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INVESTIGATION OF VARIOUS FABRICATION METHODS TO PRODUCE A 180GHz CORRUGATED WAVEGUIDE STRUCTURE IN 2MM DIAMETER 0.5m LONG COPPER TUBE FOR THE COMPACT WAKEFIELD ACCELERATOR FOR FEL FACILITY

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Abstract

Argonne National Laboratory is developing a 180 GHz wakefield structure that will house in a co-linear array of accelerators to produce free-electron laser-based X-rays. The proposed corrugated waveguide structure will be fabricated on the internal wall of 0.5m long and 2mm nominal diameter copper tube. The estimated dimensions of these parallel corrugations are 200 μm in pitch with 100 μm side length (height and width). The length scale of the structure and requirements of the magnetic field-driven dimensional tolerances have made the structure challenging to produce. We have employed several method such as optical lithography, electroforming, electron discharge machining, laser ablation, and stamping to produce the initial structure from a sheet form. The successive fabrication steps, such as bending, brazing, and welding, were performed to achieve the long tubular-structure. This paper discusses various fabrication techniques, characterization, and associated technical challenges in detail.

BACKGROUND

Free-electron laser (FEL) sources have a tremendous potential to advance scientific research in the fields of material science, medical applications, biophysical, surface science, and the broad range of condensed matter physics [1]. The lasing medium of an FEL consists of moving electrons passing through a radiation generating sources such as magnetic undulator [2, 3] or a compact accelerator such as Čerenkov wakefield [4] at nearly the speed of light. The current FELs are large, expensive, and complex systems that are not practical for the industrial or the consumers' use at this time. There is an immediate need for FEL facilities with compact, tunable, and multi-user accelerator. Reduction in size of the accelerator is a key for making affordable FEL facilities for material characterization, industrial or medical purposes. Argonne National Laboratory (ANL) is leading an effort to develop a compact, broadly tunable, high repetition rate, multi-user, and yet cost-effective accelerator for the X-ray FEL source [4, 5] based on the Čerenkov wake-field. A conceptual diagram for a high repetition rate multi-user FEL facility based on a CWA concept that is currently under development is shown in figure 1 in the reference [4]. The electrical design and particular challenges are discussed elsewhere [5]. In this paper, we are going to discuss the challenges in the fabrication of CWA structure.

Compact Collinear Wakefield Accelerator

To produce Čerenkov radiation at 180 GHz, it requires corrugated copper waveguide with dimensions in micrometric regime that can sustain ~100 MV/m accelerating field for the ~ 0.3 nC electron charge witness-bunch. The accelerating field is created by ~ 10 nC charge drive-bunch that was passed at center of the structure near the speed of light. The image in figure 2 in the reference [6] illustrates the Čerenkov wakefield concept.

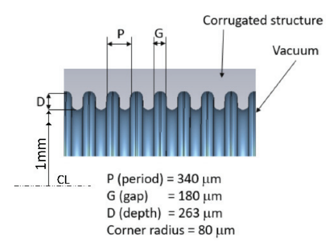

Figure 1: Schematic of corrugation inside of the copper tube.

The Schematic of the corrugation is shown in Figure 1 that is designed to produce 180 GHz wakefield Čerenkov radiation. The corrugation is created on the inside wall of the cylindrical copper (Cu) pipe with a 2 mm internal diameter. The electron bunch repetition rate is 10 - 50 kHz that is limited by the heat deposition on the interior wall due to the interaction of the electromagnetic field with the surrounding material. Strong quadrupole magnets with a 3 mm aperture control the electron beam trajectories. The field polarity of the quadrupoles is repeating at every 25-40 cm. Alignment tolerances for the quadrupoles are about 1 μm over 500mm, and the straightness requirement for the corrugated structure is 10 μmm.

Corrugated Waveguide

The structure of corrugation is being fabricated on the inner wall of a 2mm-inner-diameter copper tube with ridges facing inward. The corrugation has a period of 340 μm, the gap 180 μm, depth 263 μm, and the corner radius of 80 μm. All dimension are designed and optimized using finite element analysis and reported herein [5]. It is challenging to fabrication these 1472 repetitive corrugation structures

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integral to the CWA with extreme precision. Slight fabrication tolerance difference in the structure may give rise to unwanted RF modes. Moreover, the poor surface finish may give rise to heat deposition and breakdown voltage. The surface finish needs to be in less than 1 μm. The Schematic in Figure 1 shows the dimensions of the internal corrugations.

FABRICATION METHODS

This paper describes our investigation of various fabrication techniques in the production of CWA, focusing on the corrugated waveguide. We are utilizing several fabrication methods such as die Stamping, pressing, optical lithography, electron discharge machining (EDM), laser ablation and micro-machining, and electroforming. A part of the corrugated waveguide has been fabricated for each method to explore the possibilities. Dimensions of the fabricated structures are measured utilizing the Keyence VR3200 system to evaluate the quality of each method and discussed herein reference [6]. The results are providing us valuable information in finding the best way to fabricate 0.5m long waveguide as well as which method is appropriate to sustain high vacuum after the fabrication. The final device is 0.5-meter long waveguide with corrugation structure and will be brazed to a cooling assembly.

A brief discussion for each fabrication method are as follows:

Fabrication of Corrugated Structure

Die Stamping: One corrugation period can be divided into two parts the ridge and the trough as shown in Fig. 2a. The thickness of ridges is 160 μ m, and the thickness of the troughs is 180 μm. There is total of 1472 corrugation per 0.5-meter long waveguide comprising 1472 ridges and 1472 troughs. Each ridge and troughs can be made individually in the ring shape from the copper foil and combined them by placing them alternatively together to form a long waveguide. The solid structure can be achieved by brazing. Two stamping dies were created for the ridge and trough and stamped from copper foil with a thickness of 160 μm and 180 μm respectively. It was found that stamping method required precision cutting to maintain the inner definition of along the circumference. Quality assurance was a challenging task due to several samples to evaluate, and the slightest bend in the foil stamps can cause RF related issues such as arcing, multiple modes of resonance, and creation of virtual leak. Moreover, there will be about 2944 joints.

Pressing: This technique utilizes the plastic deformation principle to make an indentation on a semicircular shape machined channels by a corrugation patterned tool. A schematic is shown in Fig. 2b. A semicircular die was prepared with an inverse pattern of corrugation. The base diameter is kept equivalent to the inner diameter of the corrugated waveguide; thus upon deformation, the copper will be conformed to the required shape. Two copper pieces were machined with a 2mm diameter semicircular channel. The die is pressed against the copper channel to make an impression on the circular surface. After repetitive pressing and moving along the center-line of the 0.5-meter long copper sections will be patterned followed by two machined sections joined by brazing. A representative section is already made, and brazing is already planned.

Pressing or embossing technique has merit since the initial base structure can be kept straight and aligned after brazing operation. After brazing, the whole part can be machined to achieve the required shape. The biggest challenge here is to align two halves of corrugations along the length and manage the flow of melted brazing materials such a way that all corrugation is joined without spillover in the nearby channels. This challenge can be mitigated by providing the right size of the small capillary channel next to the corrugation and providing fiducials for the accurate alignment. It is challenging to stop the flow of brazing material into the corrugation.

Electroforming: Electroplating or electroforming is one of the most promising methods of fabrication. Electroforming is employed to produce the corrugated waveguide structure. The aluminum (Al) mandrel with a hole in the center along with the tube length was produced by machining, followed by electroplating copper metal on it. Then after, the mandrel was placed in a boiling bath of NaOH to dissolve the Aluminum chemically. The complete etching of Aluminum leaves behind the plated structure as the final electroformed product. These waveguides will be joined using the brazing technique to produce 0.5-meter-long waveguide. The corrugation dimensions and surface finish of electroformed components reflect the manufacturing quality of the aluminum mandrel geometry. One of the challenges is to produce maximum possible mandrel length that is limited by both the ability to maintain straightness of the 2-mm-diameter Al mandrel during machining and after the electroplating process step. Metrology analysis of the sample indicates excellent uniformity in the corrugation period, straightness, and the surface finish. Figure 2c shows the Schematic of the fabrication method.

Optical Lithography: In this technique, the corrugations were achieved on a planar surface via an optical lithography technique (refer Figs. 2d and 2g). Photoresists werecoated on a flat copper plate followed by exposing under UV through a grating mask made with corrugation dimensions. The expose photoresists were removed using a chemical process followed by etching with $FeCl_3$ solution. The flat plate then cut inappropriate widths and was bent to semicircular channels. These halves of the channels were then joined by either laser or copper welding. The measurement of the structure is shown in figure 9 in the reference to [6]. The figure shows height-exaggerated 2D profile of corrugations fabricated using photolithography on a flat copper strip. The strip then was bent and joined using laser micro-machining.

The measurement shows a modulation in patterning which could have caused during the crosslinking of photoresists. The final structure had a secondary dimension which was repeating in nature. The depth of corrugation was changing every 3 mm. This creates unwanted RF issues such as

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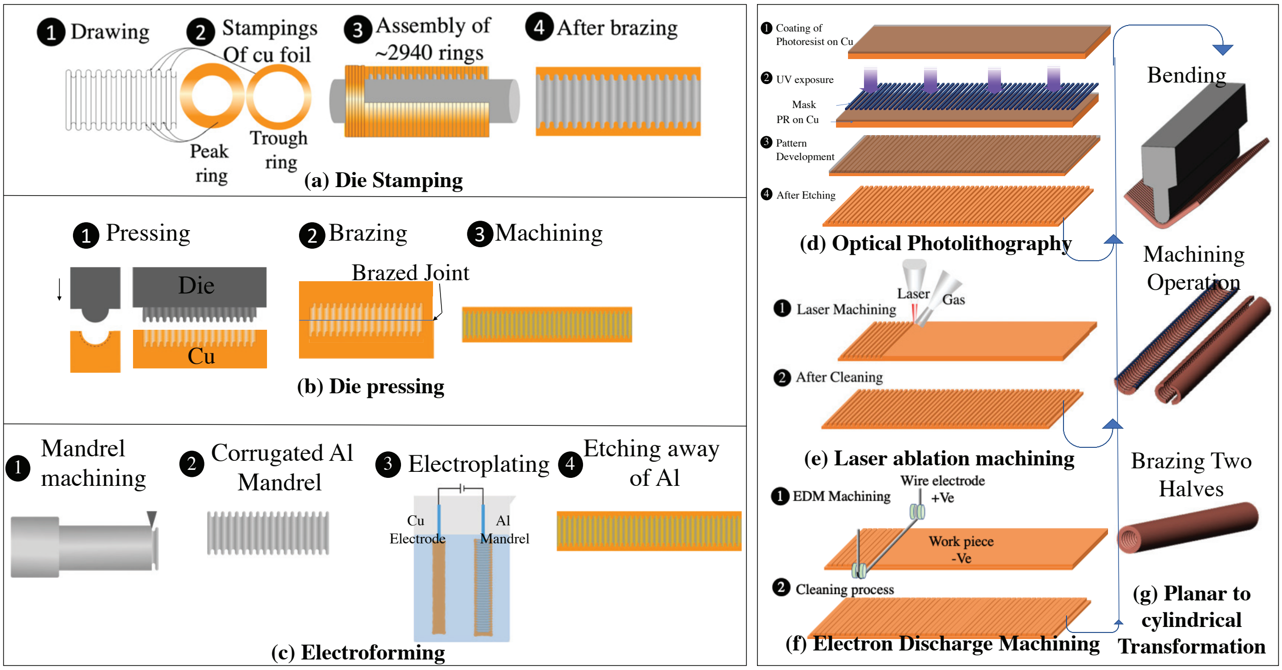

Figure 2: Figures show various fabrication techniques that were investigated for production of corrugated waveguide.

multiple resonances and unwanted wakefield effect. Laser welding was performed to join two halves of the waveguide, as shown in figure 11 in the reference [6]. The results were promising, however, very challenging to fabricate.

Laser Ablation: Similar to photolithography and EDM, the structures were fabricated using laser ablation machining and followed the same method of fabrication afterward. Also, it carries similar challenges of fabrication after bending. (refer to Fig. 2e)

Electron Discharge Machining: The planar structures were fabricated using electron discharge machining and followed the same method of fabrication, as shown in Fig. 2g. Also, it carries similar challenges of fabrication after bending.

Fabrication of Waveguide

Brazing, Laser welding, e-beam welding were investigated for the quality of the joint, as well for the bent half-cylinders to form the tubular waveguide structures

Laser Welding: Test the method, several non-corrugated half-tubes were joined by laser welding. The tubes were then cut in half to expose both sides of the welded joint for inspection. Results indicated overall good quality in the joints, although a few penetrations to the inside of the tube were evident. The weld beads were hand-laid by a highly-skilled craftsman using 125 μm [0.005"] diameter Cu wire as the filler material. This is a labor-intensive process; the workpiece motion is coordinated with the laser pulses, and the operator adds material while viewing the workpiece through a stereomicroscope. A 3D image of a laser-welded test sample shows that the nominal width of the hand-laid weld bead is only 0.6 mm.

E-beam welding: The electron beam welding of the tubes was attempted by our colleagues at Jefferson National Lab and was determined to be problematic due to heating and expansion of the thin walls of the tube during welding. The idea of forming and welding the corrugated waveguide structures has been rejected as not feasible.

Brazing: Currently, we are exploring to join two halves that are produced by the pressing method of fabrication. The final waveguide will be produced by machining the tubular shape out of the flat pieces that were joined using brazing.

SUMMARY

Several fabrication methods are being investigated to produce Cu corrugated waveguide structures. At this point, we are mainly focused on the fabrication related challenges however we are also considering the RF and vacuum related issues. Electroforming and pressing methods of fabrication deemed feasible in production of the waveguide. Metrology is an essential part of evaluation of the fabrication process and it is also helping us to understand RF issues via simulation of attainable surface finished as well, the level of attainable vacuum that is material dependent. We look forward to reporting our progress as this ambitious project moves forward.

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