RESULTS FROM THE ADVANCED PHOTON SOURCE SASE FEL PROJECT

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Abstract

Measurements of self-amplified spontaneous emission (SASE) at 530 nm were made at the Advanced Photon Source (APS) low-energy undulator test line facility (LEUTL). Exponential growth of the optical signal as a function of distance was measured and compared to theoretical estimates. SASE was first observed using a beam generated from a photocathode rf gun system. It was later repeated using beam from a thermionic rf gun system. Following a brief description of the LEUTL facility, we will present our results and initial analysis.

1 DESCRIPTION

The low-energy undulator test line facility has been configured to explore the generation and properties of SASE radiation. It consists of high-brightness electron beam sources, a linear accelerator capable of beam energies up to 650 MeV, and an undulator system complete with diagnostics for the electron beam and SASE light output. A more thorough description of the LEUTL can be found in the literature [1,2]. Here only a brief description will be given.

1.1 Electron Gun Systems

High-brightness electron bunches are generated using either a photocathode rf gun system or thermionic rf gun with alpha-magnet compression. The photocathode rf gun is a 1.6-cell Brookhaven s-band gun IV model [3,4] that employs a copper photocathode. A Nd:Glass picosecond drive laser is used to generate the electrons [5]. It is assembled from commercially available components and is timing stabilized to the rf to within 1 picosecond. This system can generate a single electron bunch of roughly 1 nC at a 6-Hz repetition rate. The thermionic rf gun is a 1-½ cell s-band gun with a tungsten dispenser cathode [6]. An alpha magnet is used to both inject beam into the APS linac and to compress the bunch to very high peak currents. An 8-ns pulsed kicker magnet is used for safety purposes to limit the total charge delivered to the linac. The result is a bunch train of roughly 23 bunches, each with approximately 48 pC of charge. This thermionic rf gun system is extremely reliable and is used as the primary injector for the APS storage ring. Nominal performance parameters of these systems when coupled to the linac and used for LEUTL testing, are listed in Tables 1 and 2.

Table 1: Photocathode RF Gun/Linac Beam Parameters

	Most Probable	Min -- Max
Energy [MeV]	217	--
ε_o rms [π mm-mrad]	5	4 -- 8
Charge/bunch [nC]	0.7	0.6 -- 0.8
Bunch Length FWHM [ps]	5	4 -- 7
Energy Spread %	0.1	< 0.1 -- 0.2

Table 2: Thermionic RF Gun/Linac Beam Parameters

	Most Probable	Min -- Max
Energy [MeV]	217	--
ε_o rms [π mm-mrad]	12	9 -- 15
Charge/bunch [nC]	0.048	0.043 -- 0.052
Bunch Length FWHM [ps]	0.35	0.33 -- 0.40
Energy Spread %	0.1	< 0.1 -- 0.2

1.2 Linear Accelerator

The APS linear accelerator consists of thirteen s-band 3-m-long travelling wave accelerating structures similar to the SLAC design. Three sets of four structures are powered each by SLEDed 35-MW klystrons. The photocathode gun is powered by a single 35-MW klystron, while the thermionic rf gun shares power with a hot spare thermionic rf gun and a single accelerating structure following the photocathode rf gun. Power distribution to these rf guns and linac structure is through s-band rf switches. In photocathode-gun mode the beam can be accelerated by all thirteen structures. One accelerating structure, the first, is not used to accelerate beam in the thermionic rf gun configuration. Maximum energy attainable in photocathode-gun mode is 650 MeV.

A bunch compression system is being installed within the linac following the fifth accelerating structure. It will be commissioned in August 2000 and will provide higher bunch peak currents for both photocathode and thermionic rf guns.

1.3 Undulator and Diagnostics System

In its present configuration the undulator system is constructed of five cells each 2.7265 m in length. The cells are made up of a fixed-gap undulator with parameters listed in Table 3 [7]. We rely on the natural focusing in the vertical direction to guide the electron beam from one undulator cell to the next. To guide the beam in the other plane, we use horizontally focusing combined quadrupole/steering magnets located between the undulator. Also located within these gaps are the primary beam and light diagnostics [8]. This allows for tune up of the beam and measurement of most of the optical properties of the SASE light as a function of distance along the undulator system, a key component in verifying that indeed the signal is SASE.

Table 3: Undulator Parameters

Undulator Period [cm]	3.3
K	3.1
Undulator Length [m]	2.4

2 SASE MEASUREMENTS

Figure 1 shows results of measurements of the SASE signal at 530 nm as a function of length along the undulator system. In this experiment the beam was generated using the photocathode rf gun system. Sequential measurements at each diagnostics station were made for a number of electron bunches. Shown are the maximum of all measurements, the average of the top 5%, and the average of all measured intensity signals. The intensity measured is an integration over all wavelengths, angles, and the duration of the electron bunch.

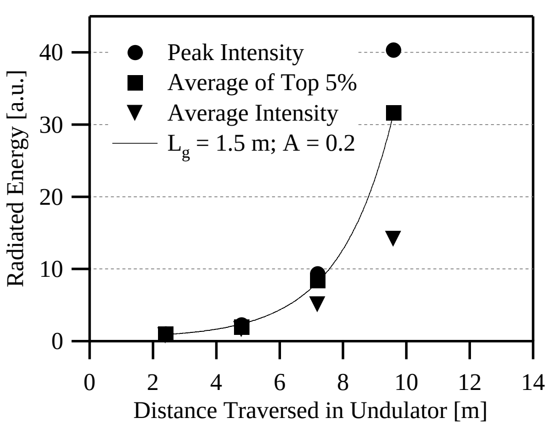

Figure 1: Radiated energy vs. distance traversed in the undulator. Photocathode rf gun electron source.

Jitter was and continues to be a problem with the photocathode rf gun system. Shot-to-shot trajectory errors were enough to reduce the gain through the undulator system to unity on some shots. Also, because our peak current was reasonably high, control of wakefields within the linac is important in maintaining good emittance properties. This is particularly true at the low-energy end of the linac. The jitter proved, however, to make proper control of wakefields a difficult task. We are still exploring the causes of this jitter; the thermionic rf gun does not suffer this problem.

Figure 2 shows data similar to that shown in Figure 1; however, this time the beam was generated using the thermionic rf-gun system. As compared with the photocathode rf gun, shot-to-shot jitter was negligible. With this electron source the intensity signal is also an integral over the entire 23-bunch train of any one linac cycle.

Electron bunches from the thermionic rf gun were optimally compressed by the alpha magnet by observing signals generated off a coherent transition radiation bunch length monitor [9]. Reconstruction of the longitudinal bunch profile was performed with the FWHM result tabulated in Table 2.

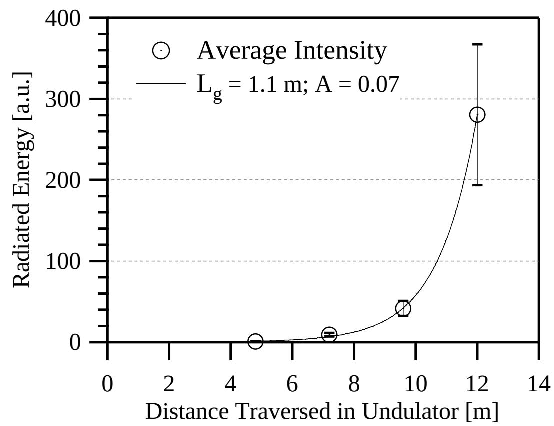

Figure 2: Radiated energy vs. distance traversed in the undulator. Thermionic rf gun electron source.

3 ANALYSIS

3.1 Gain Length

In a SASE FEL, the Fourier harmonics of the beam current $I_\omega(s,z)$ grow exponentially with position along the undulator z

$$I_\omega(s,z) \propto \exp(gz) \ .$$

Here, ω is the Fourier frequency and s is the position along the bunch. Near the optimal frequency ω_0 at the point s_0 within the bunch, where the longitudinal particle density is maximal, the factor g reaches a maximum and therefore can be represented in the form:

$$g \approx \frac{1}{2L_g}\left[1 - a(\omega-\omega_0)^2 - b(s-s_o)^2\right] \ ,$$

where L_g is the power gain length at the optimal frequency and peak current, and a and b are constants.

Integrating over all frequencies, the bunch length, and along the trajectory one finds the radiated energy W

$$W \approx \frac{L_g^2}{z} \exp\left(\frac{z}{L_g}\right) \frac{\pi}{\sqrt{ab}} .$$

The results of fitting a function of the form $A\left(L_g^2/z\right)\exp\left(z/L_g\right)$ with two parameters (A and L_g) are presented in Table 4 for both cases, photocathode and thermionic rf guns. The average of the intensity signal from the top 5% measured were used in the analysis of the photocathode rf gun data; whereas, for the thermionic rf gun, the average for all the data was used in the analysis. More details can be found in reference [10].

Table 4: Fitted Gain Length Parameters

	Photocathode Gun	Thermionic Gun
L_g [m]	1.5	1.1
A [a.u.]	0.2	0.07

The gain length, using the "most probable" values of the photocathode rf gun beam as listed in Table 1 and calculated by M. Xie's parameterization [11], is 0.7 m. The source of discrepancy between theory and the experimental is not known; however, it could be due to a number of reasons. For instance, the uncertainty in the measurements of energy spread and average beta function, in particular within the undulator, can lead to such a substantial increase in the gain length.

Similarly one can calculate the expected gain lengths when using beam from the thermionic rf gun. The "most probable" values from Table 2 predict a gain length of 1.0 m. A more complete Monte Carlo analysis using normalized three-point estimates based on the beam parameters listed in the table predicts a most probable gain length of 1.1 m with a distribution width of $\pm$ 0.2 m.

It is interesting to note that the bunch length reconstruction shows a sharp, high-current spike at the head with a trailing broad shoulder. Also, at 530 nm the FWHM length corresponds to roughly 200 optical periods. This complicates the interpretation of the results.

3.2 Shot-to-Shot Noise

A characteristic feature of the SASE light is the inherent shot noise. In the case of operations with the photocathode beam, shot-to-shot trajectory jitter through the undulators is believed to be the cause of significantly more intensity jitter than expected from the predicted shot noise. Therefore, it has not then been possible to assign error bars significant and meaningful to the stochastic nature of the SASE process.

Beam from the thermionic rf gun was much more stable. Error bars shown in Figure 2 indicate the rms spread in the gathered data. Preliminary analysis indicates that the noise is larger than can be explained by SASE. This is not surprising given the sensitivity of the gain length on the various beam parameters and other details such as the very non-Gaussian longitudinal profile of the thermionic rf gun.

4 SUMMARY

The exponential growth of the optical signal versus the undulator length in the SASE FEL has been explicitly demonstrated at 530 nm. An effective gain length of about 1.5 m was measured using a photocathode rf gun and 1.1 m using a thermionic rf gun as the source.

Due to jitter of the beam from the photocathode rf gun it is not yet possible for us to measure all electron beam properties while we are measuring the 530-nm signal. This presently prevents us from making an exact one-to-one correspondence between theory and the measured results using this electron beam source; however, measured and predicted gain lengths using the thermionic rf gun as a beam source are in good agreement.

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