High-Gain 35-GHz Free-Electron Laser-Amplifier Experiment

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A new intense-beam free-electron laser experiment, operating as a short-pulse amplifier at 35 GHz, has demonstrated linear growth rates of 1.2 dB/cm, total gain of 50 dB, and coherent emission of 17 MW, corresponding to an experimental efficiency of greater than 3%.

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The collective-interaction free-electron laser (FEL), using an intense relativistic electron beam of moderate voltage (~ 1 MeV) and low axial velocity spread ($\Delta\beta_{\parallel}/\beta_{\parallel} \lesssim 0.2\%$), offers the potential of devices capable of producing extremely high power density, continuously tunable millimeter-wave emission.[1] Such devices may have important applications both as oscillators for plasma heating[2] and as amplifiers for millimeter-wave communications and for improved high-gradient particle accelerators.[3] For this reason, there has been substantial interest in demonstrating the feasibility of practical FEL devices.

Recently, collective FEL experiments have reported very-high-power superradiant millimeter-wave emission (75 MW near 75 GHz), with broad tunability (25 to 100 GHz) and good saturated efficiencies ($\sim 6\%$).[4-6] However, superradiant FEL experiments have several important drawbacks, including broad emission linewidths ($\gtrsim 5\%$), since broadband spontaneous emission is amplified by an interaction with a broad growth bandwidth, and difficulty of theoretical modeling. In addition, since initial conditions, radiation growth, and saturation are linked by the choice of experimental parameters, they are difficult to characterize separately and optimize.

We report here on a new FEL experiment in which a narrow-band 35-GHz signal is coherently amplified to extremely high power. This experiment is free from the previous drawbacks, and additionally has the advantage of extrapolating more naturally to practical FEL devices. While intense-beam amplifier experiments based on the cyclotron maser instability have been reported,[7] this is the first reported high-gain FEL amplifier using an intense relativistic electron beam. At substantially lower currents and voltages, millimeter-wave ubitron amplifiers based on similar physical principles were first reported by Phillips.[8] In addition, several recent 10-μm FEL amplifier experiments have been reported.[9] These devices operate in the Compton regime at very high voltages and low currents, and are characterized by extremely low single-pass gains ($\sim 1\%$).

The purpose of this experiment is to test the prediction that high-gain, high-efficiency operation is possible in a collective FEL amplifier. The specific goal is to optimize gain and saturated efficiency, in order to produce a powerful short-pulse source of coherent 35-GHz radiation. The experimental setup is illustrated in Fig. 1. A high-power magnetron

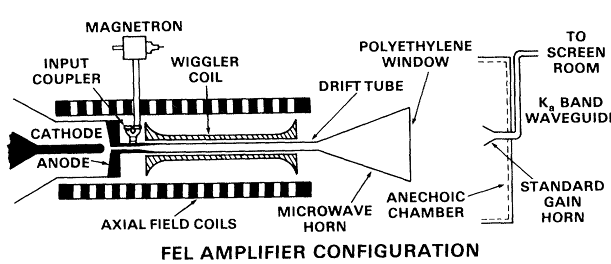

FIG. 1. Free-electron laser-amplifier experimental configuration.

($\lesssim$20 kW, ~500-nsec pulse) operating at 35.02 GHz is used as the signal source. Either the signal is sent directly through a standard K_a-band waveguide to the FEL input coupler, or it first transits a high-power attenuator to allow controlled variation of the amplitude of the injected signal. The signal is injected into the FEL interaction tube in a vertically polarized TE_{11} mode by a directional sidewall coupler (directivity ~20 dB). The coupler is constructed of two resonant slots separated by $\frac{3}{4}$ wavelength and fed by a short-slot hybrid coupler. The microwave signal is launched codirectionally in a 10.8-mm drift tube with a 6-mm-diam intense relativistic electron beam (~900 keV, 600 A, 60 nsec full width at half maximum) of very low parallel velocity spread ($\Delta\beta_{\parallel}/\beta_{\parallel} << 1\%$) produced by the VEBA pulse line accelerator.

The interaction region consists of a helically varying transverse wiggler magnetic field of 3 cm period and 63 cm uniform field length (plus input and output wiggler field tapers of 21 and 15 cm), whose magnitude is adjustable up to 4 kG. In addition, there is an applied axial magnetic field of up to 20 kG that serves both to confine the electron beam and to cause gyroresonant enhancement of the effects of the wiggler magnetic field. This axial field also affects the nature of the FEL instability[10] and can directly enhance its saturated efficiency.[11] It can also be tapered in strength to compensate for the loss of beam-wave synchronism due to kinetic energy extraction from the electron beam and thus to further enhance the amplifier saturated efficiency.[6,12] At the end of the interaction, the electron beam is disposed of to the drift tube wall. The radiation is propagated into the laboratory via a large microwave horn that tapers smoothly up to a 30-cm-i.d. polyethylene window. It is sampled by a standard-gain K_a-band horn located 1 m from the output horn. The signal is conducted through 10 m of standard waveguide into a screen room, where it is attenuated by a 30-dB directional coupler, a calibrated rotary-vane attenuator, and an adjustable bandpass filter centered at 35 GHz. Finally it is detected by a calibrated crystal detector terminated in 50 Ω.

The achievement of accurate power and gain measurements is greatly simplified for an amplifier experiment, compared to measurements of single-pulse superradiant emission. The following procedure was used. Two crystal detectors were absolutely calibrated at 35 GHz against a conventional thermistor power meter. (Two power meters were checked against each other to verify their correct operation.) One was used, via a directional coupler and calibrated attenuators, as a monitor of the output of the driver magnetron. The propagation losses to the input coupler (0.7 dB), through the input coupler (0.9 dB), and to the end of the interaction region (1.5 dB) were determined by substitution measurements against a calibrated attenuator. Thus a particular signal on the first detector corresponded to a known injected signal level. This signal was then detected in the screen room on the second crystal detector after transiting the experiment, output horn, pickup horn, waveguide, attenuator, and filter. At this point, the system was absolutely calibrated, and experimental measurement of the vertically polarized output power of the FEL could be performed at an approximately constant signal level by changing only the setting on the calibrated microwave attenuator in series with the second detector. The horizontally polarized emission was sampled by rotating the pickup horn via a waveguide twist. This was important because the circularly polarized wiggler field is expected to amplify only one circularly polarized component of the injected linearly polarized mode, which should cause equal output signals in each linear polarization. The last experimental requirement was to differentiate between the amplified signal at 35 GHz and the much-broader-band superradiant output that has been seen at very high power levels in earlier experiments under somewhat different conditions. For this purpose, a step-twist filter[13] was constructed and used to select a 3-dB bandwidth of 500 MHz centered at 35 GHz. This filter also ensured the accuracy of the total power determination, since crystal detectors are typically somewhat frequency sensitive.

The experimental strategy was to choose a beam voltage (~800 kV) that would permit approximate "grazing-incidence" operation at 35 GHz at a value of transverse velocity ($\beta_{\perp}$) that had proved optimal in earlier superradiant experiments. Grazing incidence corresponds to the tangent intersection of the curves $\omega^2 = \omega_{co}^2 + k^2c^2$ and $\omega = (k + k_w)v_{\parallel}$, where (ω, k) are the angular frequency and wave number of the output radiation, ω_{co} is the cutoff frequency of the mode of interest (TE_{11}) in the drift tube, $k_w = 2\pi/\lambda_w$ with λ_w the wiggler period, and c is the velocity of light. For FEL operation above gyroresonance, the intersection of these curves predicts the approximate resonant frequency of the interaction.[4] Since saturation can depend strongly on axial field, initial values of B_z were chosen to yield $\beta_{\perp} \approx 0.3$ at values of wiggler field (600 G to 1.4 kG) that had proved desirable in the superradiant experiment.

An initial parameter search demonstrated that very-high-power operation was possible, and that, as noted in previous superradiant experiments,[4,6] the introduction of an axial-field end taper near the end of the uniform-wiggler interaction region enhanced this power. In addition, pushing to slightly higher beam voltages improved the performance of the device. In this situation, operating at 900 keV, $B_z = 11.75$ kG, $B_r = 1.15$ kG, a 15-nsec amplified signal was observed at a gain of 30.8 dB, referred to the output of the interaction, over the 7 kW injected signal. This must be corrected upward by 3 dB, since the signal was found to be equal in both linear polarizations. The result is a peak power of 17 MW, corresponding to an experimental efficiency of $\sim 3.25\%$. This output was found to be reproducible within 20% over many experimental discharges.

An important consideration in amplifier operation is that the output power track the injected signal. More fundamentally, one would like to establish a region of stable linear amplification, in which the output power is a linear multiple of the input power. To begin such an investigation, the effect of interaction length on the power gain was investigated by progressively reducing the length of the axial field magnet in 6-cm decrements. The use of this procedure is discussed in detail elsewhere.[6] The results are shown in Fig. 2, which plots vertically polarized output power at two different input power levels as a function of total system length L, which is arbitrarily defined as the distance from the start of the wiggler entrance taper to the half-field point of the axial-field exit taper.

The first data set was taken at an injected signal level of 40 W. These data show a simple exponential growth of power with increasing system length. The best-fit line, $P_{out} = \exp[0.276(L-32 \text{ cm})]P_{in}$, tracks these data well. The expression $L - 32$ cm corrects the effective interaction length for those portions of the total system length that do not contribute to the linear gain, and also for the effect of "launching loss" into the growing mode in the interaction. This growth rate corresponds to 1.2 dB/cm, a value about one-third lower than values inferred at higher currents, voltages, and microwave frequencies from an experiment operating in a superradiant configuration.[6] No sign of saturation appears in these data, and the peak gain at $L = 72$ cm is ~ 50 dB. The true amplifier gain should probably be corrected upwards by 6 dB, since only one circular polarization is expected to grow, while both are injected equally, and since only one linear polarization is detected. Such high gains may exceed the round-trip losses due to even modest reflection coefficients at each end of the system. The fact that these data clearly show no evidence of oscillation or regenerative effects is probably due primarily to temporal isolation, since the distance from the electron diode to the output window is ~ 4 m, so that the round-trip time is ~ 25 nsec, while the usable portion of the accelerator voltage pulse is < 20 nsec.

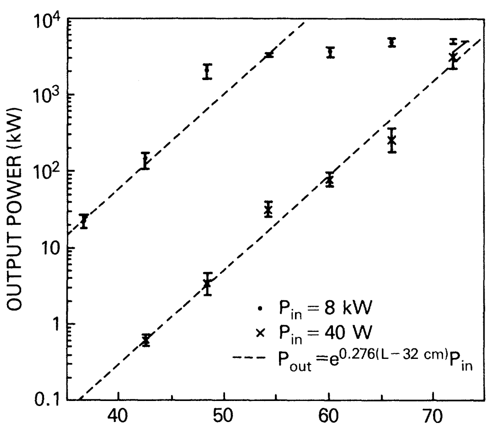

FIG. 2. FEL output power vs system length for input power levels of 40 W and 8 kW.

The second data set was taken at an injected signal level of 8 kW. In this case, clear signs of saturation appear, beginning at $L = 54$ cm. From that point, output power increases by no more than 50% over the next three 6-cm increments in length. With use of the same best-fit formula, a second line is drawn corresponding to $P_{in} = 8$ kW. It fits the unsaturated data well. This result demonstrates that gain is a linear function of interaction length. It also demonstrates that unsaturated output power is a linear function of input power, as expected in a true traveling-wave amplifier, over a factor-of-200 variation in input power.

The functional relationship of unsaturated output power to input power is shown more explicitly in Fig. 3. These data, taken at a fixed system length and at a slightly higher voltage than the previous two data sets, show the input varied by a factor of almost 1000, from 8.5 W to 8 kW. A clear linear relationship between P_{out} and P_{in} exists until saturation effects limit further increases in the output power.

It should be emphasized that these signals are true amplified signals, and not the broadband superradiant emission seen in previous experiments. While the magnetron signal is very narrow band

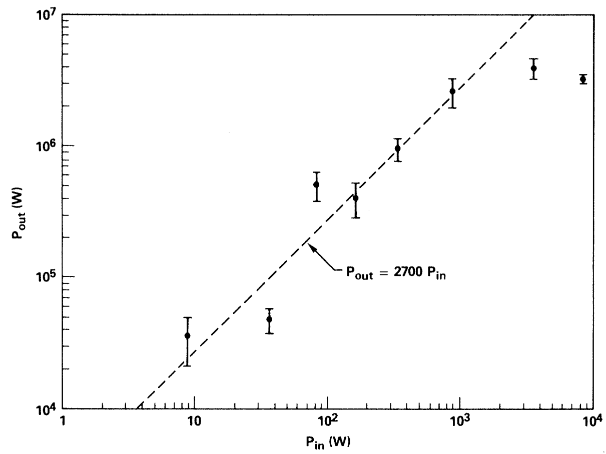

FIG. 3. FEL output power vs input power at $L = 54$ cm.

(< 5 MHz), the short output pulse length implies a minimum emission linewidth of 10 MHz. The amplified linewidth is expected to be of this order, and is found experimentally to pass easily through a 500-MHz bandpass filter. Thus the spectral power density of the peak amplified signal is at least 34 MW/GHz, and may exceed this by an order of magnitude. The superradiant emission can be measured in the absence of an injected signal, and is a function of L. At $L = 72$ cm, the measured superradiant signal through this filter is of order 10 kW, or 20 kW/GHz, more than three orders of magnitude less.

In conclusion, we have demonstrated for the first time an extremely high-power high-gain true FEL amplifier using an intense relativistic electron beam. In operation at 35 GHz, it has demonstrated coherent amplification, with peak powers of ~ 20 MW at $> 3\%$ efficiency, high gain per unit length (~ 1.2 dB/cm), and very high total gain ($\gtrsim 50$ dB). We hope to further characterize and optimize its output in future studies. It is already a unique source of coherent short-pulse microwave radiation, and shows the great potential of FEL's as high-gain amplifiers, and as powerful coherent millimeter-wave sources.

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