ENVIRONMENTAL INFLUENCES CONTRIBUTING TO WINDOW FAILURE
OF THE SLAC 50 MW KLYSTRON*

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1 INTRODUCTION

Klystron windows behave differently depending on where they are mounted: on the tube itself, in the test ring or on the dummy load.

- i) tube windows run hotter than load- or test ring windows
- ii) tube windows fail more often than load windows, but statistics is low.
- iii) tube windows may fail in spite of successful ring test of several times the klystron peak power.

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 ON THE KLYSTRON

The X-ray levels were measured with the SLAC Scintillation Survey Meter, consisting of 1"x1" cylinder of As doped plastic scintillator NE 105 mounted on a 4162B photomultiplier. The response seems to be flat down to ≈ 10 keV, and degrading quite fast below. The integrating pocket dosimeter type Landverk has been used as well. Its small fiducial volume, 2 cc, localizes the levels somewhat better and provides better averages. The response is not very well known, but considering an estimated density of the enclosure of 0.4 g/cm^2 for the stainless steel version and half that value for the aluminium version, the response should fall off below 30 keV.

FIG.1 shows some results. In one measurement a $\frac{1}{4}$ inch lead plate has been inserted between the 2 inch lead mantle of the klystron and the window, in order to estimate the hardness of the radiation.

The bulk of the radiation originates in the collector, the reduction by a factor 4 of the lead plate, 6.6 g/cm^2 , suggests a mass extinction coefficient of $0.21 \text{ cm}^2/\text{g}$. this would agree with a primary energy of 350 keV, which is about consistent with the klystron voltage of 315 kV. Note that a similar leadplate, with a pocket dosimeter on either side, was positioned away from window and wave guide. The reading 39/9 mR/hour was essentially the same, see FIG 1c.

On opened-up klystrons one observes considerable electron impact on the junction between output cavity and collector, erosion and recrystallisation. Hence the output cavity should be an appreciable source of X-rays, and, due to the wave guide penetration in the shielding, the monitors nearby show large doses.

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The radiation level on the window due to the direct hard radiation from the klystron is not high enough to fear damage: one needs mega-rads for this, whereas we find at the most 30 mR/hour.

On the other hand there could be a high intensity soft X-ray component inside the wave guide. 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. This number is based on a radiative yield of 2 parts in a thousand, an average photon energy of 150 keV and an effective collector area of 400 cm². Hence alternate generations of photons, photo-electrons and secondary electrons could go "around the bend" of the wave guide and reach the window. These processes have low quantum efficiency and are thus self-extinguishing, so that not much energy would reach the window, estimated below 1 watt. However,

the window could charge up, adding electric stress to the RF stress, which is presumably already limiting.

At this stage we do not rule out any damaging effect by radiation originating from the klystron, however, we also find X-rays around the test ring, but the klystron which drives the test ring is too far away to be responsible for the observed levels.

3 MEASUREMENTS ON THE WINDOW TEST RING

FIG. 2 shows the schematized layout and some radiation levels measured with the Survey Meter. Table 1 shows some radiation levels on the up- and down stream side of the window, measured with the pocket dosimeter. About 10 windows were surveyed. Typically the power goes up in discrete steps, lasting 15 minutes each, to the maximum power and 2 micro second pulse duration. This is followed by one at 6 micro second. The rate has been 180 pps. The maximum power has been in most cases 100 MW.

The following general observations were made:

- i) 15 minutes integrations were too short to make readings on the Landverks if the power was below 80 MW
- ii) the radiation level on the wave guide adjacent to the window, up to 15 cm either side, was considerably higher than on other parts along the wave guide ring, often by a factor ten.
- iii) near the tuner we found the same effect ii).
- iv) the radiation level was a steep function of power, see FIG.3
- v) repeated measurements showed large fluctuations, by an order of magnitude.
- vi) a strong correlation exists between radiation level, vacuum pressure and the glow on the window.
- vii) intentionally provoked light flashes (with a small magnet, see later) were accompanied by radiation bursts.

4 ELECTRONIC WIND HYPOTHESIS

The above observations can be explained by assuming inside the wave guide electron emitters. A favourite would be field emission, but any of the prerequisites for vacuum break down would do, such as the clump, particle exchange or thermal instability mechanisms.

The peak electric field at 50 MW RF in a standard wave guide is 67 kV/cm, not high enough for field emission. However field enhancement due to dirt, dust, whiskers by two orders of magnitude is known to exist and that would be sufficient. Another suggestion would be RF heating to incandescence of lossy dirt particles, may be carbonized fibers. A loss angle of 0.01 would do the trick.

The energy spectrum of the accelerated electrons is proportional to the RF power. At 50 MW it peaks at about 13 keV and the cut-off energy is 52 keV, so that the X-ray spectrum ends also there. The wall thickness of the copper wave guide is 1.8 g/cm^2 . Considering the mass extinction coefficient of copper, Tab.2, not much radiation can be detected outside the wave guide. This explains i) and iv).

The detected radiation must be produced locally, say, within one solid steradian around the perpendicular on the wave guide walls. Hence we find more radiation near the tuner and the window, because of the localized standing wave. This explains ii) and iii).

However 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. This also contributes to point ii).

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

The interception hypothesis reduces the emphasis for multipactoring, since, for this process to take place, the window needs to be positively charged. However one could have a hybrid: the central part of the window is negatively charged because of the intercepted electronic wind, which is too high in energy to expect a secondary emission coefficient larger than unity and the periphery of the window is positively charged because of energetically possible multipactoring. Clearly, this worsens the electrical stress problem!

During the pulse, space charge will build up in front of the window, deflecting oncoming electrons to the walls. 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, point v). It seems that we have here a potential avenue to explore pulse duration effects, using photo multipliers or looking at the RF structure in more detail.

Support for the electronic 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 adsorbed gas on the window is thereby disturbed, leading to light emission and vacuum pressure fluctuations, point vi). The ionized gas is of course a copious source for X-ray activity and occasional break down. This would explain vii).

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.

Windows taken out from XK5 tubes with many service hours, show distinct coloration on the area of the upstream side which corresponds with the rectangular section of the wave guide. Tests are under way to find out if thermo-luminescence occurs on the up- and not or less on the downstream side of the window.

At comparable RF power, the tube window runs hotter than the test ring window. If we believe that impacting electronic wind is responsible, then the contribution to the tube window must be comparable to the other heat sources, enumerated in my note January 6, 1984. Say, 10 to 20 watt. The contribution to the test ring window should be less, perhaps by a factor 10. The heat cannot be nil, because of the correlation 3 vi. Note that the equivalent of 20 Watt would be 7 E13 electrons of 10 keV average energy per pulse.

Whereas dust in the test ring is a plausible source for electron emission, the electron sources in the klystron must be due to high X-ray levels at the entrance of the wave guide. 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 KINEMATICS OF ELECTRONS IN WAVE GUIDE

The vector potential producing the TE_{10} mode in a rectangular wave guide has a single component in the y- direction

$$A = -(\hat{E}/\omega) \cos k'x \cos(kz - \omega t)$$

From this we obtain

$$E_y = -\partial A / \partial t = \hat{E} \cos k'x \sin(kz - \omega t)$$

and $\vec{B} = \text{curl } \vec{A}$, thus

$$B_x = -(k\hat{E}/\omega) \cos k'x \sin(kz - \omega t)$$

$$B_z = (k'\hat{E}/\omega) \sin k'x \cos(kz - \omega t)$$

$\hat{E}$ is the amplitude of the electric field in the center of the wave guide; $\omega^2/c^2 = k^2 + k'^2$; $k' = \pi/a$ and a is the width.

The non-relativistic Hamiltonian reads:

$$2mH = P_x^2 + (P_y - eA)^2 + P_z^2; m \text{ is the mass and } e \text{ the charge.}$$

H is the kinetic energy and the equations of motion are:

$$\dot{x} = (\partial H / \partial P_x) \text{ etc. and } \dot{P}_x = -(\partial H / \partial x) \text{ etc.}$$

$$\dot{P}_x = e(\partial A / \partial x)(P_y - eA)/m = e(\partial A / \partial x) \cdot \dot{y}$$

$$\dot{P}_y = 0$$

$$\dot{P}_z = e(\partial A / \partial z)(P_y - eA)/m = e(\partial A / \partial z) \cdot \dot{y}$$

P_y is a constant of the motion

$$\dot{y} = P_y/m + v \cos k'x \cos(kz - \omega t), \text{ where } v = e\hat{E}/(m\omega)$$

$$\begin{aligned} \dot{P}_x/m &= vk' \sin k'x \cos(kz - \omega t) \cdot \dot{y} \\ &= vk' \sin k'x \cos(kz - \omega t) \cdot P_y/m + \frac{1}{2}v^2 k' \sin 2k'x \cos^2(kz - \omega t) \end{aligned}$$

$$\begin{aligned} \dot{P}_z/m &= vk \cos k'x \sin(kz - \omega t) \cdot \dot{y} \\ &= vk \cos k'x \sin(kz - \omega t) \cdot P_y/m + \frac{1}{2}v^2 k \cos^2 k'x \sin 2(kz - \omega t) \end{aligned}$$

The quadratic term $\cos^2(kz - \omega t)$ in $\dot{P}_x/m$ and the sign of the other terms shows that on the average the force in the x-direction is defocusing. Assuming that electrons are born with essentially zero kinetic energy, we see that the amplitude of $\dot{y}$ lies between v and $2v$, i.e. in kinetic energy at 50 MW between 13 keV and 52 keV. The amplitudes of $\dot{x}$ and $\dot{z}$ are much less, since partial integration gives terms with amplitudes $v^2 k'/\omega = 0.14 v$; $v^2 k/\omega = 0.17 v$;

whereas $v = 0.22 c$. We obtain thus the inequalities $k|\dot{z}| \ll \omega$ and $k'|\dot{x}| \ll \omega$. With this in mind, an approximate integration may be made by assuming x and z constant over small intervals of the time and updating x, y, z and their derivatives for the next interval. The set of recurrent solutions are particularly simple if we choose $t_{n+1} - t_n = 2\pi/\omega$ and $t_0 = 0$

$$\begin{aligned}\dot{y}_{n+1} &= \dot{y}_n \\ y_{n+1} &= y_n + (2\pi/\omega)(\dot{y}_n - v \cos k'x_n \cos kz_n) \\ \dot{x}_{n+1} &= \dot{x}_n + (2\pi/\omega)(v^2 k'/4) \sin 2k'x_n \\ x_{n+1} &= x_n + (2\pi/\omega)(\dot{x}_n + (vk'\dot{y}_n/\omega) \sin k'x_n \sin kz_n - (v^2 k'/8\omega) \cdot \\ &\quad \cdot \sin 2k'x_n \sin 2kz_n) + (2\pi/\omega)^2 (v^2 k'/8) \sin 2k'x_n \\ \dot{z}_{n+1} &= \dot{z}_n \\ z_{n+1} &= z_n + (2\pi/\omega)(\dot{z}_n - (vk'\dot{y}_n/\omega) \cos k'x_n \cos kz_n + \\ &\quad + (v^2 k'/2\omega) \cos^2 k'x_n (1 + \frac{1}{2} \cos 2kz_n))\end{aligned}$$

Assuming that the electrons are born with zero kinetic energy, $\dot{x}_0 = \dot{y}_0 = \dot{z}_0 = 0$, we obtain:

$$\begin{aligned}\dot{y}_{n+1} &= 0 \\ y_{n+1} &= y_n - v(2\pi/\omega) \cos k'x_n \cos kz_n \\ \dot{x}_{n+1} &= \dot{x}_n + (2\pi/\omega)(v^2 k'/4) \sin 2k'x_n \\ x_{n+1} &= x_n - (2\pi/\omega)(v^2 k'/8\omega) \sin 2k'x_n \sin 2kz_n + (2\pi/\omega) x_n + \\ &\quad + (2\pi/\omega)^2 (v^2 k'/8) \sin 2k'x_n \\ \dot{z}_{n+1} &= 0 \\ z_{n+1} &= z_n + (2\pi/\omega)(v^2 k'/2\omega) \cos^2 k'x_n (1 + \frac{1}{2} \cos 2kz_n)\end{aligned}$$

From the last equation may be seen that the electron drifts in the direction of the Poynting vector because all terms are positive:

$$\dot{z}_{\text{ave}} = (z_{n+1} - z_n)/(2\pi/\omega) = (v^2 k'/2\omega) \cos^2 k'x_n (1 + \frac{1}{2} \cos 2kz_n)$$

The motion is two-dimensional in the median plane, $x = 0$

$$y_{n+1} = y_n - (2\pi v/\omega) \cos kz_n$$

$$z_{n+1} = z_n + (2\pi/\omega)(v^2 k/2\omega)(1 + \frac{1}{2} \cos 2kz_n)$$

A plot of corresponding points (y_n, z_n) is shown in FIG. 4. Note that this plot is not the trajectory. The trajectory wriggles between adjacent points, which are in real time a full RF cycle apart. The electron does not go far before hitting the wave guide wall. In figure 4 is profiled the height of the wave guide, which we may move up and down to suit initial conditions. In the above simplified case there is only one: the phase kz_0 . The two positions shown, allow 1 respectively 13 survival cycles and a corresponding drift of 0.7 and 1.4 cm.

The condition for multipactor, in the median plane and for bouncing off the same wave guide wall, see FIG.5, are

$$y_{n+1} = y_n$$

$$kz_{n+1} - \omega t_{n+1} = kz_n - \omega t_n$$

The impacting electron should have a kinetic energy around 600 eV for copper, which imposes some condition on $\dot{y}_{n+1}$, but preliminary calculations show that the proposed mechanism is realistic.

5 CONCLUSION

The additional heating of the klystron window is due to the intense X-ray level, produced inside the klystron, illuminating the entrance of the output wave guide. Photo-electric effect, although of low efficiency, produces enough electrons at the right location and right phase to start multipactor, which progresses with increasing intensity towards the window. The intercepted charge and the concomitant x-radiation heat the window, but the heating is not the cause of the breakdown per se.

The accumulated charge on the window creates electric stress, which comes in addition to the RF stress. It could therefore be a major cause of electrical breakdown. The coating, which is intended to carry this charge off, should have a relaxation time constant small compared to the pulse duration. Unfortunately the coating can not be made conducting enough because it conflicts with the Joule heating in the RF field.

TABLE 1 Radiation Up- and Downstream of the Window

Window	Date	Pulse us	Power MW	Up mR/hr	Down mR/hr
962A	2/22	2	50	16	40
		2	100	70	100
		6	50	40	0
		6	100	240	80
963	2/23	2	200	110	200
		6	125	72	250
974	2/24	2	150	570	560
966	2/27	2	100	6	50
		6	100	6	24
		6	50	60	10
967	2/28	6	100	20	110
968	2/29	6	100	10	50
969	3/1	2	100	4	12
		6	100	60	30
970	3/4	2	100	0	30
		6	100	36	54
972	3/5	6	60	0	6
		6	100	100	80
		6	50	0	12
973	3/7	2	100	6	24
		6	100	40	16
969	3/8	2	100	2	5
		6	100	3	12
		2	100	3	3
		6	100	4	4
969	3/9	2	50	0	0
		6	50	1	1

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FIG. 1

Radiation Levels
on SLAC 5045
Klystrons

Peak power 50 MW
Average power 50 kW
Pulse duration 6 us

b and e are measured
with SLAC Scintillation
Survey Meter, mrem/hr

a, c, and d are measured
with Landverk Integra-
ting Pocket Dosimeter,
in mR/hour

Window 969
100 MW, 2 us
3/8/84

Window 973
100MW, 6 us
3/8/84

Window 969
100 MW, 6 us
3/8/84

FIG. 2

Radiation Levels in Test Ring
measured with SiAD Scintillation
Survey Meter in mrem/hour.

Note: General Background due to
other Klystrons under test could
have been 0.5 mrem/hour.

Iron

Power (MW)	Radiation (mR/hr)
0.001	171000
0.002	171000
0.005	171000
0.010	171000
0.020	171000
0.050	171000
0.100	171000
0.200	171000
0.500	171000
1.000	171000
2.000	171000
5.000	171000
10.000	171000
20.000	171000
50.000	171000
100.000	171000
200.000	171000

Lead

Power (MW)	Radiation (mR/hr)
0.001	80000
0.002	80000
0.005	80000
0.010	80000
0.020	80000
0.050	80000
0.100	80000
0.200	80000
0.500	80000
1.000	80000
2.000	80000
5.000	80000
10.000	80000
20.000	80000
50.000	80000
100.000	80000
200.000	80000

Copper

Power (MW)	Radiation (mR/hr)
0.001	170000
0.002	170000
0.005	170000
0.010	170000
0.020	170000
0.050	170000
0.100	170000
0.200	170000
0.500	170000
1.000	170000
2.000	170000
5.000	170000
10.000	170000
20.000	170000
50.000	170000
100.000	170000
200.000	170000

FIG 3 Radiation Level vs. Klystron Power.

Table 2 Mass Extinction coefficient cm²/g

FIG 4 Locus of points (y_n, z_n) in Median Plane

FIG 5. Multipoint in Traveling Wave

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