ANALYSIS OF PARAMETER SPACE OF A KILOWATT-SCALE FREE ELECTRON LASER FOR EXTREME ULTRAVIOLET LITHOGRAPHY DRIVEN BY L-BAND SUPERCONDUCTING LINEAR ACCELERATOR OPERATING IN A BURST MODE

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Abstract

The driving engine of the Free Electron Laser in Hamburg (FLASH) is an L-band superconducting accelerator operating in a burst mode with 800 microsecond pulse duration at a repetition rate of 10 Hz. Our analysis shows that the FLASH technology holds great potential for increasing the average power of the linear accelerator and an increase of the conversion efficiency of the electron kinetic energy to the light. We show that it will be possible to construct a FLASH like free electron laser operating in 13.x nm and 6.x nm wavelength bands with an average power up to 3 kW. Such a source meets the requirements of the light source for the Next Generation Lithography (NGL).

INTRODUCTION

Microlithography uses several challenging technologies such as radiation source, mask, reticle, resist, stepper, etc. Minimum feature size scales down with the radiation wavelength, and 13.x nm band has been chosen in the middle of the 1990s for the Next Generation Lithography (see [1] and references therein). Requirements for the source are not fixed but evolve with the evolution of all the other NGL technologies involved. For instance, requirement for the average power has been increased nearly by an order of magnitude during the last ten years, and approaches two hundred Watts which exceeds present level of plasma sources by an order of magnitude. There is also a trend of the NGL assuming perspective change of the radiation wavelength to the 6.x nm band.

During the last years we observed rapid progress in the development of VUV and x-ray free electron lasers. FLASH (Free Electron Laser in Hamburg) at DESY has produced unprecedented powers of EUV radiation at the wavelengths of 13.x nm and 6.x nm [2,3]. Several schemes for a dedicated FEL-based radiation source for the NGL have been proposed during last years [4–13]. In this paper we describe the potential application for the NGL of an accelerator and FEL technology developed in the framework of the FLASH project at DESY. We show that this technology allows to construct a free electron laser operating at the wavelength of 13.x nm and 6.x nm with an average power of several kilowatts. Spectral width of the radiation (below 2%) fits well the requirements to the radiation source for the Next Generation Lithography.

FACILITY DESCRIPTION

A schematic layout of the FLASH facility is shown in Fig. 1. The electron beam is produced in a radio frequency gun and brought up to an energy of up to 1200 MeV by seven accelerating modules ACC1 to ACC7 operating at a frequency of 1.3 GHz. At intermediate energies of 150 and 450 MeV the electron bunches are compressed in the bunch compressors BC1 and BC2. The electron beam formation system is based on the use of linearized longitudinal compression realized with the help of an accelerating module operating at a frequency of 3.9 GHz [14]. After the bunch compressor BC2, the electron beam is accelerated to the target energy (450 to 1200 MeV), and produces powerful coherent radiation during a single pass through the long undulator (planar, hybrid, 12 mm fixed gap, magnetic length 27 m, period 27.3 mm, peak magnetic field 0.48 T).

All subsystems of the superconducting linear accelerator have been optimized for the burst mode of operation with a macropulse repetition rate of 10 Hz, flat-top macropulse duration of 800 μs, and maximum beam loading 9 mA within the macropulse. With these parameters the average power in the electron beam is equal to 86 kW at the energy of 1.2 GeV.

In the present feasibility study we do not deviate much from the project numbers for components used in the FLASH and European XFEL projects [15]. We assume operation of the linac in the burst mode with macropulse repetition rate of 10 Hz. Macropulse duration is equal to 0.8 ms. Bunches with a charge of 1 nC are separated by time interval of 100 ns (10 MHz repetition rate) which corresponds to 10 mA beam load within the macropulse. With these parameters average power in the electron beam is equal to 80 kW at the energy of electrons of 1 GeV.

The undulator is assumed to be hybrid planar with variable gap. We set the limit on the minimum undulator gap to

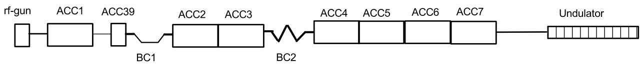

Figure 1: Schematic layout of the FLASH facility [3]. Abbreviations ACC1-ACC7, ACC39, and BC stand for accelerating module 1.3 GHz, accelerating module 3.9 GHz, and bunch compressor, respectively. Total length of the machine is 250 meters.

1.2 cm like in the FLASH project. We assume the length of the undulator segments to be 200 cm, total magnetic length of the undulator is 30 meters, and focusing beta function is equal to 200 cm. Undulator tapering is used to increase FEL efficiency [16].

OPERATION OF NGL SOURCE

We consider Self Amplified Spontaneous Emission free electron laser (SASE FEL) - single-pass FEL amplifier starting from the shot noise in the electron beam. Calculations are performed with the time-dependent simulation code FAST [17]. We optimize undulator parameters for the wavelength of 13.5 nm. Operation at shorter wavelengths is achieved by opening the undulator gap similar to operation of the European XFEL. Optimum values of the undulator period are 3.7 cm and 5 cm for the electron energies 1250 MeV and 2500 MeV, respectively. Bunch charge is equal to 1 nC, and peak beam current is 2500 A, like in FLASH project. At an appropriate optimization of the beam formation system we can expect the value of the normalized emittance below 1 mm-mrad. However, a conservative value of normalized emittance of 1.5 mm-mrad is sufficient for effective operation of a 13.5 nm FEL, and we use this number as a baseline parameter.

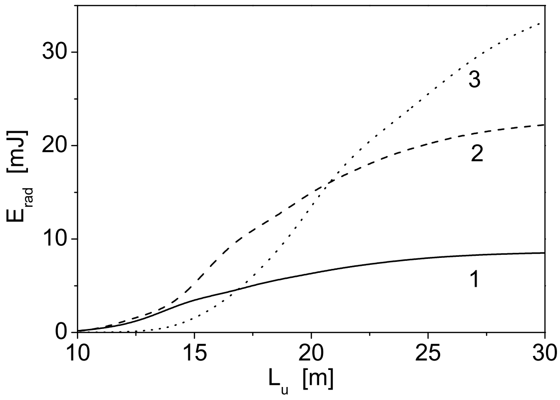

Figure 2: Energy in the radiation pulse versus undulator length. Curves 1, 2, and 3 correspond to the energy of the driving electron beam 680, 1250, and 2500 MeV, respectively. Normalized emittance is 1.5 mm-mrad. Radiation wavelength is 13.5 nm.

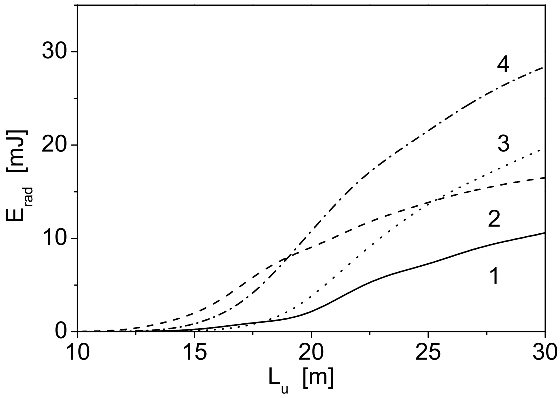

Figure 3: Energy in the radiation pulse versus undulator length. Curves 1 and 2 refer to the case of an electron energy of 1250 Mev and normalized emittance 1.5 mm-mrad and 1 mm-mrad, respectively. Curves 3 and 4 refer to the case of an electron energy of 2500 Mev and normalized emittance 1.5 mm-mrad and 1 mm-mrad, respectively. Radiation wavelength is 6.8 nm.

Results of the simulations for the case of 13.5 nm are shown in Fig. 2. With the repetition rate of 80000 pulses per second the average radiation power exceeds 2.5 kW and 1.7 kW for the energy of electrons of 2500 MeV and 1250 Mev, respectively. The FEL efficiency is about 1.8% in this case.

The FEL is tunable radiation source, and there is a simple deal to go over to different wavelength, for instance, to the next target wavelength of 6.8 nm discussed in the NGL community. Tuning of the wavelength is performed by the increase of the undulator gap. Evolution of the energy in the radiation pulse is shown in Fig. 3. Comparison of the pulse energies at 6.8 nm and 13.5 nm shows reduction of the pulse energy when going to shorter wavelength. Partially this reduction relates to nonoptimal undulator: period length has been optimized for 13.5 nm. Another factor is reduction of the FEL gain and FEL efficiency due to shortening of the wavelength. FEL efficiency can be increased with the reduction of the electron beam emittance. Curves 2 and 4 in Fig. 3 show gain curves of the SASE FEL driven by the electron beam with normalized emittance of 1 mm-mrad. Output power in this case becomes to be comparable with the case of the wavelength 13.5 nm and $\epsilon_n = 1.5$ mm-mrad. Recent developments of the laser driven rf gun demonstrated feasibility for generation of the beams with rms normalized emittance well below 1 mm-mrad [18]. Thus, we can conclude that it is technically feasible to produce 2 kW level of the average radiation power at the wavelength of 6.8 nm. It is important that the same hardware (accelerator and undulator) is used for production of the radiation with wavelength of 13.5 nm and 6.8 nm.

DISCUSSION

Up to now two technologies for the radiation source are developed by industry: laser produced plasma (LPP), and discharge produced plasma (DPP). Serious obstacle on the way to a high volume manufacturing (HVM) source is the small efficiency of these sources which requires deposition of huge power in a small volume. Another problem is the mitigation of the plasma debris required for the protection of EUV optics. Laser and plasma radiation sources may operate only at a limited set of discrete wavelengths. Each dedicated source operates at a fixed wavelength only.

An FEL based radiation source has evident advantages. The process of light generation takes place in vacuum, and there is no problem to utilize the spent electron beam (remove unused power). The problem of debris mitigation does not exists at all. There is no collector problem since the radiation is produced in the diffraction limited volume, and there is no problem with the transport of the radiation to the exposure tool. With a SASE FEL driven by 1 - 2 GeV electron beam, the available wavelength range can span from about 100 nm down to a few nanometers. This feature can be helpful for instance, for optimization of a photoresist. It is important that the same hardware (accelerator and undulator) can be used for production of tunable powerful radiation as we demonstrated in our paper. Average power of this ”clean” EUV radiation is in the range of a few kilowatts, an order of magnitude above present requirements for a HVM source. Thus, one FEL set up can replace a dozen of plasma sources. Currently microelectronic industry uses an approach of a single source for a single tool (stepper). In the case of using a powerful FEL as the source we can modify this approach to a single source for multiple tools.

The parameter space considered in this conceptual study does not deviate much from project parameters of FLASH/TESLA technology. Main idea was the demonstration of the capabilities of this technology to produce multi-kW level of output radiation power and show that properties of the radiation meet requirements of the NGL. It is important that the described device can be constructed now without additional R&D using components developed for FLASH and European XFEL. Definitely, there is a room for further optimization of the source. For instance, in the present design filling time of rf structure is comparable with flat-top part of rf pulse. Thus, average output power of the source can be increased by means of increasing the length of macropulse and corresponding reduction of the repetition rate. Alternatively, macropulse repetition rate can be increased for the price of reduction of the output power. This kind of considerations has been already analyzed in the framework of the European XFEL project [19].

Within long term of FLASH/TESLA technology development we can discuss extensions towards increase of duty factor up to cw mode of operation. This activity is also performed in the framework of TESLA Technical Collaboration. One of the problems to be solved is that of high duty cycle or cw injectors generating low emittance beams [20, 21]. The necessary replacement of klystrons by Inductive Output Tubes (IOT) seems to be possible [22]. When the injector technology becomes available, the FEL based radiation source can operate in cw mode. Application of energy recovery will allow to go over to higher output radiation powers.

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