Trends and Opportunities in Light Source Development*

George R. Neil, Thomas Jefferson National Accelerator Facility, Newport News, VA

After a decade of rather quiet growth for FELs there is a now a lot of activity in the light source community. This is the result of a combination of factors including successful operation of the third generation light sources, the establishment of a very productive user community at both synchrotrons and FELs, and the continuing technical improvements of accelerators and related technology which allow ever more challenging machines to be considered. There are a number of themes that carry this development including pushing wavelengths shorter, brightnesses higher, pulses shorter, increasing average power, and providing for multiple synchronized photon beams with multiple wavelengths. This talk will discuss some of the plans and proposals currently circulating and attempt to provide a glimpse into the near future of our field by illustrating the technologies that drive source development.

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I. Introduction

A decade ago the future of FELs was viewed as not very promising; in many places graduate students were not particularly encouraged to pursue research in light sources because the job prospects were not attractive, the areas available for original research were not viewed as particularly interesting, and the hopes for significant funding for operating either new research developments or extending user facilities were minimal. This was despite the successful operation of several user facilities around the world: UC Santa Barbara, Stanford, Vanderbilt, Duke, Orsay, FOM, FELI. The accelerator technology which drives advances in light source performance in many cases was also not a subject of particularly hot interest although in this case also there were some notable programs at DESY, Cornell, JAERI, KEK, LANL and JLab. By and large these were modest efforts with little prospect of growing into major facility projects.

In the larger light source community modest growth was also the byword. The use of second generation light sources at places such as BNL, SSRL, Orsay, Daresbury, and others was growing as users and facilities learned how to maximize the usefulness of the available photons. This was through not only light source performance improvements in lifetime, stability, and brilliance but also in the use of optical devices which manipulated the output beam to more desirable characteristics. In 1991 there were 22 second generation light sources operational. They served approximately 2000 users per year and only a small amount of internal funding was directed at substantially increasing the performance of such devices(1).

Something changed during that decade. There was a broad realization of the substantial improvements in light source performance that could be achieved through the application of continuing advances in accelerator technology. Concurrent with this development was the growing success in the application of these light sources to resolve questions of fundamental importance in areas such as protein crystallography. The protein structures that have been mapped are now driving the development of new drugs and understanding in biological processes. This parallel success on the performance side of light sources and in the application of the photons has led to the establishment of substantial light source user communities as a force in international scientific research.

Interestingly, the technology of FELs played an early contributing role in light source development (wiggler and undulator technology). Now as we look beyond 3rd generation synchrotrons, FEL technologies are again expected to play an important role. The paragraphs below briefly illustrate where the light source community now sits in terms of device performance. That is followed by a glimpse into what are believed to be the most important accelerator technology developments which are expected to drive advanced device construction and application.

Status

A. FELs

An review of FEL capabilities is given in (2). There are presently 11 FEL user facilities in the world (3). These typically operate up to ~2000 hours per year and have a substantial user base of researchers applying the light. Table 1 lists FELs currently operational and planned as user facilities with some of their key capabilities and areas of concentration. A number of the facilities have focussed their activities in one or two particular areas to provide enhanced performance for a particular set of applications. It is certainly proven true that maximal utilization of an FEL requires not only the light source to be exercised to its fullest capability but also the development of adjunct capabilities to manipulate the beam for the user. Such manipulations include pulse stretching/compression, pulse stacking for higher micropulse energy, synchronization with other laser sources, macropulse and micropulse selection and prf control, bandwidth manipulations, dual wavelength operation, frequency conversion, wide band tunability, pulse amplitude or pointing stabilization to high accuracy, and irradiance profile mapping.

Several reports on the viability of FELs as user driven light sources have appeared over the years (4,5,6). These reports have typically come to the conclusion that FELs would only be successful as user facilities in particular wavelength bands (say beyond 10 microns) because of competition from other lasers sources especially OPOs and OPAs. While it is true that FELs have enjoyed big successes in the IR wavelength bands already, they have also shown prowess in other domains and SASE FELs now offer the opportunity for extending the brightness of coherent sources into the VUV and soft X-ray regime. Specific examples of work in IR bands normally included in the range of OPOs include the discovery of interstellar TiC at FOM through the identification of spectral absorption (7), the use of an FEL beam for human brain surgery at Vanderbilt (8), the measurement of nuclear reaction analyzing power of the 2H(g,n)p reaction at 3.58 MeV through Compton scattering at Duke(9), the first comprehensive measurement of vibrational photon echos in glass forming liquids at Stanford(10), the measurement of interstitial hydrogen vibrational mode lifetimes in silicon at JLab(11), etc. This is in addition to a number of interesting measurements and developments of the FEL itself which will be treated below.

A key limitation in the performance of existing user facilities are the wavelength regions achievable. These are limited on the short wavelength side to 190 nm or so since, to date, user facilities have only operated FEL oscillators which means that high reflectivity mirrors are required. The technology of mirror coating becomes difficult below 250 nm and increasingly problematic below 180 nm except in a few narrow wavelength ranges under special conditions.

B. Synchrotron Light Sources

As a source for users, synchrotrons have several attributes which make them superior to FELs in some respects. They are able to achieve significant brilliances in wavelength bands presently inaccessible to FELs, they have long fill lifetimes at high stability so measurements can accumulate data over many hours and achieving high availability, they have many user ports which can be used in parallel thus reducing the effective cost per user. As a result of these advantages the use of now third generation light sources has grown into a sizeable international research activity. It is estimated that there are 20,000 users on 39 synchrotrons worldwide, running typically 4000 hours each and supplying an average of about 30 beamlines, and

producing on the order of 5000 publications per year in reviewed journals (12). There are at least 12 third generation sources which are specifically designed for the addition of wigglers and undulators to enhance the brilliance at specific wavelength bands. Typical performance of such systems is illustrated by Figure 1. A typical third generation facility such as the Advanced Photon Source at Argonne National Laboratory (13) has ~35 beamlines some of which are general purpose but many of which are designed by collaborations to have special capabilities for study of biological, condensed matter, or basic atomic physics research. Despite the successes of these devices and a steady flow of research output from them they are widely viewed as the end of a development line. The reason for this is that fundamental limits will prevent improvements of device performance in machines such as these by more than a factor of 50, or so. This is because stochastic heating of the circulating electron beam will set limits on the minimum emittance achievable at the high energies and currents these systems run at.
The brightness achievable from an undulator is given by

$$B_{\text{und}} = \frac{2\times10^{18}}{\varepsilon_x \varepsilon_y}\frac{N_W K^2}{1+K^2/2} \qquad \varepsilon \text{ in mm mrad}$$

In a storage ring the emittance is limited to

$$\varepsilon_x = 7.7\times10^{-4}\frac{\gamma^2}{N_{\text{cell}}^3}\,\text{nm}-\text{mrad}$$

for a Chasman-Green lattice. (14). This will limit significant output to wavelengths beyond 100 A (15).

It is evident that increasing the energy of the ring is counterproductive in terms of the emittance although it may drive the critical energy to shorter wavelengths.

An additional limitation to synchrotrons is that the pulse lengths from these systems are too long to probe most issues of molecular dynamics. The Touschek effect will limit the pulse lengths in normal operation to ~ 10 ps. One group has developed a technique to pulse slice a very short electron bunch from the circulating pulse to allow the measurement of rapid activity (16) and their may be other approaches which permit bunch length manipulations to a greater extent (17) but substantial progress in this area is not anticipated.

Recent technical performance improvements in accelerators and optical systems have enabled consideration of new light source capabilities. Key accelerator technologies in development are high brightness injectors applied to the use of self amplified spontaneous emission (SASE) to achieve FEL output in wavelength regions inaccessible to high reflectivity mirrors, techniques for synchrotron pulse slicing, the application of high average current energy recovery, and techniques for synchronously combining a number of sources for pump/probe studies. These are discussed in the sections that follow

II. Accelerator and laser technologies which drive light source development

A. Improvements driven by injector brightness development:

There are a number of groups around the world investigating the use of SASE FELs to produce UV or shorter light. Major efforts include BNL(18), TTF FEL(19), LEUTL(20), LCLS(21). These will lead to several user light sources with high peak brilliances in wavelength regions currently inaccessible. The reader is directed to the references for the design and performance specifics of these sources; an example is shown in Figure 1 plotted against some existing light sources. At present the SASE FEL technology is working its way toward shorter wavelengths from the visible into the UV with the limitation set by accelerator energy and electron beam brightness. The former is a matter of adding additional acceleration while the latter is the focus of a number of efforts. The highest electron beam brightnesses are achieved by pulsed rf guns utilizing photocathodes. High gradients are used to quickly accelerate the high charge before space charge effects degrade the emittance significantly. In addition a magnetic focussing scheme due to Carlsten (22) is used to compensate the transverse space charge effects. Probably the best results to date have been reported by BNL in achieving 0.8 nC within 1 mm mrad normalized emittance (23).

B. Improvements driven by high peak power laser technology: Pulse slicing

Very short X-ray pulses at high brightness will allow study of femtosecond molecular processes. While huge fluxes will be available when sources such as the LCLS or TTF-FEL becomes fully operational, in the meantime techniques utilizing conventional lasers have been developed to produce femtosecond X-ray pulses. The key work in this area is being performed at Lawrence Berkeley National Laboratory where a 300 fsec pulse from a high power laser was used to modulate the energy of a short pulse out of a 100 ps pulse circulating in the ALS synchrotron (16). At a subsequent energy-dispersed location a fsec pulse of synchrotron light is produced. This source can be used to perform molecular dynamics experiments and fast X-ray diagnostic development until such time as more powerful sources are developed.

C. Improvements from maturation of high average current energy recovery

Although synchrotron light sources have been extremely successful they do have a number of technical limitations:

a) The light is not coherent which limits the brilliance.

b) The ring electron beam transport lattice typically prevents the achievement of pulse lengths shorter than a few hundred picoseconds so that most chemical reactions and transient molecular phenomena are inaccessible due to their sub-100 femtosecond temporal response.

c) The use of light in a specific wavelength band requires use of a monochromator which must deal with high average fluences.

d) A practical issue is that since the dynamics of the lattice couple all devices together changing the lattice or adding long wigglers to the system is awkward. The ring layout is generally set at device construction and from that point on one must live with the available regions for insertion devices.

e) Finally both the beamline impedance must be low and the field quality of insertion devices must be very high since the beam circulates through these structures millions of times per second and any degrading effects quickly build up.

An approach to overcome limitations a, b, d, and e has been developed based on the success of high average current energy recovery in the Jefferson Lab IR Demo (24). Energy recovery from an electron beam involves taking the beam after FEL lasing or other use of the beam and sending it back through the accelerator again ~180° out of rf phase so the beam is decelerated rather than accelerated. In its most direct form, i.e., same cell energy recovery in a srf linac, the process can be exceptionally efficient. One can then consider running very high average currents through the system without the concomitant expense of high average power rf and its associated energy use. It was first suggested in 1976 (25) and subsequently demonstrated in a system without an FEL at Stanford University (26). Recently it has been extended to high average currents during FEL operation (24).

The demonstration of such same cell energy recovery of high average current in an srf accelerator has opened the door on at least two light source development areas. The first is high average power FELs. The Jefferson Lab FEL has now produced over 2 kW CW of outcoupled laser power at 3 microns. The electron beam for this was running at 4.5 mA CW in a 74.7 MHz train of 60 pC, 48 MeV sub-picosecond pulses. The machine is presently being upgraded to operation at 160 MeV which will permit lasing at > 10 kW in the IR and multi-kW in the UV region. This machine required the development of a high brightness CW injector based on a high voltage DC photo-gun. Techniques utilized by the SASE FEL community would not work since high gradient copper cavities cannot run CW due to rf ohmic losses (although lower gradients may be acceptable at low charge and future development of srf photo-guns is contemplated). The 5 mA DC gun is presently being upgraded to 10 mA and planning is underway for a 100 mA version of this source which would power a 100 kW FEL.

A second possible application of the technology has come to the fore over the last year. The use of energy recovery make it cost and energy efficient to consider high power energy recovering linacs as a substitute for synchrotrons. Advancements in CW injector performance as in the JLab FEL and the ability to put very long wigglers or undulators in the lattice make it feasible to consider higher brightnesses from these machines than is available from third generation sources while retaining similarly large numbers of user ports. There are other advantages in addition:

a) since the beam only goes through the system once, impedances are not as crucial a factor as in synchrotrons;
b) reconfiguration of the machine is easier and its transport lattice is much more flexible since all pieces are not intimately linked; and
c) finally, the electron (and therefore synchrotron light) pulse length can be very short, limited only by the longitudinal emittance.

A number of organizations are considering construction of these devices and two proposals and white papers for construction of such systems have been produced (27, 28, 29). This technology will likely be a major driver in the construction of new light sources over the next decade. Beam powers under consideration are huge, currents on the order of 0.1 A average and beam energies of 5 GeV. Essentially all the technology exists for such a system except the injector which has been designed but awaits experimental validation.

D. Combination of technologies for pump-probe studies: FELs + OPAs, Thompson scattering, FEL + synchrotron, coherent synchrotron radiation

The final technological approach which should not go unnoticed is the combination of light source technologies. This is occurring at an ever more frequent rate. By utilizing several synchronized sources analysis of materials and processes can be performed which provide information about the interaction physics heretofore unavailable. The idea is to utilize the full electromagnetic wavelength spectrum to maximize analytical capability possible in each range. Each wavelength range has particular analytical capabilities which in combination are much stronger. One example of this activity is a pump-probe source utilizing synchrotron light and light from a separate laser or OPO. Such a combination was recently used to probe the dynamics of superconductivity for example. (30)Pump-probe experiments using FEL/laser combinations have been growing as the capabilities of OPO/OPA systems increase.

In many FELs X-ray radiation is produced naturally in synchronism with the FEL pulse as the optical pulse in the FEL cavity Thompson-scatters off the electrons to produce FEL photons of higher energy. This can provide substantial levels of tunable X-ray flux for pump probe experiments with the FEL (31) . Carrying this one step further JLab intends to operate its IR and UV FEL in synchronism with a separate synchrotron allowing independent control of pulses in multiple energy bands (32). In principle, this system could provide simultaneous sub-picosecond THz light, coherent IR-UV range FEL light, 5-250 keV X-rays, all synchronized with 300 ps synchrotron light pulse with a critical wavelength of 1 nanometer (1200 eV). Alternately the FEL light could be used to pump multiple OPO/OPA systems for multiple synchronous pulses tunable over the full OPO output range. The system has already produced sub-picosecond THz pulses, synchronous with 3.1 micron FEL lasing, synchronous with X-ray pulses at 10 keV (Fig 3) (12).

III Summary

After a quiet decade of technological maturation light source development is preparing for leaps in performance which will open up new vistas of research opportunities for users. FELs now operate at high average powers; they are operational into the UV and are pushing down into the vacuum UV and soft X-ray regime. SASE based FELs will provide enormous peak powers in ultra-short pulses which will challenge experimentalists to develop new techniques for X-ray characterization and beam control but provide exciting new opportunities for research. Ultra short pulses are beginning to be offered from these tunable sources and production of ultra short X-ray pulses is expected to yield significant insights into molecular dynamics and other fundamental studies. The production of multiple synchronized wavelengths is expected to allow experiments to be performed in surface and materials effects which have be impossible up until this time. And finally the promise of advanced light sources based on high current energy recovery is expected to yield a whole new class of machines with short pulses, high brightness, and substantial operational flexibility advantages over present synchrotrons.

IV Acknowledgements

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Tables

Table 1. Some existing and proposed FEL User Facilities. Data taken from (3) which has further references for each facility. New facilities in Japan were added to the list.

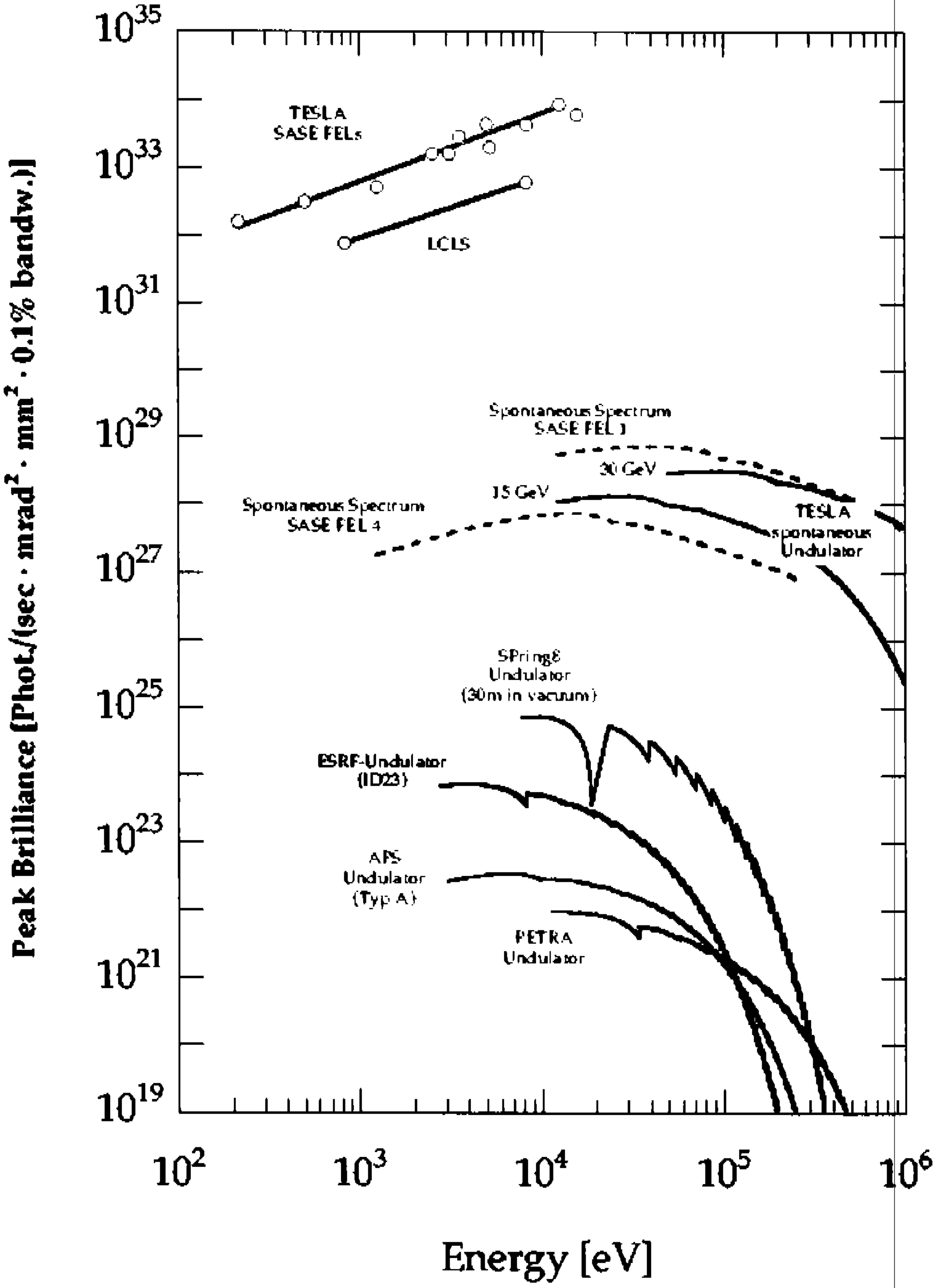
Country	Institution	Device	λ (μm)	τ_p (ps)	E_b/I_b (MeV/A)	*Ppeak* (MW)	P_{avg} (W)	Accelerator
USA	Stanford	FIREFLY	19-65	1-5	20/14	.3	.4	SCRF
		SCA/FEL	3-10	0.7	37/10	10	1.2	SCRF
	Vanderbilt	FELI	2-10	2	43/50	10	10	RTRF
	Duke	Mark III	3-10	3	44/20	2	3	RTRF
		OK-4	0.3	10	1000/350	1000	0.1	SR
	JLab	IR Demo	1, 2.9-6.6	0.6	42/50	40	2000	SCRF
		IR Upgrade	*1-15*	*0.4*	*160/100*	*500*	*10000*	*SCRF*
		UV Upgrade	*0.3-1*	*0.5*	*160/270*	*100*	*3000*	*SCRF*
	UCSB	CTST	2500-30	10^6	6/2	0.006	0.4	Electrostatic
Japan	Osaka	FELI 1	5-22	1.7	33/42	5	2	RTRF
		FELI 2	1-6	1.7	75/50	5	0.5	RTRF
		FELI 3	0.23-1.2	1.7	165/60	5	0.5	RTRF
		FELI 4	20-80	1.7	30/40	5	1	RTRF
		FELI 5	40-100	3-5	20/40	(2)	(1)	RTRF
	Tokyo	FEL-SUT	5-16	2	32/30	5	1	RTRF
	Nihon	LEBRA	1-10					RTRF
France	LURE	SuperACO	0.3	20	800/10	12	0.8	SR
		CLIO	1.8-17.5	1.5-6	70/80	10	9	RTRF
NL	FOM	FELIX-2	5-35	0.5-10	45/70	2	1	RTRF
		FELIX-1	25-110	1-10	25/70	2	0.5	RTRF
DE	*DESY*	*TTF-FEL*	*.042*	*.8*	*390/500*	*3000*	*20*	*SCRF (SASE)*
	Rossendorf	*ELBE*	*5-150*	*5*	*40/20*	*7*	*400*	*SCRF*
China	Beijing	BFEL	10-16	4	30/14	20	2	RTRF

Figures

Figure 1. Performance of proposed 4th Generation Light Sources with some existing sources for comparison. Figure reproduced from (19) by permission.

Figure 2. Projected performance of the Cornell Energy Recovering Linac source. Curve reproduced from (33) by permission.

Figure 3. Calculated and measured THz spectrum of sub-picosecond pulses produced synchronously with 3 micron FEL lasing and 10 keV Thompson scattered X-rays. The intensity of the measured signal has been normalized. Approximately 2 watts has been measured outside a limiting aperture of 1 cm in agreement with theory [12].



Peak Brilliance [Phot./(sec · mrad^2 · mm^2 · 0.1% bandw.)]
10^{35}
10^{33}
10^{31}
10^{29}
10^{27}
10^{25}
10^{23}
10^{21}
10^{19}
TESLA
SASE FELs
LCLS
Spontaneous Spectrum
SASE FEL 1
30 GeV
15 GeV
Spontaneous Spectrum
SASE FEL 4
TESLA
spontaneous
Undulator
SPring8
Undulator
(30m in vacuum)
ESRF-Undulator
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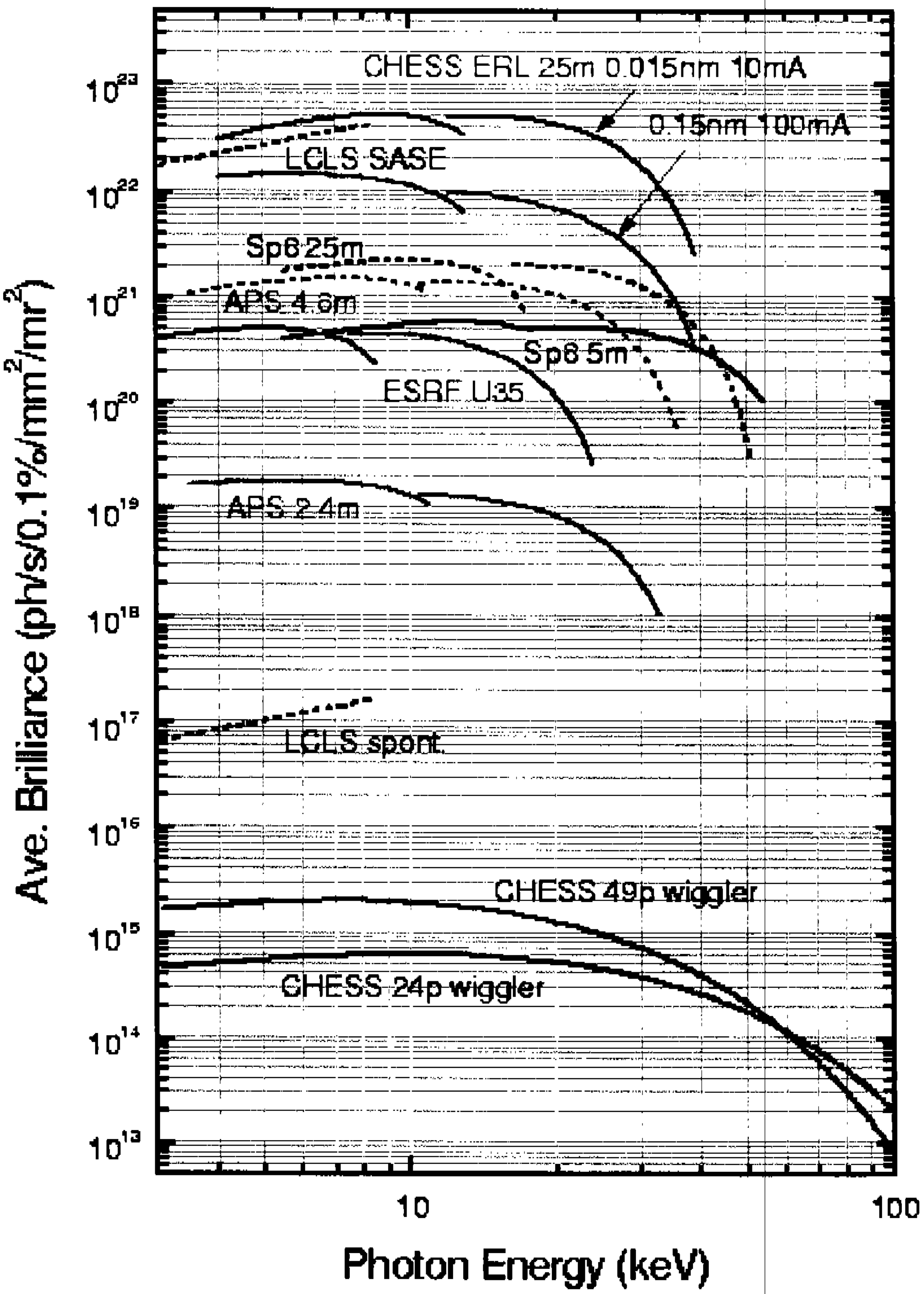
10^5
10^6
Energy [eV]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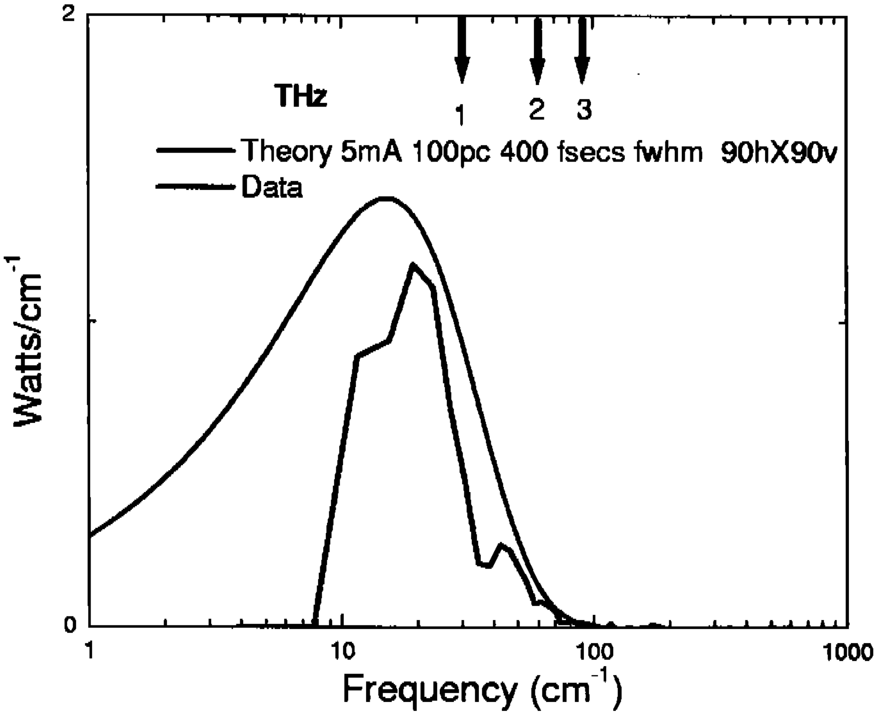
0.15nm 100mA
LCLS SASE
Sp8 25m
APS 4.8m
Sp8 5m
ESRF U35
APS 2.4m
LCLS spont.
CHESS 49p wiggler
CHESS 24p wiggler
10^{23}
10^{22}
10^{21}
10^{20}
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10
100
Photon Energy (keV)
Ave. Brilliance (ph/s/0.1%/mm^2/mr^2)


2
0
THz
1
2
3
Theory 5mA 100pc 400 fsecs fwhm 90hX90v
Data
Watts/cm-1
1
10
100
1000
Frequency (cm-1)