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FURTHER NOTES ON THE MULTIPACTOR EFFECT

S. R. Farrell, RPC Industries, Hayward, Calif.
W. J. Gallagher, Boeing Aerospace Co., Seattle, Wash.

A former article [1] presented a brief summary of "classical" opposed surfaces multipactoring and some comments on suppression and utilization of the effect; this report is a further account of the history and some recent observations concerning the phenomenon.

In the previous paper it was shown that the principal condition for sustaining first order, opposed surface multipactoring (the largest effect) is

$$\left(\frac{d}{\lambda/2}\right)^2 = \frac{e V_o}{m_o C^2 \pi} \qquad (1)$$

where d is the gap spacing, having a cyclic voltage of freespace wavelength λ and amplitude V_o across it.

If an electron impinges on one of two opposed surfaces, causing the secondary emission of more than one electron on the average, a sustained charge exchange will occur between the surfaces if when at the moment of emission the applied voltage reverses and accelerates the secondaries to the opposite surface where a similar circumstance occurs. Additionally, if the primary electron impact results in a secondary emission coefficient (SEC, or δ) greater than unity, the charge exchange will grow as δ^m, m being the number of half-cycles since initiation, to a limit set by the "perveance" of the gap. This perveance may be interpreted that space charge forces drive electrons out of the phase interval in which the "resonance" phenomenon can occur. That phase range

$$0 \le \phi \le \arctan \frac{2}{\pi} \qquad (2)$$

is defined by the condition that electrons cannot have initial or final retrograde motion i.e., electrons are limited to motion within the gap ($0<z<d$).

The SEC is, understandably, characteristic of the surface material and primary impact energy, which latter has been shown to be, [1]

$$\frac{V}{V_o} = \frac{1}{2}\left(\frac{\lambda}{\pi d}\right)^2 \frac{e V_o}{m_o C^2} \qquad (3)$$

At steady state it is obvious that, owing to the allowable phase range of multipactoring, Eq. (2), and the SEC a fraction of electrons emitted, $(\delta-1)/\delta$ are continuously lost from the process at steady state.

While multipactoring has been the proposed operating principle of several devices [2] it is also the principal cause of failure for many others, so that considerable effort has been expended on its suppression. In the early post-war years, observations of multipactoring, based on diminished output power in klystrons, [3] led to investigations intended to lessen the effect. [4] That study included a proposal to rake cavity nose cones, on the supposition that electron trajectories would not fulfill the multipactoring condition when field lines were bowed. At the present time microwave engineers not familiar with the origin of the conventional 30° nose cone rake, Fig. 1, might suppose it was done to increase the shunt impedance of the gap.

Unhappily, an axial magnetic field is generally employed in such a system, counteracting the above argument, but the decrease of opposed area for the gap was nevertheless considered beneficial, since the total current involved would be less because the gap perveance was less. However, experience has shown that at certain critical values of magnetic field intensity strong multipactoring will still occur.

With the gradual increase in the output power of klystrons, during the late 1950's, the problem diverged; that is, the familiar two-surface multipactoring persisted and a new single surface form was recognized.

In the earliest investigations of RF windows, it was thought that heating, owing to dielectric losses, developed internal stresses in the material which cracked as a consequence. Experiments on high purity alumina (0.996) with high density, hot press preparation employing variations of peak and average power (by means of duty cycle) failed to provide a definite correlation so that both field emission and multipactoring came to be suspected as the cause of failure in contrast to heat stress. To counteract the consequences of the deposition of charge on the ceramic face by field emission, a thin sputtering (20-50 Å) of titanium was proposed, although most metallurgists were of the opinion that such thin sputterings would very soon break up into "islands" when coated upon broad faces and therefore be useless for draining off charge deposition. [5] It is, doubtless, obvious that multipactoring does not result in a net deposition of charge on the ceramic.

Single surface multipactoring was first described by D. Priest as a result of a study of high power ceramic window failures. [6] The mechanism in this case involves an electric field only, parallel to the surface (therefore dielectric) and since it does not require a specific gap length, will spread to cover a large surface, delivering an exponentially increasing amount of heat to the surface as the number of RF cycles increases.

Further types of single surface, crossed-field multipactoring have also been described by D. Priest, [7] where an RF electric field and static magnetic field exist parallel to a dielectric surface or where a normal RF electric field and parallel, static magnetic field exist on either dielectric or metallic surfaces. In both types the cyclotron frequency is involved in the multipactoring "resonance". In these latter types heating of the material is an important consequence because electrons are accelerated for a complete half-cycle before impact.

Obvious remedies to suppress multipactoring included coating the surfaces with a substance having a SEC less than unity and/or modification of the cavity geometry. Generally, such coating materials have a higher resistivity than the substrate; it was therefore proposed to sputter (vacuum deposit) a film thinner than a "skin depth". Proposed substances include titanium, [8] tantalum carbide, [9] titanium nitride, [10] rhodium, [11] carbon, [12] aluminum, lithium and beryllium, the four latter being objectionable because of chemical activity or very high microwave resistivity.

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To some extent effective is modification of cavity geometry; this includes the overall aspect of the cavity (boundary conditions) as well as texturizing the surface. R. Potier et al.[13] have proposed a scheme for multipactor suppression by means of small blind holes on the supposition that primaries do not impact normally and/or there is specular secondary emission. The above so-called "method of cylinders" technique has been extended to slotting nose cones and grooving surfaces.

There is experimental justification that grazing incidence of the primary produces a high secondary yield. The SEC as a function of incident angle from the normal, θ ,

$$\delta(\theta) = \frac{\delta_o}{\cos\theta} \tag{4}$$

δ_o being the SEC at normal incidence.

In the early 1960's it became apparent that future generations of high energy physics accelerators would be of stupendous size and consume unacceptable amounts of power to operate if some means were not found to provide higher electric field gradients at a moderate power cost. That consideration motivated investigation into the practicality of superconductivity, as well as high shunt impedance structures and RF power sources of improved efficiency.

The production of high gradients in superconducting cavities has proved more difficult than was presumed. Aside from the consequences of radiation pressure and the strange mechanical properties of materials at very low temperature, the unanticipated presence of electrons in the cavity limited the achievable field gradient by depleting the input power and producing heat on collision with the cavity walls, thereby also loading the refrigeration system. This electron loading, in addition, inductively de-tunes the cavity. The Q of a superconducting cavity seems also to be limited by other residual losses of obscure origin, but some of which are the result of high RF field levels. These latter have been separated into those which are the consequence of a magnetic field parallel to the surface and those a result of a normal electric field at the surface. Briefly, H-field effects are heating, leading to thermal breakdown; the E-field effects are considerably more complex, but are basically in the nature of field emission and multipactoring. Field emission has been variously thought of as being the result of microscopic metallic "whiskers" that grow in the presence of strong electric fields at low temperatures [14] or owing to the presence of dielectric dust.[15] In the late 1970's, as a result of temperature mapping of superconducting cavity walls by means of carbon resistors, it was supposed, reasonably enough, that regions of multipactoring were localized; that development led to modification of the overall cavity geometry to suppress multipactoring. Such designs are primarily the result of simulation codes for selected boundaries.[16]

It is well known that what is called secondary emission consists of both elastically (and inelastically) reflected primaries and true secondaries. As a result of electron microscopy research, it appears that the velocity dispersion of true secondaries is amazingly small (2 v. FWHM).[17]

It is, doubtless, evident that multipactoring, as the name implies, is a resonance phenomenon in conjunction with secondary emission, and that an understanding of it involves an elementary theory of the secondary emission process.[18]

If the number of secondaries produced by each primary in the target material in the length interval dz at a depth z is denoted n(z), and the probability for such secondaries to escape the surface from a depth z to be taken as f(z), the SEC,

$$\delta = \int n(z) f(z) dz \tag{5}$$

The integral extends over the thickness of the target, although it will emerge that only a very thin depth (100 Å) is involved in the process.

It is assumed hereafter:

(1) That primaries penetrating the material move in straight trajectories along the direction of incidence; reflections of the primary are neglected and normal incidence only is considered.

(2) The loss of energy by primaries per unit length is given by Whiddington's law

$$\frac{d E_p(z)}{dz} = -\frac{A}{E_p(z)} \tag{6}$$

where A is a characteristic of the material.

(3) The number of secondaries produced per unit length by a single primary is proportional to its rate of energy loss,

$$n(z) = \frac{1}{\varepsilon} \frac{d E_p(z)}{dz} \tag{7}$$

ε being the excitation energy to produce a secondary.

(4) The probability for a secondary produced at a depth z to escape from the surface is determined by an exponential absorption law;

$$f(z) = f(o)\, e^{-\alpha z} \tag{8}$$

where f(o) is the probability of escape at the surface (work function).

Integrating Eq. (6)

$$E_p^2(z) = E_p^2(0) - 2Az \tag{9}$$

from which the depth of penetration (range) of primaries results when $E_p(z) = 0$; that is,

$$z_{pmax} = \frac{E_p^2(0)}{2A} \tag{10}$$

which is to say that Whiddington's law predicts a primary range proportional to the square of its energy. From the foregoing remarks it follows that the production of secondaries as a function of depth,

$$n(z) = \frac{1}{\varepsilon}\sqrt{\frac{A}{2(z_{pmax} - z)}} \tag{11}$$

from which it is evident that most secondaries are produced near the end of the primary range.

Thus, Eq. (5) becomes

$$\delta = \sqrt{\frac{A}{2}}\ \frac{f(o)}{\varepsilon} \int_{o}^{z_{pmax}} \frac{e^{-\alpha z}}{\sqrt{z_{pmax}-z}} \qquad (12)$$

If δ_m indicates the maximum secondary yield at primary energy E_{pmax}, there results a universal curve,[19] Fig. 2,

$$\frac{\delta}{\delta_m} = 1.32\ \frac{E_p(0)}{E_{pmax}} \int_{o}^{z_{pmax}} \frac{e^{-\alpha z}}{\sqrt{z_{pmax}-z}}\, dz \qquad (13)$$

independent of the constants A and α which characterize the material. The integral may be shown by a substitution of variable $(z_{pmax} - z) = y^2$ to be Dawson's integral

$$F(z) = e^{-z^2} \int_{o}^{x} e^{t^2}\, dt \qquad (14)$$

(NBS Hndbk. of Math. Fns., Appl. Math. Series 55 (1964) p. 298) having a maximum at z = 0.92413 at which F(z) = 0.54104.

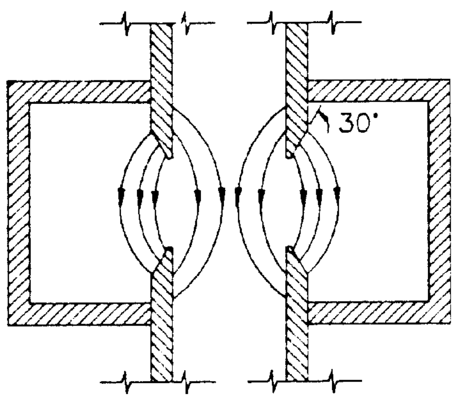

Fig. 1 RF Cavity with conventional 30° nose cone rake.

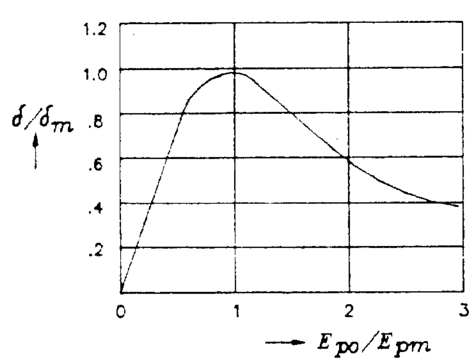

Fig. 2 Universal secondary electron emission function, eg(13).

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