FELS USING STORAGE RINGS

M. E. Couprie(1,2)
CEA DSM DRECAM SPAM, Cen-Saclay 91191 Gif Sur Yvette ; LURE Bât. 209 D 91 405 Orsay FRANCE

Abstract

Performances of Storage Ring Free Electron Lasers (SRFELs) are given, together with the FEL-electron beam interaction and prospects for short wavelength operation, in the oscillator mode or by the FEL-induced coherent harmonics in the undulator. Design of a SRFEL on a specific ring or in compatibility with Synchrotron Radiation is discussed, considering various issues including user experiments. SRFELs are replaced in the frame of the developpements for the 4th generation of sources and compared.

INTRODUCTION

FELs are coherent, tunable, pulsed light sources, first demonstrated nearly 20 years ago [1]. Largely developed in the infra-red where the gain is rather high, several user facilities mainly based on LINAC are spread over the world in such a spectral range. The gain in the UV drops and high beam quality is required, leading to the use of storage rings [2-7] or recent technologies of photoinjector on LINAC [8] and more recently, on a LINAC based facility covering various spectral range in Japan (FELI) [9]. First FEL user experiments were carried out on Super-ACO in partial compatibility with the users of synchrotron radiation, taking advantage of the temporal structure (two bunches mode) [10, 11], demonstrating that a stage of maturity has been reached.

1 GENERAL PRINCIPLES

The FEL amplifying system is produced by the interaction of relativistic electrons (of normalized energy γ) in a permanent periodic magnetic field with the light waves. The electron beam passes through the sinusoïdal vertical field of the undulator (of peak value Bo et period λ_o), emitting synchrotron radiation on the fundamental wavelength λ and its harmonics according to:

$$\lambda=\lambda_o(1+K^2/2)/2\gamma^2 \qquad (1)$$

with the deflection parameter K = 0.94 λo(cm) Bo(T). By storing this radiation into an optical cavity, and by ensuring a proper synchronization between the positron bunches and the optical pulses (so-called "detuning"), the energy exchange occurring between them into the undulator can lead to the light amplification to the detriment of the kinetic energy of the electrons, and to the laser effect. This exchange leads to a redistribution of the energy distribution of the bunch, and generally, to an increase of its width ("bunch heating"). Such sources are simply tunable by modification of the magnetic field of the undulator. The spectral range is mainly determined by the energy, and consequently, the type of accelerator.

The first visible and UV SRFELs experiments were designed on storage ring of usual beam quality, rather short straight sections so that the gain was particularly small. The gain can be artificially enhanced by employing an optical klystron [12]. It consists of two identical undulators of N periods separated by a dispersive section, creating a large wiggle of magnetic field, introducing the interference order N_d between the two undulators. The obtained radiation results from the interference from the undulators, as for two Young slits in optics. The equivalent of the optical contrast is the modulation rate f, mainly determined by the energy spread of the beam (σ_γ/γ). $f=f_o \exp(-8\,\pi 2\,(N+N_d)^2\,(\sigma_\gamma/\gamma)^2)$, f_o being the residual modulation rate due to other contributions. The gain, derivative of the spontaneous emission, is enhanced with the fringe structure. In the first undulator, the electron beam/ optical pulse interaction lead to an energy modulation in the electron bunch, tranformed into a density modulation by the dispersive section, enhancing thus the coherence of the emission from the electrons in the second undulator. The FEL gain with an optical klystron of length L_{ok} is given by :

$$G_o=1.12\ 10^{-13}\,(N+N_d)\,K^2\,L_{ok}^2\,(JJ)^2\,f\,F_f\,\rho\,/\gamma^3 \qquad (2)$$

with $JJ^2=(J1(\xi)-J0(\xi))^2$ with $\xi=K^2/(4+2K^2)$

ρ the electronic density, F_f the filling factor representing the transverse overlap between the optical and electron pulses. The gain increases for lower beam energies, high beam quality (low emittance), long interaction region (long insertion device). Nevertheless, working at low energy on a storage ring reduces dramatically the Touschek lifetime.

Besides the usual optical resonator configuration where the spontaneous emission from the undulator is amplified and leads to the laser, coherent harmonics from an external laser source can be generated by the electron/photon interaction process in a planar undulator, the efficiency being smaller for higher harmonics. VUV coherent harmonics were observed [13]. Such a scheme could also be applied for the production of coherent harmonics from the FEL itself., allowing the spectral range to be extended towards shorter wavelengths by one decade.

In addition, for the production of X-Ray radiation without mirrors, the Self Amplified Spontaneous Emission (SASE) scheme has been proposed : a beam of very high electronic density interacts with its own radiation along its progression in a very long undulator, so that the resulting emission at the end of the undulator becomes coherent. The process being demonstrated only in the infra-red, such a solution could be viewed as an alternative to more conventional schemes, requiring challenging technological performances.

2 SRFEL PERFORMANCES

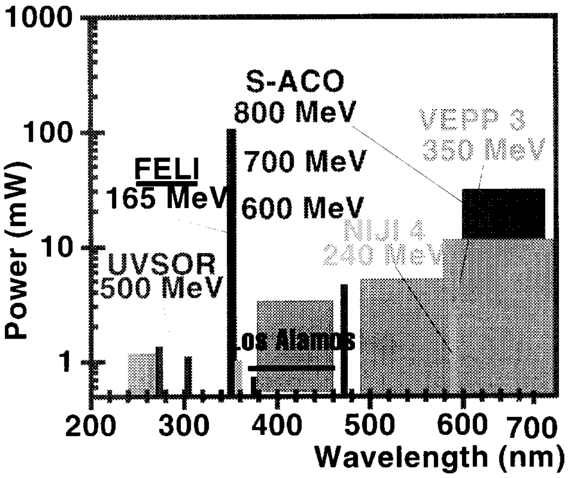

Fig. 1. Laser average power versus the spectral range for existing and shut down FEL facilities. FEL operated on Linear Accelerator are underlined.

The spectral range covered by FELs in the UV (see fig.1) is still rather limited, eventhough great expects were put in FEL. The record of the shortest wavelength is at 240 nm, obtained on the VEPP3 storage ring, where the FEL experiment is presently shut-down. Difficulties mainly come from

- a limited gain, due to rather short straight sections for the insertion device (the maximum length being of 7 m on VEPP3)
- rather long electron bunches (as on UVSOR, bunches can be shortened with harmonic cavities)
- a reduced choice of mirrors, with additional losses compared to the infra-red region, together with a hostile environment provided by the harmonics of the undulator extending towards the X-ray range.

According to the first theories of SRFELs (Renieri limit [14]), the SRFEL power is proportional to the increase of the square of energy spread induced by the interaction, and to the synchrotron radiation power Psynch (Psynch α I γ^4). Operating at a higher energy and current I as on Super-ACO provides a higher laser power and a longer laser duration.

The temporal structure of a storage ring FEL first results from that of the electron beam from which it is generated at a rather high repetition rate (~ MHz). The FEL micropulse duration is 5 to 20 times shorter than the electron bunch, ranging between 200 ps (VEPP3) to 15 ps (UVSOR) FWHM (the amplification occuring for the maximum of electronic density). It would be difficult to reach the fms range, because of the associated reduction of Touschek lifetime associated to very short electron bunches; FEL driven by LINAC with a photoinjector should be preferable for that purpose. Less than ten ps is reasonnable, assuming shorter electrons bunches on a new generation of machines. Les hope is put now in the low alpha operation because short bunches are only achieved at very low current, so with rather low peak electronic density and lifetime.

Besides, storage ring FELs can present in addition to the ps structure, a macrotemporal behaviour at the ms scale, either for bad beam stability or for particular conditions of detuning, with a natural frequency depending on the laser risetime and the synchrotron damping time or synchronised on line, on its multiples and harmonics [15]. With an artificial gain modulation, the laser can adopt a chaotic regime [16] ; a high stability is thus imperatively required.

In addition, the FEL can be operated in the Q-switched mode: the gain is artificially suppressed during 10-50 ms by changing the revolution frequency in the ring (ie tuning) or the beam orbit (transverse overlap), and suddenly reestablished. Thus, the laser starts from a non perturbated situation, with a rise-time of the order of 50 ms and presents a forced macrotemporal structure, a peak power enhanced by the order of 30, compared to the natural mode, and the pulse to pulse intensity is more stable.

The natural laser linewidth is of the order of 10^{-4}, smaller than the one given by the undulator radiation ($\Delta\lambda/\lambda$=1/nN, of the order of 10% for 10 periods). It can be narrowed using an intra-cavity etalon, as demonstrated on VEPP3 [3] leading to a relative value of 10^{-6}. The Fourier limit for gaussian beams is given by: $\Delta\lambda/\lambda = 1.5\ 10^{-6}\ \lambda(nm)/\Delta\tau$ (FWHM ps). So, for a 10 ps FEL pulse at 200 nm, the spectral resolution of a few 10^{-5} could induce a compromise between the pulse duration and the spectral resolution according to the use of the laser source.

Spectral and temporal width acheived on various FEL sources in the UV are plotted in fig. 2. Linac driven FEL provide the shortest pulses but a bad spectral resolution, to the difference of storage ring FELs. The choice should be made according to the use, depending whether energy resolution or very short pulses are required.

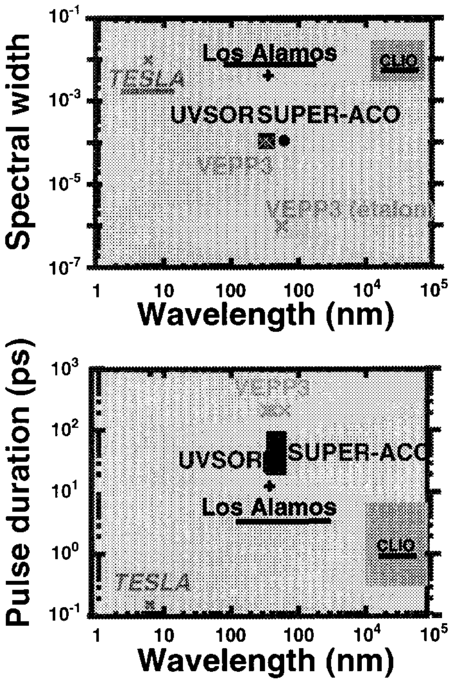

Fig. 2 : Spectral and temporal widths vs wavelength

The transverse characteristics of the laser are determined by the optical resonator, assuming a TEMoo gaussian beam. The length of the optical cavity should correspond to a sub-harmonic of the revolution frequency, for insuring the synchronism condition. Because of the longer straights sections for getting higher gains, the tendancy is now to get longer resonators (more than 50 m on DUKE, ~ 40 m on SOLEIL). Generally, the waist is ~300-400 µm and the angular divergence around 100-200 µrad. The optimization of the transverse overlap between the electron beam and the optical pulse does not require specifically very small electron beam (of the order of the waist in both directions), because the spatial coherence is determined by the optical resonator. For synchrotron radiation, limited diffraction sources require very small emittance because the spatial coherence is determined by the beam size and divergence, convoluted with the photon emission.

So far, SRFELs operated with planar undulator, producing a laser field horizontally polarized. Recently (april 1996) was installed on UVSOR an optical klystron for adjustable field from planar to helical, leading to an adjustable polarization of the laser. The modulation in the spectrum could be observed. In addition, the gain is higher in the helical mode for an equivalent length. Only the first harmonic being produced on axis, the mirror degradation should be reduced, but the production of coherent harmonics from the FEL for extention of its spectral range is no more possible.

3 SRFEL INTERACTION

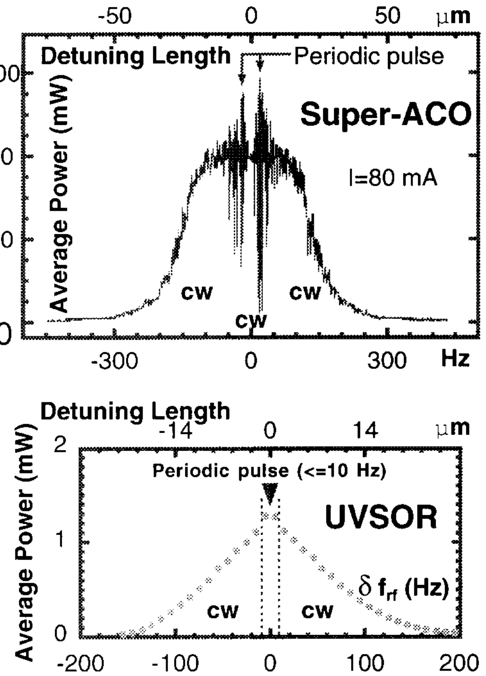

Fig 3. Experimental detuning curve

The dynamics of storage ring FELs is highly dependent on the tuning condition (synchronism between the optical pulses in the optical cavity and the bunches stored in the ring) and on the beam stability. Reproducible behaviour of the FEL versus detuning could be observed in two places. On Super-ACO, one can distinguish five zones of operation (see figure 1) [15] : zone 3 around perfect tuning with maximum power, minimum temporal and spectral widths, "cw" operation in the ms range, but with some jitter and intensity fluctuations; two adjacent zones (2 and 4), with a slight detuning, with a pulsed regime, wider distributions and smaller power; areas 1 and 5 with larger detuning: "cw" laser, more reduced power and broadened distributions, but higher stability in position and intensity. On UVSOR, the cw central region is so tiny that only a main pulsed central region appears (corresponding to zones 2 and 4) surrounded by two detuned cw regions.

The macro-temporal structure was first understood by considering the dimensionless laser intensity I increase and "bunch heating" according to:

$dI/dt = I\,(G-P)/T_O + I_S$ and $d\Sigma/dt = 2\,(I-\Sigma)/\tau_S$

with To the round-trip time, Is the spontaneous emission, P the cavity losses, $\Sigma = (\sigma\gamma/\gamma^2 - \sigma\gamma/\gamma_{off}^2)/(\sigma\gamma/\gamma_{eq}^2 - \sigma\gamma/\gamma_{off}^2)$, $\sigma\gamma/\gamma_{eq}$ standing for the energy spread without laser and $\sigma\gamma/\gamma_{eq}$ with the laser at equilibrium (Σ=I=1). With an ideal beam (without anomalous bunch lengthening), the laser interaction should "heat" the beam, and enhance the energy spread and consequently slightly the bunch length [14]. Small perturbations to the stationary solution of these coupled equations gives the natural laser oscillating period, according to [15]: $T_r = 2\pi (\tau_r \tau_s/2)^{1/2}$ with τ_r the laser rise-time $\tau_r=T_o/(G-P)$.

One can consider the pass-to-pass longitudinal evolution [17]: $y_{n+1}(\tau) = R^2\, y_n(\tau-\varepsilon)\, [\, 1 + g(\tau)] + i_s$ $y_n(\tau)$ being the longitudinal profile of the laser pulse, τ the longitudinal coordinate inside the micropulse (the origin being taken at the synchronous electron), R^2 the mirror reflectivity, ε the detuning with respect to the electron bunch and i_s the spontaneous emission. The total laser dimensionless intensity $I_l(t)$ is the integral of $y(t, \tau)$ over $d\tau$. The longitudinal distribution profile of the electron bunch can be assumed to be gaussian, so: $g = g_o \exp(-\tau^2/2\sigma_l^2)$. The laser saturation results from the laser detuning process combined with the enhancement of the energy spread leading to the gain reduction according to $g_o= g_{off}\, (P/g_{off})^{\Sigma}$, g_{off} being the inital gain without laser. This model leads to :

- Apart from the "bunch heating", the laser can also saturate (reach G=P) because of the laser micropulse jittering [18] accumulated over passes, as observed on Super-ACO around perfect tuning (where the micropulse position can change very rapidly for a very small modification of the synchronization), without great modification of the positron bunch distribution and energy spread. For a detuned condition, with smaller initial gain closer to the losses, the FEL micropulse is confined in its position and a very small increase of energy spread is sufficient to saturate. Such a phenomenon has been observed on Super-ACO, the only FEL being cw for a small detuning range around perfect synchronism.
- According to the tuning condition and the relative values of τ_r and τ_s, the response of the laser can be damped oscillator leading to a cw regime (as in zones 1, 3, 5 for the Super-ACO FEL) or oscillator of relaxation (as in zones 2 and 4).

Pass to pass evolution of the laser micropulse starting from the spontaneous emission of the undulator can also be modelized in the frequency space [20]. Such model allows the detuning curves to be simulated (see figure 4), in good agreement with the previous representation. Moreover, it seems that both the spectral and temporal narrowing of the FEL micropulse can occur towards the Fourier limit, even after the laser saturation. Experimentally, it is 5-50 time bigger than the Fourier limit. Besides, such a model allows to follow the FEL stability in response to a perturbation : clearly, the laser adopts damped oscillations of relaxation in zone 3 whereas it directly comes back to its equilibrium state in zone 5 (for the Super-ACO case), in good agreement with the experimental behaviour.

Eventhough the understanding of SRFELs dynamics (a very complex system including the beam evolution in the storage ring coupled to the FEL interaction) is progressing, some aspects were neglected so far. For instance, a new work attempts to consider both the FEL interaction together with the microwave instability [19]. A real description is required for being able to completely control the FEL.

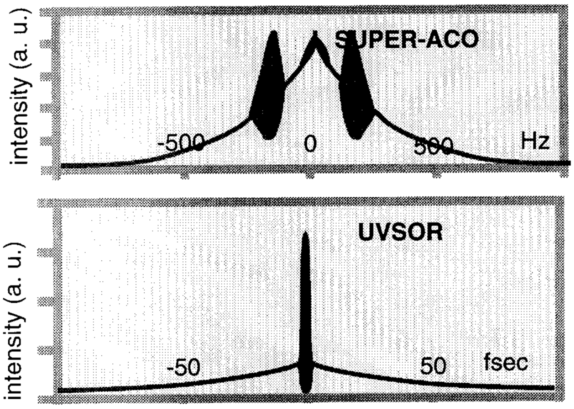

Fig. 4 : Theoretical detuning curve

4 SRFEL STABILITY FOR USERS

The feasibility of using the Super-ACO storage ring as a UV light source was demonstrated with the study of polarized fluorescence decays of the reduced nicotinamide adenine dinucleotide coenzyme in aqueous solution [10]. The temperature dependance of the two measured lifetime components led to the thermodynamical parameters of the conformational equilibrium, in good agreement with other spectroscopic techniques. The fluorescence anisotropy decays versus temperature provides an apparent hydrodynamic radius of the folded form (in good agreement with that deduced from Van der Waals models) and indicates a fast independent motion of the nicotinamide ring. The quality of the collected data fully meets the requirements for the study of more complex systems such as fluorescent compounds bound to proteins or membranes.

Moreover, a specificity of SRFELs comes from pump-probe experiments combining the FEL with synchrotron radiation, both naturally synchronized, polarised, tunable : the dynamics of the intermediate state excited by the pump beam and characterized by the probe source, being analysed by varying the delay between the two- light source. It opens a wide field of applications for storage rings FELs, where synchrotron radiation covers from the infrared to X-rays, and can apply to various scientific fields. First results were obtained on Super-ACO in interface physics for the study of the surface photovoltage effect at the semi-conductor/metal [11].

The stability is a critical issue for SFELs sources for users. In the longitudinal space, the laser micropulse jittering for its maximum power and minimum widths, but the spectral drift and the intensity fluctuations are very prejudicable for users. On Super-ACO was developed a longitudinal feedback system detecting the temporal change of the FEL micropulse at 300 Hz and reajusting the synchronisation condition with the RF frequency, allowed the laser micropulse jitter to be reduced down to 10-50 ps, the intensity fluctuations to 1 % and spectral drifts to less than the resolution of a scanning Fabry-Perot (0.01 Å)[21]. If the laser is pulsed in the central region as on UVSOR [4], a feedback should be developped in the cw detuned region. Otherwise, one can Q-switch the laser at perfect tuning, but it introduces an additional macrotemporal structure, leading to different FEL features.

In addition, one aims to operate the FEL with the higher current as possible, for getting higher gain and laser power, together with a better compatibility with the users of synchrotron radiation, but the presence of coherent modes of synchrotron oscillations generally limits the maximum threshold of operation of the FEL : a gain reduction occurs because of the evolution of the beam longitudinal distribution and the maximum of electronic density is changing in position and intensity; and if the laser can start, it is very unstable. A feedback on the quadrupolar modes of synchrotron oscillations was recently developed on Super-ACO allowing a stable operation of the source from 120 mA with high laser power (while also applying the longitudinal feedback on the FEL).

Some correlations could be established between the transverse position and angles of the beam in the undulator and the laser intensity.

User applications also require a stable lasing during a sufficient amount of time (a few hours) without significative changes of the FEL performances (power especially). Excluding the topping-up filling of the ring and as the maximum energy is limited to ~2 GeV, the laser duration is mainly related to the Touschek lifetime on the present experiments. Short laser duration (~ one hour) is the usual case for SRFELs, especially when the maximum gain is required for short wavelength operation (case of VEPP3 at 240 nm and UVSOR at 270 nm below 500 MeV). Nevertheless, the laser power is very low and the duration is too short. An opposite approach is now followed on Super-ACO, where the FEL is operated at the nominal energy (800 MeV) with more than two orders of magnitude on the laser power and 10 hours of consequent lasing per beam injection.

The final aspect concerns the stability of the mirrors, receiving the undulator spectrum extending down to the X-ray range (the harmonic content being stronger for higher beam energies and K), leading to a degradation of the losses and a possible heating. So far, multilayer dielectric mirrors are used, because of the rather low gain on the present experiments. The degradation rate under irradiation can vary between 0.2 to 40 % / A.h depending on the mirror technology (in the case of Super-ACO, which provides the worst environment, because of its higher energy of operation). Losses can be partially recovered with oxygen plasma and baking. With higher gains, metallic mirrors could be used down to 120 nm. Multilayer X rays mirrors provide more improved performances.

CONCLUSION

SRFELs appears to be very promising coherent light sources (with a full spatial coherence and not so far from the Fourier limit). First users experiments (one color and pump-probe two color in combination with synchrotron radiation) demonstrates their quality in terms of stability and that original results can be obtained. In the future, one can view a SRFEL implemented on a long straight section dedicated to synchrotron radiation, as a “complex” insertion device with a average brillance of 10^{24} phs/s/mm^2/mrad^2/0.1%BW.

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