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MECHANICAL DESIGN OF A COMPACT COLLINEAR WAKEFIELD ACCELERATOR*

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Abstract

Argonne National Laboratory is developing a Sub-THz AcceleRator (A-STAR) for a future multiuser x-ray free electron laser facility. The A-STAR machine will utilize a compact collinear wakefield accelerator (CWA) based on a miniature copper (Cu) corrugated waveguide as proposed in [1]. The accelerator is designed to operate at a 20-kHz bunch repetition rate and will utilize the 180-GHz wakefield of a 10-nC electron drive bunch with a field gradient of 100 MVm^{-1} to accelerate a 0.3-nC electron witness bunch to 5 GeV. In this paper, we discuss specific challenges in the mechanical design of the CWA vacuum chamber module. The module consists of series of small quadrupole magnets with a high magnetic field gradient that houses a 2-mm diameter and 0.5-m-long corrugated tubing with brazed water-cooling channels and a transition section. The 45-mm-long transition section is used to extract the wakefield and to house a beam position monitor, a bellows assembly and a port to connect a vacuum pump. The CWA vacuum chamber module requires four to five brazing steps with filler metals of successively lower temperatures to maintain the integrity of previously brazed joints.

INTRODUCTION

Development of a CWA accelerator presents significant engineering challenges due to the miniature scale of the components. The CWA vacuum chamber module is comprised of a corrugated tubing-strongback (CTS) unit, a bimetal vacuum flange, and a transition section (TS) unit with a bellows as shown in Fig. 1. The CTS will be fabricated from cylindrical corrugated waveguide tubes with a 2-mm ID that will be electroformed from aluminum (Al) mandrels. It will generate ~100 MV/m accelerating fields during operation, and its overall length will be about 0.5 meter long. The bi-metallic flange will be brazed to the upstream end of the CTS. The TS unit consists of an electroformed TS Cu waveguide, a TS Cu base, a stainless steel welded bellows assembly, eight flexible Cu waveguides, and diamond window assemblies. The CTS, bimetal flange, and TS units will be brazed together, then machined to be embedded into the quadrupole wiggler with alternating focusing and defocusing quadruples. Figure 2 shows two CWA vacuum chamber modules and one quadrupole wiggler assembly to reveal the structural clarity of the CWA vacuum chamber module. This paper will focus on the design of the CWA vacuum chamber module and its fabrication challenges.

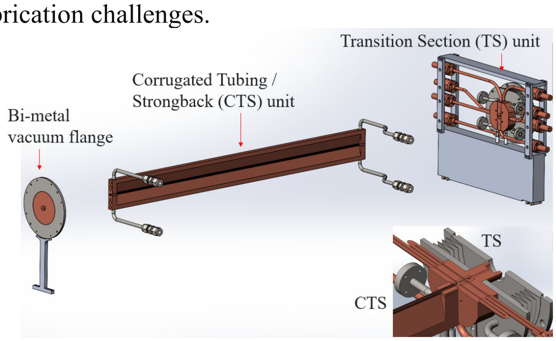

Figure 1: A vacuum chamber module and its components for the compact collinear wakefield accelerator.

DESIGN OF A CWA VACUUM CHAMBER MODULE

Various fabrication techniques to create a corrugated waveguide structure were investigated. Based on our previous study [2, 3], electroforming was selected to produce internally corrugated tube segments for the CWA vacuum chamber module. The corrugated waveguide tubes are created by electroplating Cu on an Al mandrel [3]. The Al mandrel is then chemically dissolved, leaving behind the internally corrugated Cu structure. The internal Cu surface reflects the shape and finish of the Al mandrel surface. A micro-turning process is utilized to meet the dimensional and surface quality tolerances of the mandrels. The internal dimensions of the corrugated waveguide structure are shown in Fig. 3. The maximum length of the Al mandrel is ~100 mm; therefore, several corrugated waveguide segments must be brazed together to fabricate the 0.5-m-long vacuum chamber. The waveguide segments will be inserted into a channel-cut machined Cu strongback plate, then secured by a machined Cu bar with braze filler metal spreading adequately over the tubing surfaces or using wire rods as shown in Fig. 4. If needed, all parts will be secured by jigs and fixtures, then carefully held in position for brazing in a vacuum furnace to produce a 0.5-m-long CTS unit.

During the brazing process, compression force will be applied inwards along the length using spring sheets and spacers at both ends to maintain tight surface contact of the corrugated tubes. This will help to prevent filler metal from flowing inside the inner corrugation surface area. After the post-braze cleaning process, both end surfaces of the CTS unit are milled for vacuum leak testing (see Fig. 5). The strongback sides will be milled to produce tapered surfaces to fit within the quadrupole wiggler magnet assembly as shown in Fig. 6. The strongback end surfaces will then be

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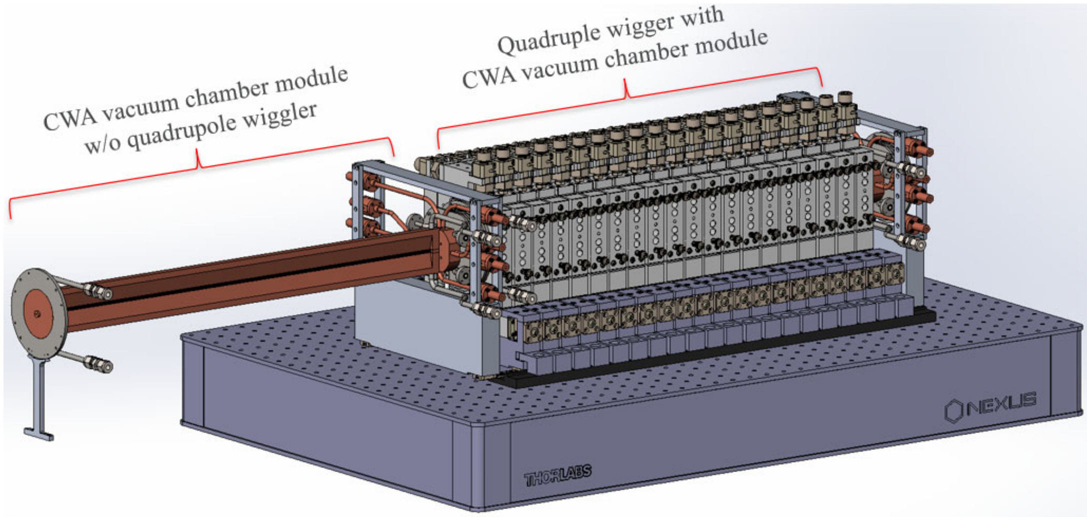

Figure 2: Two CWA vacuum chamber modules and a permanent magnet quadrupole wigger on the optical breadboard.

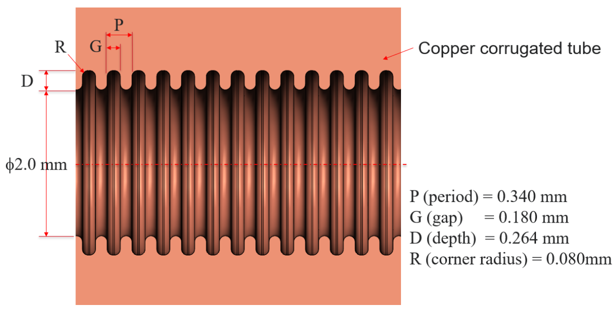

Figure 3: Schematic of corrugation inside of the copper tube.

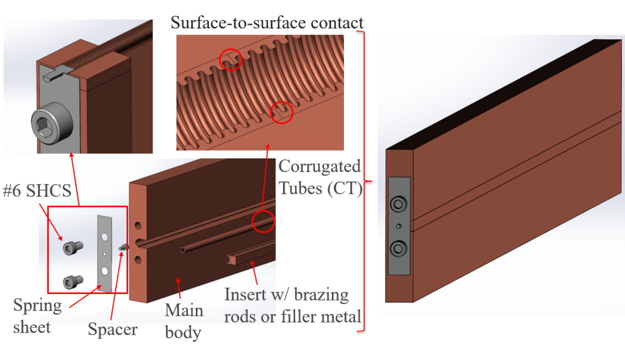

Figure 4: The components of a corrugated tubing-strongback (CTS) unit.

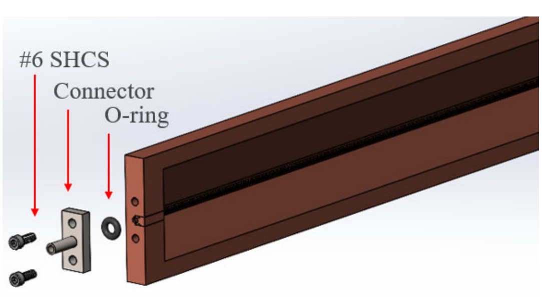

Figure 5: Schematic of leak check after brazing or machining the corrugated tubing-strongback (CTS) unit.

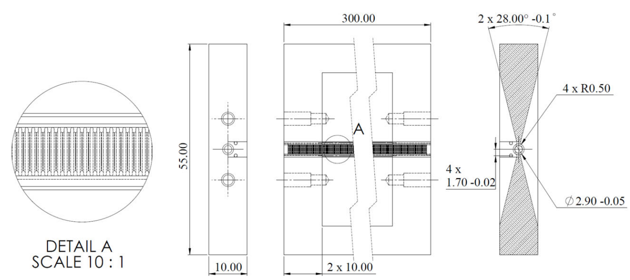

Figure 6: Machining of the corrugated tubing-strongback prototype for the quadrupole wigger magnet (unit: mm).

further machined as shown in Fig. 7(d) to prepare for the final brazing process at a lower temperature for connection to the bi-metallic flange and a 45-mm-long TS unit. The TS unit has many braze joints such as a braze joint between an electroformed TS waveguide and a TS body, eight braze joints between the TS body and eight flexible waveguides, eight brazing joints between the flexible waveguides and diamond flanges, and a joint between the TS body and the bellows assembly [4]. The CWA vacuum chamber module requires a total of 22 brazed joints that will be achieved via four to five brazing steps with filler metals (paste or wire rods) at successively lower temperatures to maintain the integrity of previously brazed joints.

FABRICATION CHALLENGES OF THE CWA VACUUM CHAMBER MODULE

Successful fabrication of the CWA vacuum chamber module relies on proper brazing and machining techniques. We expect several technical challenges in the brazing and micro-machining process during fabrication of each brazement and the final CWA vacuum chamber module, such as tolerance stack-up; base material condition; design variables including compression force along the corrugated tubes; process parameters during brazing, testing, and inspection of finished brazed assemblies, etc. In the brazing process, the following are challenges for producing a successful vacuum chamber module:

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1. Braze joint design for proper gap clearance: when we braze, a clearance of 0.038~0.050 mm will be maintained between the two joining surfaces. But a close press-fit or contact between the corrugated tubes along the length must be considered to eliminate excessive braze filler flow into the corrugated surfaces by use of compression force.
2. Surface finish on the joints to be brazed will be 32~64 RMS for drawing the filler metal into the joint and getting better capillary action.
3. Vacuum cleaning to remove oxides from stainless steel and Cu materials for better surface conditioning before brazing and post brazing.
4. Suitable brazing filler metals of successively lower temperatures to maintain the integrity of previously brazed joints. For the brazing of successive joints in the CWA vacuum chamber module, the following are recommended as filler metals (Solidus, liquidus, brazing temperature range low-high).
   a) BVAu-9, 35/65 Au/Cu (988, 1010, 1038-1066°C)
   b) BVAu-4 (949, 949, 977-1004 °C)
   c) BVAg-8 (779, 779, 779-835°C)
   d) BAg-7 (618, 651, 679-707°C)
5. Fixturing during brazing: Self-fixturing and self-aligning where possible. The use of fixture increases the cost and adds distortions to the braze assembly. To maintain a proper gap clearance, the fixture must be properly designed and used during brazing.

The standard CNC milling process can produce shapes with rounded corners of the CTS unit, but a micro-machining process, such as diamond-turning or micro-milling, can be considered due to tolerances as tight as 0.001″ or less. Therefore, care must be taken during the micro-machining process of the exterior round surfaces of the CTS unit, especially braze joints between the corrugated tubes. Undercut of the corrugated tubes can develop vacuum leaks under high-vacuum operation.

CONCLUSION

In this paper, we proposed design parameters such as braze joint geometries, clearance gap, surface roughness, and brazing filler metals of successively lower brazing temperature and technical challenges in the brazing and micro-machining of the CWA vacuum chamber module. Future work will focus on further optimization of the joint geometries, brazing filler metals, process parameters, and machining tolerances and techniques in detail to produce the CWA vacuum chamber module prototype.

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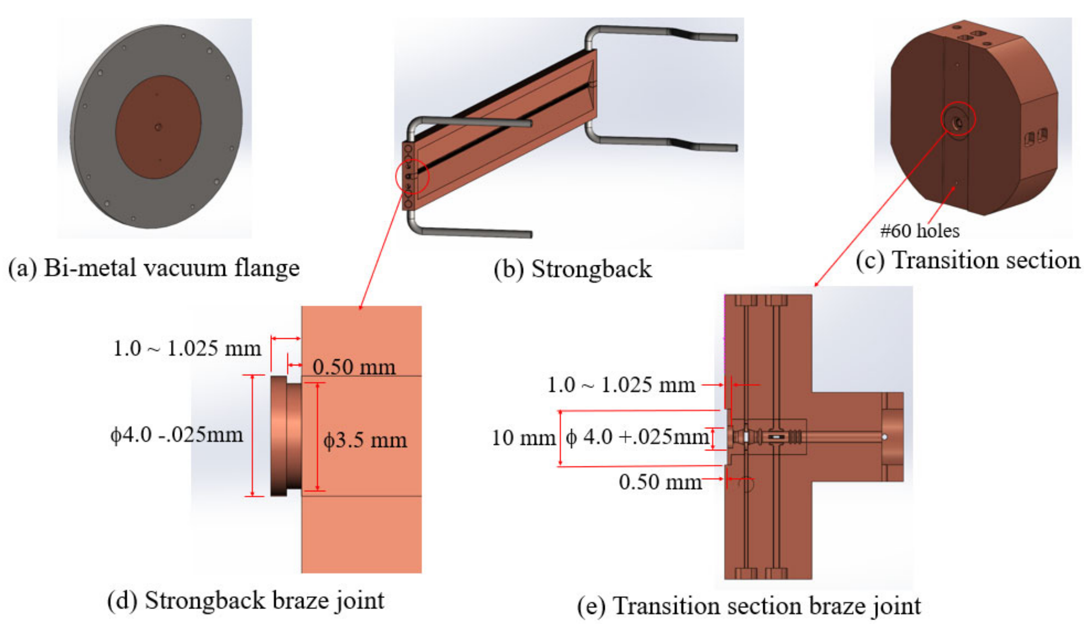

Figure 7: CWA module components and braze joints for strongback and transition section.