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Panorama of new generation of accelerator based short wavelength coherent light sources

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ABSTRACT

The newly developed intense short wavelength light sources (from Extreme Ultra-Violet (EUV) to X-rays) have open the path to the exploration of matter for revealing structures and electronic processes and for following their evolution in time. After drawing the panorama of existing accelerator based short wavelength light sources, the new trends of evolution of short wavelengths FEL are described, with some illustrations with the example of the LUNEX5 (free electron Laser a New accelerator for the Exploitation of X-ray radiation of 5th generation) demonstrator project of advanced compact Free Electron Laser.

1. Introduction

More than 50 years after the lasers discovery [1,2], the panorama of short pulse short wavelength light sources is rapidly developing.

1.1. Laboratory scale short wavelength sources

There are presently various sources available for the VUV-X-ray user community.

Laboratory-scale coherent VUV-soft X-ray sources can rely on High order Harmonic Generation in Gas (HHG) [3,4] where an intense laser beam is focused in a rare gas, which induces electron tunnel ionization, acceleration and diffusion in the atomic potential, and recombination in emitting harmonics. The cut-off energy is determined by the ionization potential of the atoms and by the ponderomotive energy scaling as the square of the laser wavelength and decreasing for longer pulse durations. HHG can be rather intense, especially with phase matching [5,6] or with harmonics of the laser field [7–10]. They are polarised usually linearly but in some cases elliptically [11–13]. They present a good transverse coherence [14]. The pulse duration can be extremely short, in the attosecond range in a femtosecond envelop [15,16]. The attosecond pulses can even be confined to one single burst [17–19]. The repetition rate is usually the one of the drive laser, ranging from a few Hz to kHz [20] and even MHz range with intra-cavity HHG [21] or fibre laser driven systems [22]. The spectral range covered by the HHG has been extended progressively towards the short wavelengths (with in particular the water window) [23–25]. Using mid infra-red driving lasers and shorter pulse drivers [26,27] enables to reach the keV region, to deliver very short pulses with a wide tuneability. Otherwise, the HHG tuneability results from that of the drive laser. High order harmonic generation can also be generated with solid targets [28] where an intense laser pulse interacts with a near discontinuous plasma-vacuum boundary, the electrons oscillate and lead to a modulation of the reflected light, which becomes no longer sinusoidal and emit a high order harmonics content. Radiation up to 3.3 Å (3.8 keV) on the 3200th harmonics has been efficiently produced [29,30]. X-ray lasers, relying on the population inversion by electron ion collision in hot highly ionised plasma operate generally in the Amplification of Spontaneous Emission (ASE) mode [31–36]. They offer step by step tuneability, 100 ps pulse duration [37–38]. Performance can be improved with seeding, such as reduced divergence and larger intensity with HHG [39,40], and a 1.46 nm inner-shell X-ray laser [41] while seeding with the Free Electron Laser.

1.2. Accelerator based short wavelength sources

Synchrotron radiation has been predicted [42–47] and observed in 1947 in the visible [47]. Accelerator based light sources [49–58] are commonly used around the world. The radiation from a relativistic particle in the magnetic sinusoidal field [48,49] has also been analysed [59] and observed [60]. Synchrotron radiation is emitted by the relativistic charged particles in bending magnets and undulators, composed of series of alternated magnetic poles and creating a periodic permanent magnetic field (amplitude B_o, period λ_o). In the case of a planar undulator creating a sinusoidal

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field in the vertical plane, on axis synchrotron radiation is emitted at the wavelength λ, so-called resonance wavelength, and its odd harmonics of order n: $\lambda = \lambda_o\ (1 + K^2/2 + \gamma^2\theta^2)/\ 2n\gamma^2$ with K the deflexion parameter, $K = 0.934\ \lambda_o(\text{cm})\ B_o(\text{T})$, θ the observation angle and γ the relativistic factor of the electrons. λ can be tuned by a modification of the undulator magnetic field (by changing the gap for permanent magnet insertion devices or the power supply current for electromagnetic insertion devices). The choice of the undulator characteristics and technology enables to optimise the desired spectral range. In the case of a vertical magnetic field (planar undulator), the electron follows a sinusoidal trajectory in the horizontal plane, leading to a horizontal polarisation. Variable polarisation can be achieved with vertical magnetic field combined to a dephased horizontal one. The undulator radiation is highly collimated. In the "undulator" regime (rather small K value), the radiation emitted at each inversion interferes constructively with the one produced in the previous inversions. The radiation presents a series of harmonics, which width depends on the observation angle, the energy spread and the emittance (product of the electron beam size and divergence). In the "wiggler" regime (large K), the radiation of the different harmonics overlaps and is similar to the dipole one, with a higher intensity.

The so-called first generation accelerator based light sources in the eighties took advantage of the parasitic synchrotron radiation emitted in the storage rings built for high energy physics.

In the mid-eighties, storage rings with moderate values of the emittance and several straight sections for undulators were developed as so-called second generation light sources dedicated to synchrotron radiation use.

In third generation light sources, the emittance is further reduced, enabling partial transverse coherence of the radiation, and several straight sections permit to install a high number of undulators and wigglers for providing a high average brilliance to the users. A spectral selection takes place with a monochromator. Synchrotron radiation is emitted in series of pulses of typically dozens of picoseconds, because of the bunch lengthening due to the interaction with the emitted microwave field [61]. To the detriment of the intensity, the duration of the radiated pulse can be however reduced with specific electron optics (low momentum compaction factor) [62,63], or with the slicing scheme via the interaction of a femtosecond laser with the electron bunches in an undulator [64,65]. Spatial coherence is achieved for wavelengths of the order of the emittance, so typically for the long wavelength part of the spectrum. The quest of full transverse coherence implies a reduction of the emittance [66], as for example, PETRA III (6 GeV, 1 nm.rad) [67], NSLS-II (3 GeV, 0.5 nm.rad) [68], MAX-IV (3 GeV, 0.24 nm.rad) [69], ESRF (6 GeV, 0.15 and 0.01 nm.rad) [70]. Longitudinal coherence (light intensity scaling as the square of the number of electrons) is achieved when the electron bunch is shorter than the considered wavelength, typically in the THz spectral region on current storage rings [80] or if a micro-bunching of the electron takes place. Synchrotron radiation from storage rings provides worldwide in a robust way picosecond duration pulses from the infra-red to the X-ray.

In order to reach a high level of longitudinal coherence, the electrons have to be set in phase, as done in a Free Electron Laser (FEL) process [71]. In a FEL, a light wave of wavelength (spontaneous emission progressing along the undulator or stored in an optical cavity, or external seed) interacts with the electron bunch in the undulator, inducing an energy modulation of the electrons; which is gradually transformed into density modulation at the wavelength and leads to a coherent radiation emission. The light can then be amplified 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. While the light gets amplified, the electron energy spread gets larger, the electron average energy gets smaller so the gain decreases and/or the resonance condition is no longer fulfilled: the FEL saturates [72]. The light travels slightly faster than the electrons (it slips over one wavelength for one undulator period (slippage)); and the undulator is limited to such a length that the light cannot escape from the electron bunch. The laser tuneability, one of the major advantages of FEL sources, is obtained by merely modifying the magnetic field of the undulator in a given spectral range set by the electron beam energy, which can be as well modified. The polarization depends on the undulator configuration. The so-called Fourth Generation Light Sources generally use linear accelerators for short pulse duration and provide longitudinal coherence thanks to the FEL process. Synchrotron radiation from energy recovery linacs (ERL) is also referred as fourth generation light source [73], since sub-picosecond pulses can also be provided. Free Electron Laser has been invented more than 40 years ago and first achieved more than 30 years ago [74] in the intra-red. The recent emergence of tuneable X-ray FEL (LCLS [75], SACLA [76], FLASH [75], FERMI [76]) sets a revolution for the scientific community and now offers the possibility to explore unknown areas of science (ultrafast phenomena [79], photoionization [80,81], imaging of cells [82,83], ultrafast demagnetization [84]...) with these unique tunable intense X-ray lasers.

The figure of merit commonly used for accelerator based light sources is the brilliance. It is defined in the general case in the frame of the Wigner distribution [85,86], inherently incorporating the complete information on the electric field. It then simply relates to the mutual coherence of the source. Practically, it can be approximated in the case of Gaussian beams and geometrical optics frame to the number of photons per 6D phase space $\Delta x\ \Delta x'\ \Delta z\ \Delta z'\ \Delta t\ \Delta w/w$ with x the horizontal position, z the vertical position, t the time, and w the pulsation. A X-ray Free Electron Laser provides a peak brilliance larger by several orders of magnitude than the usual synchrotron radiation one.

Besides, an advantage can be taken in the combination of lasers and electron beam thanks to the Compton back scattering sources [e.g. 87–95] enabling to produce compact X and gamma sources.

2. Free Electron Laser set-ups and schemes

FELs can be implemented on different types of accelerators. Storage rings provide rather long electron bunches (10–30 ps) because of the electron beam recirculation and the emittance scales as the square of the electron beam energy. Linear accelerators, single pass machines, provide quite short bunch 10 fs–10 ps duration, of interest for ultra-short pulse source production and for high electron beam densities, emittance also scales as the inverse of the energy, enabling to reach diffraction limit sources for high electron beam energies required for short wavelength operation. Energy Recovery Linac combines both advantages of the two previous accelerator types, with short pulses, few turn recirculation and energy recovery for power consumption saving, but they are less mature accelerators. Various configurations are used (see Fig. 1).

In the oscillator case, the historical configuration, the spontaneous emission is stored in an optical cavity, enabling multiple interactions between the electron beam and the light wave. The FEL was first experimentally demonstrated in 1977 in Stanford (USA) in the infra-red using the MARK-III linear accelerator [74] in the oscillator configuration on a superconducting linear accelerator. The second worldwide FEL was then achieved the visible in 1983 on a storage ring [96] in Orsay (France). It was followed by a wide development on storage rings [97–105] and on linacs [106–109]. Linewidth narrowing was achieved with a Fabry–Perot etalon [110]. Various dynamical studies were performed

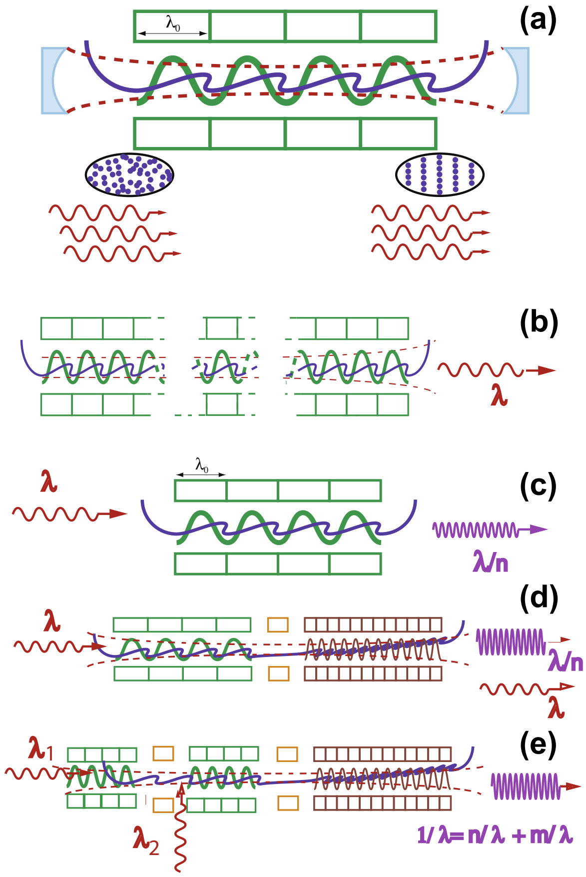

Fig. 1. Free Electron Laser configurations: (a) oscillator case with an optical cavity enabling to store the spontaneous emission (the stored spontaneous emission in the resonator is amplified), (b) Self Amplified Spontaneous Emission (SASE) where the spontaneous emission emitted in the beginning of the undulator is amplified in one single pass, (c) seeding where a coherent source (laser, coherent harmonics generated in gas) tuned on the resonant wavelength of the undulator enables to perform efficiently the energy exchange, (d) High Gain Harmonic Generation and (e) Echo Enable Harmonic Generation (EEHG) with two laser-electron beam interaction where a second energy modulation is printed on the first one, enabling for efficient up-frequency conversion.

[111–119]. The oscillator shortest wavelength (193 nm) has been obtained on the ELETRA FEL [104,120] since mirror degradation due to undulator synchrotron radiation appeared to be critical [121–123]. Transverse modes can be controlled via the optical resonator [124]. The Super-ACO FEL was first employed for users in the UV [125] and in association with synchrotron radiation for pump–probe two-colour experiments [126,127]. Gamma-rays generated by Compton Back scattering [90–92] have been extensively used at the DUKE FEL [91]. Industrial applications of kW UV FELs have been developed at Jefferson Lab [128].

In the harmonic generation configuration [129–133], an external laser tuned on the undulator resonant wavelength sent in the undulator allows for an efficient energy exchange. It was achieved in the early FEL times rapidly in the UV and VUV [134–136] and then developed further [137–140].

When targeting at short wavelengths, mirrors are becoming no longer available. A single pass configuration for the optical wave is adopted, with the Self-Amplified Spontaneous Emission (SASE) setup [141–145]: in the high gain regime, the spontaneous emission is progressively amplified, typically up to saturation in a single pass after an of exponential growth of the intensity. Once the saturation is reached, the amplification process is replaced by a cyclic energy exchange between the electrons and the radiated field [146,147]. High electron beam energies should be employed for filling the resonant condition. In consequence, in order to get a high gain, the electronic density should be high, such as for future colliders, and long undulators have to be used. The FEL size is getting larger, of the km order for the X-ray range. SASE FELs implemented on up-to-date linear accelerators are now blooming in the world. They provide tuneable coherent sub-ps pulses at short wavelengths, with record peak powers (typically GW), peak and average brilliance. In the VUV/X-ray region, following the first results on LEULT (Argonne, USA) [148], FLASH I [77] and II (Germany, 30–4.5 nm) [149] operate simultaneously for users, SCSS Test Accelerator (Japan, 40–60 nm) [150] is presently upgraded and moved. In the Angstrom (Å) region, Linear Coherent Light Source (LCLS, Stanford, USA, 1–10 keV, several mJ) [75,151] is the first tuneable fs X-ray FEL to operate for users since 2009. It uses one part of the existing SLAC room temperature linac at 14 GeV. LCLS II is under construction, with a superconducting linac and flexible polarization [152]. SACLA (5–20 keV), the second worldwide X-ray FEL extending the radiation down to 0.06 nm, operates since 2011 [76] (Japan, 8 GeV). In order to fulfil the growing user demand, new FEL facilities are under construction and will soon be available for users, such as European XFEL (0.05–4.7 nm) [153] on a high repetition rate superconducting linear accelerator, the Korean XFEL (0.06–4.5 nm) [154] and the SwissFEL (0.1–7 nm) [155] in the X-ray, and Dalian (150–50 nm) [156] and SXFEL (9–4 nm) [157] in the VUV and soft X-ray region. There are additional projects under study: MaRIE [158], PolFEL [159], MAX IV FEL [160], Turkish FEL [161], LUNEX5 [162]. The peak power in the X-ray can reached GW levels, with pulses of few femtoseconds. SASE FEL presents generally a good transverse coherence [163] and wavefront [164]. Nevertheless, the SASE emission is usually characterized by poor longitudinal coherence properties, with a temporally and spectrally spiky emission, which results from non-correlated trains of pulses [165].

In the high gain context, one can also inject a spectrally tuned laser in the undulator for the modulation to be more efficient, in the so-called seeding configuration. Besides getting more quickly the saturation, seeding also enables to suppress the spikes, to improve the longitudinal coherence and to reduce the intensity fluctuations and jitter [166,167]. Such a configuration is suitable for pump–probe two-colour user applications. The only seeded FEL users facility is FERMI@ELLETRA (Trieste, Italy) [78], using a conventional laser as a seed. The radiation is also adjustable in polarization since APPLE-II type undulators are used.

Paths towards advanced and compact FELs are open in two directions: the first one aims at providing more flexible properties, the second one at reducing the size and the operating cost of the facilities. Some of the examples will be illustrated in the case of the LUNEX5 (free electron Laser Using a New accelerator for the Exploitation of X-ray radiation of 5th generation) demonstrator of advanced and compact FEL [162] (see Fig. 2). LUNEX5 aims at investigating the production of short, intense, and coherent pulses in the soft X-ray region (4–40 nm from the first to the fifth harmonic) with 20 fs pulses. A 400 MeV L-band superconducting linac will enable a cw operation for high repetition rate (10 kHz targeted) and multiple users for a reduced operating cost. The 0.4–1 GeV Laser Wakefield Accelerator will be assessed, in view of FEL applications. The single FEL line will be composed of the most advanced seeding configurations and cryogenic undulators and will be ended by pilot user experiments to characterize and evaluate performance of these sources from a users' perspective for time resolved pump–probe studies of isolated species and for condensed matter imaging exploiting the coherence. On the fundamental wavelength, the FEL radiation ranges between 15 and 40 nm, with a peak power between 10 and 100 MW. With the superconducting linear accelerator, there are more than 10^{11}

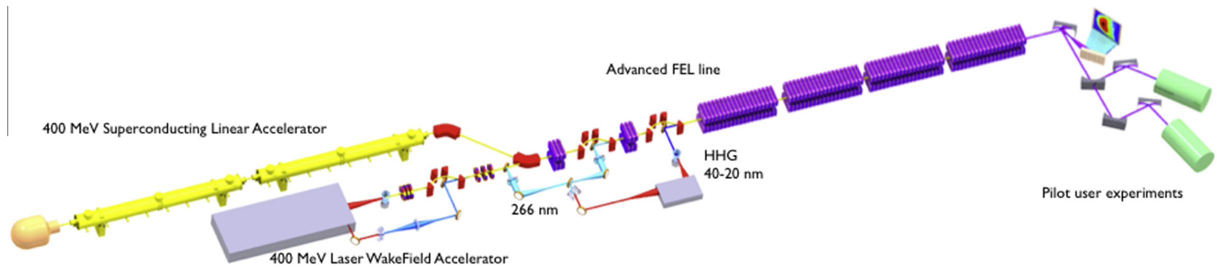

Fig. 2. LUNEX5 sketch with electron gun and two cryomodules (yellow), and phase space linearization dogleg for compression of the electron beam issued from the superconducting linac laser hutch for LWFA (grey) and electron beam manipulation transport line (strong focusing, chicane decompression, supermatching focusing), undulators (four radiators and two ECHO modulators) (purple), pilot user experimental sections (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

photons/pulse and 10^{27} peak brightness on the fundamental wavelength.

3. Developments towards advanced Free Electron Lasers

The aim is to approach diffraction and Fourier limits in a wide spectral range and more versatile properties, in order to adjust the performance to the experiment under way.

3.1. Seeding

Concerning the temporal properties, seeding enables somehow to manipulate the FEL properties. The temporal and spectral distributions of the pulse result from the seed and the FEL intrinsic dynamics. There are several seeding configurations: the High Gain Harmonic Generation scheme (HGHG) [167] where a first laser tuned on the first undulator induces a density modulation in the electron bunch, and the radiation is produced in the second undulator, which is tuned on the harmonic of the injected wavelength, the harmonic cascade configuration, where the wavelength ratio of the two stages is a ratio of integers [168]. The combination of HGHG, fresh bunch technique, and harmonic cascade has recently enabled an up-frequency conversion by a factor of 192 [169]. In particular cases, super-radiant modes exhibit further pulse shortening and intensity increase [170,171].

The seed can be an external laser wave or a short-wavelength coherent light source, such as High order Harmonics generated in Gas (HHG), as first performed on SCSS Test Accelerator at 160 nm [172] and at 60 nm [173], at SPARC with cascading demonstration [174] and at 30 nm at s-FLASH [175]. The limit in terms of spectral range arises when the seed level cannot anymore overcome the shot-noise [176,177]. Higher order harmonics of the FEL are more efficiently produced in the seeded configuration [178].

There are alternative solutions to handle to the spiky spectral and temporal structure of the SASE, such as an operation with low-charge short electron bunches [179,180], an electron beam energy chirp combined with an undulator taper [181]. Proper combinations of chicanes and undulator segments can enable to phase lock the radiation [182]. Seeding with the FEL itself is also an alternative [183] and can be efficient using a single crystal monochromator [184], as experimentally demonstrated at LCLS [185] and at SACLA [186] in the Å region and also in the soft X-ray region [187].

3.2. Towards short pulse duration or small bandwidth

Different schemes have been proposed and/or tested for achieving extremely short pulses [188–199] with a selective amplification, modulation, phase locking of the radiation from different segments, superradiance [200]. The partial FEL coherence can be taken into account in the pulse duration measurement [201]. In parallel to the quest of ultra-short pulses, very narrow spectral bandwidth could also be achieved with X FEL Oscillator [202].

3.3. Efficient up-frequency conversion

Efficient up-frequency conversion can also be achieved with two successive electron-laser interactions in two undulators, in the Echo Enabled Harmonic Generation (EEHG) scheme (so-called "echo"), by imprinting a "sheet-like structure" in phase space [203]. It has been experimentally demonstrated first up to harmonic 7 [204], and then 15 [205] on the Next Linear Collider Test Accelerator and on the Shanghai FEL Test Facility [206]. Various schemes derived from EEHG, such as the Triple Modulator Chicane [207], open perspectives for very short wavelength (Å) and short duration at moderate costs. The echo concept can also be applied to storage bring based light sources [208]. Fig. 3 and Table 1 illustrate the compared up-frequency conversion schemes considered in the case of the LUNEX5 project [209,210] using the superconducting linear accelerator. Two types of seeding for the FEL will be available: seeding by High order Harmonics in Gas (HHG) and seeding using the echo scheme. For the seeding source, a Ti-Sa oscillator (30 fs @ 800 nm), followed by a regenerative and a multipass amplifier will be split into two parts, one for tripling (266 nm) split into two branches for the echo, and injected directly in the HHG cell. The undulator line will be composed of different cryo-ready undulator segments, with 30 mm period for the modulators and 15 mm period for the radiators. There are four segments of 5 meters long radiators. Vanadium-Permendur poles and $Pr_2Fe_{14}B$ magnets are used. The on-axis magnetic field peak value is of 1.61 T at minimum gap of 3 mm at room temperature (remanence of 1.32 T, coercitivity of 1900 kA/m). At 77 K, the field reaches 1.77 T at minimum gap (remanence of 1.57 T). It appears that the amplifier configuration is not efficient, and that the echo configuration can efficiently compete the HHG seeded cascade scheme, since the saturation length is shorter.

3.4. Two-colour operation

Two-colour FEL operation was first achieved in the infra-red on the CLIO oscillator [211,212] by setting two undulators at two different gaps, i.e. two different deflection parameters. If there is sufficient margin in gain, lasing can then be achieved on two different wavelengths. The concept can also be applied to single pass FELs, by tuning the two series of undulators at different wavelengths and taking advantage of the chicane set for the self seeding for adjusting the delay between the two series of undulators providing the two different wavelengths. Again, sufficient gain is required for each series of undulator for achieving sufficient FEL power [213–215]. The concept can be derived in combination with

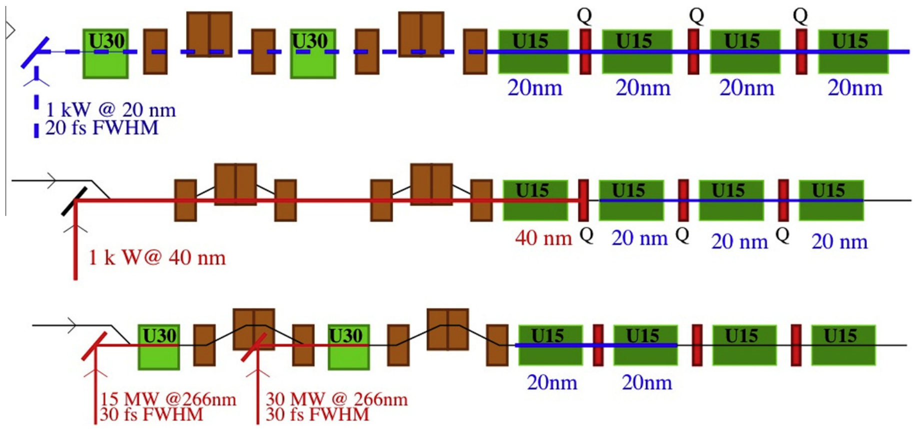

Fig. 3. Comparison of the up-frequency conversion schemes in the case of LUNEX5 FEL driven by the superconducting linear accelerator. Parameters: 400 MeV, 0.02% energy spread, 1.5 π mm mrad, 400 A, 1 ps rms, undulator U15 with 1.6 T maximum field. First: Amplifier, Second: Cascade, Third: echo enable harmonic generation.

Table 1
Comparison of the different schemes in the case of the LUNEX5 FEL at 20 nm driven by the superconducting linac. Parameters of Fig. 3.

Scheme	Saturation length (m)	Peak power (W)	Pulse duration (fs)
Amplifier	11	50	30
Cascade	11	270	25
Echo	7	65	24

self-seeding [216]. Another way is to send two successive electron bunches which can be generated at the photo-injector by pulse staking of the laser. Being delayed, the twin bunches acquire slightly different electron beam energies, and can induce then a two colour FEL [217].

In the seeding case, one can first apply a double seeding [218], as experimentally shown at FERMI [219]. One can also take advantage of the pulse splitting, which can occur for particular seed pulse duration with respect to the electron bunch length [220], as shown on FERMI@ELETTRA with a chirped seed [221]. The pulse splitting had first been evidenced while doing FEL simulations for ARC-EN-CIEL [222]. Fig. 4 shows that different dynamical regimes can be observed. In the modulator, strong radiation is emitted on the fundamental whereas the signal on the harmonics is very noisy. The energy exchange with the seed takes place and is converted in density modulation in the dispersive section. In the radiator, the radiation is slightly shifted because of the slippage (the light travels faster than the electrons). The radiation is growing exponentially while progressing along the radiator until reaching a kind of bifurcation, where the FEL radiation splits into two branches. The electrons in the middle have been too much heated (their energy spread is locally enhanced due to the interaction) and the FEL continues developing in cooler zones of the electronic longitudinal distribution. Emission is more intense in the propagation direction, leading to a dissymmetry. The pulse duration in the branches is sharper than in the main part. The splitting phenomenon occurs earlier on the harmonics.

3.5. High peak power

The FEL efficiency is usually optimised in introducing undulator tapering, i.e. magnetic field change along the longitudinal coordinate enabling to compensate the energy loss due to the emission

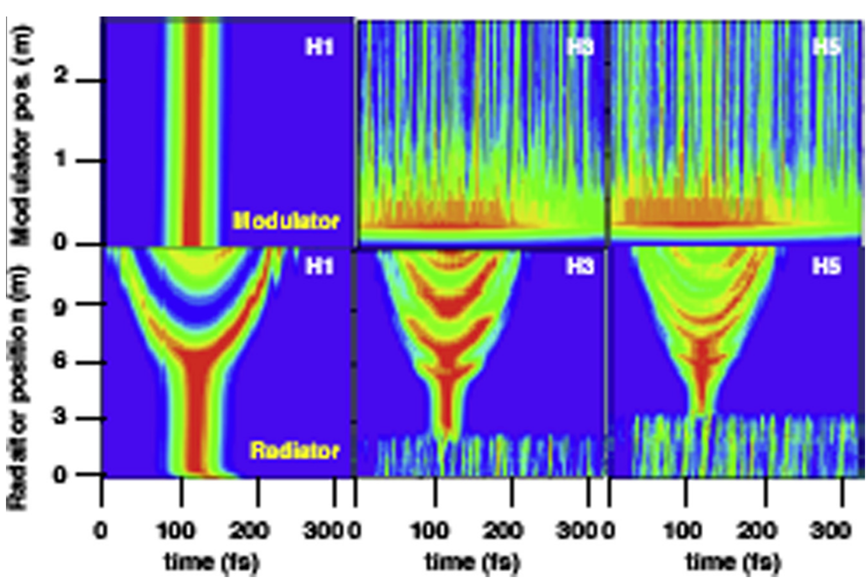

Fig. 4. Evolution of the longitudinal FEL distribution on the fundamental (left), on the third harmonic (middle), on the fifth harmonic (right) in the ARC-EN-CIEL seeded FEL case. Upper frame: modulator, lower frame: radiator. Parameters: Seed at 12.3 nm, 50 kW, with 50 fs. Electron beam : 1 GeV, 1.2 π mm mrad, 1.5 kA, initial energy 0.04%, longueur de paquet de 0.06 mm ou 200 fs rms. Modulator : period 26 mm, 100 period, K1 = 2.3. Dispersive section with R56 = 1.5 μm. Radiator of period 30 mm in the planar mode, 400 periods, K2 = 2.08. FEL simulations performed with PERSEO [223].

of radiation and to maintain the resonant condition fulfilled [224,225]. Besides, on can try to set the radiation emitted in a non heated part of the electron and to be in condition for superradiance [200]. The enhanced SASE [226] 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 towards the TW level.

3.6. Multi-user FEL

Multi-user FEL can be achieved in dispatching the electron bunches to different FEL lines [227,209] thanks to fast kickers. A scheme is shown in Fig. 5 in the case of LUNEX5. This appears to be quite appropriate with superconducting linear accelerators, as coming soon with E XFEL and LCLS II. In addition, with a proper setting of the phase of the accelerating sections, bunches with various beam energies can be kicked to different FEL lines, thereby allowing a wider spectral range [228].

3.7. High repetition rate sources

High repetition rate FEL, of interest for coincidence experiment, for imaging, for photo-emission for example, can naturally be provided by superconducting linac. One can also consider using XFEL oscillators [229] on ERLs. Very narrow bandwidth is then also produced.

4. Developments towards compact Free Electron Lasers

The other trend of exploration towards future FEL is to get smaller systems at reduced cost. There are thus particular efforts to improve the existing technologies (for instance C and X band accelerating sections), to make high field from permanent magnet undulators. In addition, it is also considered to replace some of the components by another technology.

4.1. Towards length reduction of the FEL line

A first direction is to make the FEL generation more efficient and to reduce the length of the radiation part, in using advanced schemes of seeding and echo.

Then, efforts can be devoted to the undulator for it to provide a sufficiently high field for a short period. In-vacuum undulators [230–232] enable to reach high fields by placing directly the magnets inside the vacuum chamber. By cooling down $Nd_2Fe_{14}B$ permanent magnets, the remanent magnetic field is increased by 10% and the coercivity by a factor of 3 [233–236]. $Nd_2Fe_{14}B$ based cryogenic undulators [237] operate around 130–140 K because of the Spin Reorientation Transition occurring at lower temperatures. $Pr_2Fe_{14}B$ based cryogenic undulators [238] can be directly cooled and operated at 77 K. An intense R&D is under way on superconducting undulators, which can potentially lead to high magnetic fields [239–242]. Variable polarisation, currently produced with Elliptical Polarised Undulators (EPU) of APPLE II type [243–245], which do not enable full flexibility in-vacuum, suits now the use of the DELTA undulator [246].

Besides, new technologies are also explored, such as microstructure driven laser undulator [247], surface micro-machined undulator [248], micro-machined magnet undulator [249–252], RF undulator [253] and optical undulator [254]. Fig. 6 compares the peak magnetic field achieved versus the period.

4.2. Towards length reduction of the accelerator component

Compact alternative accelerating concepts such as Laser Wakefield Accelerators (LWFA) [255], Dielectric Accelerators [256] and Inverse Free Electron Lasers [257,258] are recently emerging. Though quite challenging, one can consider using them instead of the linear accelerator, in the prospect of compact FELs [259–261].

In LWFAs [262], high-intensity laser pulses are focused in dense plasma from a gas jet, gas cell or capillary discharge targets, and an ultrahigh longitudinal electric gradient is created. This ponderomotive force pushes the plasma electrons out of the laser beam path, separating them from the ions. A travelling longitudinal electric field, whose amplitude can reach several hundred GV/m is created, typically 10,000 times larger than conventional accelerators, the characteristic length scale of the wakefield, the plasma wavelength, being of 10–30 μm. In the so-called "bubble regime" [263–266], electron beams in the 100 MeV–4 GeV range can be produced over mm distances, with energy spreads on the order of 5–10% and charge of 10–100 pC. One foresees multi-GeV electron beams with nC and few % energy spread charges in the future. Two-stage laser plasma accelerators have recently delivered GeV electron bunches with only 1% energy spread [267,268]. The colliding laser scheme [269–274] leads to 1–10% energy spread, 10–100 pC charges, 4 fs duration, with a stability range within 5–10% with control of the electron beam parameters such as

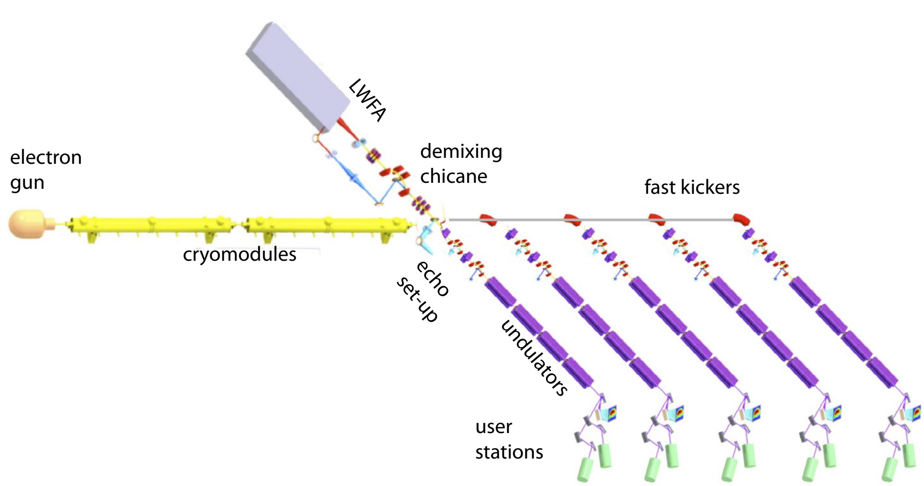

Fig. 5. Scheme of multi-user operation on LUNEX5.

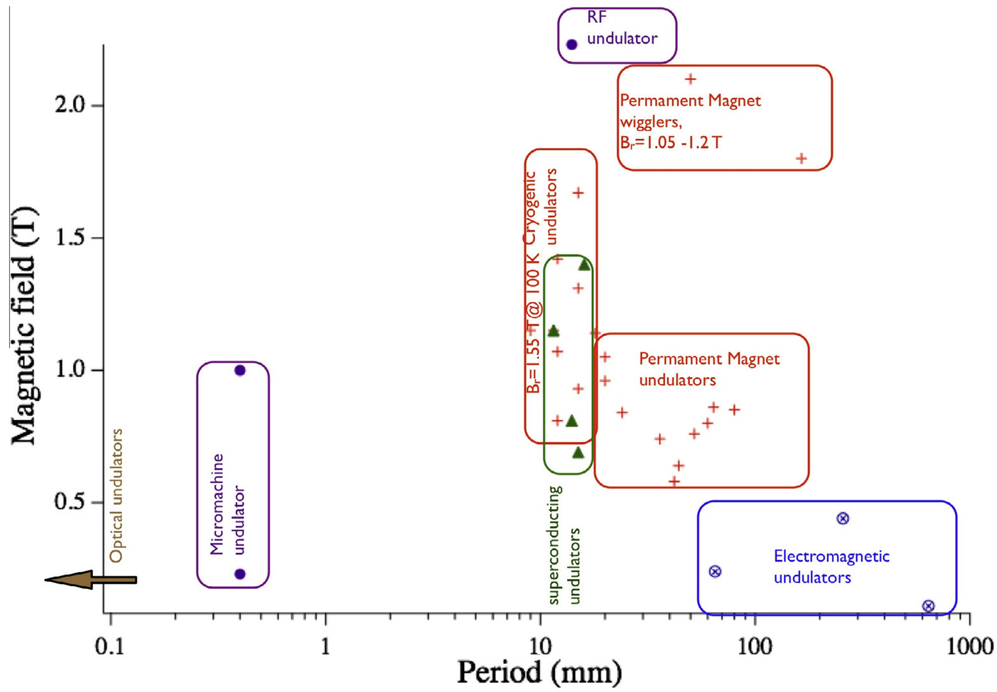

Fig. 6. Magnetic field versus period for different compact undulator technologies.

charge and energy spread. The proposed cold injection technique could provide electron beam with energies from 0.3 to 1 GeV, few tenths of pC, a few fs duration and a relative energy spread of less than 1% with a 200 TW laser. Using electron beams with the presently achieved performance in terms of energy spread and divergence however does not lead to direct FEL amplification whereas spontaneous emission from undulators has been observed [275–278]. Some electron handling and manipulation has to be implemented.

First, one can handle the beam divergence by strongly focusing with adapted quadrupoles close to the electron source [279,280]. The recently demonstrated plasma lens [281] can also be included.

For the energy spread handling, two strategies have been proposed.

The first one consists in passing the electron beam through a demixing chicane, which sorts them in energy and reduces typically the slice energy spread [282–284]. 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 [285].

The second approach consists in using a transverse gradient undulator (TGU) [286–290] with canted magnetic poles, introducing a linear transverse dependence of the vertical undulator field according to: $K(x) = K_0(1 + \alpha x)$ with α the gradient coefficient. Combined to a dispersive optic providing a transverse displacement x with the energy according to $x = \eta \Delta\gamma/\gamma$, the resonant condition can be fulfilled for $\eta = (2 + K_0^2)/\alpha K_0^2$. 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.

A first example implemented at the F. Shiller Univ., Jena, Germany with the Transverse Gradient Undulator is described. It uses the JETI-40 laser system (40 TW), which is to be focused with a 9.1 10^{18} W/cm^2 in a 3 mm gas cell filled with 95% Helium and 5% Nitrogen [291]. The transport line [292] is achromatic, and includes a 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 electromagnetic quadrupole provides a maximum gradient of 39 and 30 T/m with an 11 mm gap radius, while de dipoles deviate by 60 mrad the electron beam at 120 MeV [293]. The undulator is a superconducting Transverse Gradient Undulator consisting of two cylindrically shaped halves with NbTi coils. A prototype has been built [294–296]. 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. Detailed 1D FEL studies with 0.5–1 GeV energies, energy spread ranging from 0.1 to 0.01, 2–50 kA, 10–100 μm transverse size, undulator deflection parameter of 0.5–2.5 and period ranging from 5 to 15 mm show that achieving FEL oscillation at short wavelength (10 nm) is very challenging in the TGU configurations. LWFA electron beam parameters remain to be very critical [297].

The second example, in the frame of the LUNEX5 demonstrator, relies on the demixing chicane scheme coupled to the supermatching concept. Optimistic LWFA performance (1 μm transverse size, 1.25 mrad divergence, 1 π mm. mrad emittance, 2 fs duration, 0.1% energy spread, 20 pC charge, i.e. 4 kA peak current) were first assumed. Now, one considers more realistic parameters, i.e. an electron divergence of typically 1 mrad and an energy spread of the order of 1%. In the transport to the undulator, adequate manipulation of the electron beam phase space is then proposed to handle the rather large energy spread and divergence, as shown in Fig. 7. It consists of a "demixing" chicane sorting the electrons in energy and reduces the spread from 1% to a slice one of a few ‰ and the effective transverse size is maintained constant along the undulator (supermatching) by a proper synchronisation of the electron beam focusing with the progress of the optical wave. A test experiment of FEL amplification in the seeded configuration with such a transfer line is under preparation [298–300]. Hardware is under assembly or measurement. The reference LWFA will be produced with a 100 TW laser. First test of amplification will be carried out with the 2 × 60 TW laser presently in operation at Laboratoire d'Optique Appliquée. The best suitable regime of

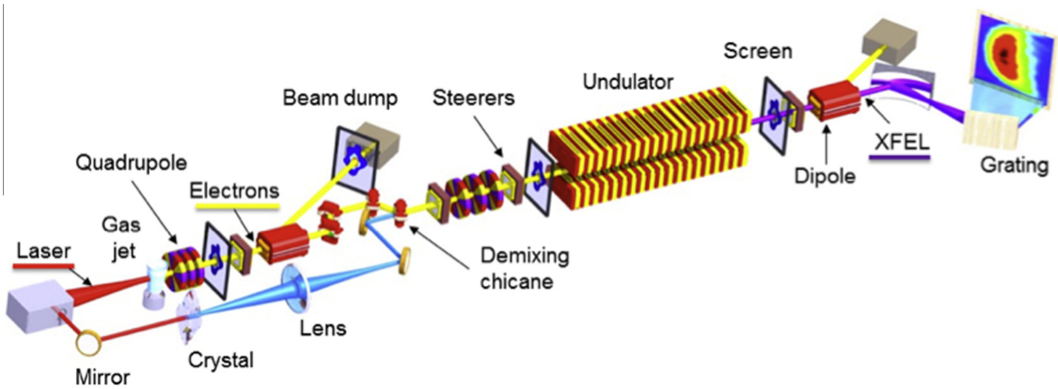

Fig. 7. The LWFA based seeded FEL conceptual scheme with a fist strong focusing with a triplet of variable permanent magnet quadrupoles located very close to the gas chamber, a chicane composed of four dipoles for energy sorting of the electron with the seed injection, and a second quadrupole set for focusing in the undulator.

operation of the LWFA for the FEL application is currently under investigation. HHG seeding will be applied. In-vacuum and cryogenic undulators will be used [301,302]. Special attention is devoted to the diagnostics [303].

Besides these two experiments, experiments are also under progress at different locations. In Strathclyde Univ. [304], electron are produced in a plasma channel, and focused by 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. A large energy spread was deduced from the spectra measurements. Experiments are also planned at LOASIS [305–307] with a decompression chicane, HHG seeding and the THUNDER undulator. At CFEL (DESY/MPG/Univ. Hamburg) is considered to use a demixing chicane [308]. Experiments are also under preparation in China.

5. Conclusion

The present blooming of X-ray Free Electron Lasers enable new investigations of matter. Without equivalent in the present light source panorama, these FELs propose new features and offer further flexibility for the users. They also tend to serve several users at the same time, for reduced operating cost. Besides, the performance and reliability of LWFAs have been significantly improved, so that LWFA appears as attractive candidate for future accelerators. The FEL application of a LWFA with 100 MeV–1 GeV electron beams provides an intermediate qualification before TeV LWFA colliders of interest in the long term for high energy physics. Provided an appropriate electron beam manipulation, FEL amplification seems to be feasible. It is still for the moment very challenging. In this prospect, the LUNEX5 demonstrator couples superconducting linear accelerator and LWFA based test facility for complementary use and test of new ideas aiming for ultra-short FEL pulses quest, production and use.

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