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Synchrotron x-rays and condensed matter/Rayonnement X synchrotron et matière condensée

X radiation sources based on accelerators

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Abstract

Light sources based on accelerators aim at producing very high brilliance coherent radiation, tuneable from the infrared to X-ray range, with picosecond or femtosecond light pulses.

The first synchrotron light sources were built around storage rings in which a large number of relativistic electrons produce “synchrotron radiation” when their trajectory is subjected to a magnetic field, either in bending magnets or in specific insertion devices (undulators), made of an alternating series of magnets, allowing the number of curvatures to be increased and the radiation to be reinforced.

These “synchrotron radiation” storage rings are now used worldwide (there are more than thirty), and they simultaneously distribute their radiation to several tens of users around the storage ring.

The most effective installations in term of brilliance are the so-called 3rd generation synchrotron radiation light sources. The radiation produced presents pulse durations of the order of a few tens of ps, at a high rate (of the order of MHz); it is tuneable over a large range, depending on the magnetic field and the electron beam energy and its polarisation is adjustable (in the VUV-soft-X range). Generally, a very precise spectral selection is made by the users with a monochromator.

The single pass linear accelerators can produce very short electron bunches (~ 100 femtosecond). The beam of very high electronic density is sent into successive undulator modules, reinforcing the radiation’s longitudinal coherence, produced according to a Free Electron Laser (FEL) scheme by the interaction between the electron bunch and a light wave. The very high peak brilliance justifies their designation as 4th generation sources. The number of users is smaller because an electron pulse produces a radiation burst towards only one beamline. Energy Recovery Linacs (ERL) let the beam pass several times in the accelerator structures either to recover the energy or to accelerate the electrons during several turns, and thus provide subpicosecond beams for a greater number of users.

A state-of-the-art of X sources using conventional (and not laser plasma based) accelerators is given here, underlying the performance already reached or forecast and the essential challenges. ***To cite this article: M.-E. Couprie, J.-M. Filhol, C. R. Physique 9 (2008).***

Résumé

Sources de rayonnement X reposant sur l’emploi d’accélérateurs. Les sources de lumière reposant sur l’emploi d’un accélérateur permettent de produire un rayonnement cohérent de très haute brillance, accordable en longueur d’onde depuis l’infrarouge jusqu’aux rayons X, avec des impulsions picoseconde ou femtoseconde (fs).

Les premières sources de rayonnement synchrotron se sont installées autour d’anneaux de stockage dans lesquels un grand nombre d’électrons d’énergie relativiste produisent du « rayonnement synchrotron » lorsque leur trajectoire est soumise à l’action

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d'un champ magnétique, soit dans les aimants de courbure, soit dans des éléments magnétiques spécifiques (onduleurs) constitués d'une succession d'aimants alternés, permettant de multiplier le nombre de courbures de trajectoire pour renforcer le rayonnement.

Ces anneaux « synchrotron » sont couramment utilisés de par le monde (il en existe plus d'une trentaine), car ils distribuent leur rayonnement simultanément à plusieurs dizaines d'utilisateurs répartis autour de l'anneau.

Les installations les plus performantes en terme de brillance sont les sources de rayonnement synchrotron dites de troisième génération. Le rayonnement produit présente des durées d'impulsion de l'ordre de quelques dizaines de ps, à haute cadence (de l'ordre du MHz), est accordable sur une large gamme, dépendant du champ magnétique et de l'énergie du faisceau d'électrons, et sa polarisation est ajustable (dans le domaine VUV-X mous). En général, une sélection spectrale très fine est effectuée par les utilisateurs à l'aide d'un monochromateur.

Les accélérateurs linéaires à simple passage offrent la possibilité de produire des paquets d'électrons de durée très courte (∼ 100 femtoseconde). Le faisceau de très haute densité électronique est envoyé dans une succession de modules d'onduleurs, permettant de renforcer la cohérence longitudinale du rayonnement produit selon un schéma de laser à électrons libres par interaction entre le paquet d'électron et une onde lumineuse. Les brillances crêtes très élevées justifient leur appellation de sources de quatrième génération. Le nombre d'utilisateurs est plus restreint, car une impulsion d'électrons produit une bouffée de rayonnement en direction d'une seule ligne de lumière. Les accélérateurs linéaires à recirculation permettent de faire passer le faisceau plusieurs fois dans les structures accélératrices soit pour en récupérer l'énergie (ERL : Energy Recovery Linac) soit pour l'accélérer sur plusieurs tours, et fournir ainsi des faisceaux subpicoseconde à un plus grand nombre d'utilisateurs.

Un état de l'art des sources X employant des accélérateurs conventionnels est donné, en soulignant les performances atteintes ou visées, et les enjeux essentiels. ***Pour citer cet article : M.-E. Couprie, J.-M. Filhol, C. R. Physique 9 (2008).***

Keywords: Synchrotron radiation; Linear accelerator; LINAC; Storage ring; Free electron laser

Mots-clés : Rayonnement synchrotron ; Accélérateur linéaire ; LINAC ; Anneau de stockage ; Laser à électrons libres

1. Introduction

Light sources, using particles accelerators, are characterised by a large spectral range combined with a high brilliance, resulting in a high degree of coherence and an important flux. The brilliance B of the optical source is defined as the photon number N per second, per spectral bandwidth $\Delta\omega/\omega$, per transverse size (Δx in horizontal and Δz in vertical directions) and per divergence ($\Delta x'$ in horizontal and $\Delta z'$ in vertical directions):

$$B = N/[\Delta x \Delta x' \Delta z \Delta z' \Delta\omega/\omega] \tag{1}$$

Thus, the closer the source to the diffraction limit ($\Delta x \Delta x' = \lambda/2\pi$, for wavelength λ) and to the Fourier limit ($\Delta\omega\Delta t \sim 1$), the higher the brilliance. The brilliance thus simultaneously characterises the produced intensity and the source coherence.

The radiation brilliance is the result of:

- The electron beam characteristics, such as its energy, the horizontal ε_x and the vertical ε_z emittances (the beam emittance is the product of its transversal dimension and its divergence), the energy spread, and the bunch length;
- The emitter magnetic element characteristics (bending magnet, undulator or wiggler);
- The emission process (spontaneous emission or synchrotron radiation from an undulator, or temporal coherent emission of the Free Electron Laser type).

Table 1 summarises the typical brilliance obtained for generation using different light sources.

Table 1
Typical average and peak brilliance for third and fourth generation light sources

	Pulse duration (ps)	Average brilliance ($\mathrm{ph/s/mm^2/mmrad^2/0.1\%BW}$)	Peak brilliance ($\mathrm{ph/s/mm^2/mmrad^2/0.1\%BW}$)
third generation	30	10^{17}–10^{20}	10^{23}
FEL fourth generation	0.1	10^{22}–10^{24}	10^{30}–10^{33}
ERL fourth generation	0.1–1	10^{19}–10^{22}	10^{21}–10^{24}

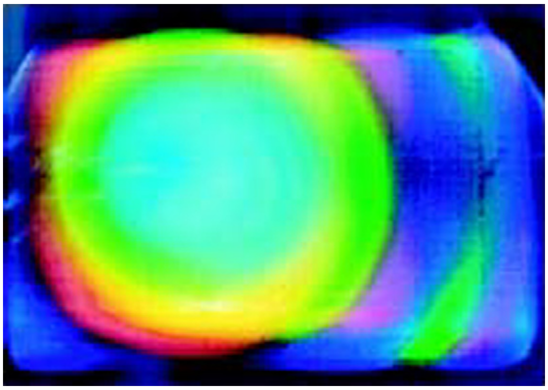

Fig. 1. Undulator radiation. Case of an undulator installed on the former Super-ACO storage ring at 800 MeV. The external rings correspond to the off-axis emission of the higher harmonics. The analysis of the undulaotr radiation leads to the evaluation of the emittance and energy spread of the beam.

The first users of accelerator based light sources were taking advantage of the parasitical use of the synchrotron radiation (white radiation emitted by accelerated relativistic particles) on collision rings. Such storage rings constituted *the first generation light sources* such as, for example ACO (France, 1971), DCI (France), SURF II (USA, 1974), INSOR (Japan), SPEAR et CESR (USA), DORIS (Germany), VEPP-3 (Russia) [1].

The *second generation* corresponds to dedicated installations, combining a limited number of insertion devices (mainly wigglers) and offering an emittance beam of intermediate value (hundreds of nm.rad) [2]. This is the case, for example, of SRS (Great-Britain), NSLS (USA), Aladdin (USA), Photon Factory (Japan), BESSY-I (Germany), Super-ACO (France), DORIS (since 1993).

The so-called "*third generation*" light sources [3] correspond to storage rings of very low horizontal emittance (1–20 nm rad), with a very good position stability and a very large number of insertion devices (undulators). For a 3 nm.rad emittance, the diffraction limit can be reached at wavelengths higher than 40 nm. In the vertical plane for which the emittance is typically ten times smaller than in the horizontal plane (operating with a low coupling), the diffraction limit is reached for radiations of shorter wavelengths (typically 0.4 nm). These storage rings are made up of numerous straight sections allowing the installation of several insertion devices [4] (undulators and wigglers producing a permanent periodic magnetic field) to make the emitted radiation more intense. These various radiation source points (bending magnets and insertion devices) permit the simultaneous use of the same electron beam at several tens of experimental stations.

In the insertion devices, the relativistic particles of normalised energy γ are transversely accelerated by an undulator creating a permanent periodic magnetic field, and they emit synchrotron radiation whose spectral characteristics depend on the magnetic field (amplitude B_0, period λ_0) and the particle energy. In the case of an undulator creating a sinusoidal field in the vertical plane, the synchrotron radiation is emitted on axis at wavelength λ, the so-called resonance wavelength, and its odd harmonics, with a linear horizontal polarisation:

$$\lambda = \frac{\lambda_0}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \tag{2}$$

where K is the deflection parameter of the undulator, i.e. $K = 0.94\,\lambda_0$ (cm) B_0(T). In the case of a helical magnetic field, the radiation is also emitted on the even harmonics, with a circular polarisation.

The wavelength λ of the emitted radiation can be varied 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). In the "undulator" regime (rather small K values), the radiation emitted at each inversion interferes with that produced in the previous inversions. These interferences can be constructive and the radiation is produced in very intense spectral ray (harmonics) form. In the "wiggler" regime ($K \gg 10$), the radiation of the different harmonics overlaps and is similar to the dipole one, with a higher intensity. A radiation image from an undulator is shown in Fig. 1.

The beam horizontal emittance strongly depends on the electron energy, the number of bending magnets as well as the magnetic focalisation strengths (optical lattice). For a given ring size, the beam emittance rises quadratically with the electron energy.

In a storage ring, the beam circulates for hours thanks to radio-frequency cavities allowing, with an electrical field, one to re-accelerate the particles at each turn and give them back the energy they have lost by synchrotron radiation. The electrons are packed in a large number of bunches with a bunch length of about ten picoseconds (FWHM), being imposed by the dynamic equilibrium linked to the high number of turns.

The electron longitudinal oscillation imposed by the radio-frequency system induces a minimum pulse duration of few tens of picoseconds, to which is added a systematic bunch lengthening following the interaction with the emitted microwave field [5]. The 'so-called' slicing techniques, using the interaction of a femtosecond laser with the electron bunches in an undulator [6], can produce subpicosecond radiation pulses in these rings. It is also proposed to flip the phase space from the transverse plane to the longitudinal direction [7]. In the slicing cases, the emitted photon brilliance is then reduced by several orders of magnitude. In the case of the CRAB cavities, the pulse duration is less reduced. The radiation temporal coherence remains limited, and the radiation is exploited in beamlines equipped with high resolution monochromators.

A substantial gain not only in peak brilliance, but also in average brilliance, in particular in the case of a superconducting based RF linac, is reached with the so-called '*fourth generation*' sources [8]. In order to free oneself from the intrinsic limitation of bunch duration reduction met in storage rings, we use simple linear accelerators or energy recovery systems. The electron beam comes in microsecond long macro-pulses containing a large number of micropulses with a duration of a few tens of picoseconds. Longer macro-pulses (in the order of ms) can be delivered by superconducting linear accelerators. Electron bursts are generated in the gun by a laser pulse illuminating a photocathode surface. The electron bunches' duration, degradated by the energy dispersion at the gun output, is reduced by the longitudinal compression with magnetic chicanes. Without recirculation, the compression process takes place in several steps between successive accelerating levels. In a linear accelerator, the beam emittance decreases when the energy increases ($\varepsilon \sim 1/\gamma$).

With a Free-Electron Laser (FEL), the radiation provided is not only based on the spontaneous synchrotron radiation emitted in an insertion device. A light wave of wavelength λ interacts with the electron bunch in the undulator, inducing an energy modulation of the electrons, which is gradually transformed into density modulation at wavelength λ and leads to a coherent radiation emission.

On a linear accelerator, the electron beam, after passing through the undulators, is stopped on an absorber. It does not keep memory of its interaction with the optical wave, and a "new" bunch interacts with the FEL each time it goes through the undulator. In present facilities, the number of simultaneous users of the FEL sources implemented on linear accelerators is noticeably reduced (typically inferior to 10) compared to third generation sources, because of the linear structure of the accelerator. The users share the Linac beamtime, since each beam pulse delivers photons to only one experimental station at a time.

The FEL emission results from three different configurations (cf. Fig. 2):

The Self Amplified Spontaneous Emission (SASE) mode [9] corresponds to a super-radiant system with electron bunches passing only once in a very long undulator. The spontaneous emission at the beginning of the undulator interacts with the electron beam by modulating it, and an intense coherent light is produced. The initial emission is thus amplified as it passes through the very long undulator.

In the oscillator mode, in a spectral range where mirrors are available, the synchrotron radiation is stored in an optical cavity and this allows interaction with the optical wave on many passes.

In the Coherent Harmonics Generation (CHG) configuration [10], a laser wave (external laser, FEL or SASE) is injected in order to interact with the electron beams in the undulator.

Among the three modes, the SASE one presents a limited temporal coherence, conveying 'spikes' in the temporal and spectral distributions, because the emission starts with noise.

For single pass sources, the injection of an external laser source on the fundamental wave of the undulator (seeding) can improve the temporal coherence in relation to SASE, reduce the gain length and limit the intensity fluctuations.

In the High Gain Harmonic Generation scheme (HGHG) [11], an injected external laser source induces modulation in density of the electron bunch in the first undulator. The radiation is produced in the second undulator tuned on a harmonic of the injected wavelength, which makes the system more compact. Then, in a cascade scheme [12], the

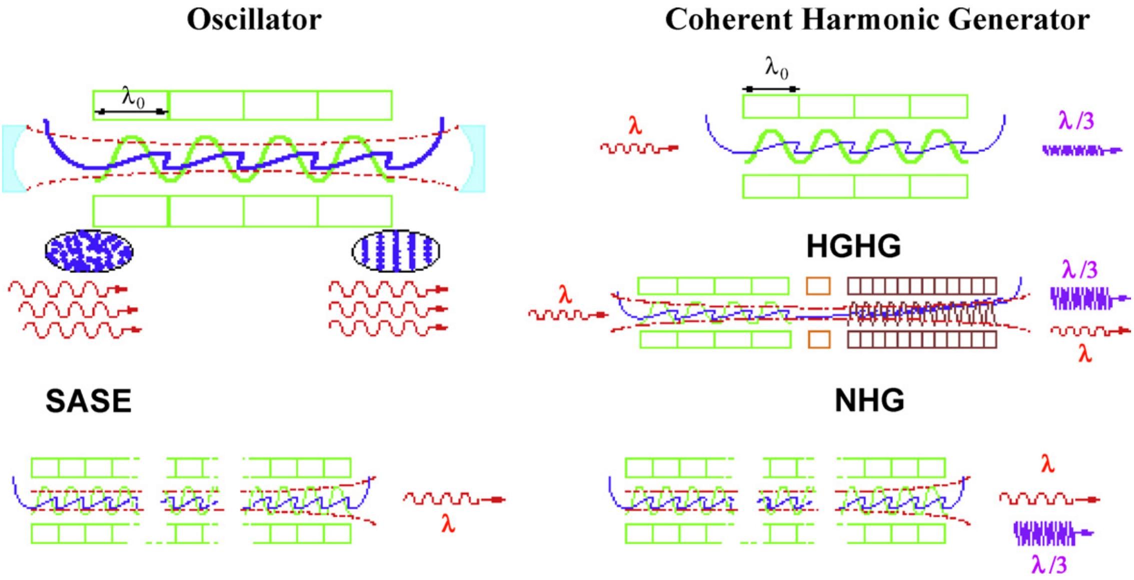

Fig. 2. FEL configurations. HGHG: High Gain Harmonic Generation NHG: Non Linear Harmonics, SASE: Self Amplified Spontaneous Emission.

radiation can be injected in a second stage of HGHG. In high gain systems, the Coherent Non linear Harmonic Generation (NLG: Non Linear harmonic Generation) of the fundamental wavelength also takes place.

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. The polarisation depends on the chosen undulator. The small signal gain is proportional to the electronic density; it varies as the inverse cube of the beam energy, and depends on the undulator length used. The operation at short wavelengths is carried out with high beam energies according to relation (2); it thus requires a long interaction length to ensure a sufficient gain. In the X-ray domain, undulators are installed at tens or even hundreds of meters to ensure radiation amplification. The performance needed for the electron linear accelerator meet that of future colliders.

For the Energy Recovery Linear Accelerators, [13] (ERL, Energy Recovery LINAC), the beam is accelerated and decelerated by the same accelerating structures, according to the relative phase between the longitudinal position of the electron bunch and the sine curve of the radio-frequency electrical field. In comparison to third generation storage rings, they allow one to operate with short electron bunches (ps and sub-ps) by relaxing restrictions linked to the longitudinal equilibrium, and the emittance increases. The beam characteristics mainly depend on those of the electron source. Undulator installation on straight sections for high brilliance sources is possible. This radiation can be emitted with a very versatile temporal structure (pulse trains with variable lengths and frequencies). Furthermore, the radioprotection constraints at the beam dump are considerably reduced thanks to the beam deceleration.

Other sources also partly cover the X-ray and VUV spectral range.

X-ray lasers operate at low repetition rates for discrete wavelengths. Interesting user experiments (such as interferometry) [14] have already been carried out with success.

High order Harmonic Generation (HHG) leads to odd harmonic emission by radiative recombination of an electron which has crossed by tunnel effect the potential barrier lowered due to the laser intense electric field [15,16]. The HHG covers a range from UV to few nm (2 nm [17]), with a high degree of spatial [18] and temporal [19] coherence, very brief (of some femtoseconds to some 100 attoseconds) [20]. They are also tuneable [21] and linearly polarised. The HHG can also be amplified in an X ray laser [22], thus improving the performance of the respective sources in a combined way.

The harmonic generation by intense laser on a solid target has shown rapid advances [23]. However, they cannot offer a completely tuneable polarisation of the source.

The VUV-X laser sources suit well exploratory studies, needing relatively high peak brilliance, with easy access conditions. By construction, these sources are naturally synchronised with a visible laser, for time resolved pump/probe studies. The HHG source delivers the shortest pulses.

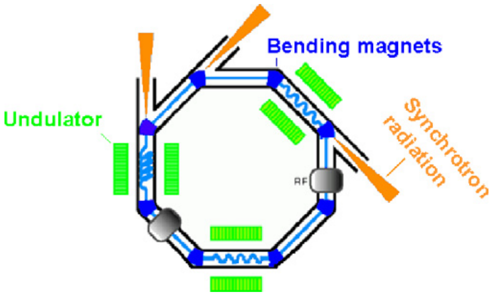

Fig. 3. Sketch of a storage ring for synchrotron radiation.

2. Third generation sources

2.1. The radiation properties

The third generation radiation sources present high brilliance at the undulators' output, with a repetition rate imposed by the electron revolution frequency in the storage ring i.e. 100 MHz, in a spectral range extending from the visible to a hundred keV. The undulator radiation is spatially coherent (transverse coherence). The temporal (longitudinal) coherence is determined by the spectral resolution (for a typical spectral $\Delta E/E \sim 10^{-5}$ obtained with a monochromator), the coherence time being $\sim$ 1 ps at 1 keV). The pulse duration is of the order of few tens of ps. The radiation is polarised; some types of undulator allow the polarisation to be continuously varied from linear to circular. These sources are well adapted to studies needing a high average brilliance and a very large stability, in intensity as well as in position, (studies with high spectral resolution), for a wide field of application. A storage ring schematic view for the synchrotron radiation is shown in Fig. 3.

Spectrally, the energy range needed is selected by the user with a monochromator, of typical spectral width $\Delta E/E \sim 10^{-5}$, and the number of electrons on the target remains high (brilliance between 10^{15} and 10^{18} $\mathrm{photons/s/0.001\%BP/mrad^2/mm^2}$). The spatial resolution obtained from the high brilliance and very effective UV-X optics enable microfocalisation down to submicronic beam size (taking advantage of the angular resolution). The very high flux allows the study of very diluted species in a very absorbent environment (for example, biological molecules in aqueous medium). The direct temporal resolution (determined by the pulse duration), on a scale $\sim$ 50 ps, is more and more used in the 3rd generation sources. The new techniques of 'slicing' by laser, and control of the electron bunches will lead to shorter durations, of the order of the picosecond, even of a hundred femtoseconds.

This high brilliance results from the more systematic use of insertion devices on the 3rd generation sources. Their construction is based on permanent or electromagnetic magnet technologies, or a combination of both. Different layouts allow the production of various helicities of the magnetic fields, and then an adjustable polarisation for the users. A typical layout for a permanent magnet system in this case is the APPLE-II type undulator [24], combining different arrays of magnets that can be translated one from the other to produce a field in the vertical or horizontal plane. Innovative solutions in terms of electromagnetic undulators have been implemented at SOLEIL [25]. A solution combining electromagnets and permanent magnets permits one to reverse the polarisation at 5 ms at the ESRF [26]. The spectral range covered by the insertion devices, even for an intermediate beam energy, is very wide: for example, with an electron beam of 2.75 GeV, the spectral ranger covered by SOLEIL goes from the visible with an 64 cm period and 10 m long undulator to the hard X (50 KeV) with a 50 mm period in-vacuum wiggler. With the technological progress permitting one to put the magnets directly in-vacuum, magnetic fields and higher photon energies can thus be reached [27]. In-vacuum insertion devices are now quite common on third generation sources. The variation of the gap and/or the current in the insertion power supplies, combined with the monochromator variation, allows the phenomena studied on the samples to be scanned in energy. The beamline scientists can then freely vary the insertion device magnetic field. In consequence, the insertion device effect on the electron beam should be as transparent as possible in order not to perturb the other users while at a fixed place in the machine. To do so, the first and second field integrals along the longitudinal position must be zero, for any gap or current value. The magnetic configurations should not create multipolar field configurations (straight or skew quadrupoles, sextupoles) that could affect the storage ring performance (emittance, lifetime, injection efficiency). It requires one to realise a very precise magnetic metrology.

However, the performance reached after magnetic measurements (integrals of the order of mT cm) being insufficient, one should apply real time corrections of the insertion device defects, by magnetic correctors "embarked on the undulator" or placed on the machine (feedforward).

Even for the out-vacuum insertion devices, the tendency is to reduce the gap as much as possible, which is made possible thanks to the NEG (Non Evaporable Getter) pumping system initially developed at the CERN for the LHC and then applied to third generation sources [28]: the chamber surface, after the titanium, zirconium and vanadium alloy sputtering, behaves like a distributed pumping system, instead of outgassing.

Fighting against the bunch lengthening to maintain a relatively short pulse duration for a high current needed for the high brilliance requires one to take particular care about the vacuum chamber impedance, in order to reduce as much as possible the microwave instability [29]. A complete modelling of the ring, as well as of the beam behaviour on a longitudinal point of view, has been worked out [30]. To maintain the beam as stable as possible with a high current leads to the use of superconducting cavities, in order to limit the longitudinal instabilities. (Diamond, CLS, Taiwan, SOLEIL) [31].

However, on a machine of intermediate energy (2.5–3 GeV) the beam lifetime is strongly limited by the Touschek effect [32]. In order to keep long lifetimes, the storage rings now often operate in top-up mode in order to maintain a stable current on the first beamline optics, and not to perturb the measurements following uncontrolled overheatings [33].

2.2. State of the art

Third generation sources of intermediate energy are already in operation in Europe: ELETTRA (Trieste, Italy) [34], BESSY-II (Berlin, Germany) [35], SLS (Swiss Light Source, Villigen, Switzerland) [36], MAX3 (Maxlab, Stockholm, Sweden) [37].

SOLEIL (Saint-Aubin, France) [38] and DIAMOND (Oxford, GB) [39] completed construction in 2006 and welcomed their first users in 2007. ALBA (Barcelona, Spain) [40] is under construction. MAX-IV (Sweden) is in project stage [41].

Outside of Europe, in the intermediate energy range, there exist ALS (Berkeley, USA) [42], CLS (Canada) [43], NSRRC (Taiwan) [44], the Australian source [45], The SHANGHAI Chinese source [46], the NSLS II project (Brookhaven national lab, USA) [47].

The hard X-ray field is specifically open to three sources: ESRF (European Synchrotron Light Source, Grenoble, France) of 6 GeV [48], providing X-rays to 40 beamlines for several thousands researchers a year, APS (Advanced Photon Source, Argonne, USA) [49] of 7 GeV and SPring-8 (Harima-ken, Japan) [50] of 8 GeV. The ESRF was the first source to operate, followed by APS and SPring-8. At DESY, the PETRA machine [51] will be soon converted from high energy physics to synchrotron radiation.

All over the world, there are almost hundred synchrotron radiation sources. Table 2 summarises the main characteristics of such sources in Europe [52].

2.3. Challenges from the accelerator point of view

2.3.1. Emittance and optics

The electron beam horizontal emittance is the result of the balance between the quantic excitation linked the synchrotron radiation emission in the magnets which induces betatron oscillations, and the damping of the transverse oscillations induced by the energy loss compensation ensured by the electric field of the RF cavity. The emittance minimisation aims at reducing the betatron oscillations amplitude in the dipoles, while maintaining a comfortable dynamic acceptance. The choice of the optics, commonly a Double-Bend Achromat or a modified Chassman-Green one, allows the minimal theoretical emittance to be reached [53], releasing the relative constraint of a zero dispersion in the straight sections.

The horizontal emittance of most of the third generation rings is of the order of few nm.rad (between 2 and 8).

The solutions for reaching a horizontal emittance below 1 nm rad are investigated on NSLS II and PETRA 3 which will take advantage of a much larger circumference than machines with comparable energy, and which will use damping wigglers, and on MAX III [54]. In such a case, the dynamic acceptance remains a very critical issue.

Table 2
Third generation synchrotron radiation centers in Europe

	ESRF	SLS	ANKA	BESSY	ELETTRA	DIAMOND	MAXIII	SOLEIL	PETRA III	ALBA
Energy GeV	6	2.4 +2.7	2.5 (1.3)	1.72	2/2.4	3	0.7	2.75	*6*	*3*
ε_h (nm rad)	4	5 7 (FEMTO)	40	6	7/9.6	2.7	13	3.7	*1*	*4*
Imax (mA)	200	350	200	300	320/140 340/150	*300*	*250*	*500*	*100*	*400*
Lifetime at $I_{\max}$ (h)	80	16 0.5%coupl. 3rd HC	20	10	23/45	*15*	*10*	*20*	*2/24*	*15*
Fast orbit Feedback	Yes	Yes (fast) XBPM (slow)		*Not yet*	Yes	Yes *(2p)*	Yes	Yes	Yes	Yes
Long. / Tra. Feedback	test	Yes	(Yes)	Yes	Yes	*TF*		*TF*	Yes	*TF*
Top-up injection	test	Yes		test	Non	*Yes*	No	Yes	Yes	Yes
Short bunches		Slicing	Low α	Slicing Low α	E at 700 MeV	*Maybe*	No	*Maybe*	*Maybe*	
Superconducting technology	*Cryo. PM und.*	H cavity *S.Bend Jan 07*	SCU14	Wiggler *S Bend* *Harm Cavity*	Wiggler H cavity	Wigglers SC cavities	SC cavities	*No*	*Wiggler*	
NEG	ID SS	ID SS		No	ID SS	ID SS	ID SS	All straight	*Strip (anti-Chambre)*	*ID SS*

The vertical emittance is the result of an oscillation transfer from the horizontal to the vertical plane. It is now well controlled on most of the recent storage rings and maintained at low values (between 10 and pm rad), lower than the diffraction limit.

2.3.2. *Pulse duration reduction*

The pulse duration reduction towards femtosecond pulses for the dynamic studies of ultra-fast phenomena investigates three directions on the storage ring. The first solution consists in reducing the momentum compaction factor that links the bunch length to the beam energy dispersion [55]. This operating mode enables one to obtain sub-picosecond pulses for stored low currents, because at higher currents, the anomalous bunch lengthening due to the microwave instability dominates. It is often used at BESSY II [56] and under test at SOLEIL.

A second solution, 'slicing' [6], consisting in making a femtosecond laser interact with the electron beam in an undulator tuned to the laser wavelength. An intense ultra-short laser pulse induces an energy modulation on a part of the electron bunch, which, after a subsequent splitting with respect to the rest of the bunch, produces sub-ps radiation in the appropriate undulator. First carried out at ALS [57], this mode is now currently used at BESSY and at SLS by the users.

A third option proposes to use a RF deflection with so-called CRAB cavities [7] in order to manipulate the electron transverse momentum inside the bunch. The beam gets through a first RF cavity, inducing a vertical deflection depending on the longitudinal position, in undulators that emit, in such a way, ps radiation, then through a second cavity that cancels the effect of the first one so as not to alter the dynamic in the rest of the ring [58]. The difficulties for such a scheme lie on the emittance rise due to non-linearities and the chromaticity correction [59]. Technological developments are launched on CRAB cavities in a CERN/Karlsruhe collaboration (2.8 GHz), at Cornell (1.5 GHz), at KEK (500 MHz), at Fermilab and at APS (2.8 GHz) [60].

2.3.3. *Position stability*

Considering the reduction of the source sizes and divergences linked to the emittance reduction, the beam is extremely small (for example, μm vertically). Beam position monitors have to reach submicronic accuracy and need sophisticated electronics. Also, fast (1–100 Hz) and slow (< 1 Hz) inverse feedback are implemented in both transverse planes, in order to maintain the electron beam trajectory fixed. Special care is taken for the building construction and support in order to reduce vibrations.

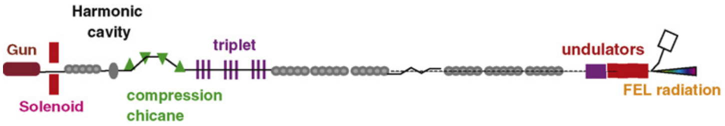

Fig. 4. Linear accelerator based FEL set-up.

2.3.4. *Perspectives from an insertion device point of view*

The recent developments seem to increase the magnetic field in the insertion devices, especially using permanent magnets kept at the liquid nitrogen temperature [61]. At present, studies are carried out at SPring-8, at the ESRF where a cryo-undulator has been recently tested with the electron beam, and at Brookhaven, where a cryo-ready undulator has been set up [62]. Studies on superconducting undulators have been carried out, particularly at ANKA [63].

3. Free Electron Laser type, fourth generation light sources

The fourth generation (FEL with coherent emission undulators from a temporal point of view) proposes femtosecond radiation sources with high brilliance on single-pass accelerators, in order to avoid the bunch lengthening due to the interaction with the radiated field on the previous turns.

Free Electron Lasers use a relativistic electron beam interacting in the periodic permanent magnetic field of an undulator with an optical wave (spontaneous emission of synchrotron radiation, external laser source for injection) to produce a polarised radiation, tuneable in wavelength, with high average and peak brilliance, and with short pulse duration. The FELs with short wavelength need a high energy beam, short period undulators producing high magnetic field and large interaction lengths, of very good beam quality in order to have electronic densities as high as possible. The specifications are similar, in this way, to those for colliders. The transverse coherence needs an electron beam emittance of the order of the operating wave length size. The longitudinal coherence depends on the Free Electron Laser configuration. A schematic description can be seen in Fig. 4.

3.1. *Characteristics*

3.1.1. *Tuneability*

The FEL's oscillators, using moderate energy beams, are adapted to the Infra-Red field. The FEL on the ELETTRA ring holds the record in the VUV for the shortest wavelength for a FEL oscillator [64]. The accurate tuneability is made by modifying the undulator magnetic field, as the beam energy change enables one to cover different spectral ranges. The FELs with short wavelength are usually set up on a linear accelerator. The non-linear harmonics operation also allows the spectral range to be extended. The non-linear harmonics can even be produced in the case of a helical undulator [65]. So, FLASH at present in SASE operation at 13 nm, 30 µJ at 690 MeV and recently non-saturing at 6 nm runs down to the water window on these non-linear harmonics [66]. A HGHG or stream of HGHG configuration allows one to increase the spectral range covered, for same beam characteristics. So, the BNL experiments have demonstrated the injection with a Ti:Sa laser on its fundamental wavelength and its 3rd harmonic as well as the use of the coherent radiation at 89 nm in molecular physics with an electron beam at 205 MeV [67]. The injection of harmonics generated in gases (and not only a Ti:Sa laser) also permits one to reduce further the LINAC beam energy for a given aimed spectral range [68]. This concept is a central issue of the optimisation of the ARC-EN-CIEL project in France, which aims at a coherent radiation at 1 nm with a beam at 1 GeV (unlike the other projects needing a higher energy for this spectral range) [69]. A demonstration in the scope of a SOLEIL/CEA/SCSS (Riken, SPring-8) collaboration carried out in Japan on SPA (SCSS Prototype Accelerator) [70], demonstrates the HHG seeding at 160 nm with coherent radiation and amplification on the fundamental and the harmonics 3 and 5, at 53 and 32 nm to an electron beam of 150 MeV [71]. The harmonics generated in the gases which have reached the water window can be used for seeding and frequency multiplication of a Free Electron Laser in the soft X domain. The experimental demonstration of the cascading HGHG scheme has not yet been performed. In the seeding case, the tuneability is applied through the injection source, or a chirp (frequency drift) at the same time on the injection source and on the electron bunch [72].

3.1.2. Transverse coherence

The transverse coherence typically needs an electron beam emittance of the order of the wavelength wanted. So, for the very short wavelengths, linear accelerators are preferred because the emittance is inversely proportional to the beam energy.

Guns with a normalised emittance as low as possible have to be used ($\varepsilon/\gamma \sim 1$ mm mrad), because the energy increase to decrease the emittance, very expensive, implies even larger interaction lengths. To combine undulators with a strong magnetic field (in-vacuum undulators, cryo-undulators) is a good strategy for very short wavelengths.

3.1.3. Temporal coherence

The SASE presents a limited temporal coherence, since the pulses exhibit spikes in the spectral and temporal distributions. Indeed, the emissions starts from noise, no correlation exist between the different density modulated trains in the electron bunch [9]. In the case of single pass sources, the seeding of an external laser tuned to the fundamental wavelength allows the temporal coherence to be improved with respect to SASE and the gain length (and therefore the undulator length for reaching saturation) to be reduced [11]. Seeding with a coherent light source permits one to keep the coherence from the original laser. High order harmonics generated in the gas are well adapted as a seeding source for the VUV-soft X ray range. In the hard X-ray domain, it is probably better to adapt the self-seeding scheme where a monochromator installed after the first undulator insures the modulation and the light amplification allows the radiation to be spectrally cleaned before the final amplification in the final undulator section [73]. Such a scheme will be tested on FLASH in 2009 [74].

3.1.4. Pulse duration

SASE radiation is established after a regime of exponential growth, with a rate given by:

$$L_{\mathrm{g}} = \frac{\lambda_0}{4\sqrt{3}\pi\rho} \quad \text{with } \rho = \frac{1}{4\pi\gamma}\left[\frac{2\pi^2}{\sigma_{\mathrm{t}}}(JJ\lambda_0 K)^2 \frac{I}{I_{\mathrm{A}}}\right]^{1/3}$$

where ρ is the Pierce parameter, I_{A} the Alfven current, σ_{t} the transverse dimension of the electrons, I the current, JJ the Bessel function term in the gain expression. The saturation power is given by $P_{\mathrm{sat}} = \rho P_{\mathrm{beam}}$. Once saturation is reached, the amplification process is replaced by a cyclic energy exchange of energy between the electrons and the radiated field.

In the case of a seeded FEL, the saturation length is reduced, and three regimes of evolution can be distinguished. First, the light pulse induces an energy modulation of the electron beam, there is no gain and the optical wave travels with the speed of light c. Then, the energy modulation is converted into density modulation, the FEL pulse grows exponentially starting from the tail of the injected pulse, with the gain length L_{g}. The minimum pulse duration after the exponential regime is limited by the FEL gain width; it is given by the cooperation length L_{c}:

$$L_{\mathrm{c}} = \frac{\lambda}{4\pi\rho}$$

The group velocity of the light wave is slightly larger than the average longitudinal speed of the electrons, and is slightly smaller than c, because of the speed reduction due to the gain process. Finally, when saturation power is reached (non-linear regime), the light pulse starts to slip faster along the electron bunch. Similar regimes are observed for the growth of the non linear harmonics. In case of pulses for which the length is between the slippage length and the width of the potential well, super-radiant modes exhibiting further pulse duration narrowing and intensity increase are observed [75].

The harmonics pulse duration is given by the limit between the pulse duration of the seed laser and the cooperation length, i.e. typically in the 100–50 fs FWHM range. The reduction of the pulse duration towards the attoseconds is also considered. The so-called “spoiling” technique introduces a slit in the electron beam distribution [76]. The “laser heater” system can also be set-up in order to enhance the energy spread. Otherwise, a process similar to the slicing for synchrotron radiation sources could be employed. A modulation by a fs pulse induces an energy dispersion which depends on the wavelength of the light pulse, can partially lead to attosecond pulses [77]. Slicing with an RF field is also considered [78].

Table 3
Fourth generation light sources in the VUV-X ray domain. Superconducting Linear Accelerator SCLinac, ER: Energy Recovery, T: FWHM pulse duration, λ: Spectral range

	E (GeV)	Accelerator	Config.	Localisation	λ (nm)	T (fs)	Statut
DUVFEL	0.3	LINAC	HGHG	BNL, USA	800–88	500	Oper.
FLASH	0.4–1	SCLinac	SASE	DESY, Germ.	40–6	25–200	Oper
BESSY FEL	2.3	SCLinac	HGHG	Berlin, Germ.	50–1	20–40	Project
SPARC	0.15–0.2	LINAC	SASE HG	Frascati, Italy	500–100	6×10^3	Const.
SPARX	1–1.5	LINAC	SASE	Frascati, Italy	14–3	30–100	Const.
FERMI	1.2	LINAC	HGHG	Trieste, It.	100–10	40–1000	Const.
4GLS	0.6–0.95	SCLinac ER	Seed	CLRC, UK	100–10	20–300	Projet
MAX-injector	0.5	LINAC	HGHG	Lund, Sweden	$\gg 90$	500–1000	Project*
MAXIV	3	LINAC	HGHG	Lund, Sweden			Project
ARC-EN-CIEL	1	SCLinac	HGHG	France	500–1	200	Project
BATES	1	LINAC	HGHG	MIT USA	0.3–100	50	Project
LUX	3	ERL	HGHG	Berkeley USA	1	10–200	Project
SCSS proto.	0.25	LINAC	seeding	Harima, Japan	400–60	130	Com.
SLS	6	LINAC	SASE	PSI, Switzerland	0.1		Project
LCLS	14.5	LINAC	SASE	Stanford, USA	0.15–1.5	230	Const.
E-XFEL	17.5	SCLinac	SASE	Hamburg, Germany	0.1–1.6	190	Const.
SCSS-XFEL	8	LINAC C	SASEseed	Harima, Japan	0.1	100	Const.
PAL	3.7	LINAC	SASE	Pohang, Korea	0.1–5	300	Project

* Prototype in construction.

3.1.5. Stability

The stability of the produced radiation in position and intensity is much higher in the case of an FEL oscillator or in that of a seeded FEL (few percent range) whereas in the SASE case, it remains of the order of several tens of percent [11]. Stability remains, however, lower than that currently achieved on storage rings. SASE regime presents pulses which vary in shape, intensity and temporal position.

3.2. State of the art of Free Electron lasers

3.2.1. History, from infra-red to VUV

The first Free Electron Laser [79] has been obtained by the team of J.M.J. Madey at Stanford 1977 in the infra-red. Various FEL oscillators were then built on linear accelerators for user applications, in the UV in particular, on storage rings. Single pass FELs (without light recirculation or with light injection) were widely developed in the 1990s [80]. In the UV, several tens of user applications have been conducted on Storage Ring or Linac based FELs. Table 3 indicates FEL facilities in the short wavelength domain, which are planned or in construction. In the VUV, several tens of user applications have been carried out. The first SASE in the VUV has been provided at LEULT (Argonne, USA) [81]. The FEL implemented on the Tesla Test Facility 1 [82] has allowed the first user applications to be carried in the VUV. The European FEL detains the record of the shortest wavelength of an oscillator in the VUV, i.e. 190 nm [64].

3.2.2. Soft X-ray domain

In soft X rays, FLASH [66] implemented on a superconducting linear accelerator operated in SASE at 30 nm in 2005, and has offered radiation down to 6.5 nm since fall 2007. FLASH attracts various users and the first works of high scientific level have been performed. The users employing pump-probe techniques should measure for each data point the jitter between the SASE and the synchronised laser, and then sort the data. SPA (SCSS Prototype Accelerator) [83] on a C band linear accelerator has recently achieved SASE at 49 nm with a 250 MeV with specific technological choices (thermo-ionic gun instead of a photo-injector, leading to a very stable beam, in vacuum undulators providing a compact set-up). A user programme is also launched.

In the case of seeding and Coherent Harmonic generation, DUV-FEL (Brookhaven National Laboratory) has recently produced coherent VUV radiation on the third and fourth non-linear harmonics for user applications, with a significant reduction of the intensity fluctuations and of the spikes [11]. Seeding with High order Harmonics generated in Gas has been demonstrated on SPA with coherent radiation at 160, 53 and 32 nm [70].

In Italy, the SPARC (Frascati), mainly dedicated to FEL studies, (SASE in the visible, HGHG and seeding with the High order Harmonics produced in Gas) has obtained the first results with an electron gun [84]. It will be extended towards shorter wavelengths with SPARXINO and SPARX, which are presently being funded. FERMI (Trieste) is a user facility under construction based on HGHG in cascade [85]. On the MAX-IV injector (Lund, Sweden) is also planned an HGHG experiment [86]. The BESSY-FEL project (Berlin, Germany) plans four stages of HGHG in cascade [87] and prepares a feasibility experiment with two stages (STARS project). The MIT-BATES (USA) project [88] which is no longer considered and ARC-EN-CIEL (Accelerator Radiation Complex for ENhanced Coherent Intense Extended Light) (France) [69] projects are based on the injection of High order Harmonics in Gas (HHG) and FEL based harmonic generation. ARC-EN-CIEL comports a third phase with energy recovery (ERL: Energy Recovery Linac) loops for undulators in the spontaneous emission regime and for an FEL oscillator, taking advantage of the recent development of multilayer optics around 13 nm for lithography. An energy increase up to 3 GeV via the loops will feed a HHG seeded FEL down to 0.3 nm. 4GLS project (Daresbury, GB) [89] mainly based on the ERL concept, has also adopted the HHG seeding for one of the FEL branches. The English project 4GLS and SAPPHIRE are not kept in their present form and a next project, of lower cost, merging more accelerators and lasers should be prepared for mid-2009. In Europe for the soft-X ray sources, ARC-EN-CIEL shares with BESSY FEL the choice of a superconducting linear accelerator for reaching high repetition rates.

3.2.3. Hard X domain

The hard X ray range requires the use of high electron beam energies. Indeed, the electron beam emittance being inversely proportional to the electron energy and the present electron gun performance remaining limited, a high energy enables to one produce diffracted limited FEL sources. For instance, projects such as SCSS (Japan), LCLS (USA) and European XFEL (Hamburg) use 8, 14 and 20 GeV electron beams, respectively (cf. Table 4).

E XFEL [90] will consist of a 2 km long superconducting linear accelerator (23 MV/m par cavity, charge of 1 nC, electron bunches of 190 fs). The repetition rate of the 650 µs long macro-pulses is limited to 10 Hz at 17.5 GeV, each macropulse consisting of 3250 bunches. The Linac can operate at a higher repetition rate, for a beam energy restricted up to 6.5 GeV. The electron beam will be distributed on five branches (with two experimental stations for each), three undulators for generating SASE radiation (0.1–0.4 nm in linear polarisation, 0.4–1.6 nm in helical to planar polarisation and two undulators in spontaneous emission mode (0.025–0.009 nm)). SASE peak and average powers will reach 10 GW and 10 W, respectively.

The LCLS (Stanford, USA) project [91] with a 14.3 GeV electron beam will cover the 0.15–1.5 Å spectral range. The project uses accelerating sections already existing at SLAC. The gub has already been successfully commissioned. LCLS will be the first hard X ray FEL opened to users (2009), followed by the SCSS-XFEL (2010) and the European XFEL (2015).

The SCSS-XFEL (Harima, Japan) at 8 GeV [92] aims at covering the 60–0.1 nm range. It is base on a C-band Linac, in vacuum undulators and a thermo-ionic gun.

Two other projects are under study, one in Korea based on a prolongation of the injector LINAC of Pohang synchrotron light source [93], with additional sections for raising the energy and in-vacuum undulators, and the other one in Switzerland aiming at pushing gun technology for lowering the emittance by 50 [94].

Table 4
Comparison of X ray FELs. The Koeran project, being rather close to the Japanese one, is not mentioned in this table. λ wavelength, gun: emittance given in π mm mrad

	LCLS	SCSS	E XFEL	PSI (Switzerland)
E (GeV)	14.3	8	17.5	5.8
LINAC	Hot	Hot band C	supra	Hot
Frequency (GHz)	3	5	1.3	3–6–12
λ (nm)	0.1–1.5	1.3	0.1–2	1
Bc(e33)	0.8–0.08		5–0.2	5–0.2
Gun (πe-6)	1	0.85	1.2	0.05
undulator	Electromagnetic	In vacuum	Hybrid	Cryo-ondulator
User Start date	2009	2010	2013–2015	

Among these different hard X ray FEL, the Linac choice generally results from the technology which has been developed extensively in the country considered. From a FEL point of view, a warm temperature Linac does not allow a very high repetition rate, as is possible with superconducting Linacs for moderate energies (less than 10 GeV). The electron beam energy is much smaller in the case of the Japanese and Korean projects, which have chosen vacuum small gap undulators: a lower energy is then required to satisfy the resonance condition, leading to a reduced cost. Self-seeding and HHG seeding are seen in the case of the Swiss project, in order to improve temporal coherence. Various studies enabling one to lead rapidly to scientific advances for the improvement of the coherence should be carried out on soft-X ray fourth generation light sources.

3.3. Technological challenges

3.3.1. Low emittance electron guns

Various types of guns are envisaged for satisfying the request for FELs (emittance of 1 µm rad, charge of 1 nC), which are difficult to reach in routine operation [95]. HF guns consist of a Cu resonant cavity in which a photocathode is placed, which is then irradiated by a laser inducing the electron emission [90]. CsTe cathodes now present good lifetimes. Dark current, emitted by field emission, can remain a difficulty. FLASH uses a RF gun equipped with a CsTe cathode and it reaches a performance close to the required objectives [96]. Studies on superconducting guns are currently being carried out [97]. An electrostatic gun ("DC gun") of 500 kV with a thermo-ionic cathode (CeB_6) has been adopted for SCSS and has demonstrated a high stability beam close to the targeted performance [98]. A dramatic reduction of the emittance is proposed at PSI, using an arrangement of field emitters [99]. The reduction of the emittance of photo-injectors aims at being only limited to the thermal emittance, with the help of an ellipsoidal shape laser [100]. Laser solutions are under study [101].

3.3.2. Emittance compensation

Emittance compensation remains a difficult task in case of HF guns [102]. In general, the transverse correlated emittance is minimised at the entrance of the first accelerating cavity with a solenoid where it becomes "frozen" thanks to the disappearance of the space charge forces during the acceleration. In a new scheme, the transverse correlated emittance is maximised with a solenoid at the entrance of the first accelerating cavity and a minimum, smaller than the previous one is obtained at the end of a long accelerating module [103]. In the case of "velocity bunching", electrons produced by a HF gun are injected at a phase corresponding to a zero field in the accelerating structure. During the acceleration, they gather around the phase of maximum acceleration. This method avoids the use of a magnetic chicane of compression [104].

3.3.3. Choice of the linear accelerator

Room temperature Linacs do not allow operation at a high repetition rate (kHz), which is appropriate for particular applications. According to the choice of frequency, high accelerating gradients can be reached. A superconducting linear accelerator permits a CW operation. It typically uses the cavity and cryomodule technology developed for TESLA [105]. The developments related to the CW operation are not yet completed, since the duty cycle of TESLA is only on 1%. In CW operation, there is an economical optimum of the gradient between 15 a 20 MV/m. The main difficulty, however, arises from the excitation of high order modes by the passing of intense bunches associated to a high average current. The produced power is thus partially evacuated by High Order Modes couplers at room temperature. It dissipates partially in the cavity walls and thus enhances the charge of the cryogenic system. The power can also propagate in the electron beam tubes and it should be dissipated with absorbers. The couplers have still to improve the coupling efficiency and be able to bear the increase of average power.

3.3.4. Bunch compression

Electrons bunches of several hundreds of fs are required at the entrance of the undulator. The bunch is compressed via a non-maximum field acceleration of the electrons, leading to a correlation phase-energy, and via the passage in a magnetic system (such as a chicane or a half-turn).

The production of Coherent Synchrotron Radiation (CSR) presents a major difficulty. An electron bunch following a curved trajectory radiates. The radiation for wavelengths longer than the electron bunch length is coherent and its power is higher than the incoherent part. The radiation from the end of the bunch can overpass the head while propagating along the cord of the trajectory. If the field is sufficiently high, the correlated emittance grows. The non-correlated emittance can also be affected by the incoherent emission [106]. Microbunching has been observed. Different chicane schemes have been proposed for minimising all these effects [107].

3.3.5. Specific issues related to the undulators

The optimisation of an undulator for a XFEL consists of several particularities [108]. CSR can lead to an instability in a very long undulator devoted to SASE radiation [109]. The roughness of the vacuum chamber walls, whose height is reduced as much as possible to provide the high magnetic field, can lead to a degradation of the emittance and the energy spread. The installation of long insertion devices introducing a natural focusing requires one to control the beam dimensions thanks to a strong focusing (betatron functions $\beta_{x,z} \sim 2$–10 m) in order to maintain small beam dimensions. The undulators are then either segmented (2–5 m modules) for introducing focusing magnets, or the focalisation is integrated in the pole geometry [110]. In vacuum undulators and further cryogenic insertion devices are a promising path of short wavelength FELs.

3.3.6. Synchronisation

Synchronisation at the order of the 10 ps time scale level between the laser and the photo-injector, the electron bunch and the seed laser, the FEL radiation and a pump laser for user applications is a topic under active study. Techniques of a synchronisation trigger given by an Ytterbium fiber laser, transmission by a fiber network, complex synchronisations and ultra-performing diagnostics can be adopted [111].

Fourth generation FEL sources reach a high peak brilliance, larger by several orders of magnitude than synchrotron third generation sources, with sub-ps pulses. High resolution studies on dilute samples, combined spectroscopy and microscopy take advantage of such a high average brilliance. Dynamical time-resolved studies on the subpicosecond time scale exploit the peak brightness. However, stability is limited in the case of SASE. A FEL allows only a rather small number of experiments to be performed simultaneously (~ 5). Fourth generation ERL based light sources offer a high stability, un large number of users on the different spontaneous emission undulators producing a sub-picosecond radiation, with a brilliance which is slightly smaller than the one of the FEL sources. The accelerator technology for fourth generation light sources, still under development, is however much more mature than that based on plasma accelerators (which is still limited to a rather large energy spread ($> 1\%$) for instance) but which opens a promising path towards ultra-compact sources [112].

4. Fourth generation light sources and Energy Recovery Linacs

4.1. General properties

Another path is explored on Linacs with the energy recovery. The electron beam, after a first acceleration, is sent back in the accelerating cavities with the opposite phase, allowing the energy to be restored to the structures. A few turns only are considered, so that the electron bunch does not have the time to be lengthened, insuring thus sub-ps pulses for users. The energy in the beam dump is reduced, limiting the radiation safety constrains. This mode of operation enables a large average current at high repetition rate, and thus a high average brilliance for a large number of radiation sources based on undulators in spontaneous emission mode. Existing or projected ERLs are generally based on superconducting Linacs for relaxing the constraints of power dissipation in Cu structures. The HF continuous regime, possible in principle, is chosen by users.

4.2. State-of-the-art

The operating or projected facilities are indicated in Table 5. Pioneering work has been conducted at Thomas Jefferson National Accelerator Facility since 1997 [113] on a superconducting Linac of 45 MeV (5 mA, 10 mm mrad emittance, 0.25% energy spread) and accommodates a high average power (several kW) infra-red FEL. Recent results have also been obtained at JAERI (Tokai, Japan) [114] and on the BINP microtron [115] which is implemented on a non-superconducting machine.

The CHESS project at Cornell [116] foresees a beam of 5 GeV and 100 mA (500 MW), with 240 TESLA type superconducting cavities (gradient of 20 MV/m), a cryogenic plant of 16 MW, an electrostatic gun of 500 keV

Table 5
ERL projects (* if an FEL is planned)

	Country	Energy (GeV)	I (mA)	Q (nC)	ε mm mrad	Frequency (MHz)	τ bunch (ps)	Injector	
JLAB IRFEL*	USA	0.04	5	0.135	10	37.5	0.5	DC/photo	Working
JAERI FEL*	Japan	0.017	5	0.5		10	40	DC gun	Working
BINP	Russia	0.012	20		20	180	100	DC gun	Working
JLab Upgrade*	USA	0.2	10	0.135		75	0.2	DC/photo	in construction
CHESS-Cornell	USA	5	100	0.077	0.01	1300	0.1	DC/photo	projet
Cornell ph. 1	USA	0.1	100	0.077		1300	0.1		projet
PERL-BNL	USA	3–7	100	0.15–0.45	18	433–1300	0.1	RF gun	projet
LUX-LBNL	USA	0.6–2.5	0.01	1		0.01	1–0.1	RF gun	4 passages
4 GLS*	GB	0.6	100	0.077		1300		?	study
ERLSYN	Germany	3.5	100						study
MARS	Russia	5.3	1	0.003		352			17 passages, study
KAERI	Korea	0.04	10						in construction
PKU*	China	5–30		0.06	3	1300			project
KEK-JAEA	Japan	5–6	100	0.1–1			<0.1		project
ARC-EN-CIEL	France	1–2	25		2	1300	0.2	DC/supra	project

equipped with a photocathode. The prototype targets a current of 100 mA at 100 MeV, a cryogenic plant of 500 W. The PERL project [117] (BNL) aims at 3 to 7 GeV, an average current of 200 mA, with TESLA types cryogenic modules. The LUX project (LBL) [118] comports a superconducting LINAC of 600 MeV recirculating four times for reaching an energy of 2.5 GeV and in vacuum undulators. The radiation will be produced by Thomson scattering of pulses of 300 fs [119] and on the fs “sliced” emission of synchrotron radiation “slicing” [120]. It has been proposed also to directly compress the X pulse with an optical system down to 60 fs, rather than the electron bunch. The 4GLS project (Daresbury) was based on a Linac of 600 MeV, with energy recovery loops and several spectral ranges [121]. The prototype has recently been operated [122]. The MARS project plans to install several undulators on different loops [123]. KEK and JAERI are gathered around a common project [124].

4.3. Technological challenges

The photo-injector, which should provide high charge and low emittance in the CW regime, remains a critical aspect. The objective of 100 mA of average current is still ten times more ambitious than what has been effectively realised so far. On going developments on DC and superconducting guns remain of major importance for future ERLs.

The development of superconducting accelerator modules has mainly been devoted to pulsed high gradient systems. The ERL operation requires an efficient extraction of the HF power, the development of couplers for the CW mode, the adaptation of the cryogenics system. . . .

4.3.1. Transverse beam dynamics

The brilliance of the electron beam should be conserved along the acceleration and deceleration, whereas the emittance is susceptible to be degraded in the Linac and in the transport lines. The optics should also insure the stability of several beams at different energies. The decelerated beam is submitted to an adiabatic anti-damping which leads to an increase of relative energy spread and transverse dimensions, which can even lead to beam loss.

4.3.2. Collective effects

In ERLs, the recirculated beam forms with the cavities, because of the field that it excites, a loop system. Instabilities can be induced, and the higher the intensity, the pass numbers and the quality factor of the cavity, the larger the instability. These questions are of particular importance since the objective is to enhance the current up to the instability limit. Transverse beam break up instabilities result from the electron beam interaction with the high order transverse modes [125]. Longitudinal instabilities result from the interaction of the electron beam with the fundamental longitudinal modes (“longitudinal beam break up”) and of high order one (“beam loading instabilities”) [126]. The electron bunch should also be decompressed in order to reduce the production of higher order modes when it goes through the Linac again.

A larger current can be achieved on ERL while the higher order modes are further damped. It appears that presently, the most severe limitation results from the transverse instabilities.

5. Conclusion

40 years after the first parasitic use of synchrotron radiation on non-dedicated storage rings, third generation light sources are reliably operating with a highly stable beam for more than ten years. With a higher and higher performance, these storage ring based sources still develop and welcome a very wide user community which benefits from the remarkable properties in term of coherence, brilliance, intensity and tuneability. They propose a high number of beamlines from bending magnets and insertion devices for users. The accelerator technologies required for these sources are very well mastered. As the use of temporal structure develops, new pump-probe experiments are settling for following the temporal evolution of structures and conformations. Such applications require sources of short pulse duration and they become the predilection domain of fourth generation light sources.

Indeed, coherent emission from Free Electron Lasers and spontaneous emission from insertion devices on ERLs open really new prospects, in extending the rich area of non-linear processes and ultra-fast dynamics opened by lasers in the visible to the VUV and X ray domain. First user applications results have already been achieved using radiation in the VUV at Brookhaven, Argonne, DESY and in the soft X ray range at DESY. A certain number of challenges remain to be solved, however, to cover the hard X ray domain. Being simple pass devices, the number of beamlines and experimental stations are in practice lower than on third generation light sources. These fourth generation light sources, which are nowadays in full expansion, appear as complementary sources in the landscape of third generation storage rings and more conventional light sources, in order to resolve scientific problematic that they only enable to access.

ERL based light sources offer a high stability, a intermediate number of users on the different undulator sources in spontaneous emission regime for sub-picoseconds radiation, and a slight lower brilliance than that provided by FEL sources.

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