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Radiation enhanced dielectric breakdown in insulating gases for NBI systems

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Abstract

During the operation of future machines such as ITER, insulating gases in the NBI systems will be subjected to a radiation field of the order of 1 Gy/s and hence the electric field threshold for dielectric breakdown could be modified. Radiation enhanced dielectric breakdown has been studied for N_2, CO_2, N_2/CO_2 mixture, SF_6, and dry air at atmospheric pressure and 20 °C. Dry air, N_2, CO_2, and N_2/CO_2 mixture all exhibit moderate radiation enhanced breakdown, with a reduction in the limiting voltage between 5 and 18% at 20 Gy/s. In contrast SF_6 does not. Following breakdown N_2 and CO_2 show no quenching of the breakdown current until the applied voltage is reduced to almost zero. Both dry air and SF_6 are good in terms of quenching the breakdown.

Keywords: Radiation; Insulating gases; ITER; Dielectric breakdown; NBI systems

1. Introduction

High energy neutral beam injectors (NBI) require the use of some kind of gas contained within an earthed pressure vessel to insulate the high voltage transmission line, and depending on the final NBI design also the ion source and accelerator tube. During the operation of future machines such as ITER, this insulating gas will be subjected to a radiation field of the order of 1 Gy/s due to the plasma nuclear reactions and also from Bremsstrahlung radiation in the NBI accelerator itself. As a consequence of this, two different possible problems are foreseen for the gas. The first is radiation induced conductivity (RIC) which will give rise to power loss and heating due to an increase in the leakage current. This problem has recently been addressed, and shown to be of concern [1–5]. The second possible problem, related to radiation enhanced dielectric breakdown, has so far received little attention. The present paper examines this potential issue.

Conventional dielectric breakdown of the insulating gas due to the high electric fields is taken into account in the design of NBI systems, not only by smooth physical shapes but also by adequate separation. However, it is possible that the electric field threshold for dielectric breakdown of the gas will be modified by the presence of ionizing radiation due to the creation of free charge carriers (electrons and ions). The restrictions im-

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posed by this radiation enhanced dielectric breakdown have to be seriously considered in any design of the NBI system. In the work presented here, a study of the effect of ionizing radiation on the electric field threshold for breakdown has been carried out for N_2, CO_2, N_2/CO_2 mixture, SF_6, and dry air at atmospheric pressure and 20 °C. SF_6 and dry air are candidate gases for the high voltage transmission line, with N_2 also now being considered. Helium, CO_2, and a 3–1 N_2/CO_2 mixture as used in electrostatic accelerators, were included in the study for completeness.

The results show that dry air, N_2, CO_2, and a N_2/CO_2 mixture all exhibit moderate radiation enhanced breakdown with a reduction in the limiting voltage threshold by about 3 to 17% at 2 Gy/s. In contrast, for SF_6 there is no reduction. Following breakdown, both N_2 and CO_2 show no quenching of the discharge current until the applied voltage is reduced to almost zero, compared with dry air and SF_6 which exhibit good quenching.

2. Experimental procedure

The experimental work has been performed in a special gas chamber mounted in the beam line of a 2 MeV HVEC Van de Graaff electron accelerator. Different gases can be introduced into the chamber at atmospheric pressure, and then irradiated through a 0.05 mm thick aluminium window either directly with 1.8 MeV electrons or with Bremsstrahlung produced by stopping the electron beam in a gold target located just before the window. In this way radiation levels from about 0.02 to 20 Gy/s have been covered in the central volume of the chamber. To examine the effect of radiation on the voltage threshold for breakdown, an 0.4 mm spark gap consisting of a tungsten needle (negative electrode) pointing at a 4 mm diameter stainless steel hemisphere (positive electrode) was placed at the centre of the gas chamber. Six different gases or gas mixtures (N_2, CO_2, N_2/CO_2 3 to 1 mixture, SF_6, dry air, and He) were introduced into the chamber, and their dielectric breakdown behaviour studied at atmospheric pressure and 20 °C.

For each gas a DC voltage was applied across the spark gap, and increased until the electrical current was observed to rise catastrophically from zero as a consequence of dielectric breakdown. The system limited the discharge current to about 10^{-5} A to avoid excessive damage to the electrodes. This initial test was carried without irradiation to determine the breakdown voltage for the particular gas in the system. The measurement was then repeated during irradiation. In this way changes in the threshold for dielectric breakdown due to ionizing radiation were measured. At the on-set of dielectric breakdown the applied voltage was continuously reduced in order to study quenching effects.

3. Results

Figs. 1–5 show the breakdown curves for dry air, N_2, CO_2, N_2/CO_2 mixture and SF_6, respectively. In the case of He, breakdown was observed below 300 V and no further measurements were made for this noble gas. Data for the unirradiated gases are given together with the curves obtained at 2 and 20 Gy/s. Without irradiation the measured leakage current was essentially zero ($\leq 10^{-11}$ A) until the threshold voltage was reached, at which point the current increased immediately to the limiting current of 10^{-5} A. This point is indicated in the figures as a vertical line. The highest threshold without irradiation was for SF_6

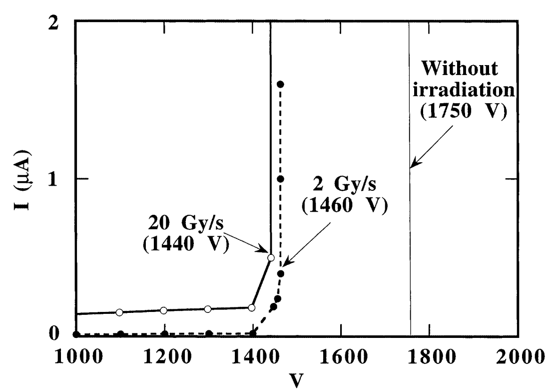

Fig. 1. Dielectric breakdown curves for dry air.

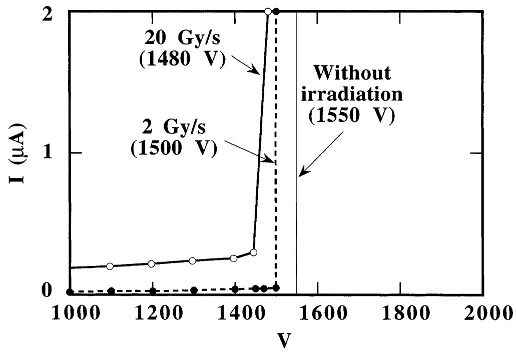

Fig. 2. Dielectric breakdown curves for N_2.

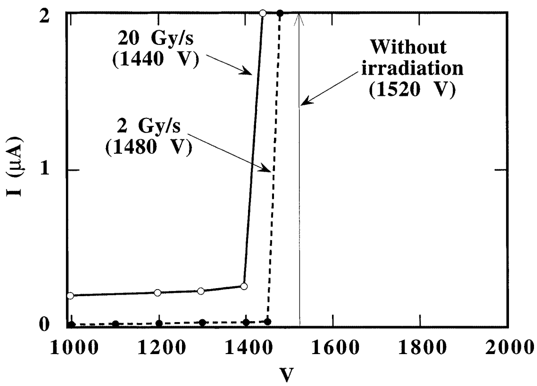

Fig. 4. Dielectric breakdown curves for $\frac{3}{4}N_2 + \frac{1}{4}CO_2$ mixture.

(2550 V) and the lowest for the N_2/CO_2 mixture (1520 V). In the presence of radiation, a small electric current proportional to the dose rate is observed even for low applied voltages due to the radiation induced conductivity of the gas [3,4]. On increasing the applied voltage, this leakage current increases slightly until the breakdown threshold is reached. The observed breakdown voltages are given in brackets in the figures. The highest threshold with irradiation at 2 Gy/s was again for SF_6 (2550 V) and the lowest for the dry air (1460 V). The voltage values measured are relative as they are system dependent [6], the more important relative decreases for all the gases or mixtures at 2 and 20 Gy/s are given in Table 1. A decrease in threshold for dielectric breakdown was observed for all the gases except SF_6. The largest decrease was for dry air (17 and 18% at 2 and 20 Gy/s, respectively). For N_2 and the N_2/CO_2 mixture, very similar results were obtained (3 and 5% at 2 and 20 Gy/s respectively), while CO_2 showed a decrease of 7 and 8% at 2 and 20 Gy/s, respectively.

Once dielectric breakdown had started the voltage applied was continuously reduced in order to study quenching effects. Following breakdown N_2 and CO_2 show no quenching of the breakdown current until the applied voltage is reduced to almost zero whereas for dry air and SF_6 the breakdown was immediately quenched if the voltage applied was reduced below the threshold value.

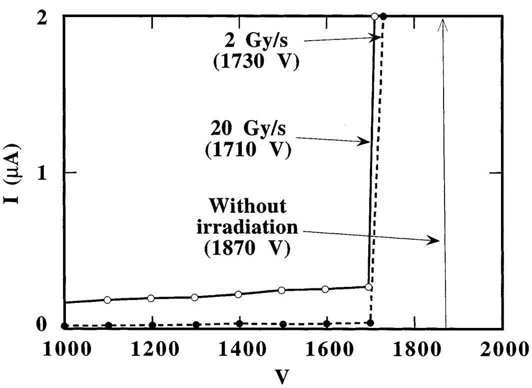

Fig. 3. Dielectric breakdown curves for CO_2.

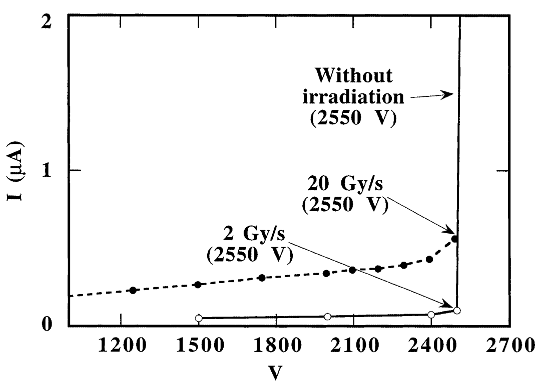

Fig. 5. Dielectric breakdown curves for SF_6.

Table 1
Relative decrease of the dielectric breakdown voltage as a function of ionizing radiation dose rate

	Dry air (%)	N_2 (%)	CO_2 (%)	N_2/CO_2 (%)	SF_6 (%)
2 Gy/s	17	3	7	3	0
20 Gy/s	18	5	8	5	0

4. Discussion

Under normal conditions, dielectric breakdown in gases results from an exponential multiplication of free electrons, known as Townsend avalanche [6]. The ever present free electrons are accelerated in the electric field gaining enough energy to ionize the gas atoms, and so produce further electron–ion pairs. In general the relative dielectric strength tends to increase with molecular weight, or effective atomic number 'Z' of the molecule, however other factors such as the ability to absorb energy in the collision or trap free electrons to form negative ions inhibiting breakdown, are also important. Fig. 6 shows the measured breakdown voltage for all the gases as a function of the effective Z. The general relative dielectric strength is observed to increase with Z for all the atomic and molecular gases (He, N_2, CO_2, SF_6). The gas mixtures (dry air, N_2/CO_2) deviate slightly from this.

Under ionizing radiation additional free electrons capable of triggering the avalanche are produced, and as a consequence the threshold for breakdown may be expected to decrease. For all the gases, except SF_6, a general decrease was observed in the breakdown threshold Figs. 1–5. The radiation enhanced dielectric breakdown observed does not depend strongly on dose rate. As may be seen, increasing the dose rate by a factor 10 only slightly decreases the threshold. The behaviour is very similar for N_2 and the N_2/CO_2 mixture as shown in Table 1. The marked difference between N_2 and dry air (approximately 80% N_2 and 19% O_2) should be noted. In the absence of radiation the dry air exhibits a considerably higher breakdown threshold. This is due to the high electron affinity of the O_2 molecule which decreases the electron mean free path quenching the breakdown process. However, under irradiation dry air and N_2 behave very similarly. This is most probably due to the fact that under irradiation some of the O_2 molecules are in an excited state decreasing their electron affinity.

Another important aspect of dielectric breakdown is quenching, the ability of the gas to recover from breakdown. In the case of dry air and SF_6 the quenching properties under irradiation were excellent, decreasing the applied voltage to only slightly below the measured threshold immediately stopped the current discharge. In contrast, N_2 and CO_2 showed no quenching, once discharge had begun the applied voltage had to be reduced to almost zero to stop the discharge. The N_2/CO_2 mixture showed intermediate quenching.

In the actual NBI system the appropriate insulating gas will be at high pressure, so far no data exists for radiation enhanced dielectric breakdown as a function of pressure. However, it is reasonable to expect that the relative effects observed remain unchanged, but further work should be done.

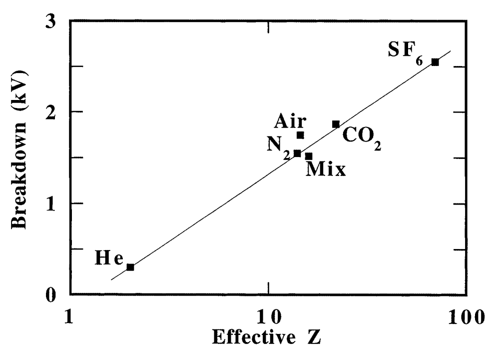

Fig. 6. Dielectric breakdown for all the gases as a function of Z.

5. Conclusions

For next step NBI applications, SF_6, dry air, and N_2 are being considered as possible insulating gases. SF_6 has shown the best behaviour in terms of dielectric breakdown. The threshold is the highest of all the gases studied here and moreover does not decrease in the presence of ionizing radiation. Furthermore, the breakdown is quenched when the voltage is decreased. Both dry air and N_2 show moderate radiation enhanced dielectric breakdown, and during irradiation their behaviour is similar, but N_2 shows almost no quenching of the discharge. The choice should therefore be between SF_6 and dry air. However, radiation induced conductivity of the insulating gases has also to be taken into account in the design of the NBI system. The radiation induced conductivity for SF_6 is about five times as high as dry air, and has been shown to be of concern [3]. The additional aspect of gas pressure remains to be addressed.

References

[1] E.R. Hodgson, 1st EU-Japan Workshop and 2nd ITER Technical Meeting on NBI, Naka, Japan, February, 1997.

[2] Y. Fujiwara, M. Hanada, T. Inoue, K. Miyamoto, N. Miyamoto, Y. Ohara, Y. Okumura, K. Watanabe, 1st EU-Japan Workshop and 2nd ITER Technical Meeting on NBI, Naka, Japan, February, 1997.

[3] E.R. Hodgson, A. Moroño, Radiation effects on insulating gases for the ITER NBI system, J. Nucl. Mater. 258–263 (1998) 1827.

[4] E.R. Hodgson, A. Moroño, Radiation induced power loss in insulating gases for ITER NBI systems, in Proceedings of the 20th Symposium on Fusion Technology, Marseille, France, 7–11 September, 1998.

[5] T. Inoue, K. Shibata, E. Di Pietro, Y. Fujiwara, R.S. Hemsworth, E.R. Hodgson, H. Iida, A. Krylov, P.L. Mondino, Y. Okumura, P. Bayetti, R.T. Santoro, Radiation analysis of the ITER neutral beam system, in Proceedings of the 20th Symposium on Fusion Technology, Marseille, France, 7–11 September, 1998.

[6] J.M. Meek, J.D. Craggs, Electrical breakdown of gases, Oxford University Press, London, pp. 1–79.