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DESIGN OF A COMPACT WAKEFIELD ACCELERATOR BASED ON A CORRUGATED WAVEGUIDE

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Abstract

A compact wakefield accelerator is being developed at the Argonne National Laboratory for a future multiuser x-ray free electron laser facility. A cylindrical structure with a 2 mm internal diameter and fine corrugations on the wall will be used to create Čerenkov radiation. A "drive" bunch producing radiation at 180 GHz will create accelerating gradients on the order of 100 MV/m for the "witness" bunch. The corrugated structure will be approximately half meter long with the entire accelerator spanning a few tens of meters. An ultra-compact transition region between each corrugated structure has been designed to accommodate an output coupler, a notch filter, an integrated offset monitor, bellows, pumping and water cooling ports. The output coupler will extract on the order of a kilowatt of power from the Čerenkov radiation unused by the witness bunch. The integrated offset monitor is a novel diagnostic which will measure the cumulative offset of the electron beam in the corrugated structure upstream of the monitor. The specific details of the rf design will be presented here.

INTRODUCTION

The generation of wakefields in dielectric and corrugated structures is a well-known phenomenon that results in the generation of high gradient electromagnetic fields [1]. Harnessing these fields for particle acceleration requires the design of a corrugated waveguide along with couplers to extract unused RF power and beam position monitors to ensure the accelerated beam is centered in the structure. The design of these components will be the focus of this paper.

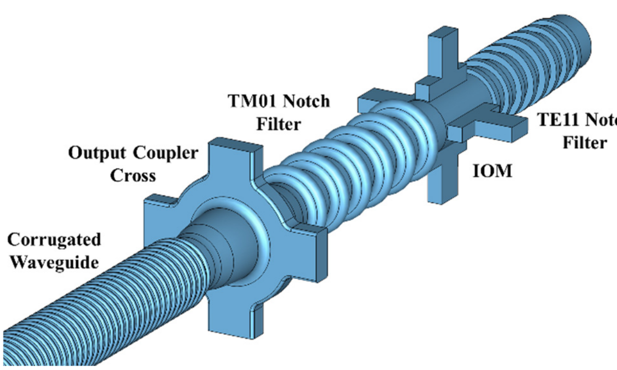
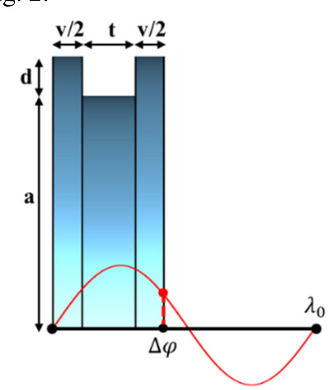


Figure 1: Corrugated waveguide and supporting RF components, showing vacuum region from CST model.

A section of the proposed accelerator is depicted in Fig. 1. Each of the components in the figure will be described and a brief explanation of design methodology will be provided. The final structure will consist of many identical sections, connected end to end by mechanical bellows. This paper will focus on the design of a single accelerating section which can then be generalized to a much longer structure.

CORRUGATION DESIGN

The corrugated waveguide is designed to support a propagating TM01 mode which is synchronous with the drive and witness bunches at the operating frequency of 180 GHz. Analytic approximations exist for estimating the corrugation dimensions [2], which are valid for small corrugation depth compared to the waveguide diameter. Simulation in CST Microwave Studio Eigenmode Solver [3] allows a more precise calculation of the corrugation dimensions for a given frequency by specifying the cell to cell phase shift in terms of the corrugation period and relating this to the phase velocity of the propagating wave. The dimensions are then found through an optimization process subject to the constrained corrugation period as shown in Fig. 2.



$$\lambda_0 = \frac{v_p}{f}$$

$$\frac{\lambda_0}{t+v} = \frac{360^\circ}{\Delta\varphi}$$

Figure 2: Corrugation unit cell with constraint equations for synchronous TM01 propagation at frequency *f*.

The resulting combinations of dimensions lie on surfaces of constant frequency in parameter space, as shown in Fig. 3. Plotting design metrics on these surfaces shows how the overall performance of the corrugated waveguide can be optimized. It is desirable to maximize both the group velocity and acceleration gradient of the corrugated structure which is accomplished by choosing a geometry in which the corrugation tooth width t is less than the vacuum width v. Also of critical importance is the transformer ratio [4, 5], which is a function of the drive bunch shape and found by simulation to be constant across all considered geometries.

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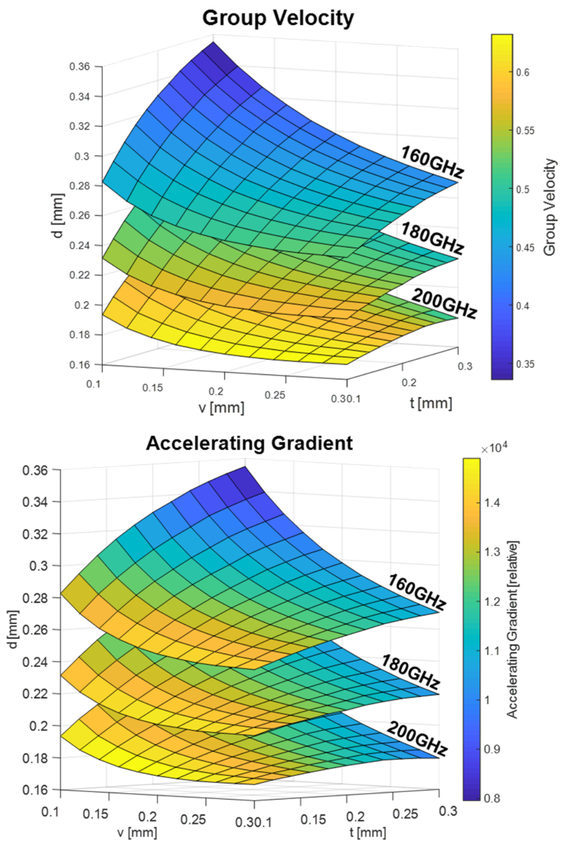

Figure 3: TM01 Group velocity and gradient vs. corrugation dimensions for structures of fixed frequency.

OUTPUT COUPLER DESIGN

The output coupler extracts unused energy in the TM01 accelerating mode from the corrugated waveguide while allowing the TE11 transverse mode to pass through to the IOM for beam offset measurement. The design, shown in Fig. 4, consists of a four-way rectangular waveguide cross, which interfaces to the circular waveguide via tapers and a circular cavity. Immediately following the output coupler cross is a notch filter, designed to reflect the TM01 mode.

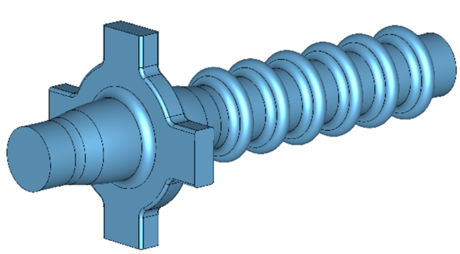

Figure 4: TM01 output coupler and notch filter geometry.

Dimensions of the waveguide components are found through an optimization process in CST. To simplify the optimization, the cross and notch filter are treated as separate components and their interaction is computed analytically, as shown in Fig. 5.

The notch filter is first approximated as a perfectly reflecting electric wall and the effective reflection coefficient S_{11}^{eff} for the entire configuration is calculated from the simulated S-parameters of the cross alone, according to (1). The optimal distance l to the electric wall is then solved for by setting S_{11}^{eff} to zero at the 180 GHz center frequency and solving the phase portion of the resulting complex equation (2). Plugging the resulting l back into the equation for S_{11}^{eff} allows the reflection coefficient for the entire structure to be calculated by simulation of the cross alone.

Because l shows up as a phase term in S_{11}^{eff}, it has a strong influence on the overall behaviour of the coupler. Its elimination from the optimization process is essential for converging on a solution in a reasonable number of iterations.

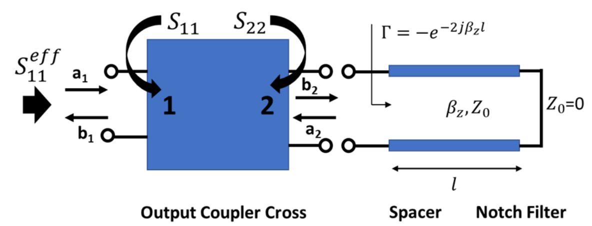

Figure 5: Model of interaction between output coupler and notch filter.

$$S_{11}^{eff} = \frac{b_1}{a_1} = S_{11} - \frac{S_{12}S_{21}}{S_{22} + e^{2j\beta_z l}} \tag{1}$$

$$l = \frac{1}{2\beta_{z0}} Arg\left(\frac{S_{12}S_{21}}{S_{11}} - S_{22}\right) + \frac{n\pi}{\beta_{z0}} \tag{2}$$

The notch filter is designed by cascading identical cylindrical grooves, each having a peak in TM01 reflection at 180 GHz. Increasing the number of grooves allows the filter to operate over a wider bandwidth, broadening the overall bandwidth of the coupler. Future work aims to reduce the number of grooves and thus the length of the coupler.

The RF characteristics of the output coupler are shown in Fig. 6. The design achieves a reflection of -30 dB at the operating frequency of 180 GHz with a -10 dB bandwidth of 8%. The overall power extracted from TM01 is >99%. The field patterns of the electric field amplitude at 180 GHz are shown in Fig. 7.

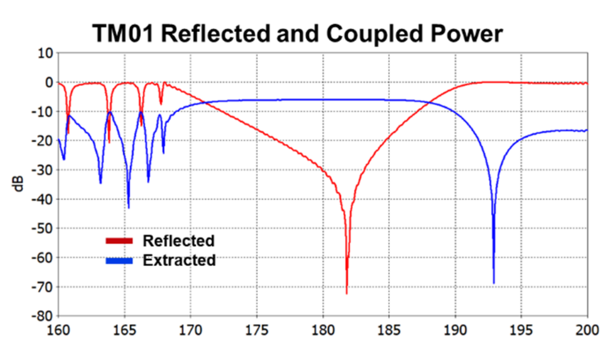

Figure 6: TM01 output coupler S-parameters for reflected and coupled power, coupling shown for one of four ports.

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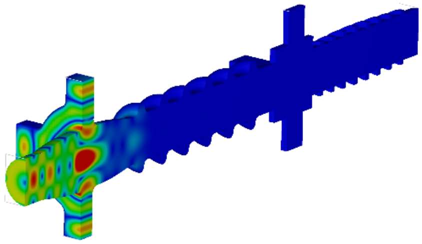

Figure 7: Break section TM01 electric field at 180 GHz.

INTEGRATED OFFSET MONITOR (IOM)

The IOM is designed to couple to the transverse TE11 modes stimulated by a beam traveling off-centre in the corrugated waveguide. These modes contain RF power which scales as the square of beam offset and can be used to measure the accumulated offset of the beam as it travels through the accelerator.

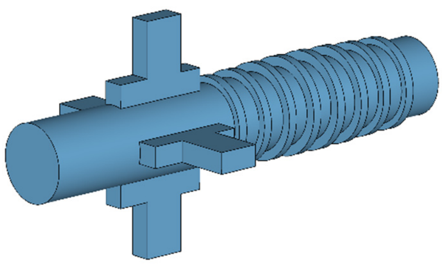

Figure 8: Integrated Offset Monitor (IOM) geometry.

The design of the IOM follows a similar procedure to that of the output coupler and takes the form shown in Fig. 8. The rectangular waveguide outputs interface to the circular waveguide via an asymmetrical step. Coupling takes place via the longitudinal magnetic field of the TE11 mode in the circular waveguide, which shares its orientation with the fundamental TE10 magnetic field in the rectangular waveguide.

The total TE11 energy from the corrugated structure is 100 nJ/μm^2 per pulse which results in power levels >1 mW/μm^2 for repetition rates in the 10s of kHz. This mode is observed to be 10 GHz above the TM01 accelerating mode, requiring the IOM to be designed with a centre frequency of 190 GHz. The resolution of the IOM is limited by the wakefield induced signal in the IOM itself which is on the order of 80 nJ/pulse. After accounting for insertion loss of the IOM, these estimated power levels result in a beam offset measurement resolution on the order of a few μm. The S-parameters and electric field patterns for the IOM, including the preceding TM01 output coupler, are shown in Fig. 9 and Fig. 10.

We expect the final resolution of the IOM to be improved by rounding the corners of the geometry which will reduce the wakefield induced background signal. Further improvement can be made by measuring only the fundamental mode of the rectangular waveguide output since most of the induced background signal is contained in higher modes which can be suppressed.

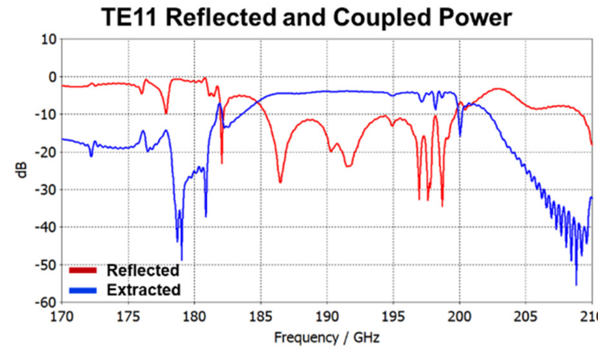

Figure 9: IOM S-parameters for reflected and coupled power, coupling shown for one of two ports.

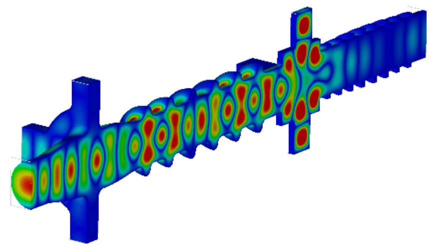

Figure 10: Break section TE11 electric field at 190 GHz.

CONCLUSION

The proposed CWA design demonstrates the possibility of creating a high gradient accelerating structure using a corrugated waveguide. We have characterized the behavior of the corrugated waveguide across a broad parameter space to find the optimal dimensions for the structure. We have also shown geometries for coupling to the TM01 accelerating mode and TE11 transverse beam offset mode, allowing power extraction and beam position monitoring. The methodology for designing the TM01 coupler and TE11 IOM allows excellent coupling to be achieved across a wide bandwidth and can be fine-tuned to achieve the required performance.

Future work will focus on further optimization of the coupling components to reduce their overall size. We also anticipate the IOM resolution can be improved by refining the structure to include rounded edges. The final design will undergo detailed thermal analysis and dimensional tolerance studies in preparation for fabrication of a prototype accelerating section.

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