THE GOUBAU LINE — SURFACE WAVES FOR BENCH TESTING OF BEAM INSTRUMENTATION AT HIGH FREQUENCIES

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Abstract

Standard setups for bench testing of beam instrumentation in the workshops usually fail when it comes to signal frequencies a lot higher than 1 GHz. A potential improvement could be provided by electromagnetic surface waves traveling along a single wire. These waves consist of the fundamental TM mode and resemble closely the radial electric and azimuthal magnetic fields around a long and thin beam of charged particles. We discuss their fundamental properties, show how they could be applied and compare calculations to measurements up to 8.5 GHz.

INTRODUCTION

Bench testing of beam instrumentation is a challenge by itself. Particle beams cannot be used because their production is too complicated; especially since well calibrated beams would be required. Usually rather simple electrical setups serve us to mimic beam characteristics. For example, the beam current is simulated by a current on a wire. It is amazing how well this works. But particle accelerators are pushing requirements to higher and higher frequencies. And we are reaching a regime where our setups, which work so well at low frequencies, start to fail. In the GHz regime impedance mismatches, resonances and reflections often render a proper interpretation of measurement results impossible. Furthermore, conditions can change drastically if the device under test moves just slightly.

An improvement could be provided by electromagnetic surface waves traveling along a single wire. These waves consist of the fundamental TM mode and mimic closely the electromagnetic fields around a charged particle beam. While we have set up our first test bench just a couple of weeks ago, successful measurements where already performed some time ago at JLab [1, 2].

In the following we will explain basic properties of surface waves, show their application to bench testing of beam instrumentation and discuss first measurement results.

ELECTROMAGNETIC SURFACE WAVES

How wave guides look like is commonly known: an electromagnetic wave propagates inside a conducting pipe. But Maxwell's equations allow another solution. The wave guide can be turned inside out, so that the wave propagates outside a cylindrical conducting surface. To understand why this is possible a simple but profound addition has to be made to the field calculation: the surface must be imperfect. It must have either a finite conductivity, some roughness or a coating.

The first evaluation of surface waves on wires has been performed more than a century ago by A. Sommerfeld [3] and has been extended just a couple of years later by F. Harms [4] and D. Hondros [5]. In 1950 G. Goubau reviewed the topic and and gave practical guide lines how to apply surface waves to signal transmission [6]. Consequently, it was him who gave his name to what is now known as the Goubau line.

Here we will explain only little of the theory, which can be found in the aforementioned papers. We will discuss the theoretical background soon in another paper [7].

The electromagnetic field of a surface wave around a straight, round wire will consist of the following three components: a radial electric field E_r, a longitudinal electric field E_z and an azimuthal magnetic field H_ϕ, which are the components of a fundamental TM mode:

$$\begin{aligned} E_r &= \frac{I e^{i(\omega t - hz)}}{2\pi r_w} \frac{h}{\omega\epsilon} \frac{H_1^{(1)}(\gamma r)}{H_1^{(1)}(\gamma r_w)} \\ E_z &= \frac{I e^{i(\omega t - hz - \pi/2)}}{2\pi r_w} \frac{\gamma}{\omega\epsilon} \frac{H_0^{(1)}(\gamma r)}{H_1^{(1)}(\gamma r_w)} \\ H_\phi &= \frac{I e^{i(\omega t - hz)}}{2\pi r_w} \frac{H_1^{(1)}(\gamma r)}{H_1^{(1)}(\gamma r_w)} \ . \end{aligned}$$

I is the signal current, ω is its angular frequency. $\gamma^2 = k^2 - h^2$ describes the deviation of the guided propagation constant h from the free space propagation constant $k = \omega\sqrt{\epsilon\mu}$. $H_0^{(1)}$ and $H_1^{(1)}$ are Hankel functions. r is the distance to the center of the wire of radius r_w. Only h is a priori unknown. But it can be derived from the fact that on the surface of the wire E_z and H_ϕ must be continuous.

The phase velocity of the wave propagating on the surface is being slowed down by surface imperfections and thus also the wave outside is slower than a freely propagating wave. Hence, h is larger than k and γ is complex. For small complex arguments the Hankel function $H_1^{(1)}(\gamma r)$ is inversely proportional to γr, i.e. near the wire E_r and H_ϕ are proportional to $1/r$. For large complex arguments $H_1^{(1)}(\gamma r)$ is proportional to $e^{-\gamma r}$, i.e. further away from the wire E_r and H_ϕ will decay exponentially.

For bench testing of beam instrumentation the field distribution has to maintain its $1/r$ dependance over the full aperture of the device under test. The range of applicability of the $1/r$ approximation depends on frequency and can be adjusted by appropriate choice of wire and surface properties. A practical limit for the maximum usable frequency should be expected at some 10 GHz. Though in principle the Goubau line can work at a lot higher frequencies.

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FIELD LAUNCHER

For proper excitation of the Goubau line a launching device is required that matches the mode in a coax cable, i.e. a quasi-TEM mode, to the TM mode. The simplest possibility is a tapered cone. Such a cone can also be used to capture the TM mode and re-feed it into a coax cable.

To avoid signal reflections along a cone its shape and the shape of the conductor inside should follow a transmission line taper with an input impedance equal to the impedance of the coax cable, e.g. a Klopfenstein taper [8].

The cone which captures the surface wave will capture only that fraction of the power which falls within its aperture. Due to reciprocity also the launching cone can only launch the same fraction. Hence, power transfer efficiency is limited, especially at low frequencies since the extension of the TM mode is larger. It is the trade-off between too small field extension at high frequencies and too inefficient power transfer at low frequencies that limits the useable signal bandwidth of a Goubau line.

The basic setup of a Goubau line is sketched in Fig. 1.

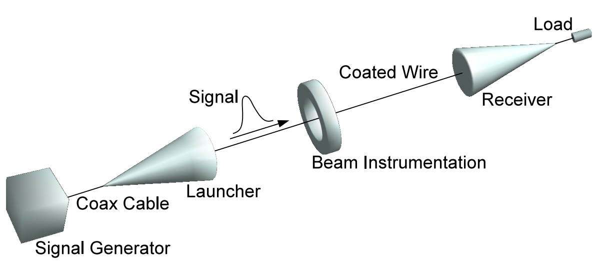

Figure 1: Sketch of a Goubau line for bench testing.

APPLICATION TO BEAM INSTRUMENTATION

A Goubau line can guide electromagnetic fields which closely resemble the electromagnetic fields around a charged particle beam. Accordingly, it can be utilized for bench testing of beam instrumentation.

Its impedance is well defined and reflections can be minimized by proper construction. The device under test will only slightly modify conditions even at frequencies a lot higher than 1 GHz. Hence, the Goubau line extents bench testing capabilities into a previously inaccessible domain.

A Goubau line could be used for bench testing of any device which is supposed to interact with transverse electromagnetic fields of $1/r$ characteristic. The fields of a particle beam are what we are interested in, but other people might find other applications. In case of beam instrumentation such devices could be, for example, beam position monitors including cavity BPMs, current transformers or wall current monitors. Another application of the Goubau line could be to excite higher order modes in accelerating cavities.

MEASUREMENTS AND DISCUSSIONS

We have set up a Goubau line using aluminium cones provided by J. Musson from JLab[1]. The wire has a diameter of 0.9 mm and is enamel coated. The shape of the conductors inside the cones was calculated to achieve an impedance evolution of the Klopfenstein type [8]. They have been assembled from brass tubes of 1 - 7 mm diameter.

A comparison of measured and calculated reflection factors S11 is shown in Fig. 2. Note that the measured S11

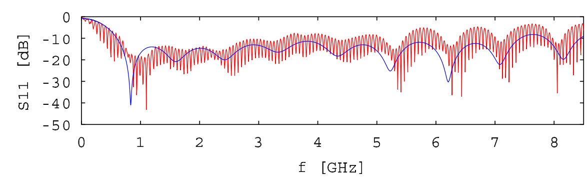

Figure 2: Comparison of calculated (blue) and measured (red) reflection factor S11.

is the reflection factor of the whole Goubau line whereas the S11 calculation was done for a single cone only. It is apparent that there is a general agreement between the two. Though they diverge towards high frequencies and the measurement contains an additional regular pattern of resonances with a distance of about 60 MHz. The divergence is most likely due to imperfections of the cones and the inner conductors which were not and cannot be taken into account in the calculations. The distance of the resonances corresponds to half the frequency of a wave with a wavelength of 2.5 m, which is the length of the wire including the conductors inside the cones. Hence, the resonances in the reflection measurement most likely correspond to higher harmonic standing waves on the wire.

Fig. 3 shows the transmission S21 of the Goubau line and the response of a current transformer (CT). The S21

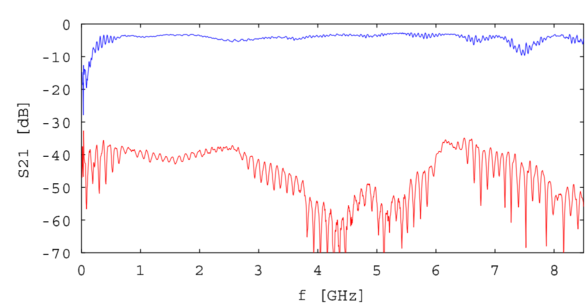

Figure 3: Measurements of transmission S21 of the Goubau line (blue) and response of a CT (red).

of the Goubau line is pretty flat. Although it shows again equidistant resonances especially at frequencies with high reflection (compare Fig. 2). In contrast, the CT response

[1] The cones where originally manufactured by S. Rubin from Rubytron Inc. who provided them to JLab for Goubau line tests.

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shows resonances with twice the distance and otherwise seems pretty arbitrary. But it is not! First, we have to take into account that our test CT will only behave well up to about 1 GHz. Second, with the present cones the excitation of the TM mode on the Goubau line below some 100 MHz is very inefficient. Hence, only a rather small bandwidth remains where we could expect a proper CT measurement.

There is a third point we need to consider: the impedance of the Goubau line. A network analyzer sends a certain power, but a CT measures current. Impedance is what connects the two. The impedance of the Goubau line can be calculated depending on frequency and wire properties [6]. The power transferred to the Goubau line can be calculated from reflection measurements. Taken together these two values allow to normalize the measured CT response to an expected CT response in a 50 Ω environment (Fig. 4).

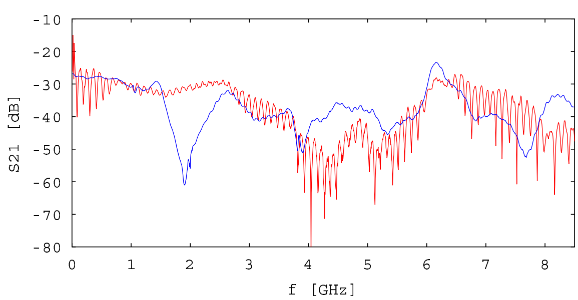

Figure 4: CT response in a spider (blue) and CT response in a Goubau line normalized to a 50 Ω environment (red).

This normalization shows that the match between CT measurements in our standard setup, a so called spider, and in our Goubau line is pretty good; especially around 1 GHz where we expected it to be good since CT and spider work well and reflections by the Goubau line are low. That the dip around 2 GHz is absent in Goubau measurements means it is an artifact of the spider measurement. These artifacts are indeed well-known and the main motivation for the development of the Goubau line.

The remaining strong periodic deviations have twice the distance in frequency as the resonances in the reflection and transmission measurements. Also this can be explained by our assumption of standing waves on the wire. The CT measures the sum of the traveling Goubau TM mode and these standing waves. Since our CT was located in the middle of the wire only every second standing wave, i.e. the half-integer multiples, will have a non-zero amplitude at this location. Consequently, resonances in the CT response will have a distance corresponding to the fundamental frequency of the standing wave.

All these measurements are very promising. They prove that our reflection calculations and our understanding of the Goubau line are correct. Furthermore, we gained already new insight in CT behavior at high frequencies. The strongest measurement errors, i.e. the periodic resonances, can be explained by a single cause: reflection. The reflection not only limits the power transfer to the Goubau line but also gives rise to standing waves between the cones.

Having identified this shortcoming allows us to start improvements. A first step will be to calculate and build better inner conductors for the existing cones. Improving the inner conductors should not be too complicated, since the current ones are made of simple brass tubes with diameters varying in 1 mm steps. In a second step we would like to build new cones which should have a larger diameter to improve launching efficiency and which should be longer to reduce reflection at low frequencies.

SUMMARY

A Goubau line allows to transmit electromagnetic waves along a single wire. The principle is based on non-radiating surface waves which are bound to the wire due to surface imperfections, e.g. a dielectric layer which can be a simple isolation. The wave, which is the fundamental TM mode, is excited on the Goubau line by a cone that performs impedance and mode matching.

The TM mode has similar characteristics as the electromagnetic fields produced by a beam of charged particles moving in an accelerator. Thus it can be used as a tool for bench testing of beam instrumentation devices.

A first setup has been assembled and tested. The results mostly confirm our expectations. We could identify reflections as a single cause for the strongest of the observed shortcomings. To reduce these reflections we will start to improve the cones and their inner conductors. This will not only increase power transfer to the TM mode but more importantly reduce standing waves between the cones.

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