INVESTIGATION OF THE ELECTROMAGNETIC FIELDS IN THE SRS R.F. CAVITY WINDOW APERTURE USING A PERTURBATION TECHNIQUE

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Abstract

This paper reports a low power experiment carried out on a 500 MHz accelerating cavity from the Daresbury SRS to investigate the strengths and distributions of the electric and magnetic fields in the region of the disc alumina window, which couples r.f. power at high levels into the cavity from the waveguide system. This work is one of the first steps in a programme of research to investigate the thermal and electrical behaviour of the window, with the ultimate aims of forming a model of high power operation and developing a mechanism to explain the series of window failures which seriously limited operation of the SRS for many months. The experimental procedure and background theory are described and an analysis of the results is presented with an outline of future areas of investigation.

Introduction

The experiment was designed to extend the work of Dykes and Garvey [1] who drilled small holes in the side of the waveguide such that a dielectric bead could be drawn across a diameter or chord of the window. By perturbation theory [2] [3] [4] [5] this should produce a small shift in the resonant frequency of the cavity/waveguide system, the magnitude of the change being proportional to the square of the electric field strength. The drawback of this method was the difficulty of inserting or removing the bead and consequently the time taken to measure the insertion shift made drift of the cavity properties possible.

This experiment was designed to allow rapid insertion or removal of the bead or perturbing object and easy relocation of the positioning mechanism between chords on the window surface and between any of four planes above the window. In its lowest position the bead is flush with the waveguide wall, though still ~ 10 mm above the window. From these four sets of readings it should be possible to extrapolate down to the window surface. In addition to the use of a dielectric (mycalex) bead a copper bead was used to couple to both electric and magnetic fields and copper and dielectric rods were used to gain some information about the direction of the fields.

A full account of the experiment is contained in a report available from Daresbury [5].

Test cavity modifications and equipment

The flexibility of the method is due to the replacement of a section of the waveguide wall each side of the window by a sliding bar, see fig. 1. This necessitated having a slot cut along virtually the whole length of the waveguide/cavity transition, which caused two problems: first, it substantially weakened the transition, (which required bracing before it could be machined) and secondly a slot would have drastically disrupted the currents in the walls. The first problem is a minor one simply requiring careful setting up of the equipment, the second was overcome by making the slider out of copper and ensuring good electrical contact using lengths of "knit-mesh" and by covering the ends of the slots on the inside of the waveguide with conducting tape which maintained the appearance from inside of a continuous wall while allowing passage of the slider behind it. Each slider has four holes in a vertical line in the centre through which is passed the nylon line which supports the beads or rods. The sliders are held in place by clamps done up by hand. The nylon line passes out through the hole, over pulleys (mounted using adjustable structure fabricated from Meccano) and on one side is attached to the slider of a linear potentiometer, for accurate positional data, on the other to a counterweight. The line was passed twice through the beads and variously through and around the rods to prevent any slippage and to keep the rods in their correct orientation.

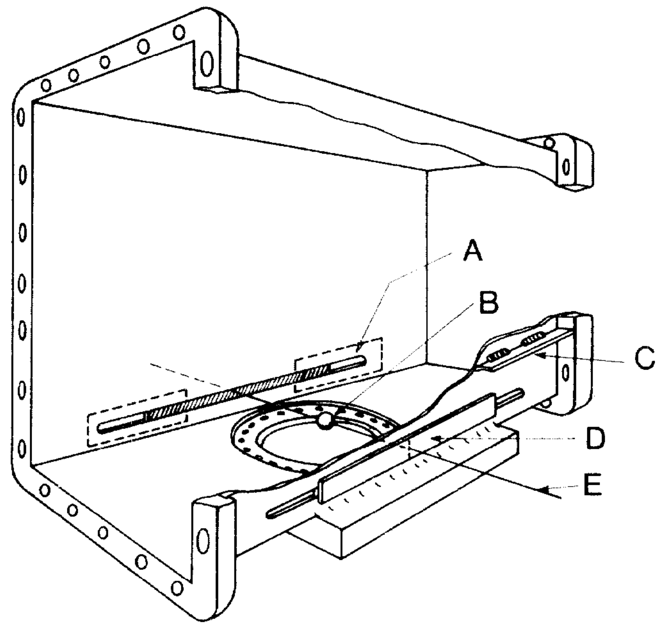

Fig. 1: Modifications to waveguide/cavity transitions: A, conducting tape; B, Perturbing object; C, Bracing; D, Sliding conductor; E, Nylon line

The standard test cavity arrangement at Daresbury is driven by a 50 kW transmitter via a high power coaxial feeder. For this experiment this was replaced by a waveguide to low power coaxial transition and fed at signal generator level from the r.f. test equipment, which consisted of a high resolution frequency synthesiser, a network analyser and reflection /transmission test boxes with an harmonic generator. These were used as in fig. 2. Noise limited the resolution, as is to be expected when trying to measure such a small perturbation.

Difficulty was experienced with signal instability and noise, however, the perturbation proved to be large enough in most cases that the noise was tolerable.

Difficulty was also experienced in trying to minimise drift of cavity frequencies. Being a very high Q cavity its resonant frequency is sensitive to tiny changes in volume or shape caused by temperature fluctuations. The water system controls the temperature to within 1°C, but within the dead-band of the control loop the temperature was fluctuating quite rapidly, causing the resonant frequency to drift up and down by up to 1 kHz over a few tens of seconds. So, during the time taken to make a measurement, by pulling the bead across the window, the frequency would drift by more than the perturbation, clearly making accurate results impossible. This was eventually cured by turning off the temperature controller, and letting the cavity temperature drift up and down with ambient temperature. Although the absolute change was much greater, the rate of change and hence drift of cavity frequency was improved by more than a factor of 10.

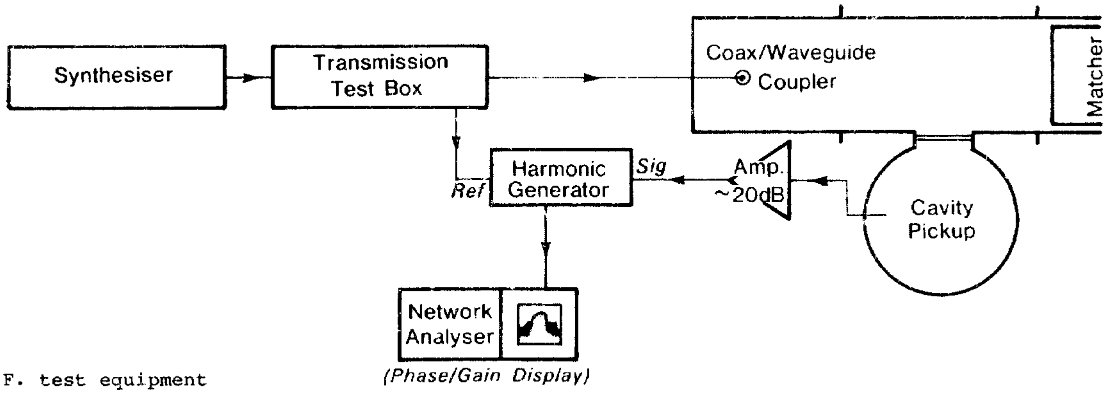

Fig. 2: R.F. test equipment

It was also demonstrated that turning off pumps, heaters, ion gauges etc. did not affect the signal/noise ratio (SNR) at the pick-up loop but applying light pressure to the cavity drift tube arms perturbed the resonant frequency significantly.

Experimental Procedure

Setting up procedure

Using the reflection test apparatus and the polar display, the matcher position was set, giving a perfect match at the resonant frequency. This was then left untouched for the rest of the experiment.

The cavity Q was obtained by measuring the - 3 dB bandwidth and the centre frequency using the transmission test set up (fig. 2). This gave the loaded $Q(Q_L)$. Theoretical unloaded Q (Q_O) is given by the formula

$$Q_O = (1 + \beta)Q_L$$

(where β = coupling factor = 1 for perfect match).

Typical values for the SRS cavity were cent. freq. 500.174 MHz, - 3 dB bandwidth of 26.5 kHz, i.e. Q_L = 18874, Q_O = 37748, at about 20°C.

Measurements

For small deviations around resonance the phase can be considered to vary linearly with frequency and because it changes so sharply (an advantage of having such a high Q system) it is a sensitive indicator of the perturbation. On the most sensitive setting of the phase display (1°/cm) a perturbation of a few hundred Hz showed up as a movement of the spot by several cm, enough to be significant above the noise.

The first thing done when taking a set of measurements with a particular perturbing object was to measure the insertion perturbation. The generator was switched to manual and the spot adjusted to the centre of the screen and frequency noted, and one slider removed to allow threading of the object onto the line. This caused the spot to move up or down the screen if the insertion shift was significant and if so it was returned to the centre by adjusting the signal generator frequency and the difference in frequencies noted.

Taking field measurements was done as follows. The perturbing object, etc. were positioned on the appropriate chord of the window, with 9 V across the linear potentiometer the position of the bead could be correlated with the x-travel of an x-y plotter. The amplitude response, on auto-sweep, was adjusted for resonance in the centre of the screen, the phase response on 1° per division looking like a steep straight line. Switching to manual the phase spot was centred. Now drawing the bead across the window the perturbation could be viewed on the screen and using the phase output from the back of the display box the phase shift was plotted on the y-axis of the chart plotter. The channel gain and offset were adjusted to give a reasonable sized graph and the apparatus was ready for a measurement. This involved lowering the pen, drawing the bead across the window and allowing it to slide back slowly, producing two traces on the paper. The pen was then raised ready to set up for the next measurement. The traces were generally coincident unless there was any drift in cavity parameters with time during the measurement, which showed up as a small y-offset between the start and end points. Usually the time taken for a set of data was short enough for this not to be a problem.

Owing to the large numbers of plots taken, it was found to be convenient to place them in sets on the graph paper, usually eight or nine could be fitted together, e.g. all readings from the central position to one edge. Groups of data taken on the same scale were calibrated in one go by setting down the pen for a couple of seconds, leaving a mark corresponding to the current frequency, then shifting the spot and pen by changing the signal generator frequency and spotting another mark on the graph paper. The frequency separation and the physical displacement serve to calibrate the plots.

The sequence of measurements was usually to set up the scales etc. on the central position then take measurements at 1 cm intervals towards one edge, return to the centre and take plots in the opposite direction. It was sometimes necessary to increase the y-channel gain towards the edges of the window if the perturbations became too small or too large, requiring recalibration of course. The signal generator power output had to be kept constant during sets of readings, otherwise there would be no consistency in E field values produced by each plot. Furthermore the generator was left running or on standby throughout the experiment, hopefully minimising any possible errors due to stopping and starting.

Analysis of Results

Approximately 280 graphs were taken, covering every object in the lowest hole (nearest the window) with the rods in both horizontal orientations, i.e. parallel to and perpendicular to the line, then with the rods vertical suspended below the line in the top hole and full maps of the mycalex and copper beads also in the top hole. Then plots were taken in holes 2 and 3 with both beads, but only for half the window as previous plots were almost symmetrical so time could be saved this way. For each set of plots relevant information such as the resonant frequency, Q, temperature, etc. were also recorded for future use if required.

Only the copper bead and copper rod parallel to the line produced significant insertion perturbations, and these were small. Data analysis was simplified by digitising the plots using a digitising tablet connected to an IBM PC. Once digitised, the data was in a form where it could be systematically manipulated to yield the field information.

The basic equation relating the electric field strength (ε) to the frequency perturbation by a dielectric sphere is:

$$\frac{\delta\omega}{\omega} = \frac{-\pi r^3 E^2 \varepsilon_o}{U} \frac{(\varepsilon r-1)}{(\varepsilon r+2)} \qquad (1)$$

where r is the radius of the bead and U is the stored energy of the system. Also the stored energy is linked to the power dissipation (P) by

$$Q = \frac{2\pi f \ U}{P} \qquad (2)$$

where Q is the quality factor for the resonance (principally determined by the cavity Q) and f is the resonant frequency.

Thus for a given input power the perturbation measurements at each point over the window area can be turned into field strength values using [1] and [2]. This was done to the data files, allowing a plot to be drawn showing contours of constant field strength over the window (fig. 3). Note that these values only indicate the magnitude of the field strength; directional information can only be obtained by using non-spherical objects such as rods, ellipsoids or discs.

A similar equation to (1) describes perturbation by conducting beads, although these perturb both the E and H fields. However, having found the E field magnitude at each point it is then possible to calculate the H field magnitudes from the second set of perturbation values. These values do not vary widely over the window surface.

The equations governing perturbation by rods are more complicated, involving form factors relating the perturbation to the geometry of the object and its orientation [4]. The perturbations measured were considerably smaller in many cases and thus quantitative results for the vector fields were not very reliable.

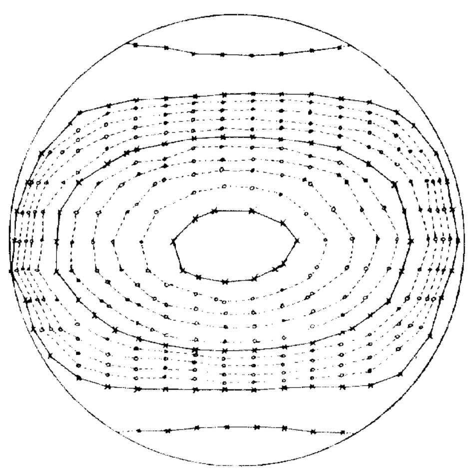

Fig. 3: E-field map of window area showing contours of constant field strengths

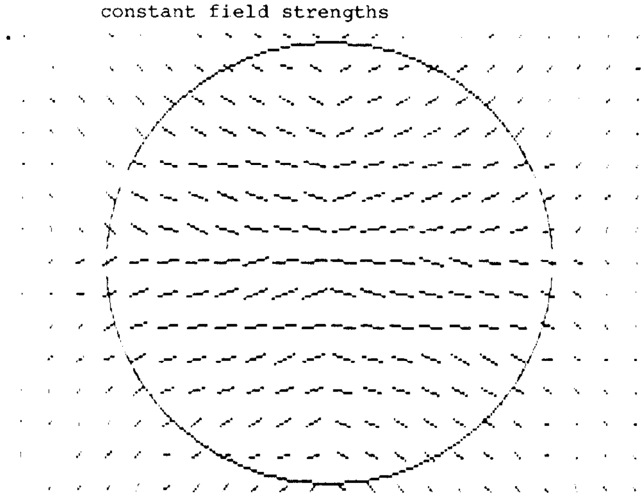

Fig. 4: Possible E-field vector pattern

However, with some subjective manipulation a qualitative suggestion of the E vector variation over the window (fig. 4) was thought to be justified.

Window losses

It is possible to extrapolate from the sets of readings in the four planes above the window down to the window surface, to make reasonable estimates of the magnitude of the E field within the ceramic. It is thus possible to estimate a value for the shunt impedance of the aperture, defined as:

$$R = \frac{\left[{}_o\int^L E.dl\right]^2}{P}$$

where the line integral is taken along a suitable path. A value of 37.8 kΩ was calculated by extrapolating to the rim of the aperture, thus for 40 kW input power a voltage of 38.9 kV would be developed across the guide at that point. If this is considered to be developed over just the window aperture, this corresponds to an average E field strength of approx. 2.6 kV/cm, extrapolating further down to the window ceramic surface yields an estimated average field strength of approx. 4.3 kV/cm. Power loss per unit volume of a dielectric such as alumina is given by:

$$\text{loss/unit vol.} = \varepsilon_o \varepsilon_r \omega E^2 \tan\delta$$

where for alumina $\varepsilon_r = 9.6$, loss tangent $\tan\delta = 0.0001$ (figs. from ref. [6]). For the SRS cavity window which is 12 mm thick × 152 mm diameter, the estimate for the field strength produces a potential dielectric loss of approx. 1080 W at 40 kW input power. This is a worst-case estimate; assuming a uniform field over the whole waveguide wall leads to a conservative value of 1.7 kV/cm at the aperture, 2.5 kV/cm at the window, ~ 365 W dissipation.

Future Areas of Investigation

It is hoped to expand upon this work by a series of measures including thermal imaging studies of the window under load and computer numerical modeling of the RF behaviour of the window aperture and of the thermal behaviour of the window, using field information from this experiment and the theoretical investigations to provide a heating profile for the ceramic. Thermal model predictions could then be compared directly to thermal imaging data. If time and facilities permit, it is hoped to turn a thermal profile of the window into a stress profile to predict failure modes.

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