Design, construction, and properties of the large plasma research device—The LAPD at UCLA

Department of Physics, University of California at Los Angeles, Los Angeles, California 90024

(Received 24 May 1991; accepted for publication 20 August 1991)

The large plasma research device (LAPD), a large, linear plasma research device designed to study space plasma processes, has been constructed at UCLA over the past four years. The LAPD has a $0.5 \times 0.5 \text{ m}^2$ oxide-coated cathode as a source which produces a 10-m-long plasma column with densities up to the mid $10^{12}/\text{cm}^3$ range. The linear machine is surrounded by a set of 68 magnet coils which can generate an axial magnetic field of up to 3000 G. The vacuum chamber has 128 radial ports to ensure excellent access for probes and antennas. An internal probe drive capable of moving a set of probes to any position within the plasma column is described in a companion paper. This machine is a scientific instrument in its own right and was designed to be versatile enough to study a large variety of phenomena. The techniques employed in the design and construction are sufficiently useful to be discussed here so that others can benefit from our experience.

I. INTRODUCTION

Funding for experimental physics programs is becoming very difficult to obtain. The inflation corrected budgets of most government agencies have shrunk; prices of materials and instrumentation continue to rise. Many excellent experimental groups have dissolved or shifted into applied physics programs. Those wishing to pursue an experimental program in fundamental research face the task of constructing a laboratory with a budget which is, most likely, one-third or one-half of what is required to purchase ready made components. This article details the design and construction of a versatile laboratory device, in which most of the fabrication was done in house. Care was taken to use the least expensive materials in innovative ways but also to produce a reliable system. Many of these techniques will be described in detail so they may be adapted by the readers. The basic components of the LAPD are a long cylindrical vacuum chamber, a solenoidal set of magnet coils, a plasma source, power supplies, and a probe drive for plasma analysis. This article covers: (a) the construction of the vacuum vessel and safety interlocks, (b) the design and fabrication of the magnets, (c) the construction and coating procedures for the oxide-coated cathode, and (d) the electronics and power supplies for the plasma source. The description of the device will be followed by a presentation of some data on the plasma characteristics. The three-dimensional internal probe drive of the LAPD is described in a companion article. The data acquisition system which is the second generation of one previously described by Gekelman and Xu will be the subject of a future paper.

II. MACHINE CONSTRUCTION DETAILS

The device consists of four stainless-steel vacuum chamber sections as shown in Fig. 1(a). A schematic drawing of the magnet and supporting cart arrangement is shown in Fig. 1(b). The first section is bell shaped with a depth of 80 cm. The heater, cathode, and anode are mounted inside this first section which in turn is mounted on a large aluminum platform. This platform section is mounted on wheels and can move freely along a set of tracks which allows easy access to the plasma source for maintenance without loss of alignment. All input power and cooling lines are attached to the end flanges of the bell. Two 1500-$\text{r}^2$/s turbo pumps are mounted on side flanges to be as close to the cathode as possible. Each turbo pump is backed by 502-$\text{r}^2$/s roughing pump. Because the rapidly spinning blades of the turbo pumps are in a strong magnetic field, Lorentz forces create torques which would soon destroy their bearings. To alleviate this problem magnetic shields were designed to reduce the field in the vicinity of the pump to acceptable levels.

The magnetic shield design was based on computations by Rikitake. A cylindrical shell geometry was chosen since the pumps are cylindrical, although a spherical shell provides the best shielding possible. In addition, the use of many thin concentric shells separated by air gaps yields improved shielding compared to one thick shell. Shielding is also better without endcaps. The optimal configuration for our system consists of two layers of 1/4-in. soft iron separated by a gap of 1/4 in. When the magnets produce an axial field of 3 kG, the maximum field strength at the location of an unsheilded pump is approximately 500 G; with just the two concentric iron cylinders the field strength drops to 80 G. The addition of one layer of 0.15-mm Nettic foil (a commercially available Ni-based alloy) placed on the inside surface of the inner cylinder reduces this field to an acceptable value of 10 G. The magnetic field distribution for the shielded configuration is shown in Fig. 2.

The vacuum control station encompasses an automatic gauge controller and safety circuitry, which closes appropriate valves in the event of an unexpected pressure increase. Other elements of the experiment that must be protected from vacuum failure or malfunction of the cooling system, such as the cathode heater elements and the heater
FIG. 1. (a) The vacuum vessel of the LAPD consisting of the four sections labeled 1–4. Also shown on the left is the movable platform supporting section 1, carrying turbo and roughing pumps, and vacuum control units. (b) Schematic drawing of the entire device. The magnets are placed on eight carts which can be moved along tracks for alignment purposes. Once in their proper position the carts are anchored to the rails.

FIG. 2. Magnetic field distribution for a shield configuration consisting of three concentric cylindrical shells; the two outer iron cylinders are separated by a gap of 1/4 in., the innermost layer is a 0.15-mm Netic foil, a commercially available nickel-based alloy.

power supply, are also interlocked through the control station.

The 10-m-long chamber is constructed from three independent sections which can be electrically isolated from each other. All sections are on tracks to facilitate their alignment with the magnets. The connection between the chamber supports (fabricated out of 4-in.-diam stainless-steel pipe) and wheels is insulated by 7/16-in. thick Glastix (machinable glass). The chambers are sealed by O-rings thick enough so that they are not flattened under vacuum to the point where the chamber flanges touch. The electrical insulation of the LAPD chamber sections is good to 500 V. The option for individual chambers to be biased at separate electrical potentials allows for operation of the LAPD as a triple plasma device with a high magnetic field. If a second plasma source is placed in Sec. IV, 10 m from the cathode, and that section is biased positively with respect to the rest of the machine, an ion beam will be driven into the main plasma. The chamber biasing is accomplished using a double grid as shown in Fig. 3 for a double plasma configuration. This scheme also permits the insertion of different sources in different sections, which is of interest because each source produces plasma with a unique set of properties (such as the ratio of the electron to ion temperature).

The machine design allows for abundant probe access. The cylindrical stainless-steel chambers had 128 4-in. holes cut into them. Stainless-steel thin wall tubing of 4-in. out-
side diameter serves to make port extensions. Identical radial access ports have the advantage that all flanges can easily be interchanged.

A portable pumpdown station, using a 50-7/s turbo pump and small (114 7/s) foreline pump, was constructed so that vacuum interlocks could be used on the radial ports to switch probes without disturbing the main vacuum. Gas is bled into the system using a piezoelectric valve and a commercially available valve controller which utilizes feedback from the vacuum gauge controller.

III. MAGNET DESIGN AND CONSTRUCTION

The design of magnets always involves several trade-offs since magnetic field strength is directly proportional to cost. First, one has to choose between conventional copper magnets and superconducting ones. Copper magnets cost much less to fabricate but require large currents to operate. The large currents must be driven by large power supplies and the generated heat must be dissipated by a cooling system. Superconducting magnets on the other hand require a continual, quite costly supply of liquid helium for cooling. Furthermore, the refrigeration system requires a large shroud and thermal insulation blankets which severely curtails radial access to the machine. On this basis, use of superconducting magnets on the LAPD was rejected.

The second decision concerns operating the magnets in steady state or pulsed mode. In the latter case cooling is unnecessary if the duty cycle is relatively low. The LAPD was designed for a 1–2 Hz repetition rate to permit reasonable signal averaging and the acquisition of large data sets. If the final magnet current of 3 kA is to be attained in 0.1 s, a back emf of \( V = L \frac{dI}{dt} \approx 88 \) V would be generated for each cluster of six magnets (which have an inductance of \( \approx 2.94 \) mH). This is not a big problem, but the continual stress on the epoxy holding the magnets together, as well as the electromagnetic disturbance caused by the pulsed magnets, would be. We have chosen a steady state magnetic field.

For steady state operation the magnets must have the lowest possible resistance to minimize heat generation. The best conducting material is oxygen-free copper. A channel for water cooling is an additional requirement. Rectangular cross-section stock was chosen for ease of winding. Since no manufacturer in the U.S. could produce the 30-m lengths required for each coil section, the material had to be imported from W. Germany. The copper stock used in the LAPD has a cross section of 18 mm × 35 mm, an elliptical water channel of 64-mm² cross-sectional area, and a resistance of \( 1.38 \times 10^{-5} \) Ω/m (at 20 °C). Each of the 68 magnet coils was wound with 14 turns—two seven-turn sections—with an inner diameter of 1.22 m and outer diameter of 1.53 m. Each coil contains 288 kg of Cu and has a resistance of 1.66 mΩ. A magnet is composed of two coils in series. With a 3-kA current the entire magnet system generates a heat load of approximately 1 MW. Computer calculations indicate that with a proper spacing of 15.3 cm between magnet pairs a highly uniform field (δB/δ < 0.5%) is obtained with a figure of merit of 1.29 G/A.

A coil winding machine was fabricated at UCLA. The details of its construction as well as the techniques of brazing and epoxying the magnets are available in Ref. 7.

The magnets are powered by seven (60 V, 3000 A) independent dc power supplies. It is, in general, not possible to reverse the output polarity of such high current power supplies by simply flipping a switch. Interchangeable end connector pieces were designed to solve this problem. This allows the magnetic field to be reversed in each magnet group, independently of the others, producing a uniform axial magnetic field, magnetic mirrors, or an axial variation in the field as the experimental situation warrants. The coils are placed on eight carts as shown in Fig. 1(b) which can be moved along tracks for alignment purposes. Once in their proper position the carts are anchored to the rails. The magnets are held together by simple clamps and proper magnet spacing is achieved with adjustable aluminum spacers. All power and water connections are made above the machine. To minimize contact resistance all exterior electrical joints were filled with silver paste before being bolted together.
IV. CATHODE AND HEATER CONSTRUCTION

In a magnetic field the first choice for the source of a dc discharge is an indirectly heated cathode. Cathodes 10 cm in diameter or smaller are commercially available. It is wise to purchase units of these dimensions instead of going through the trouble of fabricating them. Larger cathodes, such as the $0.5 \times 0.5$ m$^2$ unit constructed for this machine, or the 1-m-diam cathode previously constructed, must be manufactured in house. The following discussion details some important design considerations for the heater as well as construction and chemical preparation of the cathode.

A dc discharge plasma is created when electrons are emitted from a surface and accelerated into a gas by an electrostatic field, with an energy greater than (in practice, at least by a factor of 2) the ionization energy of that gas. Generally, noble gases (He, Ne, Ar, Kr, Xe) are used to avoid chemical reactions within the device. If the cathode is in a strong magnetic field the ionizing, or primary, electrons will have small gyroradii, and the ionization front will have the same spatial distribution as the primaries. Since the emission of primaries is greatly temperature dependent it is necessary to heat the cathode uniformly. If a pure metal was used as an electron emitter an enormous power input would be required. For example, tungsten has a melting point of 3370 °C (Ref. 9) and emits 3.5 A/cm$^2$ when heated to 2530 °C; whereas barium oxide deposited on a nickel substrate will emit several A/cm$^2$ when heated to only 900 °C. Since the radiation from a blackbody is proportional to $T^4$ it takes 80 times the power (and cooling) for W in comparison with BaO. Lanthanum hexaboride (LaB$_6$) coated cathodes have an even larger emissivity than BaO (Ref. 10) but this occurs at 1700 °C and heat management becomes a problem for larger cathodes.

The source we have constructed has three components. The first is a heater which serves to bring the second, a coated cathode, to uniform temperature. The cathode must be coated with the correct chemical mixture and held in place without warping from the heat. The third component is the anode which, in our case, is a stainless-steel mesh. The anode is held approximately 3 cm from the cathode. Biasing the cathode negatively with respect to the anode initiates the discharge.

A. Heater

In principal, the cathode can be heated in several different ways. For example, a current could be passed directly through it as in the wire of a toaster. However, due to the finite resistivity of the cathode material, a voltage drop would appear across it and the primary electron emission would have the undesirable feature of a position dependent energy distribution. Another method long used in Q machines involves bombardment of the cathode by a beam of high-energy (keV) electrons, but these devices are plagued by arcs and heating nonuniformities. The best method for producing a uniform discharge is to use an indirectly heated cathode. In this approach hollow ceramic tubes are threaded with filaments which are heated to a temperature slightly above the cathode emission temperature. The best material for the tubes is alumina ($\text{Al}_2\text{O}_3$) which has a melting temperature of 1950 °C (it will sag if unsupported at 1750 °C), and is resistant to chemical attack. The filament wire may be either tungsten (W, with $T_{\text{melt}} = 3370$ °C), or tantalum (Ta with $T_{\text{melt}} = 2851$ °C). Although we have used both, the former is preferable since tantalum at elevated temperatures may be poisoned in a hydrogen atmosphere. Tungsten becomes very brittle after being heated and any sharp bends in it may crack during heater operation. To avoid cracking at bends one should use a W wire containing 3% rhenium and heat it to a dull red color while bending. The resistivity of both metals is a function of temperature. At 800 °C the resistivity of W is $\rho_W = 27.94 \mu\Omega$ cm.

Figure 4 is a schematic diagram of the cathode and heater. Far more detail of this structure is provided in additional diagrams and text in Ref. 7. The heater consists of insulating alumina tubes threaded with W filaments connected between two water cooled Cu bus bars. The heater current is fed into the chamber along cooling lines, made of 1/4-in. copper refrigeration tubing, which are silver soldered to the bus bars. There it is distributed among 14 filaments connected in parallel. Each filament consists of two 0.76-mm W wires threaded through five alumina tubes. Since the filaments expand along their length, they are connected to the bus bars by flexible Ni strips. For stability each alumina tube is tied to alumina rods which are held by stainless-steel cross members. The full weight of the tubes and filaments is borne by stainless-steel fingers attached to the bottom cross member. Finally, the bus bars and cross members are mounted to the support frame using insulating ceramic standoffs. Behind the heater are two
nickel heat shields. Nickel is the best material to use for
shields since it has the highest reflection coefficient, \( \rho = 0.80 \) at 800 °C.

In our operating regime the heater input power varies
from 10.9 kW (880 °C) to 16.9 kW (980 °C). This is suf-
ficiently high to require cooling of the Cu bus bars, which
have a low melting point, as well as the chamber walls
which can become hot enough to be dangerous to person-
nel. The chamber is made of stainless steel and because of
its poor conductivity (\( \rho_{SS}/\rho_{Cu} > 11 \)) cooling lines welded
onto the chamber are not effective. An internal water-
cooled copper shroud was built to fit snugly inside the first
meter of the chamber where the radiation was found to be
most severe. An additional cooling structure, a water-
cooled copper sheet, is mounted behind the heater support
frame.

B. Cathode

The other major component of the source is the cath-
ode itself. It should be easily removable for cleaning and
recoating, and must remain flat and be as close to the
heater as possible. Nickel has an expansion coefficient of
1.75 \( \times 10^{-5} \) °C at 1000 °C; therefore, the LAPD cathode
will expand by 0.82 cm. If the cathode were fixed along its
perimeter it would bulge outward away from the heater by
4.3 cm. Therefore, we have chosen to hold the cathode in
a stainless steel frame with 40 Inconel springs. The springs
are connected to the frame with a screw and locking nut
combination to fine tune the tension and to center the cath-
ode; a stainless-steel link was designed to reduce heat flow
from the cathode to the springs. A heat shield was posi-
tioned to protect the springs from direct radiation (see Fig.
4). In the absence of the shield and extenders the Inconel
springs failed. More importantly, the shield, as designed,
greatly reduces radiative edge losses and therefore is
instrumental in keeping the cathode uniform in temperature
and flat. During the plasma discharge, currents of up to
4000 A are emitted by the cathode. Since the springs and
extender links are not sufficient to carry such currents, an
additional bus bar has been constructed (Fig. 4) from copper
strips and bolted to the cathode frame. Four copper
wires are used to join this bus bar to the nickel sheet at
the corners. Finally, the cathode frame is mounted to the
support frame with insulating ceramics attached to threaded
rod to accommodate the thermal expansion of the cathode
frame and to allow adjustment of the gap between the
 cathode and the heater.

C. Cathode coating

The preparation of the nickel is of utmost importance
in assuring that the coating will bind to it and be uniform.
After use, excess coating is sanded off with 320 and then
400 grade Al₂O₃ emery paper, then the surface is abraded
with steel wool until it has a very shiny appearance. Use of
water and acid cleaning solutions left surface residues
which interfered with proper binding of the coating.

The coating solution consists of a carbonate powder
and a binder. The binder is a mixture of a one percent
solution by volume of nitrocellulose in amyl acetate. It can
be purchased commercially. The triple carbonate mixture
by weight is BaCO₃ (57.2 ± 2%), SrCO₃ (38.8 ± 2%), and
CaCO₃ (4.0 ± 0.5%). The triple carbonate is best prepared
by coprecipitation to avoid inhomogeneities which can re-
sult in nonuniform emission. A coprecipitated mixture is
also commercially available. Before coating, the carbonate
powder (600 g) and binder (1.0 l) are mixed. This solu-
tion can be stored in a refrigerator for up to several
months. The solution described above is diluted by an
equal amount, by volume, of amyl acetate and placed in a
ball mill (with ceramic balls) for at least 8 h prior to
spraying.

Spraying should be done in a well ventilated area. The
chemicals are irritants, if not carcinogenic, so a mask must
be used. It is important to make the coating uniform; the
emission will be as uniform as the coating. The final coa-
ting should be between 50- and 70-µm thick. The spraying
is best done in many thin layers allowing the cathode to
dry between applications; when spraying is complete the
coating should appear bone white and fluffy. To prevent
absorption of water vapor the cathode is best placed in the
vacuum system as soon as possible. Once the pressure has
fallen below 3 \( \times 10^{-6} \) Torr, activation may begin. The
heater is slowly brought up to emission temperature while
H₂O, CO, and CO₂ gases are emitted from the cathode
coating. Figure 5 shows the partial pressures of these gases
as a function of heater power and temperature. The pres-
sure must not exceed 1 \( \times 10^{-5} \) Torr or these gases will be
reabsorbed and poison the coating. In addition, rapid evol-
ution of gases from the surface can locally pull the coating
from it which will prevent electron migration from the Ni
to the coating and thereby prevent emission. The duration
of the conversion process is proportional to the cathode area.
The 2500-cm² LAPD cathode takes 5–6 days for complete conversion at a pumping speed of approximately
3000 l/s. When the cathode has reached emission tempera-
ture (\( T_{\text{em}} > 900 ^\circ \text{C} \)) and the base pressure is below
2 \( \times 10^{-6} \) Torr the device is ready for use. The final tem-

![FIG. 5. Partial pressures of the gases (H₂O, CO, and CO₂) emitted from the cathode coating as a function of its temperature, that is, during the time of cathode activation.](image-url)
temperature of the cathode may be measured with a thermocouple or optical pyrometer; it should be an orange glowing color. Figure 6 gives the cathode emission for an Ar discharge as a function of heater temperature. (In our device the cathode temperature is approximately 60 °C lower than that of the heater.) In this range [Fig. 6(b)] the curve is best fit to $I_{\text{emit}} \propto T$, as shown. If emission exceeds 10 A/cm² the coating will rapidly degrade due to ion bombardment and local thermal runaway.

**D. The anode**

The anode is a piece of 36% transparent 40 lines/in. wire cloth spot-welded to a border made of stainless-steel strips. 24 Inconel springs attach the anode to a copper bus bar which is mounted to a frame made of stainless-steel angle. The discharge current is carried from the anode by 36 Ni strips to the copper bus bar. The anode structure is lightweight and not cooled. Current is fed to the anode with refrigeration tubing as in the case of the cathode and heater. The anode frame is mounted to the cathode frame with ceramic standoffs.

In the best of circumstances the emission from a properly prepared and outgassed oxide coated cathode is 10 A/cm². A cathode of the type described here is therefore capable of 25 kA emission current. It must be operated in a pulsed mode because the power at this emission can exceed 1 MW; furthermore, ion bombardment would soon destroy the negatively biased cathode. A pulsed experiment is no problem as long as the pulse length exceeds measurement times of interest and the repetition rate is high enough to do signal averaging and allow for reasonable data runs. The discharge requires a switch capable of handling the above power; a further requirement is that the turn off time be rapid ($t_{\text{off}} \approx 100 \mu s$) so that a clean afterglow plasma can be studied soon after the primary electrons are turned off.

**E. The discharge pulser supply**

The discharge pulser is designed to lower the potential of the cathode below that of the anode so that electrons may escape the BaO-coated surface and ionize the fill gas. The circuit requirements are that it deliver sufficient voltage (for an Ar discharge 100 V suffices) and current. The pulser must also turn off rapidly so that experiments can be conducted in an afterglow plasma free of primaries. A high duty cycle (> 1 Hz) is necessary to allow a data set to be acquired in a reasonable time span. The best choice of components is a bank of electrolytic capacitors charged to the appropriate voltage and a transistor switch which can rapidly apply or remove the bank from the plasma load. The arrangement is shown schematically in Fig. 7. In the LAPD the bank was designed to switch 100 V and 4 kA in pulses that last up to 10 ms. Presently no single transistor can do this; the switch consists of 8 power transistors working in parallel. Care must be taken such that the current is evenly shared between the transistors and that the circuit will rapidly shut down in the event of an overcurrent caused by an arc. The details of this circuitry are presented in Ref. 7.
F. The heater supply

The heater power supply design is straightforward. A 480 V motor-driven variac capable of 54 A per output leg (45 kW) is connected to an output step-down transformer and water-cooled diodes. The unfiltered output is fed to the heater by two pairs of 3/0 welding cable. To prevent the tungsten heater elements from accidental damage (the W filaments will evaporate when heated in atmosphere), the heater supply is interlocked with the vacuum controller such that it cannot be turned on if the pressure inside the LAPD is above 1 mTorr. Similarly, in case of a vacuum failure or an interruption of the cooling water flow the output of the variac is automatically reduced to 0 V.

V. PRELIMINARY DATA, LAPD PLASMA CHARACTERISTICS

The zero order plasma parameters are critical in a machine designed to study basic plasma physics. Important criteria are the degree of quiescence of the plasma and the degree of plasma uniformity that can be achieved both across and along the magnetic field. The diagnostic capabilities are also of paramount importance. The LAPD has been equipped with a three-dimensional internal probe drive which is the subject of a companion paper. Density can be mapped by a Langmuir probe mounted on a probe stalk which also holds magnetic pickup loops and has provision for an energy analyzer. The probe drive is moved using stepping motors which are controlled by the data acquisition software. One parameter of interest is the axial density variation. For many applications uniformity is desired, but an axial density gradient along the magnetic field is also of interest in certain wave propagation experiments. Since the plasma is produced by primary electrons with a mean free path which depends on the neutral gas pressure,$^{11}$ $\lambda_{\text{mfp}} = 1/\sigma(\nu)p$, where $\sigma(\nu)$ is the ionization cross section and $p$ is the neutral gas pressure. The axial density profile can be controlled by the gas fill; the ability to achieve axial density gradients in LAPD is illustrated by Fig. 8 which shows the plasma density in the center of the column as a function of axial position and Ar neutral pressure. The mean free path for collisions of 50 V primary electrons with neutrals at 1.1 mTorr is 0.79 m, and is five times that at the lower (2.2 \times 10^{-4} mm) pressure.

The discharge current, or plasma density, is also a function of the magnetic field as shown in Fig. 9. In this case the cathode was coated with two 10-cm-diam spots so that an experiment on the interaction of multiple current channels could be performed.$^{14}$ For this particular experimental setup, the discharge current rises with magnetic field and then at $B > 80$ G becomes independent of the field. This is the field for which the Ar$^+$ Larmor radius equals the current channel size.

The first volume data set was taken in an experiment which models the interaction of magnetic flux ropes. Two current channels with appreciable self fields ($B_{\text{self}} \approx 0.1B_{\text{tor}}$) are investigated in the LAPD. Data were taken at 5335 spatial locations (distributed on 21 transverse planes over 5 m of the device), and the magnetic field, B,

![Fig. 8. Plasma density as a function of distance from the cathode for three different neutral pressures. The density profile is constant at low pressures, reflecting the long mean free path for the ionizing electrons. By changing the fill pressure the axial density profile can be tailored.](image)

was measured at over 10,000 time steps. Over 48,000 Langmuir characteristic curves were analyzed for the data run. The current filaments are observed to merge while spiraling around each other. Figure 10 is a three-dimensional plot of the plasma current [$j = 1/\mu_0(\nabla \times B)$]. The system relaxes toward a force free state ($j \parallel B$) in space and time. Details of the process such as the force balance ($j \times B - \nabla P$), the magnetic helicity ($H = \oint A \cdot dB$) and space charge fields ($E = -\nabla \Phi$) are also obtainable from the data.

VI. VERSATILITY OF THE LAPD IN PLASMA EXPERIMENTS

The LAPD is a device which is highly suitable for studies of space related plasma phenomena. Its length and high magnetic field enable the study of plasma and physical

![Fig. 9. Discharge current as a function of the strength of the homogeneous magnetic field $B_0$ for two different end-anode biases. As the magnetic field is increased so does the emission, until the Larmor radius is < 10 cm which is less than half of the distance between the edge of the cathode and the chamber wall.](image)
to tailor the initial plasma state enables one to mimic conditions in the ionosphere or auroral region. While a laboratory plasma cannot exactly simulate the ionospheric environment, the basic plasma physical processes occurring in the interaction of waves with either a uniform plasma or one in which density irregularities have been created can be reproduced. Some of the important physical parameters involved in the interaction between waves and irregularities that must be reproduced in a laboratory study are listed in Table I. These include the ratio between the perpendicular and parallel density scale lengths of the irregularities, the ratio of these scale lengths to the wavelengths of the launched waves and any secondary modes produced in the interaction, and the ratio between the density scale lengths to the ion gyroradius and collisional length. Another important parameter is the ratio of the plasma frequency to the electron gyro-frequency because it affects the dispersion of whistler waves and the degree of magnetization of the plasma ions.

In the ionosphere, density irregularities occur with perpendicular scale lengths as short as ten meters and as large as several tens of kilometers. For hydrogen the ion gyroradius in the near Earth ionosphere is of order of ten meters, while for oxygen it is approximately a hundred meters. In the LAPD device the gyroradius at the highest field strengths is 0.1 cm for hydrogen and 0.6 cm for argon. In the laboratory, irregularities can be produced with perpendicular scale lengths ranging from millimeters to ten centimeters. Also since the magnetic field strength is variable, it is a simple matter to vary the ratio between the irregularity perpendicular scale size and the ion gyroradius. The ratio of irregularity scale size to the wavelengths of both fast Alfvén waves and whistler waves, observed in

![Diagram of plasma current and isocontours of constant current density](Image)

**FIG. 10.** Isosurface of constant current density $j = 0.32 \text{ A/cm}^2$ for two merging current channels. The data are displayed at time $t = 3.84 \text{ ms}$ after the current is initiated. The $j$ vectors displayed in the foreground and the current lines in three dimensions indicate that the currents spiral along the device axis as they merge.

---

**TABLE I.** The observed ranges of values of several quantities of interest in the study of space and ionospheric plasmas are compared to those achievable in the LAPD. While the values are widely disparate, it is the ratios between quantities that are important in determining the nature of the physical interactions. A significant portion of the range of ratios observed in space and ionospheric plasmas can be reproduced in the LAPD.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Range of values</th>
<th>LAPD</th>
<th>Symbol</th>
<th>Range of ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density scale lengths</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>perpendicular</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>parallel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L_i$</td>
<td>$10^{-1} \times 10^7 \text{ m}$</td>
<td>$3 \times 10^{-1} \text{ m}$</td>
<td>$0.3 \times 10^{-1} \text{ m}$</td>
<td>$L_i/L_i$</td>
</tr>
<tr>
<td>Wavelengths</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alfvén</td>
<td>$\lambda_A$</td>
<td>$10^{2}\text{--}10^4 \text{ m}$</td>
<td>$0.1\text{--}1.0 \text{ m}$</td>
<td>$\lambda_A/L_i$</td>
</tr>
<tr>
<td>whistler</td>
<td>$\lambda_w$</td>
<td>$1\text{--}10^3 \text{ m}$</td>
<td>$0.02\text{--}1.0 \text{ m}$</td>
<td>$\lambda_w/L_i$</td>
</tr>
<tr>
<td>Ion gyroradius (O⁺, He, Ar)</td>
<td>$R$</td>
<td>$5\text{--}50 \text{ m O}^+$</td>
<td>$10^{-1}\text{--}0.1 \text{ m He}$</td>
<td>$0.02\text{--}0.2 \text{ m Ar}$</td>
</tr>
<tr>
<td>Collision length</td>
<td>$L_c$</td>
<td>$10^{-1}\text{--}10^7 \text{ m}$</td>
<td>$1.0\text{--}10 \text{ m}$</td>
<td>$L_c/L_i$</td>
</tr>
<tr>
<td>Wave phase velocity</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alfvén</td>
<td>$V_A$</td>
<td>$10^5\text{--}10^8 \text{ m/s}$</td>
<td>$10^5\text{--}10^7 \text{ m/s}$</td>
<td>$V_A/V_{th}$</td>
</tr>
<tr>
<td>whistler</td>
<td>$V_w$</td>
<td>$10^5\text{--}10^7 \text{ m/s}$</td>
<td>$10^5\text{--}10^7 \text{ m/s}$</td>
<td>$V_w/V_{th}$</td>
</tr>
<tr>
<td>Thermal velocity</td>
<td>$V_{th}$</td>
<td>$2\times 10^7 \text{ m/s}$</td>
<td>$10^8 \text{ m/s}$</td>
<td>$V_{th}/V_{th}$</td>
</tr>
<tr>
<td>Frequencies</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>plasma</td>
<td>$f_p$</td>
<td>$0.05\text{--}5 \text{ MHz}$</td>
<td>$0.1\text{--}10 \text{ GHz}$</td>
<td>$f_p/f_{ce}$</td>
</tr>
<tr>
<td>elec. gyrofrequ.</td>
<td>$f_{ce}$</td>
<td>$0.5\text{--}1.5 \text{ MHz}$</td>
<td>$0.01\text{--}5 \text{ GHz}$</td>
<td></td>
</tr>
</tbody>
</table>

---

Downloaded 23 Apr 2008 to 128.97.43.195. Redistribution subject to AIP license or copyright; see http://rsi.aip.org/rsi/copyright.jsp
the ionosphere, depends upon the ratio of plasma frequency to the electron gyrofrequency, a parameter which varies with altitude in the ionosphere. In the LAPD a large variance in this parameter can be reproduced. In a low beta plasma (i.e., plasma pressure less than magnetic pressure) such as the ionosphere, the wavelength of the fast Alfvén wave is simply equal to the Alfvén speed divided by the wave frequency. The wavelength for the whistler wave is more complicated and depends upon the angle of propagation relative to the magnetic field.\textsuperscript{15} The whistler wavelength is a complicated function of frequency, angle of propagation, and ratio of plasma frequency to electron gyrofrequency. In the range of frequencies $0.01 < f/f_{ce} < 0.1$ and $0.1 < f_{pe}/f_{ce} < 10.0$ the largest wavelengths are about 4 m in the LAPD and the majority of waves have $\lambda < 0.5$ m. These wavelengths easily fit in the device.

Finally, the collisional environment of the ionosphere depends strongly upon the altitude. In the lower ionosphere collisions with neutrals are important to the plasma dynamics. At altitudes over a few hundred kilometers the dominant collision process is electron Coulomb collisions. In the discharge plasma of the LAPD both regimes can be explored. The collisional regime involving neutrals can be reproduced at higher gas fill pressures, while the collisionless regime is accessible at lower pressures where the collision mean free path is on the order of the device length.

ACKNOWLEDGMENTS

The authors greatly appreciate the great deal of advice given by Dr. B. Vancil of FDE Enterprises, Beaverton, OR concerning cathode mixtures and preparation. The work was supported by the Office of Naval Research under Contract No. N00014-91-J-1172.

\textsuperscript{3}T. Rikitake, Magnetic and Electromagnetic Shielding (Reidel, Dordrecht, Hingham, MA, 1987).
\textsuperscript{5}Kabelmetall, U.S. Representative, 309 Farmington Ave., Farmington CT, 06032.
\textsuperscript{6}S. Sackett, EFFI code available through Lawrence Livermore National Laboratory MFE (1981).
\textsuperscript{7}See AIP document number PAPS RSINA-62-2875-22 for 22 pages of detailed figures and material which supplement this article. Order by PAPS number and journal reference from the American Institute of Physics, Physics Auxiliary Publication Service, 335 East 45 Street, New York, New York 10017. The price is $1.50 for each microfiche or $5.00 for photocopies. Airmail additional. Make checks payable to the American Institute of Physics.
\textsuperscript{11}R. W. Motley, Q Machines (Academic, New York, 1975).
\textsuperscript{12}W. Kohl, Materials and Techniques for Electron Tubes, Chap. 15 in Cathode Materials and Structures (Reinhold, Stamford, CT, 1960), and references therein.
\textsuperscript{14}H. Pfister and W. Gekelman (unpublished).
\textsuperscript{15}D. B. Melrose, Instabilities in Space and Laboratory Plasmas (Cambridge University, London, 1986).