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From storage rings to free electron lasers for hard x-rays

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Abstract
The intensity of x-ray sources has increased at a rapid rate since the late 1960s by ten orders of magnitude and more through the use of synchrotron radiation produced by bending magnets, wigglers and undulators. Three generations of radiation sources have been identified depending on amplitude and quality of the radiation provided. While user facilities of the third generation were being constructed, a new concept of radiation generating devices was being developed that offers an even larger increase in peak and average brightness than had been achieved till then. The new concept of the x-ray free electron laser based on the principle of self-amplified spontaneous emission will be the basis of fourth generation x-ray source user facilities of this century.

The paper will start with a brief history of the development of x-ray sources, it will then discuss some of the differences between storage ring and free electron laser based approaches, and will close with an update of the present development of x-ray free electron laser user facilities.

1. Introduction

This paper discusses x-ray generators, a term that may not sound like much, but it labels by far the greatest success story of tool making. The paper starts with a brief history of x-ray source development, followed by a discussion of differences between storage ring and linac sources, and ends with an update of the present developments of x-ray FEL facilities. More detailed discussions of the subject can be found elsewhere [1–6].

2. Brief history of x-ray source development

Of course, it all started when Wilhelm Conrad Röntgen discovered x-rays in 1895. He received the first Nobel Prize in physics for his discovery. X-ray sources were available very soon thereafter in the form of x-ray tubes, which work by decelerating electrons in a metal cathode.

In x-ray tubes, the kinetic energy of the electrons is distributed into three channels: a line spectrum of fluorescent radiation, which is also called characteristic radiation ($\sim$50%), a continuous bremsstrahlung spectrum ($\sim$50%) and anode heating ($<$1%). The latter is what limits the brightness of this class of devices. The maximum x-ray tube brightness is achieved with a rotating anode x-ray generator at about 10^8 photons s^{-1} $mrad^{-2}$ mm^{-2}/0.1% BW. This intensity is too low for many important experiments: it requires weeks or months of exposure and the signal-to-noise ratio sets the final limitation. Stronger x-ray sources are clearly desirable. Fortunately, there are better ways of producing radiation than slamming electrons into metal.

Radiation is produced when electrons are accelerated, as is the case for linear acceleration in a radio transmitter antenna. Acceleration also occurs when the electron trajectory is bent in a magnetic field. The radiation produced through this centripetal acceleration is called synchrotron radiation or synchrotron light. If the electrons have a low, non-relativistic velocity, the radiation pattern is non-directional, as is the case with the radio transmitter antenna. When the electron velocity approaches the velocity of light, the emission pattern is folded sharply forward into a cone with an opening angle equal to the inverse of the Lorentz factor, γ. Also, the radiated power goes up dramatically.

The first direct observation of synchrotron light took place in 1945 [7]. In the 1950s cyclic electron synchrotrons were the first sources used. The development of storage rings started in the 1960s.

3. X-ray radiation from storage rings

Nowadays a storage ring synchrotron radiation source is generally setup in the following way: after being generated in an electron gun, the electrons are bunched and pre-accelerated in a short linear accelerator and a booster synchrotron. The pre-accelerated bunches are then transported to the storage ring where they are stored for many hours. As their trajectory is bent in the magnetic fields of the storage ring magnets, synchrotron radiation is produced. Some of this radiation is channelled into beamlines and transported to experimental stations. The power loss that the electrons undergo as they radiate is replenished through radio frequency cavities that are powered by high power klystron amplifier tubes.

Bending magnets in storage rings normally bend by a fairly large angle thus spreading the radiation cone over that angular range in a sweeping searchlight fashion. Only a small portion of this angular range can be captured for an experiment. Normally most of the radiation from bending magnets is not utilized in a storage ring.

This was improved with the introduction of wigglers in the 1970s. A wiggler is comprised of a large array of very short and strong bending magnets with alternating field directions. They put the electrons on a wiggle path but do not produce an overall deflection of the beam. Wigglers are not necessary for electron beam storage; they have been added to the storage ring only for the purpose of generating synchrotron radiation and are therefore called insertion devices. In a wiggler the radiation cone of each individual dipole is roughly directed into the same forward direction and the radiation of all wiggler dipoles are superimposed incoherently, thus providing a much larger amount of radiation for the experiment than a bending magnet. Most or all of the radiation of a wiggler is normally utilized.

The intensity of the radiation can be further improved, considerably, by reducing the wiggler amplitude so that the radiation cones from each dipole overlap coherently. Such a device is called an undulator. It produces an extremely intense line spectrum on top of a continuous spectrum. The intensity of the line spectrum increases as electron beam quality is improved (i.e. electron beam emittance is reduced).

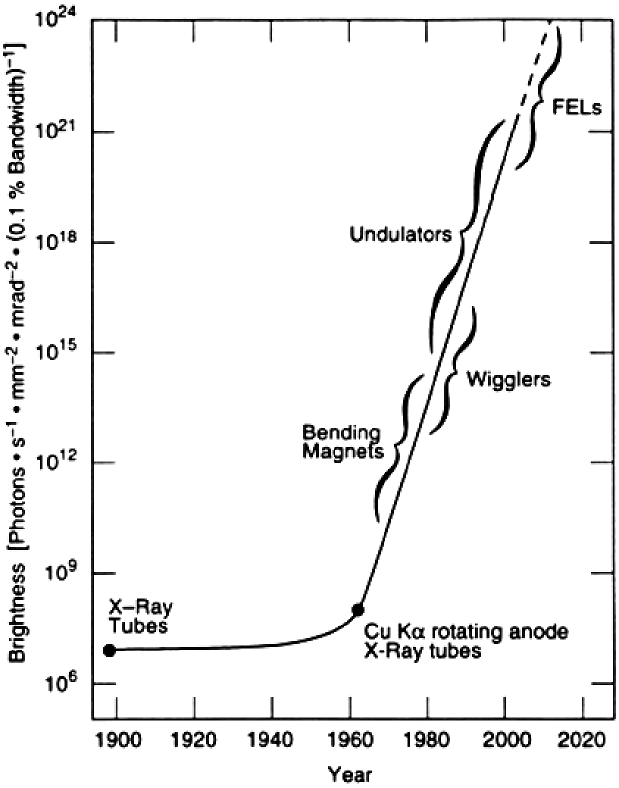

Figure 1. Development of x-ray source brightness since 1895.

The intensity of storage ring radiation sources is normally characterized as flux, i.e. the number of photons per second, or as brightness, i.e. the number of photons in a particular six-dimensional phase space volume, i.e. a measure of the concentration of the radiation.

The radiation from storage rings comes in bunches that are typically spaced by about 2 ns and have a FWHM of about 50 ps. The radiation covers a broad spectral range, it is polarized (linear, elliptical, and circular depending on the insertion device), has a small source size, is partially coherent and is highly stable.

Figure 1 shows the development of x-ray source brightness since its discovery. Over the first half of their existence, x-ray sources, in the form of x-ray tubes, did not change much in brightness. The small increase in brightness just before the onset of storage ring synchrotron radiation sources comes from the rotating anode generators.

Then in the 1970s, when electron storage rings came into existence, an extraordinary development began. X-ray source brightness started to increase exponentially with a doubling time of about 10 months. This trend has now already been sustained for almost four decades and there is no end in sight. It began with the bending magnet radiation, continued with the introduction of wigglers and undulators and will be carried on with the FELs that are discussed in more detail later in this paper.

Similarly, the number of users of x-ray sources continues to increase. The total number of annual users for just the four synchrotron light sources that are operated by the US Department of Energy (DOE), i.e. the Advanced Light Source (ALS) at Berkeley, CA, the Advanced Photon Source (APS) at Argonne, IL, the National Synchrotron Light Source (NSLS) at Brookhaven, NY and the Stanford Synchrotron Radiation Laboratory (SSRL) at Stanford, CA increased from slightly more than 1500 in 1990 to almost 7000 in 2001. In fact, it is expected that the total number of annual users will reach 11 000 by the time all beamlines are instrumented.

Currently, about 75 storage ring based synchrotron radiation (SR) sources are in operation, in construction or in advanced planning. The author is maintaining a web page, together with Herman Winick, SLAC, that lists these storage ring synchrotron radiation sources with links to the home pages of the individual facilities, where available [8].

Synchrotron radiation sources are often being characterized in terms of 'generations'. The first generation includes storage rings that have originally been designed and used for high energy physics research. Many of these machines were initially used parasitically as synchrotron radiation sources during high-energy physics runs. In some cases, synchrotron radiation research became partly dedicated and eventually the machines became fully dedicated as radiation sources as the high-energy physics programs were terminated.

As fully dedicated sources, modifications could be made that brought the performance up to second-generation level.

The second generation includes storage rings that were designed from the start as fully dedicated radiation sources. The first round of these machines was designed in the late 1970s before there was any experience with wiggler and undulator insertion devices as sources, so they were primarily designed to exploit the bending magnets, with a few straight sections for possible future implementation with wigglers and undulators.

The third generation includes storage rings, built in the 1990s and later, that were optimized for insertion devices and specifically designed for undulators, which require low emittance electron beams. These machines are generally characterized by having many straight sections for insertion devices and lower electron beam emittance than first and second-generation rings to maximize the brightness from the undulator sources.

Since the early 1990s people have been thinking of the next, i.e. the fourth, generation [9, 10]. This next generation of x-ray sources will be predominantly linac-based and of extremely bright and short pulse radiation. Advances in the creation, compression, transport and monitoring of bright electron beams make it possible to base the next generation of synchrotron radiation sources on linear accelerators rather than on storage rings. These sources will produce coherent radiation orders of magnitude greater in peak power and peak brightness than the present third-generation sources. The main directions are free-electron lasers (FELs) and energy recovery linacs (ERLs) [11].

4. Fourth generation sources

X-ray brightness and x-ray pulse length depend on the corresponding electron beam parameters, i.e. emittance, energy spread and pulse length.

In a storage ring, the source of 'conventional synchrotron radiation', geometric emittance and bunch length, are the result of an equilibrium. Typical numbers are 2 nm rad for the geometric emittance and 50 ps for the bunch length.

In a linac, the source for x-ray FELs or ERLs, the normalized emittance is determined by the electron gun. Normalized emittance is basically conserved and is only slightly degraded during linac acceleration. The geometric emittance, i.e. the ratio between normalized emittance and Lorentz factor gamma, decreases proportional as linac energy increases. This is a very desirable situation and is contrary to the situation in a storage ring where geometric emittance actually increases as the square of the energy. Bunch length in linac based sources is determined by electron bunch compression. Typical numbers are 0.03 nm rad for the geometric emittance and 100 fs or shorter for the bunch length.

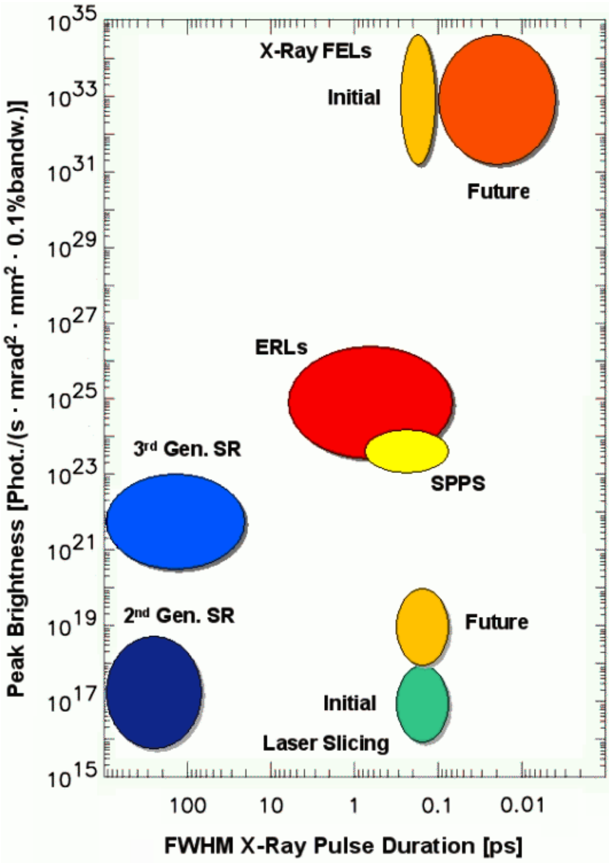

Figure 2. Peak brightness versus x-ray pulse duration for present and future classes of x-ray generators.

(This figure is in colour only in the electronic version)

Linac beams can be much brighter and pulses much shorter! They provide the necessary characteristics for ERLs and x-ray FELs. This comes at the cost of 'jitter'. Contrary to storage ring beams, which are highly stable, as mentioned above, linac beams have a considerable pulse-to-pulse jitter for beam intensity as well as for time of arrival.

Different sources can be matched to different experimental studies. Figure 2 shows a diagram in which the two important parameters of fourth generation light sources, peak brightness and pulse duration, are plotted against each other. Second generation light sources are located at the lower left corner. Third generation light sources are significantly brighter and pulse lengths can be somewhat shorter. X-ray FELs can achieve extreme peak brightness and ultra-short pulses. Pulse lengths will be as low as 100 fs initially and will go down to 1 fs and below in the future [22]. ERLs have high repetition rates and can serve many beam lines. ERLs can be optimized for short pulses or high brightness—but it is very challenging to do both. X-ray FELs can also serve multiple beam lines but require multiple long undulators. The Sub-Picosecond Pulse Source (SPPS), operating at SLAC, is presently the shortest and brightest linac based x-ray source [12].

5. X-ray FELs

Linac-based electrons with undulators are the basis of x-rays, both for conventional sources and for FELs. As the electron beam enters the undulator, it undergoes a wiggle motion, which causes it to emit spontaneous radiation. The intensity of this radiation increases linearly along the short undulator. After the end of the undulator, the electron beam is removed from the radiation beam and directed towards a beam dump, while the x-ray beam is guided by x-ray optics towards the experimental hutch. For a short undulator this spontaneous radiation is all there is. This is the conventional situation.

If the undulator is very long and the electron beam quality sufficiently high, the spontaneous radiation and the electron beam interact as they travel along the undulator axis, causing the electron beam to be micro-bunched at the resonant (x-ray) wavelength of the system. This process, which is called self-amplified spontaneous emission (SASE), causes the x-ray pulse intensity to increase exponentially until saturation occurs. The process produces a line spectrum sitting on top of a spontaneous spectrum. SASE gives 10^5 intensity gain over the spontaneous emission [14].

A typical x-ray FEL system [13] is comprised of a photocathode radio frequency (rf) gun driven by a gun laser. Acceleration is done in a number of linac sections, which typically cover about 1000–2000 m of distance. There are typically two chicane type bunch compressors along the linac, one at low energy and the second at medium energy. After the linac, the electron beam enters an undulator, which is typically 100–150 m in length. After the undulator, the electron beam is deflected by bending magnets towards a beam dump and the FEL radiation is directed by mirrors and other x-ray optics components to the experiment.

Compared to a third generation storage ring based synchrotron radiation facility, the gain factors of x-ray FEL radiation are 10^9 for the peak brightness at the FEL line (10^4 for spontaneous radiation), 10^4 for the average brightness at the FEL line, 10^9 for the coherence, i.e. 10^9 times more photons per coherent optical mode at the FEL line, and 10^3 for inverse pulse length for both the FEL line and the spontaneous radiation, i.e. the linac based radiation can be 1000 times shorter than that from a storage ring. The x-ray FEL will not replace the storage ring facility. It opens the door to new science.

The proposed SASE x-ray FEL user facilities include

- *The linac coherent light source (LCLS) at SLAC* [14, 15] will use electrons accelerated to 4.5–15 GeV by the last third of the SLAC linac to cover a wavelength range for the fundamental FEL line of 15–1.5 Å. The project is being funded by the US Department of Energy (DOE) at a total cost of between US$245 M and US$295 M. Construction will take place in the period 2006–2008. The user beam is expected early in 2009. In October 2003 the US DOE published the document 'Facilities for the Future of Science: A Twenty-Year Outlook' in which it rated the LCLS fourth in a priority list of 26 major proposals [16].
- *The European XFEL Laboratory at DESY* [17] will produce radiation with electrons in the 10–20 GeV-range from a new superconducting linac covering a wavelength range from 100 to 1 Å. The user beam is expected in 2012. The German government has indicated earlier in 2003 that they will be providing one half of the total estimated cost of 684 M€ if other European partners will make significant contributions [18]. The German government is working with other European governments to realize this funding scheme.
- *The SPARX at INFN Frascati*, which is not yet funded, will cover the same wavelength range as the European XFEL [19].
- *The MIT FEL at Bates* is being designed to cover an even larger range from 1000 Å down to 1 Å. The group is seeking funding from the National Science Foundation (NSF) in the US [20].

Table 1. Design parameters for the LCLS (including expansion phase) and XFEL projects.

	LCLS	LCLS-II	XFEL	
Fundamental FEL photon energy	8–0.8	12.4–0.25	12.4–0.2	keV
Electron beam energy	14.3–4.5	14.3–2.5	20–10	GeV
Normalized RMS slice emittance	1.2	1.2	1.4	mm mrad
Peak current	3.4	>3.4	5	kA
FEL power @ exit	8–19	100	24–100	GW
Bunch/pulse length (FWHM)	230	<100[a]	100	fs
Linac repetition frequency	120	120, 240, 360	10	Hz
Bunches per linac pulse	1	60	4000	Bunches
RMS projected x-ray bandwidth	0.13–0.47	0.13–0.47	0.08–0.73	%
Average brightness	2.7–0.2	1200–6[c]	1600–30	10^{22} [b]
FEL photons per pulse	1–29	10–100	1.2–430	10^{12}
Peak brightness @ undulator exit	1.0–0.06	10.0–0.1	5.4–0.06	10^{33} [b]

[a] As short as 1 fs with slicing. Brightness is reduced with pulse length.
[b] Photons s^{-1} mm^{-2} $mrad^{-2}$/0.1%-BW.
[c] @120 Hz.

- *The 4GLS ERL project at Daresbury*, which is also not funded yet, will include IR, VUV and XUV-FELS covering a range of wavelengths down to 123 Å (up to 100 eV in photon energy) [21].

The LCLS will be built at the existing SLAC site using the last third of the 3 km (30 sectors) long linac. A new photoinjector will be added at sector 20 and a 130 m-long undulator will be installed in the research yard downstream of the linac. Two experimental halls will be built, a near hall and a far hall, connected by a tunnel.

The 'European XFEL Laboratory' changed its name recently and modified its site layout. It was formerly known as 'TESLA XFEL'. The plan is now to locate the photoinjector at the site of the old DESY laboratory, inside the PETRA-ring area. The 1–2 km long linac will go underneath a residential area in the northwest direction. There will be several long undulators providing a beam for a number of separate beamlines. The proposal also includes options for extensions.

Selected baseline design parameters for the two leading x-ray FEL projects are listed in table 1. A second column is added to table 1 for the LCLS, labelled 'LCLS-II', which refers to an upgrade after the initial construction project is completed [22]. The pulse repetition rates are of the order of one to hundreds of pulse-trains per second. While in its initial phase, the LCLS will only have one bunch per bunch-train, its upgrade will have up to 60 bunches. The XFEL is designed to have as many as 4000 bunches per bunch train, which is possible due to the use of superconducting linac technology. The most important performance parameters are the number of FEL photons per x-ray pulse, which is of the order of 10^{12} and the peak brightness of about 10^{33} photons s^{-1} mm^{-2} $mrad^{-2}$/0.1%-BW.

The x-ray FELs constitutes such an enormous improvement in x-ray source performance and quality that it is impossible to predict many of the opportunities for discovery provided by such a facility. Nevertheless, scientists are working on establishing initial experimental program designs. For the LCLS project, for instance, a document called 'LCLS: the first experiments' [23] was developed by an international team of ~45 scientists working with accelerator and laser physics communities. They identified the six areas of femtochemistry (Dan Imre, BNL), nanoscale dynamics in condensed matter (Brian Stephenson, APS), atomic physics (Phil Bucksbaum, University of Michigan), plasma and warm dense matter (Richard Lee, LLNL), Structural studies on single particles and biomolecules (Janos Hajdu, Uppsala

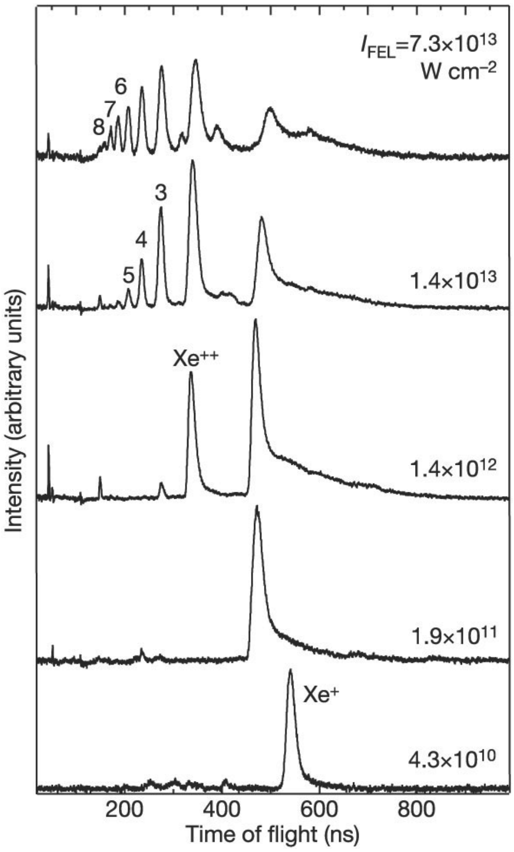

Figure 3. TOF mass spectra recorded after irradiation of 1500-atom Xe clusters as a function of power density. The power density (IFEL) is given next to each trace. The spectrum at the bottom was recorded at a reduced gain of the FEL. The intensity of highly charged ions increases with increasing power density. Experimental details: the intrinsic pulse energy of the 100 fs-long SASE-FEL pulses typically varied between 1.5 and 25 μJ. The spectra with power densities of (1.9×10^{11})–(7×10^{13}) W cm^{-2} were taken with pulses of 25 μJ energy. The power density could be lowered to 10^{10} W cm^{-2} at 1.5 μJ by moving the cluster beam out of focus. (Figure and caption taken from [24]).

University), and x-ray laser physics (the LCLS Team). The names in parentheses give the present spokesperson for the design of the experiments.

. . . but the first experiments with SASE radiation have already been conducted! During the last five years a number of test setups have been developed to test the principles of SASE FEL theory. Some of the radiation produced was directed to experimental setups and used for material analysis. One of these experiments was done at the Tesla Test Facility FEL (TTF-FEL) at DESY. A beam from the SASE test setup at a wavelength of 98 nm was focused on a cluster of 1500 Xe atoms and the resulting time-of-flight spectrum was recorded [24]. This spectrum (figure 3) is the result of a SINGLE ultra-high intense ball ($\sim$20 μm diameter) of up to about 10^{13} coherent XUV photons at a wavelength of 98 nm, enough intensity to record a detailed time of flight spectrum from a single 100 fs-long exposure of the sample, a regime, completely inaccessible for storage ring sources.

6. Summary

X-rays and soft x-rays have been an important probe of materials for basic and applied research for more than 100 years. SR has led to a revolution providing laser-like x-ray and soft x-ray beams—'big scale machines' enabling a large quantity of 'individual investigator science'. SR has very important uses impacting a wide range of scientific and technological disciplines and is well positioned to contribute to new initiatives like nanoscience and proteomics where increasing complexity requires strong multidisciplinary approaches. The SR enterprise is a major success story for the international scientific community. The future looks very 'bright' indeed.

Acknowledgments

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