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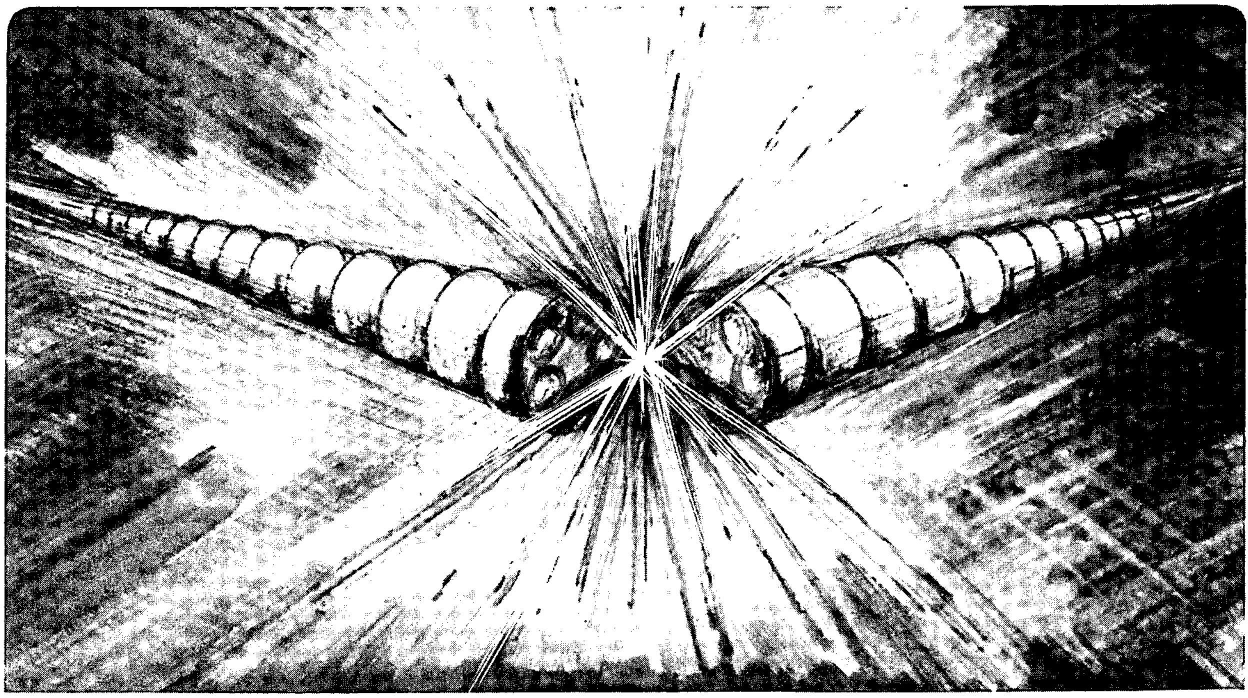

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BEAM IMPEDANCE MEASUREMENTS ON THE ALS CURVED SECTOR TANK*

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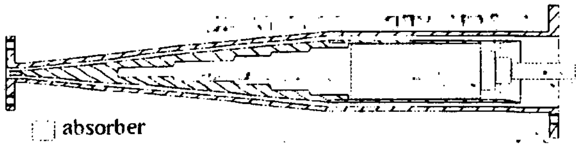

Fig.2 TMon waveguide-mode coupler

at the gap. For incoming modes the gap can be thought of as "sampling" the radial field at the wall, while absorber in the center of the inner pipe dissipates the remaining energy. The gap is not well matched to the coaxial section and at the recieving end only a small sample of the radial field energy close to the wall enters into the coaxial section. The result is that the signal is already attenuated by about 20dB before any cable or vessel losses are taken into account; however the dynamic range of the network analyzer is wide enough to accomodate this.

In the circular waveguide the TM_{01} mode cutoff is 4.82GHz and there is relatively uniform transmission up to the TM_{02} cutoff at about 11.06GHz. Above this frequency the energy is split between the two modes, giving rise to a characteristic phase roll-over pattern in the frequency response. Addition of the TM_{03} (17.34GHz) and TM_{04} (23.63GHz) modes further complicates this pattern. However because of the difference in the energy density of the modes as a function of radius, absorber placed in the center of the pipe will selectively damp the higher order modes. All the modes experience some loss and there is a tradeoff between sensitivity and flatness of the response. To interpret the results it must be assumed that the couplers launch and detect only the lowest TM mode; results indicate that with sufficient axial absorber this is not a bad approximation.

For a real impedance (e.g. the peak of a resonant object or a localized resistive object) and only one mode launched, the beam impedance Z_B can be estimated from the following formula:

$$2\pi\frac{Z_B}{Z_0}=\sqrt{1-\frac{f_c{}^2}{f_0{}^2}}(1-|S_{21}|)$$

where Z_0 is the impedance of free space (377Ω), f_c is the TM_{01} mode cut-off frequency of the beam chamber, f_0 is the frequency at which the resonance is observed and $|S_{21}|$ is the response normalized to a reference measurement through the undisturbed pipe ($|S_{21obj}/S_{21ref}|$).

Measurement Procedure

The cable layout used (fig.3) had the network analyzer positioned midway between the ends of the vessel, allowing the source and receiver cables to be about the same length. By careful arrangement of the cable joints, the change between the test and the calibration positions did not require bending of any cables, only the rotation of a few highly repeatable APC 3.5mm connector joints. Switching between the receiver cable and various cables to antennas in the antechamber was achieved using microwave switches controlled by the computer. The receiver return path through the switch was included in the calibration.

All the cables were thermally insulated but the whole system was subject to cycling of the room temperature between the day and night causing small but significant changes in length and hence phase. To be able to correct for this in the data analysis, the temperatures were recorded at the time of each measurement.

At the ends of the tank, extender sections were mounted for the absorber pads. These were clamped to the end of the sector tank to make good RF contact, and bolted to the transformer sections. Onto these were fitted either the wire tapers or the waveguide mode couplers. For the wire measurements, a 1/8" copper wire was laid in sections through the vessel with the slack carefully removed by adjusting a sliding joint on one of the tapers. Because some of the joints exhibited intermittent contacts, they were all taped over with copper tape to ensure repeatability. Inside the beam chamber, holes for the beam position electrodes and ten of the eleven metal plugs which fill diagnostic ports were masked with copper tape to provide a continuous smooth wall. One plug was left untaped so that the test resonator could be inserted.

Because of the very broad frequency range to be covered, data were taken in twelve subintervals from 2 to 26 GHz and global measurements from 1 to 26 GHz. With 801 data points in each subinterval this gave high enough resolution to show any fine structure. Calibrations were made for both "ramp" and "step" modes of the analyser and for "thru" and "one-path-2-port" types (HP nomenclature). Data were also recorded uncalibrated, for comparison.

To measure the effect of the antechamber, a series of reference measurements was taken with the slot sealed off by a conducting barrier. This recorded the response of just the beam chamber and measuring hardware so these could be normalized out of the test measurements. The slot was sealed using a flexible RF gasket which consisted of a knitted copper wire mesh around a rubber core. The seal was then removed and the measurements repeated; dividing the test response by the reference response reveals any differences due to the presence of the antechamber. To test the measurement procedure, the test resonator plug was introduced into the vessel in the untaped diagnostic port. This presented a small beam impedance (≈10Ω) which was expected to be detectable by either method.

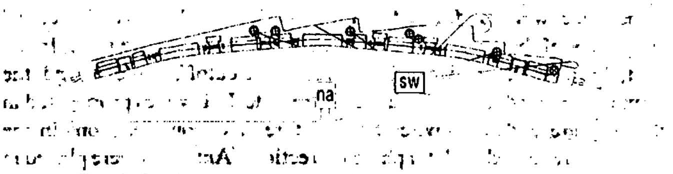

Fig.3 Cable layout (calibration shown dashed)

The response through to the antennas in the antechamber was also recorded, using a measurement taken with the slot sealed as a calibration of the internal isolation of the network analyzer

Finally, with the waveguide mode method it was possible to make a separate estimate of the total insertion loss of the chamber by comparing measurements with and without the sector tank placed between the couplers and chamber extenders. This is not possible with the wire method because of losses in the wire itself.

The data were processed on the computer to give results in terms of beam impedance Z (Ω) and the accelerator physics parameter Z/n (Ω), where n is the ratio of frequency to the orbit frequency of the machine (1.5MHz for the ALS).

Results

The results for the wire method (fig.4) show that opening the slot into the antechamber does not produce any significant resonances and the average value of Z/n is about (0.001±0.001)Ω, (Z≈6.7Ω@10GHz), about the level of repeatability between successive measurements when the beam chamber has been opened (to remove the RF gasket). Inserting the test resonator (without opening the beam chamber) shows that a further change of Z/n≈0.0012Ω, (8Ω@10GHz) can be seen.

Coupling through to the antennas in the antechamber was very small, starting at very low frequency and with no appreciable step up at the slot cutoff frequency (15GHz). The general shape of the response follows that of the antennas in free space, suggesting that perhaps the only coupling mechanism is through slight scattering of energy into TE modes by discontinuities in the chamber giving a low level background "noise" spectrum to which the antenna response is added.

The measurements taken using the waveguide mode method show better repeatability after the beam chamber was opened, perhaps because there was no wire to disturb. These results confirm there is no harmful effect from the antechamber. Indeed fig.5 shows that the average value of Z/n estimated by this method is <0.0005Ω, (Z<3.3Ω@10GHz), suggesting that most of the "change" seen by the wire is probably just due to lack of repeatability. The extra impedance due to introducing the test resonator (fig.6) is clearly seen and the magnitude agrees very well with the wire result. Higher order resonances of this test cavity are even visible.

Coupling to the antennas using the waveguide mode method was

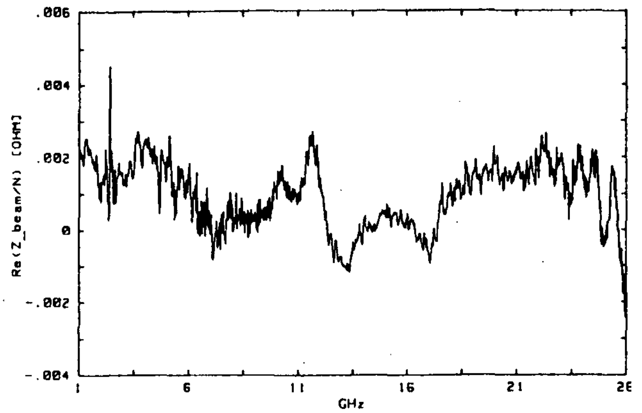

Fig.4 Impedance due to antechamber, wire method

very similar to the wire except that below the TM cutoff of the chamber the coupling was reduced (only weak TE modes propagate in the beam pipe) and below the TE mode cutoff $\approx$3.7GHz) there was no signal at all in the antechamber.

Opening of the light-beam ports or placing absorber in the antechamber or had no effect on the beam impedance measured by either method, and had only a small effect on the coupling to nearby antennas.

The final test to estimate the losses through the vessel by comparison with the extenders and transformers only could give only an indication of the broadband losses because of the difference in length (this changes the phase pattern). The results showed about 2dB loss on average, corresponding to $Z/n \approx 0.0015\Omega$, (10Ω @ 10GHz).

Conclusions

Both methods are capable of measuring very small impedances above the beam pipe cutoff; the wire method has the advantage that one seamless measurement can be made for all frequencies while the waveguide mode method works only above cutoff but can be used in situations where it is impractical to use a wire.

The test resonator shows that either method should be able to detect objects of the order of $Z/n=0.00075\Omega$, ($Z \approx 5\Omega$@10GHz). Under laboratory conditions it is possible to improve repeatability to a point where objects as small as $Z/n=0.00015\Omega$, ($Z=1\Omega$ @10GHz) can be resolved.

The broadband skin effect wall loss of the beam chamber is estimated to be approximately $Z/n=0.0015\Omega$, ($Z=10\Omega$ @ 10GHz) from the waveguide mode insertion loss experiment.

The wire and traveling wave methods show that the increase in beam impedance due to the antechamber is $Z/n<0.001\Omega$ and $<0.0005\Omega$, ($Z<6.7\Omega$ and $<3.3\Omega$) respectively. There is very little coupling to the antechamber even above the slot TM cutoff frequency of 15GHz.

The total impedance budget for the ALS is $Z/n<2\Omega$. For twelve chambers and an allowance of 10% for beam chamber losses this makes the maximum tolerable impedance $<0.017\Omega$ (Z/n).

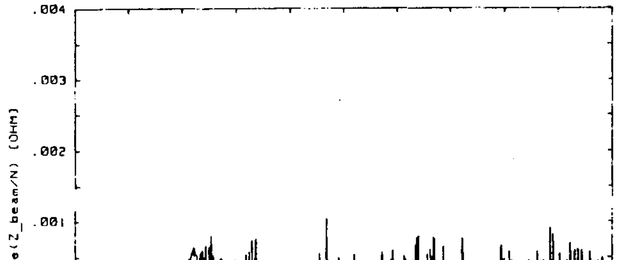

Fig.5 Impedance due to antechamber, wireless method

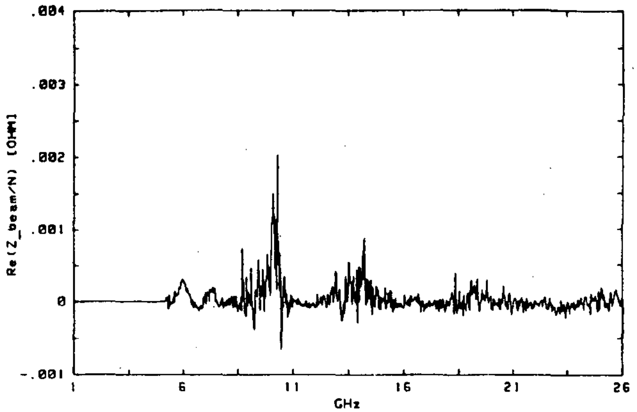

Fig.6 Impedance of test resonator, wireless method

These results show that the broadband contribution to the ALS impedance budget from the curved sector tank is very small and that there are no harmful resonances in the antechamber that might cause beam instabilities.

Acknowledgements

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