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GOUBAU-LINE SET UP FOR BENCH TESTING IMPEDANCE OF IN-VACUUM UNDULATOR COMPONENTS

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Abstract

The worldwide first in-vacuum elliptical undulator, IVUE32, is being developed at Helmholtz-Zentrum Berlin. The 2.5 m long device with a period length of 3.2 cm and a minimum gap of about 7 mm is to be installed in the BESSY II storage ring. It will deliver radiation in the soft X-ray range to several beamlines. The proximity of the undulator structure to the electron beam makes the device susceptible to wakefield effects which can influence beam stability. A complete understanding of its impedance characteristics is required prior to installation and operation, as unforeseen heating of components could have catastrophic consequences. Since its complex structure makes numerical calculations, such as CST simulations, at high frequency very resource intensive, bench testing the device may proof invaluable. A Goubau-line is a single wire transmission line for high frequency surface waves with a transverse electric field resembling that of a charged particle beam out to a certain radial distance. This can be used to measure the impedance of vacuum chamber components. A concept optimized for bench testing IVUE32-components will be discussed and progress towards the test bench set up will be shown.

INTRODUCTION

BESSY II is a third generation synchrotron light source with an electron beam energy of 1.7 GeV. There are 32 dipole magnets and 13 undulators supplying 48 beam lines with radiation ranging from infrared to soft X-ray. In September of 2018 the first in-vacuum undulator (IVU) CPMU17 [1] was installed in BESSY II to provide hard X-rays for the Energy Materials In-Situ Laboratory (EMIL) [2]. Contrary to conventional undulators where the magnets are located outside of the vacuum chamber, the magnets of in-vacuum undulators are in close proximity to the electron beam without being shielded by a vacuum chamber. Therefore a shielding foil together with a transition taper is used to protect the permanent magnets from the wakefield of the particle beam and radiation of upstream components and to allow for a smooth transition from the shape of the beam pipe to the undulator. In this configuration as the undulator gap is changed, so is the geometry of the conducting structure close to the beam. Depending on the design, this geometry can change from collimator to cavity.

Motivation

The in-vacuum design is used for undulators with a small gap and a short period allowing for high energy photons and brilliant radiation. The IVUs designed for operation at BESSY II change their geometry from a collimator to a cavity over the entire gap range. Thus the wakefield characteristics and impedance of the insertion device changes with the gap setting. This can affect beam stability and heat load possibly compromising accelerator operation. For the already installed CPMU17 beam based impedance measurements for different gap settings have been done using orbit bump and tune shift methods [3]. Grow-damp and drive-damp methods have been used as well, the results of which are presented at this conference by M. Huck *et al.* [4].

The new elliptical in-vacuum undulator IVUE32 brings even more challenges as the shielding foil is split in the middle longitudinally to accommodate the different polarization settings. Measuring and understanding the wakefield and impedance behavior of these devices is a very important step for smooth operation of the accelerator and to protect the insertion devices from damage. As the design of IVUE32 is a novel concept, measuring impedance outside of the running accelerator is desirable to avoid complicated down time.

A possible way to measure impedance is a Goubau-line test stand. A Goubau-line is a transmission line that uses a single wire to transmit surface waves. It was designed by Georg Goubau in 1950 [5] based on the work of Sommerfeld from 1899 [6]. The transverse electric field of a Goubau-line mimics that of a charged particle beam out to a certain distance. In recent years such set ups have been used to measure the impedance of accelerator components, for example at Argonne APS [7] or at Bergoz Instrumentation [8]. Impedance studies of CPMU17 suggest that the fill pattern at BESSY II requires surveys up to a frequency of 20 GHz which is significantly higher than the aforementioned test stand examples. So IVUE32 requires a new design of Goubau-line test stand.

In the following sections the design and parameters of a Goubau-line test stand, capable of measuring up to frequencies of 20 GHz, will be discussed.

THEORETICAL CONSIDERATIONS

A Goubau-line consists of a transmitter, a receiver and a dielectrically coated wire. The transmitter and receiver are usually horn antennas as shown in Fig. 1.The transmitted waves are guided as transverse magnetic surface waves on the coated wire. The transverse electric field, shown in Fig. 2, of the waves can be used to emulate the electric field of a charged particle beam.

Figure 1: Schematic of a Goubau-line consisting of two horn antennas and a dielectrically coated wire.

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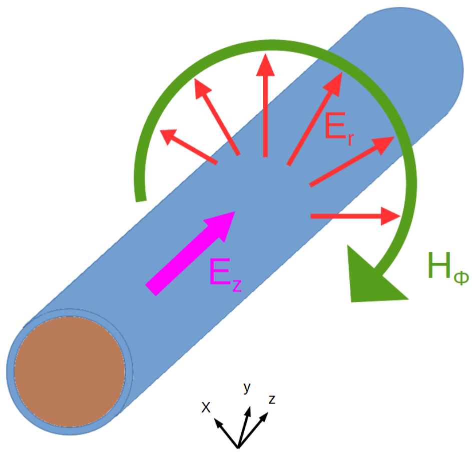

Figure 2: Schematic of field orientation of a Goubau-line. The copper conductor is shown with a dielectric coating in blue.

The formulas describing the electric and magnetic fields of the guided waves are derived in Goubaus's original paper [5] and a revision considering modern computational advances can be found in [9]. The electric and magnetic Fields are governed by cylinder functions.

The problem can be split in three distinct regions: inside of the conductor, inside of the dielectric coating, and outside of the wire. The fields are continuous across the two interfaces. This continuity can be used to numerically calculate the guided wave propagation constant as shown in [9]. Which in turn is needed to calculate the transverse electric field of the Goubau-line. The transverse electric field is described by Hankel functions

$$E_r = iA\frac{h}{\gamma_0}H_1^{(1)}(\gamma_0 r)e^{i(\omega t-hz)}, \quad (1)$$

$$E_z = AH_0^{(1)}(\gamma_0 r)e^{i(\omega t-hz)}, \quad (2)$$

$$H_\phi = iA\frac{k_0^2}{\omega\mu\gamma_0}H_1^{(1)}(\gamma_0 r)e^{i(\omega t-hz)}, \quad (3)$$

with

$$\gamma_i^2 = k_i^2 - h^2, \quad (4)$$

where h is the guided wave propagation constant, k_0 is the free wave propagation constant, and A is a complex amplitude. Close to the wire, Eq. (1) is proportional to $1/r$. In this region the field can be used to emulate a charged particle beam. As the distance to the wire increases, the Hankel function falls off exponentially. The region in which the transverse electric field can be used is determined by the radial wave number γ_0 [9]. The parameters that influence γ_0 are the frequency of the wave, the thickness of the conductor and dielectric insulation, as well as the dielectric constant of the insulation. In order to maximize the usable area, γ_0 needs to be minimized. This is achieved by a large conductor radius and a thin insulating layer with a small dielectric constant. Lowering the frequency would also decrease γ_0 but the BESSY II fill pattern requires investigations up to 20 GHz. In order to conduct meaningful measurements, the electric field needs to extend further than the aperture of the device under test.

Calculations of Wire Properties

The aperture of IVUE32 at maximum gap is around 22 mm. Therefore the aim is to design a Goubau-line with a transverse electric field extending out to about 30 mm at a frequency of 20 GHz. The calculations are done in python using the `numpy` and `scipy.special` libraries. As a maximum for the conductor diameter, 2 mm was chosen as to maintain flexibility of the wire. As a first step a readily available magnet wire was calculated. The 12 AWG (about 2 mm diameter) conductor is coated with polyamide of 81 µm thickness. The dielectric constant was taken to be 3.5. Figure 3 shows the transverse electric field as a function of the distance from the wire. The field starts to deviate significantly from the $1/r$ proportionality at about 4 mm from the wire. That is notably less than the 30 mm needed to survey IVUE32. In order to extend the electric field, a more suitable dielectric coating needs to be found. There are a wide range of dielectric coatings on the market. One example is an amorphous glass coating called Cerablak™ by atfi [10]. The material can be applied in a thin film down to 200 nm. Please note, that this product is just meant as an example and we have no affiliation with the company. A wire coated with Cerablak™ was calculated.

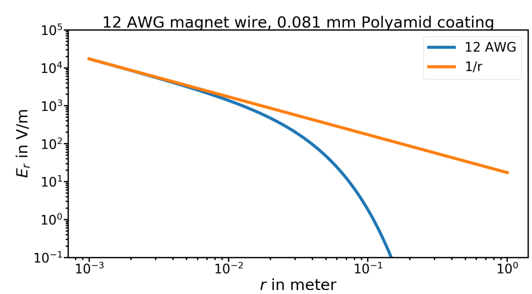

Figure 3: Amplitude of transverse electric field of a Goubau-line using a polyamide coated 12 AWG magnet wire at 20 GHz.

Figure 4 shows the radial electric field of a 1 mm diameter wire coated with Cerablak™ of various thickness. For a film thickness of less than 500 nm the electric field maintains a $1/r$ proportionality out to at least 30 mm. This would cover the aperture of IVUE32 and therefore would be a suitable option for a Goubau-line test stand. Figure 5 shows that even a wire with 0.5 mm diameter coated with Cerablak™ would produce the required field extension.

Transmitter and Receiver

The transmitter or launcher is needed to excite the surface waves on the insulated wire. Its main purpose is to match the impedance of the Goubau-line with that of the signal source, most likely a 50 Ω coaxial cable. To ensure the quality of the measurements, this should be done with minimal

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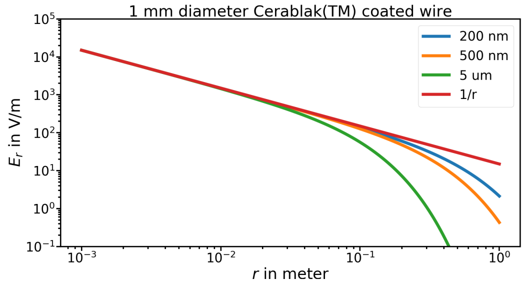

Figure 4: Amplitude of transverse electric field of a Goubau-line using a 1 mm diameter copper wire with several thickneses of Cerablak™ [10] coating at 20 GHz.

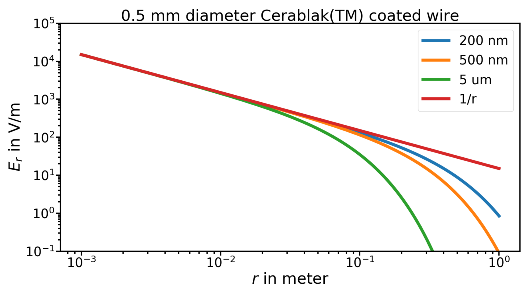

Figure 5: Amplitude of transverse electric field of a Goubau-line using a 0.5 mm diameter copper wire with several thicknesses of Cerablak™ [10] coating at 20 GHz.

reflection. The characteristic impedance of a Goubau-line is determined by the properties of the insulated wire used. B. Vaughn *et al.* [9] show how the characteristic impedance is calculated. This is done by equating the power flow through the Goubau-line to an equivalent coaxial cable. Therefore the power flow outside of the Goubau-line needs to be integrated. The characteristic impedance can then be expressed as

$$Z_{GB} = \frac{Z_0 \ln\left(\frac{b}{r_c}\right)}{2\pi}, \tag{5}$$

with

$$b = r_c \exp\left(\frac{P_0 \pi \left|\gamma_0\right|^4}{4\omega\epsilon_0 \mathrm{Re}(h)}\right), \tag{6}$$

where $Z_0 = 377$ is the intrinsic impedance of free space, r_c is the radius of the conductor, and P_0 is the power flow outside of the conductor.

Cone or horn antennas are mainly used as transmitter and receiver. These consist of the outside cone and a center conductor which together act as a coaxtial transmission line taper. How these antennas are characterized is shown by S.Y. Kim *et al.* [8]. For a given horn and taper design the refelction coefficients are calculated and minimized for the desired frequencies. The design and characterization of the antennas for the BESSY II test stand are still in progress.

CONCLUSION

Although Goubau-lines have been used to measure the impedance of vacuum chamber components for several years now, none of them measure at frequencies above 10 GHz. A new design from the ground up is therefore necessary for the IVU measurements at BESSY II. The presented calculation results show, that such a set up is achievable and what type of wire and coating is required. The design of the transmitting and receiving horn antennas needs to be finalized. A necessary network analyzer capable of handling frequencies up to 20 GHz is readily available on the market.

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