MASTER

Report to DOE on the
Evaluation of Initial Trapping Studies

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SINGLE END PLUG RF EXPERIMENTS ON PHAEDRUS

Report to DOE for Evaluation of Initial RF Studies

December 15, 1978

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I. Introduction

This report summarizes our work up to Dec. 1, 1978 on the single mirror plug of Phaedrus. The design, construction and initial experiments proceeded without major problems. We did experience some delay in receiving copper for our coils but this only resulted in a six week delay in receiving our Main Ioffe coil and did not prevent the start up of the plasma trapping experiments listed in our milestones. We also encountered some delays with High Power RF tubes but, by construction of an amplifier using LASL tubes, we were able to get back on schedule.

The results on RF trapping and heating steadily improved during the months of October and November with our best results being obtained during the last two weeks of November. These positive results are encouraging for RF heating in mirrors. Through ion cyclotron heating at ω_{ci} , we were able to increase the density by 50% and double the plasma diamagnetism of a stream gun-produced plasma. The input power to the antenna was ~ 200 kW; however, all but ~ 20 kW went into gettered titanium on the antenna. This problem will be corrected.

Our experiments to date have concentrated on heating stream gun plasmas. This plasma source has been well suited for our initial studies as it produces a hot, dense plasma over a long duration (~ 1 msec). This has made diagnostics particularly straight forward. Because of the time scale we have carried out most of our work with the 200 kW source which is capable of running for long pulses (30 msec).

Initial tests using the guns in the fast pulse mode were less straight forward due to lack of reproducibility of the gun in this mode. We are continuing our high power (e.g., Lausanne line) trapping but using

the stream mode rather than the pulse mode for the reasons mentioned above. Due to the success of the initial high power heating results we will continue to emphasize this method over the trapping of the plasma produced in the fast pulse mode.

II. Status of the Experiment

The machine is operating with good reliability although many of the systems are not in their final form but were assembled quickly in order to get the experiment running. We will have the next five months to refine the machine controls and system to make the operation more automated and refined.

We currently can operate our stabilized end plug at design magnetic field strengths of 2 kG on the midplane. The flux tubes are not recircularized due to a five month delivery delay with the recircularizing coils from Magnetic Corporation of America. This, however, is of no consequence for the end plug experiments. Current plans are to install the recircularizing coils in February. We have installed 1.2 MVA of D.C. magnet power to date and will be expanding that over the next year.

The vacuum system is operating well, with charge exchange times in excess of 1.2 msec. We will add further pumping and ballast over our original design in order to insure sufficient pumping for central cell gas feed for tandem operation and neutral beams.

The system controls were completed sufficiently to make the system operational. The system control computer is operational and is currently being connected to the experiment. The entire system should be in its final designed state before the coils for the second end cell arrive.

We have gone out on bid for the copper and winding of the remaining coils. Materials for the vacuum chambers will start by January, 1979. Assuming vendors can keep to the same delivery as for the first end plug, we will be completing the tandem on schedule.

III. Diagnostics for Initial Experiments

The diagnostics for the initial experiments were limited due to time and manpower limitations. These diagnostics have, however, allowed us to make a satisfactory evaluation of the initial experiments. We will have a single channel charge exchange analyzer, Thomson Scattering and an end loss analyzer operational in a few months which will greatly improve our diagnostic capabilities. As a result of operation with the diagnostics listed below, we will also be making modifications to improve their usefulness. These diagnostics will be interfaced to the computer over the coming months.

Diagnostics Used in Initial Experiments

The microwave interferometer measures the line density through a chord at the midplane of the plug mirror. Its free space wavelength is 4.3 mm.

Langmuir probes (2) - Both single disc electrostatic probes are located in the mirror cell proper; one, in the elliptical region of the plasma above the RF antenna; the other, at the midplane.

Diamagnetic loops (2) - Both are single turn loops. A 20 cm diameter loop can surround the midplane plasma column to measure decreasing magnetic flux or can be positioned off axis to measure the increase of flux between the plasma and the aluminum vacuum walls. A movable (in radius) 2 cm diameter loop is located in the elliptical region of the plasma.

Secondary Emission probe - A highly collimated gold surface, secondary electron emitter is located above the midplane and measures hot neutral particle flux with increased sensitivity for high energy (> 1 keV) neutrals.

It has a twin faraday cup to assure one of low ionized particle fluxes to the flat gold surface.

Fast neutral pressure gauges (4) - Three gauges consist of baffled Schultz-Phelps gauges placed on the wall in the gun guide field region, the mirror cell and the transition region between the mirror and the central cell. The gauges are calibrated with the magnetic field on and have a rise time of about 1/2 ms with room temperature H_2 . There is one nude Bayard-Alpert gauge in the central cell.

Neutral gas analyzer - One Quadrapole neutral mass analyzer is located in the central cell region. It is used to measure neutral species when the guns are in operation and for analysis of residual gas. Its rise time is limited to something greater than 100 ms due to conductance limits.

IV. Initial Plasma Produced by Stream Gun

Ti-H₂ washer gun plasmas in the stream mode have been found to vary with the number of guns used, gun current; B_z at the gun, B_{min} in the mirror, washer history, and vacuum conditions.

"Typical" plasma parameters are $T_e \sim 5 - 10$ eV, $T_i \sim 200$ eV, $n\lambda_{peak} \sim 2 - .5 \times 10^{14}$ cm⁻², λ_p (midplane) $\sim 7 - 14$ cm, τ (charge exchange) $\sim .5 - 1.5$ ms, τ (density decay) $\sim .25 - .5$ ms. Since the machine has just started operation and the diagnostics are continually being improved, "typical" is still a highly varying function.

Gun current pulses were limited to 1 ms duration and 4.5 kA peak. Two gun operation divides the current evenly between the two guns. Since the density is observed to level off after 1/2 ms, the pulse length does not limit the peak density achieved. A crowbar or short circuit was added to terminate the current in 20 μ s at any time in the 1 ms current pulse.

Two gun operation does not significantly alter the line density but spreads the plasma profile. Varying the magnetic field at the gun causes a "mode jumping" characteristic in the line density. A field of 1.5 kG or greater gives optimum performance. Varying the ratio of the mirror field to the gun field gives only a slight variation and is dominated by the absolute value of B at the gun. The gun works better at high field, i.e., 1.5 kG. This is similar to observations at LLL. Replacing a washer in one of the guns with a fresh one increased the line density by a factor of 3 - 5. After 1,000 shots this decreased to a factor of 2. The old washer was an original LLL washer. Washer lifetime is expected to exceed 2 - 3 months

of operation.

Line density decay of a stream plasma after the normal slow turn off of the gun is shown in Fig. 1. The decay fits a Fokker-Planck code simulation with the decay dominated by electron drag, T_e fixed at 5 eV. The decay shows no pattern which is trivially associated with charge exchange and hence the inferred 1.5 ms or greater charge exchange time. Neutral pressure measurements using the fast gauges with Ti gettering are consistent with this giving $n_0 \leq 5 \times 10^{-7}$ Torr during the decay period. Using all gauges, the major source of neutral flux appears to be located at the termination of the stream plasma. The ion temperature is inferred from the decay. Since the decay is electron drag dominated, this is only a "ball park" estimation.

The Langmuir probes are used to measure the profiles and give an estimate of the electron temperature in the fast swept mode. Since the probes are an obstacle they greatly reduce the ion confinement and are observed to affect the density decay. So the T_e measurement is tenuous while the density profiles with the stream on are less suspect.

PLASMA PARAMETERS WITH STREAM GUN OPERATION

	<u>Source</u>
$T_i \sim 400 \text{ eV}$	$\left\{ \begin{array}{l} n\lambda \text{ decay} + T_e \text{ measured with Langmuir} \\ \text{probe 2/3 down density gradient during} \\ \text{decay} \end{array} \right.$
$T_e \sim 5 \text{ eV}$	
$\phi_p \sim 8 - 12 \text{ volts}$	
$n\lambda_{\text{peak}} \sim 2 \times 10^{14} \text{ cm}^{-2}$	70 GHz wave interferometer
$r_p(\text{midplane}) \leq 10 \text{ cm}$	Langmuir probe profile in fan
$n \leq 2 \times 10^{13} / \text{cm}^3$	Langmuir probe profile and line density
$\tau(n) \sim 250 \text{ } \mu\text{s at } n = 2 \times 10^{12} \text{ cm}^{-3}$	70 GHz wave interferometer
$\tau(\text{charge exchange}) > 1.2 \text{ msec}$	Deduced from pressure measurement and plasma decay
$P_{H_2} \text{ during 1 ms plasma pulse} < 5 \times 10^{-7} \text{ Torr}$	Nude Schultz-Phelps gauge on wall of plug
$P_o \text{ Base Pressure} - 1-2 \times 10^{-8} \text{ Torr}$	Nude Bayard-Alpert gauge

Fig. 1

V. Ion Cyclotron Frequency Range (ICRF) Coupling Experiments

A series of experiments is currently underway to investigate the coupling, trapping, and heating properties of waves at 100 kW in the ICRF $0.8 < \omega/\omega_{ci} \sim 2$ for the enhancement of tandem mirror operation. The work has as its objectives an increased trapping and consequent density buildup of initial titanium gun-injected hydrogen plasma and an increase in the transverse ion energy, confinement time, and ambipolar potential of the trapped plasma due to heating in the ion cyclotron frequency range. In addition to this, the experiment has new topics associated with efficient coupling of waves to the mirror elliptical flux surfaces (see Fig. 2) with large aspect ratio ($a/b \approx 6$), a transverse cross-section which varies from large aspect ratio ellipses far from the midplane to nearly circular at the midplane, and finite β effects which must be incorporated in the wave heating description at elevated plasma energy densities. The theoretical question of the interaction due to mirror instabilities driven by thermal anisotropy near the ion cyclotron frequency with the supplementary heating in the ICRF is also of interest.

To trap and heat the plasma we are investigating slow ion cyclotron waves which propagate down the "magnetic beach" from the higher field region to become ion cyclotron damped at the midplane $\omega/\omega_{ci} = 1$. We are also investigating fast magnetosonic wave propagation by launching the wave slightly below the first ion cyclotron harmonic $\omega/\omega_{ci} < 2$ and allowing the

SCHEMATIC OF ICRF COUPLING, TRAPPING, AND HEATING EXPERIMENTS FOR THE END PLUG CELL
 OF THE PHAEDRUS TANDEM MIRROR.

Fig. 2

wave to propagate towards the midplane region where the first harmonic resonance occurs $\omega/\omega_{ci} = 2$ and the wave is absorbed by finite ion gyro-radius effects $k_{\perp}\rho_i \ll 1$.

For our initial experiments we have constructed electrostatic parallel plates for coupling from the Lausanne line to the low density injected plasma for trapping, a Macor insulated flat loop antenna for inductive coupling to the radial magnetic fields away from the midplane and a Macor insulated rectangular loop antenna which can be inserted just under the elliptical flux surfaces or around the plasma to couple to the axial magnetic field (see Fig. 2). The feeds and antennas have been designed to minimize skin effect and resistive losses to allow maximum coupling to plasma waves. The antenna coupling primarily to B_r has a vacuum impedance of $Z_{ar} = 0.045 + j8$ ohms at 3 MHz. The B_z antenna has a vacuum impedance of $Z_{az} = 0.045 + j9.9$ ohms at 3 MHz. Both resonant parallel capacitor and two capacitor matching circuits shown in Fig. 3 have been utilized for our low power coupling experiments ($p = 50$ W).

All coupling measurements discussed in this section were made before the high power experiments discussed in the next section. Titanium gettering was used during high power experiments which builds up on the antennas, increases the losses, and lowers the Q. Thus, the work included here is a measurement of the low power coupling without additional losses due to the titanium coating.

Fig. 3. (a) Two capacitor matching circuit.
(b) Resonant tank matching circuit.

Initial coupling experiments were first conducted on the flat antenna which couples to radial magnetic fields at a position where $f_{ci}(\text{midplane})/f_{ci}(\text{antenna}) \approx 0.8$. It has recently been suggested by Watari et al.¹ and Ohsawa et al.² that this type of antenna can couple strongly to plasma slabs near the fundamental ion cyclotron frequency. The large aspect elliptical flux surfaces in the end plug closely approximate this situation. The initial hydrogen plasma conditions correspond to $\bar{n} = 2-8 \times 10^{12}/\text{cm}^3$, $T_e = 5 \text{ eV}$, and $T_i \sim 200 \text{ eV}$ with a plasma diameter of 7 cm at the midplane. A two-capacitor match system is used to transform the vacuum antenna impedance $Z_a = 0.045 + j8$ into a desired impedance to match the generator to the plasma. Since we expect the ion cyclotron wave coupling and absorption to enhance the radiation resistance at the fundamental, we initially set the matching system to give a larger input impedance under vacuum conditions than the 50 ohm output impedance of the RF generator. Figure 4 shows the change in reflected power for constant incident power as the plasma appears for a vacuum input impedance setting of $Z_{in} = 100 + j0$ and $f/f_{ci} = 1$ at the midplane. The reflected power decreases

Fig. 4. Coupling measurements: $f/f_{ci} = 1.0$; $t = 0.2 \text{ ms/div}$,
 $\bar{n}_{\text{max}} = 8 \times 10^{12}/\text{cm}^3$.

by up to 40% indicating substantial coupling to the plasma corresponding to the density rise as shown on the interferometer trace. An RF current loop also shows a corresponding current increase as the plasma density increases. By analyzing the traces on a Smith chart it is determined that the power coupled to the plasma from the generator has a maximum efficiency of about 20% for this case.

When the magnetic field is decreased so that the hydrogen ion cyclotron resonance lies over the antenna, the reflected power increases substantially when the plasma is present. This is interpreted as a substantial reactive loading of the antenna corresponding to the slow ion cyclotron wave being cut off between the antenna and midplane.

By changing the vacuum input impedance to the matching circuit and antenna to be more inductive, $Z_{in} = 98 + j20$ ohms, we can further decrease the reflected power when the plasma is present in both cases, implying that the antenna inductance is decreased corresponding to some capacitive loading, possibly due to electrostatic coupling and surface effects.

Experiments were also conducted with a resonating capacitor placed across the antenna terminals, a current monitor on the input, and this was placed in parallel with a 50 ohm load so that the transmitter was always matched. By taking shots with the generator frequency well below, slightly below, above, and well above the vacuum resonance and noting the change in current due to plasma loading, it was concluded that the inductive reactance of the antenna decreased corresponding to capacitive and resistive loading caused by the plasma. This is in agreement with the measurements on the two-capacitor match system described previously.

The antenna which couples primarily to B_z fields was placed 24.5 cm on the gun side from the midplane of the end cell where $\omega_{ci}(\text{midplane})/\omega_{ci}(\text{antenna}) \approx 0.8$. The antenna was located 1 cm out from the last stable flux surface. Note that for this case, normal cyclotron resonant ions contributing to wave damping near the midplane have to be trapped and moving back towards the gun. For these cases, two hydrogen guns were used to fill the mirror resulting in a plasma which has $\bar{n} = 2 \times 10^{13}/\text{cm}^3$, $T_e = 5 \text{ eV}$, and $T_i \sim 200 \text{ eV}$ with a 10 cm plasma diameter at the midplane.

The two capacitor match system shown in Fig. 3 was used at 3 MHz with the resonance at the midplane. The vacuum impedance was set to $105 + j20$ ohms and the reflected power monitored for constant incident power as shown in Fig. 5. The reflected power decreases substantially corresponding to a maximum efficiency of generator power coupled to the plasma of 33%. The ion saturation current measured near the tip of the ellipse on the opposite side of the mirror peaks early in time since the density decay is faster outside the central core of

Fig. 5. Reflected power and plasma density
 $f/f_{ci} = 1.0$, $t = 0.2 \text{ ms/div.}$

the plasma. If the resonance is moved off the midplane, the drop in reflected power decreases by about 30%.

The B_z antenna was also used for fast magnetosonic wave plasma loading measurements at 6 MHz with the first harmonic resonance ($\omega = 2\omega_{ci}$) located on the midplane. Setting the vacuum input impedance to the two capacitor match

system at $190 + j20$ ohms with plasma parameters the same as in the previous case yields the reflected power and interferometer data shown on Fig. 6. The plasma loading is very substantial and corresponds to 50% of the generator power being coupled to the plasma.

Fig. 6. Reflected power and plasma density
 $f/f_{ci} = 2.0$, $t = 0.2$ ms/div,
 $\bar{n}_{max} \approx 1 \times 10^{13}/\text{cm}^3$.

The low power coupling measurements show that coupling to the plasma increases with density and is a maximum when the resonance is at the midplane. The B_r and B_z antennas have different loading characteristics when located on opposite sides of the midplane. The plasma causes the antenna inductance to decrease at the wave frequency in both cases. Since the plasma loading signature varies with the resonance position, antenna type, and wave frequency, it is anticipated that substantial power can be coupled to body waves in the ion cyclotron frequency range for plasma heating and trapping.

Low power coupling efficiencies $\eta \gtrsim 30\%$ have been achieved near the fundamental ion cyclotron frequency and somewhat higher at the first harmonic. Careful tuning of the matching circuit should improve this. Further heating experiments at elevated power levels together with coupling data will provide more information on the utilization of ion cyclotron frequency range for enhancement of tandem mirror operation.

References

1. T. Watari et al., Phys. Fluids 21, 2076 (1978).
2. Y. Ohsawa et al., Report PPG-374, Institute of Plasma Physics, Nagoya, 1978.

VI. High Power Sources

A. 200 kW

In order to conduct high power ICRF experiments at 200 kW, a 3 MHz power amplifier has been constructed and tested. The amplifier employs a single high gain triode in class C operation capable of 200 kW CW output. It is expected that operation for short pulses, on the order of milliseconds, will allow much higher output power should operation at the megawatt level be desired. Drive power of 500 - 900 W is supplied by a stable, low power oscillator amplifier chain.

As indicated in the power amplifier diagram, a straight forward tank circuit is used to transform the antenna load resistance (R_{ant}) to the level of about 600 ohms (R_{plate}) required at the tube plate. This is accomplished by proper selection of antenna inductance as determined by the value of antenna load resistance. In this circuit the choice of antenna inductance (L_{ant}) determines the impedance transformation ratio and the parallel capacitance is adjusted to obtain resonance. In particular, when R_{ant}^2 is much less than $\omega^2 L_{ant}^2$,

$$R_{plate} = \frac{\omega^2 L_{ant}^2}{R_{ant}}$$

Our choice of antenna inductance results in optimum tube loading for $\omega = 2\pi \times 3 \text{ MHz}$ and $R_{ant} = 0.1 \text{ ohm}$. Values of R_{ant} near 0.152 were measured in the presence of plasma in the low power experiments. A value of 0.05 ohm has been measured as the antenna load resistance in the absence of plasma, indicating that about one half of R_{ant} is associated with power transfer to the plasma and the other half with antenna and capacitor losses. Minimization

of these losses will be addressed in new antenna designs even though we have more than enough power including antenna losses.

The system has been operated with a plasma load in our heating and trapping experiments at an output power level of 200 kW and higher power tests will be made within a few weeks.

200 KW 3 MHz
TRANSMITTER

VI. High Power Sources

B. Lausanne Line and Arc Generator

High power trapping has been done with two sources, a Lausanne line and a form of an arc generator. The Lausanne line (see Fig. 7) is a lumped constant transmission line where the individual capacitor can be charged to simulate a standing wave on the line. We have constructed a 10Ω line which can operate a 20 MW for 2 μ sec at 3 MHz.

A second high power source, which is simpler to operate than the Lausanne, was developed as a consequence of trying to reduce spark gap losses in the Lausanne line. We placed an additional capacitor directly across the spark gap so as to reduce the arc loss by supplying these losses from a low frequency source distinct from the high frequency circuit. To our surprise we found that the Q of the powered spark gap circuit actually increased over the Q of the circuit without the spark gap. Paul Nonn recognized this as nothing more than a 1902 arc generator which was the mainstay of telegraph prior to vacuum tubes. The device takes advantage of the fact that the arc is a negative resistance element.

Our present circuit is shown in Fig. 8. It is capable of operating up to 30 kV on the antenna but for the present experiments it was operated only to 15 kV to prevent any possible breakdown. The present circuit has a maximum of 1.6 J of stored energy which can be increased to 10 J by operating at high voltage.

LAUSANNE LINE

30 MW FOR 2 μ SEC

$C = 7770 \text{ pF}$
 $L \approx 300 \text{ nH}$

Fig. 7

Fig. 8

VII. Initial Results from High Power Experiments

A. 200 kW

A series of experiments have been done to assess the effects of launching the slow ion cyclotron wave on the stream gun injected plasma with the fundamental ion cyclotron resonance near the mirror midplane. The RF power not absorbed by the gettered titanium was 5-25 kW. For these tests the B_r type antenna located half way between the midplane and the mirror throat opposite the titanium gun was used. The antenna was positioned approximately 1 cm from the plasma surface. The results of the initial runs are primarily in the form of interferometric electron density data and hot neutral radial flux data obtained from the secondary emission detector (SED) probe.

The first tests were made at reduced power of about 10 kW and indication of ion heating was obtained. Figures 9a and 9b show the output of the SED probe and the envelope of RF voltage on the antenna. The SED probe was oriented to detect hot charge exchange neutrals leaving the plasma radially at the resonance zone on the mirror midplane. This data indicates a significant enhancement in charge exchange neutral production during the RF pulse. Figure 9b was taken immediately after gettering the vacuum chamber which results in an order of magnitude reduction in background neutral pressure. Under these conditions the charge exchange flux off the fast ions produced by the RF heating pulse is expected to decrease by the reduction in the background pressure. In Fig. 9b the SED signal decreases into the noise level.

In subsequent experiments long pulses of 5 kW to 25 kW of RF power

PRELIMINARY ICRF HEATING RESULTS

Secondary emission
detector

RF burst 5 kv/cm

100 μ s/cm

Fig. 9a

After gettering
(low neutral density)

Fig. 9b

have been seen to modify the density of the mirror confined plasma as a function of time. There are two reasons for the increase in density. The ion cyclotron heating should enhance trapping of the injected plasma stream. The increase in the perpendicular energy of the trapped ions will improve their confinement reducing the loss rate. The accompanying plots show increased trapping of the stream (Fig. 10). The density is raised the fastest when the density is the highest. This is in agreement with the low power loading measurements which demonstrated more efficient coupling at high density.

Along with the density increase we also observed a doubling of the plasma diamagnetism. Since $T_i \gg T_e$ the only measurable contribution to the signal is density and ion temperature. Since the density increases by 50%, the average ion temperature must increase by $\sim 30\%$. This is also consistent with an observed doubling of the SED signal.

When the plasma is heated during density build up (see Fig. 11) and then followed by crowbarring of the gun to cut off the stream, the plasma goes unstable with large bursts of RF produced by the plasma. This should be contrasted to the case without RF, where the gun is crowbarred but the decay is quiescent. The low electron temperature without heating results in a small ambipolar hole and a stable decay. By heating with ICRF we can expect the growth rate of DCLC to increase for several reasons. The increase of the ion temperature results in a smaller a/ρ_i . The ion temperature increase should heat electrons by coulomb drag resulting in a larger ambipolar hole. Both of the mechanisms will make the plasma more unstable to DCLC.

Fig. 10

LINE DENSITY vs. TIME, SINGLE STREAM GUN

Fig. 11

We cannot verify any T_e change at this point since the Langmuir probe eliminates hot ions. A more complete understanding will have to await the completion of the additional diagnostics. It should also be noted that the large density increase of Fig. 11 is associated with the absorption of only a few kilowatts of RF since this data was taken at a density much less than that which is optimum for RF power coupling.

VII. Initial Results from High Power Experiment

B. Arc Generator Tests

A single mica capacitor has been discharged into the B_z antenna to couple the ion cyclotron wave to the plasma. The B_z antenna is located halfway between the midplane and the magnetic mirror. The circuit is resonant at 3 MHz locating the resonance on the midplane at maximum magnetic field ($B_0 = 2$ kG). Q is enhanced to approximately 300 by placing a 1 μ F capacitor across the rail spark gap. A substantial amount of power is then available over 10 microseconds.

Figure 12a shows the RF antenna current decay without plasma. Figure 12b shows the loading which occurs when plasma is present. With one gun, the maximum loading corresponds to $\sim 25\%$ of the power being coupled to the plasma. This optimum coupling was obtained with the resonance zone located off the midplane, $1/3$ of the way between the midplane and the antenna. This is to be contrasted to the low power coupling measurements which yield best coupling with the resonance zone on the midplane. This difference will be explored in future experiments. With an input energy of 0.3 Joules ($C = .0036 \mu$ F, $V = 12.5$ kV) this would lead to an average energy increase of 17 eV per particle which is below the detection threshold of our diagnostics. However these tests clearly demonstrate substantial coupling. As we increase the system voltage and improve our ability to use the spark negative resistance to provide additional power input, we will be able to substantially increase the plasma energy content by this method. With lower plasma densities ($n_0 < 5 \times 10^{12}/\text{cm}^3$) enhanced loading is frequently observed - up to 60% of the power going into the plasma (Fig. 13). As this technique

(a)

(b)

Fig. 12

Fig. 13

is perfected, we will return to attempt trapping of the plasma produced by the gun in the fast pulse mode. Due to the enhanced coupling at low density and high power, one may reasonably conclude that such trapping may be successful provided that gun reproducibility can be improved.

VIII. Conclusions and Near Term Plans

During these initial experiments we have gained considerable experience in operating the machine diagnostics, high power RF sources and carrying out RF heating. We expect to translate this into considerable improvement in machine operation, diagnostics and antenna design.

Operating high power, high Q antennas with titanium gettering has been difficult and has limited the power input to the plasma. Since titanium is evaporated over all the surfaces exposed to the plasma, the antennas are necessarily coated. Even using faraday shields over the antenna, the eddy current losses in the titanium dominate the loading after several days of heavy gettering. We will require methods to evaporate titanium from the antenna surface to keep the layer thin enough to prevent significant power loss. We will try out a new antenna design made from ceramic enclosed, water cooled copper rods which will extend across the vacuum box. This design offers considerable advantage from the coupling viewpoint and high voltage standoff. Since the rods are water cooled, it can be run in steady state. Thus we will be able to evaporate titanium from the antenna by induction heating.

With the B_z and B_r antennas we will try relocating the getters and the use of optical shields to keep titanium from building up. We will also try electron bombardment to remove titanium from ceramic surfaces. From past experience we have found that high power electron bombardment will remove titanium even from metal surfaces.

Now that the transmitter is operating well at 200 kW and we believe we can eliminate the titanium loading, we believe heating rates will be

substantial in the next series of experiments. Further improvements in diagnostics will occupy the bulk of our time during the next five months.

One can make several conclusions from the initial trapping studies presented here and as part of our milestones # 6, 7, 8.

- 1) RF trapping using the Lausanne line and the arc generator has demonstrated good coupling but this method has not been pursued to the extent that RF enhanced trapping of stream plasma has been. This was due to time limitations and physics problems associated with obtaining reproducible plasma flow boundaries with the guns operated in the fast pulsemode.
- 2) Self-trapping studies with guns in the stream mode are successful in building up end plugs. This method can be used while maintaining low charge exchange rates.
- 3) RF heating at an absorbed power level in the plasma of several kilowatts results in an increased density and ion temperature over the self-trapped plasma without RF.

Since the application of RF to mirrors was new at the time of the proposal, the Panel recommended an evaluation of the initial results. These results should be consistent with the objectives of the University of Wisconsin Program as outlined in the Panel Report. At this stage of construction we have begun to answer one of the two objectives raised. Namely, RF heating of stream plasma can "create suitable RF heated mirror plasmas" for tandem mirror operation. The next generation of experiments which will couple to the plasma ~100 kW, will yield significantly better end plug parameters.

The present experiments have shown no detrimental effects by RF. This is due to the fact that the RF is not generated by the plasma but rather from an external source. This results in a net increase in energy content of the plasma with resulting enhancement in n_e .

As it is also desirable to isolate RF trapping physics from heating of self-trapped plasmas, it is desirable to continue the high power experiments on RF trapping of plasma flowing through the loss cone with little self trapping. This work will be pursued using the higher power arc source or Laussane line.

These future experiments will be directed toward the best possible understanding of the use of RF in tandem mirrors, and specifically the application of RF to obtain the best possible parameter in Phaedrus.