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REGIMES OF OPERATION IN THE PRINCETON LARGE TORUS

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ABSTRACT

In the quest for optimum discharge conditions in the Princeton Large Torus (PLT), a variety of discharge regimes have been produced. These separate broadly into two main categories — those regimes with $m \geq 2$ oscillatory MHD instabilities and often hollow electron profiles for tungsten limiters, and those regimes for which the electron temperature is sufficiently peaked to support the internal sawtooth or near-sawtooth ($m=1$) instability. The internal sawtooth regime is found to be optimum for confinement but to be more difficult to select when low-Z impurity concentrations have been reduced with low power discharge cleaning or gettering to permit extension of the high density operation limit. Gas programming is used to cool the plasma periphery, thereby reducing the high-Z impurity concentrations and causing the current channel to constrict into the sawtooth regime, and then to attain the desired plasma density. With discharges selected in this manner, gross energetic confinement times up to ~100 msec have been obtained at densities of $\sim 10^{14} \text{ cm}^{-3}$, and very high ion and electron temperatures have been produced with neutral beam injection heating at lower densities with no observable deleterious effect on energy confinement.

1. INTRODUCTION

PLT experiments have been focused primarily on four main topics of principal interest for reactor operation: (1) energy confinement; (2) stability; (3) impurities; and (4) auxiliary heating. In order to achieve significant energy confinement times at elevated plasma temperatures and densities, auxiliary heating must be applied for discharge conditions with adequate stability and sufficiently low levels of light and heavy impurities. Consequently considerable effort has been directed toward achieving such conditions utilizing techniques developed over the past several years coupled with extensive and rapid monitoring of the discharge characteristics.

The chronology of PLT experimentation over the past few years is outlined in the succession of papers: Grove and the PLT Group (1977); Arunasalam and the PLT Group (1978); BC₁ and the PLT Group (1979); and Eubank and the PLT Group (1979b). The experiments began with discharge conditions established after pulsed discharge cleaning (PDC) (of the type employed on smaller tokamaks such as ST) which exhibited considerably improved confinement times, $\tau_E \sim 50$ msec, when pushed to the maximum densities permitted before a major disruption was encountered. Low power

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discharge cleaning [TDC] (Oren and Taylor, 1977) was then applied to reduce the light impurity influx so that the density limit could be increased (Hosea, Bobeldijk, and Grove, 1971). This resulted in enhanced heavy impurity influx as the temperature at the surface of the plasma increased (Minnov and co-workers, 1978). Consequently, the levels of power radiated from the center of the discharge exceeded the ohmic power input to the electrons and caused hollow electron temperature profiles to develop. Control over the discharge was then obtained by gas programming the radiation at the edge of the discharge to peak the electron temperature profile (T_e) early, push the discharge into the internal sawtooth regime, and to reach densities $\bar{n}_e$ in excess of 10^{14} cm $^{-3}$ in helium (He) and $\sim 5 \times 10^{13}$ cm $^{-3}$ in deuterium (D) or hydrogen (H), with energy confinement times up to ~ 70 msec in He. Afterwards, gettering was employed to further reduce the light impurity influx, permit larger gas influx, and give a density of $\sim 10^{14}$ cm $^{-3}$ and energy confinement times of ~ 80 msec for D,H plasmas. Finally, carbon and steel limiters, TDC, gettering, and gas programming were employed along with neutral beam injection at high power to achieve very high increases in the ion energy and significant increases in the electron energy.

The progression of experiments on PLT (as on other existing large tokamaks) has been toward hot, dense, well-confined plasma regimes which have relevance to the next generation of larger tokamaks and, possibly, to the toroidal reactor. Along the way, considerable insight into the influence of impurities and, with less certainty, instabilities on the discharge characteristics has been obtained. Some of the control exercised over impurities and instabilities in PLT and the effect upon discharge parameters will be presented in this paper. Emphasis will be placed on the role of gas programming and the possible influence of instabilities on plasma confinement. Further discussion of discharge control, initiation considerations, and applicability of the results from existing intermediate and low field devices to future devices will be given by Dr. Hawryluk. The discharge conditions selected for neutral beam injection heating will be alluded to, but the neutral beam results will be discussed in detail by Dr. Goldston.

A brief discussion of observed operating regimes is given in Section 2. This is followed by, in Section 3, results for gas programming, in Section 4, confinement results and the possible roles of instabilities, in Section 5, considerations for auxiliary heating, and in Section 6, a brief discussion pertaining to larger intermediate field tokamaks.

2. REGIMES OF OPERATION IN PLT

As expected (Hosea, 1974), the influence of instabilities and impurity influx are major factors characterizing the discharge conditions in PLT. Although the role of impurities is now elucidated, the cause-effect relationship of MHD instability and microinstability with confinement are not clear. The major disruption continues to place limits on high density or low-q operation and, certainly, on confinement. However, extensive scanning with multichannel soft x-ray systems (Sauthoff, von Goeler, and Stodiek, 1978) has not as yet revealed a general MHD link for this instability, although various modes of MHD oscillations are present in most cases. The deleterious effect produced on confinement by the $m = 2$ oscillations (Gorbunov, Minnov, and Strelkov, 1970), or vice-versa, continues to be observed on PLT. Thus, part of the prescription for increasing confinement is to establish the plasma in the internal sawtooth or near-internal sawtooth regime, preferably the former (Section 4).

Another proven method for increasing confinement time is to increase the plasma density (Gaudreau and co-workers, 1977). Since higher densities can be obtained for lower Z_{eff} plasmas before encountering the major disruption, several types of low-Z impurity "cleaning" have been pursued — PDC, TDC, and gettering.

After PDC conditioning in the first phase of PLT operation, the discharge characteristics obtained were similar to those found for smaller tokamaks, in most respects. Electron temperature and density profiles were peaked on axis and $Z_{\text{eff}} \approx 3-5$. However, the temperature profiles tended to be broader, and the stability regimes of internal sawtooth (or $m = 1$ oscillatory) or $m = 2$ oscillatory behavior were about equally probable. Also, the onset of the strong sawtooth regime quenched the $m = 2$ oscillation as shown in Fig. 1, in contrast to the general behavior found on ST (von Goeler, Stodiek, and Sauthoff, 1974).

Upon application of TDC, Z_{eff} was reduced considerably, but the electron temperature profile changed drastically and for most conditions was hollow. This effect on the temperature profile was found to be caused by an enhancement of tungsten impurity radiation from the center of the discharge (Hinnov and Mattioli, 1978; Hsuan and the PLT Group, 1978). Indeed, the high-Z impurity concentrations are inversely related to the low-Z impurity concentrations (Hinnov and co-workers, 1978) which provide radiation cooling in the plasma surface, thereby shielding the limiter from energetic ion bombardment and reducing the sheath voltage which reduces sputtering by impurity ions (Cohen and co-workers, 1978) or from homopolar arcs (McCracken and Goodall, 1978).

The level of tungsten radiation is apparently tied closely to the plasma edge temperature (Bol and the PLT Group, 1979) which suggests that reducing this temperature with additional gas injection should provide the control of the high-Z radiation (including iron, etc.) required to achieve low- Z_{eff} discharges with peaked temperature profiles. Figure 2 illustrates that as the gas injection was increased, the hollow profile could be peaked. However, these profiles suggest that instabilities may play a role in the transition, over rather local zones in the discharge. Moreover, continuing to the denser internal sawtooth regime and maintaining this regime is found to require rather precise control of the injected gas programming (Section 3).

The use of gettering further reduces the low-Z impurity concentrations, making it possible to inject higher levels of working gas and achieve higher densities once the internal sawtooth or near-internal sawtooth ($m = 1$) regime is attained. The deleterious effects of high-Z impurity radiation are reduced considerably when iron or carbon limiters are used (Bol and the PLT Group, 1979) since the radiation for concentrations comparable to the tungsten case is much less for iron (and T_i , etc.) coming from the limiter and/or vessel (Jensen and co-workers, 1977). However, the gas programming which is essential for the tungsten limiter is valuable for reducing the other high-Z concentrations to provide hotter plasmas, especially during neutral beam injection heating (Eubank and the PLT Group, 1979b) and rf heating. Also, similar programming techniques will undoubtedly be required to help control radiation levels from the core of the larger tokamaks of the future.

3. GAS PROGRAMMING

That injection of gas during the quasi-steady state of the tokamak discharge can be used to cool the plasma surface is well known (e.g., Hosea, Bobeldijk, and Grove, 1971) and is demonstrated for PLT in Fig. 3. However, the control of the equilibrium state and stability of the discharge by providing proper edge cooling throughout the discharge duration is the objective of the gas programming on PLT. The gas programming first used on PLT is illustrated in Fig. 4. An initial level of pressure is established for breakdown with a first gas pulse and a second longer pulse of gas provides a ramp in the pressure (in the absence of discharge). The pressure level at discharge initiation is critical for peaking the temperature profile (T_i), and the influx rate (ramp slope) and timing of the second gas pulse is critical for establishing and maintaining the desired internal sawtooth regime and for obtaining high densities.

Fig. 1. Cyclotron emission measurement of $T_e(0)$ compared to magnetic probe measurement. Onset of internal sawtooth instability suppresses $m = 2$ MHD oscillation. (PPPL 796028)

Fig. 2. T_e profiles obtained for large levels of tungsten radiation. MHD oscillatory behavior observed with magnetic probes is noted. (PPPL 796025)

Fig. 3. Hydrogen gas injection cooling of the plasma surface. V_c is the second harmonic cyclotron emission at 33 cm. (PPPL 796029)

Upon increasing the first gas level the hollow discharge is gradually forced into the peaked $m = 2$ regime as indicated in Fig. 2. Increasing this level further results typically in minor disruption(s) followed by a more abrupt peaking of the temperature profile as illustrated in Fig. 5. MHD $m = 2$ temperature oscillations are observed about the $q = 2$ surface as shown for the hollow T_e case and these are followed by sawtooth oscillations for the peaked T_e case (note the inverted sawteeth at 23 cm). The growth of the $m = 2$ oscillations are thought to be responsible for the minor disruption observed in Fig. 5.

The discharge can exhibit complicated stability behavior in the process of reaching the condition of Fig. 5. For example, in some cases the hollow T_e profile persisted and underwent relaxations (similar to external sawteeth) as shown in Fig. 6. It is possible that similarly complex behavior could be encountered in larger tokamaks for inadequate impurity control conditions.

The internal sawtooth regime established as in Fig. 5 is then maintained with the second gas pulse. Figure 7 shows the results of the transition to the sawtooth regime. Energy confinement is tripled and the density is doubled near the end of the discharge. The gas level at discharge initiation which gives this transition must be adjusted to within ~10% of the value which produces the major disruption in the discharge buildup through over constriction of the current channel. It is indicated in Fig. 7 that enhancing I_i and minor disruptions during the discharge buildup causes a lower current to be reached. Upon reducing the first gas level by ~20%, the peaked T_e discharge of Fig. 7 reverts back to the hollow case after about six discharges. This indicates that the recycling "memory" of the boundary is affected by gas stored in the vessel and/or limiter.

Tungsten radiation for the two regimes of Fig. 7 is given in Fig. 8. The level of radiation is reduced to that of the background in the peaked T_e case during the initiation of the discharge. Although the level for the two cases is similar at the end of the discharge (about one half tungsten concentration for peaked case), the enhanced ohmic heating at the center of the discharge causes the peaked profile to persist. With gettering and operation to higher density, low levels of tungsten radiation can be maintained throughout the discharge.

4. CONFINEMENT

To achieve the highest densities and confinement times for the PLT device, the internal sawtooth or near-internal sawtooth regimes have been selected. The final density obtained for these regimes can be up to about five times larger than that for the case with $m = 2$ MHD oscillations (peaked T_e) with the same second gas pulse. In fact, the onset of large internal sawteeth is associated with a greater density buildup than the near-internal sawtooth regime as illustrated in Fig. 9. Such results suggest that particle confinement is influenced by MHD stability, or that the mechanism for the density transport, presently not established, is influencing the MHD stability. In either case, it appears that the particle transport and particle confinement experience a change of state in the internal sawtooth regime. This change could be in the direction of neoclassical transport, with an associated inward particle pinch velocity, which is needed to explain the relatively peaked density profiles obtained at densities in the range of 10^{14} cm^{-3} (Schmidt and co-workers, 1978).

Electron energy confinement time is strongly influenced by radiation conditions. High density operation with negligible high-Z radiation results in electron energy confinement times of ~50 msec (Hawryluk, 1979). This confinement is clearly anomalous when compared to neoclassical theory. It is probable that instabilities — notably microinstabilities — are responsible for the electron energy transport. The electron energy confinement time predicted from density turbulence measurements

Fig. 4. Two-pulse gas programming. (PPPL 796030)

Fig. 5. Minor disruption precursor to the transition to the sawtooth regime as observed on T_e measured with second harmonic collector emission V_c . $m = 2$ oscillations $\hat{V}_c$ grow about the $q = 2$ surface prior to the minor disruption. (PPPL 796031)

Fig. 6. Relaxation hollow T_e profile regime observed for conditions similar to those of Fig. 5. Percentage fluctuation in the temperature is shown versus radius. (PPPL 773716)

Fig. 7. Gas programming of D_2 regimes after TDC. The hollow (peaked) T_e conditions are characterized by $\tau_E \sim 7$ msec (20 msec); $Z_{eff} \sim 4$ (4); and $m = 2$, sawtooth instabilities, respectively. (From Schmidt and co-workers, 1977.) (PPPL 773865)

Fig. 8. Comparison of $50 \text{ \AA}$ radiation for the two regimes of Fig. 7. (From Arunasalam and the PLT Group, 1978). (PPPL 773865)

(Mazzucato, 1978) is ~100 msec, typically. It is suspected that the turbulence is primarily of the collisionless drift type rather than the trapped-particle type, although both could be present over different zones of the plasma (Klein and co-workers, 1979). Temperature turbulence has been observed as well (Arunasalam and the PLT Group, 1978), but its effect on confinement has not been established.

Ion energy confinement appears to be approximately neoclassical (Brusati and co-workers, 1978). The ion energy confinement time τ_{Ei} values consistent with neutron flux measurements are given in Fig. 10 along with values deduced similarly for results on T-4 (Gorbunov, Zaveryaev, and Petrov, 1973), TFR (Equipe TFR, 1976), T-3 (Artsimovich, Glukhov and Petrov, 1970), ATC (Stott, 1976), and ORMAK (Berry, Clarke, and Hogan, 1974). τ_{Ei} for the sawtooth regime in PLT scales approximately as a^2 and is up to ~50% greater than the value for the $m = 2$ case (the neutron flux is larger by a factor of ~10). The reason for the improvement in the sawtooth regime is difficult to specify with the present uncertainties in the measurements of the discharge parameters but could be simply a decrease in $q(0)$.

5. AUXILIARY HEATING

In order to achieve higher plasma temperatures of more relevance for extrapolation of PLT operation to desired conditions in next generation tokamaks and possibly reactors, auxiliary heating is being employed. The application of neutral beam injection heating has given T_i values up to ~6.5 keV and electron temperatures up to ~4.5 keV (Eubank and the PLT Group, 1979a, 1979b; Goldston, 1979). Recently, rf heating experiments have begun as well (Hosea and the PLT Group, 1979) with the objective of producing high temperatures at high density, and even higher temperatures in combination with neutral beam injection.

With the increase in the energy content of the plasma produced by auxiliary heating, especially in the form of energetic ions, impurity radiation tends to be more severe. Thus, enhanced control over the high-Z impurities is essential to achieve good heating performance. As for ohmic heating alone, the strong internal sawtooth regime provides better confinement and consequently higher heating efficiency. This regime may be caused to onset with auxiliary heating of the plasma core.

At high temperatures, trapped-particle instabilities could affect confinement. A strong enhancement of density turbulence is observed for $T_i \geq 4$ keV during neutral beam injection, but with no apparent effect on the ion energy balance or the beam particles. However, investigations at high density and high temperature are required before the possibility that such instabilities may affect confinement can be excluded from reactor consideration.

6. DISCUSSION

Several scaling laws for energy confinement, based on empirical fits to present experimental results, have been derived during the last few years (Hawryluk, 1979). Impurity radiation and instability effects are generally not considered in detail in these derivations, although confinement results for the better conditions are usually chosen. Results from present experiments, such as those discussed above for PLT, strongly indicate that the energy confinement in large scale moderate field tokamaks will be much less than these laws indicate unless techniques are developed for adequate control of both impurities and instability regimes.

For such large scale tokamaks, the ohmic heating power on axis can be much less than in PLT — $\langle P_{OH} \rangle = (Z_{eff}^2/12T_e^{3/2})(5B_\phi/Rq_0\pi)^2$ with T_e in eV, B_ϕ in gauss, and R in cm. Hence, much lower levels of impurity radiation from the central region of the plasma can suffice to give a hollow T_e profile regime. It is likely that both impurity control and auxiliary heating will be required to produce

Fig. 9. Effect of transition to strong sawtooth regime on density buildup. (PPPL 796027)

Fig. 10. Ion energy confinement times deduced from neutron measurements. Confinement is improved in the sawtooth regime on PLT. (PPPL 796026)

peaked discharges in the internal sawtooth regime. As the auxiliary power in increased to achieve the desired plasma content, impurity control will become more difficult, possibly requiring the use of a divertor. In addition, stability control could become as important as impurity control and require the development of additional techniques such as programming of relevant parameter profiles with auxiliary heating and particle injection.

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