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DETERMINATION OF MAXIMUM REPETITION RATE OF A CORRUGATED-WAVEGUIDE-BASED WAKEFIELD ACCELERATOR

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Abstract

Beam-driven wakefield accelerators hold great promise toward reducing the size of contemporary accelerators. One possibility under study at Argonne National Laboratory is the use of a miniature corrugated waveguide for generation of the wakefield. The effect of electromagnetic heating by the electron beam traveling on its centerline is investigated applying the steady-state thermal analysis coupled with computational fluid dynamics, and structural mechanics. A design of the accelerator module suitable for acceleration of electrons with an energy gain up to 100 MeV m^{-1} is considered. A heat load on the waveguide inner surface with corrugations is calculated using a conservative assumption for the copper electrical conductivity at a high frequency of the electromagnetic field. It is shown that the von Mises stress caused by thermal expansion grows with the increased bunch repetition rate and reaches a yield level in a most stressed location at the bunch repetition rate of 16.5 kHz. Other effects associated with the waveguide heating, such as waveguide expansion and contraction, are quantified.

INTRODUCTION

A miniature accelerator employing a copper cylindrical corrugated waveguide is being designed at Argonne National Laboratory to produce Čerenkov radiation at 180 GHz using a high charge electron bunch traveling longitudinally on the centerline of the waveguide. The radiation field accelerates a low-charge electron bunch traveling behind with an energy gain of ~100 MeV m^{-1} [1]. The electromagnetic (EM) wave of Čerenkov radiation propagates downstream of the waveguide with a slower group velocity than the beam velocity. Interacting with corrugations, it excites surface currents responsible for the waveguide heating. As shown in Fig. 1, the waveguide is embedded into a "bow-tie"-shaped copper structure with four water cooling channels, although the optimal location of these channels and thermal conductivity from the corrugated surface to water is severely limited by external constrains. The heat load deposition gradually increases along the 0.5 m length of the waveguide and produces a temperature gradient that leads to progressively higher thermal expansion in the downstream direction. The stress from the differential expansion can lead to material tensile-yield failure, surface cracking, arcing, and beam loss. Therefore, determination of the acceptable bunch repetition rate and the ultimate performance of the accelerator are directly related to the thermal management of the average heat load deposited by the electron beam on the corrugations in a steady state operation. Quantitative analysis of the differential dimensional changes is critical for understanding of the operating conditions, and we are investigating the limits based on heat transfer, cooling, and mechanical integrity of the structure applying fully coupled multiphysics finite element analysis while the EM design [2] and prototype fabrication efforts [3] are still developing.

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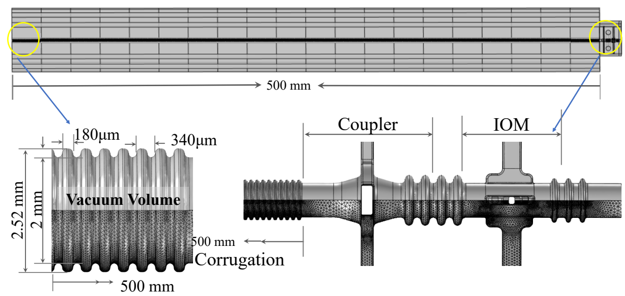

Figure 1: The corrugated waveguide and transition section showing surface mesh.

MULTIPHYSICS FORMULATION

Multiphysics calculations were performed with CST Microwave Studio® [4] and COMSOL Multiphysics® software [5]. Modeling electromagnetic heating with computational fluid dynamics (CFD) and solid mechanics in the corrugated waveguide follow the scheme shown in Fig. 2a, and are summarized in the following steps:

- Solve the electromagnetic problem in CST studio® to find the electromagnetic fields and calculate the electromagnetic surface losses on the wall.
- Apply thermal loads induced by the electromagnetic fields in the heat transfer module to perform the calculation for the temperature rise.
- Apply the flow condition in the CFD, then define the temperature field as a coupling parameter to couple both physics.
- Define the boundary conditions for the Structural Mechanics module, then create a coupling parameter that couples the temperature field of Structure Mechanics for thermal expansion.
- Have the coupled solution compute the temperature field as a fully coupled equation between the heat transfer and the CFD modules, and use it as input for the

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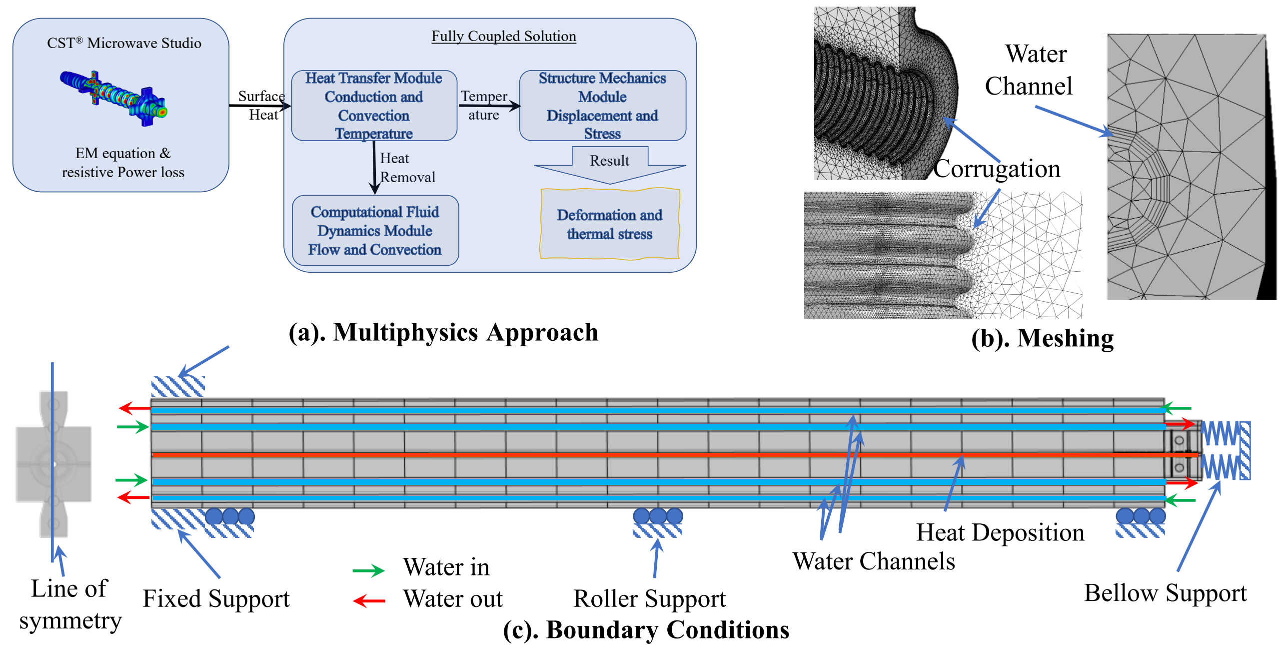

Figure 2: Information on the finite element formulation: (a) fully coupled approach of solving three physics, (b) surface meshes utilized in the study, and (c) boundary conditions used in this study.

thermal and mechanical analysis, provided that the influence of the deformation on the temperature field is negligible.

The Geometry

The corrugated waveguide geometry is shown in Fig. 1. The length of the corrugated waveguide is 0.5 m and the length of the transition section (TS) between adjacent waveguides is 25 mm. The dimension of corrugation is shown in the figure. To reduce the number of mesh elements and speed up calculations, we analyze the corrugated section only for the last 25 mm that is exposed to the highest heat load from the Čerenkov electromagnetic wave generated by the electron bunch. The RF wave is removed in the TS using the electromagnetic coupler, while a small-amplitude signal informing about the beam offset in the corrugated waveguide passes the coupler and a notch filter and is taken by the integrated offset monitor (IOM). The structure has a fourfold symmetry, and thus analyzing half of the volume is sufficient.

Materials

The copper properties that were used in the calculation are listed in Table 1. Note that the value of electrical conductivity was intentionally degraded by a factor of 2.5. This value was used to perform conservative calculations since at the time of writing we do not know either the surface roughness of the corrugations or the actual conductivity of an electroformed copper.

Table 1: Material Specifications

Parameter	Value	Units
Thermal Conductivity	400	W/(m K)
Electrical Conductivity	2.3×10^{7}	S/m
Expansion Coeff.	17×10^{-6}	1/K
Specific Heat	385	J/(kg K)
Modulus of Elasticity	190	GPa
Poisson's Ratio	0.35	

Meshing and Boundary Conditions

Meshing can be seen in Fig. 1 and Fig. 2. The mesh consists of 2,856,122 elements with an average quality of 70%. All the boundaries with allied electromagnetic heat load conditions were meshed at least three layers deep within approximately 25 μm. Figure 2c shows the boundary conditions for all the physics.

Heat Transfer

The electromagnetic field calculation was performed with CST Microwave Studio® using an electron bunch charge of 10 nC.

The heat load caused by surface currents excited by the electromagnetic wave of Čerenkov radiation was scaled linearly with the bunch repetition rate. Table 2 lists all the values for the heat load that are being absorbed on the surfaces of the corrugated waveguide and on the transition section. The corrugated and transition sections are painted with red in Fig. 2c. The natural convective heat transfer boundary condition was used for the outer surface of the device with the heat transfer coefficient of $2\,\mathrm{W\,m^{-2}\,K^{-1}}$. The water in-

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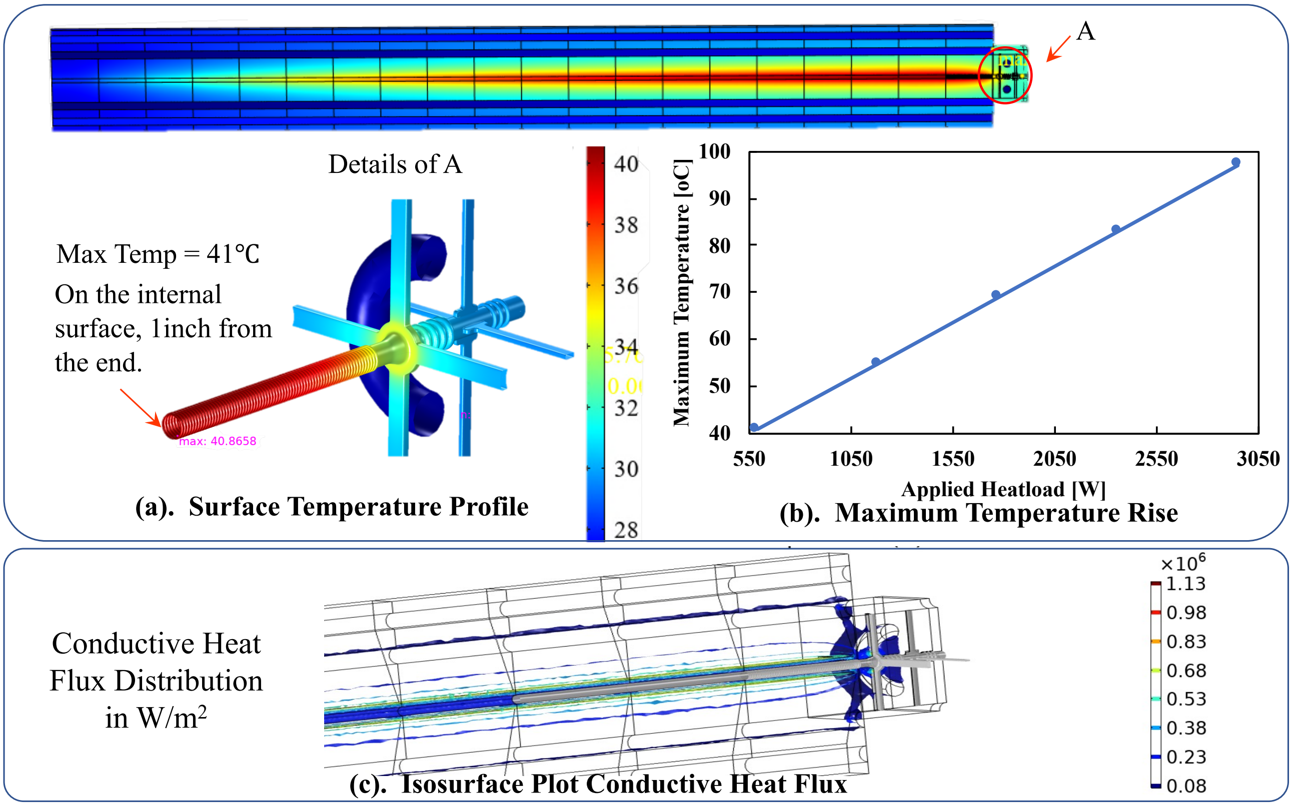

Figure 3: Results of the multiphysics simulation showing (a) surface temperature profile, (b) parametric study of applied heat load, and (c) isosurface plot of conductive heat flux in the volume.

Table 2: Heat Load from CST Microwave Studio® at 10 kHz Bunch Repetition Rate

Geometry	Value	Remark
Corrugated waveguide	589 W	Increases linearly from 0.03 W/cm at the beginning to 39.75 W/cm at the end of the waveguide.
Coupler	21.81 W	
IOM	1.2 W	

let temperature was 25.6 °C. The ambient temperature was 22 °C.

Computational Fluid Dynamics

Four water channels, two channels per side, are provided to extract the heat from the structure, as seen in Fig. 2c. The water flow direction in the closest water channels is in the e-beam travel direction, which is from left to right towards the transition section. The outer water channels flow from right to left. The heat transfer between fluid flow and the structure is done by providing a coupling parameter that calculates the heat removal by forced convective heat transfer in the CFD module of COMSOL Multiphysics®. The isothermal heat transfer condition is assumed, and therefore the coupling between computational fluid dynamics and heat transfer modules is one-way.

Solid Mechanics

All the boundary conditions are shown in Fig. 2c. The left ends of the corrugated waveguide are fixed and the structure is allowed to roll on the horizontal plane and to grow in the vertical plane. A spring foundation boundary condition is used on the right side of the transition section, since the end is connected with a bellows with a spring constant of 80 N/mm.

RESULTS

The simulation was performed at varying heat load conditions. These conditions represent the bunch repetition rate from 10 kHz to 50 kHz in increments of 10 kHz. All the plots and images in Fig. 3 show the results of the calculations for the 10 kHz case, which deposits about 600 W of heat on the walls of the waveguide. The top image in Fig. 3a shows the temperature profile of the corrugated waveguide (A) sectioned at the center. The details of ‘A’ show the temperature distribution on the corrugation and transition section. The graph in Fig. 3b shows the maximum temperature upon application of the various heat loads. The graph is linear because we assume constant thermal and electrical conductivity values. The isosurface plot in Fig. 3c shows a map of the conductive heat flux in the critical region of this section.

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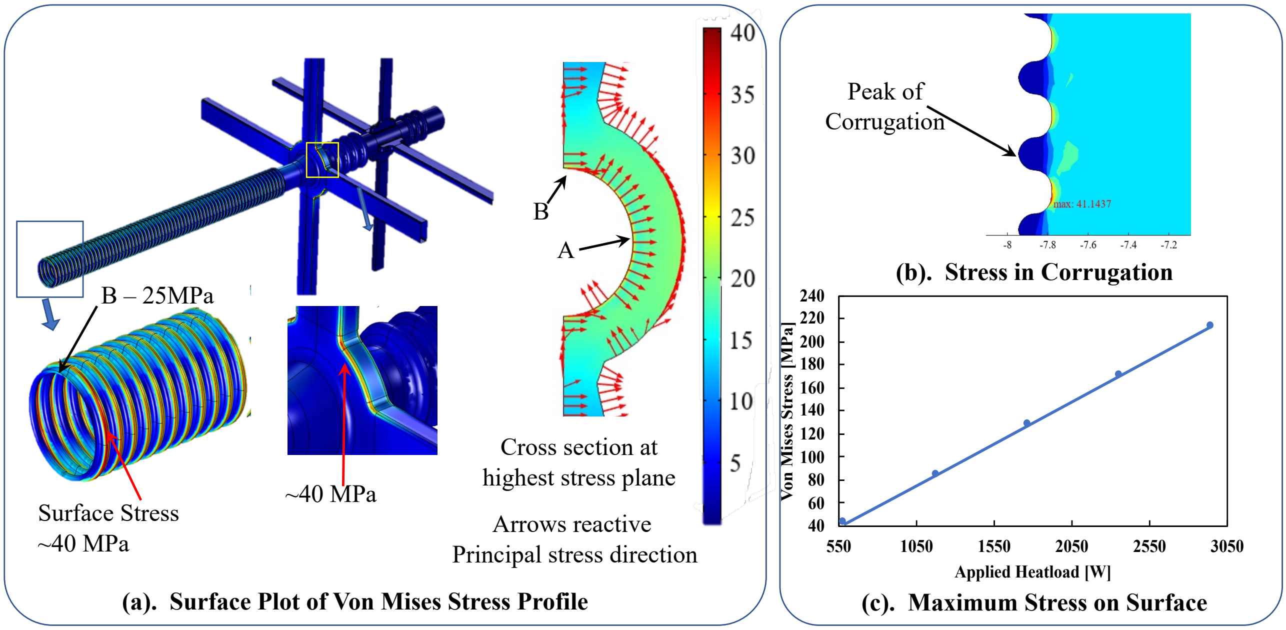

Figure 4: Results of multiphysics simulation.

Table 3: Maximum Displacement Based on the Applied Heat Load

Heat Load	Displacement
590 W	29.29 µm
1180 W	61.93 µm
1770 W	94.59 µm
2360 W	127.26 µm
2950 W	159.92 µm

The temperature rise in copper has a direct correlation with the conductive heat flux. It can be seen that the conductive heat flux value reduces near the end and towards the transition section, which represents a high rate of cooling due to a conduction cooling operation.

Figures 4a, b, and c represent the von Mises stress in the structure, while the maximum displacement at the extreme right tip of the structure is listed in Table 3. Figure 4b shows the maximum stress occurring in the trough region, which is 41 MPa, while the peak region is experiencing a lower stress. The 2D image in Fig. 4a shows the stress at the cross section is the maximum stress in the structure. The image with arrows on the surface is showing the directions for the derived principal stresses on the cross section. The outer surface near the thinnest section of the part undergoes tensile stresses, which are also higher, as shown in the images of surface stress on the right side of Fig. 4a, marked by point A. At point A, the part is being stretched, and the stresses are in the tensile regime. At point B, the stresses are lower than point A because the section thickness is higher. Figure 4c shows the maximum stress produced on the surface for the applied heat load.

DISCUSSION

The temperature rise for the 600 W case is about 15 °C above the room temperature, which is not a considerable temperature change in copper. However, the stress level at the corrugation is higher than in the bulk since corrugations can be viewed as a series of thin rings attached to the linearly expanding structure. Moreover, stresses due to thermal expansion in the high-aspect-ratio structures increase monotonically [6], and our structure has a high aspect ratio. The average temperature rise over the entire volume is about 6 °C, which leads to an average stress of 11 MPa when calculated analytically. The simulation shows similar numbers in the bulk, while a higher stress level is seen at the corrugation. The maximum value of the von Mises stress calculated for a 10 kHz bunch repetition rate is 41 MPa. The same calculations show that the yield stress is reached at 1 kW of heat load, which corresponds to a 16.5 kHz bunch repetition rate. The zone with the maximum stress is only 10 µm deep, which is an indication of the tensile stress criteria on the surface. The maximum linear expansion is 29.3 µm, and the pitch of the corrugated structure is 340 µm. There are 1470 corrugations in the 0.5-meter-long structure. By distributing the thermal expansion linearly over this number of corrugations, the change in pitch will be less than 100 nm.

SUMMARY

The miniature beam-driven wakefield accelerator based on the corrugated waveguide has been considered where the electromagnetic heat load has been deposited in a linearly increasing manner in the downstream direction of the corrugated waveguide, and thus the expansion has also increased linearly toward the transition section between the neighboring waveguides. The multiphysics model has been

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created to calculate the expansion in the long thin structure of the corrugated waveguide and related von Mises stress caused by the structure heating up from the electron beam propagating along its axis. The calculations have helped to develop an understanding of how to support the structure with a fixed support, a roller support, and a bellows support to minimize the stress.

The investigation has also helped define safe operating conditions when the maximum stress on the heat-affected zone is less than the yield strength of the material. Based on the finite element analysis study, it was inferred that for an electron beam with a bunch charge of 10 nC, the bunch repetition rate can safely be at 15 kHz.

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