TOWARDS SHORT WAVELENGTH FELs WORKSHOP*

BNL, May 21-22, 1993

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* This work was performed under the auspices of the US Department of Energy.

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EXECUTIVE SUMMARY

This workshop was called because of the growing perception in the FEL source community that recent advances have made it possible to extend FEL operation to wavelengths about two orders of magnitude shorter than the 240 nm that has been achieved to date. In addition short wavelength FELs offer the possibilities of extremely high peak power (several gigawatts) and very short pulses (of the order of 100 fs).

Several groups in the USA are developing plans for such short wavelength FEL facilities. However, reviewers of these plans have pointed out that it would be highly desirable to first carry out proof-of-principle experiments at longer wavelengths to increase confidence that the shorter wavelength devices will indeed perform as calculated. The need for such experiments has now been broadly accepted by the FEL community. Such experiments were the main focus of this workshop as described in the following objectives distributed to attendees:

OBJECTIVES

1. Define measurements needed to gain confidence that short wavelength FELs will perform as calculated.

2. List possible hardware that could be used to carry out these measurements in the near term.

3. Define a prioritized FEL physics experimental program and suggested timetable.

4. Form collaborative teams to carry out this program.

Other workshops [1,2,3,4,5,6] have begun to address the scientific opportunities such FELs would create. A comprehensive study of these

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[1] Application of Coherent XUV Radiation Workshop, Los Alamos Nat'l Lab., Feb. 7, 1986. B.E. Newnam Ed.

[2] FEL Applications in the Ultraviolet, Opt. Soc. Amer. Topical Meeting, Cloudcroft, New Mexico, March 1988. D.A.G. Deacon and B.E. Newnam Eds. J. Opt. Amer. 8 May (1989)

opportunities by the National Academy of Sciences is to start this year, funded by the Department of Energy.

Over 60 scientists from 22 institutions attended this workshop. To get a perspective on future FEL facilities, the workshop opened with a session on *Applications and Facility Plans* chaired by Martin Blume of BNL. The session began with a talk on applications and technical requirements by Erik Johnson of BNL (see section A of this report). This was followed by presentations of plans for future short wavelength FEL facilities at BNL, Continuous Electron Beam Accelerator Facility (CEBAF), Duke University, Los Alamos National Laboratory (LANL), and Stanford Linear Accelerator Center (SLAC). These are summarized in section B of this report. Following this, Andrew Sessler of Lawrence Berkeley Laboratory (LBL) chaired a panel discussion of *Defining Critical Experiments and Their Parameters*. The panel, along with contributions from workshop participants, led to a definition of the most important measurements that should be carried out in proof-of-principle experiments. These measurements are described in detail in section C of this report and are summarized below:

Four types of FELs were considered: oscillators on RF-linacs and storage rings, and linac-based FEL amplifiers using self-amplified spontaneous emission and harmonic generation.

Much of the panel's discussion focused on the direction of research in FEL amplifiers. The BNL and SLAC amplifier proposals involve electron beams produced by bright photoinjector RF guns, operating at 2856 MHz. While this technology has been quite successful, further development will be beneficial. Compensation for the space-charge component of emittance, using solenoid or quadrupole focusing of the gun beam, is also critical.

After the gun, the beam must be accelerated and the bunch length must be compressed to attain the required energy and peak current. During these processes, the emittance must be kept small with a high degree of stability. Bunch compression increases the sensitivity to jitter,

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[3] Report from the NSLS Workshop on Sources and Applications of High Intensity UV-VUV Light, E.D. Johnson and J.B. Hastings Eds. January 1990, BNL Informal Report 45499.

[4] Scientific Applications of Short Wavelength Coherent Sources Workshop; SLAC, Oct 21,1992. SLAC Report 414, W. Spicer, J. Arthur and H. Winick Eds.

[5] Prospects for a 1 Å Free-Electron Laser Workshop; Sag Harbor NY April 22-27, 1990. BNL Report 52273. J. Gallardo, Ed.

[6] Soft X-ray Science with the Duke FEL Lab Radiation Sources Workshop, Durham NC March 1993. To appear in Journal of X-ray Science and Technology, L. Knight, Ed.

making the stability difficult to achieve. A demonstration experiment is desirable for verification.

Previous SASE experiments in the exponential-growth regime were conducted at LLNL at millimeter wavelengths. It was noted that noise was higher than expected in these cases. It is critical to study, at a wavelength intermediate between millimeter waves and ultraviolet or shorter, the start-up of an FEL from noise, exponential growth over several gain lengths, and saturation. Information is needed about such issues as optical guiding and the transverse mode structure; the saturation length and power; spatial and temporal coherence; and fluctuations in position, wavelength, and power. It was agreed that infrared wavelengths are suitable for this step but it could also be done at shorter wavelengths. Two IR experiments, using SASE at UCLA (10 μm) and harmonic generation at BNL (10 μm, converted to 3 μm), are directed at these questions. This infrared work should then be followed by a similar demonstration of SASE in the VUV, at about 100 nm or shorter. The longer wigglers required in the VUV will allow tests of the sensitivity to field and steering errors, and the effect of external focusing. Techniques for building and aligning long, high-field wigglers, and for steering, focusing, and diagnosing beams within them, must be developed. These experiments would provide the confidence to proceed with the short-wavelength FEL amplifiers being proposed.

FEL oscillators have operated in the near UV, (240 nm at Novosibirsk, 350 nm at Orsay and 370 nm at LANL). The necessary electron beam brightness and current for shorter wavelength operation have been achieved at LANL and BNL. The required wiggler length and magnetic field precision have been built at a few locations. For FEL oscillators to reach the deep XUV or soft x-ray wavelength ranges, the primary obstacle is the demonstration of a wavelength-scalable optical resonator design. Such a resonator, the multifaceted-mirror ring, has been proposed, and so the critical technology-demonstration experiment for FEL oscillators (on either a linac or storage ring) would be operation with a ring resonator at a suitably short wavelength (<100 nm). The many associated issues - alignment and stability of the resonator, vacuum problems and mirror degradation, the stability of the e-beam, "high"-gain mode-distortion interactions with the empty-cavity optical mode structure, efficient outcoupling, thermal distortion of the mirrors - would necessarily be addressed by this experiment.

A session on the *Availability of Resources*, chaired by George Neil of CEBAF, followed. In this session, various groups described existing equipment that could be used to carry out proof-of-principle experiments. Equipment that was clearly not available within a time frame of 2-3 years was not considered. The equipment that might be used is described in detail in section D of this report and is summarized in the three tables below:

Table 1: Available Injectors

	Units	APEX	AFEL	BAC	BNL	Duke	CEBAF	Grumman	UCLA
E	MeV	6	17	5	4.5	.85	10	10	4.5
f	MHz	1300	1300	433	2856	2856	1500	2856	2856

Table 2: Available Accelerators

		APEX	BAC	BNL-ATF	BNL	CEBAF	Duke injec.	Duke SR	SLAC
E	GeV	0.045	0.22	0.05	0.23	0.8	.25/.8	1	<50
f	MHz	1300	1300	2856	2856	1500	2856	178	2856
T_{mac}	μS	100	250	3	3	CW	8/1	CW	3

Table 3: Available Wigglers

		BNL	LANL	LANL	NISUS	NIST	OK-4	UCLA	Thunder
λ_W	cm	1.8	1.3	2.05	3.9	2.8	10	1.5	2.18
L_W	m	2	1	1	10	2X1.8	7.14	.6	5
a_W	peak	<1.3	.8	1.25	<2	1	<5.4	.7	1.85

In most cases the equipment located at any single site was inadequate to carry out a full program of proof-of-principle experiments. This led to consideration of collaborations to collect at one site enough equipment from several sites to minimize the cost of constructing new equipment. This phase of the workshop started as a group discussion, chaired by Brian Newnam of LANL.

During this session, the workshop participants reached consensus on several criteria that would be useful in establishing a prioritized FEL experimental program for extending FEL operation into the extreme ultraviolet and beyond. It was agreed to focus our efforts on a few key experiments that would make maximum impact with limited funds. Lasing between 50-100 nm with power output greater than 10^3 above other radiation sources was set as a highly significant goal that should attract support for developing FELs as the next-generation light source.

In addition, such experiments should demonstrate principles that would enable scaling to even shorter wavelengths, e.g. ~4 nm. The period for achieving these goals was set at two to three years.

Three working groups were established to meet during subsequent sessions to develop experimental programs based on collaborations among the various institutions who could contribute hardware and/or expertise. The working groups were assigned the task of assembling relevant experiments utilizing, to the greatest extent possible, existing equipment and facilities.

These groups and their chairmen were: 1) linac-driven amplifiers (both injection-seeded and self amplified spontaneous emission) led by Alan Fisher of BNL and Kwang-Je Kim of LBL, 2) linac driven oscillators led by Charles Brau of Vanderbilt University, and 3) storage-ring driven oscillators and amplifiers chaired by John Madey of Duke University. The summaries of these working groups are presented in detail in Section E.

During those sessions, it became apparent that a great deal of FEL expertise and FEL hardware existed in the DoE laboratories and in industry largely as a result of the SDI directed energy research build-up. Clearly there is a great deal of commonality in the overall FEL research goals of DoE and DoD and that there may be strong financial incentives to encourage formation of collaborative research teams to maximize progress in FELs and to assist in the transition of the defense lasers to a "dual use" technology.

The conversion of defense technologies to civilian applications is strongly encouraged by the current administration and efforts are already underway to examine potential medical applications of military laser equipment. The short wavelength experiments developed by this workshop will also have a direct benefit for defense and medical FELs in the following areas:

1) highly efficient tunable FEL oscillators and amplifiers
2) high power, short wavelength ring resonator technology
3) ruggedized, high brightness photocathode electron sources
4) compact, transportable FEL components

Collaboration between the DoE laboratories and industrial contractors may be the only avenue to continuation of FEL development in this era of downsized research budgets.

SECTION A: APPLICATIONS

Towards Short Wavelength FELs: Solutions Seeking Problems?

Short Wavelength Free Electron Lasers:
Sources for Fourth Generation Science

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Abstract:

An outline of some important aspects (from the users perspective) of an applications oriented FEL facility are discussed. The development of the scientific case for the BNL DUV-FEL is used to illustrate, in broad terms, characteristics of an FEL project which are important in motivating interest and participation from potential users.

Introduction:

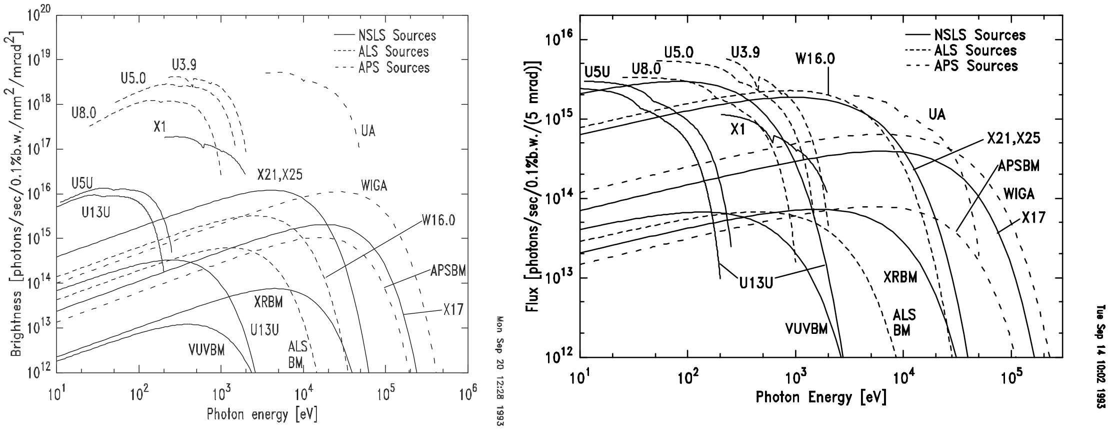
It should first be recognized that my perspective is largely dominated by my own experimental background as a user of synchrotron radiation facilities, and a recent involvement in developing the "scientific case" for an ultra-violet FEL. As a result, a certain bias is unavoidable, but some effort has gone into identifying the general features of the utility of FEL based radiation sources which for present purposes are considered to operate between the visible, and soft x-ray range (say 100 to 1 nm).

It is important to understand that the individuals attending the workshop each have their own interests and objectives. For the machine mavens, the goal is the furtherance of their research in this interesting area of accelerator physics. For the photon fiends, those truly addicted to the possibilities such a machine portends, the issue is one of motivating the construction of the right machine. The purpose of this paper is to foster some communication which might lead to a mutually beneficial interaction between these communities. To proceed in the discussion first some general considerations are mentioned, I then move to examining the case for the DUV-FEL and extracting the basic features from it, and move on to briefly mention some promising directions for applications development, and the machine parameters which will dictate the viable applications.

General Considerations:

The recent past: In preparing this paper, I was reminded of an illuminating talk given by Michael Hart at the 1991 International Synchrotron Radiation Instrumentation Meeting in Chester UK entitled "The pursuit of brilliance-how and for what?"[1]. Among the many points he makes in this article is the fact that the brightness delivered by accelerator sources has increased many decades in a relatively short time, and as the perceived metric for third generation sources, the question is posed as to how much have the improvements in source brightness benefitted the users of these facilities? To date, the answer is in doubt, since the improvements in machine performance have in most instances not been matched by the other elements of experimental systems.

The differences in parameters for second and third generation synchrotron sources are highlighted in figures 1 and 2 which show source brightness and flux[2]. If indeed an experiment is brightness limited, and the beamline elements can deliver the brightness without degradation, there are clear advantages in a third generation source. If however flux is required, or the beamline can not for whatever reason exploit the source brightness, the difference in generations is not so clear.



Figures 1 and **2**, Source Brightness and Flux for selected US synchrotrons.

It is important to avoid fixation on any single metric of a particular source, because to a user, what matters is the overall performance at their experiment. All of the parameters of the source will have some impact on the conduct of a particular experiment. The same can be said for FEL projects, as shown in figure 3, where I have included our single value plot of peak power for the BNL UV-FEL and existing sources (synchrotrons and lasers). While this is an important feature of the project, much of its utility lies in the combination of its various features.

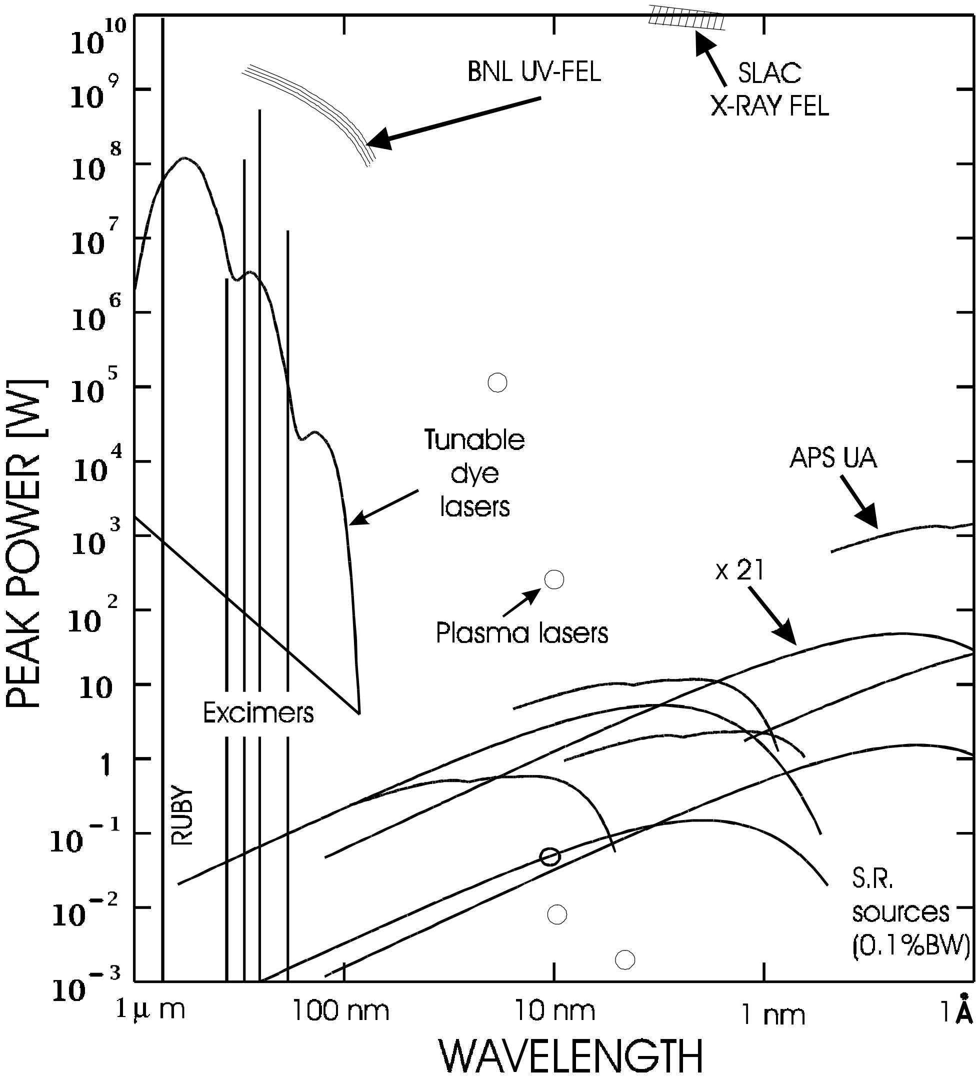


Figure 3 Peak power comparison of various sources.

The point to be emphasized is the integral nature of the experimental system from the users perspective. To the extent possible, the design of the new machines should consider its impact on the other elements of the experiment as generalized in figure 4. It includes the source, the optical transport and conditioning (focusing mirrors, monochromator, choppers, etc.), the sample, and some detection system as dictated by the experiment. All of this must be integrated including the final data analysis required when a particular experimental approach is utilized. The source design may in fact dictate or possibly obviate some elements of this system.

For example, source brightness can be meaningfully delivered if monochromators and other intervening optics are not required. Novel science may be possible based on modifications in the time structure or pulse train available from the source. The type of science engendered by the system will change radically if resonant or state selective processes may be utilized (ie source wavelength tunability). The coordination with other photon beams both in time and wavelength have proven to be the cornerstone of many experiments in chemical and atomic physics often referred to generically as "pump-probe" experiments.

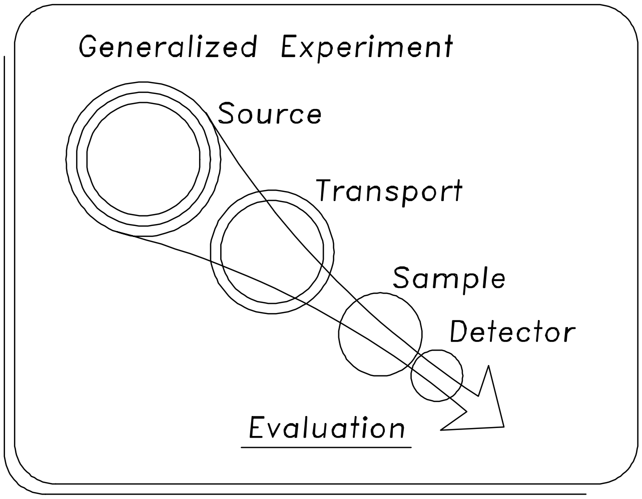


Figure 4 Generalized Experiment system

Many other attributes may combine (or conspire) to make a particular source technology the desirable avenue for a specific line of research, so the one rough jewel to recover from this discussion is that the impact of the source on the whole experiment should be considered. If the short wavelength FELs discussed at this workshop are in fact the "fourth generation"[3] sources, we need to be aware of this problem.

Development of a Scientific Case:

I use for a specific example some of the material developed for the case for the Brookhaven DUV-FEL, which is summarized on the "Three Key Points" from the viewgraph given as figure 5. This very condensed format was developed to make the DUV-FEL project recognizable and memorable for people across a broad spectrum of disciplines and perspectives. In general terms what it does is couch the project in three important areas. Firstly, it shows how the project is unique, and how it compares to its competition. Second, it explains in broad terms the applicability of the source and how its parameters couple to the physical properties of interest. Finally, it suggests its utility, which is to say the variety of ways in which it can be employed and the fact that it can be relied upon.

FIG 5

***Three Key Points Regarding the Brookhaven DUV-FEL*:**

Spectral Region:
A Gap exists in sources for intense ultra-violet radiation. It will not be filled by lasers or storage ring based sources in the foreseeable future.

Scientific Community:
This region of the spectrum covers valence and shallow core level electronic processes. Photons in this energy range can be utilized to push the frontier of science in many fields including chemical, surface, and solid state physics, biology and materials science. Specific applications in these fields have been explored, and have provided the design specifications for a source to meet these needs.

Source for Research:
The Development Ultra-Violet Free Electron Laser proposed by Brookhaven National Laboratory represents a qualitative advance in the capabilities in this spectral region. It provides an unprecedented combination of high peak power and high repetition rate along with synchronized conventional lasers for pump-probe experiments. Its output meets and exceeds the requirements of the presently proposed experiments and, because of the flexible timing and operational modes of the DUV-FEL, it will afford a unique opportunities to develop a fourth generation source for research.

Turning for a moment to the second point, the types of systems and areas of application for the machine can be enumerated. If possible, it seems prudent to seek as much diversity as possible in the applications, without diluting the original concepts beyond recognition or practicality.

Applications and Important Parameters:

Considering the vast scope of possibilities engendered by the wavelength range this workshop topic covers, I only list what I view to be exciting possibilities and note that they fall into two categories. Extensions of established science, and new frontiers. It seems to me that some of each is required. The value of extension type material is that it is grounded in research with hard data to allow quantitative signal calculations. This provides a useful measure of just how much better a particular source might be than any alternative way of making the measurement. The new frontiers are important in as much as they show that development of a new source may stimulate new science. This last case is often more difficult to make as hard data are generally not available, but it is valuable in terms of motivating user participation early in the project.

Source Parameters To Keep in Mind:

Wavelength: Defines the types of physical processes.

Tunability: Determines experimental approach.

Spectral Properties and Source Phase Space:
Both are important in defining optical system requirements. Bandwidth and Harmonic content will be of general importance.

Time Structure: Very Important Parameter
This factors in several ways, pulse duration determines not only the probe time scales, but the types of processes (linear vs multi-photon). The duty cycle will figure heavily into the experimental configuration. It will also be an important consideration in multi-color experiments in terms of synchronization.

Stability: In every sense of the word;
Position, wavelength, time jitter, intensity, and mode quality will all matter in varying degrees for each experiment.

Reliability: Every element of the experimental system must be robust.

Cost: Including construction, operation, and utilization.

Figure 6 Summary of important Source Parameters.

Finally, in figure 6, I note what I see to be the important parameters of the short wavelength FELs and choose to emphasize in particular the timing characteristics. In many ways, the various proposals I have heard for short wavelength FELs share the common feature that they offer possibilities in a space defined by time domains and wavelengths which are both extremely interesting, and otherwise inaccessible.

References

1. Michael Hart Rev. Sci. Instrum. 63 (1992) 283.
2. S.L. Hulbert and J.M. Weber. NIM A319(1992) 25.
3. I trace the parentage of this terminology to the "Workshop on Fourth Generation Light Sources" Held February 24-27, 1992 at SSRL and available as SSRL 92/02 report edited by M. Cornacchia and H. Winick.

SECTION B: FACILITY PLANS

BNL: FEL Physics Aspects of the BNL UV-FEL Proposal

Presented by Li-Hua Yu (BNL)

1: Introduction

In order to open up new research possibilities in the study of photo-induced processes in chemistry, biology and physics, we propose the construction of a subharmonically seeded single pass FEL operating in the wavelength region from 300 nm down to 75 nm. The objective is to achieve a pulse energy of 0.3 mJ at 75 nm and 1 mJ at 100 nm, continuously tunable.

The proposal is based on an available 230 MeV Linac that has a repetition rate of 10 Hz. It will be upgraded to 310 MeV with repetition rate of 360 Hz. A laser driven photocathode electron gun, developed under a collaboration between BNL and Grumman, will be installed. Calculations show that with emittance correction, this system can generate high brightness electron beam with a peak current of 300 A, normalized rms emittance of 4 π mm-mrad, and a pulse length of 6 ps. After pulse compression, the parameters are 700 A, 6 π mm-mrad, and a pulse length of 2 ps. In Fig. 1 we show the layout of the accelerator and Free-Electron Laser.

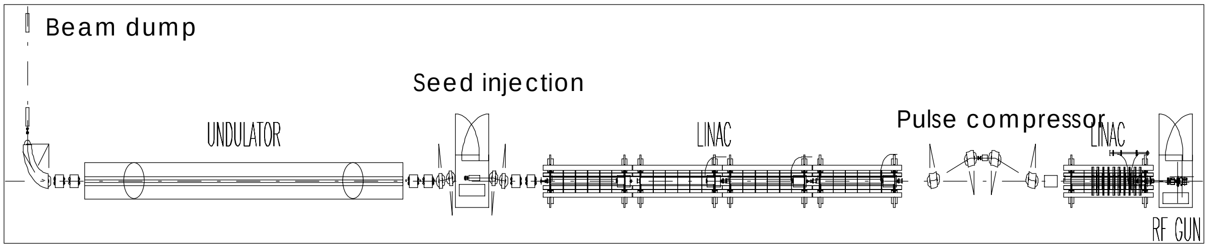


Figure 1. The BNL DUV FEL layout. (User area not shown).

The wiggler design is based on the wigglers developed for the visible FEL experiment and high gain harmonic generation experiment, currently being conducted at the BNL Accelerator Test Facility (ATF). The harmonic generation experiment serves as the proof of principle experiment for this proposal. The seed laser is proposed to be a Titanium-Sapphire laser, with its output multiplied by a crystal to provide a tunable seed ranging in wavelength from visible down to 300 nm. The proposed short wavelength is generated from this seed by further multiplication process in the FEL.

The FEL device is comprised of two wiggler magnets separated by a dispersion section (Fig. 2). To be specific, suppose the seed to be laser light at 300 nm, and the output radiation to be the third harmonic at 100 nm. In this case the first wiggler is set resonant to 300 nm and is used to energy modulate the electron beam.

The dispersion section introduces a dependence of the electron path length on energy. When the electron beam passes through the dispersion section the energy modulation results in a spatial bunching of the electron beam having a strong third harmonic component at 100 nm. Next, the coherent generation of 100 nm radiation rapidly occurs in the first few meters. There follows a transition to exponential growth that continues until saturation is approached, when tapering of the wiggler is used to extract additional energy from the electron beam.

The idea of using two wigglers, with the second wiggler resonant to one of the harmonics of the first, has been proposed originally by Boscolo and Stagno. Detailed simulations were done by Bonifacio and Scharlemann for the generation of UV radiation at the several megawatt level. In their approach, the first wiggler is long enough to reach saturation and produce strong spatial bunching, which is rich in harmonics. The second wiggler immediately follows the first, using the bunched beam to generate coherent "super radiation." This radiation reaches saturation at a few megawatts about two meters into the second wiggler. We introduce the following modification that increases the output power to hundreds of megawatts:

1. We significantly shorten the first wiggler, and control the input laser power so that the maximum energy modulation is about equal to the energy spread, but still far away from saturation.

2. We introduce a dispersion section between the two wigglers, and optimize the dispersion strength to generate maximum harmonics in the spatial bunching as in a transverse optical klystron.

3. We extend the second wiggler so that there is an exponential growth after the initial "super radiation." This is possible because of the proper control of the energy modulation in the first wiggler. If the energy modulation is too small, the harmonic component in the spatial bunching after the dispersion section is too small even when the dispersion strength is optimized. If the energy modulation is too large, on the other hand, it behaves as an equivalent energy spread in the

second wiggler, and saturation is reached too early, without achieving exponential growth after the "super radiance" section. In addition, the number of electrons trapped in the bucket in the tapered section is reduced, and energy extraction efficiency drops.

4. At the end of the exponential section, near but before saturation, we start tapering the magnetic field. This allows a much larger energy extraction, to achieve the level of one hundred megawatts at the end of the tapered section.

In the high gain harmonic generation approach that we have adopted, the FEL operates as an amplifier. Hence, the development of resonator mirrors at short wavelength is not required. The wavelength and bandwidth of the output radiation are determined by the seed laser, leading to high stability of the wavelength and narrow bandwidth. The pulse length and pulse shape of the output radiation can be adjusted by varying the input seed pulse duration and shape. A chirped output pulse can be achieved by chirping the energy of the electron beam and the frequency of the seed. This could be used to generate very short output pulses. The wavelength of the output radiation can be tuned by adjusting the electron beam energy and the wavelength of the seed. The wiggler field can remain fixed.

Figure 2. Schematic diagram of the High-Gain, Harmonic-Generation FEL

2. FEL Parameters for 100 and 75 nm

	100 nm	75 nm
<u>Electron Beam</u>		
Energy (MeV)	250	290
Current (Amp)	300	300
Norm. rms emittance (mm-mrad)	6	6
FWHM local energy spread (%)	0.1	0.1
FWHM global energy detuning range (%)	0.25	0.2
Pulse length (ps)	6	6
<u>Input Seed</u>		
Wavelength (nm)	300	300
Power (MW)	4.2	3.4
Bandwidth (x10-4)	1	1
<u>First Wiggler</u>		
Period (cm)	3.9	3.9
Magnetic Field (T)	0.64	0.77
Gap (cm)	0.6	0.6
Length (m)	2	2
Betatron wavelength (m)	16	16
<u>Dispersion Section</u>		
Length (m)	0.2	0.2
Magnetic Field (T)	0.32	0.32
Dispersion $d\vartheta/d\gamma$	1.1	1.0
<u>Second Wiggler</u>		
Period (cm)	2.2	2.2
Magnetic Field (T)	0.75	0.75
Gap (cm)	0.6	0.6
Length total (m)	12	12
Length untapered (m)	7	7
Length tapered (m)	5	5
Tapering (%)	1.2	0.5
Betatron wavelength (m)		
Gain length (m)	0.86	1.05
Field tolerance rms (%)	0.3	0.3
<u>Beam position monitor</u>		
spacing (m)	1	1
absolute calibration (μm)	80	60
sensitivity (μm)	10	10
<u>Output Radiation</u>		
Peak power (MW)	400	140
Energy per pulse (mJ)	1.2	0.4
Bandwidth (x10-4)	1	1
Energy extraction efficiency $(x10^{-5})$	2.5	0.7

The growth of the radiated power as a function of distance z along the second wiggler is plotted in Fig. 3 for 100 nm wavelength and Fig. 4 for 75 nm. In Fig. 5, we show the output power as a function of wavelength over the range from 250 nm to 75 nm.

3. Sensitivity of Output Power to Parameter Variation.

The FEL output depends strongly upon many design parameters. Here, we discuss the sensitivity of the design to parameter variations. The dependence of the output power on the normalized emittance is shown in Fig. 6 (for 100 nm output) and in Fig. 7 (for 75 nm output). Based upon these results, we conclude that we must set an upper limit on the normalized emittance,

$$\varepsilon_n \leq 8\pi \,\mathrm{mm\text{-}mrad}$$

The design value has been chosen to be 6 π mm-mrad, and it is our expectation that 4 π mm-mrad will be achievable.

In Fig. 8, we present the dependence of the output power on local energy spread, for 75 nm output and 8 mm-mrad electron beam normalized emittance. We conclude that we must set an upper limit on the local energy spread of

$$\left(\frac{\Delta\gamma}{\gamma}\right)_{FWHM} \leq 0.1\%$$

The design value has been conservatively chosen to be 0.1% although numerical simulations indicate a spread of 0.04% should be achievable.

The output power also depends on the electron current. For 75 nm output, (at ε_n=8 mm-mrad) we find:

I (A)	P_{out} (MW)
300	58
270	37

It follows that 300 A, which is our design value, should be considered as a lower bound on the current.

Figure 3. Radiated power as a function of distance z along the second wiggler at 100 nm.

Figure 4. Radiated power as a function of distance z along the second wiggler at 75 nm.

Figure 5. Output power as a function of wavelength.

Figure 6. Output power as a function of emittance at 100 nm.

Figure 7. Output power as a function of emittance at 75 nm.

Figure 8. Output power as a function of energy spread at 75 nm and 8 π mm mrad.

In Fig. 9, we plot the output power as a function of the power of the input seed, with other parameters fixed. The emittance is 8 π mm-mrad. It is seen that the output power is not very sensitive to the input laser power. A 10% input power fluctuation only causes a negligible output variation.

4. Wiggler Errors

The control of the magnetic field errors and the electron trajectory in the wiggler magnet is of critical importance. Our analysis shows that the tolerance on the peak value of the wiggler magnetic field can be taken to be

$$\left(\frac{\Delta B}{B}\right)_{FWHM} \leq 0.3\%$$

This assures that the contribution of magnetic field amplitude errors to the longitudinal phase drift results in negligible loss of gain. In order to control the electron trajectory, beam position monitors (BPM's) and trim magnet coils will be place along the wiggler with a spacing of 1m. The position of these BPM's relative to the wiggler axis must finally be determined to 40 μm precision, however, 100 μm would be sufficient for early operation. The BPM's should have a sensitivity of 10 μm.

The misalignment tolerance on the electron beam entering the second wiggler can be taken as 100 μm for early operations, with the achievement of 40 μm desirable for later operations. The effect on the output power of misalignment of the electron beam entering the second wiggler can be seen from Table 1. The data in this table was obtained from using a modified version of the FEL simulation code TDA, including three-dimensional effects.

Table 1. Output Power vs. Misalignment

Wavelength nm	75 nm	100 nm	250 nm
Misalignment μm		Output Power (MW)	
0	62	230	1050
40	45	200	970
60	35	170	910
70	29	160	880
80	24	150	857
100	--	120	700

Figure 9. Output power as a function of the power of the input seed, with other parameters fixed.

Figure 10. Gravitational deflection of a wiggler with four support points.

It turns out that the tolerance on the deflection of the mechanical structure of the wiggler, due to the separation of supports, is not very strict. In Fig. 10, we show the deflection resulting when there are four supports holding the 12 m wiggler. In this case the deflection's wavelength is λ_D=4 m, to be compared to the betatron period λ_β = 16 m. The wavenumber $k_D = 2\pi/\lambda_D$ of the deflection is

$$k_D = 4k_\beta.$$

The displacement x of the electron beam due to the deflection of the wiggler is determined by the equation

$$x'' + k_\beta^2 (x - A_D \cos k_D z) = 0,$$

where the full deflection is $2A_D$. It follows that

$$x'_{\max} \approx \frac{k_\beta}{k_D - k_\beta} k_\beta A_D = \frac{k_\beta A_D}{3}$$

From our analysis of electron beam misalignment, we see that

$$x'_{\max} < k_\beta x_m$$

where x_m = 40 μm is the misalignment tolerance of the electron beam at the wiggler entrance.

Hence, we require $A_D < 3x_m$ = 120 μm. We shall adopt a more strict tolerance,

$$\text{mechanical deflection } = 2A_D < 100\mu m$$

The tolerance on the power supplies for the wiggler can be found from the detuning curve of Fig. 11. We see that the detuning should be less than 0.1%, giving rise to the power supply tolerance

$$\frac{\Delta B}{B} \approx \frac{\Delta I}{I} < 10^{-3},$$

where I is the current in the magnet coil.

Figure 11. Output power as a function of detuning.

CEBAF: The Continuous Electron Beam Accelerator Facility

Presented by George Neil (CEBAF)

The Continuous Electron Beam Accelerator Facility is a new nuclear physics laboratory under construction in Newport News Virginia. As of June 1993, the project was more than 80% complete with the beginning of physics scheduled for FY94. Key highlights in the laboratory's progress include completion and use of Superconducting Radio Frequency (SRF) cavity and production facilities, routine testing and commissioning of accelerator subsystems, operation of the injector at its design specifications, and operation of the North Linac at 245 MeV. Cavity specifications have been exceeded by nearly a factor of two, on average, in delivered systems.

The injector configuration has been specifically modified to permit the addition of guns with capabilities beyond the thermionic gun providing baseline operation. The proposed IR demonstration FEL is to be driven at 50 MeV by a beam originating from a new DC photocathode gun followed by a pair of dedicated superconducting cavities. The beam from this new 10 MeV injector is then accelerated in two existing 20 MeV cryomodules. The FEL will produce an average power output of 700 W in the wavelength range of 4 to 25 microns utilizing an electromagnetic wiggler with a wavelength of 6 cm. Operation at the third harmonic offers the possibility of output down to 2 microns. A layout of this configuration is shown in Figure 1. The high current DC photoinjector produces 120 pC at a Pulse Repetition Frequency (PRF) of 7.677 MHz. This is bunched to 2 ps to give 60 A peak current. The photogun is currently under construction at University of Illinois. The high power, doubled YLF laser has been ordered and is due to be delivered in August 1993. The photoinjector dedicated cryomodule has been constructed and tested at greater than 10 MeV/m and it will be placed in the CEBAF tunnel during summer 1993. Construction of the remaining FEL specific hardware (wiggler, optical cavity) awaits award of the proposed IR FEL on FY94 funds.

Although the commissioning and testing schedule for nuclear physics beam is intensive for the next 2 years, the CEBAF accelerator offers an exceptional possibility for demonstration of short wavelength amplifiers or oscillators. Calculations indicate that it is quite straightforward to maintain a normalized emittance of better that 3 π mm mrad for a 300 A pulse to the full energy of the North Linac (400 MeV specified but the actual delivered energy is expected to be closer to 600 MeV). Only minor modifications would be required to extend this capability to the South Linac, also giving a high brightness beam which may exceed 1200 MeV in energy. The actual brightness would probably be limited by the injector performance so one would envision adding a different gun where the IR photoinjector is presently planned. For amplifier operation a gun such as that under construction by Grumman would satisfy requirements. For oscillator operation a long macropulse or CW operation would be desirable. It would probably take the development of a CW superconducting RF gun to offer CW operation at the brightness desired for XUV FELs. Operation with an injector such as APEX would permit sufficiently long macropulses to reach saturation in a 90 nm (and probably shorter) wavelength oscillator. Priorities for this and other programs would have to be weighed against scheduled nuclear physics tests and are especially constrained for the next two years because of commissioning activities.

Figure 1: A layout of the CEBAF accelerator with proposed IR FEL.

DUKE: Facilities Available at the Duke FEL Laboratory for Ultraviolet and Soft X-Ray FEL Research

Presented by J. M. J. Madey (Duke University)

The Duke Free Electron Laser Laboratory was designed to facilitate the development and use of a broad range of short wavelength FEL light sources. As outlined in further detail below, the facilities available to the laboratory include (1) extensive high bay and shielded experimental areas, (2) a variety of high performance accelerator/drivers and high brightness injectors, (3) general purpose diagnostic instrumentation and controls for operation of these accelerator systems and their associated electron beamlines and RF power systems, and (4) a precision, broadly tunable, multi-section electromagnetic undulator system designed for operation in the UV and XUV spectral regions.

<u>Experimental Areas:</u> The primary experimental areas available in the FEL Laboratory include:

a. A 17,600 sq. ft. high bay area (length=220', width=80', height=25') for research using the laboratory's 1 GeV electron storage ring. This area was designed to provide a stable environment for the long undulators required for operation at UV and XUV wavelengths, and to accommodate the level of radiation shielding required for ring-based FEL systems.

The concrete slab on which the ring and its associated systems is mounted was designed to limit long-term settlement to 100 micrometers. To limit dimensional changes due to temperature, the HVAC system for this area controls the temperature to within +/- 2 degrees Fahrenheit.

5,000 sq ft. of flex-lab space adjoins this area to provide space for experimental set-up, operations and storage.

b. A 350' long heavily shielded underground tunnel (width=10', height=8') adjacent to the high bay area to house the full-energy linac injector for the ring.

Eight underground concrete vaults are located adjacent to the tunnel to house up to sixteen 30 megawatt s-band klystrons and modulators.

Sufficient space is available in this tunnel to allocate up to 30' of drift space along the beamline for the linac for research on advanced FEL and/or accelerator concepts at energies up to 1 GeV.

c. A 15'x60" heavily shielded underground vault located immediately adjacent to the high bay area at the end of the linac tunnel to house the laboratory's "intermediate energy" FEL light sources.

   This vault is presently occupied by the MKIII infrared FEL system. Additional space is available in the vault to support research on advanced FEL and/or accelerator concepts at electron energies in the 10-50 MeV region.

d. A heavily shielded 10'x75" concrete vault in the basement of the Duke Physics Department for research on stand alone "intermediate energy" injector, accelerator, and FEL light source systems.

Accelerator Systems: The accelerator systems available for use within the FEL Laboratory include the Lab's 1 GeV electron storage ring, the high-brightness microwave guns used for the linac injector and MkIII FEL system, and the s-band accelerator systems used with the injector and the MkIII system. The specifications and status of these systems are described below.

a. *1 GeV Electron Storage Ring:* The mechanical, magnetic and vacuum components of this system have been installed, and work is now in progress to complete the RF, diagnostic and control systems required for operation. First injection (at 300 MeV) is scheduled for March, 1994, with full energy operation to follow within 9 months. The outline of the ring is shown in Fig. 1.

Figure 1. Outline of the Duke Storage Ring.

The main parameters for this system are summarized below:

Circumference:		107.46 meters
Length of Arcs:		19.52 meters
Length of Straight Sections:		34.21 meters
RF Frequency:		178.547 MHz
Operating Energy:		0.25 - 1.0 GeV
Number of Dipoles		40
Number of Quadrupoles:		64
Betatron Tunes:	Horiz:	9.1107
	Vertical:	4.1796
Momentum Compaction Factor:		0.0086
Acceptance:	Horiz:	56 mm-mrad
	Vertical:	16 mm-mrad
Energy Acceptance:		up to 5%
Emittance:	Horiz:	$18\text{x}10^{-9}$ m-rad
	Vertical:	$1.8\text{x}10^{-9}$ m-rad
Relative Energy Spread:		$5\text{x}10^{-4}$
Bunch Length:		1-4 cm
Max. Average Current:		0.1 Amp
Max Peak Current:		80-130 Amps
Beam Size in Undulator:	H:	0.27 mm
	V:	0.085 mm

The limits on peak and average current projected in this table are set by the estimated impedance of the present vacuum chambers and to the onset of turbulent bunch lengthening in the present single-frequency 178 MHz RF system. We estimate that the peak current of this system can be raised to 350 amps by upgrading the arc vacuum chambers and adding a 4th harmonic RF cavity for bunch length control.

b. *Microwave Electron Guns:* The microwave electron guns used for the linac injector and MkIII FEL systems employ a single cell s-band cavity driven by 2-3 megawatts of RF power to extract and accelerate the electrons from a 3mm diameter single crystal lanthanum hexaboride cathode. The electron beam emerging from the cavity is momentum analyzed and magnetically bunched in an Enge-type alpha magnet prior to injection into the subsequent accelerating cavities. The guns can be used in either the thermionic mode (by heating the cathode to 1700-1800 degrees K), or in the photoelectric mode, using an appropriate pump laser. Typical specifications for these guns are given below:

Electron Energy:		0.85 MeV
Energy Spread:		100 KeV
Normalized Emittance:	H:	8 mm-mrad
	V:	2 mm-mrad
Peak Current:	Thermionic:	40 Amps
	Photoelectric:	150 Amps
Micropulse Length:		3 picosecond
Average Current (Thermionic):		250 milliamperes
Macropulse Length:		5 microseconds

A fast electrostatic kicker is being developed for the linac injector to limit the macropulse length to a maximum of 5 nanoseconds as required for injection into the ring.

Although the past photoelectric-mode operation of these systems utilized a tripled or quadrupled, mode-locked YAG laser driver, we are currently investigating the use of a free-running pulsed nitrogen laser as a driver to support the operation of the linac injector and other applications requiring short e-beam macropulses.

c. *High Performance Linear Accelerator Systems:* The SLAC-type S-band accelerator sections used in the MkIII FEL system and the linac injector for the ring are run at relatively high gradients to minimize the effects of space charge and wake-field forces during acceleration. In particular, the accelerator sections immediately following the guns in the MkIII and injector systems are run at gradients in excess of 10 MeV per meter using the 15-30 megawatts available from the long-pulse S-band klystrons developed for the Lab by ITT.

In its initial configuration, the injector for the ring will be configured to operate at 300 MeV using the three long-pulse ITT tubes presently available to the laboratory. In this configuration, the linac could be used to provide macropulses as long as 10 microseconds in length at a rep rate of 1 Hz. As the additional RF power required for operation at energies in excess of 300 MeV will be obtained using conventional SLAC-type short pulse klystrons, the macropulse length available in the

300-1000 MeV region will be limited to a maximum of 2 microseconds.

The long-pulse klystrons used to drive the MkIII System and the first 300 MeV of the linac injector can be operated with feed-forward regulation of amplitude and phase, as first demonstrated at Brookhaven, to stabilize the energy and phase of the accelerated electron bunches. Feedforward amplitude regulation is presently operational on the MkIII system.

Diagnostic Instrumentation and Controls: The operation and acquisition of data from diagnostic instrumentation and the control of the DC and RF power systems required for operation each of the Lab's accelerator and FEL systems is supervised by an EPICS-based control system, making it relatively easy to reconfigure these systems as required for exploratory research. In particular, the Lab has the capability to "borrow" the power and controls hardware from the existing systems in the Lab, for example the MkIII FEL, to evaluate other advanced prototype FEL and accelerator systems simply by reconfiguring the patch panels for these systems.

Since power, instrumentation and control systems typically constitute a major component of the cost of new accelerator and FEL systems, this capability may prove useful in reducing the cost and time required to demonstrate and evaluate new concepts.

OK-4 Undulator System: The Duke FEL Laboratory and the Budker Institute of Nuclear Physics have signed a memorandum of understanding providing for the shipment of the BINP's OK-4 ultraviolet FEL system to Duke, the installation of this system on Duke's 1 GeV storage ring, and the cooperative pursuit of advanced short wavelength FEL technology using this hardware. The parameters of the present OK-4 system are summarized below:

Total Length (2 undulators + buncher):	7.8 meters
Undulator period:	10 cm
Length of Individual Undulators:	3.4 meters
Magnetic Field:	0-5.8 kGauss
Undulator Parameter (K):	0-5.4
Buncher Length:	34 cm
Buncher Magnetic Field:	0-12 kGauss

The precision of the magnetic field produced by this undulator is very high since it uses no permanent magnetic materials and operates at magnetic fields well below saturation.

Sufficient gain should be available using this undulator on the Duke ring and Newnam's grazing incidence resonator configuration to lase at wavelengths as short as 70 nanometers. Figures 2 and 3 show the expected gain and power output for this system assuming an average current of 100 mA as per the initial specifications for the Duke ring (listed above), and alternatively, an average current of 1000 mA assuming the installation of improved vacuum chambers, additional RF power, and a 4th harmonic RF cavity.

The intracavity peak power attainable in this system at 100 nm is shown in Figure 4, assuming the initial specifications for the ring.

In addition, the modular construction of the OK-4 system makes it possible to extend its length as required to a maximum of 27 meters by adding up to six additional undulator and buncher sections based on the design for the existing hardware. Such an "extended OK-4" or "OK-5" system could be used to evaluate a number of high priority advanced concepts including:

a. Operation at constant K to obtain very high small signal gain in the XUV and soft X-ray regions,

b. Operation with "stepped K", utilizing the initial sections of the system to sustain lasing in the visible or near-UV, and the subsequent reduced-K sections of the undulator to radiation by the bunched electron beam at the 3rd, 5th, 7th or 9th harmonics, or

c. Operation with an adiabatically varying K to secure either increased peak power in the giant pulse mode or to verify the physics of phase-displacement FEL operation.

The flexibility of such an independently tuneable, multiple section undulator would be of great value in the exploration of the possible pathways for the realization of functional short wavelength FEL systems. As an example, Figure 5 shows the improvement in small signal gain at 100 nm which could be obtained by adding one additional buncher and undulator section to the existing OK-4 system to extend its length to 12.2 meters.

Assuming that the proposals Duke and the BINP have written to fund this collaboration are approved, the existing OK-4 system should arrive in Durham no later than June, 1994. Additional time would of course be required to extend the system as described above by adding additional undulator and buncher sections.

Figure 2. Gain per pass in the OK-4 Optical Klystron at the Duke Ring.

Figure 3. Power output of the OK-4 Optical Klystron at the Duke Ring.

Figure 4. Intracavity peak power at 100 nm (initial specifications).

Figure 5. Improved gain in the OK-4 Optical Klystron. (See text).

LANL: A XUVFEL PROPOSAL at 60 nm

Presented by K.C. Dominic Chan, (LANL)

Introduction

This is a summary of a proposal prepared by Los Alamos in the summer of 1992 to develop an XUV-FEL Integrated-Circuit (IC) lithography source that has a sufficiently short wavelength to produce IC feature sizes as low as 0.05 microns and provide high-wafer throughout. The near-term goal is to develop a FEL system at 60 nm with an average power of 20 Watts by year 2000. Such a system can process sixty 30-cm-diameter wafers per hour with IC feature size of 0.2 microns. This proposal is different from most of the proposals presented in this workshop in three ways. First, the proposed device is designed for a single user. Second, it is designed for an industrial environment where compactness in important. Third, the FEL has an oscillator configuration.

The proposed system consists of four major subsystems. They are a drive-laser / photocathode subsystem, an accelerator / magnetic-buncher subsystem, a pulsed-current-wiggler subsystem, and a ring-resonator subsystem. A brief description of these subsystems is given in the following paragraphs. The specification of the system and subsystems are given in Table 1.

Drive-Laser/Photocathode Subsystem

The basic design of the drive laser will consist of a diode-pumped mode-locked Nd:YLF Oscillator and diode-pumped Nd:YLF amplifiers. The 1 µm light produced will be frequency doubled and used to illuminate a multialkaline (CsK_2Sb) cathode.

There are two advantages of diode-pumped lasers. First, the diode output can be spectrally tuned to match the Nd:YLF absorption band. It will provide wall-plug to visible-light efficiency of 5%. The better efficiency means less waste heat, smaller package, and better laser stability. Second, a diode pumped-oscillator can directly generate micropulse of 6 ps without a fiber-grating pulse compressor. This can inprove the amplitude and phase stability of the laser.

Accelerator/Magnetic-Buncher Subsystem

The accelerator will consist of four 1300 MHz standing-wave structures. The accelerator length is 10 m. It will produce a beam of 85 MeV. This accelerator design is based on Los Alamos' experience in high-brightness accelerators. To produce a high-brightness beam, the photocathode will be installed in the first cell operating at a high field gradient; a solenoid field will be used to focus the beam and produce emittance compensation at low beta; and special attention will be paid to preserving accelerating field symmetry.

Each accelerating structure will powered by a klystron (L-5081, Litton Industries) to provide flexible control of phase and amplitude control of the accelerator field. To control the field to 0.5% amplitude stability and 0.5 degree phase stability, adaptive feedforward control will be used to monitor the in-phase and quadrature field components.

A four-dipole type chicane buncher will be used to compress the micropulse. It will be located between the third and forth accelerator structure at a beam energy of 63 MeV. With a 4% energy slew over the micropulse and the buncher, the peak current can be increased from 80 A to 500 A. The cost of producing this higher current is an increase of instantaneous transverse emittance from 1 to 2 π mm mrad.

Pulsed-Current-Wiggler Subsystem

A pulsed-current wiggler is used because relatively low-energy electron beam is used to produce short wavelength. A pulsed-current wiggler has a short wiggler period and a high magnetic field. The high magnetic field allows the wiggler to operate at higher harmonics. The slotted-tube design with "Tee" slots and two-plane focussing will be used in this design. By passing a 15 kA current through such a wiggler, a peak magnetic field of 3 Tesla and rms wiggler parameter of 1.0 can be obtained.

The development of a pulsed-current wiggler is underway in Los Alamos. The major challenges are the thermal management, time variation of the field, and mechanical tolerances. The mechanical tolerances required are tube thickness uniformity of 0.1%, slot length of 10 μm, and tube concentricity of 10 μm.

Ring-Resonator Subsystem

Achieving high mirror reflectivity and resonator stability is essential to the success of the oscillator approach. They can be attained with a ring resonator consisting of multifaceted mirrors and beam expanding mirrors. The multifaceted mirrors in this design have nine facets and are coated with Al. The light is incident on these facets at grazing angle reflects well. The retroreflectivity of such a nine-facet mirror was measured to be 82%. The beam expanding mirror is used to spread the thermal load to minimize thermal distortion of the optics elements in the resonator.

Present Status

The technology required for this proposal continues to be developed at Los Alamos. This Spring, a Proof-of-Principle Experiment was completed. An electron beam of 46.6 MeV was used with a permanent-magnet wiggler operating at the third harmonic. Lasing at 375 nm was achieved with a measured micropulse power of 280 kW. Lithographic photoresists were exposed. During the experiment, three versions of a pulsed-current wiggler were tested giving information for future improvements. The Advanced Free-electron Laser in Los Alamos has been producing high-brightness electron beam between 10 and 18 MeV. The beam emittance was measured as 2.1, 3.7, and 6.5 π mm mrad at micropulse charge of 1, 2, and 3 nC respectively. These results agreed with simulations and give us confidence that we will achieve the beam quality required for this proposal.

Table 1

LOS ALAMOS XUV-FEL PARAMETER LIST

Goal

Laser wavelength	60	nm
Laser average power	20	W

Electron beam

beam energy	85	MeV
average beam power	27.54	kW
beam duty cycle	0.1	%
beam instantaneous transverse emittance		
before bunching	1	π mm mrad
after bunching	2	π mm mrad
beam instantaneous energy spread	0.05	%
beam phase stability	0.5	Degrees
micropulse charge	1.5	nC
micropulse repetition rate	216	MHz
micropulse peak current	500	A
micropulse length	2.5	ps
macropulse length	17	μs
macropulse rate	60	Hz
macropulse current	0.324	A

Drive laser/photocathode

micropulse energy	0.8	μJ
micropulse length	10	ps
micropulse rate	216	MHz
macropulse average power	173	W
CsKSb cathode		
quantum efficiency	0.5	%

Accelerator

four π/2 mode standing wave structures		
operating frequency	1300	MHz
length of structure	2.5	m
macropulse cavity loss per structure	4.5	MW
beam loading factor	60	%

Rf system

Litton L-5081

klytron peak power	30	MW
klystron average power	67	kW
duty cycle	1.2	%
gain	50	db
control margin	15	%
rf pulse width	20	µs
repetition rate	60	Hz
cavity amplitude control	<0.5	%
cavity phase control	<0.5	Degrees

Wiggler

pulsed current "Tee" slotted wiggler with two-plane focussing

$(a_w)_{avg}$	1.0	
peak magnetic field	3.03	T
pulsed current	15	kA
wiggler period	5	mm
number of periods	75	
length of wiggler	375	mm
wiggler tube inner diameter	3.0	mm
wiggler tube outer diameter	5.0	mm
small-signal gain	1200	%
extraction efficiency	0.1	%

Resonator

length	5.89	m
width	0.75	m
outcoupling coefficient	20	%
steady-state gain	92	%
circulating power	100	W

SLAC: A 2-4 nm Linac Coherent Light Source Using the SLAC Linac*

Presented by H. Winick, (SLAC) and C. Pellegrini (UCLA).
(To be published in Proc. IEEE 1993 Part. Accel. Conf.)

Abstract

We describe the use of the SLAC linac to drive a unique, powerful, short wavelength Linac Coherent Light Source (LCLS). Operating as an FEL, lasing would be achieved in a single pass of a high peak current electron beam through a long undulator by self-amplified spontaneous emission (SASE). The main components are a high-brightness rf photocathode electron gun; pulse compressors; about 1/5 of the SLAC linac; and a long undulator with a FODO quadrupole focussing system. Using electrons below 8 GeV, the system would operate at wavelengths down to about 3 nm, producing 10 GW peak power in sub-ps pulses. At a 120 Hz rate the average power is ~1 W.

I. INTRODUCTION

Two recent developments have opened the possibility to construct linac-based x-ray lasers operating at short wavelengths, down to 2 nm and eventually as low as 0.1 nm. The first is the development, at Los Alamos and elsewhere, of rf photocathode electron guns which can now deliver low emittance (3-4 mm-mrad normalized emittance), high charge (>1 nC) electron beams. The second is the development at SLAC, as part of the SLC project, of the tools and understanding associated with the transport, acceleration and compression of electron bunches without dilution of phase space density. These developments make it possible to deliver electron beams with the required phase space density to drive short wavelength lasers.

*Supported in part by the Department of Energy, Office of Basic Energy Sciences and High Energy and Nuclear Physics and Department of energy Contract DE-AC03-76SF0015

The main components of the short wavelength LCLS we have studied are (1) a high brightness, rf photocathode electron gun, (2) 7 sectors of linac, (3) beam transport and compressor systems, (4) beam diagnostics and controls, (5) a long undulator (50-60 m), (6) an enclosure to house the undulator, (7) electron beam dump, (8) mirror station, (9) a photon beam line and two diagnostic/experimental stations and (10) a building to house these stations.

In addition to the existing linac, an enclosure to house the undulator exists at the end of the SLAC linac. This is the Final Focus Test Beam (FFTB) housing completed in early 1993 for r&d associated with final focus systems for future linear colliders. There is ample room in this enclosure for the LCLS undulator. After a slight upgrade, the FFTB enclosure would provide adequate shielding for alternating operation of both facilities.

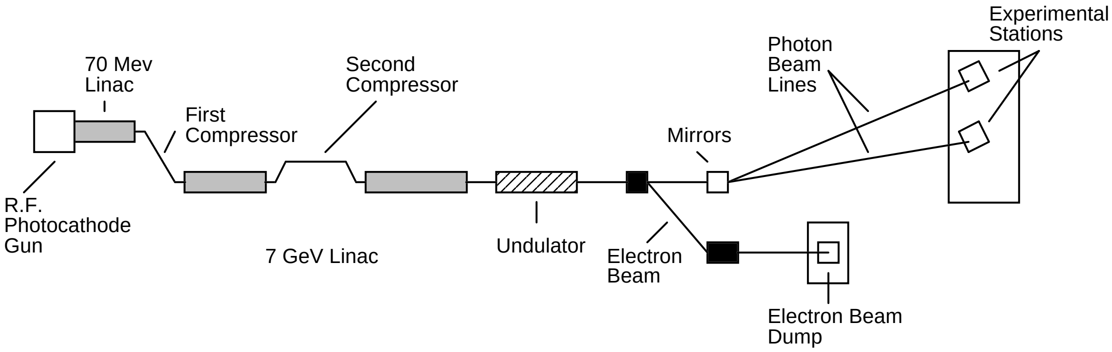


Figure 1
LCLS Schematic Overview

We propose an r&d facility aimed at the development of linac-driven, short wavelength x-ray lasers, and their scientific and technological utilization. The first laser would start operation at a wavelength around 10 nm or longer and then reach the 3 nm region. With more extensive r&d, along with the use of higher energy electrons and additional undulators, and with improvement in the performance of certain components such as the rf photocathode gun, it is expected that the facility could achieve (with additional funding) a laser functioning at even shorter wavelengths, possibly in the 0.1 nm region.

The LCLS photon beams emerge into the SLAC research yard, about 125 m from SSRL beam lines on SPEAR. Thus, once the LCLS facility is operational, it is possible to bring a beam from it and SPEAR to the same sample chamber, for pump/probe experiments for example.

The proposed LCLS operates on the principle of the FEL, but does not require an optical cavity which is difficult or impossible to make at such short wavelengths. Instead, x-ray laser operation is achieved by Self-Amplified-Spontaneous-Emission (SASE) in a single pass of an electron beam through a 50-60 m long undulator.

Although SASE theory is well developed, there is, to date, little experimental data with which to compare it since most FELs have used oscillator cavities. It is therefore important to make detailed comparisons between experiment and theory, for example to verify the accuracy and wavelength dependence of simulation codes and assumptions about startup from noise. We plan to do this initially at wavelengths around 10 nm or longer. At these wavelengths certain tolerances are more manageable. As experience is gained and tighter tolerances met, operation down to about 3 nm can be expected, still using electrons below the 10 GeV that will be available in the proposed facility. The characteristics of the light produced by the LCLS at 4 nm are projected to be:

Peak Coherent Power (GW)	≥ 10
Pulse Repetition Rate (Hz)	120
Pulse Width (1 sigma - fs)	< 160
Photons/pulse	$\geq 10^{14}$
Energy/pulse (mJ)	~3
Bandwidth (1 sigma)	$0.1 - 0.2\%$
Peak Brightness*	$\geq 10^{31}$
Average Brightness *	$\geq 10^{21}$

* photons/(s,mm^2, mrad^2) within 0.1% bandwidth

The average values of brightness and coherent power are about 3 orders of magnitude greater than projected for 3rd generation light sources such as the ALS and the peak values are about 9 orders of magnitude higher. Photon beams with this extraordinarily high brightness, coherence and peak power will make possible a wide range of experimental studies in many scientific and technical fields including x-ray imaging of biological specimens in and around the "water window" (including producing x-ray holograms of live biological specimens in a single sub-picosecond pulse); time resolved studies of condensed matter systems and chemical reaction dynamics; and non-linear processes. Because the properties of this light source go many orders of magnitude beyond that available from any other source in operation or construction, it is likely that entirely new scientific applications will be opened up. Exploratory experiments will be carried out on two diagnostic/experimental stations. With two experiments able to receive pulses, techniques will be developed for rapid switching of the beam, as well as rapid changing of beam parameters such as wavelength and intensity to meet different experimental needs.

An FY 1996 Short Form Construction Project Data Sheet has been submitted to DOE for this project. The total estimated cost is $29.45M.

II. SIMULATIONS

Extensive numerical studies have been performed using (primarily) the FRED3D and TDA3D codes. In agreement with simple models, the simulations predict that the LCLS can provide in excess of 10 GW of peak power in a subpicosecond pulse. The saturation length is about 60 m with strong focusing provided throughout the undulator. The system gain, its optimization and tolerance to beam parameter changes, wiggler errors and misalignments have been studied.[1]

The operating parameters chosen provide relative insensitivity to beam current and emittance fluctuations. By running to saturation, variations in the output radiation due to changes in the beam parameters are minimized. The requirements on the uncorrelated energy spread of the beam are tight (<0.04% rms) and are determined primarily by the desire to maintain a narrow bandwidth and maximum gain. Energy spreads twice as large as specified do not seriously degrade the (single frequency) performance. This, along with the high power (brightness) of the optical pulse, suggests that filtering could be used to narrow the line width.

According to the simulations (using a random walk), the wiggler field errors required are small (<0.2% rms) but within state of the art. Steering and alignment requirements are also tight (30 microns rms), yet less stringent than required for many future linear collider designs.

III. TECHNICAL COMPONENTS

A. RF Photocathode Gun

We have studied the design of an rf photocathode gun which can produce the beam characteristics required for reliable operation of the LCLS. The dynamics of the photoelectron beam have been modelled using both PARMELA, and an axisymmetric particle-in-cell code, ITACA. These simulations show that a one nC, 10 MeV electron beam can be produced in a 3+1/2 cell, 2.856 GHz structure, which has a pulse length of 2 psec and a normalized rms emittance of 3 mm-mrad. The major challenge in designing this source concerns reproducibility of the beam properties. In particular, due to wake-fields in the transport, it is critical that the jitter in the total charge per pulse and the injection timing be minimized [2]. We believe that a solution to these problems exists based on choice of a rugged cathode material and a commercial diode-pumped laser system with timing stabilization [3].

B. Transport, Acceleration & Compression

The bunch produced by the LCLS photo-injector must be accelerated and length compressed before injection into the undulator. In the present scheme the bunch is accelerated from 10 MeV to about 7 GeV using three linear accelerators separated by two compressors[2]. The final bunch length is about 0.05 mm (FWHM) (over a factor of 10 smaller than that produced by the photocathode gun) yielding a peak current of 2500 to 3500 A. The final energy spread is less than 0.2 % (rms).

The choices of energies at which to compress are influenced by the need to 1) control longitudinal wakefields for energy spread minimization, 2) minimize emittance growth from transverse forces, and 3) reduce the effects of time-phase jitter as well as beam intensity jitter from the injector and in the compression process.

The first compression is performed at 70 MeV where the bunch length is reduced from 0.5 mm to 0.2 mm (rms). The second compression is near 2 GeV and reduces the length to about 0.05 mm (FWHM). To study the development of longitudinal phase space in this process, a computer program is used which considers the effects of longitudinal wakefields, curvature of the RF wave, and phase and intensity jitter. The second compression is made to deliberately over-compress the bunch length beyond the 0.003 mm (rms) minimum. This over-compression and acceleration from 2 to 7 GeV allows approximate cancellation of upstream errors with downstream errors, thus providing significantly relaxed timing and intensity jitter tolerances of the injector and accelerator RF. Bunch intensity fluctuations up to 2 % and injection phase jitter of roughly ±0.5° can be tolerated[2]. After the first compression the bunch length is still nearly gaussian, but after the second compression the beam distribution is more sharply spiked and has long tails.

A second set of parameters for this length compression scheme is being studied which would provide a distribution that is more flat topped. Both distributions produce the peak current and energy spread needed to satisfy the FEL requirements.

The emittance dilution effects due to transverse wakefields, RF deflections, and dispersive effects have been modeled in the SLAC linac for this configuration assuming 150 μm random misalignments of the quadrupoles and BPMs, 300 μm rms random misalignments of the accelerating structures, and a random transverse-longitudinal coupling of $g_{rms} = 2\times10^{-4}$ for the RF deflections. A transverse beam jitter equal to the rms beam size was also assumed. At a bunch length of 200 μm (rms), we find 25 % emittance growth along the linac. Emittance growth after the second compression is negligible due to the short bunch length and small energy spread.

An experimental test of the second bunch compressor including longitudinal and transverse effects has been designed and is under consideration. [4]

C. Undulator [5]

Based on 3D simulations of a continuous single-pass field structure, the following parameter set has been established for the LCLS (water window) insertion device: 1) period = 8 cm; 2) peak field amplitude = 0.8 T; 3) K = 6; 4) total length = 60 m; 5) focussing betatron wavelength = 60 m. Design work has concentrated on a pure permanent magnet undulator structure with a superimposed focussing (FODO) field lattice generated by 40 cm long 15 T/m quadrupoles placed at 80cm intervals. To facilitate orbit and phase correction, beam position monitors are at 1.6 m intervals, with corrector coils located every 3.2 m. Work on a short prototype section is in progress to help resolve selected engineering, magnet tolerance, and field measurement issues.

D. Beam Lines & Experimental Stations [6]

Due to the extreme brevity and peak intensity of the LCLS output radiation, special emphasis has been placed on the design of the beam line system. To minimize the likelihood of sustaining damage at the expected $10^{12} W/cm^2$ normal-incidence power densities, a deflection scheme utilizing solid-state mirrors at grazing incidence has been developed [6]. Furthermore, the necessity of maintaining high reflectivity to avoid peak-power damage leads to the need for an ultra-high vacuum environment with provisions for in situ cleaning of all the reflecting surfaces. To exploit the diffraction-limited source size of the LCLS, the use of a simple monochromator configuration utilizing a single grating in a conical diffraction geometry, with the source as the effective entrance slit, is under consideration.

IV. Acknowledgements

This project benefitted greatly from a technical review in November, 1992. We thank the members of this review committee: Ilan Ben-Zvi

(Chairman), Joseph Bisognano, Luis Elias, John Goldstein, Brian Newnam, Kem Robinson, Ross Schlueter, Andrew Sessler and Richard Sheffield.

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SECTION C: REPORT OF THE PANEL DISCUSSION: Defining Critical Experiments and their Parameters

A. Sessler, LBL (Chair); B. Carlsten, LANL; J. Goldstein, LANL; K.-J. Kim, LBL; C. Pellegrini, UCLA; L.-H. Yu, BNL; A.S. Fisher, BNL (secretary)

The panel discussed the critical experiments for verifying the theoretically predicted performance of short-wavelength FELs. Four types of FEL were considered: oscillators on RF-linacs and storage rings, and linac-based FEL amplifiers using self-amplified spontaneous emission and harmonic generation.

All four need additional experiments to advance to ultraviolet and x-ray wavelengths. Due to the hardware and personnel available at various laboratories, these experiments would be distributed over several locations, although integrated FEL experiments, not just separate demonstrations of specific technologies, are desirable.

FEL amplifiers and oscillators are presently at very different stages of development. Hence, critical experiments to validate extensions of such devices to VUV and soft x-ray wavelengths are quite different. The feasibility of short-wavelength oscillators rests primarily upon demonstrations of scalable optical resonators. The requirements on electron-beam quality and wiggler length for high-gain amplifiers are substantially more demanding than for low-gain oscillators. However, beams of the necessary quality have already been produced for SLAC's SLC project. Also, FEL amplifiers dispense almost entirely with optics.

Much of the panel's discussion focused on the direction of research in FEL amplifiers. Long-term plans for amplifiers include a 75- to 300-nm harmonic-generation FEL at BNL (the DUV-FEL) and a 4-nm SASE FEL (the LCLS) at SLAC. These programs share several issues, in both electron-beam peparation and in FEL physics, which would profit from a coordinated effort.

Both amplifier proposals involve electron beams produced by bright photoinjector RF guns, operating at 2856 MHz. While this technology has been quite successful, further development will be beneficial. The BNL 1.5-cell gun has a maximum energy of 4.5 MeV. A higher-energy gun may have some advantages. To this end, Grumman and BNL are completing a 3.5-cell, 10-MeV gun, with separate feeds for the first and last two cells. Compensation for the space-charge component of emittance, using solenoid or quadrupole focusing of the gun beam, is also critical. The solenoid technique has been demonstrated at 1300 MHz at Los Alamos, where additional work is continuing to increase the level of compensation and to understand the relative importance of slice and axially integrated emittances. UCLA has begun testing a version of the BNL 1.5-cell, 2856-MHz gun with a solenoid, and a similar gun will be installed later this year at BNL's ATF.

After the gun, the beam must be accelerated and the bunch length must be compressed to attain the required energy and peak current. During these processes, the emittance must be kept small with a high degree of stability. Many of the emittance-preservation issues have been demonstrated at SLAC and LANL, but bunch compression increases the sensitivity to jitter, making the stability difficult to achieve. Calculations indicate that the requirements can be met, but a demonstration experiment is desirable for verification. An internally funded project is planned at LANL to analyze buncher physics and to construct and experimentally test a sub-picosecond buncher for 5 nC with the rms emittance of the compressed bunch less than 2 π mm mrad at less than 20 MeV.

Previous SASE experiments in the exponential-growth regime took place at millimeter wavelengths. It was noted that noise was higher than expected in these cases. It is critical to study, at a wavelength intermediate between millimeter waves and ultraviolet or shorter, the start-up of an FEL from noise, exponential growth over several gain lengths, and saturation. Information is needed about such issues as optical guiding and the transverse mode structure; the saturation length and power; spatial and temporal coherence; and fluctuations in position, wavelength, and power. It was agreed that infrared wavelengths are suitable for this step. Two IR experiments, using SASE at UCLA (10 μm) and harmonic generation at BNL (10 μm, converted to 3 μm), are directed at these questions. This infrared work should then be followed by a similar demonstration of SASE in the UV, at about 100 nm or shorter. The longer wigglers required in the UV will allow tests of the sensitivity to field and steering errors, and the effect of external focusing. Techniques for building and aligning long, high-field wigglers, and for steering, focusing, and diagnosing beams within them, must be developed. These experiments would provide the confidence to proceed with the short-wavelength FEL amplifiers being proposed.

FEL oscillators have already operated in the UV: at 240 nm and 350 nm on storage rings (at Novosibirsk and Orsay, respectively) and at 375 nm on a linac-driven device (at Los Alamos). It appears (see the report of the linac-driven oscillator working group) that a 90-nm demonstration experiment could be done with equipment available today (e.g., the Boeing 5-m Thunder wiggler and a linac combining a Los Alamos photoinjector and the Boeing 180-MeV accelerator). If the first phase of operation of the Duke 1-GeV storage ring reaches its design goals, it also should be able to drive an oscillator in the 100 to 200 nm range.

Although further improvements in undulator technology and electron beam quality are needed for FEL oscillators to reach the deep XUV or soft x-ray wavelength ranges, the primary obstacle is the demonstration of a wavelength-scalable optical resonator design. Such a resonator, the multifacet-mirror ring, has been proposed, and so the critical technology-demonstration experiment for FEL oscillators (on either a linac or storage ring) would be operation with a ring resonator at a suitably short wavelength (<100 nm). The many associated issues - alignment and stability of the resonator, vacuum problems and mirror degradation, the stability of the e-beam, "high"-gain mode-distortion interactions with the empty-cavity optical mode structure, efficient outcoupling, thermal distortion of the mirrors - would necessarily be addressed by this experiment.

SECTION D: AVAILABILITY OF RESOURCES

The goal of this session was to identify relevant facilities and experimental demonstrations for the critical tests. Eight groups presented discussions on available accelerators, injectors, wigglers, and diagnostics. A large base of hardware exists which might be applicable. However, there is a wide range in the status and availability of this hardware which would impact the cost and schedule of any proposed experiment. During the workshop it became apparent that a great deal of FEL expertise and FEL hardware exists in the DoD laboratories as a result of the SDI directed energy research build-up. Due to the current reorganization of SDI priorities, it is not clear what the availability of the equipment and laboratories will be.

The specific ensemble which would be optimal for experiments as a storage-ring-driven oscillator, linac-driven oscillator, or amplifier is presented in the panel discussions later in this workshop summary. The parameters presented are summarized in the attached tables: Table I. Injectors, Table 2. Accelerators/Rings, Table 3. Wigglers. A short discussion of the presentations by the groups are presented below.

Boeing is in the assembly stages of a high average power 10 micron oscillator system which is scheduled for completion in FY94. Although presently funded for FEL studies for ballistic missile defense this system could provide a high duty factor accelerator with reasonable emittance although the energy is too low (18 MeV) for DUV uses. There is a 120 MeV L-band accelerator that is mothballed. It transported 4 ncoul and was used for a visible FEL experiment. It could be reconstructed for use as an amplifier or oscillator although it would be necessary to add the required diagnostics and controls systems to the accelerator sections. Two different wigglers are also available (Thunder and NISUS) which look attractive for oscillators. Their field quality, length, and wavelength are well suited to an oscillator demonstration at around 200 MeV for 90 nm output.

Brookhaven is in the process of commissioning a 230 MeV S-band accelerator that can be made available for FEL activity after acceptance tests for the baseline design parameters have been accomplished. It is well suited to initial tests of SASE or seeded amplification with the addition of a suitable injector (see Grumman discussion). Operation of the system in its baseline configuration is scheduled for FY94. In addition, the BNL Accelerator Test Facility has in operation a 4 MeV photoinjector, a 50 MeV linac (soon to be upgraded to 70 MeV) and a

CO_2 laser for seeding. A 200 cm wiggler is under construction, allowing for a variety of SASE and seeded amplifiers to be tested. An oscillator experiment is also under construction, for tests in the visible to near UV region. Both experiments will be ready within one year.

CEBAF is in the process of final installation and commissioning >800 MeV of CW superconducting accelerator which would be suitable as an amplifier or oscillator with the addition of a high brightness injector. An injector port has been provided that would be suitable. However, over the next two years the schedule for commissioning and nuclear physics operation as well as the proposed high average power IR FEL precludes additional activities. Longer term programs could be considered as adjunct to the development of high average power industrially driven UV systems. Construction of a CW photoinjector is underway although as currently planned its brightness may not be sufficient to reach the DUV.

The only storage ring facility presented was that under construction at Duke. The facility will provide 0.25 to 1 GeV with initially 130 A peak current (100 mA average) at brightnesses suitable for the DUV. Plans include increase of the peak current to 350 A. Construction of the injector linac is underway and expected to come on line in FY94 at 250 MeV with future upgrade to 800 MeV. The 250 MeV linac can provide long pulse operation (<8 us). There are substantial straight sections to allow for very long wigglers or optical klystrons. At present the NIST wiggler is installed and plans are underway for the import of the OK-4 undulator from Novosibirsk. The ring has a very large energy acceptance. As discussed below the addition of an entry-level cavity for DUV would be inexpensive and straightforward.

Grumman presented the plans for their high brightness injector and superconducting wiggler which is under development in collaboration with BNL. This injector would provide a suitable output for any of the planned amplifier experiments with 150 A of peak current at S-band available at high Pulse Repetition Frequency (PRF). The superconducting wiggler is well suited to the high field and short wavelength required for a harmonically boosted amplifier and has already demonstrated excellent field quality. Grumman also presented plans for a compact IR FEL designed for 5 to 20 um output.

LANL discussed two extensive facilities which have already lased and could be further developed to provide the injected beams for DUV. The APEX system produces 350A of peak current at 47 MeV and AFEL produces 18 MeV at even higher brightnesses. Energy limitations prevent the systems alone from serving as a driver for DUV but the use of either of the injectors would provide a suitable source for either amplifier or linac based oscillator systems. The availability of these systems is good, owing to the unfortunate limited funding for their baseline FEL programs. The injectors are also well characterized (APEX is the only linac-based UV FEL to date, at 375 nm). AFEL is particularly easy to operate.

The PALADIN wiggler at LLNL is a good example of the wiggler which will be needed to achieve 4 nm amplification. Although only 25m long compared to the requirement of 50 to 70 m, its field quality is excellent. For the ultimate system at least, internal strong focusing by means of permanent magnet quads will have to be added to maintain proper beam size. The large size and operational complexity of the wiggler system including power supplies, etc. will make any commitment to its use a significant activity. It is presently available.

If equipped with a high brightness RF photocathode gun, the SLAC linac offers the possibility of delivering beams at very high energy for SASE devices operating down to about 3 nm initially and ultimately possibly at much shorter wavelength. As part of the SLC project, SLAC has developed the tools and understanding associated with the transport, acceleration and compression of low emittance electron bunches without significant loss of phase space density. Several locations for guns, compressors and wigglers have been studied for proof-of-principle experiments, including the use of the Paladin wiggler (now at LLNL) to drive SASE devices at wavelengths down to 40 nm. Additional detail about the use of the SLAC and BNL linacs can be found in the summary of the Linac Amplifier Working Group (Section E3) and in the appendices to this report.

UCLA presented plans for IR experiments relevant to the amplifier systems. It will utilize a 5 MeV photocathode gun to provide the 20 MeV linac output to a compact hybrid wiggler. A 60 cm long wiggler is available. Models indicate SASE saturation lengths of 160 cm with this system so that studies can be made of gain length, spontaneous noise, optical guiding, etc. Saturation can be studied with a suitable seed laser.

Table 1: Available Injectors

	Units	APEX	AFEL	BAC	BNL	Duke	CEBAF	Grumman	UCLA
E	MeV	6	17	5	4.5	.85	10	10	4.5
f	MHz	1300	1300	433	2856	2856	1500	2856	2856

Table 2: Available Accelerators

		APEX	BAC	BNL-ATF	BNL	CEBAF	Duke injec.	Duke SR	SLAC
E	GeV	0.045	0.22	0.05	0.23	0.8	.25/.8	1	<50
f	MHz	1300	1300	2856	2856	1500	2856	178	2856
T_{mac}	μS	100	250	3	3	CW	8/1	CW	3

Table 3: Available Wigglers

		BNL	LANL	LANL	NISUS	NIST	OK-4	UCLA	Thunder
λ_W	cm	1.8	1.3	2.05	3.9	2.8	10	1.5	2.18
L_W	m	2	1	1	10	2X1.8	7.14	.6	5
a_W	peak	<1.3	.8	1.25	<2	1	<5.4	.7	1.85

SECTION E: REPORTS FROM THE WORKING GROUPS

E1: Report of the Working Group on Linac-Driven FEL Oscillators

K. McKenna, I. Lehrman, J. Bisognano, A. Vetter, T. Smith, R. Sheffield,
D. Chan, P. Tompkins, J. Goldstein, P. O'Shay, J. Adamski, B. Newnam,
W. Barletta, G. Neil**, C. Brau*

* Session Chairman
** Secretary

I. Introduction

The objective of the following experimental program is to demonstrate operation of an rf-linac-driven FEL oscillator in the extreme ultraviolet (XUV) between 50 and 100 nm using components that will enable future scaling to much smaller wavelengths, e.g. ~ 4 nm. We have chosen 90 nm as the specific design wavelength for our demonstration oscillator and propose using resonator mirror configurations with sufficiently high reflectance to permit FEL operation on the third optical harmonic to minimize the electron beam energy. Numerical simulations of such oscillators indicate that the power output should exceed that of other XUV radiation sources by three orders of magnitude. Thus, the demonstration facility is useful in itself, as well as demonstrating principles scalable to shorter wavelengths. By using selected FEL components (injector, linac, undulator, optics) existing at or designed by the several participating FEL laboratories, we project that such a demonstration can be accomplished within two to three years, given that adequate funding is provided.

A. Critical technologies

Two of the three essential components (electron beam and magnetic undulator) of an XUV FEL oscillator have already demonstrated operating parameters sufficient to operate below 100 nm. As an example of the electron beam, use of a laser photoinjector on the Los Alamos APEX rf linac has produced a high-current (130 A), high-brightness (3 x 10^{12} A/m^2, rms) beam at 46-MeV. The rms normalized emittance at 1 nC was measured at about 2 π mm mrad. Lasing on the third harmonic at 375 nm was achieved at this energy using a 1-m permanent-magnet undulator with a 1.365-cm period.[1] When accelerated to a much higher energy, e.g. 1 GeV, and phase-compressed by a factor of three, such a beam would be bright enough for a 4-nm FEL oscillator, In addition, the existing 5-m-long, hybrid permanent-magnet wiggler (2.18-cm long), known as THUNDER and used on the Boeing Aerospace visible-wavelength FEL oscillator, meets the requirements for field strength and steering errors.[2]

The critical technology for an XUV FEL oscillator will be at the optical resonator. The mirror reflectance must be high enough to operate at the predicted optical gain. Newnam has designed a multifacet-mirror resonator configuration that, with selected films, should provide sufficient reflectance for use down to 4 nm.[3] (At 58.4 nm, the reflectance of a nine-faceted vacuum-deposited aluminum mirror was measured to be 82% after one month in a static, high vacuum of 5 x 10^{-9} Torr.) Besides initial high reflectance, the issues of contamination, thermal distortion, mirror jitter, and resonator alignment must be resolved experimentally. A major physics issue, inherent for high-gain oscillators in the XUV, will be the effect of the variable gain guiding and distortion of the optical mode by the electron beam. At start-up, single-pass gain of ~6-10x may be needed, while at saturation moderate gain of ~2-4x will match resonator losses, and this will change the gain guiding and mode distortion.

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B. Technical Approach

Strategy

A two-phase FEL oscillator experiment at a wavelength of 90 nm will provide important advantages. Phase 1 will be conducted with resonator end mirrors placed at normal incidence, the usual two-mirror configuration. At 90 nm, the normal-incidence reflectance of aluminum coatings can be very high (~85%) if they are deposited and maintained in a high vacuum.[3] Once this oscillator operates successfully, Phase 2 will proceed by replacing the linear cavity with a ring resonator with multifaceted mirrors. Although the net reflectance of both normal-incidence and multifacet mirrors is nearly the same at 90 nm, only the multifacet mirror has high reflectance at shorter wavelengths. Thus, the combination of Phases 1 and 2 offers both high probability of success at 90 nm and scalability to shorter wavelengths.

Design studies and preliminary experiments

Optical design: The optical resonator configuration will be designed to minimize the effects of mirror distortion, jitter, and mirror alignment to minimize and compensate for the effects of mirror thermal distortion. Previous theoretical studies [4],[5],[6] of these effects for multifacet-mirror resonators provide both a starting point and a basis for optimism. At each end-mirror station, a high-vacuum and coating deposition system will be designed to enable in situ coating of the mirror substrates with aluminum.

FEL simulations: Three-dimensional numerical simulations will be conducted for both 90 nm oscillators (Phase 1: semi-confocal resonator; Phase 2; multifacet mirror ring resonator) operating on the third

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harmonic. See Subsection III for initial gain simulations by J. Goldstein of LANL.

Optics tests: Preliminary tests will be conducted on a ring resonator off-line using an injected mode-locked laser to test the effectiveness of methods to minimize mirror vibrations, such as feed-forward control. Test of the effect of hole output coupling on the optical mode in the presence of very high gain will be devised.

Microwigglers: Wigglers with periods less than 1 cm and with high transverse magnetic fields, yielding an rms wiggler parameter $a_W>1.5$, offer the potential for operation on the third-harmonic at relatively low electron energies or on the fundamental wavelength with high gain using $a_W{\sim}1$. Although these technologies have yet to be proven practical, we would re-evaluate their use if they are proven viable in other experimental demonstrations.

Beam compression: A superconducting linac, such as CEBAF, could offer certain advantages when a photoinjector is integrated to provide the high beam brightness necessary for FEL operation in the XUV. A suggested means to increase the peak current is to bunch the electron beam by beating the c.w. 1.5-GHz rf input with the pulsed 1.3-GHz rf power input used for the laser photoinjector while pulsing the photoinjector with the external drive laser at 100 MHz. Such an experiment could be attempted as a separate initiative.

II. Proposed Experiment

The group considered three distinct approaches to a short wavelength oscillator using a grazing ring resonator. These included a low-energy-current c.w. approach using CEBAF, a short-pulse linac-driven oscillator using either the Duke or BNL S-band linac and a long-pulse linac-driven oscillator using the Boeing linac. All of these options would use the 5 m THUNDER wiggler and elements of the Rocketdyne/Boeing visible-wavelength grazing-incidence ring resonator.

A. CEBAF

The CEBAF accelerator is intolerant to heavy beam loading and would require modification of the available high-brightness injectors to reduce the beam charge. This could be accomplished by compressing the 10-ps pulse from the Los Alamos AFEL injector, but this technique would require a prototype test before commitment to this approach. The 1300-MHz AFEL injector could work with the 1500-MHz CEBAF frequency at a selected beat frequency. A long-pulse RF power supply for the AFEL injector would be required to get past the transient response of the CEBAF field levelers.

An additional consideration, and perhaps a very important one, is the access time to the CEBAF tunnel for the installation process. CEBAF is heavily committed to physics users during the expected installation period of this experiment.

B. Duke, BNL

The calculated gain for these experiments is high because of the good brightness of the new technology injectors but the RF macropulse length is rather short - 8 µs at Duke and 3 µs at BNL. It was considered by the group that the short macropulse would not allow a sufficient number of round trip times in the long ring resonator to examine the start-up and resonator-stability physics.

It was recognized that the modulator could be modified for longer pulse, but it was judged that the gains made within the operating envelope of the klystrons would not sufficiently reduce the risks involved with the short macropulse.

C. Boeing linac

The linac accelerator sections and RF klystrons and modulators used in the visible wavelength FELs at Boeing can be reconfigured with the LANL AFEL injector to produce a 180-MeV long-pulse linac with excellent brightness.

The accelerator will use five klystron/modulator stations. One additional klystron will power the injector. The macropulse width will be 200 µs. The accelerator will be placed in the far end of the hall compared with its original location so that the injection onto the wiggler beamline can use a simple, small-angle triple-dipole bend. The wiggler will be the 5-m THUNDER wiggler that is still in place in the laboratory.

Two resonator experiments are planned; both of these will be run on the third harmonic wavelength of 90 nm. The first experiment will use simple, normal-incidence optics in a 22-m concentric resonator cavity. The mirror tanks, mounts and alignment system from the visible-wavelength experiment will be modified to perform this test. The second experiment will use a multimirror grazing incidence ring. The Rocketdyne/Boeing visible-wavelength ring tanks, mounts and alignment system will be reused with the new optics and diagnostics.

The proposed experiment can be performed in the existing facility at Boeing without any substantial modifications. This facility has the required radiation shielding, electric power and water cooling resources. The experiment control system is a modular computerized control that can easily be configured to operate the FEL.

III. Performance

As backup for the proposed experiments, Goldstein (LANL) calculated the gain for the model system and the time to saturation. These are based on the following parameters:

Electron beam: peak current I=200 A, normalized transverse emittance ε =20 π mm-mr (90%; rms emittance would be 5 π mm-mr), fractional energy spread $\Delta\gamma/\gamma$=0.1% (FWHM), beam relativistic factor γ=331.8073 (169.55 MeV) to give resonance wavelength on the third harmonic of the THUNDER wiggler of λ=90 nm. Note that this gives an unnormalized emittance of $1.893\text{x}10^{-5}$ cm (90%), more than twice the optical wavelength. This is about where the 0.38-µm experiment at LANL operated.

Wiggler: THUNDER,[7] λ_W=2.18, B_W=9140 Gauss (peak, on the fundamental; the peak field on axis of 1 T includes a ~9% third harmonic component which is neglected here), a_W=1.8586 (peak), $N=L_W/\lambda_W$=220 (the 5-m length includes some beam position monitors), two-plane focusing (via canted poles). A circular aperture of radius 0.24 cm was put at each end of the wiggler to simulate the possible vignetting of the vacuum tube through the wiggler.

Light: resonance wavelength 90 nm, third harmonic operation, Rayleigh range = 0.5 L_W, empty cavity focal point at the center of the wiggler.

Results: The maximum single-pass small-signal gain was found to be G_{SS}=46.96 at 90.35 nm (that is, 4596%). Assume a two-mirror resonator (mirror separation 55 m, which corresponds to the old Boeing "visible oscillator" experiment) with total cavity losses per round trip of 42.4% (two mirrors of R=0.8 each, plus ~10% outcoupling). Estimating the spontaneous emission into the lowest order of Gaussian resonator mode, a multipass simulation gave a net small-signal gain of 2170% (gain through the undulator of ~39.4 instead of 37), ~12 passes needed to reach saturation (the saturated power was ~18MW at the end of the wiggler inside the resonator).

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[7] IEEE JQE QE-23, P.1497, SEPT. 1987

Keeping all parameters unchanged except the final energy spread, which is doubled to 0.2%, reduces the single-pass small-signal gain to 10.34 (934%) at λ=90.445 nm. A multiple pass simulation gave a net small-signal gain of 406% (gain through the undulator of 8.8 instead of 10.3); the laser saturated in ~20 passes at ~20 MW at the end of the wiggler.

These calculations ignore pulse slippage effects. The effects of gain guiding may vary with different resonator configurations.

IV. Linac Based Oscillator Cost Estimate

The cost estimate for the linac-based oscillator demonstration is based on consensus agreement among the working session members. In arriving at the estimate we have made the following assumptions:

- High average power is not a goal. Therefore electrical costs, special cooling costs, and radiation shielding are not included in the estimate.
- Direct Administration costs are not included.

We assume that the following items are available for use:

- A facility prepared and approved (i.e. sufficient radiation shielding) for accelerator operations, with sufficient electrical power and chilled industrial water. No major structural modifications are required.
- A 1.3 GHz photoinjector, including drive-laser, cathode fabrication hardware, and vacuum hardware.
- All necessary post-acceleration tanks at 1.3 GHz, including support structures and vacuum pumps.
- All klystrons required at 1.3 GHz along with modulators, waveguides, low-level rf drivers, feedback and feedforward controls.
- A wiggler with support structure and vacuum beam pipe.

We assume the following items do not exist or are incomplete, however major development efforts are not required:

- Some electron beam diagnostics hardware such as frame and streak cameras are available. screens and position monitors are not available, however existing drawings can be used with only minor modifications.
- Optical-beam diagnostics are largely available and no major development effort is required.
- Beam pipe and drift tubes are not available.

- A computer control system based on an existing format will be used. No major development effort required. Hardware purchases will be required.
- Most required bending and focusing magnets can be obtained from existing accelerators. Magnetic buncher will require development and new hardware.

The following items are not available and extensive development efforts are required:

- Resonator optics for Phase 1 90 nm experiment including in situ vacuum deposition of coatings.
- Resonator design and optics for Phase 2 including grazing incidence optics.

We assume an average person-year (PY) cost of $250,000. The PY cost includes $50,000 for materials and supplies.

Cost Estimate:

TASK	INSTALLATION		COMMISSIONING		SUBTOTAL	
	PY	M$	PY	M$	PY	M$
Injector	.5	0	.5	0	1	.25
Accelerator	10	2	10	0	20	5
Wiggler	.5	0	.5	0	1	.25
Optics	10	2	4	1	14	6.5
Facilities	0	1	0	0	0	1
Totals					**36**	**13**

E2: Report of the Storage Ring Working Group

S. Benson, V. Litvinenko, J.M.J. Madey*

* Session Chairman

Outline

A. Objectives
B. Assessment of Resources
C. Research Options
D. Issues Resolved (physics issues)
E. Cost and Time Estimates

A. Objectives

1. Demonstrate wavelength scalability to below 100 nm
    a. scalability of accelerator-drivers
    b. scalability of resonator technology
    c. scalability of undulator technology
2. Demonstrate an average and peak power 1000x conventional technology
3. Achieve results in less than 2 to 3 years
4. Minimize requirements for additional funding
5. Make optimal use of existing resources (facilities, equipment and people)
6. Provide entry-level research capability

B. Assessment of Resources:

1. Existing 3rd Generation Storage Rings
   candidates for evaluation include ALS and ESRF
2. Duke Storage Ring
   the only asset available in the US with acceptable performance and an uncommitted long straight section for demonstration of lasing at 100 nm; system also has upgrade capability for extension of lasing at fundamental to below 60 nm.

3. Undulators:

   a. OK-4 (Budker Inst. of Nucl. Phys., Novosibirsk)

      available as packaged, integrated system at low cost; INP has signed memorandum of understanding to support baseline UV/XUV research program: low cost upgrades available to improve gain and explore novel FEL configurations.

   b. Paladin

      low K; would need new vacuum chamber for proposed storage ring experiment.

   c. Other???

      NISUS - would need new vacuum chamber and dispersive section to perform proposed experiments.

4. Vacuum Chambers:

   available with OK-4 system

5. Resonators:

   a. OK-4

      integrated UHV resonator system available for normal incidence two-mirror resonator; includes precision mirror and basic optical diagnostics.

   b. Normal Incidence Reflectors

      high quality low loss dielectric mirrors available to 240 nanometers; useable, moderate loss (1%) dielectric mirrors available to 120 nm; high loss (10%) vacuum deposited aluminum mirrors available to 90 nm.

   c. Grazing Incidence Systems

i. LANL/Brian Newnam

has conceptual design for moderate loss resonators to 40 nm including experimental reflectance data and codes to model effects of thermal distortion.

ii. Boeing, Rocketdyne

have demonstrated an integrated grazing incidence ring resonator at 600 nm, including required alignment and stabilization technologies; some spare mirror substrates available.

6. Diagnostics:

a. Duke

will acquire some basic UV/XUV optical diagnostics as part of baseline research program; has adequate data acquisition and data processing capabilities.

b. BINP/Novosibirsk

additional basic UV/XUV diagnostics available as part of integrated OK-4 system; INP has offered to supply advanced image dissector technology to project for time-resolved e-beam and optical pulse length measurements.

c. other??

grazing incidence resonator will require an integrated alignment and stabilization system.

7. Theoretical assets (for FEL):

a. Theoretical Analysis:

available at LBL, MIT, NRL, ...

b. Simulation codes

available at LANL, LLL, MIT, CEBAF, ...

8. Human Assets (Possible Collaborators):

a. Storage Ring Physics and Technology

Nat'l Labs: BNL, LBL, ANL
Universities: MIT, Cornell, Stanford, UCLA,
Wisconsin, ...
International: INP, Daresbury, Dortmund, LURE, ...

b. FEL Physics and Technology

Nat'l Labs: LANL, LLL, LBL, BNL, NRL, CEBAF
Universities: Columbia, MIT, Stanford, UCLA, UCSD,
Naval Postgraduate School (Monterey)
Corporate: Boeing, Rocketdyne, Spectra Technology,
Deacon Research
International: INP, LURE, Daresbury, Dortmund, ...

c. Optical Technology

Nat'l Labs: LANL, LLL, China Lake
Corporate: Rocketdyne, Boeing, Deacon Research
International: LURE

C. Research Options:

$200k 1. Empirical study of e-beam quality, current, lifetime in existing 3rd generation storage rings

acquire/solicit relevant data on performance of new 3rd generation rings; analyze possible performance for sub-100 nm FEL systems

2. Demonstration/Research Program using Duke ring:

'Baseline' a. existing OK-4 system using normal incidence front surface mirrors

achieve routine lasing in UV to 120 nm;

attempt lasing at 100nm (16% gain margin); demonstrate giant pulse operation

$250k b. "extended" OK-4 system, adding one 3.5 meter undulator

- i. improved gain (>60% gain margin at 100nm; 50% gain margin at 70nm)
- ii. coherent harmonic generation/lasing (possible demonstration of subharmonic-assisted lasing)
- iii. novel FEL configurations (distributed klystron, phase displacement, ...)

$3-6 million c. (a) or (b) with grazing incidence resonator

$750k d. Landau damping cavity

improve peak current to 300 A for 4x improvement in gain, extension of lasing to below 60nm

$750k e. upgrade main RF system

improve energy acceptance to +/- 5% to increase average power output to >100 watts

D. Issues to be resolved in C above

1. Physics issues:

   a. What are the actual capabilities of the new 3rd generation light sources to support FEL operation at wavelengths below 150nm? (Option C.1)

   b. Is the ring-laser interaction well-understood? (Option C.2.a)

c. Can sub-harmonic seeding, phase-displacement amplification,or other novel techniques be used to improve the short-wavelength gain? (Option C.2.c)

2. Technology issues:

a. What impedance is realistically attainable? (Option C.1)

b. Can storage rings be made sufficiently stable for XUV FEL operation? (Options C.1, C.2.a)

c. Can tolerances be maintained while synthesizing long undulators? (Option C.2.b)

d. Will a grazing incidence resonator maintain its figure and Q in the harsh environment of a high power (10 watt) XUV FEL? (Option C.2.c)

e. Can dispersion (for linewidth control) be integrated in the ring resonators necessary for XUV FEL operation? (Option C.2.c)

f. Are available diagnostics adequate to achieve and maintain UV/XUV lasing? (Options C.2.a, b, and c)

E. Cost and Time Estimates:

1. Cost: See (C) above; note that cost estimates include only the incremental cost of the proposed research efforts; all other hardware, personnel and operating costs are assumed to be funded by Duke's baseline FEL research effort.

2. Time estimates:

test of OK-4 undulator spectrum at Novosibirsk (1st, 3rd and 5th harmonics) to demonstrate it's scalability for long FELs - Fall 1993

test of normal incidence mirror for deep UV (<200nm) at Novosibirsk - Fall 1993

shipment of OK-4 system to Duke (Baseline Program) - Spring 1994

commissioning of OK-4 system (Baseline Program) -
Fall 1994

demonstration of lasing at 100nm (Baseline Program) -
Summer 1995

extension of OK-4 undulator as per C.2.b - add 3 months to schedule; upgrade RF system as per C.2.d and e -
no change in schedule

develop, integrate and test grazing incidence resonator as per C.2.c - to be determined.

E3: Linac Amplifier Working-Group Report

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1. Introduction.

Recent developments in RF photocathode electron guns and in techniques for the preservation of electron-beam brightness in high-energy linacs make it possible to produce the bright electron beam required for an extremely-high-gain FEL amplifier. With such an amplifier, it is possible to generate short-wavelength coherent radiation, either by Self-Amplified Spontaneous Emission (SASE), in which the noise power present in the electron beam is amplified, or by Harmonic Generation (HG), in which a coherent input beam is frequency multiplied in a multi-stage wiggler. For short wavelengths, the FEL amplifier has the advantage of not requiring the development of high-reflectivity mirrors at normal incidence.

The working group agrees that current technology should make possible the construction of an FEL amplifier at ultraviolet and x-ray wavelengths down to a few nanometers. These intense, coherent beams would provide breakthrough opportunities for many experiments, such as the imaging of biological samples at wavelengths in the water window. However, in view of the fact that such a project involves a big leap in the wavelength of operating FELs, the working group found it important to first carry out FEL demonstration experiments at longer wavelengths, near 10 μm and 100 nm.

The 10 μm measurements will verify the basic FEL physics with less demanding electron-beam and wiggler parameters. Experiments in HG and SASE at 10 μm are currently being prepared at BNL and at UCLA respectively, and can be completed in the near future with a small amount of additional funding. The working group urges the FEL community to give their full support to these activities.

The 100 nm experiment, in addition to providing intense coherent radiation in a hitherto unavailable wavelength region, has the aim of comprehensively demonstrating accelerator and FEL techniques for short-wavelength generation. For efficiency, this experiment should take advantage of existing hardware available at several laboratories and should involve a collaboration program. We have discussed two examples of such collaborations, one using the new BNL 230 MeV linac and the Thunder wiggler from Boeing, and one using the SLAC linac and the

Paladin wiggler from LLNL. The group recommends strongly that at least one of these experiments be supported by the community and the funding agencies.

2. The 10 μm Experiments at BNL and UCLA

BNL is building an experiment to generate high power at the third harmonic of a 10 μm input. UCLA is preparing an SASE experiment at 10 μm. These laboratories plan to cooperate extensively, by sharing hardware and expertise. Other laboratories are encouraged to contribute to these activities.

2.1 The BNL High-Gain Harmonic Generation (HGHG) Experiment

The BNL HGHG experiment will test the principle of high-gain harmonic generation from a 10 μm seed laser. The experiment will demonstrate in the infrared the essential physics underlying BNL's DUV-FEL proposal, in which a tunable beam in the near IR will be converted to the near UV using conventional harmonic-generation crystals and used to seed an FEL designed to radiate into the VUV (down to 75 nm), where conventional high-power laser sources are unavailable. Unlike SASE, the tunability, bandwidth, and wavelength stability of the resulting beam will be determined by the laser source. Unlike FEL oscillators, there is no need for a UV resonator and its problems of mirror losses and damage.

The HGHG experiment uses BNL's Accelerator Test Facility (ATF). A 10.6 μm, 1 MW, CO_2-laser input will generate a 3.53 μm, 30 MW output in a three-stage wiggler magnet. The seed beam will modulate a 30 MeV electron beam in the first, 30 cm long wiggler, synchronous at 10 μm. The electrons will bunch in a 10 cm long dispersive section, then radiate in the third section, a 150 cm wiggler synchronous at 3.5 μm, which includes an adjustable taper over the final 125 cm.

The experiment will allow detailed measurements of harmonic generation, exponential growth, saturation, tapering, and bandwidth. The design, construction, alignment, and operation of a long, high-field, superferric (superconducting wire on iron poles) wiggler will be demonstrated, along with provisions to test the focusing, steering, and beam diagnostics that will be essential for the DUV-FEL.

The project is now under construction. At present, the CO_2 laser is available. Grumman has built, and BNL has tested, two pairs of superferric wiggler sections (25 cm each). Recently, two additional sections have been machined to extremely tight tolerances to correct small field errors measured in the earlier sections. The performance should now be fully satisfactory. The full wiggler assembly is scheduled to be delivered one year from now. The experimental beam line is expected to be completed in the summer of 1994, and the experiment will then start in the fall.

2.2 The UCLA 10 μm SASE Experiment

A compact, infrared, high-gain, FEL amplifier is being constructed at UCLA to verify the FEL physics relevant for future short-wavelength systems. In this experiment, a 3.5 MeV beam generated by an RF photcathode gun with a copper cathode (Brookhaven-type gun, at 2856 MHz) will be accelerated by a plane-wave transformer (PWT) linac to ~17 MeV. The expected beam parameters are summarized in Table 1. When sent through the existing Kurchatov undulator, which has a 1.5-cm period, a 60 cm length (40 periods) and a peak field of ~7.25 kG (K ~ 1), this beam will produce 10 μm radiation. The system operates with single bunches. The expected FEL performance is given in Table 2.

Initially, UCLA will study gain length as a function of the beam parameters, start-up from noise, and saturation starting from a seed-laser pulse. Further studies will include optical guiding, coherence, slippage effects, additional saturation studies (i.e., superradiance). A second undulator would make possible studies of saturation from SASE, operation in an optical-klystron configuration, and e-beam focusing between the undulators.

The timetable for the project is highly dependent on the support received from the community. This is a (financially) modest program, and small contributions make a big impact. The undulator is complete, the gun has been commissioned, the linac has been cold tested and a basic CO_2 system is being donated (on loan) from Livermore (ATA).

The system is presently shut down for shielding construction. Beneficial occupancy should occur by October 1993. UCLA estimates up to 6 months for beamline construction and linac commissioning. Now is the time when outside assistance will help speed up completion of the project. Major areas of work include: RF computer control, drive-laser amplitude and timing-jitter stabilization, beam diagnostics (specifically BPMs), and CO_2 diagnostics in the time domain (autocorrelator?). General laboratory equipment would also significantly enhance the rate of work. These items are detailed in a supplemental list.

Energy	~17	MeV
Emittance (normalized, rms)	~5	π mm-mrad
Energy spread (rms)	0.1	%
Peak current	200	A
Pulse length (rms)	2	ps
Repetition rate	0--5	Hz

Table 1. Expected beam parameters for the UCLA FEL.

Power gain length	<7.6	cm
FEL parameter (ρ)	$\sim 10^{-2}$	
SASE saturation length	160	cm
Saturated power	~20	MW
Peak power at 60 cm	~1	kW

Table 2. Simulation performance of the UCLA FEL.

3. The 100-nm SASE Experiment

A 100-nm demonstration experiment is considered an important step toward achieving an ultraviolet or x-ray FEL user facility. To minimize expenses, the working group concentrated on scenarios that utilize hardware available at various laboratories. It was determined that an SASE experiment at 100 nm can be carried out by employing one of the wigglers built for the SDI program and either the SLAC linac or the BNL 230 MeV linac, which is currently being commissioned.

3.1 Accelerator and FEL Issues to be Studied

3.1.1 FEL Physics

All the issues that will be discussed have been studied and understood theoretically, but still require thorough testing in experiments.

An SASE FEL operates in the high-gain regime, starting from noise. In most experiments external quadrupole or sextupole focusing is added to the natural undulator focusing to increase the electron beam density and thus increase the gain. The high-gain regime for a tightly focused beam at short wavelength can only be attained if diffraction is controlled by optical guiding in the FEL.

The high-gain regime, as well as start-up from noise, have been demonstrated in experiments at LLNL and MIT at long wavelengths, in the millimeter region, but not at shorter wavelengths. The amount of noise present in the beam is essential to determine the undulator length needed for saturation. The effect of fluctuations in the noise on the final saturated power and on the undulator saturation length have not been studied experimentally. The line width for a process starting from noise also requires information from experiments.

To summarize, the main physics issues to be explored experimentally are:

- the high-gain regime, including effects like optical guiding, and additional focusing;
- startup from noise and lethargy;
- the saturation length and saturation power;
- the line width at saturation;
- fluctuations in the power level, and in line width; the statistical properties of the radiation.

3.1.2 Electron-Beam Transport and Compression

Photocathode RF guns have produced very bright beams. For a UV or x-ray FEL, the low normalized emittance must be preserved during acceleration while the peak current is increased by bunch compression. Partial demonstrations of this possibility have been done at SLAC in connection with the linear collider, but this work needs to be extended to the parameter range characterizing a short-wavelength FEL.

When discussing beam transport and bunch-length compression, we need to consider four issues: (1) the degree of compression required; (2) the longitudinal wakefield, which increases the correlated energy spread and becomes harder to compensate in shorter bunches; (3) the transverse wakefield and RF deflections, which dilute the transverse emittance and are more severe for longer bunches; and (4) the effect of current and phase jitter, which change the bunch length and peak current, and therefore, the gain length of the FEL. The first issue, the optimum degree of compression, is determined by FEL physics, using analytical theory or simulations.

Given the degree of bunch-length compression that is desired, the effects of longitudinal and transverse wakefields and the effect of jitter must be balanced. The effects of wakefields have been studied in the SLAC S-band structure, assuming a 15 MV/m acceleration gradient and a bunch charge of 1 nC. The results are summarized in Fig 1, which shows the peak-to-peak energy spread and transverse-emittance dilution at the end of a 7 GeV linac. The apparent "knee" in the energy spread at $\sigma_s \sim 100\text{-}200\ \mu\text{m}$ arises when the RF cannot be used to compensate the longitudinal wakefield due to very short bunches. The transverse emittance dilution was calculated from the average of 10 random distributions with 300 μm rms accelerator structure misalignments and 150 μm rms quadrupole and BPM misalignments; trajectory bumps were not used to reduce the emittance dilution.

Fig 1. Transverse emittance dilution (solid curve, with scale at left) and peak-to-peak energy spread (dashed curve, with scale at right) as a function of the bunch length after acceleration to 7 GeV in the SLAC linac. The emittance dilution is scaled to the initial emittance $\gamma\varepsilon_{x,y} = 3$ mm mrad. The plotting symbols indicate the calculated points.

Although the RF cannot fully compensate for the longitudinal wakefield when accelerating a very short bunch, one can compress so that the head of the bunch initially has a lower energy than the tail. As the bunch is accelerated, the longitudinal wakefield removes the energy difference. This is the approach that is used in the 4-nm SASE FEL proposed by the LBL-LLNL-SLAC-UCLA collaboration and refered to as the LCLS. Here, two stages are used to compress the bunch length by over a factor of 20, achieving a peak current in excess of 3 kA; the work is described by K. Bane, T. Raubenheimer, and J. Seeman in SLAC-PUB-6200.

Finally, we turn to the effect of the phase and intensity jitter. In both cases, the jitter changes the (δz) correlation which will change the bunch length after compression. With phase jitter, the change in bunch length can be estimated simply. When the longitudinal emittance is extremely small, we can neglect the uncorrelated energy spread and calculate the bunch length after a single compression:

$$\sigma_z(\Delta\varphi) = \sigma_{z0}\left|1 - R_{56}k_{rf}\,\frac{\sin(\varphi+\Delta\varphi)}{\cos\varphi}\right|,$$

where $\Delta E = V_{RF}\cos\varphi >> E_0$, σ_{z0} is the initial bunch length, φ is the nominal RF phase, and $\Delta\varphi$ is the phase jitter.

Now, the change in the bunch length is:

$$\frac{1}{\sigma_z^*}\frac{d\sigma_z}{d\Delta\varphi} = \frac{\sigma_{z0}^*}{\sigma_z^*}\left(\frac{\sigma_z^*}{\sigma_{z0}^*} \pm 1\right)\cot\varphi$$

where the * denotes the design value, the negative sign corresponds to under-compressing, and the positive sign is for over-compressing. Notice that the sensitivity primarily depends upon the degree of compression.

At this point, we can perform a similar calculation to include the effect of a second compression. In this case, two terms in the expression can be chosen to cancel. In the design of the compression system for the LCLS, this cancelation eased the tolerance on the phase jitter from ±0.04 ps to ±0.45 ps for a 10% variation of the peak current. Finally, we can estimate the phase tolerance for a single compressor generating a 1 kA beam in the proposed 250 MeV BNL linac. Equation (2) predicts a phase tolerance of ±0.5 ps to limit the current jitter to 10%; this value agrees with the results of preliminary simulations.

3.2 Collaborations and Available Hardware

Table 3 of section D lists the parameters of various wigglers. Three of these, Thunder, Nisus and Paladin were built for SDI projects and in principle might be available for a 100 nm experiment. Table 1 of that section lists RF photocathode guns which could be used.

The SLAC linac is available for a short-wavelength FEL experiment if it can be scheduled to avoid interference with the high-energy experimental program. BNL is commissioning a 230 MeV linac built originally for the compact light-source project. If funds are available, this linac could be dedicated to the FEL program.

Possible SASE experiments using this equipment are listed in Table 3. In the table, a "natural" focusing of equal strength in the horizontal and vertical directions using parabolic pole-face shaping is generally assumed. The FEL performance could be further optimized by introducing stronger focusing using quadrupoles; special permanent-magnet quadrupoles are assumed in the final Paladin example, which also includes an upgrade to a higher field. It is clear from the table that either the SLAC linac with the Paladin wiggler or the BNL linac with the Thunder wiggler is suitable for the 100 nm SASE experiment. A photocathode gun is needed for either of these experiments. In collaboration with BNL, Grumman has developed a 3.5-cell gun, which could be used for the BNL SASE experiment. SLAC does not have a gun, but could perhaps get a copy of the Grumman gun after it is tested at BNL. In the longer term, BNL wants to build a wiggler for harmonic generation at 100 nm, and the Thunder wiggler would then be available for other projects.

Linac/ Wiggler	λ_w	K_w	γ	λ	I	σ_z	β_x	σ_γ/γ	$\gamma\epsilon_x$	ρ	L_G	L_{sat}	P_{sat}
	cm		10^3	nm	kA	μm	m	10^{-4}	μm	10^{-3}	m	m	GW
SLAC/								2	3.5		.5	10	2.4
Paladin	8	2.0	1	120	2	20-40	18	2	5	5	1.2	24	2.5
								4	3.5		1.0	20	2.6
								1	3.5		2.0	40	2.9
"	8	2.0	2	30	2	20-40	18	1	5	2	2.3	46	2.8
								2	3.5		2.1	42	2.8
"	8	4.0	4	22	2		2	2	3.5		1.4	28	5.8
Nisus	3.9	2.0	1	59	2			2	3.5	4	.65	13	2.2
BNL/								2	3.5		.34	6.8	.5
Thund.	2.2	1.5	.45	115	1			4	3.5	4	.35	7.0	.5
								2	5		.40	8.0	.4
"	2.2	2.0	.45	160	1			2	3.5	5	.26	5.2	.64
Nisus	3.9	2.0	.45	290	1			2	3.5	6	.39	8	.76

Table 3. Calculated parameters for SASE FEL experiments. Several cases are repeated to test sensitivity to electron-beam energy spread and emittance.

3.3 Project Scope for Two Reference SASE Experiments

3.3.1 The Paladin Wiggler at SLAC

A demonstration experiment using the SLAC linac and the Paladin undulator is being proposed to study FEL physics in the wavelength range near 120 nm. The studies include (1) production of an electron beam with the phase-space parameters needed for future 2--4 nm FELs and (2) short-wavelength SASE FEL physics: start-up from spontaneous radiation, fluctuations, photon linewidths, and the power spectrum. This project would take advantage of available equipment at SLAC, existing expertise in the dynamics of low-emittance, high-energy electron beams, and the potential availability of the Paladin wiggler.

The demonstration experiment would generate a low-emittance electron bunch of about 1 nC using a new RF photocathode gun located in the SLAC tunnel. The beam would be accelerated in 300 m of the existing SLAC linac, reaching 0.5 to 2 GeV. Along the way, two new bunch compressors at 100 and 500 MeV would compress the bunch length from 500 μm to 20--40 μm. A partly existing transport line would deliver the beam from the linac to the Paladin wiggler, which would be located in the Final-Focus Test Beam enclosure. The resulting beam and wiggler parameters are listed in Table 3, and a schematic layout is shown in Fig 2. A power gain length of the order of 0.5 m can be obtained with a saturated output power of 2.4 GW.

Future options for extended experiments are (1) to strengthen the wiggler field and add internal electron focusing, and (2) to increase the beam energy to explore FEL physics at shorter wavelengths, down to 25 nm. Another possibility is to use the Nisus wiggler, which requires no power supplies. The parameters for several of these cases are also given in Table 3.

A very rough cost estimate indicates that the 120-nm experiment could be completed for approximately 6 M$, with 1 M$ each for the RF gun, the first and second bunch compressors, and the electron transport near the FEL, and about 2 M$ for moving and repowering Paladin.

The "time early" schedule for completion of this project is the fall of 1994, with first beam in the winter of 1994-1995. A more cautious schedule would be for a completion date in the summer of 1995, with first beam following in the fall. Two additional scenarios for demonstration experiments at SLAC were developed after the workshop. These are presented in the appendix to this report.

3.3.2 The Thunder or Nisus Wigglers at BNL

A 230 MeV S-band linac is available at the National Synchrotron Light Source at BNL. This linac will be ready for experiments in the early summer of 1993. There is a window of opportunity of about two years in which this linac may be fully dedicated to a demonstration experiment. Possible demonstration experiments on this linac include (1) the production of high-brightness electron beams, using the latest techniques of emittance correction; (2) the application of bunch-compression techniques and (3) the exploration of short-wavelength FEL physics issues relevant to VUV and soft x-ray devices: startup from spontaneous radiation, coherence, saturation and seeding.

The demonstration experiment can include all or parts of the following plan: Replace the linac's thermionic gun with the Grumman photoinjector, inject into the linac using solenoid-lens focusing for emittance correction, accelerate the beam to about 70 MeV, compress the bunch, accelerate again to 230 MeV, and inject directly into a wiggler. The available building will be sufficient for this operation with the exception of a shielding extension to cover part of the wiggler and the beam dump. The pulse repetition rate is 10 Hz. The parameters calculated for this experiment are given in Table 3, and the experimental layout is shown in Fig. 4. Using a 230 MeV beam and the Thunder wiggler, with its 2.2 cm period and 7.3 kG field, the radiation will be at 115 nm. A compressed current of 1000 A at a normalized rms emittance of 3.5 mm mrad gives a power gain length of 34 cm. That will provide enough length to study startup from spontaneous emission and the mechanisms of the exponential-growth regime. With an external seed (a conventional laser and gas-jet harmonic generation), saturation and seeding can be studied. With the Nisus wiggler (see Table 3) saturation can be reached at a wavelength of 160 nm. Preliminary cost estimates indicate that the 115-nm experiment can be completed for approximately 4 M$ (1 M$ for each of the RF gun system, bunch compressor, and wiggler operation). Installation can begin immediately, with first photoinjected beam in about one year. The complete experiment may be finished in two years from the start of funding.

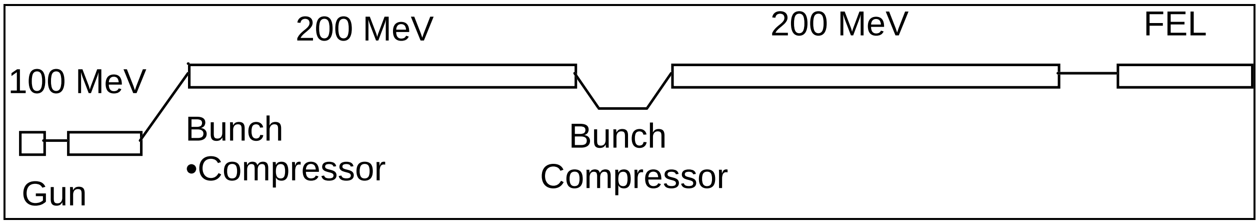

Figure 2. Schematic layout of a 120 nm FEL test at SLAC using the Paladin wiggler.

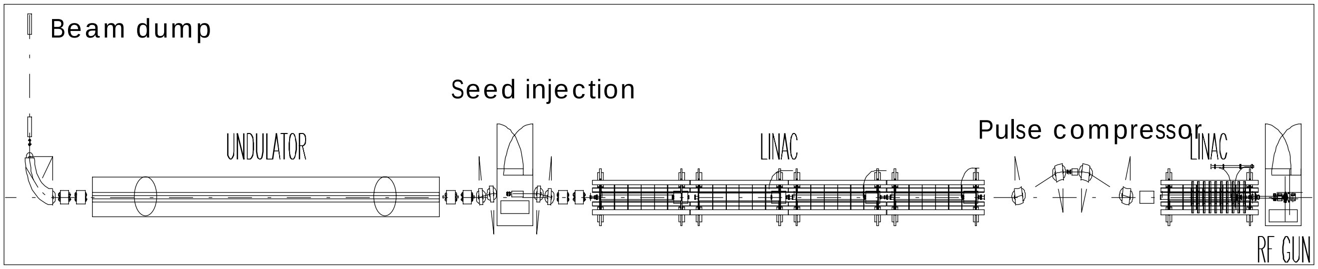

Figure 3. Schematic layout of a 115 nm FEL test at BNL

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4. Beyond the 100 nm Demonstration

Two proposals for ultraviolet and x-ray FEL amplifiers could be appropriate experiments to follow the 100 nm demonstration. In addition to FEL technology development, both intend to provide users with a source of intense, short-wavelength, coherent beams. These would then be test beds for future "fourth generation" light sources. Brookhaven is proposing to build the DUV-FEL, which will operate between 75 and ~300 nm using harmonic generation from a seed beam produced by a conventional laser. The three-part wiggler will have an overall length of 14~m with a period of ~2.2 cm (in the 12 m radiating section). SLAC is proposing the LCLS, a source of coherent x-rays between 3 and ~10 nm that will use self-amplified spontaneous emission. Because this amplifier must start from noise, the wiggler length will be even greater, ~60 m; the period will be ~8 cm.

These experiments will require advanced wiggler and electron-beam technology. Many of these techniques are being explored now, but all will require continued effort and support. Both FELs will use long wigglers and short wavelengths, and so will demand accurate wiggler alignment and low field errors. To transport the electron beam through the wiggler, periodic diagnostics and steering must be built into the narrow wiggler gap. Focusing will require curved pole faces at BNL, while a lattice of external quadrupoles is planned at SLAC. The Brookhaven proposal includes ideas to address these issues, and SLAC has begun investigating them as well. Initial tests will be possible with the 2-m wiggler for the Harmonic Generation experiment at BNL's Accelerator Test Facility (seeded at 10 μm), but these techniques will need further experimental development as the wiggler length increases. A high-brightness electron beam will be necessary for both projects. BNL and Grumman are now completing a 3.5-cell, 10 MeV, RF photocathode electron gun that should provide a suitable source. Bunch compression is essential for both the BNL and SLAC experiments. The SLC project at SLAC has developed the techniques to transport, accelerate, and compress electron bunches without dilution of phase-space density.

Brookhaven proposes to produce its desired wavelength by bunching the electron beam in the first section of the wiggler using a subharmonic from a conventional laser. This approach, which offers both a shorter wiggler and a narrower bandwidth (determined by the seed laser), will receive its first test in the 10 μm experiment at ATF. In addition to the wiggler and electron-beam development discussed above, the extension of the harmonic-generation concept into a UV user facility will also require work on the production of a seed beam that is broadly and rapidly tunable.

5. Conclusions

At present, high-power tunable radiation for wavelengths shorter than 100 nm is available from synchrotron-radiation facilities at a peak power of 10 W or less. Depending on the linac used, FEL amplifiers can generate hundreds of megawatts to several gigawatts of tunable, coherent peak power at short wavelengths. By following up the recent progress in techniques for the production and preservation of high-brightness electron beams, and for the construction of precise wiggler magnets, *it it is within the capability of current technology to construct FEL amplifiers for wavelengths as short as a few nanometers.* The discussion in this working group has shown a step-by-step approach toward the construction of short-wavelength FEL user facilities. The 10 μm experiment will verify the basic physics with less demanding electron-beam and wiggler parameters. The 100 nm experiment, in addition to providing intense coherent radiation in a hitherto unavailable wavelength region, will test comprehensively the accelerator and wiggler techniques for a shorter-wavelength FEL amplifier.

Amplifier experiments at 10 μm are currently being pursued by two institutions and will be completed in the near future, given a small amount of additional funding. The working group discussed several cost-effective scenarios for the 100-nm experiment utilizing existing accelerator components and wigglers. It is projected that the experiment will cost a few million dollars and can be finished in 2--3 years. Because of the limited funding available, it is important that different laboratories collaborate by exchanging personnel and equipment. After this experiment is successfully completed, the accelerator and user communities will be ready for the construction of FEL user facilities in the nanometer region that will provide breakthrough scientific opportunities.

Appendix 1: The Workshop Schedule

Friday, May 21

8:30 Welcome - N. Samios, BNL
8:40 Opening remarks. I. Ben-Zvi, BNL, and H. Winick, SLAC.

8:50-11:30 Applications and Facility Plans. Chair: M. Blume, BNL
8:50 Applications and technical requirements. E. Johnson, BNL.
9:20 Twenty minute presentations on present proposals and outline of future facility plans for short wavelength FEL sources:
L.H. Yu, BNL
G. Neil, CEBAF
J. Madey, Duke
10:20 Break
10:35 Resume session:
D. Chan, LANL
H. Winick, SLAC
C. Pellegrini, UCLA

11:35-2:00 Defining critical experiments and their parameters. Panel Discussion. Chair: A. Sessler, LBL.
Panelists: B. Carlsten, LANL; J. Goldstein, LANL; K.-J. Kim, LBL; C. Pellegrini, UCLA; A. Sessler, LBL; L.H. Yu, BNL.

12:30 Lunch and break.

1:00 Panel Discussion continued.

2:00-3:30 Availability of Resources. Chair: G. Neil, CEBAF.
Ten minute presentations by institutions. Propose what equipment and facilities are available for the previously determined demonstration experiments. Point to any presently planned experiments that are applicable.

J. Adamski, Boeing
S. Krinsky, BNL
J. Bisognano, CEBAF
J. Madey, Duke
I. Lehrman, Grumman
P. O'Shea, LANL
(TBA), LLNL
J. Seeman, SLAC
A. Schwettman, Stanford
C. Pellegrini, UCLA

Friday, May 21 (Continued)

3:45 Break

4:00-5:45 Discussion: An experimental program. Chair: B. Newnam, LANL

Group discussion to develop a prioritized FEL experimental program and suggested timetable. Determine Working Groups and their respective chairs.

5:45 Break

6:00 Dinner

8:30 Working Groups Session. During this and the following working group sessions, the individual groups will develop a program plan and summarize group discussions in a written document for inclusion in the workshop report (please bring portable computers for word-processing).

Saturday, May 22

8:30 Working Groups Session.

10:00 Break

10:30 Working Groups Session.

12:30 Lunch and break.

1:00-2:50 Report on and discuss summaries from Working Groups. Chair: J. Madey, Duke.

2:50 Closing remarks. I. Ben-Zvi, BNL, and H. Winick, SLAC.

3:00 **Workshop Ends**.

3:15 Tours of the BNL Accelerator Test Facility (K. Batchelor) and the 230 MeV linac (R. Heese).

Appendix 2: List of Participants

Workshop co-chairs: I. Ben-Zvi, BNL and H. Winick, SLAC.

Program Committee members:

Adamski	John L.	Boeing Defense & Space Group
Bisognano	Joseph	Continuous Electron Beam Acc. Facility
Krinsky	Samuel	Brookhaven National Laboratory
Lehrman	Ira S.	Grumman Corporate Research Center
Madey	John M.	Duke University
Pellegrini	Claudio	University of California at Los Angeles
Scharlemannn	Ernst T.	Lawrence Livermore Nat. Lab
Schwettman	H. Alan	Stanford University
Sessler	Andrew	Lawrence Berkeley Laboratory
Sheffield	Richard	Los Alamos National Laboratory (chair)

Appendix 3: Contributions to the proceedings (not presented at the workshop):

A 100 nm Oscillator FEL Using the SLAC Linac

C. Pellegrini, UCLA and A. M. Sessler, LBL

1. Introduction

At the workshop Towards Short Wavelength FELs consideration was made of two linac options for the generation of 100nm radiation. One consisted of a SASE FEL using the SLAC linac and the Paladin wiggler. This option was estimated to cost about 5 M$. The second option consisted of an harmonic generation FEL, using the BNL 230 MeV linac and the Thunder undulator. This option was estimated to cost about 4 M$.

We propose to use this oscillator using the SLAC linac at 1 GeV and a short undulator, to lase at 100 nm. We estimate the cost for this option to be much less than the two options considered at the Brookhaven Workshop.

This option requires a photocathode injector similar to (if not identical with) the Los Alamos 20 MeV gun. The beam from the gun is accelerated to about 1 GeV and then injected into the optical resonator. No bunch compression or damping is required in this scheme, with considerable saving in complexity and cost. The wiggler needs to be only a few meters in length, a considerable saving over the use of Paladin.

2. Analysis

The 1 GeV beam has the following properties:

Beam current $I_p = 250 \text{ amp}$

Beam energy $E = 10^9 \text{ volt}, \quad \gamma = \frac{E}{mc^2} = 1.957 \times 10^3$

Emittance $\varepsilon = \frac{3 \times 10^{-6}}{\gamma} \text{ m}, \quad \varepsilon = 1.533 \times 10^{-9} \text{ m}$

Energy spread $\sigma_E = 10^{-3}$

We take an undulator having the following properties:

Undulator period $\lambda_u = 0.06 \text{ m}$

Undulator length $L_u = 3 \text{ m}$

Undulator number of periods $N_u = \dfrac{L_u}{\lambda_u}$

Undulator peak field $B_u = 0.6 \text{ tesla}$

Undulator parameter

$$a_u = B_u \frac{\lambda_u c}{2\pi mc^2} \qquad a_u = 3.364$$

The radiation wavelength is given by $\lambda = \lambda_u \dfrac{1+a_u^2}{2\gamma^2}$ $\qquad \lambda = 9.647\times10^{-8} \text{ m}$

Notice that we are using a helical undulator.

To evaluate the small signal gain we assume that the radiation spot size is obtained by assuming Rayleigh length equal to the undulator length. Given the beam emittance it is easy to make the electron beam spot size smaller than the radiation spot size.

Radiation beam spot size $w = \left(\lambda \dfrac{L_u}{\pi}\right)^{0.5}$ $\qquad w = 3.035\times10^{-4} \text{ m}$

The beta function needed to focus the electron beam to a spot equal to that of the radiation is

$\beta = \frac{w^2}{\varepsilon}$, or $\beta = 60.092$ m

The small gain formula is (we have chosen an optimum detuning):

$$G = 2^{1.5}\left(\lambda^3 \lambda_u\right)^{0.5} \frac{a_u^2}{\left(1+a_u^2\right)^{1.5}} \frac{I_p}{I_A} \frac{\pi}{w^2} N_u^3$$

For our case we obtain G=0.341.

This gain is adequate to operate an oscillator. With mirror losses of 10% the net gain is about 20% per pass. Thus with 50 passes the FEL saturates. The saturation power is approximately given by

$$P = \frac{I_p E}{N_u}$$

giving $P = 5 \times 10^9$ watt

3. Discussion

The advantage of this proposal is:

a. it requires no modification to SLAC (no compressors)

b. it can use as a gun the existing and operating Los Alamos AFEL gun/accelerator complex

c. it can use a pulsed, helical wiggler similar to the one built recently at UCLA, at a very low cost

d. it needs a new optical cavity, but given the large gain the requirements on tolerances for the cavity are not severe

This proposal is only an initial exploration of this concept, and could be further optimized. Nevertheless, it appears as if an oscillator FEL, for small cost, could be shown to be the gene of a very powerful, very intense, 100 nm radiation. We believe that this unique source would be of great interest to chemists, and as such capture the world's attention. In addition the proposed facility would check much FEL physics, and open the way to even shorter wavelengths using linac driven FELs.

120 nm SASE FEL Demonstration Experiment at SLAC

C. Pellegrini, J. Seeman, and H. Winick
for the FEL Group

A demonstration experiment using the SLAC linac and the PALADIN undulator has been investigated to study FEL physics in the wavelength range near 120 nm. The studies include (1) the production of an electron beam with phase space parameters needed for future 2-4 nm FELs and (2) short wavelength SASE FEL physics: startup from spontaneous radiation, fluctuations, photon linewidths, and power spectrum. This project would take advantage of available equipment at SLAC, existing experitise in low emittance-high energy electron beam dynamics, and the potential availablitity of the PALADIN undulator.

The demonstration experiement would generate a low emittance electron bunch of about 1 nC using a new RF photocathode gun located in the SLAC tunnel. The beam would be accelerated in 300 m of existing SLAC linac reaching 0.5 to 2 GeV. Along the way two new bunch compressors at 100 MeV and 500 MeV would compress the bunch length from 500 mm to 20-40 mm. A partly existing transport line would deliver the beam from the linac to the PALADIN undulator to be located in the FFTB enclosure. The resulting beam and undulator parameters are listed in Table 1 and a schematic layout is shown in Figure 1. A power gain length of order 0.5 m can be obtained with a saturated output power of 2.4 GW.

Future options for extended experiments are (1) to strengthen the wiggler field and add internal electron focusing and (2) to increase the beam energy to explore FEL physics at shorter wavelengths, down to 25 nm. Another possibility is to use the NISUS undulator, which requires no power supplies. Several of these new examples are listed in Table 1.

A preliminary cost estimate indicates that the 120 nm experiment could be completed for approximately 6 M$ with 1 M$ each for the RF gun, the 1st and 2nd compressors, and the transport near the FEL, and about 2 M$ for moving and repowering PALADIN.

A "time-early" schedule for completion of this project is the fall of 1994 with first beam in winter of 1994-1995. A more realistic schedule would be for a completion date in the summer of 1995 with first beam in the fall of 1995.

Table 1 Parameters for an FEL test with the SLAC Linac and the PALADIN undulator.

Parameters	Nominal PALADIN	Higher E + PALADIN	NISUS	2 GeV+ Focus +Higher Field PALADIN
Energy (MeV)	500	1000	500	2000
σ_E / E (%)	0.02	0.02	0.02	0.02
$\gamma\varepsilon_{x,y}$ (mm-mrad)	3.5	3.5	3.5	3.5
I peak (amp)	2000	2000	2000	2000
Bunch length (mm)	20-40 μm	20-40 μm	20-40 μm	20-40 μm
Undulator period (cm)	8	8	3.9	8
Undulator field (kG)	2.7	2.7	5.6	5.4
Undulator β (m)	18	18	----	2
λ (nm)	120	30	60	22.5
Power gain length (m)	0.5	2.1	0.65	1.4
Saturated power (GW)	2.4	2.8	2.2	5.8

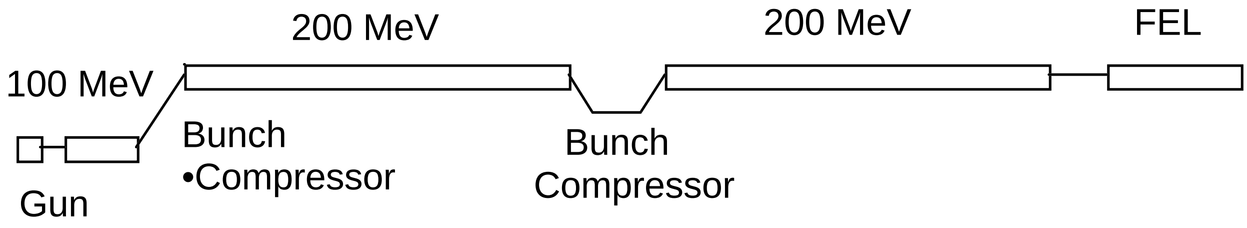

Figure 1 Schematic layout of a 120 nm FEL test at SLAC using PALADIN.