ELECTRON MULTIPLICATION IN CAVITIES

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Summary

A computer program which simulates the multiplications of electrons in cavities using Monte Carlo techniques has been developed. This electron multiplication program has provided an understanding of the x-ray energy spectrum produced by cavities and of x-ray photographs taken of cavities at high fields. Also, this simulation has predicted two new effects: (1) an electron avalanche multiplication effect which is non-resonant in nature (as opposed to the well known resonant electron multi-pactoring), and (2) electrons produced in this way tend to form a low energy (on the order of 10 eV) electron cloud near the cavity major diameter.

Introduction

Superconducting accelerators and separators require the achievement of high electromagnetic fields in superconducting cavities. Electron loading in superconducting cavities with frequencies below about 2 GHz is the principal factor which limits the maximum fields achieved[1-4]. Some initial experimental observations on the x-ray energy spectrum produced by electrons impacting with the cavity walls and on the spatial distribution of the cavity x-radiation source suggested that multiplication of electrons in cavities should be investigated. Toward this end, a computer program which simulates electron multiplication in cavities has been developed. This simulation program has provided a more quantitative understanding of the experimental observations and has also predicted two new effects.

Initial Experimental Observations

Single and multi-cell superconducting niobium L-band TM_{010} mode cavities in the frequency range of 1.2 - 1.3 GHz excited to peak axial electric fields of about 10 MV/m are found to produce a large amount of x-radiation on the order of 100 mR/h at 1 m from the cavity[2]. Figure 1 shows the general shape and the electric field lines for a single-cell TM_{010} mode cavity. This cavity is about 20 cm in diameter and 10 cm in length. The electric field lines are principally parallel to the axis with a maximum field value at the axis and a decreasing value with increasing radius which goes to zero at the cavity major diameter. The magnetic field lines are circles around the cavity axis with a field value of zero at the axis and an increasing value of field with increasing radius. The individual cells of multi-cell cavities have similar dimensions and field distributions.

The x-radiation spectrum from a superconducting niobium cavity at 1.2 GHz with a peak axial electric field of 10.4 MV/m was measured using a 7.5 cm diameter by 7.5 cm long NaI(Tl) crystal scintillator, photomultiplier, and multi-channel analyser system. For the x-radiation energy range measured, the scintillator has a very high efficiency for producing a pulse in the photo peak region. The solid line in Fig. 2 (the dots are the experimental data) is a plot of the x-ray energy spectrum from the cavity viewed through about 3 mm of niobium, 5 mm of aluminum, 0.5 mm of iron, and 100 mm of helium liquid. The counting rate used in obtaining this spectrum was about 800 counts per second and the nominal pulse decay time was about 1 μs. Thus, chance coincidences

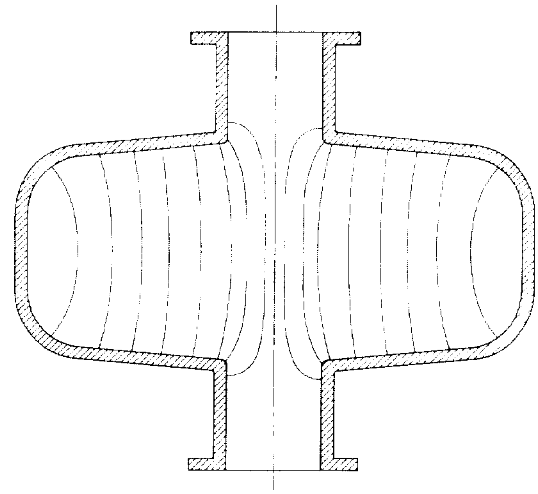


Fig. 1. Cross-sectional view of single-cell L-band cavity with electric field lines indicated by solid lines.

do not have any significant effect on the energy spectrum observed. One rather interesting observation is that, although the maximum energy an electron can achieve in one traversal of the cavity is about 0.55 MeV, electrons in excess of 1.0 MeV are impacting with the cavity wall in as much as x-rays in excess of 1.0 MeV are detected.

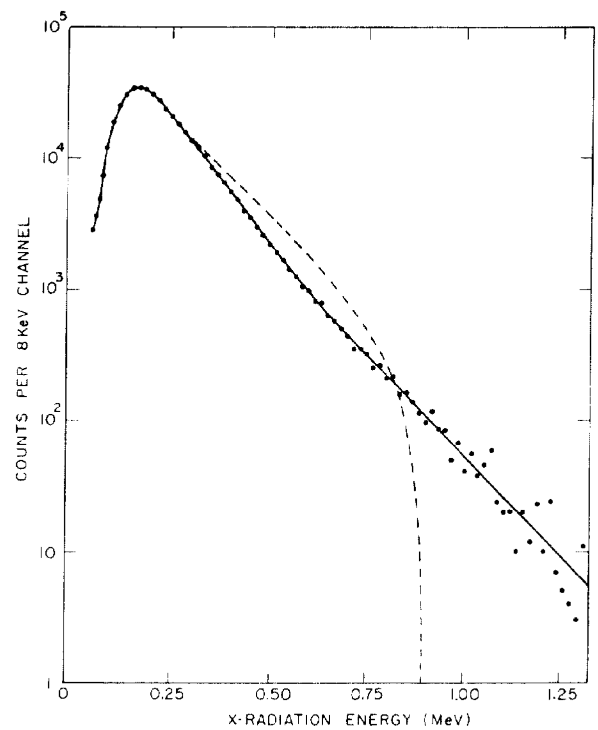
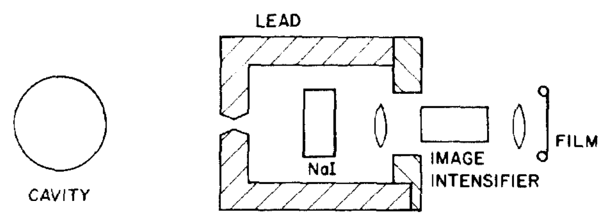


Fig. 2. X-radiation energy spectrum from a superconducting L-band cavity. The dashed line is a calculated x-radiation energy spectrum based on the electron multiplication simulation program.

Further observations on x-radiation from L-band cavities were made with the pin hole camera shown in Fig. 3. Here x-rays from a cavity were imaged by the 6 mm diameter pin hole onto a NaI(Tl) crystal block which converted the x-radiation into a very faint light image. This light image was then focussed onto the cathode of a four stage image intensifier tube and ultimately recorded on film[5]. An exposure took about 60 s, for an x-radiation intensity of about 25 mR/h at 1m from the cavity, and had an overall resolution of about 8 mm.



COMPONENTS OF γ-RAY CAMERA

Fig. 3. Schematic of the x-ray camera.

A typical x-ray photograph is shown in Fig. 4 and should be compared with the cavity shown in Fig. 1. The x-radiation intensity is axially symmetric and is concentrated on the cavity ends and beam pipes. The x-radiation intensity from the major radius is somewhat less than the cavity ends, but it is emphasized at the cavity equatorial plane where there is a thin region of niobium due to an electron-beam weld.

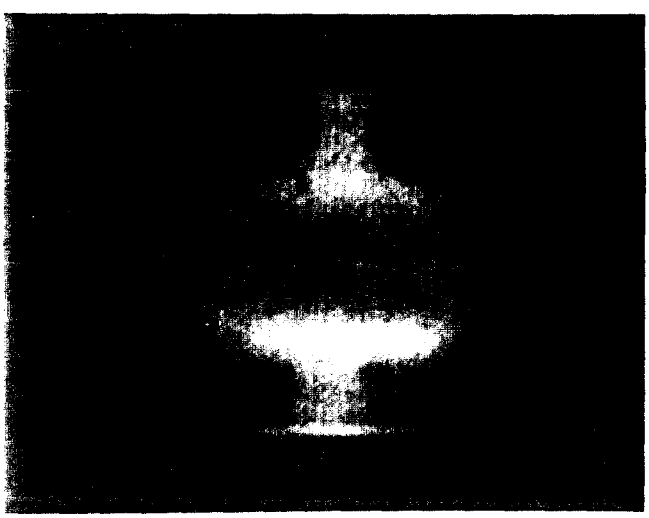


Fig. 4. X-ray photograph of L-band cavity shown in Fig. 1.

For technical reasons it was not possible to take x-ray photographs from a number of different directions of the cavity shown in Fig. 1. However, for another cavity without beam pipes, it was possible to take x-ray photographs with the axis of the cavity rotated at various angles with respect to the axis of the x-ray camera. These photographs shown in Fig. 5 again show that the x-radiation distribution was generally axially symmetric and that the x-radiation penetrating the cavity wall and dewar was much larger on the cavity ends, particularly nearer the cavity axis, than on the cavity major diameter. Although it is not clear in Fig. 5, a spot with about a 1 cm diameter on one cavity end shows a somewhat higher x-radiation intensity than its surroundings. There is no evidence in the photographs of a line x-radiation source one might naively expect from a point source of slow electrons due to a single electron field emitting projection.

The Electron Multiplication Simulation Program

These experimental observations have been investigated by means of an electron multiplication simulation computer program which uses the cavity fields calculated by the LALA program[6]. Given an initial electron the simulation program calculates by step integration the path of an electron through the cavity until it impacts with the cavity wall. A Monte Carlo estimate is then made of the number and momentum of any secondary particles, and these are followed in turn. The processes involved are secondary emission (production of slow electrons), backscattering (production of not more than one electron), bremsstrahlung (production of photons), and the photo-electric and Compton effects (production of electrons from bremstrahlung x-rays, which is very rare). Numerical values of the secondary emission and back-scattering are taken from references 7 and 8.

Figure 6 is a typical computer plot of the trajectories in z-r space of ten initial electrons and their second and higher generation electrons produced by the electron multiplication simulation program. In Fig. 6, the cavity interior is outlined by the vertical shading. The program produces the position and momentum of each electron on impact. To keep computing time and complexity of these plots within reasonable limits, an avalanche is normally stopped after 70 electrons have been produced. Typically about half of the initial electrons each produce at least 70 electrons for the conditions investigated. In general, electrons near the cavity axis tend to have high impact energies and electrons near the major diameter tend to have low impact energies.

A calculated x-radiation energy spectrum based on the electron multiplication simulation program was made for the conditions under which the x-radiation spectrum given in Fig. 2 was taken. Eighty-eight initial electrons were used in the calculation, and their initial position and phases reflected the belief that in this case field emitted electrons are the source of initial electrons. The eighty-eight initial electrons multiplied in number to a total of [illegible] impact electrons in excess of [illegible] keV. The x-radiation spectrum was calculated based on the energy and numbers of impact electrons, the use of thick-target bremsstrahlung production, and the absorption of x-rays by the cavity walls and dewar system[9]. The result of the calculation is shown in Fig. 2 as a dashed line. The agreement with the experimental results is quite satisfactory: the energy of the maximum x-ray counting rate is the same as the experimental data within 10 keV, and the calculated curve follows the experimental curve to within a factor of two out to 0.[illegible] MeV. The experimental decrease of the relative counting rate from 0.20 MeV to 0.75 MeV is a factor of 0.00[illegible], and

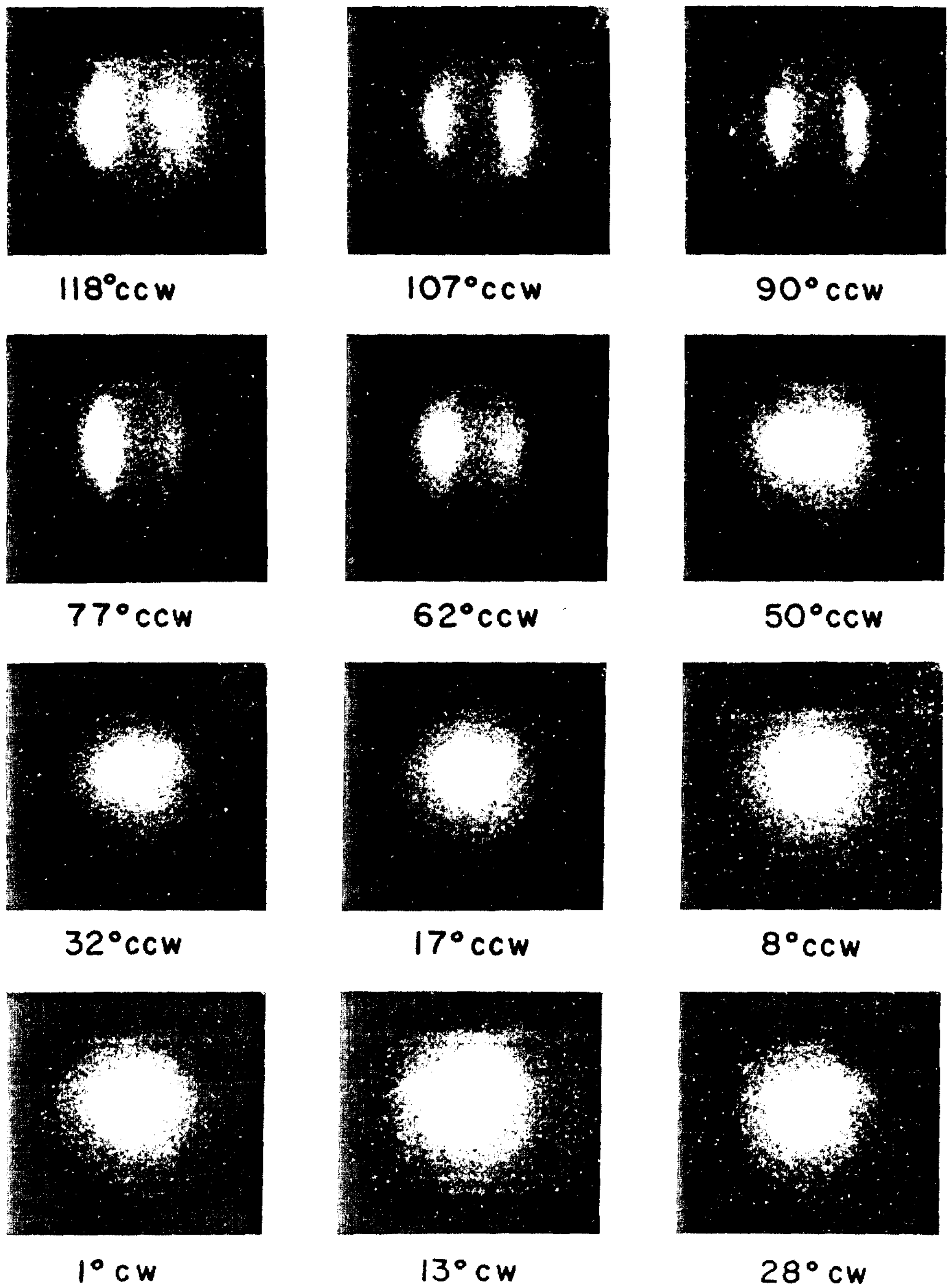


Fig. 1. Series of x-ray photographs from different directions of L-band cavity without beam pipes. The different photographs are for various angles between the cavity axis and the x-ray camera axis.

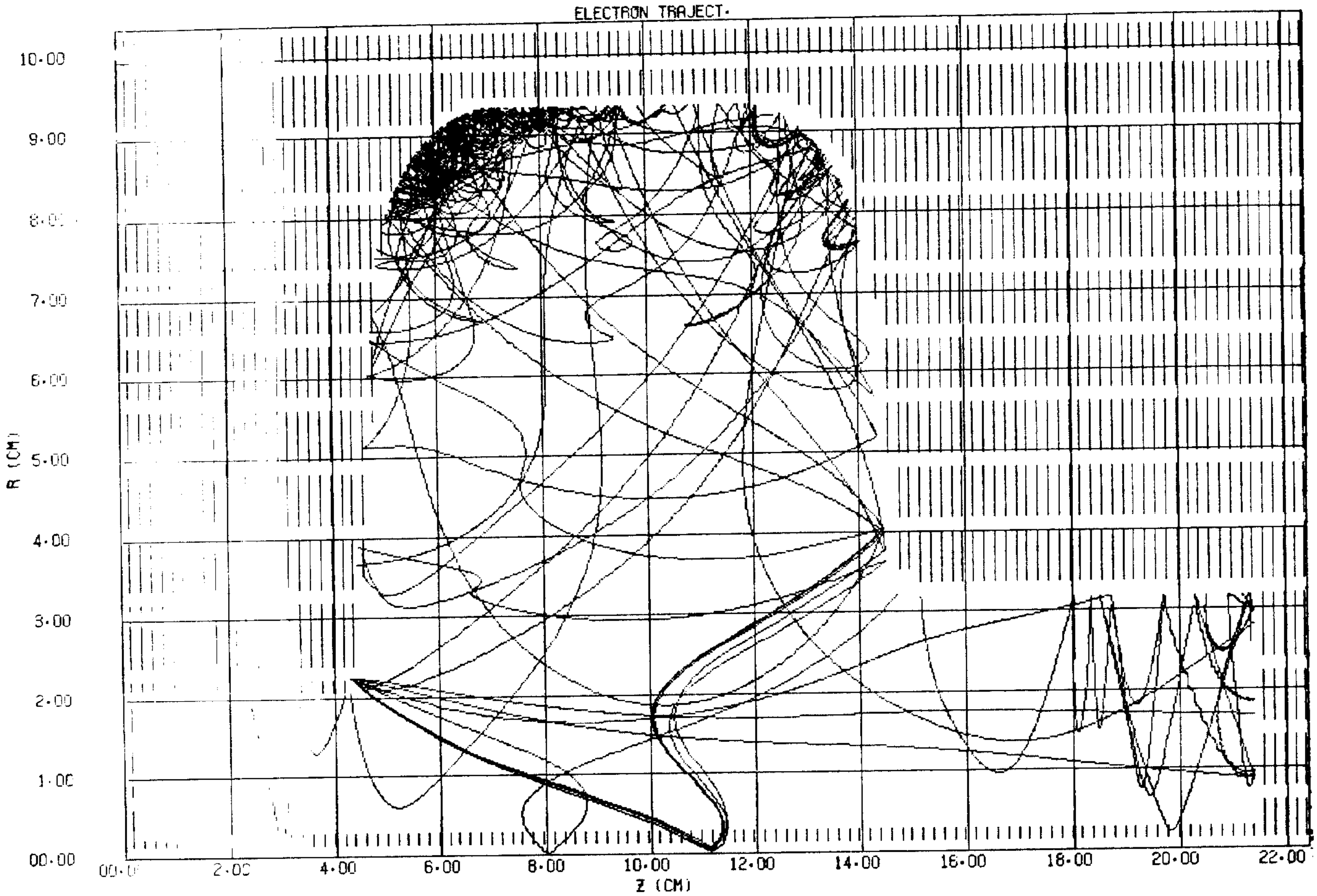


Fig. 6. A typical computer plot of the trajectories in z-r space of ten initial electrons and their second and higher generation electrons produced by the electron multiplication simulation program.

the calculated decrease is a factor of 0.016. It should be pointed out that the error of the calculated energy spectrum is quite large at the higher energies because, for example, there are only two impact electrons with energies greater than 0.75 MeV. The small number of electrons involved also explain the cutoff of the calculated energy spectrum at about 0.9 MeV. The highest impact electron energy was 0.89 MeV which is considerably higher than the 0.55 MeV an electron can achieve in a single cavity traversal. This higher energy electron is explained by back-scattering with rather low energy loss, and it achieved its total energy in about four cavity traversals.

The electron multiplication simulation program also satisfactorily explains the generally axially symmetric distribution of the penetrating x-radiation even if the source of slow electrons were from a single point. The trajectories of initially slow electrons lie in a plane defined by the cavity axis and the point source of electrons since the purely radial and longitudinal electromagnetic forces on the initially slow electrons completely dominate the trajectories. However, the simulation program shows that backscattering at higher energies, which can take the electrons out of this plane, is a dominant process for production of the most energetic electrons which are responsible for the penetrating x-radiation.

Two unexpected phenomena are predicted by the electron multiplication simulation program. First, there is an avalanche electron multiplication effect, which is non-resonant in nature (as opposed to the well known resonant electron multi-pactoring process). Second, the large quantities of electrons produced in this way tend to form a low energy (on the order of 10 eV) electron cloud near the major diameter of the cavity. Figure 6 shows an electron avalanche which is developing a low energy electron cloud.

While most of the simulation has been done for L-band cavities, simulations have also been made for S and X-band cavities. It appears at present that the avalanche effect is slower at higher frequencies. One simulation run was also made for an aluminum L-band cavity with a very thin niobium surface layer. This also seemed to slow down the avalanche effect.

Subsequent Experimental Observations

An attempt has been made to observe the presence of low-energy electrons near the cavity major diameter. A cavity with a 2.5 cm diameter hole located on the cavity major diameter was utilized to place a dc probe 5 mm in diameter about 2.5 cm away from the surface of the cavity. The current flowing to this probe could be measured as a function of applied dc voltage. During what was believed to be ordinary electron multipactoring, currents up to -300 μA were measured coming from the probe when 100 V was applied to the probe. This current decreased about a factor of 0.1 when the applied voltage was zero, which indicated the electrons typically had energies on the order of 10 eV. This result is consistent with the prediction that slow electrons are found near the major diameter of the cavity. However, at a higher field (a peak axial electric field of about 8 MV/m), where x-radiation was about 100 mR/h at 1 m from the cavity, an upper limit was placed on the current of about 10 nA.

Conclusions

It has been possible to develop an electron multiplication simulation program that (1) produces a spectrum of electron impact energies which in turn can be used to calculate an x-radiation energy spectrum which is in agreement with the experimental x-radiation energy spectrum, (2) shows the penetrating x-radiation intensity distribution to be axially symmetric and larger near the axis on the cavity ends which is in agreement with x-radiation photographs, and (3) predicts a cloud of low energy electrons near the cavity major diameter which is in agreement with experimental measurements with a dc probe. The simulation also predicts an electron avalanche at higher fields which has not yet been observed. Further experimental and theoretical investigations are planned.

Acknowledgements

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