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Columbia University
in the City of New York

SPECTROSCOPIC STUDY OF TURBULENT HEATING
IN THE HIGH BETA TOKAMAK - TORUS II

by

George E. Georgiou

1979

Research supported by DOE Contract EY-76-S-02-2456

Plasma Laboratory

School of Engineering & Applied Science

Columbia University

New York, N.Y. 10027

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George E. Georgiou

Submitted in partial fulfillment
of the requirements for the degree of
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Columbia University

1979

ABSTRACT

SPECTROSCOPIC STUDY OF TURBULENT HEATING

IN THE HIGH BETA TOKAMAK- TORUS II

George E. Georgiou

Visible spectroscopy, involving line profile and line intensity measurements, was used to study the turbulent heating of the rectangular cross-section high-beta tokamak Torus II. The spectroscopy was done in the visible wavelength region using a six channel polychrometer having $0.2 \text{ \AA}$ resolution, which is capable of radial scans of the plasma. The plasma, obtained by ionizing helium, is heated by poloidal skin currents, induced by a rapid ($\tau_R \sim 1.7 \text{ \mu sec}$) change of the toroidal magnetic field either parallel or anti-parallel to the initial toroidal bias magnetic field, which converts a cold toroidal Z-pinch plasma into a hot tokamak plasma. In anti-parallel operation, line broadening of Helium II $4686 \text{ \AA}$ and impurity lines (silicon and oxygen from the glass vacuum vessel walls) indicates that strong turbulence ($\tilde{E} \sim 30 \text{ kV/cm}$ microscopic plasma wave electric field at frequency $\omega \sim \omega_{pi} \sim 3 \times 10^{10} \text{ rad/sec}$ for 25 GW anti-parallel heating power), possibly of ion-acoustic origin, develops during the heating phase. The turbulent $\tilde{E}$ -fields maximize in the region of maximum induced poloidal skin current ($\propto \partial B_T / \partial R$). The resulting high-

beta tokamak plasma, with $\langle \beta \rangle_V \sim 10\%$ and $n_e \sim 10^{15} \text{ cm}^{-3}$, has an initially peaked radial ion temperature profile ($T_i \sim 180 \text{ eV}$ at the plasma center for 25 GW anti-parallel heating power). Within $\sim 10 \text{ } \mu\text{sec}$, the He II-determined ion temperature becomes nearly spatially flat ($T_i \sim 75 \text{ eV}$) and then decreases slowly in time. T_i and E scale roughly as the anti-parallel bias heating power. However, the frequency of the turbulence increases at lower ($\sim 12 \text{ GW}$) anti-parallel heating power. In parallel bias field operation, the induced skin current is lower by roughly a factor of 5 and measureable turbulence does not develop. The He II-determined ion temperature at 25 GW parallel heating power is comparable to that at 12 GW anti-parallel operation. The measured line profiles also indicate a macroscopic poloidal circulation of the plasma ions, which is charge and mass independent, and is possibly due to an $E_r \times B_T$ drift. The macroscopic radial electric field $E_r \sim 100 \text{ V/cm}$ is strongest at the plasma edges corresponding to a poloidal rotation which vanishes at the plasma center. Electron temperature was determined from impurity ionization rate, line-to-continuum, and X-ray flux measurements and was found to be the same as T_i during the high beta equilibrium phase (after heating is completed). The impurity ionization rates also indicate $\sim 1\%$ silicon and $\sim 2\%$ oxygen impurity concentration; impurity line radiation accounts for most of the observed plasma cooling on a 15 μsec time scale. Details of turbulent heating derived from the analysis of

ion line profiles are found to be consistent with theories describing heating from ion acoustic turbulence. The spectroscopically observed turbulence level can be used to estimate that the plasma electrical resistivity due to turbulence should be ≈ 100 times the classical Spitzer value; this is consistent with experimental values obtained with magnetic field probes. The level of ion-acoustic turbulence can be used to predict theoretically an ion heating rate which agrees with experiment.

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This dissertation is dedicated to my parents.

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I. INTRODUCTION

In recent years, tokamak devices^{1,2,3} have made considerable progress in the areas of plasma heating and stability to become one of the major programs for developing fusion power reactors. One major difficulty in their exploitation as fusion power generators is their low beta. The plasma beta is defined as the ratio of the plasma energy ($n_i kT_i + n_e kT_e$) to the magnetic field energy ($B^2/8\pi$) in the same plasma volume, and is a measure of the capability of a given magnetic configuration to contain plasma. Because of the equilibrium magnetohydrodynamic condition of pressure balance, most magnetic configurations have $\beta \lesssim 1$. Furthermore, β is important for the reason that fusion power output in a magnetically confined system is proportional to the square of beta.⁴ Contemporary tokamaks have $\beta \sim 1\%$ ($n_e \sim 10^{13} \text{ cm}^{-3}$, $T_e \sim 1 \text{ keV}$, $B \sim 25 \text{ k Gauss}$): i.e., the energy used in confinement is 100 times the plasma energy.

For a circular cross-section tokamak configuration, the plasma volume averaged β can be written as⁵

$$\langle \beta \rangle_V = \frac{I}{A j_{\phi 0}} \frac{1}{q_0^2} \frac{A}{\pi R_0^2} \beta_p$$

where I is the toroidal plasma current, A is the poloidal cross-section area, $j_{\phi 0}$ is the current density on the magnetic axis (minimum magnetic field), q_0 is the safety factor on the magnetic axis, R_0 is the major radius of the magnetic axis and the poloidal beta $\beta_p \equiv 8\pi \langle p \rangle / B_p^2$ and p is the plasma pressure. The safety factor q is a measure of magnetic rotational transform: i.e., $q = r B_T / R B_p$, where r is the minor radius, B_T is the toroidal magnetic field and B_p is the poloidal magnetic field.

Typically, there are two equilibrium models for the solution of the magnetohydrodynamic equations in tokamak geometry. These correspond to low beta conventional tokamak and high beta tokamak expansions. In the conventional tokamak expansion, the plasma does not affect the vacuum toroidal magnetic field, $B_p / B_T \approx \epsilon$, $\beta_p \approx 1$ and $\beta \approx \epsilon^2$, where ϵ is the inverse aspect ratio, $\epsilon \equiv \frac{a}{R_0}$, and a is the plasma radius. This is similar to a Z-pinch in which the poloidal magnetic field confines the plasma and the toroidal magnetic field is used for stability. The high beta tokamak expansion uses a jump in the toroidal magnetic field across plasma surface $\approx \epsilon$, $B_p / B_T \approx \epsilon$, $\beta_p \approx \epsilon^{-1}$ and $\beta \approx \epsilon$. This is typical of a θ -pinch in which the toroidal magnetic field provides both plasma confine-

ment and stability. The small poloidal magnetic field ($B_p < B_T$) in the high beta tokamak expansion is provided to lessen the toroidal plasma drift to the machine wall.

Stability of the plasma equilibrium against a given type of instability places restrictions on each of four parameters in $\langle \beta \rangle_V$.⁵ Typically, instabilities can be classified by mode numbers. Perturbations of the type $\exp[i(n\phi + m\theta)]$ are considered where n is the toroidal mode number, i.e., the number of periods a disturbance has in going once around the toroidal direction $\phi \rightarrow [0, 2\pi]$, and m is the poloidal mode number, i.e., the number of periods a disturbance has in the poloidal cross-section $\theta \rightarrow [0, 2\pi]$. The mode numbers, n and m , are restricted to integer values because of periodicity constraints on the toroidal and poloidal angles ϕ and θ . Stability of the plasma can be considered by calculating the change in potential energy of the plasma-magnetic field system, δW , produced by a given perturbation. The plasma is stable against this perturbation if $\delta W < 0$.

Stability of kink modes ($m = 1$ distortions of the plasma) requires $dj_\phi/dr < 0$ and $q > m/n$ or a region of zero current of thickness $\delta \sim \frac{a}{2m}$ at the surface of the plasma ($r = a$). Stability of internal ideal modes requires $q > 1$ everywhere within the plasma. Thus, ideal low mode number instabilities can be stabilized and low beta tokamaks operate with parabolic current density profiles with $q_0 \sim 1$ and q_a (q at the plasma edge) ~ 4 .

One method to increase β is to elongate the cross-section, i.e., use the third factor in $\langle \beta \rangle_V, A/\pi R_0^2$, and increase the poloidal cross-section area, A , by making the plasma non-circular. Ideally, the gain in β of the elongated cross-section over the circular cross-section is simply the ratio of the two areas. However, plasma stability restricts the stable (critical) β .⁶ Very elongated cross-sections are unstable to axisymmetric modes ($n = 0$ corresponding to vertical shift perturbations of the plasma). Elongation also increases the stability requirement from $q > 1$ for circular cross-sections to $q > 2/(2-\beta)$. As a result, for a doublet cross-section, the critical β is a factor of ~ 2 higher than the circular cross-section for an optimized height to width ratio ~ 4 and aspect ratio (R_0/a) ~ 3 . For elliptic cross-sections, the optimized shape has a major to minor radius ratio ~ 2 , aspect ratio ~ 3 and a gain in β of a factor of 2 above the circular cross-section. Typically, maximum stable β is $\sim 10\%$. In the higher β cases, the mode structure of unstable MHD waves is a combination of kink modes and "ballooning modes."

"Ballooning modes" characteristically appear at the outer region (larger major radius) of the plasma where magnetic field curvature is unfavorable, i.e., bowed outward. As β increases, the increased potential energy of the plasma causes a bending of the magnetic field lines. Ballooning modes become stable when the energy increase of

the plasma is less than the energy increase of the bending field lines,⁵ i.e.:

$$r \frac{d\beta}{dr} < C \frac{r}{R} \left(\frac{2\pi R}{\ell} \right)^2 \quad C \approx 1$$

where ℓ is the length over which the magnetic field lines bend. Consequently, stability is a function of shear (dq/dr) and pressure gradient (dP/dr).

Since the tokamak configuration can be stabilized with regards to low beta instabilities, it is believed that the stable beta limit of a tokamak will be determined by instabilities of "ballooning mode" nature. Recent theoretical calculations^{8,9} have predicted the existence of an MHD stable high beta parameter zone. These calculations were mostly for an ideal non-resistive model plasma. Even though the behavior of resistive modes at high beta, collisional and finite Larmor radius effects on ideal and resistive modes, and elongation effects are uncertain, these predictions give encouragement to further theoretical and experimental study of high beta configurations.

High beta plasmas have been formed in pulsed experiments. In the Garching Belt Pinch IIa,⁶³ elongated cross-section plasmas with β between 10% and 80% ($T \approx 100$ eV, $q_a \approx 3.5$) have been contained for ~ 45 MHD instability growth times. The toroidal screw pinch SPICA⁶⁴ at Jutphass was able to maintain peak $\beta \approx 20\%$. ($T \approx 60$ eV,

$n \sim 5 \times 10^{15} \text{ cm}^{-3}$) for $\sim 100 \mu\text{sec}$ (~ 40 MHD instability growth times). The existence of force-free currents ($\mathbf{j} \times \mathbf{B} = 0$, current parallel to magnetic field) in the dilute plasma edges was observed and may have been responsible in part for the high beta stability. Torus II⁷ has observed gross stability for $\sim 35 \mu\text{sec}$ (~ 30 MHD instability growth times) with peak $\beta \sim 30\%$ and plasma volume average $\langle \beta \rangle_V \sim 10\%$. The Torus II plasma resembles somewhat the TEE experiment at Julich⁶⁵ and the STP experiment at Nagoya⁶⁶ in respect to the use of rapid heating by a pulsed-power system. However, these devices have circular cross-section, lower density and positive toroidal bias fields.

In the Columbia University Torus II machine, a cool toroidal Z-pinch* plasma is transformed into a hot, high beta tokamak magnetic configuration and heated within a few microseconds by the application of a strong ($\sim 1 \text{ kV/cm}$), fast rise time ($\tau_R = 1.7 \mu\text{sec}$) poloidal electric field arising from a rapid change in the applied toroidal magnetic field. The rapid change in the toroidal magnetic field drives dissipative skin currents in the plasma, thereby heating the plasma. The Torus II machine is described in further detail in the first section of Chapter II of this thesis.

In devising a heating scheme for preparing the high

* The toroidal Z-pinch is characterized by $B_p \sim B_T$, $q_0 < 1$ and is unstable to kink modes.

beta tokamak Torus II, we considered several possible modes of heating. One possible heating method for a pulsed experiment is fast compression, typical of θ -pinches, resulting in a $\beta \sim 1$. However, β drops quickly on a microsecond time scale because of the anomalous transport¹⁰ of the over-compressed state. Another possible heating scheme is Joule heating: i.e., the resistive dissipation of an induced plasma current. With classical resistivity, the heating rate is of millisecond time scale and is too slow to overcome radiative power losses from the plasma in a pulse experiment; accordingly, classical ohmic heating restricts operation to $\beta_p \sim 1$. With the induction of anomalous resistivity ~ 100 times classical, classical Joule heating is enhanced and the heating rate becomes of microsecond time scale. By applying a strong transverse electric field, the electrical resistivity increases¹¹ as E_θ^ℓ where $\frac{1}{2} < \ell < 2$. The applied electric field induces a skin current transverse to the toroidal magnetic field. In this skin region, the current density, j , may be sufficient to give the electrons a drift velocity $V_d = j/ne$ greater than the local ion sound speed, C_s . When $V_d > C_s$, microturbulence develops^{12,13} and results in an enhanced electrical resistivity^{13,14} and heating.¹⁵

The use of turbulent heating is a relatively well explored subject^{16,17,18} and its application to Torus II has been numerically studied,¹⁹ yielding encouraging results. It is of particular value since it provides a way

to alter the magnetic geometry and increase the plasma energy density in a time scale short compared to typical MHD instability growth times. Since the instabilities driven by the turbulence are microinstabilities, the plasma can be confined in a suitable magnetic trap, in our case the tokamak configuration of Torus II.

Turbulence manifests itself in a spectrum of driven plasma waves and their associated large amplitude plasma wave electric fields. These turbulent fields are observed in this thesis through the measurement of ionic line profiles of Helium II 4686 Å and plasma impurities. These line profiles are presented and discussed in Chapter IV for various operating modes of Torus II. After analysis of these line profiles, turbulent electric fields ~ 30 kV/cm are typical during rapid heating. The analysis of these line profiles makes use of previously developed theories of plasma wave electric field effects on radiating hydrogen-like ions^{20,21,22} and parallels previous experimental work.^{16,23,24} The ion-plasma wave interaction effects on radiated line profiles will be discussed in Chapter III. (Mathematical derivations of these theories will not be included in this thesis for the reason that these derivations are available in the referenced literature. and no modification of these theories was made to allow for the interpretation of the line profiles observed in the Torus II experiment.) Recent experiments involving the induction of turbulence, and using line profile mea-

surements as a diagnostic---mostly using the plasmas of a linear θ -pinch or an electromagnetic shock wave apparatus---will be briefly discussed in Chapter III.

After the turbulence decays and the high beta tokamak plasma is formed, the radiated line profiles are determined by Doppler broadening and the plasma ion temperature can be obtained. These ion temperature results will be presented in Chapter IV, again for the various operating modes of Torus II. Typically, the central plasma ion temperature was ~ 100 eV. Impurity line profiles are also presented in Chapter IV for comparison with the helium profile determined ion temperature.

During the high beta tokamak phase, the ions and electrons should have equilibrated in temperature since the ion-electron equilibration time ~ 5 μ sec for Torus II.²⁵ Therefore, to provide a comparison for the ion temperature determined from ion line profiles, the electron temperature was estimated spectroscopically by several methods: impurity ionization rates,^{26,27} line to continuum intensity ratios,^{28,29} and soft X-ray flux.³⁰ The results of these electron temperature measurements are presented and discussed in Chapter V. (A brief discussion of the physics involved in the theory of the measurement is also given. Mathematical derivations are again omitted since they are adequately discussed in the literature cited.) Approximately equal ion and electron temperatures also give confidence in the Doppler broadening measurements.

In the final chapter, Chapter VI, the spectroscopic observation of turbulent fields is related to the spectroscopic determinations of temperature: i.e., we discuss the turbulent heating mechanisms involved in the Torus II experiment. The enhanced electrical resistivity is related to the level of turbulence (the ratio of the plasma wave electric field energy to the plasma particle energy) through the increase in the effective particle collision frequency produced by the plasma wave-particle interactions.¹⁴ The turbulence level is ~ 100 times above thermal level and is responsible for heating ions by ion scattering from plasma waves.¹⁵ Since the Z-pinch plasma, discussed in the appendix, is observed to consist mainly of excited neutral helium atoms, a substantial fraction of the turbulent heating energy given to the plasma during the heating phase goes into fully ionizing it (ionization potential ~ 50 eV for helium). The cooling of the plasma is discussed in terms of impurity line radiation from the concentrations observed in the impurity ionization rate measurement of the electron temperature.

The spectroscopy experiment performed on Torus II and discussed in this thesis was done with a six channel polychrometer capable of radial scans of the plasma. The polychrometer arrangement was versatile enough to view $\sim 2 \text{ \AA}$ with $\sim 0.2 \text{ \AA}$ resolution used to obtain the line profile presented in Chapter IV while being easily converted to cover a range of $\sim 1000 \text{ \AA}$ with $\sim 10 \text{ \AA}$ resolution used

for the various electron temperature and impurity studies. The spectroscopy apparatus will be discussed in greater detail in the second section of Chapter II.

Spectroscopy is a relatively uncomplicated method of diagnosing a plasma. Spectroscopic data, if analyzed with care, can result in measurements (with typical large errors due to weak theoretical dependence on plasma parameters) which are as valid as other plasma diagnostic measurements: e.g., Thomson and CO_2 laser scattering. Spectroscopy has the advantage that the measurement does not require as critically an aligned apparatus as is typical of the light scattering diagnostics used to measure temperature, density and fluctuations. Light scattering experiments detect signals which are somewhat smaller than those observed in spectroscopy, thus making large signal to noise ratios more difficult to realize. The main disadvantage of spectroscopy is associated with the convolution of various effects acting on a radiating system and leading to difficulties in the data analysis. A convolution of effects also exists in the analysis of scattering data, but is not as critical as in spectroscopy experiments. Scattering experiments are also able to achieve greater accuracy than spectroscopy experiments. CGS units are used in this thesis except for power (in gigawatts), energy (in joules), electric field (in volts per centimeter), temperature (in electron volts) and wavelength (in Angstroms). Time scales are in microseconds.

II. DESCRIPTION OF EXPERIMENT

II.1 General Machine Description and Plasma Formation

Columbia University Torus II is shown schematically in Figs. II.1a and II.1b. Some of the parameters are listed in Table 1. The machine^{33,34} has a glass vacuum vessel, of toroidal geometry, with an elongation ($h/w = 25.4 \text{ cm}/12.6 \text{ cm}$) of 2 and aspect ratio ($R_0/(w/2) = 22.5 \text{ cm}/6.3 \text{ cm}$) of 3.5. $R = R_0$ is the radial location of the poloidal cross-section center measured from the axis of symmetry of the machine (major radius $R = 0$). The toroidal vacuum chamber rests on a table and the vacuum system, consisting of a 400 liter/sec turbomolecular pump and a mechanical forepump which pump the chamber through a series of gate valves, is suspended from a frame mounted from the laboratory ceiling.

The vacuum chamber consists of two coaxial pyrex cylinders, of height $h = 25.4 \text{ cm}$ and difference in radii $w = 12.5 \text{ cm}$, sealed by flat ring-shaped pyrex plates (i.e., a top and bottom 60 cm diameter glass plate, $\sim 2 \text{ cm}$ thick with a 30 cm diameter hole cut out of the center of the glass plate) which press down on viton gaskets. Vacuum

Figure II.1a COLUMBIA UNIVERSITY HIGH BETA TOKAMAK TORUS II;
Arrows indicate direction of current flow in
external coil system. (Not to scale.)

Table 1: COLUMBIA TORUS II SUMMARY

TORUS: GLASS VACUUM VESSEL

MAJOR RADIUS	$R_0 = 22.5 \text{ cm}$
WIDTH	$w = 12.5 \text{ cm}$
HEIGHT	$h = 25.4 \text{ cm}$
FILL GAS	12 mT HELIUM

TOKAMAK CONDITIONS:

n_e	$\sim 10^{15} \text{ cm}^{-3}$
T	$\sim 100 \text{ eV}$
$q(a)$	~ 2
$\langle \beta \rangle$	$\sim 10\%$
B_T	$\sim 5\text{-}10 \text{ kG}$
I_p	$\sim 30 \text{ kA}$
PLASMA WIDTH	$2a \sim 4 \text{ cm}$

Figure II.1b Torus II vertical layout (side view).

sealing is done by pressing down on a top lucite plate (above the top glass plate, a rubber spacer and a lucite spacer) against the torus and the table by applying tension on the eight nylon rods provided around the circumference of the torus (see Fig. II.2). Typically, the vacuum chamber achieves a base pressure of $\sim 3 \times 10^{-7}$ Torr.

The plasma is initiated by discharging various capacitor banks which provide large electrical currents through various coils wrapped around the torus vacuum chamber. Current-carrying cables which feed the toroidal bias magnetic field, ohmic heating and vertical field coils are brought through the laboratory floor from a room directly below which contains a series of capacitor banks. On the main laboratory floor are four two-stage Marx capacitor bank modules (with maximum rating of 20 kJ, 100 kV, each stage charged to ± 50 kV) arranged in toroidal quadrants and connected to the fast toroidal field circuit via four isolated parallel plate transmission lines. Because of the accompanying high voltage insulation, access to the plasma is only through the top of the torus.

The fill gas is 12 millitorr of helium and is made to flow continuously through the vacuum chamber by feeding gas into one vacuum line (with its respective gate valve closed) and pumping only on the other vacuum line. The discharge of capacitor banks into the various coils around the vacuum chamber induces various electrical cur-

Figure II.2 Applied magnetic fields and coil currents for Torus II. I_{OH} is the ohmic heating-air core transformer current for preionization and Z-Pinch; B_V is the vertical magnetic field and B_T is the applied toroidal magnetic field for bias and heating (1 Tesla = 10 kGauss). Shown for parallel operation.

rents to flow in the fill gas, producing and heating the plasma.

The preparation of the plasma can be divided into four stages: preionization, toroidal Z-pinch, fast heating and high beta tokamak. The time dependence of various currents and magnetic fields is shown schematically in Fig. II.2 to illustrate these four stages of the Torus II experiment. Preionization is done using a 9 MHz RF oscillator coupled to the plasma by means of antennae wrapped around the glass vacuum lines, and then discharging a small capacitor bank (80 kA with 10 μ sec rise time) through the "ohmic heating air core transformer." In addition, a slow toroidal bias magnetic field, obtained by passing a current (140 kA with 60 μ sec rise time) through the "slow toroidal field coils," begins to rise during the preionization phase.

After preionization, a toroidal Z-pinch with temperature $T \sim 5\text{-}10$ eV, electron density $n_e \sim 5 \times 10^{14} \text{ cm}^{-3}$, compressed toroidal bias magnetic field $B_T(R_0) \sim 2$ kG and toroidal plasma current $I_p \sim 50$ kA is created by pulsing a capacitor bank (330 kA with 8 μ sec rise time) through the air core transformer. Radial equilibrium of the toroidal Z-pinch requires the imposition of a vertical field ~ 1 kG to contain the outward force of the toroidal plasma current. The toroidal current "pinches" the plasma to about one third the chamber width (i.e., plasma width ~ 4 cm) thereby isolating the plasma from the walls. Some

ionization and impurity stripping also occur during this phase.

During the heating phase, a high beta tokamak plasma is formed by rapidly ($\tau_R = 1.7 \mu\text{sec}$) changing the toroidal magnetic field, B_T , by 5-10 kG. This process permits the rearrangement of the magnetic geometry into a tokamak configuration and allows for heating in a time short compared to typical magnetohydrodynamic instability growth times.

(MHD instability growth times are typically of order several Alfvén transit times: i.e., the time needed for an Alfvén wave of velocity $V_A \equiv (B_T^2 / 4\pi n_i m_i)^{1/2}$, where n_i and m_i are, respectively, the ion number density and ion mass, to travel around the toroidal circumference, $2\pi R_0$, of the machine. This time is $\sim 1 \mu\text{sec}$ for typical Torus II operating conditions in helium.) The magnetic field can be changed to a direction either parallel or antiparallel to the initial toroidal bias field. The peak power (hereafter referred to as "heating power") used to change the magnetic field is as high as 50 GW into the toroidal load and is provided by the four two stage Marx bank units arranged in toroidal quadrants. To maintain radial equilibrium, the vertical field is simultaneously increased by another 1 kG; this is required because of the increased plasma temperature. At 50 GW heating power, the applied poloidal electric field at the vacuum vessel surface is $E_{\theta,A} \sim 1.2 \text{ kV/cm}$. The Marx bank provides a peak current $\sim 1 \text{ MA}$ through the "fast toroidal field circuit."

Radial plasma motion due to temperature can be simply understood by considering a toroidal ring of infinitely long plasma with inner radius R_1 and outer radius R_2 and pressure $p = nkT$. The plasma pressure force per unit length at R_1 is $2\pi R_1 p$ radially inward and that at R_2 is $2\pi R_2 p$ outward. Therefore, there is a net radial force tending to push the plasma outward, whose magnitude increases with temperature. If this ring of plasma also carries a toroidal current, the direction of this current is opposite on opposite sides of the ring. Since opposing currents repel each other, the toroidal plasma current also causes an expansion force. In Torus II and other toroidal machines, these outward forces are cancelled by the imposition of an external vertical field, B_v , and the plasma ring will expand to an equilibrium radius R_e , where the vertical magnetic field force $2\pi R_e \frac{B_v^2}{8\pi}$ per unit length is equal to the net expansion forces of the plasma pressure and current.

Fig. II.3 shows the temporal and radial dependence of the toroidal magnetic field---obtained from a pair of balanced magnetic field probes---for 12 GW ($E_{\theta,A} \sim 600$ V/cm) heating power and parallel operation.⁷ (In this figure and all further discussion, time $t = 0$ denotes the application of the heating pulse.) For parallel operation, the toroidal magnetic field responds to the fast heating pulse by rising relatively uniformly across the machine radius until the Z-pinch magnetic field ($t = 0$ μ sec) is

Figure II.3 Radial dependence of the toroidal magnetic field (in Tesla) for various times; from magnetic field probes; 12 GW PARALLEL BIAS AND HEATING OPERATION.

transformed into a tokamak configuration within 1 μ sec.

For anti-parallel operation, the rapid field reversal induces prominent poloidal skin currents on the edge of the plasma which are driven microscopically unstable, thereby resulting in an enhanced electrical resistivity effect which converts some of the magnetic energy into thermal energy of the plasma. The case of field reversal is shown in Fig. II.4 for 12 GW anti-parallel heating power.⁷ It can be seen that the application of the heating pulse induces a strong poloidal skin current ($j_\theta \propto \partial B_T / \partial r$) ~ 1 cm thick which rapidly penetrates into the plasma, and that the Z-pinch configuration ($t = 0$ μ sec) again evolves into a tokamak configuration in ~ 5 μ sec.

The difference between parallel and anti-parallel operation with respect to the induction of skin currents can be understood in terms of the magnetic field gradients. Consider the case of 12 GW heating power as shown in Figs. II.3 and II.4. The application of the heating pulse corresponds to applying a boundary condition of $B_T = 4$ kG at the vacuum chamber walls. Since the initial toroidal bias field is ~ 2 kG, parallel operation corresponds to $\partial B_T / \partial r \sim 2$ kG/cm, and anti-parallel operation corresponds to $\partial B_T / \partial r \sim 6$ kG/cm. Thus, the poloidal skin current is less for parallel operation than anti-parallel operation.

The poloidal current density in this skin layer for 12 GW anti-parallel operation is typically $j_\theta \sim 5 \times 10^3$ A/cm², implying an electron drift velocity $v_D = j_\theta / n_e e \sim 5 \times 10^7$

Figure II.4 Radial dependence of the toroidal magnetic field (in kG) during heating and toroidal field reversal; from magnetic field probes; 12 GW ANTI-PARALLEL BIAS AND HEATING OPERATION.

cm/sec. This velocity is an order of magnitude larger than the ion sound speed, $C_s = [(kT_e + kT_i)/m_i]^{1/2} \approx 6 \times 10^6$ cm/sec in Torus II. Measurements of the current density and induced electric field in fact imply a local plasma resistivity ≈ 100 times enhanced over classical Spitzer resistivity, perpendicular to the magnetic field ($\eta_\perp = 1.3 \times 10^4 Z \ln \Lambda / T_e (\text{°K})^{3/2}$ ohm-cm). This resistivity is consistent with the observed diffusion time ($\tau_D \equiv 4\pi\epsilon^2 / \eta c^2$ where $\epsilon \equiv \frac{1}{B} \frac{dB}{dr}$ is the magnetic field gradient scale length and η is the resistivity) of the magnetic fields (≈ 1 μ sec). The toroidal plasma current also rapidly decreases from ≈ 50 kA during the Z-pinch to ≈ 30 kA after heating, corresponding to an $L/R \approx 4$ μ sec decay time during heating where L is the plasma inductance and R is the plasma resistance. Using the inductance of a rectangular toroid with the above plasma $L/R \approx 4$ μ sec results in a resistivity of $\approx .3$ Ω -cm parallel to the magnetic field, assuming that the region affected by the enhanced resistivity is ≈ 1 cm thick layer at the plasma edges, compared to a classical Spitzer resistivity parallel to the magnetic field of $\approx 10^{-3}$ Ω -cm. Hence, the enhanced resistivity due to microturbulence appears to be roughly isotropic.

After the heating phase, a high beta tokamak is obtained with $T \sim 100$ eV, $n_e = 2 n_i \sim 10^{15}$ cm $^{-3}$ and plasma volume average beta $\langle \beta \rangle_V \approx 10\%$.¹⁹ (The electron density is inferred from the compression at a known fill pressure. Preliminary CO₂ laser interferometry results are in agree-

ment with this estimate.³⁵ The temperature is derived from a variety of spectroscopic ion and electron temperature measurements which will be discussed in detail in the following text.) The plasma poloidal cross-section, initially having an elongation of ~ 4 , tends to become more circular for $t \sim 15$ sec and is held in radial equilibrium for ~ 30 μ sec. Note that all capacitor banks (except for the slow toroidal bias field bank) are crowbarred (shorted out of the electrical circuit) at the peak of the heating pulse, and the current in the circuit decays with the $L/R \sim 60$ μ sec characteristic of the inductance and resistance of the current carrying cables and coils. The toroidal plasma current decays with a plasma $L/R \sim 30$ μ sec during the equilibrium phase of plasma containment.

The radial motion of the luminous plasma was recorded by a visible light streak camera (IMACON). Fig. II.5 shows streak photographs for anti-parallel operation at various heating powers. It can be seen that the Z-pinch forms inside of the annulus center (R_0), quickly moves outward during heating because of the toroidal plasma current and increased temperature, and then slowly drifts back to R_0 during the high beta equilibrium because of the imbalance of radial forces at later times due to different decay times of the applied vertical field (~ 60 μ sec) and the toroidal plasma current (~ 30 μ sec). (At maximum heating power, 50 GW anti-parallel, the plasma moves outward too far to be accessible to our diagnostics. Apparently, the

Figure II.5 Radial and vertical streak photographs for the various phases of the Torus II experiment. Dashed arrow indicates beginning of the heating phase.

applied vertical field is insufficient in strength to overcome the outward expansion. Thus, Torus II is rarely operated at maximum heating power.) If the location of the maximum toroidal plasma current density corresponds to the location of the plasma pressure maximum, then the plasma center corresponds to the magnetic axis as measured by magnetic field probes. The magnetic axis of the Z-pinch is at $R \approx R_0 - 1$ cm, quickly moves outward during heating to $R \approx R_0 + 1.5$ cm at 12 GW anti-parallel heating power and $R \approx R_0 + 3$ cm at 25 GW anti-parallel heating power, and then slowly returns toward R_0 during the high beta equilibrium phase.

The plasma is vertically well-centered, as is witnessed again by a visible streak camera (STL). Vertical equilibrium is achieved by passive control, using conducting hoops at the outside top and bottom of the torus (not shown in Figs. II.1a and II.1b). If the plasma moves away from vertical center ($Z = 0$), image currents are induced in these conducting hoops and the plasma is forced back to vertical center.

II.2 Spectroscopy Experiment

Line radiation³⁶ of helium as well as silicon and oxygen impurity ions was observed in the visible region (4000 Å - 7000 Å) using the apparatus shown in Fig. II.6. A one centimeter chord of light was viewed in the vertical direction; the light was deflected through 90° by a glass prism and focused onto the entrance slit of a McPherson grating spectrometer by a 15 cm focal length lens. This spectrometer has an interchangeable plane reflecting grating of 10 x 10 cm² area in a Czerny-Turner arrangement with one meter focal length concave mirrors between the entrance slit and the grating and the exit plane. For ion line profile measurements, a 2400 line/mm grating blazed at 3000 Å was used to give a linear dispersion of 3.3 Å/mm near $\lambda = 4700 \text{ Å}$, decreasing with increasing wavelength, at the exit plane of the spectrometer. Coarser resolution, used in total line and continuum band intensity measurements, was obtained by using a 600 line/mm grating, blazed at 3000 Å, and giving a linear dispersion of 15.8 Å/mm at the exit plane of the spectrometer. The spectrometer also provided a means of holding photographic film at the exit plane. This allowed for the taking of spectrograms covering a range of $\sim 1500 \text{ Å}$ when the 600 line/mm grating was used. The entrance slit of the spectrometer was typically ~ 20 microns wide.

A six channel polychrometer was mounted at the exit

Figure II.6 General layout of spectroscopy experiment; Poloidal cross-section.

plane of the spectrometer (Fig. II.7) with the fiber guides going to the individual photomultiplier tubes assembled on a mount which fits the film holder accessory of the McPherson. For line profile measurements, each polychrometer channel consisted of an 80 micron thick, and 18 mm high, line to spot glass fiber optic guide, giving a channel width of $\sim 0.25 \text{ \AA}$ at $\lambda = 4700 \text{ \AA}$, and a type RCA 4832 side-on photomultiplier tube. This photomultiplier has a gallium-arsenide photocathode with essentially constant sensitivity for the range of $2000 \text{ \AA} - 9000 \text{ \AA}$. To avoid cross-talk between channels, the spacing between channels was chosen to be $\sim 0.4 \text{ \AA}$. Thus, the polychrometer covered $\sim 2 \text{ \AA}$ and most line profiles could be taken on a single shot. Lines wider than $2 \text{ \AA}$ required some shot-to-shot wavelength scanning, in which case, the first channel of one shot monitored the same wavelength band as the sixth channel of a previous shot. For total line and continuum band intensity measurements, $\sim 1 \text{ mm}$ thick lucite light guides were used. Typically, only two channels were used for these measurements. The separation of these channels could be as much as $\sim 1000 \text{ \AA}$ by choosing spacers of appropriate thickness.

Each photomultiplier output was terminated with $4800 \text{ \Omega}$ and the signal was transmitted by a line driver circuit, using a National Semiconductor LH 0033 CG fast operational amplifier, terminated at $50 \text{ \Omega}$ down RG 58 coaxial cable and displayed on oscilloscopes inside a screen

(a) Front view of polychrometer

(b) Side view of polychrometer

(c) Rear view of polychrometer;
Installed at exit
plane of spectrograph.

Figure II.7 Six channel polychrometer. (Scale: photomultiplier shield has 1.5 inch diameter.)

room. Due to the existence of large amounts of electrical noise, caused primarily by the radiated electromagnetic power of the high energy pulsed discharge of the capacitor banks associated with the Torus II experiment, the photomultiplier tube electronics was enclosed in a 3 mm thick aluminum chassis. The tubes were enclosed by μ -metal lined with copper, except for a small slot to allow dispersed light into the photomultipliers. The signal-carrying coaxial cables were double shielded and ran through copper or aluminum conduit to the screen room. Ground loops, which are a major source of electrical noise pickup,³⁷ were avoided by making certain that all electrical components had a common ground derived from the screen room. Since most of the electrical noise had ~ 10 μ sec time period, low pass filters of RC ~ 10 msec were used on all the power supplies needed for photomultiplier and line driver operation. These precautions resulted in a light signal to electrical noise ratio ~ 4 for most of the duration of the Torus II experiment.

Wavelength calibration of the polychromometer was done by using neutral lines from commercially available spectral tubes. For example, He II 4686 Å calibration employed the 4680 Å Cadmium I, 4692 Å Xenon I and 4713 Å Helium I atomic lines. A check on this method of wavelength calibration was done occasionally by pulse discharging a small capacitor array across a helium spectral tube to observe He II 4686 Å. Comparing the two methods resulted in a typical

wavelength calibration error of $\pm .05 \text{ \AA}$. The relative sensitivities of the channels were determined by using $4713 \text{ \AA}$ He I or a white light source. The relative sensitivities were found to vary by as much as a factor of 3 and had to be divided out in order to compare the signal from different channels or to draw a line profile. Typical relative sensitivity errors were $\sim 5\%$.

The polychrometer arrangement was necessary because of the large shot-to-shot fluctuation in light intensity, as was observed by a monitor looking at the total light intensity of the line whose profile was being measured. In this case, a chord of light was viewed in the vertical direction (but 90° away in the toroidal direction) by a spot to line fiber light guide and dispersed by a 0.5 meter Jarrell-Ash monochrometer with $16 \text{ \AA/mm}$ linear dispersion. An RCA 931A side-on photomultiplier tube, enclosed in a copper can, terminated at 50Ω and displayed on an oscilloscope via double shielded coaxial cable without a line driver, was used to detect the dispersed light. Fig. II.8 shows the relative toroidal location of the various diagnostics discussed in this paper.

Since the plasma can move radially due to an imbalance between the applied vertical field (60 μsec decay time) and that due to the toroidal plasma current (30 μsec decay time), the spectroscopy experiment was designed to be capable of radial scanning. The radial motion of the plasma was tracked with a visible light streak camera and more

Figure II.8 Top view of Torus II showing the toroidal location of the various diagnostics.

precisely defined by magnetic field probe measurements. It should also be noticed that the plasma is optically thin for the chord length (~ 20 cm) observed by this experiment.³⁸

The optical depth calculation for the He II 4686 Å line transition proceeds as follows. A plasma is optically thin over a length ℓ if

$$d = 5.4 \times 10^{-9} \lambda (\mu/T)^{1/2} N \ell < 1$$

where N is the number density of absorbers of the line transition with wavelength λ . The absorbers have a mass μ relative to hydrogen and are in a plasma of temperature T .

For He II 4686 Å and $T=50$ eV, a plasma is optically thin over a length of 20 cm if $N < 7 \times 10^{11} \text{ cm}^{-3}$. Use of the steady state corona model for plasma radiation⁶⁷ indicates that the density of fully ionized helium is $>10^3$ times larger than that of singly ionized helium. Further noting that He II has four strong line transitions, of which 4686 Å is one, indicates that the absorbers of He II 4686 Å have less than one fourth the density of once ionized helium, i.e., $N < 3 \times 10^{11} \text{ cm}^{-3}$ in a helium plasma of density 10^{15} cm^{-3} . Thus, plasmas of 20 cm length are optically thin for He II 4686 Å line radiation when $T > 50$ eV, i.e. radiation from all portions of the vertical chords viewed in the Torus II experiment is seen under the plasma conditions $T_i > 25$ eV and $n_i = 10^{15} \text{ cm}^{-3}$.

It should also be noted that for $T=10$ eV, the condition for optically thin plasma is $N \ell < 3 \times 10^{13}$ and this plasma is optically thin over approximately 4 cm to He II 4686 Å.

III. ANALYSIS-THEORY OF LINE PROFILES

After using an appropriate theory to describe the plasma environment effects on the energy levels of a radiating ion or atom, analysis and interpretation of spectral line profiles can give information on microscopic electric fields (Stark effect) and ion motion (Doppler effect). The Stark effect results from plasma wave electric fields^{16,20-24,39-43} characterized by a scale length greater than the plasma Debye length $\lambda_D = (kT_e/4\pi n_e e^2)^{1/2}$ and from the plasma electron density,^{28,44} resulting in a microscopic electric field of scale length $<\lambda_D$ due to the approximately dipole Holtzmark microscopic electric field of the moving and colliding plasma ions and electrons. The Doppler effect results in a broadening of an emitted line due to the microscopic velocity distribution (i.e., temperature) of the emitting plasma ions and in a shift of the line center if there exists a dominant macroscopic plasma velocity. In reality, the density Stark effect on HeII 4686 Å can be neglected when compared to the Doppler effects at $n_e \sim 10^{15} \text{ cm}^{-3}$ and $T \sim 20 \text{ eV}$.⁴⁴ However, the plasma wave electric field Stark effect is comparable to the Doppler effect when turbulence (i.e., large ampli-

tude plasma waves) exists in the plasma.^{16,24} Therefore, all electric fields (except the macroscopic applied electric field $E_{\theta,A}$) referred to in the following discussion are a result of large amplitude plasma waves.

Stark effects on a hydrogen line profile due to plasma wave electric fields can be separated into several regions which depend on the frequency ω of the plasma wave electric field relative to the natural line width W_n , $W_n \sim 6 \times 10^{10}$ rad/sec for He II 4686 Å.^{16,20,21} Low frequency wave oscillations ($\omega \lesssim$ ion plasma frequency $\omega_{pi} = (4\pi n_i Z^2 e^2 / m_i)^{1/2} \sim 3 \times 10^{10}$ rad/sec for Torus II) cause a quasi-static broadening of the line. High frequency wave oscillations ($\omega \gtrsim$ electron plasma frequency $= (4\pi n_e e^2 / m_e)^{1/2} \sim 2 \times 10^{12}$ rad/sec for Torus II) cause a non-adiabatic broadening of the line, analogous to the broadening due to electron impacts in the density Stark effect. Thus, in the expression for the line profile, low frequency oscillations are accounted for in the distribution function of the electric field amplitudes which cause the splitting of the line into Stark components and high frequency oscillations are included in the half-width of each individual Stark component.

Fig. III.1 shows qualitatively the line profile as a function of oscillation frequency for Hydrogen α -like (change in principal quantum number of 1) and Hydrogen β -like (change in principal quantum number of 2) lines.¹⁶ Low frequency plasma wave electric fields produce wing

Figure III.1 Schematic representation of Hydrogen α -like and Hydrogen β -like line profiles as a function of plasma wave electric field frequency ω for (a) thermal plasma (i.e. no plasma wave turbulence); (b) $\omega \lesssim \omega_{pi}$ turbulence and (c) $\omega \lesssim \omega_{pe}$ turbulence.

peaks on H_α and deepen the dip in the central (unshifted) feature of H_β (Fig. III.1b). High frequency oscillations cause an excessive broadening of the line (Fig. III.1c). For comparison, Fig. IV.1a shows line profiles typical of a cold thermal plasma where only the density Stark effect is important. The distinction between H_α and H_β occurs because of the lack of an unshifted Stark component in the case of H_β which is attributed to the symmetry of the upper state of H_β with respect to the lower state of H_β . Note that HeII 4686 Å, a principal quantum number $4 \rightarrow 3$ transition, is similar to Paschen α which, in turn, is similar to Hydrogen α .

Fig. III.2 shows qualitatively the effect of plasma wave electric field strength on the H_α -like line. For low frequency ($\omega \lesssim \omega_{pi}$) oscillations, shifted Stark components begin to appear about the line center. The intensity of the shifted components increases while the central Stark component intensity decreases with increasing plasma wave electric field strength. (The decrease in the central component intensity with increasing shifted component intensity can be seen from the total line intensity given by²⁸

$$\int_{\text{line width}} I_{nn'}(\lambda) d\lambda = \alpha f_{nn'} N_n$$

where α is a constant, $f_{nn'}$ is the oscillator strength of

the transition and is constant for a given type of discharge, and N_n is the number of ions in the upper state n of the transition. Thus, for a given density of emitters, the total line intensity is a constant and the central intensity decreases as the line wing intensity increases. For a complete quantum mechanical treatment of the intensity of individual Stark components, see pages 74-94 of reference 39.) At sufficient plasma wave electric field strength, the central intensity decreases below the shifted component intensity and the resulting line profile exhibits a central dip (Fig. III.2b). This central dip in He II 4686 Å has been observed in previous experiments^{16,23} and has been attributed to Stark splitting with low frequency electric fields ~ 20 kV/cm.

For low frequency oscillations, $\omega \sim \omega_{pi}$, in a cold plasma, the plasma wave electric field, E , appears constant in time, compared to the characteristic radiating time of the ion and linear Stark splitting of the ion energy levels by an energy amount proportional to $Ze a_0 \tilde{E}$ occurs.^{16,21} Here, Ze is the nucleus charge and $a_0 = \hbar^2/m_e e^2$ is the Bohr radius. This results in a nearly symmetric splitting of the HeII 4686 Å line. The plasma wave electric field, arising from low frequency plasma waves of electrostatic nature, can be found using the expression^{21,39}

$$\Delta\lambda_{SS} = \frac{3h^2\lambda_0^2}{8\pi^2 m_e Z e c} (n^2 - n'^2) \tilde{E} \quad (\text{III.1})$$

Figure III.2 Schematic representation of Hydrogen α -like line profiles for (a) $\omega < \omega_{pe}$ and (b) $\omega < \omega_{pi}$ plasma wave turbulence as a function of increasing plasma wave electric field.

where λ_0 is the unperturbed wavelength, $\Delta\lambda_{SS}$ is the measured displacement of the Stark split peak from λ_0 , and n and n' are the principal quantum numbers of the upper and lower states of the transition.

For high frequency ($\omega \sim \omega_{pe}$) oscillations, the qualitative structure of hydrogen-like lines is again a function of the plasma wave electric field strength (Fig. III.2a). When the Stark splitting is less than the plasmon energy (i.e., $Zea_0 \tilde{E} < \hbar\omega_{pe}$), satellites located at ω_{pe} away from the unshifted line center appear about the unshifted line. When $\tilde{E} > \hbar\omega_{pe}/Zea_0$, the central feature of the line appears excessively broadened. For HeII 4686 Å, $\tilde{E} \sim 10$ kV/cm defines the transition in structure.

With the occurrence of high frequency fourier components $\omega \sim \omega_{pe}$ in a cold plasma, the time dependence of the microscopic electric field acts to broaden, instead of discretely split the ion energy levels. The resulting line profile consists of an excessively broadened central feature. The plasma wave electric field, $\tilde{E}$, can be measured from the full width half maximum, $\Delta\lambda_S$, of the wavelength profile by using^{21,24}

$$\Delta\lambda_S = \frac{3}{4} \frac{\hbar\lambda_0^2}{2\pi m_e Z e C} (n^2 - n'^2) \tilde{E} \quad (\text{III.2})$$

If the Holtzmark electric field ($E_H \propto n_e^{2/3} \sim 10$ kV/cm for $n_e \sim 10^{15} \text{ cm}^{-3}$) is used for $\tilde{E}$, equation (III.2) reduces

to the density Stark effect,⁴⁴ which is caused by collisional encounters with the radiating ion. Thus, in the impact approximation theory of line broadening,²⁸ the high frequency microscopic plasma wave electric field replaces the dipole electric field due to the moving plasma electrons interacting with the radiating ion.

When plasma waves with $\omega \sim \omega_{pe}$ exist with lowered electric field strength ($E \sim 10$ kV/cm for HeII 4686 Å), satellites appear about the unshifted line frequency located at multiples of ω_{pe} from the unshifted line.^{22,40} These satellites result from a plasmon of energy ω_{pe} interacting with the broadened ion energy levels.⁴¹

If $\omega \sim \omega_{pe}$ and $\omega \sim \omega_{pi}$ plasma waves exist simultaneously, the Stark split components given by equation (III.1) are broadened by an amount given by equation (III.2).²¹ Electron plasma frequency satellites may also be observed if moderate amplitude plasma waves exist at $\omega \sim \omega_{pe}$.

Finite ion temperature (microscopic velocity distribution of plasma ions) by itself introduces Doppler broadening of the line profile features. The Doppler full width at half maximum intensity, $\Delta\lambda_D$, is given by^{28,44}

$$\frac{\Delta\lambda_D}{\lambda_0} = 7.7 \times 10^{-5} (T_i(\text{eV})/\mu)^{1/2} \quad (\text{III.3})$$

where μ is the ion mass relative to hydrogen. Therefore, it becomes difficult to measure electric field strengths

in the case of $\omega \sim \omega_{pe}$ turbulence unless the ion temperature, T_i , is known. Conversely, erroneously high values of T_i can result when large amplitude plasma waves with $\omega \sim \omega_{pe}$ exist and are not included in the analysis. However, turbulence with $\omega \sim \omega_{pi}$ can still be measured since Stark splitting of the radiated line is observed in our experiment.

A macroscopic plasma velocity, V , further complicates the interpretation of line profiles by introducing a shift $\Delta\lambda$ of the line center by

$$\frac{\Delta\lambda}{\lambda_0} = \frac{V}{C} \quad (\text{III.4})$$

Since (in order to gain an acceptable signal to noise ratio-----mainly electrical noise in the case of a pulsed experiment like Torus II) large diameter chords of light are viewed, any or all of the above line broadening mechanisms can be important at any given time. Expectations are that Stark effects are important mainly during the heating phase, say $t \sim 5 \mu\text{sec}$, since magnetic field probes indicate the disappearance of strong skin currents by this time. In addition, motion of the plasma, so that different portions of the plasma are in the viewing area at any given time, is important. (Note that the imposition of ~ 5 kG magnetic field results in a Zeeman splitting of $\sim .1 \text{ \AA}$ compared to the $\sim .5 \text{ \AA}$ shifts measured in this

experiment. Therefore, Zeeman splitting is negligible.)

Electric field Stark effect measurements have been previously done in other turbulent heating experiments, notably θ -pinch and electromagnetic shock wave experiments.^{16,23,24,31,42,45,46}

At the University of Maryland, Griem and Kunze²⁴ observed excessively broadened central components of HeII 4686 Å and HeII 3203 Å in a fast θ -pinch with electron density $\sim 7 \times 10^{13} \text{ cm}^{-3}$. The two line profiles were used to determine consistently an ion temperature of $\sim 2 \text{ eV}$ and collective plasma wave electric fields $\sim 15 \text{ kV/cm}$. (Note that in Torus II, HeII 3203 Å is inaccessible because of the glass vacuum vessel. Thus, turbulent electric field strengths cannot be determined from an excessively broadened central feature of HeII 4686 Å unless the ion temperature is known.) These results, were consistent with satellite intensity measurements on neutral helium done by Kunze and Griem⁴² using the theory for the intensity of ω_{pe} satellites about forbidden line transitions derived by Baranger and Mozer.⁴³ (Note that in Torus II, since $T_i \sim 50 \text{ eV}$ after heating, only the strongest line of neutral helium, HeI 5876 Å, was observed. No neutral lines with forbidden components could be found.) Again using a University of Maryland fast θ -pinch experiment, Nee and Griem⁴⁵ measured Hydrogen $n\alpha$ line profiles ($n = 13 \rightarrow 12$, $\lambda = 88.7\mu$ and $n = 12 \rightarrow 11$, $\lambda = 69.0\mu$) and observed strong

symmetric satellite features with intensity comparable to that of the unshifted line but displaced by ω_{pe} from it. These satellites were interpreted as being caused by plasmon-atom interactions in a turbulent plasma with low frequency oscillations enhanced by a factor of 10^3 above the thermal level at $n_e \sim 10^{14} \text{ cm}^{-3}$ and $T_e \sim 1 \text{ eV}$.

In the θ -pinch experiments, there was no spatial resolution in the measurements. In shock wave heating experiments produced by rapidly reversing the magnetic field using external currents,^{16,23} Hydrogen β was observed to be excessively broadened in the shock front and both Hydrogen α and Hydrogen β were observed to be Stark split behind the shock front. In the toroidal cusp experiment, TORMAC at Lawrence Berkeley Laboratory, Stark broadened Hydrogen β was used to measure turbulence.³¹ More recently, Stark broadening of Hydrogen β spectrum has been used to measure the RF ($\sim 5 \text{ GHz}$) electric field $\sim 100 \text{ kV/cm}$ produced by an electron beam machine microwave source.⁴⁶

Thus, there exists considerable evidence for the use of the Stark effect to obtain microscopic plasma wave electric field strengths. Once the Stark effect is known and accounted for in the line profile, then the Doppler effect yields the ion temperature.

IV. PRESENTATION AND DISCUSSION OF LINE PROFILES

The data in this chapter will be representative of the heating and high beta containment phases of the Torus II experiment. The Z-pinch phase will be discussed in the appendix. The presentation and discussion of line profiles will be divided into several sections, depending on heating power (applied electric field) and emitter. It will also become clear that the analysis of these line profiles will be different for the turbulent heating phase and the equilibrium high beta tokamak phase, the difference being the relative importance of the plasma wave electric field Stark effect discussed in Chapter III.

A large portion of this chapter will be devoted to the discussion of the He II $4686 \text{ \AA}$ line since this line is most representative of the helium plasma. (The neutral He I $5686 \text{ \AA}$ line appears with the plasma temperature only by virtue of charge exchange with a hot He^+ ion. Since, as will be discussed in the appendix, the charge exchange mean free path for $\text{He}_{\text{HOT}}^+ + \text{H}_{\text{COLD}}^0 \rightarrow \text{H}_{\text{COLD}}^+ + \text{H}_{\text{HOT}}^0$ is approximately equal to the plasma size, neutral helium does not characterize the plasma accurately.) The Silicon III $4683.7 \text{ \AA}$ was observed on the lower wavelength side of

He II 4686 Å on shots when the plasma moved further out than usual and may have even touched the outer radial wall. These "bad shots" occurred occasionally without any noticeable difference in the capacitor bank discharge characteristics and were neglected in the data analysis. On "good shots" the plasma was relatively well centered and the Si III 4684 Å line did not complicate the analysis of He II 4686 Å.

Since the glass vacuum vessel did not allow observation of He II 3203 Å, impurity line profiles mostly of Si II 5041.03 Å and Si III 4716.15 Å which were brighter than the visible oxygen impurity lines, were used to check some of the results inferred from He II 4686 Å. These profiles will also be presented in this chapter. The impurity line profile results also give reassurance that the bad experience of the TORMAK experiment,^{31,32} in which the ion temperature derived from Doppler broadening of He II 4686 Å in a hydrogen plasma with 10% helium impurity disagreed with the electron temperature measured by Thomson scattering by over an order of magnitude, would not be encountered in this experiment. Note that the ion and electron temperatures should be approximately equal after an energy equilibration time ($\tau_{ie} \sim 5 \mu\text{sec}$ for Torus II).²⁵ Independent electron temperature measurements in Torus II by several optical methods will be presented in the following chapter.

Line profile data were taken during runs with and

without the pair of balanced magnetic field probes, used to obtain magnetic field mappings similar to those in Figs. II.3 and II.4, inserted into the plasma. Under certain conditions, magnetic field probes were observed to alter the line profiles significantly. This will become clear in the last section of this chapter in which He II 4686 Å line profiles are discussed in the context of the plasma perturbations caused by the magnetic field probes. Consequently, all the line profiles presented in the earlier sections of this chapter were taken without any perturbing diagnostics in the plasma.

IV.1a General Characteristics of Line Intensities

The signals from photomultiplier tubes looking at different parts of a given line were amplified as previously discussed and displayed on dual beam oscilloscopes (Tektronix 7844). Fig. IV.1 shows the oscilloscope traces of four of the six photomultiplier outputs near He II $4686 \text{ \AA}$ for a single "good shot" along with the monitor looking at $4686 \text{ \AA} \pm 8 \text{ \AA}$ from another "good shot." Both shots were taken at the machine annulus center $R = R_0$ and at 25 GW anti-parallel heating power ($E_{\theta,A} \sim 900 \text{ V/cm}$). The time scale on all these traces is $5 \text{ \mu sec/division}$.

From the polychrometer channel outputs covering $.2 \text{ \AA}$ of the line, it can be seen that the heating pulse (applied at the time indicated by the arrow and referred to as $t = 0$) ionizes He II, indicated by the initially increasing and then decreasing signal of the spike at $0 \leq t \lesssim 2 \text{ \mu sec}$. (This can be better seen in Fig. IV.2 which shows the same channels on the expanded time scale of $2 \text{ \mu sec/div}$. The very fine time resolution, $\sim 0.1 \text{ sec}$, required during the heating phase was achieved by using a sweep speed of $0.5 \text{ \mu sec/div}$.) Part of the decay in light intensity is due to the motion of the plasma away from the viewing area. Thus, there was enough He II light at all radial R locations and all times to insure a signal to electrical noise ratio $\gtrsim 4$. (When $S/N \lesssim 2$, the average noise as derived

Channel 1, $\lambda=4684.22 \text{ \AA}$
 100 mV, $5\mu\text{s/div}$
 Rel. Sensitivity=1.2

Channel 2, $\lambda=4684.64 \text{ \AA}$
 200 mV, $5\mu\text{s/div}$
 Rel. Sensitivity=2.1

Channel 3, $\lambda=4685.16 \text{ \AA}$
 200 mV, $5\mu\text{s/div}$
 Rel. Sensitivity=1.4

Channel 3, $\lambda=4685.68 \text{ \AA}$ (line center)
 100 mV, $5\mu\text{s/div}$
 Rel. Sensitivity=1.0

Monitor, $\lambda=4686\pm 8 \text{ \AA}$, $5\mu\text{s/div}$

Figure IV.1 Photomultiplier signals from four of the six polychrometer channels and monitor. Arrow indicates initiation of heating; 25 GW anti-parallel heating power.

Figure IV.2 Photomultiplier signals from four of the six polychrometer channels. Arrow indicates initiation of heating; 25 GW anti-parallel heating power. Channel specifications same as in Figure IV.1.

from the average of three shots in vacuum was subtracted from the photomultiplier outputs.) As the plasma cools and moves back towards $R = R_0$, He II is observed to increase ($10 \lesssim t \lesssim 15 \mu\text{sec}$), flatten out ($15 \lesssim t \lesssim 25 \mu\text{sec}$) and then decrease ($t \gtrsim 25 \mu\text{sec}$) as the plasma recombines. (As will be seen in the following discussion, the plasma energy actually decays by $t \gtrsim 35 \mu\text{sec}$. The positive signals appearing on some of the traces in Fig. IV.1 for $t > 30 \mu\text{sec}$ are electrical noise pickup associated with the ringing of the bias bank. This noise is difficult to shield against in the limited space allowed for the photomultiplier tubes and their electronics because of the long ringing period ($\sim 240 \mu\text{sec}$) of the bias bank which is not crowbarred in the Torus II experiment.

The monitor trace, also shown in Fig. IV.1, indicates the same features with regards to the total line intensity as were observed with regards to the polychrometer channel band responses. The monitor was shown from a different shot to indicate the non-reproducibility in time of these features from one shot to the next. In addition, the magnitude of both the monitor and the channel signals varied by as much as 50% from one shot to the next. The appearance and magnitude of the heating pulse intensity spike ($0 \lesssim t \lesssim 2 \mu\text{sec}$) was reproducible from one shot to the next. The non-reproducibility in the plasma light for $t > 2 \mu\text{sec}$ could very well be due to slight differences in

plasma motion from shot to shot since slight differences in plasma location are well detected with ~ 1 cm diameter bundles of light viewed by the spectroscopy experiment. Shot-to-shot variations in the light intensity could also be explained by a slightly more outward motion of the plasma, thereby introducing more impurities to cool the plasma. Correspondingly higher impurity line intensities were observed on shots when the He II 4686 Å line was brighter.

IV.1b Derivation of Line Profiles from Line Intensities

The line profiles shown in this chapter were obtained after dividing the measured channel signal (less electrical noise) by calibration factors for the photomultiplier relative sensitivity, channel bandwidth and oscilloscope sensitivity. The wavelength resolution for these profiles is equal to the channel bandwidth of $\sim 0.2 \text{ \AA}$. The six channel polychrometer system was designed to take line profiles of width $\sim 2 \text{ \AA}$ on one shot. Thus, impurity line profiles, typically $< 2 \text{ \AA}$ wide, were taken on a single shot. He II $4686 \text{ \AA}$ lines, particularly during the heating phase, were wider than $2 \text{ \AA}$ and only half the line profile was taken on a single shot. The two halves of the line profile were matched by making sure that the signal from the overlapping channel (see Chapter II, section 2) was not more than 10% different between the two shots. Line profiles shown in this chapter with no error bars are "one shot profiles." A uniform 10% error, although not shown, can be associated with these profiles because of the 5% errors in the channel relative sensitivities and measurement from the oscilloscope traces.

The error bars shown on the remaining line profiles are associated with the shot-to-shot light intensity fluctuation as expressed by the mean deviation of at least four shots. The general shape of the line profile is unaltered by the averaging process: i.e., the profile struc-

ture is the same for all the shots analyzed. When ion temperature is inferred from a gaussian line profile, the error is associated with the mean deviation of the full width at half maximum intensity of at least four such profiles. The gaussians were drawn by doing a linear fit to the logarithm of the intensity as a function of the square of wavelength change. Points on the profile differing by more than 25% from the best linear fit were included as singularities in the line profile. The meaning associated with these points will become clear in following portions of this chapter.

The rather insensitive square root dependence of full width on ion temperature for Doppler broadening (Eq. III.3) coupled with the previously discussed wavelength calibration error of $\pm 0.05 \text{ \AA}$, is reflected in the $\sim 30\%$ error when $T_i \lesssim 100 \text{ eV}$. The wavelength calibration error also introduces $\sim 30\%$ error in the plasma wave electric fields measured from the Stark splitting of He II $4686 \text{ \AA}$ (Eq. III.1). A gaussian fit to a Stark broadened He II $4686 \text{ \AA}$ line would introduce $\sim 50\%$ error in the plasma wave electric field,²⁴ as measured from its full width using Eq. III.2, since the wings of a Stark broadened line fall in intensity at a rate somewhat less than gaussian.

IV.2 Line Profiles for 25 GW Heating Power ($E_{\theta,A} \sim 900$ V/cm)

IV.2a Helium Line Profiles at 25 GW Anti-parallel Heating Power ($E_{\theta,A} \sim 900$ V/cm)

Fig. IV.3 shows the time development of the He II 4686 Å line profile taken using the spectroscopic set-up shown in Fig. II.6 and discussed in Section II.2 at the center of the poloidal cross-section, $R = R_0$, using an anti-parallel heating power of 25 GW (applied poloidal electric field $E_{\theta,A} \sim 900$ V/cm) and with no magnetic field probes inserted into the plasma. On the basis of this figure, it can be seen that the analysis of helium ion line profiles must be separated into two time intervals, the turbulent heating phase ($t \lesssim 5$ μsec) and the high beta tokamak phase ($t > 5$ μsec). These time intervals can also be correlated with the penetration of the poloidal skin current into the plasma (Fig. II.4). The He II 4686 Å line profiles also indicate the existence of some of the line broadening and shifting mechanisms discussed in Chapter III with regards to hydrogenic lines.

At a time $t = 0.6$ μsec, Stark splitting (Fig. IV.3a) can be observed. Using Eq. III.1, microturbulence ~ 30 kV/cm with $\omega \lesssim \omega_{pi}$ is determined. To within the localization of the spectroscopic measurement, this microturbulence can be associated with the poloidal skin current region. In addition, this part of the plasma is seen to have a

Figure IV.3 Profile of He II, line center at $4685.7\text{\AA}$ at a radial location $R=R_0$, without magnetic field probes in plasma.

25 GW Anti-parallel Heating Power.

(a) $t=0.6 \mu\text{s}$, (b) $t=1.0 \mu\text{s}$, (c) $t=2 \mu\text{s}$ and (d) $t=10 \mu\text{s}$.

Intensity in arbitrary units. Arrow indicated Doppler velocity shifted component. * indicates Stark split components.

macroscopic velocity $\sim 8 \times 10^6$ cm/sec.

$\tilde{E} \lesssim 30$ kV/cm implies, through the use of Poisson's equation, that the density fluctuations δn with a wave number k are $\delta n / \tilde{n} \sim 10^{10} \text{ cm}^{-2}$. To choose a characteristic wavelength, we take $k \sim \omega_{pi} / V_D$ or $\lambda = 10 \lambda_D$ since $V_D \sim 10 C_s$ (Debye length $\lambda_D \sim 3 \times 10^{-4}$ cm for $T_e \sim 100$ eV, $n_e = 5 \times 10^{14} \text{ cm}^{-3}$), giving an ion density fluctuation $\delta n / n \sim 10\%$. If fluctuation scale lengths are longer, then $\delta n / n$ is correspondingly higher.

At $t = 1.0 \mu\text{s}$, the plasma has moved radially outward⁴⁷ so that a region more towards the plasma center is now in view. Fig. IV.3b indicates a line profile which may be broadened by enhanced plasma wave electric fields at $\omega \lesssim \omega_{pe}$. Since the ion temperature is not well known at this time, no realistic estimate of the microscopic electric fields can be made either. However, to within the localization of the spectroscopic measurement, $\omega \lesssim \omega_{pe}$ turbulence can be associated with the plasma ahead of the poloidal skin current. This part of the plasma also has a macroscopic velocity $\sim 5 \times 10^6$ cm/sec.

At $t = 2.0 \mu\text{sec}$ (Fig. IV.3c), a part of the plasma towards the inside is being viewed. No turbulence is apparent and a temperature estimate of $T_i \sim 60 \pm 30$ eV can be made by using either the shifted or unshifted feature of the line profile. In the absence of turbulence at $t = 2.0 \mu\text{sec}$, we find the macroscopic velocity $\sim -5 \times 10^6$ cm/sec: i.e., the velocity of a part of the plasma being

observed has changed direction in going from the outer to inner plasma edge (note the blue shifted feature of the line profile in Fig. IV.3c). This follows from the fact that the red shifted feature at $t < 1.4 \mu\text{sec}$ ---labeled as macroscopic velocity in Figs. IV.3a and b---was observed to move towards shorter wavelength as time increases. At $t > 1.4 \mu\text{sec}$, the blue shifted peak appears. This suggests a poloidal circulation of the plasma which may be caused by an $E_r \times B_T$ drift (see Section IV.2b). The resulting macroscopic electric field E_r is then radially inward, of magnitude $\sim 100 \text{ V/cm}$.

At this point, it may prove valuable to discuss the reasons for not drawing a gaussian for all the profiles shown in Fig. IV.3. Fig. IV.4 shows "one-shot" He II $4686 \text{ \AA}$ line profiles, again at $R = R_0$ and 25 GW ($E_{\theta,A} \sim 900 \text{ V/cm}$) heating power without perturbing probes in the plasma, during the heating phase at time intervals of $0.2 \mu\text{sec}$.

If a gaussian profile is fitted to the data points instead of the profiles shown, then the half width is seen to increase in time: i.e., the line originating closer to the center of the plasma is wider than that from the plasma edge.⁴⁷ If the profile is then taken to be Doppler broadened, the temperature of the plasma center is higher than that at the edges. Since the poloidal skin current (Fig. II.4) is strongest at the plasma edge for $t \lesssim 1 \mu\text{sec}$, the opposite would be expected to occur: i.e., the plasma

Figure IV.4 "One shot profiles" of He II 4685.7 Å at $R=R_0$,
 25 GW Anti-parallel Heating Power;
 No magnetic field probes in plasma;
 (a) $t=0.4 \mu\text{s}$, (b) $t=0.6 \mu\text{s}$, (c) $t=0.8 \mu\text{s}$, (d) $t=1.0 \mu\text{s}$.
 Doppler velocity shifted components, $\Delta\lambda > 1\text{\AA}$, not plotted.

edge should be heated before the center. This edge heating has been observed elsewhere.^{17,18,48,49} In Torus II, as will be discussed in a later section of this chapter, edge heating has been experimentally observed at 12 GW ($E_{\theta,A} \approx 600$ V/cm) anti-parallel heating power (He II 4686 Å line profiles do not exhibit what is interpreted as Stark splitting at this heating power). Edge heating has also been predicted by a numerical simulation.¹⁹ These considerations lead us to believe that the electric field Stark effect is responsible for line broadening during the heating phase and that the He II 4686 Å line profile is as shown in Figs. IV.3 and IV.4.

A radial scan of the He II 4686 Å line profile during fast heating leads to the following conclusions:

- (1) $\omega \sim \omega_{pi}$ plasma wave turbulence is restricted to ~ 1 cm thick layer at the skin of the plasma, correlating, within spatial resolution, with the poloidal skin current layer.
- (2) $\omega \sim \omega_{pe}$ plasma wave turbulence probably extends ahead of the poloidal skin current layer.
- (3) Turbulence lasts for ~ 2 μ sec. (Note that this turbulence is driven for the risetime of the heating bank $\tau_R = 1.7$ μ sec. After crowbarring, no driving mechanism exists and $\omega \sim \omega_{pi}$ and $\omega \sim \omega_{pe}$ waves are quickly damped as they travel into the plasma.)
- (4) There is a macroscopic velocity which corresponds

to a poloidal circulation of particles in the plasma, largest in magnitude near the edges.

This macroscopic velocity persists for $\sim 15 \mu\text{sec}$.

During the high beta tokamak equilibrium phase, He II has a gaussian profile (Fig. IV.3d), indicating that Doppler broadening dominates. Fig. IV.5a shows the radial dependence of the He II-determined ion temperature at various times using 25 GW ($E_{\theta,A} \sim 900 \text{ V/cm}$) anti-parallel heating power. It should be noted that an initially peaked radial ion temperature profile ($T_i \sim 180 \text{ eV}$) becomes spatially flat with $T_i \sim 75 \text{ eV}$ during the time of high beta equilibrium ($10 \leq t \leq 30 \mu\text{sec}$). Fig. IV.5b shows the central plasma ion temperature, as well as the ion temperature at $R = R_0$, as a function of time. Note that the ion temperature is not given for $0 \leq t \leq 2 \mu\text{sec}$ because of the large plasma wave electric field Stark effect during this time period.

However, an estimate of T_i at $R=R_0$ can be made for $t=.5 \mu\text{sec}$ by noting the barely observable central dip in the Stark dominated He II 4686 Å profile of figure IV.3a. At $E \sim 30 \text{ kV/cm}$, the Stark split components are located at $\Delta\lambda \sim \pm .5\text{Å}$. If these components are Doppler broadened by 1Å corresponding to $T_i=25 \text{ eV}$, then the sum profile would be flat between $\Delta\lambda=\pm .5\text{Å}$. Thus, $\sim 1\mu\text{sec}$ into the heating phase, $T_i \sim 25 \text{ eV}$.

One further note should be made. The rather slow temporal change in T_i for $t>15\mu\text{sec}$ is consistent with the

Figure IV.5 (a) Radial dependence of the He II-determined ion temperature during the high beta tokamak phase, at $t = 5 \mu\text{s}$ and $15 \mu\text{s}$. 25 GW anti-parallel heating power.
 (b) Temporal behavior of the He II-determined ion temperature at plasma center and chamber annulus center $R = R_0$. 25 GW anti-parallel heating power.

notion of equilibrium. At $t > 15 \mu\text{sec}$, the magnetic field flux contours, as derived from magnetic field probes, change slowly in time,⁶⁸ possibly indicating that a plasma equilibrium configuration has been reached.

IV.2b Impurity Line Profiles, 25 GW Anti-Parallel Heating Power ($E_{\theta,A} \sim 900$ V/cm)

To further understand the nature of the poloidal circulation and to see whether the He II-determined ion temperature obtained for the high beta tokamak phase is reasonable, line profiles of impurities coming from the glass vacuum vessel walls, particularly of Si III 4716.65 Å, were measured at the plasma center ($R = R_0 + 3$ cm) and at $R = R_0$. Neutral helium is not observed during this time period. Therefore, He I 4713.15 Å does not present a complication in the analysis.

Si III, being helium-like, is not expected to exhibit a strong linear Stark effect at $n_e \sim 10^{15}$ cm⁻³. Doppler broadening is expected to be the dominant line broadening mechanism and is measurable for Silicon ion temperatures $\gtrsim 100$ eV. Fig. IV.6 shows semi-logarithmic plots of the intensity of the Si II 4716.65 Å line as a function of the square of the wavelength change from line center for various times, $t = 3$ μsec, 4 μsec, 10 μsec and 18 μsec, near the plasma center. Note that resulting line profiles are nearly gaussian except for earlier times ($t = 3$ μsec and 4 μsec) in which the profiles are asymmetric (points at $\Delta\lambda = + .47$ Å). This asymmetry possibly indicates a macroscopic velocity $\sim 4 \times 10^6$ cm/sec coming from a portion of the plasma outside its center: i.e., $R > R_0 + 3$ cm. At best, the signal to noise ratio was ~ 2 for only three of

Figure IV.6 Profiles of Si III 4716.65 Å at plasma center for various times. Plotted in form of logarithm of intensity as a function of the square in wavelength change from line center. 25 GW anti-parallel heating power.

the six polychrometer channels and only these signals are plotted in Fig. IV.8. Note that a Doppler broadening of $1 \text{ \AA}$ on Si III $4717 \text{ \AA}$ corresponds to a silicon ion temperature of $\sim 210 \text{ eV}$ since silicon has seven times the mass of helium. Thus, narrow silicon lines are expected and the polychrometer channels viewing the wings of the silicon lines are not expected to give significant signal.

At the plasma center, Si III $4717 \text{ \AA}$ was observable only for $t \lesssim 20 \text{ \mu sec}$. For $t \gtrsim 15 \text{ \mu sec}$ it was possible to observe Si II $5041.03 \text{ \AA}$ and this line was used to extend the impurity measurements up to later times $15 \leq t \leq 30 \text{ \mu sec}$. Fig. IV.7a shows a typical Si II $5041 \text{ \AA}$ line profile for $t = 18 \text{ \mu sec}$. The line profile is again gaussian indicating that Doppler broadening is dominant. (For $t \lesssim 15 \text{ \mu sec}$, Si II $5041 \text{ \AA}$ was distinctly non-gaussian on the higher wavelength side of the line center, again possibly due to a macroscopic velocity $\sim 5 \times 10^6 \text{ cm/sec}$. The data points from which a non-gaussian Si II $5041 \text{ \AA}$ line profile can be drawn are shown by a "x" in Fig. IV.7a.)

The ion temperature measured from Si III $4717 \text{ \AA}$ for $t \leq 18 \text{ \mu sec}$ and from Si II $5041 \text{ \AA}$ gaussian line profile at the plasma center is shown in Fig. IV.7b. Note that the temperature derived from Si II is in good agreement with that derived from Si III, possibly indicating that Si III recombines during the cooling period ($5 \text{ \mu sec} \leq t \leq 10 \text{ \mu sec}$) to form Si II. However, the ion temperature as measured from the half width of silicon lines was

Figure IV.7 (a) Profiles of Si II 5041.03 Å for $t = 8 \mu\text{s}$ and $18 \mu\text{s}$, $R = R_0 + 3\text{cm}$.
 (b) Silicon impurity ion temperature at plasma center.

25 GW anti-parallel heating power.

~ 100 eV greater than that measured from He II $4686 \text{ \AA}$. The observed equilibration in temperature between impurity and helium ions is also slow compared to the energy equilibration time of silicon in helium of $\sim 5\text{-}10 \text{ }\mu\text{sec}$ given by the classical Spitzer equation.²⁵ The difference in silicon and helium temperatures and their slow equilibration in Torus II casts doubt as to whether ionic lines of impurity or doping elements can be used as a measure of the ion temperature of the bulk plasma in a pulsed experiment of microsecond time scale. The higher silicon temperature may indicate that He II Doppler broadening underestimates the ion temperature.

In addition, near the plasma edge $R = R_0$, Si III profiles indicated a macroscopic velocity of magnitude close to that of He II: i.e., the poloidal circulation is charge and mass independent. This result was also indicated by O II $4414.9 \text{ \AA}$ and Si II $5041 \text{ \AA}$. (Note that at the plasma edge oxygen impurity was observable in the visible region. However, as oxygen migrated toward the plasma center, it was probably further ionized and its radiation would be mostly in the ultraviolet region of the spectrum and hence not accessible to this experiment.) A likely cause for the mass circulation of plasma is an $E_r \times B_T$ drift, where $E_r \sim 100 \text{ V/cm}$ (note plasma potential $\phi \sim kT_e \sim 100 \text{ volts}$) follows from the Doppler shift measurements. (Since the circulation is largest at the plasma edges, E_r is also largest at the plasma edge.) One possible cause for the

temperature difference between helium and silicon could be this macroscopic radial electric field. Impurities formed at the vacuum vessel walls could gain energy as they migrate to the center in this electric field.

IV.2C Helium Line Profiles, 25 GW Parallel Heating Power

$$(E_{\theta,A} \approx 900 \text{ V/cm})$$

Fig. IV.8 shows profiles of He II 4685.7 Å taken at $R = R_0 + 3 \text{ cm}$: i.e., slightly outside the radial location of the plasma center for $t = 1, 5$ and $9 \text{ } \mu\text{sec}$. Semi-log representation (i.e., log of the intensity as a function of change in the square of wavelength from line center) is used, and the higher wavelength side of the line only is plotted. Fig. IV.9a shows the intensity as a function of wavelength change for a time $t = 5 \text{ } \mu\text{sec}$. It should be noted that all these line profiles are quite well approximated by a gaussian and that there appears to be no distinction between the heating phase ($t < 5 \text{ } \mu\text{sec}$) and the high beta tokamak phase ($t \gtrsim 5 \text{ } \mu\text{sec}$). This is taken to mean that no measureable microscopic plasma wave turbulence develops for the case of parallel operation.

From the full width at half maximum of the gaussian He II 4686 Å line profiles, the ion temperature can be determined by using Eq. III.3. The ion temperature as a function of time is shown in Fig. IV.9b. It should be noted that the maximum central ion temperature is $\approx 50 \text{ eV}$ for parallel operation as compared to $\approx 150 \text{ eV}$ for anti-parallel operation at the same heating power. The relatively large error bars in Fig. IV.9b are again largely attributable to the insensitive dependence of ion temperature on half width for Doppler broadening.

Figure IV.8 He II 4685.7 Å line profiles in semi-logarithmic form for various times. 25 GW parallel heating power.

The lack of turbulence, as observed spectroscopically, in parallel operation is consistent with the lack of a strong induced poloidal skin current: i.e., the electron drift speed is on the order of the ion sound speed. The lowered ion temperature is also consistent with the lack of turbulence since the ions are partly heated by the scattering of ion acoustic waves, induced by the turbulence from the ions.¹⁵ The electrons are also observed to be colder for parallel operation than anti-parallel operation at the same heating power (see next chapter). The lowered electron temperature is also consistent with the lack of turbulence since the electrons are heated by the enhanced resistive dissipation of the skin current, an effect caused by the turbulence.^{12,13,19} A numerical simulation of Torus II heating also indicates a lowered plasma temperature for parallel operation.¹⁹ These associations of turbulence with heating will be discussed in more detail in a later chapter of this thesis.

IV.3 Line Profiles for 12 GW Anti-parallel Heating Power

$$(E_{\theta,A} \approx 600 \text{ V/cm})$$

Fig. IV.10 shows the time development of the He II 4686 Å line profile at the center of the poloidal cross-section, $R = R_0$, using an anti-parallel heating power of 12 GW (applied poloidal electric field $E_{\theta,A} \approx 600 \text{ V/cm}$) and with no magnetic field probes inserted into the plasma. On the basis of these profiles, it can be concluded that there is a distinct difference between 25 GW (section IV.2a, Fig. IV.3) and 12 GW anti-parallel heating power.

Figs. IV.10a, b and c at times $t = 1.2, 1.6$ and $5 \mu\text{sec}$, respectively, possibly indicate the existence of plasma frequency satellites about the unshifted line wavelength. The location of these satellites gives an electron density $n_e \approx 6 \times 10^{14} \text{ cm}^{-3}$ ($\omega_{pe} \approx 1.5 \times 10^{12} \text{ rad/sec}$). The error in this density estimate is large ($\sim 50\%$) due to the fact that the location of the satellite is uncertain to the bandwidth of the polychrometer channel. Thus, the turbulence induced at lower heating powers is found to be of higher frequency ($\omega \approx \omega_{pe}$) and lower magnitude ($E \lesssim 10 \text{ kV/cm}$) than the turbulence induced at higher powers. Also, the turbulence does not appear to be localized to the skin of the plasma since the He II 4686 Å profiles for $t \lesssim 5 \mu\text{sec}$ all show the existence of ω_{pe} satellites. (Note that a time scan of the line profile at a fixed radial location is equivalent to a radial scan of the line profile.)

Figure IV.10 Profiles of He II 4685.7 Å for various times at $R=R_0$; 12 GW anti-parallel heating.

Intensity in arbitrary units. Arrow indicates Doppler velocity shifted component.
 * indicates ω_{pe} satellites.

since heating of the plasma causes a rapid outward motion of the plasma.)

For times $t > 5 \mu\text{sec}$, a macroscopic velocity $\sim 5 \times 10^6$ cm/sec becomes evident in the line profile. The lower wavelength component of the He II 4686 Å line profile shown in Fig. IV.10d for $t = 16 \mu\text{sec}$ has a macroscopic velocity Doppler shift as its most likely explanation. The relatively broad velocity feature may be due to a range of velocities coupled with thermal Doppler broadening. The existence of macroscopic motion at earlier times $t \lesssim 5 \mu\text{sec}$ is also possible and may be used to explain the flat appearance of the He II 4686 Å line profile at $t = 5 \mu\text{sec}$ between $\Delta\lambda \sim -.5 \text{ Å}$ and $\Delta\lambda \sim -1.2 \text{ Å}$. It should also be noted that the inner edge of the plasma is at $R = R_0$ for $t \gtrsim 2 \mu\text{sec}$.

The outer edge of the plasma was observed at $R = R_0 + 3 \text{ cm}$ through the measurement of the impurity lines of O II 4414.19 Å and Si II 5041.03 Å. These impurity line profiles at $R = R_0 + 3 \text{ cm}$ and 12 GW anti-parallel heating power had gaussian central features but indicated a red shifted feature at $\Delta\lambda \sim .8 \text{ Å}$ corresponding to a macroscopic velocity $\sim 5 \times 10^6$ cm/sec. Thus, the macroscopic velocity again appears to be a poloidal circulation, dominant near the plasma edges and independent of the particle mass. Furthermore, the poloidal circulation is the same in magnitude for both 12 GW and 25 GW anti-parallel heating power, indicating that, if the circulation is an

$E_r \times B_T$ drift, the ratio E_r/B_T is a constant. Note that B_T decreases by a factor of ~ 1.5 in going from 25 GW to 12 GW anti-parallel heating power.

Fig. IV.11 shows the ion temperature at $R = R_0$ derived from the half width of the central component of the He II 4686 Å line and at $R = R_0 + 3$ cm derived from the half width of the central component of Si II 5041 Å. Also shown in this figure is the He II-determined ion temperature at $R = R_0 - 1.5$ cm. The lower value of T_i at $R = R_0$ at $t = 1.5$ μ sec is a result of plasma motion and can be taken to indicate that the edge of the plasma is heated before the plasma center. This edge heating effect can also be seen from noting that the He II-determined ion temperature at $R = R_0 - 1.5$ cm is greater than that at $R = R_0$ for times $t \lesssim 1.5$ μ sec. The sudden decrease in ion temperature at $R = R_0 - 1.5$ cm for $t > 2$ μ sec is largely due to the outward motion of the plasma. It should be noted that the He II-determined ion temperature falls quickly to ~ 20 eV after 10 μ sec.

It is very unlikely that the plasma temperature is not symmetric about the plasma center, and all indications thus far from He II 4686 Å measurements are that it is. From magnetic field measurements, it can be seen that the plasma center is located at approximately $R = R_0 + 1.5$ cm for 12 GW anti-parallel heating power and $t \gtrsim 3$ sec. Thus, one would expect the temperature at $R = R_0$ to be approximately the same as at $R = R_0 + 3$ cm since both radial lo-

Figure IV.11 Ion temperature determined from Silicon II impurity and Helium II plasma ion line profiles for various radial locations. 12 GW anti-parallel heating power.

cations are an equal distance from the plasma center. However, the Si II-derived ion temperature is ~ 100 eV greater than the He II-determined ion temperature (Fig. IV.11).

O II 4414 Å also showed this trend. Thus, it is doubtful that impurity-determined ion temperatures are representative of the plasma temperature, again possibly due to the existence of the macroscopic radial electric field inferred from Doppler shifted components of He II and impurity lines.

IV.4 Effect of Magnetic Field Probes on Spectral Line Profiles

Line profile of He II 4686 Å were taken during runs when a pair of magnetic probes were in the plasma as shown in Fig. II.8. Fig. IV.12 shows the effect of these probes at $t = 5 \mu\text{sec}$, $R = R_0$ and 25 GW ($E_{\theta, A} \approx 900 \text{ V/cm}$) anti-parallel heating power upon the He II 4686 Å line. Stark splitting (Fig. IV.12a) indicates microturbulence in the case with probes. Without probes in the plasma (Fig. IV.12b), He II 4686 Å has a nearly gaussian profile, showing no evidence of enhanced microscopic electric fields. (Note that turbulence is not expected at such a late time following the "heating" and "soaking in" of the magnetic fields.)

The line profile measurements were done at a toroidal location downstream from the probes, in the direction of ion current flow (Fig. II.8). Theory^{50,51} indicates that the ion density in the probe wake depends on $\exp(-V_0/V_{Ti})$, R_0 and ρ_i where V_0 is the ion drift speed associated with a current density $n_i ZeV_0$, $V_{Ti} \equiv (T_i/m_i)$ is the ion thermal speed, R_0 is the probe diameter, $\rho_i \equiv V_{Ti}/\omega_{ci}$ is the ion Larmour radius, and ω_{ci} is the ion cyclotron frequency. The length of the probe wake increases with increasing T_i and R_0 .

At 25 GW heating power, when $T_i > 100 \text{ eV}$, a probe wake of length $\sim 20 \text{ cm}$ forms and affects a portion of

Figure IV.12 Effect of magnetic field probes on He II 4686 Å line profile. 25 GW anti-parallel heating power. Profiles measured 18 cm away from magnetic field probes in direction of toroidal ion plasma current and in the probe wake.

the plasma being viewed by the line profile measurement. The Stark splitting gives roughly the same level of turbulent electric field as before (~ 30 kV/cm), indicating that the probe sets up turbulence, even at later times ($t > 2$ μ sec) when no turbulence driving mechanism exists. On the other hand, at 12 GW heating power, when the He II-determined ion temperature is ~ 50 eV, the presence of magnetic probes has no apparent effect on the He II 4686 $\text{\AA}$ line profiles. This may indicate that the probe wake is < 15 cm, in agreement with the temperature scaling of the probe wake length, and additional collisional effects.

For $t > 10$ μ sec, He II 4686 $\text{\AA}$ (with probes) is gaussian indicating an ion temperature ($\sim 60 \pm 15$ eV) equal to that without probes in the plasma. This is not meant to say that probes do not affect the ion temperature, since temperature changes $\sim 10\%$ would be hidden in the typical 30% errors associated with Doppler broadening when $T_i \lesssim 100$ eV.

The probe wake was further investigated by looking at the total intensity of a line radiated near the probes. Particular attention was paid to He II 4686 $\text{\AA}$ which showed an increased intensity for $t \gtrsim 5$ μ sec when compared to its intensity at the same location without the probes. A line to continuum ratio²⁸ measurement indicates a lowered electron temperature in the vicinity of the probes. However, due to the inaccuracy of this method for $T_e \gtrsim 30$ eV, no quantitative measurement of the electron temperature

effects of the probes could be made.

V. SPECTROSCOPIC ELECTRON TEMPERATURE MEASUREMENTS

During the high beta tokamak phase of the Torus II experiment, the ion temperature is expected to be approximately the same as the electron temperature, since the collisional Spitzer ion-electron energy equilibration time $\sim 5 \mu\text{sec}$.²⁵ For an electron temperature estimate the polychrometer of Fig. II.7 was modified, into that of Fig. V.1, to look at total line and $\sim 15 \text{ \AA}$ continuum band intensity by using a 600 line/mm grating and 1 mm thick lucite light guides. Typically, only two photomultiplier tubes were used. The two tubes could look at wavelengths separated by as much as $1500 \text{ \AA}$ by using opaque material spacers as thick as $\sim 10 \text{ cm}$.

Several methods are available for the measurement of the electron temperature by spectroscopy in the visible spectrum region. The most common method is the total line intensity to continuum band intensity ratio measurement which is related to electron temperature through the use of the local thermodynamic equilibrium model for radiation emitted by the plasma.^{28,29} A second method is by measuring the time dependence of the total line intensity and relating the resulting ionization or

- (a) 1mm thick lucite light guides.
- (b) Opaque material spacer, allows for up to 1500 Å between photomultiplier tubes (PMT).
Screws (c), provided in a blackened aluminum plate (d) which fits into the film plate holder (e) at the exit focal plane of McPherson spectrograph, hold lucite light guide and spacer assembly in place.

Figure V.1 Schematic diagram of two channel polychrometer used for total line and 15 Å continuum band intensity measurements.

recombination rate of the emitting ions to the electron temperature by using the time dependent corona model for plasma line radiation.^{26,27} An added feature of this rate measurement is that the impurity concentration of a given element can also be measured when an impurity ion line is used. Both of these methods were used on the Torus II experiment and will be discussed in detail below. Comparisons will be made with the electron temperature as measured by an X-ray diagnostic⁷ which relates the soft X-ray to the temperature associated with the electrons in the fast portion of the electron velocity distribution function.³⁰

The statement that soft X-ray measurements observe the higher energy tail electrons can be seen from the equation relating the emission intensity of free-free continuum radiation, I , to frequency, ν ³⁰

$$\frac{dI}{d\nu} \propto n_e n_i Z_i^2 (T_e)^{-1/2} \exp(-h\nu/T_e)$$

where Z_i is the plasma ion charge and $h\nu$ is the energy of the emitted photon. It can be seen that the emission of a given photon energy is related to electron temperature, T_e , and that the continuum maximum shifts toward the X-ray region (increasing ν) as T_e increases. Alternatively, the X-ray continuum is governed by the hotter tail (faster) plasma electrons. Note that T_e is derived

from the slope of dI/dv (for free-free continuum emission) plotted as a function of v .

The validity of soft X-ray measurements for bulk plasma electron temperature determination can be seen from estimates of the electron-electron collision time, slowing down time of fast electrons by thermal plasma electrons and energy equilibration time between hot and thermal electrons. For ~ 1 keV soft X-ray channel electrons in a 100 eV, 10^{15} cm^{-3} background plasma, these times are $\sim 1 \text{ } \mu\text{sec}^{25}$ and it is not unlikely that soft X-ray flux temperature measurements are characteristic of the plasma electron temperature.

V.1 Preliminary Spectroscopy

Preliminary to all of the quantitative visible spectroscopy experiments involving the use of photomultiplier tubes was the identification of radiated lines from the helium discharge of Torus II. For this purpose, the spectroscopy apparatus shown in Fig. II.6 was used with a 600 line/mm grating installed in the McPherson with film at the exit plane of the spectrometer. Fig. V.2a shows a typical spectrogram for a single Torus II helium discharge at 25 GW anti-parallel heating power covering a wavelength range from 6000 Å (far right) to 4200 Å (far left of picture) with a linear dispersion of 15.8 Å/mm and an entrance slit of 30 micron width.

When the spectrogram was viewed under a microscope, the average width of the line was ~ 2 Å, leading to a design of the polychrometer width of 2 Å used in the line profile measurements discussed in Chapter IV. The ~ 2 Å line widths also led to the choice of channel widths ~ 10 Å when total line intensity measurements were of interest. Silicon and oxygen lines were found to be the dominant impurities. Most of the impurity measurements were performed on silicon since its lines appeared to be brighter than the lines of oxygen and therefore are expected to exhibit a better light signal to electrical noise ratio. Furthermore, a relatively wide band of the spectrum at a wavelength larger than (but near to) He II

4686 Å containing no lines was observed on the spectrograms; this led to measurements in this region for the continuum intensity used in the He II line-to-continuum ratio electron temperature measurements.

The presence of sodium lines is due to the fact that the Torus II vacuum chamber is made of pyrex glass which has $\sim 12\%$ NaO_2 composition. It is not unlikely that some of this sodium, along with the silicon and oxygen, is released from the pyrex walls during the plasma discharges. The noticeable lack of nitrogen lines is indicative of the good vacuum achieved in the experiment. The helium fill gas is not introduced until the vacuum chamber has a base pressure $\leq 3 \times 10^{-7}$ Torr.

The ~ 2 Å width of He II 4686 Å indicates an ion temperature of ~ 100 eV consistent with that derived at from line profile measurements presented in Chapter IV. However, since the width of the line as it appears on film is highly dependent on the exposure of the film by the plasma light intensity, the width of the lines on the spectrogram is only a crude indication of a modestly hot temperature. Furthermore, there is no time resolution in these photographic measurements. The desire for time resolution coupled with what appeared to be a modestly hot plasma gave encouragement to the previously described line profile measurements. Similarly, the relative intensity measurements derived from spectrograms are also dependent on film exposure. Thus, any quantitative mea-

surement of plasma parameters from relative intensity requires the use of photomultiplier tubes, and these measurements are described below.

(a) Typical spectrogram (15.6 Å/mm) of helium discharge in Torus II,
 $R=R_0$.

25 GW anti-parallel heating power.
 Lines not identified are other silicon, oxygen, sodium and neutral helium line transitions.

(b) Time dependence of Silicon impurity lines, $R=R_0$.
 25 GW anti-parallel heating power.

Figure V.2

V.2 Impurity Line Intensity Measurements

The ionization rate of impurities can be related to the electron temperature of the plasma and the number density of impurities in the plasma by making use of the time-dependent corona model. The model assumes that:

(1) the rate of change of the plasma parameters is slow compared to the atomic lifetime of the excited level from which the line originates; (2) the free electron thermalization time is less than the time over which plasma parameters change; (3) ionization is by collision of a free electron with an atom or ion in its ground level and that recombination is radiative; (4) step-wise ionization occurs only: i.e., $Z \rightarrow Z + 1 \rightarrow Z + 2$, etc; and (5) spectral line radiation is produced by an inelastic electron collision exciting an ion from its ground state and the subsequent decay of the excited level to the ground state.

Under these assumptions, which are valid for once ionized states when $n_e < 5 \times 10^{14} \text{ cm}^{-3}$ at $T_e = 50 \text{ eV}$ (e.g., He II, Si II, O II) and the validity of which varies as $n_e \lesssim k(Z + 1)^6 T_e^{1/2} \exp [(Z + 1)^2 / T_e]$ where k is a constant and Z is the ion charge,²⁶ the ionization rate can be written as

$$S(T_e, \chi_Z, Z) \equiv (n_e \tau_{\text{ion}, Z})^{-1} \\ = \frac{1.1 \times 10^{-5}}{\chi_Z^{3/2}} \frac{\zeta_Z \left(\frac{kT_e}{\chi_Z} \right)^{1/2}}{6 + \frac{kT_e}{\chi_Z}} \exp(-\chi_Z / kT_e) \quad (\text{V.1})$$

where an ion of charge Z with ionization potential χ_Z , having ζ_Z electrons in its outer shell is in a plasma with electron temperature T_e ; n_e is the electron density (in cm^{-3}) and $\tau_{\text{ion},Z}$ is the time (in seconds) required to ionize from charge Z to charge $Z+1$. Fig. V.3 shows a plot of $n_e \tau_{\text{ion},Z}$ (in $\text{cm}^{-3} \mu\text{sec}$) for various stages of ionization of silicon as a function of electron temperature, T_e (in eV). For example, this curve indicates that a silicon impurity in a plasma with $n_e = 10^{14} \text{ cm}^{-3}$ with $T_e \sim 50 \text{ eV}$ will be twice ionized (i.e., will be in a Si III state) within $1 \mu\text{sec}$.

When τ_{ion} is experimentally taken to be the time over which a total line intensity goes from zero to maximum, then it can be assumed that all the impurity density is in the charge state associated with the observed line. By taking the ratio of Eq. V.1 for two successive stages of ionization of charge Z and $Z+1$, then T_e can be estimated from

$$\frac{\tau_{\text{ion},Z+1}}{\tau_{\text{ion},Z}} = \frac{\chi_{Z+1}}{\chi_Z} \frac{\zeta_Z}{\zeta_{Z+1}} \frac{(6 + \frac{kT_e}{\chi_{Z+1}})}{(6 + \frac{kT_e}{\chi_Z})} \exp [-(\chi_Z - \chi_{Z+1})/kT_e] \quad (\text{V.2})$$

by measuring the time for the corresponding lines to go from zero to maximum. It should be noted that the most sensitive portion of this equation to T_e is $kT_e \sim \chi_{Z+1} - \chi_Z$. Hence, the accuracy of this method does not decrease appreciably

Figure V.3 Product of electron density (n_e) and ionization time (τ_{ion}), for various stages of ionization, as a function of electron temperature (T_e). From time dependent corona model.

ciably with increasing electron temperature as long as higher stages of ionization are used for the measurement. On the other hand, higher stages of ionization require the measurement to be done in the vacuum ultraviolet region of the spectrum.

Fig. V.4 shows Eq. V.2 plotted for the ratio of the time required for Si II $\rightarrow$ Si III divided by the time required for Si I $\rightarrow$ Si II: i.e., τ_{III}/τ_{II} . For example, at $T_e \sim 20$ eV it takes ten times as long for Si II $\rightarrow$ Si III as it does Si I $\rightarrow$ Si II. In the case of Torus II, the time required to reach the maximum intensity of Si II 5670 Å (charge state Z in Eq. V.2) and Si III 4553 Å (charge state Z + 1 in Eq. V.2) was measured. The typical time dependence of these two lines is shown in Fig. V.2b for 25 GW anti-parallel heating power at $R = R_0$. The time for Si II 5670 Å to go from zero to maximum is $\tau_{II} \sim 2$ μ sec and for Si III 4553 Å, it is $\tau_{III} \sim 8$ μ sec. Thus, consulting Fig. V.4 for $\tau_{III}/\tau_{II} \sim 4$, the electron temperature is $T_e < 100$ eV during the high beta tokamak phase of Torus II. Fig. V.2b also shows that, Si III increases in intensity as Si II decreases in intensity ($5 \leq t \leq 12$ μ sec), indicating that step-wise ionization indeed occurs. Consulting n_T for Si II in Fig. V.3, with $\tau = 2$ μ sec and $T_e = 100$ eV, the silicon impurity density can be estimated to be $\sim 1 \times 10^{13}$ cm⁻³ or 1% of the helium ion plasma density. The oxygen impurity density is probably 2% of the helium ion density since glass is Si O₂. A 1% silicon and 2%

Figure V.4 Ratio of $\tau_{ion}(Si I \rightarrow Si II)$ and $\tau_{ion}(Si II \rightarrow Si III)$ as a function of T_e .

oxygen impurity concentration would not alone account for the rapid cooling of the ions (and probably electrons) observed during $5 \leq t \leq 10 \mu\text{sec}$ (see Figs. IV.5b and IV.11).^{53,54,55} A more complete discussion of energy loss in Torus II is given in section 2 of chapter VI.

The silicon impurity number density is estimated from n_e in figure V.3. At $R=R_0$, the edge of the plasma is observed⁴⁷ where the intensity of visible wavelength silicon lines is observed to be greater than the intensity of visible wavelength He II lines. This implies, after accounting for the different line oscillator strengths, a larger density of impurities than helium in the "low density cloud" surrounding the main plasma column. Thus, for once ionized silicon, $n_{\text{imp}}(\text{Si II}) \sim n_e \sim 10^{13} \text{ cm}^{-3}$ in this "low density cloud" region.

In the strict sense, use of the $n_e \tau_{\text{ion}}$ vs. T_e plot (figure V.3) should be only for the Si V state since the majority of silicon impurities would be at least four times ionized at $T_e=100 \text{ eV}$ and $n_e \sim 10^{14} \text{ cm}^{-3}$. Similarly, the accuracy of T_e as derived from the ratio of ionization times would increase if Si IV and Si V ionization times were used. Unfortunately, line radiation from silicon states more than twice ionized would be in the ultraviolet wavelength range and inaccessible to this experiment.

V.3 He II Line to Continuum Ratio Measurement of Electron Temperature

An alternate method for measuring the electron temperature in a helium plasma is by measuring the ratio of the He II 4686 Å line intensity to the intensity of light in a band of continuum near the line. As the electron temperature increases, the line intensity should decrease while the continuum intensity should increase.* Therefore, the line to continuum intensity ratio is a decreasing function of temperature and has the following functional dependence when the line intensity is assumed to follow local thermodynamic equilibrium:²⁸

$$\frac{I_l}{I_c} \propto \frac{1}{\lambda_0 \Delta \lambda} \frac{1}{kT_e} \exp [(E_\infty - E_l)/kT_e] \quad (V.3)$$

* The intensity of the line is proportional to the number of ions in the state associated with the radiated line.²⁸

As the temperature increases, the number of particles, being given by a Boltzmann distribution e^{-E/kT_e} , with E being the energy of the emitting state, decreases. Continuum is taken to be free-free Bremsstrahlung radiation and free-bound recombination-continuum radiation and is seen to be a complicated, but increasing, function of electron temperature.^{28,56}

where E_{∞} is the ionization potential, E_{ℓ} is the energy associated with the lower state of the radiative transition, λ_0 is the wavelength of the transition, I_c is the intensity of the continuum in a wavelength band of $\Delta\lambda$ and I_{ℓ} is the intensity of the line. Note that the ratio is most sensitive in the region $kT_e \sim E_{\infty} - E_{\ell}$ which corresponds to $T_e \sim 20$ eV for He II 4686 Å.

The continuum intensity is related to the electron density. When the Saha equation is used to relate the density of ions in a given ionization state to the electron density, a procedure which is allowed only under the assumption of local thermodynamic equilibrium, the line to continuum ratio becomes independent of density. When local thermodynamic equilibrium is not strictly valid, the density of ions in a given ionization state appears in the line intensity equation and the electron density appears in the continuum intensity equation. Therefore, the line to continuum ratio cannot be strictly used for a simple estimate of the electron temperature. However, when T_e increases, the number of particles in lower ionization states decreases (e.g., see Fig. V.2) and the intensity of the lines associated with these ionization states decreases. Continuum intensity is an increasing function of T_e . Therefore, the line to continuum ratio is still a decreasing function of T_e . In addition, further inaccuracies are introduced in the line to continuum ratio measurement when the impurity density is comparable to the density of

ions radiating the line being measured. The continuum associated with the impurity line (e.g., Si III 4683 Å close to He II 4686 Å) will tend to increase the "clean plasma" continuum level, leading to an overestimate of the electron temperature.

The line intensity to 100 Å wavelength band continuum intensity is plotted in Fig. V.5 as a function of electron temperature. For $T_e \leq 45$ eV (500×10^3 °K), the figure is as it appears in Griem.²⁸ For $T_e > 45$ eV, a linear extension of Griem's curve has been added since for $T_e > E_\infty - E_\ell$, the temperature dependence of the line to continuum ratio is basically proportional to $\exp [(E_\infty - E_\ell)/kT_e]$. However, it should be emphasized that the local thermodynamic equilibrium model for He II 4686 Å line radiation is strictly not valid for $T_e > 50$ eV and $n_e \sim 10^{15}$ cm⁻³, thereby introducing large errors (~50%) for temperature estimates ~ 50 eV in Torus II. The general decreasing trend of the line to continuum ratio with increasing T_e is still valid.

Fig. V.6 shows the time dependence of He II 4686 Å and a 15 Å band of continuum centered at 4725 Å for the cases of 50 kV and 75 kV anti-parallel heating power and $R = R_0$. If I'_ℓ is the signal measured from the He II 4686 Å oscilloscope trace and I'_c is the signal measured from the continuum oscilloscope trace and assuming that I'_c and I'_ℓ have been adjusted for the possibly different oscilloscope gains, then Fig. V.5 can be used to obtain T_e when

Figure V.5 He II line to continuum intensity ratio (I_g/I_c) for ionized Helium lines as a function of T_e .

(From Griem, Reference 28)

12 GW anti-parallel power

He II 4686 Å
50 mV/div, 5 μs/div

15 Å continuum around 4724 Å
10 mV/div, 5 μs/div

application of heating pulse ($t=0\mu\text{s}$)

25 GW anti-parallel power

He II 4686 Å
50 mV/div, 5 μs/div

15 Å continuum around 4724 Å
10 mV/div, 5 μs/div

Figure V.6 Total He II 4686 Å line and 15 Å band continuum intensity oscilloscope traces for 12 GW and 25 GW anti-parallel heating power.

$$\frac{I_l}{I_c} \approx \frac{I'_l - I'_c}{7I'_c}$$

The factor of 7 occurs from the adjustment of the 15 Å band of continuum viewed by the measurement on Torus II to the 100 Å band used to obtain Fig. V.5.

Measurements of the line to continuum ratio in Torus II indicate $T_e \lesssim 80$ eV for $t > 5$ μsec in the case of 25 GW anti-parallel heating power and $T_e \gtrsim 50$ eV for $3 < t < 5$ μsec dropping to $T_e \lesssim 50$ eV for $t > 10$ μsec, in the case of 12 GW anti-parallel heating power. Note that these estimates of electron temperature are not inconsistent with the ion temperature as determined from the He II 4686 Å line width (see Fig. IV.5b and IV.11).

The X-ray measurement of the temperature in Torus II⁷ operated at 25 GW anti-parallel heating power indicates that $T_e \gtrsim 150$ eV at $R = R_0 + 3$ for $t \gtrsim 1$ μsec and $T_e \lesssim 100$ eV for $t > 5$ μsec. At 12 GW anti-parallel heating power, the X-ray flux was insufficient to be detected, indicating that $T_e < 100$ eV.

Thus, the various methods used to determine T_e ---ionization rate of impurities, line to continuum ratio and soft X-ray flux---indicate $T_e \lesssim 100$ eV for 25 GW anti-parallel heating power. The measurements also confirm that the ions and electrons are in fairly close equilibrium in the plasma and give confidence in the He II-determined ion

temperature discussed in Chapte IV.

Additional evidence for a modestly warm Torus II plasma is the fact that neutral helium is not observed until late in time ($t > 25 \mu\text{sec}$ -- consult figure A.1 in the appendix). This indicates that a He II to He I line intensity ratio as discussed by Griem²⁸ cannot be taken accurately and that T_e is greater than 10 eV.

VI. DISCUSSION OF HEATING AND COOLING MECHANISMS IN TORUS II

VI.1 Interpretation of Enhanced Resistivity and Ion Heating from Turbulence

The soft X-ray measurements briefly discussed in Section 4 of Chapter V indicate that the electron temperature rises to ~ 175 eV within 1 μ sec after the 25 GW anti-parallel heating power pulse is applied. An extrapolation of Fig. IV.5b to times $t < 5$ μ sec indicates that the ion temperature is ~ 50 eV during the heating phase. Thus, $T_e > T_i$ during the heating phase and ion acoustic turbulence is expected to develop.^{17,57-59} From the presentation and discussion in Sections 2a and 2b of Chapter IV, low frequency ($\omega \lesssim \omega_{pi}$) plasma waves with large amplitudes ($E \lesssim 30$ kV/cm, $\delta n/n \lesssim 10\%$) were observed during the heating phase when Torus II is operated at 25 GW anti-parallel heating power. The frequency of the turbulence further indicates an ion acoustic origin.

The energy content of plasma waves relative to the plasma energy

$$\zeta \equiv \frac{\langle E^2 \rangle / 8\pi}{n_e k T_e} \quad (\text{VI.1})$$

can be used as a measure of turbulence. For a thermal plasma^{21,42}

$$\zeta \sim (18\pi^2 n_e \lambda_D^3)^{-1}$$

where λ_D is the Debye length ($\sim 3 \times 10^{-4}$ cm for Torus II). Taking $n_e = 5 \times 10^{14} \text{ cm}^{-3}$ and $T_e \sim 100 \text{ eV}$ gives $\zeta \sim 3 \times 10^{-6}$ for a thermal plasma compared to $\zeta \sim 5 \times 10^{-3}$ during the heating phase of Torus II. Thus, the energy content in plasma waves during heating is several thousand times above the thermal level. This is not uncommon for turbulence associated with the excitation of longitudinal plasma waves.^{14,42,60}

The induced turbulence produces a spectrum of plasma waves and the resulting wave-particle interactions increase the effective collision frequency. The ion acoustic waves are driven unstable if the electron drift velocity resulting from the induced poloidal skin current ($V_d = j/n_e e$) is greater than the local ion sound speed. When this occurs, the enhanced electrical resistivity can be explained in terms of the drift instability of ion acoustic waves^{14,59} through an enhanced effective collision frequency, ν_{eff} :

$$\nu_{\text{eff}} = \omega_{ce} \left(\frac{m_e}{m_i} \right)^{1/2} \left(\frac{\omega_{pe}}{2c^2} \right) \left(\frac{4\pi n_e m_e}{B_T^2} \right) \zeta \ln \left| \frac{4\pi n_e m_e}{B_T^2} c^2 \right| \quad (\text{VI.2})$$

where $\varepsilon = \frac{1}{B_T} \frac{\partial B_T}{\partial r}$ is the magnetic field gradient and ω_{ce} is the electron cyclotron frequency. (Note that the electrical resistivity, η , is related to the collision frequency, ν , by $\eta = 4\pi\nu_{eff}/\omega_{pe}^2$.) During the heating phase of Torus II (25 GW anti-parallel heating power), $\nu_{eff} \approx 5 \times 10^9 \text{ sec}^{-1}$. This is to be compared with the Spitzer 90° electron-ion collision frequency²⁵

$$\nu_{ei} = 3.1 \times 10^6 Z n_i T_e^{-3/2} \ln \Lambda$$

(n_i is in cm^{-3} , T_e in eV and Coulomb logarithm $\ln \Lambda \approx 10$) of $\approx 4 \times 10^7 \text{ sec}^{-1}$. Thus, the electrical resistivity during the heating phase is ≈ 100 times Spitzer value and in agreement with the value obtained from the magnetic field probe measurements discussed in Section 2 of Chapter 2. This enhancement in electrical resistivity is in agreement with data obtained in similar ($\omega_{pe}/\omega_{ce} \approx 10$) experiments.⁶¹ The resulting enhancement in ohmic dissipation (ηj^2) mainly heats the plasma electrons.

Ions are heated when ion-sound oscillations are scattered by the ions, which thereby obtain a fraction of the wave energy. An estimate of this heating rate^{15,58} gives

$$\frac{dT_i}{dt} \approx 10^{-1} \zeta^2 T_e \omega_{pi} \quad (\text{VI.3})$$

$\approx 50 \text{ eV}/\mu\text{sec}$ for 25 GW anti-parallel heating power operation of Torus II, so that one expects---on theoretical (magnetic field effects are neglected because $\omega_{pi}/\omega_{ci} \approx 10$)

grounds---a time constant for wave energy transfer to the ions on the order of a few microseconds in our apparatus.

The turbulence is observed to last for $\sim 2 \mu\text{sec}$. The He II 4686 Å line profile at this time may indicate the existence of a hotter ion component. This has previously been experimentally observed⁶ and is believed to be partly responsible for the stabilization of ion sound turbulence.⁷

A simplified local energy accounting can be performed at the skin of the plasma during the heating phase assuming a characteristic heating time $\tau \sim 1 \mu\text{sec}$ and a gradient scale length on the order of the skin depth $\sim 1 \text{ cm}$. The local ohmic dissipation at the skin $\eta j^2 \tau$ with electrical resistivity $\eta \sim 2 \times 10^{-2} \text{ ohm-cm} \sim 100$ times Spitzer value and current density $j \sim 5 \times 10^3 \text{ A/cm}^2$ is 0.5 Joules/cm^3 . The energy used in changing the magnetic field structure by $\sim 5 \text{ kG}$ during heating is $\sim 0.1 \text{ J/cm}^3$. An average plasma volume acquires an energy (taking $n_e kT_e + n_i kT_i$ with $n_e = 2n_i \sim 10^{15} \text{ cm}^{-3}$ and $T_e = 2T_i \sim 100 \text{ eV}$) of $\sim 0.05 \text{ J/cm}^3$. Since, from the discussion in the appendix, the Z-pinch plasma contains excited neutral helium atoms, a comparable amount of energy ($\sim 0.1 \text{ J/cm}^3$) deposited at the skin of the plasma is used to ionize completely the helium atom (ionization potential = 54.4 eV/particle). It is not unlikely that the induced turbulence transfers the heat to the core of the plasma. (Note from Fig. 6b that the plasma center does not reach its maximum temperature until 5 μsec after

the heating pulse is applied.)

Torus II has an alternate mode of operation, in which the fast toroidal magnetic field change is applied parallel rather than anti-parallel to the initial toroidal bias field. In this mode, the magnetic field probes detect significantly less poloidal skin current than in the field reversal mode of operation. The He II 4686 Å line shows no evidence of turbulence developing (i.e., Doppler broadening appears to dominate) and the He II-determined ion temperature, at 25 GW parallel heating power, reaches a maximum of ~ 50 eV compared to ~ 200 eV for 25 GW anti-parallel operation, and equal to that obtained for 12 GW anti-parallel operation. This points to the advantages of anti-parallel operation in terms of heating efficiency.

For the case of 25 GW parallel heating power operation, no turbulence is observed to develop, and the ion heating rate due to turbulence is zero. Thus, the electrons are heated by classical ohmic dissipation of the toroidal plasma current and the small induced skin current. The ions are heated by electron-ion collisions over a time period corresponding to the classical Spitzer ion-electron energy equilibration time.

In the case of 12 GW anti-parallel heating power operation, the induced turbulence is approximately a factor of three less in amplitude than at 25 GW anti-parallel heating power operation. Thus, from the ion heating rate equation VI.3, the ion heating from turbulence is signifi-

cantly reduced (by a factor of 5-10 compared to that of 25 GW anti-parallel). As a result, the ions are heated mainly as a result of collisional ion-electron equilibration.

In conclusion, we have found that turbulent heating in the Torus II experiment results in a hot high beta tokamak. The enhancement of electrical resistivity is manifest in the current and magnetic field measurements, the achievement of elevated temperature, and there is spectroscopic evidence for strong fluctuating microfields. We, therefore, believe that those experiments point out a potentially important application of turbulent heating: the rapid formation of hot high beta compact toroidal plasmas.

The plasma beta, $\beta = (n_e k T_e + n_i k T_i) / (B^2 / 8\pi)$, can be calculated assuming $T_e = T_i$ and using the T_i profile of figure IV.5a. The density profile is taken to have peak $n_i = 10^{15} \text{ cm}^{-3}$ at the plasma center (maximum T_i location), and $n_i = 5 \times 10^{14} \text{ cm}^{-3}$ at the plasma edge ($\approx 2 \text{ cm}$ from the plasma center). The magnetic field has a magnitude of 6 kG for 25 GW anti-parallel heating power and 4 kG for 12 GW anti-parallel heating power.

At $t = 5 \text{ } \mu\text{sec}$ for 25 GW anti-parallel heating power, the peak $\beta \approx 55\%$ results from peak $T_e = T_i = 150 \text{ eV}$ and $n_e = 2n_i = 2 \times 10^{15} \text{ cm}^{-3}$. Assuming uniformity in the toroidal and vertical directions, the volume average $\langle \beta \rangle_V \approx 20\%$.

At $t=15\mu\text{sec}$ for 25 GW anti-parallel heating power, the peak $\beta \approx 25\%$ corresponding to $T_e=T_i=75\text{ eV}$ maximum. Again, assuming uniformity in the toroidal and vertical directions, $\langle\beta\rangle_V \approx 10\%$. For comparison, when $t>10\mu\text{sec}$ for 12 GW anti-parallel heating power operation of Torus II, $\langle\beta\rangle_V \approx 5\%$.

Furthermore, it should be noted that the calculation of $\langle\beta\rangle_V$ is very dependent on the density radial profile. In the above calculations, it was assumed that the density radial dependence is similar to that of the ion temperature as derived from line broadening. It should be noted that a more constant density profile will result in a higher $\langle\beta\rangle_V$. For example, if the density is constant within the entire plasma, i.e., $n_e(r)=2n_i(r)=2 \times 10^{15}\text{ cm}^{-3}$, $\langle\beta\rangle_V$ has values twice higher than those given above.

VI.2 Radiation Cooling of Torus II Plasma

After the heating phase the ions, and probably also the electrons (since the electron temperature diagnostics discussed in Chapter V indicate that $T_e \sim T_i$), go through a cooling phase between $t \sim 5 \mu\text{sec}$ and $t \sim 10 \mu\text{sec}$ (see Fig. IV.5b). The ion temperature loss rate is $\sim 10 \text{ ev}/\mu\text{sec}$.

The impurity ionization rate measurements described in Section 2 of Chapter V indicate that silicon and oxygen are present in the plasma with concentrations of $\sim 1\%$ and 2% , respectively. Since the radiated power in the form of lines from silicon and oxygen is approximately equal,⁵³ consider the line radiation power loss from a plasma with $\sim 3\%$ (i.e., $1.5 \times 10^{13} \text{ cm}^{-3}$) concentration of oxygen. Furthermore, the time-dependent corona model (Eq. V.1) indicates that, at $T_e \sim 100 \text{ eV}$, nearly all of the oxygen present in the plasma would be three times ionized. (Note that the ionization state is not important since, within the error of the ion and electron temperature measurements, the power radiated in the form of lines of O II, O III, O IV or O V is equal for all of these ionization states.⁵³)

The power radiated from a given ionization stage is the summation of the power radiated from each line originating from the given ionization stage multiplied by the probability ($\propto e^{-(E_u - E_l)/kT_e}$ where E_u and E_l are the upper and lower level energies of the transition) of each line occurring. The power in each line is related to the oscilla-

tor strength of the line multiplied by the number of oxygen ions.²⁸ After doing the necessary calculations, the power radiated by O IV causes a plasma electron to lose^{27,62,69}

$$dT_e/dt \sim 6.3 \times 10^{-12} (T_e)^{-1/2} n_0 e^{-19/T_e} \text{ eV}/\mu\text{sec} \quad (\text{VI.4})$$

where T_e is in eV and the oxygen impurity number density is in cm^{-3} . For Torus II conditions at $5 \lesssim t \lesssim 10 \mu\text{sec}$, $T_e \sim 100 \text{ eV}$ and $n_0 \sim 1.5 \times 10^{13} \text{ cm}^{-3}$ resulting in an electron temperature, and presumably an ion temperature, drop of $\sim 8 \text{ eV}/\mu\text{sec}$. This is to be compared to $\sim 10 \text{ eV}/\mu\text{sec}$ measured ion temperature drop.

Furthermore, the radiation temperature profile relaxes from a peaked to a flat profile within $\sim 10 \mu\text{sec}$. A possible reason for this profile change is heat conduction from the hotter plasma center to the cooler plasma edges. When the energy reaches the edge, it is radiated away at a faster rate by the impurities at the edges. (Note the T_e dependence of Eq. VI.4: i.e., if $T_e \sim 50 \text{ eV}$, $\frac{dT_e}{dT} \sim 10 \text{ eV}/\mu\text{sec}$.)

Thus, it is possible for the plasma center to lose $\sim 10 \text{ eV}/\mu\text{sec}$ because of impurity radiation. A more accurate and detailed energy accounting would require radial profiles of electron temperature, electron density and a more accurate determination of the impurity concentration than the one determined by impurity ionization rates in the visible region of the spectrum. This information is not available

at present, and an accurate energy accounting during the high beta tokamak phase of Torus II will not be attempted here.

VI.3 Summary of Results and Concluding Remarks

The Z-pinch phase is observed to consist of an excited neutral helium gas with $T_i \sim 5$ eV and a degree of ionization ~ 10 -20%.

The heating phase, at 25 GW anti-parallel heating power, is characterized by low frequency ($\omega \sim \omega_{pi}$), large amplitude ($E \sim 30$ kV/cm) plasma wave turbulence, possibly of ion-acoustic origin, and associated with the skin current region of the plasma. An enhancement of the electrical resistivity by ~ 100 times the classical Spitzer value is observed. The turbulence levels ~ 1000 times thermal result in an ion heating ~ 50 eV/ μ sec. However, a comparable amount of energy is taken up by the complete ionization of helium. Perhaps, the heating efficiency associated with the turbulent heating in Torus II would increase, by as much as a factor of 2, if the Z-pinch phase was better ionized.

At 12 GW anti-parallel and 25 GW parallel heating power, the turbulence level is spectroscopically observed to be significantly lower than that at 25 GW anti-parallel heating power. According to theory, this results in the negligible heating of ions by turbulence and the ions are believed to be heated by electron-ion collisions.

With 25 GW anti-parallel heating power, the ion temperature peaks during the high beta tokamak phase at a central plasma ion $T_i \sim 150$ -200 eV. The initially peaked

radial ion temperature profile relaxes to a relatively constant radial profile with $T_i \sim 75$ eV after ~ 10 μ sec. This cooling can be caused by a $\sim 1\%$ silicon and $\sim 2\%$ oxygen impurity concentration. However, more definitive statements on plasma energy loss must await a more detailed diagnosis of the Torus II plasma.

For comparison, at 12 GW anti-parallel and 25 GW parallel heating powers, $T_i \sim 50-75$ eV maximum, relaxing to $T_i \sim 20$ eV after ~ 10 μ sec. This indicates the increased efficiency of anti-parallel heating operation, perhaps due to the larger induced skin plasma current resulting in higher turbulence levels.

During the experiment, at times $t \sim 15$ μ sec, impurity ions coming from the vacuum chamber walls are observed to have a macroscopic rotational velocity, possibly due to a charge and mass independent $E_r \times B_T$ drift. Consequently, the temperature measured from impurity line profiles was observed to be higher (by an amount approximately equal to the energy the impurities would gain traveling into the plasma from the radial electric field E_r) than the temperature measured from He II 4686 Å line profiles. This possibly means that, depending on the plasma creation processes, impurity or "doping" ion line profiles cannot be used to determine a plasma temperature less than several hundred electron volts.

From the above observations, one can say that the Torus II plasma is acceptable for high beta stability

studies. However, I believe it can be improved by:

(1) Increasing the degree of ionization of the Z-pinch so that more of the heating power is used for heating and not ionizing the plasma. Increasing the Z-pinch ionization would also reduce charge exchange losses between the neutral and ionized plasma components. At present, the ringing of a small capacitor bank for pre-ionization forms the plasma which, because of no balancing external vertical field, eventually contacts the outer wall. Because of macroscopic plasma motion considerations at later times, the Z-pinch is initiated at a time when the pre-ionized plasma has contacted the outer vacuum vessel wall. Thus, in effect, the pre-ionization is essentially zero when the Z-pinch begins and the pre-ionization energy is essentially wasted. Providing an appropriate external vertical magnetic field to prevent the pre-ionized plasma from contacting the wall would increase the degree of ionization at the beginning of the Z-pinch phase, resulting in further increasing ionization during the Z-pinch.

(2) Reducing the impurity concentration. It is not unlikely that allowing the pre-ionized plasma to contact the vacuum vessel wall introduces a significant portion of the plasma impurity content. Thus, the impurity concentration would also be reduced if the pre-ionization phase has an appropriate external vertical field. Reducing the impurity concentration results in higher

plasma temperature (lower line radiation losses are seen from Eq. VI.4), higher stages of ionization for the remaining impurities and perhaps an order of magnitude lower impurity line radiation losses.^{53,55}

(3) Increasing the plasma current decay time. Since the plasma electrical resistivity decreases as $T_e^{-3/2}$, a decrease in impurity content would result in the plasma temperature being maintained for a longer time, hence an increased L/R decay time for the plasma current.

These three suggestions address the desire for higher beta maintained for a longer time. Higher beta would result from the improved energy content of the plasma resulting from lower impurity concentrations. The plasma beta decay time, necessarily related to the temperature decay time, would increase since the dominant impurity line radiation losses are decreased. Furthermore, the energy loss time constant would increase because of the ohmic dissipation occurring over a longer time scale. Thus, a high beta plasma would be maintained for more instability growth times, allowing for longer stability studies.

VI.4 Suggestions for Further Spectroscopic Research of Torus II

Observation of He II 3202 Å would provide an important check on the results inferred from He II 4686 Å. In addition, simultaneous measurements of He II 3202 Å and He II 4686 Å during the heating phase of Torus II could possibly allow for the determination of both plasma wave electric field amplitudes and plasma ion temperature. Measurement of He II 3202 Å would require quartz window access to Torus II, a quartz prism and quartz lens for introducing light into the spectrograph (see Fig. II.6). A polychrometer arrangement is, unfortunately, difficult to construct because of the difficulty associated with the manufacture of ~ 50 micron x 18 mm line to spot quartz fiber optics guides and shot-to-shot line profiles would be required. Quartz access would extend impurity measurements to higher ionization stages with wavelengths between 2000 Å and 4000 Å.

A method of directly obtaining the turbulence level associated with the heating phase of Torus II is by observing the intensity of plasma frequency radiation which in Torus II is in the sub-millimeter region ($\lambda \sim 300$ microns). However, the advantage over line profile measurements is that the uncertainty (and disagreement among researchers in plasma physics) in interpreting the line profile would be eliminated. In addition, a plasma frequency measurement

would provide a check on the turbulence levels inferred from He II 4686 Å.

It may prove interesting to see whether the difference in the He II and impurity ion temperatures necessarily means a "doping" ion temperature would not be equal to the plasma ion temperature. For this measurement, Torus II could be operated with a mixture of helium and $\sim$ 2-5% "doping" element, perhaps neon. Ion line profile measurements of both helium and "doping" ions could then be taken using either the present visible spectroscopy apparatus or one modified with quartz optics and shot-to-shot scanning.

APPENDIX

LINE PROFILES OF NEUTRAL HELIUM

Measurements were performed on neutral helium line radiation at $R = R_0$ for 12 GW and 25 GW anti-parallel heating power. Primary attention was paid to He I 5876 Å (actually a double state 5875.62 Å and 5875.97 Å) which appeared to be the brightest of the natural helium lines. Fig. A.1 shows schematically the time dependence of the total line intensity of He I 5876 Å and He II 4686 Å as a function of time. The Z-pinch ($-6 \leq t \leq 0$ μsec) is characterized by the appearance of excited neutral helium and by the lack of a measureable level of ionized helium ions, perhaps indicating a rather low degree of ionization for the Z-pinch at its edges. The application of the heating pulse is accompanied by the rapid extinction of neutral helium lines and the rapid increase in the He II intensity. Note that He II never decreases to zero intensity during the high beta tokamak phase whereas neutral helium, for all practical purposes, is at zero intensity until $t \approx 30$ μsec when recombination $\text{He}^+ \rightarrow \text{He}^0$ begins to occur. The intensity of He II for $2 < t < 10$ μsec decreases with increasing heating power.

Figure A1 Schematic representation of He I 5876 Å and He II 4686 Å total line intensities as a function of time. (Relative intensity of lines can be taken correctly from graph.) He II intensity during $2 < t < 10 \mu\text{s}$ decreases with increasing heating power. Near burn-out of He II is achieved during this time period with 50 GW anti-parallel heating power.

Due to the prominence of He I 5876 Å, and because of the lack of other neutral or ionized helium lines, this line was used to characterize the Z-pinch. Fig. A.2a shows a "one-shot" profile of He I 5876 Å just prior to the application of the heating pulse ($t = 0$). This profile appears asymmetric about $\Delta\lambda = 0$ ($\lambda_0 = 5875.62$ Å) because of the appearance of the less intense He I 5875.97 Å line on the red wing (extended to larger wavelength by the Holtzmark density Stark effect) of He I 5875.62 Å. If He I 5875.62 Å is assumed to be gaussian and symmetric, then the lower wavelength (blue side) points can be used as a measure of the ion temperature during the Z-pinch. This temperature is ~ 5 eV since Doppler broadening implies $T(\text{eV}) \sim 18 [\Delta\lambda_{1/2}^2 (\text{Å})]$.^{28,44} In actuality, the line profile is also affected by the density Stark effect and, strictly, $T \sim 5$ eV.

Under the assumption of a symmetric He I 5875.62 Å, the red side of the central line component can be taken to be similar to the blue side. Thus, subtracting a Doppler broadened central component with $T \sim 5$ eV from the entire line profile results in the appearance of the red wing of the line. This red-shifted component of He I 5875.62 Å is shown in Fig. A.2b at $t = 0$ μsec and $R = R_0$. Note that $\sim 30\%$ of the line intensity is in the red-shifted component. (In this figure, the existence of He I 5875.97 Å becomes apparent. Note that He I 5875.97 Å also has an extended red wing characteristic of the density Stark ef-

Figure A2 (a) He I 5875.62 Å line profile, $t=0\mu\text{s}$, $R=R_0$ (end of Z-Pinch, and beginning of heating).

(b) Red wing ($\Delta\lambda > 0$ Å portion) of profile in figure A2 (a).

Dashed portion may not really exist and may be due to the mathematical convolution methods used.

fect.) Noting that the density Stark effect causes a shift and broadening,^{28,44} and using the fact that the half-width of a density Stark broadened profile is given by⁴⁴

$$\Delta\lambda_{\frac{1}{2}}(\text{\AA}) = 2.5 \times 10^{-9} \alpha_{\frac{1}{2}} n_e^{2/3} (\text{cm}^{-3})$$

where $\alpha_{\frac{1}{2}} \sim .06$ ²⁸ results in an edge electron density $n_e \sim 2 \times 10^{14} \text{ cm}^{-3}$ for the Z-pinch. (Because of the complications presented by He I 5875.97 $\text{\AA}$, the half-width of the red-shifted component of He I 5875.62 $\text{\AA}$ was determined only from the lower wavelength side of Fig. A.2b.) This small degree of ionization (~ 10 -20%) is consistent with preliminary CO₂ laser interferometry data.³⁵

Neutral He I 5876 $\text{\AA}$ line profiles during the heating phase are shown in Fig. A.3 at $R = R_0$ for 12 GW and 25 GW anti-parallel heating power ($\Delta\lambda = 0$ corresponds to $\lambda_0 = 5875.62 \text{\AA}$). From the higher wavelength side of He I 5875.97 $\text{\AA}$, a temperature of ~ 15 eV can be estimated. However, the uncertainty in this estimate is large ($\sim 100\%$) because of the appearance of both He I 5875.62 $\text{\AA}$ and 5875.97 $\text{\AA}$ and the possibility of a macroscopic velocity Doppler shift on the higher wavelength side of He I 5875.62 $\text{\AA}$. The neutral line profiles are sufficiently similar at 12 GW and 25 GW anti-parallel heating power to argue that the helium plasma has similar parameters, independent of heating power. It can also be argued that neutral helium

Figure A3 He I 5876 Å line profiles during heating, $t=0.6\mu\text{s}$, $R=R_0$;
 (a) 12 GW anti-parallel heating power and
 (b) 25 GW anti-parallel heating power.

is not representative of the plasma for times $t > 0$: i.e., after the Z-pinch phase.

A likely reason for the existence of a "hot" neutral helium at the plasma temperature is charge exchange with a singly ionized helium ion at the plasma temperature: i.e., $\text{He}_h^+ + \text{He}_c^0 \rightarrow \text{He}_h^0 + \text{He}_c^+$. (The existence of a "hot" He^+ is also by virtue of charge exchange with a hot He^{++} : i.e., $\text{He}_c^+ + \text{He}_h^{++} \rightarrow \text{He}_h^+ + \text{He}_c^{++}$.) During the heating phase, He I is seen to decrease in intensity (thus, the number of neutral helium decreases). Thus, the collision frequency between He^0 and He^+ decreases. (Conversely, He II increases in intensity during the heating phase, and the collision frequency between He^+ and He^{++} increases.) Alternatively, the charge exchange mean free path ($\sim 1/nQ$ where Q is the charge exchange cross-section and n is the number density of background particles; for He^0 , He^+ charge exchange, n is the density of He^+ ; for He^+ , He^{++} charge exchange, n is the ion plasma density of He^{++}) can be considered. Since the cross-sections for He^0 and He^+ charge exchange and He^+ and He^{++} charge exchange are approximately equal,⁶ the charge exchange mean free path for He^0 and He^+ is larger than that for He^+ and He^{++} by a factor $\sim n(\text{He}^{++})/n(\text{He}^+) \gg 1$. Thus, the plasma in Torus II after the Z-pinch phase is closer to that described by He II 4686 Å than to that described by He I 5876 Å.

REFERENCES

1. L.A. Artsimovich, Nuclear Fusion 12, 215 (1972).
2. H.P. Furth, Nuclear Fusion 15, 487 (1975).
3. M. Murakami and H.P. Eubank, Physics Today 32, 25 (1979).
4. D.J. Rose and M. Clark, "Plasmas and Controlled Fusion," (MIT: Wiley, New York, 1961).
5. J.A. Wesson, Nuclear Fusion 18, 87 (1978).
6. J.P. Friedberg and W. Grossman, Phys. Fluids 18, 1494 (1975).
7. P.G. Weber, T.C. Marshall and R.A. Gross, in Proceedings of the Ninth European Conference of Controlled Fusion and Plasma Physics, (Oxford, England, 1979).
8. B. Coppi, et al., Nuclear Fusion 19, 715 (1979).
9. H.R. Strauss, et al., Princeton Plasma Physics Lab. Report #1535 (1979).
10. R.C. Davidson and N.A. Krall, Nuclear Fusion 17, 1313 (1977).
11. R.C. Davidson and N.T. Gladd, Phys. Fluids 18, 1327 (1975).

12. E.C. Field and B.D. Fried, Phys. Fluids 7, 1937 (1964).
13. S.M. Hamburger, Culham Laboratory Report #CLM-P426 (1975).
14. N.A. Krall and D.L. Book, Phys. Rev. Lett. 23, 574 (1969).
15. L.I. Rudakov and L.V. Korablev, Sov. Phys. JETP 23, 145 (1966).
16. E.K. Zavoisky, et al., Nuclear Fusion Supplement 12, 81 (1972).
17. F. Soldner, et al., Phys. Rev. Lett. 39, 194 (1977).
18. C.T. Dum, et al., Phys. Rev. Lett. 32, 1231 (1974).
19. T.C. Marshall and H.C. Lui, Phys. Fluids 19, 1417 (1976).
20. H.A. Blokhintsev, Phy. Z. Sov. Union 4, 501 (1933).
21. G.V. Sholin, Sov. Phys. Doklady 15, 1040 (1971).
22. W.R. Rutgers and H.W. Kalfsbeck, Z. Naturforsch 309, 739 (1975).
23. E.K. Zavoisky, et al., Sov. Phys. Doklady 15, 823 (1971).
24. H.R. Griem and H.-J. Kunze, Phys. Rev. Lett. 23, 1279 (1969).

25. L. Spitzer, "Physics of Fully Ionized Gases " (Inter-science, New York, 1963, p. 135.
26. R.W.P. McWhirther in "Plasma Diagnostic Techniques," R.H. Huddlestone and S.L. Leonard, eds., (Academic Press, New York, 1965).
27. L.S. Scaturro, thesis, Columbia University Plasma Laboratory Report #68 (1976).
28. H.R. Griem, "Plasma Spectroscopy," (McGraw-Hill, New York, 1964).
29. N. Brenning, Royal Institute of Technology, Department of Plasma Physics, Stockholm, Sweden, Report # TRITA-EPP-78-16 (1978).
30. T.F. Stratton in "Plasma Diagnostic Techniques," R.H. Huddlestone and S.L. Leonard, eds., (Academic Press, New York, 1965).
31. B.R. Myers and M.A. Levine, Rev. Sci. Instrum. 49, 610 (1978).
32. M. Greenwald, et al., Bull. Am. Phys. Soc. 23, 859 (1978).
33. P.G. Weber, Bull. Am. Phys. Soc. 23, 875 (1978).
34. R.A. Gross, P.G. Weber, T.C. Marshall in Proceedings in Small Toroidal Device Users Meeting DOE-ET-G-05-5918

(1978).

35. G.A. Navratil, private communication.
36. Spectral lines were identified using:
 - (a) A.R. Striganov and S.V. Sventitskii, "Tables of Spectral Lines of Neutral and Ionized Atoms," (IFI/PLENUM, New York, 1968).
 - (b) "MIT Wavelength Tables," G.R. Harrison, ed. (Wiley, New York, 1938).
37. H.W. Ott, "Noise Reduction Techniques in Electrical Systems," (Wiley, New York, 1975).
38. J. Richter in "Plasma Diagnostics," W. Lochte-Holtgreven, ed. (American Elsevier, New York, 1968).
39. N. Ryde, "Atoms and Molecules in Electric Fields," (Almqvist and Wiksell, Stockholm, 1976).
40. H. de Kluiver and W.R. Rutgers, FOM-Instituut voor Plasmaphysica--Jutphaas Internal Reprint 75/104 (1975).
41. D.D. Burgess, Space Science Rev. 13, 493 (1972).
42. H.-J. Kunze and H.R. Griem, Phys. Rev. Lett. 21, 1048 (1968).
43. M. Baranger and B. Mozer, Phys. Rev. 123, 25 (1961).
44. W.L. Wiese in "Plasma Diagnostic Techniques," R.H.

Huddleston and S.L. Leonard, eds., (Academic Press, New York, 1965).

45. T.-J.A. Nee and H.R. Griem, Phys. Rev. A 14, 1853 (1976).
46. R.E. Shefer and G. Bekefi, Phys. Fluids 22, 1584 (1979).
47. An analysis of the radial dependence of the toroidal magnetic field for various times results in the location of the magnetic axis as a function of time. Using this information and knowing the plasma width to be ~ 4 cm allows us to infer the region of the plasma viewed by the spectroscopic measurement.
48. P.L. Mascheroni, et al., Phys. Fluids 22, 347 (1979).
49. K.W. Gentle, et al., Phys. Fluids, 22, 1558 (1979).
50. J. Waldes and T.C. Marshall, Plasma Physics 13, 837 (1971).
51. N. D'Angelo and S.V. Goeler, Phys. Fluids 9, 309 (1966).
52. A.C. Kolb and R.W.P. McWhirther, Phys. Fluids 7, 519 (1964).
53. G. Bateman, Max Planck Institut für Plasmaphysik (Garching, Germany), Report IPP 1/131 (1973).
54. H. Krause, Max Planck Institut für Plasmaphysik

(Garching, Germany), Report IPP 1/150 (1974).

55. R.N. Byrne and C.K. Chu, Phys. Fluids (to be published).
56. J.D. Jackson, "Classical Electrodynamics," (Wiley, New York, 1962).
57. N.T. Glad, Plasma Physics 18, 27 (1976).
58. C.T. Dum, Max Planck Institut für Plasmaphysik (Garching, Germany), Report IPP 1/153 (1977).
59. C.T. Dum, Max Planck Institut für Plasmaphysik (Garching, Germany), Report IPP 1/154 (1977).
60. G. Zelenin, et al., Sov. Phys. JETP 31, 1009 (1970).
61. V.A. Suprunenko, et al., Plasma Physics 15, 353 (1973).
62. D. Dücks and H.R. Griem, Phys. Fluids 9, 1099 (1966).
63. O. Gruber, et al., in Proceedings of Sixth IAEA Conference on Plasma Physics and Controlled Nuclear Fusion Research 1976, (IAEA, Vienna, 1977), Vol. 1, p. 311.
64. C. Bobeldigk, ibid., Vol. 1, p. 351.
65. P.G. Carolan, et al., in Proceedings of Third Topical Conference on Pulsed High Beta Plasma, (Culham, 1975).

66. K. Hirano, et. al., in Proceedings of Sixth IAEA Conference on Plasma Physics and Controlled Nuclear Fusion 1976, (IAEA, Vienna, 1977), Vol. 2, p. 311.
67. L.L. House, Astrophysical Journal, Vol. 8, Supplement 1, p. 307 (1964).
68. P.G. Weber, Private Communication.
69. R.V. Jensen, et. al., Princeton Plasma Physics Laboratory Report #1334 (1977).