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3D-Simulations of Transverse Optical Modes of the Free Electron Laser Resonator with Hole Output Coupling

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Abstract. The transverse construction of optical modes in the wiggler is calculated and the numerical simulations of the free-electron laser hole-coupled resonator are carried out. These 3D-simulations include optical amplitude distributions, modes evolvement of optical field and the influence of hole-radius on the distributing of modes. The numerical simulations confirm that the fraction of the even-order modes increase in the start-up stage and then decreases in the exponential gain stage. Moreover, it is found that the fundamental mode is dominant in the saturate stage. Based on this observation, we estimate the optical output coupling by using the the fundamental mode. It is found that the numerical results and the first-order estimate are in good agreement for a range of the hole size.

Key words: Free-electron laser; optical resonator; mode analysis; numerical simulation.

1 Introduction

Output hole has important impact on the structure of transverse optical modes. It also introduces many difficulties in calculating the optical loss and output coupling. The earlier theory [1, 2] studied the characters of transverse optical modes to the cold-cavity case using the Fox-Li procedure [3]. In general, the results are in good agreement with the experimental ones for gas laser and chemistry laser due to the fact that the corresponding medium is uniform in the intercavity. However, for free electron laser (FEL) system, the radius of the electron beam is very slim, and the gain and the optical guiding from electron beam make the loaded and unloaded cavity cases very different. For example, Pantell et

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al. [4] and Xie and Kim [5] observed that many modes can coexist in the cold-cavity of FEL, but this is not true in the loaded FEL cavity case. Krishnagopal et al. [6] and Faatz et al. [7] carried out 2D-simulations to the FEL hole-coupled resonator considering the influence of the electron beam. The profiles of the optical modes were simulated in [8]. The three-dimensional (3D) simulations of a waveguide FEL oscillator was done by Shu et al. [9]. Recently, some new optical resonators of FEL have been developed, see, e.g., [10, 11]. For short Rayleigh length FEL resonator, Blau et al. [12] investigated the problem of the optical mode distortion. From the point of view of modes, the research of the interaction of optical and electron beam is useful in understanding the rule of FEL hole-coupled resonator and for adjusting the hole-size in the experiments.

In this work, we will study the transverse optical modes of the FEL hole-coupled resonator by using our FEL oscillator codes (3-DOSIFEL) [13, 14]. To our knowledge, there have been very few detailed 3D simulations in this direction. The paper is organized as follows. Firstly the optical modes are estimated by some series expansion methods. Then the transverse construction of optical modes in the wiggler is calculated for the FEL hole-coupled resonator with the consideration of the gain and optical guiding effects. These 3D-simulations include amplitude distributions and modes evolvement of optical fields, and the distributing of modes in the entrance and on the mirrors as a function of the hole-radius. The transverse construction of the optical field will be determined by the gain and optical guide of the electron beam, and the diffraction and the hole coupling output. The numerical simulations confirm that the proportion of the high-order modes will increase in the start-up stage then decrease in the exponential gain stage. Moreover, the fundamental mode is dominant in the saturate stage. Based on these facts, the estimate for the optical output coupling is obtained by using approximations for the fundamental modes.

2 The estimate of the optical modes

The transverse spread of optical modes can be expressed as

$$E_s(x,y,z) = \sum_{m,n=0}^{\infty} A_{mn}(z) g_{mn}(x,y,z). \tag{2.1}$$

For ordinary FEL system, the stable cavity consists of two concave mirrors. The transverse modes g_{mn} are composed of the i products of Hermite-Gaussian modes in the x-direction and y-direction [15].

Consider the interaction between electron beam and optical beam. It can be obtained from the resonant condition that

$$\frac{d}{dt}\left[(k_w + k_z)\,z - \omega t - (m+n+1)\tan^{-1}(z/z_r)\right] = 0, \tag{2.2}$$