV and electron temperatures of 4.0 keV. Experiments employing wave heating in the ion cyclotron and lower hybrid range of frequencies are also underway or planned for the near future.

The PLT plasma is one of the most thoroughly diagnosed fusion plasmas ever studied, employing over thirty individual measurements. Because of systematic uncertainties some of the most important plasma parameters, such as ion temperature, are measured in several different ways. From the diagnostics point of view perhaps the greatest difficulty in PLT was to obtain adequate spatial profiles of plasma parameters. As will be seen in several examples below, this task was accomplished quite admirably by the PLT physicists. Parameters of the PLT device are given in Table 1.

Ref. K. Bol, et al., in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 7th Int. Conf., Innsbruck, 1978) vol. 1, IAEA, Vienna (1979) 11,
H. Eubaek, et al., in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 7th Int. Conf., Innsbruck, 1978) vol. 1, IAEA, Vienna (1979) 167.

Table 1: PLT Parameters

Major radius R	132 cm	
Minor radius a	40 cm	
B_{ϕ} (kG)	32 kG	
Pulse Length:	1 sec 150 msec	Ohmic Heating Neutral Beam Injection
	<u>Ohmic Discharge</u>	<u>Neutral Beam Heated Discharge</u>
I_{ϕ} (kA)	350 $\rightarrow$ 550	400
$B_{\theta}(r=a)$ (kG)	1.8 $\rightarrow$ 2.8	2.0
$n_e(10^{14} \text{ cm}^{-3})$	.3 $\rightarrow$ 1	.2 $\rightarrow$.35
Z_{eff}	$\sim$ 1	2 $\rightarrow$ 4
$T_i(\text{keV})$	$\leq$ 1.2	$\leq$ 6.5
$T_e(\text{keV})$	$\leq$ 1.5	$\leq$ 4.0
$\tau_{Ei}(\text{msec})$	50 $\rightarrow$ 100	$\sim$ 25
$\tau_{Ee}(\text{msec})$	$\sim$ 40	20 $\rightarrow$ 30

Fig. 1. The PLT tokamak

11.8. The TMX Experiment

The TMX experiment at Lawrence Livermore Laboratory is currently the largest operating tandem mirror device. The basic configuration consists of a straight solenoidal section with magnetic mirrors at each end. The high density hot ion mirror plasmas at the ends are sustained by neutral beam injection. Electrons are heated collisionally by the hot ions confined in the mirrors. Ions confined in the solenoid are heated collisionally by the electrons. Future experiments may employ supplementary wave heating at the electron cyclotron and ion cyclotron frequencies. The minimum B mirrors at the ends are designed to give a pressure weighted favorable curvature along a flux line which provides MHD stability. Because of the consequent non-circular flux tube distortion at the mirrors, transition coils between the mirrors and solenoid are necessary to match onto a circular flux tube in the solenoid.

Since ion-ion scattering rates are slower than electron-electron scattering rates by $\sqrt{\frac{m_e}{m_i}} \left(\frac{T_e}{T_i} \right)^{3/2}$, a single cell hot ion mirror machine develops a positive ambipolar potential ϕ to electrostatically confine the electrons while the ions are confined magnetically for an ion-ion collision time τ_{ii} . The essence of the tandem mirror is to use this ambipolar potential to plug the end losses of a straight solenoid. In the tandem mirror, electrons are confined by an overall positive ambipolar potential ϕ_e which adjusts to maintain equal ion and electron loss rates. Ions in the solenoid are confined electrostatically by a potential difference ϕ_i between the solenoid and mirror end plugs. The potential ϕ_i is related to the electron temperature T_e and the plasma densities in the mirrors (n_p) and the solenoid (n_c) by

$$\phi_i = T_e \log \frac{n_p}{n_c}.$$

The confinement time τ_c of the central cell ions in this potential barrier is

$$\tau_c = \tau_{ii} g(R) \frac{\phi_i}{T_i} \exp(\phi_i/T_i)$$

where τ_{ii} is the ion-ion scattering time, T_i the temperature of ions in the solenoid, $g(R) = \sqrt{\pi} (2R+1) \log (4R+2)/4R$ and R is the center cell mirror ratio = B (mirror)/ B (solenoid). Because of the Boltzmann factor $\exp(\phi_i/T_i)$ confinement in the solenoid is greatly improved compared to the classical ion-ion scattering time $\tau_{ii}(\text{sec}) = 4.2 \times 10^{10} T_i(\text{keV})^{3/2}/n(\text{cm}^{-3})$. Because of this improved confinement fusion reactor studies of the tandem mirror yield a fusion power gain Q (= fusion power output/auxiliary heating input) in the range 5 to 10 whereas $Q \approx 1$ for mirror confinement alone.

Typical parameters of the TMX device are given in Tables 2 and 3. The subscript p refers to the mirror end plugs and subscript c to the solenoid. The data in Table 3 have been obtained with up to 400 kW of trapped neutral beam injection power in the mirror end plugs. The ratio $n_c \tau_c / n_p \tau_p$ measured experimentally in Table 3 is the enhancement in confinement due to the Boltzmann factor $\exp(\phi_i/T_i)$. Evidently these early experiments in TMX have established the existence of the potential barrier at the mirror end cells and the improved confinement due to this barrier. From the

diagnostics viewpoint, the most difficult problems are accurately measuring the axial potential profile along each field line and unraveling the factors which determine the energy confinement of the center cell ions.

Ref. T. K. Fowler, B. G. Logan, Comments Plasma Phys. Controlled Fusion, 2, 167 (1977).

F. H. Coensgen, et al., Phys. Rev. Lett., 44, 1132, 1980.

Fig. 2. The TFX experiment

TANDEM MIRRORS WITH AMBIPOLAR BARRIERS AT THE ENDS

Fig. 3.

Table 2: TMX Parameters

Mirror end cell:

Plasma radius	7 cm
Central magnetic field	10 kG
Mirror ratio, R_p	2
Mirror to mirror length	90 cm
Plasma volume	6 l ³

Solenoid:

Plasma radius	30 cm
Plasma length	5.5 m
Plasma volume	1700 l ³
Magnetic field	1 kG
Mirror ratio, R_c	20 (to mirrors)

Pulse length	25 msec
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TMX PARAMETERS

	TMX MAX	Shot 46 9/26/79		
		TMX	TAMRAC**	RF TAMRAC***
$n_p (10^{13} \text{ cm}^{-3})$	4	2.5		
$j_{\text{end}} \text{ A/cm}^2$	1	0.9		
$T_{\text{ep}} (\text{eV})$	260	140	106	121
$n_c (10^{13} \text{ cm}^{-3})$	3	1.0	1.7	1.1
$T_{\text{ic}} (\text{eV})$	360	74	29	78
$\phi_i (\text{V})$	100 to 300	128*	58	138
$n\tau_c 10^{10} \text{ cm}^{-3}\text{s}$	7	3.1	7.7	3.1
$n\tau_c/n\tau_T$	9	3.1	4.0	2.9
$\hat{\beta}_c$	0.14	0.06	0.09	0.09

* $T_e \ln n_p/n_c$ consistent with ϕ diagnostic

**TAMRAC input: observed n_p and j_{end} , W_i in plug = 13 keV

***TAMRAC input includes 150 KW of rf power in center cell

II.C. ZT-40

The ZT-40 device at Los Alamos Scientific Laboratory is a toroidally axisymmetric device that employs a magnetic configuration known as the reversed field pinch (RFP). The RFP has some similarities to the Tokamak but differences in the mode of operation lead to features that may be advantageous from the viewpoint of a fusion reactor. The similarities and differences are easily seen by a comparison of minor radius profiles of toroidal (B_ϕ) and poloidal (B_θ) magnetic field. Because of the Kruskal-Shafranov constraint on the safety factor $q = rB_\phi / RB_\theta \gtrsim 1$, tokamaks have $B_\phi \gg B_\theta$ and have low aspect ratio $A = \frac{R}{a} \approx 3$ in order to maximize the ohmic heating current I_ϕ that can be driven without violating the Kruskal-Shafranov condition. RFP's on the other hand operate with $B_\phi \sim B_\theta$ and $q < 1$ and have aspect ratio unrestricted by the choice of I_ϕ . MHD stability is provided by high magnetic shear ($\frac{dq}{dr} \neq 0$ anywhere inside the plasma) and by wall currents. The highly sheared profile is produced by reversing the toroidal field component between the central plasma and the wall. The different q profiles have two consequences;

- (1) the RFP may operate at higher ratios of plasma to magnetic field energy densities than Tokamaks and
- (2) for a given toroidal field B_ϕ the RFP may operate with higher ohmic heating current I_ϕ .

As a result ohmic heating of an RFP plasma may exceed that in a Tokamak by up to two orders of magnitude and may be sufficient to heat the RFP to ignition without supplementary heating. A disadvantage of the RFP from a reactor

viewpoint is that large amounts of magnetic energy must be recirculated between burn cycles in order to get a net power balance.

The ZT-40 device presently employs a non-conducting Al_2O_3 vacuum wall to allow a wide range of field rise times to be explored. The Al_2O_3 wall is surrounded by a conducting wall that is split at four current feed points around the toroidal direction and acts as primary of the toroidal current transformer with the plasma as the secondary. Twelve iron yokes around the torus form the magnetic core of this transformer. The conducting wall is also split the long way around the torus to allow penetration of toroidal flux provided by the windings on the outside of the conducting shell.

The ZT-40 device is in an early stage of operation. Some of the design parameters for ZT-40 are given in Table 4. Compared to other fusion plasma devices ZT-40 has rather high density and the large fluctuations that occur during set-up of the magnetic field configuration require good time resolution. Because of the importance of the magnetic field configuration to MHD stability of the RFP it would be desirable to make internal non-perturbing measurements of magnetic field. So far this has not been attempted on ZT-40.

General Ref. for RFP's;

H.A.B. Bodin, "Reversed Field Pinches," Proc. Third Topical Conf.

Pulsed High Beta Plasmas, Culham, 1975 (Pergamon Press).

Fig. 4. Tokamak and Reversed Field Pinch Profiles

(a) Tokamak

(b) Reversed Field Pinch

ZT-40

Table 4: Parameters of ZT-40

I_{ϕ} (MA)	0.6
τ_{rise} (ms)	.0025 - 1
τ_{decay} (ms)	1 - 5
Major radius (cm)	114
Minor Radius	
inner wall (cm)	20
Conducting shell	22
Core flux swing (V-s)	2
Estimated plasma parameters	
T(eV)	150 - 200
$n(\text{cm}^{-3})$	$0.1 - 5 \times 10^{15}$

II.D. The EBT Experiment

The EBT (Elmo Bumpy Torus) at Oak Ridge National Laboratory is a non-axisymmetric toroidal device consisting of twenty-four toroidally linked mirrors. The plasma in EBT consists of two parts; the bulk toroidal plasma and the hot electron annuli confined in each mirror cell. The purpose of the electron annuli is to create a local depression in magnetic field strength which stabilizes flute-interchange modes by producing average minimum B. The bumps or corrugations in field intensity provided by the mirror coils cause ions and electrons to drift in poloidal angle on closed drift surfaces, thus averaging out the drift due to toroidal field gradient which would push the plasma to the wall. The net poloidal drift however also depends sensitively on the ambipolar electric fields. The EXB induced drift can cancel the VB and curvature drifts for a certain class of particles. To obtain comparison with theoretical transport models it was vital to measure the space potential and this was successfully done with a heavy ion beam probe.

The toroidal plasma and the hot electron annuli in EBT are heated by electron cyclotron resonance heating (ECRH). Because accessibility requires the plasma frequency be less than the electron cyclotron frequency this leads to an upper limit on density $n_e \approx \pi \frac{m f_{ce}^2}{e^2} \approx 4 \times 10^{12} \text{ cm}^{-3}$ at $f_{ce} = 18$ GHz. For this reason the density in EBT is presently lower than in most fusion plasma devices and this makes some diagnostic measurements difficult. This difficulty is partially offset however by steady state operation and the large amount of access allowed by the high aspect ratio and twenty-four identical plasma cells.

EBT-I was the first Elmo Bumpy Torus to operate, and the parameters measured for this device are summarized in Table 4. It has since been upgraded to EBT-S and the projected parameters for the upgrade are also given in Table 5.

Ref's: R. A. Dandl, et al., Oak Ridge National Laboratory Report No. ORNL/TM-6457-1978.
P. L. Colestock, et al., Phys. Rev. Lett., 40, 1717, 1978.

Table 5: EBT-I and EBT-S Parameters

<u>EBT</u>	<u>EBT-I</u> (measured)	<u>EBT-S</u> (projected)
B (midplane)	4.5 KG	7.0
B (mirror)	9.0 KG	14.0
R	150 cm	Same
a	18 cm	Same
Microwave power	60 kW, 18 GHz 30 kW, 10.6 GHz	200 kW, 28 GHz 60 kW, 18 GHz
Hot electron annulus		
n_e	$2 - 5 \times 10^{11} \text{ cm}^{-3}$	Same
T_e	100 - 200 keV	100 - 500 keV
β_{ring}	10 - 40%	Same
Toroidal plasma		
n_e	$1 - 4 \times 10^{12} \text{ cm}^{-3}$	$2 - 6 \times 10^{12} \text{ cm}^{-3}$
T_e	150 - 600 eV	300 - 800 eV
T_i	70 - 150 eV	100 - 200 eV
β_{max}	.2 - .6%	.5%
R	150 cm	Same
a (midplane)	10 cm	Same
Volume	400 l	Same
Pulse length	Steady state	Same

Photograph of EBT-I.

Fig. 6.

III. Basic Diagnostics

- A. Interferometry - electron density
- B. Thomson Scattering - electron temperature, density
- C. Electron cyclotron emission - electron temperature
- D. Charge exchange analysis - ion temperature

III.A. Interferometry

The frequency f_0 of electromagnetic radiation used to measure plasma density profiles must be sufficiently greater than the electron plasma frequency $f_{pe} = \frac{1}{2\pi} \sqrt{\frac{4\pi n e^2}{m_e}}$ so that (1) the beam propagates and (2) the beam refraction is not intolerable. For interferometry the wave propagation vector is generally perpendicular to B and the polarization of the electric field is parallel to B (o - wave). Then the plasma dielectric is independent of magnetic field and in the cold plasma limit is simply $\epsilon_p = 1 - \frac{f_p^2}{f^2}$.

The phase shift of such a beam propagating along a chord length L through the plasma

$$\begin{aligned}\phi_p &= \frac{2\pi}{\lambda_0} \int_0^L (1 - \sqrt{\epsilon_p}) dx \\ &= \frac{\pi}{n_c \lambda_0} \int_0^L n dx \quad n \ll n_c.\end{aligned}$$

Measurement of ϕ_p then gives the plasma line density $\int_0^L n dx$. The critical density (n_c), wavelength (λ_0) and line density per 2π fringe shift are given in Table 6 for some common interferometry sources. Generally, a multi-chord measurement is made to obtain profiles of $\int n dx$. In order to be sure of the measurement path refraction of the beams due to the plasma density gradient must be small. Specifically the angle of deflection of a beam propagating along a chord x with transverse density gradient $\frac{dn}{dy}$ is

$$\alpha(y) = \frac{1}{2} \int \frac{1}{\epsilon_p} \frac{d\epsilon_p}{dy} dx.$$

Evaluating this for a parabolic cylinder

$$n = n_o \left(1 - \frac{x^2}{a^2}\right) \left(1 - \frac{y^2}{a^2}\right) \text{ gives the deflection angle}$$

$$\alpha_{\max} = \frac{n_o}{n_c} + \theta \left(\frac{n_o}{n_c}\right)^2$$

at a chord height

$$y_{\max} = \frac{a}{2} + \theta \left(\frac{n_o}{n_c}\right)$$

To avoid excessive refraction then one should choose a radiation source frequency that gives a critical density $n_c \approx 5 + 10 n_o$.

A schematic of a simple interferometer using homodyne detection of the plasma induced phase shift ϕ_p is shown in Fig. 8(A). The reference leg signal $A_1 \cos(2\pi f_o t)$ and the plasma leg signal $A_2 \cos(2\pi f_o t + \phi_p)$ are combined in a mixer to give an output at the difference frequency $A \cos \phi_p t$ where $A \sim A_1 A_2$. The problems with this type of scheme are; (1) the output is amplitude dependent, (2) the sensitivity depends on phase and is very weak at $\phi_p = m\pi$, (3) the quadrant of ϕ_p is unknown so there may be ambiguity on whether the plasma density is increasing or decreasing. A common way of avoiding these difficulties is using the heterodyne detection system in Fig. 8 (B). The heterodyne system uses two oscillators split by a difference frequency Δf . Signals from the oscillators are mixed to form the reference signal $A_1 \cos(2\pi \Delta f t)$ and the plasma signal $A_2 \cos(2\pi \Delta f t + \phi_p)$ at the I.F. frequency Δf . The reference signal is then split and a 90° phase shift inserted in one leg. Mixing these with the plasma signal then gives quadrature outputs proportional to $A \cos \phi_p$ and $A \sin \phi_p$. In order to remove amplitude dependence the IF signals are usually amplified and clipped to produce square wave outputs of uniform amplitude. The square wave outputs are then filtered at the IF frequency to recover cosine waveforms with uniform amplitude.

Table 6: Wavelength, cutoff frequency and line density per fringe for some common interferometer wavelengths:

Source	λ_0	$n_c = \frac{\pi m e f_o^2}{e^2}$	$\int n d l$ per 2π fringe shift
Klystron	4 mm (70 GHz)	$6 \times 10^{13} \text{ cm}^{-3}$	$5 \times 10^{13} \text{ cm}^{-2}$
Klystron	2 mm (140 GHz)	2.4×10^{14}	1×10^{14}
HCN	337 μm	10^{16}	6.6×10^{14}
CH ₃ OH	119 μm	8×10^{16}	2×10^{15}
CO ₂	10.6 μm	10^{19}	2×10^{16}
HeNe	3.39 μm	10^{20}	6.6×10^{16}

Diagrams of three practical realizations of heterodyne interferometers are shown in Figures 9 to 11. The 2 mm microwave interferometer in Figure 9 is used on the TMX experiment at LLL. The scheme is somewhat more complex than Figure 8(B) because of double down conversion in the receiver section and automatic frequency control (AFC) of the second IF frequency. The two klystrons are tuned to a frequency difference $\Delta f_1 \approx 700$ MHz. No attempt is made to feedback control Δf_1 so this frequency is allowed to drift. The master oscillator signal from the plasma is fed into the receiver section (R.F. in) where it is mixed with the local oscillator (L.O. in) to yield a signal proportional to $\cos(2\pi\Delta f_1 t + \phi_p)$. This signal is in turn mixed with the output of a voltage tuned oscillator (VTO) with frequency equal to the sum of the two I.F. frequencies, $\Delta f_1 + \Delta f_2$, $\Delta f_2 = 60$ MHz, giving an output proportional to $\cos(2\pi\Delta f_2 t + \phi_p)$ (I.F. out). Mixing the master and local klystrons gives the reference signal $\cos(2\pi\Delta f_1 t)$, which is fed into the receiver section (Ref. in) and mixed with the VTO to give an output $\cos(2\pi\Delta f_2 t)$ (Ref. out). The plasma signal (IF out) and reference signal (Ref. out) are then mixed in the phase comparator section to give $\cos\phi_p$ and $\sin\phi_p$. The plasma IF signal is fed into a limiter (amplified and clipped) and then filtered to remove amplitude variation of the $\sin\phi_p$ and $\cos\phi_p$ presentations. The amplitude of the reference leg is stable enough not to need a limiter. The 60 MHz reference signal in the phase comparator section is fed through a 60 MHz frequency discriminator to regulate the VTO at $\Delta f_1 + 60$ MHz (AFC section). Since the IF frequency is high the interferometer signal can be used to monitor density fluctuations in the ion cyclotron range of frequencies (5 + 20 MHz). This is done by mixing the plasma and reference legs before the limiter and displaying the output through a band pass filter (5 + 20 MHz).

Figure 10 shows an application of the heterodyne technique to FIR lasers developed by Wolfe, et al.. Two CH_3OH lasers are optically pumped with a 12 watt CO_2 laser at $9.6 \mu\text{m}$, and each have output power 5 mW in a single transverse mode at $118 \mu\text{m}$. The modulation frequency $\Delta f = 1 \text{ MHz}$ of the CH_3OH system is set by manually adjusting the cavity length of one of the lasers while monitoring one of the mixed outputs with a spectrum analyzer. The outputs are combined to produce a reference signal at detector $D_1 = A_1 \cos(\Delta \omega t)$ and the plasma signal at detector $D_2 = A_2 \cos(\Delta \omega t + \phi_p)$. The detectors are liquid helium cooled Li-Ge photo conductors. The outputs of the detectors are filtered, amplified and clipped to produce two square wave trains with only the zero crossings preserved for phase measurement. The phase shift ϕ_p is related to the time delay Δt between wave trains by $\phi_p = 2\pi \Delta f \Delta t$. One method that has been developed to display the phase is to use the clipped detector output D_1 to set and D_2 to reset a flip-flop, thus producing a train of pulses of width Δt . Integrating this pulse train with a low pass filter gives an output proportional to $\frac{\Delta t}{\tau} = \frac{\phi_p}{2\pi}$. As the plasma builds up ϕ_p increases from zero to 2π and then resets to zero each time ϕ_p passes through a fringe. An example of a density measurement using this technique on the Alcator tokamak is shown in Figure 11. A digital phase comparator has also been developed which displays total phase shift rather than phase shift module 2π .

A seven chord HeNe ($3.39 \mu\text{m}$) heterodyne interferometer developed by Jacobsen for 2T-40 is shown in Figure 12(a),(b). A PbMoO_3 acousto-optic Bragg cell driven by a local oscillator at 40 MHz splits off a first order diffracted reference beam that shifted in frequency 40 MHz from the zero order

beam. Beam splitters divide each of the outputs into seven beams. The seven beams are recombined after a double pass through the plasma onto InAs photodiodes. The photodiode outputs are amplified and mixed with the local oscillator in a quadrature phase detector. The 40 MHz bandwidth and $6.6 \times 10^{16} \text{ cm}^{-2}$ line density per 2π fringe shift enable this system to follow the relatively fast density excursions in ZT-40.

Ref. W. Cummins, Rev. Sci. Inst. 41, 234. (1970)

S. Wolfe, et al., Applied Optics, 15, 2645 (1976).

A. Jacobsen, Rev. Sci. Inst., 49, 673 (1978).

Fig. 8: Schematic of Microwave Interferometer

(A) Homodyne detection

(B) Heterodyne detection

Center-cell, microwave-interferometer, phase-detection circuit.

Fig. 9. TMX 2mm Interferometer

Fig. 10. Submillimeter laser interferometer (from Wolfe, et. al. Applied Optics, 15, 2645. 1976)

Fig. 11. Example of density measurement on the Alcator tokamak using a CH_3OH interferometer (from A. Gondhalekar et. al., in Plasma Physics and Controlled Nuclear Fusion Research, (Proc. 7th Int. Conf. Innsbruck, 1978) vol. 1, IAEA, Vienna (1979) 199

ZT-40 MULTICHORD INTERFEROMETER: OPTICAL SCHEME

Fig. 12(a)

ZT-40 MULTICHORD INTERFEROMETER:

ELECTRONIC SCHEME (ONE OF SEVEN DETECTORS IS SHOWN)

Fig. 12(b).

III.B. Thomson Scattering

Thomson scattering, the observation of Doppler broadening of radiation scattered incoherently by the plasma electrons, is nearly the universal method of measuring the electron temperature in magnetic fusion plasma experiments. Incoherent scattering of radiation by electrons is characterized by the "α" parameter being much less than unity. If $\vec{k}_0$ is the incident wave vector and $\vec{k}_s$ the scattered wave vector, the α parameter is the inverse product of $\Delta k = \vec{k}_s - \vec{k}_0$ and the plasma Debye length, which is the shortest plasma correlation length.

$$\alpha = \frac{1}{\Delta k \lambda_D} = \frac{1}{2} \sqrt{\frac{4\pi n_e e^2}{kT_e}} \frac{1}{k_0 \sin \frac{\theta}{2}}$$

where θ is the scattering angle. The usual case in fusion plasma experiments is to use a ruby laser ($\lambda_0 = 6943\text{\AA}$) for the radiation source and to choose the scattering angle $\theta = 90^\circ$. Numerically then $\alpha = 5.25 \times 10^{-9} \left(\frac{n_e (\text{cm}^{-3})}{T_e (\text{eV})} \right)^{1/2}$ which is always small compared to unity. For a Maxwellian distribution of electrons with temperature T_e , density n_e and an incident laser flux P_0 (photons/cm²), the scattered flux $P(\lambda)$ (photons/cm³-str-cm(λ)) is

$$P(\lambda) = P_0 n_e r_0^2 \frac{c}{2 \lambda_0 \sin \frac{\theta}{2}} \left(\frac{m}{2 \pi k T_e} \right)^{1/2} \exp \left(- \frac{m c^2}{8 k T_e} \left(\frac{\Delta \lambda}{\lambda_0} \right)^2 \frac{1}{\sin^2 \frac{\theta}{2}} \right)$$

where $r_0 = \frac{e^2}{mc^2}$ is the classical electron radius and m is the electron mass. For $\theta = 90^\circ$ and $\lambda_0 = 6943 \text{ \AA}$ the Doppler half-width of the scattered radiation at the $\frac{1}{e}$ point is then

$$\begin{aligned} \Delta \lambda_{\frac{1}{e}} &= \sqrt{\frac{8kT_e}{mc^2}} \lambda_0 \sin \frac{\theta}{2} \\ &= 27.4 (T_e(\text{eV}))^{1/2} \text{ \AA} \end{aligned}$$

so that measurement of the width of $P(\lambda)$ gives the electron temperature. The shape of $P(\lambda)$ is generally measured with a multi-channel polychromator. Multiplying $P(\lambda)$ by the solid angle $\Delta\Omega$ of the spectrometer viewing the scattered radiation, the length l of beam viewed by the spectrometer and the cross sectional area of the laser beam and integrating over λ gives the ratio of the total number of photons scattering into the detector ($N_{\text{scatt.}}$) to the total number incident ($N_{\text{inc.}}$),

$$\frac{N_{\text{scatt.}}}{N_{\text{inc.}}} = n_e r_0^2 l \Delta\Omega.$$

Measurement of the absolute number of scattered photons can therefore also be used to measure the local electron density. Typically $l \sim 1 \text{ cm}$, $\Delta\Omega \sim .01 \text{ str}$ and the ruby laser pulse is 4 joules ($N_{\text{inc.}} = 1.4 \times 10^{19}$ photons) giving

$$\frac{N_{\text{scatt.}}}{N_{\text{inc.}}} \sim 8 \times 10^{-28} n_e$$

and $N_{\text{scatt.}} = 1.12 \times 10^{-8} n_e$. Therefore the number of scattered photons is 12 to 15 orders of magnitude less than the incident flux for cases of interest. Extreme care must be taken in the design of optical components to avoid stray light getting into the viewing optics. This is usually done by careful alignment and design of the forward beam dump, use of narrow dielectric filters that reject $6943\text{\AA}$ in the viewing optics, and a viewing dump. In the case of theta pinch experiments where the quartz discharge tube did not allow entrance and exit ports and beam or viewing dumps a three grating spectrometer has been developed to reject $6943\text{\AA}$ (R. Siemon). This type of arrangement is also used on ZT-40. When account is taken of the optical transmission efficiency of the viewing optics and spectrometer (typically 10 to 20%) and the low quantum efficiency of photocathodes in the red region (~ 6% for S-20 although GaAs cathodes offer some improvement) the total number of scattered photons per laser pulse is not large. As a result Thomson scattering measurements are routine only for $n_e \geq 10^{13} \text{ cm}^{-3}$ although measurements have been made on EBT with $n_e = 2 \times 10^{12} \text{ cm}^{-3}$. In that case the steady state and long term stability of the experiment allowed electron temperatures to be measured by accumulating data over many laser pulses.

The spectral response of Thomson scattering spectrometers is generally calibrated by lamps with known spectral output. Absolute calibration is accomplished by filling the plasma vacuum chamber with a gas density equivalent to the plasma electron density and observing the intensity of the unshifted Rayleigh scattered light. An exception is the triple grating spectrometer. Since the triple grating spectrometer cannot pass $6943\text{\AA}$ it is

not possible to absolutely calibrate it so it is used to measure T_e only. Plasma light can add a background to the scattered ruby light and also saturate the photo-detectors if they are on for the entire duration of a plasma shot. Since the ruby laser pulse is short (~ 50 nsec) the detectors are gated on only during the pulse to avoid saturation. Plasma background light is usually subtracted from the data by an additional gating of the detectors just before or after the laser pulse. In addition Hydrogen H_α radiation ($6563\text{\AA}$) is usually blocked in the spectrometer.

Two systems of different complexity are shown in Figures 13 and 14. Figure 13 is the system in use on a mirror end cell of TMX and is relatively standard. The ruby laser output is 10 joules. The optics is set up so scattering along a 1 cm segment of the laser path can be observed at five radial positions = - 5, 0, + 5, + 10 and + 15 cm. The three diffraction grating polychromators each have ten wavelength channels and allow simultaneous viewing of any three of the five radial positions. A very sophisticated system that is used on PLT is shown in Figure 14. The most notable feature of this system is that it can simultaneously measure the electron temperature and density at 56 radial positions along a 90 cm diameter through the PLT vessel. The ruby laser output is 2-4 joules and has exceptionally low divergence ($\sim .25$ m rad) so the beam width is only 2 mm along the chord through the plasma. To record the large amount of data required development of a novel spectrometer. The 3 mm x 900 mm laser beam is focused onto an image dissector by a wide angle 25 cm focal length $f/2$ lens with magnification 0.56. The image dissector is made of light pipes. The entrance of the image dissector has 56 elements 1.6 mm wide by 6.3 mm long spaced along the image of the laser beam. Each 6.3 mm segment is rotated 90° and stacked to form a new image 6.3 mm wide by 125 mm high at the output of

the dissector, which is then the entrance slit to the spectrometer. Relay optics carries the image to a diffraction grating and detector. The detector consists of a gated micro-channel plate (MCP) image intensifier and a silicon intensified target (SIT) TV tube. It provides twenty $70\text{\AA}$ wavelength channels for each spatial position from $5500\text{\AA}$ to $6900\text{\AA}$ (quantum efficiency of the S-20 photocathode falls off rapidly above $7000\text{\AA}$ so only the spectral region on the short wavelength side of $6943\text{\AA}$ is observed). The amount of light that can be collected by this spectrometer system is determined by the 40 mm diameter of the MCP. A sample of T_e and n_e radial profiles taken with this instrument on PLT is shown in Figure 15. The very good radial resolution of this diagnostic was useful for identifying hollow T_e and n_e profiles during PLT discharges with a tungsten limiter. The limiters were replaced by graphite and stainless steel for the peaked profiles in Figure 14. Accurate knowledge of the radial T_e profile allows a calculation of the I_ϕ current distribution. This is done by using the measured loop voltage and the neoclassical formula for plasma resistivity, which depends on T_e . From this the surfaces of integer q can be estimated as shown in Figure 14.

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Fig. 13. TMX Thomson Scattering System

Fig. 14. PLT Thomson Scattering System (M. Bretz et. al.
Applied Optics, 17, 192. (1978)

Diagram of the PLT Thomson scattering system.

Fig. 15. Example of PLT Thomson Scattering Data
(I. Eubank et. al., Plasma Phys. and Cont.
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Single-shot electron temperature and electron density profiles from Thomson scattering. Error bars on the points are determined from least-squares fit to the scattered spectrum at each radial position. Solid line through the points is a spline fit to the data. Arrows indicate integral q surface positions.

III.C. Electron Cyclotron Emission

A useful technique that has recently been developed for measuring electron temperature in Tokamaks is electron cyclotron emission at the fundamental or second harmonic. The technique is most useful when the electron cyclotron layer can be shown to radiate as a blackbody, in which case the optical depth $\tau \gg 1$, and under conditions with low runaway electron populations, which can distort the emission spectrum. The emission measurements are generally made along a major radius chord perpendicular to the toroidal field. The specific radiated power per cm^2 per str per unit frequency interval is

$$I(f) = \frac{kT_e}{c^2} f^2 \left[1 - e^{-\tau} \right]$$

where τ is the optical depth of the cyclotron emission layer for a particular mode. For the fundamental $f = f_{ce}$ the optical depths for the ordinary(o) and extraordinary(e) modes are;

$$\tau_o = \frac{\pi^2 R}{c} \frac{f_{pe}^2}{f_{ce}} \left(\frac{kT_e}{mc^2} \right) \left(1 - \frac{f_{pe}^2}{f_{ce}^2} \right)^{1/2}$$

$$\tau_e = 2 \sqrt{2} \pi \frac{R}{c} \frac{f_{ce}^3}{f_{pe}^2} \left(\frac{kT_e}{mc^2} \right)^2 \left(1 - \frac{1}{2} \frac{f_{pe}^2}{f_{ce}^2} \right)^{1/2}$$

where R is the major radius of the Tokamak. Because τ_e contains an

additional factor $\frac{kT_e}{mc^2}$, the condition $\tau \gg 1$ is

most easily satisfied for the ordinary mode. In order to propagate the ordinary mode must satisfy $f_{pe} < f_{ce}$ and for this reason the technique is better suited to tokamaks than mirror plasmas such as TMX. The dependence of $I(f)$ on n and T_e is complex except when $\tau \gg 1$. For $\tau \gg 1$, blackbody conditions obtain and the specific radiated power is linearly related to T_e . Since the cyclotron layer corresponding to a specific frequency defines a surface of constant magnetic field strength, spatial profiles of T_e can be obtained by sweeping the radiation detector frequency as long as the magnitude of B varies significantly in the plasma volume. This works to advantage in Tokamaks where the main toroidal field varies as the inverse major radius coordinate $B_{tor} \sim 1/R$.

If we assume a typical tokamak magnetic field strength $B = 32$ kG, $f_{ce} = 90$ GHz and electron temperature $kT_e = 1$ keV, the specific radiated blackbody power is

$$I(f = 90 \text{ GHz}, T_e = 1 \text{ keV}) = 1.4 \times 10^{-15} \text{ watts/cm}^2 \text{ str Hz}$$

which is quite low so sensitive detectors are needed. The required detectors have been built using millimeter microwave and for infrared technology. The detectors are absolutely calibrated with noise tubes or a blackbody radiating at a known temperature (eg. a mercury arc lamp).

Figure 16 shows a microwave heterodyne receiver used on PLT (Efthimion, et al.) to measure ordinary fundamental emission. The set-up also includes a transmitter klystron on the inside of the torus for transmission

measurements. For emission measurements the transmitter is turned off, the IF bandwidth is increased to $\Delta f = 400$ MHz. The local oscillator is periodically swept from 60 to 90 GHz every 10 msec to obtain radial profiles of T_e .

Figure 17 shows radial profiles of T_e taken throughout an ohmic discharge of PLT. For the conditions of the figure the blackbody condition $\tau \gg 1$ is not satisfied for $r > 20$ cm, whereas the emission seems to be blackbody for all radii. The explanation is that wall reflection from the stainless steel vacuum chamber enhances the emission to blackbody levels. The specific emission corrected for wall reflection is

$$I(f) = \frac{kT_e}{c^2} f^2 \frac{(1 - e^{-\tau})}{1 - be^{-\tau}}$$

where b is the wall reflection coefficient. The measurements suggest $b = 0.95$. The data in Figure 17 compare well with Thomson scattering data at one instant in time. The main advantages of this technique over Thomson scattering are the considerable simplification of hardware and the ability to obtain the time history of T_e on a single shot. Electron cyclotron emission measurements on PLT have also shown the fundamental extraordinary mode is emitted at the blackbody level although the theoretical formula for optical depth would indicate $\tau_e \ll 1$. (J. Hosea, et al., Phys. Rev. Lett., 39, 408, 1977).

Ref. R. Cano, in Diagnostics for Fusion Experiments, E. Sindori, C. Wharton, Eds., Pergamon Press, 1979, pg. 191.

P. Efthimion, et al., Phys. Rev. Lett., 44, 396, 1980.

FIG. 1. Block diagram of the experimental arrangement.

Fig. 17. W_{ce} Emission Profiles of Electron Temperature in PLT
(P. Efthimion et. al., Phys. Rev. Lett. 44, 396, 1980)

III.D. Charge Exchange Analysis

Ion energy in magnetic fusion plasma devices is generally measured at present by one of three methods; analysis of charge exchange neutrals, line width of impurity radiation lines and absolute value of neutron emission intensity. All three of these methods work satisfactorily and in the case of PLT plasmas, where they have been used simultaneously, have been shown to give estimates of ion temperature that agree after various corrections have been made. At present analysis of charge exchange neutrals however has the greatest universality. It works independently of whether hydrogen or deuterium is the majority ion species. Neutrons depend on using deuterium. Impurity line widths require the presence of a certain concentration of impurities which, from the standpoint of reducing radiation loss, it is desirable to minimize. Furthermore the radial location of a particular charge state is dependent on the electron temperature profile.

Charge exchange analysis depends on the existence of a neutral density n_0 in the plasma interior, which however can be quite low ($\sim 10^{10} \text{ cm}^{-3}$) and still give useful results. Plasma ions undergo resonant charge exchange with these neutrals, some fraction of these reach the plasma surface without being ionized and analysis of their energy distribution then gives the distribution of plasma ion energy. The charge exchange reaction rate σv_{cx} is large and relatively insensitive to energy variation, varying between $.4 \times 10^{-7}$ and $1.4 \times 10^{-7} \text{ cm}^3/\text{sec}$ for relative D energy in the range 0.1 keV to 100 keV. Because of the attenuation of neutrals incident on the plasma surface, the neutral density peaks on the edge of the plasma and can fall to very low levels in the interior of large devices. Consequently the emitted

neutrals are weighted toward the plasma surface and can lead to underestimating the ion energy of the interior plasma. With computer models of neutral particle transport however it is possible to correct the data for this effect. Also it has become common to view a region of the plasma where energetic neutral beams are being injected, and these penetrate deeply enough to substantially increase the neutral density in the plasma interior.

Charge exchange analyzers generally consist of a gas stripping cell, tandem magnetic and electrostatic energy analysis to provide mass discrimination, and then several detector channels so an energy distribution can be obtained by simultaneous measurements. In order to obtain useful results it is necessary to calibrate the relative detection efficiency of the different channels as functions of energy with an atomic beam set-up. In some cases an absolute calibration is also made so the analyzer also gives the total neutral flux leaving the plasma surface.

Two examples of multi-channel charge exchange analyzers are shown in Figures 18 and 19. The first is the apparatus used to measure ion temperature on FLT together with the ion source used to calibrate it (S. Davis, et al.). The stripping cell is 10 cm long with .3 cm entrance/exit apertures and operates with He gas at $3 - 12 \times 10^{-3}$ torr. After leaving the stripping cell ions are deflected by a 120° zero order focusing magnet. The energy E_n (keV) of particles in the n-th channel is related to the magnet strength B (kG) by

$$E_n = \frac{1}{20.7 \text{ m}} r_n^2 B^2$$

where $m(\text{AMU})$ is the ion mass and r_n the radius of curvature of the n -th channel (4.0, 5.7, 6.9, 8.0 and 8.9 cm). The channel energies are in the multiples of 1, 2, 3, 4 and 5 times the energy of the lowest channel. After leaving the magnet the ions pass through cylindrical curved plate electrostatic analyzers according to the radial force balance equation $\frac{mv^2}{r} = eE(r)$ where $E(r)$ is the electric field between plates. The ions are detected by channel electron multiplier detectors with their inputs biased negative 3 kV to accelerate the ions and eliminate the drop in detector efficiency at low energy. The detectors are operated in the pulse counting mode (5 to 10 MHz max. count rate). In actual use on PLT the detector outputs are scaled for 1 msec intervals and the data analysis program averages the data over 10 msec intervals. The analyzer has been calibrated from .75 to 40 keV.

Figures 19(a), (b) show the charge exchange analyzer that was used on the 2XIIB mirror machine at LLL (W. Mexsen et. al.), which had parameters similar to one of the TMX mirror end cells described above ($n(0) \approx 10^{14} \text{ cm}^{-3}$, $E_i = 12 \text{ keV}$, $T_e = 100 \text{ eV}$). Since the ions in a mirror machine do not have a Maxwellian distribution like tokamaks, where a straight line fit to the high energy tail of $\log F(E)$ suffices to determine T_i , it is desirable to have a larger number of channels. The analyzer in Fig. 19(a) has fifteen channels with the lowest normally operating at 0.5 keV and the highest at 40 keV. Also, since the pulse length of the experiment is 10 to 25 msec it is desirable to have greater time resolution than the PLT analyzer described above. The stripping cell is 28 cm long with .95 cm diameter apertures and is operated at $0.5 \times 10^{-3} \text{ Torr } N_2$. Ions leaving the stripping cell enter a magnet with a 15 cm radius pole face. The energy E_n (keV) of ions in the n -th channel is related to deflection angle θ_n by

$$E_n = \frac{1}{20.7 \text{ m}} B^2 R^2 \cot^2 \frac{\theta_n}{2}$$

where $B(\text{kG})$ is the magnet field strength, $R(\text{cm})$ the effective radius of the pole face and m (AMU) the ion mass. The channels occur at 4.5° intervals from 18° to 54° and at 9° intervals from 54° to 108° . After leaving the magnet, ions enter one of fifteen electrostatic analyzer-detectors shown in Fig. 19(b). The electrostatic analyzers are 90° deflection parallel plate type with ion energy E related to deflection plate voltage V_p by $E = (x/2d)V_p$ where $d \approx 7.7 \text{ cm}$ is the plate separation and $x = 19.7 \text{ cm}$ is the distance between entrance and exit apertures. The detectors consist of secondary electron emission cups biased at negative 18 kV to accelerate the ions, aluminized plastic scintillators where the secondary electrons deposit their energy and photomultiplier tubes. The detectors can operate in a pulse counting mode but are generally run in the current mode. The detector outputs are digitized at 100 kHz by transient recorders. It will be noted that in Fig. 19(a) there is also a single channel auxiliary analyzer. This analyzer was absolutely calibrated with an atomic beam apparatus and used as the standard to calibrate the fifteen channels of the multi-channel analyzer.

The stripping cell efficiency for the analyzers shown in Fig. 19(a) falls to about 0.2% at 0.5 keV and this is about the lower energy limit for which gas stripping cells can be used. Since in EBT it is desirable to obtain accurate measurements below 0.5 keV, a special cesium heat pipe charge exchange cell was developed for that experiment. In this case the

incident hydrogen neutrals pick up an electron from the cesium and negative ions are analyzed. Figure 20 shows a comparison of the efficiencies of the cesium cell and an N_2 stripping cell. At 100 eV the cesium cell is more than two orders of magnitude more efficient than the gas stripping cell.

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Fig. 18. PLT Charge Exchange Analyzer (S. Dav's et.al., PPPL-1478)

Fig. 19(a). 2XIIB Charge Exchange Analyzer (W. Nexsen et.al., RSI, 50, 1227, 1979)

Fig. 19(b) Detail of electrostatic analyzer and detector for the charge exchange analyzer in Fig. 19(a)

Fig. 20. Comparison of Nitrogen and Cesium Cell Efficiencies
(R. Dandl et.al., ORNL/TM-6457).

Efficiency of nitrogen stripping cell and cesium heat pipe charge-exchange cell as a function of incident neutral particle energy in geometry used for ion temperature measurements.

IV. Some Additional Diagnostics

- A. Soft X-Rays
- B. VUV Spectroscopy
- C. Heavy Ion Beam Probe
- D. Bolometry
- E. End Loss Analyzer

IV.A. Soft X-Rays

Soft x-rays ($1 \rightarrow 10$ keV) and ultra-soft x-rays (100 eV $\rightarrow$ 1 keV) are an extremely versatile diagnostic for fusion plasma devices with electron temperature exceeding several hundred eV. Usually this radiation region is dominated by the impurity recombination radiation continuum and the $K\alpha$ lines of metals Fe, Cu, Ni etc. present in the discharge as impurities, although the bremsstrahlung radiation continuum is also present. Since the recombination and bremsstrahlung continuum are proportional to $\exp(-h\nu/kT_e)$, the slope of a semi-log plot of radiation intensity versus x-ray energy $h\nu$ gives a measurement of electron temperature. The enhancement of the continuum above that for a pure hydrogen plasma gives an estimate of $Z_{\text{eff}} = \sum_i n_i Z_i^2 / n_e$ which characterizes the overall impurity content of the plasma. Measurement of the Doppler widths of the metallic $K\alpha$ lines with a high resolution crystal spectrometer yields estimates of the ion temperature. Finally, since the radiated x-ray intensity depends on density n_e , electron temperature T_e , and the effective charge composition of the plasma Z_{eff} , it is sensitive to fluctuations of these quantities and may be used to study MHD instabilities.

An example of a pulse height x-ray detector system used on PLT (S. von Goeler) is shown in Fig. 21. The system consists basically of a set of lead collimation holes and four lithium drifted silicon surface barrier detectors cooled to liquid nitrogen temperature. X-rays stopping in the detectors create a number of electron-hole pairs proportional to their energy and sorting these with a pulse height analyzer gives the x-ray

spectrum from approximately 2 to 13 keV. Four detectors are used to maintain high counting rates in the low energy region but avoid distortion of the high energy tail by pulse pile up. Foils that absorb the low energy region x-rays are placed in front of the detectors used to measure the high energy x-rays. The set-up also includes a hot electron emitting filament and target for calibrating the system with the characteristic $K\alpha$ line radiation.

Figure 22 shows an example of the illustrative data that can be obtained about MHD instabilities by observing the total x-ray emissivity along chords through the plasma. The example is from PLT (N. Santhoff et al.). The detector array used in this case differs from that shown in Fig. 21 since the primary aim is to obtain space and time information. Twenty silicon surface barrier detectors viewed the plasma through a single slot, forming a kind of pinhole camera. The output current from the detectors is digitized at up to 1 MHz. The chordal averaged data are then inverted to give local emissivity (N. Santhoff et al.). Contour and three dimensional plots of emissivity are shown in Fig. 22 at one instant in time preceding a "minor disruption." An $m = 2$ island structure is clearly displayed and thought to be due to a tearing mode instability that forms on a rational q surface, in this case $q = 2$. A side benefit of this analysis is that the radial position of the $q = 2$ surface is accurately determined and thus gives accurate information on the internal current distribution that can be compared with q profiles estimated from Thomson scattering.

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Fig. 21. (from S. von Roeler in "Diagnostics for Fusion Experiments" Pergamon 1979)

Fig. 22. (from N Sauthoff et.al.,
Nucl. Fusion, 18, 1445. 1978)

FIG.7a. Contours of equal X-ray emissivity for the $m = 2$ mode.

FIG.7b. Three-dimensional plots of emissivity within a cross-section, viewed from four different angles.

IV.B. VUV Spectroscopy

Vacuum ultraviolet spectroscopy ($100 \text{ \AA}$ to $2000 \text{ \AA}$) is useful for studying the concentration of charge states of the light elements and the low ionization states of heavier elements. Table 7 lists the wavelengths of the strongest transitions of C, N, and O. An example of a recently developed VUV spectrometer (R. K. Richards, et al.) is shown in Fig. 23. The spectrometer uses a normal incidence 0.4 m concave diffraction grating. Pinhole imaging through the entrance slit of the spectrometer provides spatial imaging at the detector. The detector is fabricated from two micro-channel plates backed by a 22 segment anode so that information is accumulated simultaneously on 22 chords through the plasma. The anode signals are processed by close coupled pulse amplitude discriminators and scaled in a multi-channel counter. The maximum count rate of a single channel is $2 \times 10^6 \text{ Hz}$ with the gain set at 1×10^5 so reasonable statistics can be obtained with $100 \text{ } \mu\text{sec}$ gating time. This instrument is therefore capable of producing time resolved spatial profiles of a particular impurity line which should make it a very flexible tool for studying the radial transport of impurities. The efficiency of the detector alone is about .09. The efficiency of the complete spectrometer is 10^{-3} at $400 \text{ \AA}$ and falls to 6×10^{-5} at $1200 \text{ \AA}$. The quantum efficiency of the detector decreases rapidly above $1250 \text{ \AA}$ while decrease in reflectivity of the grating sets the lower limit at $300 \text{ \AA}$. The entrance and exit slits of this spectrometer are normally set for $1 \text{ \AA}$ resolution.

Figure 24 shows a layout of a VUV spectrometer used on EBT. Since this is a steady state plasma device, adequate spatial profiles are obtained with a single detector and scanning mirrors. Figures 25(a) and (b) show three dimensional plots of the emissivity of AlI and AlII. The vacuum vessel of EBT is made of Al. The impurity ion densities in EBT are typically very low, the density of AlII is $5 \times 10^7 \text{ cm}^{-3}$ at the center of the toroidal plasma with $n_e \approx 1.5 \times 10^{12} \text{ cm}^{-3}$.

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R. K. Richards, et al., Rev. Sci. Inst. 51, 1 (1980).

Table 7. Wavelengths of Strongest Transitions of C, N, and O.

Charge State	λ (Å)		
	C	N	O
I	1657	1200	1302
II	1336	1086	834
III	977	992	835
IV	1548	765	790
V	41	1239	630
VI	34	29	1032
VII		25	22
VIII			19

Fig. 23. Multi-channel imaging VUV Spectrometer (from Richards et.al., RSI, 51, 1, 1980)

FIG. 1. The imaging process using the concave grating monochromator. EUV light rays from points A and B in the plasma pass through the entrance slit, are diffracted to the exit slit by the grating, and then fall on points A' and B', respectively, along the detector. The dispersion direction is in the plane of the figure.

FIG. 2. Detector cross section. See text for detailed description.

Geometry used for spatial scanning of uv light from plasma in the midplane of EBT-1. Distance along light path to spectrometer focussing mirror is 2.75 m.

Fig. 25(a).

Al I Emission from from EBT-I (from Dandl et.al.,
ORNL/TM-6457)

Light intensities from Al I at $\lambda = 2151 \text{ \AA}$ as a function of angle of view (θ) from top (RCY) and side (RCX) ports (dotted line - observed solid line - reconstructed). Lower drawing is reconstructed emission distribution in midplane calculated using iterative algebraic reconstruction technique.

Fig. 25(b). Al II Emission from EBT-II, (from Dandl et.al., ORNL/TM-6457)

Light intensities from Al II at $\lambda = 1671$ Å and reconstructed emission distribution in the midplane calculated using iterative algebraic reconstruction technique.

IV.C. Heavy Ion Beam Probe

Although the first application of the heavy ion beam probe technique to a fusion plasma device was on the ST tokamak at Princeton the most recent applications have been plasma space potential measurements on EBT-I and TMX. The fundamental relationship of the space potential to the physics of the later two devices makes this a very important diagnostic. The basic idea of using a heavy ion beam to measure space potential is indicated in Figure 26. A singly ionized heavy ion (K^+ , Rb^+ , Cs^+ , Tl^+) is injected perpendicular to the main magnetic field of the experiment. As the ions proceed through the plasma a certain fraction becomes doubly ionized by electron impact ionization. As a result they leave the plasma with an energy $e\phi_p$ greater than the initial beam energy W_b where ϕ_p is the plasma potential at the ionization point. Measuring the energy $W_b + e\phi_p$ of the doubly ionized beam at the detector and comparing it to the primary beam energy W_b gives the space potential ϕ_p . Fixing the beam energy, angle of injection and detector position defines the spatial volume element of measurement. By varying the beam energy and injection energy, the space potential of the plasma cross section can be mapped out.

The beam voltage V_b of a singly ionized heavy ion of mass m_i is related to the local radius of curvature ρ_i and magnetic field strength B by:

$$V_b = \frac{1}{2} \frac{e(B\rho_i)^2}{m_i c^2}$$

Since the primary beam must cross the minor diameter, ρ_i must be of the order of the minor radius of the device. As B and the size of machine increases this leads to higher beam voltages that are somewhat compensated by choosing an ion of heavier mass. Nevertheless it generally works out that one is measuring plasma potentials ϕ_p of the order of a few tenths of a percent of V_b . As a consequence the detector schemes developed by the Rensselaer group have high resolution and are feedback regulated to the ion beam extraction voltage to obtain accurate results. The intensity I^{++} of the secondary beam is related to the intensity I^+ of the primary beam by

$$I^{++} = I^+ n_e l \frac{(\sigma v)_{ei}}{v^+}$$

where n_e is the electron density, $(\sigma v)_{ei}$ the electron impact ionization rate, l the length of beam path viewed by the detector and v^+ the beam velocity. As a result it is in principle possible to obtain additional information on the spatial profile of n_e and electron temperature by heavy ion beam probing. This task is more difficult than the ϕ_p measurement however so most often it is only the ϕ_p information that has been obtained.

Figure 27 shows the general layout of the ion beam probe used on EBT-I (Colestock, et al.). Figure 28 shows typical scans of ϕ_p in orthogonal directions on EBT-I and a derived contour plot. The upshot of these results is that the ambipolar electric field on EBT points radially inward. This causes cancelation of the ∇B poloidal drift of ions in the tail of the distribution, causing a small fraction of the ions to diffuse more rapidly

than the bulk population. As a result a negative space potential builds up in the center to balance this ion loss with the electron loss rate. To obtain these results the energy of the Rb^+ beam was varied from 8 to 30 keV while the magnitude of space potential is of the order 100 V. The maximum space potential is of the order of twice the ion temperature T_i and about equal to the electron temperature for the EBT mode of operation shown in Figure 28.

A similar heavy ion beam probe setup developed by Rensselaer (G. Hallock, R. Hickok) in collaboration with the TMX group is shown in Figure 29. The ion probe is set up in the center cell section of TMX. Comparison of the potential measured by this probe with the space potential of the mirror end plugs gives the depth of potential well confining the ions in the center cell. The mirror end plug potential is measured with gridded end loss analyzers described below. A complication of TMX compared to EBT is that TMX is a pulsed experiment, so greater time resolution is required. An example of some TMX data is shown in Figure 30 with the beam scanned radially through the plasma on successive shots. The data shown indicate a positive 300 volt space potential near the center of the plasma.

- Ref. P. Colestock, et al., Phys. Rev. Lett., 40, 1717, 1978
F. M. Bicniosek, et al., Rev. Sci. Inst., 51, 206, 1980.

Fig. 26- (from R. Dandl, et al ORNL/TM-6457)

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Schematic drawing showing path of injected Rb^+ ions and orbits of secondarily ionized Rb^{++} ions from various points along beam path.

Fig. 27. (Ref. R. A. Dandl, et al, Oak Ridge National Laboratory Report No. ORNL/TM-6457, 1978).

General layout of heavy-ion beam probe system used in EBT-I. Secondary detector is a graded-field, parallel plate energy analyzer.

Fig. 28 (from Phys. Rev. Lett., 40, 1717 1978).

Space potential measured in EBT-I as a function of position in the midplane (T-mode conditions). The computer-generated perspective view includes data taken at various energies and angles of beam incidence and then "spline-fits" the data to present the smoothed display. No data is taken outside the points where the maximum potentials are found.

Fig. 29. (From DKK).

Fig. 30. (From TXX).

Radial profile of center-cell potential measured by HIBP.

IV.D. Bolometry

Although most of the material presented thus far has involved rather sophisticated instrumentation, there are many instances in plasma physics where important information can be gained with simple setups. Two of these -- bolometry to measure radiated power and a gridded end loss analyzer to measure current escaping along open field lines of a mirror machine -- are described briefly in these last two sections. In some ways it would have been intriguing to develop just how far one can go with diagnostics of this level of sophistication, but it would probably give too limited a viewpoint for an introductory survey lecture.

Except for the magnetic energy that gets dumped back into the external circuitry of a tokamak, all of the energy that goes in winds up in two places -- on the limiter or on the vacuum wall. Power that is lost by cross field transport winds up on the limiter and power lost by impurity radiation and charge exchange goes to the wall. Thermocouples are used to measure the temperature rise of the limiter and bolometers measure power radiated to the wall.

Figure 31 shows a schematic of a bolometer constructed for the ATC tokamak (Hsuan, et al). Colimated arrays of similar detectors are in use on PLT. The bolometer consists mainly of a nickel foil disk 3 cm in diameter and 25 microns thick. A lightweight thermistor ("thinistor" manufactured by VECO) is mounted on the back to measure the temperature rise. The nickel foil is sandwiched between two copper rings making good thermal contact to the foil. Ten layers of electroformed Ni mesh with concentric holes cut to fit the transparency of the zeroth order Bessel function, which is the

lowest thermal mode of a circular disk, mask the front of the disk. In this way the time behavior of the disk is predominantly that of the fundamental mode. For this particular design the resolving time was less than 5 msec and the decay time of the lowest mode was 2 sec. The bolometer then integrates the total radiated energy during a plasma shot and the instantaneous power can be obtained by differentiation.

Figure 32 shows some data taken during discharges in PLT with a scanning bolometer (i., Bol. et al). The data have been Abel inverted to obtain the total radiated power out to a radius r , and are compared to the Ohmic heating power at the same radius. The data show the effect of gettering with graphite limiters. With no gettering $Z_{\text{eff}} = 3.8$, the radiation loss is confined to the edge and rises to about 80% of the ohmic heating power. With gettering Z_{eff} drops to 1.0 and the radiated power is less than half the ohmic heating power.

Ref.: H. Hsuan, et al, Nucl. Fusion, 15, 657 1975

K. Bol, et al., Proc. 7th Int'l Conf. on Controlled Nuclear Fusion, Innsbruck, 1978 (IAEA, Vienna, 1979), vol. 1, 11.

Fig. 31. Schematic of ATC Bolometer (from Hsuan, et al, Nucl. Fusion, 15, 657, 1975).

Comparison of Ohmic input power and bolometric measurements. Power is integrated from center to radius r . Ohmic power $P_{\text{Ohm}}(r)$ deduced from Thomson scattering profiles of electron temperature and density. P_{NAB} from Abel-inverted profiles obtained with narrow-angle scanning bolometer.

(a) Typical for ungettered discharges with carbon or steel limiter. Limiter carbon.

(b) Gettered, carbon limiter

(c) Gettered, carbon limiter

(d) Same discharges as (c) during neutral injection with 2.2 MW, commencing at 450 ms

IV.E. End Loss Analyzer

In a linear machine such as TMX the input power is either radiated to the wall, strikes limiters that may be present near the mirror throats or escapes along field lines to the end walls. Calorimeters and gridded analyzers may be used to conveniently measure the end loss. Figure 33 shows a schematic of an electrostatic gridded end loss analyzer presently in use on TMX (D. Grubb, A. Molvik). It consists basically of four grids and a plane collector plate. The first two grids are grounded, the third grid is ramped positive to measure the ion energy spectrum and the fourth grid is biased negatively to repel electrons from the plasma and suppress secondary electrons emitted from the collector. The collector measures the ion current that passes over the barrier of the ion repeller grid. Since the end mirrors of TMX have positive potential ϕ (Fig. 3) one expects that ions flowing into the analyzer will reach the collector until the bias on the suppressor exceeds ϕ . Sweeping the voltage on the ion repeller and looking for the break in ion collector current then gives a valuable estimate of the plasma potential ϕ at the end mirrors. Combined with the heavy ion probe measurement of the center cell potential ϕ_e , the difference $\phi - \phi_e = \phi_i$

is the potential barrier height confining ions in the center cell of TMX. The grid spacing in Figure 33 has been chosen to be less than the Debye length $\lambda_D = \sqrt{\frac{kT_e}{4\pi n e^2}}$ of the flowing plasma, and the biased grids are double grids to reduce the tendency for potential holes between grid elements. The spacing between grids is chosen to avoid space charge saturation with the anticipated current densities. Typically the current density at the analyzer is 3 mA/cm^2 . Figure 34 shows typical data

obtained with the end loss analyzer. Initially the ion repeller voltage is zero and the currents large. The ion repeller voltage is then swept repetitively and the modulation of the ion current is evident. The ion current density in Figure 34 is referenced to the center of mirror end cell where $B = 10$ kG, and is 154 times higher than the actual measured current density at the detector where $B = 65$ G. The plasma potential ϕ of the mirror end cell plasma and an estimate of the ion temperature of the streaming plasma deduced from this data are shown in Figure 35. Figure 36 shows the potential measured by the end loss analyzer and the thallium beam along with some other data. It is apparent that there is a 300 volt difference in potential between the center cell and end mirror, although the measurement errors are rather large.

V. Concluding Remarks

In these notes an attempt has been made to give an overview of current practices in magnetic fusion diagnostics. As is evident from some of the examples chosen great progress has been made obtaining spatial and temporal information on a single shot and more is sure to come with larger machines on the horizon. Unfortunately because of lack of time in preparing these notes some important topics were left out. Particularly I would have liked to include some information on neutron detection, the use of collective scattering in the small α limit to obtain information on plasma fluctuations and an outline of requirements for digital acquisition and computer reduction of data.

The examples that I chose to discuss are weighted toward the largest machines. There are of course many devices in the magnetic fusion program that are smaller and more exploratory. In these cases it is well to weigh carefully the complexity of diagnostic that is warranted and not let it overwhelm the basic goal of finding a new and worthwhile operating regime.

In the preparation of this review I chose freely from the research efforts of a large number of ingenious and dedicated people to whom I am grateful. Hopefully these cursory notes will inspire obtaining a deeper understanding by reading the original references.

Electrostatic end-loss analyzer.

End-loss current versus time; the ion repeller voltage is swept.

Fig. 35. (from TMX).

Time resolved measurement of plug potential and center-cell ion temperature.

Fig. 36. (from F. Goensgen, et al., Phys. Rev. Lett., 44, 1132, 1980.)