Design Considerations on a High Power VUV FEL

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Abstract.

We analyse the dynamical behaviour of a FEL operating in the VUV in a configuration of coupled oscillator/amplifier. The role of the oscillator is that of producing a modulation in the longitudinal phase space of the e-beam, causing a fast start up of the laser signal in the amplifier. The possibility of enhancing the output power by tapering the amplifier section is also discussed.

1. INTRODUCTION

A premodulated electron beam may allow the generation and growth of a coherent FEL signal. Experimental programs aimed at realizing FEL operating in the VUV and exploiting the seedless amplification process have been proposed [1-3].

One of the most efficient way to induce a periodic modulation at the wavelength scale, in the longitudinal phase space distribution of an e-beam, is the FEL process itself. Modulation is due to the interaction between the electrons, the undulator and a coherent e.m. field copropagating with the e-beam and nearly resonant with the fundamental harmonic (see Tab I). The bunching occurs either at the fundamental and at higher harmonics. If the e-beam is extracted from the modulating section and injected in a second undulator tuned at a second harmonic of the first, the bunching provides the start-up seed and the subsequent amplification if the gain is large enough. The modulation may be realized with an external laser and an undulator as suggested in refs. [1-2], or with a FEL oscillator as shown in [3]. A layout of the latter configuration, which will be the subject of this contribution, is shown in fig. 1.

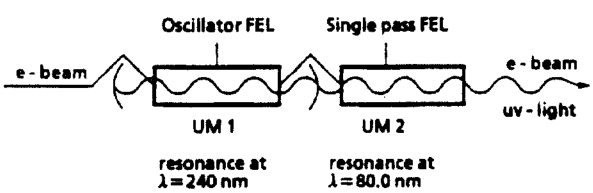

Figure 1. Layout of a FEL in the modulator/amplifier configuration.

We analyse the modulator and the amplifier sections, discussing the interplay between the two parts and presenting the basic design features for a short wavelength FEL based on the oscillator amplifier concept. It is worth stressing that the parameters considered for both the modulator and the amplifier are merely indicative i.e. they are not the result of an optimization, as well as completely arbitrary is the choice of the operating wavelengths.

Table I: List of the symbols used through the contribution

Resonance Condition	$\lambda_r = \frac{\lambda_u}{2\gamma^2}\left(1+K^2/2\right)$
Bessel factor correction	$f_B(\xi) = J_0(\xi) - J_1(\xi),\ \xi = \frac{1}{4}\frac{K^2}{1+K^2/2}$
r.m.s. energy spread	$\sigma_\varepsilon,\quad \mu_\varepsilon = 4N\sigma_\varepsilon$
e-beam current	I_E
e-beam cross section	Σ_E
Alfven Current	$I_A \cong 17$ KA
Small Signal Gain Coefficient	$g_0 = \frac{8\pi N^3}{\gamma^3}\frac{(\lambda_u K f_B(\xi))^2}{\Sigma_E}\frac{I_E}{I_A}$
Small signal Gain	$G_{MAX} = \frac{0.85 g_0 + 0.19 g_0^2}{1+(1.7+0.32 g_0)\mu_\varepsilon^2}$
Saturation Intensity	$I_s\left[\frac{MW}{cm^2}\right] \cong 6.9 \cdot 10^8 \left(\frac{\gamma}{N}\right)^4 \frac{1}{(\lambda_u[cm]\, K\, f_b(\xi))^2}$

2. DESIGN CONSIDERATIONS

2.1 The modulator

The first section is a FEL oscillator with an undulator of N_1=40 periods, period length $\lambda_u^{(1)}$=4.25cm and strength $K_1 = \sqrt{2}$. A cavity length of 3m has been chosen to allow the insertion of e-beam guiding elements. The e-beam parameters displayed in table II yield the operating wavelength around 241 nm.

Table II: E-beam parameters

Energy	215 MeV
Micropulse duration	10 ps
Energy Spread	0.1%
Micropulse frequency	108.33 MHz
Peak Current	200 A
Normalized Emittance	9 mm mrad

According to the definition of the gain per pass listed in Table I, and assuming the electron beam contained in the laser mode, we have $G_{MAX} \cong 0.5$. The saturation intensity is I_s=31.6 GW/cm^2. The dynamical behaviour of the oscillator may be predicted using the following rate equation

$$I_{n+1} = I_n\left\{1+(1-\eta)G\left(I_n/I_s\right)-\eta\right\} \tag{1}$$

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where η are the overall losses and G(x) is defined as [4]

$$G(x) = G_{MAX}\frac{1-e^{-\beta x}}{\beta x}, \quad \beta = 1.0145\,\frac{\pi}{2} \qquad (2)$$

The results of this preliminary simulation are shown in fig.2 where the intracavity intensity growth vs the round trip number is shown for different values of the cavity losses.

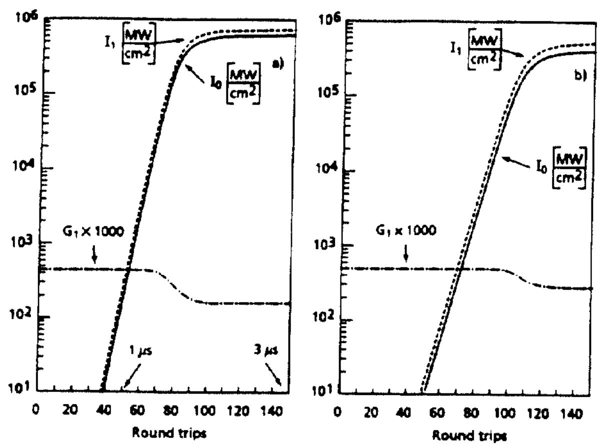

Fig. 2 Oscillator dynamics vs. round trip number. The cavity length is 3m, i.e. 50 round trips= 1μs. I_0 is the intracavity power I_1 is the output power. In (a) η=14%, in (b) η=20%.

Increasing η, the steady state intracavity power may be reduced significantly. This parameter must be kept far from the saturation value to avoid a large induced energy spread in the modulator that could inhibit the operation in the amplifier. The value of the intracavity intensity must be set according to the desired bunching coefficient amplitude. We recall that at the lowest order in the field amplitude, the bunching induced may be expressed as [5,6]

$$b_n(\tau) \cong i\frac{(0.9457\pi)^{2n}\tau^n\left(I/I_s\right)^{n/2}}{n!2^n}\frac{1}{2\pi}\int_{-\infty}^{\infty} e^{-in\nu\tau}\frac{\partial^n}{\partial \nu^n}f(\nu)d\nu \qquad (3)$$

where $f(\nu)$ is the beam energy distribution and $\tau = ct/N\lambda_u^{(1)}$.

2.2 The amplifier

After passing through a drift section, of the order of 1m to avoid de-bunching due to the energy spread, the beam is injected in the amplifier section, whose undulator has a period of 1/3 of that of the first undulator. The effects of the premodulation can be simulated in the amplifier as an equivalent input seed I_b. The intensity growth of a high gain FEL amplifier seeded by a pre-modulated beam is indeed provided by the relation [7]

$$I\left[\frac{MW}{cm^2}\right] \cong I_b\left[\frac{MW}{cm^2}\right]\exp\left(4\sqrt{3}\pi\rho\, z/\lambda_u\right) \qquad (4)$$

where

$$\rho = \frac{1}{4\pi}\left(\frac{\pi g_0}{N^3}\right)^{1/3} \qquad (5)$$

and where

$$I_b\left[\frac{MW}{cm^2}\right] = 5.77*10^{-7}\pi^2|b_3|^2\gamma\rho\,\frac{I_E[A]}{\Sigma_E[cm^2]} \qquad (6)$$

The saturation occurs when the laser power is ρP_E where P_E is the e-beam power. Imposing therefore

$$I = \rho\, P_E/\Sigma_E, \qquad (7)$$

using eq. (6), (4) and (3), and assuming a monoenergetic beam, we can estimate the bunching coefficient b_3 necessary to yield the saturation power after a length z_s

$$|b_3| \cong 3\,e^{-2\pi\sqrt{3}\rho\left(z_s/\lambda_u\right)} \qquad (8)$$

This relation specifies the amount of intracavity power in the oscillator which provides the desired output amplified power. With the current specified Table II and assuming K_2=K_1, and $\lambda_2 = \lambda_1/3$, we get $\rho = 2.27*10^{-3}$ and a maximum attainable power P_L=2.4*10^5 MW/cm^2. To reach saturation within 300 undulator periods (4.25m of undulator length) and a drift section between the undulators of 0.6 $N_1\lambda_u^{(1)}$ we have that the first undulator intracavity intensity must be 1.4*$10^{-3}I_s$.

2.3 Numerical Analysis

The above analysis does not account for a number of important aspects of FEL dynamics, i.e. we have not included the inhomogeneous broadening due to the e-beam qualities and the effects of the energy spread induced by the interaction in the modulator. The informations provided are anyway almost correct when the bunching induced in the modulator is small. We expect that when this quantity is large, we have a degradation of the beam energy spread, which inhibits the amplification process in the second undulator. This effect is clearly shown in fig. 3, where the output power versus the laser power in the oscillator is shown. The simulation has been obtained with a 1D code including energy spread effects. The maximum power after the amplifier undulator of 300 periods, is reached when the oscillator intensity is $10^{-3}I_s$. In fig. 4 is shown the amplifier power versus the longitudinal position for different values of the oscillator intracavity intensity. The transitions from the quadratic growth of the signal to the exponential regime, and to the saturation can be easily distinguished.

The saturation length is a decreasing function of the induced bunching as shown in the previous section.

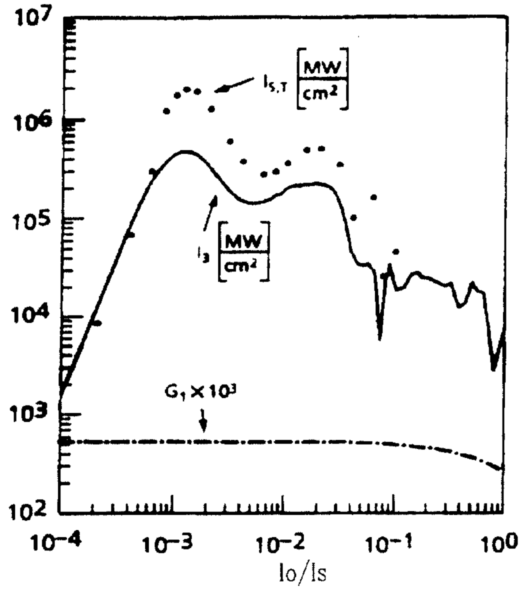

Fig. 3 Intensity after the amplifier (solid line) and oscillator gain (dashed line), vs. the intracavity intensity of the oscillator. The dots refer to the tapered case.

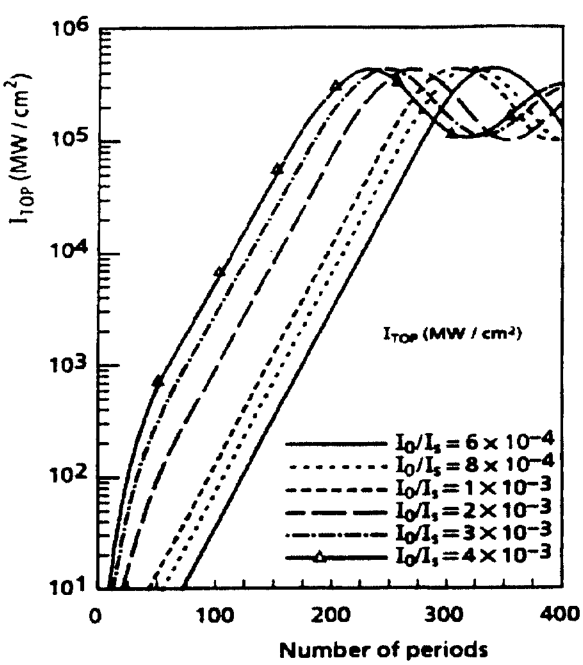

Fig. 4 Output power vs. number of periods of the amplifier section, for different oscillator intracavity intensity.

A numerical analysis allows also to test the tapering of the undulator in the amplifier. The dots in fig. 3 are relevant to a tapering of the amplifier section where the magnetic field varies as displayed in fig. 5.

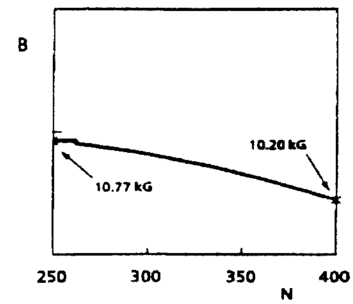

Fig. 5 Magnetic field tapering vs. period number

3. CONCLUDING REMARKS

We summarized the key issues of a quite complicated device, just briefly discussing the relevant design, and omitting most of the details concerning the optical cavity, the problems of pulse propagation in the modulator section, the effects of energy spread and emittances, or the problems related to the e-beam transport system. We address to ref.[8] for a more detailed description.

4. REFERENCES

[1] I. Ben Zvi, F.F. Di Mauro, S. Krinsky, M.G. White and L. H. Yu, "Proposed UV Facility at BNL", Nucl. Instrum. & Meth. **A304**, pp. 181-186 (1991).

[2] R. Bonifacio, L. De Salvo Souza, P. Pierini and E.T. Sharleman, Nucl. Instrum. & Meth. **A296**, pp. 787-790 (1990).

[3] R. Barbini, F. Ciocci, G. Dattoli, A. Dipace, L. Giannessi, G.Maino, C. Mari, A. Marino, C. Ronsivalle, E. Sabia and A.Torre, "80 nm FEL design in an oscillator amplifier configuration", in proceedings of the "Prospects for a 1 A Free Electron Laser", Sag Harbor, New York, April 22-27, 1990 J. C. Gallardo Editor (BNL 52273)

[4] G. Dattoli, S. Cabrini, L. Giannessi, "Simple model of gain saturation in free-electron lasers"Phys. Rev. **A44**, pp. 8433-8434 (1991)

[5] L.H. Yu, "Generation of intense UV radiation by sub-harmonically seeded single pass Free Electron Laser" Phys. Rev. **44A**, pp. 5178-5193 (1991)

[6] G. Dattoli, L. Giannessi and A. Torre, "Unified view of Free Electron Laser Dynamics and of Higher Order Harmonics Electron Bunching" J. Opt. Soc. Am. **10B**, pp. 2136-2148 (1993)

[7] G. Dattoli, L. Giannessi, P. L. Ottaviani and A. Torre, "Dynamical Behaviour of Free Electron Laser operating with a pre-bunched beam", to be published in Phys. Rev. **E49**, (June 1994)

[8] F. Ciocci, G. Dattoli, A. De Angelis, B. Faatz, F. Garosi, L.Giannessi, P.L. Ottaviani and A. Torre, "Design considerations on a High Power VUV FEL " submitted to IEEE J. Q. E.