Transverse Beam Impedance Measurement. A New Coaxial Method.

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Abstract

Coupling bunch and μ-wave instabilities can strongly affect the beam behavior in cyclic accelerators. Stability conditions depend not only on the beam characteristics, but also on its interactions with the surrounding enviroment. Transverse coupling impedance and transverse kick are two parameters usually used, in frequency and time domain respectively, to study this kind of interaction. A new procedure of measurements is proposed in order to calculate the transverse impedance.

I. INTRODUCTION

A Φ Factory machine, DAΦNE [1], has been proposed at the National Lab. of INFN of Frascati - Italy- (a general talk is presented elsewhere at this conference). The goal of this accelerator is to reach a luminosity of 10^{32} cm^{-2} sec^{-1} at 510 MeV. To achieve this requirement high currents, short bunch lengths, long lifetimes and high stable beam are required. All these requirements are strictly related to the design of the whole machine and they can be affected by intrabeam scattering, μ-wave instabilities, coupled bunch instabilities, whose thresholds are linked to the vacuum chamber geometry, to RF cavity properties depending on the interaction of the bunch with the surrounding structure (coupling). A problem of great importance is to keep both longitudinal and transverse machine impedances at a low value. This means that all the accelerator components like kickers, bellows, etc. that can give a big contribution to the total impedance, have to be carefully designer and tested before the installation. From this the necessity of a laboratory method to measure impedance follows, which has to be used as a feedback on the design of the machine elements.

We propose to use the coaxial wire method [2] instead of the frequency perturbation one [3], because of the low quality factor (Q) linked to the low impedance to be measured in our components. The technique transforms the Device Under Test [DUT] in a coaxial line by putting in two wires [4],[5],[6]. In this paper a proper procedure has been developped in order to deembend the transverse impedance due to the DUT.

II. IMPEDANCE CALCULATION

The measurement is performed by means of a two-wire transmission line located on the axis of the beam. The line has a resistance R_O, an inductance L_O and a capacitance C_O per unit length. The device under test (DUT), by means of the coupling, produces an extra term $\zeta = R+jX$, so that the propagation constant of the line becomes

$$k_d = \sqrt{(\omega L_O - jR_O - j\zeta)\,\omega C_O} \qquad (1).$$

As a consequence, the scattering parameter, **referred to the characteristic impedance of the line**, becomes:

$$S_{12}^{od} = \exp(-j\,k_d\,L) \qquad (2)$$

where L is the total length of the line.

If the same measurement is performed replacing the DUT with a smooth pipe of uniform cross section, the scattering parameter becomes:

$$S_{12}^{or} = \exp(-j\,k_r\,L) \qquad (3),$$

where

$$k_r = \sqrt{(\omega L_O - jR_O)\,\omega C_O} \qquad (4).$$

If the distributed impedance ζ, induced by the device, is small compared to the quantity $(Ro+j\omega Lo)$, we may linearize the propagation constant k_d as a function of ζ and get

$$S_{12}^{od} / S_{12}^{or} = \exp(-\zeta L/2\,Z_O) \qquad (5),$$

where the characteristic impedance Z_O is

$$Z_0 = \sqrt{\frac{(R_O + j\omega L_O)}{j\omega C_O}} \qquad (6).$$

Finally the transverse impedance is

$$Z_T = 2\,\frac{c}{\omega}\,\frac{Z_O}{\Delta^2}\,\ln(S_{12}^{or}/S_{12}^{od}) \qquad (7),$$

where Δ is the distance between the two wire centers of the line.

III. THE MEASURING TECHNIQUE PHILOSOPHY

Allowing for the scattering matrix **S**, we see, according to its definition, that this quantity is a function of a reference impedance Z_c :

$$\mathbf{S} = (\mathbf{Z} - Z_c\,\mathbf{I})(\mathbf{Z} + Z_c\,\mathbf{I})^{-1} \qquad (8).$$

This can be better seen, in the case of a symmetrical device, from the expression of the scattering parameters as a function of the hybrid parameters:

$$S_{12} = \left[\frac{h_{12}}{2Z_c}\left(1 - \frac{Zc}{Zo}\right)^2 + h_{11} + j\sqrt{1 - h_{11}^2}\,\right]^{-1} \qquad (9)$$

$$S_{11} = S_{22} = \frac{h_{12}}{2Z_0}\left[\,1 - \left(\frac{Zc}{Zo}\right)^2\,\right]S_{12} \qquad (10).$$

Most measuring devices give the values of the scattering parameters calculated on the basis of the equations (9) and (10) with $Z_c = 50\ \Omega$.

On the other hand, if the value of Z_c can be set equal to the charactericstic impedance Z_0 of the two wire transmission line, then the scattering parameters take the form

$$S^o_{12} = h_{11} - j\sqrt{1 - h^2_{11}} \quad (11)$$

$$S^o_{11} = S^o_{22} = 0 \quad (12).$$

In this case, and only in this case, the scattering parameter $S_{12}{}^o$ can be correctly interpreted as the phasor $\exp(-j\theta)$, whose complex angle is the phase lag and the attenuation of a progressive wave along the wires (see eqs. 2,3).

In order to measure correctly the scattering parameters, we adopt the following procedure:

i) we measure the entire scattering matrix $\mathbf{S^c}$ for a configuration formed by the two spacers, directly connected, and the two adaptors, as depicted in figure (1a);

ii) we measure the entire scattering matrix $\mathbf{S}$ for a configuration formed by the device, two spacers and two adaptors, as depicted in figure (1b).

It has been shown [7] that the scattering parameter S^o_{12} referred to the characteristic impedance Z_0 can be calculated according to the formula

$$S^0_{12} = \frac{1}{2S^c_{12}\,S_{12}}\left\{\frac{1}{2}\left(|\mathbf{S^cL} - \mathbf{L\,S}| - |\mathbf{S^c} - \mathbf{S}|\right) + \right.$$

$$\left. - j\sqrt{|\mathbf{S^cL} - \mathbf{L\,S}|\,|\mathbf{S^c} - \mathbf{S}|}\right\} \quad (13),$$

where $\mathbf{L}$ is $\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$

Applying this procedure to both the device under test and the reference pipe, we may obtain S^{od}_{12} and S^{or}_{12} by plugging in eq. (13) $\mathbf{S^d}$ and $\mathbf{S^r}$ respectively. Finally resorting to eq. (7), we get an accurate evaluation of the transverse impedance. Conversely, errors could arise, if one adopts the standard procedure, namely using eq. (9).

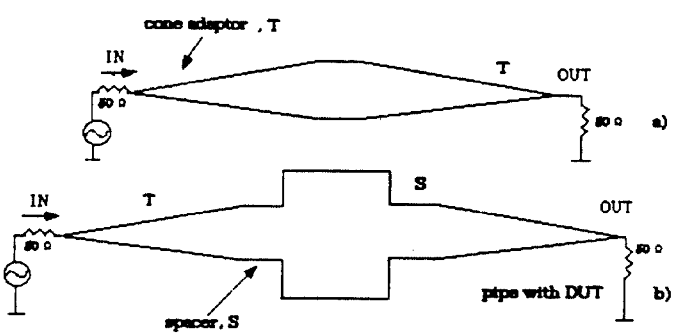

Figure 1. Schematic diagram of experimental set-up: a) cone adaptors; b) test structure.

IV. EXPERIMENTAL RESULTS

The measurements were performed on a Accumulator kicker prototype 90 cm long and with a diameter of 20 cm (fig.2). The pipe used for the spacers (5 cm each) has an elliptical shape, as the real vacuum chamber will have, with two semiaxis of 5.2 cm and 1.75 cm respectively. Two cones, 50 cm long, have been used to slowly match the elliptical tube to the N connectors on both ends. Two 1 mm wires, spaced 10 mm, were stretched in the tube center. An elliptical tube, same spacer shape, of a total length equal to the kicker plus the two spacers has been used as reference pipe inserted between the tapers.

For the data acquisition and for the remote control of the instrumentation an Hp 9000/300 computer has been used connected to the measurement system (Network Analyzer (N.A.), Sweep Oscil., etc.) through an Hp-IP bus. Transmission measurements have been performed in the frequency range between *1 and 500 MHz*.

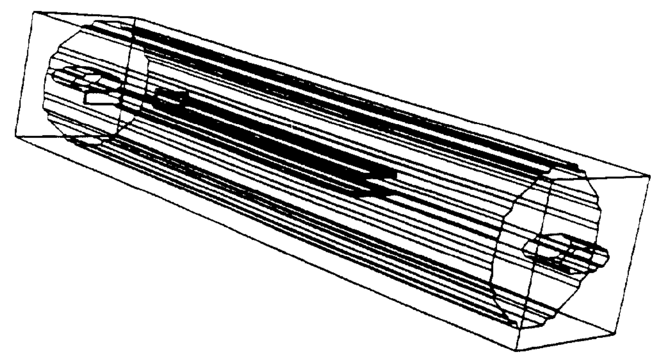

Figure 2. Accumulator kicker

The transverse impedance, calculated by means of the present procedure is reported under fig. (3), while the one calculated by means of the standard method is reported in fig. (4). Comparing the two results the following comments are in order:

a) the resonances appearing in fig. (3) are those foreseen from numerical simulation; however the spike close to 330 MHz cannot be explained. We have reasons to belive that this arises from the ambiguity in the numerical calculations in the square root in eq.(13).

b) the coupling resistance, calculated by means of the present procedure, is positive except in a very small frequency range (see above), while the one calculated by the standard methods exhibits negative valuesin wide range of frequencies;

c) the discrepancy is even more relevant when we calculate the transverse kick, where the resistance is weighted by the inverse of frequency, as the value is wrong at low frequencies.

d) from the FFT analysis, shown in fig. (5), we learn that the multiple reflections have been largely suppressed.

Finally it has to be pointed out that the goodness of the results is very sensitive to the matching of the feeding line to the adaptors, as the large amount of experimental data has shown. The results are even better if the matching is done by means of a resistive lumped circuit, improving in this way the signal-noise ratio by reducing the contribution of multiple reflections.

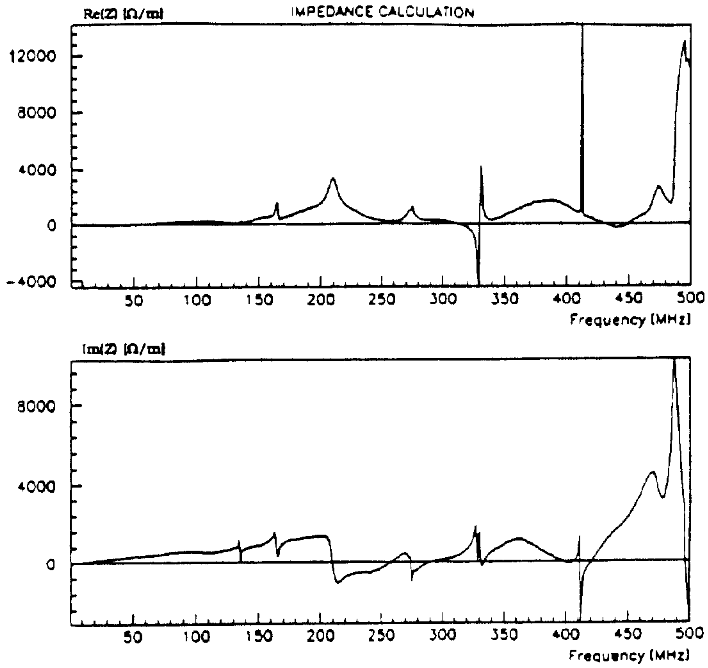

Figure 3. Transverse impedance calculated by present method.

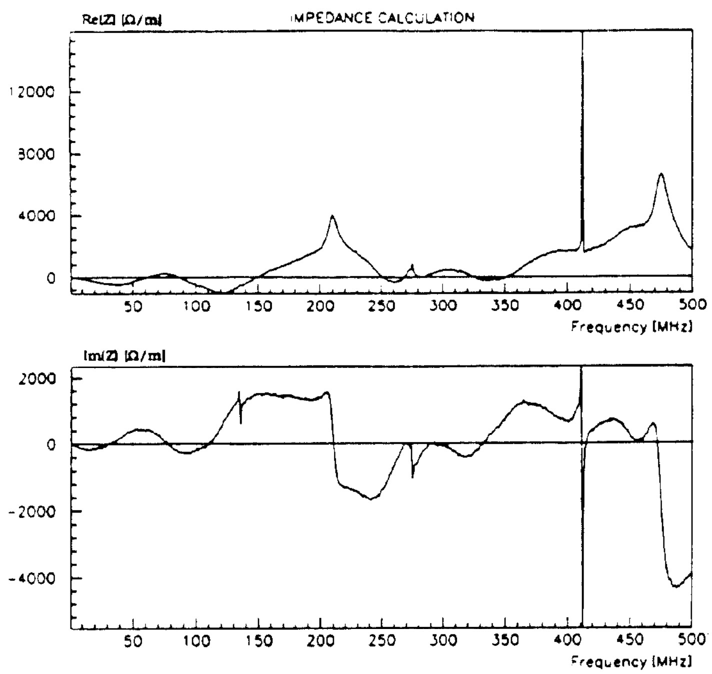

Figure 4. Transverse impedance calculated by standard method.

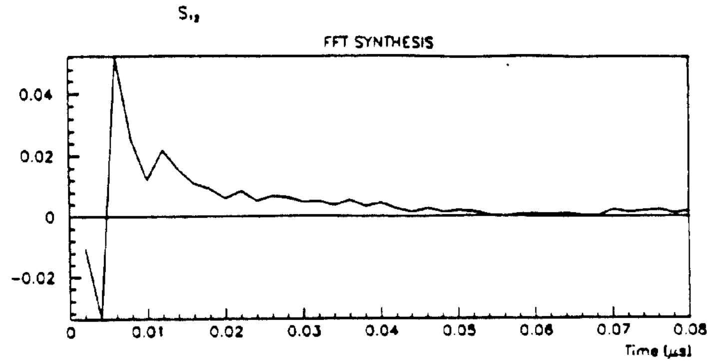

Figure 5. Time domain FFT of the kicker trasmission coefficient calculated by present method.

Table (1) shows the values of the transverse kick [8] calculated from the measurements obtained with the present method and the ones produced by computer simulations [9], for different bunch lengths σ. The agreement looks interesting.

σ [cm]	4	6	8	12
k (exp.) [V/pCm]	**12.27**	**11.20**	**9.96**	**7.50**
k (sim.) [V/pCm]	**16.95**	**11.88**	**9.26**	**6.40**

Table 1. The transverse kick. Comparison between measured data and numerical simulations.

V. REFERENCES

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