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DESIGN OF A W-BAND CORRUGATED WAVEGUIDE FOR STRUCTURE WAKEFIELD ACCELERATION

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Abstract

Current research on structure wakefield acceleration aims to develop radiofrequency (RF) structures that can produce high gradients, with work in the sub-terahertz (sub-THz) regime being particularly interesting because of the potential to create more compact and cost-effective accelerators. Metallic corrugated waveguides at sub-THz frequencies are one such structure. We have designed a W-band corrugated waveguide for a collinear wakefield acceleration experiment at the Argonne Wakefield Accelerator (AWA). Using the CST Studio Suite, we have optimized the structure for the maximum achievable gradient in the wakefield from a nominal AWA electron bunch at 65 MeV for high-frequency structures. Considering a 10 nC symmetric Gaussian bunch with an rms length of 0.5 mm, we achieved an accelerating gradient of 84.6 MV/m. The gradient can be further improved with longitudinally shaped bunches, as will be studied in the future. Simulation results from various codes were benchmarked with each other, and with analytical models, with good agreement. We are investigating the mechanical design, suitable fabrication technologies, and the application of advanced bunch shaping techniques to achieve high-gradient high-efficiency acceleration in this structure by raising the transformer ratio.

INTRODUCTION

Structure Wakefield Acceleration (SWFA) in the terahertz (THz) and sub-THz regime are attractive as compact and cost-effective accelerators due to their small transverse sizes. THz wakefield structures could achieve a high gradient from the strong beam-structure interaction, enabled by a high shunt impedance from the frequency scaling. The wakefield is highly confined in a short RF pulse, which could lead to high-efficiency acceleration. Furthermore, both the high frequency and the short RF pulse length could reduce the probability of RF breakdowns at a certain gradient from previous studies [1].

In one scheme of SWFA, collinear wakefield acceleration (CWA), the drive bunch travels in a structure to generate a wakefield and the witness bunch is accelerated in the same structure. A key figure of merit in the CWA scheme is the transformer ratio, defined as the ratio of the accelerating gradient at the witness bunch to the decelerating gradient at the drive bunch. The transformer ratio for longitudinally symmetric bunches could not pass 2 theoretically, which limits the achievable efficiency of wakefield accelerators. Longitudinal bunch shaping techniques [2] could break this limit, and when applied to THz structures [3] [4], this could lead to high-gradient high-efficiency wakefield acceleration.

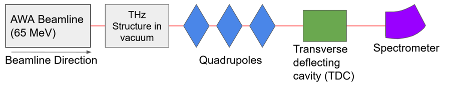

Figure 1: Schematic diagram of a collinear wakefield experiment at the AWA 65 MeV electron beamline, with the THz structure chamber and an LPS system.

In this paper, we present the design of a W-band corrugated waveguide at 110 GHz for a beam test at the Argonne Wakefield Accelerator (AWA). The AWA beamline makes use of the L-band electron gun and linacs to produce 65 MeV electron bunches. We plan to have a CWA experiment on the corrugated waveguide, where the gradient in the structure would be measured with a single-shot longitudinal phase space (LPS) measurement system, consisting of a set of quadrupoles, a transverse deflecting cavity, and a spectrometer. A schematic diagram of this experiment is shown in Fig. 1.

ANALYTICAL THEORY

Corrugated waveguides have been studied analytically using various approaches. One theory [5] considered the waveguide as a series of resonant cavities connected by apertures, where the apertures are treated as perturbations. The method breaks down when the aperture radius is not far less than the wavelength of the TM_{010} cavity mode. Another theory [6] studied corrugated waveguides excited by relativistic electron bunches. It assumed that the corrugation depth and the cell period were far smaller than the aperture radius, and that the corrugation depth was not much less than the cell period. The accelerating gradient E_z in the fundamental mode predicted by this theory when the corrugated waveguide is excited by a Gaussian bunch (with charge q and rms length σ) can be found as [6]

$$E_z = \frac{1}{4\pi\epsilon_0}\frac{2q}{a^2}e^{-\omega^2\sigma^2/2c^2} \tag{1}$$

with a being the aperture radius, ω being the fundamental angular frequency, ϵ_0 being the vacuum permittivity, and c being the speed of light. This theory is a good description in the high frequency range when $k = \omega/c \gg 1/a$.

For comparison, we utilized a numerical code, the CST Studio Suite, to simulate more general cases, as will be pre-

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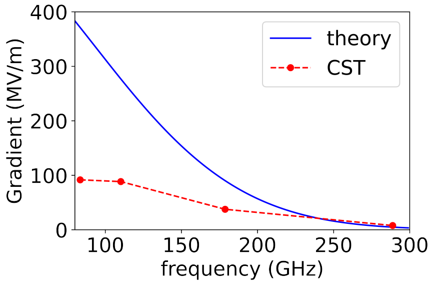

Figure 2: Comparison of the gradient from the analytical theory and CST simulations, for a drive bunch with 10 nC charge and 0.5 mm length. A good agreement can be seen in the high frequency range.

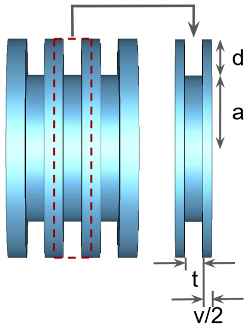

Figure 3: The unit cell (right), with its positioning in a set of cells outlined (left).

sented in the following section. The gradient values from the analytical theory [6] and CST are shown in Fig. 2. The aperture radius for all structures was kept at 1.016 mm but the corrugation depth and period of the cells were changed to vary the frequency. There is some discrepancy between simulated results and the theory in the low frequency range, however they converge at higher frequencies, when the assumptions needed for the derivation of Eq. (1) are better satisfied.

SIMULATIONS

Desired features of the W-band corrugated waveguide for wakefield acceleration include a high gradient from a charged bunch, low RF loss, and a suitable beam aperture for good charge transmission. We used multiple numerical solvers in CST to find a structure with such characteristics.

Unit Cell

The unit cell design of the W-band corrugated waveguide was performed using the Eigenmode solver of CST. The structure was simulated as a vacuum space (as shown in Fig. 3) with copper background and periodic boundaries.

Table 1: Final Design Parameters of the Unit Cell

Aperture radius (a)	1.016 mm
Corrugation depth (d)	0.5 mm
Plate thickness 1 (t)	0.254 mm
Plate thickness 2 (v)	0.254 mm
Frequency (f)	110.2 GHz
r/Q	36.5 kΩm
Group Velocity (v_g)	0.261 c
Nominal AWA bunch charge (q)	10 nC
Bunch RMS length (σ)	0.5 mm
Accelerating gradient (E_z)	85.8 MV/m

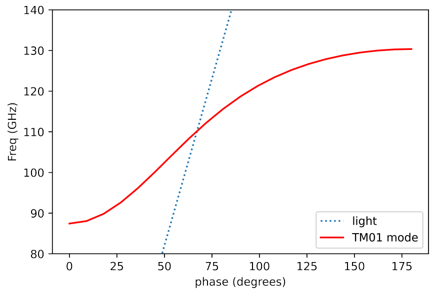

Figure 4: Dispersion curve of the TM_{01} mode simulated in the CST Eigenmode solver.

Figure 4 shows the dispersion diagram of the fundamental TM_{01} mode with an interaction frequency of 110 GHz with a relativistic electron beam. Key design parameters are outlined in Table 1. The gradient E_z is calculated as

$$E_z = \frac{2qk_L}{1-\frac{v_g}{c}} e^{-\omega^2\sigma^2/2c^2} \tag{2}$$

where v_g is the group velocity and k_L is the loss factor per unit length, as $k_L = \frac{\omega}{4}\frac{r}{Q}$ where r is the effective shunt impedance and Q is the quality factor. This gradient value calculated from the eigenmode unit cell parameters will also be benchmarked with the value from wakefield simulations using a full structure, as will be discussed later in the paper.

Full Structure with Matching Cells

A full periodic structure with the above unit cell design was simulated in the CST Microwave Studio. The 80-cell structure is shown in Fig. 5 (vacuum space in blue) with a set of matching cells and beam pipes on either end. The width of the matching cells was kept at 0.254 mm, the same width as the two widths from the unit cell (t and v) in order to allow for easier construction. Two waveguide ports are defined at the two ends, and the resulting S_{21} parameter can be seen in Fig. 6. A good passing band is created around the design frequency of 110 GHz.

Wakefield Simulations

We next simulated the same structure in the CST Particle Studio using the Wakefield solver. The structure is excited by a 65 MeV electron bunch available at AWA, with the bunch parameters from Table 1 implemented. Figure 7

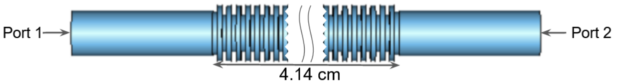

Figure 5: The full 80-cell structure with a set of matching cells. The matching cells had a radius of 1.166 mm and a width of 0.254 mm. The beam pipe had a radius of 1.216 mm. A break cuts out the middle section of cells.

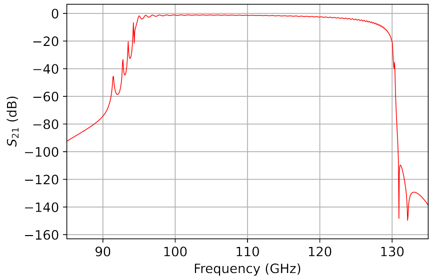

Figure 6: S_{21} parameter as a function of frequency.

shows the longitudinal electric field present in the structure as the bunch passes through. An accelerating gradient of 84.6 MV/m at the witness bunch can be achieved with the 10 nC symmetric drive bunch. With a longitudinally shaped bunch, the accelerating gradient could be improved even further . Figure 8 shows the wake impedance and wake potential from the same simulation.

Benchmarking

Two types of benchmarking were carried out between various codes. First, we compared the CST Eigenmode gradient values, calculated using Eq. (2), with those simulated in full-structure CST Wakefield runs. The result is shown in Fig. 9. A good agreement with a maximum of 1.4% error was found from the cases studied. Second, we used another wakefield simulation code, ECHO1D [7], to simulate the same 80-cell structure as in CST. The results from both codes can be seen in Fig. 9, with a good agreement.

As can be seen from both benchmarking tests, the discrepancy seen is small and we can be confident in our results from CST.

ONGOING AND FUTURE PLANS

We are currently working on the mechanical design and fabrication of the W-band corrugated waveguide. Some potential fabrication technologies under investigation are electroforming, wire-EDM, laser micromachinging, and additive manufacturing. We plan to fabricate a prototype and test it using a setup similar to the one shown in Fig. 1, with advanced bunch shaping techniques applied.

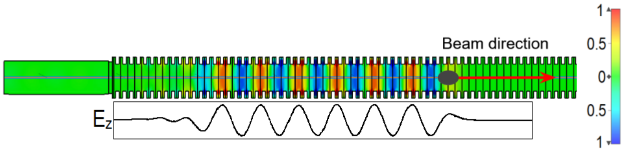

Figure 7: Longitudinal electric field excited by a 10 nC relativistic electron bunch, with a peak accelerating gradient of 86.4 MV/m on axis.

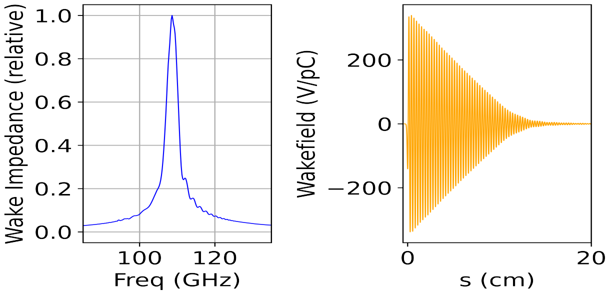

Figure 8: Simulated wake impedance (left) and wake potential (right).

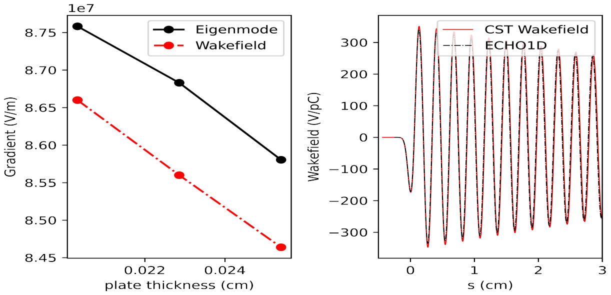

Figure 9: Benchmarking of: CST Eigenmode vs. Wakefield solver (left), and CST Wakefield vs. ECHO1D (right).

CONCLUSION

SWFA in the THz regime is a promising advanced accelerator concept because of the possibility to create compact, cost-effective, high-gradient and high-efficiency structures. A W-band corrugated waveguide was designed at 110 GHz, and for a 65 MeV Gaussian drive bunch of 10 nC with an rms length of 0.5 mm, we found a peak accelerating gradient on axis of 86.4 MV/m available to a trailing witness bunch. Benchmarking between various numerical codes shows good agreement. We are in the process of fabricating a prototype structure for testing at AWA, with an LPS system and advanced bunch shaping techniques implemented to further improve the accelerating gradient.

ACKNOWLEDGEMENTS

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