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POSSIBILITIES FOR FUTURE SYNCHROTRON RADIATION SOURCES

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Abstract

The landscape of present accelerator based light sources is drawn. The photon beam brightness increases opens new areas of user applications, both with the arrival of low emittance rings getting closer to diffraction limit and the advent of X-ray Free Electron Lasers, providing agility in terms of performance (two colors, attosecond pulse....). Finally, the path towards light sources using alternate accelerator schemes, such as plasma acceleration is discussed.

INTRODUCTION

The 20th century saw the rapid development of vacuum tubes, in particular the klystron [1] where bunching is a key process for wave amplification. Accelerator based light sources rely on the emission of synchrotron radiation, first observed in 1947 [2], by accelerated relativistic particles of Lorentz factor γ subjected to a magnetic field, generated for example in bending magnets in circular accelerators. The radiation is collimated in a thin cone of typically $1/\gamma$ angle thanks to the relativistic projection of angles. It covers a wide spectral range from the infra-red to the X-rays. It is pulsed, with a repetition rate and bunch duration depending on the accelerator type. Synchrotron radiation from Insertion Devices (ID) (undulators and wigglers) which create a periodic permanent magnetic field (amplitude B_u, period λ_u) with alternated poles was considered in the mid 20th century [3]. For a planar undulator creating a vertical sinusoidal field, the radiation from the different periods N_u can constructively interfere and emit on-axis at the resonant wavelength λ_r and n^{th} order odd harmonics: $\lambda_r = \lambda_u(1 + K_u^2/2 + \gamma^2\theta^2)/2n\gamma^2$, with K_u the undulator deflexion parameter $K_u = 0.94\lambda_u(cm)B_u(T)$ and θ the observation angle. Variable polarisation can be provided, depending on the undulator helicity. The wavelength can be tuned by the electron energy or by the undulator magnetic field. It is well collimated ($\sigma'_p = \sqrt{\lambda/4L_u}$), has a small source size ($\sigma_p = \sqrt{\lambda_r L_u}/2\pi$), resulting photon emittance ($\epsilon_p = \sigma_p\sigma'_p = \lambda_r/4\pi$), and an associated Rayleigh length $Z_p = \sigma_p/\sigma'_p = L_u/\pi$ [4, 5]. The homogeneous linewidth $\Delta\lambda/\lambda = 1/nN_u$ can be broadened with multi-electron emission (emittance and energy spread terms).

Stimulated emission, in black-body studies [6], was first analysed as addition of photons to already existing ones, and not as the amplification of a monochromatic wave with phase conservation. In «quantum» microwave sources (masers (microwave amplification by stimulated emission of radiation)), the klystron electron beam amplification is replaced by stimulated emission of excited molecules introduced in a microwave cavity resonant for the frequency of the molecule transition [7]. The use of an optical resonator [8] was proposed to extend the radiation to the optical spectral range, and the first Ruby laser was achieved [9]. The vacuum tubes came back into play with the invention of the Free Electron Laser (FEL) [10] with free electrons in an undulator field to replace the molecule in optical cavity for short wavelength operation. 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 λ, the phased electrons then emit coherently emission at λ and its harmonics. This wave-electron interaction can lead to a light amplification to the detriment of the electron kinetic energy. The small signal gain is proportional to the electronic density, varies as γ^{-3}, and grows with the undulator length. FELs can be implemented on various accelerators : storage rings with rather long electron bunches (10-30 ps), linacs with 10 fs -10 ps bunch, energy recovery linac with short pulses, few turn recirculation and low power consumption... FELs are tuneable by merely modifying the magnetic field of the undulator in a given spectral range set by the electron beam energy. On linacs, FEL radiation can be emitted in ultra short pulses. The polarization depends on the undulator configuration. It can easily be changed form linear to circular, using suitable undulators.

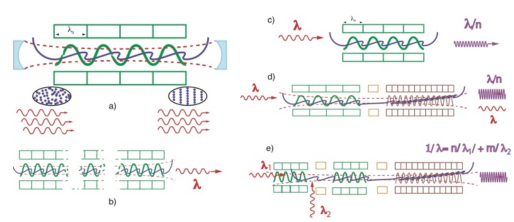

Figure 1: Free Electron Laser configurations : a) oscillator, b) SASE, c) seeding d) HGHG e) EEHG.

Different configurations are used (see Fig. 1). In the historical oscillator mode (a), the synchrotron radiation spontaneous emission stored in an optical cavity enables interaction on many passes. FEL oscillators cover a spectral range from THz to VUV, where mirrors are available. FEL was first achieved in 1977 on a superconducting linac (Stanford, USA) in the infra-red [11]. and then in 1983 on the ACO storage ring (Orsay, France) [12] in the visible and coherent harmonic generation was measured. FEL oscillators cover a spectral range from the THz to the VUV [13]. In the Self Amplified Spontaneous Emission (SASE) (b) setup [14–16], the spontaneous emission is exponentially amplified thanks to a collective instability in a single pass. Once the saturation is reached, the amplification process is replaced by a cyclic energy exchange between the electrons and the radiated field. The emission usually presents poor longitudinal coherence properties, with temporal and spectral spiky emission [17], resulting from non correlated trains of pulses. SASE suits for short wavelength FELs because of the limited perfor-

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mance of mirrors. Thanks to the development of high quality electron guns and to recent accelerator advances (high peak current, small energy spread, low emittance), linac based single pass SASE FEL are blooming worldwide [18]. They now provide tuneable coherent sub-ps pulses in the UV/X-ray region, with record peak powers (MW to GW). For suppressing the spikes, improving the longitudinal coherence, reducing intensity fluctuations jitter and saturation length, a typical strategy consists in seeding (c) the FEL amplifier with a seed that possesses the required coherence properties [19]. The configuration can be set in the high gain harmonic generation (HGHG) (d) where the seed is tuned onto a first modulator, while the harmonic emission is produced by a radiator tuned on the harmonic of the radiation [20]. HGHG can be set in cascade. The Echo Enabled Harmonic Generation (EEHG) (e) [21, 22] ("echo") with two successive laser–electron interactions enables efficient up-frequency conversion : A first laser of wavenumber k_1 tuned on the resonant wavelength of a first modulator applies a first energy modulation ΔE_1, electrons move according to their energy in the chicane of strength $R_{56(1)}$ inducing a striated phase space with multiple energy bands, the spread in one band being smaller than the electron beam energy spread σ_γ. The second laser (wavenumber k_2) tuned in a second modulator sets an additional energy modulation, imprinting a sheet-like structure in phase space. A second moderate chicane rotates the phase space upright, resulting into density modulation, with high frequency components. Since the energy spread of a single band in much smaller than σ_γ, a moderate energy modulation at this stage is sufficient. The echo wavenumber k_e is linked to the wavenumber of the two lasers k_1 and k_2 by $k_e = nk_1 + mk_2$, or in wavelength $\lambda_e = \lambda_1\lambda_2/(n\lambda_2 + m\lambda_1)$, n and m being integers. Echo enables a high up frequency conversion since the bunching factor decays in $|m|^{-1/3}$ as compared for HGHG to $2e^{-0.5(2\pi m R_{56(1)}\sigma_\gamma\lambda_1)^2}|J_m(2\pi m\Delta E_1 R_{56(1)}/E\lambda_1)|$ [19] with σ_γ the relative energy spread. The echo scheme also relaxes the requirement on laser power and slice energy spread, since the HGHG requires the energy modulation to be $\sim m$ times larger than the initial energy spread. In addition, the bunching being rather insensitive to phase space imperfections, because of the applied non linear gymnastics, transformed limited pulses are likely to be achieved.

LIGHT SOURCES FOR USERS

The longitudinal coherence length is given by $l_c = \lambda^2/\Delta\lambda$. The brightness distribution $\mathcal{B}$ in phase space is based on the Wigner distributions [4, 23–28], as $\mathcal{B}(\overrightarrow{\chi_i}, \overrightarrow{\chi_i'}, s, \omega, \widehat{u}) = \frac{\epsilon_0\omega^2 I}{2\pi^2 hce}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\overrightarrow{E}(\overrightarrow{\chi_i'} + \frac{\overrightarrow{\xi}}{2}, s, \omega)\widehat{u*}.\overrightarrow{E^*}(\overrightarrow{\chi_i'} - \frac{\overrightarrow{\xi}}{2}, s, \omega)\widehat{u}\times \exp(-i\frac{\omega}{c}\overrightarrow{\chi_i}.\overrightarrow{\xi})d^2\overrightarrow{\xi}$ with $\widehat{u}$ the polarization state, $\overrightarrow{E}$ the electric field, $\overrightarrow{\chi_i}$ the transverse position (x,z), $\overrightarrow{\chi_i}'$ the angles (θ_x, θ_z), $*$ complex conjugate. It is simply related to the mutual intensity $\mathcal{M}(\overrightarrow{\chi_i}, \overrightarrow{\xi_i}, s, \omega, \widehat{u}) = \langle\overrightarrow{E_i}(\overrightarrow{\chi_i} + \frac{\overrightarrow{\xi}}{2}, s, \omega)\widehat{u^*})(\overrightarrow{E_i^*}(\overrightarrow{\chi_i} - \frac{\overrightarrow{\xi}}{2}, s, \omega)\widehat{u})$ by : $\mathcal{M}(\overrightarrow{\chi_i}, \overrightarrow{\xi_i}, s, \omega, \widehat{u}) = \frac{he}{2\pi\epsilon_0 cI}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\mathcal{B}(\overrightarrow{\chi_i}, \overrightarrow{\chi_i'}, s, \omega, \widehat{u})\exp(-i\frac{\omega}{c}\overrightarrow{\chi_i'}\,\overrightarrow{\xi})d^2\overrightarrow{\chi_i'}$. The on-axis brightness satisfies $|\mathcal{B}_0 = \mathcal{B}_0(x = 0, z = 0, x' = 0, z' = 0, s, \omega = \omega_r, \widehat{u})| \leqslant 4\Phi(\omega, \widehat{u})/\lambda^2$, with $\Phi(\omega, \widehat{u})$ the spectral flux, and gives information on the transverse coherence of the source. The Wigner phase space plots exhibit X-shape that come from the extended nature of the source [24]. The degree of spectral transverse coherence (ability to reach the diffraction limit) is defined as $\zeta_{tc} = \lambda^2\mathcal{B}_{at}/\mathcal{F}$ with $\mathcal{B}_{at}$ the average spectral brightness [28] integrated over transverse coordinates. Practically, when the electron beam emittance $\epsilon_e > \lambda/4\pi$, the trajectory inside the ID induces small deviation in position and angle and the electron beam focusing is not not too much modified, the Gaussian approximation can be used. It is given by : $\mathcal{B} = (\frac{w}{\pi c})^2\mathcal{F}(\omega, \overrightarrow{u})\exp\left(-\frac{\theta_x^2}{2\Sigma_x'} - \frac{\theta_z^2}{2\Sigma_z'} - \frac{x^2}{2\Sigma_x} - \frac{z^2}{2\Sigma_z}\right)$, with $\Sigma_i = \sqrt{\sigma_{ie}^2 + \sigma_{ip}^2}$ and $\Sigma_i' = \sqrt{\sigma_{ie}'^2 + \sigma_{ip}'^2}$ convolutions between the electron/ photon beam sizes and divergences, $i = x, z$. $\mathcal{B}$ can then be simplified as the number of photons per second and per unit of phase space. One gets : $\mathcal{B}_{at} = \mathcal{B}_0/4$ and $\zeta_{tc} = (\lambda/4\pi)^2/\Sigma_x\Sigma_z\Sigma_x'\Sigma_z'$.

Accelerator light sources are classified in generations [29–31]. The first one utilized of the parasitic synchrotron radiation emitted in storage rings initially built for high energy physics. The second generation was developed on dedicated storage ring accelerators. The storage ring based third one arose on with reduced emittance using in general Double Bend Achromat lattice (DBA) and high number of insertion devices, providing partial transverse coherence and higher brightness. Light pulses are limited in terms of pulse duration to a few ps, unless adopting the slicing scheme with a reduced total flux [32]. The trend is now to evolve towards diffraction limited storage ring, with a sub nm.rad emittance [33]. Fourth Generation Light Sources provide short pulse duration thanks to single pass accelerators (linacs or energy recovery linacs) and longitudinal coherence by setting in phase the emitting electrons thanks to the FEL process, achieving unprecedented peak brightness.

Since the laser invention, the FEL advent in the X-ray domain (fourth generation light source) half a century later, has opened new areas for matter investigation (structure and dynamics) on unexplored domains with higher temporal resolution. Ultra- intense X-ray FELs give access to the unexplored domain of X-ray non linear optics under extreme conditions [34, 35]. In addition, the femtosecond XFEL can be combined to an optical laser for pump (manipulating the internal electronic state)/probe experiments, enabling to provide molecular movies (tracking of structure and electronic states) and process dynamics [36,37]. Besides, taking advantage of the coherence and of the femtosecond FEL duration, and considering that the diffraction can take place before the destruction of the sample [38], coherent diffraction imaging [39] can be applied to tiny, fragile crystals in solution [40] even at a high repetition rate [41] (with the so-called serial crystallography technique) and single particules such as virus [42] with very good spatial resolution below

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1 nm. XFELs permits imaging of living cells [43], i.e. in a jet containing non synchronized cell cultures undergoing active growth. Dynamics of proteins can be followed by pump-probe measurements [44], as for example enabling to see the trans-to-cis isomerisation of the chromophore in the photoactive yellow protein [45]. The improved transverse coherence offered by storage rings is now suitable for coherent diffraction techniques [46] including ptychography [47] or for X-ray photon correlation spectroscopy [48], techniques which have been pioniered by XFELs. Small spot sizes on the sample offer new instrumental opportunities for RIXS for sensitively analyzing inhomogeneous samples and single shot parallel detection of incident and emitted photons [49]. Flux density is also a main feature of interest for the users.

LOW EMITTANCE RINGS

Enhancement of the flux, proportional to N_u, and thus of brightness, can result from undulator development. The recent development of cryogenic permanent magnet and superconducting undulator enables to shorten the period while enhancing the magnetic field for providing an equivalent spectral range and to accommodate more periods for a given spectral range and available length. For user application taking advantage of the brightness, the transverse coherence can be approached with an emittance reduction.

At equilibrium between quantum excitation and radiation damping, the natural horizontal emittance ϵ_{x0} and energy spread are given by [50]: $\epsilon_{x0} = C_q \gamma^2 \frac{\langle H/|\rho^3|\rangle}{J_x \langle 1/\rho^2 \rangle}$ and $\sigma_{\gamma 0} = \sqrt{C_q}\gamma\sqrt{\frac{\langle |1/\rho^3| \rangle}{J_z \langle 1/\rho^2 \rangle}}$ with $C_q = 3.84 \times 10^{-13}$ m, $H(s)$ the dispersion invariant $H = \gamma_T \eta^2 + 2\alpha_T \eta\eta'^2 + \beta_T \eta'^2$ with γ_T, β_T and α_T the Twiss parameters [51], η and η' the dispersion function and derivative. Different approaches can be considered for lowering the emittance [33, 52]. First, the energy reduction, even apparently straightforward, comes in contradiction with the obtention of hard X-ray radiation on ID, and the possible Intra Beam Scattering issues. Second, the horizontal damping partition number J_x can be increased with the installation of damping wigglers in zero dispersion straight sections [53] as for example on PEPX, PETRA III, NSLS II [54], but to the detriment of the straight section length for beamlines ID. Third, the partition number J_x can be enhanced with horizontally defocusing gradient in dipoles, steered off quadrupoles or with transverse gradient undulators or Robinson wigglers in non-zero dispersion straight section [55]. The emittance reduction is accompanied with an afferent energy spread increase, that has to be avoided for maintaining the undulator spectral purity Fourth, as the natural horizontal emittance ϵ_{x0} for an isomagnetic lattice simplifies as : $\epsilon_{x_0} = F\frac{E^2}{N_d^3}$ with F a constant depending on the lattice design, N_d the number of dipoles, Multi Bend Achromat (MBA) lattices [56] are nowadays generally adopted for the new generation of "diffracted limited storage rings". The progress of the vacuum chamber technology with NEG pumping, the development of compact performant magnets enable the present advent of such rings, such as MAX IV, SIRIUS, ESRF and a blossom everywhere of new light sources under design or construction all over the word. Besides, the betatron function should be matched to the Rayleigh length of the photons $\beta = Z_p$ and thus $\sigma_e/\sigma'_e = \sigma_p/\sigma'_p = L_u/\pi$. Sub nm emittances enable to enhance the Gaussian coherent fraction by typically two orders of magnitude and to approach the diffraction limit $\epsilon_p = \sigma_p \sigma'_{ph} = \lambda/4\pi$ down to the X-ray range. In reality, when the electron and photon emittance get similar, the Wigner formalism shows that even smaller emittance would be necessary [28, 57]. Various challenges arise: Strong focusing magnets with combined functions (permanent magnet based solutions), impedance issues, injection (swap out, longitudinal injection...), vacuum chamber should with integrated pumping, such as NEG or antichambers. Harmonic cavities are often employed to lengthen the bunch and the lifetime, leaving less flexibility for generation of short pulses. Various solutions are considered : CRAB cavities, echo [58] (SLS-II), short and long bunches with two cavities of 3rd and 3.5th harmonic frequencies (BESSY).

PERSPECTIVES WITH FELS

Presently, agility in FEL performance are proposed thanks to advanced electron beam manipulations. Seeding is developed for enhancement of longitudinal coherence. Direct seeding has been extended to short wavelengths with High order Harmonics generated in Gas (HHG) [59–62]. The required energy modulation for sufficient bunching at nth harmonic scales as $\sim n\sigma_\gamma$, and the gain deteriorates for n $\sim$15, setting a limit to the 15th order per stage [63, 64] and to 70 for two stages [65]. For the X-ray range, self-seeding can be applied [66–68]. After its invention, an echo coherent harmonic emission has been rapidly demonstrated on harmonics 3 and 4 [69] the Next Linear Collider Test Accelerator (NLCTA) at SLAC, on DSUV-FEL in SINAP [70], then 7 [71], 15 [72], 19 at nm on SXFEL [73], 75 [74] on NLCTA, up to 101 [75] at FERMI at 2.6 nm. Significant gain was achieved on the third harmonic on DSUV-FEL on H3 [70] (5 orders of magnitude), H11 at 24 nm [73] and on H45 FERMI [75] down to 5.9 nm at 1.5 GeV. Enhanced stability as compared to HGHG configuration is demonstrated. As the bunching factor changes smoothly for consecutive harmonic numbers, multicolor operation has also been measured at 5.7 and 5.9 nm. EEHG could be extented down to the water window, either with an EEHG set-up alone, or combined with a HGHG one afterwards [76] or with a triple modulator chicane scheme [77].

Two color FEL enable now X-ray X-ray pump probe user experiments with one single bunch and undulator segments differently tuned [78–80], with pulse splitting [81, 82] or with twin bunches [83, 84].

Great progresses with ultra short single spike SASE pulse using various electron beam manipulation shaping or FEL specific regime are achieved [85]. Very recently, 280 (480) as FWHM at 0.9 (0.5) keV [86] were achieved with unprecedented power (tens of μJ), opening new areas of exploration

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that HHG can not access. CW operation is also under way with EuXFEL and NSLSII.

Polarization is controlled on demand [87].

Optic vortices can also be produced [88].

FEL oscillators come back into play for the X-ray regime [89] for high repetition rate low bandwidth XFELs or for driving kW average power EUV lithography.

OTHER DIRECTIONS

For a longer future term, one can think of alternative accelerator concepts, such a dielectric acceleration [90], inverse FEL [91], plasma acceleration. In the case of laser plasma acceleration [92,93], the electron divergence and energy spread should be properly handled for an FEL application [94–98]. Undulator radiation has been successfully be observed after proper electron beam transport along the COXINEL manipulation line [99–101]. Electron beams with low divergence, energy spread associated with high charge/MeV in a reliable basis are still needed for the demonstration of laser plasma acceleration based Free Electron Laser.

CONCLUSION

Present accelerator light sources serve a wide community interconnecting people. They are extremely reliable and robust. X FEL evolving toward high repetition rate, simultaneous multi-user operation and storage rings enhancing the degree of transverse coherence are getting closer. Coherence related imaging that started efficiently on XFEL, will be able to take advantage of nearly circular beams from DLSR, with a nanoresolution combined with chemical, physical, electronic and magnetic properties of complex objects (non destructive). Femtosecond XFEL imaging applications can then be applied to tiny, fragile crystals and single particules with very good spatial resolution. Pump/probe experiments with XFELs will continue to enable investigations in ultra fast dynamics, in particular with the advent of attosecond intense pulses, surpassing HHG in power. The ultra intense FELs are also unique tool for X-ray non linear optics under extreme conditions. MBA storage ring light sources will open a new era with full / partial transverse coherence for coherent diffraction imaging, tomography, scattering. Next, we are looking toward further emittance reduction, smaller energy spreads, longer straights for short period high field ID. FEL are the most intense lasers in the X-ray range. Advanced properties are achieved for users with various gymnastics to shape the electron beam. We are foreseeing CW operation, TW pulses, XFELO, compact echo based FEL, further beam manipulations.... Active research is working on light sources with advanced acceleration concepts.

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