POTENTIAL OF THE FLASH FEL TECHNOLOGY FOR THE CONSTRUCTION OF A KW-SCALE LIGHT SOURCE FOR THE NEXT GENERATION LITHOGRAPHY*

E.L. Saldin, E.A. Schneidmiller, V.F. Vogel, H. Weise, M.V. Yurkov
Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany

Abstract

The driving engine of the Free Electron Laser in Hamburg (FLASH) is an L-band superconducting accelerator. It is designed to operate in pulsed mode with 800 microsecond pulse duration at a repetition rate of 10 Hz. The maximum accelerated beam current during the macropulse is 10 mA. In this paper we analyze the parameter space for optimum operation of the FEL at the wavelength of 13.5 nm. 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. Thus, it will be possible to construct a FLASH like free electron laser operating at the wavelength of 13.5 nanometer with an average power up to 2.6 kW. Such a source meets the physical requirements of the light source for the next generation lithography.

INTRODUCTION

The roadmap for the development of the next generation lithography has been formulated by industry in the middle of the 1990s (see [1, 2] and references therein). A target goal was to follow Moore's law in the reduction of a feature size by a factor of two in two years [3]. During the last two decades the progress in the feature size reduction has been provided by reducing the wavelength of light sources (lasers) used. Now conventional lasers reached their limit. Immersion and photoresist technologies aiming for a feature size below the $\lambda/4$ limit reached their boundaries as well. That is why it was decided to base the next generation lithography (NGL) on a completely new light source – a plasma source producing extreme ultraviolet light at the wavelength of 13.5 nm aiming for a feature size of 20 nm. Microelectronic technology itself contains several challenging technologies inside such as mask, reticle, resist, stepper, etc. Here we discuss only the problem of the light source. 15 years of development of light sources for the NGL allowed to make significant progress, and a 20 W source for a beta-level EUV scanner has been delivered to industry this year [4]. However, it is generally accepted that the problem of light source for high volume manufacturing (HVM) is not solved yet.

Requirements for the source are not fixed but evolve with the evolution of all the other technologies involved. For instance, requirement for the average power (after intermediate focus (IF), in-band spectrum ±2% around 13.5 nm, etendue of the source output < 3 mm^2-sr) has been increased nearly by an order of magnitude during the last ten years, and approaches two hundreds Watts.

During the last years we observed rapid progress of Self-Amplified Spontaneous Emission Free Electron Lasers (SASE FELs) [5,6]. The jump in the wavelength was about five orders of magnitude, from 12 μm in 1997 down to 0.15 nm in 2009 [7–9]. FLASH (Free Electron Laser in Hamburg) has produced unprecedented powers for EUV radiation at a wavelength of 13.5 nm, a target goal for the next generation lithography (NGL) [8]. Previous studies proposed several schemes for a dedicated FEL-based radiation source for the NGL [10–15]. In this paper we analyze 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 the technology developed allows construction of a free electron laser operating at the wavelength of 13.5 nm with an average power of several kilowatts.

LAYOUT OF THE FACILITY

The TESLA project (TeV Energy Linear Accelerator) has been developed by an international TESLA collaboration since the beginning of the 1990s. More than 50 institutions from 12 countries were involved in the development of superconducting RF technology for a high energy electron-positron linear collider and for a driver-linac for an X-ray free electron laser (XFEL) [16,17]. Recently TESLA Collaboration has been transformed into the TESLA Technical Collaboration (TTC) aiming development technology of superconducting accelerators, and gave birth to two independent XFEL projects: FLASH (Free Electron Laser in Hamburg) and the European XFEL. The FLASH facility is driven by a superconducting linear accelerator and operates on the DESY site [18]. The aim of this project is to serve as a user facility, and gain experience for the XFEL project realization [19]. After an energy upgrade to 1.2 GeV scheduled for the end of this year, FLASH will produce tunable coherent radiation at a wavelength down to 4.5 nm, an ultimate peak power on a few GW level, and peak brilliance exceeding by eight orders of magnitude those values obtained from the third generation synchrotron radiation sources.

---

[*] FEL 2009 Conference, MOPC54

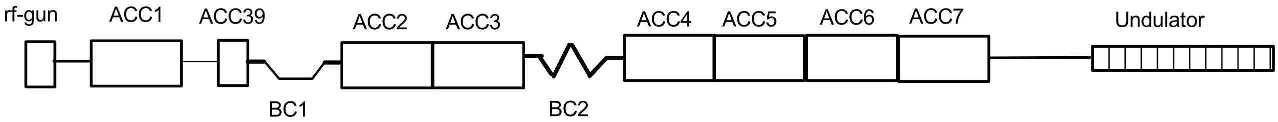

Figure 1: Schematic layout of the FLASH facility [20]. Abbreviations ACC1-ACC7, ACC39, and BC stand for accelerating module 1.3 GHz, accelerating module 3.9 GHz, and bunch compressor, respectively. Total length of the machine is 250 meters.

Table 1: Characteristics of FEL based radiation sources for the NGL

	FLASH	NGL-680	NGL-1250	NGL-2500
Electron energy, MeV	680	680	1250	2500
Bunch charge, nC	1	1	1	1
Peak current, A	2500	2500	2500	2500
Normalized emittance, mm-mrad	1.5	1.5	1.5	1.5
rms energy spread, MeV	0.5	0.5	0.5	0.5
Macropulse duration, ms	0.8	0.8	0.8	0.8
Micropulse rep. rate, MHz	9	10	10	10
# pulses in macropulse	7200	8000	8000	8000
Macropulse rep. rate, Hz	10	10	10	10
Undulator period, cm	2.73	2.73	3.5	5.0
Undulator length, m	27	30	30	30
Radiation wavelength, nm	13.5	13.5	13.5	13.5
FEL parameter ρ	0.0025	0.0034	0.0042	0.0047
FWHM spectrum bandwidth, %	2	2	2	2
Energy in the radiation pulse, mJ	1.4	8.5	22	33
Peak power, GW	5.6	34	88	130
FWHM pulse duration, fs	250	250	250	250
FWHM spot size, mm	0.17	0.3	0.2	0.1
FWHM angular divergence, μrad	30	48	54	64
Average radiation power, W	100	680	1760	2640

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 130 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 linear longitudinal compression realized with the help of an accelerating module operating at 3.9 GHz. 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 pulsed mode operation with a macropulse repetition rate of 10 Hz, flat-top macropulse duration of 800 μs, and maximum 10 mA beam loading within the macropulse. With these parameters the average power in the electron beam is equal to 96 kW at the energy of 1.2 GeV. High power in the electron beam is the main basis for the generation of high EUV radiation power.

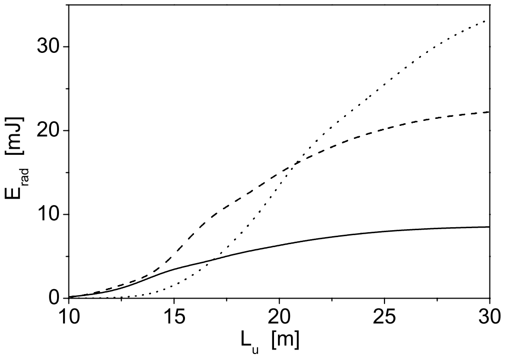

Figure 2: Energy in the radiation pulse versus undulator length. Solid, dashed, and dotted lines correspond to the energy of driving electron beam 680, 1250, and 2500 MeV, respectively.

PROPERTIES OF THE RADIATION

In the following we optimize the SASE FEL operation at the wavelength of 13.5 nm. We assume parameters of

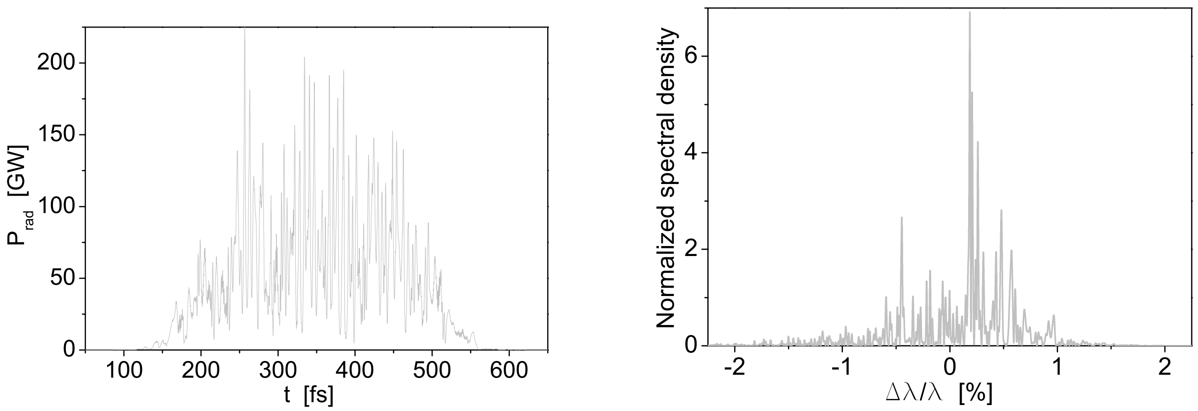

Figure 3: Temporal (left) and spectral (right) structure of the radiation pulse. FEL parameters correspond to NGL-1250 option compiled in Table 1.

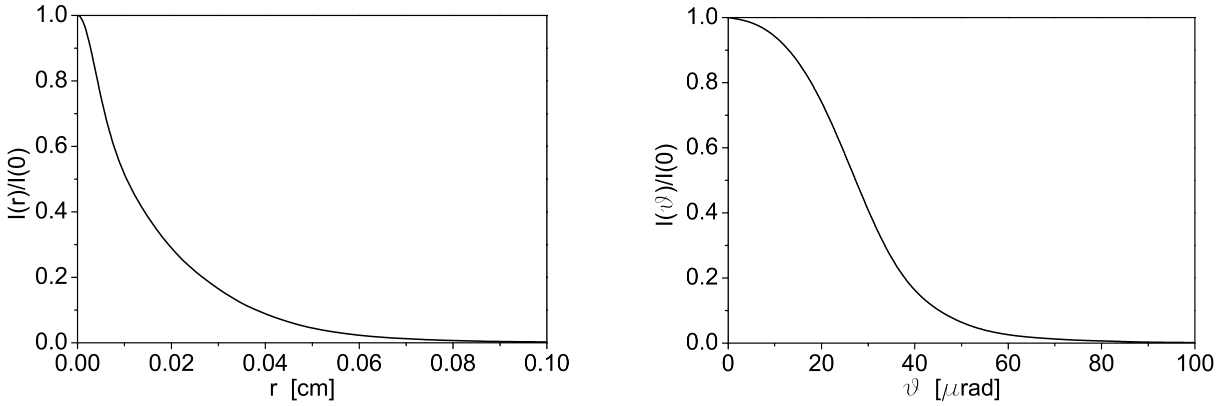

Figure 4: Distribution of the radiation intensity in the near (left plot) and far (right plot) zone. FEL parameters correspond to NGL-1250 option compiled in Table 1.

the electron beam as given in Table 1. This parameter set is compiled on the base of our experimental experience from FLASH with an appropriate correction for the above mentioned linearized bunch compression scheme. We optimize the FEL parameters by varying the energy of the driving electron beam between 625 Mev and 2500 MeV. Calculations are performed with the time-dependent simulation code FAST [21]. The undulator is assumed to be hybrid planar, and the limitation of minimum 1.2 cm is imposed on the undulator gap. Another technological boundary relates to segmentation of the undulator: we assume the length of undulator segments to be 200 cm, and focusing quadrupoles are installed in the undulator intersections. Thus, the minimum focusing beta function is equal to 200 cm.

Calculations show that within the given parameter range the optimum beta function is always below 200 cm, thus the value of the beta function of 200 cm has been fixed in all calculations. General feature is that shorter gain length is achieved at a shorter undulator period, and at smaller undulator gap. In the studied case we deal with high power electron and photon beams, and the matter of concern is to provide sufficient aperture for the transport of both beams. We set the limit on the undulator gap to 1.2 cm.

Another step for our optimization relates to an optimum choice of the undulator tapering in order to increase the FEL efficiency. In all cases we assume a total magnetic length of the undulator of 30 meters. Results of the simulations are shown in Fig. 2. We discover that within the given parameter space undulator tapering is a very powerful tool for increasing the FEL efficiency, roughly by about a factor of five with respect to the saturation efficiency. The results obtained are very impressive: for a chosen electron energy of 2500 MeV, the average radiation power exceeds 2.5 kW. At a reduced electron energy (1250 MeV) we find an average radiation power of 1.7 kW. The FEL efficiency is about

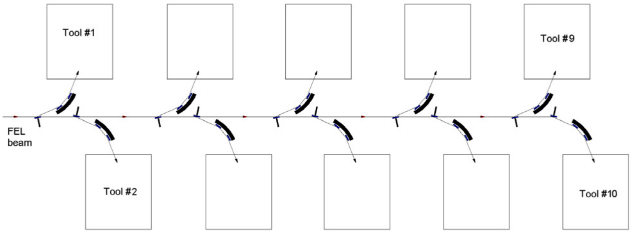

Figure 5: Integration of FEL-based NGL source in the factory using an approach of ”single source” - ”multiple tools”.

1.8% in this case. In conclusion we present the main characteristics of the radiation pulse in Figs. 3 and 4: temporal and spectral properties, intensity distribution at the undulator exit, and angular distribution in the far zone.

DISCUSSION

Up to now two technologies for the light source are developed by industry: laser produced plasma (LPP), and discharge produced plasma (DPP) [1, 2]. Serious obstacle on the way to a 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. The proposed solution to aim for an FEL based NGL source has evident advantages. The process of light generation takes place in vacuum, and there is no problem to utilize the spent electron beam. 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. Finally, the average power of this ”clean” EUV radiation is in the range of a few kilowatts, an order of magnitude above the requirements of a HVM source. Thus, a single FEL 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 (see Fig. 5). A solution based on the use of FELs is also much more flexible in terms of the possibility to change the required wavelength.

ACKNOWLEDGEMENT

We thank R. Brinkmann, G. Shirkov, and A. Sissakian for their interest in this work. We thank E. Syresin for useful discussions. During the EUVL Symposium in Barcelona we had the possibility for stimulating discussions with our colleagues from the FEL community and from industry, and we especially thank V. Banine, A. Endo, M. Goldstein, E. Minehara, U. Stamm, and X.J. Wang. We also thank V. Bakshi and A. Endo for an invitation to discuss the potential of FELs for the next generation lithography.

REFERENCES

[1] Vivek Bakshi (Editor), EUV Sources for Lithography, SPIE Press Monograph, Vol. PM149, 2006. by Vivek Bakshi (Editor).

[2] Vivek Bakshi (Editor), EUV Lithography, SPIE Press Book, Vol. PM149, 2008.

[3] Gordon E. Moore, Electronics, Volume 38, Number 8, April 19, 1965.

[4] Vivek Bakshi, EUV Sources Come Back as Top EUV Lithography Concern, Semiconductor International, July, 2009. http://www.semiconductor.net.

[5] Ya.S. Derbenev, A.M. Kondratenko, and E.L. Saldin, Nucl. Instrum. and Methods **193**(1982)415.

[6] J.B. Murphy and C. Pellegrini, Nucl. Instrum. and Methods A **237**(1985)159.

[7] M. Hogan et al., Phys. Rev. Lett. **81**(1998)4867.

[8] W. Ackermann et al., Nature Photonics, 1 (2007)336.

[9] P. Emma, First lasing of the LCLS X-ray FEL at 1.5 A, presented at the Particle Accelerator Conf., Vancouver, May 2009.

[10] Brian E. Newnam, Proc. SPIE, Vol. 1343 (1991) 214.

[11] C. Pagani et al., Nucl. Instrum. and Methods A 463(2001)9.

[12] G. Dattoli et al., Nucl. Instrum. and Methods A 474(2001)259.

[13] M. Goldstein et al., Proc. 27th FEL Conference, Stanford, 2005, p. 422.

[14] E.L. Saldin et al., Free electron laser as a potential source for EUV lithography, talk at the EUVL Source Workshop, Barselona, 2006.

[15] E. Minehara et al., A multi-kW EUV light source driven by energy-recovery linac, talk at the EUVL Source Workshop, Barselona, 2006.

[16] Conceptual Design of 500 GeV e+e- Linear Collider with Integrated X-ray Facility (Edited by R. Brinkmann et al.), DESY 1997-048, ECFA 1997-182, Hamburg, May 1997.

[17] TESLA Technical Design Report, DESY 2001-011, March 2001 http://tesla.desy.de/new_pages/0000_TESLA_Project.html.

[18] T. Åberg, et al., A VUV FEL at the TESLA Test Facility at DESY, Conceptual Design Report, DESY Print TESLA-FEL 95-03 , May 1995.

[19] Altarelli, M. et al. (Eds.), XFEL: The European X-Ray Free-Electron Laser, Technical Design Report. Preprint DESY 2006-097, DESY, Hamburg, 2006 (see also http://xfel.desy.de).

[20] B. Faatz et al., FLASH status and upgrade, Proc. FEL 20O9 Conference, WEOA02.

[21] E.L. Saldin, E.A. Schneidmiller, and M.V. Yurkov, Nucl. Instrum. and Methods **A 429**(1999)233.