SLAC–PUB–15900
January 2014

FEL oscillator for EUV lithography*

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Abstract

The development of radiation sources for extreme ultraviolet lithography (EUVL) has lately received a considerable attention. One of the promising approaches to the problem utilizes a free-electron laser (FEL) as a high-power radiation source. The current interest of the semiconductor industry is focused on the wavelength of $\lambda = 13.5$ nm. In this work we consider an FEL with a short-period undulator and a relatively small beam energy. The immediate advantage of such a choice would be a compact FEL design and a small beam power, handling of which does not require an electron beam energy recovery. In addition, using an FEL oscillator scheme allows one to considerably increase the conversion efficiency of the system.

Talk presented at Mini-Workshop on High Power FEL Source for EUV Lithography
Santa Monica, CA, USA
January 23 - 24

* Work supported by the U.S. Department of Energy under contracts No. DE-AC02-76SF00515 and DE-AC02-05CH11231.

I. INTRODUCTION

The development of radiation sources for extreme ultraviolet lithography (EUVL) in semiconductor industry has received a considerable attention in the last several years [1]. The immediate industry interest is focused on the wavelength of $\lambda = 13.5$ nm. One of the promising approaches to the problem is to use a free-electron laser (FEL) as a high-power radiation source [2–4]. This approach relies on a well established technology of a superconducting accelerator to generate a relativistic, high-current, high-repetition-rate electron beam which can produce a kW level of EUV radiation when sent through an undulator tuned to the desired wavelength.

While a conservative choice of FEL parameters requires a relativistic beam with the beam energy in the range of 1 GeV in combination with a well established undulator technology based on permanent magnets, in this paper we consider a more aggressive strategy which assumes a short-period undulator and a relatively small beam energy. The immediate advantage of such a choice would be a more compact FEL design and a smaller beam power, handling of which does not require an electron beam energy recovery. In addition, we propose an FEL oscillator which uses a small fraction of the reflected FEL power transmitted to the entrance of the FEL with the help of reflective multi-layer mirrors. As simulations show, such a seeding of the beam allows one to considerably increase the fraction of the electron beam energy converted into the FEL radiation.

II. FEL PARAMETERS

The proposed scheme of the FEL is shown in Fig. 1. It includes a superconducting linac to accelerate the beam to the energy of ~ 250 MeV. The beam is then sent, through a 180 degrees bending magnet, to a helical superconducting undulator, terminated by a beam dump. A small fraction of the beam radiation is reflected by a system of mirrors and is transported to the undulator entrance, while most of the radiation is transmitted through an opening in the mirror to the lithography installation.

The proposed beam parameters are summarized in Table I. We assume a peak beam current of 100 A to avoid the need of a bunch compression. Note, however, that the bending magnets between the accelerator and the undulator that turn around the beam trajectory

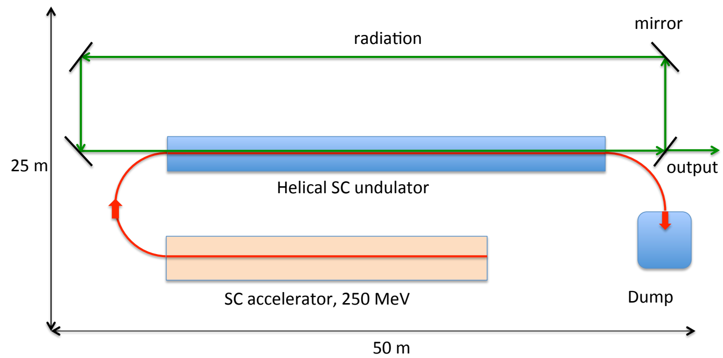

FIG. 1. Layout of the FEL source of EUV radiation for lithography.

TABLE I. Beam parameters

Beam energy	240 MeV
Bunch charge	0.1 nC
Bunch length (flat profile)	1 ps
Peak current	100 A
Normalized slice emittance	0.3 mm mrad
Relative energy spread	10^{-4}
Length of accelerator	30 m
Repetition rate	5 MHz

shown in Fig. 1 can be used for the beam compression in case of need. Taking as a guide the accelerating gradient equal to that of the European XFEL accelerator [5], 23.6 MV/m, and assuming a filling factor of 2, we expect that the accelerator length should be in the range of 20 m. An optimization which takes into account the cost of the refrigeration might somewhat lower the accelerating gradient, and hence to increase the length. It seems reasonable to expect that the linac should fit into the length of about 30 m.

The wavelength of an FEL with a helical undulator is given by the following formula:

$$\lambda_{\mathrm{FEL}} = \frac{\lambda_u}{2\gamma^2}\left(1 + K^2\right) ,$$

where $\gamma = E/mc^2$ is the relativistic factor, K is the undulator parameter, and λ_u is the undulator period. As it follows from this formula, given a relatively small beam energy, we have to use a short-period undulator. A superconducting helical undulator with the undulator period $\lambda_u = 11.5$ mm, the undulator parameter $K = 0.92$ and the free beam aperture $a = 5.85$ mm is described in Ref. [6]. We expect that making the vacuum chamber aperture somewhat smaller one can decrease the undulator period to about $\lambda_u = 5$ mm keeping at the same time the undulator parameter in the range of $K = 0.4$. The parameters of the FEL undulator used in computer simulations presented in the next section are listed in Table II. The amplitude of the magnetic field in the undulator $B_0 = 0.85$ T. This undulator

TABLE II. Parameters of the undulator

Period	5 mm
Free beam aperture	3 mm
Undulator parameter	0.4
Beta function	1.3 m
Undulator length	30 m

provides a natural focusing of the beam with the beta function $\beta_x = \beta_y = 1.3$ m.

Note that while the choice of $\lambda_u = 5$ mm and $K = 0.4$ is an aggressive one, one can make it somewhat less challenging by increasing λ_u to 7-8 mm (and keeping the undulator parameter the same) for the cost of raising the beam energy by 20-30%.

III. SIMULATIONS OF FEL PERFORMANCE

Simulations presented in this section were carried out using computer code Genesis [7]. We first simulated the SASE regime in which the radiation process starts from shot noise in the beam. The gain length for the chosen FEL parameters calculated using Ming Xie's formulas [8] gives $L_g = 0.64$ m. The results of this simulation are shown in Fig. 2 for two undulator configurations—without and with undulator tapering. One can see that the SASE radiation in the undulator reaches the power level of about 30-50 MW at about 10 m length. The undulator tapering does not help much in this case.

A much more efficient energy extraction from the beam can be achieved by intercepting a small fraction of the output radiation and seeding it to the entrance of the beam, as shown

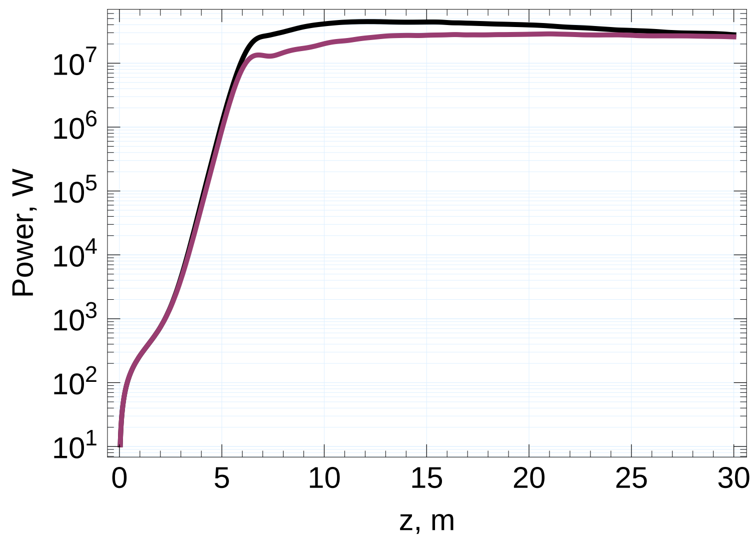

FIG. 2. Simulated SASE radiation from the FEL: black line—with tapering, magenta line—without tapering.

in Fig. 1, in combination with a proper tapering of the undulator. The input peak power to the FEL used in the simulations was 100 kW. The tapering was optimized to obtain the maximal value of the output power. The plot of function $K(z)$ used in the simulations is shown in Fig. 3.

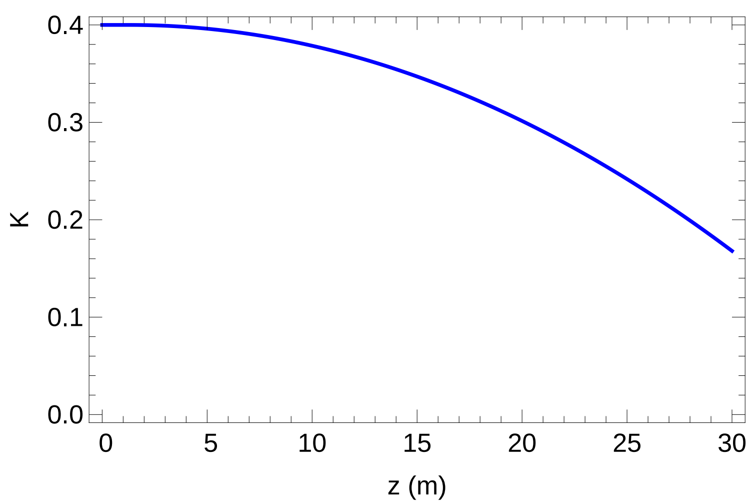

FIG. 3. The parameter K versus z.

Simulation results for the normalized beam emittance equal to 0.3 micron are shown in

Fig. 4. One can see that the exit radiation power is close to 1 GW. Multiplying this by the

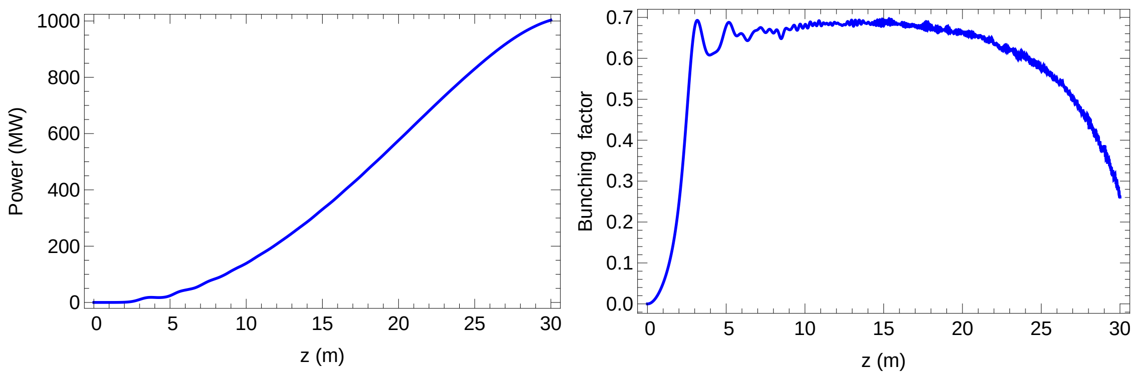

FIG. 4. The FEL power (left) and the bunching factor (right) along the undulator.

bunch length of 1 ps and taking into account the repetition rate of 5 MHz, we find the FEL power in this case of about 5 kW. Note that the averaged beam current in the system is 0.5 mA, and the electron beam power is about 120 kW. About 4.1% of the beam energy is converted into radiation.

We also simulate the case of the normalized beam emittance of 0.5 micron. The result is shown in Fig. 5. The exit radiation power is approximately equal to 700 MW, translating

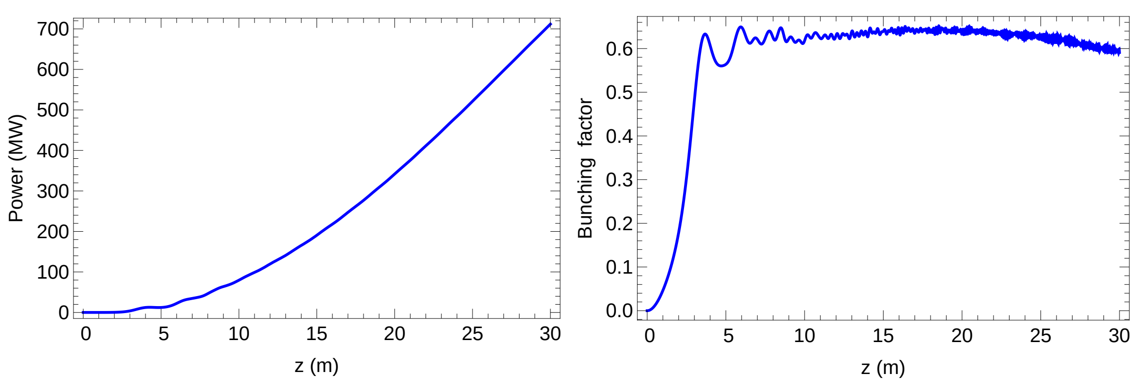

FIG. 5. The FEL power and the bunching factor.

into the average EUV power from the system of about 3.5 kW.

IV. ACKNOWLEDGEMENTS

We are grateful to Y. Ivanyushenkov for discussions of issues related to superconducting undulators. M. S. thanks Matthias Reinsch who carried out some of the initial FEL simulations and G. S. thanks Yuantao Ding for help with computer program Genesis.

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