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STABILITY AND HEATING OF A POLOIDAL DIVERTOR TOKAMAK

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ABSTRACT

Five experimental studies--two stability and three heating investigations--have been carried out on Tokapole II, a Tokamak with a four node poloidal divertor. First, discharges have been attained with safety factor q as low as 0.6 over most of the column without degradation of confinement, and correlation of helical instability onset with current profile shape is being studied. Second, the axisymmetric instability has been investigated in detail for various noncircular cross-sectional shapes, and results have been compared with a numerical stability code adapted to the Tokapole machine. Third, application of high power fast wave ion cyclotron resonance heating doubles the ion temperature and permits observation of heating as a function of harmonic number and spatial location of the resonance. Fourth, low power shear Alfvén wave propagation is underway to test the applicability of this heating method to tokamaks. Fifth, preionization by electron cyclotron heating has been employed to reduce the startup loop voltage by ~ 60%.

Five experimental studies--two stability and three heating investigations--have been carried out on Tokapole II, a Tokamak with a four node poloidal divertor. After a brief machine description in section I, we describe discharges with q ~ 0.6 over most of the cross-section without degradation of confinement (II), observation of axisymmetric instability in dee, inverse dee and square equilibria (III), high power fast wave ion cyclotron resonance heating (IV), studies of spatial shear Alfvén wave resonances for heating (V), and reduction of the startup loop voltage by ~ 60% by microwave preionization at electron cyclotron resonance (VI). The axisymmetric instability work and preionization studies have been described in detail elsewhere and are therefore only briefly mentioned here.

I. Machine Description[1,2]

Four copper toroidal rings inside a 50 cm major radius 44 x 44 cm vacuum chamber provide plasma shaping and an octupole vacuum field. Toroidal plasma current driven in the vicinity of the octupole null creates a poloidal divertor tokamak with a poloidal magnetic flux plot as shown in Figure (1) with $n \sim 10^{13}$ cm^{-3}, $T_e \sim$ 100 eV, $T_i \sim$ 60 eV, $B_T \sim$ 8 kG (max), $I_{pl} \sim$ 40 kA. In addition to spectroscopic, interferometric and charge exchange diagnostics, internal probes allow direct measurement of the poloidal magnetic flux plot, and profiles of q, electric field and current density. Measured flux plots agree with the numerical prediction. Proper ring positioning provides dee, inverse dee or square cross-section equilibria.

II. $q < 1$ Discharges

The q(r) profile has been determined directly in Tokapole II by measuring the magnetic field on a 2 cm x 2 cm grid over the plasma cross section, and evaluating $1/2\int(\partial\phi/\partial\theta)\,d\theta$ around a flux surface, where θ and ϕ are the toroidal and poloidal angles. The q profiles thus obtained are typically constant over 80% of the tokamak part of the discharge (Figure 2), although the poloidal field nulls cause q to become infinite at the divertor separatrix.

The effect of the q profiles on the internal disruptions is being studied. Flat q profiles with q as low as 0.6 have been obtained. In some cases large sawtooth oscillations, as observed on the soft xray and magnetic probe signals, onset when the increasing plasma current drives q below 1. These sawteeth, which may produce as much as a 25% fluctuation in the poloidal magnetic field at the divertor separatrix, do not appear to significantly reduce energy confinement time. Under other conditions we have obtained the flat $q = 0.6$ discharges with no observed internal disruptions.

The benign quality of the internal disruptions, when present, and the absence of sawteeth even though $q = 0.6$, may be the result of the flatness of the current density profile or the noncircular shape of the current channel. The energy source which drives the resistive tearing mode, responsible for the tokamak and minor disruptions, is the current density gradient. In Tokapole II the current density gradient is localized to the region near the divertor separatrix, and thus, disruptions may be confined to a small part of the plasma crossection even if $q < 1$ over the bulk of the plasma. Also, recent work by J.A. Holmes et al.[3] indicates that noncircularity has a stabilizing effect on the resistive tearing mode.

Two possible effects can contribute to the flat j profile. Firstly, the plasma is bounded by a magnetic limiter, not a material one, and therefore, the current is not forced to zero at the Tokamak edge. Current is permitted to flow in the "scrape-off" region, which is normally operated without divertor baffles. Secondly, although the confinement time agrees with the empirical

Tokamak scaling laws, the low toroidal field (~ 2.5 kG) of these low q experiments creates a short confinement time (~ 300 μsec) perhaps making temperature gradients difficult to sustain.

Presently we are concentrating on discovering the ultimate lower limit on q, clarifying the effect of shear and noncircularity on disruptive instability, and measuring the time dependence of q within a sawtooth period (~ 200 μsec).

III. Axisymmetric Instability

The stability of dee, inverse dee and square cross-section plasmas to axisymmetric modes has been investigated experimentally through direct measurement of the poloidal magnetic flux plot with internal magnetic probes.[2,4] Experimental results are compared with predictions of two numerical stability codes--the PEST[5] code (ideal MHD, linear stability), adapted to Tokapole geometry and a code[6] which follows the nonlinear evolution of shapes similar to Tokapole equilibria. Experimentally, the square is vertically stable and both dees are unstable to a vertical nonrigid axisymmetric shift. The central magnetic axis displacement grows exponentially with a growth time

~ 450 μsec ~ 10^3 poloidal Alfvén times ~ plasma L/R time. Thus, the growth is slowed by passive feedback from the rings and wall; but the feedback is limited by the finite plasma resistivity which causes damping of the induced image currents. Precise initial vertical positioning of the plasma allows passive feedback to nonlinearly restore vertical motion to a small stable oscillation with a period about equal to the above growth time.

The PEST code, ignoring passive feedback, predicts all shapes to be unstable with the square having the slowest growth with growth times ~ poloidal Alfvén times. With passive feedback, all are stable. Thus, both experiment and code agree that the square is the most stable shape, but experiment indicates the destabilizing effect of plasma resistivity. In both code and experiment, squarelike equilibria exhibit a relatively harmless horizontal instability. Further detailed comparisons between code and experiment have also been made.[4]

IV. Ion Cyclotron Resonance Heating

High power fast and slow wave ICRF studies in a single component hydrogen plasma have been completed. The application of 70 kW to the ions at 12 MHz with a single turn, ceramic insulated, center-tapped, Faraday shielded antenna raises the body temperature from 35 to 75 eV and generates tails comprising 8% of the plasma to 320 eV as measured by charge exchange (Figure 3). The second harmonic has been found to be the most efficient heating frequency for a given voltage applied to the launching structure. Experimentally, however, application of sufficient power to overcome coupling inefficiencies up to the maximum attainable 4 times the cyclotron frequency on machine axis raises the ions to the same temperature. The use of the slow wave at the fundamental is relatively ineffective and increases the ion temperature only $\simeq$ 25%. Magnetosonic heating in a poloidally diverted tokamak with low edge density below that needed for propagation requires that the launching device be as close to the current channel as possible. Substantial charge exchange loss caused by wall reflux and rf ionization of the H_2 blanket surrounding the plasma column and magnetic limiters limits the attainable temperatures. Plasma loss to the copper hoops is evidenced by an ~ 15 increase in the spectroscopically measured Cu I radiation with the application of rf. The electron density increased ≃ 20% with the application of rf. The heating is by the m = 0 and m = +1 modes as determined by insertable rf probe coils and by the negligible heating in the absence of a mode. Additionally, substantial edge heating and severe impurity influx occurs below the normal cutoff density by a propagating m = +1 mode first described by Paoloni[7]. No electron heating occurs. The use of the antenna as the frequency determining element has allowed mode tracking due to the imposed reactance[8] of an eigenmode with a 40% increase in power deposition of a passing mode over the theoretical deposition with a fixed frequency source. This technique should work well in a large device with a high density of eigenmodes with suitable preselection of the $k_{||}$.

V. Shear Alfvén Wave Propagation

Wave coupling to the plasma through the spatial shear Alfvén resonance has been proposed as a plasma heating technique.[9,10] Low power (< 50 kW) wave coupling experiments are underway on Tokapole II to assess the applicability of this technique to tokamaks. It is important to examine the effect of toroidicity and noncircularity on the wave coupling as pictured by the standard one dimensional theory. The internal rings can serve as the launching structure, eliminating the need for constructed antennas. By grounding a ring to the tank at one of its supports and driving one of the other two supports, rf current is driven through the rings with the current returning through the tank itself. The third support remains insulated and unused and thus a toroidal mode number $n = 2$ is dominant. Poloidal mode numbers may be chosen as $m \approx 1$, 2 or 4 simply by driving the proper number of rings.

One dimensional theory predicts resonance to occur when the poloidal wave phase speed matches the local Alfven speed, i.e. $\omega/k_{11} = V_A(\underline{X})$. Thus the frequency may be chosen arbitrarily if a suitable parallel wavelength is imposed by the antenna structure. In this experiment, with $\omega/2\pi \sim 1$ MHz, adjustment of the equilibrium parameters should allow placement of the resonant magnetic surface either near the axis or the separatrix edge region where $q \rightarrow \infty$. Local resonances in the fluctuating magnetic field are indeed observed. For example, when the antenna is configured for an $m = 2$, $n = 1$ mode by driving each ring 180^o out of phase with its neighbor, resonances are observed on both sides of the separatrix (Figure 4) which is located at ~ 8 cm from the minor axis. In this case, some plasma is allowed to occupy the "scrape-off" region at $r > 8$ cm. The wave poloidal magnetic field is enhanced locally by a factor of 20 over its vacuum value which is roughly uniform spatially over the displayed region. The observed surface of resonance does indeed coincide with a magnetic surface, as expected for this mode.[11] Furthermore, as appropriate for a shear Alfven resonance, the wave magnetic field is polarized predominantely perpendicular to the equilibrium field; i.e., the wave radial and poloidal fields are similar in magnitude and structure but little wave toroidal field exists. However, as the plasma is noncircular, as well as toroidal, a prediction of the resonant surface location by a two dimensional theory is necessary before the desired waves can be definitively identified as shear Alfvén resonance. Such a calculation is underway, as well as power coupling and wavelength measurements to determine whether an escalation to high power heating is in order.

VI. Startup with Electron Cyclotron Resonance Heating (ECRH)[12]

One possible means for surmounting the technological requirement of a high startup loop voltage is the application of ECRH to produce a plasma of modest conductivity prior to the onset of ohmic heating.[12] On Tokapole II ECRH preionization is applied (16 kW at 9 or

16 GHz for ~ 1 msec) when the magnetic field is purely toroidal so that the resonance zone is a vertical cylinder. The observed effect is a reduction in the loop voltage on axis by ~ 60% (20 V → 8 V). The reduction lasts about 300 μsec with negligible effect after ~ 1 msec. Detailed measurements of spatial loop voltage and current profile evolution are obtained during the startup phase.

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FIGURE CAPTIONS

Fig. 1: Numerical Poloidal Flux Plot of Tokapole II.

Fig. 2: Radial q profiles for $q < 1$ discharges. The divertor separatrix is at $r \sim 6$ cm. q is measured directly with internal magnetic probes.

Fig. 3: Increase in body and tail temperatures vs ICRH power.

Fig. 4: Radial profile of wave poloidal magnetic field (in arbitrary units) at $f \sim 1$MHz, with and without plasma present, in shear Alfven wave experiment.

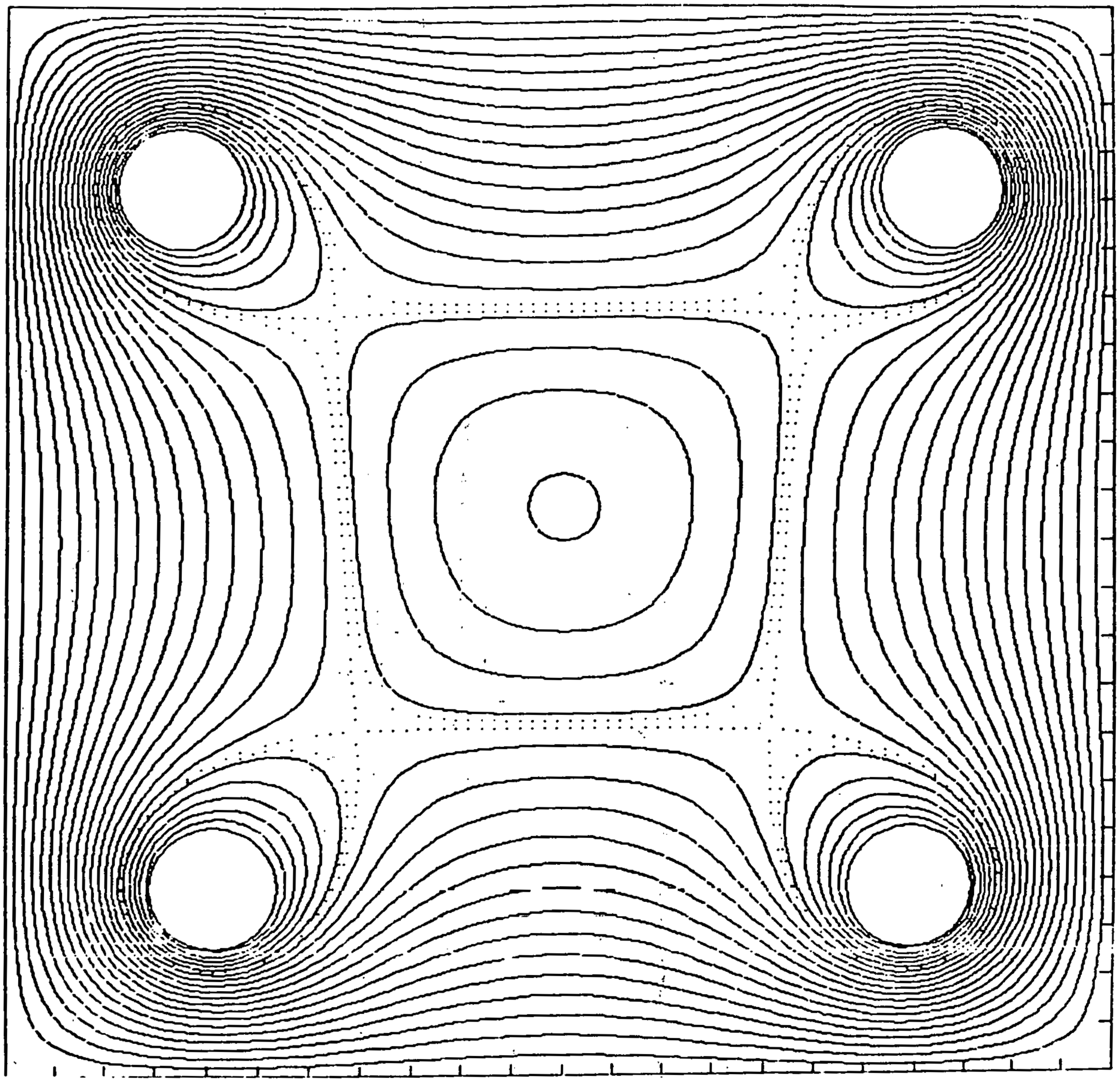


FIGURE 1

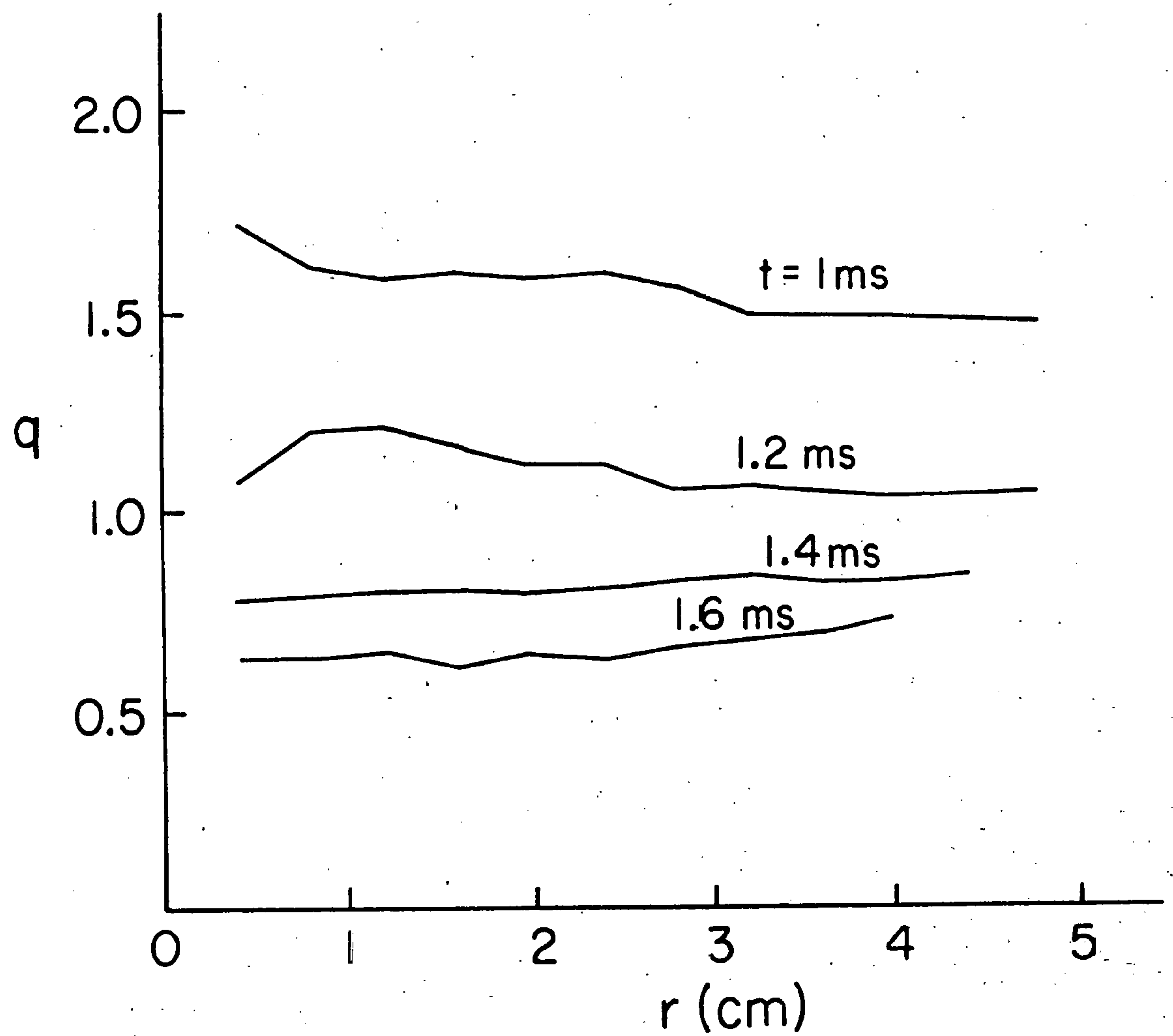
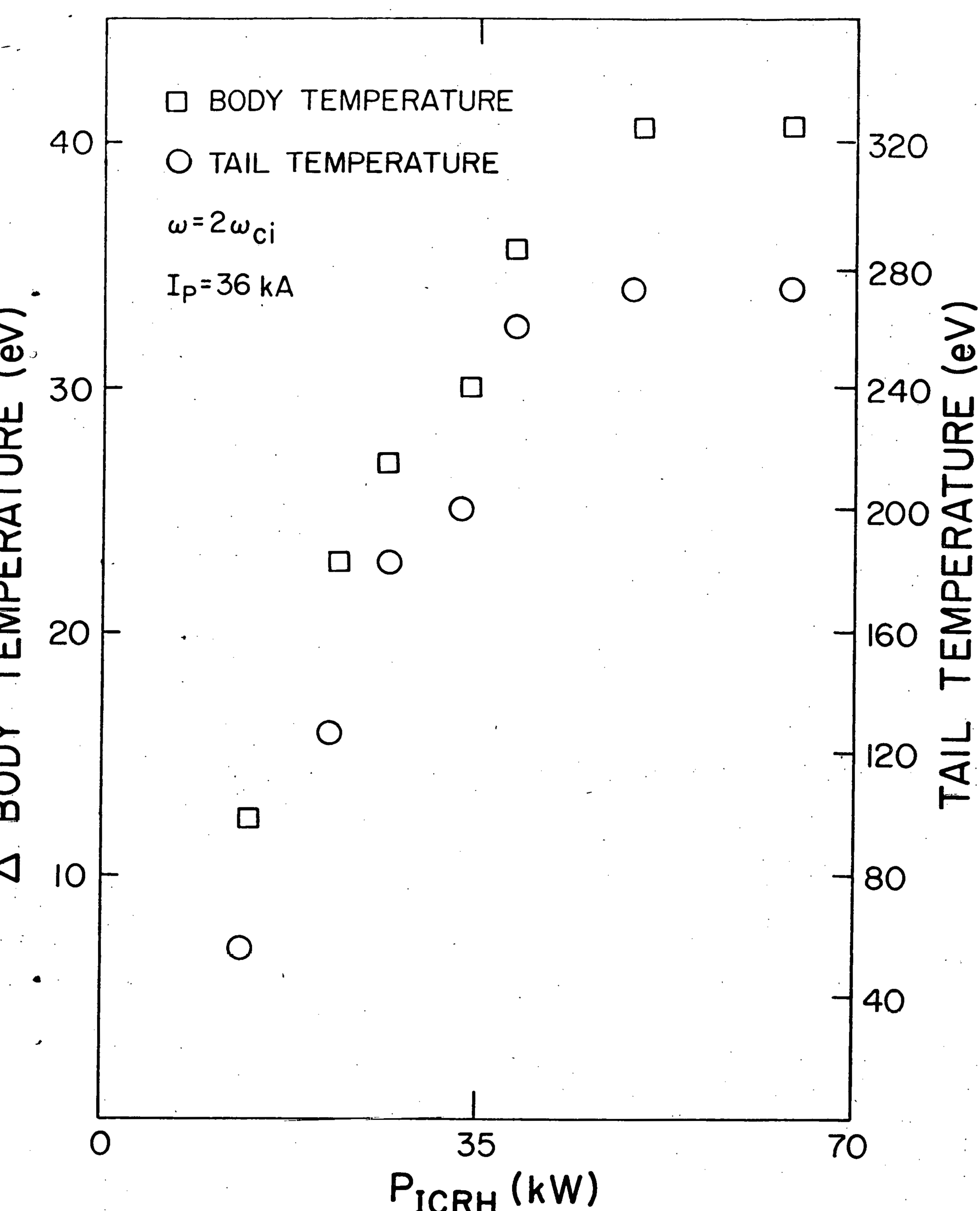


FIGURE 2



BODY TEMPERATURE
TAIL TEMPERATURE
ω=2ω_ci
I_P=36 kA
40
30
20
10
320
280
240
200
160
120
80
40
Δ BODY TEMPERATURE (eV)
TAIL TEMPERATURE (eV)
0
35
70
P_ICRH (kW)

FIGURE 3

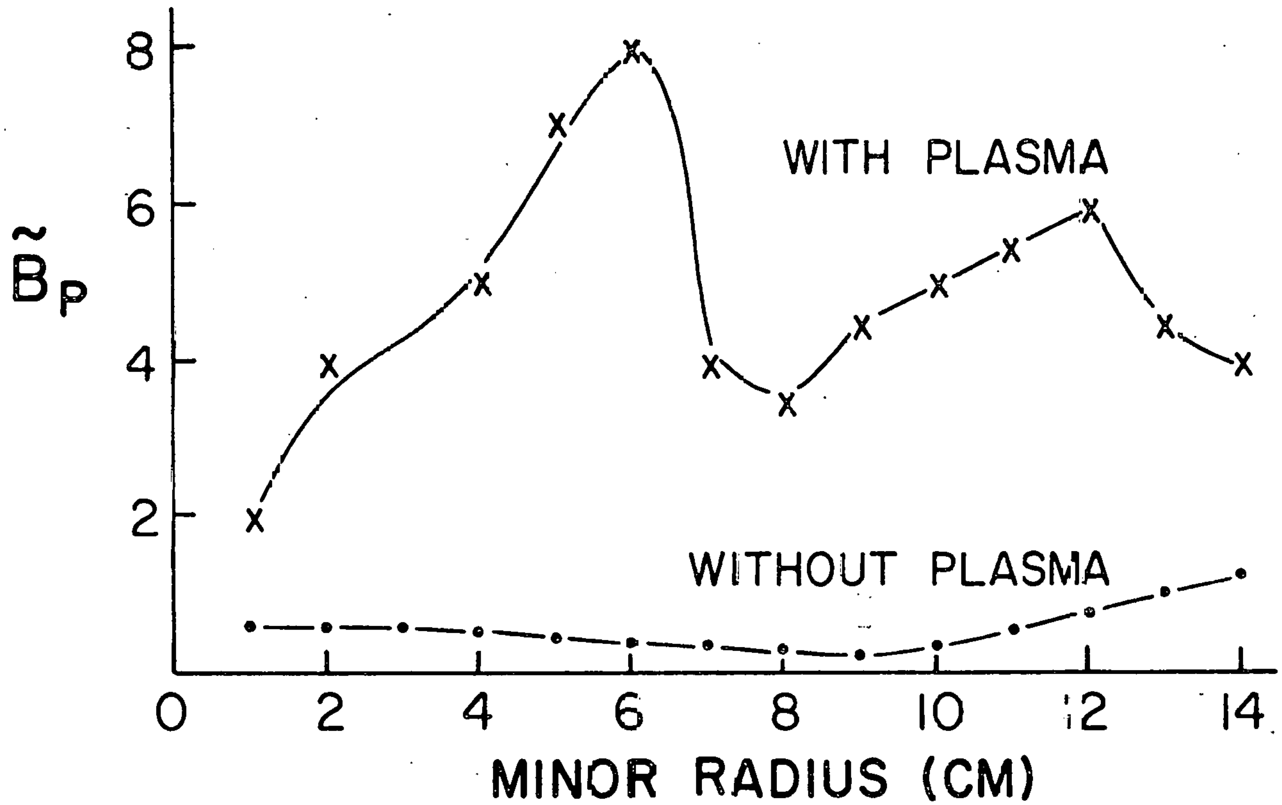

8
6
4
2
$\tilde{B}_P$
WITH PLASMA
WITHOUT PLASMA
0
2
4
6
8
10
12
14
MINOR RADIUS (CM)

FIGURE 4

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