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# Radiation effects on insulating gases for the ITER NBI system

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## Abstract

The radiation induced leakage current in dry air and $SF_6$ has been measured as a function of dose rate, voltage, and electrode separation in order to assess the problem for the ITER NBI system insulating gas. The results indicate that for the high voltages involved, the leakage current is a function of the gas volume rather than the electrode separation. This leads to very high leakage currents for the NBI system, with power losses greater than 1 MW being predicted. The present results represent an extrapolation from 25 kV to 1 MV, and further work is under way to increase the experimental voltage and perfect a theoretical model to enable more reliable predictions to be made.

## 1. Introduction

In recent years considerable concern has been expressed about the possible radiation induced degradation of solid insulating materials under a fusion radiation environment, and by implication in those required for the ITER NBI accelerator system. However, in contrast little or no attention has been paid until very recently to the problem of the insulating gas which will be required around the NBI high voltage feed line, ion source and accelerator. This gas, in the present design $SF_6$, 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 gas 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, the radiation effect must be quantified and taken into account in the engineering design of the NBI system. To date this potential problem has received little attention, with the first results which indicated that a problem did exist being presented in [1,2], and further results in [3,4].

In this short paper the results for air and $SF_6$ are given. These show that the gas does not behave like a solid insulator, but that the leakage current (gas electrical conductivity) is a function of the gas volume. The extrapolated implications to the 1 MV ITER NBI scale indicate that megawatts of power could be lost due to this radiation induced leakage current. The full results for all the gases studied together with radiation enhanced breakdown data will be given in an extended paper [5].

## 2. Experimental procedure

Six different gases or mixtures ($N_2$, $CO_2$, dry air, $SF_6$, He, $N_2 + CO_2$) have been examined at atmospheric pressure and 20°C to determine their general behaviour under irradiation. Here only the results for dry air and $SF_6$ will be presented, extended results will be given elsewhere [5]. The experiments have been carried out in a special gas chamber mounted in the beam line of a 2 MeV an de Graaff electron accelerator, with the gases being irradiated through a $0.05 \times 10^{-3}$ 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 20 Gy/s have been covered.

Different 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 and

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applied voltage/field for a well defined guarded cubic volume ($3 \times 10^{-6}$ m$^3$) was measured to obtain absolute values. This guarded volume was defined between two parallel square copper plate electrodes separated by $1.5 \times 10^{-2}$ m. One of the square plates, $2.5 \times 2.5 \times 10^{-4}$ m$^2$, formed the common high electrode, while the opposite plate consisted of an inner $1.5 \times 1.5 \times 10^{-4}$ m$^2$ square central electrode and an outer square guard electrode separated from the central electrode by $2 \times 10^{-3}$ m and with an outside dimension equal to the opposite common electrode. Secondly, the effect of the radiation on the voltage threshold for electrical breakdown was determined, to be reported elsewhere [5]. Thirdly, the dependence of the gas conductivity on electrode separation was examined. This was performed using two circular cross section stainless steel bar electrodes of $6 \times 10^{-3}$ m diameter, which were varied in separation from $10^{-3}$ to $9 \times 10^{-3}$ m. For these three experiments the radiation beam was perpendicular to the electric field direction, and the radiation field within the volumes examined, uniform to within 15%. To obtain a well defined uniform irradiation volume, the electron beam was defocused and collimated by thick stainless steel collimators, which in the case of the guarded volume produced a $10^{-2} \times 10^{-2}$ m beam, and in the case of the bar electrodes produced beams equal in section to that defined by the bar electrode diameter and the electrode separation. The initial part of the work was carried out on gas volumes of approximately $10^{-6}$ m$^3$, and electrode separations of up to about $10^{-2}$ m. However in view of the results obtained, the measurements were then extended to dimensions of up to 1 m in order to be able to extrapolate the measurements made in the present work to the relevant NBI system size. To do this two $0.6 \times 0.6$ m$^2$ aluminium electrodes were employed. One of these electrodes with a $3 \times 10^{-2}$ 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 $5 \times 10^{-3}$ to 1 m. In the case of air the measurements were made continuously from $5 \times 10^{-3}$ to 1 m, and in the case of SF$_6$, which was contained within a telescopic chamber, measurements were made from $5 \times 10^{-3}$ to 0.35 m, and then fixed measurements at 0.5 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. In this case due to the divergence of the electron beam after passing through the aluminium window and in the air or SF$_6$, a divergent cone results, and the area covered by the beam increased with distance, being approximately 16 times greater at 1 m, and the ionizing dose rate 16 times less, as confirmed by radiation dosimetry in the irradiated volume carried with a standard ionization chamber and AEA Harwell red perspex dosimeters. However this divergence results in the product of the dose rate and the irradiated volume per unit length being constant, for any region parallel to the electrodes.

## 3. Results

Some of the initial results for the characterization of dry air and SF$_6$ measured in a guarded cell for different dose rates and applied voltages are given in Fig. 1. These show the typical well known gas conductivity form with the current increasing from zero in a sub-linear way and tending towards a saturation value as the applied voltage is increased [6,7]. The results indicate that at saturation the electrical conductivity for SF$_6$ is approximately five times higher than for dry air. Extended results [5] from 0.02 to 20 Gy/s show that the saturation level when reached, is proportional to the dose rate. It may be seen in the figure that at 2 Gy/s the SF$_6$ leakage current does not reach saturation for the maximum applied voltage of 1500 V, corresponding to 100 kV/m.

The radiation induced leakage current in dry air at saturation was then studied as a function of electrode separation. For the small distances involved, the current was observed to increase linearly with increasing electrode separation, as may be seen in Fig. 2 for two different dose rates. Measurements were then carried out for dry air and SF$_6$ at 1 Gy/s for electrode separations up to 1 m with applied voltages of from 3 to 25 kV. The measured conductivity/leakage current is a complex function of electrode separation and electric field strength, as may be seen in Fig. 3 for dry air. The leakage current increases with increasing electrode separation, but then reaches a maximum and decreases for larger distances. The height of the maximum increases with voltage, and moves to larger distance (electrode separation). In Fig. 4 data for dry air and SF$_6$ at 3 kV

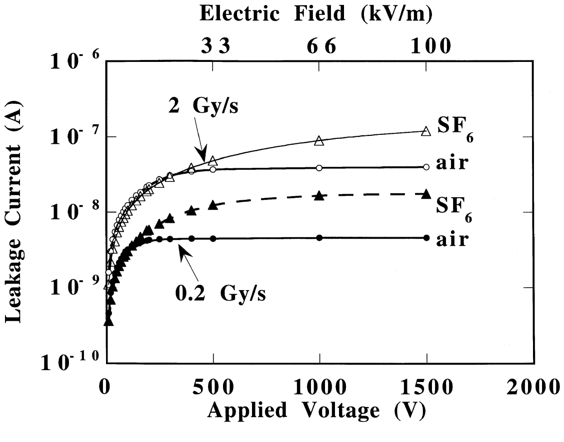

Fig. 1. Radiation induced leakage current as a function of applied voltage for dry air and SF$_6$ irradiated at 0.2 and 2 Gy/s. The irradiated volume of gas is $1.5 \times 10^{-6}$ m$^3$.

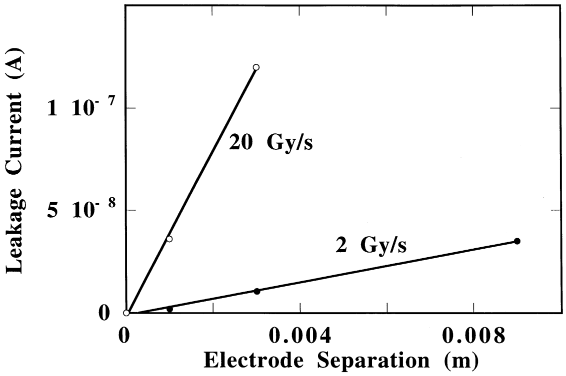

Fig. 2. Radiation induced leakage current for dry air with an applied voltage of 2 kV as a function of electrode separation.

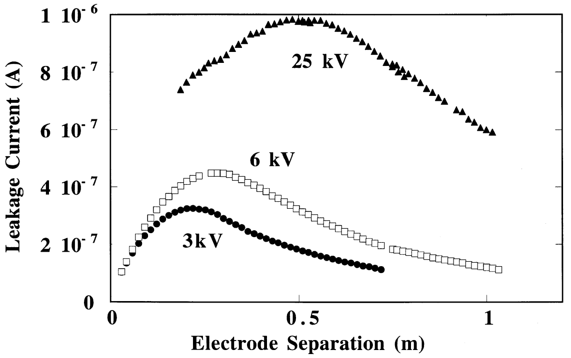

Fig. 3. Radiation induced leakage current for air irradiated at 1 Gy/s as a function of electrode voltage and separation.

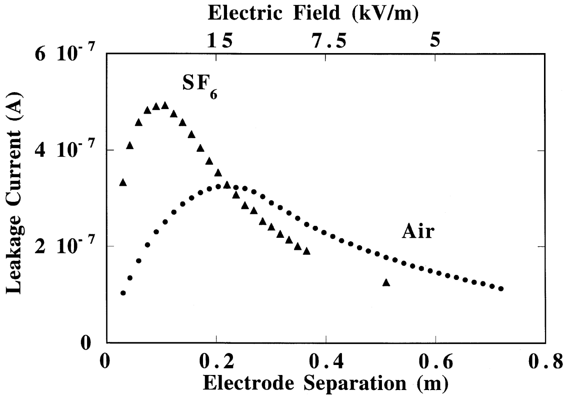

Fig. 4. Radiation induced leakage current for air and $SF_6$ irradiated at 1 Gy/s at 3 kV as a function of electrode separation.

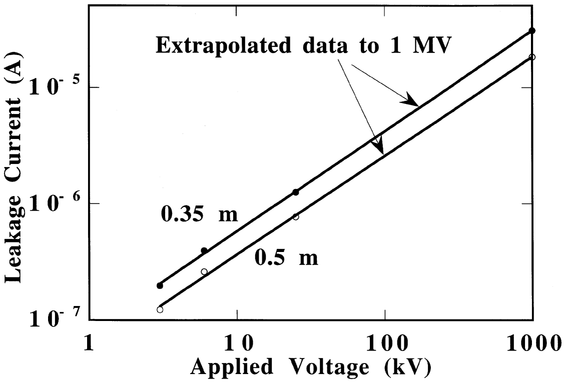

Fig. 5. Radiation induced leakage current for $SF_6$ irradiated at 1 Gy/s for electrode separations of 0.35 and 0.50 m as a function of applied voltage. The straight lines, of slope 0.85, are fits to the data at 3, 6, and 25 kV extrapolated to 1 MV.

are given. From the measurements it may be seen that both gases show a similar behaviour, but that the maximum for $SF_6$ occurs for a smaller distance, and that at large distances the $SF_6$ becomes the better insulating gas. In Fig. 5 data for $SF_6$ for electrode separations of 0.35 and 0.50 m as a function of applied voltage are given. These data points have been fitted and extrapolated to 1 MV.

## 4. Discussion

The results given in Fig. 1 indicate that both dry air and $SF_6$ for the range of ionizing dose rates of interest for the NBI system behave in a similar way, and present the well known form of saturation with applied voltage [6,7]. For low voltages the gas shows an near ohmic-like behaviour due to the dominance of charge recombination, but at higher voltages saturation is reached. The observation of saturation implies that the charge carrier lifetimes are large and for the geometry and distances used all, or a fixed proportion of the charge is being collected. The results also show that under the same conditions the saturation leakage current for $SF_6$ is approximately five times higher than that for dry air. The results given in Fig. 2 show that for the small volumes studied, the leakage current increases linearly with increasing electrode separation. Hence the gas conductivity cannot be expressed as for solid insulators in terms of Siemens per metre (S/m), but must be given in terms of total current per unit volume. This is a consequence of the long carrier lifetime. Even for the low voltage region below saturation, the behaviour is sub-linear [5] and the leakage current cannot be expressed in terms of conductivity. From these results, the extrapolated saturation leakage currents for dry air and $SF_6$ at atmospheric pressure and 1 Gy/s, were found to be about 0.013 and 0.065 A/m$^3$, respectively. This implies losses greater than 1 MW in the 1 MV NBI system insulator gas.

In view of this potentially serious problem, the possibility of collecting charge from outside the small bar electrodes distorting the results for the increasing electrode separation, and in general the very large extrapolation involved, the experimental work was then extended to permit gas conductivities to be measured during irradiation with large electrodes to cover the whole irradiated region, and for electrode separations of up to 0.5 m for $SF_6$ and 1 m for dry air. The results given in Figs. 3 and 4 show that the leakage current does not continue to increase as observed for small distances (Fig. 2), but reaches a maximum value and then decreases. These maxima correspond to a transition from the saturation region where charge recombination is small to the low electric field region where recombination begins to dominate. In this latter region the leakage current should decrease as $(\text{distance})^{-1}$, i.e. as in a solid insulator. The data in Figs. 3 and 4 follow such a trend. The available data for $SF_6$ at 0.35 and 0.5 m for 1 Gy/s are given in Fig. 5, extrapolated to 1 MV. From these results the predicted current for $SF_6$ at atmospheric pressure, 20°C, with 0.5 m electrode separation and 1 MV is $\approx 0.05$ A/Gy/s/$m^3$. This is in good agreement with the data for small electrode separations. For the size of the present ITER NBI system this would result in megawatts of power being lost.

It is important to note the practical experimental difficulties in obtaining a uniform irradiation field for such large electrode separations and volumes. In these experiments the irradiated volume was maintained within the volume defined by the two electrodes, but the dose rate decreased along the field direction. However for the 0.5 m case the dose rate only decreased from 1 to 0.25 Gy/s while the irradiated volume per unit length increased by a corresponding factor of 4. From the data given in Fig. 1 and the extended data available [5], for this dose rate range the leakage current (generated free charge) per unit volume is proportional to the dose rate. Hence it is reasonable to assume that the total charge generated per unit length is approximately constant, and that the results obtained are representative of those for a uniformly irradiated volume. It must be further pointed out that the results still represent a large extrapolation as the maximum applied voltage (25 kV) was $\ll 1$ MV. Leakage current for larger applied voltages must be determined. Furthermore the influence of gas pressure must also be assessed. An increase in the gas pressure will on the one hand increase the leakage current due to an increase in the number of charge carriers generated, but it will also decrease the carrier lifetime causing the leakage current to decrease. Work is underway to modify the experimental system to enable higher voltages to be applied to the electrodes and a theoretical model has been developed to provide more reliable estimates for the power loss [5].

## 5. Conclusions

Present available data indicates that large radiation induced leakage currents will be produced in the ITER NBI insulating gas system giving rise to unacceptably high power losses. This potentially serious problem has to be further examined due to the large extrapolations and experimental difficulties involved. Theoretical work underway will help to provide a more reliable data base.

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