# REGENERATIVE AMPLIFIER FEL

D. C. Nguyen, L. M. Earley, N. A. Ebrahim, C. M. Fortgang, J. C. Goldstein, R. F. Harrison, W. A. Reass, J. M. Kinross-Wright, R. L. Sheffield, and S. K. Volz
Los Alamos National Laboratory, Los Alamos, NM87545, USA

*Abstract*

We present experimental results of saturation of the Regenerative Amplifier Free-Electron Laser (RAFEL) at Los Alamos. RAFEL is a multi-pass self-seeded self-amplified spontaneous emission (SASE) FEL that uses a low-Q optical cavity to re-inject a small fraction (less than 10%) of the optical power into a high-gain undulator. The low-Q optical cavity consists of two imaging paraboloids and two annular mirrors that out-couple more than half of the generated radiation. The output radiation achieves saturation within a few passes through the undulator and the saturated optical power exceeds the single-pass SASE power by six orders of magnitude. Under normal operating conditions, the Regenerative Amplifier FEL produces between 1 and 2 J of infrared energy in each macropulse. The maximum output energy is 2.1 J over a 15 μs macropulse containing 1600 micropulses. We deduce each micropulse has an optical energy of 1.3 mJ over a nominal 16 ps pulse length. The optically measured extraction efficiency is 1.8% whereas the electron beam energy deceleration as measured with the electron spectrometer is 3.5%, indicating that only half of the generated optical power is detected. In addition, the optical spectra exhibit spectral spikes characteristic of the high-gain SASE FEL.

## 1 REGENERATIVE AMPLIFIER FEL

The SASE FEL has evolved from a laboratory curiosity to the technology of choice for the fourth generation light source [1]. In a SASE FEL, a high-current electron beam traversing a long undulator first emits radiation and then develops density modulations that grow with distance. The density modulation amplifies the generated radiation exponentially with distance to a very high power level in a single pass through the undulator. Large single-pass gains have been demonstrated in the mm-wave and infrared regions of the spectrum. Recent SASE experiments have produced high gains in the visible and the vacuum ultraviolet. Future plans are to achieve saturation by increasing the undulator length, and to shift the SASE wavelength to the x-ray regions.

An alternative approach to saturation without substantially increasing the undulator length is to use a low-Q optical cavity to re-inject a small fraction of the optical power exiting the undulator to restart the amplification process. Starting the optical amplification from coherent optical power instead of the spontaneous noise allows the FEL to reach saturation in a few passes. Using a low-Q optical cavity with a large out-coupling allows most of the optical power to exit the cavity, thereby reducing the risk of optical damage and increasing the amount of light that exits the cavity as useful power.

In the one-dimensional treatment of high-gain FEL, the optical power as a function of undulator length is given by

$$P(z) = \frac{1}{9} P(0) e^{\frac{z}{L_G}}$$

where *P(0)* is the optical power injected into the undulator, and $L_w$ is the SASE power gain length. With re-injection, the initial power at $z$=0 of the $(n+1)^{th}$ pass can be expressed in term of the feedback fraction and optical power at the undulator exit of the $n^{th}$ pass,

$$P(0)_{n+1} = R_n P(L_w)_n$$

The optical feedback fraction $R_n$ can be variable such that as the FEL approaches saturation, the optical beam becomes more concentrated on-axis, and more optical power is allowed to exit the feedback cavity. This variable out-coupling feature also reduces the optical power density of the feedback mirrors.

One disadvantage of the RAFEL concept with respect to SASE is the need for optical feedback mirrors. However, since the required feedback fraction is only a few percent, the mirrors used in the optical feedback cavity do not need to have very high reflectivity. Also, the mechanical alignment tolerance of the low-Q optical feedback cavity is much less stringent than that of the conventional high-Q optical resonators. In an RF linac FEL, due to the pulse structure of the electron beam, the mirrors must be spaced so that the optical pulse from the previous pass overlaps with the next electron bunch in the undulator. The feedback cavity needs to re-inject the optical pulses in synchronization with the electron bunches to a precision of about one-half the bunch length. With picosecond electron pulses, the RAFEL detuning length is expected to be a few millimetres. In contrast, conventional infrared FEL optical resonators must maintain optical cavity length detuning to less than a few tens of microns.

## 2 EXPERIMENTAL SETUP

### *2.1 Experimental Layout*

The RAFEL concept has been implemented at the Advanced FEL facility at Los Alamos. The key components of the RAFEL experiment include a high-current integrated photoinjector-linac, a high-gain, high-efficiency undulator, and a low-Q optical feedback cavity. Figure 1 schematically depicts the RAFEL experimental layout. A unique feature of this FEL design is a straight beam path from the accelerator to the undulator with only one electron optical element, a solenoid. The solenoid is used to focus the electron beam to the undulator entrance located 0.4 meter downstream of the solenoid. This feature facilitates operating the machine at different beam energies without significantly changing the matching conditions. The undulator and beamline components are mounted on a 6 ft. x 10 ft. vertical optical table. The undulator is designed to provide two-plane sextupole focusing to maintain the same electron beam radius throughout the undulator [2]. The undulator is bracketed with two annular mirrors that form part of the optical feedback cavity. The electron beam converges through the hole in the first annular mirror to a spot 0.2 mm in radius at the undulator entrance. Both the electron and the FEL beams go through the large hole in the downstream annular mirror. The high-power optical beam is allowed to expand before exiting the beamline through a KBr window to the right of Fig. 1. After traversing the second annular mirror, the electron beam enters a spectrometer dipole, turns 120°, and terminates in the beam dump located in the ground.

The optical feedback is provided by a simple ring cavity consisting of two flat annular mirrors, two spherical mirrors, and two cylindrical mirrors. The two sets of spherical and cylindrical mirrors essentially form two 90° paraboloids. The effective focal lengths of the upstream and downstream 90° paraboloids are 0.433 m and 0.730 m, respectively. The upstream annular mirror has a 5-mm-diameter hole, and the downstream one has a 12-mm-diameter hole. Approximately one-third of the optical power exiting the undulator is reflected by the downstream annular mirror and focused to the undulator entrance by the two 90° paraboloids. Thus, two-thirds of the optical power exits the feedback cavity as useful FEL power. Of the one-third of the optical power that is reflected, we estimate only 4% is actually re-injected into the undulator.

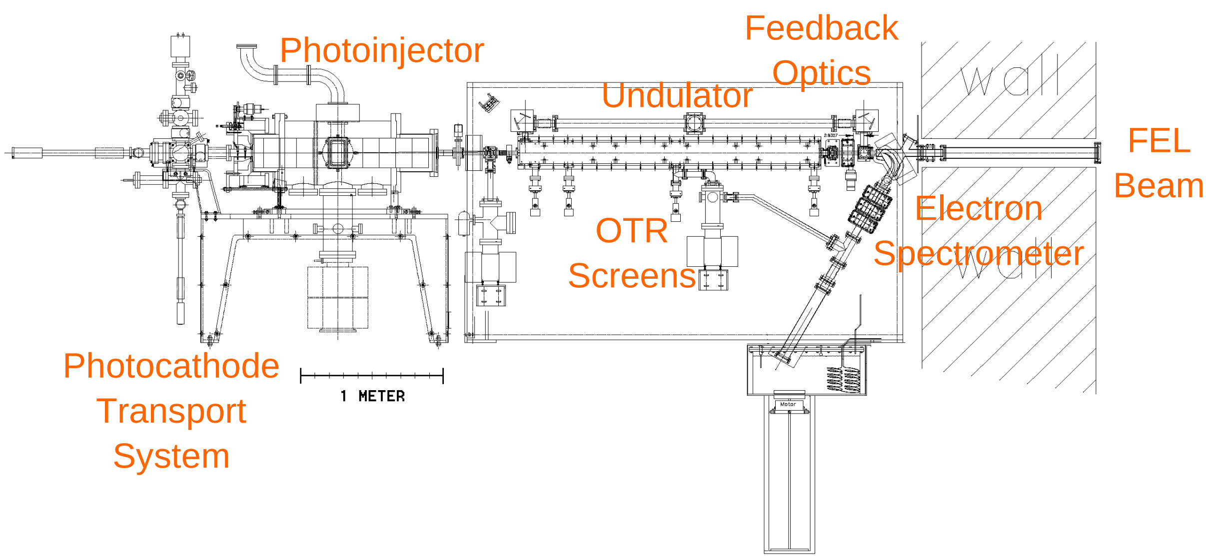


Figure 1. Experimental Layout of the Regenerative Amplifier Free-Electron Laser at Los Alamos.

### *2.2 Experimental Parameters*

The experimental parameters for the high gain SASE experiment at the Advanced FEL facility have been described in details elsewhere [3]. The recent RAFEL results were obtained with a new RF system consisting of a single Thomson-CSF 2104U klystron powered by a compact pulsed power modulator. The new RF station is capable of generating 21 MW of 1300 MHz power to drive the Advanced FEL linac. The linac produces a high-brightness electron beam with up to 20 MeV beam energy and 0.5 A average current over a 20 µs macropulse at a pulse repetition rate of 10 pps. The maximum usable macropulse is about 15 µs due to the accelerator cavity fill time. Table 1 lists the main RAFEL experimental parameters.

*Table 1: RAFEL Experimental Parameters*

| Parameter | Symbol | Value |
|---|---|---|
| Energy | $E_b$ | 16.3 MeV |
| Peak current | $I$ | 260 A |
| Bunch charge | Q | 4.5 nC |
| Bunch length | $\tau$ | 16 ps |
| Emittance* | $\varepsilon_n$ | 7 π-mm-mrad |
| Energy spread | $\sigma_\gamma$ | 0.5% |
| Undulator period | $\lambda_w$ | 2 cm |
| Undulator length | $L_w$ | 2 m (1 m uniform) |
| On-axis field | $B_w$ | 0.7 - 0.5 Tesla |
| Energy taper | $\Delta\gamma/\gamma$ | 12.5% |
| Wavelength | $\lambda$ | 16.5 μm |
| Gain length | $L_G$ | 15 cm |

## 3 EXPERIMENTAL RESULTS

### 3.1 SASE Performance

We determined the SASE single pass gain by adjusting the micropulse charge from 0.01 to 5 nC and measured the average infrared power exiting the undulator with a mercury cadmium telluride (HgCdTe) detector. By adjusting the micropulse charge, we also varied the electron beam peak current. At low current, the optical power varies linearly with *I*. At high current, the observed signal increases exponentially with *I* to the one-third power. The measured HgCdTe signal is plotted versus peak current on a semi-logarithmic scale in Fig. 2.

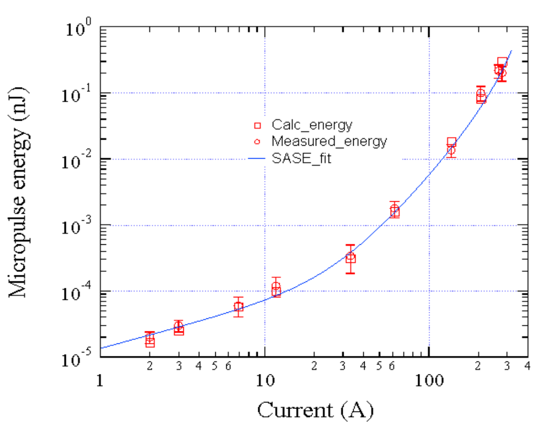


Figure 2: Semi-logarithmic plot of measured SASE micropulse energy versus peak current.

### 3.2 RAFEL Performance

With the low-Q optical feedback cavity, we observed an optical power that exceeded the SASE power by more than six orders of magnitude. The optical power quickly reaches saturation after the linac cavity field and the electron beam current achieve their steady state values (Fig. 3). The measured energy integrated over a 15-μs macropulse (~1600 micropulses) was 2.1 J, yielding a micropulse energy of 1.3 mJ in each 16-ps micropulse. The corresponding average power during the macropulse is 140 kW, and the peak power during a micropulse is estimated at 80 MW. Since these results were obtained with 4.5 nC of charge at 16.3 MeV, corresponding to 74 mJ of energy in each electron micropulse, we deduced 1.8% of the beam power was converted to FEL light exiting the cavity.

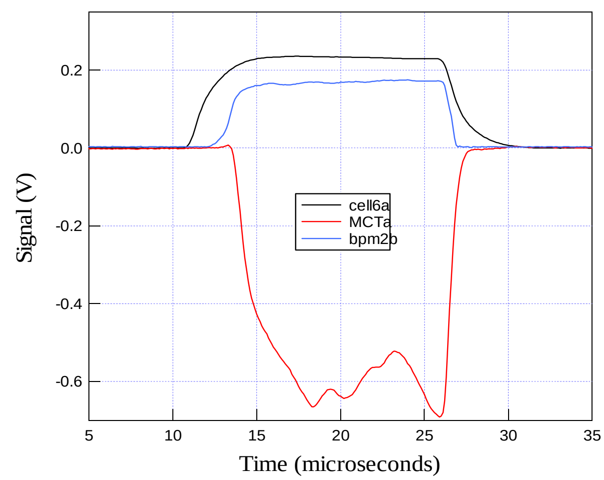


Figure 3: Plots of RF field in the linac (top trace), electron bunch charge (middle trace) and HgCdTe detector signal (bottom trace) as a function of time. The infrared power impinging on the HgCdTe detector has been strongly attenuated.

We can also vary the RAFEL macropulse length by adjusting the RF pulse length, up to the limit set by the klystron modulator (about 20 μs). The observed RAFEL macropulse energy depends linearly with macropulse length (Fig. 4). Based on this data, we believe deleterious thermal effects such as transient mirror heating and optical damage do not play an important role in determining the macropulse energy. This also suggests that one can increase the RAFEL macropulse energy by simply lengthening the electron beam macropulse. Future works will involve modification to the RF modulator to operate at the longer macropulse length.

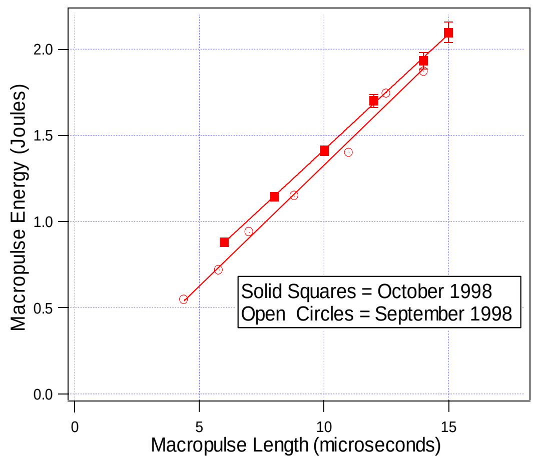


Figure 4: Plots of macropulse energy versus macropulse length. The two different sets of data were collected on different days.

We can also improve the RAFEL performance by increasing the electron bunch charge. FELEX simulations predict that as much as 5 mJ of infrared energy can be attained in each micropulse if the bunch charge is increased to 6 nC (Fig. 5). Presently, the RAFEL micropulse energy is limited to 2 mJ or less because we could only produce up to 4.5 nC per micropulse with the available RF power. It is interesting to note that there exists a threshold around 2 nC below which the current is not sufficiently high for the RAFEL process to take place.

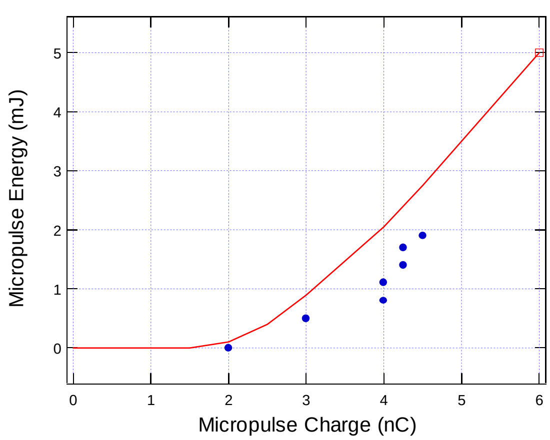


Figure 5: Plots of micropulse energy versus micropulse charge. The line is estimates based on FELEX simulation (square) and the circles are experimental measurements.

We also measured the FEL output pulse energy versus the optical feedback cavity detuning length. The RAFEL has a large detuning length of 1 mm full-width at half maximum (Fig. 6), considerably longer than the typical FEL oscillator detuning length of tens of microns. The RAFEL large detuning length greatly relaxes the requirement for mechanical stability of the optical feedback cavity.

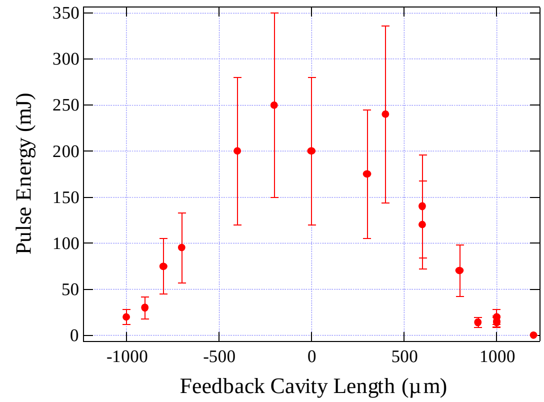


Figure 6: Plots of macropulse energy versus optical feedback cavity length.

The RAFEL optical spectrum was measured with a McPherson grating spectrometer. Both the observed and calculated spectra exhibit multiple peaks characteristic of the high-gain FEL. The observed spectrum is somewhat broader than the FELEX simulations with more structures at shorter wavelengths. The width of the spikes can also be used to deduce the radiation bunch length.

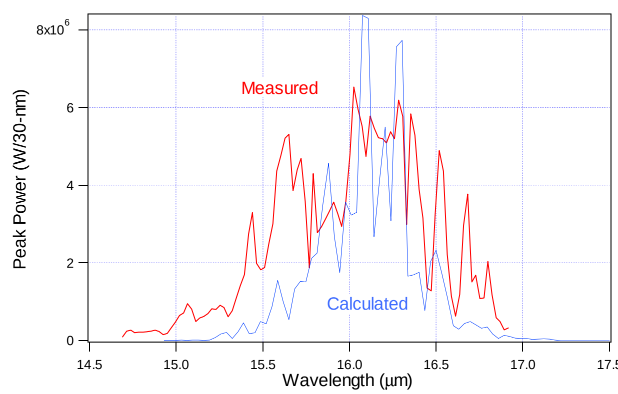


Figure 7: Measured (red) and calculated (blue) infrared spectra of the RAFEL output. The spikes are caused by different co-operation lengths of the high-gain FEL.

## *3.3 Energy Spectrometer Measurements*

The electron beam energy spectrometer provides an alternative measurement of the FEL efficiency, independent of optical power measurements that are susceptible to optical power loss. A comparison between the measured median electron energy with and without the FEL interaction yields the electron beam energy loss as a result of the FEL interaction. We can turn "off" the FEL interaction by inserting a beam block in the optical feedback cavity. As seen in Fig. 6, the electron energy spectrum obtained with the FEL interaction turned "on" exhibits a broad low-energy tail that is not present in the spectrum without the FEL interaction. By integrating the two curves and calculating the difference in the median beam energy, we obtain the FEL efficiency without the complication of optical power loss. The FEL efficiency as measured with the electron spectrometer is 3.5%, almost a factor of 2 higher than the 1.8% efficiency measured optically. The broad distribution of low-energy electrons as low as 13% of the initial beam energy confirms our suspicion that the undulator taper is too strong, causing the electrons to "spill" out of the bucket along the tapered undulator section.

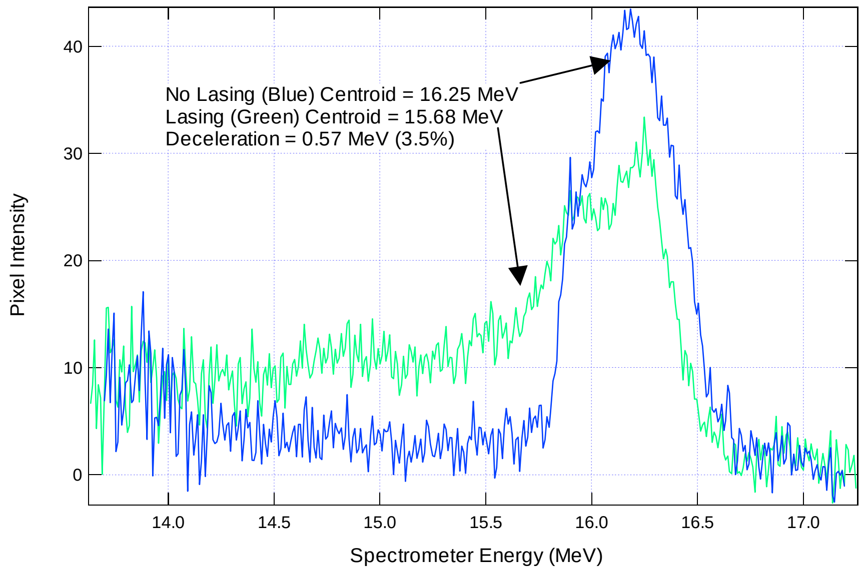


Figure 6. Electron beam energy exhibits a 3.5% mean energy shift, indicating an FEL efficiency of 3.5% as measured with the electron energy spectrometer.

## 4 CONCLUSIONS

We have experimentally achieved saturation with SASE by adding a low-Q optical feedback cavity in a new FEL arrangement called the Regenerative Amplifier FEL. The experimental requirements for RAFEL are a high-brightness electron beam, a high-gain undulator, and a simple optical feedback cavity to re-inject the optical beam back to the undulator entrance. The low-Q optical feedback cavity is less susceptible to mechanical misalignment and optical damage than the conventional FEL optical resonator.

Although very high optical power has been achieved with the 12.5% tapered undulator, our data indicate that the taper is too large. The aggressively tapered undulator causes the electrons to spill out of the FEL ponderomotive potential and form a broad distribution of energy in the electron energy spectrum. By optimizing the undulator taper, we can significantly improve the RAFEL performance.

From the electron beam spectrometer measurement, we deduce an FEL efficiency of 3.5%, almost a factor of 2 higher than the optically measured efficiency of 1.8%. Work is ongoing to investigate this discrepancy and to improve the performance of the Regenerative Amplifier FEL.

## REFERENCES

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[3] D.C. Nguyen et al., *Phys. Rev. Lett..*, **81**, 810, 1998.