FIRST OPERATION OF THE HAP/MOPA TRAVELING WAVE STRUCTURE AT BOEING FEL*

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Abstract

The first of six 1.3-GHz, 18-cell, constant impedance, traveling wave linac structures has been placed under RF power and used to accelerate an electron beam. The design of the structures and low power measurements of insertion loss and group delay are described. The observed voltage gain under high power is compared with predictions based on low power measurements and URMEL calculations for the accelerator mode in a single cell.

1 INTRODUCTION

A set of six 1.3-GHz traveling wave linac structures was partially fabricated in the late 1980's for an FEL accelerator project (known as HAP/MOPA) which was terminated before completion. These structures were left in varying stages of completion, only one being fully ready for operation. Under current plans to complete a kilowatt-capable, visible FEL [1] at the Boeing FEL facility in Seattle, fabrication and tuning of these linac structures have been completed, and installation in the beam line is in progress. The sections, of which the first has been operated with electron beam under high RF power, will produce roughly 80% of the energy gain required for FEL operation in the visible spectrum.

2 STRUCTURE DESIGN

The linac structures, shown in Fig. 1, are of the traveling wave type, operating in the $3\pi/4$ mode at a frequency of 1.3 GHz. The design is adapted from an earlier series of traveling wave linac sections built and operated for the Visible Oscillator FEL [2].

2.1 Design objectives

Designed specifically for FEL applications which demand very low beam emittance with high peak current, these sections feature beam apertures which are very large (approximately 5 cm) for a structure operating at this
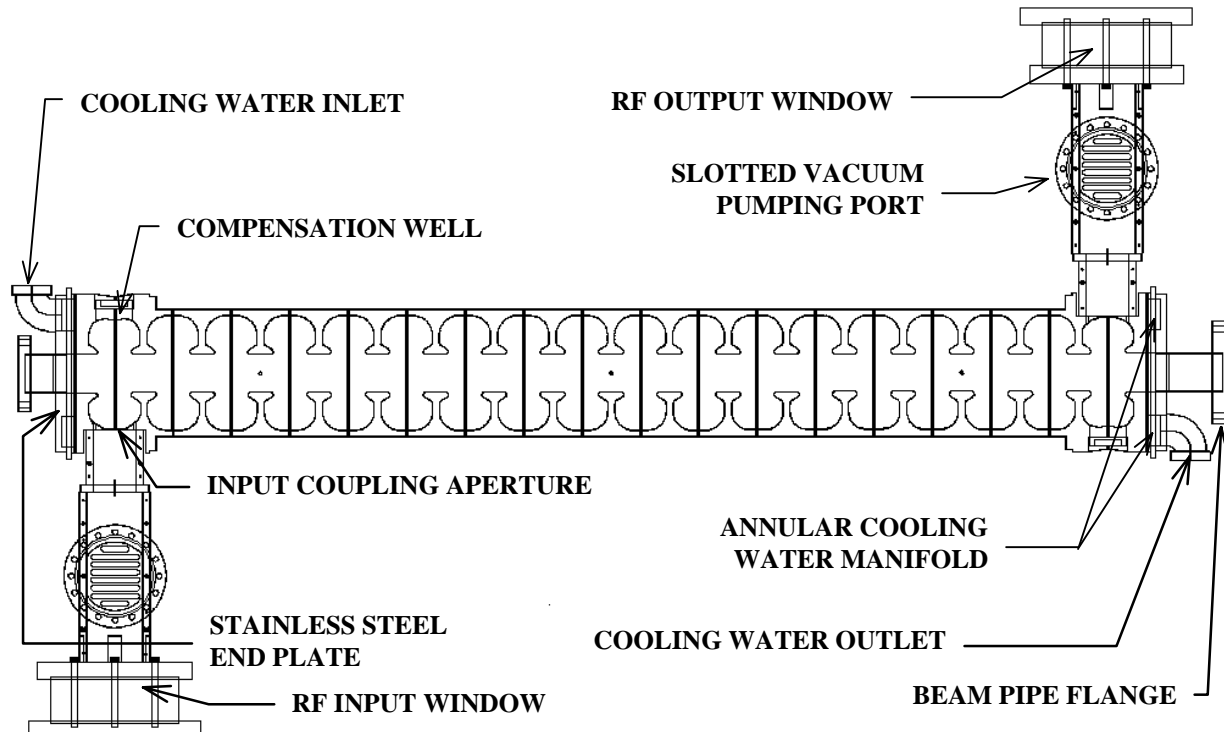

Figure 1. 18-cell constant impedance traveling wave linac section, shown without cooling water jacket.

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frequency in order to minimize emittance growth due to transverse wake fields. If the cells were of the conventional disk loaded geometry, such large apertures would produce excessive cell-to-cell coupling, so that the group velocity would be far too high to achieve reasonable gradients with the 10 MW of RF input power available. By introducing a modest nose cone around the aperture, the intercell coupling is brought down to the desired level while improving the R/Q ratio for the cell. Further improvement in shunt impedance is obtained by rounding the outside contour of the cell. Finally, the shift in operating mode from the typical disk loaded structure phase advance of $2\pi/3$ to $3\pi/4$ provides a little more space into which to fit the noses and allows for a slight reduction in number of irises, which also improves the wake field performance of the section.

The present structures, whose principal parameters appear in Table 1, retain the cell geometry and operating mode of the earlier structures. They differ from the earlier structures in being much shorter (18 cells *vs.* 35) and in being of constant impedance instead of constant gradient. They also feature extended coupler boxes with slotted pumping ports. These changes allowed for substantial reduction in fabrication costs, and are expected to yield improvements in operating vacuum and effort required to condition to high field, and in the sensitivity of the beam energy gained in the structure to fluctuations in cooling water temperature. There will be a slight penalty in the theoretical efficiency of the structure, but this will be offset by improvement in thermal sensitivity.

PARAMETER		VALUE
Operating frequency	f_o	1.3 GHz
Number of cells	N	18
Electrical length	L	1.56 m
Cell-to-cell phase shift		3/4 π
Normalized phase velocity	v_p/c	1.0
Normalized group velocity	v_g/c	.35 %
Fill time	τ	1.5 μs
Field attenuation parameter	α	.192 neper/m
Insertion loss (no beam)		2.6 dB
Shunt impedance/unit length	V_a^2/P_c	33 MΩ/m
Wave impedance	V_a^2/P_i	22.4 MΩ
Beam impedance	$-dV_a/dI_b$	7.2 MΩ
Physical length		1.76 m
Beam aperture (end-to-end)		5.56 cm

Table 1. HAP/MOPA traveling wave linac section parameters.

2.2 Mechanical design

The present structures retain the fabrication approach, cooling and RF coupling concepts, RF window types, and numerous mechanical design features of the earlier structures. The interior cells are formed by brazing together stacks of solid OFHC Cu parts, each of which has the last half of one cell and the first half of the next cut into its top and bottom sides, respectively. All cooling occurs at the cylindrical outer surface of the cells, where de-ionized cooling water flows longitudinally along the structure in the ~ ¼ inch gap between the copper exterior cell surface and the stainless steel water jacket (not shown in Fig. 1) A fiberglass insulating jacket, also not shown in Fig. 1, covers the water jacket, providing thermal isolation between the structure and its cooling system (which is required to maintain the structure at 45 C, even when operating at negligible average power) and the surrounding air.

The outer walls of the end cells are made thick enough (~ 1 inch) to allow for longitudinal holes to carry cooling water from the annular manifold cut into the stainless steel end plate brazed to the end wall, across the end cell, to the end of the water jacket which falls over the iris joining the end cell to its neighbor. Cooling water connections are made to stainless steel elbows welded into holes in the stainless end plates which lead to the annular manifolds cut into the back sides of the end plates.

Conflat end flanges are welded onto stainless steel tubes brazed into the end walls of the structure. Conflat flanges are also brazed over the slotted pumping ports on the input and output coupler waveguide boxes to allow the attachment of cryopumps. Pumping speed through the coupling apertures will be greater than through the beam pipes, and moving the pumps to the couplers reduces congestion around the beam diagnostic boxes which attach to the ends of the linac sections.

3 LOW POWER ELECTRICAL MEASUREMENTS

At the operating frequency, the measured phase length of the 18-cell structure varies with frequency at the rate of $525°$/MHz, implying a normalized group velocity

$$\frac{v_g}{c} = \frac{\phi}{f}\frac{1}{d\phi/df} = .00356 ,$$

where $\phi = 3\pi/4$ is the phase advance per cell at the operating frequency. This is consistent with results of the cavity code URMEL [3], from which a normalized group velocity of .00351 is deduced based on the difference between the TM_{010} mode frequencies for electric and magnetic boundary conditions imposed in the center of the iris between cells (these boundary conditions correspond to the conditions in an infinite structure operating in the "zero" and π modes, respectively).

The structure insertion loss at the operating frequency has been measured at 2.6 dB, or 0.144 dB/cell. This is related to the cell quality factor Q_o through the relation

$$\frac{\Delta P_f}{P_f} = -\frac{\phi}{Q_o\,(v_g/c)} ,$$

where P_f is the RF power flowing through the cell. The corresponding Q_o is 19630, which is also consistent with the URMEL result (19990).

4 PERFORMANCE PREDICTIONS

A simple spread sheet calculation shows that the load line equation for the structure is

$$V_a(I_b) = \sqrt{R_s P_i} - R_b I_b,$$

where R_s = 22.4 MΩ and R_b = 7.2 MΩ (based on URMEL result R/Q = 71.75 Ω for a single cell) and where P_i is the input RF power and I_b is the beam current.

5 HIGH POWER OPERATION

The first of the traveling wave linac sections was installed in the beam line following the 433.3 MHz standing wave structures (Fig. 2). During the first day of operation, the structure was conditioned to accept 4 MW with a 30 μs RF pulse length at a repetition rate of 1 Hz. A few days later, the structure accepted 8 MW for a 100 μs pulse duration, still at 1 Hz prf, with a return loss slightly in excess of 20 dB. This being judged sufficient for the subsequent beam tests, further conditioning to higher power was deferred.

For acceleration tests in early May, 1996, the beam was produced by illuminating a K_2CsSb photocathode situated in the first cell of the 433.3 MHz accelerator with a mode-locked, frequency-doubled Nd:YLF laser running at a frequency of 108.3 MHz, with average beam current on the order of 10 mA. The beam energy at the entrance to the traveling wave linac structure was 20.7 MeV. With an RF input power of 6.3 MW to the traveling wave structure, the beam energy increased to 32.4 MeV, for an accelerating voltage of 11.7 MV in the traveling wave structure. Both the RF power measurement and the energy gain have an estimated experimental error of at least ±5%. For 6.3 MW input power and .01 A beam current, the load line equation above predicts an accelerating voltage of 11.8 MV, well within the experimental error.

6 ACKNOWLEDGMENTS

REFERENCES

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[2] J.L. Adamski, et al., "The Boeing 120 MeV RF Linac for FEL Research," IEEE Trans. Nucl. Sci., **NS-32,** No. 5, Oct., 1995, p. 3397.

[3] T. Weiland, DESY **83**-005, 1983 and DESY M-82-24 (1982) and Nucl. Instr. and Meth., **216** (1983) p. 329.

AXIAL FIELD COIL (TYP)
PHOTOCATHODE VAPOR DEPOSITION SYSTEM
PHOTO-INJECTOR CAVITIES
DRIVE LASER INJECTION PORT
433 MHz 3-CELL ACCELERATOR STRUCTURES
1300 MHz ACCELERATOR STRUCTURE
HIGH POWER BEAM DUMP
CHICANE
LOW ENERGY BEAM DUMP
1300 MHz KLYSTRON
433 MHz 5-CELL ACCELERATOR STRUCTURES
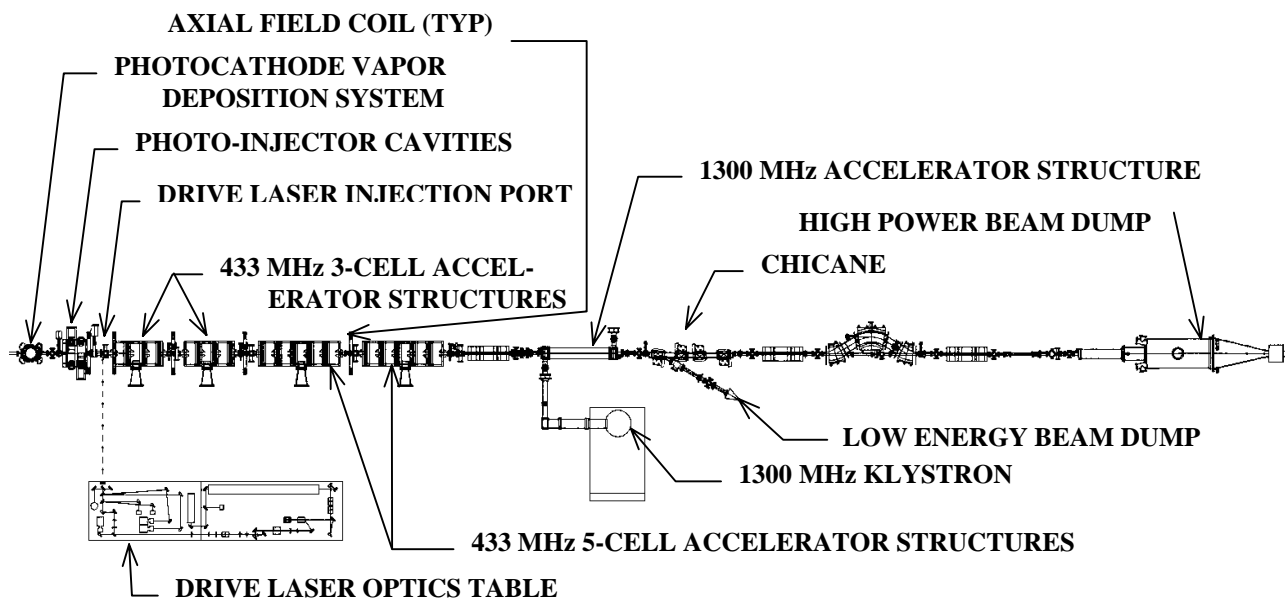DRIVE LASER OPTICS TABLE

Figure 2. Beamline layout for first high power operation of HAP/MOPA linac section.