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Goubau-Line Set Up for Bench Testing Impedance of IVU32 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. To understand and measure the IVU's impedance characteristics a Goubau-line test stand is being designed. 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. A concept optimized for bench testing IVUE32-components will be discussed, microwave simulations will be presented, and progress towards a test bench prototype will be shown.

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1. 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 insertion devices 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 at BESSY II in order to provide hard X-rays for the Energy Materials In-Situ Laboratory (EMIL) [2]. In conventional undulators the magnet rows are located outside of the vacuum chamber which provides shielding from the wakefield of the particle beam and radiation of upstream components. IVUs on the other hand put the magnets in direct proximity of the electron beam. Necessary shielding to protect the magnets is provided by a thin metal foil. The shielding foil also acts as a taper to smooth out the transition from the beam pipe cross section to the undulator aperture. Therefore 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.
A second IVU, IVUE32 [11], is currently being developed at BESSY II. It is an elliptical undultor of the APPLE-II type. IVUE32 features four individually movable magnet rows which requires a longitudinal slit in the shielding foils. The split shielding foils further complicate the design of the transition taper between the beam pipe and the undulator magnets.

1.1. Motivation

IVUE32 is a novel design concept with unknown impact on wakefield characteristics and beam dynamics. The impact on beam stability is difficult to simulate. The planar CPMU17 was successfully characterized using beam based measurements. Orbit bump and tune shift measurements have been performed with different gap settings [3]. Grow-damp and drive-damp methods have been utilized as well by M. Huck *et al.* [4]. Because of the split foils described above, characterizing IVUE32 during user operation brings unknown risks. The ability to measure impedance outside of the running accelerator is desirable to avoid complicated down time. A Goubau-line test stand is a way to realize that ability.
A Goubau-line is a single wire transmission line that utilizes 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 successfully been used to measure the impedance of accelerator components, for example at Argonne APS [7] or at Bergoz Instrumentation [8]. Based on impedance studies of CPMU17, sampling frequencies up to 20 GHz are required to simulate the BESSY II fill pattern [9]. The following sections will discuss the design parameters of a Goubau-line test stand, capable of measuring up to frequencies of 20 GHz.

2. Theoretical Considerations

The main parts making up a Goubau-line are a transmitter, a receiver and a dielectrically coated wire. Horn antennas are usually used as transmitter and receiver shown in Fig. 1. The transmitted waves are guided as transverse magnetic modes on the coated wire. Figure 2 shows the orientation of electric and magnetic fields along the coated wire. The electric E_r, E_z and magnetic H_ϕ fields are described

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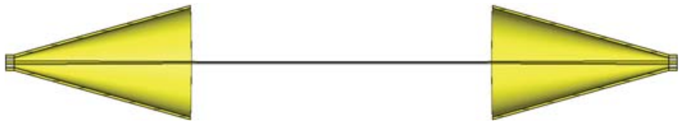

Figure 1. Schematic of a Goubau-line consisting of two conical horn antennas and a dielectrically coated wire similar to the design at Argonne APS [7].

by cylinder functions. The corresponding formulas are derived in Goubau's original

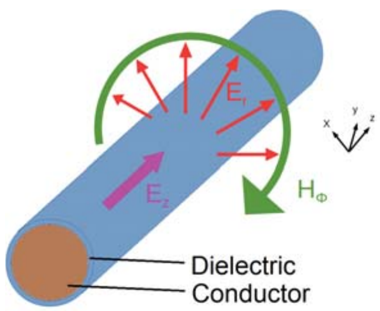

Figure 2. Schematic of field orientation of a Goubau-line. The transverse electric field E_r mimics the field generated by a charged particle beam.

paper [5] and in a revision considering modern computational advances by B. Vaughn *et al.* [10]. To understand the functionality of the Goubau-line, three distinct regions have to be considered: the conductor, the dielectric coating, and outside of the wire. The continuity of the fields across the interfaces of the conductor and dielectric, and dielectric with free space respectively, can be used to numerically calculate the guided wave propagation constant and the transverse electric field of the Goubau-line. The fields outside of the wire are described by Hankel functions [10]

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

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

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

with

$$\gamma_i^2 = k_i^2 - h^2 \tag{4}$$

where h is the guided wave propagation constant, k_0 is the free wave propagation constant, and A is a complex amplitude. The radial electric field in Eq. (1) is proportional to $1/r$ close to the wire. Therefore it can be used to emulate a charged particle beam before falling off exponentially at greater distances from the wire. The usable region is determined by the radial wave number γ_0 [10]. The frequency of the guided wave, the thickness of the conductor and dielectric insulation, as well as the dielectric constant of the insulation determine γ_0. Minimizing γ_0 extends the distance from the wire at which the Goubau-line can emulate the fields of a charged particle beam. In order to conduct meaningful measurements, the electric field needs to extend further than the aperture of the device under test.

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2.1. 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. For this the optimum wire properties need to be determined, the corresponding 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 $\varepsilon_r = 3.5$. Figure 3 shows the transverse electric field as a function of the distance from the

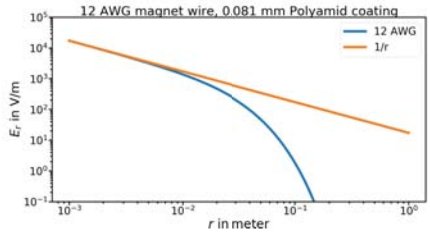

Figure 3. Amplitude of transverse electric field of a Goubau-line using a polyamide coated 12 AWG magnet wire at 20 GHz.

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 available on the market. In order to determine the needed thickness of the coating a 1 mm diameter copper wire with various thickness of dielectric coating with $\varepsilon_r = 4$ was calculated. Figure 4 shows

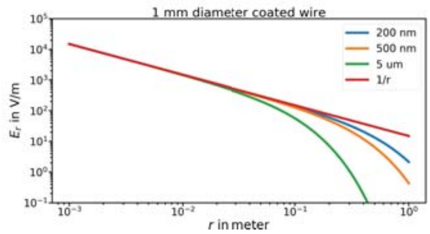

Figure 4. Amplitude of transverse electric field of a Goubau-line using a 1 mm diameter copper wire with several thicknesses of $\varepsilon_r = 4$ dielectric coating at 20 GHz.

that for a coating 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.

2.2. Characteristic Impedance

In order to impart the surface waves onto the Goubau-line, the characteristic impedance of the coated wire needs to be calculated. The characteristic impedance of the Goubau-line depends on the wire parameters and also the frequency of the guided waves. It can be calculated with an equivalent TEM expression as shown by B. Vaughn *et al.* [10].

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

where $Z_0 = 377\,\Omega$ is the intrinsic impedance of free space, r_c is the radius of the Goubau-line conductor, and b is the radius of the outer conductor of an equivalent coaxial cable. This equivalent radius is obtained by equating the power flow through the Goubau-line to an equivalent coaxial cable

$$P_{eq} = \frac{1}{2}\mathrm{Re}(V_g I_z^*) = \frac{4A^2\omega\epsilon_0 \mathrm{Re}(h)}{\pi\,|\gamma_0|^4} \ln\left(\frac{b}{r_c}\right) \tag{6}$$

$$V_g \approx \frac{iAh}{\gamma_0^2}\left(H_0^{(1)}(\gamma_0 r_c) - H_0^{(1)}(\gamma_0 b)\right) \tag{7}$$

$$I_z = \frac{2\pi\sigma A r_c}{\gamma_0} H_1^{(1)}(\gamma_0 r_c)\left(\frac{k_0}{k_c}\right)^2 \tag{8}$$

with

$$k_c = \omega\sqrt{\mu_0\left(\frac{\sigma}{i\omega} + \epsilon_0\right)}$$

where σ is the conductivity of the Goubau-line wire. Equation (6) is solved numerically for b and the characteristic impedance is then obtained via Eq. (5). Figure 5 shows

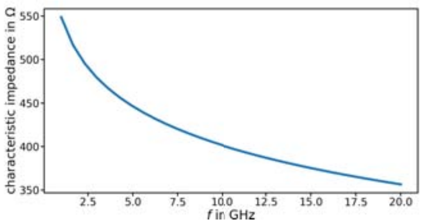

Figure 5. Characteristic impedance of a Goubau-line using a 1 mm diameter copper wire coated with 500 nm of dielectric with $\varepsilon_r = 4$ as a function of frequency.

how the characteristic impedance of a Goubau-line using a 1 mm diameter copper wire coated with 500 nm of $\varepsilon_r = 4$ dielectric changes with the frequency of the guided wave.

2.3. Transmitter and Receiver

To excite the surface waves on the insulated wire a transmitter or launcher is needed. Cone or horn antennas are mainly used for that task. These consist of the outside cone and a center conductor which together act as a coaxial transmission line taper. 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, the impedance transition should be as smooth as possible in order to minimize reflections. As shown in Fig. 5 the characteristic impedance of a Goubau-line depends on the frequency of the guided wave. For the fill pattern at BESSY II we expect an impedance response from the IVUs between 10 and 20 GHz. Over that frequency range the

characteristic impedance of the Goubau-line varies between 350 and 400 Ω. Therefore a perfectly smooth impedance transition is not possible over the measured frequency band.
There are several possible designs for the transmission line taper. For example at the Argonne Advanced Photon Source a conical antenna was used together with a six-section matching transformer as a taper [7]. Another example would be an antenna with a Gaussian profile together with a Klopfenstein taper used by Bergoz Instrumentation [8]. The optimal design depends on the frequency band, the maximum accepted reflection coefficient and the space available.
Microwave simulations using CST Studio Suite [12] are used to design the matching section for the Goubau-line test stand.

3. Impedance Matching

In order to achieve a good signal to noise ratio for the measurements, reflections in the transmission from the coaxial cable to the Goubau-line need to be minimized. Reflections occur at impedance mismatches in the transmitting structure. To find these impedance discontinuities, time domain reflectometry (TDR) is used. TDR compares the incoming time signal to the reflection at a port. From that time signal the location of an impedance discontinuity can be determined. The structure design can then be optimized in that area. To optimize the design a Goubau-line with only one transmitter and an open end is simulated in CST Studio. The scattering parameter S_{11} is used as quality metric for a transmitter design. The S_{11} parameter compares the incoming signal to the reflected signal at a port. It is a measure of reflection as a function of frequency. As an example two different transmitter designs are shown in Fig. 6 The two transmitters differ at the transition from the coaxial cable to the

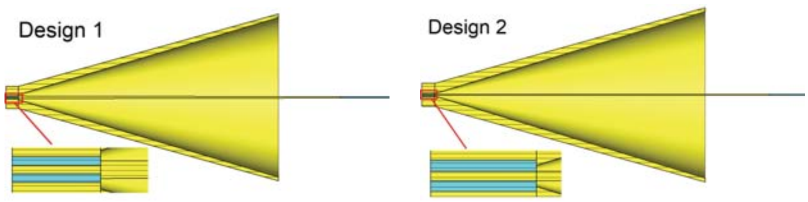

Figure 6. Two design examples of a Goubau-line transmitter section with different transitions between coaxial feed line and antenna. Parts in yellow are made of copper, cyan represents dielectrics.

horn antenna. The two designs are simulated and compared. Figure 7 shows the S_{11} parameter for both designs. The two designs show different frequency responses in the S_{11} parameter. A lower magnitude means less signal is reflected and transmission quality is higher. Looking at the TDR data shown in Fig. 8, a sharp increase in impedance can be seen at around 0.2 ns for both designs. The sharp impedance increase corresponds to the transition from coaxial cable to the horn antenna. High derivatives in TDR hint to impedance discontinuities which cause reflections. This shows that the transmitter designs can be improved at the transition from coaxial cable to horn antenna.

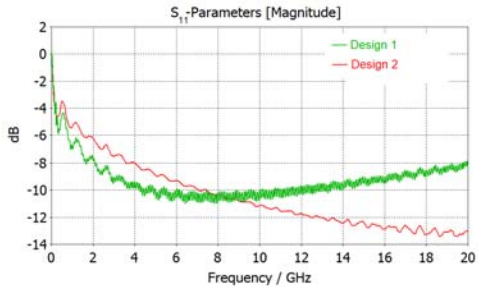

Figure 7. Comparison of S_{11} parameter for two transmitter designs.

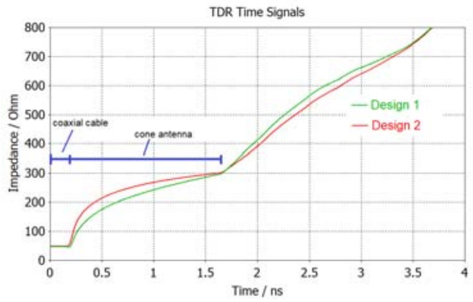

Figure 8. Time Domain Reflectometry shows the change of impedance inside a transmitting structure. Two different designs are compared. Steep gradients in impedance cause undesired reflections.

4. Conclusion

A Goubau-line test stand is essential for the smooth commissioning of new in-vacuum undulators at BESSY II. Extending the frequency range of a Goubau-line to 20 GHz comes with new challenges. Matching the impedance of a transmitting structure at high frequencies is difficult and requires precise design and manufacturing. The presented calculation results characterize the wire parameters that achieve the required field extension over the desired frequency range for the IVU measurements at BESSY II. The characteristic impedance of a Goubau-line utilizing said wire parameters has been calculated over the desired frequency range.
The Transmitter design is still being optimized using CST simulations. The goal is to decrease the S_{11} parameter magnitude below 16 dB for frequencies above 8 GHz.
Following that, a prototype will be built and the calculations will be confirmed with measurements

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