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Effect of grating surface loss on the Smith–Purcell free-electron laser

D. Li[a,*], K. Imasaki[a], Z. Yang[b], Gun-Sik Park[c], S. Miyamoto[d], S. Amano[d], T. Mochizuki[d]

[a]*Institute for Laser Technology, 2-6 yamada-oka, suita, Osaka 565-0871, Japan*
[b]*Institute of High Energy Electronics, University of Electronic Science and Technology of China, Chengdu 610054, PR China*
[c]*School of Physics, Seoul National University, Seoul 151-747, Republic of Korea*
[d]*LASTI, University of Hyogo, 3-1-2 Koto, Kamigori, Ako, Hyogo 678-1205, Japan*

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Abstract

The effect of dissipative loss in the grating surface on a Smith–Purcell free-electron laser is investigated with the help of a two-dimensional particle-in-cell simulation. The simulation model supposes an open grating driven by a continuous electron beam. With present parameters, simulation results show that such a device can oscillate on absolute instability, Bragg condition and convective instability when ignoring the surface loss. The growth rate is found to be dependent of beam energy, and it decreases when the surface loss is involved. It is shown that surface loss impacts a lot on the Bragg region. Comparisons of simulation results with the latest theory are reported.

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Keywords: Smith–Purcell; Free-electron laser; Surface loss; THz source; Particle-in-cell simulation

1. Introduction

As a promising alternative in development of a compact, tunable and powerful THz source, the Smith–Purcell free-electron laser (SP-FEL) has attracted many attentions in recent years [1–5]. The SP-FEL can be realized on the configuration of an open grating [6–10], which is different from the conventional configuration, ''orotron'' or ''ledatron'' [11,12].

When an electron passes close to the surface of a grating, it not only emits Smith–Purcell radiation, but also excites the evanescent wave [13,14]. The evanescent wave, with the frequency below the minimum of the allowed Smith–Purcell frequency, travels along a grating and undergoes partial diffraction and partial reflection at both ends of the grating. The diffraction portion can propagate in free space and can be utilized as free-electron laser. The dispersion relation of the evanescent wave, as shown in Fig. 1, is similar to the backward-wave oscillators (BWOs) and traveling-wave tubes (TWTs), since a grating can be regarded as a kind of slow-wave structure. The frequency of an evanescent wave is determined from the intersection point of the dispersion curve and the beam line, as shown in Fig. 1, meaning that the beam velocity is synchronous with the phase velocity of the wave, and then the energy can exchange between them. From Fig. 1, we know that the group velocity can be positive, negative or zero. When the interaction occurs at a positive group velocity, the wave and the beam move in the same direction. Such an interaction induces convective instability, and the device operates in the manner of TWTs [15]. When the group velocity is negative, the wave and the beam move in opposite direction. In this case, the interaction leads to absolute instability, and the device can operate without external feedback, like BWOs [15]. The top of the dispersion curve gives zero group velocity, which is called Bragg condition.

The case of absolute instability for a SP-FEL has been much addressed [6–9]. On the other hand, Andrews and co-workers predicated that there is possibility for such a device to start oscillation based on the convective instability, since

*Corresponding author. Tel.: +81 6 6879 8789; fax: +81 6 6878 1568.
E-mail address: dazhi_li@hotmail.com (D. Li).

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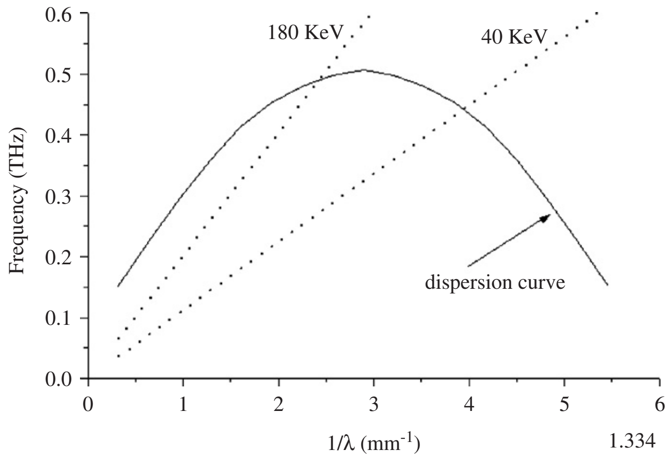

Fig. 1. Dispersion relation for our grating.

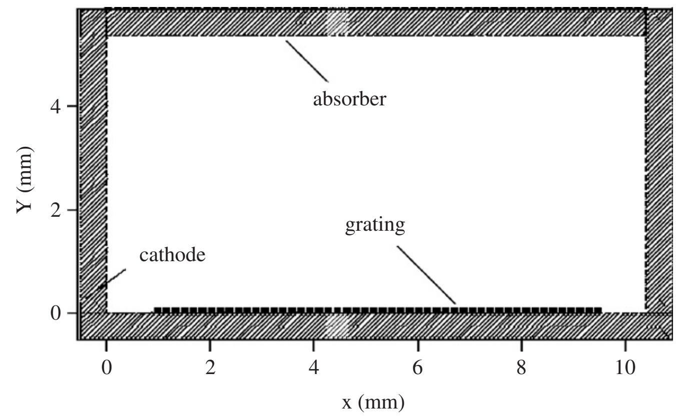

Fig. 2. Simulation geometry.

the wave reflects at both ends of the grating, acting as an external feedback system [15]. In this paper, we address on the effect of grating surface loss on absolute instability, convective instability and Bragg condition, with the help of a two-dimensional particle-in-cell code, MAGIC [16], a code for simulating processes involving interactions between space charge and electromagnetic fields. Simulations are performed with and without involving the surface loss of grating, respectively, to demonstrate the effect of the loss on a SP-FEL operation.

2. Simulation description

The simulation geometry is shown in Fig. 2. A grating with rectangular form is set at the center of the bottom of the simulation box. The surface of the grating is assumed to consist of conductor whose grooves are parallel and uniform in the z direction. We use a sheet electron beam with finite thickness of 24 μm, and place its edge 34 μm above the top of the grating. It is a perfect laminar beam produced by the MAGIC algorithm and is generated from a cathode located at the left boundary of the simulation box. In their analysis, Andrews and Brau supposed that the entire region above the grating was filled with uniform beam [6], which is different from our model. The electron–wave interaction and radiation propagation occur in the vacuum area, which is enclosed by a special region (called *free-space* in MAGIC language), where the incident electromagnetic waves and electrons can be absorbed. The whole simulation area is divided into a mesh with rectangle cells of small size ($\delta x = 17.3\,\mu\text{m}$, $\delta y = 17.3\,\mu\text{m}$) in the region of beam propagation and grating, and large size ($\delta x = 17.3\,\mu\text{m}$, $\delta y = 51.9\,\mu\text{m}$) in the rest of the region. The Cartesian coordinate system is adopted with origin at the center of the grating. Since it is a two-dimensional simulation, it assumes that all fields and currents are independent of the z coordinate. And it should be noted that the current value mentioned in this paper represents the current per meter in the z direction.

Table 1
Main parameters for simulation

Grating period	$L = 173\,\mu\text{m}$
Groove width	$w = 62\,\mu\text{m}$
Groove depth	$d = 100\,\mu\text{m}$
Period number	$N = 50$
Electron beam energy	$E = 40$–$140\,\text{keV}$
Current	$I = 648\,\text{A/m}$
Beam thickness	$\sigma = 24\,\mu\text{m}$
Beam-grating distance	$\delta = 34\,\mu\text{m}$
External magnetic field	$B_x = 2\,\text{T}$

The main parameters of the grating and electron beam are summarized in Table 1. The electron beam energy varies in the following simulation. The external magnetic field is used in order to ensure stable beam propagation above the grating. Note that some parameters of the grating, such as period length, groove depth and width used in our simulation are the same as those in Dartmouth experiment [1]. However, the grating length in our simulation is shorter than that used in Dartmouth experiment because of the limited capacity of our computers. In addition, the form of the beam is different since we use a sheet beam and the experiment used a round one.

As to the diagnostics, MAGIC allows us to observe a variety of physical quantities such as electromagnetic fields as functions of time and space, power outflow, and electron phase-space trajectories [16]. We can set the relevant detectors anywhere in the simulation area.

3. Simulation results

3.1. Ignoring surface loss

We first perform simulations at ignorance of the surface loss, i.e., the grating is supposed to be a perfect conductor. The beam energy is chosen to cover the absolute instability, Bragg condition and convective instability. According to the theoretical analysis of Andrews and Brau, the beam line of 125 keV intersects the top point of the dispersion curve