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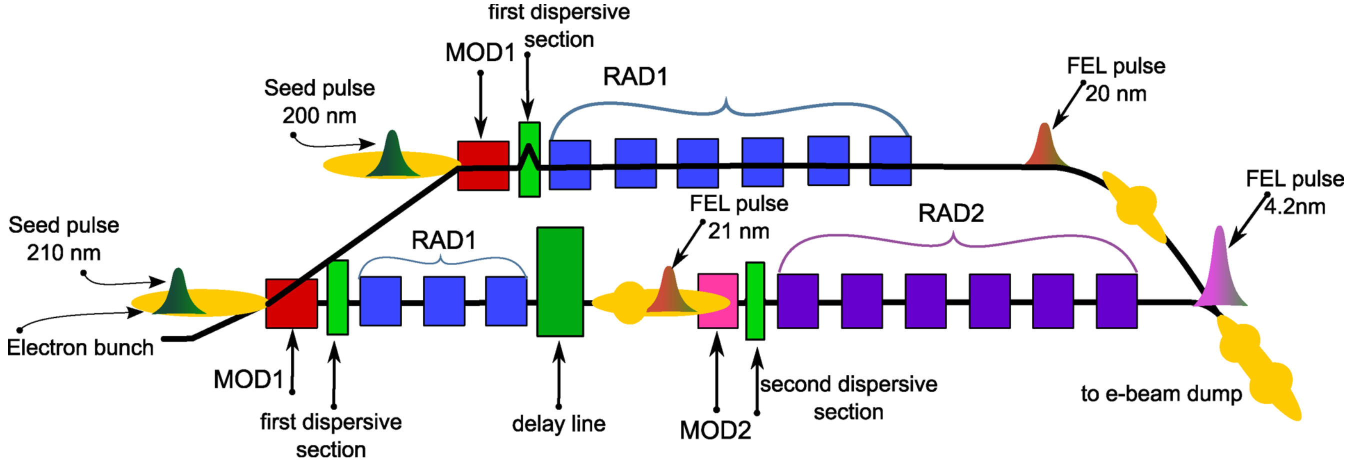

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Next-Generation Light Sources in 2010

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(Invited Paper)

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Abstract: As electron beam quality and control continue to improve, so do the capabilities of free-electron lasers (FELs). Significant advances have occurred in the field over the last few years and have greatly enabled the end users of the FELs, i.e., those doing cutting-edge research via use of the extremely high-brightness FEL light pulses. After a brief review of the basics of FELs, we describe the present frontiers of FEL research and development (R&D), along with several of the most recent demonstrated advances.

Index Terms: Photon sources, coherent sources, free-electron lasers, tunable lasers, particle accelerators, synchrotron radiation, linear accelerators.

1. FEL Basics

A high-energy electron traveling through a sinusoidally varying transverse magnetic field will emit light with a characteristic wavelength

$$\lambda = \frac{\lambda_u}{2\gamma^2}(1 + K^2/2)$$

where λ_u is the period of the magnetic field, γ is the normalized electron beam energy, and K is the normalized peak magnetic field strength.

If a bunch of N electrons are randomly distributed in phase space (with a bunch length longer than the wavelength given above), and if there is no significant interaction between the electrons (each electron radiates independently), the resultant electromagnetic (EM) wave from each electron has a random phase and, therefore, adds incoherently (the field grows like the square root of N and the power is proportional to N).

In a free-electron laser (FEL), the electrons are forced to radiate in phase, i.e., coherently [1]. This is done by allowing the ensemble of electrons to both move in the sinusoidally varying magnetic field of an undulator or wiggler magnet and interact with a strong EM field of wavelength equal to the resonant wavelength above. This interaction forces the electrons into “microbunches” spaced by the resonant wavelength. Once this begins, the electrons in the microbunches radiate coherently and enhance the present EM field. Exponential growth is inevitable until saturation is reached. The resultant coherent signal emitted by the electron bunch is then many orders of magnitude higher in power than the incoherent signal from an unmicrobunched beam.

An interesting aspect of FELs is that they are continuously tunable in wavelength via either changing the electron beam energy γ or strength of the magnetic field K. There is also no classical limit on how short a wavelength is attainable by an FEL; however, quantum effects ultimately create a limit in the very hard X-ray regime.

2. Key Ongoing FEL Research and Development Areas

Technology enhancements are driving the capabilities of FELs into new realms. Improvements in the electron beam brightness (high charge in a small 6-D phase space) have lead to major advances in the wavelengths that are obtainable [2].

Timing and synchronization control is also critical to FEL performance, particularly if used in seeded configurations or in user applications requiring pump-probe configurations. Enhancements in this area have been able to show timing and synchronization stabilities over hours that are sub 10s of femtoseconds (fs) over kilometers [3].

The use of a seed source to both improve the temporal coherence and intensity stability of the FEL is also of major interest and is being pursued by just about all new amplifier proposals or projects that are either operational or under construction [4].

In other areas of the FEL landscape, energy-recovery linacs continue to improve in performance and are enabling high-average powers required by the user community [5], the desire for compactness is driving novel subsystems such as laser/plasma wakefield accelerators and mini undulators [6], and there are concepts to extend FEL oscillator performance into the X-ray wavelength regime [7].

3. Some Highlights of 2010

There have been a number of advances over the past couple of years in FELs, and we will highlight some, but certainly not all, of them. Those interested in the current status of FELs should refer to the large volume of work presented at the annual International Free-Electron Laser Conferences [8]. Below are a few of the more recent accomplishments around the world.

After a near flawless commissioning 2 years ago, the Linac Coherent Light Source (LCLS) at the SLAC National Accelerator Laboratory has delivered high-quality, very-high-peak power X-ray pulses to a wide range of experiments [9]. With its up-to-14.35-GeV electron beam, X-ray output pulses at photon energies of 8 keV, peak powers upward of 9 GW, and pulse lengths below 100 fs make it ideal for the exploration of materials of subnanometer size and now, most recently, of a noncrystalline biological sample with a single optical pulse [10]. In 2010, they tested a second harmonic afterburner scheme [11] to achieve higher powers on the desired harmonic. This is one of a few schemes proposed by the FEL community to increase the harmonic powers in FELs [12]. Also, the LCLS has measured the harmonic content of the FEL [13]. The harmonic content agrees with the code predictions and with the harmonic to fundamental ratios seen in previous, longer wavelength comparisons [14].

In a separate, but related, experiment at SLAC, the concept of echo-enabled harmonic generation (EEHG) was successfully tested [15]. Here, a seed laser is used, together with energy dispersion, in a manner that imprints on the electron beam microbunching structure at very high harmonics of the seed laser wavelength. This prebunched beam can then be made to radiate at this new wavelength. EEHG represent a very real possible means of achieving near-direct seeding into the X-ray wavelengths.

The FEL Division at Thomas Jefferson National Accelerator Laboratory (JLAB), who are most noted for their work involving the use of an energy-recovery linac in achieving a world record in FEL average power (14 kW in the infrared), have now, with an addition to their system, extended their capabilities into the vacuum ultraviolet (VUV) range and have delivered 10-eV (124 nm) FEL pulses. A hole out-coupling mirror on their UV line operating at 370 nm in the fundamental delivered this VUV harmonic light to a calibrated VUV photodiode. They measured 5 nJ of fully coherent light in each 10-eV micropulse, which represents approximately 0.1% of the energy in the fundamental. An example of their early success of operating at 400 nm is shown in Fig. 1, where the average output power indicated is 100 W [16].

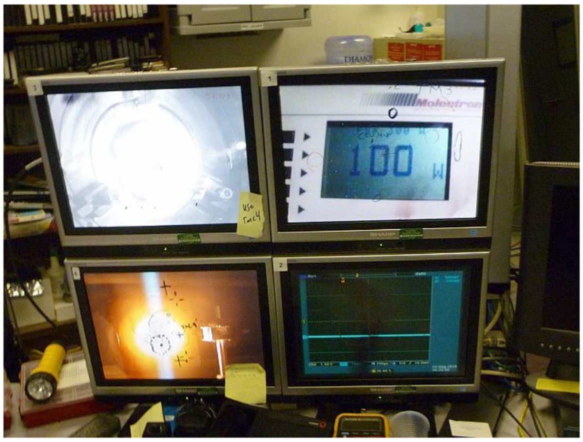

Fig. 1. Jefferson Lab high average power UV demo at 400 nm fundamental. (Upper left) Scatter from high reflectivity mirror. (Upper right) Average power. (Lower left) Light scatter from power probe. (Lower right) Time-dependent diagnostic.

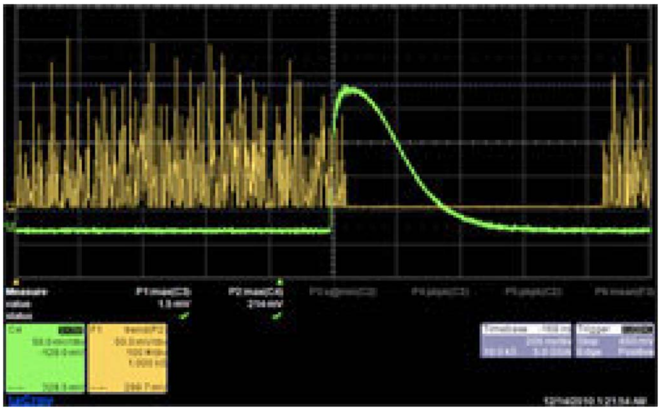

Fig. 2. First measurements of seeded coherent emission from FERMI@Elettra. Green shows the time profile of a single pulse (the photodiode is in saturation due to the intensity of the FEL pulse). Yellow shows a series of (left) seeded FEL pulses and (center-right) no seed.

Another recent addition to this new breed of FEL user facilities is the FERMI@Elettra FEL User Facility (FERMI) at the Sincrotrone Trieste in Basovizza, Italy. At FERMI, the first of two FEL lines was recently completed and commissioning started. FERMI utilizes a unique seeding scheme called High-Gain Harmonic Generation (HGHG) [17] in order to reach shorter wavelengths, stabilize the FEL power, and enhance the longitudinal coherence. Also, it is unique that FERMI uses what are called APPLE II-type undulator magnets that allow the facility to provide the user community variable polarization from linear to both helicities of circular polarization, permitting an additional means of probing the samples under study. Once fully functional, FERMI will provide users with photons in the wavelength range of 100 nm to 4 nm. Notably, FERMI achieved first coherent emission in December 2010 [18]. The first signals are shown in Fig. 2.

Another facility in Italy, i.e., Sorgenta Pulsata e Amplificata di Radiazione Coerente (SPARC), in Frascati, Italy, is making exciting progress [19]. Although not designed as an end-user facility, SPARC was constructed with a full user facility, i.e., Sorgenta Pulsata e Amplificata di Radiazione X-ray (SPARX), in mind. Its goal is as an R&D test bed to further the understanding of beam generation for FELs, the seeded FEL process in various configurations, and benchmarking FEL codes. 2010 was a particularly successful year for them as they were able to successfully lase in a

Fig. 3. Recent aerial picture of the SPring-8 research grounds, including the soon-to-be completed XFEL.

variety of seeding configurations, thus paving the way for other user facilities using seeding as a primary means of improving and controlling the quality of the FEL pulses.

Meanwhile another method of seeding the FEL was pursued at the SPring-8 Compact Self-Amplified Spontaneous Emission (SASE) Source (SCSS) Test Accelerator in Harima Science Park City, Japan. Following their success of operating the SASE-based FEL at VUV wavelengths, and in preparation for their current project the X-ray FEL, they have added a seed source based on the output of a high-harmonic generation (HHG) table-top laser system. With this, they have been able to achieve direct seeding of the FEL at 61 nm and have amplified the signal by many orders of magnitude [20].

4. Coming Soon

This new breed of light source, i.e., the modern FEL user facility, has been dubbed the "Next-Generation" synchrotron light source or, in other circles, 4th-generation light sources. They are distinguished by extremely high peak brightness (photons/sec/mm^2/mrad^2/$(0.1\%$ BW$)$ compared with the current 3rd-generation light source and are very complimentary in nature to these 3rd-generation sources. (For a more complete list of light sources and a further description, see the website http://www.lightsources.org.) Although there are now a few 4th-generation light source user facilities constructed and operating, there are a number on the way. Below is a list of some of these.

1) The European X-ray Laser Laboratory—XFEL [21]
   - This 3.4-km-long X-ray laser facility is Europe's answer to the LCLS. It starts in Hamburg, Germany, and runs underground to the outskirts of the city, where the experimental hall will be.
2) LCLS II [22]
   - This is an upgrade to the LCLS I that includes an additional FEL line optimized for soft X-rays along with additional experimental stations.
3) SwissFEL [23]
   - To be located at the Paul Scherrer Institute in Switzerland, this FEL will use a combination of either SASE operation, seeded operation with an HHG source, or possibly even the more

exotic but perhaps even more capable concept EEHG to provide a broad user community a selection of output beam properties, spanning the EUV region to hard X-rays.

4) SPring-8 Joint project for FEL [24] (Fig. 3)
   - This is the follow-on project to the SCSS mentioned above. It is scheduled for first beam tests in 2011 and will be a SASE FEL utilizing some very interesting concepts such as a thermionic electron source and in-vacuum undulators. It is Japan's entry into the field of upcoming 4th-generation X-ray light source user facilities. The goal will be to achieve hard X-rays for a broad user community.

5. Summary

2010 proved to be exciting for FEL experiments conducted by many enthusiastic teams. Concepts for improving FEL performance continue to be developed, and several FEL-based next-generation light sources are being delivered for use by users of synchrotron light source laboratories worldwide.

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