SINGLE PASS FELs

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Abstract

The RF linacs are now considered as a good electron source for infra-red lasers, ranging from the visible or near-infrared (~1μm) to the middle infra-red (~100μm) spectral regions. Several devices of that type, aimed at being user facilities, are now under constructions in various places of the world : USA, Japan, China in particular. The electrostatic accelerator, since its delivers a dc electron beam, can drive a FEL with a very high spectral purity in the far-infrared range (typically 100 μm to a few mm). The research now focuses on the followig points : - improvement of the beam brightness, by using photocathodes for examples, in order to be able to produce lower laser wavelengths an/or higher power - Realization of low energy (~1 MeV) high current and high duty cycle devices for plasma physics applications - Realization of short period undulator associated with low emittance beam in order to reduce the size and cost of an FEL working at a given wavelength.

A single pass FEL is a configuration in which the accelerated electrons pass only once in the light amplifier (constituted by the electrons themselves travelling through the undulator or some magnetic or electric combination of fields). The light itself may pass once through the amplifier (Super-radiance) or several times (oscillator configuration). The single pass FEL is opposed to the storage ring FEL in which the same electron bunch passes almost indefinitely in the amplifier. Before going further let us point out that more than 90% of the works in the FEL field deal with the single pass lasers so that our review of a so vast subject can be only very schematic. I refer the reader to the last four FEL conferences [1-4] and references therein.

I - Optical gain of the Compton FEL

In this section we will restrict ourselves to the case of the Compton FEL(2 waves interaction) since it covers most of the spectral range. The Raman FEL in which a third, plasma wave, developps into the process is practically restricted to the production of mm & cm waves. The light of intensity I passing through the amplifier (Fig.1) is amplified so that, in the elementary theory[5] the "small signal" gain is given by :

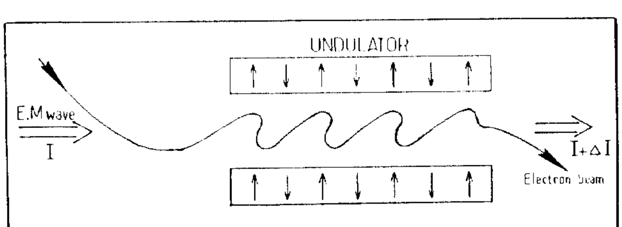

Fig.1 : Sketch of an FEL amplifier

$$G(\lambda) = \frac{I + \Delta I}{I}$$

$$= \left(\frac{L_{und}}{\gamma}\right)^3 \frac{K^2}{\lambda_o} \frac{J}{\Sigma_e + \Sigma_o} F_{inh}(\sigma_\theta, \sigma_\gamma)$$

where λ_o = undulator period
K = undulator parameter
γ = reduced energy
$\lambda = \frac{\lambda_o}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$ wavelength
J = electron beam peak current
Σ_e = electron beam transverse cross section
Σ_o = optical beam transverse cross section
$L_{und} = N\lambda_o$
$F_{inh}(\sigma_\theta, \sigma_\gamma)$ = Inhomogeneous bradeging

That last term arises from to the fact that electrons which propagates with different velocities and at different angles do not produce the same wavelenght :

$$\lambda = \frac{\lambda_o}{2\gamma^2}\left(1 + \frac{k^2}{2} + \gamma^2\theta^2\right)$$

and $\frac{\Delta\lambda}{\lambda} \cong 2\frac{\Delta\gamma}{\gamma}$ energy spread

$\cong \frac{\gamma^2\theta^2}{1 + K^2/2}$ angular divergence

these values have to be compared to $\frac{\Delta\lambda}{\lambda} \sim \frac{1}{2N}$, width of the gain curve. Therefore the electron beam entering the FEL is optimized with a high peak current, a low emittance (since both the transverse cross section and divergence have to be minimized) and a low energy spread. The numbers generally admitted are the following.

emittance : $\varepsilon = 4\pi\sigma\sigma_\theta \sim \lambda$

so that ε scales $\sim\frac{1}{\gamma^2}$ and ε_n (normalized emittance) as $\sim\frac{1}{\gamma} \sim\lambda^{1/2}$

energy spread : $\frac{\sigma_\gamma}{\gamma} \leq \frac{1}{4N}$

It follows that the lower is the FEL wavelength, λ, the lower have to be the emittance and the energy spread (since one has to increase the number of periods, N , to compensate the term $1/\gamma^3$ in the gain). One has also to increase J as long as this does not spoils the other beam qualities (the gain goes approwimately like the normalized beam brightness $\frac{\hat{I}}{\varepsilon_n^2}$ or $\frac{\hat{I}}{\sigma_\gamma \varepsilon_n^2}$) In practice the state of the art accelerators have to be used for FEL experiments. Even so the shortest wavelength obtained up to now is 210 nm with an oscillator on an storage ring[6] and 106 nm by harmonic generation[7]. At high gain ($G \geq 1$) the gain expression is different but the physics discussed above still holds particularly to determine the smallest wavelength atainable, which is ever determined by the "small signal gain" regime.

II - Comparaison between Single Pass & Storage Ring FELs

Wavelength range : The storage rings (SR) work at high energy and become unstable below typically 200 MeV. Therefore the SR will be reserved in the future to experiments in the XUV ($\lambda \leq 100$ nm) spectral range.

The linac have an almost unlimited energy range (E>500 MeV is useless for FELs) and are definitely the good choice for all the other FEL applications : visible, IR, FIR, mm waves spectral ranges, power applications. For the XUV the situation is not yet clear. Proposals have been made to use an RF linac in this range[8].

Beam quality : SR can have very low emitance and energy spread (down to 10^{-4} in σ_γ/σ at low current). However the peak current is in practice limited (turbulence...) to about 10 Amp.

linac exhibit various performances at various energies with different types of acceleration. RF linacs have recently demonstrated excellent performances : $I \sim 10\text{-}10^3$ Amp and $\varepsilon_n \sim 10\text{-}100$ πmm mrad[1-4]. Electrostatic accelerators have the capability of excellent energy spread ($\sim 10^{-4}$) and emittances but lower peak currents (<10 Amp). Induction linacs have the capability of enormous peak currents (~10 kAmps).

Stability : The SR are very stable. The beam stability (energy, position...) is essential for FELs and is difficult to reach with most of the linacs particularly with pulsed RF linacs.

Cost and availability : None of the previously built linacs has exhibited sufficient beam qualities (I, ε_n, σ_γ and stability) to allow laser oscillation (only amplifier experiments have been conducted on induction linacs). New accelerators have had to be constructed to make FEL oscillators and their optimization has taken years (Los Alamos, Boeing, Stanford...).

In the past existing SR have been used to make FEL oscillators in the near UV-visible[6]. However this situation is changing an special SR have to be designed[6] in order to reach the XUV (Duke in the US and Dortmund in FRG). Therefore SR FELs are becoming much more costly than single-pass FELs.

III - User's point of view

A decade ago FELs were built in the goal to study the physics of them. Now, new lasers can be constructed only to study a new application or to become a user facility. Let us examine very briefly the potential applications of the FEL :

- Plasma heating either by mm waves (200-300 GHz) aimed at thermonuclear fusion in magnetic confinement or by near UV-visible wavelengths for inertial fusion. In the first case several MWatts of light power have to be produced during several seconds which implies tens of MWatts in the electron beam, which looks rather difficult. A prototype is underway at Livermore[9]. The latter case is still more difficult from several point of view and, to our knowledge, no projet does exist.

- Isotope separation either at 16 µm or in the visible. At 16 µm an RF linac appears to be not able to produce the required bandwidth ($\Delta\lambda \sim 10^{-4}$) together with the high efficiency and average power. The required peak power (~10 MWatt) appears far from present[10] performance of an electrostatic accelerator FEL (10 kWatt) which energy, in addition would be rather high (10-15 MeV). In the visible the problems are still more difficult.

- Defense applications : they are rather for from the authors field of expertise, but one may assert without much risk that they look very difficult even if they benefit from enormous funding[11].

- Fundamental research : The FEL can be an excellent tool for research in many fields of science : Solid State Physics (particularly surfaces), Molecular Physics, Photochemistry, Chemistry, Medicine[12],... The intrinsic tunablity of FELs together with some other versatile properties (pulse length, peak power) make them desirable as optical source at wavelength were no other tunable lasers do exist. In fact outside the near UV-visible range almost no tunable lasers are available. The X and XUV regions are not yet covered by FELs (but are by synchrotron radiation particularly with undulators) so that the IR and FIR are today of particular interest. Novel physics experiments have been done in FIR (Santa Barbara[13]) and IR facilities (Mark III[14]). Given the cost and complexity these FELs have obviously to be organized in "user facilities", possibly doing FEl fundamental research or accelerator development at the same time. The most popular ones are IR FELs (1 to 100 µm typically) developped on RF linacs or microtrons, more than a dozen being presently being built throughout the world[3,4].

- Others : Many possibilities are explored, together with related techniques : RF source for high gradient accelerators, Raman FEL, Cerenkov FEL, Inverse FEL, Beat-wave accelerator... A complete review of these is outside the limited scope of this paper.

IV - Discussion by spectral regions

The types of accelerators used for FELs can be classified in relation with the FEL spectral region, the energy increasing when the wavelength decrease.

Millimeter waves :
- Raman type FELs using electron guns ($E \leq 1$ MeV, $\lambda \geq 1$ mm) or small induction linacs
- Compton type FELs using 5-10 MeV induction linacs for plasma heating
- Cerenkov FELs in which the undulator is replaced by a dielectric slab[15] or a metal gratings. They use various type of accelerator. They will find application probably only if they can reach the FIR region where their compactness would be appreciated.

Far-infrared (FIR, $\lambda \simeq 0.1$ - 1 mm) ; Let us recall first that if a light pulse has a duration Δt, its minimum spectral content is such that :

$$\Delta\nu\, \Delta t \sim 1 \qquad \text{(Fourier limit)}$$

or $$\frac{\Delta\lambda}{\lambda} = \frac{\lambda}{c\Delta t} = \frac{1}{n} \qquad \text{(relative bandwidth)}$$

where n is the length of the pulse expressed in number of wavelengths. A long pulse accelerator is desirable at long wavelengths in order to obtain a good resolution. For that reason Elias[13] has used a Van de Graaf to make the first FIR FEL.

However electrostatic accelerator can produce a reasonnable duty factor, since they have low charging curretns, only if one recirculate the beam which is delicate and necessitates a tandem accelerator/deccelerator. Also the voltage drop during the pulse, since the recovery is not perfect, is a severe problem. One expects ultimately a relatice bandwidth as low as 10^{-7} - 10^{-8} although this is sen is still somewhat controversial.

Visible - Infrared (λ = 0.4 - 100 µm) : This is the kingdom of RF linacs : Room temperature or superconducting, linear or microtrons or Racetrack microtrons, travelling or standing wave, 3 GHz - 1.3 GHz - 433 MHz or else, 10-100 MeV typically.

"Power" applications : Los Alamos, Boeing, White Sands, Bruyères-Le-Châtel... These centers are developping photocathode RF guns[16] and low frequency accelerating cavity in order to obtain much charge in the electron bunch ($\geq$ 10 n Coul.).

"User facilities" : Developping in the U.S., Europe, China, Japan, ... These use generally more conservative techniques like thermo-ionic guns, 3 or 1.3 GHz linacs, sometimes super-conducting sections (most of the time already existing like in Stanford and Darmstadt). Even so an IRFEL remains relatively costly and needs numerous and specialized teams since the requirements in terms of beam quality and stability, as explained before, are very stringent.

Short-wavelengths (XUV, $\lambda < 0.1$ µm) : This is clearly a very interesting spectral region since it is very difficult to attain with other lasers. However it becomes increasingly difficult to obtain sufficient optical gain as λ is decrease since the gain evolves as $\sim 1/\gamma^3$. Also as γ increase the accelerator becomes more costly and cumbersome and tens of kilowatt of dc power are stored in the beam which make the radiation problems very severe. If one makes long (L_{und} > 10m) undulators to produce gain their realization becomes difficult as well as the beam control and steering inside them. Furthermore the beam quality and stability required have still to be demonstrated experimentaly. Up to now only one experiment involving a single pass device has been proposed[8]. However the short wavelength FEL is a field of intensive theoretical research : Gain calculations, accelerator design, undulator research (micro-undulator, electro-magnetic wave "undulator")...
In particular a super-radiant FEL would ease some of the accelerator problems (use of high gradient accelerating techniques, short pulses leading to low average current) and most of the optical problems dealing with the lack of good cavity mirrors in XUV region. (Fig.2)

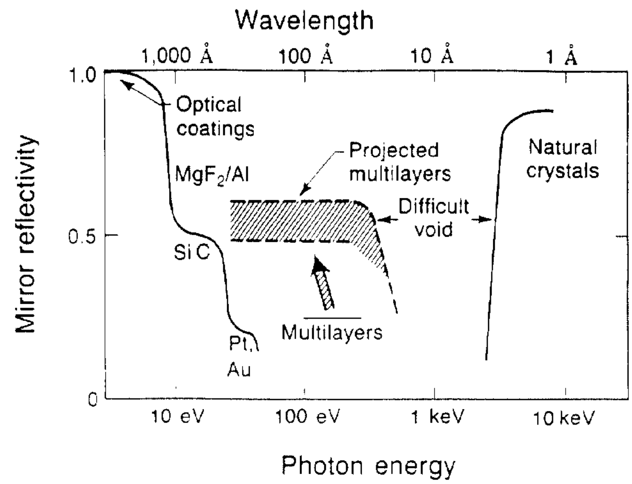

Fig.2 : State of the art mirror reflectivity at normal incidence, from ref.19

V - Novel ideas

Among the novel ideas a few are extensively studied and could lead to real improvement. Let us discuss briefly two of them :
Micro undulators : Undulators of periods shorter than $\simeq$ 1 cm (see ref.3-4). For a given FEL wavelength the accelerator energy is smaller, the acelerator, as well as the whole set-up, is more compact, and the radiation problems are less severe particularly if one goes below 15 MeV ($\approx$ threshold for neutron production. Also it could allow an electrostatic accelerator to feed an IR FEL[17]. However this technique has some drawbacks :

- One has to work at magnetic gap $\leq \lambda_o/2$ so that the beam focusing and steering in very small chambers become critical.
- The optical beam is diffracted by such a small vacuum chamber (smaller than the gap by a few mm) particularly in the IR.
- The parameter K is small ≤ 1. No FEL has been run yet with a micro-undulator so that our experimental knowledge of beam behavior inside it is still very limited.

For their realization various techniques are employed : Pure permanent magnet type, Hybrid Iron-permanent magnet, pulsed linear or helical electromagnets. Pulsed electromagnets seem the more promising to reach the shortest periods.

Gas-loaded FELs[18] If one add a gaz atmosphere into the electron "vacuum" chamber the resonnant wavelenght becomes :

$$\lambda = \lambda_o \left| 1 - \frac{nv}{c} \right|$$

where v = electron velocity
n = gaz reel index of refraction

Then λ can be arbitrarily decreased by increasing n (pressure of the gaz : 0.1 to 0.5 atm. in practice). The optical gain is even increased when rising n. In practice the available gain is driven by the emittance increase due to the passage of the beam through the gaz filled chamber, which length has to be restricted as much as possible to the undulator length. A first experiment has been achieved on Mark III[18] showing a 20% variation in the FEL output wavelength by changing the H_2 gaz pressure.

The interest of this technique would be to lase down to λ=50 nm (using Helium) with only typically 50 MeV electrons, using accelerators already built for IR FEL facilities.

Coherent spontaneous emission

An interesting by-product of an RF linac based FEL is the emission of coherent "spontaneous" (or synchrotron) emission by the bunched beam passing through a magnetic structure. When an electron bunch emits synchrotron radiation at a wavelength, λ, comparable or shorter than the RMS length of the bunch, σ, the emitted intensity, instead of being proportionnal to the number, Ne, of electrons inside the bunch, tends to become ~ N_e^2. Since N_e^2 10^8-10^{10} this effect may be very important. If the bunch is gaussian then the emitted intensity, I_{coh} can be written :

$$I_{coh} : f(\lambda)\, N_e\, I_{inc}$$

$$f(\lambda) = \left(\int e^{i\frac{2\pi}{\lambda}\vec{n}\vec{r}}\, S(r)\, dr\right)^2$$

$$= e^{-2\pi^2\sigma^2/\lambda^2}$$

(where $\vec{n}$=direction of observation, S(r)= shape of the bunch)

This effect has been recently experimentally demonstrated in Sendaï[20]. However the $f(\lambda)$ dependance is very different from that predicted with a gaussian bunch, probably due to the fact that the longitudinal electron distribution is very dissymetric. As a result with an electron bunch FWHM of about 1 mm (3 psec) the emitted radiation is coherent down to at least 0.4 mm. Moreover the Japanese team has used the synchrotron radiation emitted in a bending magnet.Since its angular divergence is very high ($\geq 10/\gamma$) most of it was probably lost before reaching the detector. On an FEL RF linac the emission could be much more important since :

• One will use the undulator in which the radiation from tens of poles add since the vacuum chamber will act as a waveguide for the FIR wavelengths, which means that the incoherent radiation is already increased by several order of magnitude.

• The FEL RF linac are designed so that much charge is in the bunch (N_e is big ~10^{10}) andthey have long macropulses (to allow the laser buil-up) so that the average current is much more important thant in the previous experiment (100 μA instead of 0.25 μA).

Therefore the FIR coherent radiation produced with the new generation of FEL RF linacs[4] may well be in the future a very interesting source for FIR spectroscopists.

VI - Conclusion

Since 10-12 years single pass FELs have suscited a vast interest worldwide. Dozens of projects are underway throughout the word (only 2 storage rings being built for FEL). Many kinds of accelerators, perhaps of almost all kinds, are used to feed FELs. Thousands of papers have been published on the subject which is only briefly and tentatively summarized here. The FEL has already proven applications as an incomparable research tool providing coherent IR and FIR radiation to the scientific community. At short wavelengths (XUV) the question remains open to know wether or not the single-pass FEL is an answer to the need of such lasers. At long wavelengths (IR and FIR), even if the FEL can be considered as being mature, the realization of such a device is still a difficult task needing state of the art accelerator technology as well as optical developments (outside the scope of this paper). The today issues in FEL research are then : - Compactness - Bandwidth improvement - Efficiency - XUV lasers -

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