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GOUBAU-LINE SET UP FOR BENCH TESTING IMPEDANCE OF IVUE32 COMPONENTS

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Abstract

IVUE32 is the world first elliptical in-vacuum undulator, being developed at HZB. With a period length of 32 mm and a minimum gap of 7 mm, the 2.5 m long insertion device (ID) will be installed in the BESSY II storage ring, delivering soft X-rays to several beam lines. In-vacuum undulators put complex structures in close proximity of the particle beam which makes them susceptible to wake field effects. These effects can cause beam instabilities and unwanted heating of undulator components, possibly damaging them. Therefore understanding the impedance characteristics of the device prior to installation is paramount. Numerical studies, e.g. CST simulations of such complex structures become very resource intensive for high frequencies, making the ability to bench test such a device invaluable. A Goubau line is a single wire transmission line for high frequency surface waves that can mimic the transverse electric field of a charged particle beam out to a certain distance, allowing for impedance measurements of IDs outside of the working accelerator. The status of a Goubau-line set up, optimized for measuring IVUE32-components, will be presented.

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]. As previously described in [3] IVUs require shielding foils between their magnets and the accelerator beam. The second IVU for BESSY II, IVUE32 [4], is currently under developement. The APPLE II configuartion poses even greater design challenges than the planar CPMU17. 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.

Motivation

Without a vacuum chamber wall between the beam and the undulator magnets, both CPMU17 and IVUE32 change their geometry from a collimator to a cavity over the entire gap range. This has an impact on wakefield characteristics and beam dynamics. The impact on beam stability is difficault to simulate. Beam based impedance measurements using orbit bump and tune shift methods have been done for the already installed CPMU17 with different gap settings [5]. Grow-damp and drive-damp methods have been utilized as well by M. Huck *et al.* [6]. The novel design of IVUE32 brings even more challenges as the shielding foil is split in the middle longitudinally to accommodate the different polarization settings. Therefore the impact on beam stability and accelerator operation are difficult tu simulate and predict. Beeing able to measure impedance outside of the running accelerator is desirable to avoid complicated down time. As introduced in [3] a Goubau-line test stand is a possible way to measure impedance of insertion devices. Designed by Georg Goubau in 1950 [7] based on the work of Sommerfeld from 1899 [8], a Goubau-line is a transmission line that uses a single wire to transmit surface waves. Its transverse electric field can be used to mimic that of a charged particle beam. Goubau-line set ups have been successfully used to measure the impedance of accelerator components, for example at Argonne APS [9] or at Bergoz Instrumentation [10]. Studies of CPMU17s impedance suggest that the fill pattern at BESSY II induces effects up to a frequency of 20 GHz which is significantly higher than the aforementioned test stand examples.

The following sections will discuss the design parameters of a Goubau-line test stand, capable of measuring up to frequencies of 20 GHz.

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

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 [9].

transmitted waves are guided as transverse magnetic modes the coated wire. Figure 2 shows the orientation of electric and magnetic fields along the coated wire. The electric and magnetic Fields are described by cylinder functions. These formulars are derived in Goubau's original paper [7] and in a revision considering modern computational advances by B. Vaughn *et al.* [11]. Three distinct regions can be considered: inside of the conductor, inside of the dielectric coating, and outside of the wire. The continuity of the fields accross the interfaces of these regions can be used to numerically calculate the guided wave propagation constant [11] and

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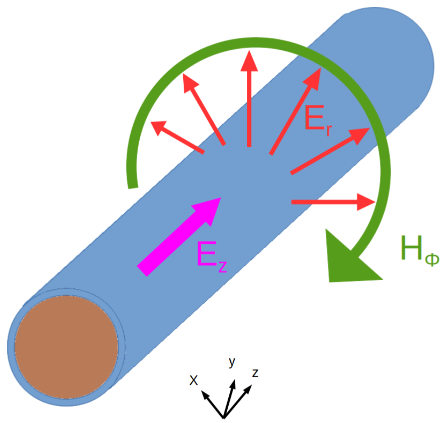

Figure 2: Schematic of field orientation of a Goubau-line. The copper conductor is shown with a dielectric coating in blue.

the transverse electric field of the Goubau-line. The fields outside of the wire are described by Hankel functions

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

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

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

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 (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 [11]. 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 wich 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.

Wire Properties

IVUE32 has a maximum aperture of around 22 mm. A Goubau-line with a transverse electric field extending out to about 30 mm at a frequency of 20 GHz is needed to survey IVUE32. As shown in [3] a 1 mm diameter copper wire coated with 500 nm of Cerablak™ [12] produces the desired field parameters. Figure 3 shows the amplitude of the radial electric field for a 1 mm diameter copper wire with different coats of Cerablak™ [12].

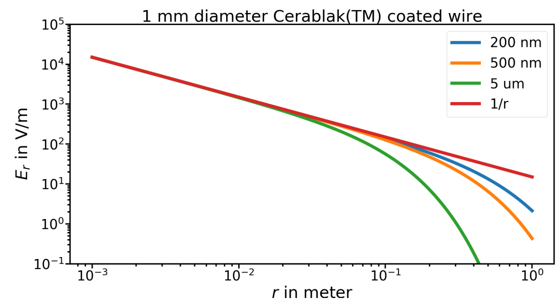

Figure 3: Amplitude of transverse electric field of a Goubau-line using a 1 mm diameter copper wire with several thicknesses of Cerablak™ [12] coating at 20 GHz.

Characteristic Impedance

In order to impart the surface waves onto the Goubau-line, the characteristic impedance 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 equvalent TEM expression as shown by B. Vaughn *et al.* [11].

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

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 4 shows how the characteristic impedance of a Goubau-line using a 1 mm diameter copper wire coated with 500 nm of Cerablak™ [12] changes with the frequency of the guided wave.

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,

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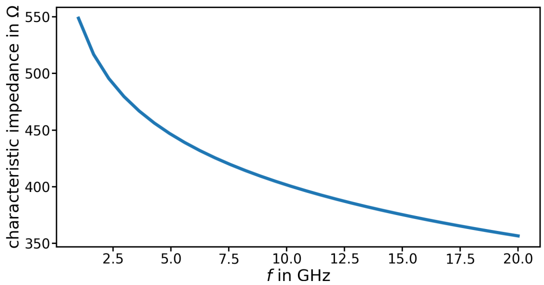

Figure 4: Characteristic impedance of a Goubau-line using a 1 mm diameter copper wire coated with 500 nm of Cerablak™ [12] as a function of frequency.

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. 4 the charcteristic 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 measuered 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 [9]. Another example would be an antenna with a Gaussian profile together with a Klopfenstein taper used by Bergoz Instrumentation [10]. The optimal design depends on the frequency band, the maximum accepted reflection coefficient and the space available.

The design and characterization of the antennas for the BESSY II test stand are still in progress.

CONCLUSION

In order to extend the frequency range of a Goubau-line test stand to 20 GHz a new design from the ground up is necessary. The presented calculation results show, which type of wire and dielectric coating can achieve the required frequency range necessary for the IVU measurements at BESSY II. The characteristic impedance of the Goubau-line has been calculated over the desired frequency range. The design of the horn antennas and tapers still needs to be finalized.

As a next step, coated wire for the Goubau-line will be ordered and first reflection coefficient measurements will be set up.

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REFERENCES

[1] J. Bahrdt *et al.*, "Characterization and Implementation of the Cryogenic Permanent Magnet Undulator CPMU17 at Bessy II", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019, pp. 1415–1418. doi:10.18429/JACoW-IPAC2019-TUPGW014

[2] K. Lips *et al.*, "EMIL: the Energy Materials in-Situ Laboratory Berlin – a Novel Characterization Facility for Photovoltaic and Energy Materials", Sep. 2015

[3] P. I. Volz, S. Grimmer, M. Huck, and A. Meseck, "Goubau-Line Set Up for Bench Testing Impedance of In-Vacuum Undulator Components", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper THPAB057.

[4] J. Bahrdt, W. Frentrup, S. Grimmer, C. Kuhn, C. Rethfeldt, M. Scheer, and *et al.*, "In-Vacuum APPLE II Undulator", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 4114–4116. doi:10.18429/JACoW-IPAC2018-THPMF031

[5] M. Huck, J. Bahrdt, H. Huck, A. Meseck, and M. Ries, "Transverse Broad-band Impedance Studies of the New In-vacuum Cryogenic Undulator at Bessy II Storage Ring", in *Proc. IBIC'20*, Santos, Brazil, Sep. 2020, pp. 263–267. doi:10.18429/JACoW-IBIC2020-THPP26

[6] M. Huck, J. Bahrdt, A. Meseck, G. Rehm, M. Ries, and A. Schaelicke, "Experimental Studies of the In-Vacuum-Cryogenic Undulator Effect on Beam Instabilities at BESSY II", presented at the 12th Int. Particle Accelerator Conf. (IPAC'21), Campinas, Brazil, May 2021, paper WEPAB134.

[7] G. Goubau, "Surface Waves and Their Application to Transmission Lines", *Journal of Applied Physics*, vol. 21, pp. 1119-1128, 1950. doi:10.1063/1.1699553

[8] A. Sommerfeld, "Ueber die Fortpflanzung elektrodynamischer Wellen längs eines Drahtes", *Ann. Phys.*, vol. 303, pp. 233-290, 1899. doi:10.1002/andp.18993030202

[9] M. P. Sangroula, R. R. Lindberg, R. M. Lill, and R. Zabel, "Measuring vacuum component impedance for the Argonne Advanced Photon Source upgrade", *Phys. Rev. Accel. Beams*, vol 23, p. 082803, 2020. doi:10.1103/PhysRevAccelBeams.23.082803

[10] S. Y. Kim, F. Stulle, C. K. Sung, K. H. Yoo, J. Seok, K. J. Moon, *et al.*,"Characterization of the Goubau line for testing beam diagnostic instruments", *J. Instrum.*, vol. 12, p. P12016, 2017. doi:10.1088/1748-0221/12/12/p12016

[11] B. Vaughn and D. Peroulis, "An updated applied formulation for the Goubau transmission line", Journal of Applied Physics, vol. 126, p. 194902, 2019, doi:10.1063/1.5125141

[12] Applied Thin Films Inc., https://www.atfinet.com