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# SUMMARY OF THE LINAC BASED RADIATION SOURCES WORKING GROUP

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## 1. INTRODUCTION

Technological advances have occurred in the past few years that have made linac based Free-Electron Lasers (FEL) promising candidates for the generation of short wavelength radiation. Although the FELs utilize undulators or wigglers, they produce stimulated radiation rather than the spontaneous emission found in insertion devices on the second and third generation sources of today. This stimulated emission process endows the FEL with properties presenting unique opportunities in many fields of science. Among these characteristics are:



- Coherence
- Spectral Brightness
- Peak Power
- High Average Power

Additional scope for experimental growth is provided by the flexible pulse structure of linac based sources, making possible developments in high resolution timing experiments.

Figure 1 shows the peak power of several possible short wavelength FELs as compared with existing and third generation synchrotron radiation sources. The parameters of these calculations made by the working groups will be discussed later in this summary, but clearly show that these sources meet our definition of a fourth generation source by virtue of gains of an order of magnitude or more in any important parameter. This attribute is further underlined by figure 2 which shows the brightness of the FELS (defined for FELs as the number of photons per second over the square of half the wavelength) as compared to the facilities of today. The brightness for FELs is given per 0.1% bandwidth as for the other sources, however FELs have a natural bandwidth which is often much better than 0.1%.

The demands placed upon fourth generation light source parameters by the desires of potential users are nearly as various as the types of accelerators discussed in this workshop to produce the radiation. This is only natural, in as much as fourth generation sources and experiments are at a comparable (early) stage of development, and will tend to grow together and define each other.

While we work on the design of the radiation source, it is important that we anticipate the science it will engender. This is particularly important for short wavelength FELs where we anticipate a leap in performance that is many orders of magnitude above any extant source. It appears that many experiments could be made possible by linac based sources.

Although it is not the goal of this workshop to identify the scientific opportunities for 4th generation source, it appears that many experiments could be made possible by linac based sources for which even third generation sources are clearly inadequate.

Rather than identifying specific examples, it is perhaps more fruitful to group the experiments into families by application, and consider the characteristics used to evaluate proposed sources. This can be done, in part, by making the generalization that experiments employ the radiation either as a system pump or probe.

Pumping can be regarded as preparing a system for study, taking the form of changing the state of the sample, or initiating some type of structural or electronic transition. In many cases, this requires a state selective beam, implying high resolution so that adjacent states are not populated, but often requiring high peak power because of the need to achieve sufficient population density. For example, in gas phase photochemistry $10^{15}$-$10^{16}$ photons per pulse are required in a bandwidth of $10^{-3}$ or better.

On the other hand, probe experiments take the form of system interrogation, either by state selective analysis, or at shorter wavelengths structural analysis by scattering phenomenon. For example, in chemical dynamics' applications, the probe beam requires very high peak power of as much as $10^{18}$ photons per pulse to assure complete ionization although in many instances the bandwidth restrictions are not as demanding as on the pump beam. Other applications that require high peak power at short wavelengths are crossed beam experiments in chemistry and intensity-intensity correlation measurements in solid state.

Many experiments have been devised which require both pump and probe radiation, most notably within the chemical dynamics and atomic physics communities. In some cases "conventional" sources can be employed, while in others, linear accelerator based synchrotron radiation technology appears to be appropriate for both parts of the experiment.

Another dividing line that separates experiments is the use of peak power and average output power. For experiments that may be regarded as employing linear spectroscopy, that is ones in which single photon transitions are important, high average power is important. In many instances experiments of this type may be served by a high repetition or DC light source. Where this generalization breaks down depends on several factors including lifetime effects, sample dilution or preparation problems. For example, in phosphorescence experiments of biological systems where the lifetime of excited states may be from microseconds to a second, the repetition rate and duty cycle figure prominently in designing the experiment (and therefore source). For solid state photoemission spectroscopies, further limits may be imposed by space charge effects, typically at the level of $10^{13}$ - $10^{14}$ photons/s on sample (in the requisite bandwidth). In experiments of this type, a linac based pulsed light source has significant advantages over storage rings.

Other defining parameters are the radiation wavelength and bandwidth. For example, essentially all bonding chemistry is characterized by wavelengths longer than 75 nm. At these relatively low energies, the pulse duration and time structure become important due to Fourier Transform limitations on resolution and possible implications on time resolved experiments. As wavelengths approach 1 nm, this becomes less of an issue and opens new avenues for structural studies, since molecular motions occur on the sub-picosecond time scale. A source that could supply sub- meV resolution in the .1 to 1 keV regime would be of tremendous value in solid state physics studies like heavy Fermion systems including high $T_c$ superconductors. A new family of applications will become possible in scattering experiments if the source energy can be pushed to a few keV while preserving the brightness and coherence properties of an FEL.

In addition, there are many experiments that will be able to take advantage of the advances in two or more properties of FELs. The combination of coherence and high peak power opens up the possibility of single shot holography in the "water window", or the development of time dependent correlation spectroscopy. Both examples are extremely important applications of high power, short wavelength FELs. It does not take long to realize that essentially every parameter by which the output of a fourth generation source might be characterized will cover several orders of magnitude. It is unreasonable to expect that one light source, or even one type of light source will conveniently define the next generation source.

For this reason we looked at several possibilities. Invited presentations to the working group on linac based radiation sources covered various key subjects, aiming at establishing the ground work for various machine designs. Robert Palmer discussed ultra-high brightness electron sources and the fundamental limits on their performance. Joseph Bisognano presented the basics of calculating longitudinal and transverse emittance dilution in linacs, beam transport and wigglers. Tor Raubenheimer covered electron pulse compression and its effects on beam quality. Rodolfo Bonifacio discussed superradiance, two wiggler harmonic generation and short pulse phenomena. Brian Newnam talked about short wavelength FEL oscillators and the use of multifacet mirror resonators. Li-Hua Yu addressed the subject of subharmonically seeded FEL amplifier techniques and optimization. Kwang-Je Kim presented an approach to the calculation of peak power versus wavelength of linac based FELs. Phillip Sprangle addressed a number of fundamental questions in FEL theory, including the emittance limit on wavelength and average power considerations. Finally, Andrew Sessler described the idea of beam conditioning which is aimed at overcoming the basic limitations which emittance places on FEL performance.

Design issues of FEL light sources were worked out in a few sessions, including sub-group sessions. We have also discussed the question of R&D necessary for the development of high quality FEL light sources. A high priority was placed on laser photocathode rf gun development, emittance preservation and FEL mechanism studies.

The next sections describe the technological foundation for high brightness beams, the design of FELs using these beams and recommendations for research and development in FEL physics.

## 2. TECHNOLOGICAL FOUNDATION FOR HIGH-BRIGHTNESS BEAMS.

### 2.1 Introduction

Work on high-brightness electron beams has been driven by the advent of the free- electron laser. To minimize the beam energy required for matching an electron pulse into a wiggler, beam emittances at least a factor of four better than previous state of the art (20 to 30 mm-mrad normalized) are required. On the basis of further developments in electron source technology, we now believe it is possible to generate an electron beam with a normalized rms emittance of 1.5 mm-mrad at 1 nC. This emittance was used as the baseline emittance for the FEL performance calculations.

FEL gain is a strong function of the peak current in the electron pulse. The electron pulse duration produced by these ultra-bright sources is, right now, limited to 3 to 10 ps. Technology developed for temporally compressing electron pulses in colliders can take a 3 to 10 ps pulse and further reduce the pulse length to 1 ps or less. This compression can give peak currents of 1 kA or greater resulting in a very high FEL gain. The short pulses have a further advantage of generating short pulse x-ray radiation that will lead to a new class of users' applications.

### 2.2 Electron Source Development

An electron source that can produce a very high-brightness beam is the photoinjector. The principle behind a photoinjector is to place the source of electrons directly in the high-gradient rf cavity. The electron source is turned on by the application of a short- duration laser pulse that is synchronized to the accelerator rf system. The electrons are then accelerated to relativistic energy before exiting the first accelerator cavity. Electrons produced from this cathode thus have a reduced space-charge induced emittance growth and retain the original temporal duration of the laser pulse.

The contributions to the emittance of photocathode rf guns can be written [Palmer, using formulation by Kim]:

Thermal emittance (assuming electron thermal energy of 0.3 eV)

$$\epsilon_n^{thermal} \sim 3\times10^{-4}\sigma_r$$

where $\sigma_r$ is the radius of the cathode. The rf effects contribute

where E is the rf electric field at the cathode, $\omega$ is the rf angular frequency and $\sigma_z$ is the rms bunch length. The space charge contribution is:

$$\epsilon_n^{rf} \sim \frac{1}{2\sqrt{2}}\left(\frac{eE}{mc^2}\right)\left(\frac{\omega}{c}\right)^2 \sigma_r^2 \sigma_z^2$$

$$\epsilon_n^{sc} \sim \frac{\pi}{2}\left(\frac{mc^2}{eE}\right)\frac{I}{I_A}\frac{1}{3\sigma_r/\sigma_z+5}$$

where $I_A = 17000$ A.

As pointed out by Palmer, with present technology the 6D phase space is about one third the Kim estimate by removal of the tail distribution, but yet four orders of magnitude above the intrinsic limit.

Two techniques to further reduce emittance are either by using very high accelerating fields or by introducing phase space corrections. High accelerating fields have two advantages. First, the higher the gradient the more is the reduction in the emittance growth due to space charge. Second, high fields allow the generation of smaller electron thermal energy spreads from the cathode by increasing the current density that may be extracted.

Fields of over 100MV/m have been generated in photoinjector cells. The minimum emittance that can be generated by any electron source is ultimately limited by the thermal spread of the electrons from the cathode. The electron beam temperature is proportional to the cathode radius. At a cathode radius of 3 mm, the electron beam's thermal emittance is 1 mm-mrad. For high-gradient cells very-high charge densities can be obtained, implying that very small radius cathodes can be used. Small radius cathodes can give very small limiting emittances. For example, to generate 1 nC at 100 MV/m a spot radius of 30 $\mu$m is required for an electron beam thermal emittance of $\epsilon_n = 10^{-2}$ mm-mrad.

Phase space corrections rely on an unusual property of this type of source, which is that very little longitudinal mixing occurs in the electron pulse. This yields a pulse that has correctable correlations in both transverse and longitudinal phase spaces. By proper design of the electron beam focusing, the correlations can be removed, yielding lower emittances.

The small amount of longitudinal mixing also means that high divergences at the ends of the electron pulse do not mix in time with the middle of the pulse. Any part of the FEL radiation pulse does not simultaneously interact with the entire electron pulse. Therefore the effective brightness of the electron pulse is much higher than a rms calculation over the entire electron beam distribution would indicate. Electron beam simulations directly coupled to FEL simulations have demonstrated increased performance due to the higher brightness in the middle of the electron pulse.

The electron beam simulation codes have been bench-marked for beams of 4 mm-mrad normalized emittance. These codes give an effective normalized beam emittance of better than 1.5 mm-mrad and an effective energy spread of 0.05% at 1 nC for the photoinjector shown in

Fig. 3. This electron accelerator is scheduled for beam in April 1992.

Two experiments using photoinjectors that have made emittance measurements are the ATF at BNL and the APEX FEL at LANL. The ATF uses a robust, low quantum efficiency, long-life copper or yttrium cathode. APEX uses a high quantum efficiency, short-life multi-alkali cathode that requires an UHV system. Both the ATF and the APEX experiments have achieved a transverse emittance of 4 mm-mrad.

The above mentioned experiments are based on room-temperature accelerators. The duty factors for these machines are probably limited to near 1%. Another type of electron source [Serafini] is a superconducting photoinjector. A superconducting gun would have the advantage of cw operation, making control easier and could provide high pulse repetition rates. The maximum repetition rate is limited by high order mode excitation. Taking the reference design of the TESLA beam (800 bunches of 10 nC each and a 1 ms bunch separation), the maximum repetition rate is 10 MHz. The drive laser for this gun would require 4 W average power. The power loss in HOM (High Order Modes) is 3 W inside the rf gun cavity. This is a reasonable 5 W/m. Simulations for a superconducting design give an rms normalized emittance of 5 mm-mrad at 2 nC with an energy spread of 5 keV at an energy of a few MeV.

A method to enhance the FEL gain and diminish the restriction on emittance has been described [Sessler]. In the 'Beam Conditioning' method this is accomplished by introducing a correlation between energy and amplitude of transverse betatron oscillations in just such a way as to reduce the spread in longitudinal velocity. This method is not an emittance reduction technique, but the reduction in the spread of longitudinal velocity improves the performance of the FEL. The conditioning is done in a periodic focussing channel, say a FODO array, with $TM_{210}$ cavities that deliver incremental energy to electrons in proportion to their amplitude of betatron oscillation.

The beam conditioning method is particularly effective when strong focussing is available in the wiggler. In a specific example of a 30 Å FEL, the electron beam has $\epsilon_n = 2\,\pi$ mm-mrad, an energy spread of $4.4 \times 10^{-4}$ and only 80 A peak current. In a natural focussing wiggler, with a beam energy of 1.562 GeV and a betatron wavelength of 82.9 m, the power e-folding length is 25.6 m. In a conditioned beam with plasma focussing, electron beam energy of 1.24 GeV and betatron wavelength of 0.62 m, the e-folding length is 1.54 m.

## 2.3 Beam Transport - Wakefields

The linac beams being discussed have 6 times lower emittance than is possible with present storage ring technology. A major concern in the propagation of a beam this bright is emittance dilution due to wakefields. Two wakefield sources are the accelerator structure and the small wiggler tube. The calculations for wake-fields and FEL designs presented in the next section assumed:

Compressed peak current I=1000 A

Electron bunch length after compression $(2\pi)^{1/2}\sigma_t=1$ ps
Energy spread $\sigma_E/E=2x10-4$ (for $E\geq500$ MeV)
Normalized rms emittance $\epsilon_n=1.5$ mm-mrad
Wiggler length $L_W=30$ m

The formulas used for these calculations [Bisognano] are included in the appendix following this working group report. The calculations of bunch compression (next sub-section) are presented in the proceedings [Tor Raubenheimer]. Following The result of the calculations is that these beam parameters are consistent with a 3 GHz structure at 100 MV/m (representing a pulsed machine) or a 500 MHz structure at 15 MV/m (representing a superconducting rf machine). The 3 GHz structure is closer to the limit in terms of transverse emittance growth than the 500 MHz structure.

The working group looked at steps and wall resistance in a 30 m wiggler with a 2 mm gap radius. The wiggler is considered separately because of its much smaller aperture. The following results were obtained:

- energy perturbation at the $10^{-4}$ rms level
- emittance degradation at the 25% level
- shorter wigglers will not exhibit significant emittance growth due to wakefields.

The working group felt that long wigglers require a more detailed study.

## 2.4 Increasing Beam Current to 1 kA by Magnetic Compression

When considering bunch compression for an FEL driver, the two primary issues are the transverse emittance dilution due to space charge forces and the energy spread induced by the bunch compression. The transverse emittance dilution due the space charge determines the minimum energy at which the compression can be performed. In a properly designed bunch compressor, this dilution scales roughly as [Raubenheimer]:

$$\Delta\epsilon_n \approx 5I/\gamma^2$$

Where I is the peak current after compression in amps and $\Delta\epsilon_n$ is the normalized rms emittance dilution in $\pi$ mm-mrad. Thus to preserve an emittance of 1 $\pi$ mm-mrad while compressing to 1 kA peak current, the compression should be performed at energies above roughly 50 MeV.

The other important quantity is the energy spread. When compressing the bunch length, the longitudinal emittance remains (approximately) invariant. Thus, if the bunch length is reduced, the energy spread is increased by the same factor. The energy spread decreases as $1/\gamma$ with subsequent acceleration. Thus, to achieve the small energy spread required by the FEL, the bunch is compressed at as low an energy as possible, namely, the minimum energy allowed by the space charge emittance dilution.

Finally, there are two additional advantages of compressing at low energies. First, the bunch compressor is simpler and smaller at low energy, and second, the transverse wakefields decrease as the bunch length is decreased. It is difficult to correct the energy spread induced by the longitudinal wakefields when the bunch becomes very short. This energy spread is usually corrected by phasing the bunches off the crest of the accelerating rf field to accelerate the tail of the bunch more than the head, thereby cancelling the effect of the longitudinal wakefields.

## 3. FEL CONFIGURATIONS.

### 3.1 Introduction

The principle of the free electron laser has been demonstrated in the long wavelength region. The main challenge of building FELs in the wavelength length region shorter than 1000 Å is to overcome the fact that high reflectivity mirrors for optical cavity are not readily available. Several approaches are possible:

In the amplifier approach, the gain in single pass is made high enough that an optical resonator is not used. The requirements on the electron beam quality and the undulator are demanding. The input signal for the amplifier can be either electron beam noise, in which case the amplified signal is called Self Amplified Spontaneous Emission (SASE), or a suitable laser, which serves as a seed for the amplifier or for harmonic generation into the short wavelength region.

In the oscillator approach, the single pass gain is made reasonably high so that FEL lasing is possible with XUV resonator mirrors. Multifaceted mirrors, currently under development, enhance the reflectivity and power handling capability. Finally the master oscillator power amplifier (MOPA) combines the advantages of the amplifier and the oscillator approaches.

In the following we describe the basic conceptual designs and anticipated performance of these devices.

### 3.2 FEL Oscillator

In an FEL oscillator, the radiation is stored in an optical cavity building up in intensity over many passes, finally reaching a saturation level. The strategy for FEL oscillators at 1000 Å or shorter wavelength [Newnam] is to develop mirrors with sufficient reflectance to ease the gain requirement, therefore relaxing the requirements on the electron beam quality and the length of the undulator magnet. The spectrum is also transform limited, leading to a narrower bandwidth compared to that of SASE.

The oscillator approach and the development of the crucial optical technology are presently being pursued most actively by the Los Alamos group. By optimum choice of the mirror material and a multifacet mirror configuration, a reflectance from 80% to 35% was predicted in the wavelength region between 600 Å to 40 Å. It is then possible to design oscillator FELs based on an 8 m resonator length in which the minimum single pass gain is ten times the predicted loss. The parameters and performance of such FELs are summarized in Table 1. The calculations done at the workshop have been confirmed by single-wavefront, single-pass 3-D numerical simulations by John C. Goldstein. The calculations do not take into account secondary effects such as Gaussian mode distortion by the outcoupler, mirror thermal deformation or gain guiding. The beam parameters are as described in the previous section ($\epsilon_n$ (rms)$=1.5\ \pi$ mm mrad,

$I=1000$ A, $\sigma_\gamma/\gamma=2\bullet10^{-4}$) . The reflectance values (R) in Table 1 are per 180 degrees bend mirror. They do not include possible degradation due to vacuum pollution or the outcoupling (Out), which is presented under a separate column. The last row of the table assumes a crystal reflector providing 90% reflectance at 4 Å and a larger current, 2000 A. The gain ($G_{sat}$) is the corresponding saturated gain and $\eta$ is the power extraction efficiency from the electron beam. The wiggler parameters for all cases are similar except for the length. The length is presented in terms of the number of periods (N). The wiggler period is 1 cm and the peak field assumed is 1.52 Tesla.

The average output power of the oscillator FEL is intrinsically high, but is limited by the thermal loading on the mirrors. An average power of 200 watts, arbitrarily limited by the choice of an 8 m resonator, is predicted for the FELs in Table 1.

Table 1.

| λ (Å) | R (%) | Out (%) | $G_{sat}$ | E (MeV) | $N_W$ | η (%) | $P_{peak}$ (MW) |
|---|---|---|---|---|---|---|---|
| 600 | 80 | 39 | 2.6 | 120 | 52 | .021 | 160 |
| 120 | 60 | 34 | 4.2 | 269 | 150 | .054 | 65 |
| 40 | 35 | 32 | 12.1 | 466 | 400 | .019 | 31 |
| 4[a] | 90[b] | 36 | 1.4 | 1475 | 500 | .0013 | 139 |

a) In this case the current is 2000 amperes.
b) Bragg reflector.

### 3.3 Subharmonically seeded single pass FEL.

The subharmonically seeded single pass FEL [Yu] uses multiple wiggler magnets separated by dispersion sections to generate and amplify short wavelength FEL radiation from a long wavelength conventional laser. This approach overcomes the resonator issues of the FEL oscillator and provides an improvement in bandwidth over the SASE approach. The wiggler length in this approach is intermediate between the oscillator and SASE methods The tunability is limited only by the tunability of the conventional seed laser.

To be specific, let us describe the design of a subharmonically seeded FEL operating in the 'water window'. We can reach 40Å from convenient near UV conventional lasers by three frequency-quadrupling steps. The optimal electron beam energy is approximately 730 MeV (Using the beam current and quality cited above).

We start with a seed laser at 2560 Å and a power of 7 MW. The seed laser pulse length is 300 fs, one third of the electron bunch length and positioned on the tail end of the electron bunch. A first wiggler, 1.5 m long is used to modulate the electron-beam energy. This is followed by a dispersion section to produce spatial bunching with a strong fourth harmonic component at 640 Å. The second wiggler, also 1.5 m long is resonant at 640 Å. Upon passing through the second wiggler the prebunched electron beam radiates coherently at 640 Å. The radiation has a characteristic quadratic dependence on distance traversed in the wiggler within the first two gain-lengths. There is then a transition to exponential growth.

When the 640 Å radiation power reaches 16 MW, we use a strong dispersive section to delay the electrons relative to the radiation by 300 fs. This brings the radiation to a fresh portion of the electron bunch that has not interacted with radiation and has the original beam energy spread. We repeat the process, bunching the electrons with the 640 Å radiation in a 1 m long wiggler, followed by a dispersive section and generate 9 MW of 160 Å in the next 1.2 m long radiator wiggler. Finally the 160 Å radiation is slipped to the front of the electron bunch and using a 2 m bunching section we generate now 40 Å in an 11 m long radiator. This wiggler is long enough to amplify the radiation to saturation and include a tapered section. The output power is about 400 MW at 40 Å with a bandwidth better than $10^{-4}$. The wiggler periods vary from 3.82 cm at the long wavelength end to 1.2 cm at the output end.

### 3.4 Self-Amplified Spontaneous Emission

When a sufficiently bright electron beam passes through a long undulator, the spontaneous synchrotron radiation is amplified to an intense, coherent radiation pulse known as SASE. In the parameter regimes at which we are interested, SASE can provide gigawatts of diffraction limited coherent radiation. The advantages of the SASE approach are that it requires neither optical cavity nor an input seed laser. However, the requirements on electron beam brightness and the length of the undulator are most demanding. Also, the bandwidth of SASE is not much smaller than $10^{-3}$.

The performance of SASE FELs has been estimated during the workshop [Kim]. The assumptions in this calculation are: a. the normalized electron beam emittance 1.5 $\pi$ mm-mrad, b. the peak current is 1000 A, c. the rms energy spread is $2.2 \times 10^{-4}$, d. the undulator (Halbach design hybrid) magnet gap 4 mm, and e. the electron beam focussing is provided naturally by the undulator magnetic field (with equal focussing in the horizontal and vertical directions through curved pole faces). The period length is optimized for maximum output power.

The total length of the undulator is assumed to be 30 m. In the first part, the undulator parameter is uniform and the SASE power grows exponentially towards saturation. Saturation takes place when the electrons lose enough energy to get out of the resonance condition. When the saturation occurs before 30 m, then the remainder of the wiggler length is tapered, by reducing the magnetic field quadratically as a function of position along the wiggler. Tapering allows the extraction of additional power from the electrons by maintaining the resonance condition as the electrons transfer energy to the radiation field.

Without tapering, a peak power of $4.5 \cdot 10^8$, $3.6 \cdot 10^8$, $1.8 \cdot 10^8$ and $6.5 \cdot 10^6$ watts are predicted at wavelength 1000, 100, 20 and 10 Ångstroms, respectively. For wavelength longer than 20Å the saturation length is shorter than 30 m so that tapering can be introduaced to increase the output power, to 30 GW and 36 GW at 1000 and 100 Å, respectively. These numbers are presented in Table 2. $L_{wiggler}$ is the total length of the wiggler, (untapered and, where applicable tapered).

The performance of SASE FELs can be further enhanced by introducing additional external focussing of the electron beam. Assuming a fixed focussing strength, the scaling of the high gain FELs is such that it favors a high energy electron beam. Examples based on the SLAC linac at 10 and 50 GeV were presented [Pellegrini, Table 2, footnotes a,b)], predict $2 \times 10^{12}$ W at 40 Å and $25 \times 10^{12}$ W peak power at 1 Å.

Table 2. SASE amplifier parameters

| λ (Å) | 1000 | 100 | 40[a] | 20 | 10 | 1[b] |
|---|---|---|---|---|---|---|
| E (GeV) | 0.325 | 0.8 | 10 | 1.8 | 3.25 | 50 |
| $P_{satur.}$ (MW) | 450 | 360 | 5000 | 175 | 0.65 | 3500 |
| Photon/sec[c] | $2 \bullet 10^{18}$ | $2 \bullet 10^{17}$ | $2 \bullet 10^{15}$ | $2 \bullet 10^{16}$ | $3 \bullet 10^{13}$ | $4 \bullet 10^{13}$ |
| Brightness[c] | $8 \bullet 10^{20}$ | $8 \bullet 10^{21}$ | $6 \bullet 10^{20}$ | $2 \bullet 10^{22}$ | $10^{20}$ | $10^{22}$ |
| $P_{taper}$ (GW) | 30 | 36 | 2000 | | | 25000 |
| Photon/sec[d] | $1.5 \bullet 10^{20}$ | $2 \bullet 10^{19}$ | $7 \bullet 10^{17}$ | | | $2 \bullet 10^{18}$ |
| Brightness[d] | $6 \bullet 10^{22}$ | $8 \bullet 10^{23}$ | $2 \bullet 10^{23}$ | | | $10^{27}$ |
| $L_{gain}$ (m) | 0.24 | 0.66 | 5.0 | 1.8 | 3.1 | 14 |
| $\lambda_W$ (cm) | 2.0 | 1.75 | 10 | 1.75 | 2. | 11 |
| $\epsilon_n$ (mm mrad) | 1.5 | 1.5 | 2.5 | 1.5 | 1.5 | 1. |
| $I_{peak}$ (kA) | 1 | 1 | 2 | 1 | 1 | 5 |
| $\sigma_\gamma/\gamma$ ($10^{-4}$) | 2.2 | 2.2 | 4 | 2.2 | 2.2 | 4 |
| $2\sigma_{pulse}$ (ps) | 1 | 1 | 0.16 | 1 | 1 | 0.16 |
| $L_{wiggler}$ (m) | 9.6 | 30 | 75 | 30 | 30 | 102 |

(a) This column describes an FEL based on beam performance of the SLAC linac with currently available guns.

(b) This column describes an FEL based on expected parameters of the SLAC linac with photocathode electron guns and enhanced wiggler focussing [Pellegrini].

(c) Variables for the saturated power before tapering. The photon rate and brightness are calculated assuming a 10 kHz (average) pulse repetition frequency except for the SLAC linac where 120 Hz was used. Brightness is in photons per second per 0.1% bandwidth per $mm^2$ $mrad^2$.

(d) Same as (c), except that the output power out of the tapered wiggler is used.

### 3.5 Master Oscillator Power Amplifier (MOPA)

MOPA is the combination of a lower power oscillator and an amplifier section to provide high peak power. The oscillator provides the seed radiation to drive the final amplifier stage in the same way presented in the SASE and the harmonic generation sections. The advantage of this approach is that the a seed laser and harmonic generation are not required. One disadvantage is increased system complexity. Another is the electron energy-spread created by the oscillator which affects the amplifier's performance. The working group did not estimate the parameters and performance of a MOPA, but the power level should be comparable to that of the amplifier approaches.

### 3.6 The pulse length of FEL radiation.

Free-Electron Lasers based on linacs provide short pulses of radiation (order of one ps), as a result of the short electron pulse length provided by linacs. The working group has discussed several other interesting mechanisms for the attainment of very short pulses in the 1-1000 Å range.

One way to produce FEL pulses shorter than the electron pulse length is by using a short seed pulse starting from a short-pulse conventional laser with multiple harmonic generation.

Another scheme of producing extremely short X-ray pulses has been discussed. The FEL mechanism produces strong bunching of the electrons on the scale length of the FEL radiation wavelength (100 fs in one example). These multi-kiloampere bunchlets could be sent into a wiggler to produce pulse trains of (spontaneous) synchrotron radiation [Bonifacio].

An exotic technique to produce intense, ultrashort pulse is based on the phenomena of FEL super radiance [Bonifacio]. It was predicted by the Milano group that slippage coupled with high gain will cause an intense radiation spike, the intensity of which is proportional to $N_e^2$ (therefore the name of superradiance), at the tail of the electron distribution.

## 4. RESEARCH AND DEVELOPMENT.

The working group investigating Linac based Light Sources identified critical areas where Research and Development are required to strengthen the technological basis before constructing the next generation of high power, short wavelength sources. The recommendations are listed in order proceeding from the electron gun to the undulator region:

1) Development of high duty-factor, high-brightness electron guns. The goal is to produce a 1% duty factor gun with 1nC charge/bunch, 1.5mm-mrad normalized transverse emittance, and 0.02% normalized energy spread. The working group adopted the definition of the gun to include laser, cathode, initial RF acceleration, and emittance preservation up to about 20 MeV. Successful demonstration of this system is the primary prerequisite to operation of FEL configurations investigated by the working group. Further developments in computational research are recommended. We anticipate the demonstration of an electron source with these parameters would benefit other branches in applied science.

2) Development of a superconducting RF laser-photocathode gun to operate CW. Demonstration of the SRF gun would permit construction of high average power light sources.

3) Development of photocathode material with the goal of producing 0.1% quantum efficiency at visible wavelengths in a 10 nTorr RF environment. Long lifetime under high average power conditions is the end goal, required for the operation of a reliable light source.

4) Demonstrate acceleration up to about 50 MeV and pulse compression to obtain 1kA peak current while preserving 1.5mm-mrad emittance.

5) Study wakefield effects in the 2-4mm gap range for undulators extending up to 10-50m length. Computational studies and experimental verification are recommended.

6) Linac-Based FEL Amplifier Development

I Investigate FEL physics and performance in the exponential regime. Experimental areas of primary concern include microbunch characterization, emittance dilution, slippage, photon beam coherence, chirp, bandwidth, sidebands and optical guiding.

The working group recommendation is to perform experiments at the shortest possible wavelengths (preferably sub-micron) before construction of a light source to reach the 10nm range. New diagnostic techniques will need to be developed.

II Research efficient seed laser sources.

III Proof-of-principle demonstration of two wiggler harmonic generation FEL.

7) Linac-Based FEL Oscillator Development

Development of resonator optics in the 1-100nm range. High reflectance multi-facet mirrors and output couplers with thermal and vibrational stability properties commensurate with short wavelength lasers under large power loads are required. Studies of FEL oscillator properties including bandwidth and sideband generation in the sub-micron range are recommended.

## APPENDIX: IMPEDANCE FORMULAS FOR WAKE FIELD ESTIMATES. [BISOGNANO]

1. Longitudinal impedance.

The induced energy spread is given by

$$\Delta E \sim 2 k_l Q e$$

$$k_l^{cavity} = \frac{Z_0 c}{2\pi^2 a}\sqrt{\frac{g}{\sigma}}$$

The cavity impedance is reduced by $1/N^{1/2}$ per cell up to $N_{eff}$.

$$k_l^{periodic} = \frac{Z_0 c}{2\pi}\frac{1}{a^2} l$$

$$k_l^{resistance} = \frac{1}{a}\Gamma\left(\frac{3}{4}\right)\frac{c}{4\pi^2}\left(\frac{Z_0\rho}{2}\right)^{1/2}\frac{1}{\sigma^{3/2}} l$$

$$k_l^{step} = \frac{Z_0 c}{2\pi^{3/2}}\frac{1}{\sigma}\ln\frac{b}{a}$$

2. Transverse impedance

The emittance degradation is given, for small $\eta$, by

$$r_e = 1 + \frac{x_0\eta}{2\pi}\sqrt{\frac{\gamma_i}{\beta\epsilon_n}}$$

down by $1/N^{1/2}$ up to $N_{eff}$ per cell,

$$\eta = \frac{6\,eQ(k_\perp/l)\,L_{acc}}{k_\beta\,(E_f-E_i)}\ln\left(1+\frac{E_f-E_i}{E_i}\right)$$

$$k_\perp^{cavity} = \frac{Z_0 c}{4\pi}\frac{1}{a^3}\sqrt{\pi g\sigma}$$

$$k_\perp^{periodic} \sim \frac{Z_0 c}{4\pi}\frac{1}{a^4}\sigma l$$

$$k_\perp^{resistance} \sim \frac{1}{8}\frac{c}{a^3}\sqrt{Z_0\rho}\frac{1}{\sqrt{\sigma}}l$$

$$k_\perp^{step} \sim \frac{Z_0 c}{2\pi}\frac{1}{\pi^{1/2}a^2}\ln\frac{b}{a}\ln\frac{b}{\sigma}$$

(cavity when $2l\sigma > (b-a)^2$; bunch 'sees' wall).

3. Notation and warnings.

$Z_0=377\Omega$
$\Gamma(3/4)\approx 1.23$
l=length of structure, cell period
g=gap of cavity
a=beam pipe radius
b=outer radius
$x_0$=beam offset
$\rho$=wall resistivity
$\sigma$=bunch length
$E_i$=initial energy
$E_f$=final energy
$\epsilon_n$=normalized emittance
Q=bunch charge
$\beta$=betatron function
$k_\beta$=betatron wavenumber
$N_{eff}\approx ka^2/l \approx a^2/(\pi\sigma l)$=number of cells which can interfere
N=number of cells, each of length l

$k=\omega/c$; typical $k \approx 1/(\pi\sigma)$

All the above estimates are for short bunches, that is
$ka >> 1$; $ka >> l/a$; $ka >> l^2/ag$; etc.

Multicavity regime requires $\sigma\pi g << a^2$; i.e. $N_{eff} >> 1$ and $l >> g$ (which is often violated). Also $N >> l/g$; etc.

Resistive wall $\omega^{1/2}$ approximation fails at low and high frequencies. In particular, check whether

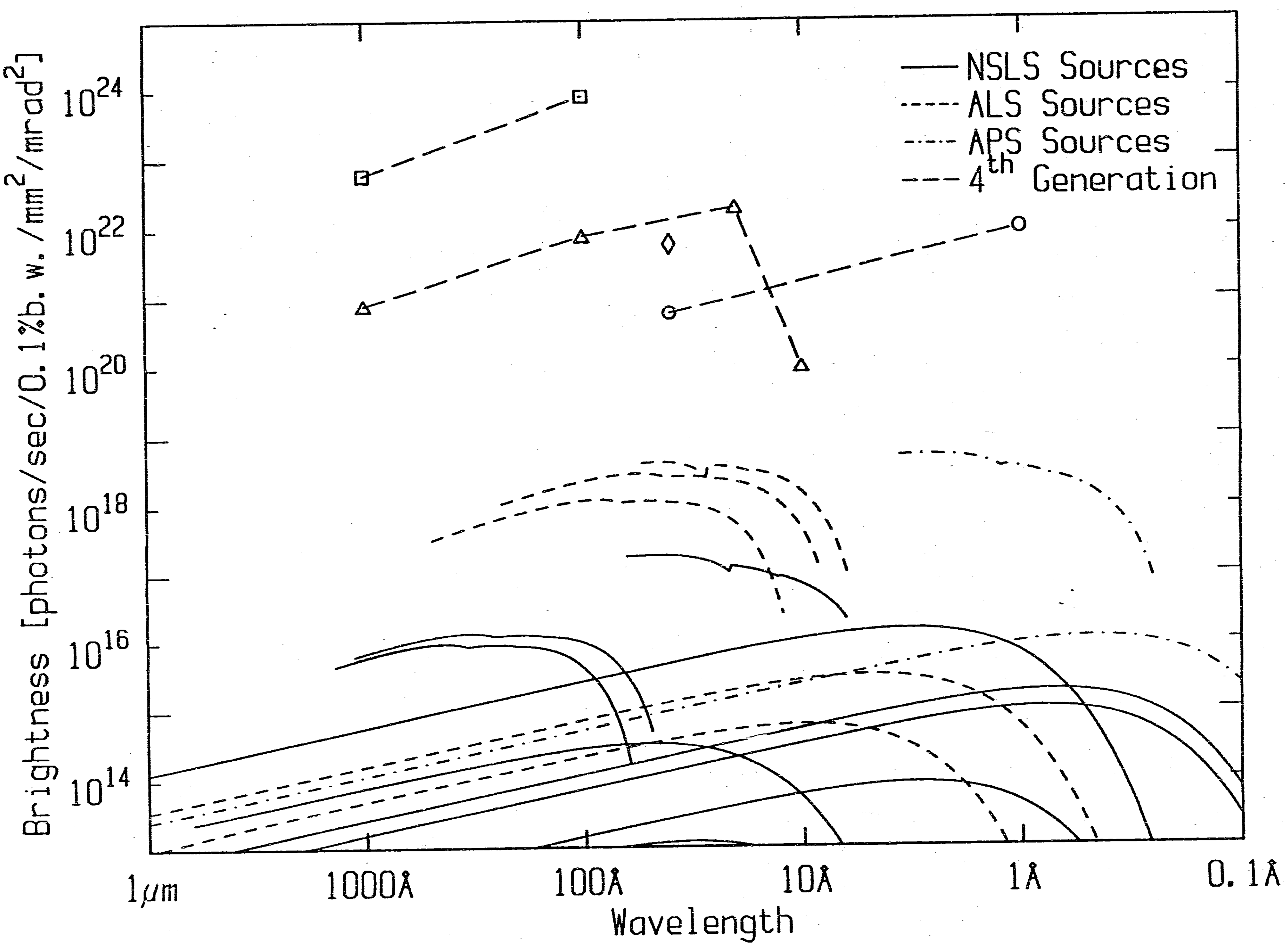
$$\sigma > \left(\frac{\rho}{Z_0 a}\right)^{1/3} a$$

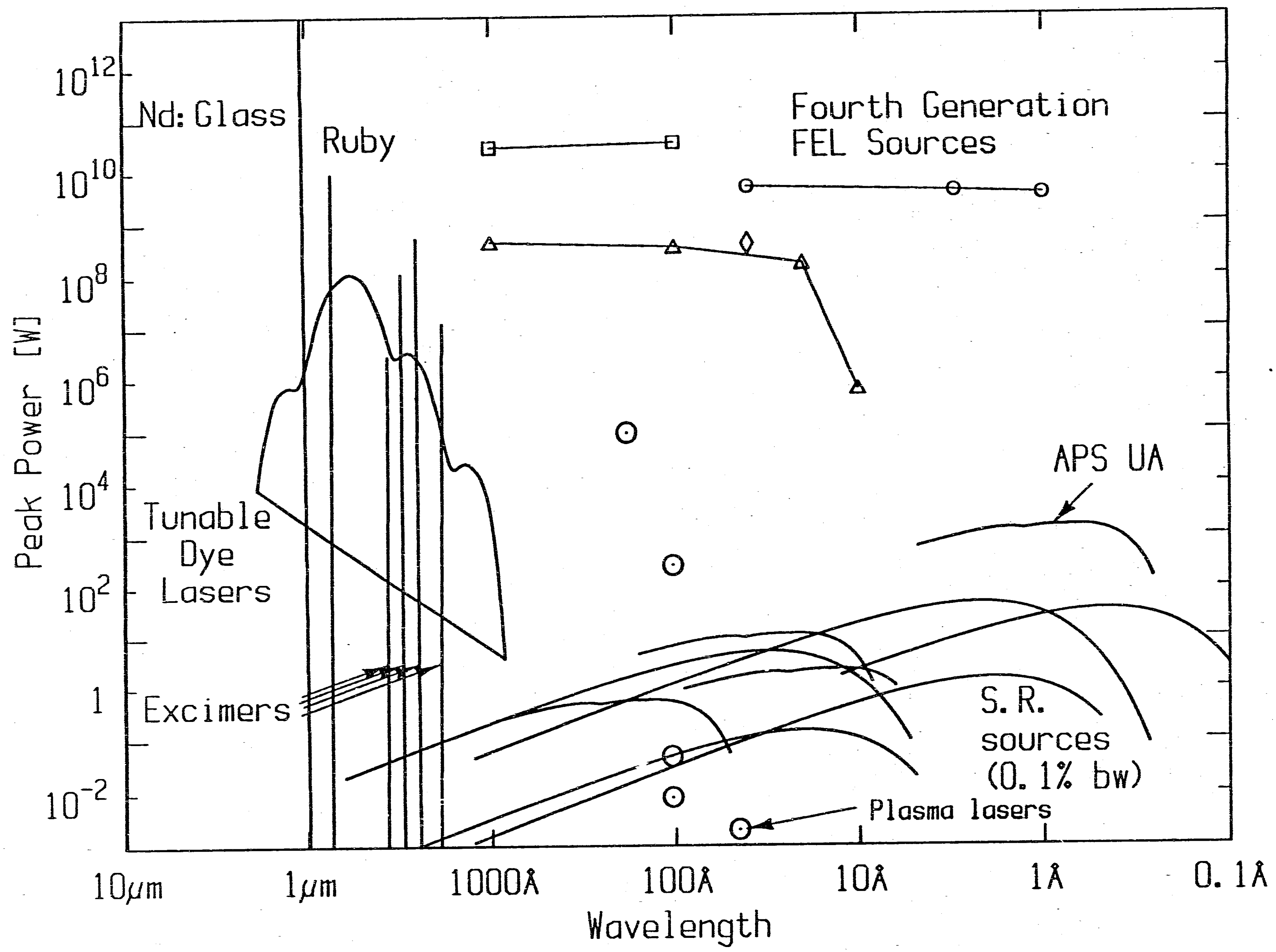
Figure captions

Figure 1 Peak power of various existing laser and synchrotron sources (both second and third generation) compared to calculations for fourth generation FELs. The triangles are for an FEL design based on self-amplified spontaneous emission (SASE) saturated power. The squares are SASE output power including wiggler tapering. The open circles are SASE saturated power for a design utilizing the existing SLAC linac. The diamond shaped point at 40 Å is the subharmonically seeded FEL example.

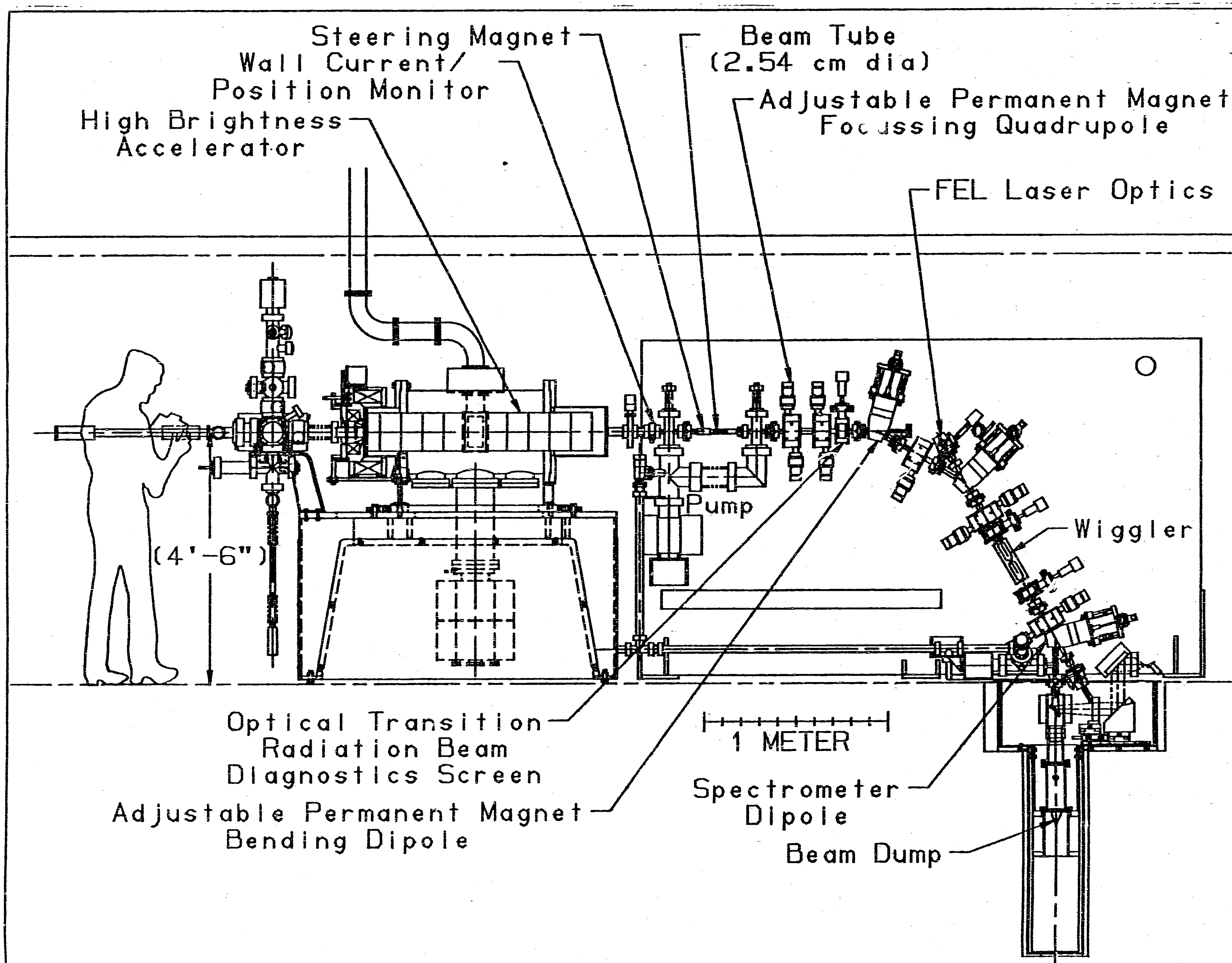
Figure 2 Brightness of second and third generation synchrotron sources compared with that of the calculated FELs. The triangles are for an FEL design based on self-amplified spontaneous emission (SASE) saturated power. The squares are SASE output power including wiggler tapering. The open circles are SASE saturated power for a design utilizing the existing SLAC linac. The diamond shaped point at 40 Å is the subharmonically seeded FEL example.

Figure 3 The Compact FEL system at Los Alamos National Laboratory. This system is designed to perform at the beam brightness levels which have been assumed for the fourth generation FEL sources. The system design is based on an integrated approach to a high brightness electron source combined with a high brightness accelerator and transport system.


NSLS Sources
ALS Sources
APS Sources
4th Generation
Brightness [photons/sec/0.1%b.w./mm²/mrad²]
10²⁴
10²²
10²⁰
10¹⁸
10¹⁶
10¹⁴
1μm
1000Å
100Å
10Å
1Å
0.1Å
Wavelength



Peak Power [W]
$10^{12}$
$10^{10}$
$10^{8}$
$10^{6}$
$10^{4}$
$10^{2}$
1
$10^{-2}$
Nd: Glass
Ruby
Fourth Generation
FEL Sources
Tunable
Dye
Lasers
Excimers
APS UA
S. R.
sources
(0. 1% bw)
Plasma lasers
10μm
1μm
1000Å
100Å
10Å
1Å
0. 1Å
Wavelength


Steering Magnet
Wall Current/
Position Monitor
High Brightness
Accelerator
Beam Tube
(2.54 cm dia)
Adjustable Permanent Magnet
Focussing Quadrupole
FEL Laser Optics
Pump
Wiggler
(4'-6")
Optical Transition
Radiation Beam
Diagnostics Screen
Adjustable Permanent Magnet
Bending Dipole
1 METER
Spectrometer
Dipole
Beam Dump

# END

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