I. INTRODUCTION

The physics of the interaction between plasmas and high power waves with frequencies in the electron plasma frequency range is of importance in many areas of space and plasma physics. A great deal of laboratory research has been done on the interaction of microwaves in a density gradient when \( \omega = \omega_{pe} \) in unmagnetized plasmas.\(^1\)\(^-\)\(^3\) There is also a long history of experiments on ionospheric heating and afterglow vs discharge potential.

Both helical antennas\(^13\),\(^14\) on a large scale and a disk exciter on the skin depth scale\(^15\),\(^16\) have been used. The properties of shear Alfvén waves have been studied in a magnetic beach configuration,\(^17\) as well as the influence of field line resonances on the wave.\(^18\) More recently, nonlinear Alfvén waves generated by a maser have been reported.\(^19\) In this paper, the Alfvén waves are radiated by a pulse of field aligned suprathermal electrons, which are generated in the interaction between the plasma and the microwaves at the electron plasma frequency.\(^12\) This shows similarity with a previous experiment involving laser produced plasmas, in which Alfvén waves were generated by a pulse of fast electrons.\(^20\),\(^21\) The Alfvén waves in the present work can be explained theoretically by Cherenkov radiation of shear Alfvén waves by the field aligned suprathermal electrons. This theoretical model will be the subject of a future paper.

The paper is organized as follows. Section II describes the experimental setup of the experiment, and the basic probes. Section III presents the high frequency microwave measurements, both in \( O \) mode and \( X \) mode. Section IV describes the suprathermal electrons, and their dependency on the input power of the microwaves, both in \( O \) mode and \( X \) mode. Section V outlines the properties of the observed Alfvén waves.

II. EXPERIMENTAL SETUP

The experiment is performed in the upgraded LAPD. The LAPD is a linear device, which produces a highly magnetized quiescent plasma, capable of supporting Alfvén waves. A schematic of the machine is shown in Fig. 1. The plasma is formed by a pulsed discharge\(^22\) \((I_d = 3.5 \text{ kA})\) between cathode and anode which are 52 cm apart. The cathode is a pure nickel sheet which has been coated with BaO and is heated to a temperature of close to 900 \(^\circ\)C. The anode is a 50% molybdenum mesh which is biased positively with respect to the cathode. The electron beam thus formed collisionally ionizes the fill gas (helium). The discharge typically lasts for 8–10 ms, and is pulsed at 1 Hz. The plasma is highly reproducible. It is 18 m long, and has a diameter of

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50 cm, which is more than 100 ion Larmor radii across at a background field of 1000 G.

Figure 2 shows the electron temperature and plasma density during a typical plasma shot. Two regimes can be identified, namely the main discharge when the electrons are warm \( (T_e = 6 \text{ eV}) \), and the afterglow when the electrons are cold \( (T_e < 0.5 \text{ eV}) \). The density decay time is much longer than the electron temperature decay time, and is long compared to the typical duration of the experiment \((\approx 50 \mu s)\). Most of the experimental runs were done in the afterglow (typically 500 \( \mu \text{s} \) after the termination of the discharge), so that both the electron and ion populations are cold.

In the experiment, a high power pulse of 9 GHz microwaves is launched through a side window in the machine. The start of the microwave pulse is taken as \( t = 0 \) in the experiment. The \( z \) location of the horn is taken as \( z = 0 \), while \( x = y = 0 \) denotes the center axis of the machine. The microwaves enter the machine through a window at \( x = -60 \text{ cm}, y = 0 \text{ cm} \). The microwave source is a magnetron with fixed frequency at 9 GHz, and pulse length 0.5 \( \mu \text{s} \) or 2.5 \( \mu \text{s} \) (not continuously variable). The output power of the source can be varied continuously to a maximum output of 100 kW. The output power is measured by tapping off part of the microwave power, attenuated by 70 dB, from the waveguide assembly using a directional coupler. The microwaves are launched with a pyramidal horn antenna, with aperture 11.4 cm by 9.2 cm, and an axial length of 10.2 cm. Experiments were done with the microwaves both focused and unfocused by a lens. Measurements in air determined that the lens increases the power density by a factor of 5. The polarization of the waves can be chosen by rotating the horn. Two lens increases the power density by a factor of 5. The polarization of the waves can be chosen by rotating the horn. Two

The microwaves propagate into the radial density gradient of the plasma, across the background field \( \mathbf{B}_0 \). The density \( n_{\text{crit}} \) determined by \( \omega_{\text{pe,crit}} = \omega \) corresponds to \( n_{\text{crit}} = 10^{12} \text{ cm}^{-3} \) for a 9 GHz wave. The peak density in the plasma is between \( 1.52 \times 10^{12} \text{ cm}^{-3} \), so that the center of the plasma is optically thick for the incoming microwaves. The background field \( \mathbf{B}_0 \) was varied from 1 kG to 2.25 kG. The electron cyclotron frequency \( \omega_{ce} \) is between 30% and 70% of the pump frequency, so that \( \omega_{ce} < \omega_{pe,crit} \) for all background fields.

Measurements include microwave intensity measurements, low frequency \( f \approx 3 \text{ MHz} \) magnetic field measurements and flow measurements. The microwave intensity was measured using a three axis dipole probe, with the output signal rectified by crystal diodes. Low frequency magnetic field oscillations were measured with an inductive pickup probe consisting of three orthogonal coils. The coils were differentially wound to reduce electrostatic pickup. Density and flow measurements were done with a Mach probe. Density measurements are calibrated using a 56 GHz microwave interferometer. Magnetic field data were obtained in several transverse planes, typically 30 cm by 30 cm at different axial locations, both upstream and downstream from the horn antenna. Computer-controlled probes, mounted on the probe drive, are moved to any point in an \( x \)-\( y \) plane. The ball valve (Fig. 1) connects the probes mechanically to the machine, and allows for three-dimensional motion.

In the presentation of the results it is important to point out the many different time scales at play. The important time scales range from a tenth of a nanosecond to several milliseconds, a difference of 7 orders of magnitude. The shortest time scale is the period of the launched microwaves, which is 1 ns. This is also the frequency of the plasma waves and X mode waves with which the microwaves interact as they propagate in the plasma. The microwaves are on for 0.5 \( \mu \text{s} \) or 2.5 \( \mu \text{s} \), which means that each pulse has on the order of \( 10^4 \) oscillations in it. Although we use the term “microwave pulse,” for the microwaves themselves the pulse is nearly steady state. Another important plasma scale is the ion plasma frequency, which for our parameters is about 100 MHz, corresponding to a period of 10 ns. One microwave pulse is equal to about 10 ion plasma periods. This indicates that ion dynamics can play an important role during the microwave pulse. For example, the microwave pulse is long enough for ponderomotive effects to become important. As we descend in the frequency scale, the next lowest is the
ion cyclotron frequency. The microwave pulse is on the order of one ion cyclotron period. Longer intervals are then on the time scale of Alfvén waves, which will constitute a large part of this paper. Plasma flows are observed at times up to 2 ms after the microwave pulse turns on. With regard to spatial scales, it is important to know how the density scale length compares to the vacuum wavelength of the microwaves ($\lambda_0=3.33$ cm). The density increases from 0.5 $\times$ $10^{12}$ cm$^{-3}$ to 1.5 $\times$ $10^{12}$ cm$^{-3}$ in approximately 10 cm, which is 3 vacuum wavelengths of the microwaves. The size of the heated spot in the unfocused scenario is about 20 cm, compared to about 5 cm in the focused scenario.

Another important parameter is the fluid nonlinearity, defined as $|E|^2/nT$. To get a feel for the values of $|E|^2/nT$ one can use the vacuum electric field in this formula. For a 70 kW microwave pulse, with a beam radiation cross section of 10 cm$^2$, the magnitude of the vacuum electric field is about 7 $\times$ $10^6$ V/m. For a density of $10^{12}$ cm$^{-3}$ this corresponds to values of $|E|^2/nT$ of 0.6 for the afterglow and 0.05 for the discharge. The electric field calculated here is just the vacuum electric field and the values of $|E|^2/nT$ therefore do not take into account the beam spread or beam focusing of the microwaves in the plasma.

### III. MICROWAVE PROPAGATION

Measurements of the microwave electric field were done with a 3-axis dipole probe. Data were taken in transverse planes and in radial lines. The measurements were done without the lens, and in the afterglow. To ensure maximum power transfer to the plasma, the horn antenna was positioned flush with a side window of the machine. There was no probe access opposite the horn (at $z=0$), so probe data were acquired 1 port downstream from the horn antenna ($z=32$ cm). The signals from the probe were rectified with calibrated crystal diodes, so that only amplitude levels are measured.

Figure 3 shows the electric field intensity of the microwaves in a transverse plane. The microwaves are $O$ mode polarized ($E=E_z$). These data are taken in the initial stage of the microwave pulse, right after the turn-on of the source. Intensity levels are given in colors and are normalized to the maximum intensity at that time. Overplotted are density contours which were taken from a separate density measurement, obtained from ion saturation current measurements which were calibrated with a microwave interferometer. The solid curve corresponds to the location where the 9 GHz microwave frequency matches the plasma frequency ($\omega_0=\omega$). The inner dashed curve is the $L$ cutoff for the $X$ mode ($\omega^2_{pe}=\omega(\omega+i\sigma_0)$). The outer dashed curve corresponds to the location of the upper hybrid resonance ($\omega^2=\omega^2_{pe}+\omega_{ce}^2$). The waves are incident from $x=60$ cm and propagate up to the $\omega_{pe}$ cutoff for the $O$ mode. The amplitude peaks at densities just below the $O$ mode cutoff, as expected from the theoretical dispersion relation. There is also some penetration of the microwaves to higher densities, up to the $L$ cutoff. These signals are attributed to $X$ mode waves. One of the reasons for the appearance of the $X$ mode waves is that the microwave horn does not launch pure $O$ mode microwaves, and that a fraction of the launched waves are $X$ mode polarized. Also, the reader should keep in mind that the measurements are not obtained at $z=0$, in line with the horn antenna, but at $z=32$ cm. The Gaussian width of the antenna radiation pattern is on the order of 15–20 cm, as measured in air (unfocused scenario). The measurements at $z=32$ cm are partly due to microwaves travelling obliquely to the background field, and partly due to microwaves undergoing multiple reflections between the plasma and the machine walls.

The microwaves also travel to the other side of the plasma. This is expected since the machine walls are not absorbing to microwaves, and the microwaves are reflected between the plasma edge and the machine walls. Local hot spots, such as at $(x,y)=(20$ cm, 7 cm) in Fig. 3, can therefore generate interactions at places where one would not expect it.

The measurements in the $X$ mode are shown in Fig. 4. The experiment was done in the same plasma as in Fig. 3.
The solid curves are the L cutoff and the upper hybrid resonance. The spatial extent of the microwave intensity measurements and the density measurements do not completely overlap. This is a problem for the upper hybrid resonance curve, since the density measurement is interrupted at $x=20$ cm. A circle was fitted to the upper hybrid resonance curve, and is plotted as the dotted line in Fig. 4. The $R$ cutoff is not shown since it falls outside of the measurement plane. The distance between the $R$ cutoff and the upper-hybrid resonance is approximately 3 cm, on the order of one vacuum wavelength of the microwaves $\lambda_0 = 3.33$ cm. Figure 4 shows that the microwave intensity peaks on the overdense side of the upper hybrid contour. This suggests that tunneling to the upper-hybrid resonance is achieved. The microwaves propagate up to the $L$ cutoff. This is consistent with the theoretical dispersion relation of the wave. The highest amplitude waves are observed on the high density side of the upper hybrid layer, and the intensity drops off quickly at higher densities, and vanishes at the $L$ cutoff. The smaller intensity peak at the $\omega_{pe}$ cutoff is attributed to $O$ mode waves. Just as in Fig. 3 there is some polarization mixing.

With simultaneous measurements of the plasma density and the microwave intensity, at different magnetic fields $B_0$, it is possible to determine the location of the microwave peak intensity with respect to the density and the magnetic field. Both the density and the microwave intensity were measured along radial lines, for magnetic fields ranging from 1 kG to 2.25 kG. Figure 5 shows the density profile and microwave intensity profiles for the $X$ mode and $O$ mode at $B_0=1.5$ kG. The profiles are taken immediately after the microwave turn-on. With these profiles one can extract the peak of the microwave intensity versus density. Figures 6 and 7 show the results for the $O$ mode and $X$ mode polarization, respectively. The error bars on the plot indicate the spatial extent of the peak intensity. The maximum intensity is plotted as a cross on the plot, whereas the error bars indicate the full width at half maximum. The location of the peaks was obtained in the beginning of the microwave pulse, about 10 ns after the turn-on. At these early times, there is no density modification.

For the $O$ mode, the theoretical dispersion relation predicts the peak intensity to be just below the cutoff density where $\omega_{pe} = \omega$. There is good agreement between theory and experiment. The results for the $X$ mode are plotted in Fig. 7. The relevant cutoffs and upper-hybrid resonance are also shown. It is clear that the peak intensity follows the upper hybrid resonance. The peak occurs at densities between the upper hybrid resonance and the $L$ cutoff. Direct tunneling to the upper-hybrid resonance is achieved. Identifying the location of the peak electric fields is important, since it will be shown in the next section that a burst of suprathermal electrons can be traced to these locations.

The microwave intensity measurements were all done in planes perpendicular to $B_0$, and in radial lines along $x$. No measurements were done along the $z$ axis, and no measurements were done in line with the horn, at $z=0$ cm. To complement the experimental data, a WKB calculation was done in an $x$-$z$ plane. The calculation is done for a slab model, with the magnetic field in the $z$ direction, the density...
gradient in the \( x \) direction, and \( y \) as the ignorable direction. A Gaussian localized source was used to model the antenna. At \( x=0 \) cm the axial profile of the waves propagating into the density gradient, is proportional to \( \exp(-z^2/d^2) \). The Gaussian profile is imposed on \( E_z \) in the \( O \) mode and on \( E_y \) in the \( X \) mode. Note, \( x=0 \) here means the point where the waves enter the plasma, where the density is zero. The amplitude of the reflected waves is determined by matching the \( \text{WKB} \) solution with the Airy solution near the cutoff. Figures 8 and 9 were obtained with \( B_0=1 \) kG, Gaussian width \( d=1 \) cm and a density which increases from 0 to \( 1.4 \times 10^{12} \) cm\(^{-3} \) in 40 cm. The slope is more gradual than it would be in the experiment, and the Gaussian width \( d \) is also smaller than in the experiment, by a factor of 10. These parameters were chosen this way to illustrate the difference in wave propagation between the \( X \) mode and the \( O \) mode. A larger Gaussian width and steeper density gradient would result in the beam staying more collimated as it propagates into the gradient, both in the \( X \) mode and \( O \) mode.

Figure 8 shows a snapshot in time of \( E_z \) in the \( O \) mode. The colors are scaled to the maximum field at that time. From Fig. 8 the main features of the \( O \) mode can be identified. There is a cutoff at \( \omega_{pe} = \omega \), and the wavelength increases with increasing \( x \). The waves stay reasonably collimated all the way up to the resonance. When these waves are displayed in a movie, one sees that the wave propagates near \( x=0 \) cm, but as it approaches the cutoff it develops more and more into a standing wave pattern. The wave fronts oscillate up and down, and do not propagate.

Figure 9 shows the result in the \( X \) mode for the same plasma conditions \( E_z \) is plotted. This picture was obtained by assuming that the density gradient is shallow, and that there is no tunneling to the upper-hybrid resonance. This was chosen in order to simplify the calculations, because only the \( R \) cutoff is of importance then. This is different from the experiment where tunneling to the upper-hybrid resonance does occur. In the \( \text{WKB} \) model, tunneling is neglected. The different propagation characteristics are immediately obvious. The waves, emanating from \( x=z=0 \), spread out along the magnetic field axis as they approach the \( R \) cutoff. The incident waves are therefore strongly defocused. The reflected waves do not interfere that much with the incoming waves, in contrast to the \( O \) mode. There is no standing wave pattern developed. The reflected waves leave the plasma far from the source, around \( z=\pm 40 \) cm. Note that if the Gaussian width \( d \) were bigger, the waves would remain more collimated, and there would be more interference between incoming and reflected waves. This will be the case in the experiment. From these figures it is obvious that the microwave intensity in the \( O \) mode near the cutoff will be higher than in the \( X \) mode.

The different beam spread in the \( O \) mode and the \( X \) mode has strong implications on the experiment. In order to get similar values of \( |E_z|^2/nT \) in the plasma for both modes, one would need to inject more power in the \( X \) mode than in the \( O \) mode. The incident power in the \( X \) mode spreads out more, and therefore lowers the energy density in the wave. This was observed in the form of a higher threshold for Alfvén wave generation in the \( X \) mode. More details will follow in Sec. IV.

### IV. SUPRATHERMAL ELECTRONS

Signatures of suprathermal electrons can be found in the Mach probe data, by looking at the two faces which have their normals parallel to the magnetic field. The Mach probe was biased negatively, so as to collect ion saturation current, with a bias typically larger than 50 V. The ion saturation current on the probe tip facing the microwave interaction region shows a sharp decrease shortly after the microwaves are turned on, even going negative in some cases, while the probe tip facing away from the microwave interaction region does not show this decrease. The drop in ion saturation current on the one face is due to energetic electrons, with energy greater than the applied probe bias, reaching the probe. By taking the difference between the currents collected by the two probe tips one can subtract out the ion contribution to the current. The measured current densities can be compared to the thermal current densities, \( j_{th}=n_{th}v_{th} \), which is approxi-

![FIG. 8. (Color) WKB solution for \( E_z \) in the \( O \) mode, at fixed time and for \( B_0=1 \) kG, Gaussian width \( d=1 \) cm. The colors are normalized to the maximum of \( |E_z| \).](image1)

![FIG. 9. (Color) WKB solution for \( E_z \) in the \( X \) mode, at fixed time and for \( B_0=1 \) kG, Gaussian width \( d=1 \) cm. The colors are normalized to the maximum of \( |E_z| \). Note, tunneling is neglected in the WKB model.](image2)
A snapshot of the current density, measured with the Mach probe, is plotted in Fig. 10. In this experimental run the microwaves were broadcast from \(x=\pm 60\) cm, \(y=0\) cm. The data were taken in the afterglow at \(z=66\) cm, with the microwaves not focused and \(O\) mode polarization, and for a 2 kG background magnetic field. A few density contours are overplotted. The thick contour at \(n=10^{12}\) cm\(^{-3}\) is the location of the cutoff for the \(O\) mode polarized microwaves. The strongest currents are observed on the underdense side of this contour, nearly in line with the horn. This is consistent with the microwave electric field measurements. Note that the data from Figs. 3 and 10 were obtained in different data runs, which explains why the density contours are different. Nonetheless, these pictures show that both the microwaves and the suprathermal electrons have their peak at the same \(x\)-y locations with respect to the cutoff location, and the suprathermal electrons are therefore accelerated in the vicinity of these strong electric fields.

Evidence of suprathermal electrons was also observed in magnetic field data. The field aligned current can be obtained from measurements of \(B_x\) and \(B_y\) in an \(x\)-\(y\) plane by taking the curl of the magnetic field, \(j_z = e/4\pi \mathbf{V}_\perp \times \mathbf{B}_\perp\). Figure 11 shows the spatial location of this current at \(z=3\) m for the same conditions as in Fig. 10. The microwaves were \(O\) mode polarized, not focused and the background field was 2 kG. The contour corresponding to the cutoff layer is again overplotted. The strong currents near the horn antenna just outside the cutoff density are in agreement with the Mach probe data. The main difference with the Mach probe data is that the current due to all electrons is now measured, not just the current due to the most energetic electrons. The Bdot probe picks up the plasma return currents (colored dark blue-black in Fig. 11). These return currents are carried by plasma electrons, which are not energetic enough to be measured on the Mach probe. Currents made up of less energetic electrons are also observed at locations at the other side of the plasma. These currents are generated by locally strong microwave electric fields, that reached the other side of the plasma through multiple reflections between the plasma edge and the machine wall.

Measurements with the Bdot probe were done in transverse planes, at several axial locations along \(z\). Figure 12 shows a snapshot in time of the ac magnetic field, at \(t=1.2\) \(\mu\)s. At this time, the bulk of the suprathermal electrons is located between \(z=64\) cm and \(z=128\) cm. The fastest electrons have already reached the plane at \(z=384\) cm. These electrons are a factor of 4 faster (factor of 16 in energy) than the bulk of the suprathermal electrons. This demonstrates that the suprathermal beam has a wide spread in energy. The actual current densities can be calculated in each plane from the curl of \(\mathbf{B}\). Typical values are on the order of 500 mA/cm\(^2\) (with focused microwaves). The total current in the suprathermal beam is on the order of several amperes.

When investigating the generation mechanism of suprathermal electrons, it is necessary to know how \(v_{\text{be},e}\), \(v_A\), and \(v_{\text{osc}}\) compare to each other. Most of the experiments were done in the afterglow, where \(v_{\text{be},e}\) is on the order of 3 \(10^7\) cm/s, whereas in the discharge \(v_{\text{be},e}\) goes up to \(10^8\) cm/s. The Alfvén speed \(v_A\) ranges from \(10^8\) cm/s to 2.5 \(10^8\) cm/s. \(v_{\text{osc}}\) is defined as the velocity of an electron oscillating in an external electric field. From Newton’s law \(F = m\text{dv}/dt\) one finds that the magnitude of \(v_{\text{osc}}\) is defined as \(eE/m\omega\). For a 70 kW microwave pulse, with a beam cross section of 10 cm\(^2\), the magnitude of the electric field in vacuum is \(7 \times 10^4\) V/m. An electron oscillating at 9 GHz would then have a velocity \(v_{\text{osc}} = 2 \times 10^7\) cm/s, which is on the order of the electron thermal velocity in the afterglow. Such an electron travels \(10^{-3}\) cm in half a microwave period. This is the maximum distance it travels before the field reverses, and the electron is forced the other way. From this simple calculation we can conclude that direct acceleration of electrons out of the interaction region is not possible. An electron cannot travel far enough to get out of the interaction region before it sees a field reversal.

To investigate the generation mechanism of the suprathermal electrons further, a series of experiments was done in which the dependence of the suprathermal electrons on the microwave input power was investigated, for different background magnetic fields, both in the \(O\) mode and \(X\) mode. The data show in all cases a linear behavior between the ampli-
tude of the suprathermal electron peak with respect to the input power of the microwaves. Therefore, the current density of these electrons is proportional to \( \frac{E_{\text{microwaves}}^2}{E_{\text{microwaves}}} \).

Figure 13 shows the dependence of the amplitude of the electron current on the input power. The current was measured with the Mach probe, thus this plot shows the dependence of the most energetic electrons. The measurements were done in the afterglow, with \( O \) mode polarized microwaves and for a 1.5 kG background magnetic field. The microwaves were focused with the lens, which will also be the case for the following plots shown in this section. The amplitude of the current pulse is found to be linearly proportional to the input power of the incident microwaves, or in other words \( j_z \) for the most energetic electrons is proportional to \( E_{\text{microwaves}}^2 \). Furthermore, there is a threshold of about 5 kW for the generation of this current.

Figure 14 shows the time traces themselves, all normalized to the same amplitude. Apart from the trace at 68 kW, the peaks all overlap for the first peak. The second peak is due to heating and associated plasma drifts. The shape of the second peak does change with input power of the microwaves, but the drift speed of the first peak is the same for all these traces. Changing the power of the microwaves therefore only increases the number of electrons in the suprathermal beam, but does not change the speed or the temporal width of the beam. It is possible that the speed and temporal width have a \( \sqrt{E} \) dependence, but the range of \( E \) in the experiment is too limited to clearly demonstrate this. The microwave power was changed by a factor of 6, which means that \( \sqrt{E} \) only varies by a factor of 1.5. To investigate if there is a \( \sqrt{E} \) dependence one would have to vary the power by a factor of 1000 or more, to clearly see a difference.

The measurements obtained with the magnetic field probe are plotted in Fig. 15. The amplitude of the current pulse is again linear with respect to incident \( |E_{\text{microwaves}}|^2 \) and the threshold is at about 5 kW. The magnetic field probe measures the current carried by all the electrons. The dependence on the input power is the same as for the most energetic electrons (Mach probe data, Fig. 13). This indicates that the bulk of the suprathermal electron pulse and the most energetic electrons in the pulse are both generated by the same mechanism. And as a consequence the distribution function of these electrons is most likely a smooth distribu-
tion function with a long tail, from a few eV up to energies higher than 75 eV.

It is now interesting to compare the $O$ mode with the $X$ mode, as plotted in Figs. 15 and 16. For the $X$ mode, there is a linear relationship between the input power and the amplitude of the current pulse, just as for the $O$ mode. However, the threshold value is a factor of 2 higher for the $X$ mode. This is consistent with the different propagation characteristics for the $O$ mode and $X$ mode, as explained in Sec. III. A direct comparison between the WKB calculation and the experiment is not possible since tunneling to the upper-hybrid resonance was neglected in the WKB calculation, while it is clear that tunneling is achieved in the experiment. Nonetheless, the WKB picture of Figs. 8 and 9 is consistent with the measurements of Figs. 15 and 16. The microwaves in the $X$ mode tend to defocus while the waves in the $O$ mode remain well collimated. To obtain the same microwave intensity in the plasma one will therefore have to inject more power from the outside into the plasma. Since the input power is measured at the microwave source and not in the plasma itself, the threshold value measured in the $X$ mode will be higher than in the $O$ mode.

The reader should keep in mind that the results in the $X$ mode in Fig. 16 could also be interpreted as showing a $P^2$ or $P^3$ dependence, with no threshold or very low threshold. It is hard to determine the exact dependence. In any case, the comparison with the $O$ mode does show that more input power is needed in the $X$ mode than in the $O$ mode.

The exact acceleration mechanism of the suprathermal electrons is still under investigation. At present, the authors speculate that it is related to nonlinear density modifications near the horn antenna. The incident microwaves dig a density cavity through the ponderomotive force. The resulting density profile will initially have a structure similar to the WKB pictures of Figs. 8 and 9. High local microwave intensity corresponds to low density, and vice versa. The density profile becomes inhomogeneous along $z$, with a density hole at $z=0$ and sharp density increases on both sides of it. The pump frequency now matches the plasma frequency in a

FIG. 13. Dependence of the peak amplitude of the suprathermal electron current (energy $>75$ eV) on the input power of the $O$ mode polarized microwaves (focused microwaves).

FIG. 14. Suprathermal electron signature measured by the Mach probe for different microwave power levels, normalized to the 68 kW case, for focused $O$ mode polarized microwaves.

FIG. 15. Dependence of the peak amplitude of the suprathermal electron current burst (from magnetic field data) on the input power of the $O$ mode polarized microwaves, for $B_0=1.5$ kG.

FIG. 16. Dependence of the peak amplitude of the suprathermal electron current burst (from magnetic field data) on the input power of $X$ mode polarized microwaves, for $B_0=1.5$ kG.
much more narrow region around this density hole, narrow enough to allow for direct acceleration of electrons out of the microwave interaction region.

V. ALFVÉN WAVES

The suprathermal electrons are followed by a series of oscillations, as measured with a 3-axis magnetic loop probe. Magnetic field data were acquired in x-y planes and on lines parallel to the x axis, at different z locations along the machine. The data shown are obtained with a 10 or 15 shot average and with no frequency filtering performed. Figure 17 shows a snapshot in time of the transverse magnetic field vectors in an x-y plane at z=3 m (B_0=2 kG). Overplotted is the density contour that corresponds to n=10^{12} cm^{-3}, which is the location where the microwave frequency matches ω_pe. The microwaves were not focused in this set of experiments, and were O mode polarized. The magnetic field oscillations are observed in a layer about 15 cm wide, near the critical density contour. The strongest waves are excited in the plasma on the side nearest the horn. Microwave reflections and scattering at the critical density contour and at the machine wall enable interactions around the entire column. On the left side of the plot the magnetic field vectors wrap around a region of a few cm along x and 10 cm long along y. This indicates that there is an axial current in that region. Note that the location of this current exactly corresponds to the location of the fast electrons in Fig. 10.

Figure 18 shows typical time traces of B_x, and their power spectra, at two different axial locations. The parallel component B_x is an order of magnitude smaller than the transverse components. The magnetic perturbations are on the order of 50 mG (δB/B_0=0.01%). With the microwaves focused, the first peak can reach 1 Gauss (δB/B_0=0.1%), while the following oscillations remain on the order of 100 mG. The first peak due to the burst of fast electrons is much more pronounced when the microwaves are focused.
The dependence of the group speed on frequency can be studied through a wavelet analysis, as shown in Fig. 20. A typical $B_t$ trace at $z=1$ m was used in this analysis. An exponential function was fitted to the amplitude of the wave. This time trace was subsequently divided by this exponential, as to bring out the oscillations at later times. This trace and the original time trace are shown in the insert in Fig. 20. The wavelet analysis is then done on the bottom trace. The wavelet clearly shows an increase in frequency up to $f_{ci}$ as time increases. The frequency starts out at 0.9 $f_{ci}$ for the initial oscillations and ends up at $f_{ci}$ for the late-time oscillations. The higher frequency components therefore have lower group velocities. The shear Alfvén wave dispersion has this property.

The general features of the magnetic oscillations are consistent with the properties of shear Alfvén waves. The transverse components of the wave, $B_x$ and $B_y$, are larger than the longitudinal component $B_z$, by a factor of 10. The waves have a cutoff in frequency at $f_{ci}$. They are collimated along field lines.

To further check that these are shear Alfvén waves, one needs to compare the measured dispersion with the theoretical dispersion relations. In order to do this, $k_\parallel$, $k_\perp$, and $\omega$ need to be measured. The perpendicular wave number can be estimated from a radial cut from the data in Fig. 17. The calculation was done for a similar plane with $B_0=1$ kG. This gave a value of 0.31 cm$^{-1}$, or $k_\parallel=2\pi/20$ cm$^{-1}$. The frequency was 340 kHz±13 kHz, therefore $\omega/\omega_{ci}=0.89\pm0.034$. The parallel wave number is obtained by examining the phase delay between time traces of a magnetic component of the wave, obtained on the same field line, but at different axial locations (in this case at $z=0.67$ m and at $z=1.0$ m). These are plotted in the insert of Fig. 21. The temporal difference between the phase maxima in the two traces is $0.62\pm0.05$ $\mu$s. Since $k_\parallel=\omega/\Delta z$ with $\Delta z=32$ cm, $k_\parallel=0.040\pm0.005$ cm$^{-1}$. The measured values can now be compared to the theoretical dispersion relation. The lines plotted in Fig. 21 correspond to the theoretically predicted dispersion relations for Alfvén waves. These curves were calculated by solving the dispersion relation

$$n_\perp^2 n_\parallel^2 = (n_\perp^2 - \epsilon_x)(n_\parallel^2 - \epsilon_e) + \epsilon_{ce}(n_\perp^2 - \epsilon_e)/(n^2 - \epsilon_x),$$

for different values of $k_\perp$, and with $T_e=0.5$ eV ($n_\perp=k_\perp/k_0, n_\parallel=k_\parallel/k_0$). The value for the measured magnetic oscillations is indeed near the theoretical predicted value for $k_\perp=2\pi/20$ cm$^{-1}$, within experimental error. Since $v_{th,e} < v_A$ the waves can be cataloged as inertial shear Alfvén waves.

A parameter that can be changed in the experiment is the electron temperature $T_e$. This is done by performing the experiment at different delay times within a plasma shot. During the discharge, $T_e$ is measured to be on the order of 6 eV. Once the main discharge shuts off, the electron temperature drops to less than 1 eV in tens of microseconds, whereas the background density decays much slower and is therefore approximately constant on these time scales.

These two different electron temperatures have a large impact on the experiment, both on the microwave absorption and on the Alfvén waves. As discussed in Sec. IV, the ratio $|E|^2/nT_e$, where $E$ is the vacuum electric field of the incident...
microwaves, drops from 0.6 in the afterglow to 0.05 in the main discharge. These numbers were calculated for \( n = 10^{12} \text{ cm}^{-3} \) and \( T_{e,\text{discharge}} = 6 \text{ eV} \) and \( T_{e,\text{afterglow}} = 0.5 \text{ eV} \). The fluid nonlinearities will therefore be larger in the afterglow than in the discharge.

Not only the degree of nonlinearity changes, but also the propagation properties of the Alfvén waves. In the afterglow the electron thermal velocity is \( 3 \times 10^7 \text{ cm/s} \), whereas in the discharge \( v_{\text{th},e} = 1.1 \times 10^8 \text{ cm/s} \). Typical Alfvén speeds in helium vary from \( 6.5 \times 10^7 \text{ cm/s} \) to \( 10^8 \text{ cm/s} \), for \( n = 10^{12} \text{ cm}^{-3} \) and magnetic fields ranging from 0.6 kG to 2 kG. In the afterglow the waves are in the inertial regime, since \( v_{\text{th},e} < v_A \). In the discharge however, the Alfvén waves are borderline kinetic. Landau damping is an important factor in the discharge, since the electron thermal speed and the Alfvén speed are roughly equal.

The weaker drive for the Alfvén waves in the discharge and the close proximity of \( v_{\text{th},e} \) and \( v_A \) result in waves which are not as clean as the Alfvén waves in the afterglow. Figure 22 compares a time trace of \( B_\parallel \) from the discharge and one from the afterglow. In the afterglow the waves are very monochromatic, whereas in the discharge the waves have a broad spectrum. The discharge trace still shows oscillations with frequency close to \( f_c \). They are however merely a ripple in the signal. Both these traces were obtained with focused microwaves. The initial peak, due to the suprathermal electrons, is then much more pronounced than in the unfocused case (Fig. 18).

The fact that the waves are observed right after the suprathermal electrons pass by, and the fact that the waves are centered on the same field lines where the suprathermal electrons are observed, leads to the theory that the waves are generated by these electrons. In fact, the waves are a wake left behind by the suprathermal electrons, much like a boat moving through water. In a future paper a theoretical model will be proposed to calculate the Cherenkov radiation of shear Alfvén waves by a moving charged source. The model agrees remarkably well with the experimental data. The predicted time traces and spectrum (Fig. 18), and the peak frequency vs \( B_0 \) behavior (Fig. 22) are reproduced by this model. The authors therefore state, with confidence, that the shear Alfvén waves are Cherenkov radiated by the pulse of suprathermal electrons.

**VI. CONCLUSIONS**

In summary, we have observed the generation of Alfvén waves by a process which initially involved waves in the electron plasma frequency range, four orders of magnitude higher in frequency.

The microwave intensity measurements showed that the incident microwaves lead to strong localized electric fields. In the \( O \) mode the peak intensity is located on the underdense side of the plasma frequency cutoff. In the \( X \) mode the peak is on the overdense side of the upper-hybrid resonance. A pulse of suprathermal electrons was observed to stream along the field lines, out of these high electric field regions. These suprathermal electrons have an average drift speed on the order of the Alfvén speed, but there are outliers with energy greater than 75 eV. The amplitude of this electron current is linear with the intensity of the incident microwaves (\( E_{\text{microwaves}} \)), and exhibits a threshold value for the microwave power, below which no suprathermal electrons are observed. The threshold is higher for \( X \) mode polarized waves than for \( O \) mode polarized waves. The origin of this threshold is still an open question, and could be related to density profile modification.

Magnetic perturbations were observed in the wake of the suprathermal electrons. These perturbations were identified as arising from inertial shear Alfvén waves. The time traces of the wave look like traces from a single frequency damped oscillator, with frequency close to \( \omega_c \). For different magnetic fields, and different microwave powers, the frequency of the wave always remains close to \( \omega_c \). The Alfvén wave generation can be explained by Cherenkov radiation of Alfvén waves by the suprathermal electrons (to be discussed in a future paper).

The results presented in this paper show that Alfvén waves are generated whenever a pulse of field aligned electrons, with velocities on the order of the Alfvén speed, is present in the plasma. The pulse of field aligned suprathermal electrons in this paper is a by-product of the plasma-microwave interaction. In space and laboratory plasmas, there are many instances in which pulses of field aligned electrons are observed, generated by various processes. Alpha particle creation in fusion plasmas is one example. Examples from space physics include magnetic reconnection events and solar flares. Cherenkov radiation of Alfvén waves is of importance in all these cases, as long as the speed of the electrons is on the order of the Alfvén speed. Finally, these experiments may be useful to the ionospheric heating community in the interpretation of their data.

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