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ELECTRON WIND IN STRONG WAVE GUIDE FIELDS*

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ABSTRACT

The x-ray activity observed near highly powered wave guide structures is usually caused by local electric discharges originating from discontinuities such as couplers, tuners or bends. In traveling waves electrons are shown to move in the direction of the power flow. Seed electrons can multipactor in a traveling wave, the moving charge pattern is different from the multipactor in a resonant structure and is self-extinguishing. Given sufficient primary sources, the charge density in the wave guide will modify impedance and propagation constant of the wave guide. An estimate is made of the radiation level inside the output wave guide of the SLAC, 50 MW, S-band, klystron. Possible contributions of radiation to window failure are discussed.

1. INTRODUCTION

Since the early sixties klystron windows have been coated with a very thin film of titanium in a more or less oxidizing atomsphere.[1] Somewhat later titanium nitride coated windows were advocated.[2]

The purpose of the coating has been two-fold: suppression of the multipactor and prevention of charge accumulation. Multipactor produces heat and charge accumulation produces electric stress and both could lead to window failure.

Figure 1 shows a section through the 50 MW klystron collector. Lately, a power splitter and recombiner has been mounted in the output wave guide, so that each of the two windows carry half the power and increase therefore the reliability.

At present, there is enough statistics to show that windows behave different depending on where they are mounted: on the tube itself, in the test ring or on the dummy load.

a) Tube windows run hotter than load- or test ring windows.

b) Tube windows fail more often than load windows.

c) Tube windows may fail in spite of successful ring test of several times the nominal power.

d) The power splitter on the klystron did not significantly reduce the failure rate.

The above gives the impression that window failure is also dependent on environmental influences. Now the x-ray intensity around the klystron, the output wave guide and the window is very conspicuous. Hence we set out to explore cause and effect in more detail.

2. MEASUREMENTS OF RADIATION LEVELS

Klystron

Figure 2 shows some results. A primary energy of 450 keV, which is about consistent with the klystron voltage of 315 kV is measured, if suitable absorbers are inserted.

The entrance of the wave guide is flooded by a continuum of photons, produced inside the klystron, and perhaps as high as 10^{11} photons per square cm per pulse. Hence alternate generations of photons, photo-electrons and secondary electrons could go "around the bend" of the wave guide and reach the window. Except for secondary emission in a restricted energy band, these processes have low quantum efficiency and are thus self-extinguishing.

Test Ring

The observed radiation levels are much lower in the test ring and shown in Fig. 3 for a circulating power of 100 MW. The test with absorbers shows that the x-rays are less hard than those observed on the klystron. A most interesting finding has been that weak localized magnetic fields applied on the wave guide some distance away from the window can influence the glow pattern on the window and may even provoke violent discharges on the window.

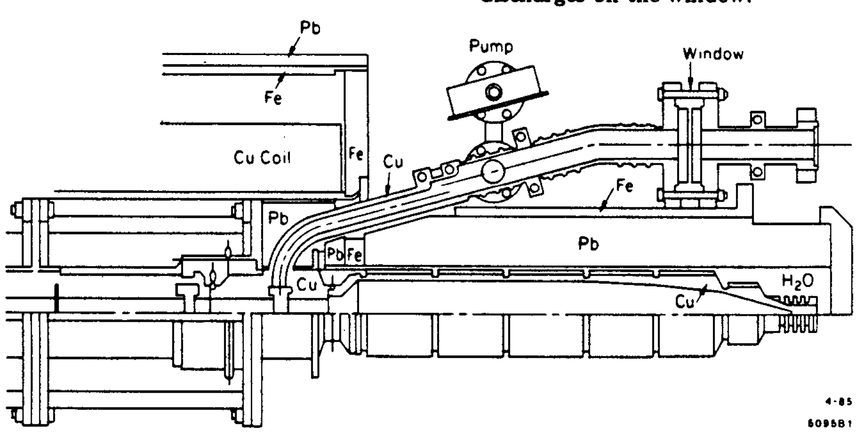

Fig. 1 Section of 50 MW klystron collector, output wave guide and window.

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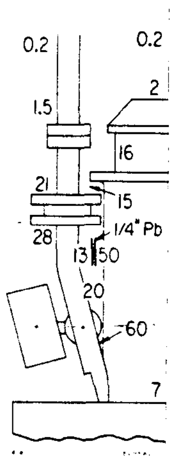

Fig. 2 Radiation level on SLAC-50 MW klystron. The numbers are in mR/hour.

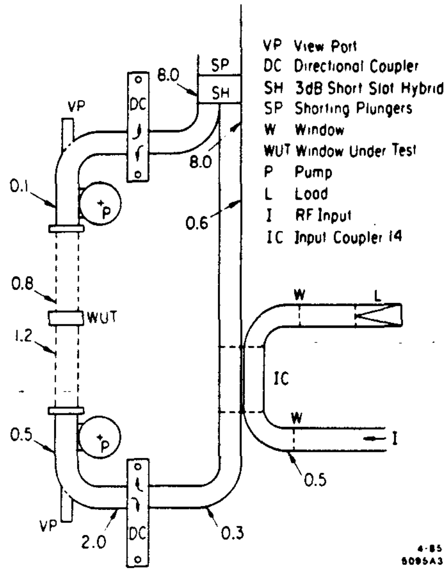

Fig. 3 Radiation level on window test ring at 100 MW RF power. The numbers are in mR/hour.

Thermoluminescence

Windows show distinct coloration on the area of the upstream side which corresponds with the rectangular section of the wave guide. Tests have shown that appreciable thermoluminescence occurs on the up– and not or less on the down stream side of the window. Quantification of the effect seems difficult since the ceramic is more or less opaque and the irradiation soft, so that surface saturation is reached already after several hours of ring test.

3. ELECTRON WIND HYPOTHESIS

The above observations can be explained by assuming inside the wave guide electron emitters. The most likely source for the output wave guide would be photo electric emission, but in the case of the test ring one should also suspect effects of dust collected during the frequent change overs.

The energy spectrum of the accelerated electrons has a cut off proportional to the RF power, so that the x-ray spectrum ends also there. It is close to 1 keV per MW power. The wall thickness of the copper wave guide is 2.8 g/cm^2. Considering the mass extinction coefficient of copper at, say, 40 keV of about 4.6 cm^2/g, only 2 ppm of the radiation can be detected outside the wave guide.

The kinematics of electron motion in a traveling wave shows an average drift in the direction of the power flow. Hence we must also suspect sources of radiation upstream from the point of detection. This leads to the belief that the window effectively stops some flow of charge which would prevail, given a distributed source of emitters all along the ring.

The intercepted electron wind will charge the window, since the semiconducting coating has a relaxation time constant comparable to the pulse duration. Thus electric stress builds up, which adds to the RF stress, possibly a major cause of electrical break down.

During the pulse space charge will build up. Now a space charge density of 10^8 electrons per cc would reduce the vacuum permittivity by one part in a thousand, thereby detuning the resonant ring! It would explain nicely the difficulty in keeping the ring tuned at high power levels and explains also the difficulty to obtain reproducible measurements.

Support for the electron wind hypothesis is found by applying weak localized magnetic fields along the wave guide ring. The localized fields tend to disturb the charge distribution, which persists up to the window. The equilibrium of the absorbed gas on the window is thereby disturbed, leading to light emission and vacuum pressure fluctuations. The ionized gas is probably a copious source for x-ray activity and occasional break down.

The above effect has been observed at all power levels down to 20 MW. For weak magnetic fields we have observed the establishment of a new equilibrium, resulting in the subsidence of the light emission. Most interesting has been the test with the localized magnetic field applied on the wave guide opposite to the window, proving that disturbances can take a 90 degree bend and the tuner as well.

The kinematics, see next section, show that electrons do not go far before hitting the wave guide wall again. Secondary emission would be essential to maintain a steady charge transport. Normally multipactoring is charge oscillation between two fixed locations in a RF standing wave. However in a traveling wave, our case, the same could happen if the locations are moving with the drift velocity. The only difference is that traveling wave multipactor must be *turned on*.

4. ELECTRONS AND PHOTONS

The vector potential $\vec{A}$ producing the TE 10 mode in a rectangular wave guide and the non-relativistic Hamiltonian H of an electron in the RF field suffice to describe the motion of the electron.

$$A_y = -(\hat{E}/\omega)\cdot\cos(k_1 x)\cdot\cos(k_3 z - \omega t)$$
$$2mH = P_x^2 + (P_y - eA_y)^2 + P_z^2$$

$k_1 = \pi/a$, a is the width of the wave guide = 72.1 mm. $\omega^2/c^2 = k^2 = k_1^2 + k_3^2 = 3576\ m^{-2}$, $\hat{E} = (4kWZ/(abk_3))^{1/2} = 67kV\ cm^{-1}$ for power $W = 50MW$, $b = 34.0\ mm$ is height of the wave guide, $Z = 377\ ohm$ is the vacuum impedance. Putting $\omega t = \tau$, $k_1 x = \xi$, $\omega y/v = \eta$, $k_3 z = \varsigma$, $\omega^2 v^{-2} k_1^{-2} = A$ and $\omega^2 v^{-2} k_3^{-2} = B$ yields the set

$$A\ \partial^2\xi/\partial\tau^2 = -\cos\xi_0\cos\varsigma_0\sin\xi\cos(\tau\text{-}\varsigma) + \frac{1}{2}\sin 2\xi\cos^2(\tau\text{-}\varsigma)$$
$$\partial\eta/\partial\tau = -\cos\xi_0\cos\varsigma_0 + \cos\xi\cos(\tau\text{-}\varsigma)$$
$$B\ \partial^2\varsigma/\partial\tau^2 = +\cos\xi_0\cos\varsigma_0\cos\xi\sin(\tau\text{-}\varsigma) - \frac{1}{2}\cos^2\xi\sin 2(\tau\text{-}\varsigma)$$

in which we assume the electron starts in (ξ_0, ς_0) at $\tau = 0$ and with zero velocity. The set can be solved numerically by the method of finite differences in τ. It appears that the dominant motion is in the direction of the electric field with an amplitude $2v$, where $v/c = e\hat{E}/(m\omega c) = 0.22$, so that the maximum energy an electron can have is about 52 keV for 50 MW RF power and is proportional to this power. The force in the x-direction is defocusing and the drift velocity in the z-direction is in first approximation $\langle\dot{z}\rangle/c = \frac{1}{2}(v^2/c^2)\cdot\cos^2 k_1 x$ and would be 2.4% in the center of the wave guide. Only a small fraction of the electrons may reach the maximum energy, before interception by the wave guide walls. Figure 4 shows the energy spectrum of intercepted electrons, assuming they started out at zero energy and were uniformly generated on the surface, for instance by photo electric effect. The tail electrons produce the x-radiation, one would eventually observe outside the tube or wave guide.

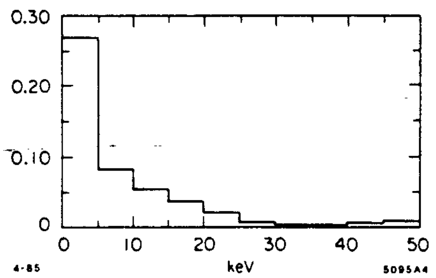

Fig. 4 Energy spectrum of intercepted electrons in wave guide at 50 MW RF power.

The relation between measured radiation level outside the wave guide and the energy spectrum of the electrons inside the wave guide is given by:

$$x = \frac{\Omega/(4\pi)}{5.49\ 10^{10}} \int_0^{\hat{E}} dE_\gamma \left\{ \eta_{air}(E_\gamma) \cdot E_\gamma \cdot \exp(-s \cdot \eta_{Cu}(E_\gamma)) \cdot \int_{E_\gamma}^{\hat{E}} dE_\beta \cdot f_1(\hat{E}, E_\beta) \cdot f_2(E_\beta, E_\gamma) \right\} \quad (Rs^{-1})$$

in which f_1 is the energy spectrum in keV^{-2} cm^{-2} s^{-1} of the electrons, which we give the dimension of a flux because of the dominance of the electron motion parallel to the electric field. $\hat{E}$ is the cut off energy determined by the RF power. f_2 is the energy distribution, in keV^{-1}, of bremsstrahlung and characteristic x-radiation of a single electron of energy E_β, so that the integral on the right displays the gamma spectrum inside the wave guide. The attenuation $(\Omega/4\pi) \cdot \exp(-s \cdot \eta_{Cu}(E_\gamma))$ multiplies for the gamma flux outside the wave guide, where η_{Cu} is the mass extinction coefficient and s the thickness of the copper. We assume that a flat fraction of the solid angle contributes to the external gamma flux, say, $\Omega = 1$ sterradian. The specific loss in air is then given by multiplying the external flux by $\eta_{air}(E_\gamma) \cdot dE_\gamma$ and integrating with dimension (keV g$^{-1}s^{-1}$). The Röntgen equivalent is 5.49 10^{10} keV g^{-1}, so that the end result is expressed in Rs^{-1}. Since f_1 has the shape of Fig. 4, the normalizing factor of f_1 is found with the above relation.

The electron density is now found with

$$n = 2 \int_0^{\hat{E}} \left\{ f_1(\hat{E}, E_\beta)/v_\beta \right\} dE_\beta \quad (cm^{-3})$$

where the velocity $v_\beta = (2E_\beta/m)^{1/2}$. The factor 2 is on behalf of the up– and down electron flux in the y-direction. Applying the above for external x-radiation of 1 mR/hour:

$$j_y = e \int f_1\ dE_\beta \simeq 10\ uA\ cm^{-2}$$

(intercepted current by wave guide walls)

$$W_y = e \int f_1\ E_\beta dE_\beta \simeq 0.08\ W\ cm^{-2}$$

(heat dissipation in wave guide)

$$n = 2 \int f_1/v_\beta\ dE_\beta \simeq 2.8\ 10^4\ cm^{-3}$$

(electron density in the center)

$$j_z = e\ n\ \langle \dot{z} \rangle \simeq 2\ uA\ cm^{-2}$$

(This is the *electron wind*)

5. CONCLUSIONS

Around the klystron one measures the hard x-radiation of, say, 450 keV, generated by the electrons hitting the collector. This signal usually swamps the soft x-radiation of, say, maximum 50 keV produced in the output wave guide. The origin of the soft component must be sought in the flooding of the output cavity with collector radiation, so that successive generations of photons, photo-electrons and secondary electrons are propagated towards the window. The drift imparted to the charges helps to overcome kinks and bends in the wave guide.

Measurements around the test ring show that a soft component of, say, 1 mR/hour is probably detrimental to the klystron performance. For instance the heat dissipation W_y may be comparable to the RF losses in the wave guide, $W_{RF} = 1.345\ W\ cm^{-1}$ (linear). The charge density n is a factor 1000 higher because of the duty cycle so that detuning effects are probable. A non-conducting window will charge up and repel the oncoming electrons, j_z, so that the ceramic will be electrically stressed. A sufficiently conducting coating on the window will remove the electric stress but may cause too much Joule heating due to the RF wave.

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