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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

# A status report on the development of a high power UV and IR FEL at CEBAF

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**Abstract**

Previously we presented a design for a kiloWatt demonstration industrial UV FEL [1]. Progress has been made in resolving several design issues identified in that work. More exact simulations of the injector have resulted in a better estimate of the injector performance. A more compact lattice has been designed meeting the design requirements for the UV FEL, and a new design point has been studied which greatly increases the threshold for longitudinal instabilities. A stability analysis of the RF control system has found that only minor modifications from existing CEBAF controls will be necessary to allow them to be used with a high-current, energy-recovery accelerator. Designs for the optical cavity length and figure systems have been conceptualized and a model of the corner-cube resonator is being built and tested. Finally, three-dimensional simulations of the FEL have been carried out which show that the laser should exceed its minimum design goals for average power.

## 1. Introduction

At the 16th International FEL Conference, we described the design of a UV free-electron laser (FEL) featuring a superconducting accelerator and energy recovery [1]. This design would test the technologies necessary for scale-up to a 100-kW-class free-electron laser for industrial processing. The design consists of a 10 MV high-brightness electron injector, a two-pass, 190 MeV accelerator, and a wiggler within a 64 meter optical resonator. The exhaust electron beam from the FEL is decelerated for energy recovery and dumped at 10 MeV.

We have carried out a design optimization procedure to streamline the accelerator and FEL design, reduce the overall project risk, and resolve several problematic issues. The risk was reduced by quantifying the performance degradation from the elements that have the most technical risk and spreading the performance sensitivity evenly among the critical technologies. We have identified the critical issues in the design of a UV FEL driven by an energy-recovery linac:

- One must achieve high brightness with a continuously pulsed, high-charge electron beam.
- Emittance growth in such a machine must be carefully controlled.
- An accelerator with a net synchrotron tune of one half is inherently unstable and must have active feedback control [2].
- Beam losses in a high power machine must be kept very small both for machine protection and to ensure RF stability.
- Mirror coatings in the deep UV are lossy. This leads to problems with poor output coupling and mirror distortion.

We also considered other parameters which might affect FEL performance. In all other cases, either the FEL performance was insensitive to the parameter or the parameter was easily achieved.

Several key parameters were changed from the original design. A design optimization versus electron bunch charge found that a charge of only 135 pC was nearly optimum for our baseline design. The repetition rate of the

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injector was therefore changed to 37.425 MHz. We found that bunching at 200 MeV can produce quite short bunches. We now assume a bunch length of only 0.5 ps with a peak current of 270 A, and our goal for the normalized transverse emittance at the FEL is $11\pi$ mm mra$11\pi$ mm mrad. It is assumed that the wiggler will be the same as those now being used in the Advanced Photon Source at Argonne National Laboratory. These have a 3.3 cm wiggler period and 72 periods.

## 2. Injector

We have enhanced the injector model to include accurate three-dimensional fields for the superconducting cavities and accurate two-dimensional models for the solenoids and the buncher cavity [3]. The space charge algorithm was improved and benchmarked against ISIS [4]. The new simulations indicate that a 135-pC bunch can be accelerated to 10 MeV and injected into the accelerator while maintaining normalized transverse and longitudinal emittances of less than $5\pi$ mm mrad and $20\pi$ keV deg.

An injector test stand is under construction at CEBAF to test the injector design. A shielded enclosure has been modified to accept the injector. Rooms to house the control system, the photocathode drive laser, and the high power supply have been constructed. The vacuum chambers, $SF_6$ tank, and the support structure for the gun are complete. High voltage electrodes are almost complete and assembly has begun on the gun. The cryounit and RF systems are scheduled to be completed by the end of this year. Prototypes of high power windows and high power couplers have been fabricated and successfully tested.

## 3. Lattice design

We have modified the previous lattice design to improve the injection and extraction of the 10 MeV beams and to decrease the footprint of the accelerator [5]. The new design allows the energy of the accelerator to be changed independently from the injector and allows operation at half energy with only one accelerating pass for infrared operation. A bypass has been designed to accommodate a 5.4 meter optical klystron for infrared operation.

## 4. Energy stability

Recirculating, energy-recovering accelerators exhibit instabilities which arise from fluctuations of the cavity fields. Energy changes can cause beam loss on apertures, or, when coupled to $M_{56}$, phase oscillations. Both effects change the beam induced voltage in the cavities and can lead to unstable variations of the accelerating field. Stability analysis for small perturbations from equilibrium has been performed [2] and the threshold current for the CEBAF FEL has been determined to be 300 μA. The model has been extended to include amplitude and phase feedback, with the transfer function of the feedback presently modeled as a low-pass filter. It was found that, for small variations, modest gain frequencies, well within CEBAF's RF control system capability, are required to stabilize the system.

## 5. Resonator modeling

To handle the high average power density in the UV demo with reasonable mode quality we plan to use a retro-reflecting, re-imaged, ring resonator (or R5 resonator) [6]. The R5 resonator is a negative-branch, unstable resonator with scraper output coupling. This design has the advantage of using all reflective surfaces. The lowest order mode of this resonator has a top hat profile at the scraper and an Airy profile at the wiggler. Simulations both with a Beer's-law gain profile and FELEX [7] show that the presence of the wiggler bore and a gain medium rounds the top hat profile and reduces the output coupling for a given magnification. The gain of this mode is less than that of a Gaussian mode. Gaussian mode simulations at 200 nm predict a gain of 125% while FELEX predicts approximately 100%. The Gaussian simulation predicts a peak power output of 130 MW while the FELEX simulation predicts a power output of 70 MW. Given a duty cycle of $1.8 \times 10^{-5}$ the average power is then greater than 1300 W. An interesting feature of the FELEX simulations is that the power output is insensitive to the electron beam focussing, contrary to expectations.

A serious disadvantage of the R5 resonator design is the need for six reflections in each round trip. Though mirrors are quite adequate for wavelengths longer than 250 nm, the reflectivity of mirrors in the deep UV is typically 98–99% for normal incidence and is usually only about 92% for a 54° p-plane reflection. We are working with the University of Arizona Optical Science Center to develop deep UV optics with higher p-plane reflectivity. If this does not work, we will use a roof-top reflector with all s-plane reflections, which is quite adequate for the kiloWatt demonstrator but is not scalable to the 100 kW device.

To test such issues as depolarization, net reflection, length control, and figure control, we are building a full size mockup of the R5 resonator using mirrors with reflective coatings at 630 nm. This will allow us to test the basic design of the resonator before building the final device.

## 6. Conclusions

Optimization studies for the UV FEL have produced a robust design that meets the minimum requirements of the users. Several potential problems have been extensively studied and found soluble. We are continuing the study of the emittance growth of short electron beams, which might be enhanced by coherent synchrotron emission, and overall phase and gradient stability of energy recovered systems. The lattice is also being optimized to reduce component count and cost.

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