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High-Power, High-Frequency, Annular-Beam Free-Electron Maser

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Abstract

We have developed a 15-17 GHz free electron maser (FEM) capable of producing high power pulses with a phase stability appropriate for linear collider applications. The electron beam source is a 1 μ s, 800 kV, 5 kA, 6-cm-dia annular electron beam machine called BANSHEE. The beam interacts with the TM_{02} 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. We studied the phase stability by analyzing the dispersion relation for an axial FEL, in which the rf field was transversely wiggled and the electron trajectories were purely longitudinal. Detailed particle-in-cell simulations demonstrated the transverse wiggling of the rf mode and the axial FEL interaction and explicit calculations of the growing root of the dispersion relation are included to verify the phase stability.

Background and Research Objectives

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. A second important issue is that at high power, the rf power density becomes too high for the standing-wave, rf cavities used in high frequency klystrons. 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 the fundamental mode power density limitation by operating in a higher-order mode in a large-diameter microwave structure.

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With the demise of the Superconducting Super Collider, the future of high energy physics depends on whether or not the Next Linear Collider (NLC) is built. This 1 TeV electron-positron collider is now the focus of the advanced development work within the DOE High Energy Physics Office with the hope that within the next 4 to 6 years the groundwork will be done and construction can begin. The cost of microwave energy to power the NLC is the major cost driver. Simple power considerations show that an accelerator's efficiency increases as the frequency is increased and that the rf power requirement increases as the gradient is increased. This scaling leads one to a combination of higher frequencies and powers. An operating rf frequency of 20 GHz is considered by the international advanced accelerator community to be a good compromise for the operating frequency of advanced high-energy accelerators such as the NLC. Currently, there is no viable rf source for NLC-type accelerators. Several terawatts of microwave power is needed at 20 GHz to drive the NLC. Current achievable power levels in experimental, not commercial, tubes at 10 GHz and above are limited to about 50 MW. At SLAC, X-band (11 GHz) klystrons have reached 60 MW after 5 years of intensive effort. They hope to eventually reach 100 MW, but even SLAC admits there is little promise that they will ever exceed 150 MW, and this is at 11 GHz, not 20 GHz which is the more desirable frequency. At 100 MW per source the NLC will require roughly 20,000 microwave power systems. At \$1M per system the capital cost is staggering. The cost of operation and maintenance of 20,000 systems over a 20 year life-cycle is even more staggering. There are yearly international workshops devoted to exploring the options of developing rf sources to meet these NLC accelerator requirements. There are simply no sources available now which can be scaled to produce the gigawatt power levels per unit needed above 10 GHz. A tube with 1 GW of output power would reduce the microwave system requirements by an order of magnitude in just the capital cost alone.

The output power from klystrons does not scale favorably as one goes to higher power and higher frequency, simply because klystrons operate in the fundamental mode and the power density becomes extremely high since their size scales inversely with frequency. A way to avoid this fundamental limitation is to use a microwave device which extracts power in a higher-order mode in a larger microwave structure.

In 1992, Conde and Bekefi demonstrated high efficiency at high frequency by testing an FEM that produced 61 MW at 33 GHz at 27% efficiency, although with poor phase stability [2]. This tube was driven by a 750 kV, 300 A, 30 ns, solid electron beam. We believe that we can extend this work at 17 GHz to high power (0.5 GW), and with good phase stability, by using an annular electron beam. FEM phase stability has been examined in detail by Carlsten [Publication 1] 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 [Publication 2].

Our research objectives were:

- (1) Demonstrate the axial FEM mechanism.
- (2) Measure the phase of a low gain and low power FEM to verify phase stability.
- (3) Build and test a high-power FEM.
- (4) Understand the theoretical aspects of the FEM interaction.
- (5) Model the FEM interaction of our experiment.

Importance to LANL's Science and Technology Base and National R&D Needs

The device we are proposing here will enable the next generation of linear accelerators to be built. This device will have impact in these areas:

(1) High energy physics. Next Linear Collider type machines will not be built unless there is a breakthrough of this type in rf sources. (2) Rf weapons and countermeasures. Many electronic systems are vulnerable to 10 GHz and higher frequency radiation. At this time, there is no high-power rf source available in this band. Because of the small size and simplicity of this device, one can envision applications as a weapon or jammer. We can make contributions to the state-of-the-art in microwave generation in two areas: (1) phase stability and (2) high-power generation/extraction.

Scientific Approach and Accomplishments

Our nominal design for a phase-stable axial FEM, coupled with our 600 keV electron beam, is defined by these design parameters: Wiggle period = 3.5 cm, Beam pipe radius = 3.37 cm, Beam annulus radius = 2.92 cm, Ripple amplitude = 7%. This design nominally has a gain of 3 dB per period, or 45 dB of gain in 15 periods (52.5 cm total length). We planned to operate the high-power experiment in two modes. First, we operate the FEM in the low current mode (approximately 800A beam current). This will be done because the dominant jumps in the output phase occur in the relatively long exponential growth part of the FEM and by keeping the gain low we will more easily suppress unwanted oscillations. Second, we increased the beam current to 5kA to generate as high an output power as possible. The major issues associated with the high power operation are mode hopping and eliminating oscillations. 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 μ s 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 rippled 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 electron beam expands beyond the end of the solenoid and is 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.

Description of Phase Stability Problem

In a klystron, the phase of a cavity is completely determined by the absolute phase of the harmonic current at that location. If the beam energy is shifted slightly by $\delta\gamma$, we can expect that the output phase will shift by $\delta\Phi = -(\beta_e L / \gamma(\gamma+1))(\delta\gamma / (\gamma-1))$ where L is the total device length, the electron propagation number is $\beta_e = \omega / \beta c$, and where ω is the frequency of operation and β is the beam axial velocity normalized to the speed of light. This phase shift can be quite large - tens of degrees per cent change in the beam voltage, for operation near 17 GHz.

The phase shift in an FEM due to the transit time effect is the same as for a klystron. However, the effect of the space-charge wave and the transit time of the electron beam are not separable in a FEM as they are in a klystron. This will introduce new physical effects, including the possibility of using fluctuations in the space-charge wave to counter fluctuations in the beam's transit time through the device.

Phase Stability Scheme

The phase stability scheme is based on setting up a correlation between the beam voltage and the space-charge wave. The output phase can be made stable if the phase

change from the space-charge wave cancels the phase change from the change in the transit time. If we assume that the growing rf mode components have an $e^{j\omega t - \Gamma z}$ exponential behavior, this dispersion relation can be derived for the FEM:

$$(\beta_e + j\Gamma)^2 - ((j\Gamma)^2 - k^2) \hat{\beta}_q^2 (\Gamma - k_w) + \beta_1^2 = 2C^3 \beta_1^4$$

where the cold (no beam) rf mode propagation constant $\beta_1 = \omega / v_{phase}$, the gain parameter C is proportional to the beam current divided by $\gamma\beta^3$, all to the 1/3 power, and the normalized space-charge wavenumber $\hat{\beta}_q^2 = 4\chi \frac{I}{I_A} \ln \frac{r_w}{r_b}$, where now r_w is the wall radius, r_b is the beam annulus radius, I is the beam current, I_A is about 17 kA, and χ_o about 0.6. By manipulation of the space-charge wavenumber by controlling the beam-wall spacing, the growing mode solution of the dispersion relation can be made first-order phase stable.

High-power space-charge considerations

In order to achieve high power at modest modulator voltages (750 keV or less), an intense electron beam (current at least a few kA) must be used. As the electron beam is transported in a beam pipe, there are electric and magnetic fields existing between the beam and the pipe wall, with an associated energy density. The total beam energy (the sum of the beam's kinetic and the potential energy in these fields) is conserved. As a result, as the beam current is increased, less and less of the initial, injected beam energy stays kinetic and more becomes potential energy. The minimum total energy (kinetic plus potential) required to transport a beam down a pipe can be expressed by:

$$\gamma_{\min}^{\frac{2}{3}} = \left(\frac{PE + KE}{m_o c^2} + 1 \right)^{\frac{2}{3}} = \left(\frac{I_{\text{peak}}}{8.5 \text{ kA}} \log \frac{a}{r_b} \right)^{\frac{2}{3}} + 1$$

Note that the minimum beam energy can be decreased by reducing the beam-to-wall spacing. For the case we are considering (the beam radius $r_b = 2.92$ cm and the pipe radius $a = 3.37$), γ_{\min} is about 1.137 and we can in principle extract up to 88% of the initial beam kinetic energy of 600 keV before the beam stops and forms a virtual cathode. The beam after a modest 20% extraction (500 MW of rf) will not be close to the space-charge limit. This level of extraction would not be possible with either a solid electron beam driven FEM

or klystron because the beam current would exceed the space-charge limiting current and beam propagation would be disrupted.

Experimental Progress

Our experimental efforts have concentrated on developing various components for the high-power experiment. Many of these components are unique to the FEM experiment. The FEM experiment uses highly overmoded waveguide (approximately 25 modes can propagate) and therefore components such as an input coupler, directional couplers, and a high-power waveguide load are non-standard.

We designed and fabricated a high-power slow-wave structure (SWS). The electron beam-rf wave interaction takes place in a 21" long SWS which consists of a piece of circular waveguide whose outer diameter has a 7% undulation. After examining several possibilities for fabricating this structure (taking into account both cost and schedule) we decided to hydroform the piece. We also designed and prototyped a 6-way input coupler. This device couples the power from the 100 kW magnetron to the FEM. The coupler has 6-fold symmetry and is oriented so that it couples to an azimuthally symmetric TM mode. Various types of waveguide loads have been developed. We require a load that exhibits high-attenuation and low reflectivity in order to eliminate spurious device oscillations. After some design and measurement, we have utilized several layers of different kinds of space cloth to produce a load that has the desired properties. Our present load has a reflectivity of 17 dB and attenuates the rf 22 dB, which was adequate for our initial low gain experiments.

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 [3,4] for previous intense pulse microwave sources. A novel multi-layer absorber for the calorimeter was developed using Contex textile sheets from Milliken [5]. We have prototyped directional couplers that exhibit the desired coupling and directivity for various TM modes. These couplers will be used to make power measurements and also provide a sample of the output to be used in phase measurements. The pulse characteristics of the FEM were measured using three circular waveguide loop directional couplers [6]. Each loop directional coupler was optimized for a particular mode either TM_{01} , TM_{02} or TM_{03} . Second, we have demonstrated and calibrated a technique that uses a pressure gauge as an energy diagnostic. By placing the high-power load between two vacuum windows we have experimentally demonstrated that there is enough convection heating of the air to record a measurable pressure rise. We have done these

measurements at energy levels comparable to those we expect in the high-power experiment. The calorimeter contains a sealed air cell with one window for the vacuum on the input side and another window seal for the air on the back side. A pressure gauge measures the rise in cell pressure due to the increase in temperature of the absorbing sheets. The final design of the absorbing load used twelve sheets.

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.

All circular waveguide diagnostics were tested and calibrated in a circular waveguide test bed. Various modes could be launched in the test bed to measure the diagnostics response. All modes were verified using the liquid crystal sheets.

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. 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 the square of the electric field.

Results from the high current (3000 A) FEM experiment indicate that the amplified signal is concealed by oscillations occurring with a larger power level. Measurements show oscillations at 11.2 and 16.4 GHz at a power level of a few megawatts. Our amplifier would need a minimum of 20 dB of gain for the output signal to equal the oscillation peak power.

Results for the low current (800 A) FEM experiment indicate phase stable gain of 6dB at 15.5 GHz. The rf input for this case was 25kW. The pulse length for the phase stable gain was 300 ns. Interaction occurred in the beam voltage range from 450 to 600kV.

The following is a list of major accomplishments for this LDRD:

- (1) Invention of stable, annular beam lowbitron (patent application initiated).
- (2) Invention of axial free-electron maser (patent granted). [Publication 4]
- (3) Invention of inverse axial free-electron laser accelerator (patent application initiated). [Publication 5]
- (4) Invention of the rippled-beam free-electron laser (patent application initiated). [Publication 8]
- (5) Detailed theoretical analysis of phase-stability in the small-signal regime.
- (6) Design of axial FEM using phase-stability condition.
- (7) Design and fabrication of 6-way input waveguide coupler.
- (8) Design and fabrication of high-power circular waveguide load.
- (9) Design and fabrication of high-power FEM slow-wave structure.
- (10) Design and fabrication of circular waveguide multimode directional coupler.
- (11) Design and fabrication of high-power circular waveguide calorimeter. [Publication 7]
- (12) Experimental demonstration of axial FEM interaction.
- (13) Experimental demonstration of phase-stability scheme in the small-signal regime.
- (14) Enabling technology that allows the economical construction of advanced accelerators (including the NLC) requiring high-frequency, very high power sources.
- (15) Enable the construction of 10-30 GHz high-power microwave weapons.

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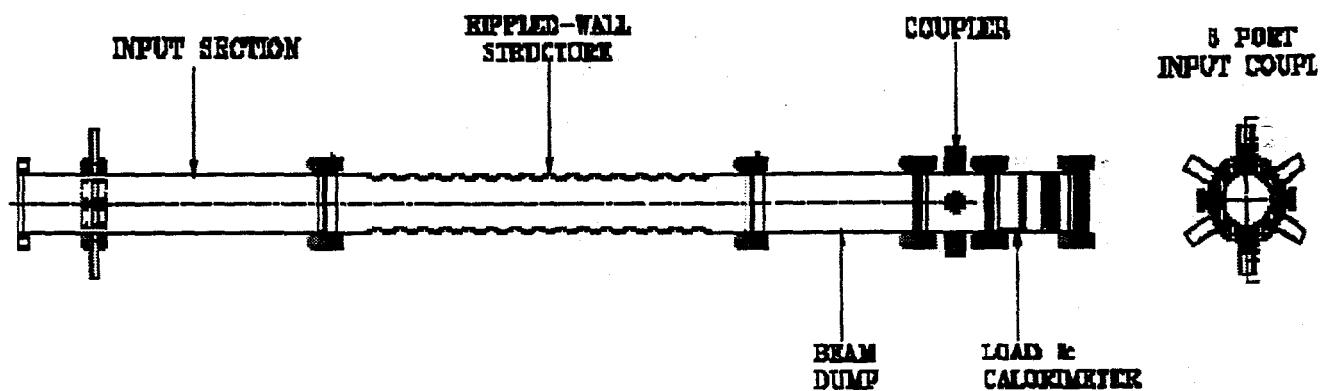


Figure 1: Cross sectional view of the FEM experiment.