Towards the next generation of short wavelength light sources

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Abstract. After the laser revolution, a major breakthrough comes from the short wavelength free electron lasers that offer tunable mJ power short pulse light sources for users. Present features and new perspectives will be discussed.

1. Introduction
Accelerator based synchrotron radiation light sources [1, 2] such as high brilliance third generation ones using storage rings at MHz repetition rate with few picosecond pulse duration are widely employed by the scientific community. Lasers, developed more than fifty years ago [3, 4] have completely changed the research landscape and they are used in current life. Free Electron Lasers (FEL) [5] operating a short wavelengths combine the properties of these two sources by merging the development of vacuum tubes and particle accelerators. The proposition of Free Electron Laser (FEL) [5] aimed at merging the development on vacuum tubes / particle accelerators and the properties of the newly discovered lasers. In addition, it aimed at being able to operate at short wavelength.

The FEL spontaneous emission is the synchrotron radiation generated by a relativistic electron beam wiggling in an undulator creating a permanent periodic (period \(\lambda_u\)) magnetic field \(B_u\). It consists of a series of harmonics of order \(n\) according to the so-called resonance condition: \(\lambda = \lambda_u(1+K^2/2)/2n\gamma^2\) with the deflection parameter \(K_0=0.934\lambda_u (\text{cm})B_u (\text{T})\) and \(\gamma\) the normalized electron beam energy to its rest energy. The light wave of wavelength \(\lambda\) interacts with the electron bunch in the undulator, inducing an energy modulation of the electrons, which is gradually transformed into density modulation at \(\lambda_u\), enabling phased electrons to emit coherently emission at \(\lambda\) and its harmonics of order \(n\). The light wave-electron interaction can lead to a light amplification to the detriment of the kinetic energy of the electrons. The small signal gain is proportional to the electronic density and varies as the inverse of the cube of the electron beam energy, depending on the undulator length. The FEL wavelength is tuned by changing the undulator magnetic field in a given spectral range set by the electron beam energy. The polarization depends on the undulator configuration.

The first FEL [6, 7] in the infra-red using the MARK-III linear accelerator (Stanford, USA) in the oscillator configuration occurred twenty years after the laser discovery. The second FEL was then achieved the visible in 1983 on a storage ring [8] (Orsay, France). Very quickly afterwards, the UV and VUV were reached with harmonic generation [9-11]. Oscillators have been limited so far in terms of short wavelengths down to 190 nm [12], on the ELETTRA storage ring FEL with limited gain.

In the seventies and eighties, the theory of high gain FEL was developed [13-15]. It was then considered to start from the spontaneous emission and reach saturation in the high gain regime [16-
19], in the so-called Self Amplified Spontaneous Emission (SASE) regime in the single pass configuration. After the light amplification, the electron energy spread is enlarged, their average energy being reduced so the gain decreases and/or the resonance condition is no longer fulfilled: the FEL saturates. The SASE FEL was then understood as a collective instability [20]. The 3D and time dependent effects considerations led to describe the spectral and temporal properties of SASE, with the distribution consisting of spikes, determined by the cooperation length [21, 22]. Demonstration experiments started at long wavelengths [23, 24]. The significant progresses achieved on high brightness electron gun (and in particular with photo-injector) and on linear accelerators, as required for linear colliders, have permitted the SASE FELs to operate in the UV and X-ray domain where long undulators and high electron beam density (small emittance and short bunches) are used for ensuring a sufficient gain on large scale facilities (with overall length of 100 m-1 km for 1 Å). The spiky distribution associated with jitter and intensity fluctuations being prejudicial for users, different strategies have been applied to limit them, such as low charge operation [25], a combination of electron beam chirp and undulator taper [26]. Besides, suppression of spikes, reduction of intensity fluctuations, jitter and saturation length has been successfully proposed [27] and achieved [28] in seeding the FEL with a laser tuned at the undulator resonant wavelength. Seeding improves the longitudinal properties of the FEL.

2. Short wavelength FEL nowadays

VUV-X FEL linac based light sources have rapidly developed in the world [29]. They provide tunable coherent sub-ps pulses at short wavelengths, with record peak powers (typically GW), peak and average brilliance. FEL user facilities (FLASH1 and 2 [30, 31], FERMI@ELETTA in the seeded configuration [32], LCLS [33] and SACLA [34] in the hard X-ray) enable to harvest new scientific results in unexplored scientific areas. Additional X-ray FEL centers are under construction [35-40] for users, as shown in Table 1. There are also different proposals.

| Location          | Wavelength (nm) | Duration (fs) | E (GeV) | Year            |
|-------------------|-----------------|---------------|---------|-----------------|
| FLASH I           | Germany         | 80-4          | 0.5-1.25 | 2005            |
| FLASH II          | Germany         | 45-4          | 0.37-1.25 | 2014            |
| FERMI- FEL1       | Italy           | 80-20         | 1.25    | lasing 2010     |
| FERMI- FEL II     | Italy           | 140-4         | 1.25    | lasing 2012     |
| LCLS              | USA             | 4.4-0.11      | 15.4    | lasing 2009     |
| SACLA             | Japan           | 0.08-0.25     | 8       | lasing 2011     |
| E-XFEL            | Germany         | 0.05-4.7      | 17.5    | under construction |
| SwissFEL          | Switzerland     | 0.1-1        | 2.5-5.8 | under construction |
| Pohang FEL        | Korea           | 0.06-4.5      | 3.15    | under construction |
| LCLS-II (SLAC)    | USA             | 0.05-6        | 2.4-15  | under construction |
| MaRIE (LANL)      | USA             | 0.02          | 12      | proposal        |
| SXFEL (SINAP)     | China           | 9-4           | 8.84-2  | under construction |
| HXFEL (SINAP)     | China           | 6             |         | proposal        |
| Dalian FEL        | China           | 150-50        | 0.3     | under construction |
| PolFEL            | Poland          | 10            | >0.8    | proposal        |
| MAX IV FEL        | Sweden          | 0.1-10        | 6       | proposal        |
| LUNEX5            | France          | 4-40          | 0.4     | proposal        |
| Turkish FEL       | Turkey          | 1-100         | 0.3     | proposal        |
3. Seeding: towards advanced properties and compactness

Direct seeding at short wavelength can be performed using high order Harmonics generated in Gas [45, 46], as demonstrated on SCSS Test Accelerator at 160 nm [47] and at 60 nm [48], at SPARC with cascading demonstration [49] and at 30 nm at s-FLASH [50]. The limit in short wavelength source seeding arises when the seed level cannot anymore overcome the shot noise [51]. Seeding enables also to more efficiently produce the nonlinear harmonics [52, 53]. Besides theoretical work [54], frequency up-conversion can be achieved thanks to different schemes: High Gain Harmonic Generation scheme (HGHG) [55] (a first laser tuned on a first undulator induces a density modulation in the electron bunch, leading to radiation produced in the second undulator tuned on a harmonic of the first undulator resonant wavelength), harmonic cascade (the wavelength ratio of the two stages is a ratio of integers) [56], the fresh bunch technique [57] (the FEL radiates with electron non heated by the first interaction). A factor 192 could be achieved [58]. Seeding also gives control over the FEL process and enables to handle its longitudinal properties in getting closer to the Fourier limit. Depending on the seed characteristics with respect to that of the electron bunch, different regimes such as super radiance [59], pulse splitting [60, 61] can be observed.

In the SASE case, self-seeding has been proposed, using the FEL produced in first undulator segments spectrally cleaned in a monochromator as a seed for amplification in the second part of undulator segments [62]. The use of a crystal monochromator makes the concept easily applicable [63] and led to demonstrations in the hard [64, 65] and soft [66] X-ray regions. Self-seeding enables a control of the FEL properties.

The Echo Enabled Harmonic Generation [67] (EEHG), benefiting of two successive laser electron interactions (or even three [68]) without equivalent in optics, enables efficient up-frequency conversion by imprinting a “sheet-like structure” in phase space [69-71].

4. Towards advanced properties

The two-color FEL concept, earlier by implemented in the infra-red [72-73], can be applied to the X-ray domain in the SASE regime, either tuning the two series of undulators at different wavelengths [74-76], the delay being adjusted by a chicane, or by using twin bunches at different energies [77], enabling also operation in the self-seeded case. In the external seeding case, one can take advantage of the pulse splitting effect [78] combined with chirp [79], or apply a double seeding [80, 81].

In the quest towards in attosecond pulses and high peak power, several strategies are proposed: emittance spoiler [82], energy chirped electron beams used as a seed for a second stage [83] or with optical post-compression [84], selective amplification [85-87], electron energy modulation in a small part of the electron bunch with a few cycle laser [88-90], combination of the slotted foil with eSASE [91], generation of a few cycle XFEL [92], multiple slotted foil combined to small delay between the undulators segments [93] enabling reaching TW level in a super-radiant mode [94] with tapering [95].

The Enhanced SASE [96] concept (a first laser imprints a modulation in an undulator before being further accelerated in the next sections) enables also to reach high peak powers. The partial FEL coherence can be taken into account in the pulse duration measurement thanks to an analysis based on the Wigner distributions [97]. In parallel to the quest of ultra-short pulses, very narrow spectral bandwidth (0.0001 %) can also be achieved on X FEL oscillators [98] on energy recovery linacs [99].

FEL also evolves toward high repetition rates, thanks to superconducting linear accelerator, with E XFEL and LCLS II aiming at a CW operation. Multi-user operation and associated operating cost reduction is achieved by a simultaneous operation of different FEL branches by kicking the electron bunches, as presently achieved on FLASH. Multiplexing on different FEL lines can also occur at different electron beam energies, enabling to widen the spectral ranges of the different FELs [100].
5. Towards compact FEL

Another evolution trend is the search for compactness. Besides seeding and up-frequency conversion, one considers implementing the FEL using a compact accelerator or undulator.

In a Laser Wakefield Accelerator (LWFA) [101], an intense laser pulse drives plasma density wakes to produce, by charge separation, strong longitudinal electric fields, with accelerating gradient than can reach a hundred of GV/m [102]. Electrons have to be set at a proper phase with respect to the wake, to be efficiently accelerated. Besides the usual bubble configuration [103], various schemes have been tested to achieve the most suitable performance in terms of electron beam properties: colliding scheme [104], optical transverse injection [105], shock front injection [106], ionization injection [107], plasma channel [108], frequency chirp [109].... LWFA can nowadays produce electron beams in the few hundreds of MeV to 1 GeV range [110-114] with a typical current of a few kA [115] with reasonable beam characteristics (relative energy spread of the order of 1% [116], normalized emittance of ~ 1π.mm.mrad [117-119]. Repetition rate is still limited.

This new accelerating concept could thus be qualified by a FEL application [120, 121]. LWFA based undulator radiation has been observed, even at short wavelengths [122-125]. But achieving FEL amplification remains to be demonstrated: the difficulty comes from the intrinsic properties of the electron beam. Indeed, for an energy of a few hundreds of MeV, while linac beams exhibit typically 1 mm transverse size, 1 µrad divergence with 1 mm longitudinal size and 0.01% energy spread, plasma beams more likely provide 1 µm transverse size, 1 mrad divergence with 1 µm longitudinal size and 1% energy spread. An adequate beam manipulation through the transport to the undulator is needed for FEL amplification. The beam divergence requires a strong focusing with adapted quadrupoles close to the electron source [126-127] and / or with a plasma lens [128]. For the energy spread handling, a first approach consists in passing the electron beam through a demixing chicane, which sorts them in energy and reduces typically the slice energy spread by a factor of 10 [129-131]. Taking advantage of the introduced correlation between the energy and the position, the slices can be focused in synchronization with the optical wave advance, in the so-called supermatching scheme [132].

A second approach to handle the large energy spread of LWFA consists in using a Transverse Gradient Undulator (TGU) [133-137] with canted magnetic poles, that generates a linear transverse dependence of the vertical undulator field in the form of $K(x)=K_0(1+\alpha x)$ with $\alpha$ the gradient coefficient. Associated to an optic with dispersion introducing a transverse displacement $x$ with the energy according to $x = \eta \Delta \gamma / \gamma$, the resonant condition can be fulfilled provided $\eta = (2 + K_0 ^2) / \alpha K_0 ^2$. Taking into account the energy dependence, the gain length can then be re-expressed. This technique greatly reduces the sensitivity of the FEL gain length dependence on the energy spread.

Different test experiments are under preparation (see Table 2). The F. Shiller Univ., Jena/KIT collaboration [138-140] uses the JETI-40 laser system focused in a 3 mm gas cell filled with 95% Helium and 5% Nitrogen, an achromatic transport line [139] (first quadrupole triplet, an achromat with four quadrupoles surrounded by two dipoles for a dogleg, and a second triplet of quadrupoles for matching in the undulator). The undulator is a superconducting TGU consisting of two cylindrically shaped halves with NbTi coils [141-143]. A first beam transport has been experimentally tested and showed that it is doable. However, it led to larger values of the electron beam divergence and energy spread than expected, while alignment is very critical [144]. In France the LUNEX5 [145] advanced and compact FEL demonstrator project combines a superconducting linac, a LWFA and a single undulator line with advanced seed schemes (HHG seeding, echo) for the production of short, intense, and coherent pulses in the soft X-ray region (4-40 nm) and pilot user experiments to characterize and evaluate performance of these sources from a users’ perspective. The Laser Wakefield Accelerator will be assessed, in view of FEL applications. In this context, a test experiment is under preparation [146, 147], under the demixing chicane combined to supermatching, with a first target wavelength of 200 nm. The equipment including 200 T/m permanent magnet quadrupoles of variable strength, in-vacuum undulators of period 20 mm and 15 mm with cryo-ready operation are under preparation [148, 149], diagnostics [150] and will be transported to Salle Jaune of Laboratoire d’Optique Appliquée, where a 2x60 TW laser will be used to produce the electrons. HHG seeding will be applied. In
Strathclyde Univ., the application is considered [151] using electron produced in a plasma channel, and two sets of focusing quadrupoles (permanent magnet and electromagnet types). Electron beam has been measured after the transport and after an undulator with integrated focusing [125]. A large energy spread (15%) was deduced from the spectra measurements. Experiments are also planned at LOASIS [152-154] with a decompression chicane, HHG seeding and the THUNDER undulator. At CFEL (DESY / MPG / Univ. Hamburg) is considered to use a demixing chicane [155]. There are also experiments under preparation in Shanghai at SIOM (with a 200 TW laser). In the frame of the ImpACT collaboration in Japan, efforts are conducted to reduce the emittance and the energy spread, together with the pointing stability, studies on a 4mm period 0.4 T peak field undulator are carried out. Other compact acceleration concepts are attractive for FEL applications, such as dielectric accelerators [156-158] or Inverse Free Electron Lasers [159-161]. There are also important progresses in compact undulators [162].

Table 2. Parameters of some proposed LWFA based FEL test experiments.

| Laser source | Laser energy (TW) | Electron energy (MeV) | Electron energy spread (%) | Charge (pC) | Electron parameters transverse/longitudinal | Undulator (type, number of periods X period length, peak field) | FEL (nm) |
|-------------|-------------------|-----------------------|-----------------------------|------------|---------------------------------------------|-----------------------------------------------------------------|----------|
| COXINEL SOLEIL/SOLEIL/LOA/LOA (France) | 180-400 | 1 | 34 | In-vacuum, 200 x2 cm periods, 1 T | Cryo-ready: 300 x1.5 cm, 1.6 T | 200-40 |
| | 2 x 60 | 120 | 10 | 10 | Transverse size:1 µm, 1 µrad, 4 µm, 2.5 mrad, 2.5 mrad, 2.5 fs, 4 µm, 2.5 mrad, 2.5 | Superconducting TGU, 100 x1.55 cm, 1.74 T at 1.1 mm gap, 149T/m | 10 |
| | Jena/KTH (Germany) | 40 |  | | Chicane, supermatching | | |
| | LUX /CFEL (Germany) | 200 | 0.1 | 50 | 1 mrad | 1 mrad, 1 mrad, 3 fs | 241 |
| | Strathclyde (Great Britain) | 100 | 0.1 | 50 | Chicane | Two sets of quadrupoles | |
| | Berkeley (USA) | 20 TW | 500 | 0.25 | 100 | 120 fs | 241 |
| | | BELLA, slice | | | | | |

6. Conclusion

The emergence of high power tunable X-ray FELs with femtosecond pulse duration constitutes a major scientific revolution, after the one brought by the laser invention. They enable to reveal new feature of matter and its evolution in time. New directions for providing further flexibility, enhanced performance and compactness are taken by source developers.

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