HIGH AVERAGE POWER OPTICAL FEL AMPLIFIERS*

I. Ben-Zvi**, D. Kayran and V. Litvinenko, Collider-Accelerator Department, Brookhaven National Laboratory, Upton NY 11973 USA

Abstract

Historically, the first demonstration of the optical FEL was in an amplifier configuration at Stanford University [1]. There were other notable instances of amplifying a seed laser, such as the LLNL PALADIN amplifier [2] and the BNL ATF High-Gain Harmonic Generation FEL [3]. However, for the most part FELs are operated as oscillators or self amplified spontaneous emission devices. Yet, in wavelength regimes where a conventional laser seed can be used, the FEL can be used as an amplifier. One promising application is for very high average power generation, for instance FEL's with average power of 100 kW or more. The high electron beam power, high brightness and high efficiency that can be achieved with photoinjectors and superconducting Energy Recovery Linacs (ERL) combine well with the high-gain FEL amplifier to produce unprecedented average power FELs. This combination has a number of advantages. In particular, we show that for a given FEL power, an FEL amplifier can introduce lower energy spread in the beam as compared to a traditional oscillator.

This property gives the ERL based FEL amplifier a great wall-plug to optical power efficiency advantage. The optics for an amplifier is simple and compact. In addition to the general features of the high average power FEL amplifier, we will look at a 100 kW class FEL amplifier is being designed to operate on the 0.5 ampere Energy Recovery Linac which is under construction at Brookhaven National Laboratory's Collider-Accelerator Department.

INTRODUCTION

FELs of high-average power are becoming objects of interest and practicality. In the past few years we are witnessing the growth of a new class of particle accelerators, that of high-power, high-brightness electron beams. This emerging technology is enabled by the combination of high-brightness electron sources and high-current SRF Energy Recovery Linacs (ERL). While the current state-of-the-art is at about 10 kW power [4] (the Jefferson Laboratory FEL upgrade), there is interest in much higher CW power. The emerging technology of ampere-current, few micron normalized emittance electron beams enables extremely high average power Free-Electron Lasers as well as other applications, such as a new generation of extreme brightness light sources, high-energy electron coolers of high-energy hadron beams, high luminosity polarized electron-hadron colliders, compact Thomson scattering X-ray sources, terahertz radiation generators and more. All of the progress made to date in the high average power FEL arena was based on the use of FEL oscillators. In this paper we will look at the FEL amplifier as an alternative to the FEL oscillator for generating very high average power.

FEL amplifiers and oscillators share a lot in common. In this particular application of high power, clearly the amplifier has one great advantage over an oscillator, that being the absence of resonator optics in the amplifier. As we shall see later on, there is another advantage, that of a potential higher efficiency. The resonator optics pose a number of problems, best discussed in an article devoted to high-power FEL oscillators. In short, these are the high intra-cavity power and the need to employ an outcoupler, a complicated element in a high power cavity. The advantage of the oscillator is the shorter wiggler.

First we will look at a few important milestone in FEL amplifier development. Then we will consider the prospects of generating high average current, high brightness electron beams that are required for high average power FEL amplifiers. This is a fundamental demand for generating high average power FELs. Then we will look at the potential of these beams to generate high FEL power in the near IR and visible wavelength range and some of the issues, such as the gain length, efficiency and Rayleigh range of the FEL.

Before going into some examples of FEL amplifiers, let us set a definition for the purpose of this work: While a SASE FEL is also an amplifier, this very important FEL class will not be covered here. We will restrict this paper to FELs that start from some laser seed.

Historically, the first operation of an FEL [1] at Stanford University was in an amplifier mode

A 2.4 kGauss 5.2m long superconducting helical undulator was used for the amplification of a 10.6 micron CO2 laser seed. The 70 mA (peak) electron beam was provided by the Stanford Superconducting Accelerator. Resonance was established about an electron beam energy of 24 MeV, and a peak gain of 7% was measured. This demonstration and work that followed started the age of the FEL. Many FEL amplifiers and oscillators followed, but here we shall dwell only upon a few.

The next interesting FEL amplifier was the PALADIN [2] FEL at Lawrence Livermore National Laboratory. It also used a CO2 laser as a seed. The energy of the induction accelerator was about 45 MeV. Induction accelerators can produce very high peak currents, but the Livermore "Advanced Test Accelerator" suffered from very poor beam quality, even after the 10 kA beam was filtered down to 600 amperes or so. The wiggler was a planar electromagnet and permanent magnet hybrid, with a period of 8 cm. This FEL hit a few milestones, such as

* Work performed under the auspices of the U.S. Department of Energy, and partially funded by the DOD Joint Technology Office and the Navy.
** ilan@bnl.gov

amplification to saturation, very high power (over 20 MW) over a very long pulse of 70 ns and demonstration of gain guiding.

The third noteworthy FEL amplifier is the High-Gain Harmonic-Generation (HGHG) FEL [3] at the BNL Accelerator Test Facility. Interestingly enough this device was also seeded by a CO2 laser, but by using a three-stage wiggler (modulator, buncher and an amplifier tuned to the second harmonic) the output radiation was 5.3 microns. Thanks to the high beam brightness of the ATF, the output power at 5.5 microns was 35 MW. The particular significance of the HGHG is its ability to reach to short wavelengths, starting from longer wavelength seed lasers. The HGHG FEL thus confers the seed laser properties to short wavelength devices, such as extremely short pulse capability, coherence and stability. A

These few amplifier examples illustrate that FEL amplifiers are capable of a high peak power. The application of FEL amplifiers to high average power requires a continuous stream of electron bunches, exactly as is the case for FEL oscillators. Thus a CW, high average current accelerator is essential for a high average power FEL of any type.

Finally, a very advanced design of a very high-power FEL amplifier design was presented by Pagani et al [5]. This interesting design proposes a 1 GeV superconducting ERL with energy spread debunching. It would use 2 nC bunches at 6.1 MHz to produce 0.5 MW radiation at 260 nm to 500 nm, driven by a 1 W seed laser.

HIGH-CURRENT HIGH-BRIGHTNESS SRF ELECTRON ENERGY RECOVERY LINACS

What is required by way of technology in order to get a high average current with a reasonable gradient? The high average current necessitates CW operation of the machine, thus SRF is required. Furthermore, currents of a fraction of an ampere at hundreds of MeV have hundreds of megawatt beam power, therefore high average current also requires energy recovery to be practical.

Some immediate consequences of this is that no high-power input couplers necessary in the energy recovered structures of the linac (although certainly there are always parts of the accelerator that are not energy recovered, and thus require high power input couplers).

Another consequence is that high Qext operation is desirable to minimize RF power requirements. This brings up issues such as stability against microphonics, but relieves us of the issue of pulsed Lorentz force due to the CW operation. The control issues are also complicated by the very high reactive power of the beam and call for significant efforts in the stability of the machine and advanced feedback circuits. The issues of microphonics, stability of the RF control system and high Q_{ext} are beyond the scope of this paper, but suffice to say that recent progress has been made in where a Cornell digital cavity control system was tested at the JLab ERL at a current of 5 mA and external Q of $1.2{\cdot}10^8$, achieving an amplitude stability of about 10^{-4} and phase stability of 0.02 degrees [6].

CW operation also means that the dynamic load on the helium refrigerator will be a dominant cost issue. The optimization of a CW machine in terms of capital and operating costs will push the optimal gradient to a low level; say of the order of 20 MV/m.

Now we must consider the most challenging item for a high-current ERL: Higher Order Mode (HOM) power generation and beam breakup. The amount of HOM power generated by a cavity in an ERL (including the return current) is determined by the expression

$$P_{HOM} = 2Iqk_l$$

Where I is the beam current, q is the bunch charge and k_l is the longitudinal loss factor, which is given approximately by

$$k_l \approx \frac{\Gamma(0.25) Z_0 c}{4\pi^{2.5}} \frac{1}{a} \sqrt{\frac{dN}{\sigma}}$$

Where a is the aperture radius, d is the cell length and N is the number of cells per cavity, Z_0 is the impedance of vacuum and c the speed of light.

The amount of HOM power can be extremely high, particularly for high current and high charge operation.

Another aspect of HOMs is the multi-bunch, multi-pass beam breakup. In this case damping of the higher order modes is essential for getting a high threshold current for the Beam Break Up (BBU). The current generation of SRF linac structures is not stable or just marginally stable in ERLs with currents over ~100 to ~200 mA, certainly not for one ampere. The main issue here is damping of the dipole modes, but going to a lower frequency also helps. This subject was recently treated extremely well in ref. [7]. The following approximate equation shows the main parameters that affect the BBU threshold:

$$I_{th} \approx \frac{-2c^2}{e(R/Q)_m Q_m \omega_m T_{12} \sin(\omega_m t)}$$

The dependence of the BBU threshold on mode frequency ω_m and the shunt impedance $(R/Q)_m$ of the HOMs is clear, and the message is clear: Good damping of the HOMs is essential for high threshold currents. Other aspects of CW linacs to be considered include refrigeration and mechanical stability.

The refrigeration load is proportional to the surface resistance, which is given by the sum of the BCS surface resistance and the residual surface resistance. For a magnetically well shielded cavity it is possible to get a residual resistance of one nΩ or less. It is practical to work at temperatures of about 1.8K to 2K. However, temperatures significantly below 1.8K become problematic, requiring overly massive helium pumps and bringing about loss of thermal conductivity of the niobium, which plunges rapidly below about 1.8K.

Thus we would like to minimize the BCS surface resistance of the niobium as long as it is above 1 nΩ, using temperatures in the 1.8 to 2K range. We find that at 1.8K the BCS surface resistance is slightly above 1 nΩ at

700 MHz, but more than four times that much at 1.3 GHz.. That means that the refrigeration load of the linac is significantly reduced at 700 MHz relative to 1.3 GHz, even after taking account of the reduced R/Q of the fundamental mode. It turns out that a lower frequency also makes the cavity more stable mechanically. This may seem counterintuitive at first, but it is nevertheless correct.

The BNL 5-cell ampere-class cavity [8,9,10] is being constructed in collaboration with AES and JLab for the purpose of electron cooling of RHIC and for the eRHIC electron-ion collider. The BNL design aims to address the most extreme HOM conditions.

The main features of this design are a low frequency of 703.75 MHz, very large cavity irises (17 cm diameter) and extremely large beam pipe, 24 cm in diameter. The beam pipe is large enough to propagate all the HOMs to the ferrite HOM load, which is at room temperature on either side of the cavity. As a result of these design features the cavity is a “single mode” cavity, all HOMs are strongly coupled to the HOM damper, and the loss factor is very low. The cell shape also enhances mechanical stability.

Some of the notable features of this cavity are an extremely low longitudinal loss factor, about 0.6 V/pC (excluding the fundamental and for a bunch length of 1 cm), and a very high mechanical resonance frequency of about 100 Hz. The peak surface electric field to accelerating field ratio is 1.97 and the magnetic field ratio is 5.78 mT/MV/m. The Lorentz detuning coefficient is 1.2 Hz/(MV/m)^2.

The next accelerator issue is to generate a high-current (ampere-class), low emittance, high bunch charge electron beam. The laser-photocathode RF gun (or “photoinjector”) has proven its capability to produce the high bunch charge (over 1 nC) with extremely good normalized emittance, of the order of 1 micron. However, the common photoinjector is a pulsed device, using a copper cavity structure with fields of the order of 100 MV/m. This technology is not easily adaptable to produce CW beams and still maintain the high electric fields necessary for good emittance at nC bunch charges. An approach that resolves this problem is the application of a superconducting RF gun.

The SRF gun can produce the high fields and operate CW. The tricky part is the insertion of an efficient photocathode into the gun. The Rossendorf RF gun [11] resolved this problem very well, however that gun is designed for low beam currents. At BNL we are planning to use a 703.75 MHz superconducting RF photoinjector [12] designed to provide up to 1 ampere of beam current. The special features of the BNL design are the damping of the higher order modes through the beam pipe, a particular shape of the gun and application of dual fundamental input couplers to provide a megawatt RF power.

The shape of the gun is selected to conform to the following requirements: 1) Provide output energy vs. input phase curve that gives higher acceleration to the bunch tail than its head. This feature counters the energy spread introduced by the space charge of the bunch; 2) Minimize surface electric fields; 3) Provide focusing of the beam in part through a recessed cathode; 4) Avoid multipactoring levels; 5) Minimize surface electric fields; 6) Use an intra-cryostat High Temperature Superconductor solenoid on the beam pipe in close proximity to the gun for additional focusing and emittance compensation.

PROPERTIES OF THE FEL AMPLIFIER

The rationale for using an amplifier in high-power applications is based on two issues: Optical damage and wall-plug efficiency.

Optical damage

In this section we will discuss the optical damage issues of high-power FELs and show that an amplifier enjoys some advantages over an oscillator in this respect.

The limitation stemming from optical damage under CW conditions is about 100 kW/cm^2. Comparing the case for an oscillator and an amplifier, we observe that the oscillator must deal with a high circulating power and need for an out-coupler. These elements are subjected to a considerably higher power, depending on the outcoupling fraction. Thus, all else being equal (same output power, same wavelength, same Rayleigh range) the oscillator will need mirror spacing larger by the square root of the cavity Q. That makes the amplifier (with a Q=1) more compact. In addition, the oscillator requires two mirror arms while the amplifier has only one high-power optical path. Furthermore, the amplifier’s first turning mirror can be tilted, reducing the power loading of the mirror by sinθ (θ is the tilt angle).

Of course, when saying above that the Rayleigh range of the amplifier and oscillator should be equal for the above comparison to hold, we have to show that this is indeed so.

First we turn to the experiment. A Rayleigh range of about 5 cm already been demonstrated in the VISA experiment [13]. This was a result of the high beam brightness and the strongly focusing wiggler.

Next, assuming a short enough gain length, we can look at the 1-D analytic theory. Using results from Ming Xie [14], he provides us with the Rayleigh range

$$L_R = \frac{2k_r\sigma^2}{4\,\mathrm{Re}(a)\left(1+\left(\dfrac{\mathrm{Im}(a)}{\mathrm{Re}(a)}\right)^2\right)}$$

where k_r is the radiation wave number, σ is the electron beam rms size (Gaussian distribution is assumed), and

$$a = \frac{1}{4}\sqrt{\frac{\left(2\cdot 3^{-0.5}\right)^3}{\eta_d\bar{s}^2}-1}\,,\qquad \bar{s} = s - i\eta_w$$

s is the solution of the 1-D cubic equation,

$$is\overline{s}+\eta_d\overline{s}^2-2\sqrt{\left(2\cdot 3^{-0.5}\right)^3\eta_d\overline{s}}=0$$

where η_d is the diffraction parameter and η_w is the detuning parameter,

$\eta_d=\frac{L_{1D}}{2k_r\sigma_x^2}$, $\eta_\omega=2k_W L_{1D}\Delta\nu$ and $\Delta\upsilon$ is the fractional laser frequency change, k_W is the wiggler wave-number, and L_{1D} is the one dimensional gain length.

It turns out that in the VISA case the Ming Xie result is in reasonably good agreement with the experiment. The 3-D simulation GENESIS [15] is in outstanding agreement with the experiment [13].

In addition to the above, there are techniques of shortening the Rayleigh range of an amplifier by various means. The original suggestion in this direction was made by P. Sprangle et al. [16]. In this scheme, the electron beam is focused tightly towards the end of the wiggler, leading to a pinch in the laser beam. In the example of Sprangle et al the Rayleigh range is reduced from 22 cm to 3.6 cm. Experimental work is being carried at BNL on demonstrating an FEL with a short Rayleigh range [17].

The conclusion is that a high-gain amplifier with a strong focusing wiggler, a small emittance electron beam and possibly some additional manipulation of the electron beam will provide a very short Rayleigh range.

Wall plug efficiency

In this section we shall describe how the wall-plug to radiated power efficiency of an ERL based FEL amplifier can be significantly increased, reducing the power wasted in the beam dump as well as the cost and space taken by high power RF equipment.

The ERL presents an interesting platform for FEL operations. The ERL has an injector, providing an average current I at a kinetic energy V_i. A high power FEL will use a high current injector and thus $P_i=IV_i$ is high, possibly in the megawatt range. Compared to this power we may neglect for the purpose of this discussion all other power expenditures such as magnet power supplies, helium refrigerator etc. The linac, which is energy recovering, raises the beam energy to V with a negligible energy investment. The FEL output power is approximately $P=\rho IV$ (saturation, untapered wiggler), and the lasing introduces a peak-to-peak energy spread ΔE. P is our output product, and P_i is our energy investment. The dumped power is $P_D=P_i-P$. Thus it is natural to define an efficiency for an ERL driven FEL as $\eta=P/P_i$ and try to maximize it. This will also minimize the dumped power. It is worth mentioning that minimizing the dumped power will save construction money, save operating money and reduce the radiation from the beam dump.

There are a number of techniques of maximizing P, but actually it is important to maximize η. High power CW klystrons are expensive (at about $5/watt), bulky and consume a lot of power. Thus as we maximize η we reduce P_D, which also reduces P_i. For a given current that will reduce V_i.

How can we minimize V_i? There are a few considerations that drive V_i. The first one, 1, applies only to FEL amplifiers. The others apply also to an oscillator FEL, such as 2,3 and 4. Item 3 in this list is not new [5] but due to its relevance is mentioned here.

1) The FEL amplifier provides a convenient way to control the detuning (for a given amplified radiation wavelength, change of the beam energy relative to the resonance energy), taper the wiggler with various profiles and phase shift the electron bunches relative to the bucket. It turns out that such a combination of controls can improve η considerably, as noted by P. Sprangle et al. [20]

To get a simple comparison to a traditional oscillator, we note that for an oscillator with N periods wiggler the energy fraction converted to FEL power is 1/4N. The total fractional energy spread is given by 2/N. Dividing the two quantities gives us $\eta=1/8$. What about an amplifier? Let us use a simple example of a tapered wiggler. Let α be the fraction of the bunch trapped in the decelerating separatrix, which is decelerated to energy E_1. Assume that the rest of the beam stays at the original energy E_0. The energy spread (neglecting the size of the separatrix) is E_0-E_1. The extracted energy is $\alpha(E_0-E_1)$. This results $\eta=\alpha$. If we capture half the electrons and taper the wiggler enough to be able to neglect the size of the separatrix, then η can be 0.5, a large improvement over the basic oscillator's 0.125. If we can capture at any point the electrons that were not originally captured by the separatrix, we may improve η even more.

Working with 1-D theory, it is easy to write a small program that integrates the equations of motion [21] of the electrons in the wiggler and see what η one can achieve. The results which were achieved (without necessarily getting the best possible result) were $\eta=0.64$ with a 5.7% fractional energy extraction. This was achieved using a combination of detuning, slight taper at about the middle of the wiggler, a phase shift and taper at the end of the wiggler.

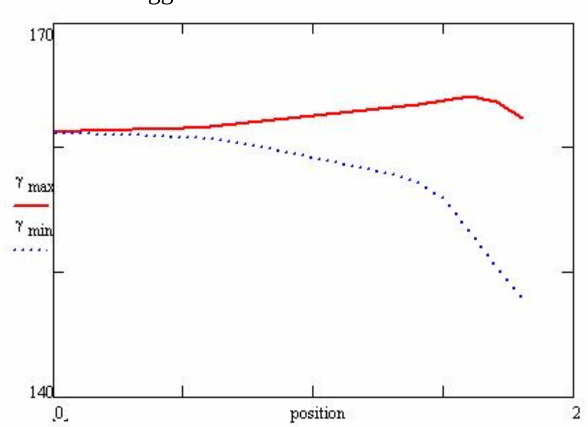

Figure 1: The relativistic energy factor of the electrons with the maximum energy (red continuous curve) and the ones with the lowest energy (blue dots) as a function of position along the wiggler.

Note that by manipulating the separatrix towards the end of the wiggler by a combination of taper and phase shift the highest energy electrons were decelerated.

2) The need to accelerate the electron beam to a sufficiently high energy in order to merge the ERL low energy beam entering the ERL linac from the injector with the high energy beam returning for deceleration. It has been considered that bending a high-charge, low energy beam leads to a large emittance increase in the bend plane. This requirement has been dealt with by the work of the electron cooling group at BNL [18]. By using a new beam merger layout, the "Z-bend", the emittance increase in the bend plane which traditionally plagued any magnetic bend in a low-energy, high-brightness linac has been reduced to a negligible value. Thus emittance increase due to low injection energy can be tamed to preserve the beam quality.

3) Providing a debunching cavity. The energy spread introduced by the FEL can be reduced to some extent by stretching the electron bun and then debunching it with a dedicated debunching cavity. This approach does not require dephasing one of the ERL cavities and thus unbalance the energy recovery. The debunching cavity operates at a zero crossing phase and thus does not spend or extract energy from the beam. The limit to which this debunching can be applied is limited by the area of the longitudinal phase space and the curvature of the decelerating field of the ERL. Thus there is an maximal degree of reducing the energy spread by debunching. This method was described earlier [5].

4) The beam dump acceptance. The decelerated beam to be dumped carries a large fraction of the energy spread introduced by the FEL.

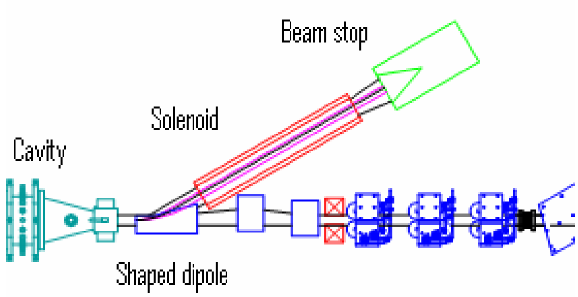

Figure 2: Beam dump with a large energy acceptance

The larger this fraction is, the lower can be the beam dump energy (and consequently the injector energy V_i). Below we describe this simple but extremely effective beam dump optical system. The large acceptance beam dump is shown in Figure 2. It consists of a low field, shaped dipole magnet and a solenoid. This 8 cm diameter, 1000 Gauss solenoid confines the beam with a large energy spread and leads it to the beam stop. The shaped dipole provides an extra kick to the higher energy electrons to reduce the initial angular spread of the beam entering the solenoid. Simulations show that a beam with 1.4 nC bunches, at a kinetic energy of 2.5 MeV, with energy spread of dE= +/- 1MeV and a normalized emittance of 10 microns RMS will be easily accepted by the system, that is an energy acceptance of +/- 40%.

Finally, let us also mention that an amplifier allows one to inject a number of harmonics of the seed laser, arranged in a way practiced in accelerator physics harmonic bunching to increase the trapping efficiency.

DESIGN OF A HIGH POWER FEL AMPLIFIER AT BNL

We propose the construction of a high power FEL amplifier at BNL, using the ERL elements described above which are under construction by Advanced Energy Systems, Inc., our industrial partner in all these developments.

The layout of the system is described in Figure 3. The system is compact due to the amplifier configuration and thus the elimination of a resonator. Another measure of its compactness is due to the two-pass ERL. The cryomodule will contain two 5-cell cavities, each providing 20 MV acceleration. The final energy for the FEL amplifier is 80 MeV. A harmonic cavity is provided at the first pass to linearize the longitudinal phase space. The SRF laser-photocathode RF gun is shown on the left. The undulator will be about 3 m long, however there is enough space to provide an even longer undulator. The system is shown with the new design of the beam dump.

The FEL performance parameters for this ERL were calculated using Ming Xie's [14] expressions. It is expected that a 3-D FEL simulation will result somewhat different results, in particular a slightly longer gain length and Rayleigh range due to space charge effects [19].

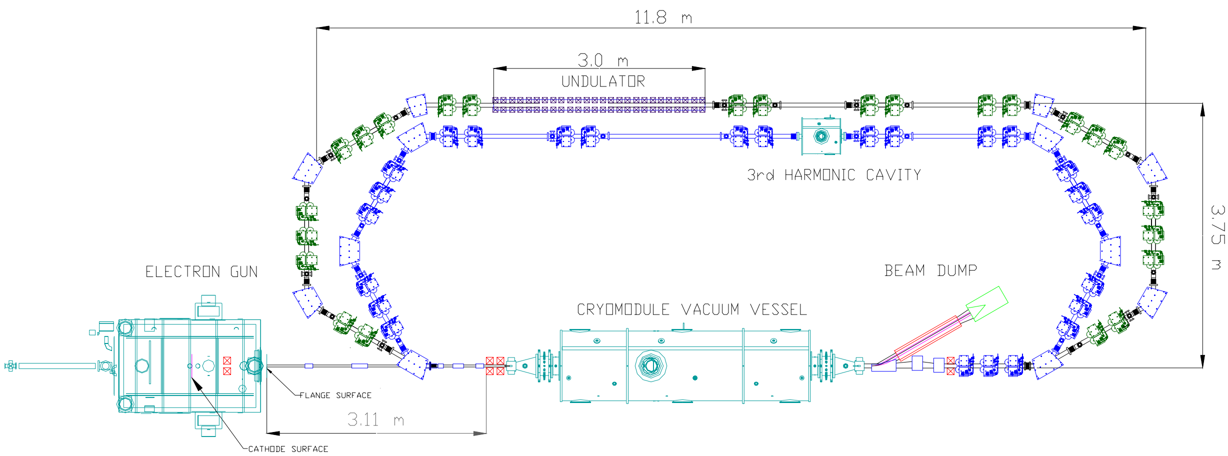

Figure 3 Layout of the proposed FEL amplifier.

Table 1: Expected parameters of ERL-based FEL amplifier at BNL.

Energy	80 MeV
Bunch charge	1.4 nC
Current (average)	0.5 ampere
Emittance, normalized	_3.3 µ rms
Energy spread	_~0.3%
Peak current	_254 amperes
Wiggler length	_3.2 m
Wiggler period	_3.2 cm
Betatron wave number	_3.5 m^{-1}
Wiggler gap	_1 cm
Field, Nd:Fe:B Halbach	0.36 T
Input seed power to makes 100 kW	10 W
Wavelength	_1.03 µm
FEL gain length	_28.5 cm
ρ	~ 0.01
FEL power at saturation	_0.39 MW
Rayleigh range	_5 cm

It worth mentioning that FEL saturation power for the above system is 0.39 MW, hence 100 kW level can be achieved within a large margin for error. The parameters include no detuning or tapering. Or any other methods to enhance efficiency described above. The system described above will put to the test a number of the elements described above, such as a high efficiency FEL amplifier, a two turn superconducting ERL with harmonic correction of the acceleration wavefront, a superconducting RF gun with high-brightness and high average current and the Z-bend merger.

SUMMARY

We presented briefly the development of FEL amplifiers of various types and then concentrated on the issues of high power FEL optical amplifiers. High power in this context is the range between 100 kW and 1000 kW average power. We discussed the features of high-current, high-brightness superconducting energy recovery linacs in the context of the required ampere class average current electron beams, and noted the development of ERL cavities and superconducting laser photocathode RF gun capable of achieving the required performance, as exemplified by the BNL / AES devices currently under construction. Following that we addressed the main issues of high power FEL amplifiers. We noted the advantage of the amplifier which is the absence of a resonator cavity with the high intra-cavity power which makes oscillators susceptible to radiation damage and pointed out that the amplifier can achieve the short Rayleigh range that allows one to place the first optical element not too far from the wiggler. Then we discussed the improvement of the wall-plug power which can be made in an amplifier configuration and significant reduction of the beam dump power by various means. In particular we introduced the possibility of reducing the energy spread introduced by the FEL for a given radiation power by a combination of detuning, tapering and phase-shifting, showing a remarkable improvement in this measure. We described two new beam optical elements developed by our team, the Z-bend and the large energy acceptance beam dump. Both elements are related to the trend to increase the efficiency and reduce the injector energy. In particular the Z-bend preserves the beam quality in a low energy ERL beam merger. Finally we described a proposal for a multi 100 kW-range FEL amplifier, to be constructed around the ERL under construction at BNL.

ACKNOWLEDGEMENTS

This manuscript has been authored by Brookhaven Science Associates, LLC under Contract No. DE-AC02-98CH10886 with the U.S. Department of Energy. The United States Government retains, and the publisher, by accepting the article for publication, acknowledges, a world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for the United States Government purposes. Partial support by the U.S. Department of Defense High Energy Laser Joint Technology Office is acknowledged.

REFERENCES

[1] L.R. Elias, W.M. Fairbank, J.M.J. Madey, H.A. Schwettman and T.I. Smith, "Observation of Stimulated Emission of Radiation by Relativistic Electrons in a Spatially Periodic Transverse Magnetic Field", Phys. Rev. Let. **36**, 717 (1976)

[2] Miller, J.L.; Chambers, F.W.; Chong, Y.P.; Edighoffer, J.A.; Orzechowski, T.J.; Prosnitz, D.; Scharlemann, E.T.; Halbach, K.. "High Gain 10.6-micron Free-electron Laser Amplifier", IEEE Lasers and Electro-Optics Society Conference Proceedings. LEOS '88, p.349, 2-4 Nov. 1988.

[3] L.-H. Yu, M. Babzien, I. Ben-Zvi, L.F. DiMauro, A. Doyuran, W. Graves, E. Johnson, S. Krinsky, R. Malone, I. Pogorelsky, J. Skaritka, G. Rakowsky, L. Solomon, X.J. Wang, M. Woodle, V. Yakimenko, S.G. Biedron, J.N. Galayda, E. Gluskin, J. Jagger, V. Sajaev, I. Vasserman, High-Gain Harmonic-Generation Free-Electron Laser, Science, **289** (2000) 932

[4] G. Neil, "The JLab High Power ERL Light Source," Proceedings ERL'05 workshop, Newport News, VA, March 20-23, 2005.

[5] C. Pagani, E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, "Design Considerations of a MW-Scale, High-Efficiency, Industrial-Use, Ultraviolet FEL Amplifier", Proceedings of EPAC 2000, Vienna, Austria, p. 773 (2000).

[6] M. Liepe, et al, "Pushing the Limits: RF Field Control at High Loaded Q", proceedings PAC'05, Knoxville TN, May 16-20, 2005.

[7] G.H. Hoffstaetter and I.V. Bazarov, "Beam-breakup instability theory for energy recovery linacs", Phys. Rev. ST AB 7, 054401 (2004).

[8] R. Calaga, "Optimizing the cavity shape for ERLs", Proceedings ERL'05 workshop, Newport News, VA, March 20-23, 2005.

[9] R. Calaga, I. Ben-Zvi, Y. Zhao and J. Sekutowicz, "High Current Superconducting Cavities at RHIC", Proc. EPAC'04, 5-9 July 2004, Lucerne, Switzerland, BNL-72065-2004-CP.

[10] R. Calaga, "ERL 5-cell cavity design for high currents", proceedings 2005 International SRF Workshop, Cornell University, July 10-15, 2005.

[11] D. Janssen, "Review on superconducting RF guns", proceedings 2005 International SRF Workshop, Cornell University, July 10-15, 2005.

[12] R. Calaga, I. Ben-Zvi, X. Chang, D. Kayran, V. Litvinenko, "High Current Superconducting Gun at 703.75 MHz", proceedings of the 2005 International SRF Workshop, Cornell University, July 10-15, 2005.

[13] A. Murokh et al.,"Properties of the ultrashort gain length, self-amplified spontaneous emission free-electron laser in the linear regime and saturation", Phys. Rev. E **67**, 066501 (2003).

[14] Ming Xie, "Exact and Variational Solutions of 3D Eigenmodes in High Gain FELs", LBNL-44381, CBP Note-323, 1999

[15] S. Reiche, "GENESIS 1.3: a fully 3D time-dependent FEL simulation code", Nuclear Instruments and Methods in Physics Research A **429** (1999) 243}248

[16] P. Sprangle, B. Hafizi, and J. R. Peñano, "Design of a Compact, Optically Guided, Pinched, Megawatt Class Free-Electron Laser", IEEE J. of Quantum Electronics **40**, 1739 (2004).

[17] L.-H. Yu, et. el., "Short Rayleigh Range Free Electron Laser Amplifiers", Proceedings 2005 International FEL Conference, Stanford CA, August 22-26, 2005, TUPP044.
T. Watanabe, et. al., "Design Studies of a Short Rayleigh Length FEL Amplifier Based on the VISA Undulator", Proceedings 2005 International FEL Conference, Stanford CA, August 22-26, 2005, TUPP046.

[18] D. Kayran and V. Litvinenko, "A Method of Emittance Preservation in ERL Merging System", Proceedings 2005 International FEL Conference, Stanford CA, August 22-26, 2005, THPP071.

[19] Sven Reiche, private communication.

[20] P. Sprangle, C.-M. Tang, W.M. Manheimer, Phys. Rev. A **21**, 302 (1980)

[21] N.M. Kroll, P.L. Morton and M.N. Rosenbluth, "Variable parameter Free Electron Laser", Presented at the ONR Workshop on Electron Generators of Coherent Radiation, Telluride, Colorado, August 13-17, 1979.) SLAC Pub.2371, 1979.