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Overview

The original tandem mirror concept combined quadrupole mirror end cells with axisymmetric end cells. Central cell ion confinement was provided through electrostatic confinement by the end cell potentials. Increased end cell potentials were achieved by increasing end cell density with neutral beam injection. A major problem with this design turned out to be azimuthal asymmetries associated with nonuniform heating and fueling which led to poor radial plasma confinement. The Phaedrus program was first to achieve axisymmetric tandem mirror operation. Other Phaedrus experiments demonstrated that ion and electron heating as well as ion plugging end cell potentials and thermal barrier-like electron plugging potentials could also be achieved with Ion Cyclotron Range of frequency RF (ICRF).

"Axisymmetric" tandem mirror operation was first achieved on the Phaedrus Tandem Mirror and was a major advance for the tandem mirror program. Only circular magnet coils were operated in this mode. MHD stability was provided by a combination of pressure weighted stability from B field curvature, which was weakly destabilizing combined with stabilizing ponderomotive force¹ provided by ICRF from a variety of antennas (which were not quite axisymmetric). ICRF mode control was obtained by using rotating field antennas². This type of antenna was invented in Kyoto, Japan, but was first tested in a fusion-related application on the Phaedrus Tandem mirror. It consisted of two dual half turn antennas that were phased with respect to each other. The wave azimuthal mode was determined by the relative phasing. By phasing two dual half turn antennas spaced 1m apart it was possible to suppress the propagating $m = +1$ fast in the region outside the antennas. MHD stability adjusted by adjusting relative antenna phase. Photograph of Phaedrus-B Tandem Mirror (see Figure 1).

Goulding³ developed a novel startup technique that employed a combination of ECH (resonant near the end of the central cell) and ICRF. A key feature of this technique was to heat electrons initially hotter than 10 eV. When $T_e > 10$ eV, ICRF near ω_{ci} could evanesce to the center of the plasma to sustain the discharge. Higher initial densities, at lower T_e did not sustain after the ECH pulse was turned off.

The original experiments on Phaedrus by Ferron et al⁴ which demonstrated MHD stabilization by ponderomotive force showed stabilization when ω was greater than ω_{ci} and destabilization when ω was below ω_{ci} . However, Browning et al⁵ demonstrated interchange stability with $\omega < \omega_{ci}$ could also be achieved under the appropriate conditions. The effects of ponderomotive stability were modeled with the code Antena⁶, written by McVey at Wisconsin, early in the Phaedrus program and then improved by McVey at MIT. The code allowed modeling of realistic density and temperature profiles in uniform magnetic fields and was extrapolated to qualitatively treat non-uniform mirror fields. The Antena code indicated that ponderomotive stability did not scale well for providing stability in fusion devices because the required RF fields appeared to be too high. However, later work in Japan indicated it might be suitable for providing MHD stability for a mirror-based neutron source.

Figure 1

We also reported⁷ that ion confining potential barriers could be achieved with ICRF by pumping electrons out of the end cells⁸ and that thermal barrier-like potentials could be achieved with ICRF.

Later, we undertook an effort at better understanding ICRF, in response to a DOE effort to better model ICRF antenna operation. In 1989, we reported^{9 10} wave data, which served to benchmark a model tokamak ICRF antenna in the Phaedrus central cell by the code ANTENA. In our knowledge, this was the first time an RF antenna code was benchmarked by direct field measurements in a "fusion" plasma.

In 1989 Meassick¹¹, Intrator^{12 13}, and, Browning¹⁴ refined our understanding of ponderomotive effects.

Roberts et al. reported $m = -1$ Alfvén wave beach heating of two-ion mirror plasmas^{15 16 17 18}. Magnetosonic waves, launched across the magnetic field at the RF antenna, mode converted to shear Alfvén waves at the Alfvén resonance surface. The shear Alfvén waves propagate along the spatially varying magnetic field provide ion heating at the "magnetic beach" location where $\omega = \omega_{ci}$. This work established many of the concepts that helped in the demonstration of Alfvén wave current drive.

One novel feature of the RF on all versions of the Phaedrus Tandem Mirror was that no Faraday shields were used. Conducting side limiters were used on the central cell antennas and insulating limiters were used on the end cell antennas.

The success of ICRF experiments on the Phaedrus Tandem Mirror led to the design and construction of the Phaedrus-T Tokamak. This machine employed the iron core and vacuum system recycled from ISX-A experiment. The ports were re-machined to provide better access for RF antennas and diagnostics. New toroidal field coils, compatible with the power supplies that had been used on the Phaedrus Tandem Mirror, were designed and constructed. A rectangular inner bore design was chosen to allow for a future upgrade to a non-circular cross section tokamak. The evolution of Phaedrus coil configuration is shown schematically in Figure 2.

The Phaedrus-T Tokamak had a plasma volume of approximately 1.3 m^3 and a planned RF power of up to 2 MW (see Figure 3). Thus, power densities as high as 1.5 MW/m^3 , comparable to those planned for fusion devices, were planned. In addition, the surface to volume ratio was much higher than in a fusion device. This made Phaedrus-T a good device to develop techniques to reduce impurity generation. In addition Phaedrus-T had an extensive diagnostic set (for a University experiment), see Figure 4.

Experiments on RF antennas on the Phaedrus Tandem Mirror central cell were directed to the question of ICRF edge plasma interactions^{19 20}.

In addition to RF studies, the tandem mirror provided an opportunity to carry out a variety of investigations of mirror physics. These include studies of radial transport²¹. Of whistler

Phaedrus History

1. Plato's dialog (400 BCE)

Evolution of B field Coil Sets

2. Original Phaedrus (1980)

3. Axisymmetric (1983)

4. Phaedrus-B (1985)

5. Phaedrus-T (1988)

Figure 2

Figure 3

Figure 4

While the Phaedrus-T tokamak was originally aimed at RF helicity current drive, the first step was to reduce impurity generation, and to explore mode conversion and mode coupling. We identified the physical cause behind the impurity generation. It was a result of SOL plasma potential Φ_p increases with RF with respect to the conducting antenna limiters. $\Delta\Phi_p$ and impurity generation were substantially reduced by using insulating BN limiters together with no Faraday shields, reminiscent of our previous work with ICRF in the Phaedrus tandem mirror. Impurity generation was further reduced by careful attention to the wall conditions. Phaedrus-T was the first tokamak in the US to employ boronization with trimethyl boron, o-carborane, and decaborane. The combination of newly boronized surfaces, the use of helium glow discharges between tokamak discharges and insulating limiters was found to result in almost elimination of RF impurity generation.

As our studies progressed it became apparent that Alfvén wave current drive had not yet been observed in a tokamak and this was a fundamental technique for which understanding was needed in order to interpret any low frequency wave current drive phenomena. Because of this, the demonstration and understanding of Alfvén wave current drive was established as the first current drive goal.

Alfvén wave current drive (AWCD) had been the goal of the TCA experiments in Switzerland. While TCA demonstrated coupling to the Alfvén spectrum and kinetic Alfvén waves and worked out many of the basic theoretical issues, it did not achieve AWCD. Experiments were plagued by rf induced density increases from uncontrolled fueling.

Phaedrus-T experiments succeeded in demonstrating electron heating by Alfvén waves and then AWCD but were terminated before a good understanding was achieved. Preliminary results were generally consistent with theoretical predictions but the role of trapped electrons was not established and this is an important question. Preliminary experiments also found evidence of plasma rotation induced by Alfvén waves²⁶. The particle balance effects on Phaedrus-T (with low particle recycling was found to be very different from TCA (which appeared to have high wall recycling), apparently the result of very different wall treatment. High recycling on TCA led to poor heating and such an effect was also seen in Phaedrus-T when operated with covered antennas²⁷.

In addition to Alfvén wave studies, diagnostic development continued throughout the program. For example, improvements in probe techniques^{28 29} were needed to discover the mechanism of impurity injection. A small effort led by Fiksel^{30 31} was also carried out to explore the use of gaseous divertors.

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DETAILED DESCRIPTION OF RESULTS FROM THE LAST FOUR YEARS

FIRST EXPERIMENTAL DEMONSTRATION OF AWCD

The major success of the Phaedrus-T experimental effort was the first demonstration of Alfvén wave current drive (AWCD) [1,2] in a tokamak. Loop voltage drops indicated that 30-55% of the toroidal current (20-32kA out of 64 kA total current), was driven with rf at $\omega = 0.7 \omega_{ci}$ with a coupled rf power of 200W. Current drive experiments were performed at 7 MHz, with the magnetic field adjusted to give $\omega/\omega_{ci} = 0.7$ on axis. AWCD experiments employed $\pi/2$ phasing while Alfvén wave heating experiments employed π phasing between the antenna straps. Experiments with $-\pi/2$ phasing did not find loop voltage drops although similar increases were found in Z_{eff} . This is consistent with the wave spectrum asymmetry found in current-carrying cylindrical plasmas [3].

Representative Phaedrus AWCD results are given in Fig. 1. A loop voltage drop $\Delta V_{loop}/V_{loop} = 0.36$ was observed. Thomson scattering indicated that the decrease in V_{loop} was not associated with an increase in T_e (for the particular discharges shown in Fig.1). RF was coupled into the plasma at 110 μ sec and lasted 50 μ sec with a peak coupled RF power, P_{RF} , of 210 kW, see Fig. 1b. Upon application of the RF, the loop voltage V_L abruptly decreased to its minimum value in about 2 μ sec. Averaging over 18 discharges, the maximum fractional V_L drop, $V_M = (V_O - V_{RF})/V_O$, where V_O is the average loop voltage between 105 μ sec and 110 μ sec and V_{RF} is the average between 112 μ sec and 117 μ sec, was 0.37. Individual V_M ranged from 0.35 to 0.40. The V_L remained at this minimum level for 10 μ sec, then slowly rose from this minimum. When the RF was terminated, the V_L abruptly increased to a value that exceeded the original ohmic V_L . This temporal behavior of V_L was dependent upon the RF power coupled into the plasma. The RF power ramped up in approximately 1 μ sec to reach 75% of full power, then ramped more slowly to reach its peak power in about 10 μ sec and decays over the next 40 μ sec to 60% of its peak power. The V_L normalized to RF power, $V_N = V_O + (V_O - V_L) \times P_{RF}/P_{RFmax}$ where V_L is evaluated at P_{RFmax} , is approximately constant after the first 10 μ sec of coupled RF power suggesting that to first order the temporal behavior of V_L after the first 10 μ sec is due primarily to the decreasing RF power, see the dotted line V_N in Fig. 1a. The normalization procedure is supported by the approximately linear dependence that the V_M has on applied RF power, shown in Fig. 2.

The measured IP, shown in Fig. 1c, was maintained constant within ± 0.25 kA. The observed fluctuations in the measured IP were found to be uncorrelated with the fluctuations in the measured V_L suggesting that these small current fluctuations had negligible impact on the measured V_L . Since plasma inductance, L , is a function of

plasma position, the position was programmed to remain constant and it varied by only 0.002 m from the ohmic position prior to the application of RF to the plasma position during RF. The small fluctuations in position were not accompanied by a noticeable change in the V_L . Finally, the $\langle n_e \rangle$ was controlled by decreasing the gas puffing by 15% during the application of RF and the resulting $\langle n_e \rangle$ was constant within the bit noise of the $\langle n_e \rangle$ measurement.

The Thomson scattering measured T_e profiles and the temporal behavior of the visible bremsstrahlung emission, $j(r)$, measured along a chord through the center of the plasma are shown in Fig 3. The Thomson scattering measured T_e profiles are calculated by averaging the raw spectral data from 18 discharges during the RF at $t=115 \mu\text{sec}$ and 20 discharges prior to the RF at $t=109 \mu\text{sec}$. Except for the point at $r=3.5 \text{ cm}$, these T_e profiles show little difference within experimental error and the calculated change in conductivity is approximately a 2% increase which is within the error of the measurement. For the observed RF generated drop in V_L to be a result of an increase in temperature, a volume averaged temperature, $\langle T_e \rangle$, of 370 eV during the RF would be required, whereas $\langle T_e \rangle$ calculated using Thomson scattering data and assuming a 30 eV temperature near the plasma boundary is $274 \pm 32 \text{ eV}$. From these observations, we concluded that the observed drop in V_L during the application of RF was not due to an increase in T_e .

FIG. 1. Representative plasma response to applied RF power: (a) is the loop voltage, V_L , and normalized loop voltage, V_N ; (b) applied RF power, P_{RF} ; (c) total plasma current, I_P ; (d) plasma average density, $\langle n_e \rangle$; and (e) radial position.

FIG. 2. Fractional loop voltage drop, ΔV , as a function of RF power. The line is the least squares fit ($\Delta V = mP_{RF}$) to the data.

FIG. 3. (a) Thomson scattering measured temperature profiles that were determined from averaging the raw spectral data over 18 discharges for RF and 20 discharges for no RF and (b) visible bremsstrahlung emission, $j(\lambda)$, averaged over two shots and smoothed.

CURRENT DRIVE LOCATION AND THE LOOP VOLTAGE RESPONSE

The loop voltage response to an rf current drive is determined by the toroidal electric field diffusion due to finite electric conductivity. A general solution for an arbitrary time-dependent J_{rf} and a time-dependent conductivity with an arbitrary but stationary spatial profile has been obtained by Litwin [1995a]. This solution indicates that for a localized current drive the shape of the loop voltage response depends sensitively on the current drive location. By comparing the experimentally measured loop voltage response with the solution of the inhomogeneous diffusion equation, the current drive location and magnitude can be obtained. For the Spitzer resistivity profile consistent with Thomson scattering measurements we find that the loop voltage response in experiments reported by Wukitch et al. [1995] is consistent with an off-axis current drive at localized in the vicinity of $r/a \approx 0.5$ [Litwin 1995b]. In figure Fig. 1 we show the time dependence of the normalized loop voltage drop defined as $[V(t)-V_0] P_{rf}(t=135) / [V(t=135)-V_0] P_{rf}(t)$ where P_{rf} is the coupled rf power and $V=V_L/Z_{eff}(t)$ with V_L being the measured loop voltage. The thin line denotes the experimental values and the thick line is calculated by solving the resistive diffusion equation for a Gaussian driven current profile, with a half-width $d=0.12 a$, localized at $r = 0.5 a$. Here it has been assumed that plasma resistance rises from $13.5 \mu\Omega$ to $15.4 \mu\Omega$ (corresponding to, e.g., Z_{eff} increasing from 1.9 to 2.2 at a constant temperature) upon the rf turn-on.

Fig.1

Assuming that the current drive takes place at the Alfvén wave resonance one can now deduce the wave phase velocity at the current drive location which is necessary in order to make a comparison between the experimental and theoretical current drive efficiencies (see next section). To do so, we obtain $k_{||} = (n + m/q) / R_0$ from the Alfvén wave resonance condition, discussed earlier, assuming that fully ionized carbon, with concentration f_C , is the dominant impurity. If $Z_{eff} = 2.2$, $f_C = 0.053$. For density and temperature profiles as before, one finds that $k_{||} R_0 = 4$, and $\omega/k_{||} v_{te} = 1.8$. These numbers

are in an approximate agreement with the results of modeling with the aid of the cold plasma toroidal full-wave code LION [Villard 1987]: the power deposition is seen to peak at $\ln l \sim 4-5$, with $m \sim 1-2$ (the antenna vacuum spectrum in the discussed experiments is dominated by $n < 0$ modes). If $Z_{\text{eff}} = 2.5, f_C = 0.071$ and one finds that $\omega/k_{\parallel} v_{te} = 2.2$ in this case.

Recently we have conducted experiments at higher plasma densities ($n_0 = 4.6 \times 10^{12} \text{ cm}^{-3}$) and rf power (450 kW). In these experiments, unlike those reported in Wukitch [1995], rf power level was held approximately constant throughout the rf pulse. Upon rf turn-on, central electron temperature increased from 440 eV to 510 eV and Z_{eff} rose from 1.9 to 3.1, respectively. Taking this into account we analyzed the loop voltage response in these experiments in the manner described above. The result of this analysis is shown in Fig. 2.

Fig. 2.

The theoretical curve (thick line) corresponds to current drive at $r/a = 0.52$. From the Alfvén wave resonance condition one then deduces that $\omega/k_{\parallel} v_{te} = 2.3$.

The current drive localization is consistent with the expectation that the current is driven at the Alfvén wave resonance. By changing the magnetic field magnitude, the position of the resonance can be affected. In experiments with varying magnetic field a modification of the loop voltage response has been observed. By comparing the experimentally measured ratio of the transient and asymptotic loop voltage drops with the one calculated from the solution of the diffusion equation, the current drive location as a function of the magnetic field strength has been inferred. The results of this analysis are shown in Fig. 3:

Fig. 3.

(vertical bars denote estimated uncertainty). The dependence of the current drive location on the magnetic field strength that the above figure implies is qualitatively similar to the dependence of the mean radius of absorption, obtained with the aid of the LION code. This dependence is shown in Fig. 4 (albeit for a higher density than in the experiments discussed above):

Fig. 4.

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TRAPPING AND CURRENT DRIVE EFFICIENCY

For phase velocities, discussed in the previous paragraph, trapping effects on the current drive efficiency are not dramatic, but potentially measurable. The Ehst - Karney formula indicates that trapping reduces the current drive efficiency by 33% in the case of $Z_{eff} = 2.2$ for which the normalized current drive efficiency = 3.2 for the low-density case. The minimum current drive efficiency (which assumes all the power from the antenna goes into driving current that causes the observed loop voltage drop) in the experiment is 0.13 A/W. However, the real current drive efficiency is higher. Because of an imperfect directionality of the antenna, the rf drives both co- and counter-currents. The energy density in the co-direction is approximately 8 times larger than in the counter-direction,

as indicated by both measurements and computations of the antenna vacuum spectrum; at the same time, the LION code indicates that the power absorption is approximately symmetric for $n \approx \pm 5$. Thus the real current drive efficiency is a factor 1.3 larger than the value inferred from the loop voltage drop and absorbed power. The dimensionless efficiency inferred from experiments is thus $\tilde{\eta}_{exp} = 2.1$. If $Z_{eff} = 2.5$ during the rf pulse, the inferred value of the current drive efficiency is 0.15 A/W implying $\tilde{\eta}_{exp} = 2.5$ compared to the Ehst-Karney value $\tilde{\eta}_{E-K} = 3.6$. Thus the minimum current drive efficiency inferred from experiments is 65-70% of the Ehst-Karney efficiency.

In the higher-density and higher-power experiments, discussed in the previous section, the minimum current drive efficiency was 0.06 A/W. This is consistent with the density increase by the factor 2.3. The minimum normalized efficiency $\tilde{\eta}_{exp} = 2.2$, 66% of the value predicted from the Ehst-Karney formula.

The above numbers are, in fact, only the lower bounds on the true current drive efficiency in the experiment since not all power emitted by the antenna is absorbed by the plasma. While at present there exists no measurement of this power, it is quite likely that only a fraction of the emitted power is absorbed by the bulk of the plasma: temperature appears little affected by rf. If, for example, an L-mode scaling of the energy confinement time is adopted, and the stored energy increase is assumed as given by the upper limit of the temperature uncertainty, one arrives at an estimate that less than 25% of power is absorbed in the bulk of the plasma. While it is not known whether the energy confinement time in Phaedrus-T follows the L-mode scaling, the measured particle confinement time appears to follow it. Therefore it appears quite likely that the current drive efficiency is greater than the Ehst-Karney value and possibly also greater than the one predicted by Fisch and Karney [Fisch 1981]

A definitive understanding of the role of trapped particles requires operation in a regime where trapped particle effects could be more pronounced, viz. $V_\phi < v_{te}$. Since v_ϕ is the order of the Alfvén velocity, this would require an increase of β by at least 3 (while keeping Z_{eff} low). This could be achieved by either increasing the electron temperature or density. In this context a higher mass-to-charge ratio for plasma ions would also be beneficial.

In preliminary experiments to investigate the wave coupling at higher β 's, the phase of the antenna which determines the excited vacuum wavelengths was scanned between -0.75π and π . The data, shown in figure 1a, indicate that as the density is increased the phase at which the electron coupling (measured by the fractional change in loop voltage) peaks shifts from $.5\pi$ to π . The corresponding central plasma density is $4.5 \times 10^{12} \text{ cm}^{-3}$ and $10 \times 10^{12} \text{ cm}^{-3}$, respectively. In figures (b) and (c), the electron coupling data are plotted versus the phase of the antenna divided by the square root of the average density in normalized units. Note that these distinct peaks from figure (a) now overlap. The data in figure (c) is the same data as shown in figures (a) and (b) with data points with similar phase divided by the square root of the density values averaged together. This suggest

that we can couple to a mode in the plasmas with β that are approximately a factor of 2 larger.

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Figure (a) The electron coupling (measured by the fractional change in loop volts) plotted as a function of antenna phase. The rf power was approximately 300 kW and the B_0 was 6.8 kG. The lines drawn are fitted polynomials to guide the eye.

Figure (b) The electron coupling versus phase divided by the square root of the density. The numbers correspond to different densities with the density increasing with increasing numbers. These are the same points as that plotted in figure (a).

Figure (c) The average electron coupling plotted versus the antenna phase divided by the square root of the density. The drawn curve is to guide the eye. The points were calculated by averaging points together that had similar antenna phase divided by the square root of the density values.

Z_{eff}

Z_{eff} measurements are important for the interpretation of AWCD experiments. The current drive is inferred from a drop in loop voltage which can not be explained by measured changes in plasma conductivity, T_e, Z_{eff}, n_e, rf power or plasma inductance.

A simple relationship exists between the radiated bremsstrahlung power, the plasma electron temperature, the electron density and Z_{eff}.

$$E_{\text{brem}} = 1.5 \times 10^{-28} n_e^2 Z_{\text{eff}} g_{\text{ff}} / (\lambda^2 T_e^{1/2}) \text{ W/cm}^3 \text{ nm sr}$$

The electron temperature profile is obtained from Thomson scattering. The density profile is obtained from microwave interferometry. A Z_{eff} averaged over the diameter of the plasma can be obtained by setting the angle to view the r = 0 cm chord. This measurement is useful for monitoring shot to shot changes in plasma impurities. It is also helpful for day to day monitoring of wall conditioning along with SPRED and RGA measurements. For detailed studies the detector viewing angle can be changed from shot to shot and chordal averaged signals from different plasma radii are acquired. An Abel inversion then gives the Z_{eff} profile. Interference filters are easily changed so that profiles of H-alpha, C impurity, and O impurity can also be obtained. Absolute calibrations for the different filters are obtained with a tungsten ribbon lamp.

The visible bremsstrahlung diagnostic utilizes 523.6 nm interference filters and photomultiplier tubes. The device is located 12 cm below midplane. A shutter has been installed to prevent change in window transmittance caused by exposure to boronization. The viewing angle can be changed in steps of 2.5° by an index locator. The upward viewing angle of 25° is limited by the vertical field coils. The downward viewing angle of 35° is limited by the neutral energy analyzer. The plasma can be viewed from -33.5cm to +7 cm. When 20 – 30 kA of AWCD was applied, the average Z_{eff} was measured to increase from 1.8 to 2.5. Measurement uncertainties in T_e and n_e profiles cause an uncertainty in Z_{eff} of ± 0.3. Z_{eff} measurements are also utilized in studying electron trapping effects and impurity profiles occurring in H mode plasmas.

REFLECTOMETRY

Reflectometry techniques are being developed (preliminary data are discussed below) to determine the radial location and relative amplitude of density fluctuations at the rf frequency. In particular, such density fluctuations are expected at the Alfvén resonance if mode conversion to Kinetic Alfvén Waves takes place. The techniques used are simple and inexpensive to implement.

The reflectometer system consists of a YIG oscillator that can be swept in frequency from 26.5 to 40 GHz in 4 ms, a launch antenna, a receive antenna, a broad band mixer and an RF spectrum analyzer used as a high gain receiver. For density fluctuations with wavelengths greater than the incoming microwave signal (~ 0.8 cm), the reflected microwave signal observed by the reflectometer is localized near (within 1-2 cm) the critical reflection surface [Bretz, 1992]. This is true for both O-mode and X-mode waves. The wave modes excited by the rf are expected to have wavelengths greater than 2 cm except near the outside edge of the tokamak plasma. Therefore, the reflected microwave signal is expected to provide a local measurement of the density fluctuations at the rf frequency.

Trace (b) of Figure 1 shows a peak in the amplitude fluctuation profile (in arbitrary units) at the rf frequency localized around $r=10$ cm. The corresponding magnetic field on axis (B_0) is 6.5 kG and the peak density is $9 \times 10^{12} \text{ cm}^{-3}$. Traces (a) and (c) are for $B_0 = 6.0$ and 7.5 kG, respectively. For trace (a) the hydrogen cyclotron frequency is located in the plasma on the low field side, directly in front of the antenna and the rf induced fluctuations are reduced over the plasma radius. This is consistent with the theoretical prediction that the waves would be unable to penetrate the plasma in this regime. For the data shown in trace (c), the $S=0$ surface is expected to be in the plasma at approximately $r=5$ cm on the low field side. The waves are expected to be excluded from the region between the plasma core and the $S=0$ surface. The data of trace (c) clearly show a reduction in the fluctuation amplitude within $r = 10$ cm.

The $S=0$ surface can also be moved along the major radius by adding deuterium (charge to mass ratio of 0.5). As shown in Figure 2 ($B_0 = 6.8$ kG), as the concentration of deuterium is raised the $S=0$ surface moves from the high field side of the plasma to the low field side of the plasma. At 7 MHz, this is expected to eventually eliminate wave penetration into the plasma core and to move the peak rf fluctuations to larger minor radii as the concentration of deuterium is increased. The peak signal amplitude migrates to larger radii with increasing deuterium concentration and the signal is absent in the case of full deuterium. These observations are in agreement with the predicted theoretical scaling for the Alfvén resonance.

In addition to the rf fluctuation measurements, reflectometry can also be used to measure the radial location of the $q=2$ surface. This aids in yielding a measure of the q profile and can monitor changes in the q profile due to rf. The $q=2$ location is identified by correlating the MHD fluctuation spectrum measured with an array of Mirnov coils ($m=2$) and the spectrum measured by the reflectometer. The reflectometer MHD signal peaks at a frequency where its reflection layer corresponds to the local plasma density at the $q=2$ surface.

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Figure 1: Variation of the density fluctuations at the RF frequency versus radius for a.) $B_0 = 6.0$ kG, b) 6.5 kG and c) 7.5 kG for an rf power of 300 kW and a peak plasma density of $9 \times 10^{12} \text{ cm}^{-3}$. The reflectometer signal at the rf frequency is normalized to reflected microwave power, the density scale length, and the antenna strap current. Assuming a parabolic density profile, the critical surface where the microwaves reflect is determined by the local density, the magnetic field (X-mode only) and the frequency of the microwaves.

Vary Ion Species Reflectometer Shows Spatial Structure

Figure 2

STACKED STRIPLINE ANTENNA DEVELOPMENT

RF experiments in the Alfvén frequency range present a significant challenge to the antenna, primarily because the loading resistance is very low in the frequency range where $\omega < \omega_{ci}$. This low loading (approximately 0.2 ohms in Phaedrus-T) means that large antenna currents must flow for a given power input, and this generates large voltages, 20 to 30 kV in our case. The power we can couple to the plasma is then limited by either voltage standoff or impurity generation.

In order to investigate the trapping problem in low phase velocity current drive, and to gain some experimental flexibility, we decided to install an antenna on the high field side of Phaedrus-T. In this case, the loading resistance and the voltage issue become even more serious problems, because the feeders to carry the current to the high field side must be long, increasing the antenna inductance and therefore the voltage, and the available clearance for voltage standoff is much less.

For these reasons, a new type of antenna, the Stacked Stripline Antenna [Probert, 1995], was developed. A drawing of this antenna is shown in Fig. 1. The basic idea of this design is that, by breaking up the strap into many shorter straps and feeding them in parallel, the voltage can be reduced by $1/N$ where N is the number of "straplets." By making the straplets wider, taking advantage of the relaxed clearance requirements at the lower voltage, an even lower inductance and, therefore, voltage can be obtained. A pair of SSL antennas was built and installed into Phaedrus-T during this grant period, and operated at power levels up to 300 kW input, about 150 kW coupled. The results include:

- Demonstration that the impurity generation is less than for the low field side antenna under similar operating conditions. Data were obtained indicating that the capacitive loading effects of the plasma on the antenna were much reduced.
- A decoupler was developed which, while connected externally and not included in the primary current loop of the antenna and resonating capacitors, can still achieve good, load independent decoupling
- Small current drive effects were observed. A comparison of the current drive power scalings for the SSL and conventional antenna is shown in the subsection entitled "Antenna Issues for Trapped Electron Studies" in Proposed Studies.

[Probert, 1995] P.H. Probert, S.P. Oliva, G.R. Winz, D.J. Hoffman, J.B.O. Caughman, and W.L. Gardner, "Design and Initial Tests of a Low Voltage Stacked Stripline Fast Wave Launcher in the Phaedrus-T Tokamak", Nuclear Fusion, 36: (4), p. 421-433, Apr 1996.

Fig. 1 Schematic drawing of a single SSL unit, 2 of which are installed side by side on the high field side of Phaedrus-T. Current flow, as shown by the arrows, is in a poloidal plane, and the straplets have been canted to follow the equilibrium magnetic field.

H-MODE AND OTHER BIASED ELECTRODE EXPERIMENTS

Positively biased electrode H-modes have been produced and studied in Phaedrus-T in collaboration with En Yao Wang of the Southwestern Institute of Physics in Chengdu, People's Republic of China, and Sean Regan and Michael Finkenthal of the Johns Hopkins University. Highlights from this work included:

- First ever production of biased electrode H-modes in the presence of significant, sub-threshold (i.e., not enough power to initiate the H-mode) auxiliary (Alfven wave) power ($P_{AW} \approx 2P_{OH}$) [Xin Wang, 1995].
- Alfven waves were found to increase particle transport while the H-mode decreased it [Xin Wang, 1995].
- H_{α} emission suggested that the improvement in particle confinement with the H-mode is greatest on the low field side [En Yao Wang, 1995].
- Radial conductivity data compared well with theory [En Yao Wang, 1995].
- With the onset of the H-mode, the spatial peak in the XUV (eXtremely Ultra Violet) radiation and the width of that peak were found to move away from the plasma center and narrow, respectively, and these results were successfully modeled with the TRANPS code from Princeton.

When the work began, it was hoped that AWCD experiments could be performed in H-mode plasmas in addition to ohmic plasmas. Since that time, however, successful AWCD experiments have demonstrated the importance of density control; and the uncontrolled density rise associated with the H-mode make this a difficult mode in which to conduct AWCD experiments.

Recent biasing efforts have led to the successful development of a biased electrode technique for the measurement of global particle flow I_p to the tokamak boundaries [the principle of the technique is described in Diebold, 1995]. The bias needs only to be on for a fraction of a millisecond for I_p to be measured and, hence, density control is not an issue (the density doesn't change much during a millisecond of bias).

With this method, we have measured the effect of Alfven waves and glow times on global particle confinement time τ_p ($\tau_p = (\text{the number of electrons in the tokamak})/I_p$) and recycling coefficient R ($R = 1 - (I_g / I_p)$, where I_g is the rate of gas puff $\times e$ (the charge of an electron)). The duration of the between shot helium glow (which was varied between 0.5 to 8 minutes) was not found to affect τ_p . During ohmic (ohmic power ≈ 75 kW, $B \approx 0.68$ T, $n \approx 5 \times 10^{12} \text{ cm}^{-3}$) τ_p was measured to be approximately 6 ms

while during 180 kW of rf power τ_p was measured to be between 3.5 and 4 ms (for both π phasing and $\pi/2$ phasing). The tentative conclusion from these data is that "rf fueling", i.e. the need for the operator to cut back on the gas puffing during rf, is due primarily to hydrogen gas (rather than impurities) coming off the tokamak boundaries.

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[En Yao Wng, 1995] En Yao Wang et al., "Biased H-Mode Experiments in Phaedrus-T", Nucl. Fusion (1995).

[Diebold, 1995] D.A. Diebold, N. Hershkowitz, J. Pew, J. Sorensen, T. Tanaka, R. Walsh, E.Y. Wang, X. Wang, and G. Winz, "Phaedrus-T Probe Techniques", Rev. Sci. Instrum., 66 (1), pp. 434-436, 1995.

COLLABORATIONS

Our collaboration with En Yao Wang of the Southwestern Institute of Physics in Chengdu, People's Republic of China (March 1993 through April 1994), and Sean Regan and Michael Finkenthal of the Johns Hopkins University (throughout the entire, Nov. '92 to present, grant period) is described in detail in the "H-mode and other biased electrode experiments" section. For several weeks in the spring of 1993, Hiromasa Takeno of Kobe University in Japan investigated the effects of the phase between antenna straps on edge plasma parameters. Also, Bill Reass of Los Alamos National Laboratory designed the present Phaedrus-T transmitter and will help with the proposed transmitter modification (which is described in detail in its own section entitled "transmitter modification").

BORONIZATION DEVELOPMENTS

Amorphous boron/carbon films deposited by a dc glow discharge of a 0.9 helium + 0.1 trimethylboron gas mixture are used routinely in the Phaedrus-T tokamak to apply an oxygen gettering layer to the vacuum vessel walls. This technique is referred to as trimethylboron boronization (TMB boronization). The vacuum vessel is boronized once or twice per week (every day when high power rf experiments are run) for three hours (400 V, 0.5 A glow discharge). The deposited film thickness has been measured to be 40 nm to 50 nm. To ensure film uniformity two gas injection ports and two glow discharge anodes are employed. Freshly boronized walls result in improved plasma performance. Radiation losses and Z_{eff} are reduced. Oxygen, carbon and metallic impurity concentrations in the plasma are reduced as measured by the SPRED UV spectrometer. A four minute He glow discharge is utilized between plasma shots to further condition the walls. Molecular hydrogen adheres readily to freshly boronized surfaces and the four minute He glow is necessary to remove this layer of hydrogen. Particle fueling and recycling from the walls is thus reduced and density control of the plasma is enhanced.

Auger analysis of a silicon sample exposed to TMB boronization indicated that the stoichiometry of the applied film had a boron/carbon ratio of $B/C = 1/5$. ASDEX experiments suggest that high B/C film composition is superior in view of carbon

impurity and CO recycling. We have investigated several techniques to increase the B/C ratio. The first technique is referred to as o-carborane enhanced TMB boronization. A molecular oven containing o-carborane powder ($B_{10}C_2H_{12}$) is introduced into the vacuum chamber. After the TMB glow discharge is initiated the molecular oven is heated in order to sublimate o-carborane vapor into the glow. The resulting film was determined to have $B/C = 1$. Film compositions with B/C greater than 1 can be obtained by sublimating o-carborane or decaborane ($B_{10}H_{14}$) into a pure He glow. O-carborane sublimated into He glow produced $B/C = 7/2$ in the film. Decaborane sublimated into He glow produced $B/C = 8$. Both o-carborane and decaborane are solid at room temperature with small vapor pressures and need to be heated to sublimation at $200 \rightarrow 300$ degrees centigrade. The molecular oven is radiantly heated by an encircling cage of tungsten filaments.

REPLACEMENT OF THE FARADAY SHIELD WITH AN INSULATOR

We owe in part our success in obtaining the first ever Alfvén wave current drive and heating results to the replacement of our Faraday shield with insulating side limiters. This replacement worked so well that we haven't used a Faraday shield since. Measurements of voltages induced on the sides of our Faraday shield and the process by which these voltages were induced have been described in detail by Tanaka [Tanaka, 1993]. The processes by which these induce voltages transferred power to the edge plasma have also been understood. Sorensen et al. [Sorensen, 1995] have found that the power coupled from the Faraday shield to the edge plasma was reduced from nearly 10 kW (for 40 kW of rf input power) to a few hundred watts by the replacement of the Faraday shield with insulating boron nitride side limiters. Roughly two thirds of the 10 kW was found to couple to electrons that passed through a potential gradient while crossing field lines. Approximately 3 kW was found to be couple to ions falling through the rf enhanced sheaths at the Faraday shield and tokamak limiter.

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(A)accepted paper
(S)sumitted paper

*22 Reprints removed for
separate processing*

Appendix

People of Phaedrus

Richard Post
Jay Kesner
Robert Conn
John Scharer
Fred Brown
John Conrad
Robert Breun
Igor Svatoslavsky
Donald K. Smith
Donna Smatlak
Larry Yujiri
Tom Pian
Richard Siemon
Karl Karcher
Steve Golovato
John Howard
Jim Yugo
Richard Torti

Steve Horne
David Pirkle
David Brouchous
Steve Ross
Jim Callen
Dave Gamage
Mike Morin
Harold Persing
Rick Goulding
Paul Nonn
Greg Kant
Jim Pew
Robert Walsh
Gerry Butz
Larry Peranich
Rick Moyer
H. Watari
K. Adati

Peter Brooker
Dave Kucik
Brian McVey
Art Molvik
Noah Hershkowitz
Jim DeKock
S.T. Chang
Brian Nelson
Jim Browning
Steve Messick
Greg Severn
Dave Sing
Doug Roberts
John Ferron
Paul Fetherston
Jeff Radke
Bill Zimmerman
Inutake
Mase
Y. Yasaka
Chung Chan
Y.W. Wen
Peng
E.Y. Wang
Mark Carter
Robert W. Johnson
B. Lee
Dan Diebold
Richard Majeski
John Meyer
Christof Litwin
Misha Kishinovsky
Paul Probert

Tom Intrator
Paul Moroz
John Tataronis
Dana Edgell
W. Li
Eric Benck
S. Yan
H.Y. Che
B. Cui
Mark Doczy
Andre Karyukin
Doug Keil
T. Tanaka
Jim Sorenson
Mirko Vuckovic
Ray Fonck
X. Wang
Steve Wukitch
George McKee
Steve Oliva
Eric Kile
Gennaky Fiksel
Pat Caliva
Pam Wagner
Barbara Griffith
Cynthia Eddy
Kris Kringle
Kevin Cronin
Steve Kidwell
Y.J. Kim
Brian Rusnack
Keith Siebert
Mike Harper

Where Phaedrus People are in 1999:

Christof Litwin- University of Chicago, research in Solar Physics
Greg Winz- University of Wisconsin, research in Pegasus
Robert Breun- University of Wisconsin and self- employed
Tom Intrator- Los Alamos National Laboratory
John Tataronis-University of Wisconsin, Professor
Dan Diebold- M.S. in Finance, working in industry
Paul Probst- University of Wisconsin, research in MST and Pegasus
Paul Moroz- self-employed
Misha Kishinsky- Advanced Energy
Noah Hershkowitz- University of Wisconsin, research in Plasma-Aided Manufacturing
Paul Nonn- University of Wisconsin, research in MST and Pegasus
Dave Brouchous- Hutchinson Technology, Inc., research in Plasma Etching