DESIGN AND CONSTRUCTION OF A 33 GHz BRAZED ACCELERATOR WAVEGUIDE FOR HIGH GRADIENT OPERATION

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Abstract

This paper discusses design and construction features of a precision machined and brazed traveling wave structure for use as a high gradient 33.3 GHz electron linear accelerator test section in a Two Beam Accelerator.[1] Design emphasis was directed at meeting an RF filling time requirement of $12<T_F<16$ns, and at fabricating a test structure that would provide guidelines for demonstrating average accelerating fields of approximately 300 MV/m (maximum surface fields of 650 MV/m). Microwave measurement data, obtained during construction, are described and include a phase dispersion simple cold test technique for accurately predicting the structure filling time. A companion paper[2] discusses plans for high power testing of both this brazed structure and a hybrid brazed/electroformed structure, using the Electron Laser Facility[3] ELF at LLNL.

Introduction

To be compatible with the short pulse, high RF power capability at ELF, the operating frequency and filling time of the high gradient accelerator (HGA) test structure, were specified as approximately 33.3 GHz and $12\text{ns}<T_F<16\text{ns}$, respectively, with a design objective input VSWR $\leq$ 1.10.

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 centerline 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 appendage pumps.

A $2\pi/3$ mode, $v_p=c$, disc loaded traveling wave structure was chosen for the HGA because the ratio of maximum surface field to average accelerating field could be maintained at less than 2.2; high gradient breakdown threshold data could be compared directly with previous RF breakdown experiments performed on similar geometry structures at lower frequency;[4] and accurate cavity, disc iris shaping and sidewall iris coupler design information was available from a wide variety of previously constructed research accelerators designed to operate at lower frequencies.

Design Considerations

Before proceeding with a detailed design of the accelerator waveguide, it was necessary 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, and the filling time design objective of 14 ns. A total of 34 ($2\pi/3$ mode $v_p=c$) 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 99 mm ($11\lambda_0$).

In principle, for a given constant gradient waveguide, once the desired values of L, T_F and, hence, the attenuation parameter (τ) have been established, the individual cavity parameters can be specified and the design essentially completed. Other factors, however, sometimes have a strong influence on the final design of an accelerator waveguide, and this was especially the case for this 33.3 GHz test structure.

Field Gradient Profile

For example, 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 HGA 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 coupler sparking. (Sapphire windows have been 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.)

Also, 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 (±25 to 50 microinch) associated with the critical dimensions of the 33 GHz cavities, batch machining with a minimum number of program changes to the CNC diamond turning lathe and coordinate measuring inspection equipment is highly recommended, 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. One means of achieving this reduction, while still maintaining the operational advantages of a constant gradient waveguide, is the adoption of a quasi-constant gradient design. This design technique,[5] 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 $2\pi/3$ mode segments of increasing impedance, interconnected by matched transition regions. The uniform segment cavity dimensions, and the number of cavities per segment, are selected to satisfy specific field or high order mode requirements,[6] while the transition regions are arranged to minimize voltage reflections.

For example, in satisfying the 33 GHz HGA test requirement, 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 0.10254", 0.09586", 0.09071" and 0.08540", respectively; and for a peak 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 (667.5), 310.1 (661.3) and 292.3 (614) MV/m, respectively. 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.

Harmonic Mean Group Velocity $(v_g)_{hm}$

While the field gradient profile is determined by the relative values of the distributed iris diameters, it is the absolute values of these diameters that establish the individual cavity group velocities and, therefore, the overall filling time for a given length structure. Regardless of the impedance distribution, the filling time (T_F) for an n-cavity $2\pi/3$ mode, v_p = c

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waveguide can be defined explicitly by the harmonic mean group velocity $(v_g)_{hm}$ as follows:

$$T_F = L/(v_g)_{hm} \qquad (1)$$

where

$$(v_g)_{hm} = \left[\frac{1}{n}\sum_{i=1}^{n}\left(\frac{1}{v_g}\right)_i\right]^{-1} \qquad (2)$$

For $2\pi/3$ mode waveguides that also contain varying phase velocity cavities having $v_p/c = \beta_w \neq 1$, the filling time can be expressed as:

$$T_F = \sum_{i=1}^{n}\left(\frac{z}{v_g}\right)_i = \frac{1}{3f}\sum_{i=1}^{n}\left(\frac{\beta_w}{v_g/c}\right)_i = \frac{n}{3f}\left[\left(\frac{v_g/c}{\beta_w}\right)_{hm}\right]^{-1} \qquad (3)$$

where

$$\left(\frac{v_g/c}{\beta_w}\right)_{hm} = \left[\frac{1}{n}\sum_{i=1}^{n}\left(\frac{\beta_w}{v_g/c}\right)_i\right]^{-1} \text{ is the harmonic mean } \frac{v_g/c}{\beta_w}$$

for n cavities. Unlike the majority of linac designs, the HGA test structure was not influenced by the need to satisfy a given beam loading specification, and emphasis was placed on demonstrating the desired field gradient profile and filling time. The final set of iris diameters, scaled from previously compiled and empirically confirmed 9.5 GHz design data, was obtained by iterative computations to give a harmonic mean group velocity of 0.0245c (±.001c), i.e., T_F = 14 ns. Although the group velocity was expected to remain constant with accurate geometric scaling, the normal 3/2 frequency scaling law for voltage attenuation (I) was expected to become less valid with decreasing millimetric wavelengths because of the increasing difficulty of maintaining the micro-geometric relationship between the RF skin depth (δ = 13.7 microinches [0.35 µm] at 35 GHz) and the surface texture, including grain boundary surface dislocations. It is interesting to note, for example, that with lathe turned cavity components, the lay direction on all the internal surfaces are at right angles to the TM_{01} mode RF current paths.

Thus, when designing practical millimetric structures, allowance for some additional degradation of Q and r should be made, especially 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. Empirically corrected microwave parameters for the final brazed and tuned HGA structure are tabulated in a concluding section of this paper.

Cavity Geometry and Vacuum Considerations

The poor pumping conductance along the beam centerline, due to the small disc apertures (~2.5 mm) and the side wall iris coupling holes (~2.5 × 2.75 mm), was improved by machining radial pump-out holes[7] through the thick walls of the main body cavities, and encasing the waveguide with a stainless steel vacuum jacket. In addition, pumping manifolds were connected from the vacuum jacket to the input and output beam drift tubes contiguous to the RF coupler blocks. Details of the radial pump-out holes are shown in the Figure 1 cavity diagram, together with the dimensions of the disc separation, thickness and aperture radii.

Fabrication and Microwave Measurements

An initial series of metallographic and SEM surface inspection investigations provided guidance for selection of the OFHC copper and the machining parameters used in fabrication of the cavities. Where applicable, previously developed in-house techniques, used for high power, lower frequency accelerator waveguides, were adapted to the construction of this 33 GHz brazed structure. In particular, the number of separate cavity components and brazed joints were minimized by maintaining our practice of 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 ±50 microinches (±1.25 µm) and with Ra surface finishes of approximately 2 microinches. For the final machining operation, a CNC diamond turning lathe, designed for contoured micromachining, was used with a single crystal natural diamond tool having a point radius of 0.0010 ±.0001". 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 Figure 1).

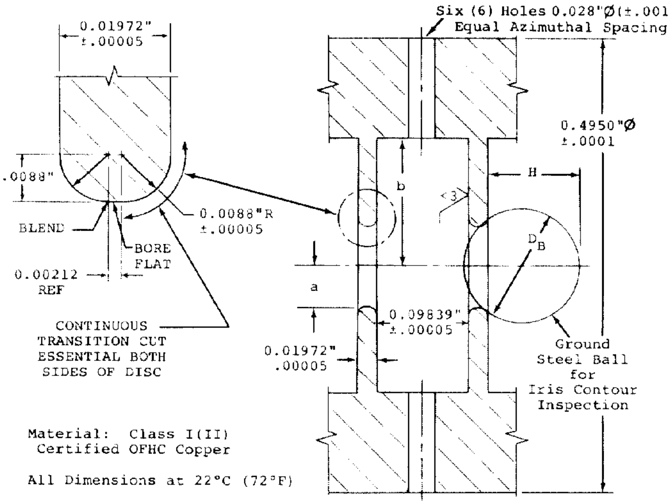


Figure 1. Cavity Details for 33.3 GHz, $2\pi/3$ Mode, v_p = c Waveguide.

Machining dimensions were determined by scaling, as well as by cold stack measurements, with allowance for anticipated brazing changes and the need for a very slight amount of compression tuning. Tuning recesses machined in the thick wall of the cavity were designed to minimize degradation of the internal surface finish. After measurement acceptance and prior to final inspection, the aperture radii were polished to a high surface finish using 6 µm and 3 µm diamond polishing compound and exacting cleaning procedures, based on metallographic surface preparation techniques.

The overall accelerator waveguide comprised three brazed sub-stacks, the main body cavity numbers 8 through 28, and the input and output coupler end assemblies shown in Figure 2. The sub-stacks were brazed with 35Au/65Cu alloy (1030°C) using precision fixtures to maintain cavity concentricity and alignment to ±.0001".

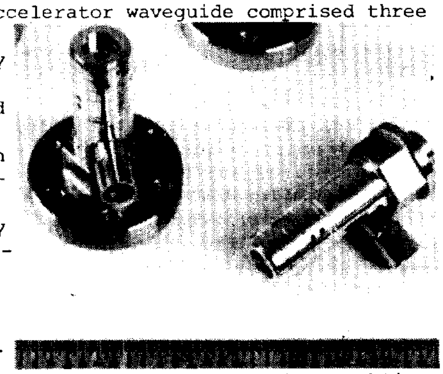
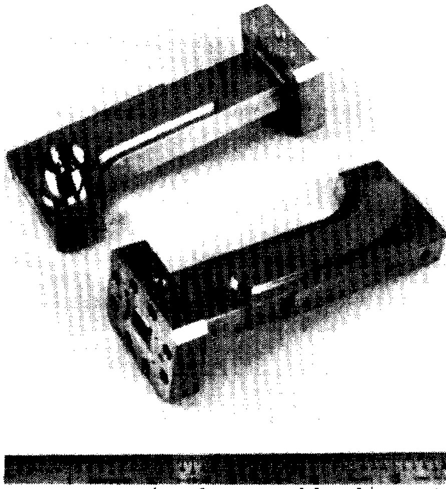


Figure 2. Input & Output RF Coupler Brazed Sub-Assemblies.

The input and output RF feeds were designed to avoid flange connections and discontinuities in the high field region close to the accelerator couplers by combining matched $4\lambda_g$ long 90° E-bend tapered impedance transitions with $7\lambda_g$ long linear taper sections in integrally machined and brazed overall assemblies, as shown in Figure 3. The high peak RF power, oversize WR28 stainless steel RF/vacuum flanges, shown brazed to these assemblies, were designed to accurately align and extrude the internal edges of the metal gasket to form high compression, smooth internal RF joints. (Granular, highly annealed copper gaskets are not recommended for high field gradient joints of this nature.)



The tapered transitions had highly polished internal surfaces; and the cross-section dimensions in the E-field plane (and orthogonal to this plane) varied from .4000" (×.2800") at the oversize WR28 flange, to 0.0984" (×0.2800") at the accelerator coupler interface.

Figure 3.

Tapered 90° E-bend High Power RF Feeds.

Conveniently removable, linear tapered RF feed transitions were used to facilitate step by step matching and inspection of the offset coupler cavity assemblies. Coupler iris final filing and edge polishing required removal of approximately .0016" and repetitive inspection and measurement with a high power toolmaker's microscope — while constantly taking precautions to avoid contamination and damage to the cavity internal surfaces. The Kyle[8] technique was used to match and tune the coupler cavity sub-stacks. After brazing the E-bend transitions (and vacuum jacket end flanges) to the coupler sub-stacks using 50Au/50Cu alloy (990°C), all three sub-stacks were azimuthally and longitudinally aligned and final brazed using a precision jig assembly and Silcoro 60 alloy (865°C).

A programmable RF signal generator and source locking counter provided a highly stable and precisely adjustable RF source for the microwave measurement program. Each cell was nodal tuned to a phase accuracy of ±2° using a cantilevered tuning plunger and a precision fixture that enabled the plunger to be positioned within .001" of the center of each cell without contacting the highly polished disc apertures (the minimum radial clearance at the output end was 0.003"). A view of the accelerator waveguide after tuning and prior to closing the surrounding cylindrical vacuum jacket is shown in Figure 4.

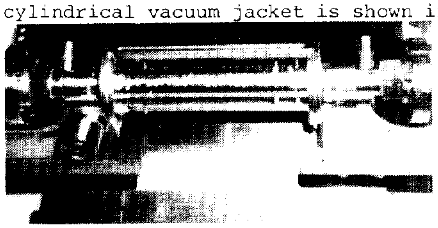


Figure 4.

Final Tuned Accelerator Waveguide and E-bends Prior to Closing the Vacuum Jacket.

Final RF measurement data, including the resonant frequency shift due to evacuation of the accelerator waveguide, are included in the Table I summary of microwave parameters. The VSWR of the tuned structure, including the E-bend transitions and a flat termination, was 1.08 at resonance, <1.20 over a 56 MHz passband, and <1.50 over an 82 MHz passband; and phase dispersion measurements gave $(d\theta/df) = 5.15°/\text{MHz}$ for the centerline cavities.

Relationship of Phase Dispersion and Filling Time

Expressing the total phase length of the accelerator waveguide as $\theta = 2\pi z/\lambda_g$,

$$d\theta/df = 2\pi z \, d(1/\lambda_g)/df = 2\pi z/v_g \quad . \tag{4}$$

Thus, for a non-uniform impedance n-cavity, $2\pi/3$ mode structure,

$$\frac{d\theta}{df} = 2\pi \sum_{i=1}^{n} \left(\frac{\beta_w \lambda_0}{3 v_g}\right)_i \quad ,$$

and for $\beta_w = v_p/c = 1$,
$$\frac{d\theta}{df} = \frac{2\pi n}{3} \lambda_0 \, (1/v_g)_{hm} \tag{5}$$

where $(v_g)_{hm}$, the harmonic mean group velocity, is given by Equation (2). Since $L = n\lambda_0/3$, $d\theta/df = 2\pi L/(v_g)_{hm}$;

and from Equation (1), $\quad T_F = (d\theta/df)/(2\pi) \quad . \qquad (6)$

The waveguide filling time can, therefore, be determined directly from a convenient and simple RF cold test that measures the change in phase of the centerline structure caused by a small change in frequency. Thus, using the measured phase dispersion, the HGA filling time is given as $T_F = 5.15/360 = 0.0143$ µs.

TABLE I. SUMMARY OF FINAL MICROWAVE PARAMETERS

Total Number of $2\pi/3$ Mode, $v_p = c$ Cavities	34
Resonant Frequency in Air at 23.1°C, 29.94"Hg & 68.7% RH.	33.3760 GHz
Resonant Frequency in Vacuo at 23.1°C.	33.3858 GHz
Phase Shift per Cavity	120 deg
Total Voltage Attenuation (τ)	0.395 Np
Input Group Velocity	0.0324c
Output Group Velocity	0.0172c
Harmonic Mean Group Velocity	0.0237c
Phase Dispersion	5.15 deg/MHz
Filling Time	14.3 ns
Frequency/Temperature Dependence	- 0.56 MHz/°C
Shunt Impedance Range.	155 → 168 MΩ/m
Axial Accelerating Field (Maximum in Cavity No. 21)	$31.0\sqrt{P_0\,(\text{MW})}$ MV/m
Maximum Surface Electric Field (Disc No. 11)	$66.8\sqrt{P_0\,(\text{MW})}$ MV/m

A view of the completed HGA assembly, including the U-shaped vacuum transfer manifolds and the main pumping manifold is shown in Figure 5.

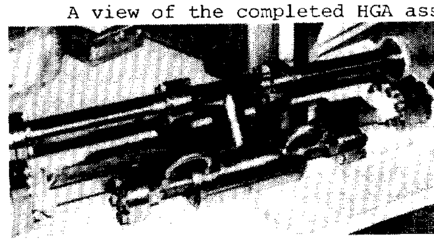


Figure 5. HGA Prior to Vacuum Bakeout.

High power 33.3 GHz ceramic windows, fabricated in oversize WR187 waveguide, and 46 cm long electroformed nonlinear tapers were attached to the HGA input and output E-bend feeds, and the overall assembly, supported by a stainless steel strongback, was high temperature vacuum processed. An initial 420°C bakeout of only the HGA structure was followed by a 250°C bakeout for the overall assembly. The final system was pinched-off and the vacuum maintained in the 10^{-9} Torr range with three 2 ℓ/s sputter ion pumps. A view of the HGA illustrating the 1.5"OD vacuum jacket, the beam output titanium window, and the output RF taper interface flange is shown in the companion[2] paper Figure 2.

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