DETERMINATION OF FAILURE MECHANISMS OF R.F. CAVITY APERTURE WINDOWS.

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Abstract

Failures of the SRS RF cavity windows seriously disrupted operations of the Daresbury SRS in 1983. This paper reports the results and conclusions of a long term study of the window environment and the mechanisms leading to failures. This involved both experimental investigations and computation of the electromagnetic fields in the window aperture together with computer simulations of the temperature and stress profiles leading to failure. The experimental field mapping was performed using a perturbation technique [1] and the MAFIA 3-D codes were used for the computer field modelling. The thermal and stress analyses were performed using the ANSYS finite element package.

The modelling strategy is described and the factors leading to failure are discussed. Conclusions are drawn with relevance to the SRS RF window failures and also to high power window design in general.

Introduction

The RF Cavity windows are used to couple power from the waveguide system into the four accelerating cavities of the Synchrotron Radiation Source (SRS). The Klystron can provide up to 70kW per cavity at 500MHz, although in practice typical beam currents required approximately 30kW per cavity. A spate of failures in 1983 seriously disrupted operation of the SRS, although the source was able to continue working at reduced energy and current in late '83 and early '84. Operations at full specification were resumed in June 1984. According to records there were ten failures between 1980 and 1984 with several more windows changed showing dangerous symptoms. The failed windows appear to have cracked suddenly, with signs of high temperatures, such as melting or glazing, on some. Lossy patches or markings were observed on many windows, with surface resistivity as low as 10MΩ/square.

The crisis was resolved by a combination of measures, including monitoring of the ceramic temperature, and reducing the temperature of the window water supply, but the biggest improvement came from raising the ceramic within the coupling aperture, putting the window further out from the intense cavity fields .

This project was established to investigate the mechanisms which could generate heat in the ceramic and the possible modes of failure that could result. A full report was submitted to the university as a Ph.D. thesis [2].

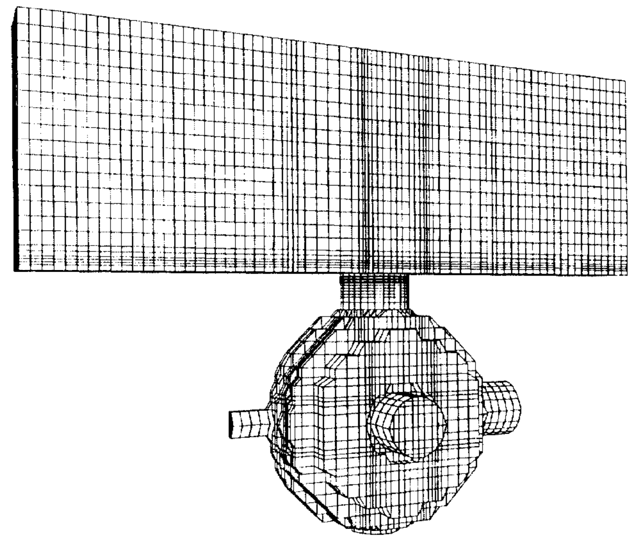
All the processes thought to contribute to window heating absorb power from the RF fields so the first step was to determine the field strength and distribution in the window aperture. This was approached by experiment using a perturbation technique,[1], and with computer simulation using the MAFIA 3D modelling codes [3] from DESY.

Calculations of the losses enabled the generation of heating profiles for the ceramic. The likely effects of multipactor were also considered. The heating profiles were used as input to a thermal-stress model, using the ANSYS finite element package [4]. The temperatures were compared to observations of high power window tests and the stresses considered with relevance to the likely mode of failure.

Experimental Field Mapping

The experiment to investigate the aperture fields used small dielectric and copper spheres to perturb the fields, producing a shift in the resonant frequency related to the field strength. Measurements were taken over the surface of the window on a square grid, and in four horizontal planes above the window surface. It was not practical to take measurements at or below the level of the ceramic. The fields were calculated for a typical maximum power of 40kW resulting in a rough estimate of the peak field of 200-250kV/m. The peak field due to a traveling wave in the aperture would only be 23kV/m so the fields are dominated by the standing wave.

Fig.1. MAFIA mesh for cavity etc.



Computation of Fields

The numerical computation of the fields within the window aperture is not simple. Only recently have fully 3D codes appeared and sufficiently powerful computers become widely available to allow routine solution of realistic 3D problems. Of the codes available the MAFIA programs from the German accelerator centre DESY were chosen because of the useful pre- and post-processors, availability (free of charge to non-profit organizations), and because of the growing number of users in the accelerator community.

For this application the MAFIA frequency domain solvers were used, which find the resonances in a closed structure up to some limit set by the user. Only the first mode of the SRS cavity was needed for this study. MAFIA enables a certain amount of flexibility in the mesh spacing and this was used to get the best fit to the cavity shape in the critical areas of the beam pipes, nose cones, side ports and most importantly for the window aperture, see fig.1. The need to include the waveguide means there is only one plane of symmetry through the structure. Such planes allow modelling of smaller sections of the structure, reducing the number of points needed or allowing all the available points to be used in a smaller volume thus increasing the accuracy, as in this case.

The addition of the waveguide section to the model creates a new problem because while one end of the transition section is terminated by a sliding short circuit matcher the source cannot be arbitrarily terminated in the model without introducing errors. There is no facility at present in MAFIA to simulate a 'matched' or 'open' boundary condition at this point, however in this case it was possible to employ a carefully placed short circuit termination because for the fundamental frequency the matcher position for zero reflection is known. If there is a perfect match it is possible by reciprocity to envisage traveling waves into or out of the cavity which give identical field distributions. A combination of two such traveling waves yields a pure standing wave solution with zero planes in the source waveguide where termination of the model by a short circuit would have no effect. Experiments in the test cavity showed there to be two types of matcher positions giving a perfect match, presenting either capacitive or inductive reactances at the aperture. Models were run with the window in the raised and original positions and both types of matcher position. This source termination is only valid at the fundamental frequency as for any other mode the match is not perfect and reciprocity does not apply.

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The results showed field distributions in the window positions that were very similar to those found by the perturbation experiment. The maximum electric field strength for 40kW was about 250kV/m in the raised position and about 400kV/m in the original position. The values on the upper surface of the raised window were about 220kV/m and 230kV/m for the capacitive and inductive matcher positions, which compare favourably with the figures from the perturbation experiment. The field strengths calculated by MAFIA at the positions of the perturbation measurement planes were within the estimated probable error of the experimental values. The original dielectric losses would have been about 2.5 times greater than in the raised position, at about 250W and 100W for Alumina. The anti-multipactor coating applied to the window, with a normal surface resistivity of >500MΩ/square would contribute only 3W or 1.2W respectively, but the lossy patch observed on some windows, with a resistivity as low as 10MΩ/square could add 12W or 5W, and the marking known as the 'tiger skin' (because of its shape) could have added 40W or 16W

For the TE_{10} mode in the source waveguide the peak field should be 27.7kV/m. The value from the MAFIA runs averaged 24.2kV/m, about 13% low. The uncertainty in the window fields due to the source guide termination is therefore less than 1% and 1.5%.in the original and raised positions .

The shunt impedance of the cavity from the MAFIA data was 7.7MΩ (accelerator physics definition, transit time corrected), compared to 6.7MΩ measured. The discrepancy is partly due to the slightly optimistic Q calculated by the code, which neglects fabrication details such as welds and bolted joints. In addition the coarseness of the mesh used to model the critical nose cone area may have resulted in slight errors in the field distribution along the beam path.

The measurements and calculations were performed for an empty cavity, with no beam loading. In practice the beam requires about 275kW/amp, so for a 250mA beam requiring 50kW/cavity, 17kW per cavity goes straight into the beam and the standing wave field experienced by the window is only equivalent to 33 kW into an empty cavity. This means that the calculated losses represent a worst case and that beam loading may actually give the windows an easier time, and moreover future higher beam currents may not necessarily make the situation worse.

The field distributions and the estimates of additional losses were used to generate heat input profiles for the thermal-stress modelling

Thermal-Stress Analysis

The academic release of the ANSYS Finite Element package [4] was used, but ultimately the accuracy was limited by the number of elements available. For more detailed calculations the full commercial release would be needed. Due to the symmetry of the field profile only one quarter of the window needed to be modeled. Using the radial mesh in fig.2 and the heating profiles from the perturbation and MAFIA data, temperature profiles for the windows were calculated, see fig.3. Difficulties prevented non-linear analysis on the academic release, so it was not possible to simulate the behaviour expected to lead to thermal runaway at high powers. There was good agreement however between the lower power figures and the measured data.

Using only the heating input for dielectric loss gave rise to temperature increases at 40kW of 28.6°C and 11.8°C for original and raised window positions (0.71 and 0.3 °C/kW). As expected.these increases even in the original position are too small to cause any problems.

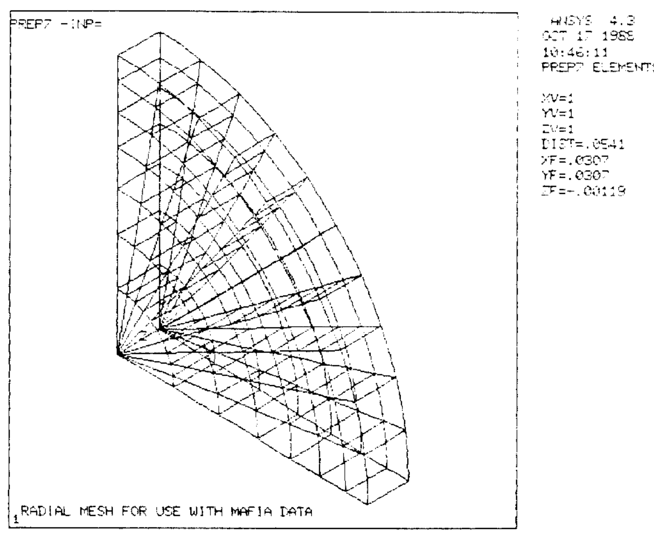
A stress model was constructed for the ceramic subject to atmospheric pressure and the results showed the whole window in tension with the maximum stress in the centre of the bottom face of 4.6MN/m^2 which is small compared to the ultimate tensile strength (UTS) of Alumina (234MN/m^2). The thermal stresses were also modeled separately and for the original window position the maximum tensile stress was 11.9MN/m^2 , at the edge on the beam axis, while the centre was in compression with about 8MN/m^2 (compressive strength of Alumina is >2GN/m^2).

Combining the atmospheric and thermal stresses into one model resulted in a maximum tensile stress in the raised position of about 13.5MN/m^2. Doing the same for the original position resulted in a maximum of 24.8MN/m^2 still only just over 10% of the UTS.

To investigate the effect of additional heat input from the lossy markings further runs were performed including the 12W from the lossy patch, concentrated in an area about 30mm in diameter, and the 40W from the tiger skin, distributed mostly in a narrow line along the beam axis, about 50mm long.

The thermal simulations gave rises of 55.3°C for the lossy patch, (air side 46.5°C, 1.16°C/kW), and 73.3°C for the tiger skin, (air side 62.8°C, 1.6°C/kW). These figures correspond quite well with the observations of bad windows in the test cavity. Using these profiles for the stress model the maximum Von Mises stress (the most relevant parameter to failure) was 37.5MN/m^2 for the patch and 51MN/m^2 for the tiger skin. This represents a fairly large fraction of the UTS (nearly 22%) which given the possibility of higher losses from worse markings, or weakness due to imperfections in the ceramic could make the safety of the window marginal. The temperatures however are well below those required to cause glazing or melting of the ceramic.

Fig.2 Radial mesh for ANSYS model

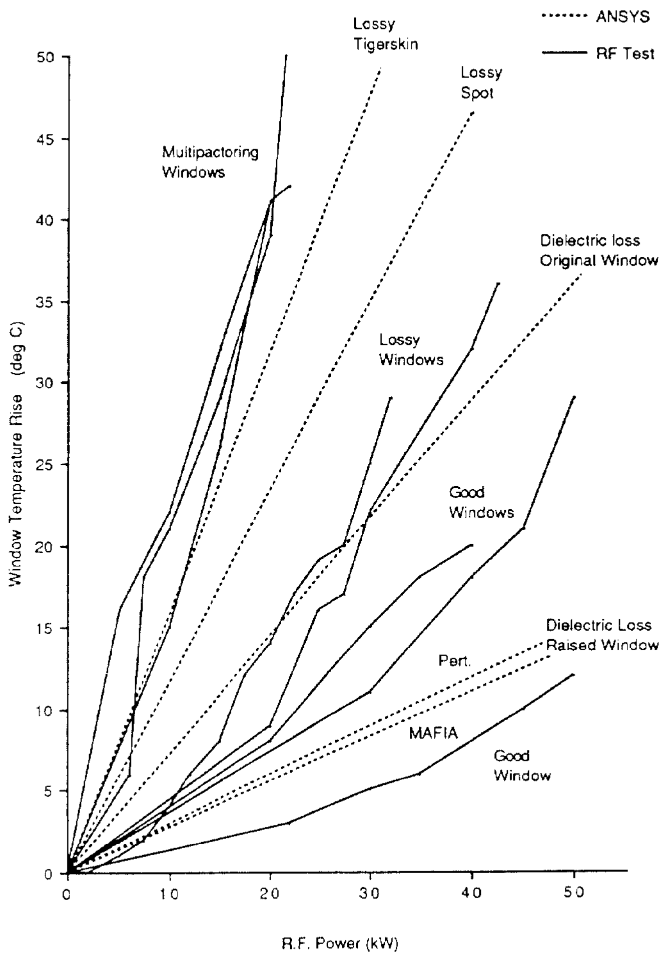


Non-Linear Effects

The Lancaster installation of ANSYS could not be made to run in the non linear mode so all the runs were performed with linear material properties. However the properties of Alumina vary quite markedly with temperature, for example at 1000°C the UTS is about 60% of its cold value, and at 800°C the thermal conductivity drops to less than 23% of its room temperature value, while dielectric loss increases by 100%. These factors produce non-linear behaviour and eventually thermal runaway with increased power. While the linear models are acceptable for the low temperatures calculated above it is not safe to extrapolate to much higher power or loss levels. Evidence in the form of glazing or melting of the ceramic (Alumina melts at 2072°C),suggests that in some cases thermal runaway may have occurred.

In an attempt to qualitatively assess the possible failure modes at higher losses two more runs were performed, with the dielectric losses from the original position at 40kW (about 250W), but with an arbitrary additional surface loss of 200W. In the first case the extra heat was evenly distributed and the temperature rise was only of the order of 200°C, however the stresses exceeded the UTS at the edge of the window by a considerable margin. In the second it was concentrated in the tiger skin pattern producing a very large temperature rise in the centre, more than sufficient to melt the ceramic even without thermal runaway effects, while the maximum stress levels were still less than the UTS indicating that the window would melt before breaking.

Fig.3 Calculated and measured window temperature profiles



Failure Mechanisms

The models predict two possible modes of failure, either due to tensile stress at the edge of the ceramic under fairly uniform heating, or by melting in the centre with concentrated heat input. In the first case the expected mode of fracture would be a crack running across the diameter of the window in line with the beam, probably initiated at some small surface imperfection near the maximum stress point. The other mechanism would be more complex, starting with the softening of the centre of the window. This may then transfer stress to the edge of the window causing mechanical failure, or alternatively a small patch in the centre of the vacuum surface may become isolated and reach melting point before the bulk temperature increase causes mechanical failure. Examples have been seen which fit each of these modes. It is possible that the rate of heat build up and the precise nature of the lossy films determine the type of failure. In any case clearly a relatively small amount of power (<500W) is required to initiate the failures. These figures do not take account of any possible contribution from multipactor which converts power from the RF field into heat at the surfaces involved. It is quite possible for multipactor to provide the amount of power required to break the window and this might account for the sudden failures of windows which had previously shown no bad symptoms. The conditions required to sustain a multipactor discharge could occur with a small change any one of a number of field and surface parameters.

Possible Countermeasures

The windows were already treated with a thin coating of evaporated copper (so called 'copper black'),to prevent multipactor discharges, but the effectiveness of this coating may have become reduced by contamination from the vacuum system, and the growth of the surface markings. The SRS now has increased pumping capacity in the cavities to keep the vacuum as clean as possible.

The flexibility of the inner tube means there is little or no resistance to radial expansion. Indeed the thermal expansion coefficient of copper ($16.6\times10^{-6}/°C$) is almost twice that of Alumina ($8.4\times10^{-6}/°C$) so it may actually increase the tensile stress at the interface. Use of a material with a more closely matched expansion rate, such as Titanium ($8.5\times10^{-6}/°C$) may help, or a material with a lower expansion rate such as Tungsten ($4.5\times10^{-6}/°C$) could be used to provide a degree of resistance, perhaps in a band incorporated into the current design.

As a first test of this idea the model of the original window with 40W dissipated in the tiger skin pattern was re-run with rigid boundary conditions to prevent any radial expansion.This had the effect of keeping the whole window in compression, the maximum Von Mises stress in the centre was larger at $116MN/m^2$, but this was still less than 6% of the compressive strength ($>2GN/m^2$). By careful matching of the properties of the materials it should be possible to reduce this further still by allowing a controlled amount of radial expansion.

Another way to reduce the thermal load on the window would simply be to relocate the ceramic to a region of lower field. Raising the ceramic in the window aperture reduced the temperature rise by about 59% and the stress by about 46% but also reduced the coupling factor of the aperture although it was still sufficient for all current and foreseen operating conditions. As a general guide it would be preferable to avoid siting a window where it will intercept even the fringes of a high Q standing wave resonance but if it is not possible good mechanical design of the window assembly should reduce the likelihood of failures.

Conclusions

The strategy for the field modelling with MAFIA and for handling the traveling wave component in the source waveguide has given results that agree well with experimental measurements. The thermal analyses using ANSYS produced results which compare favourably with observations of high power operation in the test cavity. The stress models, although limited by the wavefront size in the academic release and the problems which prevented non-linear analyses, nevertheless have provided insights into the possible failure modes of the windows and suggested possible countermeasures.

Ever increasing computer power and the continued development of codes such as MAFIA should make analyses of this type easier and more versatile in the future. The principles established in this study should be applicable to a wide range of problems in the accelerator community and elsewhere.

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References

[1] R.A.Rimmer, Proc. 1987 IEEE Part. Accel. Conf., Washington D.C., pp1842-4

[2] R.A.Rimmer,'High Power Microwave Window Failures' Ph.D.Thesis, Lancaster University, U.K., 1988.

[3] 'Reports at the 1986 Stanford Linac Accelerator Conf., Stanford, USA, June 2-6 1986', DESY M-86-07, June 1986.

[4] ANSYS finite element package from Swanson Analysis Systems Inc., Johnson Road, PO Box 65, Houston, PA 15342-0065, USA.