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WIRE MEASUREMENT OF IMPEDANCE OF AN X-BAND ACCELERATING STRUCTURE [†]

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Abstract

Several tens of thousands of accelerator structures will be needed for the next generation of normal conducting linear colliders known as the GLC/NLC (Global Linear Collider/Next Linear Collider). To prevent the beam being driven into a disruptive BBU (Beam Break-Up) mode or at the very least, the emittance being significantly diluted, it is important to damp down the wakefield left by driving bunches to a manageable level. Manufacturing errors and errors in design need to be measured and compared with prediction. In this paper a bench-top method of measuring transverse impedances in X-band accelerating structures is described. Utilizing an off-axis wire the S parameters are measured and converted to impedance. Measurements in a damped and detuned structure built for GLC/NLC are presented and the results are discussed.

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Abstract

Several tens of thousands of accelerator structures will be needed for the next generation of normal conducting linear colliders known as the GLC/NLC (Global Linear Collider/Next Linear Collider). To prevent the beam being driven into a disruptive BBU (Beam Break-Up) mode or at the very least, the emittance being significantly diluted, it is important to damp down the wakefield left by driving bunches to a manageable level. Manufacturing errors and errors in design need to be measured and compared with prediction. In this paper a bench-top method of measuring transverse impedances in X-band accelerating structures is described. Utilizing an off-axis wire the S parameters are measured and converted to impedance. Measurements in a damped and detuned structure built for GLC/NLC are presented and the results are discussed.

INTRODUCTION

One option in building a next generation of linear collider is to use normal conducting X-band accelerating structures. These structures have been carefully designed and studied for over a decade for the GLC/NLC [1]. One main concern in their design is the minimization of wakefield effects. Wakefields are excited by charged particles in the accelerating structures and influence the motion of subsequent particles or bunches. In particular, transverse fields are of concern, as they cause large increase in the emittance or, in the worst case, BBU [2].

To prevent this, the frequencies of the modes which comprise the wakefield are forced to add de-constructively by detuning the frequencies of the cells. Initially the wake decays with a Gaussian functional form. However, as there are a finite number of cells, eventually the modes must add coherently. This causes the wakefield to rise to unacceptably large values. To prevent this from occurring, a fraction of the wake is coupled out to four manifolds, which run collinear with the axis of the accelerator. Several such damped and detuned structures have been built and studied. The most advanced in this series is the RDDS1 (rounded damped detuned structure) [3]. It has a length of 1.8 m with a $2\pi/3$ phase advance per cell. A 60 cm accelerator structure with a $5\pi/6$ phase advance per cell is currently being fabricated [4].

Even though electromagnetic field simulation codes as well as circuit models have proven to give accurate results, the increasing complexity of the structures requires wakefield measurements to be performed in order to be sure that the fabricated structures behave as expected. Previously, the main setup for such measurements in GLC/NLC structures has been the ASSET facility [5], where transverse fields are excited and sampled by a beam. Although this method is quite precise, it has the drawback of requiring expensive beam time at an accelerator facility.

An alternative and somewhat complementary method is the wire method [6,7]. Here a metallic wire takes the place of the beam and a high frequency measurement is conducted in the laboratory. The fundamental idea behind the wire method is to simulate the beam-structure interaction by propagating a short current down a wire inserted in an accelerating structure.

Alternatively, one can measure the transmission curve in the frequency domain in order to study the transverse impedance, which is related to the wakefield $W_\perp$ by:

$$Z_\perp(\omega) = \frac{-i}{c}\int_{-\infty}^{\infty} W_\perp(\zeta)\exp\left(-i\omega\frac{\zeta}{c}\right)d\zeta\,, \qquad (1)$$

where ω is the angular frequency and c the light velocity. In the frequency domain one can distinguish the individual resonances of the structure, the higher order modes (HOM), constituting the wakefield:

$$W_\perp(\zeta) = \sum_n 2k_{\perp,n}\sin\left(\omega_n\frac{\zeta}{c}\right)\exp\left(-\frac{\omega_n}{2Q_n}\frac{\zeta}{c}\right). \qquad (2)$$

Here ω_n, Q_n and $k_{\perp,n}$ are the angular frequency, quality factor and kick factor of mode n.

In our measurements we chose to measure in the frequency domain. For transverse wakefields, two wires placed symmetrically around the axis have been used previously. This kind of measurement has the advantage of decoupling the odd and even modes. On the other hand, aligning the two wires may be rather difficult, particularly for X-band structures. For this reason we chose to use a single off-axis wire for our measurements.

In the next section we present the setup, built at SLAC, to measure transverse wakefields. The measurements made in RDDS1 are described in the final main section.

METHOD

Setup

Fig. 1 shows the setup of the wire measurement. A wire of diameter 300 μm is placed at an offset in the device

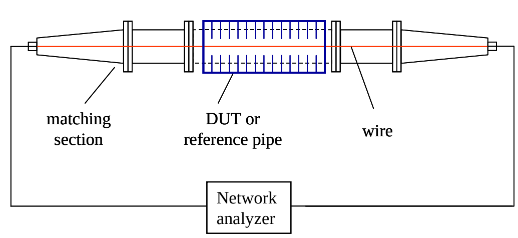

Figure 1: Sketch of the wire measurement setup.

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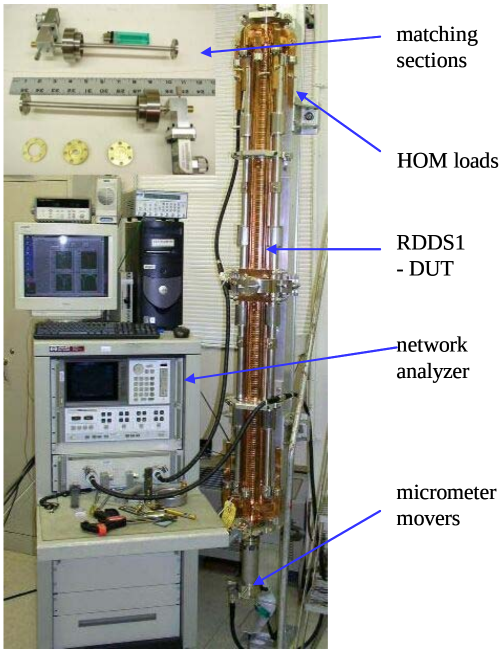

Figure 2: Wire measurement setup.

under study (DUT). Two adapters are utilized to match the impedance of the wired structure to a 50 Ω high frequency cable. A network analyzer is utilized to measure the scattering (S) parameters. In Fig. 2 one can see a picture of the setup. The 1.8 m long RDDS1 structure is mounted vertically, in order to avoid an appreciable saggitta in the wire. The supports to the lower matching section can be seen. The upper inset shows the matching sections together with the purposely built calibration elements. The wire can be moved transversely by slightly bending the tubes of the adaptors.

The network analyzer has been calibrated at the ports constituted by the flanges of the structure. The setup has a broad bandwidth, which ranges from 11 GHz to 18 GHz. The elements which limit the bandwidth are the waveguide-to-coax adaptors. This setup is sufficiently broadband to measure the entire first dipole pass-band in RDDS1.

Principle

Alignment of the wire is based on the amplitude of the transmission parameter S_{21} of modes at the low and high frequency end of the first dipole band. These two extremes correspond to alignment in cells in the first and last part of the detuned structure.

S_{21} is measured for various positions of the wire, for the DUT (S_{21}^{DUT}) and, for a reference tube (S_{21}^{REF}) having the same length as the structure. The impedance can be calculated based on various models. We use the so-called log formula, as it is best suited for long structures [8]:

$$Z_{\|} = -2Z_0 \ln \frac{S_{21}^{DUT}}{S_{21}^{REF}} \left(1 - \frac{1}{2\gamma_0 d} \ln \frac{S_{21}^{DUT}}{S_{21}^{REF}} \right), \qquad (3)$$

where Z_0 and γ_0 are the characteristic impedance and the propagation constant of the coaxial line and d is the length of the structure.

MEASUREMENTS

Transmission Parameter S_{21}

S_{21} measured for a relative position of the wire, with respect to an arbitrary reference, of x = 0.24 mm (the plane containing the input coupler) and y = -0.48 mm is shown in Fig. 3. The wire is about centered in the y plane and at an offset in x. The dipole band is present between about 14 and 16.5 GHz. In the presence of the wire, the mode frequencies are shifted with respect to the unperturbed case [9]. In Fig. 3 one can distinguish some of the individual dipole resonances, particularly between about 14.5 and 15.5 GHz. Although they are rather difficult to distinguish, detailed spectra indicate that there are also HOMs present at higher and lower frequencies.

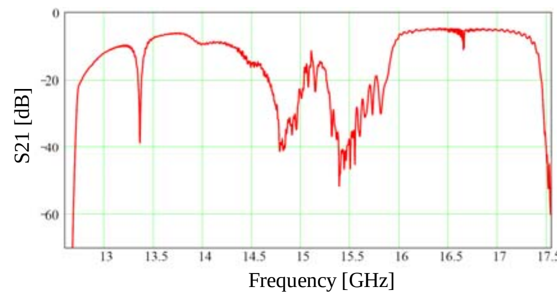

Figure 3: S_{21} as a function of frequency for x = 0.24 mm and y = - 0.48 mm.

In principle, one expects to see an overall Gaussian-like S_{21} curve [10]. However a fabrication error in the central region of this structure, has led to a deformation of the frequency spectrum in the neighborhood of 15 GHz. The larger peak at about 15.8 GHz is due to the decoupling from the manifold of the last few cells of the structure. The high peak at about 13.4 GHz is not a structure mode and has been observed in previous measurements.

The red continuous curve in Fig. 4 is a detail of the spectrum in Fig. 3. About five individual HOM peaks can be distinguished in frequencies between approximately 14 GHz and 14.2 GHz. The same plot shows other curves for several x positions. One observes how while the wire moves in one direction, both the frequency and the amplitude of the modes change. One can decouple the individual peaks and extract information about individual modes from this curve, in particular about the modal loss

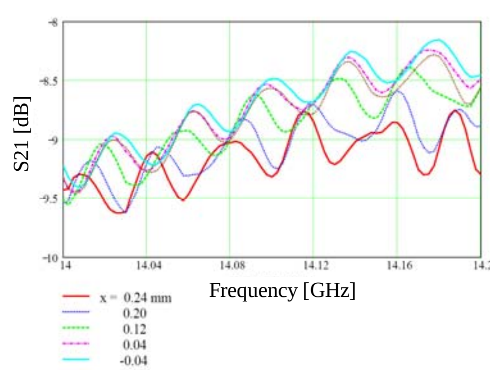

Figure 4: S_{21} as a function of frequency for several wire positions (y = -0.48 mm).

factor. This will be the subject of a future paper.

From S_{21} the frequencies of the modes can be estimated for each wire position. This is shown in Fig. 5 for the same frequency window. One can clearly follow the quadratic variation of the frequency of each mode with the wire position. This shows that the wire measurement is also suitable for measuring cell misalignments in detuned structures, where each mode couples strongest to the beam (or wire in our case) in a certain cell.

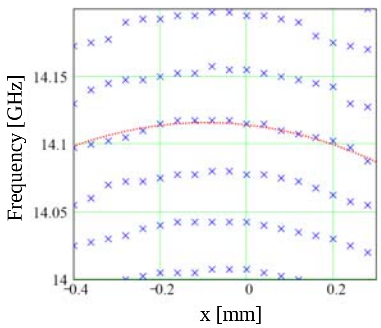

Figure 5: Peak frequencies as a function of the x wire position (y = -0.48 mm).

Transverse Impedance

From the S_{21} measurement one can calculate with eq. (3) the impedance of the dipole pass-band as a function of frequency. In order to obtain the transverse impedance (in principle independent of the transverse position of the wire) the longitudinal impedance is normalized with respect to $(c/\omega)/(x^2 d)$. Fig. 6a displays the impedance obtained from the transmission parameter shown in Fig. 3 and an application of eq. (3). For the sake of comparison, the spectral function of RDDS1 as predicted by a circuit model [11] (where the frequency errors that occurred during fabrication are included) is illustrated in Fig. 6b. It is interesting to observe in both curves frequency errors in the neighbourhood of 15 GHz. One can distinguish in the measurement recorded in Fig. 6a a rise in the impedance above 14.5 GHz. The modes below this frequency have a low kick factor and therefore they couple weaker to the wire and give a lower signal. The same reasoning applies at high frequencies.

Apart from the difficulties inherent in the method (e.g. applicability of the model used and sufficiently good electrical contacts), complications arise from the errors in the fabrication of this structure. This impedes quantitative comparisons with spectral function predictions. Also, wire movements in both planes were coupled, making the normalization of the transverse impedance to the offset from the structure axis rather difficult.

In conclusion, the setup has been improved and the two transverse planes are now adequately decoupled. Furthermore, the reason for the frequency errors occurring in the center of the structure is well understood and will be avoided in future structures. Thus, it is anticipated that there will be minimal frequency errors in the forthcoming damped and detuned structures planned

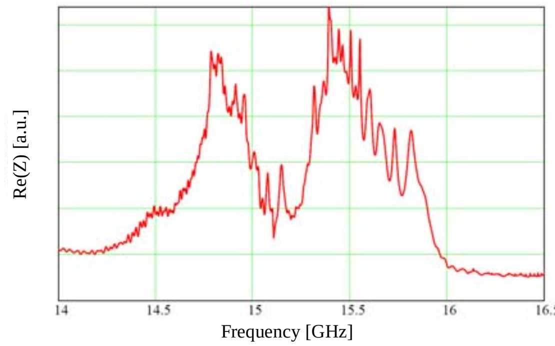

Figure 6a: Impedance obtained from the S_{21} in Fig. 3.

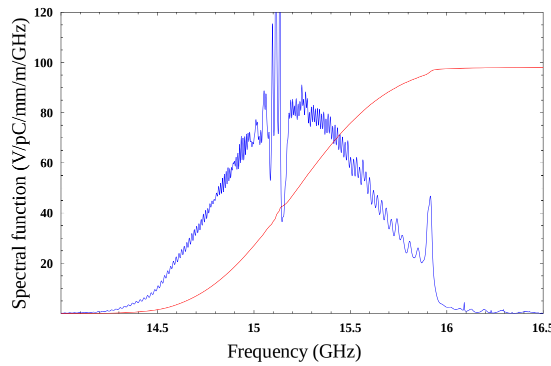

Figure 6b: Spectral function [10] as obtained from a circuit model [11]. The frequency errors in the middle of the spectrum, due to the deformation of the middle cells, are taken into account.

for measurement later this year. Also, we intend to explore the possibility of extending the measurement technique to investigate the modes in L-band TESLA [12] accelerating cavities in the context of the ILC (International Linear Collider) [13]. Finally, we note that integration of the beam impedance will allow an estimation of the individual kick factors of the dipole pass-band.

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