Ar II Laser Generated by Landau Damping of Whistler Waves at the Lower Hybrid Frequency

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Lasing of the 488-nm Ar II line has been demonstrated in the central 1.2 cm of a 4.5-cm-diam rf-produced magnetoplasma at pressures of 1 Pa. The external rf antenna excites an $m=1$ whistler wave at the lower hybrid launch frequency which produces a highly ionized plasma. The inferred population inversion and the correspondence between measured wave phase velocity and the upper energy levels of the observed transitions suggest that Landau damping of the wave can selectively distort the electron distribution function at an energy equivalent to the phase velocity of the wave.

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Argon-ion gas lasers commonly consist of a narrow (≤ 1.6-cm) low-pressure argon column excited by passing a current between two electrodes situated at either end. The output power is somehow limited by instabilities generated by the current passing through the plasma.[1] Considerable power is also dissipated in heating the argon gas which transfers its energy to the vacuum tube walls which in turn can become hot, leading to thermal stability problems for the optical cavity. Sputtering of the electrodes can lead to decreased lifetime and impurities in the lasing medium.

We have constructed a novel rf plasma excitation system which eliminates or considerably reduces these problems and offers the possibility of high output powers in the visible and ultraviolet. A 160-cm-long 4.5-cm-diam glass discharge tube terminated by quartz plates at the Brewster angle was mounted coaxially to fourteen pancake magnetic field coils capable of producing a magnetic field (B_0) up to 0.16 T with a uniformity of $\pm 3\%$. The gas inlet and vacuum pumps were mounted at the same end of the tube so that the pressure was constant over the length of the discharge tube. The base pressure was 10^{-4} Pa with an operating pressure of around 1 Pa. Adjustable external mirrors of 99.2% reflectivity and 600 cm radius defined the stable optical cavity.

The plasma was generated by coupling rf power to a double-loop antenna external to the tube and oriented to produce an oscillating magnetic field normal to the axis of the plasma. This structure is known to excite whistler (helicon) waves and generate a highly ionized plasma.[2,3] Optical emissions were measured using a 1-m monochromator and calibrated optical system. A 3-mm microwave interferometer and single Langmuir probe were used to obtain the absolute value of the electron density. The small-signal optical gain was measured along the axis of the plasma with a low-power argon-ion laser. The rf power was pulsed on for 5 msec with a duty cycle of 5% to allow effectively continuous monitoring.

The plasma parameters reach a constant value about 2 msec after the rf is switched on. The radial variations of plasma density, spontaneous emission of Ar II and gain at 488 nm are shown in Fig. 1 for $B_0=0.08$ T and 3.5 kW of 7-MHz rf power. The central electron density corresponds to 100% ionization with a roughly inverse radial dependence out to the walls. The spontaneous-emission profile varies approximately as the square of the density profile suggesting that the plasma electrons are exciting the upper levels of the radiating lines directly from the ground state and that the system is very close to simple coronal equilibrium.[2] Optical gain occurs in the center of the plasma with a dimension of ~ 1 cm, corresponding to the full width at half maximum (FWHM) of the electron density. These measurements are consistent with the plasma being generated in a thin axial column and radially diffusing to the walls with a mean free path of ion-neutral collisions of some tens of cm.

There is evidence (Fig. 2) of a plateau in the rise of density with rf power at powers between 2 and 3.5 kW. This is attributed to the creation of doubly ionized argon ions as evidenced by the rapid increase of the Ar III 351-

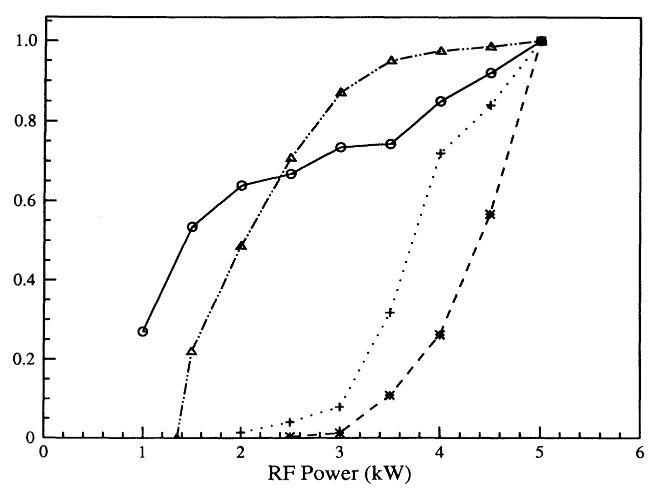

FIG. 1. Radial profiles of electron density (o, in units of 10^{19} m^{-3}), 488-nm Ar II spontaneous emission ($\triangle$, in arbitrary units), and 488-nm optical gain per pass (*, in %). All for rf power of 3.5 kW and magnetic field of 0.075 T.

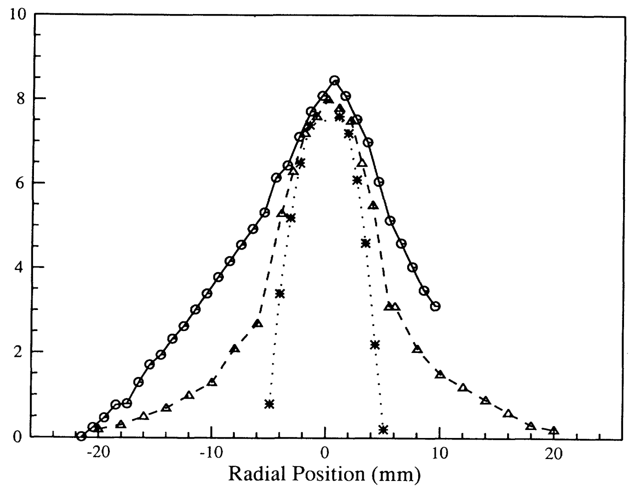

FIG. 2. Electron density (○), Ar III 351-nm-line spontaneous emission (+), Ar II 488-nm-line small-signal optical gain (△), and Ar II 488-nm-line laser output (*) as functions of rf power. All in arbitrary units and for magnetic field of 0.075 T.

nm line above 3 kW. The saturation of the small-signal gain is probably due to the decreasing number of Ar II ions and the preferential excitation of higher-energy states of Ar II and Ar III. The laser output has a threshold at 2.5 kW due to cavity losses and increases rapidly with rf power.

Figure 3 shows that all plasma parameters are sensitive to variations of B_0. At around 0.05 T, the spontaneous emission of the Ar II 488-nm line increases rapidly and the FWHM of the plasma density drops significantly as B_0 increases. Optical gain appears at 0.06 T. Both the spontaneous emission and the gain of the Ar II 488-nm line reach their peaks at 0.07 T and then gradually decrease for higher fields, while the Ar III emission has a maximum at 0.10 T which corresponds to the maximum in the plasma density. At the highest B_0, the plasma density has reached a constant value but the emission of both Ar II and Ar III have decreased significantly. The fact that all plasma parameters have their extremum in the range of 0.07 to 0.12 T implies there is some kind of resonance for B_0 in this range.

A possible explanation for the separation of the peaks of Ar II and Ar III emissions is that the whistler wave excited by the antenna interacts with the electrons to supply the extra energy required to selectively excite the upper states of the transitions. To check this hypothesis, we have measured the axial variation of the wave field outside the discharge tube with a small electrostatically compensated rf magnetic field probe. Amplitude and phase measurements show the whistler to be a standing wave with wavelengths ranging between 30 and 80 cm. From this the phase velocity of the wave can be calculated and converted to an equivalent energy using the relation

$$\tfrac{1}{2} m v_\phi^2 = E_r ,$$

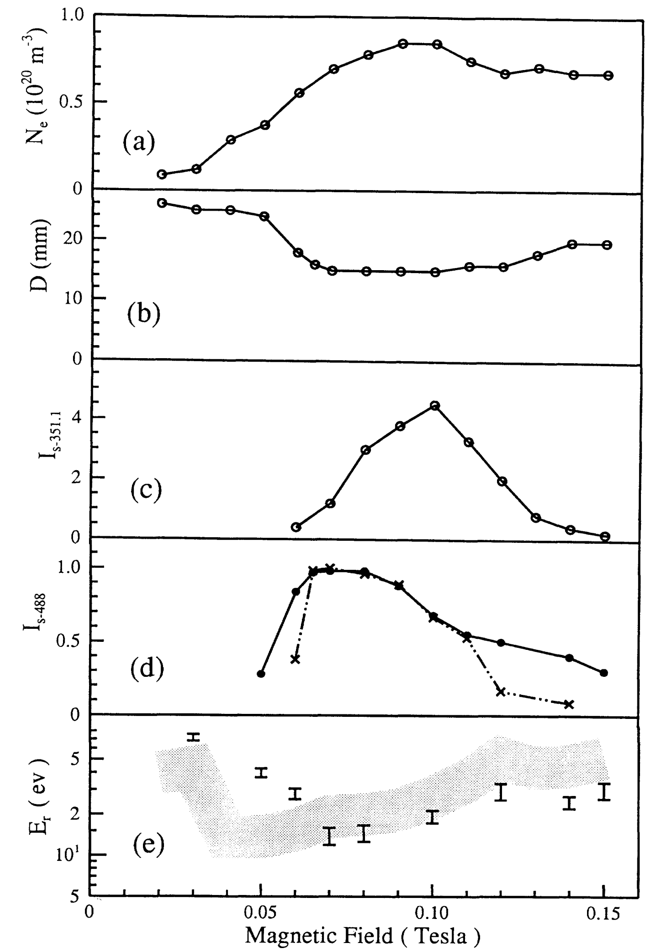

FIG. 3. (a) Electron density, (b) full width at half maximum of electron density, (c) spontaneous emission of Ar III 351-nm line, (d) small-signal optical gain, ×, and spontaneous emission, ●, of Ar II 488-nm line, and (e) equivalent energy. All as a function of magnetic field, for rf power of 3.5 kW.

where m is the mass of an electron and v_ϕ $(=f\lambda)$ is the phase velocity of the wave.

These results are plotted in Fig. 3(e) along with a theoretical curve obtained from a simplified whistler dispersion relation derived by Chen.[4] We have assumed the wave propagates in a column of diameter equal to the FWHM measured in Fig. 3(b) with a volume-averaged density within the column given by Fig. 3(a). A $\pm 20\%$ uncertainty in the density is given by the width of the shaded area in Fig. 3(e). Given the simplicity of the model, the agreement is quite good in both form and magnitude, and confirms that the measurements outside the column are indicative of the wavelength inside the plasma.

The equivalent energy E_r has a minimum of around 15 eV at the maximum of the Ar II emission and increases to about 20 eV at the maximum of the Ar III emission. These energies are close to the upper-level energies of

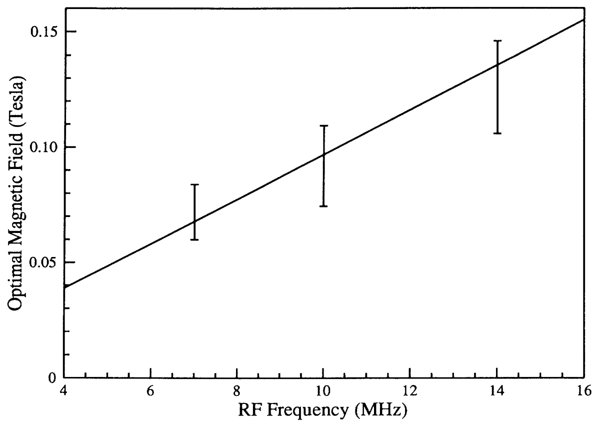

FIG. 4. Optimal magnetic field for maximum optical gain as a function of rf frequency.

the respective states (19.68 and 25.93 eV) implying that electrons are resonantly accelerated by the wave to the wave velocity.

In a theoretical analysis, Chen[4] has suggested that this may be due to Landau damping of the whistler wave which in a resistive cylindrical plasma has an electric field component parallel to B_0. This can interact directly with the electrons and distort the distribution function. The mean free path (λ_{mfp}) for Landau damping is ~ 30 cm and the λ_{mfp} for excitation is ~ 100 cm which is somewhat less than the column length. Hence this could provide an efficient means for transferring energy to the electrons which subsequently suffer inelastic collisions in the column.

The efficiency of this process would also depend on the coupling efficiency of the rf power into the wave. Calculations[5] using a fluid model to determine the coupling of a finite double-loop antenna to a cylindrical magnetoplasma have shown that the antenna loading (measured by the resistive component of the back emf) shows a strong maximum at the lower hybrid frequency [$\omega_{LH} = (\omega_{ce}\omega_{ci})^{1/2}$, where ω_{ce} and ω_{ci} are the electron and ion gyrofrequencies]. The loading has a functional dependence on B_0 very similar to the gain curve shown in Fig. 3(d). In Fig. 4 the B_0 required for optimum gain is plotted for three different rf frequencies. There is good agreement with ω_{LH} shown by the solid line.

Optical gain and lasing action have been measured in a low-pressure rf-excited argon magnetoplasma with a tube diameter of 4.5 cm, nearly 3 times the diameter of the largest argon laser tube reported so far. The experimental results are consistent with a simple model where the external rf excites a whistler wave at the lower hybrid launch frequency. There is evidence that Landau damping provides a source of nonthermal electrons with energies adequate to overpopulate the upper levels of the appropriate Ar II transitions and lead to gain. This new, electrodeless form of excitation might overcome some of the limitations of the standard methods of laser excitation.

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