A HIGH-POWER COMPACT REGENERATIVE AMPLIFIER FEL

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Abstract

The Regenerative Amplifier FEL (RAFEL) is a new FEL approach aimed at achieving the highest optical power from a compact rf-linac FEL. The key idea is to feed back a small fraction (<10%) of the optical power into a high-gain (~10^5 in single pass) wiggler to enable the FEL to reach saturation in a few passes. This paper summarizes the design of a high-power compact regenerative amplifier FEL and describes the first experimental demonstration of the RAFEL concept.

1 INTRODUCTION

Self-amplified spontaneous emission (SASE) has been demonstrated experimentally in the mm-wave, far-ir and mid-ir regions.[1] Recent interest in SASE has shifted toward shorter wavelengths as this provides the basis of the fourth generation light sources emitting coherent tunable radiation in the deep uv and x-rays. Existing designs of x-ray SASE FELs, however, call for very long wigglers (tens of meters).[2]

One way of reducing the wiggler length is to use optical feedback to synchronously inject the optical power from one pass back to the front of the wiggler to seed the optical buildup of subsequent passes. We called this idea the regenerative amplifier FEL (RAFEL). With a large single-pass gain, the amount of optical feedback can be quite small, e.g. <10%. Since mirrors can easily provide that kind of reflectivity, even in the deep uv and x-ray regions, a small amount of optical feedback translates into substantial saving in the number of gain lengths needed for saturation. Furthermore, this approach allows us to control the output frequency and amplitude and to use a strongly tapered wiggler for improved extraction efficiency. Compared to traditional FEL oscillators, the RAFEL outcouples >90% of the intracavity power, thereby reducing the risk of optical damage while maximizing system efficiency. The RAFEL output efficiency is essentially equal to the FEL extraction efficiency.

2 EXPERIMENTAL SETUP

The RAFEL concept was implemented on the compact Advanced FEL test stand at Los Alamos with the philosophy of a simple system design and minimum number of components. The key components of the RAFEL experiment include a high-current, high-brightness electron linac, a high-gain, high-efficiency wiggler and an optical feedback loop. Figure 1 schematically depicts the RAFEL experimental setup. As details of the RAFEL experimental implementation have been reported elsewhere,[3] only the pertinent parameters of the RAFEL experiment are summarized in this paper (see Table I).

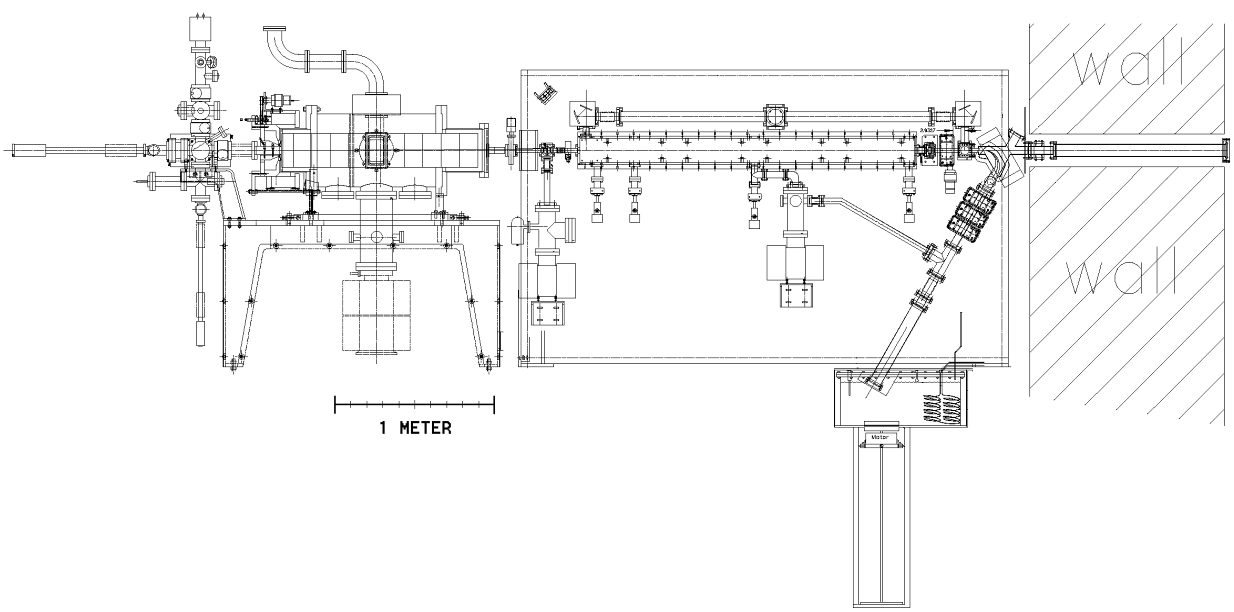

Figure 1. Experimental setup of the regenerative amplifier FEL.

Table I: Summary of experimental parameters

Beam Energy	E	16.5 MeV
Peak current	I_{peak}	3–300 A
Charge/bunch	Q	0.01–5 nC
Bunch length	τ	3.5–16 ps
Bunch separation	T	9.23 ns
Normalized emittance*	ε_n	<7 mm-mrad
Energy spread	$\Delta\gamma/\gamma$	<0.5%
rms radius inside wiggler	r_b	0.2 mm
Wiggler period	λ_w	2 cm (fixed)
On-axis field	B_0	0.7 Tesla
Wiggler length	L_w	1 m uniform 1 m tapered
Taper rate		30% in B
Wiggler gap		5.9–9.5 mm
Betatron period	λ_β	1 m
Wavelength	λ	16.2 µm
FEL parameter*	ρ	0.02
Gain length (3-D)*	λ_G	7.8 cm
Slippage length	L_S	1.7 mm

* At 300 A peak current

The requisite electron beam has been characterized and reported in Ref. [3]. The permanent magnet wiggler has nearly equal two-plane focusing via the sextupole components of the magnetic field.[4] Beam size measurements using OTR screens confirmed the near circular profile and the constant beam radii in the wiggler. The feedback loop consists of two annular mirrors and two 90° paraboloids, forming a simple ring resonator.[5] The present output mirror has a 12 mm diameter hole instead of the designed 14 mm hole.

The forward-directed spontaneous, SASE and RAFEL lights were detected with a sensitive HgCdTe detector. The 16 µm micropulses were detected with a fast Cu:Ge detector. Optical energy measurements were made with calibrated Molectron J50 pyroelectric detectors.

3 RESULTS AND DISCUSSION

The RAFEL without the feedback optics is a SASE experiment with a 1 m uniform wiggler. The observed intensities of the SASE micropulses are completely random with amplitudes varying by more than a factor of ten (Fig. 2). Since the electron beam parameters cannot change significantly on the nanosecond time scale, the SASE amplitude variation are most likely caused by differences in the start-up conditions.

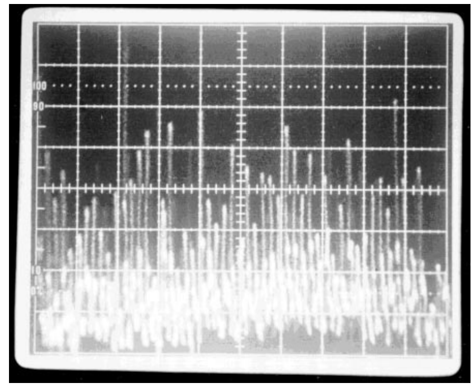

Figure 2. Oscilloscope trace of SASE at 16 µm as detected with a helium cooled Cu:Ge detector.

To determine the SASE single-pass gain, we varied the micropulse charge from 0.01 to 5 nC and measured the infrared light generated in a single pass. The results are plotted on a log-log scale in Fig. 3. The sudden break from linear dependence (slope=1) to quadratic dependence (slope=2) at 0.2 nC is attributed to transition from spontaneous to SASE. From the ratio of the measured SASE power at 5 nC to the spontaneous power at the end of the first gain length, an average SASE gain of X500 is inferred. As the SASE power fluctuates by a factor of ~10 from micropulse to micropulse, we expect the peak gain to be 3 times higher.

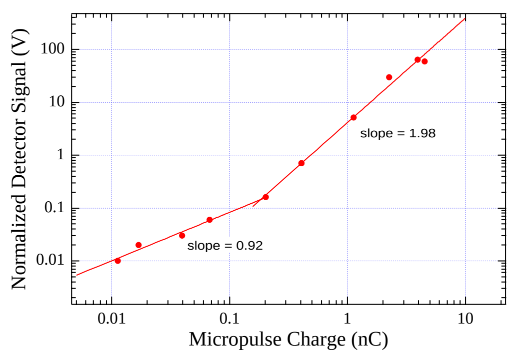

Figure 3. Plot of attenuation-corrected HgCdTe signal vs. micropulse charge on log-log scale.

Shortly after installing the feedback loop, we observed an optical power more than six orders of magnitude above SASE. The measured energy integrated over an 8 µs macropulse (~900 micropulses) was 0.35 J. If the Fresnel loss of the ZnSe vacuum window is accounted for, we have generated 0.5 J of 16 µm light over 8 µs, corresponding to a 60 kW average power over the macropulse. Since these results were obtained with 3 nC electron bunches, we deduced 1% of the beam power was converted to FEL light.

Unlike an FEL oscillator, the RAFEL has a large feedback cavity detuning curve with a fwhm ≥ 1 mm (Fig. 4). The optical buildup near saturation exhibits a large gain (~X6 assuming 66% cavity loss), although this is much less than the small-signal gain which we could only infer from the SASE measurements. As there are two pulses in the feedback cavity, two sets of micropulses build up from different initial conditions and achieve saturation at different times (Fig. 5). Because of the large outcoupling, the cavity ringdown is fast: the FEL power drops by a factor of 3 in successive passes (Fig. 6). From the ringdown measurements, we estimated that the present outcoupling is less than 66%. This outcoupling differs from the expected 90% partly because of the smaller hole in the output mirror.

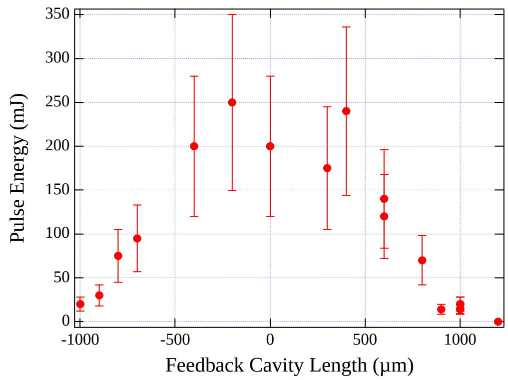

Figure 4. RAFEL feedback cavity detuning curve

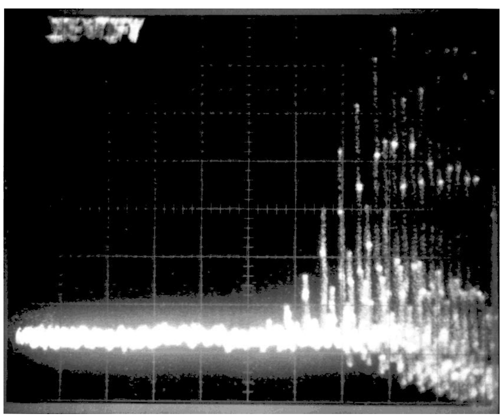
Figure 5. Fast buildup of RAFEL to saturation.

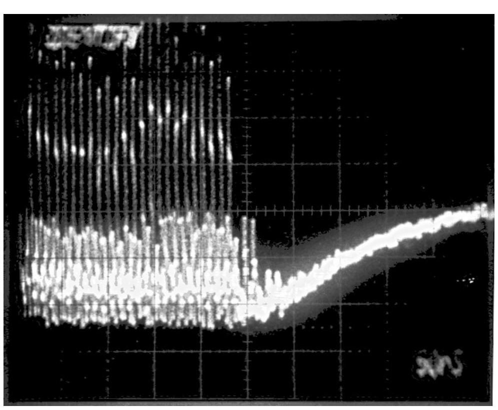
Figure 6. RAFEL ringdown shows optical power decaying by a factor of 3 in successive passes.

4 CONCLUSION

We have demonstrated for the first time the regenerative amplifier FEL concept. A single-pass gain greater than 500 was inferred from the plot of SASE intensity versus charge. The RAFEL produced 0.5 J per macropulse at 16 µm, corresponding to 60 kW average power, over an 8 µs macropulse, and a 1% output efficiency. Experiments are in progress to characterize this new regime of FEL operation.

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