Determination of initial recombination of ions created in quasi-pulsed radiation fields

Mieczysław Zielczyński,
Natalia Golnik,
Michał A. Gryziński

Abstract. A new method is proposed for the determination of ion collection efficiency due to initial recombination process only, in a high pressure ionization chamber, operating in a quasi-pulsed radiation field. It is shown that the influence of undesirable volume recombination can be eliminated using a semi-empirical formula. The unknown function of the chamber polarizing voltage, included to the formula, can be found experimentally in the investigated radiation field, using the approach proposed in the paper. The function is the same for all radiation fields with similar time structure.

Key words: initial recombination • volume recombination • ionization chambers • pulse radiation

M. Zielczyński✉, M. A. Gryziński
Institute of Atomic Energy,
05-400 Otwock/Świerk, Poland,
Tel.: +48 22 7180037, Fax: +48 22 7180200,
E-mail: m.zielczynski@gazeta.pl

N. Golnik
Institute of Precision and Biomedical Engineering,
Warsaw University of Technology,
8 St A. Boboli Str., 02-525 Warsaw, Poland

Ion recombination in high pressure ionization chambers

There are three main processes influencing the ion collection efficiency in high pressure ionization chambers: initial (local) recombination, volume recombination and back diffusion of ions.

Initial recombination occurs between oppositely charged ions generated in the track of a single charged particle. Initial recombination dominates over other kinds of recombination at gas densities of at least several kg/m³, electrical field strength above 1 kV/m and the absorbed dose rate in the gas below ~ 1 Gy/h. The ion collection efficiency in the initial recombination process depends on linear energy transfer (LET) of ionizing gas particles and it does not depend on the dose rate, hence of its changes in time.

Volume recombination occurs between ions generated in tracks formed by different ionizing particles. It depends on the absorbed dose rate in the gas cavity, hence on the measured current i. It does not depend neither on particle energy, nor on LET and other parameters describing the radiation quality. This kind of recombination is a dominant process of ion recombination at high dose rates, in ionization chambers with large distance between electrodes and at low gas density. All the above factors are cross-correlated, i.e. the chambers with a smaller distance between electrodes can operate at higher dose rates or at lower polarizing voltage.

Back diffusion, i.e. the motion of some fraction of ions in opposite direction against the electrical field, depends only on voltage between electrodes and on the temperature, being independent of the dose rate, of LET and of the time structure of the radiation field. It

is assumed that the ion collection efficiency due to the back diffusion is also independent of the gas parameters (like pressure, molecular weight, composition). At room temperatures, the back diffusion of ions is essential at low voltages only (below ~ 5 V).

Initial recombination occurs in a very short time after formation of the charged particle track, until the ions diffuse from the track. The volume recombination takes place at all times of ion collection in the chamber. This means that the initial and volume recombination can be considered as consecutive processes, i.e. the ions that may recombine in the volume recombination process are those which have avoided the initial recombination.

Ion collection efficiency

Ion collection efficiency (absolute) f, is defined as the ratio of measured current i to the saturation current. Usually, it can be determined experimentally, but sometimes it is more convenient to approximate it by a relative ion collection efficiency, which is the ratio of the ionization current measured at a voltage U, applied to the chamber, to the current measured at the maximum voltage which can be applied to the chamber. The maximum voltage is the voltage above which the multiplication of ions and unwanted dark currents are considerably high.

The ion collection efficiency in the ionization chamber (and also the relative ion collection efficiency), can be expressed as:

$$(1) \qquad f = f_i \cdot f_v \cdot f_d$$

where f_i is the ion collection efficiency in the initial recombination process (f_i is the relative efficiency, if also f is the relative); f_v is the ion collection efficiency in the volume recombination process (at situations considered here value of f_v is the same also for relative ion collection efficiency); f_d is the ratio of the number of ions which avoided back diffusion to the ions available for the process.

High-pressure recombination ionization chambers [2, 5] are the detectors for mixed radiation dosimetry. Ion collection efficiency values $f_i(U)$, for the initial recombination process in such a chamber, are needed in order to determine the dose distribution vs. LET and the radiation quality factor, for the radiation with unknown composition. Therefore, a correction is usually necessary to eliminate the influence of the volume recombination and back diffusion of ions.

The portion of ions, which avoided back diffusion, is easy to derive from the formula of Langevin [3]:

$$(2) \qquad f_d = 1 - \frac{2k_B \cdot T_0}{eU} + \frac{2}{\exp(U / k_B \cdot T_0 - 1)}$$

where k_B is Boltzman's constant; e – charge of an electron; T_0 – absolute temperature.

More difficult is to eliminate the influence of the volume recombination. For steady radiation, the ion collection efficiency in the volume recombination process f_{vs}, at a given polarizing voltage U, can be expressed [1] as:

$$(3) \qquad f_{vs} = \frac{1}{1 + \dfrac{a \cdot i}{U^2}}$$

For pulse radiation with the repetition time T, the ion collection efficiency f_{vp}, can be approximated by:

$$(4) \qquad f_{vp} = \frac{1}{1 + \dfrac{b \cdot T \cdot i}{U}}$$

where a and b are constants for a certain ionization chamber. For pulse radiation, the symbol i in the formula (4) is the mean ionization current, averaged over the repetition time. The coefficients a and b depend on the distance between electrodes, on the shape of electrodes and on the gas parameters (gas composition, purity, pressure). Relationship between these parameters and these coefficients a and b is poorly known, because the partial pressure of gas components are slightly changing during years due to diffusion through the chamber walls and connectors. More accurate is an experimental determination of the coefficients a and b for a definite ionization chamber. The coefficient a can be determined, using formula (3), from the measurements of the relative ion collection efficiency at different dose rates in a steady radiation field. The coefficient b can be determined using formula (4) from similar measurements as for the coefficient a, but performed in a pulse radiation field. Such measurements are usually performed in photon or electron radiation fields in laboratory conditions.

Definition of quasi-pulsed radiation

The term "pulse radiation" is usually understood as a radiation field, which changes periodically with repetition time T, and with radiation pulse duration time $\tau < T$ (usually $\tau << T$). In order to specify the conditions, where formulas (3) and (4) can be used, the term "pulse radiation" should be defined more precisely. For the purposes of this work, the pulse duration time and the repetition time will be related to the ion collection time t_c, in the chamber considered. The radiation is classified as a pulse one, if the following conditions are fulfilled:

$$(5) \qquad \tau << t_c \leq T$$

If the ions, created in the gas cavity, are of different mobility, i.e. of different time of collection, then, the conditions (5) should be fulfilled for all the ions.

Any radiation field, in which the conditions (5) are not fulfilled, is called here a quasi-pulsed radiation. In some particular cases such radiation is classified as a steady radiation, i.e. formula (3) can be used for the determination of the f_v and for further corrections of the volume recombination influence. Such a case is when $t_c >> T$. In this case, the ionization current i in formula (3) is the mean current. Formula (3) can be used also when $\tau >> t_c$. However, in such case, the ionization current i should be considered as the current in the pulse duration time τ.

Volume recombination in quasi-pulsed radiation fields

In common case of quasi-pulsed radiation, also when there are both pulse and steady components of radiation or when the time structure of radiation is unknown – neither Eq. (3) nor (4) can be used. In our approach it is assumed that, in such cases, the ion collection efficiency in the volume recombination process can be approximated by:

$$(6) \qquad f_v = \frac{1}{1 + \dfrac{i}{F(U)}}$$

where $F(U)$ is an unknown function of the voltage applied to the chamber. The dependence of f_v on the measured current i, is the same, in the proposed Eq. (6), as in the earlier known formulas for steady (3) and pulse (4) radiations.

Ion collection time

Ion collection time t_c, in a parallel-plate ionization chamber can be determined from the relation:

$$(7) \qquad t_c = \frac{d^2}{k \cdot U}$$

where d is the distance between electrodes and k is the ion mobility. In typical ionization chambers, operating in saturation conditions, t_c is of the order of small fraction of seconds. It is usually much larger in a recombination chamber because it operates sometimes at low voltages and also because of higher density of the gas, hence lower ion mobility comparing to a chamber operating at low gas pressure. For example, t_c in the graphite recombination chamber KG-2 type ($d = 15$ mm) [5], filled with CO_2 up to the pressure of $p = 5$ MPa and operating at voltages below 3 V is of the order of minutes.

The same radiation field can be considered sometimes as a steady, pulsed or quasi-pulsed radiation from a point of view of the volume recombination in a chamber operating at different voltages. This is, of course, possible to consider such radiation field as a quasi-pulsed and to use universal formula (6) in the whole range of the polarizing voltages.

Determination of $F(U)$ and $f_i(U)$

In order to establish the functions $F(U)$ and $f_i(U)$ it is sufficient to perform measurements of the relative ion collection efficiency at different voltages applied to the chamber, at least at two levels of dose rate, in the investigated quasi-pulsed radiation field. If the radiation field is created by a pulse reactor – the different level of the dose rate can be achieved, e.g. by changing the reactor power. In radiation fields created by an accelerator, the absorbed dose rate in the chamber cavity can be changed (without changing quality and of time structure of radiation), e.g. using different intensity of ions injected into the accelerator. All the dose rates

should not be too high (volume recombination should be negligible at the highest voltage applied to the chamber) and also not too low (in order to avoid the influence of the radiation background, caused, e.g. by activation).

Combining Eqs. (1) and (6), for two levels of the dose rate, one gets a set of two equations for two values of i, with two parameters: F and f_i, to be calculated for each voltage U. No information is needed about the time structure of radiation, about configurations of chamber electrodes, or about the gas parameters. Solving the mentioned set of equations, one has:

$$(8) \qquad F = \frac{f_2 \cdot i_2 - f_1 \cdot i_1}{f_1 - f_2}$$

$$(9) \qquad f_i = \frac{f_1}{f_d} \cdot \left(1 + \frac{i_1}{F}\right)$$

where indices 1, 2 concern measurements at two different levels of dose rate. Ones established function $F(U)$ can be used for the volume recombination corrections at all measurements in radiation field of that time structure, also in different places, where the radiation quality can be different.

Accuracy of the $F(U)$ determination can be improved if more than two dose rates are used. The highest accuracy is usually achievable when $f_1 - f_2 = 0.03 \div 0.1$. Special attention should be paid during the measurements at low voltages, when corrections for the volume recombination are more essential. All side effects, affecting the electrical field strength in the chamber cavity (as contact potentials, input potential of electrometer, charge memory effect on the electrodes [5]) should be taken into account. The charge memory effect, observed after an exposition of the tissue-equivalent ionization chamber to high dose (of order of greys) can disturb the effective voltage between electrodes by more than 3 V. Influence of the zero displacement can be eliminated by making the measurements at both polarities, or (better) by establishing the value of the external voltage, at which the measured ionization current equals to zero.

Example of application

The proposed method and the relations (8) and (9) have been used to improve the accuracy of the $f_i(U)$ determination using the GW-2 recombination chamber (gas: 1.6 MPa CO_2, electrodes spacing: 8.5 mm) [5], using the data obtained earlier in the field of the pulsed fast reactor IBR-30 ($\tau = 50$ µs, $T = 0.16$ s) [4]. Saturation curves of the chamber, shown in Fig. 1, concern a reactor power ~ 0.5 kW, 4 kW, 20 kW and corresponding values of the current for the chamber operated at voltage 1000 V: 0.85 nA, 6 nA and 29 nA, respectively.

The function $F(U)$, calculated according to formula (8) and using the saturation curve mentioned above is shown in Fig. 2. The saturation curve $f_i(U)$ concerning the initial recombination only, obtained using formula (9) and numerical data of $F(U)$ are presented in Fig. 1 as the upper curve. The method used made it possible to extend the $f_i(U)$ curve to low-voltage region, where the volume recombination was very high, even at lowest
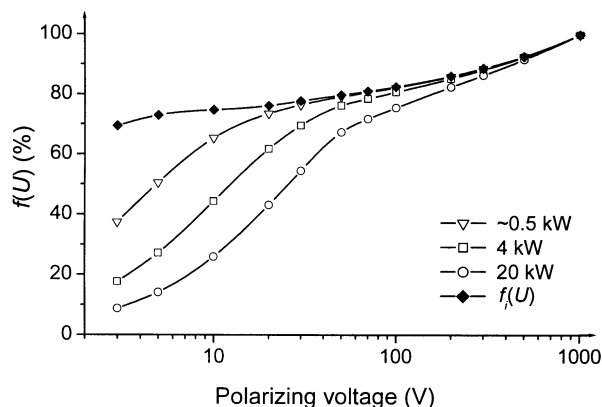
Fig. 1. Relative ion collection efficiency in GW-2 chamber in the beam of the pulsed reactor IBR-30.

dose rate. The obtained function $F(U)$ is proportional to U^2 in low-voltage region and nearly proportional to U above ~ 120 V. So, the radiation field of the IBR-30 reactor can be considered as a steady one at voltages below ~ 50 V applied to the GW-2 chamber, hence formula (3) can be used at such voltages. Above ~ 120 V, formula (4), concerning a pulse radiation, should be used. In the voltage range 50 to 120 V, values of $F(U)$ should be taken from Fig. 2. This does not contradict with the relation between the repetition time T of the reactor and the chamber's ion collection time t_c, calculated using estimated value of ion mobility in CO_2 at a pressure of 1.6 MPa.

Conclusion

The method presented makes it possible to determine the ion collection efficiency separately in the initial and in the volume recombination processes in gas of the ionization chamber placed in radiation field of any time structure. It is needed, however, to change the dose rate without changing the quality factor and the time structure of radiation.
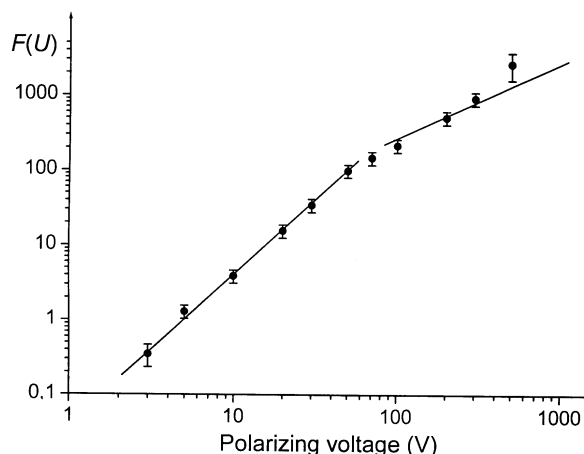

Fig. 2. Function $F(U)$ (concerning the volume recombination) calculated using the data from Fig. 1.

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