

IMPEDANCE MEASUREMENTS ON BUTTON ELECTRODES*

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Abstract

In the Advanced Light Source, there will be about 400 capacitive button electrodes in the beam position monitor (BPM) system, hence the contribution of each button to the machine beam impedance must be very small. We have measured the impedance of a single button as sensed by a coax connected directly to the button surface. This method is very sensitive and did not require a model of the total beam chamber as would the usual wire method. The measurements covered the range 0.1-to-20 GHz. The proportionality factor between the button impedance and the beam impedance depends upon geometry and frequency and was obtained from the measured sensitivity of a developmental BPM at low frequency. Discontinuities in the connection of the coax to the face of the button introduce parasitic effects that must be accounted for in interpreting the data. Below 5 GHz the results compare very well with responses computed from mechanical dimensions of the electrode. Above 15 GHz corrections for the parasitic elements become more uncertain but the accuracy of the method is still adequate. The results show multiple resonances, a prominent example being for one button a beam impedance peak of ~ 1 ohm with a Q of 500 at 16 GHz.

Introduction

It is desired that the position-monitoring electrodes, as designed for the Advanced Light Source (ALS), present an acceptably low impedance to the electron beam in order to avoid exciting coupled-bunch instabilities or heating of the electrodes from induced currents. These concerns require that resonant responses of any one of the 400 assumed identical electrodes have peak beam impedances that are less than 2.5 ohm within the frequency range from 0.5-to-20 GHz.

Description of electrodes

Each pickup is a coaxial structure as sketched in Fig. (1) having a 7.6 mm diameter exposed surface flush with the wall of the beam tube and connected to a 50 ohm cable. Further details of the electrode are found in reference [1]. Measurements with a wire excited at 500 MHz have shown the coupling impedance of a single button to the beam to be $Z_p = 0.05$ ohm as a pickup driving a $R_o = 50$ ohm load. At low frequency the button has capacitance $C = 20$ pF.

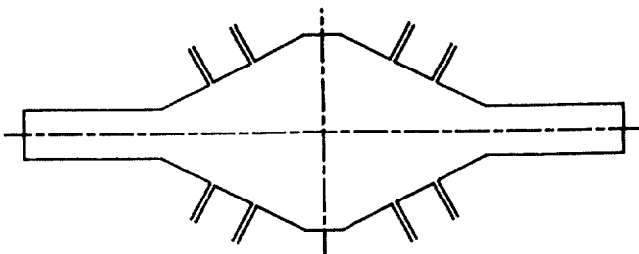


Fig. 1 Schematic cross-section of ALS beam chamber with four button electrodes.

Method

For measuring the beam impedance, we chose to avoid the complexities of the wire method extended to 20 GHz, which is well above the beam-tube cutoff frequency of 5 GHz. Instead, we measured the impedance Z_e presented at the face of a single button and from that calculated the beam impedance.

From the longitudinal beam impedance Z_B , a voltage

$$V_B = I_B Z_B \tag{1}$$

is imposed upon the beam current I_B . Applying reciprocity relations to the circuit in Fig. (2), we have

$$V_B I_B = -(I_e Z_e) I_e \tag{2}$$

where I_e is the current induced in the button by the beam. Combining eqs. (1) and (2) we find

$$Z_B = Z_e (I_e / I_B)^2 \tag{3}$$

The ratio I_e / I_B is proportional to frequency f and from the values of R_o , C , and Z_p at 500 MHz we obtain

$$I_e / I_B = j(3.3 \times 10^{-3}) \frac{f}{5 \times 10^8} \tag{4}$$

At the highest frequencies this ratio becomes smaller than the above value, being about 30% lower at 20 GHz. We have not applied this correction to the results. If in using this method to find Z_B coupling data at one frequency were not available, one could calculate the ratio I_e / I_B for a reasonably simple geometry.

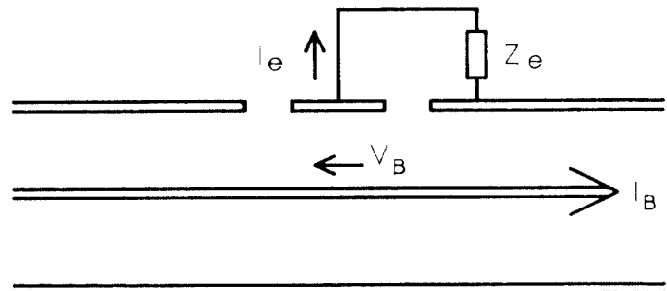


Fig. 2 Model of the button showing relevant currents and voltages.

Measurement Set-Up

One way to assess the button impedance Z_e is to connect the button directly to a coaxial measuring system. Then a transition piece is required in order to adapt the outer diameter of the button to a standard coaxial cable. Fig. (3) is the sketch of a possible arrangement: it simply consists of a coaxial line with abrupt changes in cross section. The diameter of its outer conductor matches the 8.8 mm of the button surround and changes abruptly to the dimension of a standard SMA connector. Its center rod is the prolongation of the SMA center conductor. It contacts the center electrode of the button, leading to another impedance step. The length of the inner and outer conductors of the test fixture have to be carefully matched in order to insure a good contact with the button. A drop of soft solder on the center of the button proved to be helpful. The device is chosen long enough so as to allow higher order modes below cutoff to be sufficiently attenuated from one discontinuity to the other.

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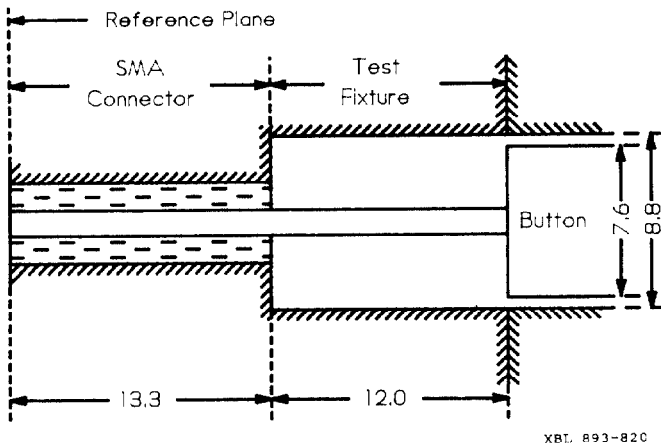


Fig. 3 Cross section of the test fixture (dimensions in mm).

The data are taken with an HP8510B network analyzer (NWA) which must be calibrated for highest precision. The data are transferred to a computer where they can be processed. The interface between the NWA and the button, i.e. the SMA connector of the test fixture, defines the reference plane for the measurements. However the impedance measured in this plane is not the actual button impedance Z_e which is hidden by the discontinuities of the transition piece and therefore has to be de-embedded. Fig. (4) shows the equivalent circuit used to calculate Z_e from the measured reflection coefficient S_{11} . The transmission lines with subscript 1 and 2 represent the SMA connector and the transition piece respectively. The capacitances model the effect of the step discontinuities. They can be evaluated following well-known procedures [2]. The parameters needed for the calculation of the elements of the equivalent circuit are the mechanical dimensions of the set-up which are indicated in the Figs. (3) and (4). The approach requires the higher order modes which can be coupled to be below cutoff. The first possible mode is the TM_{01} which has a cutoff frequency of about 40 GHz and is therefore non-interfering. In principal Z_e should be augmented by a capacitance which takes into account the fringing fields when the button radiates into the beam tube. This effect has been neglected here.

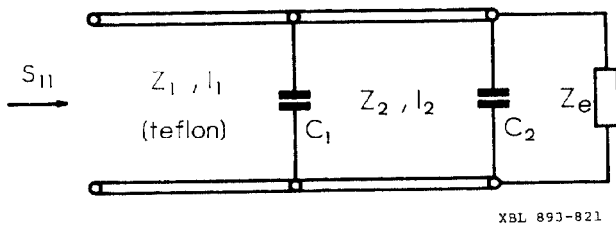


Fig. 4 Equivalent circuit of the test fixture for the case with direct contact.
($Z_1 = 50$ ohm, $l_1 = 13.3$ mm, $Z_2 = 116.1$ ohm, $l_2 = 12.0$ mm, $C_1 = 18$ fF, $C_2 = 250$ fF).

In a second experiment a modified set-up was used: the center conductor was made shorter by 0.3 mm thus coupling only capacitively to the center electrode of the button. The resulting equivalent circuit is shown in Fig. 5. The end capacitance of the antenna has now two components, accounting for the different places where the field lines terminate. In order to determine these two quantities, measurements with an open and a short circuit instead of the button have to be performed first. Once the capacitances have been deembedded from these runs the button can be connected, measured and its impedance calculated.

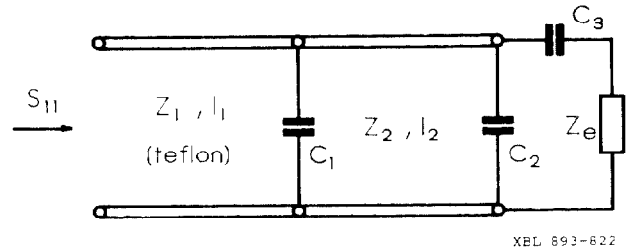


Fig. 5 Equivalent circuit of the test fixture for capacitive coupling.
($Z_1 = 50$ ohm, $l_1 = 13.3$ mm, $Z_2 = 116.1$ ohm, $l_2 = 11.7$ mm, $C_1 = 18$ fF, C_2, C_3 from calibration measurements).

Results

The measurements covered the range 0.1-to-20 GHz which is well below the cutoff frequency of the first higher order mode excited in the coaxial test fixture. For a higher resolution the frequency range has been subdivided into four intervals. As a typical result Figs. (6) and (7) show the button impedance in two of these intervals. In the range 0.1-to-5 GHz (Fig. (6)) there is only one resonance at 3.3 GHz. Its unloaded Q is approximately 17. The peak button impedance is 130 ohm. With eqs. (3) and (4) this gives a beam impedance of 0.06 ohm for a single button. A resonance with a higher Q factor can be seen in Fig. (7) which shows the upper frequency range. At 16.2 GHz the button resonates with a Q of 470 and a peak impedance of 63 ohm. This corresponds to a beam impedance of 0.7 ohm.

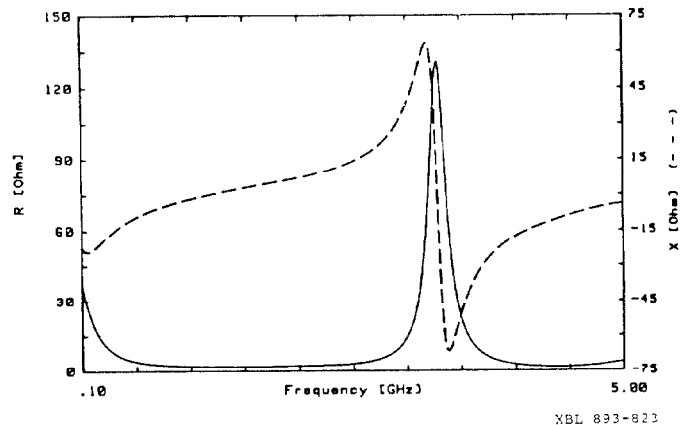


Fig. 6 Real and imaginary parts of the measured button impedance in the frequency range 0.1-to-5 GHz.

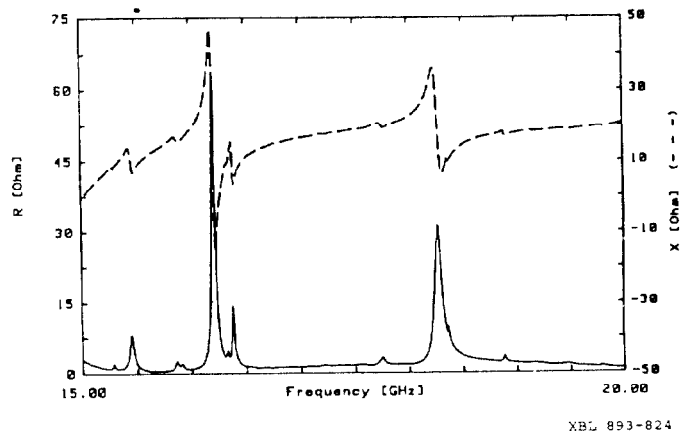


Fig. 7 Real and imaginary parts of the measured button impedance in the frequency range 15-to-20 GHz.

In order to boost the confidence in the measured results the button impedance has also been calculated. A very crude transmission line model has been used to simulate the changing cross sections between the face of the button and the 50 ohm output line. Mechanical dimensions of limited accuracy were used to determine the parameters of the equivalent circuit. Assuming lossless lines the model agrees very well with measured results up to 5 GHz except for the shunt resistance of the resonant peak which is higher in the model. The figure can be improved by introducing losses in the transmission lines. An exact comparison would however involve more precision in the characterization of the button which is not quite the initial aim.

The button impedance at the magnitude shown by the measurements is not critical for the beam in the ALS. However the numbers presented above are subject to errors. In order to assess their influence the parameters of the deembedding circuit have been varied (the lengths by about 2%, the line impedance of the test fixture by 5% and the capacitances by 10%). The effect of these variations has been studied in the frequency range 15-to-20 GHz. The peak impedances changed by as much as a factor of 2 for some of the parameters. Although this is not crucial in the present case, especially if one considers the very large tolerances assumed, some caution is advised if highest precision is needed.

The results of the measurements with the capacitive coupling prove to be more sensitive to circuit parameters. The capacitances C_2 and C_3 which should be fairly constant exhibit strong variations with frequency. The button impedance itself follows the same pattern as measured with the other method: the resonance frequencies and the Q factors are in good agreement in both cases. The peak impedances

however differ significantly, especially the higher ones. Below 3 GHz the coupling becomes so weak that the signal disappears in the noise.

Several factors may influence the accuracy of the results in this method:

- the residual errors and the noise of the NWA which are most likely harmful at the lower frequencies where the measured signals become very small,
- the accuracy of the embedding circuit,
- the validity of the measurement of C_2 and C_3 which is based on the assumption that C_2 and C_3 can be determined separately. The open-circuit calibration is also problematic.

Conclusions

A very sensitive method for measuring beam impedance has been presented. Provided the object is small enough the useful frequency range can be extended well beyond the cutoff frequency of the beam chamber in which the object will eventually be used. The accuracy proved to be adequate for the example studied here. Tighter mechanical tolerances would be required if higher accuracy were needed.

References

- [1] J. Hinkson, J. Johnston, I. Ko, "Advanced Light Source (ALS) Beam Position Monitor," proceedings of this conference.
- [2] N. Marcuvitz, Waveguide Handbook, MIT Radiation Laboratory Series, Mc. Graw-Hill 1951.