

THE DUKE FEL LIGHT SOURCE FACILITY

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Abstract

FEL research has proceeded during the last twenty five years from marginal proof of principle experiments to the construction and operation of devices optimized to provide the unique properties (peak power, tunability, and odd-wavelength capabilities) of most interest to the user community. The commissioning of the major facilities of the Duke FEL Laboratory constitutes another milestone along this path: the development of an integrated, FEL-based, research facility offering the opportunity to explore the capabilities and applications of high power, synchronized, multi-wavelength IR, UV and Gamma-ray FEL light sources. The size, cost and capabilities of such facilities appear uniquely well suited to the resources and interests of multi-disciplinary research universities.

1 INTRODUCTION

Since Ken Robinson's first musings more than thirty years ago that coherent radiation might be obtained from an appropriately designed undulator and accelerator-driver, free electron lasers have drawn attention as possible successors to incoherent e-beam based bend magnet and undulator light sources. That the technology has yet to reach the stage of widespread application is indicative of the barriers to understanding and implementation which have had to be surmounted.

Within this context, work on free electron lasers can be divided into three distinct, if overlapping, phases. The first phase, beginning with Robinson's work and continuing for perhaps 10 years past the first operation of an "optical" FEL at Stanford in 1976, focussed on the analysis of FEL operation. Though analysis and simulation continue through as vital and productive enterprises, it is also clear that the basic issues associated with FEL operation have been resolved. In this sense, the "theoretical" phase of FEL research can be characterized as nearly complete.

The "hardware" phase of "optical" FELs (infrared and shorter wavelengths) began with the first experiments at Stanford, and continues through current date, with dramatic, continuing progress in the development of high performance linac and storage ring accelerator-drivers, precision undulators, and advanced optical systems. Indeed, it has largely been the progress in e-beam and undulator hardware which has transformed FEL technology from its humble and struggling beginnings to the very respectable levels of performance now routinely attainable in the infrared, and to the recent demonstrations of UV lasing, x-ray and gamma ray production via Compton backscattering. Continued progress in these supporting technologies make it reasonably certain that capabilities of FEL technology will also continue to

advance, at least through the UV, XUV and soft x-ray regions.

The third phase of this effort might be called the "implementation" or "economic" phase, in which the objective has been to match the available technology with the applications best suited to exploit the capabilities of the technology, and most capable of supporting the costs to develop and operate the required hardware. The first efforts along these lines were begun in the mid 1980's as sponsors were found to support the exploration of the applications of the then-available prototype hardware in medicine and materials science in the United States, Europe, Japan and China.

While the results obtained to date in this third phase of the effort are encouraging, this third phase - perhaps the most critical with respect to the future of the technology - remains at an early stage of development. The developments described below reflect the efforts we have made at Duke to promote the advancement of FEL technology as part of this third phase of the effort to develop the free electron laser.

1.1 Comments on Siting Issues

The criteria by which success of an operating FEL light source facility will be measured are easy to identify: the facility should offer state-of-the-art performance, be inexpensive to build and operate, and be highly productive when evaluated in terms of the number of research projects accommodated or the utility or impact of the research performed. Note that these criteria involve both technical and siting issues: construction and operating costs will clearly depend both on the choice of technology and the skills and cost of labor, while productivity will depend both on the intrinsic capabilities of the technology and the skills and access of the investigators committed to exploring the technology.

A key issue for such FEL research centers is the number of users to be served. The challenge here is that FELs are, by their nature, devices which can serve only a limited number of users (typically one!) at a time. Though this restriction can be eased somewhat the implementation of one or more strategies to multiplex the electron beams and/or optical beams used or produced in such facilities, this restriction remains more or less intrinsic to the technology: like table-top lasers, FELs are limited in the number of users they can serve at any given time. As a consequence, FELs can not hope to justify their existence through the number of users they serve, but rather through the quality or impact of the of the research they support.

These three criteria: capabilities, cost, and productivity appear at this point in time to favor the deployment of small and medium-scale FEL technology, optimized to achieve one or more state-of-the-art capabilities, in university laboratories in which cost can

be shared with these institutions' educational and training programs, and in which expedited access can be provided to a modest number of active research groups capable of pursuing the opportunities made possible by the technology. In general, this situation is reminiscent of the time 50 years ago in which the accelerator technology available to support nuclear and high energy physics was in its infancy, and the bulk of research was performed in small- and medium-scale university research facilities.

As described in further detail below, these considerations have led to the development at Duke University of a complementary series of FELs, FEL- and e-beam based light sources, and accelerator-drivers designed to facilitate the exploration of the capabilities and applications of FEL technology in basic and applied research. The site of the facility, on the Duke campus in the Research Triangle of North Carolina adjacent to North Carolina State University, the University of North Carolina at Chapel Hill, and Research Triangle Park promotes easy access to the facility by research groups affiliated with these centers.

2 THE DUKE FACILITY

The FEL light sources and accelerator-drivers available for use within the Duke FEL Laboratory are housed in a dedicated 50,000 sq. ft. facility sited on the Duke campus next to the Triangle Universities Nuclear Laboratory. These devices include a 1 GeV electron storage ring located in the Laboratory's main bay, an ultraviolet FEL system (the OK-4 FEL) installed on the south straight section of this ring, the 280 MeV linac injector for the ring located in an underground tunnel extending 450' to the east of the Laboratory, and an independently operable infrared FEL (the MkIII FEL) located in a shielded cave adjacent to the Laboratory.

The choice of accelerator technology implemented in these devices reflects both the demanding technical requirements for FEL operation and the need to minimize acquisition and operating costs. The peak power output and tuning range of FELs are determined, primarily, by the peak current, emittance, and energy of the electron beam used as the lasing medium. Other characteristics of interest—optical pulse length, format, and average power output—follow from the time structure of the e-beam. Several means are now available to generate the e-beams required for state-of-the-art operation at infrared, ultraviolet, and extreme ultraviolet wavelengths, exploiting, respectively, the characteristics and capabilities of high gradient microwave gun injector technology and low emittance, medium energy storage ring technology.

For research facilities such as the FEL Lab at Duke, simple pulsed linac technology is attractive for operation at the lower electron energies required for infrared operation. As most of the infrared applications efforts to be pursued required either high pulse energies or high (Ghz) repetition rates, a single klystron S-band linac using a microwave thermionic gun and modified for long pulse operation to provide electron energies up to 45 MeV. With a peak current of 40 amps, this accelerator-driver permits operation of the MkIII infrared FEL system

at wavelengths as short as 1.5 microns as described in further detail below.

For the e-beam energies and currents required for ultraviolet and extreme ultraviolet FEL operation, the economy and simplicity of storage ring accelerator-drivers make that technology an attractive choice for the exploratory short-wavelength research projects to be pursued in the Duke Laboratory. Storage ring technology also provides the means to generate high peak power optical pulses in the q-switched mode of FEL operation, and also the capability to support the operation of a range of conventional undulator and bend-magnet synchrotron radiation light sources as adjuncts to FEL operation. The recently commissioned OK-4 FEL system described below, based on the Laboratories 1 GeV storage ring driver, has generated coherent light at wavelengths as short as 345 nanometers in the ultraviolet, and also been used to demonstrate the generation via intracavity Compton backscattering of near-monoenergetic polarized gamma rays at energies up to 16 MeV.

The emittance, current, and energy of the e-beams produced by the injectors and accelerator-drivers for these FELs make them useful instruments in their own right for advanced research on high brightness and high current electron beam physics and technology, including the development of new e-beam based light sources.

2.1 The MkIII FEL

The MkIII FEL was designed to satisfy the requirements projected for research on the applications of tunable, short pulse infrared laser technology in laser surgery. Projected specifications for this application included a tuning range covering from 1 to 10 microns, megawatt instantaneous peak power, (micro)pulse widths of the order of a picosecond, (macro)pulse widths of the order of 10 microseconds, and (macro)pulse energies of the order of 10-100 millijoules. Similar specifications apply for research in multiphoton photochemistry, the other major field of use for this device.

Analysis of these specifications in 1982 indicated that these requirements could be fulfilled using a single-section SLAC S-band linac driven by a long-pulse 30 megawatt klystron to achieve operation over the required energy range (28-45 MeV). A novel electron gun technology developed for this system, employing a thermionic lanthanum hexaboride button cathode mounted within a single-cell S-band accelerating cavity followed by an alpha-magnet momentum analyzer and buncher, provided the high current, low emittance e-beam required for operation [1].

The MkIII FEL system was first operated at Stanford University in 1985 [2]. Following the transfer of the FEL Laboratory to Duke in 1988, the MkIII was installed and recommissioned in the Laboratory's new facilities in 1991. The current operating specifications for this system are summarized in Table 1. Harmonic generation in phase-matched lithium niobate can be used to efficiently double the IR output of the MkIII for coverage of the spectral region at wavelengths shorter than 2 microns.

In addition to the uses contemplated for this system in surgery and multi-photon IR photochemistry, the high (2.856 GHz) rep rate train of optical pulses generated by the MkIII can be phase locked to enhance the spectral brightness by a factor of 39, thereby achieving unprecedented levels of spectrally pure, tunable, single mode optical radiation for applications requiring high spectral resolution and stability [3].

With the exception of the time lost due to the transfer of the Laboratory in 1988 and to a series of klystron-related problems in 1995 and 1996, the MkIII has reliably delivered more than 1000 hours a year of infrared radiation to its users in every year since it was first operated at Stanford.

Table: 1 Operating Parameters of the MKIII FEL System

Wavelength range	1.4 - 9.1 μm
Macropulse repetition rate	Single shot - 15 Hz
Macropulse duration	0.5 - 4 μs
Macropulse energy	1 - 100 mJ
Optical pulse repetition rate	2.86 GHz
Optical pulse width (uncompressed)	0.5 - 3 ps
Optical pulse energy	6 μJ
Peak power (uncompressed)	0.5 - 3 MW
Spectral width (transform limited)	0.3% - 2%
Strehl ratio (diffraction limited)	> 0.8

2.2 The OK-4 FEL

The OK-4 FEL system was developed in collaboration with the Budker Institute of Nuclear Physics in Novosibirsk, Russia. The system utilizes Duke's 1.1 GeV electron storage ring, and the OK-4 undulator and optical system originally developed and commissioned at Budker for use on the VEPP-3 storage ring.

Table: 2 Recent Duke Storage Ring Electron Beam Parameters [10]

Operational Energy (GeV)	0.25 - 1.1
Circumference (m)	107.46
Impedance of the ring, Z/n (Ω)	2.75 ± 0.25
Stored current (mA)	
multibunch	155
single bunch	20 / 9
Bunch length, σ_s (ps)	
natural (low current)	15
with 5 mA in single bunch	60
Relative Energy spread σ_E/E	
natural (low current)	$2.9 \cdot 10^{-4}$
at 5 mA in single bunch	$1.1 \cdot 10^{-3}$
Peak Current (A)	
with 5 mA in single bunch	12
with 20 mA in single bunch	31
Horizontal Emittance (nm * rad)	
5 mA / bunch @ 700 MeV	< 10
3 mA / bunch @ 500 MeV	< 9

The Duke ring was designed with a 34 meter straight section to accommodate a long conventional

undulators for FEL operation at extreme ultraviolet wavelengths, and to support circulating e-beams with the peak current and emittance required for operation at these wavelengths. The design of the ring is particularly noteworthy for its dynamic aperture: the lattice will contain without loss a circulating electron beam with an energy spread as large as $\pm 5\%$, permitting, in principle, the production of optical pulses with peak powers in excess of a gigawatt in the giant pulse mode [4].

The OK-4 undulator is configured as an optical klystron, comprised of two 10 cm period, 3.3 meter long electromagnetic wigglers separated by a buncher. The OK-4 optical resonator is symmetric, employing two spherical mirrors by one half the circumference of the ring with radii selected to achieve a 3.3 meter Rayleigh range equal to the length of the individual undulators [5].

The Duke storage ring was commissioned in the fall of 1994 prior to the installation of the OK-4 FEL system. The undulator and its vacuum system was installed in 1995. The e-beam parameters obtained following installation of the undulator are summarized in Table 2. Based on these e-beam parameters, the optical gain predicted for the OK-4 optical klystron and the optical losses estimated for the OK-4 resonator, the system has in its present configuration the capability to lase at wavelengths as short as 150 nanometers [6].

Table: 3 Measured Parameters of the OK-4 FEL [11]

Tuning Range (3.5 mA / bunch)	345 - 413 nm
Gain per pass (3.5 mA / bunch, 345 nm)	> 9%
Extracted Power (8 mA, single bunch, 380 nm)	0.15 W
Induced e-bunch length, σ_s (ps)	
low current	~35
with 3.5 mA in single bunch	~200
Induced energy spread (3.5 mA / bunch), σ_E/E	0.35%
FEL pulse length (ps)	
low current	~2.5
with 3.5 mA in single bunch	~20
Linewidth σ_λ/λ	$4 \cdot 10^{-4}$
Lasing life-time	2 - 4 hours

Lasing was demonstrated using the OK-4 system in the wavelength region between 345 and 413 nanometers in November 1996. The performance attained in this series of runs is summarized in Table 3. The parameters summarized in Table 3 correspond closely to those predicted by simulations of the system [7].

One of the most impressive results obtained during the November, 1996 run was the demonstration of the production of polarized, near monoenergetic gamma rays via intracavity Compton backscattering. In these experiments, a second bunch was injected into the ring separated from the first bunch by half the circumference of the ring. In this configuration, the laser radiation stored in the optical cavity collided head-on with the second stored bunch, yielding back-scattered Compton photons with energies up to 16 MeV. Measurements of the spectrum of

the backscattered photons showed that the energy spread could be reduced to 1.2% by collimation, in full accordance with theory [8]. The properties of the backscattered photons, allowing for the anticipated improvements in stored optical power and electron current, are of significant interest for applications ranging from precision nuclear spectroscopy to radiotherapy.

Instabilities in the power supply for the OK-4's buncher magnet in the November, 1996 run interfered with attempts to achieve lasing at shorter wavelength. However, the performance obtained at 375 nanometers, and the close correlation between simulations of the system and the observed laser parameters, give confidence that lasing can be extended to 193 nanometers and below in the system's present configuration. Improved performance should be possible following completion of the crotch chambers and absorbers required for high current operation.

2.3 Two-Color Operation

Considerable care was taken in the design of the Duke storage ring to insure that the circumference of the ring was an integral multiple of the RF wavelength (10.5 cm) at which the MkIII FEL operates. Given this integral relationship, the RF oscillators driving the high power RF systems for the ring and the MkIII can be phase-locked to permit the synchronized generation of infrared, ultraviolet, x-ray and gamma-ray pulses from these systems for use in two-color pulse-probe or two-color excitation experiments.

A proof of principle two-color IR/UV induced fluorescence experiment was conducted in 1995 to demonstrate this capability using the infrared light produced by the MkIII and the incoherent undulator radiation produced by the OK-4 FEL system [9].

3 ORGANIZATION AND FUNDING

The operating costs of the FEL light sources available in the Duke FEL Laboratory are financed by the Office of Naval Research's Medical FEL (MFEL) program through the Duke MFEL Center which provides beam time, specialized instrumentation, and other services to the researchers working in the fields of research supported by that program. These efforts currently include research on IR and UV laser surgery, imaging, and the detection and analysis of pathogens.

The development and commissioning of the MkIII and OK-4 systems, their injectors and accelerator drivers has been a joint effort of the Air Force Office of Scientific Research, the Army Strategic Defense Command and Army Research Office, the Office of Naval Research, and private donors. Special thanks are due the Office of Naval Research and the Medical FEL Program for the funds required to construct the beamlines and many other improvements required to serve the applications-oriented research efforts supported by that program.

4 FUTURE PROSPECTS

In the broadest terms, the mission of the Duke FEL Laboratory is to establish and nourish the partnership between researchers, technologists and engineers necessary

to explore and evaluate the utility of FEL technology in basic and applied research. Only through such a partnership can the ingredients necessary to design, develop and apply this new technology be assembled in useful form.

It can reasonably be asserted that, with the commissioning of the major facilities of the Duke FEL Laboratory, a number of the key ingredients necessary to establish this partnership have been set in place: the operation of this facility demonstrates with reasonable clarity that the scientific and engineering community can provide the physical assets required to establish this partnership in a site as favorable as might be imagined with respect to the exploration of the technology. The commitment of operating funds by the Medical FEL program and the involvement of the researchers supported by that program is also reassuring.

What remains to be demonstrated is the broad intellectual contact and understanding which is a precondition both to the effective utilization of the technology and to the determination the lines of future development most critical to the interests of the research community. The attainment of this contact will require a continuing commitment not only to user support but to bilateral communications and understanding, a challenge equal to any of those with which we have had to deal in the prior phases of FEL development. The implementation of a collaborative, multidisciplinary approach to the applications research programs, encouraging the continued involvement and contributions of the FEL and accelerator technologists responsible for the facility, appears essential to bringing the technology to the point of successful application.

At Duke, we look forward in addition to the expansion of the physical facilities available to support the applications oriented research programs of the Laboratory and the MFEL Center, particularly the construction of the Keck Life Sciences Research Laboratory supported by a grant from the Keck Foundation, and the furnishing of this facility through an equipment grant funded by the Office of Naval Research. Construction of this facility will expand the space available for applications-oriented research by nearly an order of magnitude, to 5000 sq. ft.

We also look forward to the initiation of collaborative research programs in those additional areas of research which have the prospect of securing some benefit through the exploitation of FEL technology including those opportunities in spectroscopy, materials and nuclear research which have evoked the most active expressions of interest from our colleagues.

5 REFERENCES

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