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A model for radiation induced conductivity in neutral beam injector insulator gases

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Abstract

A theoretical model for the radiation induced conductivity of gases has been developed. The model gives the electrical current as a function of voltage, gas volume, pressure, molecular atomic number and ionizing dose rate. Different experiments have been carried out in a Van de Graaff electron accelerator in order to check the model. The model is found to predict the observed experimental data to such a degree as to give confidence in the extrapolated predictions.

1. Introduction

For 'Next Step' fusion devices such as ITER, neutral beam injectors will require the use of some type of gas contained under pressure within an earthed pressure vessel to insulate the high voltage transmission line, ion source, and accelerator tube. This insulating gas will be in a radiation field of the order of 1 Gy/s due to the plasma and the NBI accelerator itself. The radiation will cause ionization in the gas and hence an increase in the electrical conductivity. As this is a source of power loss due to the corresponding leakage current which in addition will produce heating and possibly breakdown [1], the radiation effect must be quantified and taken into account in the engineering design of the NBI system.

Initial experimental results for the radiation induced leakage currents in dry air and SF_6 at atmospheric pressure indicated that large power losses ($\simeq$1 MW) would occur in the ITER NBI system. These initial results were obtained for gas volumes of approximately 3×10^{-6} m^3, electrode separations of 1.5×10^{-2} m, and voltages of approximately 1 kV. Hence the conclusions for the NBI system represented an extremely large extrapolation. Work was then extended for electrode separations of up to 1 m and voltages to 25 kV for dry air and SF6 at 1 Gy/s [2,3].

Due to the experimental difficulty in obtaining data for larger volumes and voltages, and in particular for gas pressures > 1 bar, a model has been developed which makes predictions for the gas conductivity (leakage current) in terms of electric field, ionizing dose rate, and pressure. The model takes into account the effect of dose rate, electrode separation/electric field, and gas pressure on the production and lifetime of the electron–positive ion pairs, and is found to predict the observed experimental data to such a degree as to give confidence in the extrapolated predictions. The model predicts that the charge carrier lifetime should be proportional to (dose rate)$^{-0.5}$, in agreement with the available data. It accounts particularly well for the anomalous results on electrode separation, but most important it makes predictions for gas pressure indicating that the leakage current is not a simple function of the pressure. The results enable one to predict with confidence the expected leakage current for the ITER NBI system, data for which is not readily available experimentally.

2. Theoretical model

If the lifetime of an electron–ion pair is τ, the probability of recombination in time dt is dt/τ. For a total number N pairs the number of recombinations is;

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$$dN = -N dt/\tau \quad (1)$$

giving on integration;

$$N(t) = N(0)\exp(-t/\tau). \quad (2)$$

On applying an electric field the charges drift towards the corresponding electrodes. The drift velocity of the ions is several thousand times slower than that of the electrons, and it is the ions therefore that govern the integrated measured current. The probability that an ion reaches an electrode is given by $\exp(-t/\tau)$ where t is obtained from;

$$v \text{ (drift velocity)} = E\mu/p, \quad (3)$$

where E is the electric field, μ the mobility ($\mu \propto 1/m$ m the mass), and p the pressure [4].

For a given volume $dV = Adx$, where A is the area and x is measured in the field direction, the number of ions per unit time which reach the electrode (i.e. measured current) is proportional to the number produced per unit time multiplied by the probability of reaching the electrode;

$$dI = (nZ_m\phi\sigma)A\,dx\exp(-t/\tau), \quad (4)$$

where n is the total number of gas molecules per unit volume proportional to the pressure p, Z_m the molecular atomic number, ϕ the ionizing dose rate, and σ the cross-section for ionization.

The time between ion production and arrival at the electrode depends on the distance from the point of production to the electrode. Hence (4) must be integrated from 0 to L (electrode separation), remembering that $t = x/v$ and $E = V/L$. Integrating we obtain;

$$I = (nZ_m\phi\sigma\tau\mu VA)/(pL)[1 - \exp(-(L^2p/(\tau\mu V)))]. \quad (5)$$

At equilibrium one expects the lifetime τ to be inversely proportional to the density of ion pairs (higher density higher probability of recombination) i.e. $\tau \propto 1/N$. The density of ion pairs is a function of the ionizing dose rate and the gas pressure (number of molecules). The production rate of ion pairs may be written;

$$dN/dt = a\phi p - bN_{ion}N_e, \quad (6)$$

where a and b are constants, and the number of ions and electrons are approximately equal, i.e. $N_{ion} \simeq N_e$ $(= N)$. Hence at equilibrium;

$$N^2 \propto \phi p, \text{ giving } N \propto (\phi p)^{0.5}. \quad (7)$$

Hence one obtains $\tau \propto 1/(\phi p)^{0.5}$, giving;

$$\tau = \tau_0/(p\phi)^{0.5} \quad (8)$$

substituting in (5) we obtain;

$$I = (nZ_m\phi^{0.5}\sigma\tau_0\mu VA)/(p^{1.5}L)[1 - \exp(-(L^2\phi^{0.5}p^{1.5}/(\tau_0\mu V))]. \quad (9)$$

2.1. Behaviour for high voltage (field) and large volumes

For $L \gg (\tau\mu)E/p$ (large volume/electrode separation) (9) reduces to

$$I = (nZ_mA\phi\sigma\tau\mu V)/(p^{1.5}L), \quad (10)$$

$$\text{i.e. } I \propto (Z_mA\phi^{0.5}\sigma\tau_0\mu V)/(p^{0.5}L), \quad (11)$$

i.e. the current is directly proportional to the applied voltage, and inversely proportional to the electrode separation (Ohms law for solids) and the square root of the pressure.

For $L \ll (\tau\mu)E/p$ (high voltage/field saturation condition) (9) reduces to

$$I = nZ_m\phi\sigma AL, \quad (12)$$

$$\text{i.e. } I \propto pZ_m\phi\sigma AL, \quad (13)$$

i.e. the current is directly proportional to the gas pressure, the molecular atomic number, the gas volume and the ionizing dose rate.

3. Experimental procedure

The experiments have been carried out in special gas chambers mounted in the beam line of a 2 MeV Van de Graaff electron accelerator, with the gases (N_2, CO_2, dry air, SF_6, He, $N_2 + CO_2$) being irradiated through an 0.05×10^{-3} m thick aluminium window, either with Bremsstrahlung produced by stopping the electron beam in a gold target, or directly with 1.8 MeV electrons. In this way radiation levels from 0.02 to 200 Gy/s have been covered. The experimental set-ups permitted an electric field to be applied to the irradiated volume of gas, and the electric current flowing through the ionized gas to be measured in order to study different aspects of the effect of radiation on the gas conductivity. Firstly, the dependence of the gas conductivity on dose rate, applied voltage/field and pressure for a well defined guarded cubic volume (3×10^{-6} m^3) was measured. This guarded volume was defined between two parallel square copper plate electrodes separated by 1.5×10^{-2} m. Secondly, the dependence of the gas conductivity on electrode separation was examined. To do this two 0.6×0.6 m^2 aluminium electrodes were employed. One of these electrodes with a 3×10^{-2} m diameter hole at its centre was fixed at the end of the accelerator beam line on an insulated flange, the other electrode was held parallel at distances from about 5×10^{-3} to 1 m. In this way the gas volume between the two electrodes was irradiated by an extracted electron beam in a direction parallel to the applied electric field. Further experimental details are given elsewhere [2].

4. Results

Fig. 1 shows the radiation induced conductivity for different gases irradiated in the guarded cell (electrode distance 1.5×10^{-2} m) at 0.02 Gy/s as a function of voltage. This shows the typical well known gas conductivity form with electrical current increasing from zero in a sub-linear way and tending towards a saturation value as the applied voltage is increased [4,5]. Expression (9) was used to fit the experimental data. Particularly, the model predicts a saturation value proportional to Z_m for sufficiently high electric fields, see Eq. (12). Experimental saturation values taken from Fig. 1 are represented in Fig. 2 as a function of Z_m clearly showing the expected linear dependence.

Experimental curves similar to those in Fig. 1 were obtained for dry air irradiated at 0.2, 2, 20, and 200 Gy/s and fitted using expression (9). This is shown in Fig. 3. From these fittings the lifetime was calculated in arbitrary units as a function of dose rate. This is represented in Fig. 4 where the dependence on the square root of dose rate is clearly shown, in agreement with Eq. (8).

Dry air and SF6 were irradiated at 1 Gy/s and the voltage and electrode separation were varied. Both experimental data and theoretical fittings are shown in Fig. 5 for a voltage applied of 3 kV. The current increases with increasing electrode separation, then reaches a maximum and decreases for larger distance.

The behaviour with pressure can be seen in Fig. 6 where data for dry air irradiated at 0.02 Gy/s at 1 and 3 bar respectively are shown. One sees that for voltages less than 35 V the current is higher for air at 1 bar than at 3 bar, but at higher voltages the situation reverses.

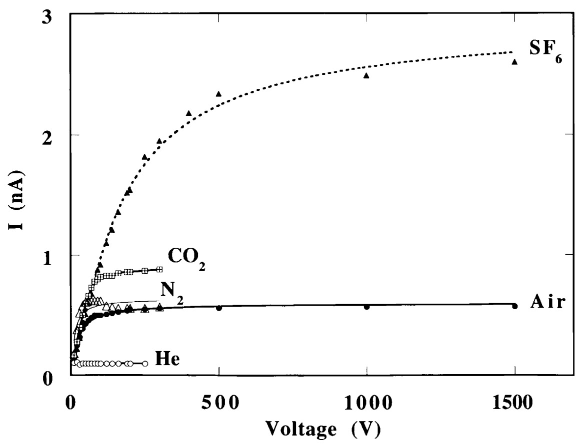

Fig. 1. Radiation induced leakage current at 0.02 Gy/s as a function of voltage for different gases, together with theoretical fits.

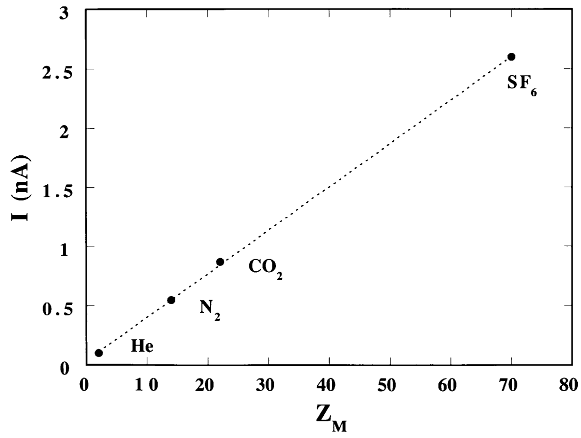

Fig. 2. Radiation induced leakage current at saturation as a function of molecular atomic number for the data shown in Fig. 1.

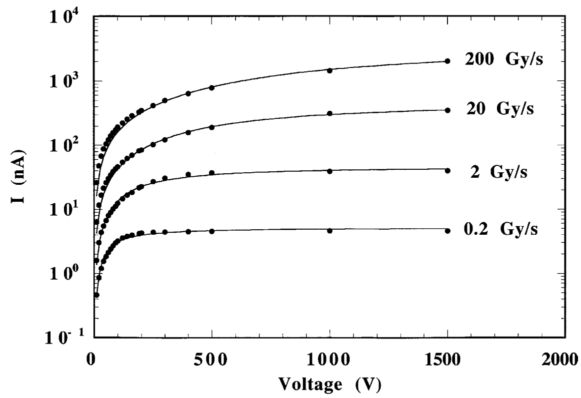

Fig. 3. Radiation induced leakage current as a function of voltage for air irradiated at different dose rates with theoretical fits.

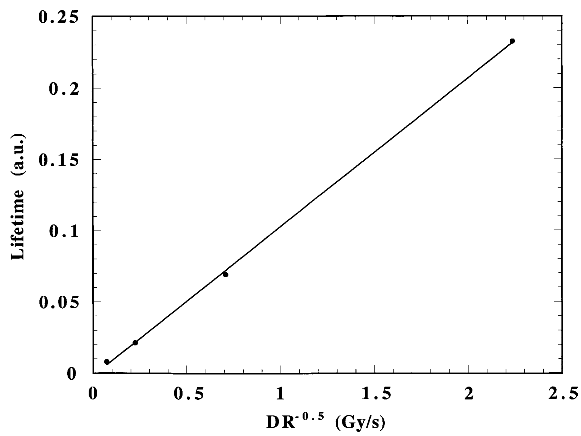

Fig. 4. Electron–ion pair lifetime for air as a function of the square root of dose rate.

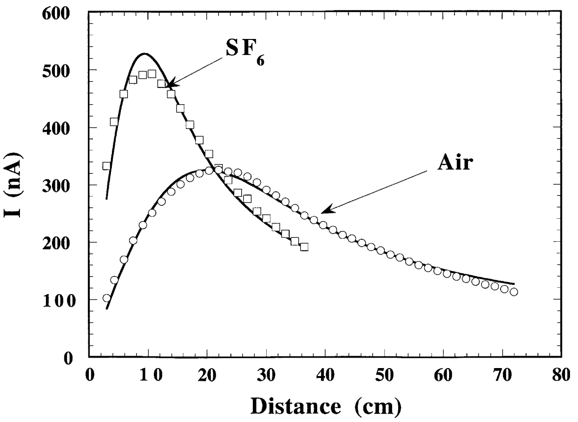

Fig. 5. Radiation induced leakage current for air and SF_6 irradiated at 1 Gy/s as a function of electrode separation at 3 kV, together with theoretical fits.

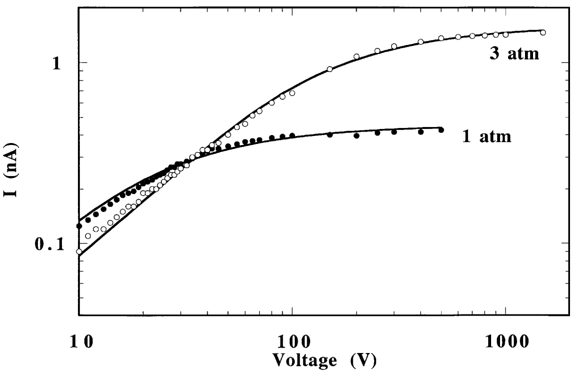

Fig. 6. Radiation induced leakage current for air irradiated at 0.02 Gy/s as a function of electrode voltage and pressure, with fits.

5. Discussion

The results shown in Fig. 1 are in good agreement with the model presented here. For high enough voltages saturation should be reached as all the electron/ion pairs produced by ionizing radiation reach the corresponding electrodes. This is expressed mathematically by Eq. (12). The model predicts that the saturation value is proportional to Z_m and ionizing dose rate. This agrees very well with experimental data as shown in Figs. 2 and 3.

The complex dependence on electrode distance observed experimentally is very well fitted and explained by the model (Fig. 5). For small electrode distances the current increases linearly with distance (all the electron/ion pairs are collected). As the electrode distance increases the electron/ion recombination process becomes more probable, the radiation induced conductivity reaches a maximum and then decreases as the inverse of electrode distance (Ohm's law for solids).

The behaviour with pressure can be seen in Fig. 6 where data for dry air at 1 and 3 bar and 0.02 Gy/s are shown together with model predictions. One sees that the current is higher for air at 1 bar than at 3 bar by a factor of about 1.7 ($\simeq\sqrt{3}$), as predicted by Eq. (11). Once the voltage is high enough the current measured is higher for the higher pressure, and we reach the $I \propto p$ regime (see Eq. (13)).

Despite the simplicity of the principles from which the model is developed, the dependence of the leakage current with important engineering parameters such as size (gas volume), dose rate, pressure, gas molecular weight and voltage (field) becomes extremely complex. The experimental data obtained are in good agreement with the theory, which enables one to predict with confidence the expected leakage current for the gas around the high voltage transmission line, ion source, and accelerator tube in the ITER NBI system. The results support the earlier experimental findings which indicated unacceptably large losses due to radiation induced leakage currents.

6. Conclusions

From simple principles a model has been developed which gives the radiation induced leakage current in gases as a function of voltage, electrode separation, pressure, molecular atomic number, and ionizing dose rate. Available experimental results are in excellent agreement with theoretical predictions, and hence enable one to predict with confidence the expected leakage current for the ITER NBI system, data for which is not readily available experimentally.

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