BEAM IMPEDANCE MEASUREMENTS ON THE ALS CURVED SECTOR TANK,

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Abstract

The 10 m long ALS curved sector tank is formed from two shells out of which the beam chamber is machined. Vacuum pumping and photon stops are located in an antechamber connected to the beam tube through a 1cm slot. In order to determine whether the beam is significantly coupled to the antechamber, measurements of longitudinal beam impedance were performed up to 26 GHz, well above the cutoff frequency of the beam pipe. Two different schemes were used: In the first, the wire method was adapted for above cutoff; in the second, the impedance was detected from the response to TM-waves propagated in the aperture without a wire. Temperature at various locations in the setup was recorded for later phase corrections. Antennas were placed in the antechamber to detect radiated power or possible resonances. A reference measurement was made with the slot sealed by a flexible gasket of knitted wire. The seal was then removed and the response with antechamber recorded. The setup was checked by inserting known obstacles. Both measurement methods provided equally low numbers with Z/n < 0.001 Ohm over the whole frequency range. No resonances attributable to the antechamber were observed.

Introduction

The twelve straight sections of the ALS storage ring are connected by curved sections containing magnets, light ports, pumping equipment and pick-up electrodes. The vacuum tank for each 10m curved sector is made by welding together two shells machined from solid billets of aluminum. The inside of the vacuum chamber has been designed to minimize the beam impedance due to structures such as pumping ports and photon stops. This is achieved by putting them in an antechamber, separated from the beam chamber by a continuous slot 1cm high (fig.1). This should ensure that there is no coupling out into the antechamber until at least 15GHz, so the beam should not drive any resonances there. Such interactions could cause beam instabilities and limit the maximum current which may be stored.

Since the ALS was designed to have a low emittance beam it was important to verify that the chamber design was successful in isolating the beam from potential resonant structures in the antechamber. Because the bunch length is short, it was required to investigate the possibility of harmful resonances up to the slot cutoff frequency (15GHz) and beyond. The traditional method for measuring beam impedance has been to study the response of the vessel as a coaxial structure either in the time domain, using a pulse [1], or in the frequency domain using a network analyzer [2]. The latter method has not generally been used above the vessel cutoff frequency.

For this experiment we have devised techniques to allow the coaxial wire method to be used above cutoff, and developed a new wireless method, for use above cutoff only. These methods are described briefly in the next two sections and reported fully elsewhere at this conference [3].

An HP8510B network analyzer under the control of a data acquisition program on an HP 9816 computer was used to perform measurements up to 26GHz. Because of the length of the tank extra low loss cable was used, and precautions were taken against thermal effects.

A small rectangular test cavity in a removable plug was measured in the laboratory and introduced into the real vacuum chamber to verify that the methods were working properly during the full scale tests.

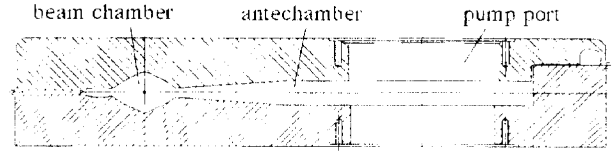

Fig. 1 Typical ALS chamber cross section

Wire Method Above Cutoff

In an idealized infinite beam chamber waveguide modes excited by a resonant object above cutoff propagate with a phase velocity different from the beam velocity so the average coupling is zero. The energy lost to these modes can be considered as a "radiation impedance" in parallel with the shunt impedance of the object. In a conventional wire measurement, tapers used to transform from the impedance of the vessel section to the 50Ω of the cables will reject waveguide modes (and higher order coaxial modes) that may propagate in the vessel above cutoff. This leads to standing waves in the chamber which can give erroneous results. In the new procedure, absorbing material (Emerson & Cuming Eccosorb AN73) is placed between the object and the tapers to absorb the extra modes and simulate the case of the infinite vessel. This also reduces the transmitted TEM signal on the wire but with sufficient dynamic range on the network analyzer this can be accomodated. For small objects the beam impedance is calculated in the same way as below cutoff with

$$Z_B = 2Z_L(S_{21ref}/S_{21obj} - 1)$$

where S_{21ref} is the response through a smooth reference vessel containing identical absorbers (or in this case the same vessel with the object removed or masked with conducting tape), and Z_L is the characteristic impedance of the coaxial wire in the vessel.

To ensure good positioning of the wire in such a long curved vessel a styrofoam guide was used to keep it centered. Electroformed Chebyshev tapers were used for the wire measurements providing very good response from 550MHz upwards.

Waveguide Mode Method

In the new wireless method special couplers are used to launch the first TM waveguide mode in the beam chamber. To simplify fabrication the couplers are made with circular symmetry (fig.2) using a standard sized pipe which has a TM_{01} mode cutoff just below that of the vessel. The circular waveguide mode is then transformed through a gradual transition to the beam chamber geometry. Small pads of absorber between the transformer and the beam chamber damp any reflections from this transition. The couplers consist of a linear coaxial taper to transform from the 50Ω cable geometry to the diameter of the outer circular pipe (1.875" I.D.), followed by a 5" long straight section, using a smaller standard sized pipe (1.625" O.D.) for the inner conductor. At the end of this section the inner conductor ends abruptly forming an annular gap which excites waveguide modes in the pipe that have constant radial electric field around the azimuth (TM_{0n} modes). The outer conductor was electroformed in copper. Five small nylon screws are used to fine tune the alignment of the inner conductor as misalignment can excite TE modes in the pipe because of asymmetry in the fields

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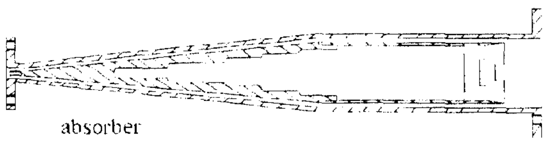

Fig 2 TMon waveguide-mode coupler

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 cutoff 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

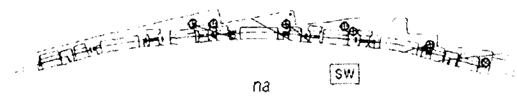

Fig.3 Cable layout (calibration shown dashed)

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.

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

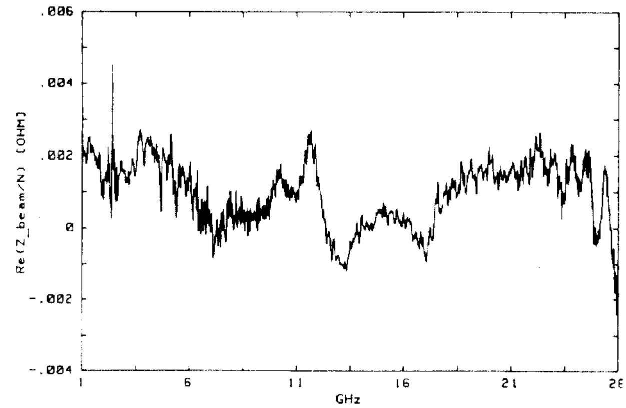

Fig.4 Impedance due to antechamber, wire method

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 ≈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≈0.0015Ω, (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=0.00075Ω, (Z≈5Ω@10GHz). Under laboratory conditions it is possible to improve repeatability to a point where objects as small as Z/n=0.00015Ω, (Z=1Ω @10GHz) can be resolved.

The broadband skin effect wall loss of the beam chamber is estimated to be approximately Z/n=0.0015Ω, (Z=10Ω @ 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 <0.001Ω and < 0.0005Ω, (Z <6.7Ω and <3.3Ω) 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<2Ω . For twelve chambers and an allowance of 10% for beam chamber losses this makes the maximum tolerable impedance <0.017Ω (Z/n).

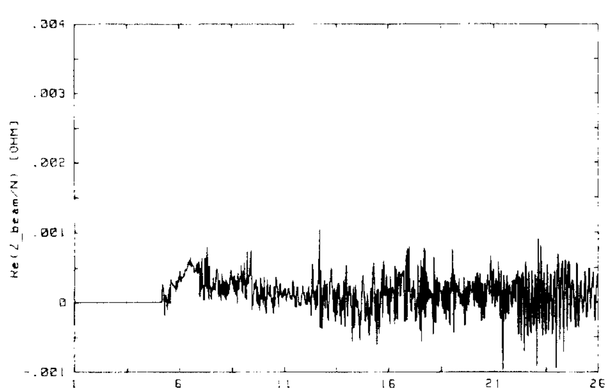

Fig.5 Impedance due to antechamber, wireless method

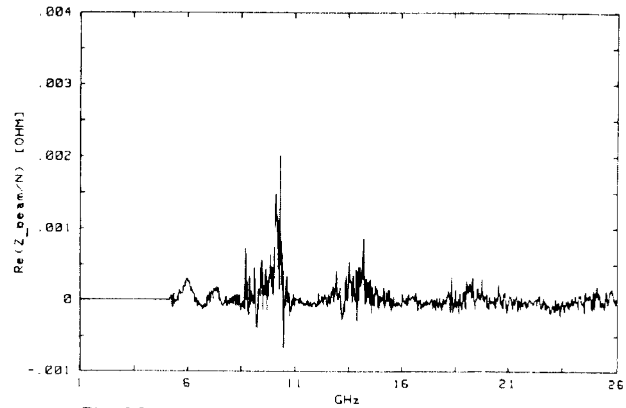

Fig.6 Impedance of test resonator, wireless method

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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