DESIGN AND FABRICATION OF 33 GHz HIGH-GRADIENT ACCELERATOR SECTIONS

D. B. Hopkins, and A. M. Sessler
Lawrence Berkeley Laboratory
Berkeley, Ca. 94720

H. A. Johnsen
Sandia National Laboratory
Livermore, Ca. 94550

J. C. Farmer, W. K. Kelley and C. P. Steffani
Lawrence Livermore National Laboratory
Livermore, Ca. 94550

J. Haismon and B. Mecklenburg
Haismon Research Corporation
Palo Alto, Ca. 94303

Abstract

As part of a two-beam accelerator research program, ~33 GHz accelerator sections have been designed and fabricated by both the machined-and-brased technique and the electroforming technique. These procedures are summarized in this paper. Special requirements included a filling time of about 14 ns, ± 1.25 μm dimensional tolerances, input VSWR ≤ 1.10, radial vacuum pumping for each cell, and a capability for a 200-300 MV/m accelerating gradient. A 34-cavity, 2π/3 mode, quasi-constant gradient, v_p = c, disc-loaded traveling wave structure was chosen for the 33 GHz cavities, batch machining with a minimum input/output iris couplers.

Design Considerations

The source of high 33 GHz microwave power available to us for testing structures was the LLNL ELF free-electron laser (FEL) 

Design and Fabrication of 33 GHz High-Gradient Accelerator Sections

A constant gradient design was initially chosen because of its many advantages. However, the adoption of a strictly constant gradient design requires each disc iris aperture and each cavity diameter to be machined with different dimensions. Considering the extremely tight tolerances (±0.6 to 1.3 μm) associated with the critical dimensions of the 33 GHz cavities, batch machining with a minimum number of program changes to the CNC lathe and coordinate measuring inspection equipment was highly desirable to ensure acceptable yields and to minimize costs. Thus, there is a distinct advantage in reducing the number of different cavity dimensions required for a given structure design. Our method for achieving this was to adopt a quasi-constant gradient design. This technique, previously used for a wide variety of medium energy, high peak RF power S-band linacs constructed for synchrotron injectors, pulse stretcher rings and high duty factor research facilities, makes use of a plurality of uniform 2π/3 mode segments of increasing impedance, interconnected by matched transition regions. The uniform segment cavities per segment, are selected to satisfy specific field or high order mode requirements, while the transition regions are arranged to minimize voltage reflections.

An additional concern influenced our choice. A strictly constant gradient design will always result in the maximum surface field occurring at the beginning of the structure because the ratio of this field to the average accelerating field decreases with reduced iris diameter. However, for the 33 GHz tests, it was considered desirable to have the maximum surface field occur approximately half way along the waveguide to increase the probability of demonstrating breakdown thresholds well within the body of the structure, without being limited by input iris coupling sparking. In satisfying the 33 GHz HGA test requirements, the surface and accelerating field gradients were maximized towards the center of the structure by a small impedance adjustment of the uniform segments. The final waveguide assembly comprised four uniform impedance segments having iris diameters of 2.6045, 2.4348, 2.3040 and 2.1692 mm respectively. Figure 1 shows details of the cavity design. Unlike the majority of linac designs the HGA test structure was not influenced by the need to satisfy a given beam-loading specification. Emphasis was placed on demonstrating the desired field gradient profile and filling time, T_p.
when scaling from 2856 MHz. Although diamond polishing procedures were used on the HGA disc apertures (and some disc surfaces), after scanning electron microscope (SEM) surface studies on a variety of cavity samples, the S-band scaled design values for I were arbitrarily increased by an 8% factor.

From the above considerations, it was possible to establish an overall length for the structure and to select a range of group velocities consistent with the desired field gradient profile along the structure which met the filling time design objective of 14 ns. A total of 34 cavities were selected for the final test structure, giving an overall electrical length of 4080 degrees and a distance between input and output coupler midplanes of 99mm (11λ,). For an input RF power of 100 MW, the average accelerating field (and maximum surface field) at Z=0, L/3, 2L/3, and L are designed to be 293.3 (648.1), 307.9 (697.5), 310.1 (663.1) and 302.1 (634.1) MV/m, respectively.

**Machined and Brazed HGA**

In order to demonstrate the best possible performance, emphasis was placed on metallurgical studies of the OFHC copper components, achieving and maintaining a high surface finish on the cavity walls, minimizing contamination—especially due to airborne particles—and on providing a high vacuum in the 10^-8 to 10^-9 Torr range. The latter was achieved by increasing the center line pumping conductance and by arranging for the overall test assembly, including oversized tapered rectangular waveguides and input and output ceramic RF windows, to be high temperature vacuum processed and sealed-off with attached sputter ion appliance pumps. The number of separate cavity components and brazed joints were minimized by machining cup shaped cavities (disc and spacer combined) with interlocking pilots to assist in stacking and accurately positioning the braze alloy. Unlike prior practice, however, the critical cavity dimensions were machined to tolerances of less than ±2.25 µm and with R₃ surface finishes of approximately 0.08 µm. For the final machining operation, a CNC diamond turning lathe, designed for contoured micro-machining, was used with a single crystal natural diamond tool having a point radius of 25.4±2.5 µm. This tool was specially shaped with radial cutting edges, top rake and clearance angle to enable programmed contoured cuts to be made in one continuous movement along the flat surface of the disc and through the contoured small diameter aperture (refer to Figure 1).

For this waveguide, adoption of the quasi-constant gradient design resulted in a substantial reduction (from 34 to 10) of the number of different dimensional settings necessary to fabricate the precision contoured iris apertures required for the overall assembly. The poor properties of Cu, however, led to the substitution of CuAl, brazed to the cavity by cup shaped mandrels. After brazing and machining cup shaped mandrels upon which copper is electrodeposited. The quality of the braze is determined by the surface finish and the quality of the brazed joint. The braze alloy is placed on metallurgical studies of the OFHC copper components, achieving and maintaining a high surface finish on the cavity walls, minimizing contamination—especially due to airborne particles—and on providing a high vacuum in the 10^-8 to 10^-9 Torr range.

**TABLE I. FINAL MICROWAVE PARAMETERS**

<table>
<thead>
<tr>
<th>Cavity</th>
<th>No. of Cavity No.</th>
<th>Total Number of Cavity No.</th>
<th>Resonant Frequency in Air at 23.1°C</th>
<th>Resonant Frequency in Air at 23.1°C</th>
<th>Phase Shift per Cavity</th>
<th>Total Voltage Attenuation (t)</th>
<th>Input Group Velocity</th>
<th>Output Group Velocity</th>
<th>Harmonic Mean Group Velocity</th>
<th>Phase Dispersion</th>
<th>Filling Time</th>
<th>Frequency/Temp Dependence</th>
<th>Total Number of 2/3 mode, vₑ = c</th>
<th>Axial Accelerating Field</th>
<th>Axial Accelerating Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8</td>
<td>2</td>
<td>670.5 mm Hz &amp; 68.7% RH</td>
<td>33.775 GHz</td>
<td>120 deg</td>
<td>0.99 Np</td>
<td>0.0234 c</td>
<td>0.0172 c</td>
<td>0.125 c</td>
<td>5.15 deg/MHz</td>
<td>14.3 ns</td>
<td>-0.56 MHz/°C</td>
<td>34</td>
<td>31.0 µV/mHV/m</td>
<td>6.68 µV/mHV/m</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>21</td>
<td>66.8 µV/mHV/m</td>
<td>33.855 GHz</td>
<td>0.032 c</td>
<td>0.125 c</td>
<td>0.125 c</td>
<td>0.32 c</td>
<td>0.032 c</td>
<td>5.15 deg/MHz</td>
<td>14.3 ns</td>
<td>-0.56 MHz/°C</td>
<td>34</td>
<td>31.0 µV/mHV/m</td>
<td>6.68 µV/mHV/m</td>
</tr>
</tbody>
</table>

Sapphire windows were integrated into the accelerator test assembly to enable viewing (arc detection) along the beam centerline and in the tapered E-bend rectangular waveguide assembly connected to the input coupler. Additionally, a 0.1 mm-thick titanium window was installed at the electron beam output port to facilitate later measurements on accelerated electrons. All of the accelerator subassemblies were hydrogen furnace-brazed at temperatures in the range of 1040 to 860°C.

**Figure 2. Input and Output Coupler Brazed Sub-Assemblies**

After final microwave tuning and matching, the overall assembly was baked out at 250°C, sealed-off, and delivered under vacuum. It is being maintained at a vacuum level in the 10^-7 Torr range while awaiting a high-power microwave source for testing. (The ELF facility was dismantled in March, 1987, to make way for the rebuilding of the ETA induction accelerator.)

**Electroformed HGA**

The electroforming method requires the machining of a disposable mandrel upon which copper is electrodeposited. The mandrel is then chemically etched out. Our goal was to produce an HGA having the same dimensions and mechanical tolerances as were achieved in the brazed unit described above. To ensure that the ELF
tests would be comparing only the two accelerator sections and not just the input/output couplers, the couplers for this HGA were made identical to those of the brazed structure. Moreover, each included five machined cavities in a brazed subassembly. These were to be joined to the HGA later by electroplating. The electroformed section described in this paper therefore has 24 cavities.

The required cylindrical mandrel has 25 slots of width 0.50089 mm, spaced by 2.4991 mm and cut to varying depths of approximately 3 mm. The rounded slot-root was permitted to be fully radiused, to simplify preparation of the cutting tool. Because of the limited usage necessary, a carbide tool was selected. The nose of the tool was precision-ground to a circular radius accurate to ±0.48 μm and with a cutting edge smoothness of < 0.076 μm (Rz). The common 6061-T6 aluminum alloy was used for the mandrels. We intended to microscopically inspect finished units for voids before plating them.

The mandrels were machined at LLNL on a Pneumo precision T-base lathe which had an air-bearing spindle, vibration isolation system, laser feedback, and an Allen-Bradley computerized numerical control system capable of one-microinch resolution. During machining, the mandrel and chuck were bathed in temperature-regulated cutting fluid. The entire room was temperature regulated to < 0.1 °F. Details of the machining operation are given in reference 5. The initial acceptable part yield was poor. As problems were overcome, however, the yield increased to at least two "good" mandrels per day with perhaps one out-of-tolerance mandrel being produced every day or two. Nine good mandrels were finally produced. We anticipated that the numerous possible pitfalls in handling and in subsequent electroforming steps might require several re-starts with new mandrels. The machining computer program was checked by carefully measuring the key diameters and spacings on test mandrels. Subsequent mandrels were first checked on an optical comparator, then precision measured by a granite slab-mounted Laserluc13 capable of one-micronich resolution and two-microinch repeatability. Optical interferometry was employed to confirm the three-microinch surface finish of the curved slot-root, the slot sidewalls, and the outer finished diameters. No final polishing of surfaces was planned since this might leave small, irregular particles embedded in the mandrel. These could, in turn, become embedded in the copper plating and reduce ultimate arcing thresholds. A finished mandrel is shown in Figure 4 along with three lucite masks, discussed below.

A variety of copper-plating studies was conducted5 in a search for the best technique for achieving our requirements for (1) reliable deep-slot plating, (2) low porosity, inclusions and grain size, (3)

![Figure 4 Mandrel and Lucite Masks](image)

precisely replicated mandrel surface, and (4) negligible void formation and outgassing at bakeout temperatures as high as 450°C. We finally chose a cyanide copper bath which consisted of 64 gm/l copper cyanide, 112 gm/l sodium cyanide, and 19 gm/l sodium hydroxide. The organic additives were Allied Kelto Isobrite Nos. 625 and 630 at 3.1 and 0.5 vol. %, respectively. The part was rotated at 10 rpm. At an optimum dc plating current density of 21.5 A/m² a hyperline, velvet grain structure developed which remained fine and randomly oriented even after a 650°C bakeout. Some outgassing studies were performed. Acid-copper electroforms produced significant outgassing of carbonaceous species. The cyanide-copper parts outgassed relatively little by comparison. Further tests are required to quantify these results. To avoid a "seam" at the periphery of each slot and possible trapped fluids, we decided to limit the slot plating thickness to ±0.15 mm. This left a ±0.15 mm circumferential opening at each slot which would permit later cleaning, improving the vacuum environment. If no further plating were done, however, the electroform would be weak and flexible, like a long bellows, after the mandrel was chemically etched out. To provide the necessary strength, we electroformed three longitudinal strengthening ribs onto the plated mandrel. These were equally spaced in azimuth. Figure 5 shows a ribbed HGA, produced to demonstrate feasibility. In the final HGA, however, the rib width and radial thickness were to be larger. Microwave power loss considerations required the radial pumpout holes to be 2.8 mm long copper. Also, deep counterbored holes were required in the ribs to facilitate the microwave tuning of cavities. Thinned cavity wall regions thus produced would be intentionally deformed in the tuning process. The lucite masks shown in Fig. 4 were designed to produce the larger electroformed ribs.

Budget restrictions and the cessation of ELF operations forced the termination of this effort before the final HGA could be electroformed, joined to the input/output couplers, tuned and baked out. We believe that the most difficult, but achievable, remaining tasks were the joining of the electroform to the coupler subassemblies, with adequate dimensional control, and the thorough cleaning of the final assembly. Comparing the two HGA fabrication techniques, it has now been demonstrated that a 33 GHz HGA can be machined, brazed, and tuned in a relatively straightforward manner. Moreover, these have the considerable advantage of using superior copper having low gas content so that they may be baked out at a temperature of 900°C. The resulting cleanliness and purity of critical copper surfaces might be difficult to match in an electroformed HGA and would likely permit higher ultimate gradients.

References