COHERENCY OF MAGNETIC–BREMSSTRAHLUNG EMITTERS AND PROSPECTS FOR THE X–RAY FELS

E. Bulyak, V. Kurilko,
NSC KIPT, Kharkov, Ukraine

Abstract

Quantitative results of the theoretical analysis of the data obtained by experimental investigations of the FEL characteristics are presented. The data are based on series of efficiency measurements of FEL–amplifiers and FEL–oscillators performed in the leading research centers. Regarding the data, the analysis aims at searching for dependence of coherence level of stimulated radiation emitted by electrons on their relative volume density. In order to describe this dependence quantitatively two parameters are introduced: the coherence factor (C) and the number of coherent emitters (Q). The fact of the dependence existence is proved: the factor C is shown to be monotonously increasing function of its argument Q. Number of coherent emitters is evaluated for a series of the soft X–Ray FELs designed to be driven by SLAC linac.

1 INTRODUCTION

As is well known [1], the Free Electron Lasers (FELs) driven by ultrarelativistic high current electron beams (UREB) are prospective sources of coherent X-ray radiation with wavelength down to subnanometers. A few projects of those lasers driving by the Stanford electron linac were published in last years [1, 2, 3]. These projects are based on using the self excitation of a non-equilibrium system “UREB+undulator”. Nevertheless, realization of the SASE mode of operation requires sufficiently high spatial density of the electron beam [4]. The matter is that the structure of the self field of the spontaneous undulator radiation (SUR) does not permit to provide coherent bremsstrahlung of individual radiators by this field at low density of the beam (when every electron is in far zone of the field of it’s neighbors [4]). Under these conditions non-equilibrium system “UREB+undulator” operates in the mode of a classical incoherent undulator radiation source (SURS).

Present report is aimed at clarifying the condition of the margin of X-ray laser self-excitation being met in projects [1, 2, 3]. A method of quantitative estimation of the coherence level in microwave bremsstrahlung field is proposed in section 2 and validated through the scope of published papers on experimental investigations of microwave coherent sources of radiation of the FEL-type (section 3), corresponding analysis of the X-ray FEL projects [1, 2, 3] is made (section 4).

2 THEORY

We describe the quantitative characteristics of the electron beam bremsstrahlung coherency level with the coherency factor (C), defining this factor as ratio of the peak power of the coherent UREB microwave radiation ($P_{\rm coh}$) to the peak power of incoherent radiation emitted by individual electrons of the same beam in the same undulator ($P_{\rm inc}$) [5][1]:

$$C \equiv \frac{P_{\rm coh}}{P_{\rm inc}} = \frac{m_0c^2(\gamma-1)}{FL}\,\eta. \qquad (1)$$

Here m_0c^2 is the electron rest energy; γ is its relativistic factor; F — the amplitude of bremsstrahlung force of an electron with the field of it’s SUR in the undulator; L is the undulator length; η — the FEL efficiency.

Analytical asymptotes for C could be derived for the idealized 1D model of the Compton FEL in which the monoenergetic nondiverging electron beam is passing through the periodic helical undulator [5][2]:

$$C = \frac{3}{8\pi^2}\frac{\gamma-1}{\gamma}\left[\frac{Q^2D}{r_0\gamma K^2}\left(\frac{D}{\gamma^2\lambda}\right)^4\right]^{1/3}\times \begin{cases} 1, & \text{amplifier} \\ (3.5\alpha)^{-2/3}, & \text{oscillator} \end{cases} \qquad (2)$$

Here D is the undulator period length; K — the undulator dimensionless field amplitude; r_0 — the electron classical radius; λ — SUR wave length; Q — number of in phase emitting electrons; α — the relative power losses per one resonator round–trip; the upper string in RHS of (2) corresponds to the amplification mode (MOPA) whereas the lower — to the oscillating mode (SASE).

Number of in phase emitting electrons (Q) can be estimated by two models (which produce similar results).

Thus, the similarity of the FEL to TWT (see [1]) yields a phenomenological relation [5]:

$$Q = n_0\lambda^2 D f_{\rm TWT}; \qquad f_{\rm TWT} = \frac{1}{16\pi}. \qquad (3)$$

where n_0 is the average space density of the beam particles; $f_{\rm TWT}$ — the coherency form factor for the TWT model.

[1] This factor was initially defined for Tomson scattering in [6] (see also [4]).

[2] Parameter K^2 for a plane undulator should be replaced by it’s averaged value over the period, $K^2/2$.

The coherency region within the scope of this model is defined as a cylinder with the radius $R_{\mathrm{coh}} \equiv \frac{\gamma_{\parallel}^2 \lambda}{2\pi}$ and the height $H_{\mathrm{coh}} \equiv \frac{\lambda}{2} = \frac{D}{4\gamma_{\parallel}^2}$.

From the other hand, analysis of the space structure of the Green function for coupled electromagnetic interaction of the undulator emitters also yields the formula (3) for the Q_{GF}, with a slightly larger form factor f_{GF} [7]:

$$Q_{\mathrm{GF}} = n_0 \lambda^2 D f_{\mathrm{GF}}; \qquad f_{\mathrm{GF}} \simeq 2 f_{\mathrm{TWT}}. \tag{4}$$

3 EXPERIMENT

The above described theory predicts decreasing in the coherency factor C while number of the in–phase emitting electrons Q is diminishing: $\frac{\partial C}{\partial Q} > 0$. If this result of the theory is valid then the diminishing must have been observed in published investigations on FEL. For validating the last consideration, analysis of the data on the Compton FEL amplifiers [8, 9, 11, 10, 12] as well as on the FEL–oscillators [13, 14, 15, 16, 17] has been done for the wavelength ranged from millimeters to micrometers. Calculations proved the existence of decreasing in the coherency factors with diminishing of number of the in–phase emitters (see Table 1).

Table 1: FEL oscillators

Param	[13]	[14]	[15]	[16]	[17]
λ, mkm	3.42	2.60	9.80	4.70	400.00
$\log Q_{\mathrm{exp}}$	1.49	2.99	3.52	4.32	4.40
$\log C_{\mathrm{exp}}$	3.55	4.65	6.35	7.11	7.10

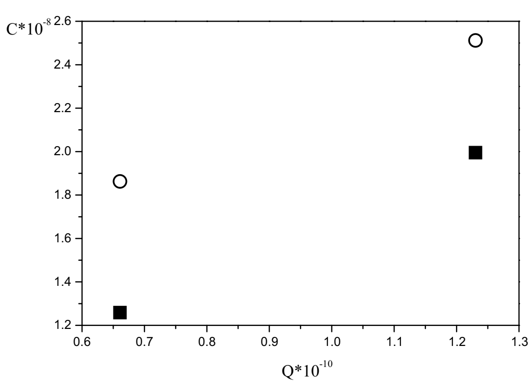

Figure 1: $C(Q)$ for FEL–amplifiers, MOPA mode [8, 9]; hollow circles — theory, solid squares — experiment.

For the millimeter range FEL–amplifiers a greater number of in–phase radiators ($\log Q_{\mathrm{amp}} \approx 6...10$) is corresponded a greater value of the coherency factor ($\log C_{\mathrm{amp}} \approx 7.8 \ldots 8.3$, see Figs. 1,2). Common for the scope of calculated data is that results yielded from the idealized theoretical models exceed those calculated from the experimental measurements. The gap between the theory and the experiment is wider in the case of the SASE–mode.

4 SUMMARY

Both the theory (section 2) and the scope of experimental data (section 3) manifests decreasing in the coherency factor with diminishing of the number of the in–phase emitters Q. Similar features can be seen from the project parameters of the subnanometer FELs, presented in [1, 2, 3].

Estimation of the subnanometer X–ray FEL projects was made based on calculation of the expected number of in–phase emitters for the parameters listed in [1, 2, 3]. Calculated results are presented in the Table 2. As it follows from the data in the table, expecting numbers of the in–phase emitting electrons for the subnanometer X–ray FELs are comparative to unity. Physically it means that described projects dedicated for using of operating modes close to the self–excitation threshold of the non–equilibrium "UREB+undulator" system. In particular, it is implicitly manifested by relatively small ratios of the total yields of the coherent and incoherent radiation power:

Table 2: X–Ray FELs

Param	[1]	[3]	[2]	[2]
λ, nm	0.10	0.15	0.15	0.45
Q_{GF}	1.10	3.50	5.20	45.00
C_{NS}	0.04	0.06	0.37	1.33

$$C_{\mathrm{NS}} \equiv \frac{P_{\mathrm{coh}}^{(\mathrm{NS})}}{P_{\mathrm{inc}}}. \tag{5}$$

Here $P_{\mathrm{coh}}^{(\mathrm{NS})}$ is the power of coherent radiation, calculated

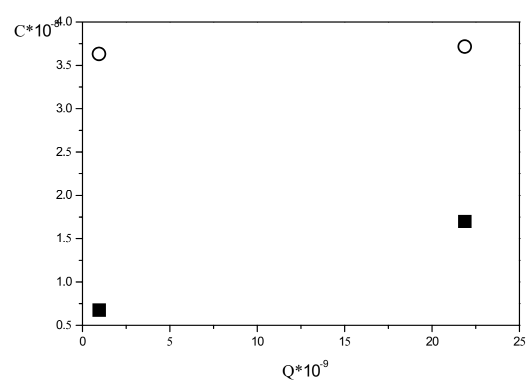

Figure 2: $C(Q)$ for FEL–amplifiers, SASE mode [10, 12]; hollow circles — theory, solid squares — experiment.

in [1, 2, 3],

$$P_{\rm inc}[\rm GW] = \frac{r_0}{3D}(2\pi\gamma K)^2 N_{\rm sat} I_b[\rm kA]$$

is the total incoherent microwave power emitted by all electrons of the same UREB in the same undulator.

As it can be seen from Table 2, inequality $C_{\rm NS} < 1$ takes place for $\lambda \leq 0.15$ nm in the region $Q \leq 5$. From this it follows, in particular, that accounting for effect of SUR on beam dynamics in the short wave range is required[3]. Desirable is to carry experiments not only at 120 MeV (the FATE experiment [2]), but at a few GeV where the SUR effect is more significant. Also it would be desirable to measure the response $C(Q)$ over the interval $1 \leq Q \leq 20$ increasing Q with build up of the peak beam current.

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