ANNULAR-BEAM, 17GHz FREE-ELECTRON MASER EXPERIMENT

L. M. Earley, B. E. Carlsten, M. V. Fazio, C. M. Fortgang, P. C. Haddock, W. B. Haynes
Los Alamos National Laboratory, Los Alamos, N.M. 87545

Abstract

Experiments have been conducted on a 15-17 GHz free electron maser (FEM) for producing a 500 MW output pulse with a phase stability appropriate for linear collider applications. The electron beam source is a 1 μs, 800 kV, 5 kA, 6-cm-dia annular electron beam machine called BANSHEE. The beam interactes with the TM_{02} and TM_{03} mode Raman FEM amplifier in a corrugated cylindrical waveguide where the beam runs close to the interaction device walls to reduce the power density in the fields. This greatly reduces the kinetic energy loss caused by the beam potential depression associated with the space charge which is a significant advantage in comparison with conventional solid beam microwave tubes at the same beam current. The experiment operates in a single shot mode with a large number of diagnostics to measure power, frequency and energy.

1 INTRODUCTION

Future linear colliders require microwave power sources in the 10-30 GHz frequency range with output powers of at least several hundred megawatts. The klystron has historically been the source of choice for accelerator applications. For output power levels above several hundred megawatts, new approaches are needed for microwave power generation. One example is a microwave tube based on a large diameter annular electron beam instead of the small diameter solid beam used in a klystron [1]. More power can be transported in an annular beam because the space charge limiting current in an annular beam is higher than in a solid beam of the same voltage and current. Free-electron lasers and FEMs have demonstrated high peak power and extraction efficiencies. An FEL or FEM offers the possibility of a way to avoid this fundamental power density limitation by operating in a higher-order mode in a large microwave structure. In 1992, Conde and Bekefi tested an FEM that produced 61 MW at 33 GHz at 27% efficiency [2]. This tube was driven by a 750 kV, 300 A, 30 ns, solid electron beam. FEM phase stability has been examined in detail by Carlsten [3] for an axial interaction FEM with an annular beam operating in the exponential growth regime. Fazio presented a background description of the development of the Los Alamos FEM [4].

2 EXPERIMENTAL SETUP

The FEM experimental configuration is shown in Fig. 1. The FEM is run on the BANSHEE pulsed power electron beam machine which produces the 500-800 kV annular electron beam with a stainless steel field-emission cathode. The beam has a nominal 2.8 cm radius with a thickness of 4 mm. The beam drift pipe has a 3.6 cm mean radius. The input microwave pulse to this amplifier is supplied by a surplus military magnetron. The input pulse is adjustable from 0.3 to 3 μs at a peak power of 100 kW. The magnetron frequency can be varied from 15.5 to 17.5 GHz. The magnetron output is coupled from WR-62 rectangular waveguide through a six-way power divider and fed symmetrically into the circular waveguide. This waveguide feed was designed to reduce the number of higher order modes which could couple into the FEM circular waveguide input section. The input section is followed by the rippled wall structure with 15 ripple periods. The ripple wavelength is 3.5 cm with a 7% ripple modulation. After the ripple wall structure is a section of cylindrical waveguide which acts as the beam dump. A pulsed solenoidal magnet operating at 0.5 T is used to confine the beam from the cathode to 10 cm beyond the end of the rippled structure. The electrons spread after the end of the solenoid and are absorbed on the waveguide walls over an area large enough to avoid damage. A permanent magnet dipole is located another 10 cm downstream to prevent any electrons from reaching the diagnostics. Two types of diagnostics are located in the circular waveguide after the beam dump section. The directional couplers are used to measure the pulse shape, power and frequency while a calorimeter acts as a waveguide load and energy measuring device.

3 DIAGNOSTICS DESCRIPTION

Diagnostics were developed for this experiment to operate in circular waveguide with a diameter of 7.2 cm for frequencies between 12 and 18 GHz. The energy of each FEM pulse was measured using a five channel circular waveguide calorimeter. Similar calorimeters have been developed [5,6] for previous intense pulse microwave sources. A cross sectional view of the calorimeter is shown in Fig. 2. A novel multi-layer absorber for the calorimeter was developed using Contex textile sheets from Milliken [7]. An optimized multi-layer absorber has an S_{11} of -20 dB when measured with an HP8510 network analyzer. The Contex sheets are

0-7803-4376-X/98/$10.00 © 1998 IEEE

available in a large range of resitivities from a few Ω/□ to hundreds of kΩ/□.

The multi-layer absorber was an excellent match over a broad frequency range since most of the modes of interest had characteristic impedance greater than 300 Ω which varied slowly with frequency since most modes were far from cutoff. The first several sheets are high resistivity to reduce reflections. The resistivity is then lowered for each sheet. Table 1 shows the resistivities for the sheets in the final design of the calorimeter.

Absorber number	Resistivity
1,2	28 kΩ/□
3,4	16 kΩ/□
5,6	8.5 kΩ/□
7-10	500Ω/□
11,12	70Ω/□

Table 1. Calorimeter load absorbing sheet resistivities in order from the input of the device.

The calorimeter contains a sealed air cell with one Lucite window for the vacuum on the input side and another window seal for the air on the back side. A Setra model 239 pressure gauge measures the rise in cell pressure due to the increase in temperature of the absorbing sheets. The sensitivity of the pressure calorimeter was 70 mV/J for a volume of 200 cm^3.

Most of the energy that is deposited on the absorbing sheets is located near the thermistors for the TM_{02} and TM_{03} modes. More than 50% of the energy is absorbed by the last two sheets. The last sheet is thermally isolated from the rest by a foam insulator. Thermistors are placed on the last sheet only. Four thermistors located every 90^o around the azimuth of the absorbing sheet, measure the temperature rise of the microwave absorber. The final design of the absorbing load used twelve sheets. The thermistors are connected to a bridge circuit which provides an output voltage proportional to the microwave energy of the FEM. The four channel thermistor calorimeter had a sensitivity of 20 mV/J.

The pulse characteristics of the FEM were measured using three circular waveguide loop directional couplers [8]. Each loop directional coupler was optimized for a particular mode either TM_{01}, TM_{02} or TM_{03}. The measured signals from each of the loop couplers were divided into several paths. One path was sent to a crystal detector, another path went through a bandpass filter to a crystal detector and the third path went to a heterodyne frequency measuring circuit. In this way signals from different modes and frequencies could be measured separately.

The beam current was measured at the diode and at three locations along the beam path using Rogowski coils. The magnetron output signal was measured prior to the six way divider input section. Three B-dots measure microwave signals in the circular waveguide before and after the rippled wall section.

All circular waveguide diagnostics were tested and calibrated using a gated 100 W traveling wave tube (TWT). A circular waveguide test bed was constructed for these calibrations. Various modes could be launched in the test bed to measure the diagnostics response. All modes were verified using the liquid crystal sheets. Power coupled from the TWT into the circular waveguide was monitored with conventional microwave directional couplers.

4 EXPERIMENTAL RESULTS

The FEM experiment has been operated in the beam OFF condition to determine a baseline for the diagnostics. Both the calorimeter and loop coupler measure the coupled power from the magnetron into the circular waveguide. The coupled power varies with frequency and mode. The six way coupler can excite both TM_{02} and TM_{03} modes from 15.5 to 17.5 GHz. Power coupled into the FEM structure varied with frequency from 2 to 25 kW. The drive mode was measured by removing the calorimeter and allowing energy to radiate out the open waveguide. Liquid crystal sheets with thick film carbon absorbers attached, monitor the radiated mode pattern in the waveguide. In this way we were able to photograph the mode pattern at a given frequency and measure the signal from the loop coupler to determine power. The mode pattern on the liquid crystal sheet displayed the J_1 Bessel function for a given TM mode. The response of the carbon absorber on the liquid crystal sheet was power density, which corresponds to E^2. Then, by installing the calorimeter we could measure the pulse energy of the magnetron for approximately 100 pulses and determine the peak power. Thus, we were very confident of our mode and power level of the drive signal to the FEM.

Initial results from this FEM experiment indicate that the amplified signal is concealed by oscillations

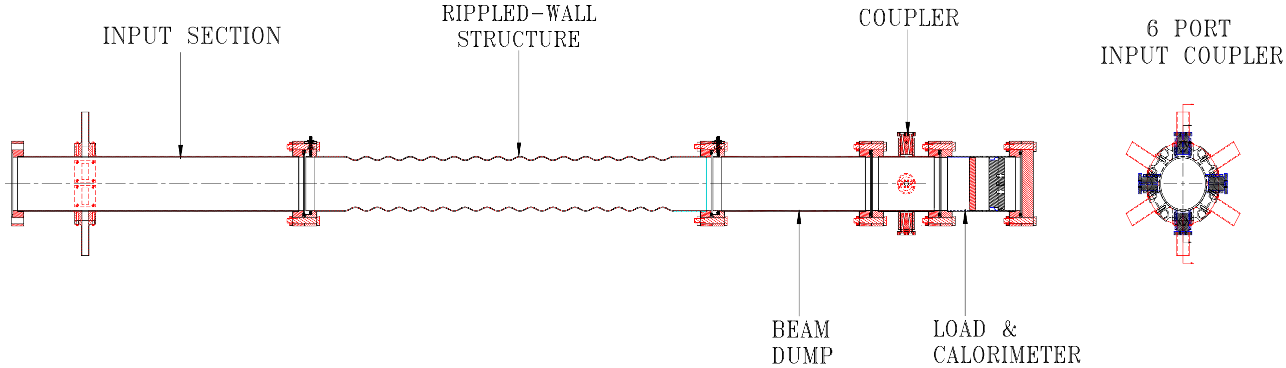

Figure 1. Cross sectional view of the FEM experimental configuration.

with a larger generated power. Measurements show oscillations at 11.2 and 16.4 GHz at power level of a few megawatts. Our amplifier would need a minimum of 20 dB of gain for the output signal to equal the oscillator peak power. We are currently working to increase the coupled power from our magnetron which would increase the amplifier drive.

The signals from the calorimeter five channels agree within 20%. The measured pulse energies were less than 1 J and the resolution for the calorimeter was approximately 50 mJ.

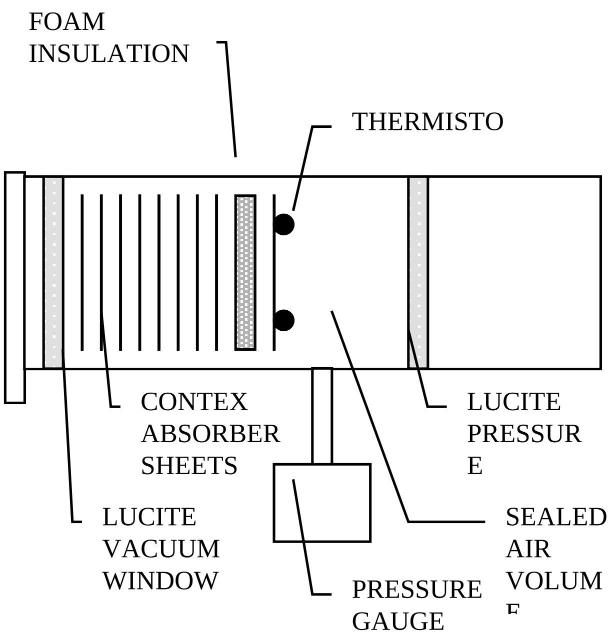

Figure 2. Cross sectional view of circular waveguide calorimeter.

5 CONCLUSION

The initial FEM experiments have been completed. The measurements from the diagnostics are excellent. We have not been able to measure the amplification process due to unwanted oscillations.

Our plans include reducing the beam current below 1 kA and increasing our coupled drive power to 40 kW. The unwanted oscillations should be reduced to the point that amplification can be measured. In addition we will explore both TM_{02} and TM_{03} modes to determine mode growth rates. Once we clearly measure amplification in the desired mode, we will explore parameters to optimize the FEM interaction.

REFERENCES

[1] P. Wilson, "RF Sources for 5-15 TeV Linear Colliders," presented at 3rd ICFA Workshop on Pulsed RF Sources for Linear Colliders (RF96), April 8-12, 1996, Hyama, Japan.

[2] M. E. Conde and G. Bekefi, "Amplification and superradiant emission from a 33.3 Ghz free electron laser with a reversed guide magnetic field," *IEEE Trans. Plasma Sci*., **20**, 240 (1992).

[3] B. E. Carlsten, "Enhanced phase stability for a raman free electron laser amplifier in the exponential growth regime," *Physics of Plasmas*, **2**, 10, p.3880 (Oct. 95).

[4] M. V. Fazio et. al., "The Development of an Annular-Beam High power Free-Electron Maser for Future Linear Colliders," Proc. XVIII International Linear Accelerator Conference, pp. 228-230, August 1996.

[5] L. M. Earley et. al., "Comprehensive approach for diagnosing intense single-pulse microwave sources," Rev. Sci. Instrum. 57 (9), pp. 2283-93, Sept. 1986.

[6] C. B. Wharton, L. M. Earley, and W. P. Ballard, "Calorimetric measurements of single-pulse high-power microwaves in oversized waveguides," Rev. Sci. Instrum. 57 (5), pp. 855-8, May 1986.

[7] H. H. Kuhn, "Characterization and Application of Polypyrrole-Coated Textiles," *Intrinsically Conducting Polymers: An Emerging Technology*, Kluwer Academic Publishers, pp. 25-34, 1993.

[8] L. M. Earley, W. P. Ballard and C. B. Wharton, "New Directional Couplers for Multimode Circular Waveguides Applied to Intense Pulsed Microwave Systems," *IEEE Trans. on Nuclear Science*, Vol. NS-32, No. 5, pp. 2921-3, October 1985.