R. F. HEATING NEAR THE LOWER
HYBRID FREQUENCY IN THE FM-1
SPHERATOR

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ABSTRACT

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Plasma heating experiments at frequencies near the lower hybrid frequency have been carried out at modest powers (.05-4kW). The antenna structure operating at 68 MHz was comprised of two plates driven out of phase on the exterior of the plasma. High electron heating efficiency (>40%) in both helium and argon plasmas was observed with only a weak density dependence. At low densities ($n_e \leq 1 \times 10^{11} \text{ cm}^{-3}$), the heating was uniform across the plasma while at higher densities the heating was preferentially on the exterior portion of the plasma. The heating of the exterior of the plasma was found not to correspond to absorption at the lower hybrid resonance layer. The electron heating efficiency was found to be a weak function of rf power when the incident rf power was varied from 1 to 15 times the experimentally observed threshold power for parametric instabilities. Ion temperatures were determined by measuring the Doppler broadening of an Argon ion line using a Fabry-Perot interferometer. Low efficiency main body ion heating (1-3%) was observed.

MASTER

1. INTRODUCTION

It is generally agreed that in order to attain temperatures required for ignition in a tokamak fusion reactor, supplementary plasma heating, in addition to ohmic heating will be required. This concept is inherent in the proposal for a Two Component Torus [1,2] and is the basis for the research presently being conducted to study plasma heating by both neutral beam injection [3] and rf heating [4]. Recently, there has been considerable interest, both theoretical and experimental, in plasma heating at frequencies near the lower hybrid frequency. This interest stems in part from two very practical considerations. The first is the availability of megawatt power supplies at these frequencies which will be required to heat the next generation of fusion research devices. The second is the engineering advantage of being able to use open ended waveguides to launch the wave. This is in contrast with ion cyclotron resonance heating which requires a large internal coil structure [4].

Recent studies near the lower hybrid frequency have centered around three main topics - first, mode conversion, wave propagation and penetration into the plasma [5-26]; second, measurements of plasma heating [27-40] and third, the excitation of parametric instabilities [41-52]. The main emphasis of this paper will be our measurements of plasma heating and heating efficiency in the FM-1 spherator. In FM-1, plasma confinement is relatively well understood. Thus, accurate measurements of heating efficiency can be made and the effects of rf heating on plasma confinement can be evaluated. In order to supplement our study of plasma heating,

experiments have been conducted to measure wave propagation and the excitation of parametric instabilities. These experiments will be discussed in conjunction with our measurements of plasma heating.

The paper is organized as follows: in Sec. 2, the experiment is described, in Sec. 3, measurements of wave propagation are discussed, in Sec. 4, measurements of plasma heating, and in Sec. 5, measurements of parametric instabilities. Possible heating mechanisms are discussed in Sec. 6 while in Sec. 7 a comparison is made with previous experiments. Sec. 8 is a brief summary.

2. EXPERIMENT

The plasma was produced in the FM-1 spherator by electron cyclotron resonance heating (ECRH) at 10.6 GHz. The plasma density was between 2×10^{10} - $5 \times 10^{11} \text{ cm}^{-3}$ while $T_e \sim 4 \text{ eV}$ and $T_i \sim 1 \text{ eV}$ during ECRH. The particle and energy confinement have been extensively studied previously [53]. The results of that study were that the particle confinement time is $\sim 1 \text{ sec}$ depending upon plasma density and temperature while the energy confinement time $\sim 1\text{-}3 \text{ msec}$ being limited by the charge exchange rate. That the particle and energy confinement is fairly long and well understood is important in understanding the results of the heating experiments.

Because of our relatively low plasma densities and magnetic fields, the maximum lower hybrid frequency in a hydrogen plasma is less than $\sim 100 \text{ MHz}$. At these frequencies near the lower hybrid frequency, the wave cannot be coupled to the plasma by a waveguide structure. Rather, an antenna structure as shown in Fig. 1 was used to couple the rf radiation into the plasma.

The antenna structure operating at 68 MHz is comprised of two plates (20 cm wide and 50 cm long separated by a 10 cm gap driven out of phase on the exterior of the plasma along the poloidal field, the dominant magnetic field in this region. The rf generator was capable of delivering a maximum of 4 kW to the plasma. The parallel wavelength along the magnetic field imposed by the antenna structure was much less than the free space wavelength, thus enabling the rf fields to penetrate into the plasma. The distance between the plasma and the antenna structure was short (~ 5 cm) enabling the radiation to penetrate thru the evanescent region without significant attenuation. This antenna structure proved to be very efficient in plasma heating and could be well matched to the plasma with the reflected power being less than 5% of the forward power.

3. PROPAGATION

The propagation and penetration of waves near the lower hybrid frequency has recently received considerable attention [5-26]. The propagation of the slow mode along resonance curves has been calculated and observed in several experiments [9,11,13,17,19,20,21]. In addition, the excitation of the whistler mode or fast mode has been investigated [23]. The antenna structure used in this experiment could excite either the fast or the slow mode. Because of the complicated magnetic field geometry and the large $k_{\parallel}$ spectrum imposed by the antenna, calculation of the potential structure in the plasma seemed unfruitful. The approach taken in the study was to measure the potential structure in order to attempt to identify the dominant mode in the plasma. This was

done in a manner similar to the experiment reported by Hooke and Bernabei [11]. The amplitude and phase of the potential was measured by a triaxially shielded rf probe in the vicinity of the antenna structure. If the electrostatic mode was excited according to the calculations of Bellan and Porkalab [19] for a plate in a linear device, resonant cones should be present. Thus, a change in phase and amplitude of the probe should have been measured as the probe crossed the resonant cone. Furthermore, the change in phase should be proportional to the local index of refraction which is dependent upon the electron density, ion mass and magnetic field. Experimentally, no localized change in phase and amplitude was observed. Typically, the phase change was on the order of $\pi/2$ between the levitated ring and the outside of the plasma. This large radial wavelength is not consistent with the dispersion relation for the slow mode.

Depending upon the plasma density and the parallel wavenumber, $k_{||}$, the fast mode could either propagate or be evanescent. Even when the fast mode is evanescent for typical plasma parameters, the decay length is considerably larger than the plasma radius. Thus, the energy from the antenna structure could be coupled to the plasma by means of the fast mode. The very small phase change in the radial direction is also in qualitative agreement with the fast mode being present.

When the amplitude of the parametric instabilities was measured, other indirect evidence was obtained about the mode in the plasma. According to the calculations of Karney and Bers [45] and Porkolab [48], if the slow mode was excited, parametric decay should be localized along resonance cones. This was not observed.

Thus, though the pump mode has not been identified by direct measurement, it appears that the dominant mode excited by the antenna structure is the fast mode.

4. PLASMA HEATING NEAR THE LOWER HYBRID FREQUENCY

4.1 Electron Heating Efficiency

The electron heating experiments were conducted in the after-glow of a ECRH plasma by applying a short pulse ($\sim .2-.4$ ms) of rf which is much shorter than the energy confinement time. Figures 2 and 3 are spatial profiles of the electron temperature measured by a Langmuir probe before and after rf heating in a helium plasma. The electron heating was found to be uniform throughout a magnetic flux surface and not localized near the antenna structure. The incident rf power was kept low so that the final electron temperature was typically ≤ 3 eV. This temperature was not an upper limit for at higher rf powers, the electrons could be heated up to ~ 20 eV. The temperature was kept low in order to be able to neglect the energy loss by radiation and ionization in determining the heating efficiency. As shown in Fig. 2, for low densities $n_e \leq 10^{11} \text{ cm}^{-3}$ the heating was uniform across the plasma while at higher densities, Fig. 3, the heating was mainly on the exterior of the plasma. When this experiment was performed in an argon plasma, similar results were obtained. The rf frequency in both cases was greater than the lower hybrid frequency. Thus, the heating on the outside did not correspond to absorption at the lower hybrid resonance layer. Also, the fact that the results are independent of ion mass (in helium ω/ω_{LH} was between 1.1 and 4.6 while in argon it was between 3.6 and 15) suggests that the

fast mode is dominant since the propagation of the fast mode is less sensitive to ion motion than the slow mode.

The electron heating efficiency was defined as the energy absorbed by the rf energy from the antenna structure. It is simply given by

$$\epsilon_e = \frac{\int \Delta T_e n_e dV}{\int_0^\tau P dt},$$

where ΔT_e the change of the electron temperature, n_e the electron density, and P the rf power radiated from the antenna for a time τ were measured. The integral over the plasma volume was evaluated for the given magnetic flux surface. The electron density was measured by means of a Langmuir probe and a 4 mm microwave interferometer. As shown in Fig. 4, the electron heating efficiency was very high and comparable for both argon and helium. The experimental error in the measurement of the electron heating efficiency was $\sim \pm 30\%$.

The electron heating efficiency was also studied as a function of rf power to determine if there was a sudden increase in plasma heating above the threshold for parametric instabilities. This was done at a fixed density by varying the pulse width from 100-400 μsec and the change in electron temperature from $\Delta T \sim 1-3$ eV. As shown in Fig. 5, the electron heating efficiency was found to be essentially independent of rf power. The rf power was varied in both cases (one for a peak electron density of $1 \times 10^{11} \text{ cm}^{-3}$ and the other for an electron density of $2.5 \times 10^{11} \text{ cm}^{-3}$) from the threshold power required for exciting parametric instabilities to ~ 15 times the threshold power. This strongly suggests that the electron heating is not due to the observed parametric instabilities.

4.2 Ion Heating Efficiency

The ion temperature was determined before and after the rf heating by measuring the Doppler broadening of a helium or an argon ion line using a Fabry-Perot interferometer. High power pulsed experiments (0.5 - 2 kW) were conducted in an ECRH plasma. The increase in ion temperature in an argon plasma is shown in Fig. 6 as a function of time. The final ion temperature was limited by charge exchange. Low efficiency main body ion heating between 1 - 3% was observed in an argon plasma, while no significant increase in the Doppler broadening of the helium ion line was observed. Because the helium line was weaker in intensity than the argon ion line, a heating efficiency in helium of less than 2 - 3% was not measurable.

The electron temperature and density did not change substantially because the initial temperature was high and further heating resulted primarily in line radiation. Thus, the observed increase in ion temperature was not due to collisional ion heating by the electrons but directly due to the rf.

4.3 Effects on Plasma Confinement

Probably the most important aspect of any plasma heating method, other than its heating efficiency, is its effect on plasma confinement. The effects of plasma heating near the lower hybrid frequency on plasma confinement was studied by measuring the intensity of the line radiation. Under steady state conditions of constant temperature and density, the particle confinement time, τ_p , is equal to the ionization time τ_{ion} . The intensity of the light I is proportional to the electron density divided by the excitation time, τ_{ex} . When the neutral density and electron

temperature is sufficiently large as in our experiment for a highly excited level in hydrogen $\tau_{\text{ex}} \propto \tau_{\text{ion}}$. Thus,

$$I \propto \frac{n_e}{\tau_{\text{ex}}} \propto \frac{n_e}{\tau_{\text{ion}}} \propto \frac{n_e}{\tau_p}.$$

Because τ_{ex} and τ_{ion} is proportional to the neutral density, the intensity of the light is also proportional to the neutral density. A comparison was made of the plasma heated by ECRH and by rf heating near the lower hybrid frequency. In both cases a steady state plasma was obtained of the same electron and neutral density. On the other hand, the electron temperature, which changed very little was determined in the two cases by the plasma confinement time and the ionization time. Light intensities were measured by a 1/2 m monochromator for various lines and densities. The plasma confinement time of the rf heated plasma was found to be ~ 2 times smaller than that of the ECRH plasma. The decrease in plasma confinement is probably consistent with the earlier observation of preferential heating of the exterior of the plasma where the confinement is poorer. Recent experiments on Proto-Cleo using TTMP heating [54] and on ST using ICRH [55] have demonstrated that under certain circumstances rf heating can decrease plasma confinement [54] or cause disruptive instabilities [55]. Our results are quite encouraging because rf heating near the lower hybrid frequency was found not to significantly degrade the plasma confinement.

5. PARAMETRIC DECAY INSTABILITIES

Parametric decay instabilities were observed in the vicinity

of the antenna structure. The frequency selection rule

$$\omega_0 = \omega_1 + \omega_2 ,$$

where ω_1 and ω_2 are the low and high frequency sideband was found to be well satisfied. Table 1 summarizes the measurements of the frequency of the main peak of the low frequency sideband as a function of ion mass and magnetic field. Surprisingly, the frequency of the sideband was insensitive to the ion mass and does not appear to be closely related to the ion cyclotron frequency. The low frequency decay structure is qualitatively consistent with the excitation of non-resonant ion quasi-modes [48] driven by nonlinear electron Landau damping if the parallel wavelength of the low frequency mode is determined by either the high frequency mode or the poloidal mode structure. In this case, $\omega_1/k_{\parallel} v_{the}$ would be relatively fixed and independent of ion mass. A comparison was made of the theoretical threshold with the experimentally observed threshold power. This was accomplished by estimating the electric field in the plasma from the power radiated by the antenna structure and by calculating the Poynting vector. Fair agreement between the theoretical and experimental threshold was obtained. Nonetheless, a detailed study of the low frequency mode was not made and the mode was not directly identified.

The amplitude of the low frequency decay spectrum was found to be a function of pressure and of power as shown in Fig. 7. At low pressure, the threshold for instabilities is higher but the amplitude of the decay spectrum is found to saturate at a much higher level than for high pressure. Because of this effect, the

experiment to measure the heating efficiency was conducted at low pressures to obtain the largest change in amplitude of the decay spectrum as a function of power. Also, the threshold for instability was observed to decrease with increasing density. When the gas pressure is increased, the main effect is to decrease the ion temperature. The electron temperature and density is relatively fixed by the ionization rate which is a steep function of electron temperature. Thus, Fig. 7 can be interpreted as showing the effects of ion temperature on the decay spectrum.

Probe measurements of the amplitude of the decay spectrum was observed to indicate an interesting spatial variation. Because of accessibility constraints unlike the other probes which were located at $z = 0$ (see Fig. 1), this probe was located at $z = -8.9$ cm and its horizontal motion was referenced to the center line of the ring which is at $r = 76.2$ cm as shown in Fig. 1. As shown in Fig. 8, at low powers the profile is peaked towards the ring. As the power is increased, the region of instability is broadened and moves out toward the density maximum which occurs at ~ 11.5 cm from the center line of the ring. As previously discussed at high density ($n_e \geq 1.0 \times 10^{11} \text{ cm}^{-3}$), the heating is localized on the exterior of the plasma and thus the spatial profile of the decay waves does not follow the spatial electron heating profile. This does not rule out the possibility that the decay waves are involved in plasma heating since the modes could be excited in one region and propagate and damp in another.

6. HEATING MECHANISM

One aspect of this study has been to determine the mechanism

for the high efficiency electron heating. Several mechanisms have been considered and as will be discussed none of them satisfactorily explain our results.

6.1 Linear Damping of the Pump Mode

The two possible mechanisms are (1) electron Landau damping and (2) collisional damping. For typical plasma parameters $\omega/k_{\parallel} v_{the} \geq 40$ where $k_{\parallel}$ is determined by the antenna structure. Thus, electron Landau damping appears to be negligible.

The possibility of collisional damping has been experimentally evaluated and some theoretical estimates have been made. The distance in which the energy in the pump wave would decrease by $1/e$ for a homogeneous plasma is $\Lambda = v_{g\perp}/2\gamma$ where $v_{g\perp}$ is the group velocity perpendicular to the magnetic field and γ is the linear damping rate of the mode. In Fig. 9, Λ is plotted as a function of density for the slow mode with $T_e = 3$ eV and $k_{\parallel} = .1 \text{ cm}^{-1}$. One observes that for high densities a considerable portion of the wave is damped on the exterior of the plasma while for low densities the wave would penetrate and damp throughout the bulk of the plasma, in qualitative agreement with the data. Quantitatively, more heating on the outside is observed than would be predicted by this simple model even when one accounts for the large $k_{\parallel}$ spectrum of the antenna. Another significant objection to the model is if as it appears that the fast mode is excited then Λ is much greater than the plasma thickness and the preferential heating on the outside at high densities cannot be explained.

Experimentally, collisional damping was evaluated by measuring the spatial heating profile as a function of the initial electron

temperature. When electron-ion collisions are the dominant collision frequency, Λ is proportional to $T_e^{1.5}$. Hence, the spatial heating profile should depend upon the initial electron temperature. The spatial heating profile was found not to vary with the initial plasma temperature. Thus, collisional damping does not appear to be consistent with the spatial heating profile.

6.2 Plasma Heating by Parametric Instabilities

Many authors have discussed the possibility of plasma heating by exciting parametric instabilities [42-52]. As discussed in Sec. 5, parametric instabilities have been observed in the vicinity of the antenna structure. Because the electron heating efficiency did not vary significantly with power and hence the amplitude of the decay waves, it appears that the parametric instabilities are not strongly related to the electron heating.

The very modest ion heating in an argon plasma on the other hand may be related to the excitation of parametric instabilities and the damping of the low frequency sideband on the ions. All of the ion heating experiments were conducted far above threshold because of the low heating efficiency. The fact that the amplitude of the low frequency waves varies with pressure and hence ion temperature is suggestive (though not conclusive) that the waves damp on the ions. Rough estimates of the energy in the low frequency sideband using the Manley-Rowe relation are consistent with the power input to the ions.

As mentioned previously electron-ion collisions could not account for the observed ion heating. Also, mode conversion at the lower hybrid frequency was impossible in an argon plasma because $\omega > \sqrt{\omega_{ci}\omega_{ce}}$.

7. DISCUSSION

Recently, plasma heating at frequencies near the lower hybrid frequency have been observed in several experiments often under quite different circumstances [28-35, 37-40, 43,46]. In this section, the results of our experiment will be compared with several other recent experiments. There are several difficult problems associated with making a detailed comparison, for instance:

- (1) In many experiments measurements of heating efficiency were not made partially because plasma confinement was not well understood as well as for other reasons.
- (2) In many experiments the spatial heating profile was not measured.
- (3) In some experiments the principal diagnostic was diamagnetic loop measurements which do not differentiate between electron and ion heating.
- (4) Also to our knowledge no experiment has attempted to evaluate the effects of rf heating near the lower hybrid frequency on plasma confinement. Thus, no comparison is possible.

Nonetheless, even though a detailed comparison cannot be made in many cases with the literature, a discussion of the different experiments would appear worthwhile.

The earliest measurement of high heating efficiency (~ 40%) was reported by Glagolev et al. [28] in a linear device. This encouraging result was confirmed by Motley et al. [40] also in a linear device who observed a heating efficiency between 10 and 50% depending upon filling pressure and input power. These results are essentially in agreement with our experiment where the heating

efficiency is typically greater than $\sim 40\%$. One significant difference between our experiment and that of Motley et al. [40] is that they observed the electron heating efficiency to decrease as a function of rf power while in our experiment the electron heating efficiency did not vary with power. This effect may be because when the rf power was increased in their experiment the density also increased. We have observed (see Figs. 4 and 5) that the electron heating efficiency decreases weakly with increasing electron density which might resolve the difference. The decrease in heating efficiency at higher densities has also been observed by Galaktionov et al. [27]. Ion heating has been observed by several authors [27,31,33,38,43,46]. Our measurements of ion heating efficiency are in fair agreement with Motley et al. [40]. In several other high power experiments [28,30,31,33], the ion temperature was found to increase substantially. Whether this is indicative of high ion heating efficiency is not known.

The spatial electron heating profile has been observed to peak on the outside of the plasma by Glagolev et al. [28], Brusati et al. [32], and Raimbault and Shohet [38]. This is in fair agreement with our experiment with the exception that we found uniform heating across the bulk of the plasma at low densities. Raimbault and Shohet [38] explained the preferential heating of the exterior of the plasma as a warm plasma effect affecting the wave propagation. This mechanism does not explain our results because of our lower electron temperature. Also, our experimental results were similar for an argon and a helium plasma. Thus, the spatial profile did not depend upon ω_o/ω_{LH} . It appears

that further theoretical work is required to understand the spatial electron heating profile.

There also appears to be some differences in the various experiments as to the plasma heating mechanism. Both Galaktionov et al. [27] and Krämer [37] attribute the heating due to collisional damping. In most other experiments, some form of collisionless absorption, either linear or non-linear, appears to take place. Raimbault and Shohet [38] explain the electron heating as due to electron Landau damping by the hot electron tail. Because of our lower electron temperature and lack of a hot electron tail, this mechanism could not account for our heating. Several authors have claimed that parametric instabilities may account for their observed heating [29,30,43,46]. Chang and Porkolab [46] correlated the plasma heating with the excitation of ion quasi-modes, a non-resonant instability. They observed that the electron heating decreased when $\omega_o/\omega_{LH} > 3$ corresponding to the parameter range in which resonant instabilities are excited as opposed to the ion quasi-modes. Our heating results on the other hand do not correlate with the excitation of parametric instabilities as shown by Fig. 5. The difference between our experiment and that of Chang and Porkolab [46] is not understood.

Several heating mechanisms have also been proposed to understand the ion heating reported in the various experiments. Chang and Porkolab [44] attributed the ion heating to the excitation of ion quasi-modes while T. K. Chu et al. [43] attributed the heating to the excitation of resonant ion cyclotron decay instabilities. In a high power heating experiment, Voloshko et al. [31] observed

strong ion heating when $\omega_{LH} > \omega > \omega_{ci}$ and attributed the heating as due to ion cyclotron damping of the pump wave. In this experiment, the electron density was low and the frequency of the wave corresponded to between the second and sixth harmonic of the ion cyclotron frequency. Ion cyclotron damping of the pump waves was not applicable in our experiment because the pump frequency corresponds to $\sim 800^{\text{th}}$ harmonics of the ion cyclotron frequency in an argon plasma. In our experiment, the ion heating appears to be consistent with the excitation of parametric instabilities.

8. SUMMARY

The antenna structure, which appeared to excite the fast mode, was very effective in coupling the rf energy to the plasma. The high efficiency electron heating results ($> 40\%$) are quite encouraging while only very modest ion heating (1-3%) was observed. Furthermore, the electron heating efficiency was found to be a weak function of density and power. The electron heating results can not be quantitatively explained by linear damping, either electron Landau damping or collisional damping, or by parametric instabilities. It appears that further theoretical work is required to explain the electron heating mechanism. Another significant result was that the plasma confinement was not adversely affected.

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Table I summarizes the measurements of the low frequency decay spectrum as a function of ion mass and magnetic field:

PLASMA	MAIN PEAK OF THE LOW FREQUENCY DECAY SPECTRUM (MHz)	B(kG)	f_{ci} (MHz)
H	4.0	2.8	4.3
	2.5	1.2	1.8
D	2.0 and 4.0	2.8	2.1
He	3.5	2.8	1.1
	2.2	1.2	0.46
Ne	1.2 and 3.5	2.8	0.21
Ar	Broad Peak at 3-6	2.8	0.11

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Fig. 1. Illustration of the antenna structure used to couple the rf radiation to the plasma in the FM-1 spherator.

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Fig. 2. Temperature and density profile before and after plasma heating for a helium plasma.

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Fig. 3. Temperature and density profile after plasma heating for a helium plasma.

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Fig. 4. Electron heating efficiency as a function of peak electron density for a helium and an argon plasma.

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Fig. 5. Electron heating efficiency as a function of rf power for a helium plasma.

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Fig. 6. The increase in ion temperature in an argon plasma as a function of time.

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Fig. 7. The amplitude of the low frequency decay waves in a helium plasma as a function of power for $p = 0.8 \times 10^{-5}$ torr. and 2.0×10^{-5} torr.

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Fig. 8. The amplitude of the low frequency decay waves in a hydrogen plasma as a function of distance from the center line of the ring and as a function of power.

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Fig. 9. The collisional absorption length perpendicular to the magnetic field as a function of density for a helium and an argon plasma.