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Section A

Numerical studies of the multi-cavity free-electron laser *

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Consideration is made of a free-electron laser with many optical cavities where the cavities communicate with each other, not optically, but through the electron beam. Numerical simulation results in the one-dimensional approximation, but including nonlinearities, are presented. The multi-cavity free-electron laser (MC/FEL) can be employed to avoid the slippage phenomena, and thus to make pico-second pulses of infrared radiation. Three examples of this application are presented.

1. Introduction

There are many uses for brief, intense pulses of radiation. At long wavelengths it is not possible to directly employ a free-electron laser (FEL) for this purpose since the intrinsic slippage in a FEL, between light and electrons, implies that the light pulse will not be as brief as the electron pulse. One can modify the group velocity (readily done when the wavelength is of the order of the light pipe) and thus make the light pulse stay with the electron pulse, and this has been shown, experimentally, to be possible [1]. This method, group velocity modification, is, however, difficult and, most importantly, limited to rather long wavelengths. Another possibility is to "chirp" the light pulse and then compress it, but this technique is difficult to employ with intense pulses.

Still another possibility is to employ a multi-cavity free-electron laser (MC/FEL) [2]. The idea of ref. [2] is rather straightforward. One simply makes the FEL optical cavities sufficiently short that the slippage length, in one optical cavity, is less than the electron pulse width. When the electrons reach the end of one cavity they go on to the next, but the radiation remains trapped within that cavity.

In this paper we present numerical simulation results and examples of the MC/FEL. Analysis of performance is presented in ref. [2].

2. The concept

The MC/FEL consists of a number of short optical cavities, each with a length less than the slippage distance between the electrons and the radiation. A small hole is drilled at the center of the walls separating the cavities so that the electrons can pass through from one cavity to the next; however, the radiation emitted with a particular cavity remains largely confined within that cavity. Coherent radiation is extracted only from the last cavity. A schematic of the proposed layout is given in fig. 1.

At first, one might think that the FEL, in a MC/FEL, will not work very well, for its effective length is just an optical cavity length and therefore not very long. However, the electrons, which move on to the next cavity, are bunched and the FEL action in the next cavity is significant. One is reminded of an optical klystron [3] or of the "gain cavities" in a regular klystron. In fact, in our numerical studies we see that even when the first few cavities have a net loss (so that the gain is not adequate to overcome the mirror losses) the MC/FEL still "works", i.e., the later cavities (which now experience bunched electrons and thus have more gain) are soon experiencing a build-up of radiation to a very high value.

By making the optical cavities confocal, one can reduce the radiation moving from one cavity into the next; i.e., improve the reflection coefficient from the end mirrors (which must have holes for the electron beam to go through). One should note that radiation moving from one cavity to the next is not a serious matter, since the radiation will have slipped out of the electron pulse and therefore no longer be amplified. Just as in a regular klystron, the light is only removed from the last cavity and, thus, the reflection coefficient for this last cavity is much lower than for the other cavities.

3. Equations

The equations of motion for dynamics in a MC/FEL are given by the full nonlinear equations of motion

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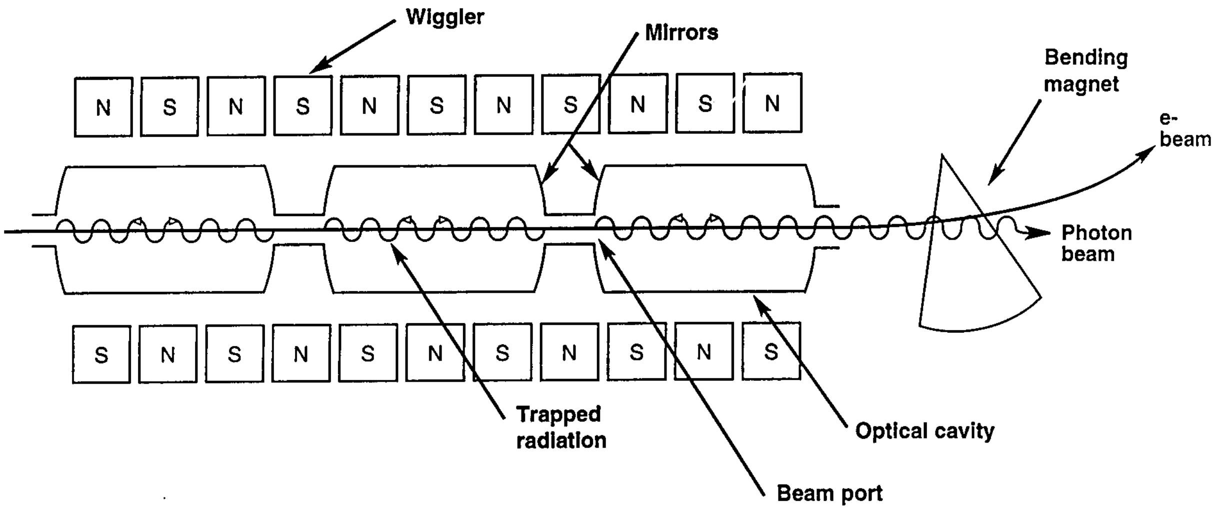

Fig. 1. Conceptual layout of a multi-cavity FEL.

which, following the notation of Bonifacio, Pellegrini and Narducci [4], are

$$\left(\frac{\mathrm{d}\theta_j}{\mathrm{d}t}\right) = \omega_0\left(1 - \gamma_R^2/\gamma_i^2\right) + \frac{1}{2\gamma_i^2\lambda}[JJ]\left[\alpha\ \exp(\mathrm{i}\theta_j) + \mathrm{c.c.}\right], \tag{1a}$$

$$\left(\frac{\mathrm{d}\gamma_j}{\mathrm{d}t}\right) = \frac{-ec\kappa}{2mc^2\gamma_j}[JJ]\left[\alpha\ \exp(-\mathrm{i}\theta_j) + \mathrm{c.c.}\right], \tag{1b}$$

$$\frac{1}{c}\frac{\mathrm{d}\alpha}{\mathrm{d}t} = 2\pi n_0\frac{\kappa}{\Sigma}\left\langle\frac{\mathrm{e}^{-\mathrm{i}\theta_j}}{\gamma_j}\right\rangle. \tag{1c}$$

Here α is the complex amplitude of the electric field, θ_j is the phase of the jth electron relative to the electromagnetic field, and γ_j is its energy in units of mc^2. ω_0 is the wiggler frequency, κ is the wiggler parameter, and λ is the wavelength of the radiation field. The resonant energy is γ_R, the electron density is n_0 and Σ is the effective transverse cross section of the beam, describing the overlap of the beam with the radiation field. The average $\langle \cdots \rangle$ is carried over all electrons in the bunch. $[JJ]$ is the usual Bessel function factor that is unity for helical wigglers.

Table 1
Three examples of multi-cavity free-electron lasers

Parameters	First example	Second example	Third example
λ [μm]	10	100	1000
τ_{pulse} [ps]	1	2	10
λ_w [cm]	1.0	2.0	2.5
a_w	1.0	1.0	1.0
Wiggler length [m]	1.5	0.7	0.3
Cavity length [cm]	25	10	5
N	6	7	6
r_{beam} [mm]	1.0	1.0	1.0
I_{peak} [A]	5	10	5
γ	27.4	12.2	4.3
Slippage length [cm]	30	12	7.5
ρ	3×10^{-3}	1×10^{-2}	3×10^{2}
P_{beam} [MW]	140	124	22
P_{out} [MW]	3.5	8.0	4.0
P_{out} [MW] (for single cavity)	1.2	2.6	1.2

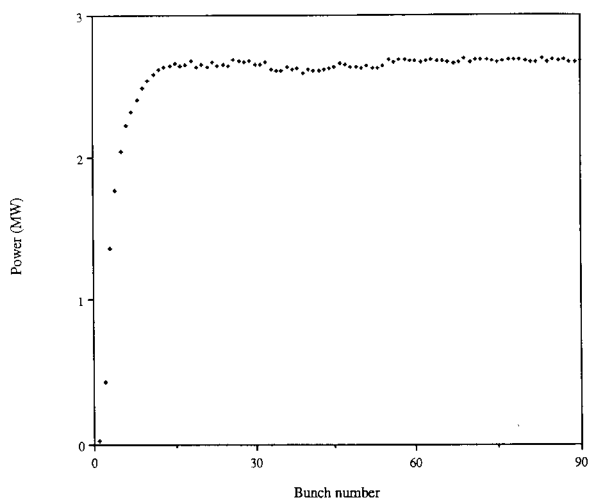

Fig. 2. Power output as a function of bunch number for a single optical cavity whose length is equal to the total wiggler length of the corresponding multi-cavity FEL. All other parameters used are those given for the second example in table 1.

4. Numerical simulations

In this section, we numerically study the performance of three MC/FELs. The full nonlinear equations of motion given in eq. (1) are used in the simulations. Parameters for the three MC/FEL examples are listed in table 1. In all these cases, the reflection coefficient R is taken to be equal to 0.98. However, the reflection coefficient for the right-hand wall of the output (i.e., final) cavity is taken to be equal to 0.95 to allow for outcoupling of radiation. The pulse length and the cavity lengths are calculated values obtained by requiring that slippage be negligible.

First, we obtain the power output from a single optical cavity with the wiggler length given in table 1. In contrast to conventional FEL oscillators, the length of the optical cavity is equal to the wiggler length in our case. Next, we study a MC/FEL whose total length is equal to the length of the single cavity considered above. The length of individual optical cavities in the MC/FEL is taken to be slightly smaller than the slippage length. All other parameters remain the same. The first $(N-1)$ cavities are used to bunch the electrons. Output power is extracted from the final (Nth) cavity.

In the final two rows of table 1, we compare the output power obtained in a single long cavity with that obtained in the corresponding MC/FEL. In all three examples studied, we see that the power output in the final cavity of the MC/FEL is larger than the power output in a single long cavity. A more detailed comparison of the power evolution in the two cases is given in figs. 2 and 3. Only the second example ($\lambda_s = 100$ μm) is considered. Fig. 2 shows the evolution of power as a

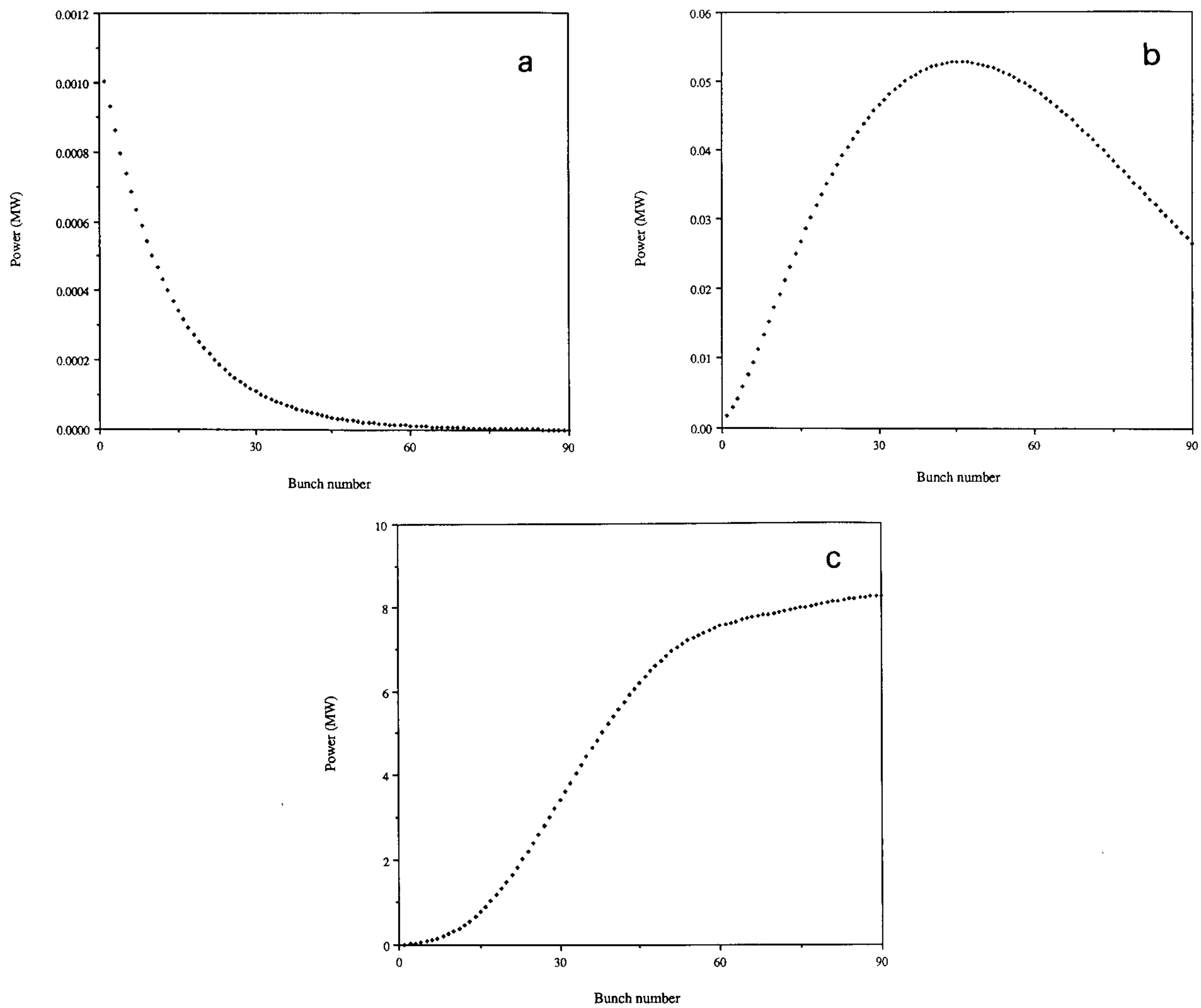

Fig. 3. Power output in a multi-cavity FEL. The parameters used are those given for the second example in table 1. (a)–(c) show the power output as a function of bunch number in the first, fourth and seventh cavity, respectively.

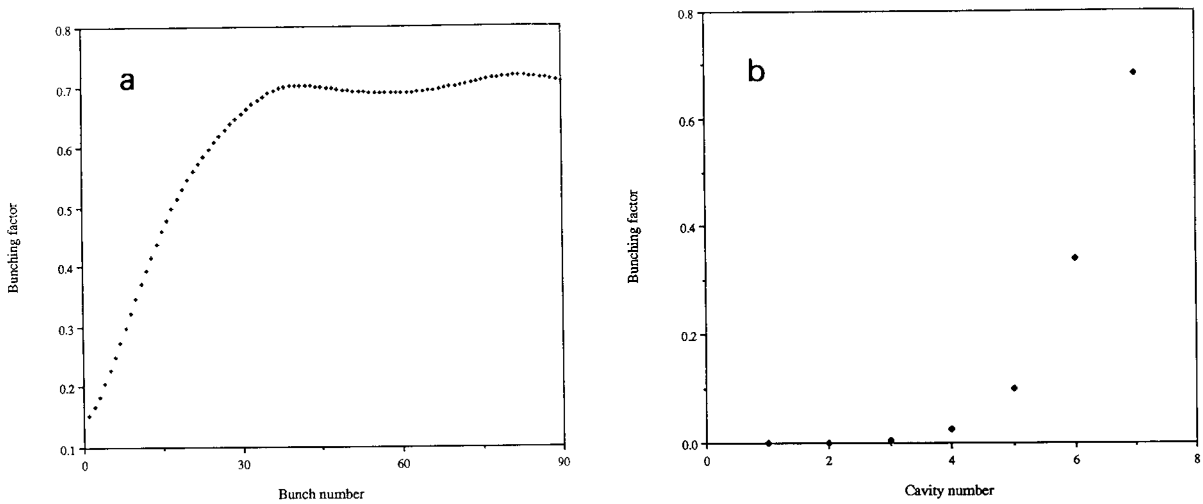

Fig. 4 Evolution of the bunching factor $|\langle e^{i\theta}\rangle|$ in a multi-cavity FEL. The parameters used are those given for the second example in table 1. (a) Shows the bunching factor at the end of the last cavity as a function of bunch number. (b) Shows the bunching factor for the last bunch as a function of cavity number.

function of electron bunch number in the single cavity case. Figs. 3a, 3b and 3c show the corresponding evolution in cavities 1, 4 and 7, respectively, for the MC/FEL. As noted earlier, power output in the final cavity of the MC/FEL (see fig. 3c) is higher than the corresponding power output in a single long cavity (see fig. 2). We observe that the MC/FEL works despite losing power in the first cavity (see fig. 3a). This is because the first cavity manages to bunch the electrons slightly even though it is losing power. Figs. 4a and 4b show the evolution of the bunching factor $|\langle e^{i\theta}\rangle|$ in a MC/FEL. As expected, the bunching factor is seen to increase both as a function of cavity number and bunch number.

5. Conclusions

There are a number of conclusions to be drawn from this work:

First, that the concept (see fig. 1) of a multi-cavity free-electron laser (MC/FEL) is a valid concept, i.e., that a MC/FEL can be expected to work.

Second, that a MC/FEL will overcome the slippage between radiation and particle beam so that it can produce radiation pulses as brief as electron pulses (even when slippage would suggest that the radiation pulse is longer than the particle pulse).

The third conclusion is that the peak power produced in a MC/FEL can be even higher than in a single cavity FEL, because the saturation condition implies that power increases as the optical cavity is reduced in length. In practice one should design an FEL so that the optical cavity is made as short as possible, while still having a net gain per pass, so as to produce the maximum peak power.

Further work of a theoretical nature, which remains yet to be done, is to study the concept in 2D, including diffraction phenomena, proper study of optical mode structure and reflectivity, etc. (We do not expect the principle of the MC/FEL to be modified, but the "real numbers" will surely be different.)

Finally, then, it seems likely that MC/FELs will provide an interesting new capability of FELs. First, however, some experimental study of the concept is called upon.

References

[1] J. Masud et al., Phys. Rev. Lett. 58 (1987) 763.
[2] S. Krishnagopal, G. Rangarajan and A. Sessler, Lawrence Berkeley Laboratory Internal Report LBL-32220 (1992).
[3] N.A. Vinokurov, The Optical Klystron Theory and Experiment, dissertation of The Institute of Nuclear Physics, Novosibirsk (1986).
[4] R. Bonifacio, C. Pellegrini and L. Narducci, Opt. Commun. 50 (1984) 373.