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THE LOS ALAMOS HIGH-BRIGHTNESS ACCELERATOR FEL (HIBAF) FACILITY*

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Abstract

The 10-μm Los Alamos free-electron laser (FEL) facility is being upgraded. The conventional electron gun and bunchers have been replaced with a much more compact 6-MeV photoinjector accelerator. By adding existing parts from previous experiments, the primary beam energy will be doubled to 40 MeV. With the existing 1-m wiggler ($\lambda_w = 2.7$ cm) and resonator, the facility can produce photons with wavelengths from 3 to 100 μm when lasing on the fundamental mode and produce photons in the visible spectrum with short-period wigglers or harmonic operation. After installation of a 150° bend, a second wiggler will be added as an amplifier. The installation of laser transport tubes between the accelerator vault and an upstairs laboratory will provide experimenters with a radiation-free environment for experiments. Although the initial experimental program of the upgraded facility will be to test the single accelerator master oscillator/power amplifier configuration, some portion of the operational time of the facility can be dedicated to user experiments.

During the past several years, the 10-μm Los Alamos FEL program has been very successful in the development of FEL technology. Table 1 shows a list of major accomplishments at the facility since it was commissioned in 1981. Fig. 1 shows the basic facility configuration. During fiscal 1989, the conventional electron gun and bunchers are

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being replaced with a photocathode RF gun based on technology developed at Los Alamos [1]. This change plus the addition of an existing fourth accelerator tank used on the energy recovery experiment [2] will raise the primary electron beam energy to 40 MeV. The original optical resonator will remain basically unchanged, but installation of a second wiggler [3] will allow investigation of the single accelerator master oscillator/power amplifier (SAMOPA) concept.

If the degradation of the beam quality caused by the FEL interaction in the first wiggler can be sufficiently minimized, then the SAMOPA can be as efficient as a conventional, two-electron beam MOPA. A substantial cost savings results by elimination of the second accelerator system. The SAMOPA concept is of interest for space-based FEL applications.

Fig. 2 shows the Los Alamos FEL reconfigured into the High-Brightness Accelerator FEL (HIBAF) facility. Replacing the conventional high-voltage electron gun and bunchers with a photocathode RF gun significantly improves the brightness of the resulting electron beam. HIBAF is the first FEL designed using the integrated numerical experiment (INEX) approach. INEX calculations indicate that the emittance of the electron beam can be decreased by a factor of 4 to 8 when compared to that of conventional high-voltage gun and buncher systems. The photoinjector accelerator tank (fig. 3) is an on-axis coupled device operating at 1300 MHz with an average acceleration gradient of 10 MeV/m. Table 2 describes the relevant design features of this device.

Photocathodes will eventually be fabricated in groups of six and stored in a portable "6-pack" container. After the 6-pack is attached to the accelerator, the cathodes can be selected one at a time and inserted into the first cell of the accelerator without breaking vacuum. Based on previous experimental results [4], we expect each cathode to last at least four weeks at the HIBAF duty factor. Hence, a 6-pack of cathodes should be sufficient for six months of operation.

The photocathode drive laser is a frequency doubled Nd:YLF laser operating at 527 nm The laser is mode locked at the 12th subharmonic of the 1300 MHz accelerator frequency

Pockels cells are used to select a 100-μs time slice of micropulses. A divide-by-5 chopper reduces the micropulse repetition rate to the 21.67-MHz rate required by the 7-m optical resonator. Fig. 4 summarizes the properties of the photocathode drive laser and of the resulting electron beam from the photoinjector.

The 6-MeV beam from the photoinjector is accelerated to 40 MeV by three side-coupled accelerator structures. An achromatic and isochronous 60° bend brings the electron beam into the optical resonator cavity. Table 3 summarizes the beam characteristics expected at the entrance to the first wiggler. Table 4 shows the expected FEL gains and saturated power levels using various wigglers with HIBAF operating in the oscillator mode.

Following the first wiggler, a 150° bend is used to transport the electron beam to the second wiggler (fig. 2). Reconfiguration of the layout of the accelerator and resonator would have allowed installation of the second wiggler without the large angle bend. However, one of the programmatic goals is to demonstrate that the electron beam quality can be preserved through the large angle bends that are typical of MOPA configurations and of energy recovery schemes. Table 5 summarizes expected gain values for SAMOPA operation using a wiggler provided by Rockwell International [3].

The primary HIBAF program goals are (1) to demonstrate operation of a high quantum efficiency photocathode RF gun on an accelerator, (2) to demonstrate production and transport of very high brightness electron beams, (3) to validate, calibrate, and develop beam diagnostic instrumentation suitable for such high-brightness beams, (4) to validate and calibrate INEX, the computational model used to design HIBAF and other FEL devices [5,6], (5) to demonstrate viable SAMOPA operation, (6) to use the facility as a test bed for new concepts [7], (7) to demonstrate the maintenance of electron-beam quality through large angle bends, and (8) to provide high quality, variable wavelength laser beams to the outside user community. With the existing 2.7 cm period oscillator wiggler, the HIBAF facility can provide beams with wavelengths varying from about 100 μm in the far infrared down to 2.7 μm when lasing on the fundamental. By a combination of harmonic operation, frequency doubling, and short-period wigglers, beams with wavelengths well into the ultraviolet can be made available.

To better accommodate outside users, as well as FEL experiments, the FEL beam is directed out of the accelerator vault and into an upstairs laboratory. This arrangement provides easy access to experiments during operation and protects personnel and sensitive electronic equipment from the high-radiation levels present in the vault.

The HIBAF facility should provide electron beams whose high-current brightness far exceeds those available at most other facilities. To produce such high-brightness beams, careful attention must be paid to all parts of the beam transport lines to minimize both the longitudinal and transverse wakefields. Effects that are completely negligible for 150- to 200-π·mm·mrad emittances become serious contributors to degradation of beam quality with 40- to 50-π·mm·mrad beams.

Such high-quality electron beams also require improvement of the diagnostics devices used previously [8]. In particular, the beam emittance will be derived from optical transition radiation (OTR) [9]. As a cross check of the OTR method, these emittance values can be compared to values obtained using more conventional but less accurate techniques. Beam-energy spread and beam micropulse information can be obtained by using a combination of magnetic spectrometers with fast and slow deflectors [10] with improved resolution. Some of the improved resolution comes naturally as a result of the reduced beam emittance; the remainder comes from improvements to the particular devices and their method of employment. For more detailed discussions of the HIBAF diagnostics, see refs. [11-13]. Additionally, the HIBAF beam quality will be sufficiently high so that the facility can be used as a test bed for debugging new FEL devices and concepts. For example table 6 shows the FEL performance expected using a short-period wiggler.

All these concepts, devices, and developments lead very naturally into what we believe to be the next generation FEL—the "compact" FEL. The combination of photocathode RF gun, high gradient accelerator structures, and short period wigglers leads to a device that is compact. Fig. 5 shows one concept for a compact FEL. The entire accelerator, photocathode drive laser, and FEL optical resonator fit on the top of a conventional 8- by 20-ft optical table. Typically, the RF drive would occupy an area of equal size. However, by using superconducting accelerator cavities and energy recovery, it is conceivable that the RF system could be included on the same table.

In conclusion, the HIBAF facility will provide one of the brightest electron beams available anywhere for continued investigation of FEL technology. Such a bright beam requires extreme care in the design and implementation of beam transport systems. Although the primary goals of the facility are to continue the development of FEL technology and the verification of the INEX design approach, some portion of the operational time can be devoted to outside user experiments. High-quality laser beams can be produced with wavelengths from the far infrared into the ultraviolet, hence, providing a unique facility for physics investigations.

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Figure Captions

Fig. 1. Outline drawing of the old Los Alamos FEL facility as it was configured from 1981 to 1988. Shown in the figure are the high-voltage electron gun with the subharmonic and fundamental buncher cavities, the two accelerator tanks, the 60° isochronous bend, the 6.9-m laser resonator, and the 1-m wiggler.

Fig. 2. Outline drawing of the Los Alamos FEL facility reconfigured into the HIBAF. Shown in the figure are the photoinjector accelerator, followed by three conventional accelerator tanks. The old 60° bend has been replaced with an isochronous and achromatic bend. The laser resonator remains as before, but the installation of a 150° bend brings the electron beam out of the resonator and directs it into a second wiggler. The FEL beam produced in the oscillator is co-directed with the electron beam into the second wiggler to produce SAMOPA operation.

Fig. 3. Cutaway drawing of the photoinjector accelerator tank. The accelerator is an on-axis coupled structure operating at 1300 MHz. To facilitate the high-vacuum requirements of the photocathode, the six-cell accelerator is encased in an insulated vacuum manifold and can be baked at up to 300°C. The vacuum is maintained by a combination of a 500 ℓ/s triode ion pump and a titanium sublimation pump. The RF power is iris coupled into the last cell of the accelerator through the WR-650 waveguide shown in the figure.

Fig. 4. Summary of the properties of the photoinjector drive laser and of the resulting electron beam produced by the photoinjector accelerator.

Fig. 5. Conceptual arrangement of a compact FEL design. The combination of photoinjector, high gradient accelerator, and short-period wiggler reduces the footprint of an FEL device to a very reasonable size. The RF power system would occupy an area of roughly equal size.

Table 1

Highlights of the Los Alamos FEL program since 1981

1981-82	Amplifier Experiment	
		Demonstrated 4% extraction efficiency with tapered wiggler amplifier
		Measured optical gain
1983-84	Oscillator Experiment	
		Achieved 10 kW output at 10 μm
		Demonstrated "perfect" optical quality
		Demonstrated tunability from 9 to 35 μm
1985-86	Energy Recovery Experiment (ERX)	
		70% of electron-beam energy recovered
		• Demonstrated stable FEL operation during recovery
		Demonstrated 2% energy extraction in oscillator
1987-88	FEL Experiments	
		Demonstrated sideband suppression using Littrow grating
		Demonstrated 5% extraction efficiency using prebuncher
		Validation of computer design codes
		Demonstrated lasing on 3rd harmonic (4 μm)
		Measured harmonic content to 7th harmonic

Table 2

Specifications for the 1300-MHz Photoinjector Linac

Electrical Properties:	
Frequency	1300 MHz
Accelerating field:	
Cell #1	26.0 MV/m
Cell #2	14.4 MV/m
Cells #3-6	10.0 MV/m
Duty factor	0.1%
Coupling factor	5.2%
Expected Q (85% SUPERFISH)	19800
Expected shunt impedance (ZT^2)	35.0 MΩ/m
Power requirements (85% SUPERFISH)	
Structure copper losses	1810.0 kW
Beam loading	600.0 kW
Length	63.415 cm
Beam performance requirements:	
Output energy	6 MeV
Bunch charge	5 nC
Beam current (average)	0.1 A
(peak)	300.0 A
Emittance (90%, normalized)	≤50 π·mm·mrad

Table 3

Predicted HIBAF beam characteristics at the oscillator wiggler

Electrical Properties:	
Beam energy	40 MeV
Energy spread	0.2%
Macropulse repetition rate	1 Hz
Macropulse length	10-100 μs
Micropulse repetition rate	21.67 MHz
Micropulse length	16 ps
Emittance	$<50\ \pi\cdot$mm$\cdot$mrad
Bunch charge	5 nC
Peak current	310 A

Table 4
Predicted HIBAF performance in the oscillator mode. The assumed electron-beam parameters are 41-MeV beam energy, 50-π·mm·mrad emittance (90%), 0.25% energy spread, and 250-A peak current. Case W1 is the existing LANL 1-m wiggler with a 12% linear taper. Case W2 is the existing LANL 1-m wiggler with a 30% parabolic taper. Case W3 is case W2 with the addition of a prebuncher wiggler. Calculations courtesy of J. C. Goldstein

A. Small signal gain values

Wiggler case	Small signal gain	Wavelength (μm)
W1	113	2.65
W2	43	2.70
W3	60	2.73

B. Power and efficiency for 20% gain

Wiggler case	Wavelength (μm)	Saturated power (GW)	Efficiency (%)
W1	2.775	3.0	3.7
W2	2.800	3.5	3.7
W3	2.725	5.0	5.5

C. Power and efficiency for 10% gain

Wiggler case	Wavelength (μm)	Saturated power (GW)	Efficiency (%)
W1	2.800	6.5	4.4
W2	2.800	9.0	5.8
W3	2.700	12.0	8.7

Table 5
Predicted HIBAF SAMOPA operation gain parameters. The assumed electron-beam parameters are 40-MeV beam energy and 50-π·mm·mrad emittance (90%). Calculations courtesy of J. C. Goldstein

Peak current	Small signal gain		Saturated signal	
	($\Delta\gamma/\gamma$ = 0.25%	0.50%)	(Pin = 1 MW	10 MW)
250 A	210	104	16.7	4.9
400 A	1067	600	48.2	8.8

Table 6
Expected HIBAF oscillator performance with a short-period wiggler ($\lambda w = 3$ mm). The assumed electron-beam parameters are 40-MeV beam energy, 50-π·mm·mrad emittance (90%), 0.25% energy spread, and 250-A peak current. Calculations courtesy of J. C. Goldstein

	N = 37 Periods (Lw = 11 cm)	N = 100 Periods (Lw = 30 cm)
Rayleigh range	25.0 cm	15.0 cm
Small signal gain	15.5%	64.0%
Optical wavelength	379.2 nm	375.0 nm
Power at saturation	1.0 GW	0.6 GW
Saturated gain	4.7%	6.1%
Saturated wavelength	386.0 nm	386.0 nm
Extraction efficiency	0.48%	0.35%