PRODUCTION OF QUIESCENT ALKALI PLASMAS USING POROUS IONIZERS

C. Forbes Dewey, Jr.

University of Colorado and Joint Institute for Laboratory Astrophysics, Boulder, Colorado, USA

Abstract

The "Q-Machine" originally developed by RYNN and D'ANGELO has proved to be a powerful tool for studying fully-ionized plasmas. In practice, the two previous schemes for ion production (collimated atomic beams and high alkali vapor pressure) have exhibited several unsatisfactory features. This paper describes the use of porous Tungsten-Tantalum emitters for producing fully-ionized plasmas of improved symmetry, reproducibility, and uniformity. A theoretical plasma sheath model is derived to predict the operating characteristics of porous emitters, and the theory is applied to the Q-machine configuration. A compact prototype ionizer has been constructed and is described in detail.

1 This research was supported by the Advanced Research Projects Agency under Contract DA - 31 - 124 - ARO(D) - 139.

2 Present address: Institut für Plasmaphysik GmbH, Garching b. München, Germany


601
I. INTRODUCTION

The most common arrangement presently used to produce ions in Q-machines consists of a refractory metal end plate illuminated with a collimated neutral beam of alkali metal (or barium). The plate is heated to electron emission temperatures, and its work function $e\Phi_w$ usually exceeds the ionization potential $e\Phi_i$ of the incident atoms.

The neutral beam arrangement has been refined considerably since its original use by RYNN and DIANGELO /1/ but the uniformity of neutral flux across the emitter surface is still somewhat unsatisfactory, particularly if an attempt is made to confine the beam to the plate surface. Perhaps even more disturbing is the fact that direct measurement of the impinging neutral flux distribution is quite difficult and rarely attempted. Although it is possible to fill the experimental chamber with alkali neutrals and thereby guarantee uniform illumination (the "vapor pressure mode" of KNECHTLII and WADA /2/), this scheme has a number of operational disadvantages and is infrequently applied.

This paper demonstrates the feasibility of porous ionizers for quiescent plasma production and describes a prototype ionizer developed for use in a Q-machine. A unified plasma sheath theory, applicable both to Q-machines and ion beam devices, is used to predict the operating conditions which may be achieved with porous ionizers.

II. PLASMA FLOW THROUGH A POROUS MEDIUM

An analysis was begun in 1964 to determine the feasibility of using porous emitters as improved ion and electron sources for quiescent alkali plasmas. Such emitters were envisioned as generic adaptations of the porous emitters used in ion engines (/3/, /4/). According to the prevailing theories (/5/ to /8/), the pore diameter was required to decrease monotonically as the temperature and ion current density increased in order to assure that the emerging gas
was highly ionized. The combination of small pore diameters and high temperatures, when extrapolated to Q-machine operating conditions, suggested that the porous matrix would rapidly become impermeable because of sintering.

Accordingly, the initial effort of this program was directed to developing binary tungsten-tantalum alloys which exhibit extreme resistance to sintering. The permeability lifetime of porous ionizers was increased by more than a factor of 20 by taking advantage of the Kirkendall effect in the W-Ta system /9/.

Of equal importance was the recognition that previous theories describing the gas flow through the pores (which were based on a space-charge-limited model of ion production) were incorrect at electron-emission temperatures. For the conditions of interest (T = 1600 - 2500°K, I > 10^{-4} amp/cm^2, pore diameters ≤ 10^{-3} cm) a plasma exists within the pores with a Debye length small compared to the pore diameter. This situation is properly described by a steady-state balance of ion, electron, and neutral fluxes across the thin electrostatic sheaths adjacent to the pore surfaces.

In constructing a general theoretical model, we shall first consider the "Hohlraum Problem" of a plasma in equilibrium with confining walls at a temperature T. Several analyses of this problem have appeared, notably those of FOWLER /10/ who wrote down the answer directly from statistical considerations, AUER /11/ who considered the plasma diode, and von GOELER /12/ who applied the result to Q-machines. von GOELER'S approach will be adopted because it will be useful in describing nonequilibrium situations later.

The two basic assumptions are: (a) recombination collision lengths are large compared to the pore diameter d; and (b) the sheath thickness is small compared to d. In equilibrium, the ion, electron and neutral fluxes reaching the wall from the plasma are

\[ \mathbf{J}_i = \left( n \vec{V}_i / 4 \right) \cdot \begin{cases} \exp (e V_0 / kT) & \text{if } V_0 > 0 \\ 1 & \text{if } V_0 < 0 \end{cases} \]

\[ \mathbf{J}_e = \left( n \vec{V}_e / 4 \right) \cdot \begin{cases} \exp (-e V_0 / kT) & \text{if } V_0 > 0 \\ 1 & \text{if } V_0 < 0 \end{cases} \]

\[ \mathbf{J}_0 = \left( n_0 \vec{V}_i / 4 \right) \]

(1) (2) (3)
where \( n \) is the plasma density, \( n_0 \) the neutral density, \( \bar{v} \) the mean velocity \( (8kT/nm)^{1/2} (\bar{v}_1 = \bar{v}_0) \), and \( V_0 \) is the potential of the plasma with respect to the wall. The corresponding outwardly-directed fluxes originating at the wall and reaching the plasma are

\[
\mathbf{J}_i = (\mathbf{j}_0 + \mathbf{j}_i) \cdot \begin{cases} \mathbf{P}^* & , V_0 > 0 \\ \mathbf{P} & , V_0 < 0 \end{cases} \\
\mathbf{J}_e = (n \bar{v}_e/4) R \cdot \begin{cases} \exp(eV_0/kT) & , V_0 > 0 \\ 1 & , V_0 < 0 \end{cases} \\
\mathbf{J}_o = (\mathbf{j}_o + \mathbf{j}_e) \cdot \begin{cases} (1-P^*) & , V_0 > 0 \\ (1-P) & , V_0 < 0 \end{cases}
\]

The terms \( R, P, \) and \( P^* \) appearing in these equations are defined as follows. \( R \) is simply the Richardson-Dushman electron emission

\[
R = \left( \frac{4AT^2}{en\bar{v}_e} \right) \exp(-e\Phi_w/kT)
\]

where \( \Phi_w \) is the work function of the surface and the coefficient \( A \) has the theoretical value \( (4\pi m_e k^2/n^3) = 120.4 \text{amps/cm}^2\cdot{0.9} k^2 \). \( P \) is the probability that an ion or neutral striking the surface is ionized, and is calculated from the Langmuir-Taylor relation /13/.

\[
P = (1 + \psi_0/\psi_1)^{-1}
\]

\[
(\psi_0/\psi_1) = \text{(neutral evaporation rate)/(ion evaporation rate)} = (g_o/g_1) \exp[-e(\Phi_w - \Phi_d)/kT]
\]

where \( e\Phi_1 \) is the ionization potential of the atom and \( (g_o, g_1) \) are the statistical weights of neutrals and ions (\( g_o = 2 \) and \( g_1 = 1 \) for the alkali metals). \( P^* \) is the "effective probability of
ionization" and is calculated from Eqs. (8) and (9) by replacing the work function $e\bar{\omega}$ by an "effective" value $e(\bar{\omega} - V_o)$. In obtaining Eqs. (4) and (5), use has been made of the fact that a plasma potential $V_o > 0$ will force a fraction $[1 - \exp \left(- (eV_o/kT)\right)]$ of the ions back to the surface each time they try to penetrate the sheath.

Eqs. (1) - (6) represent a determinate set of equations to predict the particle fluxes and the sheath voltage $V_o$ for any specified temperature and density. Of particular interest is the neutral/ion ratio, correct for all $V_o$,

$$\frac{n_o}{n_i} = \frac{(\nu_o/\nu_i)}{\exp \left(\frac{eV_o}{kT}\right)} = \left(\frac{1 - P^*}{P^*}\right) \exp \left(\frac{eV_o}{kT}\right) = \left(\frac{1 - P^*}{P^*}\right)$$

$V_o$ becomes negative for sufficiently high temperatures because of the large electron emission at the surface. The ionization fraction in the plasma then exceeds the ionization fraction $(1 - P)/P$ existing at the wall. For the opposite extreme of low electron emission $(V_o > 0)$, the plasma density at a fixed gas pressure becomes small and in the limit $V_o >> 1$ the assumption $\lambda_D << d$ becomes invalid. The space-charge-limited equations should be applicable in this low-temperature limit.

In two recent papers, FORRESTER /14/ and BATES and FORRESTER /15/ have attempted to remove the discrepancies between earlier space-charge theories and experimental observations by arbitrarily ignoring the reduction of ion emission with $V_o > 0$. This is patently incorrect because the fraction of ions with a Maxwellian distribution of velocities which surmount a potential barrier $V_o > 0$ is $\exp(-(eV_o/kT))$, and $V_o = 0(kT)$ if $T$ is close to the "transition temperature" for negligible surface coverage by an alkali metal.

Before considering the problem of a free boundary, the following features of the "Hohlraum Problem" should be noted. First, the velocity distribution functions are Maxwellian everywhere, and all temperatures are equal. Second, there is no dependence on geometry provided $\lambda_D << d$. Third, the equilibrium model requires detailed balancing of the fluxes of each species separately: $\overline{J_e} = \overline{J_e}$, $\overline{J_1} = \overline{J_1}$.
and $\mathbf{j}_0 = \mathbf{j}_0$. Finally, the equilibrium result is not modified by the presence of a magnetic field (SPITZER /16/).

III. PLASMA EMISSION AT A FREE BOUNDARY

While the collisionless "Hohlraum Problem" provides a rigorous model of the equilibrium plasma state within the porous material, it is much more difficult to obtain an exact analysis for the non-equilibrium interface between the porous material and the external plasma or vacuum environment.

The difficulties may be envisioned by considering the configurations given in Fig. 1. Suppose we neglect surface diffusion and consider first the flux of neutrals through the pore. The pore is idealized as a circular tube of length-to-radius ($L/a$) connecting an interior Hohlraum with the surface. It is justifiable to neglect interparticle collisions. Some fraction of the neutrals entering the tube from the Hohlraum will be transmitted to the exterior without collision; the remainder strike the tube wall, are absorbed, and suffer one of the following fates:

1. Emission as a neutral, and:
   (a) free-flight to the exterior
   (b) free-flight to the Hohlraum
   (c) reabsorption on the tube wall

2. Emission as an ion and history (a), (b), or (c) above.

Similar genealogies may be constructed for the ions and electrons.

A formal solution to this difficult problem has been obtained /17/ by neglecting the influence of electric fields within the plasma (i.e. outside the surface sheaths) on ion and electron trajectories and assuming isotropic emission of each particle from the outer edge of the sheath. Although this calculation is too lengthy to reproduce here, one important general conclusion should be noted: in the case of ion extraction with $V_0 > 0$, the

3 The contribution of surface diffusion and the influence of alkali surface coverage on the work function will generally be small in the plasma mode with surface electron emission. It is possible to include these effects at the expense of additional complexity.
fractional ionization of the emerging gas is significantly
greater than the ionization for a pore of negligible length.

For \((L/a) \to 0\), the particle currents extracted from the plasma
are simply equal to the random thermal fluxes \((nV/4)\). The random
ion current \(I_1 \equiv (enV_1/4)\) is given in Fig. 2 as a function of
the Hohlraum temperature and the ion-neutral ratio \((n_o/n_1)\). This
relation may be derived in the following manner. In equilibrium,
\(T_e = T_o\) and Eqs. (2) and (5) may be combined to give a relation for
\(n(T,V_o)\). Eq. (9) is used to eliminate \(V_o\) and the theoretical value
for \(A\) is inserted. The result is simply the Saha equation

\[
\frac{n^2}{n_o^2} = 2\left(\frac{\sigma_i}{\sigma_o}\right)\left(\frac{2 \pi m_e k T}{\hbar^2}\right)^{3/2} \exp - \left(\frac{e \Phi}{k T}\right)
\]

(10)

Rearrangement of the Saha equation yields the ion current density

\[
I_i \equiv \left(\frac{enV_i}{4}\right) = \left(\frac{\sigma_i}{\sigma_o}\right)\left(\frac{m_e}{m_i}\right)^2 \left(\frac{n_o}{n}\right) A T^2 \exp - \left(\frac{e \Phi}{k T}\right)
\]

(11)

The form of the equation for \(I\) is very instructive. For a given
neutral fraction in the effusing stream, the ion current density
in the Hohlraum approximation is independent of the surface work
function. [The ratio \((n_o/n_1)\) is, of course, strongly dependent
upon the surface work function and temperature: see Eq. (9).]

This result is quite discouraging with regard to ion engine
applications because the available ion current is very small for
all values of \((n_o/n_1)\) less than one. It must be emphasized, how-
ever, that these equilibrium calculations for \((L/a) \to 0\) are
quite pessimistic compared to the nonequilibrium calculations
with \((L/a) > 0\) /17/. Although no numerical results are yet
available, the informative experiments of HUBER /18/ and LE BIHAN
and MAUGIS /19/ suggest that the ion current at a given value of
\( \frac{n_0}{n_1} \) may be a factor of 10 or more larger than the current predicted by the Hohlraum approximation\(^4\).

Application of the Hohlraum approximation to the Q-machine configuration can be effected by recognizing that the total particle flux of each species from the porous emitter is the sum of two terms. The first term is the random flux \( F(n^1 \vec{V}/4) \) from the pores, where \( F \) is the pore fraction of the surface area and \( n^1 \) is the plasma density in the pores. The second term is the contribution from that fraction \((1 - F)\) of the surface which is solid and for which relations similar to Eqs. (6)-(13) may be written.

By analogy with the Hohlraum sheath analysis, the incoming fluxes \((n^1 \vec{V}/4)\) of ions and electrons are divided into two parts. Those particles striking the pores are assumed to be completely absorbed by the plasma within the pores, while the particles striking the solid surface contribute to the local surface sheath.

The analysis is completed by making the following assumptions:

\begin{enumerate}
  \item The problem is completely one-dimensional; radial gradients and radial diffusion are neglected.
  \item The surface sheath voltage \( V_0 \) and the sheath voltage \( V'_0 \) within the pore are distinct, and no instability or anomalous production mechanisms exist. Also, \( V_0 \neq V'_0 \) is assumed not to effect the fluxes between the pore and the plasma.
  \item All neutrals leaving the emitter are assumed lost to the problem (i.e. the plasma diameter is small compared to its length and the emerging neutrals are not collimated).
  \item Recombination collisions reduce the returning charged-particle fluxes by \((\sigma n^2 L/2)\), where \( \sigma \) is the "effective" coefficient for radiative recombination.
  \item The absence of equilibrium conditions (i.e. the absence of an exactly Maxwellian velocity distribution function for the particles accelerated from the wall to the plasma) does not significantly effect the sheath calculations given by Eqs. (1)-(6).
\end{enumerate}

\(^4\) In the experiment reported in References 18/ and 19/, \((L/a) = 0.75, V_0 >> 0, \) and \( \lambda_D < a. \) The collected electron current was approximately equal to \((en \cdot \vec{V}_e/4)\) and the collected ion current 10 times \((en \vec{V}_i/4)\). The increase in ion current was attributed to "extraction" of ions from the ion-rich sheaths.
For negligible recombination, the above assumptions are well-satisfied because the loss of ions is mainly caused by end-wall recombination and is small because the ionization probability \( n^* (V_o > 0) \) or \( P (V_o < 0) \) is close to unity. The density ratio \( (n'/n) \) increases with increasing recombination, and the sheath voltages \( V_o \) and \( V_o' \) may differ considerably. How drastic this effect will be in violating assumption b) has not been determined.

The resulting equations relating the plasma conditions in the pores and the plasma are:

\[
\begin{align*}
\text{If } V_o > 0, \quad R &= \exp\left(-\frac{eV_o}{kT}\right) - \left(\frac{F}{1-F}\right) \left(\frac{(n'/n) - 1}{1} + \left(\frac{1}{F}\right) \left(\frac{2\sigma nL}{V_e}\right)\right) \\
(n'/n) &= 1 + \left(\frac{1}{F}\right) (1 - P^*) + \frac{1}{F} \left(\frac{2\sigma nL}{V_e}\right) \\
\text{If } V_o < 0, \quad R \exp\left(eV_o/kT\right) &= 1 - \left(\frac{F}{1-F}\right) \left(\frac{(n'/n) - 1}{1} + \left(\frac{1}{F}\right) \left(\frac{2\sigma nL}{V_e}\right)\right) \\
(n'/n) &= 1 + \left(\frac{1}{F}\right) \left[\exp\left(eV_o/kT\right) - P\right] + \frac{1}{F} \left(\frac{2\sigma nL}{V_e}\right)
\end{align*}
\]

The two equations for \( (n'/n) \) are obtained by equating the total ion flux \( \mathcal{J}_i \) from the wall to the sum of the total ion flux \( \mathcal{J}_i^* \) from the plasma plus the recombination flux \( \sigma n^2 L/2 \). The two equations for the normalized Richardson current \( R \) are obtained by an equivalent electron balance. In Eqs. (12) and (14), the first term on the right-hand side represents the net flux from the plasma which reaches the surface, the second term, \( [F/(1-F)] \cdot [(n'/n) - 1] \), is the excess electron flux from the pores (referred to the fraction of solid surface), and \( (1-F) \cdot (2\sigma nL/V_e) \) is the normalized electron recombination flux.

Fig. 3 presents the results of typical calculations for a tungsten-tantalum porous ionizer and cesium. With no recombination, the temperature-density relation for a porous emitter is identical
with the result for a solid emitter with the same work function. In the case of the solid emitter, wall recombination is balanced by the ionization of neutrals supplied by an atomic beam; for a porous emitter, the balance is maintained by an excess ion flux from the pores. Neglecting recombination, the density ratio \((n'/n)\) can be written

\[
\left( \frac{n'}{n} \right) - I = \left( \frac{I - F}{F} \right) \left\{ \begin{array}{ll}
(I - \rho^*) & , V_o > 0 \\
\exp \left( \frac{eV_o}{kT} \right) - P & , V_o < 0
\end{array} \right.
\]

For \(V_o > 0\), \((n'/n) > 1\) but for \(V_o < 0\) the ratio may be greater or less than 1. Reducing the pore fraction \(F\) magnifies the difference between \(n'\) and \(n\).

The presence of recombination limits the maximum density achievable in the plasma. As \((2\sigma n L/\nu_1)\) increases, the pores supply an increasingly large fraction of the ions. This reduces the surface temperature required to maintain a fixed value of \((eV_o/kT)\). The dramatic behavior of the temperature-density curves as the maximum density is approached suggests an interesting method of determining the recombination cross-section \(\sigma\).

IV. DEVELOPMENT OF A PROTOTYPE IONIZER

An ionizer assembly has been constructed for use in a Q-machine. A schematic diagram is given in Fig. 4. The porous tungsten-tantalum emitter is heated by radiation from the solid tungsten anode directly behind it. The anode is, in turn, heated by electron bombardment from a spiral cathode.

Two desirable features of this emitter assembly should be noted. First, the entire assembly (excluding the cesium oven) is very compact, with a maximum envelope of 8 cm dia. by 7.6 cm long. This allows the entire emitter system to be assembled, aligned, and installed as a unit in a relatively modest 10 cm dia. vacuum vessel. In the University of Colorado "Q + P"-machine (this is our terminology for a Q-machine with porous emitters), the inside diameter of the confining magnetic coil is 13 cm with a
2.5 cm dia. plasma column. The resulting magnetic field power requirement is considerably less (roughly a factor of 3) than the power required for similar plasmas at other laboratories.

The second feature of importance is the uniform ion emission which is obtained with this configuration. The oven temperature establishes the cesium pressure in the space between the anode and the porous emitter, and this allows a uniform and controlled flow of cesium through the porous matrix to the emitter surface. An early model exhibited large emission peaks at the outer edge of the button because some gas bypassed the porous matrix and flowed through the small space between the emitter and the supporting tantalum shell. This was eliminated by vapor-depositing a thin layer of tungsten over the external surface of the assembly, and then machining 0.05 mm from the porous button to remove the coating on the emitting surface.

In the development of this ionizer assembly, by far the most difficult problems were fabrication and welding. The tantalum shells were die-punched at room temperature from flat sheet, and considerable trial and error was required to achieve acceptable shapes. The most difficult operation was obtaining vacuum-tight welds between the thin tantalum shells and their thick mating parts. After considerable experimentation with brazing, inert-gas welding, and electron-beam welding, the only satisfactory method of joining the porous button to the tantalum shell was found to be laser welding. All other joints were formed with either electron-beam or laser welding, the latter being more satisfactory but more expensive.

The prototype emitter has been successfully operated at high temperatures without cesium, and a systematic investigation of the operating characteristics predicted by Fig. 3 is in progress.

V. CONCLUSIONS

Porous emitters appear to be an improved method of producing quiescent plasmas. Uniform delivery of cesium to the surface of
the emitter is guaranteed by the uniformity of the pore structure. The compactness of the entire assembly allows significant reductions in the capital investment for confining magnetic fields and vacuum vessels. Difficult alignment problems associated with atomic beams are eliminated because the entire oven-emitter system is an integral unit. The need for an additional external port for the atomic beam oven is also eliminated.

The theory of porous emitters predicts operating characteristics substantially in agreement with the operating characteristics of solid emitters. The only significant differences occur at high density where the normalized recombination flux \( (2\sigma nL/\bar{\nu}_1) \) is of order unity. It may be possible to use this high-density behavior to determine the recombination coefficient \( \sigma \).

A prototype emitter assembly has been developed for use in a Q-machine, and experiments are in progress to verify the theory presented in this paper.

ACKNOWLEDGEMENTS

I wish to thank Dr. G. von Gierke of the Institut für Plasma-physik for his generous hospitality during the preparation of this paper. Discussions of the theory with Dr. J.F. Waymouth of the Sylvannia Research Laboratory and Dr. Walter Kroll of the Universität Bonn are also gratefully acknowledged. The difficult fabrication of the porous emitter assembly was accomplished by S.D. Graham of the University of Colorado.
REFERENCES

/7/ D. Zuccaro, R.C. Speiser, and J.M. Teem, pp 107-139 of Ref.3
/8/ G.M. Nazarian and H. Shelton, pp 91-106 of Ref.3
/12/ S. von Goeler, Phys. Fluids, 7, 463 (1964)
/16/ L. Spitzer, "Physics of Fully-Ionized Gases" (2nd Ed.), Interscience, N.Y. (1962)
/17/ C.F. Dewey, Jr., "Transpiration of a Thermal Plasma Through a Tube", to be published

/19/ R. Le Bihan and D. Maugis, Annales de Radio-Électricité, 20, 126 (1965)
Fig. 1 Free-boundary models for plasma analysis.

Fig. 2 Equilibrium ion flux from a hohlraum.
FIG. 3 PLASMA CONDITIONS IN A Q-MACHINE USING POROUS EMITTERS

CONDITONS
\[ e\phi_w = 4.36 \text{ eV} \]
\[ e\phi_i = 3.89 \text{ eV} \]
\[ A = 1204 \text{ amps/cm}^2 - \sigma \text{ eV} \]
\[ F = 0.25 \]

FIG. 4 POROUS IONIZER ASSEMBLY FOR USE IN A Q-MACHINE

1. BASE ASSEMBLY
   347 SS
2. INSULATOR
   \( \text{Al}_2\text{O}_3 \)
3. HEAT SHIELDS
   TANTALUM
4. CATHODE AND ROODS
   TUNGSTEN
5. ANODE
   TUNGSTEN
6. POROUS EMITTER
   50\% W-50\% TA
7. ANODE SHELL
   TANTALUM
8. DISC SHELL
   TANTALUM
9. SUPPORT RING
   TANTALUM