EXTENDED PARAMETRIC EVALUATION FOR 1Å FEL – EMITTANCE AND CURRENT REQUIREMENTS

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Abstract

In the synchrotron radiation community there is a strong request for high-brightness, coherent X-ray light pulses, especially in the 1 to 0.1 nm wavelength range. A Free Electron Laser (FEL), driven by a linear single-pass accelerator, is today the most promising mechanism able to produce such radiation. Since the electron beam brightness plays a major role in the laser saturation process and in the final energy of the driving linac, many laboratories are presently working on a new generation of low emittance sources. The present analysis will give an indication about the FEL behaviour versus the undulator parameters and the slice beam quality (emittance, current, energy spread).

INTRODUCTION

At short wavelength the transversal coherence of the FEL radiation and therefore the gain length can strongly be compromized due to the transversal emittance of the electron beam. As shown by L-H Yu and S. Krinsky [1], with an external focusing the normalized emittance will have a negligible effect on the FEL interaction if :

$$\varepsilon_n << \varepsilon_{nc} = \frac{\beta}{L_g}\frac{\gamma\lambda_S}{2\pi} \qquad (1)$$

where β is the betatron function, γ the Lorenz factor, λ_s the radiation wave length and L_g the gain length.

According to equation (1) the beam energy can be reduced and therefore the facility costs only if the emittance is "sufficiently" small.

The present state of the art electron sources intended for the next generation of light source facilities (LCLS [2] and TESLA-FEL [3]) can provide 1 nC beams with normalized slice emittances close to 1 mm mrad [4]. Recently, the importance of developing high brightness beam sources with emittances at least one order of magnitude smaller than the present status has been emphasized [5], and new gun designs proposed [6,7,8]. A systematic parametric analysis of the FEL interaction with an ultra-bright beam is therefore necessary to achieve a consistent set of specifications for the gun, the LINAC and the undulator.

Model

In this analysis we are using the analytical theory developed by L-H Yu et al. [9] which simultaneously includes the effects of the energy spread, emittance, and focusing of the electron beam, as well as the diffraction and the optical guiding of the radiation field. A Gaussian beam energy distribution, a uniform longitudinal density and a uniform water-bag distribution U(R,R') in the 4-dimensional transverse phase space R=(x,y) and R'=(x',y') are assumed:

$$U(\vec{R},\vec{R}') = \frac{\beta^2 n_0}{\pi R_0^2}\,\Theta\left(\frac{R_0^2}{\beta^2} - \frac{R^2}{\beta^2} - R'^2\right) \qquad (2)$$

where Θ(v)=1 for v>0 and Θ(v)=0 for v<0. The transverse electron density profile is then parabolic:

$$g(\vec{R}) = n_0\left(1 - \frac{R^2}{R_0^2}\right) \quad \text{for } R < R_0 \qquad (3)$$

The gain length is calculated by numerically solving the dispersion relation resulting from the linearized Maxwell-Vlasov equations (see [9] for details).

PARAMETRIC ANALYSIS

Reference Case

As a reference we assume a normalized emittance close to the state of the art ε_n=1.2 10^{-6} mrad, and an energy spread σ_E near 10^{-4}, which is comparable to the energy spread induced by the quantum fluctuation along the undulator [10] for energies near 20 GeV. All our evaluations are made for planar undulators.

Table 1: Reference case parameters

ε_n	1.2 10^{-6}
σ_E	10^{-4} and 2 10^{-4}
Peak	5000 [A]
Beta func. β	31 [m]
Radiation λ	1 Å

The gain lengths at optimum detuning versus the undulator period are shown in Fig. 1, and the corresponding beam energies in Fig. 2.

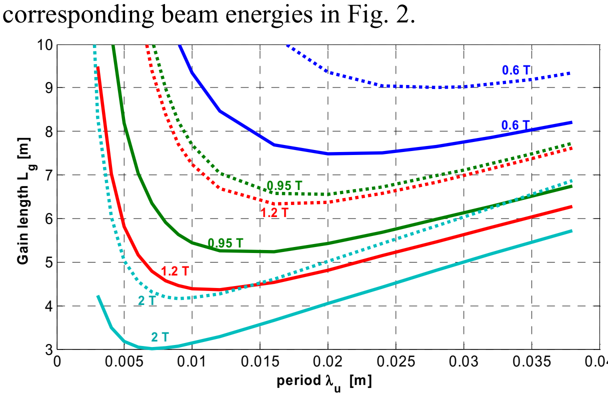

Figure 1: Reference case, gain length vs. undulator period for four peak magnetic fields. Continuous line σ_E =10^{-4}, dotted line σ_E =2 10^{-4}.

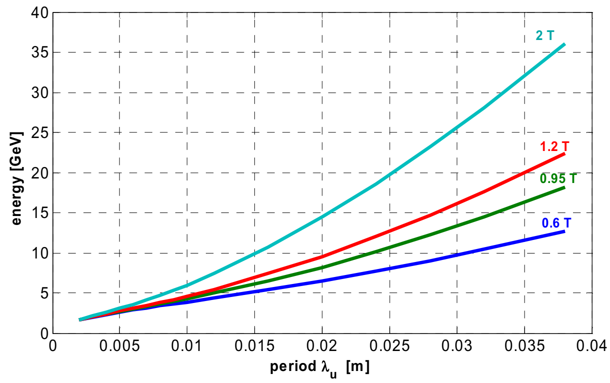

Figure 2: Electron beam energy vs. undulator period (resonant condition).

In this case a high magnetic field is clearly preferable in term of saturation length and final linac energy but undulators above 1 T with periods below 15 mm would require a challenging narrow physical aperture, typically g≈3 mm for λ_u=10 mm. This has to be compared with present designs such the TESLA XFEL[3], with an undulator of 38 mm period, 10 mm gap and 1.06 T. Wake field effects on short pulses with high peak current may limit the minimal undulator aperture.

Emittance and Peak Magnetic Field

A smaller emittance has a strong impact on the FEL gain length and allows operation at lower peak current. The possibility to reduce the charge could considerably help to preserve the emittance at low energy at the source where space-charge effects are dominant. The optimum β function decreases with the emittance:

$$\beta_{opt} \sim 16 \text{ m for } \varepsilon_n = 5\ 10^{-7} \text{ [mrad]}$$
$$\beta_{opt} < 1 \text{ m for } \varepsilon_n < 1\ 10^{-7} \text{ [mrad]}$$

Operation at β optimum for emittances smaller than 10^{-7} is difficult to realize. However the gain length (~1.5m) only increases smoothly with the β function. For the two lowest emittances a β of 4.77 m has been chosen, in those cases the gain length can degrades of ~35%.if increasing β to 15.9 m

Table 2: Parameters at low emittance

ε_n [mrad]	σ_E	β [m]	I [A]
5 10^{-7}	10^{-4}	15.9	500
1.10^{-7}	10^{-4}	4.77	500
5 10^{-8}	10^{-4}	4.77	500

Comparing Fig. 3a with the reference case we note that increasing the current by a factor 10 largely compensates the emittance degradation from ε_n=5 10^{-7} to ε_n=1.2 10^{-6}. This is roughly in agreement with the analytical scaling of the gain length L_g given by Saldin et al. [11], which at low energy spread is:

$$L_g \propto \varepsilon_n^{5/6} / \sqrt{I} \qquad (4)$$

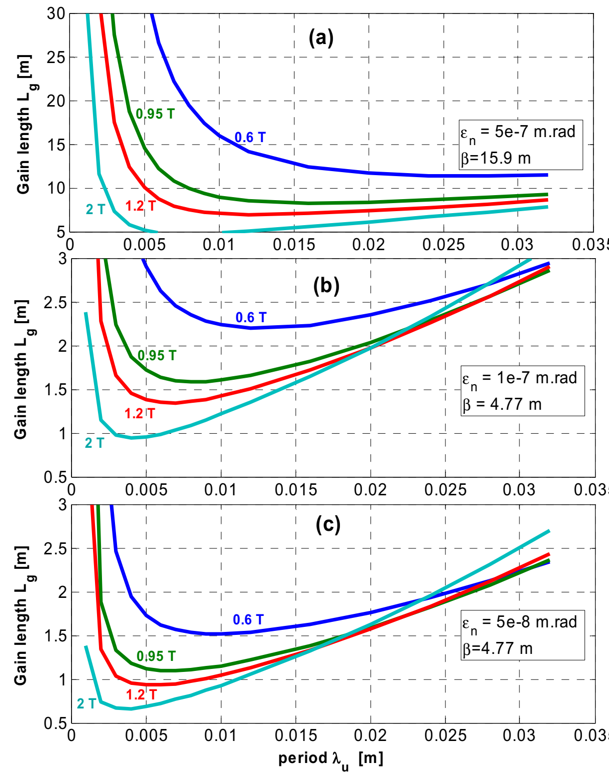

Figure 3: Gain length vs. undulator period for different peak magnetic field and emittances: (a) ε_n=5 10^{-7} mrad, (b) ε_n=10^{-7} mrad, (c) ε_n=5 10^{-8} mrad.

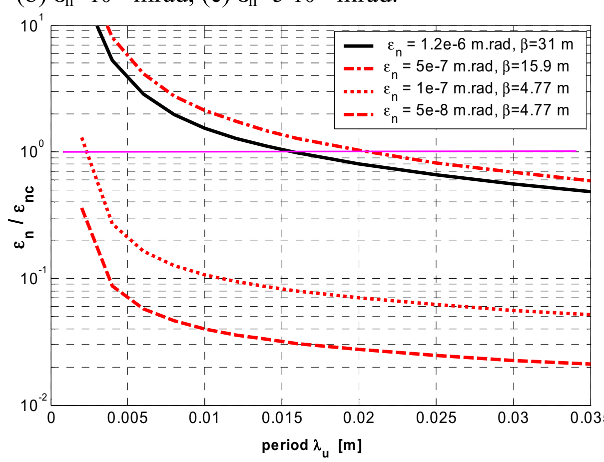

Figure 4: Ratio between normalized emittance ε_n and critical emittance ε_{nc} as given in Eq (1) for 0.95 T peak magnetic field.

Analyzing in Fig. 4 the criteria given by Eq. (1) for the case with 0.95 T peak field, we observe that the regimes covered by the reference case and the ε_n=5 10^{-7} [m rad] scenario are still emittance dominated, while for the two lowest emittances the criteria is fulfilled down to approximately 5mm undulator period. In Fig. 3 the gain length scales approximately linearly with the emittance according to Eq. (4), although we are slightly outside the parameter range considered by Saldin.

From figure 3b and 3c we conclude that for small emittances there is no advantage to use a high field undulator for periods λ_u>15 mm, where an undulator K factor of 1.4 should be sufficient.

Current

In order to reach a reasonable gain length currents up to 5kA are foreseen in the present 1Å FEL proposals. At low emittance the peak charge can be reduced according to (4), and many problems related to wake field, compression chicanes and beam collimation someway relaxed.

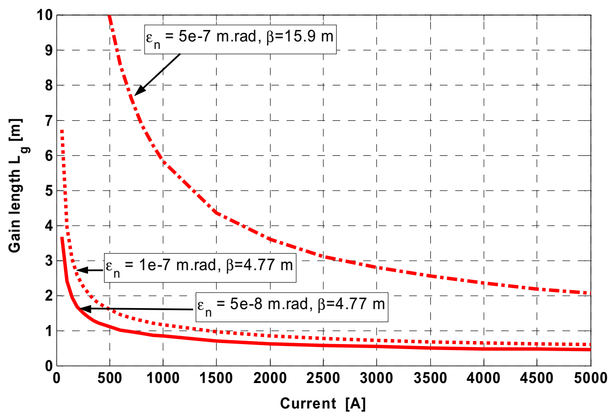

Figure 5: Gain length versus peak current for an undulator period of 8 mm and 0.95 T peak field. Continuous line ε_n=5 10^{-8}, dotted line ε_n=1 10^{-7}, dash dotted line ε_n=5 10^{-7}.

Fig. 5 shows the gain length behavior versus current for an undulator period of 8mm and a peak field of 0.95 T. For the parameters considered in Fig. 5 the Gain length shows a slightly different scaling with current for the different emittances: Table 3 summarize the scaling factors obtained from a fit on the numerical results and clearly indicates that the gain length scaling vs. current is more favorable at higher emittances.

Table 3: Scaling versus current

ε_n [m rad]	L_g scaling
5. 10^{-7}	$L_g \propto I^{-0.69}$
1. 10^{-7}	$L_g \propto I^{-0.49}$
5. 10^{-8}	$L_g \propto I^{-0.43}$

According to the present analysis a current of 500 A seems a good compromise for emittances 1 10^{-7} [m rad].

CONCLUSIONS

The parametric analysis for 1Å FEL versus an improved electron beam emittance shows that an undulator period between 10 and 15 mm operating at a gap between 3 and 5 mm can be used. The resulting linac energy could then be adjusted around 5GeV, which is quite positive concerning the accelerator size and cost.

At emittances below 1 10^{-7} mrad the current needed to reach a reasonable gain length relaxes considerably. The charge produced by the electron gun could be decreased from the usual 1 nC to 0.1 nC reducing the space-charge contribution to the emittance growth at low energy.

Beside the difficulties inherent the low emittance electron sources a major R&D effort as to be made as well concerning the undulator technology. Beside Super Conducting undulators, the recent works on cryogenic permanent magnet undulators presented by T. Hara et al [12] shows that a short period undulator (table 4) with peak magnetic fields matching the scenarios presented in this paper may be feasible.

Table 4: Possible cryo undulator

period [mm]	Gap [mm]	Peak field [T]
8	3	0.94
10	3	1.28
10	5	0.64
15	5	1.07

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