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R. F. SUSTAINED MAGNETOPLASMAS IN ARGON, HELIUM, AND NITROGEN

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ABSTRACT

Four mechanisms thought to be important in understanding plasma production in microwave plamsa sources are: 1.) collisional phase mixing, 2.) single particle cyclotron resonance, 3.) bounded plasma resonance, and 4.) standing Bernstein wave resonance. By examining the luminosity of the plasma as the magnetic field is swept, one can identify the mechanisms operating for a particular set of plasma conditions. In this paper we report observations carried out on three gases used in the MACOB plasma source at pressures of 0.1 to 100 mTorr and for magnetic fields of from 0 to 3 kG. Regions on the B vs. p diagram for each of the gases have been identified where one or more of the basic mechanisms is observed to be important. Mechanisms 1.) and 2.) appear to be able to account for the observed plasma densities. Process 3.) does not appear to be important for plasmas generated in a strong magnetic field gradient, and process 4.) appears to be operative but not required to explain the observed plasma densities.

INTRODUCTION

Many plasma sources (Lisitano, 1968; Lisitano, 1970; Aubert, 1971) make use of a microwave coupling structure located in a magnetic field to generate plasma. Usually the source will be found to operate over such a wide range of pressure and magnetic field that more than one physical mechanism is probably responsible for transferring energy from the r.f. field to the sustained plasma. If the pressure is sufficiently high, electron-neutral collisions will provide the phase mixing necessary for electrons to gain energy in the oscillating field. If the pressure is low, but the magnetic field is near the value necessary to produce single particle cyclotron resonance, we will observe excellent energy transfer, even though the electron-neutral collision frequency is low.

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If the plasma density is sufficiently high and if it is localized to a small region of space, one can observe bounded plasma resonances and resonances which have been attributed to the establishment of a standing Bernstein wave pattern across the plasma column, transverse to the magnetic field.

We have undertaken a parametric study of argon, helium, and nitrogen to determine the ranges of magnetic field B, and pressure p, over which these mechanisms can be observed in order to better determine which are fundamental to the plasma generation process.

I. APPARATUS

The measurements were carried out in the MACOB (MAgnetically Confined, Overdense, Bounded) plasma source (Sanders, 1972) Fig. 1, which makes use of a microwave cavity, located in the field gradient of a magnetic mirror confinement field. A 0.8 m x 0.016 m cylindrical quartz tube passes axially through a microwave cavity confining the plasma in the cavity to a cylindrical region having a radius small compared to the r.f. free space wavelength. One end of the tube passes through the stainless steel end plate of the main vacuum chamber.

The main pyrex vacuum chamber is 2.6 m long and 0.15 m in diameter and occupies most of the volume of the solenoidal magnetic field. The base pressure of the system is typically 10^{-7} Torr and the operating pressure is typically 0.1 to 100 mTorr. A vacion pump is used to maintain the base pressure and a mechanical rough pump with a molecular sieve trap is used to bring the pressure down to 0.1 mTorr. Pressure measurements for this work were made with two standard thermocouple gauges, one located near the pumping station and one in the gas manifold.

Power of up to 125 W at 2.45 GHz is coupled to the driver cavity by means of a large r.f., H-field probe. Plasma densities are measured by observing the frequency shift of the maximum r.f. signal transmitted through a second, fixed dimensional diagnostic cavity, located between the driver cavity and the main vacuum chamber. The r.f. signal is provided by a 10 mW 1.8 - 4.2 GHz sweeper.

The measurement of the different gas plasmas is carried out by filling the chamber with the gas under investigation, starting from a base pressure of 10^{-7} Torr up to the desired operating pressure. We do not pump on the system while the measurements are being made. The vacuum system is sufficiently free of leaks, that the pressure remains constant over the typical ten hour data run.

Magnetic field measurements are made with a Hall effect probe and complete field mapping measurements have been performed in the field region occupied by the cavities so that the field at any point within either cavity can be inferred from the indications of a gaussmeter probe mounted in a "standard position" along the outside of the driver cavity.

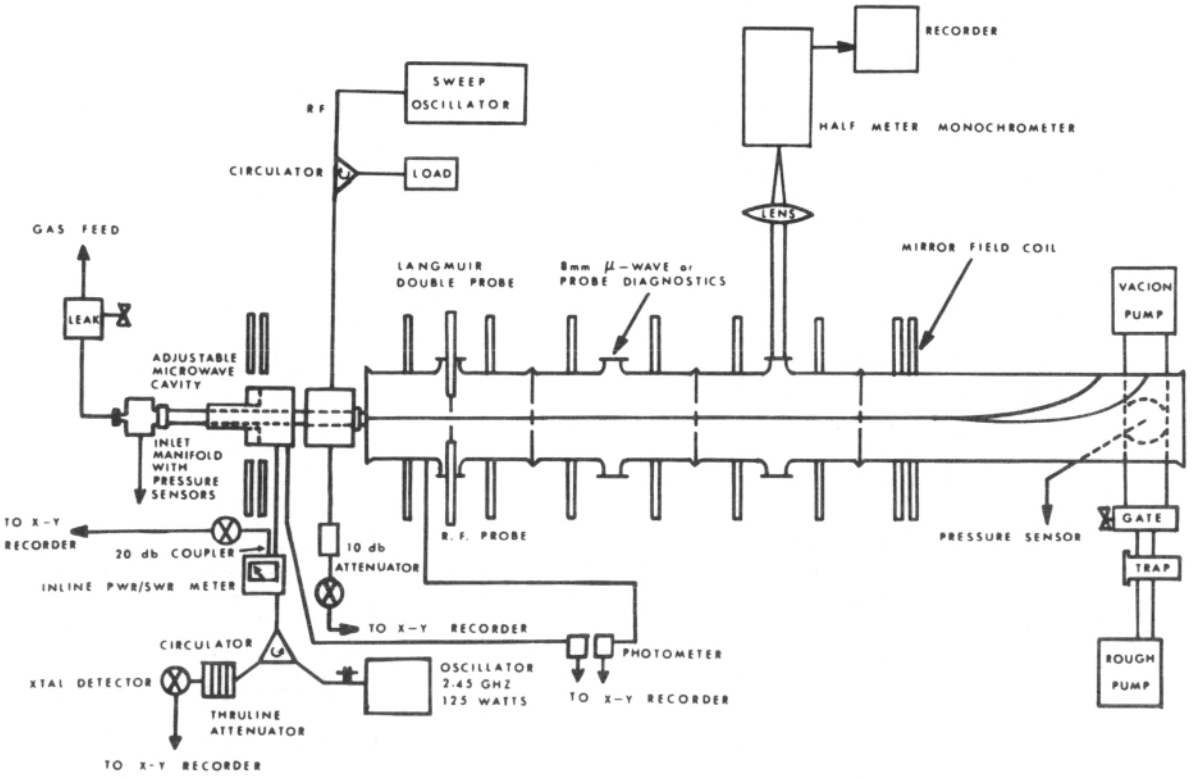

Figure 1. Principle components of the MACOB plasma source.

Plasmas have been created using the TE_{111}, TM_{011}, and TE_{211} modes of the driver cavity. The measurements cited in this paper are all for plasma generated using the TE_{111} mode excited by a large loop probe located in the cavity side wall. The modes are tuned by changing the length of the cavity. Frequency shifts of the TE_{111} and TM_{011} modes of the diagnostic cavity have been used to infer the density as the plasma passes from the driver cavity into the main chamber.

The luminosity of the plasma in the driver cavity and in the main vacuum chamber is measured with photometers. Plasma outside the driver cavity is referred to as the "tongue".

II. PLASMA CHARACTERIZATION

It has been shown (Messian and Vandenplas, 1969) that by observing the plasma luminosity as a function of magnetic field, one can identify bounded plasma resonances, and resonances at harmonics of the cyclotron frequency which indicate the presence of standing Bernstein waves. Previous work has dealt with the generation of these resonances in a uniform field. However, it is clear from Fig. 2 that the MACOB plasma luminosity exhibits these characteristic resonances even though the plasma generation takes place in a magnetic field gradient. We have used these observed resonances in the luminosity versus magnetic field data as one property by which to characterize the plasma.

BERNSTEIN WAVE RESONANCE

Well defined minima in recordings of the luminosity versus magnetic field for magnetic fields satisfying

$$\omega_c/\omega = n/m \qquad 1.)$$

with n and m integers and the electron cyclotron frequency

$$\omega_c = eB/m$$

with e the magnitude of the electron charge in Coulombs, m the mass of the electron in kilograms, and B the magnetic induction in Tesla, have been attributed to the presence of a standing Bernstein wave (Bernstein, 1958; Dreicer, 1965; Stone and Auer, 1965) pattern across the plasma column. Fig. 2 is a trace exhibiting the resonances at fields satisfying the conditions for Bernstein wave propagation. The dispersion relation for these waves indicates that they cannot be generated when condition 1.) is satisfied, but rather, depending upon the plasma temperature and density, for magnetic fields either slightly above or below the fields given by this condition. Thus we expect a minimum luminosity when condition 1.) is satisfied.

BOUNDED PLASMA RESONANCE

The internal eleetric field of a uniform, cylindrical dielectric rod having a dielectric constant κ, placed in a uniform electric field of magnitude E_o is given by:

$$E_i = 2E_o/(1 + \kappa) \qquad 2.)$$

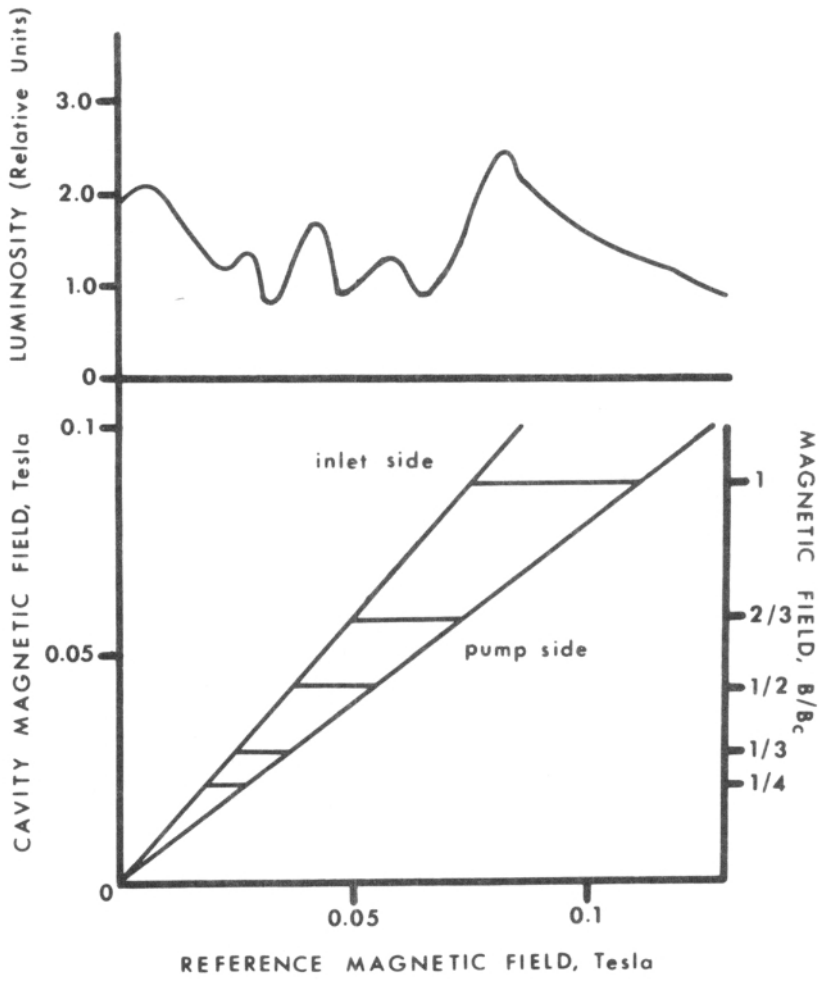

Figure 2. The minima in plasma luminosity occur when Bernstein wave generation is no longer possible, B/Bc = n/m. (Bc is the magnetic field at which cyclotron resonance takes place; n and m are integers.) Since the driver cavity is located in a field gradient, this condition can be satisfied for a range of reference field values.

For a plasma, κ can be less than zero and hence resonances are possible when $\kappa = -1$. In a cylindrical geometry the resonance occurs for $\omega = \omega_p/\sqrt{2}$ rather than at the plasma frequency,

$$\omega_p = Ne^2/m\varepsilon_o$$

with N = the electron density per cubic meter, and ε_o = the permitivity of free space. This resonance is the lowest order resonance of a series of multipolar, cylindrical, bounded plasma resonances.

For a plasma contained in a dielectric tube having an inner radius b, an outer radius c, and a dielectric constant $\kappa_t = \varepsilon_t/\varepsilon_o$, and located in a magnetic field, the condition for a bounded plasma resonance (Vandenplas, 1968) is given by

$$\omega_p^2/\omega^2 = \Omega_{\pm n} \qquad 3.)$$

with

$$\Omega_{\pm n} = (1 + \kappa_t|Q_n/P_n|)(1 \pm \beta) \qquad 4.)$$

$$P_n = \varepsilon_o(b^{-2n} - c^{-2n}) + \varepsilon_t(b^{-2n} + c^{-2n})$$

$$Q_n = \varepsilon_o(b^{-2n} + c^{-2n}) + \varepsilon_t(b^{-2n} + c^{-2n})$$

$$\beta = \omega_c/\omega$$

ω = the r.f. source radian frequency, and with n an integer defining the multiple order of the resonance.

If a steady state, r.f. discharge tends to adjust its density so as to maintain a resonance condition with the r.f. field (Leprince, 1971), one would expect the luminosity of the magnetoplasma, at fixed pressure and magnetic field, to have two possible values, corresponding to operation on either of the two branches of the resonance given by Equation 3.). Plasma operating conditions which give rise to a luminosity versus magnetic field trace exhibiting the characteristics of either resonance branch will be termed "bounded plasma conditions". Figure 3 shows an argon trace which suggests that the plasma might be fixed to a bounded plasma resonance, at least for $B < B_c/2$, where $B_c = m\omega/e$.

THE JET

At sufficiently high pressure and for magnetic fields greater than the cyclotron field, a high density plasma is observed in the main vacuum chamber. If conditions are chosen properly, milliwatts of r.f. can be observed far down the plasma column. Evidence of a parametric decay process (Chang, 1972) has been reported for helium and argon under jet conditions. The jet seems to correspond to the high density plasma produced by Lisitano (Lisitano, 1970) and suggested as a possible fusion plasma injection source. Fig. 4 indicates the luminosity characteristics recorded by a photometer looking into the driver cavity and by one looking at the tongue in the main chamber.

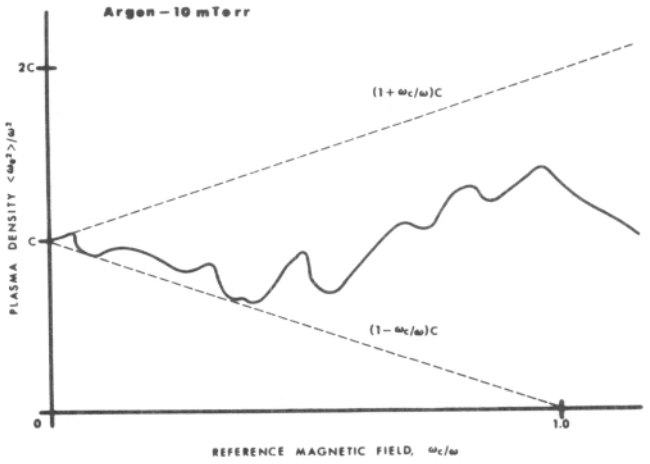

Figure 3. R.f. sustained argon plasmas appear to follow the lower branch of a cylindrical multipole resonance for low magnetic fields.

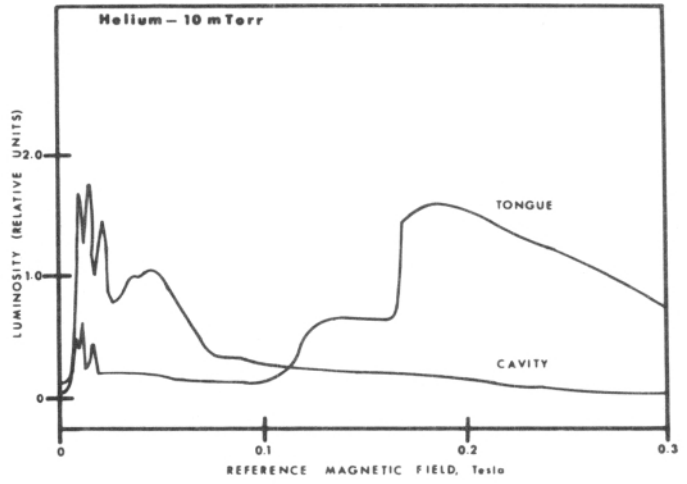

Figure 4. The intense luminosity of the ejected plasma tongue for fields greater than the cyclotron resonant field defines the jet condition. The tongue photometer sensitivity is x10 that of the cavity.

THE SUSTAINED PLASMA

Luminosity traces exhibiting neither the bounded plasma characteristics nor the jet characteristic define the "sustained plasma" operating mode. The mechanisms responsible for steady state plasma generation in this mode are assumed to be the conventional mechanisms of collisional phase mixing (Allis, 1956) and cyclotron(MacDonald, 1966) resonance.

III. DATA

The data were taken with a constant incident power of 100W. The perturbation resulting from the use of the large H-field probe was sufficient to lift the TE_{111} mode degeneracy producing a 130 MHz splitting between the cavity resonance described by an even function (TE_{111}^{e}) of the cylidrical coordinate θ, and that described by an odd function, (TE_{111}^{o}). The high frequency (TE_{111}^{e}) mode, typically had a Q of 970 in the absence of plasma. The effect of plasma loading was inferred by monitoring the corresponding mode in the diagnostic cavity. Typically we would observe the TE_{111} diagnostic cavity mode at 3.36 GHz and notice frequency shifts in the range of 20 to 70 MHz. The loaded Q's in the diagnostic cavity were typically in the range of 350 to 150.

Pressures were measured with Haystings VT-5 gauges and DV-5 gauge tubes calibrated for air. The pressure data is corrected for the specific gases. To obtain the p vs. B plots we made use of forty-three data points for argon, thirty-six data points for helium and thirty-one data points for nitrogen. The Bernstein wave resonances gradually wash out at high pressure. The exact pressure at which the process is complete is somewhat ill-defined. As the pressure is lowered, the range of magnetic field over which resonances are observed gradually narrows until only the single cyclotron resonance peak remains.

HELIUM

Fig. 5 shows the operating regions of the MACOB device using helium. The plasma no-plasma boundary defines the conditions at which the plasma is extinguished as one moves from the plasma region to a no-plasma region by changing the magnetic field at constant pressure. These boundaries depend slightly on the state of tune of the cavity and hence are only good to about 5%. We notice that at low pressure, the plasma exists only in a narrow region about the cyclotron field. Breakdown is easily initiated as the magnetic field is swept from high or low fields towards the cyclotron resonance. Bernstein wave peaks and a well-defined jet have been observed in helium. No indication of bounded plasma resonance has been observed.

ARGON

Fig. 6 represents the operating characteristics of argon. Argon exhibits all four of the plasma characteristics. A well-defined jet

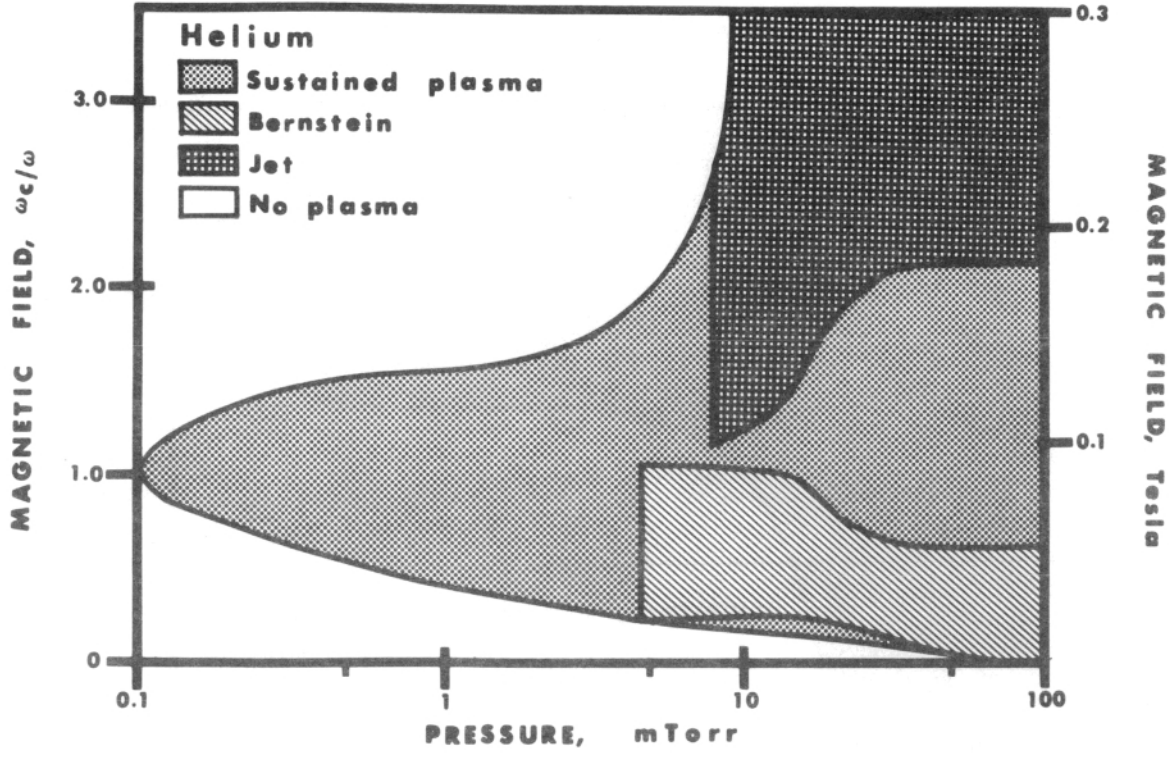

Figure 5. Helium plasma existence regions for 100W incident power and TE_{111} mode excitation.

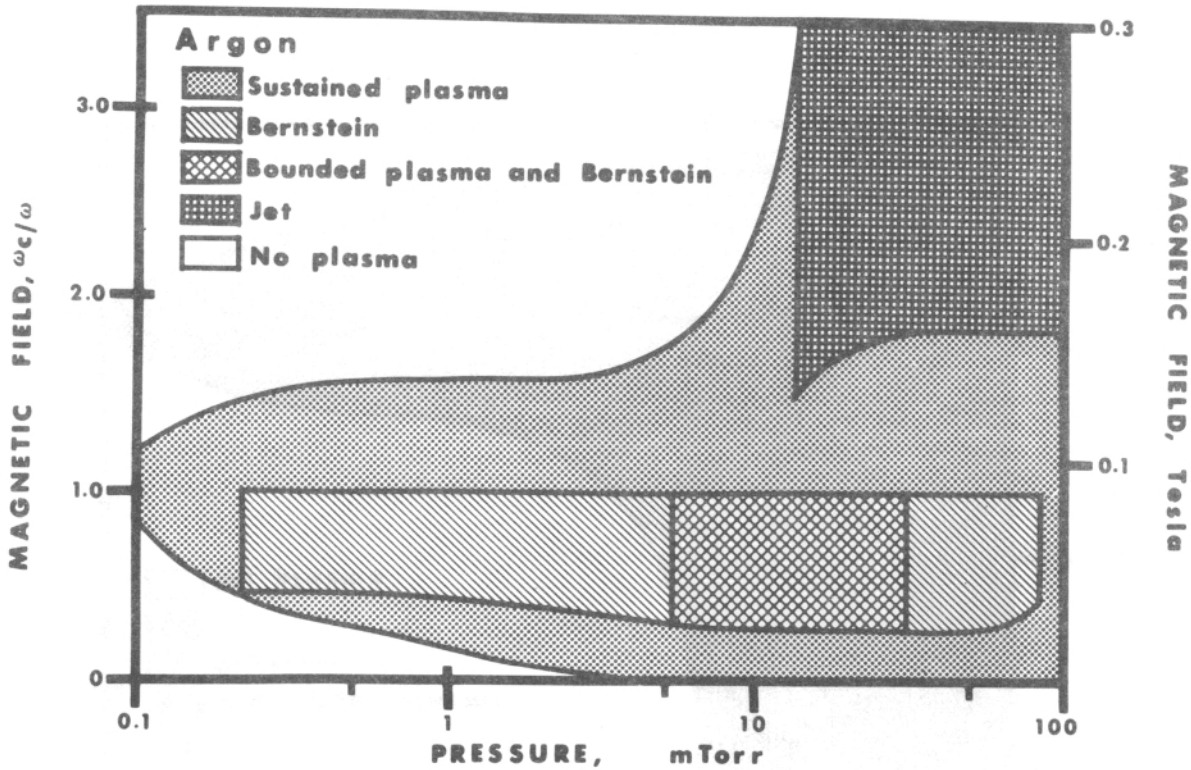

Figure 6. Argon plasma existence regions for 100W incident power and TE_{111} mode excitation.

has been observed and plasma production can take place at low pressure near cyclotron resonance. Only argon exhibits the bounded plasma behavior. There exists a range of pressures for which the bounded plasma and jet characteristics occur simultaneously.

NITROGEN

Well-defined Bernstein resonances have been observed for nitrogen and are indicated in Fig. 7. No bounded plasma behavior can be identified. A short jet was observed, but only at very high pressure. Under these conditions the high base pressure in the main chamber tends to limit the length of the jet.

IV. DISCUSSION

Consideration of the B-p diagrams for the three gases used in this study suggests that bounded plasma resonances do not play a very important role in the generation of plasma in this type of source. This conclusion has been supported by a series of measurements of plasma density using microwave cavity frequency shifts to determine the density of the plasma as it passes through the diagnostic cavity into the main chamber. The density in the driven cavity is then inferred by comparing the luminosity in the driver cavity with that in the diagnostic cavity. It is assumed (Leprince, 1968) that for constant operating pressure, plasma density is proportional to luminosity.

TABLE 1

The Bounded Plasma Resonances of the MACOB Plasma Source, $\omega_p^2 = Ne^2/m\varepsilon_0$

Cylindrical Multipole Order (m)	$\frac{\text{Plasma Density}}{\text{Cutoff Density}} = \frac{\omega_p^2}{\omega^2}$	Plasma Density N (cm^{-3})
Dipole (1)	2.28	1.70×10^{11}
Quadrupole (2)	2.82	2.10×10^{11}
Hexapole (3)	3.48	2.59×10^{11}

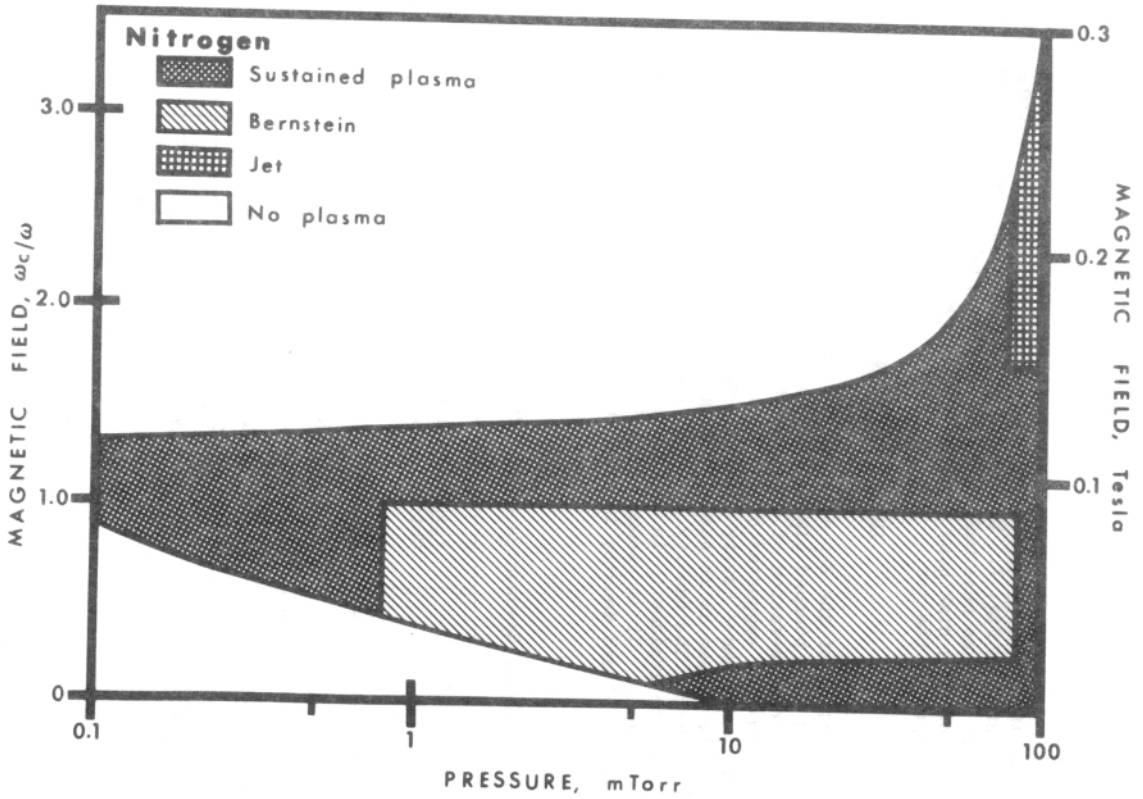

Figure 7. Nitrogen plasma existence regions for 100W incident power and TE_{111} mode excitation.

Table I indicates the densities calculated from Eq. 3 for the three lowest bounded plasma resonances which can occur in our device. The measured zero field densities are typically $1.7 \times 10^{12} cm^{-3}$. This density is more than an order of magnitude greater than that which would result if the plasma adjusted its density to maintain the dipole resonance condition. To check the possibility that we were operating in a higher order mode we systematically lowered the power to the plasma hoping to observe mode transitions. No discrete low density states were observed. Rather, the density and luminosity could be reduced continuously until it extinguished. It should be noted that discontinuous changes in luminosity could be observed for non-zero values of the magnetic field. However, the zero field density appeared to be independent of which high field mode the plasma assumed prior to reducing the field to zero.

Because of the presence of a field gradient in the plasma generation region, it is not unexpected that well-defined bounded plasma resonances are not observed. However, it is somewhat surprising that the densities are greater than that which would be achieved through the plasma resonance phenomena and that well-defined Bernstein wave resonances are observed. Consideration of Fig. 5, 6, and 7 suggest that in the pressure range of 1 to 100 mTorr, Bernstein wave generation is very prominent and might be an important energy transfer mechanism for a source like this. These results are especially surprising in the light of the work of Crawford, (Crawford, Harp, and Mantei, 1967) who found it difficult to excite Bernstein waves in a field gradient.

In Table II we present the results of a simple calculation of power absorbed by electrons in a magnetic field in the presence of electron-neutral collisions. We have also estimated the energy loss rate for plasma diffusing out of the driver cavity. The expressions used to make these estimates are given in the Appendix. We have assumed a plasma density of $5 \times 10^{11} cm^{-3}$ at a base pressure of 10 mTorr corresponding to a 2% ionization. The maximum electric field within the cavity was estimated to be 4.8×10^{3} V/m using (Ingraham and Brown, 1967):

$$E_{max} = (P_{net} Q_{\ell}/\omega\eta)^{\frac{1}{2}} \qquad 5.)$$

with P_{net} = 5W and Q_{ℓ} = 150. η is the form factor appropriate to the cavity mode excited by the particular choice of coupling probes. The plasma volume within the cavity is $16 cm^3$. $\langle P_{lost} \rangle_{B=\infty}$ is calculated using $\Lambda = \pi/L$ for the characteristic diffusion length, an assumption which implies the lack of diffusion of particles across the magnetic field.

Table II suggests that the ordering of the gases according to the ease of plasma formation at 10 mTorr is given by Ar, N, H and He. There should be no plasma production for B = 0, but as we move toward cyclotron resonance, energy transfer to the electrons becomes very efficient. At $\omega_b = \omega[1 \pm \frac{1}{2}]$ the energy transfer to the electrons is 2.2 times the energy transfer at zero field.

TABLE II

Energy Balance Parameters for a 10 mTorr Operating Pressure.

	Argon	Nitrogen	Hydrogen	Helium
Electron-Neutral Collision Frequency, ν (sec^{-1})	(5×10^7)[a]	(4.3×10^7)[b]	(6.7×10^7)[c]	(2.6×10^7)[d]
Ionization Potential V_i (Volts)	15.76	14.54	13.60	24.58
Effective Field (B = 0) E_{eff} (Volts/meter)	7.4	6.5	10.	3.8
Power Loss (B = 0) $\langle P \rangle_{loss}$ (W)	1.6	4.7	35.	72.
Absorbed Power (B = 0) $\langle P \rangle_{abs}$ (mW)	240.	220.	330.	120.
Power Loss (B = ∞) $\langle P \rangle_{loss}$ (mW)	28.	80.	644.	1200.
Absorbed Power ($\omega_c = \omega$) $\langle P \rangle_{abs}$ (kW)	1.58	1.84	1.18	3.05

a. A. D. MacDonald, Microwave Breakdown in Gases, (John Wiley & Sons, Inc., New York, 1966), page 20.
b. Ibid. p. 161.
c. Ibid. p. 19.
d. Ibid. p. 19.

Comparison of $\langle P_{lost} \rangle_{B=\infty}$ and $\langle P_{abs} \rangle_{B=0}$ indicates that the collision frequency in argon and nitrogen is sufficient at 10 mTorr to provide the requisite energy transfer from the r.f. field to the electrons, provided we have a magnetic field strong enough to eliminate the transverse diffusion of the plasma. Enhanced energy transfer due to cyclotron resonances is not required for the maintenance of the plasma. To generate a hydrogen plasma a magnetic field equal to half the cyclotron field will provide sufficient resonant energy transfer to sustain the plasma. A helium plasma is very much dependent upon cyclotron resonance for its maintenance.

V. CONCLUSIONS

We described the MACOB plasma source and we reported the range of pressure and magnetic field for which we can generate argon, helium and nitrogen plasma. We have observed a plasma effect which we call the jet, and we have seen resonances in the plasma luminosity vs. magnetic field data which appear to be related to the presence of standing Bernstein waves. We have not been able to observe conditions in which the plasma assumes a density corresponding to a bounded plasma resonance.

We have made estimates of the rate of energy transfer from the r.f. field to the plasma. We find that for a typical plasma at a pressure of 10 mTorr that the collisional phase mixing resulting from electron-neutral collisions in argon or nitrogen is sufficient to sustain the plasma against diffusion losses in a weak magnetic field.

Estimates of the energy transfer from the r.f. field to the electrons for typical plasmas formed at a neutral gas pressure of 10 mTorr suggest that collisional phase mixing resulting from electron-neutral collisions and/or cyclotron resonant energy transfer is sufficient to account for the presence of plasma in the MACOB driver cavity. The role of standing Bernstein waves in this device is an interesting one but perhaps not a fundamental one.

ACKNOWLEDGEMENTS

We wish to express our appreciation to Mr. Robert Perry who assisted in many of the measurements and who diligently kept the MACOB source operating during the course of this work. This research was supported by the Office of Research and Projects of the Southern Illinois University at Edwardsville.

APPENDIX

Absorbed Power Density

The average absorbed power density for plasma described by a complex conductivity, $\sigma = \sigma' + j\sigma''$ is given by:

$$\langle p \rangle' = \tfrac{1}{2}(\vec{J} \cdot \vec{E}^*) = \tfrac{1}{2}\sigma' E_0^2 \qquad 6.)$$

where $\vec{E} = \vec{E}_0 \, e^{-j\omega t}$ and $\vec{J} = \sigma \vec{E}$.

Assuming $\sigma' = \frac{\omega_p^2 \varepsilon_0 \nu}{\omega^2+\nu^2}$, (Brown, 1966), we have

$$\langle p \rangle'_{abs} = \frac{Ne}{m\nu} \left(\frac{\nu^2}{\omega^2+\nu^2}\right)\left(\frac{E_0}{\sqrt{2}}\right) = \frac{Ne^2}{m\nu} E_{eff}^2 \qquad 7.)$$

where E_{eff} is the field strength of the d.c. electric field which would produce the same absorbed power density.

In the presence of a magnetic field (Brown, 1966)

$$\sigma' = \frac{\omega_p^2 \varepsilon_0 \nu}{2} \left[\frac{1}{\nu^2+(\omega-\omega_c)^2} + \frac{1}{\nu^2+(\omega+\omega_c)^2}\right] \qquad 8.)$$

and $$\langle p \rangle'_{abs} = \frac{Ne^2}{m\nu} (E_{eff})^2 \qquad 9.)$$

with $$E_{eff}^2 = \frac{\nu^2}{4} \left[\frac{1}{\nu^2+(\omega-\omega_c)^2} + \frac{1}{\nu^2+(\omega+\omega_c)^2}\right] E_0^2 \qquad 10.)$$

In our calculations we assume that the spatial variation of the TE_{111}-mode electric field over the plasma volume is adequately taken into account by replacing the $E_0 \sin kz$ dependence by the average $E_0/\sqrt{2}$. If the plasma column is taken to be uniform, the average absorbed power is given by:

$$\langle P \rangle_{abs} = \langle P \rangle'_{abs} V$$

where V is the plasma volume.

Power Lost

We assume that the rate at which plasma energy is lost to the walls of the confinement vessel is given by:

$$\langle P \rangle_{lost} = \frac{NV}{\tau} \left[E_{Ti} + E_{Te} + 3E_i\right] \qquad 11.)$$

where
- τ is the energy confinement time
- E_i is the ionization energy
- E_{Te} is the electron thermal energy $\approx E_i/3$
- E_{Ti} is the ion thermal energy ≈ 0
- V is the plasma volume = 16 cm^3

We estimate τ from the relation: $\tau = \Lambda^2/D$ 12.)
where Λ is the diffusion length given by (Brown, 1966):

$$\frac{1}{\Lambda^2} = \frac{\nu^2}{\nu^2+\omega_c^2} \left[\frac{2.4}{r}\right]^2 + \left[\frac{\pi}{\ell}\right]^2 \qquad 13.)$$

and D is the diffusion coefficient. We use the kinetic theory

expression

$$D = \frac{v^2}{3\nu} \qquad 14.)$$

We assume that the ion sound speed is the appropriate speed to use in Eq. 14 in which case:

$$v^2 = \frac{3kT_e}{M_i} \qquad 15.)$$

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