SOME NUMBERS ON THE SLAC KLYSTRON WINDOWS*

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1 SLEEVE LOSSES

The attenuation in our standard copper rectangular wave guides at 10 cm wave length is known to be 0.7 db/100 ft. Thus the attenuation constant would be $0.7/(30 \times 8.686) = 2.69 \times 10^{-3} \text{ m}^{-1}$. If the wave guide were made of 70/30 Cupro-nickel, the same alloy the window sleeve is made of, the attenuation constant would go up by the inverse square root of the ratio of the conductivities (skin effect formula), i.e. by a factor $(5.7 \times 10^7 / 2.5 \times 10^6)^{\frac{1}{2}} = 4.77$. Thus the attenuation constant would be $\beta = 12.8 \times 10^{-3} \text{ m}^{-1}$. The length of the sleeve $L = 23 \text{ mm}$. Hence a piece of rectangular wave guide of equal length would, at 50 kW incident average power, sustain resistive losses $= 2 P \beta L = 29.54 \text{ Watt}$.

The contention is that 30 Watt is representative for the actual losses which occur in the window sleeve:

- i) the wave pattern is the same, i.e. TE₁₀ in rectangular wave guide $\approx$ TE₁₁ in the round pillbox.
- ii) the sleeve circumference is somewhat larger, by 25%, so that the losses tend to be less, but this is offset by the small standing wave in the pillbox.
- iii) last but not least, the losses thus calculated are high enough to ring the alarm bell anyway.

2 DIELECTRIC LOSSES

A plane wave traversing at normal incidence a dielectric slab, or the principal wave in a coaxial line produce dielectric losses given by:

$$P d \omega \delta / v$$

where $P = 50 \text{ kW}$ is the incident power (average); $d = 3.175$ is the slab thickness (of the window); $\omega = 2\pi \times 2.856 \times 10^9 \text{ sec}^{-1}$ is the

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circular frequency; $\delta = 1 \times 10^{-4}$ is the loss angle and $v = c/\epsilon_r^{1/2} \approx 10^8$ m/s is the velocity of the wave in the dielectric, Al2O3. The above equation yields:

$$\text{Dielectric Losses} = 2.85 \text{ Watt}$$

The contention is that about 3 Watt is representative for the dielectric losses in the window:

- i) v should now read the group velocity of the TE11 mode in the dielectricum, but the difference is only a few percent.
- ii) the standing wave will increase the losses somewhat, but
- iii) these losses are small anyway as compared to the resistive losses.

3 RESONANCES

Assuming there are harmonics in the klystron output, resonances in the window-pillbox system could absorb harmonic power if:

$$\Delta = |f_{\text{harm}} - f_{\text{res}}| / f_{\text{harm}} \text{ is comparable to } 1/Q$$

and if the coupling agrees.

The resonances go under the name ghost modes, pillbox modes and hybrid ghost modes. The likelihood of satisfying above condition is rather small and we have not been able to prove that harmonic resonances are accidentally excited. However resonances are temperature sensitive. We measured on some as much as 20 MHz shift for 100 °C increase. Hence during warm-up of the pillbox a resonance may lock in on a harmonic and keep the window at an elevated temperature.

The above condition is not necessary for a resonance close to the fundamental frequency, because the incident power level is high. We find

$$P_{\text{abs}} \approx P_{\text{inc}} \cdot (4Q^2 \Delta^{2+1}) \cdot Z/(R+Z)$$

Q is the quality of the resonance, say, $Q = 1000$

Z is the impedance of the wave guide, say, 500 ohm

R is the resistive component of the resonance, say, 10 kohm

Thus if $P_{inc} = 50$ kW and $\Delta = 0.01$ we find $P_{abs} = 6$ Watt

The example is not entirely academic, because a resonance has been found ^{at} 2832 MHz on all windows currently in use, see Fig 1, showing

- a) the transmission spectrum in the wave guide near the load
- b) the signal (magnetic) quite close to the window

Q and Δ agree with observation but the value of R is ad hoc, hence no definite statement can be made about the amount of heat associated with this resonance.

4 MULTIPACTORING AND COATING

The abundant literature on the subject provides little quantitative information. Although we understand most of the phenomena, successful windows are made by trial and error.

It looks to me that multipactoring is easier to achieve in a traveling wave than in a standing wave, because free charges tend to drift in the direction of the Poynting vector. Hence the window tends to charge up positively, establishing a restoring force essential to obtain multipactoring. It explains also why we observe more multipactor on the downstream face of the window, because secondary electrons can participate in the process from zero escape energy to, say, the potential of the (+ve) charged window. On the upstream face the useful interval is from the drift velocity in eV and the potential of the plate. We should also note that most of the secondary emission spectrum is in the low energy range.

The semi conducting coating will neutralize the charge build up, but

it will also produce Joule heating. The lower limit of the surface resistivity would therefore be 10 Megohm square, i.e. 2.5 watt each face. It is hard to say if this is adequate for removing excess charges. The natural relaxation time of Al₂O₃ is 100 sec. The coating would reduce that to the order of several microseconds, comparable to the pulse duration, so that end-of-pulse effect might show up.

In the current ring tests we observe light and we associate this with multipactoring and therefore heating. The test lasts typically one shift and comprises 14 stages. We start at reduced pulse length and average power and observe nearly always a glow of some sort. At the end of the test the glow has disappeared more often than not. The regime is then 6 μ s, 50 kW ave., 50 Mw peak.

If we maintain light = heat, then there should be no worry. However we can and should improve our means of observation by using a photo diode or photo multiplier, so that we may correlate the light intensity with the pulse train.

I think it is a wrong policy to test production windows at 200 MW peak power, because the high field may initiate micro fissures, transport of metal and what not. There is no way to find out about possible damage, other than building the window in a klystron and hope for the best.

5 SLEEVE TEMPERATURE

a) Resistive losses.

In the absence of water cooling (which is not popular because of high risk), the sleeve conducts the heat in a symmetric fashion to either end of the sleeve which ~~are~~^{is} brazed to heavy stainless steel flanges. The flanges are water cooled, thus calculated temperatures are with reference to those flanges. In the z-direction the incident heat

is uniform, because we have a traveling wave. In azimuthal direction the incident heat follows Fig. 2. It is the result of the losses associated with the H_θ variation, which goes with $\sin \theta$, and the H_z variation, which goes with $1.96 \cos \theta$. The relative amplitude 1.96 is the result of the geometry of the pillbox. The average temperature rise in the middle of the sleeve is given by:

$$T_{ave} = Q L / (8 k A) = 56.8 \text{ } ^\circ\text{C}$$

where $Q = 30$ Watt is the total resistive heat

$L = 2.3$ cm is the total length of the sleeve

$k = 0.23$ Watt $\text{cm}^{-1} \text{ } ^\circ\text{C}^{-1}$ is the coefficient of thermal conduction

$A = \pi \times 8.4 \times 0.025 = 0.66 \text{ cm}^2$ is the cross section of the sleeve

The maximum temperature in the $\theta = 0$ plane, see Fig. 2, is $89.9 \text{ } ^\circ\text{C}$, and the minimum in the $\theta = \pi/2$ plane is $23.5 \text{ } ^\circ\text{C}$

b) Dielectric losses.

The losses are distributed over the area of the ceramic according to Fig. 3. The resulting heat flow is shown dotted in Fig. 2, resembling a $\sin^2 \theta$ distribution. We note that this pattern is shifted by 90° with respect to the resistive losses and tends to reduce the temperature extremes of the latter. The average sleeve temperature in the middle amounts to:

$$T_{ave} = Q L / (4 k A) = 11.3 \text{ } ^\circ\text{C}$$

where $Q = 3$ Watt is the total dielectric loss. The azimuthal temperature variation would fluctuate between 0 and $22.6 \text{ } ^\circ\text{C}$.

c) Heat flow equalization

Several effects tend to reduce the differences between extreme temperatures, since we have used in a) and b) rather simplified models:

- i) the heat flow in the sleeve is assumed to be axial. The error is believed to be small because of the high aspect ratio of circumference/length = 11.5
- ii) air convection around the sleeve will equalize a little
- iii) since most of the heat is produced in the sleeve, the ceramic acts as bypass for the hot- and cold spot therein. The equalizing effect may be significant, but can not be complete because of the relatively poor heat conductance of the ceramic:

$$(kA/L)_{\text{ceramic}} / (kA/L)_{\text{sleeve}} \approx 0.3$$

d) Measured temperatures

The temperature in the center seems to agree with our calculation. However the edge temperatures agree less well, in particular the expected azimuthal variation. It looks that the measurement needs re-doing, perhaps the insulating button of the thermo couple has heat conductance (kA/L) comparable to the sleeve conductance which, as we know is not very high.

e) Measured losses

The agreement is quite good. At 50 kW average power the total losses are in the 50 Watt range. This includes the losses in the stainless steel flanges and the copper gaskets.

6 STRESSES

We deal only with thermal stresses in the ceramic window, because the sleeve, in which the window is brazed, is very ductile. However the sleeve has all the same a large influence on the thermal stress because of the equalizing heat flow, discussed in 5c. Hence the heat flow entering the window may be several times the heat produced in the window.

In simplified two-dimensional problems the stress σ is proporti-

onal to the modulus of elasticity E, the temperature difference T, and the linear coefficient thermal expansion α .

$$\text{strain } \epsilon = \sigma/E = C \Delta T$$

This applies for instance to circular symmetric cases, where Poisson's ratio drops out (Timoshenko). If the heat were produced uniformly over the disc, it may be shown that

$$\epsilon_r = -\Delta T/4 \quad \text{and} \quad \epsilon_\theta = 5\Delta T/4 \quad \text{and} \quad T = Q/(4\pi k d)$$

Now $T = 10^\circ\text{C}$ for $Q = 11$ Watt, so that $\epsilon_r = 2 \times 10^{-5}$ and $\epsilon_\theta = 10^{-4}$ for $\alpha = 8\text{ppm}$

Now the maximum working strain for Al2O3 (Alumina 995) is 10^{-3} , hence ϵ_θ is still on the safe side, but the actual non-uniform heat flow may reduce the safety margin appreciable.

The obvious remedy would be to make the sleeve of pure copper or of copper plated 70/30 Cupro-nickel. In both cases the RF sleeve losses would be reduced by a factor 4.5, that is a loss of only 6 Watt, but the use of pure copper clamps the circumference of the ceramic to a constant temperature, a degree or so above the stainless steel housing. In the alternative of heat conduction through the copper nickel alloy, the rim temperature would be about 13°C average, but with more variation around the circumference, and perhaps compensating the uneven distribution of the dielectric losses.

7 BREAKDOWN

Our ultimate concern is the life time of the window. Although we have no actual proof, we believe to improve the life time by reducing losses, temperature levels and differences, i.e. working on long term effects.

However the short term effects are more harmful. For instance, the electric field amplitude in the center of the window is about 45 kV/cm (without posts) at 50 MW peak power. A small bubble or void inside the ceramic would enhance the the field strength therein by a factor $2\epsilon_r$, which brings us close to 1 MV/cm, i.e. close to the onset of field emission. It is well known that, say, one mm bubbles, vacuum or not, are detrimental to the life time by creating hot spots, leading in the long run to puncture. Hence the ceramic should be selected accordingly, say, bubbles < 0.1 mm.

Other short term effect are whiskers and protuberances. They may enhance the field at the tip by several orders of magnitude. Self heating may eventually blow off the whisker, so that the ring test is a good instrument to clean this up.

Protuberances are potentially more dangerous. I suspect in particular the braze between sleeve and ceramic: it projects quite often beyond the edge of the ceramic. Field enhancement ^{may} easily be a factor 100. Metal may then be sputtered on the ceramic, which could be the fore-runner to the puncture. Anyhow, this is what one observes on many breakdowns: a darkish smear on the ceramic fanning out from the puncture to the edge.

The braze, no matter how well done, can always be criticized, depending on what magnifying glass you use. I think the braze is a hasard to long life, and that's why I proposed to get rid of the braze and use shrink fit windows.

The life time may be dependent on the pulse duration. It is well known that the development of a hot spot or the build up of critical space charge demand time, which could be of the order of the pulse length. Again, the observation with fast photo devices would resolve these end-of-pulse effects.

Fig. 1

Transmission spectrum
window # 851, AL 995

- a) signal pick up in
wave guide nearest
load
- b) signal nearest window

Fig. 2

Azimuthal dependence

- a) resistive losses
in the sleeve
- b) heat flow in sleeve
due to dielectric
losses

Fig. 3

TE 11 wave pattern

- direction of E
- lines of constant
power density

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