Development of a Strategy for Modelling Operation and Failure of High Power R.F. Windows

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Abstract

The paper describes the current state of a study of previous RF window failures in the SRS accelerating cavities. A strategy is being developed to model the electromagnetic, thermal and mechanical (stress) behavior of these windows. The method is based on computer-numerical modelling of the window geometry using the MAFIA electromagnetic analysis software, and the ANSYS finite element package to perform the thermal and stress analyses. Some of the problems encountered and comparisons with experimental work are also described.

Introduction

The Synchrotron Radiation Source (SRS) at Daresbury uses four 500MHz accelerating cavities fed from waveguide through coupling apertures containing Alumina disc windows (see Fig.1). These typically pass about 30kW each but the RF system can supply about 70kW per cavity if rquired. Failures of these windows, usually by cracking but sometimes accompanied by localised melting of the ceramic, seriously disrupted operation of the SRS between 1980 and 1983 [1]. A program of work was undertaken to cure the problem, resulting in the windows being raised by one inch in the apertures and the installation of temperature monitoring equipment in the SRS [2]. These measures have prevented any further failures in service to date. The most likely explanation for the failures seems to have been an increase in the transmission losses caused either by a deposit on the vacuum side of the window, or some process leading to modification of the anti-multipactor coating used. This is a microscopic layer of finely divided copper (so-called 'copper black') which is evaporated onto the vacuum surface to control the secondary emission properties and usually has a very high resistance. This heating may have been compounded by other heating mechanisms such as multipactoring in the cavity or on the window. The work described here is part of a Ph.D. project based at Daresbury Laboratory and involving Lancaster University Engineering Department and EEV Co Ltd.

It was decided to concentrate the investigation on the primary loss mechanisms (dielectric and ohmic heating) and to attempt to develop a method of modelling window operation and predicting the power level and mode of failure.

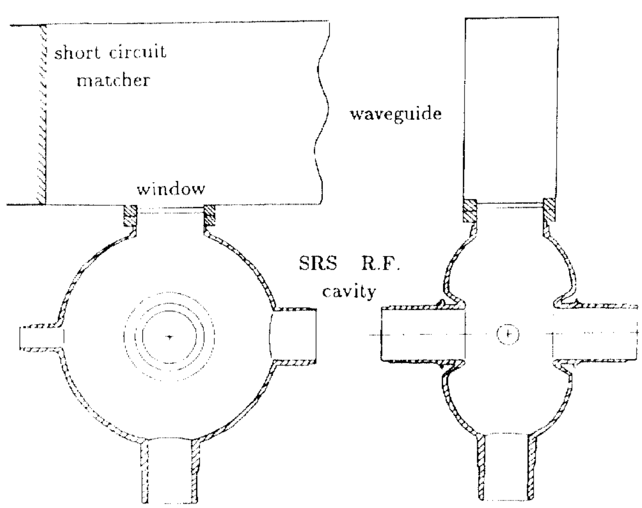

Fig.1 SRS R.F. Cavity/Waveguide configuration

Modelling Strategy

Any attempt to quantify the RF losses in the window ceramic or conducting films is reliant upon knowledge of the field strength and distribution in the window region. Experimental work has been performed to map the fields in the aperture using a perturbation technique [3] but there are obviously practical limits to the accuracy obtainable by this method especially if the geometry of the system is inconvenient. A parallel line of investigation has been to attempt a computer-numerical model of the structure to determine the configuration of the standing-wave resonance of the cavity, which the window intercepts as it couples out through the aperture. Such a model has only recently become possible through advances in computational power and availability of fully 3D modelling codes. The state-of-the-art accelerator design code MAFIA [4] was obtained from DESY and installed on the Daresbury central NAS AS/7000 computer for this purpose.

Knowledge of the RF field configuration in the window region and the properties of the ceramic and any coatings or contaminants allows the generation of a heating profile for the window. This can be used in a conventional 3D thermal modelling program to establish the steady state temperature distributon or even a time history after application of RF power. Lancaster University Engineering Dept. has the commercial Finite Element package ANSYS [5], which can perform 3D thermal and mechanical analyses, installed on their VAX 11/750. Once a temperature distribution has been established, taking into account non-linear behavior of the materials if necessary (these can lead to thermal runaway effects), then a stress analysis can be performed. This can evaluate stresses caused by thermal expansion, atmospheric pressure and external forces due to assembly, subject to the mechanical constraints imposed by the system.

The combination of these steps should allow modelling of the behavior of the window under a variety of conditions, enabling simulation of the factors thought to contribute to the failures.

Field Modelling using the MAFIA codes

The MAFIA codes installed on the NAS AS/7000 computer contain pre- and post-processors and frequency- and time-domain solvers for high frequency electromagnetic problems. Fully 3D modelling is characterised by the large demands made on machine memory and run-times required. On the AS/7000 computer the number of mesh points available for the model is constrained to 60,000 which limits the resolution to $45 \times 70 \times 19$ for the SRS cavity/waveguide geometry (employing one symmetry plane). Employing a variable mesh spacing along each coordinate axis this allows a mesh spacing of 10mm to be achieved in critical areas of the model such as the window and the cavity nose cones, relaxing to 20mm in less important areas. This results in a reasonable approximation to the actual shape (see fig.2) and the field values vary smoothly once a few mesh points away from the edge of the model. First results have been obtained by choseing a length of source waveguide which leaves the space above the window essentially non-resonant (mid way between two waveguide modes) at the cavity fundamental frequency. The distance from the window to the matcher short circuit is that used in the test cavity to give a perfect match at 500MHz (no beam loading), but nearer by one guide wavelength to save on mesh points. Fig.3 shows a contour plot of the E-field of the cavity fundamental mode coupling out through the aperture into the waveguide (no ceramic), produced by the MAFIA postprocessor P3. The roughly hemispherical nature of the contours out in the waveguide suggests that a suitably sized dome window may

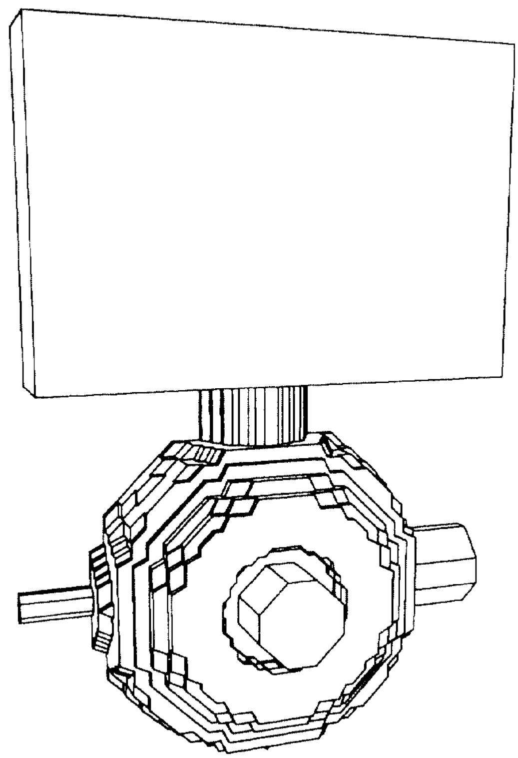

Fig.2 MAFIA model of SRS R.F. Cavity/Waveguide

be able to operate in much lower field strengths. Solving models of even this modest resolution requires several hundreds of minutes of CPU time and many Mbytes of storage. Future availability of more powerful computers should alleviate these problems however.

One limitation with a frequency domain solver of the type used in the MAFIA codes is that it can only find standing wave resonances of a structure and cannot in general be used to find the travelling wave properties. It has always been assumed that the field levels in the case of the SRS window aperture due to the cavity standing wave are much higher than the travelling wave component.(Trials are underway with the code to verify that this is actually the case by comparing the standing wave amplitude predicted by the code with that of a travelling wave for the same power into the cavity). However out in the waveguide this may not be true and different window configurations (eg: dome) may require this to to be taken into account. The problem with this type of solution is modelling the waveguide from the power source. With a geometry known to give a perfect match at the resonant frequency it should be possible to employ reciprocity and envisage travelling waves of equal amplitude in opposite directions through the structure forming a pure standing wave solution. Thus appropriate termination of the computer model should produce exactly the same resonance and the standing wave field amplitude found by this method will be twice that of a single travelling wave. Trials will be conducted soon to verify this technique too. Unfortunately as it stands this method cannot be used to model geometries where there may not be a perfect match because reciprocity no longer applies. In the future other types of code may be able to solve these types of problem, for example by working in the time domain where it is possible to simulate net power flow into, out of or through a structure (the MAFIA time-domain solver doesn't work in quite this way as it is designed for simulation of wake-field effects induced by charged particle bunches traversing the structure).

Figure 2 shows the geometry being used to model the SRS cavity and waveguide system using the maximum number of mesh points available on the current installation. Future releases of the MAFIA codes will allow inclusion of very lossy materials in the solution phase which may allow simulation of 'open' boundary conditions or mode-damping measures to be employed (at present materials are treated as ideal and the loss is only taken into account when calculating the quality factor (Q) etc..) . At Daresbury plans are being made to install the next release of the MAFIA codes on a new CONVEX computer which should dramatically improve the size and speed of models possible.

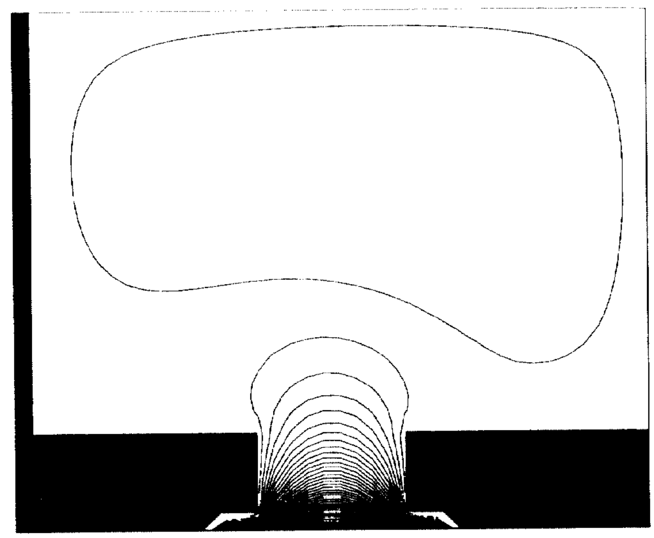

Fig.3 Contour plot of cavity fundamental mode E-Field coupling into waveguide

Thermal/Stress modelling with ANSYS

ANSYS is a conventional Finite Element package which uses a different data format to the MAFIA field modeling code so at present the generation of a suitable heat-input profile is done manually, although there is no reason in principle why it couldn't be automated at a later date. The structure to be modelled is meshed with standard thermal or mechanical elements on a set of nodes, which could be made to coincide with MAFIA mesh points or experimental data points. Material properties are defined and may vary with temperature by specifying the coefficients of a polynomial or using a table of known values between which the program can interpolate if necessary. The heat-input profile is defined at the nodes and boundary constraints are applied to those nodes known to be held at fixed temperature. The heat-input profile can also be made to vary with temperature which is important as the losses in the window increase with temperature while the thermal conductivity drops. This leads to the unstable thermal runaway situation. The analysis is then performed until a steady-state temperature distribution is obtained or a time-history is completed. So far trials have been carried out using data from the perturbation experiment and a two dimensional linear model simulating just the dielectric loss component. Results of these trials using the mesh in fig.4 have produced very encouraging results showing a temperature rise due to dielectric loss which agrees very well with experimental data. Fig.5 shows some temperature profiles of windows measured in the test cavity. The temperatures are monitored by an infra-red device and represent the average over a small patch in the centre of the air side of the ceramic (temperatures in the middle of the vacuum side of the window may be well in excess of those observed in some circumstances). Fig.5 shows three examples of good windows that were used succesfully in the SRS and have temperature rises of between 0.2 and 0.6 degC/kW .This agrees well with the ANSYS 2D linear model based on the perturbation experiment data which predicts 0.32 degC/kW, for just the dielectric loss. This suggests that for 'well behaved' windows the primary loss mechanism may be dielectric heating despite the low loss factor of the high purity Alumina used. Also shown in Fig.5 are profiles of two windows which ran hot (0.7 – 0.9 degC/kW) but didn't fail. These showed evidence of having grown a slightly higher conductivity patch on the vacuum surface while in the machine, suggesting that ohmic losses

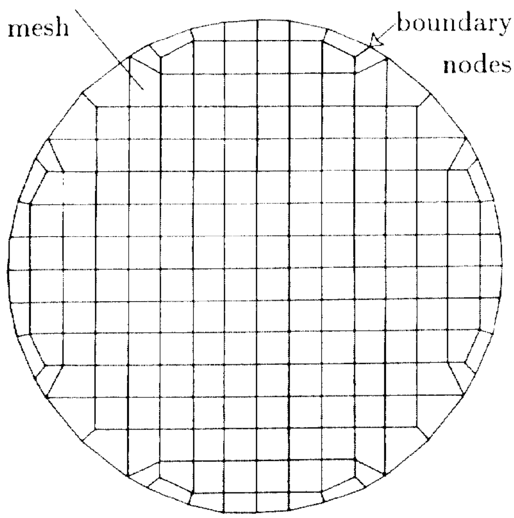

Fig.4 Finite Element mesh for ANSYS 2D linear analysis

were becoming significant. Of the three worst windows on the graph one had an experimental graphite coating on the air side to stop DC charging but which proved to be very lossy while the other two had insufficient or no anti-multipactor coatings. Characteristic glowing of the ceramic was noted and one of the windows failed very quickly in the test cavity. Temperature rises in excess of 1.5 degC/kW are indicative of serious problems with these windows.

The results from the thermal model are passed to the stress modeller and incorporated with other factors, such as atmospheric pressure etc..., into a mechanical simulation which should yield the deformation and stresses of the window. From this information it should be possible to predict where and how failure will occur and possibly to simulate the process in time steps.

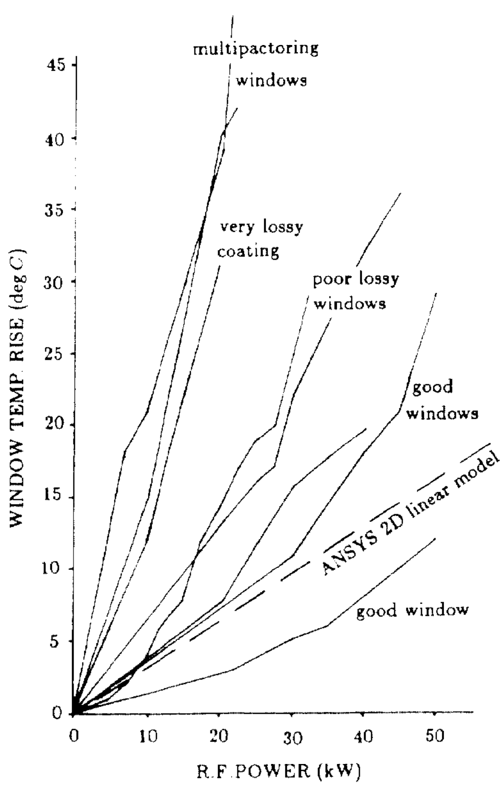

Fig.5 Window temperature rise vs R.F. power transmitted

Conclusions

The successful integration of these processes should provide a means of modelling some of the primary factors involved in causing the failures of the SRS windows. Furthermore it will allow the evaluation of alternative designs on thermal and mechanical grounds. Future developments in the field may allow the simulation of multipactoring in 3D strucures, which could be included when compiling the heating profile of the ceramic. The method may also prove applicable to a wider range of problems than windows, such as waveguide components like matchers, loads, couplers etc...

First results based on the experimental data from the perturbation measurements agree well with data obtained in the test cavity and observations of the SRS. The immediate work ahead involves completing the trials with the MAFIA codes and obtaining reliable results for the window fields, and development of a 3D non-linear ANSYS model to take account of variations through the depth of the ceramic and its non-linear thermal and mechanical properties.

Acknowledgements

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