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Die nachstehende Arbeit wurde im Rahmen des Vertrages zwischen dem Max-Planck-Institut für Plasmaphysik und der Europäischen Atomgemeinschaft über die Zusammenarbeit auf dem Gebiete der Plasmaphysik durchgeführt.

Abstract

Simple and economic production of plasma can be achieved over a wide range of plasma parameters by exciting electrodeless, slotted-line radiating structures with microwave power. These plasma sources, which originate from fusion research, are suitable for applications in both low-temperature and thermal plasma chemistry.

1. Introduction

Plasma reactor properties such as constancy of performance, ease of handling, simplicity, size and cost are important requirements for many plasma-processing facilities. To avoid contamination due to electrodes, radiofrequency and microwave equipment is usually employed in many plasma reactors. The inductive coupling of radiofrequency power is limited, however, to frequencies below 200 MHz and the choice of operating frequency is mainly governed by cost and aspects of handling and shielding. Microwave reactors employing waveguides and cavities, on the other hand, have restricted dimensions of the order of the field wavelength, and the magnitude of the field can significantly vary in the reactor.

These shortcomings may be avoided by using the slotted-line surface radiators developed in fusion research in the sixties. The structures are very broad-band and uniformly radiate the em field energy from the container walls. This produces a uniform plasma having dimensions almost independent of the field wavelength.

In a recent paper, "Production of a Large-diameter ECR Plasma with a Lisitano Coil" (1988), Y. Kawai et al, /1/ demonstrated the production of a uniform plasma of density $n_e > 10^{11}$ cm^{-3} and temperature $T_e > 5$ eV in a large cylindrical volume having a diameter D = 40 cm and a length L = 170 cm by using a 2.4 GHz magnetron with a modest power of 1 kW. The plasma exhibit a negligible amount of impurities sputtered from the grounded, all-metal radiating structure. As will be seen, these uniform large-volume plasmas are very suitable for various applications of low-temperature plasma chemistry.

For the production of high-density thermal plasmas, slotted-line structures of small diameter allow one to concentrate microwave power into small volumes having cross-sectional dimensions of down to 1/30 of the vacuum field wavelength. With a modest microwave power input of a few kW, these structures generate plasma jet densities of the order of several kW/cm^2, comparable to those of conventional high-temperature plasma arcs and torches. The plasma jets generated by Lisitano coils are, however, very stable and involve no problems of arcing or metal sputtering.

2. Slotted-Line Radiators

Figure 1(a) shows a simplified form of a slotted-line radiator, known in the field of fusion research as the Lisitano (L) Coil /1, 2, 3, 4/. The structure consists of a long transmission line slotted on a metal cylinder which is generally surrounded by an outer coaxial shielding cylinder and fed with a radiofrequency.

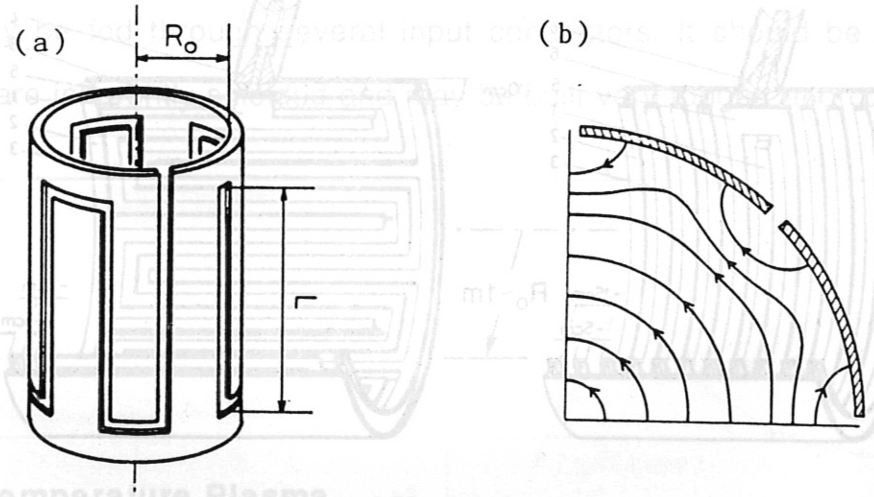

Fig. 1(a): Outline of slotted-type Lisitano coil; (b) lines of electric force in coil, $R_o > \lambda / 2$.

If the length of the slots is chosen as half of the wavelength, the electric field of each slot may be assumed to be in phase. Figure 1(b) shows the typical field distribution inside the coil. It is clearly similar to that of a TE_{011} mode in a cavity when the slots increase in number. However, an important property of this device is that one can obtain such field configurations without meeting the conducting-sheet boundary conditions of cavity resonators, which require large volumes at low frequencies.

Unlike in cavity resonators, the field intensity is uniformly distributed inside a L coil. In particular for $R_o < \lambda/2$, where R_o is the radius of the L coil and λ is the wavelength of the radiofrequency, the electric field intensity increases monotonically toward the slots. However, when one has $R_o > \lambda/2$, the electric field intensity peaks inside the coil and the magnetic field intensity always peaks at the centre /1/. The radiofrequency power is therefore supplied near the centre of the coil even if the diameter becomes larger and gas discharge occurs. In other words, a uniform plasma with a large diameter can be obtained by using a slotted-type L coil of large diameter if sufficient radiofrequency power is supplied.

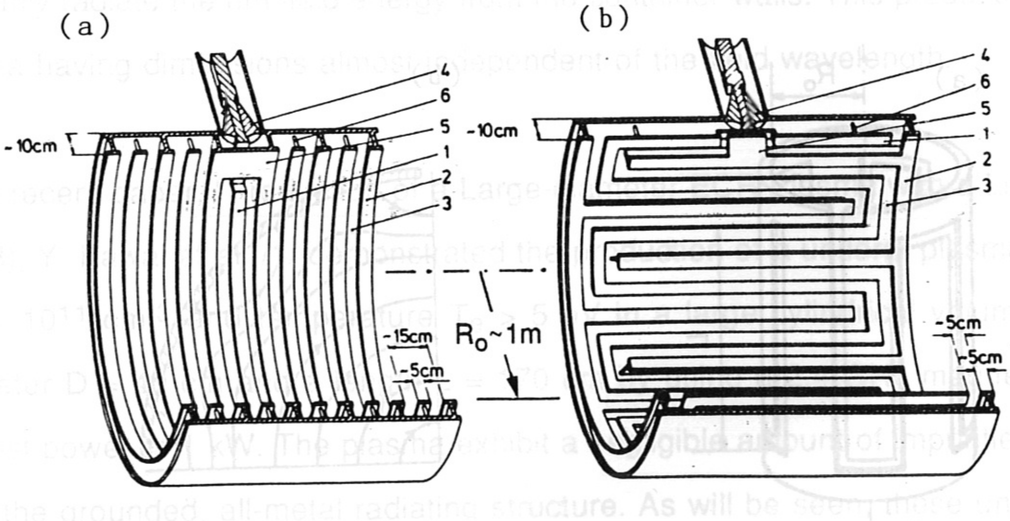

Fig. 2: Slotted-line radiators: (a) helical and (b) interdigital. 1) central conductor; 2) lateral conductor; 3) slot; 4) vacuum-tight feed-through; 5) shielding for the coaxial feed-through; 6) gas feed hollow rod.

Figure 2(a) and (b) shows two versions of slotted L structures. In (a) the slots are wound helicoidally in the poloidal direction; in (b) they are wound interdigitally as in Fig. 1(a). These structures can be made very large, with the diameter and length being of the order of one metre. The field wavelength can be chosen in the range $\lambda/60 < R_0 < 3\lambda$; for $R_0 \sim 1$ m, the frequency range would be 5 MHz < f < 900 MHz.

The slotted-line radiating structures of Fig. 2 were proposed for producing a uniform target plasma for ohmic and additional heating in fusion machines. Owing to the radiofrequency skin effect, the field originates from the edges of the slot line, from which it radiates towards the plasma; in particular, the radiofrequency electric field across the slots determines the polarization of the launching waves, such as magnetosonic waves, Alfvén waves and ion cyclotron frequency waves.

The radiating structures of Fig. 2 may be employed in plasma chemistry for the production of a non-magnetized or magnetized low-temperature plasma. The structures may be designed in keeping with the particular form of a given reactor. To assure the uniformity of the field distribution inside the reactor, the radiofrequency energy may be fed through several input connectors. It should be noted that the structures are inherently shielded and may be built very rugged and compact for safe operation.

3. Low-Temperature Plasma

As reported by Y. Kawai et al. /1/, a uniform, low-temperature plasma of large volume was produced by using a slotted-line structure of 40 cm i.d. and 9 cm length. Figure 3(a) shows a schematic of the experimental apparatus. As seen in Fig. 3(b), the discharge reaches saturation and decays within ~ 1.3 ms after the microwave power is, respectively, turned on and off. Figures 3(c) and (d) show the radial profiles of n_e and T_e at various gas pressures. Apparently, n_e and T_e are almost uniform inside the L coil at pressures below ~ 2 x 10^{-4} torr. In order to obtain a uniform plasma at higher pressures, the microwave feeder should be shielded as shown in Fig. 2 and the input power must be increased in order to assure the availability of an energy of at least 20 eV for the production of each electron-ion paar within the average flight time of the ions in the reactor.

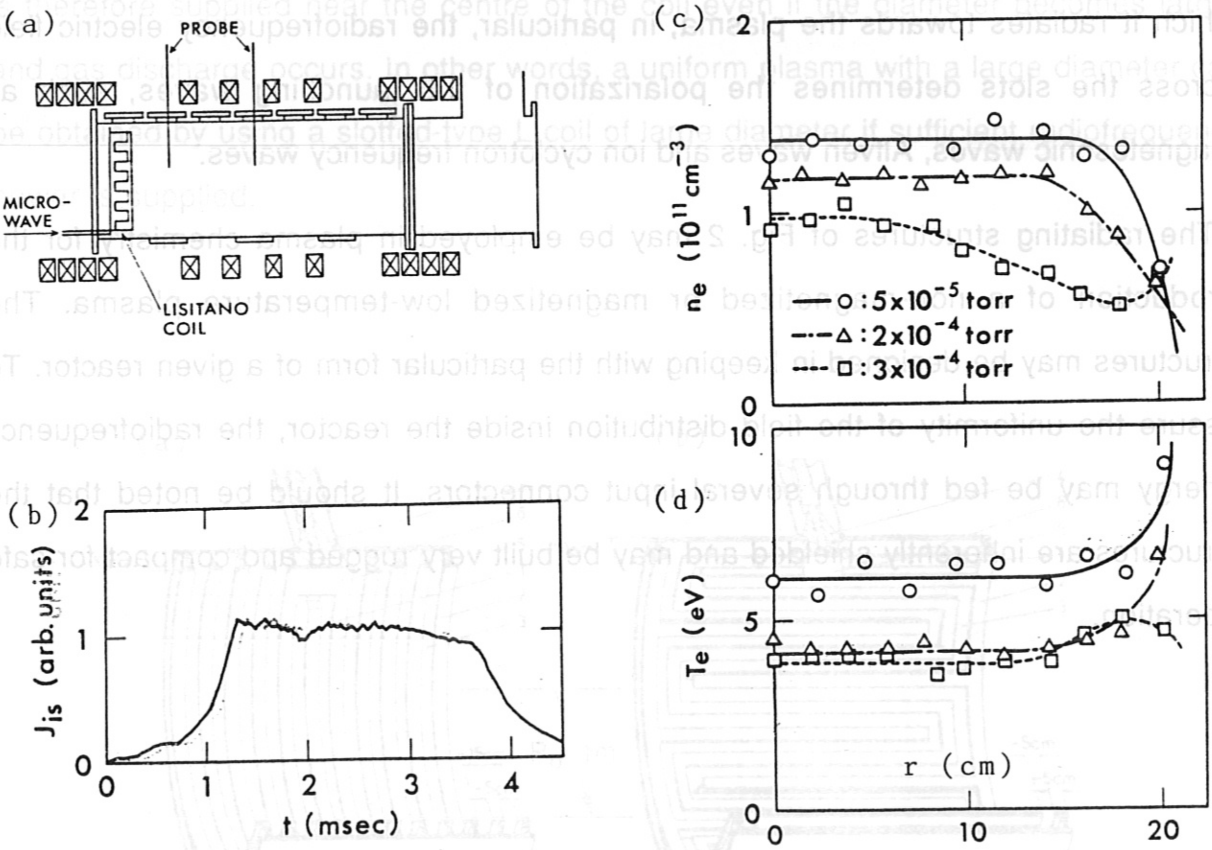

Fig. 3(a): Schematic of the experimental apparatus; (b) ion saturation current; (c) and (d) radial profiles of n_e and T_e (courtesy of Y. Kawai et al. /1/).

As predicted by calculations of Y. Kawai et al., a uniform plasma having a diameter of six times the wavelength, i.e. ~ 70 cm at 2.45 GHz, may be obtained with the L coils /1/.

As predicted by calculations of Y. Kawai et al., a uniform plasma having a diameter of six times the wavelength, i.e. ~ 70 cm at 2.45 GHz, may be obtained with the L coils /1/. These experimental and theoretical results of Kawai et al. /1/ demonstrate the feasibility of producing large volumes of uniform plasma by exciting grounded, all-metal L coils with the 2.45 GHz microwave power of low-cost magnetrons. As needed in plasma chemistry, the plasma produced may exhibit high degree of purity if the L coil metal is properly chosen /4/ and the microwave feeder is appropriately shielded.

In the above experiment of Y. Kawai et al. the plasma is magnetized and is produced at the cyclotron resonance frequency, $f_{ce} = eB/m_e$, of the electrons. As shown in Fig. 4(a) and (b), the plasma can, however, be produced at any value of the confining magnetic field B, and even an unmagnetized plasma may be generated if the applied microwave or radiofrequency power and / or the neutral gas pressure is sufficiently increased /5/.

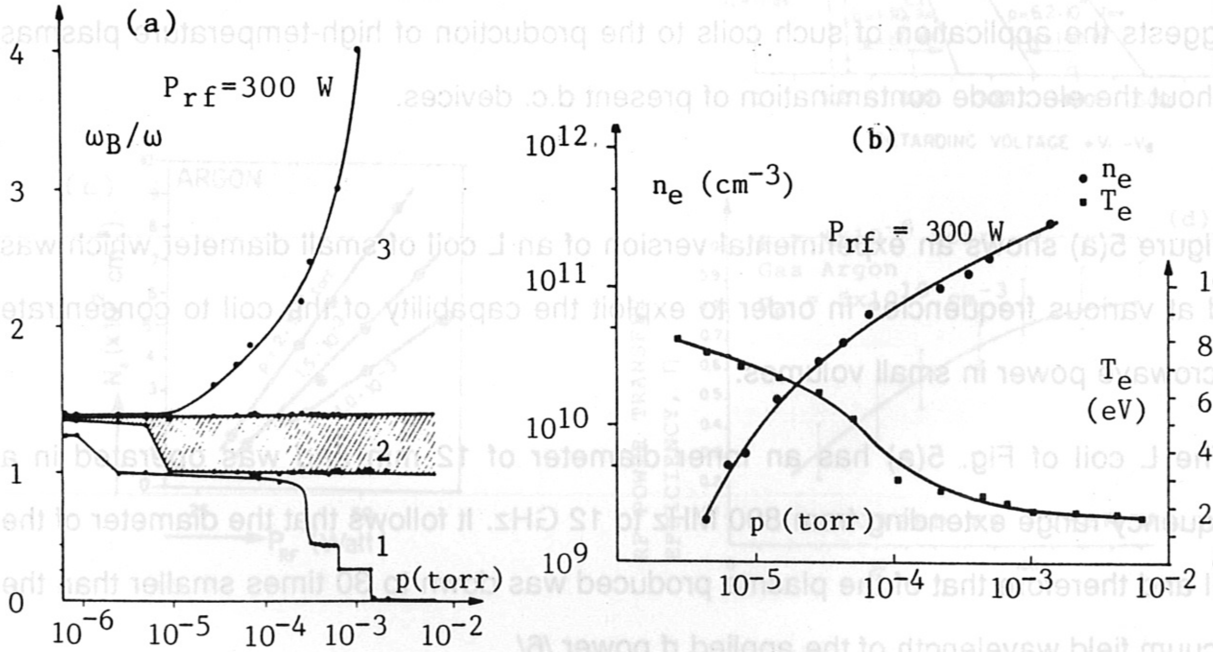

Fig. 4(a) Plasma regions vs neutral gas pressure and magnetic field; (b) electron temperature and density vs gas pressure.

In Fig. 4 the plasma has a diameter of 20 cm and a length of 200 cm /5/. For equal n_e and T_e as in the previous experiment of Y. Kawai (see Fig. 3) the applied microwave power scales as the volume of the plasma produced. The equality of the applied microwave power per unit plasma volume of the two experiments confirms the reproducibility and constancy of performance of plasmas generated by L coils.

4. Microwave Plasma JET

High-temperature thermal plasma has hitherto been produced by plasma arcs and torches owing to their property of concentrating high levels of d.c. electric power in small volumes between the electrodes. Unlike all other wave coupling devices, the exclusive property of the L coils to concentrate microwave power in small volumes suggests the application of such coils to the production of high-temperature plasmas without the electrode contamination of present d.c. devices.

Figure 5(a) shows an experimental version of an L coil of small diameter which was fed at various frequencies in order to exploit the capability of the coil to concentrate microwave power in small volumes.

The L coil of Fig. 5(a) has an inner diameter of 12 mm and was operated in a frequency range extending from 800 MHz to 12 GHz. It follows that the diameter of the coil and therefore that of the plasma produced was down to 30 times smaller than the vacuum field wavelength of the applied rf power /6/.

Owing to the careful design of the coaxial transition to the input gap of the slotted line, no impedance matching device is necessary. In the absence of plasma the reflected power is large because the slotted transmission line is short-circuited at the end of the line. In the presence of plasma, however, an excellent broadband impedance match is obtained.

Since the volume of the rf plasma coupling region inside the L coil is of the order of 6 cm^3, a high value of rf power concentration, ~ 15W/cm^3, can be reached for low rf input power levels of about 100 W. The measurements of Fig. 5 show the high value of plasma parameters corresponding to such levels of rf power concentration per unit volume.

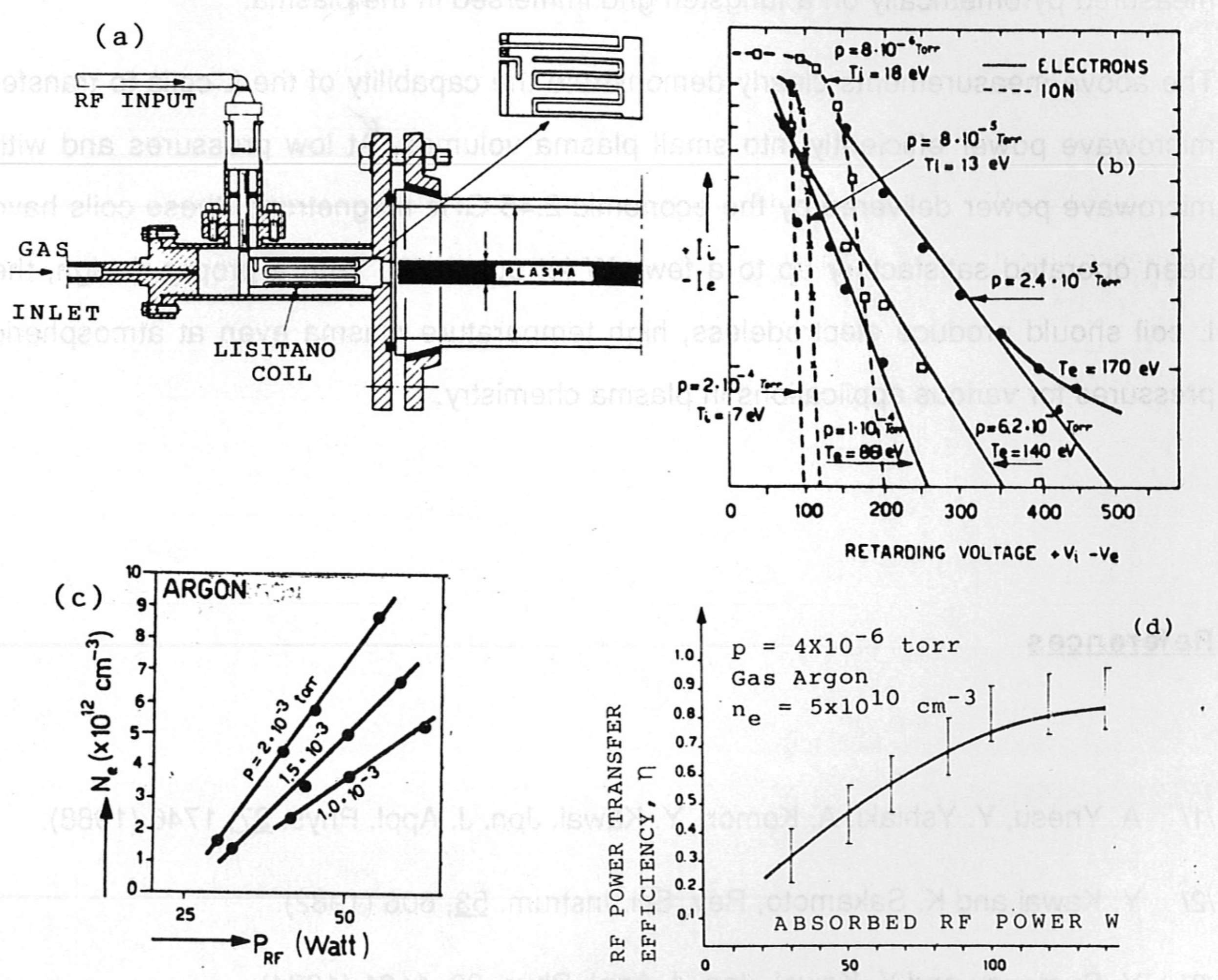

Fig. 5(a): Experimental set-up of small diameter plasma jet; (b) ion and electron energy distribution; (c) electron density vs rf power; (d) efficiency of the plasma jet.

For the low neutral argon gas pressure indicated in Fig. 5(b), the measured axial energy of the electrons, T_e ~ 100 eV, is one order of magnitude higher than that of the ions, T_i ~ 10 eV. In Fig. 5(b) the jet power density of the plasma was limited to 10 W/cm^2 to avoid damaging the grids of an electrostatic energy analyzer.

Figure 5(c) shows the relatively high density values, n_e ~ 10^{12} cm^{-3}, reached at relatively high neutral gas pressures with modest rf power input levels of about 100 W. Figure 5(d) shows the high efficiency, η ~ 90%, of the rf power transfer by the L coil, measured pyrometrically on a tungsten grid immersed in the plasma.

The above measurements clearly demonstrate the capability of the L coils to transfer microwave power efficiently into small plasma volumes. At low pressures and with microwave power delivered by the economic 2.45 GHz magnetrons, these coils have been operated satisfactory up to a few kW jet power /6/. With a proper design, the L coil should produce electrodeless, high temperature plasma even at atmospheric pressures for various applications in plasma chemistry.

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