

〈Review〉

## Theoretical Aspects Associated with Pulsed Ionization Chamber

Sun-Tae Hwang and Jhong Chan Ahn

Korea Standards Research Institute

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### 펄스 이온전리함에 관련된 이론적 양상

황선태 · 안종찬

한국표준연구소

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#### I. Introduction

The instruments for detecting nuclear radiations which were well known to early workers in the field of radioactivity were ionization devices. As new techniques and components have become available, the range of radiation detectors has been developed exploiting various basic methods. By far the most important change in nuclear radiation detectors in recent years is the development and thus wide-scale use of semiconductor radiation detectors.

Over the past three decades, the demand for detectors has been increased many fold by the atomic energy projects. The large-scale industrial plants and nuclear power plants are requiring instruments for the routine assay of radioactive materials emitting radiations. The increasing supply of artificial radioisotopes for various purposes today creates a similar and growing demand. The growing tempo of research in the fields of medical and reactor health physics calls for the provision of specialized types of instruments, some of which are needed on a comparatively small scale, such as miniaturized ionization chamber, and some of

which must be designed for a particular experiment. Uranium prospecting and mining, spent fuel reprocessing, and radioactive waste disposal have made necessary the provision of detectors in which the main requirement is for portability and ruggedness.

In this report, the overall description is confined to the general review of the pulsed ionization chamber(PIC) system as a nuclear instrumentation system which was developed by Ellis[1] who concluded that the PIC technique for plasma diagnostics was an effective and significant tool for the study of plasmas in high pressure gases.

#### II. Summary of Related Theories

##### II-1. Gaseous Ionization Media

The process of ionization in a gas results in the production of electrons, positive ions, and molecules in excited states as outlined in Fig. 1, which illustrates the course of events in a gaseous ionization detector, where, the electrons and ions in a gas experience only short range forces from the gas molecules and their mutual interactions take place effectively only during periods of collision.

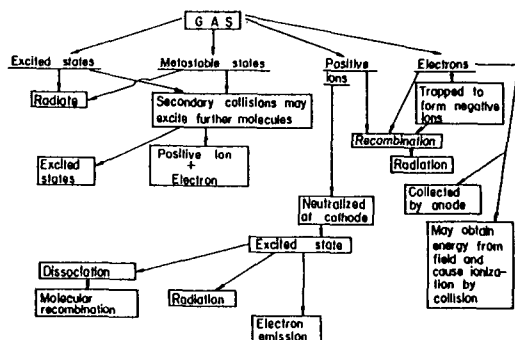


Fig. 1 Energy Loss Processes of Charged Particle in a GAS.

The mean free path of a charge carrier for collision with neutral molecules thus becomes of dominating importance. When the molecular diameter is taken to be  $3 \times 10^{-8}$  cm, the mean free path in a gas is assumed to be  $10^{-5}$  cm at 760 torr and to vary inversely with the pressure at the temperature being held constant [2].

When the field energy of gaseous ions is small compared with the thermal energy, the average drift velocity in the field direction  $\bar{w}$  may be expressed as

$$\bar{w} = \mu \cdot (E/p) \quad (2-1)$$

where  $E$  is the electric field strength,  $p$  is the gas pressure and  $\mu$  is known as the mobility. Values of  $\mu$  have been summarized in a convenient form by Wilkinson [3].

According to Sharpe [4], positive ions being of molecules mass  $M$  have a mobility

$$\mu_+ \sim \lambda_0 e / (12kTM) \quad (2-2)$$

where  $\lambda_0$  is the mean free path of the ions among the gas molecules at 760 torr. The mean free path has the value

$$\lambda = 1/n\sigma \quad (2-3)$$

where  $n$  is the density of molecules and  $\sigma$  is the effective collision crosssection. So long as the energy gained by an ion from the applied electric field remains small compared with the thermal energy,  $(3/2)kT$ , the mean free path will be constant and thus  $\mu_+$  will be independent of  $E/p$ . For very high electric fields of the order of  $4 \times 10^5$

V/cm at 760 torr. this condition no longer holds and the mobility  $\mu \propto (E/p)^{-1}$  [4].

## II-2. Distinction between a Plasma and an Ordinary Ionized Gas

Plasma is a state of matter composed at least partly of high densities of mobile charged particles. Gases, liquids, and solids can exhibit plasma behavior. The high density and highly mobile charge in a plasma is responsible for a very important electrical property. There is always some small degree of ionization in any gas. However, any ionized gas can not be called a plasma, of course. A useful definition of plasma is as follows [5]:

"A plasma is a quasineutral gas of charged and neutral particles which exhibits collective behavior."

By "quasineutral" we mean plasma is neutral enough so that one can take  $n_+ = n_- = n$  where  $n$  is a common density called the plasma density. On the other hand, by "collective behavior" we mean motions that depend not only on local conditions but also on the state of the plasma in remote regions as well.

According to Chen [5], the criteria for an ionized gas to be a plasma are as follows:

(a) It should be dense enough that the Debye length  $\lambda_d$  is much smaller than the dimension  $L$  of a system of interest:  $\lambda_d \ll L$ .

(b) The collective behavior requires the number of particles in a Debye sphere,  $N_d$ , is much larger than 1:  $N_d \gg 1$ .

$$\text{where } N_d = n(4/3)\pi\lambda_d^3.$$

(c) For the gas to behave like a plasma rather than a neutral gas, the relation  $\omega\tau > 1$  is required.

where,  $\omega$  is the frequency of typical plasma oscillations and  $\tau$  is the mean time between collisions with neutral atom.

As indicated above, it is convenient to introduce

the concept of the Debye length in order to distinguish a true plasma from an ordinary ionized gas. Now, let us develop a theory for the Debye length  $\lambda_d$ .

The density of classical particles in a force field in which the potential energy of the particles is  $U = U(x)$  is given by [6]

$$n(x) = n_0 \cdot \exp[-U(x)/kT] \quad (2-4)$$

where  $n_0$  is the density density where the particles have zero potential energy. In an electric force field, the potential energy of a charged particle is related to the electric potential function  $U = q \cdot V$  where  $q$  is the charge of a particle and  $V = V(x)$ . Since  $q = -e$  for an electron, therefore, the electron density in the sheath field is

$$n_e = n_{e0} \cdot \exp[eV/kT] \quad (2-5)$$

In general, positive ion density is

$$n_i = n_{i0} \cdot \exp[-ZeV/kT] \quad (2-6)$$

where  $Z=1$  for singly charged ions,  $Z=2$  for doubly charged ions and so forth. Eqs. (2-5) and (2-6) relate the densities of the charge species to the electric potential.

The electric potential, on the other hand, is related to the charge density by Poisson's equation,  $\nabla^2 V = -4\pi \rho / \epsilon_0$  where  $\epsilon_0$  is the dielectric constant of the electrolyte and  $\rho$  is the net charge density,

$$\rho = Ze n_i - e n_e \quad (2-7)$$

Eqs. (2-5) and (2-6) may be inserted into Eq. (2-7) to obtain a differential equation for the potential function as follows:

$$\nabla^2 V = -4\pi e / \epsilon_0 [Z n_{i0} \cdot \exp[-ZeV/kT] - n_{e0} \cdot \exp[eV/kT]] \quad (2-8)$$

In principle, this equation can be solved to obtain the electric potential,  $V = V(x)$  from which the particle densities and the electric field can be obtained. In practice, however, Eq. (2-8) is very difficult to solve without employing a simplifying assumption. Let us now assume the followings [2]:

- (a) The ions are in a Boltzmann distribution at an equilibrium temperature  $T$ .
- (b) The potential energy of the charges due to

their separation is small compared to their thermal energy so that  $ZeV \ll kT$ .

(c) The microscopic variations of potential resulting from the discrete nature of the particles may be neglected.

Here using the series,  $\exp(\pm s) \approx 1 \pm s$  for  $s \ll 1$ , Eq. (2-8) becomes

$$\nabla^2 V = -4\pi e / \epsilon_0 [Z n_{i0}(1 - ZeV/kT) - n_{e0}(1 + eV/kT)] \quad (2-9)$$

If we utilize the fundamental charge neutrality of the plasma interior,

$Z n_{i0} = n_{e0}$ , Eq. (2-9) reduces further to

$$\nabla^2 V = d^2V/dx^2 = 4\pi e / \epsilon_0 kT [Z^2 n_{i0} \cdot eV + n_{e0} \cdot eV] \quad (2-10)$$

Hence

$$d^2V/dx^2 = (1/\lambda_d^2)V \quad (2-11)$$

where

$$1/\lambda_d^2 = 4\pi e^2 (Z^2 n_{i0} / \epsilon_0 kT + n_{e0} / \epsilon_0 kT) \quad (2-12)$$

and thus

$$\lambda_d^2 = [4\pi e^2 / \epsilon_0 kT (Z^2 n_{i0} + n_{e0})]^{-1} \quad (2-13)$$

Noting that  $\lambda_d$  has the dimension of length, the general solution to Eq.(2-9) is

$$V(x) = A \cdot \exp(-x/\lambda_d) + B \cdot \exp(x/\lambda_d) \quad (2-14)$$

Applying the boundary condition that  $V(x) \rightarrow 0$  for large distance from the origin of coordinates, the final solution is

$$V(x) = V_0 \cdot \exp(-x/\lambda_d) \quad (2-15)$$

Eq. (2-15) represents a potential function that decays exponentially into the plasma with the Debye length  $\lambda_d$ . This screened coulomb potential becomes quite small at distances much greater than  $\lambda_d$ .

The Debye length is an important parameter of any plasma because it may be considered to be a measure of the size of the screening ion cloud surrounding the given ion. This length is the fundamental minimum distance over which collective plasma effects occur. Hence a fundamental restriction on the definition of a plasma is that it should be large in extent compared with its own Debye length,  $\lambda_d$ .

From Eq. (2-13) it is frequently customary to treat the two terms on the right hand side seper-

ately, defining one as a screening length for electrons and the other for the positive ions. Thus the electron screening length  $\lambda_e$  is

$$\lambda_e = [\epsilon_0 kT / 4\pi e^2 n_{e0}]^{1/2} \quad (2-17)$$

Thus a screening length can be determined for each of the species of particle in the gas. These lengths are different from the Debye length associated with the gas as given by Eq. (2-13). In a gas consisting of singly charged positive ions and electrons at the same temperature, we see that  $n_{e0} = n_{i0} = n$  and the relationship of the various screening lengths is as follow [7] :

$$\lambda_e = \lambda_i = \sqrt{2} \lambda_d \quad (2-18)$$

As indicated so far, the Debye length varies directly with the square root of the temperature and inversely with the square root of the density of the ions. In order that there is the requisite electrostatic interaction between particles, the Debye length must be considerably less than the minimum dimensions of ionized medium. If this condition is not satisfied, the medium only behaves like a collection of free charges. The foregoing derivation assumes that the Debye length is large compared with the interparticle distances.

### II-3. Plasma Kinetics Associated with PIC

The pulsed ionization chamber system was a new mode of gas filled ionization chambers. In its initial stages, the PIC system was applied to the measuring of ionization densities, recombination parameters, and neutron flux density. Markwell [7] demonstrated a wide range neutron flux measurement capability for the PIC system and Ellis [8] indicated that the PIC system provided an alternative to a multichamber wide range neutron detection instrumentation.

In the PIC associated plasma kinetics, a formulation for the time rate of change for the electron density with the presence of an ionization source may be given as the following electron balance equation:

$$dn_e/dt = S + \alpha_d \nabla^2 n_e - \sum_r \beta_r n_e^r \quad (2-19)$$

where  $\alpha_d$  is the diffusion coefficient and it is assumed that the number densities for the electrons and ions are equal. The source term,  $S = S(t)$ , represents the rate of production of electron-ion pairs while the losses are characterized by a diffusion loss term and a summation over all other mechanisms which contribute to the loss of the plasma.  $\beta$ 's are the loss coefficients for the  $r$ -th order mechanism.

In the steady state ionized gas kinetics, however, a simplified description of the growth of electron density, or ionization density, can be given by the following equation :

$$dn_e/dt = S + \alpha_d \nabla^2 n_e - (\beta_1 n_e + \beta_2 n_e^2) \quad (2-20)$$

where  $\beta_1$ ,  $\beta_2$  are the first and second order loss coefficient, respectively.

The loss mechanism by free or ambipolar diffusion is quite insignificant with respect to high pressure gas flow channels. For the high pressures, the diffusion term in Eq. (2-20) can be dropped and thus the electron growth equation becomes

$$dn_e/dt = S - (\beta_1 n_e + \beta_2 n_e^2) \quad (2-21)$$

However, if diffusion is the dominant charge loss mechanism as an approximation, the diffusion loss term can be replaced by  $(\alpha_d/\lambda^2)n_e$  where  $\lambda$  is the characteristic diffusion length for the plasma [9].

The approximated Eq. (2-21) describes that over the ionization density range where the PIC has been applied, only first and second order loss mechanism exist and also it should be noted that this equation takes into account three basic loss mechanism diffusion, recombination and electron attachment.

For steady state or equilibrium conditions where ionization is uniformly distributed through ionized gas volume,  $dn_e/dt = 0$  and Eq. (2-21) reduces to the quadratic relationship

$$\beta_1 n_e + \beta_2 n_e^2 = S \quad (2-22)$$

If  $S = S(t)$  is time independent, the solution to Eq. (2-22) is

$$n_e = -\beta_1/2\beta_2 + [(\beta_1/2\beta_2)^2 + S/\beta_2]^{1/2} \quad (2-23)$$

According to Ellis, for the PIC operation with collection circuits of which RC time constants are large as compared to the collection time and the signal voltage developed across the cylindrical chamber is

$$V = -en_e(v/C) \cdot [1 - 1/\ln(r_b/r_a)^2] \quad (2-24)$$

where  $v$ =sensitive volume of the chamber,

$C$ =total circuit capacitance,

$r_b, r_a$ =diameters of the shell and anode, respectively.

By coupling Eq. (2-23) and (2-24), a direct relationship between output voltage and source rate is obtained as follows:

$$V = (ev/2C\beta_2) \cdot [-\beta_1 + (\beta_1^2 + 4\beta_2 S)^{1/2}] \cdot [1 - 1/\ln(r_b/r_a)^2] \quad (2-25)$$

This equation can be used to determine the loss coefficients,  $\beta_1$  and  $\beta_2$ .

#### II-4. Loss Mechanisms for Electrons

There are three basic mechanisms by which electrons can be lost from the plasma produced in the PIC: (1) diffusion, (2) recombination and (3) electron attachment.

(1) Diffusion: Diffusion is a random motions of the individual particles. An ionized gas incurs a loss of the ionization from neutral atoms and molecules by the diffusion to the walls of the container. In the absence of any interaction between the charged species, the particles move through the volume of the gas or plasma with velocities dependent on their mass.

(a) Mutual diffusion: The mutual diffusions occur in a gas with uniform total pressure but with nonuniform composition. For very low charge densities less than  $10^4$  electrons/cm<sup>3</sup>, each of the charged species behaves as a separate gas and moves by diffusion through the neutral gas without an appreciable number of interactions[2]. This process is sometimes known as free diffusion of electrons. Hence, the free diffusion is important

only at very low charge densities,  $n_e \leq 10^4$  electrons per unit volume and at pressures of less than one torr [10]

(b) Ambipolar diffusion: The concept of ambipolar diffusion was first introduced by Schottky in 1924. Osgood also has proposed a theory to account for ambipolar diffusion and has performed its measurements in the plasma volume [11]. Ambipolar diffusion is the simultaneous diffusion of two types of particles. This diffusion occurs when both species of the charged particles in an ionized gas diffuse with the same velocity. It results when a deviation of charge quality produces electric forces which tend to restore the charge balance and to oppose the charge separation [10]

According to Ellis, it can be shown that the ambipolar diffusion coefficient,  $\alpha_{a-d}$ , is twice the value for the positive ion diffusion coefficient if the electrons and ions are in thermal equilibrium, and that  $\alpha_{a-d}$  varies inversely with the pressure of the gas and is also a function of the absolute temperature.

In gaseous plasmas, the mobile charge densities,  $n_e$  and  $n_i$ , are essentially equal so that for these cases the ambipolar diffusion coefficient is [6]

$$\alpha_{a-d} = (\mu_- \alpha_{++} + \mu_+ \alpha_{--}) / (\mu_- + \mu_+) \quad (2-26)$$

where  $\alpha_{--}, \alpha_{++}$  are the diffusion coefficients of electrons and ions, respectively. Furthermore, for particles that can be described by Maxwellian statistics, the diffusion coefficient is related to the mobility by Einstein's relation[6],  $\alpha_d = (kT/e)\mu$ . For this type of particle, the ambipolar diffusion coefficient reduces to

$$\alpha_{a-d} = k(T_e + T_i)/e [\mu_- \mu_+ / (\mu_- + \mu_+)] \quad (2-27)$$

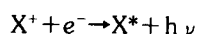
$$= 2kT/e [\mu_- \mu_+ / (\mu_- + \mu_+)], \quad T_e = T_i = T.$$

An interpretation of Eq. (2-27) is that ambipolar diffusion occurs at a rate characteristic of the sum of the temperatures of the charge species but with a mobility dominated by the less mobile of the two.

(2) Recombination: Recombination implies the

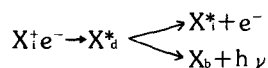
combination of negative and positive ions present in a gas volume to result in neutral particles. According to the manner in which the excess energy of the electron-ion system is carried away, the following classification is made:

(a) Radiative recombination



This reaction was first studied in 1923 by Kramers who was concerned with calculating the intensity of the X-rays emitted from a solid target bombarded by fast electrons [12]. For radiative recombination, the excess energy is carried away in the form of a photon. This process is the inverse of photoionization. Radiative recombination proceeds at a slow rate and is normally of no significance except in very tenuous plasmas. However, it is surely the most important recombination process in the high atmosphere [2].

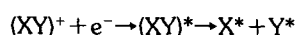
(b) Dielectronic recombination



The mechanism of the process, dielectronic recombination was discussed by Bates [12] in 1943. Dielectronic recombination is the process of inverse autoionization. In this process the electron is captured by the ion  $X_i^+$  into some excited state of the a complex atom  $X$  and the excess energy of recombination is taken up by a second electron which then also occupies an excited state.

It may revert to the ionic state,  $X_i^+$ , by the process of autoionization in which one electron is ejected. However, it is possible that the doubly excited atom  $X_d^*$  may undergo a radiative transition or dissociation and drop to some state,  $X_b$  which is not subject to autoionization. If this occur, dielectronic recombination is said to have taken place. Fig. 2 illustrates the dielectronic recombination sequences [13].

(c) Dissociative recombination



Dissociative recombination exists when an electron collides with a diatomic positive ion. There is

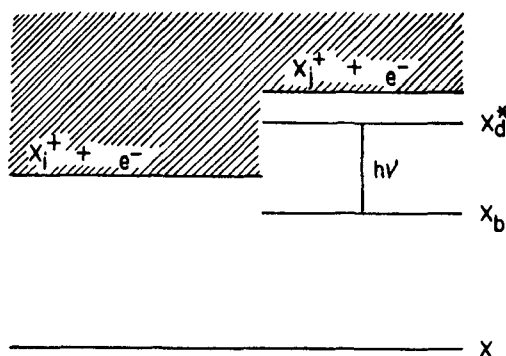


Fig. 2 Energy Level Diagram for Dielectronic Recombination Sequences.

a high probability that the system will separate as two neutral atoms with the excess energy being carried away as kinetic energy or the formation of excited states of either or both neutral atoms. This process was first proposed by Bates [14]. Dissociative recombination takes place when a radiationless transition occurs to some state of the molecule,  $XY$ , in which the atoms recede one from another and gain kinetic energy under the action of mutual repulsion. Fig. 3 illustrates schematically the dissociative recombination [15].

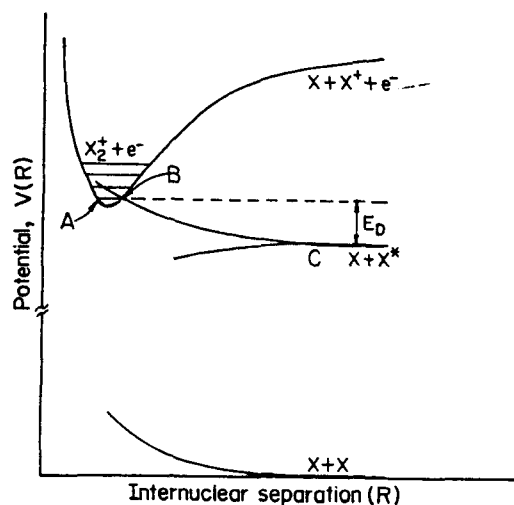


Fig. 3 Schematic Representation of the Dissociative Recombination Process.

Initially, the system is composed of a molecular positive ion and an electron (State A). If repulsive curve (B-C) of an excited state of the molecule crosses the molecular ion-electron curve at the appropriate point, the system may jump to this state of the molecule and begin to dissociate. Once the internuclear separation has increased slightly, the system can no longer revert to its original state by autoionization and the electron is trapped as the molecule continues to dissociate (State C) [2].

(d) Three-body recombination



The theory for the three-body process was originally presented by J.J. Thomson. In the three body recombination, a charged particle loses sufficient kinetic energy by a collision with a neutral atom enabling the charged particle to recombine with a nearby ion of opposite sign. The third body can become an atom, a molecule or an electron. In three body electron-ion recombination (Process A), a heavy particle acts as the third body. Reaction A is from early consideration. Recent work, however, has shown that reaction B, in which the third body is an electron, may be quite fast at high electron-ion densities above about  $10^{14}$  ip/cm<sup>3</sup> [2].

(3) Electron Attachment: Another very important source for loss of electron in gases, particularly if certain impurities are present, is negative ion formation by electron attachment. Electron attachment is due to a tendency for the electrons to attach themselves to the neutral atoms or molecules with which they collide, thus forming negative ions. Although the charge density remains unchanged, the process may serve as a precursor to recombination. The negative ions thus formed may be recombined by ion-ion type of recombination mechanism. This process further results in charge neutralization by charge transfer and subsequent dissociative recombination.

The rate of attachment varies increasingly with

pressure. However, the variation of attachment coefficient which is defined as the probability of attachment per collision of an electron with neutral molecules or atoms depends on the character of the attachment method.

If attachment is the dominant loss process of the electrons in the plasma after the source term goes to zero, the decrease of electron density for low energy electrons is given by [16]

$$\left[ \frac{dn_e}{dt} \right]_a = -f_a n_e [-K_1 n(y) n_e - K_2 n(y) n(x) n_e] \quad (2-28)$$

where  $f_a$  represents the attachment frequency for an individual electron.  $K_1$  is the two-body and  $K_2$  is the three-body attachment coefficient. The densities of the electronegative impurity and third body atoms or molecules are given by  $n(y)$  and  $n(x)$ , respectively.

Electrons can be removed from the plasma by a combination of the above three mechanisms. In the case of both recombination by two body and electron attachment, if the negative ions thus formed can be assumed to recombine very rapidly with positive ions, the negative charge density can be represented by the electron density. Thus, the loss equation is given by

$$\frac{dn_e}{dt} = (\beta_1 n_e + \beta_2 + \beta_3 n_e^2) - f_a n_e \quad (2-29)$$

where source term was assumed to be zero like in Eq.(2-28).

Such an expression indicates the difficulty of interpreting measurements when several mechanisms of charge loss are present. In setting up a lumped parameter model to express the electron losses, the continuity equation can be written as a differential equation where the loss coefficients are aggregate expressions for several processes. According to Ellis [8], therefore, a following equation represents a combination of all the effects which are taking place:

$$\frac{dn_e}{dt} = S(t) - \sum_i \beta_i n_e^i(t) \quad (2-30)$$

In considering the differential equation which describes the electron density with respect to time,

the ionization source term,  $S(t)$ , must be defined. For instance, neutron induced ionization within the reactor core is expressed as

$$S(t) = S_n = \sigma N_a \phi_{th} \bar{E} / \bar{W} \quad (2-31)$$

where,  $\sigma$  = thermal neutron cross section, 5327 b for  $^3\text{He}$  [17],

$N_a$  = atom density of the filling gas in the PIC,

$\phi_{th}$  = thermal neutron flux density,

$\bar{E}$  = average energy deposited in the filling gas by the (n,p) reaction,

$\bar{W}$  = average energy required to produce an electron-ion pair.

On the other hand, according to Lamarsh [18], all thermal neutrons lumped together can be written as

$$\phi_{th} = (2/\sqrt{\pi}) n_t V_{th} \quad (2-32)$$

where,  $n_t$  = total neutron density in the reactor core,

$$v_{th} = (2kT/m_n) = 1.284 \cdot T^{1/2} \times 10^4 \text{ cm/s.}$$

### III. Experimental Measurements

#### III-1. Average Energy to Form an Ion Pair

In order to adequately develop a study involving ionization in gases by the passage of charged particles, it must be considered how much energy loss is required for a given amount of ionization in a field of ionizing radiation. The mechanism by which a charged particle loses its kinetic energy or is deflected from its original path may be categorized into four principle types as follows [19]:

(1) Inelastic collisions with bound atomic electrons are usually the primary means by which an energetic charged particle loses kinetic energy in an absorber.

(2) Inelastic collisions with a nucleus have a high probability of resulting in a quantum of radiation being emitted and the incident particle experiencing a deflection.

(3) An elastic collision with a nucleus causes the incident particle to be deflected but there is no radiation or excitation of the nucleus.

(4) An elastic collision with an atomic electron results in the deflection of the incident particle where energy and momentum are conserved and the energy transfer is usually less than the lowest excitation potential of the electron.

In general, each incident charged particle in a stopping media experiences many collisions of each type mentioned above before it is brought to rest.

In determination of the energy required to form one ion pair by measuring the ionization, the relative saturation must be considered in order to ascertain the total ionization created by the charged particle. When an ionization chamber is used as the device for investigating loss parameters of the filling gas, measurement of the ionization current along with an energy distribution for the ionizing events leads to unique determination of  $\bar{W}$  in Eq.(2-31) for the specific gas. Under the condition of  $n_i = n_e = n$ , the measured ion-chamber current,  $I$ , corrected for the relative saturation can be expressed as the following relation utilizing Eq.(2-32):

$$I = (\sigma N_a \cdot \phi_{th} \cdot v) (\bar{E} / \bar{W}) e \quad (3-1)$$

Now the energy required to form one ion pair,  $\bar{W}$ , can be determined from Eq. (3-1).

$$\bar{W} = (\sigma N_a \cdot \phi_{th} \cdot v) \bar{E} e / I \quad \text{eV/ip} \quad (3-2)$$

where the quantity,  $\sigma N_a \cdot \phi_{th} \cdot v$ , represents the reaction rate in the chamber.

#### III-2. Diffusion and Recombination Parameters of the Plasma

The time dependent development of the charged particle density is described by the inhomogeneous and non-linear differential equation shown in Eq. (2-19). In the absence of an ionization source, the decay of plasma is related to the loss coefficients. However, it must be determined whether the decay of the plasma is diffusion dominated or recombination dominated for a sufficient length of time in order to establish the re-



spective parameter. More concretely, for dominant diffusion, Eq. (2-19) may be rewritten to describe the electron density as follow :

$$dn_e/dt = -\alpha_d \nabla^2 n_e, \quad (3-3)$$

while the differential equation for loss of ions by pure ideal recombination in time is given by

$$dn_e/dt = -\gamma n_e^2 \quad (3-4)$$

where positive and negative ions are present in equal numbers and  $\gamma$  is recombination coefficient in  $\text{cm}^3/\text{e} \cdot \text{s}$ .

Although each mechanism has its own numerical value of the coefficient describing the recombination, the use of lumped coefficients will not alter the shape of the curve representing the electron density as a function of time [13].

The solution to Eq. (3-4) can take following form :

$$n_e(t) = n_e(0) / [1 + n_e(0)\gamma t] \quad (3-5)$$

If  $n_e(0)$  and  $n_e(t)$  can be measured at respective known times,  $\gamma$  can be obtained from the following relationship :

$$\gamma = (1/t) \cdot [1/n_e(t) - 1/n_e(0)] \quad (3-6)$$

This method of evaluating  $\gamma$  is known as the "method of decay."

If electrons and ions are produced as a constant rate and a state of equilibrium is reached, the differential equation for growth of electron is

$$dn_e/dt = S - \gamma n_e^2 \quad (3-7)$$

and the equilibrium electron density at infinite time will be given by

$$n_e(\infty) = (S/\gamma)^{1/2} \quad (3-8)$$

Accordingly

$$\gamma = S/n_e^2(\infty) \quad (3-9)$$

where, if  $n_e(\infty)$  and  $S$  are known or can be measured,  $\gamma$  may be determined. This is known as the "equilibrium method."

If, however, the electron density has not reached an equilibrium value, Eq. (3-7) may be solved by integration to yield

$$n_e(t) = (S/\gamma)^{1/2} [\exp(2\sqrt{S/\gamma} t) - 1] / [\exp(2\sqrt{S/\gamma} t) + 1] \quad (3-10)$$

If  $n_e(t)$  is evaluated for two values of  $t$  and  $S$ , then

$\gamma$  is evaluated. This is known as the "method of growth."

In the presence of a source, diffusion and ideal recombination are the only processes being considered for Eq. (2-19). According to Ellis, the mean particle density,  $\bar{n}(t)$ , has the following form:

$$\bar{n}(t) = \frac{\int_{r_a}^{r_b} n(r,t) 2\pi r dr}{\int_{r_a}^{r_b} 2\pi r dr} \quad (3-11)$$

where,  $r_a$  and  $r_b$  are the inner and outer radii of the coaxial configuration of the PIC.

In view of the linear and non-linear processes occurring in the space-time development of the charged particle density, a solution for Eq. (2-19) is suggested as

$$n(r,t) = N(t) \cdot n^*(r,t) \quad (3-12)$$

Therefore, substitution of the solution (3-12) into Eq. (3-11) and then into Eq. (2-19) yields the following differential equation for the mean particle density by letting  $\alpha_d = D$ .

$$\partial n(t)/\partial t = \bar{S} - \bar{D}[\bar{n}(t)] - \bar{\gamma}[\bar{n}(t)]^2 \quad (3-13)$$

With this relationship, the apparent diffusion coefficient and apparent recombination coefficient are given by the following expressions, respectively :

$$\bar{D} = D \frac{\int_{r_a}^{r_b} (1/r) \frac{\partial}{\partial r} (r \partial n^*/\partial r) 2\pi r dr}{\int_{r_a}^{r_b} n^*(r,t) 2\pi r dr} \quad (3-14)$$

$$\bar{\gamma} = \gamma \pi (r_b^2 - r_a^2) \frac{\int_{r_a}^{r_b} [n^*(r,t)]^2 2\pi r dr}{[\int_{r_a}^{r_b} n^*(r,t) 2\pi r dr]^2} \quad (3-15)$$

The mean ionization source is given by the following expression :

$$\bar{S} = \frac{\int_{r_a}^{r_b} S_0 2\pi r dr}{\pi (r_b^2 - r_a^2)} \quad (3-16)$$

Where,  $D$  and  $\gamma$  are the actual diffusion coefficient and actual recombination coefficient, respectively. Fig. 4 is a graphical description of the ratio of the apparent diffusion coefficient to the actual

diffusion coefficient as a function of the geometrical parameters of the coaxial PIC system[1].

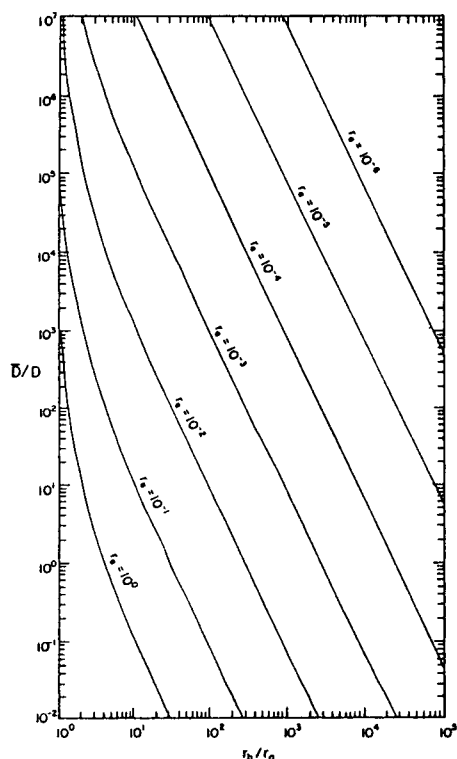


Fig. 4 Ratio of Apparent Diffusion Coefficient to Actual Diffusion Coefficient as a Function of System Radii.

### III-3. Electron Density Determination

The electron density can be determined from voltage signal of the pulsed ionization chamber. The scheme of this method of investigation is the observation of the current from the drifting electrons and ions due to the applied potential on the chamber. Experimentally, the arrangement in Fig.5 consists of rapidly applied voltage for a relatively short period of time to the ion-chamber in order to impart a drift velocity to the electrons and ions that are distributed throughout the chamber volume. The high voltage is applied for a sufficient length of time to collect the electrons.

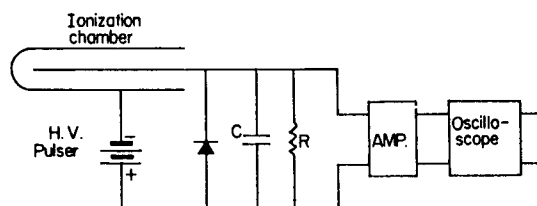


Fig. 5 Signal Output Circuit of the PIC System.

The carrier current,  $I_{CR}$ , is produced by the motion of the charged particles in the sensitive volume of the chamber and is a summation of the current of the electrons, the positive ions and the negative ions. That is,

$$I_{CR}(t) = I_e(t) + I_i(t) + I_n(t) \quad (3-17)$$

The total current in the external circuit,  $I(t)$ , consists of the carrier current in the chamber and the displacement current for the capacitance of the chamber.

Thus,

$$\begin{aligned} I(t) &= I_{CR}(t) + I_C(t) \\ &= I_{CR}(t) + C \, dV_C/dt \\ &= I_{CR}(t) - C \, dV_R/dt \end{aligned} \quad (3-18)$$

The observed voltage in the external circuit across the resistor  $R$  is related to the currents as follow :

$$V_R(t) = RI_{CR}(t) + RC \, dV_C/dt \quad (3-19)$$

Additional capacities in the system, particularly cable capacitance leading to the amplifier, are in parallel with  $R$  and the amplifier. Thus, Eq. (3-19) becomes

$$\begin{aligned} V_R(t) &= RI_{CR}(t) + RC' \, dV_C/dt \\ &= RI_{CR}(t) + RC' \, dV_R/dt \end{aligned} \quad (3-20)$$

where  $C' = C + C_{add}$

For cylindrical geometry of the ion-chamber and a homogeneous distribution of the charge within the chamber,  $I_{CR}(t)$  is a constant and  $V_C(0) = 0$ . Thus, the complete solution to Eq. (3-20) is given by

$$V_R(t) = RI_{CR} [1 - \exp(-t/RC)] \quad (3-21)$$

This equation can be related to the electron density since the time required for charge collection is much less for the electrons than for the ions.

(1) Parallel plate configuration

For a small RC time constant, the time for electron collection  $t_e \gg RC$

$$V_R(t) = [R n_e \cdot e v / t_e] (1 - t/t_e) \quad (3-22)$$

For a large RC time constant,

$$V_R(t) = n_e \cdot e v t / C t_e \quad (3-23)$$

For a small RC time constant, the exponential term in Eq.(3-21) becomes negligibly small and the electron density can be given by

$$V_R(t) = R I_{cr}(t) \quad (3-24)$$

It means the voltage is proportional to the carrier current,  $I_{cr}$ .

(2) Cylindrical coaxial configuration

For  $r_b/r_s > 10$ ,

$$V_R(t) = [R n_e \cdot e v / t_e \cdot 2 \cdot \ln(r_b/r_s)] \cdot [1 - \exp(-t/RC)] \quad (3-25)$$

For a large RC time constant,

$$V_R(t) = n_e \cdot e v t / C t_e \cdot 2 \cdot \ln(r_b/r_s), 0 \leq t \leq t_e \quad (3-26)$$

Measurement of the voltage signal at the end of electron collection provides a direct method of determining the electron density in the sensitive volume of the chamber. Fig. 6 illustrates the time dependence for the voltage signal  $V_R(t)$  during electron collection[1].

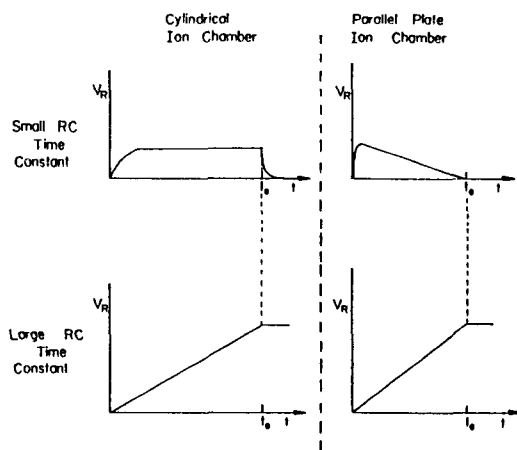


Fig. 6 Voltage Signal Time Dependence for Large and Small RC Time Constants, and Parallel Plate Cylindrical Geometries.

Now utilizing Eq. (3-23) and (3-26) at  $t=t_e$ , the maximum voltage signal can be readily derived in each case. That is, with a large RC time constant for the parallel plate configuration,

$$V_R(t_e) = n_e \cdot e v / C \quad (3-27)$$

and for the cylindrical coaxial configuration,

$$V_R(t_e) = n_e \cdot e v / C \cdot 2 \cdot \ln(r_b/r_s) \quad (3-28)$$

In the PIC system which was developed by Ellis and his coworkers, the relationship for signal voltage was given by [8]

$$V(t) = \frac{1}{C} \int_0^{t_e} I(t) dt = -\frac{en_e v}{C} \left[ -H^2 - \frac{1 - H^2(1 - \ln H^2)}{\ln(1/H)^2} \right] \quad (3-29)$$

where  $H = r_s/r_b$ .

When  $r_b^2 \gg r_s^2$ , Eq. (3-29) for  $V(t_e)$  in terms of electron density  $n_e$  is reduced to one involving only constant parameters of the chamber geometry and output capacitance  $C$  as follows :

$$V(t_e) = (-e n_e v / C) [1 - 1/\ln(r_b/r_s)^2] \quad (3-30)$$

In this equation the factor,  $1/\ln(r_b/r_s)^2$ , is due to the unaltered positive ion distribution which is assumed to be constant. On the other hand, at the ion collection time  $t$ , the voltage is expressed by

$$V(t) = e n_e v / C \quad (3-31)$$

Thus the voltage is exactly proportional to the electron density,  $n_e$ .

In Eq. (3-30), however,  $n_e$  is given by

$$n_e = -[V(t_e) \cdot C / e v] \cdot [1 - 1/\ln(r_b/r_s)^2]^{-1} \quad (3-32)$$

Consequently measurement of the voltage at the end of electron collection allows determination of the electron density in the sensitive volume of the PIC.

#### IV. Conclusions

The PIC technique as a tool for detecting and measuring radiation was evaluated for its possible application for the measurements of electron densities in other experiments. The PIC method was also considered to be applicable for fast-response

neutron flux measurements in a LMFBR[8].

The PIC system was shown to be an effective instrument for obtaining the plasma kinetics parameters necessary for evaluating the loss characteristics of an ionized gas system[20]. The gamma compensated pulsed ionization chamber showed considerable promise for use as a system for reactor power measurement[22].

An ionization chamber measures the ionization produced by a particle in passing between electrodes. In particular, the pulse-type ionization chambers still play an important role in the area of radiation detection. A newly developed pulsed mode of operation of ionization chambers had a wide range capability for neutron flux and reactor power measurements, independence of high temperature insulator leakage and ionized gas kinetics effects, freedom from recombination effects.

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