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VACUUM ANALYSIS OF A CORRUGATED WAVEGUIDE WAKEFIELD ACCELERATOR

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Abstract

The vacuum level in a 2-mm-diameter, 0.5-m-long copper corrugated waveguide tube proposed for a compact high repetition rate wakefield accelerator has been investigated. The analytical calculations have been found to be in good agreement with the result of computer modeling using the finite element method. A representative experiment has been conducted using a smooth copper tube with the same inner diameter as the corrugated tube. The vacuum level calculated for this experiment agrees well with the measurement.

INTRODUCTION

The sustainable operation of all accelerators requires high vacuum within the vacuum chamber [1], which is very challenging for the long tubular chamber with a small-diameter opening that is employed in a miniature collinear wakefield accelerator (CWA)—A-STAR—under development at Argonne National Laboratory. This accelerator uses a corrugated waveguide and sub-terahertz Čerenkov radiation produced by an electron bunch traveling longitudinally on the centerline of the waveguide [2].

This paper focuses on vacuum analysis of the accelerator. The 2-mm-inner-diameter, 0.517-m-long corrugated vacuum chamber of the accelerator module will be assembled from five 100-mm-long, thin-wall corrugated tubes. It will operate with 1-GeV, 10-nC electron bunches that will be coming to the accelerator with a 15-kHz repetition rate, producing Čerenkov radiation, inducing surface currents on the corrugation, and depositing about 800 W of heat distributed over the entire accelerator module [3]. As a result, the chamber will heat up from room temperature to ~50 °C [4]. The heat load increases along the length of the structure, causing a progressively higher thermal outgassing in the downstream direction. Additionally, an electroforming fabrication technique will be used to produce the corrugated waveguide [5]; therefore, due to hydrogen trapping [6], a higher outgassing rate is expected in the electroformed copper compared to the oxygen-free copper used in the accelerator applications.

While the accelerator chamber fabrication concept is still being developed [7], we performed a preliminary vacuum analysis using the chamber dimensions presented in [7] and report it here in the first section.

A major concern for the accelerator module fabrication is the integrity of the brazed joints between the adjacent corrugated waveguide sections. Therefore, we fabricated a 152-mm-long mock-up vacuum chamber containing three 2.1-mm-inner-diameter, 50-mm-long oxygen-free copper tubes without corrugation and measured vacuum in two

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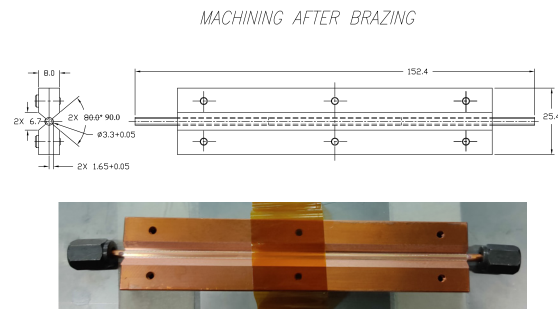

Figure 1: Test piece of the vacuum chamber showing dimensions (top) and the machined chamber (bottom).

setups: a) with these joints enclosed and brazed inside the copper block, and b) after machining the copper block to obtain a vacuum chamber profile. The machined chamber has a thin (<0.9-mm-thick) section exposed to atmospheric pressure, as seen in Fig. 1. The result of this experiment is reported in the second section.

VACUUM CALCULATIONS

Analytical Estimation

For vacuum calculations we modeled the corrugated waveguide as a smooth tube with an effective diameter d=2.26 mm and an effective length ℓ= 0.95 m that has the same surface area as a 2-mm-diameter, 0.517-m-long tube with corrugations. We calculated the tube's molecular flow using the engineering formula [8]

$$C(x) = 12.1\frac{d^3}{x} \tag{1}$$

that defines the conductance C in liter/sec for a tube with an internal diameter d and length x in cm. Expecting pumping efficiency to be limited by the tube's conductance, and assuming use of pumps on both sides of the vacuum chamber, we obtained a result for the vacuum pressure as a function of the relative distance along the tube length $\xi = x/\ell$:

$$P(\xi) = \pi R \frac{\ell^2}{12.1 d^2}\xi(1-\xi), \tag{2}$$

where R is the outgassing coefficient, and we ignore here a small variation of this coefficient with the temperature. Using R= $3.6\times10^{-11}\ \frac{\mathrm{torr\,L}}{\mathrm{cm^2\,s}}$ for copper after backing [6, 9], we calculated the vacuum pressure at the center of the tube as $P(1/2) \simeq 1.5\times10^{-6}$ torr.

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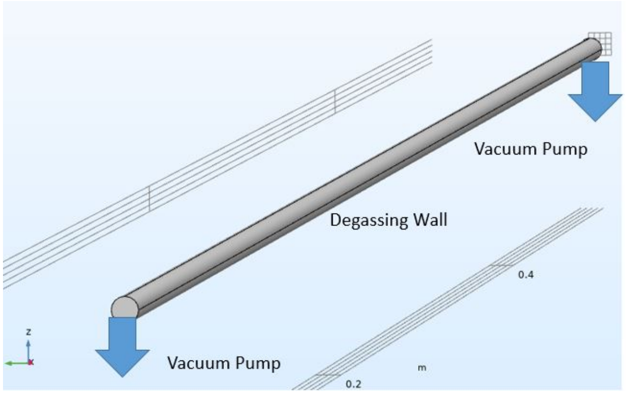

Figure 2: The 517-mm-long, 2-mm-inner-diameter corrugated copper tube with corrugation depth of 0.26 mm modeled as a 950-mm-long, 2.26-mm-inner-diameter smooth copper tube.

Simulation Result

The simulation was performed using the COMSOL multiphysics molecular flow module with the parameters listed in Table 1. The model geometry is shown in Fig. 2. Two pumps were attached to the system on either end. Both pumps operated at a pump speed of 1 liter/sec. A constant outgassing flux was assumed to be emitted from the walls of the tube with an outgassing coefficient of $3.6{\times}10^{-11}\ \frac{\text{torr L}}{\text{cm}^2\ \text{s}}$ [6, 9].

Table 1: Parameters used in Simulation

Parameter	Value
Temperature	293.15 K
Molar mass	0.028/kmol
Pump speed	1 liter/sec
Outgassing rate	$3.6{\times}10^{-11}\ \frac{\text{torr L}}{\text{cm}^2\ \text{s}}$

The maximum pressure of $7{\times}10^{-7}$ torr occurred at the center of the tube since the vacuum pumps were allocated at both ends. The simulation result is shown in Fig. 3. We note that the analytical estimation agreed with this result within a factor of 2.

The long, smooth tube may not perfectly represent the practical case of a corrugated tube, however, since it only accommodates the total surface area of the corrugations in the simulation.

EXPERIMENT

The prime focus of the experiment was investigation of the brazed joints between adjacent corrugated waveguide sections as discussed in the introduction. However, instead of the 100-mm-long corrugated tubes produced via the electroforming process, we used 2.1-mm-diameter, 50-mm-long oxygen-free copper tubes without corrugation, but with a similar wall thickness of 0.9 mm. This is about the same thickness as the wall of the corrugated tube in the middle of the ridge in the corrugation profile. We also benchmarked our vacuum simulation. Specifically, we used vacuum measurements to find the outgassing coefficient that would produce the best fit of simulations to the experiment.

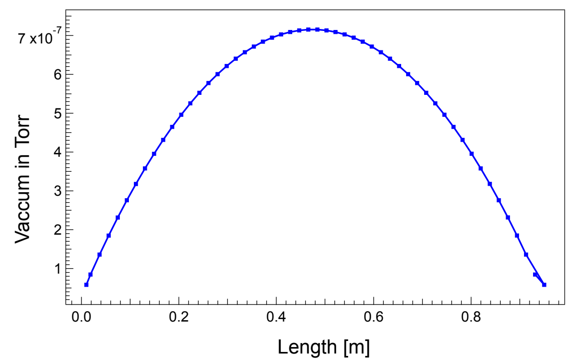

Figure 3: Molecular flow simulation result of the total pressure for an equivalent 0.95-m-long copper tube.

Figure 4 shows the fabrication steps of the 0.95-m-long copper mock-up chamber. Figure 4e shows the vacuum testing setup before machining the designed profile of the chamber. The vacuum pumps is located on one side of the chamber, and the vacuum gauge is located on the opposite side of the chamber.

The system was pumped down for 48 hours, and the base pressure at room temperature before baking was $4.5{\times}10^{-7}$ torr. Figure 5 shows two graphs. The blue line is the vacuum pressure versus time, and the red line is the ramp-up and ramp-down of the baking temperature versus time. After the ramp-down process, the system was brought down to room temperature, and the vacuum pressure was $1{\times}10^{-7}$ torr. The final pressure after baking improved over 24 hours to $8.5{\times}10^{-8}$ torr. To obtain this vacuum pressure in simulation, we had to use $R = 7{\times}10^{-11}\ \frac{\text{torr L}}{\text{cm}^2\ \text{s}}$, which is not surprising considering the typical uncertainty for the outgassing coefficient in the literature [6, 9].

After machining the mock-up vacuum chamber to the required shape shown in Fig. 1 and, thus, exposing the brazed tubes to atmospheric pressure over a large fraction of the circumference and length, the second vacuum test was performed. Figure 6 shows this measurement. The final vacuum pressure degraded to $2.1{\times}10^{-7}$ torr, which can be attributed to a thin section of the tube, but the integrity of the brazed joints was not compromised in the fabrication process.

SUMMARY

The steady state molecular flow simulation was performed based on the outgassing condition that develops due to heat load. The simulation with boundary conditions shown in Fig. 2 was performed on a 2-mm-diameter, 0.95-m-long copper tube without corrugation representing the actual surface area of the 0.517-m-long vacuum chamber with corrugation. The outgassing coefficient for the oxygen-free copper after backing was used to simulate the gas load. In the

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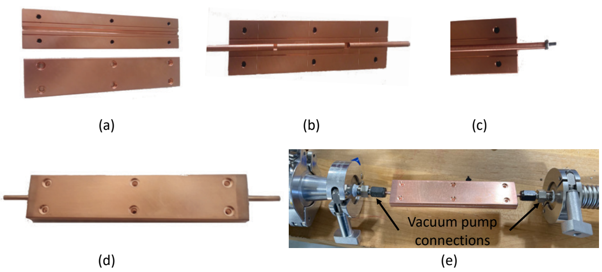

Figure 4: Fabrication process for a mock-up vacuum chamber. (a) Preparation of two halves before brazing, (b) three 50-mm tubes assembled in the channel, (c) assembled vacuum chamber with titanium rod inserted for clamping via application of spring force, (d) brazed chamber without machining operation, and (e) vacuum chamber on testing rig attached with vacuum pumps.

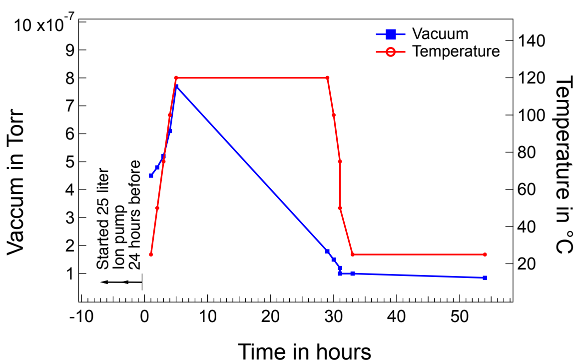

Figure 5: Vacuum testing with baking out process.

result shown in Fig. 3 we predict a maximum pressure of 7×10^{-7} torr and a line average pressure of 5.6×10^{-7} torr.

However, the long, smooth tube may not perfectly represent the practical case of the corrugated tube and, thus, our next goal is to fabricate and study the vacuum holding capacity of the 0.3-m-long vacuum chamber with three 0.1-m-long corrugated tubes.

The vacuum testing results shown in Figs. 5 and 6 using a mock-up vacuum chamber are in good agreement with each other. In both cases, the vacuum level improved after baking and sustained an equilibrium between outgassing and pumping that confirms the successful brazing process. Exposing the brazed tubes to atmospheric pressure over a large fraction of the circumference and length slightly degraded the vacuum pressure, which can be attributed to the thin section of the tube.

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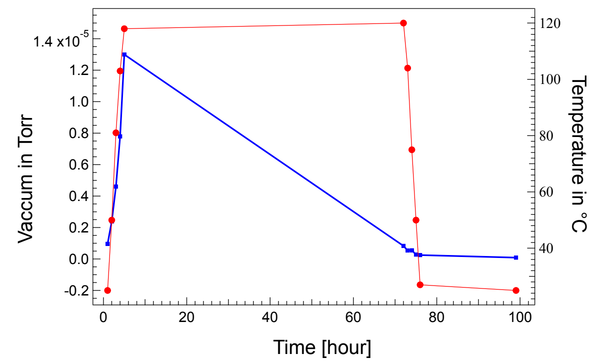

Figure 6: Vacuum testing with baking out process after machining the chamber.

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