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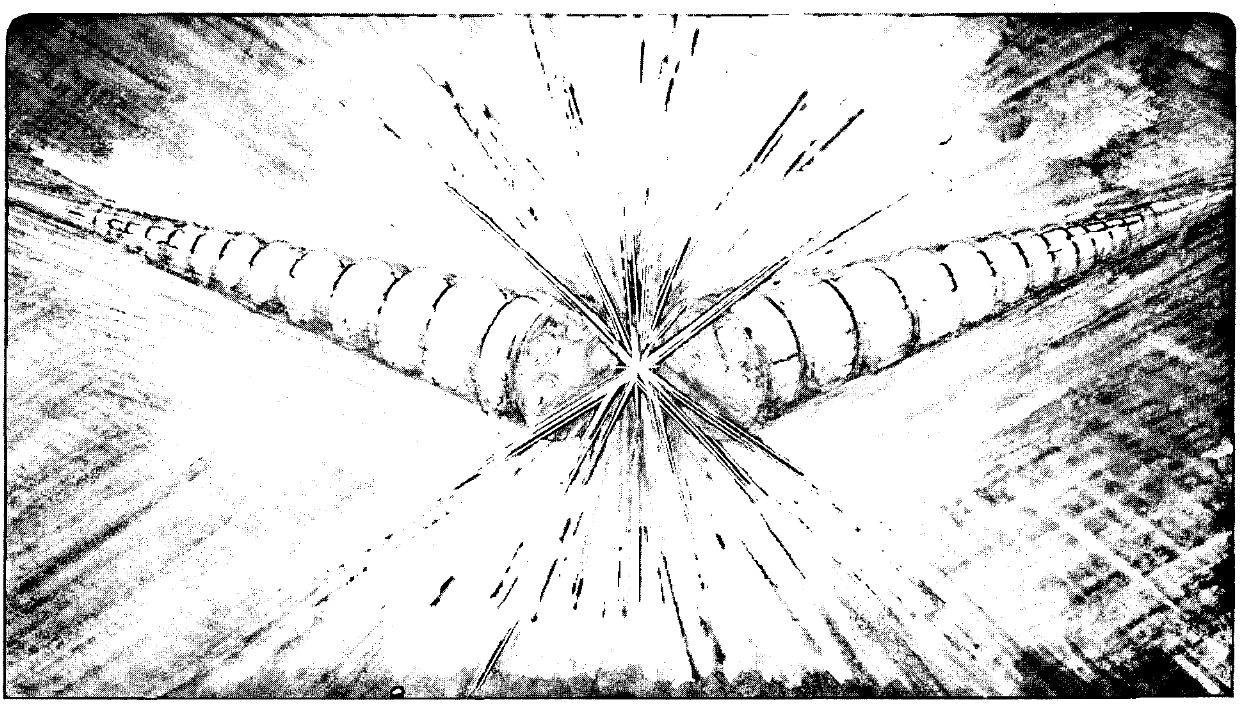

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UV X-Ray Free Electron Lasers Through High-Gain Single Pass Amplifier: Basic Principles and Issues*

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UV/X-RAY FREE ELECTRON LASERS THROUGH HIGH-GAIN SINGLE PASS AMPLIFIER: BASIC PRINCIPLES AND KEY ISSUES*

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Abstract

We review the basic principles of high gain free electron laser amplifier in single pass configuration for generation of intense, tunable radiation for wavelength shorter than 1000 Å. Two schemes are discussed: For wavelength region between 1000 - 100 Å, the high gain harmonic generation of a coherent input radiation can be used. For x-ray wavelength as short as a few Å, the self-amplified spontaneous emission is currently the only known free electron laser scheme. We also present a brief introduction of various key issues in realizing these schemes, which will be discussed in detail in other papers in these proceedings.

1. Introduction

At present the only practical, tunable radiation source in the wavelength region shorter than 1000 Å are various synchrotron radiation devices. High gain free electron lasers (FELs) will be able to provide tunable, intense, coherent radiation in this wavelength region with brightness several orders of magnitudes higher than that from synchrotron radiation. Figure 1 shows the performance of various radiation sources in the wavelength region shorter than 1000 Å.

The current shortest wavelength record for FELs is 2400 Å achieved at Novosibirsk TOK oscillator [1]. Given sufficiently bright electron beams, high-gain FEL amplifier in single pass configuration can in principle extend the FEL operation to arbitrarily short wavelengths by eliminating the need for

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high-reflectivity normal-incidence mirrors. Two schemes are envisioned: With a very bright electron beam in a long undulator, the single pass gain may be so high that the noise signal present in the beam is amplified to an intense coherent radiation. This is called the self-amplified-spontaneous-emission (SASE) scheme [2], and is the basis of the Linear Coherent Light Source (LCLS) proposal at SLAC to generate coherent radiation for wavelengths as short as 1.5 Å [3]. Another scheme applicable for wavelengths between 1000 and 100 Å is based on the harmonic generation mechanism in a high-gain FEL starting from available coherent input radiation [4, 5]. The scheme, called the high-gain harmonic generation (HGHG) is the basis of the DUV proposal at BNL [6]. The production of high brightness electron beams necessary for these proposals became feasible with the development of the laser driven RF photo cathode gun [7].

The purpose of this paper is to describe the basic physics of SASE and HGHG schemes, and to provide an introduction to various issues in realizing them. Detailed discussion of these issues are contained in five papers in these proceedings [8,9,10,11,12].

2. Basic Physics

2.1 High-Gain FEL

The interaction of the electromagnetic field of the radiation beam with electrons in an undulator induces a modulation of the electron density. The density modulation leads to a higher radiation intensity, and the higher intensity in turn causes stronger density modulation. Thus, it is expected that the density modulation as well as the radiation intensity will under certain circumstances grow exponentially as $\exp(z/L_G)$, where L_G is known as the (power) gain length. The basic scaling of a high gain FEL amplifier is determined by the dimensionless parameter [2]

$$\rho = \left(\frac{e^2 Z_0 \, n \, K^2 [JJ]}{32 \, \gamma^3 \, mc^2 \, k_u^2} \right)^{1/3} , \qquad (1)$$

where e is the electron charge, $Z_0 = 377 \, \Omega$, n the electron density, m the electron mass, c the speed of light, γ the electron energy in units of mc^2, $k_u =$

$2\pi/\lambda_u$, λ_u the period length of undulator magnet, $K = e B_0/(k_u mc)$, B_0 the peak magnetic field of the undulator, and [JJ] the usual factor involving Bessel function in the case of a planar undulator.

The power gain length in the exponential growth regime is proportional to k_u/ρ. Also the gain bandwidth and the efficiency at saturation are both given approximately by ρ.

In a 1-D model with vanishing energy spread, the gain length is given by $L_G^{1-D} = 1/(2\sqrt{3}\, k_u \rho)$. Including the 3-D diffraction effect [13,14] and the electrons' betatron motion [15,16,17,18,19] the gain will be reduced. However, the reduction is small if

$$2k\varepsilon_x \lesssim 1 \ , \quad (2)$$

$$L_G^{1-D}/L_R \lesssim 1 \quad , \quad (3)$$

$$\sigma_\gamma/\gamma < \rho \quad . \quad (4)$$

Here $k = \omega/c = 2\pi/\lambda$ is the radiation wave number, ε_x the rms electron beam emittance (considered the same in the x and y plane), and L_R the Raleigh length given by $L_R = 2k\langle x^2\rangle = 2k\,\varepsilon_x\beta$, where β is the value of the betatron function, and σ_γ the rms energy spread. The inequality (2) can be interpreted to be the requirement that the area of electron beam phase space be smaller than that of the radiation beam. The inequality (3) is the statement that diffraction is not important in one gain length. The inequality (4) is the statement that the gain bandwidth of high gain FEL is about ρ.

As an example consider the case of a 10 Å FEL. The emittance in view of Eq. (2) should be about 10^{-10} m-rad. Assuming that the relative energy spread is a few times 10^{-4}, it is necessary from Eq. (4) that the value of ρ be about 10^{-3}. Inserting suitable values for other parameters, it can be shown from Eq.(1) that the required current is a few kA. Thus the requirement on electron beam qualities is very stringent.

2.2. High Gain Harmonic Generation (HGHG)

The schematic diagram for HGHG is shown in Fig. 2: A coherent UV input is provided by passing the output of a conventional laser through a nonlinear crystal. The FEL device is consist of two undulators; the first undulator is resonant with the wavelength of the coherent input and induces modulation in the electron beam energy. The energy modulation becomes density modulation with Fourier components in the input wavelength as well as in higher harmonics. The second undulator is resonant with a higher harmonic, for example, the third harmonic. Thus there is an exponential growth of the radiation at third harmonic of the input wave length[4]. The efficiency of the scheme is further increased by introducing a dispersive section between two undulators and a tapered section at the end[5].

The coherence of the HGHG output is high, as it is the same as the input coherent radiation. However, the scheme is not suitable for x-ray generation because a suitable input coherent radiation is not available.

The parameters of the DUV proposal, which is listed in HGHG, is listed in Table 1[6].

2.3 Self Amplified Spontaneous Emission (SASE)

As a beam of electrons travels through a long undulator, spontaneous radiation is emitted in the beginning, which is a collection of randomly distributed wavetrains of length $N\lambda$, where N is the number of the undulator periods seen by the beam. The average radiation intensity of the spontaneous radiation is proportional to the total number of electrons, and increases linearly with N. With an electron beam of sufficiently high intensity and brightness, the electron distribution starts to develop local density modulations with the periodicity of the radiation wavelength, which are randomly distributed over the electron pulse. The radiation intensity then increases exponentially as a function of N. In this exponential gain regime, the average power spectrum as a function of the distance along the undulator, $z=N\lambda_u$, is of the form

$$\frac{dP}{d\omega} = e^{z/L_G} S(\omega,z) \left(\frac{dP}{d\omega}\right)_{noise} , \qquad (2)$$

where $S(\omega,z)$ is a function describing the frequency dependence of the gain, and $(dP/d\omega)_{noise}$ is the effective input signal due to the beam noise. In a 1-D model, the latter term can be expressed in the following form [15]:

$$\left(\frac{dP}{d\omega}\right)_{noise} = \frac{\rho E_0}{2\pi} \quad , \tag{3}$$

where $E_0 = mc^2\gamma_0$ is the energy of a single electron. This power can be interpreted [20] as the spontaneous power emitted in one gain length.

The exponential growth stops, or saturates, when the density modulation becomes near 100%. The electron distribution at saturation is a superposition of local density modulations of period λ and length l_c (coherence length)$=\lambda/\rho$) randomly distributed over the electron pulse [21,22]. The corresponding radiation profile is a collection of randomly distributed wavetrains of length l_c. Thus the temporal coherence characteristics of SASE are similar to that of the spontaneous radiation, the spectral bandwidth being given approximately by $\lambda/l_c = \rho$. Assuming the modulation within one coherence length is complete, the radiation intensity from one local density modulation is proportional to the number of electrons in one coherence length squared. Summing up contributions from all local density modulation, one finds that the total radiation power is enhanced compared to that of the undulator radiation by a factor equal to the number of electrons in one coherence length.

SASE is important as the only known scheme at present to extend FELs to wavelengths as short as a few Å. Figure 3 is the schematic layout of the LCLS proposal to generate x-rays down to 1.5 Å based on SASE using the SLAC linac[3]. Table 2 gives the major parameters of the LCLS proposal. Figure 4 shows the result of the GINGER simulation showing the evolution of the SASE temporal profile at different points along the undulator.

The transverse coherence of SASE is determined by the gain competition of higher order transvers modes. When $2k\varepsilon_x >> 1$, violating the inequality (2), the gain of the higher order transverse modes is comparable to that of the many transverse modes, i.e., the radiation is transversely incoherent. When the inequality (2) is approximately satisfied, as is the case for the LCLS proposal, the growth of the higher order modes is suppressed [19]. The radiation is then completely coherent transversely. Figure 5 shows the mode profiles and growth rates for some of the higher order transverse modes in the case of LCLS proposal.

3. Accelerator Configurations

The requirements on electron beams for operation of high gain amplifiers are very stringent, as can be seen from the electron beam parameters in Tables 1 and 2. Among various accelerators, linacs are currently the preferred option as the driver for high gain FEL amplifiers for short wavelengths. With the traditional injectors based on thermionic gun and bunchers, the brightness of the linac beams has been usually low due to phase space dilution in the bunching process. However, a new type of injectors based on the laser driven RF photocathode gun developed recently at LANL and other laboratories [7] has the capability of producing very high brightness electron beams directly with beam pulse structure suitable for RF acceleration. The accelerator configurations for the DUV project as well as the LCLS project are both based on a laser driven RF photocathode gun and a linac.

4. Key Issues

Five papers in these proceedings discuss critical issues in realizing the generation of short wavelength coherent radiation through linac based high gain FEL amplifiers. The first paper deals with the of laser driven high brightness photocathode guns[8]. The issues are the quantum efficiency of the photocathode materials, various emittance degradation effects [23] and how to correct them [24], and the drive laser stability. The second paper deals with the beam compression and transport [9]. The beams coming out of the photocathode gun need to be further compressed to increase the peak current. In the design of the compressor and the beam transport system through the linac and the long undulator, great care must be exercised to avoid various phase space dilution effects. The third paper deals with the undulator construction [10]. The required undulator must have strong magnetic field, many periods especially in the case of SASE, strong focussing field, and tight error tolerance. There are several options for the magnet designs; the electromagnet, the permanent magnet, and the superconducting magnets. The fourth paper deals with the assessment of simulation codes in their capability to predict the performance of the FELs accurately [11]. There are several simulation codes available with different capabilities. It is important to cross check the codes with each other, with theory, and with experiment. The fifth paper deals with the milestone experiments that should be carried out before embarking on the construction of a user facility for an x-ray FEL [12]. It is crucial to test various hardware components, such as the photocathode gun, as well as to carry out integrated experiments at longer wavelengths at 10 microns and at 1000 Å.

5. Conclusions and Discussions

In this and the five other papers in these proceedings, the basic physics and key issues in generating short wavelength radiation through high gain FEL amplifiers in single pass configuration are examined. These discussion shows that the high gain FEL amplifier concept based on a linac is within the current technological capability providing exciting scientific opportunities [6,25].

Several alternative options were not included in this discussion; The FEL oscillator technique may also be extended to wavelength shorter than 1000 Å by utilizing grazing incident reflections [26]. A special by-pass of a storage ring is another accelerator option for high gain FELs [27,28]. It may be possible to condition the electron beams to ease some of the electron beam quality requirements [29]. These options are an important part of the total R&D effort towards the generation of short wavelength radiation via FEL mechanism.

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Figure Captions

Fig.1. Performance of various radiation sources in short wavelength region (Figure provided by E. Johnson, Brookhaven National Laboratory).

Fig. 2 A schematic illustration of high gain harmonic generation (HGHG) scheme.

Fig. 3 LCLS Schematic overview

Fig. 4 The result of GINGER simulation for LCLS showing the evolution of SASE temporal profiles (Figure provided by W. M. Fawley).

Fig. 5 Mode profiles and growth rate for the higher order transverse modes for the LCLS proposal (Figure provided by Ming Xie)

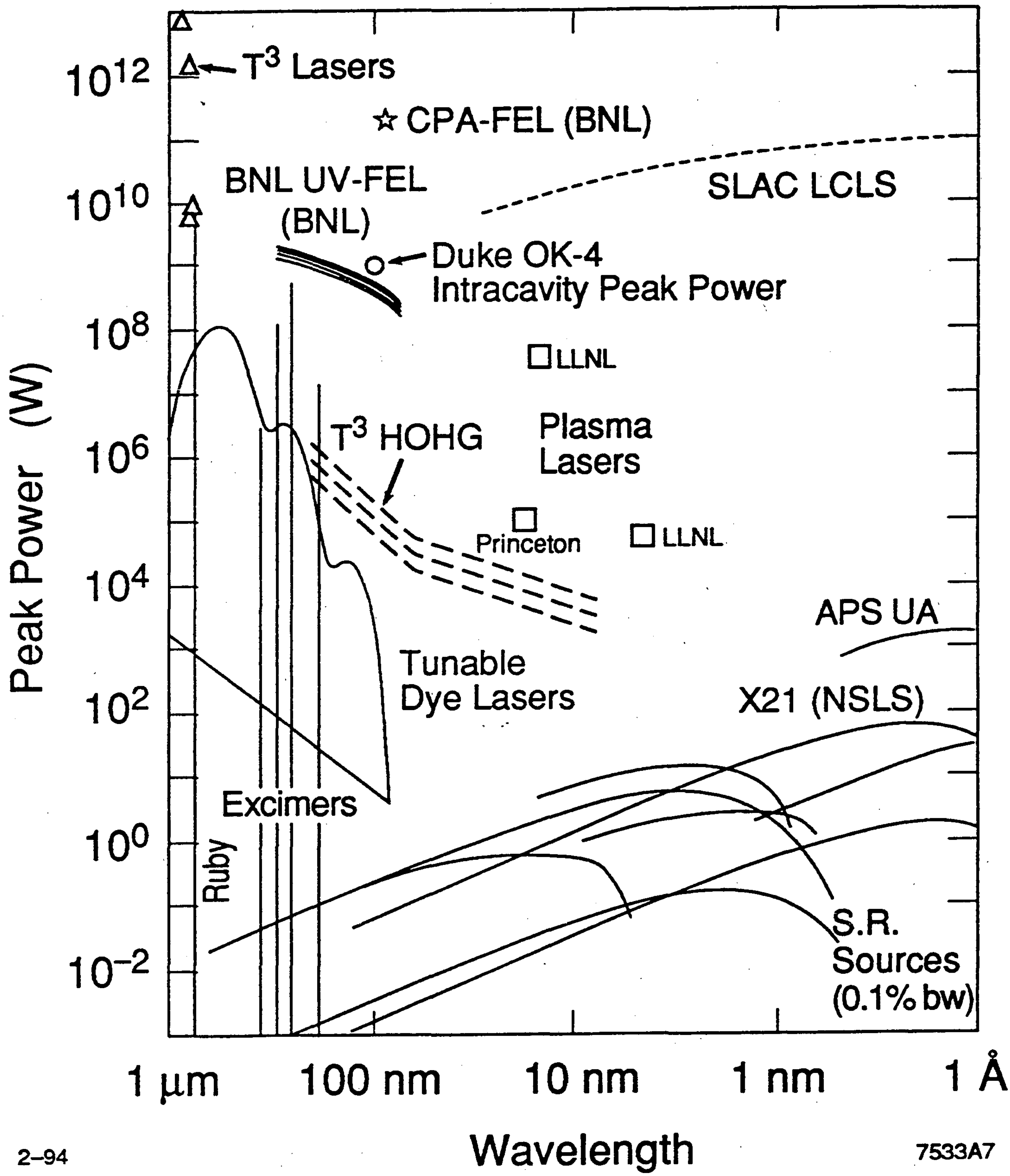
Table 1 Major Parameters for the DUV Project [6]

Optical Beam		
Wavelength range	3000Å to 750Å	
Bandwidth	10^{-4} or trans. lim.	
Peak power	~ 10^8 to 10^9 w	
Energy per pulse	.3 mJ to 10 mJ	
Repetition rate	360 Hz	
Pulse length range	0.2 to 5 ps	
Electron Beam	100 nm	75 nm
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 FWHM (ps)	7	7
Input Seed		
Wavelength (nm)	300	300
Power (MW)	2.5	3,4
Bandwidth $\Delta \lambda/\lambda$ ($\times 10^{-4}$)	1	1
First Wiggler (Modulator)		
Period (cm)	3.9	3.9
Magnetic Field (T)	0.64	0.77
Length (m)	2	2
Betatron wavelength (m)	16	16
Dispersion Section		
Length (m)	0.2	0.2
Magnetic Field (T)	0.32	0.34
Dispersion $d\theta/d\gamma$	1.1	1.0
Second Wiggler (Radiator)		
Period (cm)	2.2	2.2
Magnetic Field (T)	0.75	0.75
Length total (m)	12	12
Length untapered (m)	5	6

Table 2 Possible LCLS Parameters for 1.5Å [3]

case A: single undulator resonant at 1.5 Å
case B: first undulator resonant at 4.5 Å followed by second at 1.5Å

Radiation Wavelength	case (A)	case (B)	
λ(Å)	1.5	4.5	1.5
λ_u(cm)	2.67	4.0	3.0
B_0(T)	1.17	1.14	0.98
undulator type	helical	helical	helical
undulator length	40	20	20
β_0(m)	7	3.6	3.6
normalized emittance	1	1	1
E_e(GeV)	15	15	15
peak current(kA)	5	5	5
relative energy spread	$2x10^{-4}$	$2x10^{-4}$	$2x10^{-4}$
bunch length (m)	60	1.4	40
output power (GW)	60	1.4	40

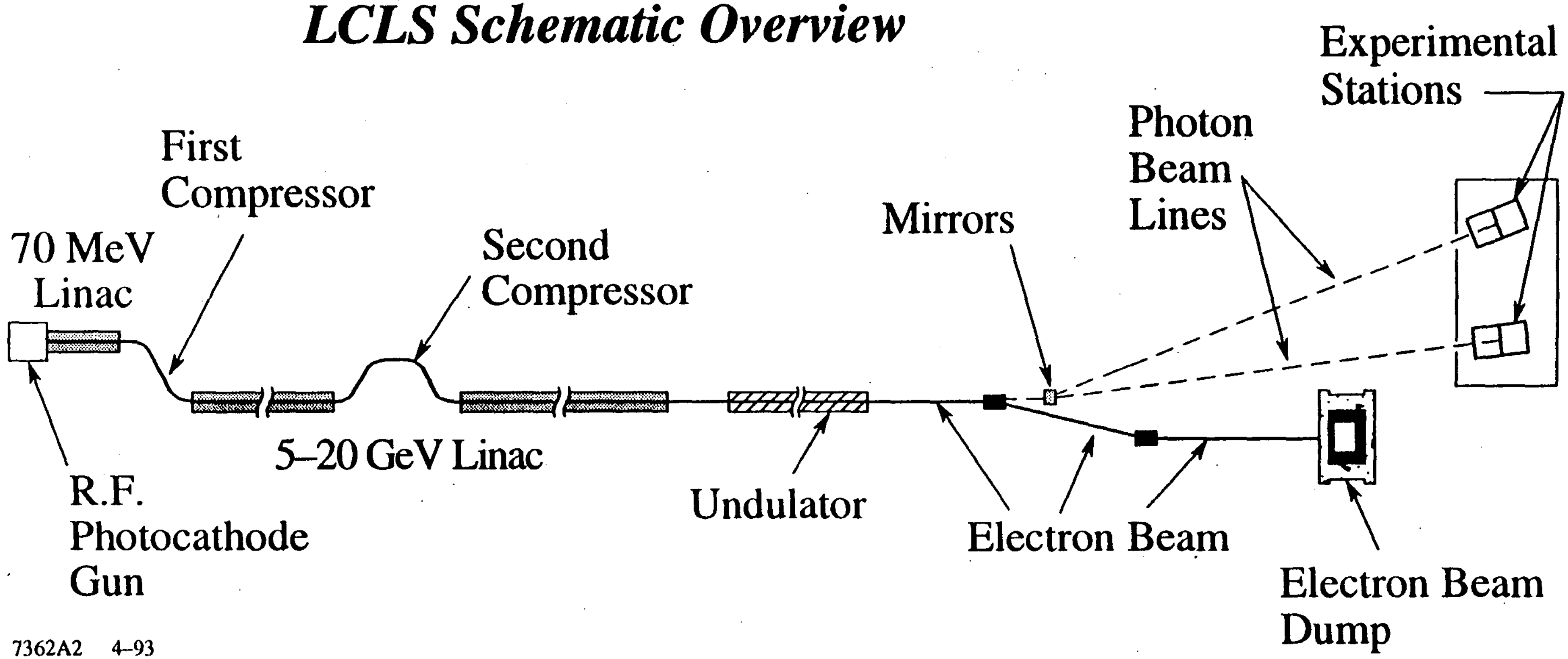


T3 Lasers
CPA-FEL (BNL)
BNL UV-FEL
(BNL)
SLAC LCLS
Duke OK-4
Intracavity Peak Power
LLNL
Plasma
Lasers
T3 HOHG
Princeton
LLNL
APS UA
Tunable
Dye Lasers
X21 (NSLS)
Excimers
Ruby
S.R.
Sources
(0.1% bw)
10^12
10^10
10^8
10^6
10^4
10^2
10^0
10^-2
Peak Power (W)
1 μm
100 nm
10 nm
1 nm
1 Å
Wavelength

2–94

7533A7

LCLS Schematic Overview



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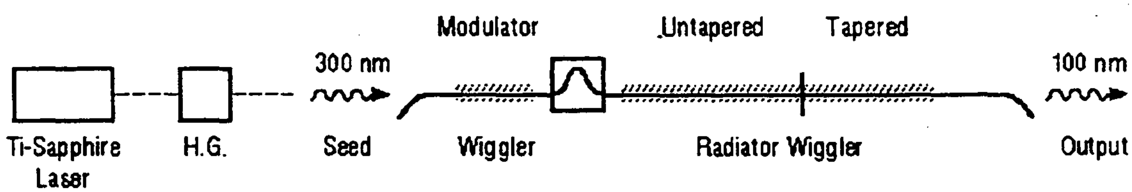
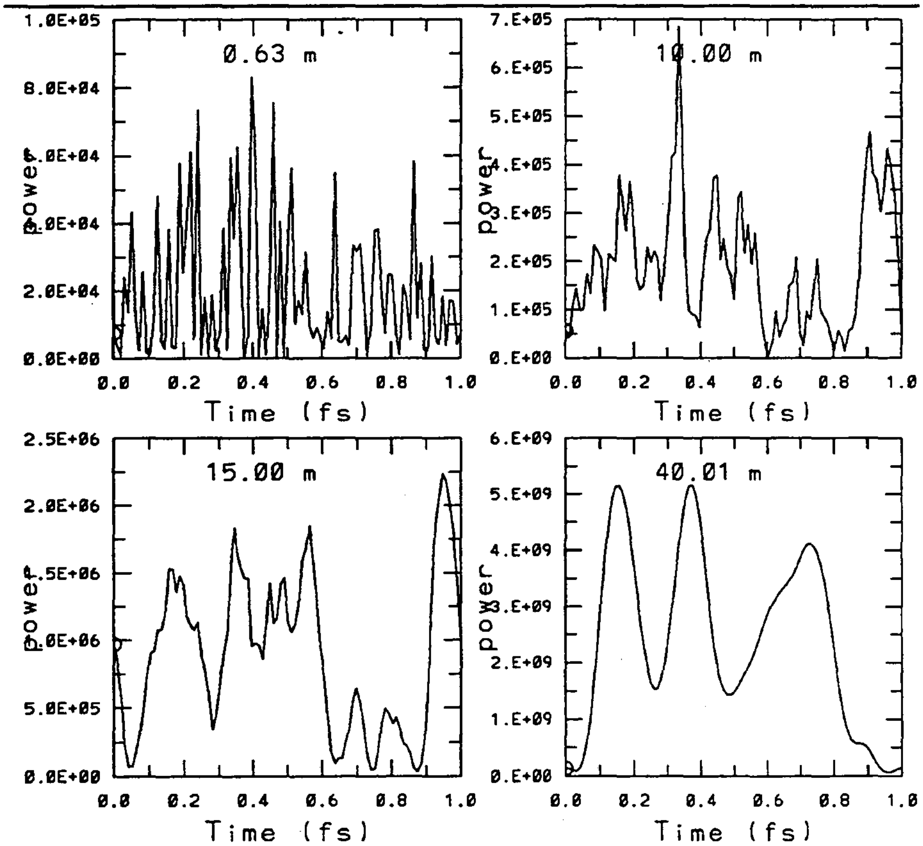
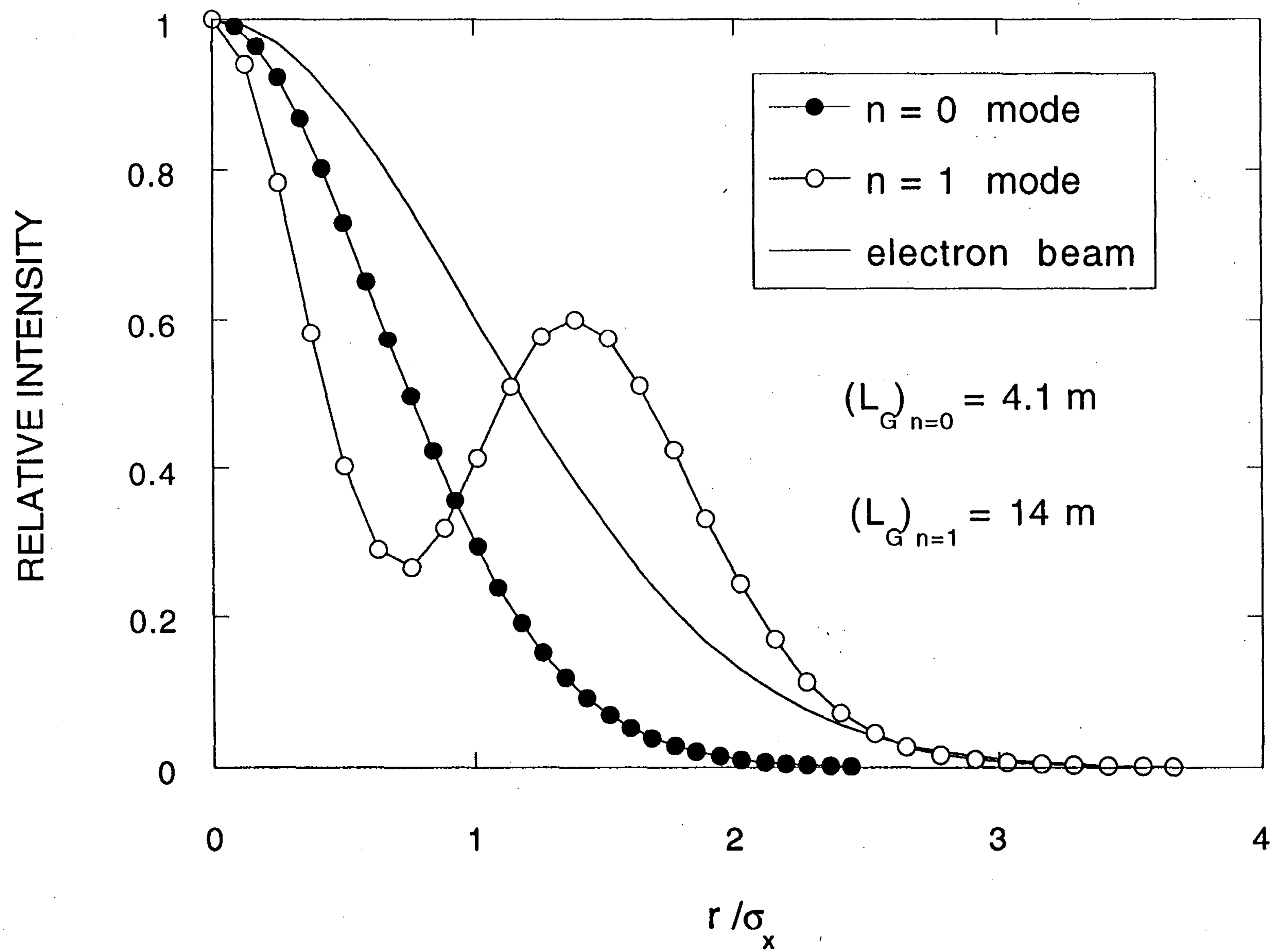


Modulator
Untapered
Tapered
300 nm
100 nm
Ti-Sapphire Laser
H.G.
Seed
Wiggler
Radiator Wiggler
Output

Laser Power (watts) vs. Time



TRANSVERSE MODE PROFILES FOR 1.5 Å LCLS



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