EXTREME ULTRAVIOLET (EUV) SOURCES BASED ON SYNCHROTRAON RADIATION*

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Abstract

The production of Extreme Ultraviolet radiation (13.5 nm or 11.3 nm wavelength) by relativistic electrons as a source for the Next Generation Lithography (NGL) based on the EUV-concept (13.5 nm or 11.3 nm wavelength) is discussed. The requirements of the lithography community are as follows: output power of 50 to 150 W within 2% bandwidth and a maximum of 500 W outside this bandwidth. It is shown that among all other synchrotron radiation devices only a Free Electron Laser (minimum beam energy 500 MeV) can (under certain circumstances) fulfil these requirements.

1 INTRODUCTION

Lithography, the technique for manufacturing microelectronic semiconductor devices such as processors or memory chips, presently uses deep UV (DUV) radiation. The main radiation source is the ArF excimer laser [1] at a wavelength of 193 nm. Future sources will be F_2 lasers at 157 nm and eventually H_2 lasers at 127 nm.

In order to reduce the size of the elements further, advanced lithography technologies (Next Generation Lithography: NGL) based on EUV photons (13.5 nm wavelength), X-ray photons (1 nm wavelength), electrons, and ions are being investigated by chip makers and equipment manufacturers.

EUV lithography is being considered as one of the most promising. The requirements for the source are as follows:

- Wavelength: 13.5 nm (≅ 92 eV) or 11.3 nm
- Bandwidth: 2%
- Output power: 50 to 150 W (various phases) and
- a maximum of 500 W outside this bandwidth.

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The development of a suitable source is one of the big challenges in EUV lithography. At present powerful sources of EUV photons may be based on either plasmas [2] (produced by laser irradiation or by gas discharges) or on relativistic electrons (synchrotron radiation) [3]. In this paper we compare storage ring sources with Free Electron Laser sources. The paper is a condensed version of a report prepared early in 2000 for the German Federal Ministry of Education and Research.

2 STORAGE RING BASED SOURCES

The spectral power ΔP of the emitted synchrotron radiation in Watts per eV, per mrad horizontal angle ϑ and integrated over the vertical angle is [4]

$$\frac{\Delta P}{\Delta\vartheta}\left[Watt/mrad\vartheta/eV\right] = 8.73\frac{E^4[GeV]I[A]}{r[m]}G_2(y)$$

$$\text{with } G_2(y) = y^2\int_y^\infty K_{5/3}(\eta)d\eta \text{ and } y = E_{Phot}/E_c$$

I is the stored beam current, E is the energy of the stored beam and K is the modified Bessel function. E_{Phot} is the photon energy and E_c is the critical photon energy

$$E_c\,[eV] = 2218.3\frac{E^3[GeV]}{r[m]}$$

The total emitted power integrated over the circumference within the 2% bandwidth at 13.5 nm is shown in fig. 1 for various storage ring energies. The stored current is in all cases 1 A.

Similar statements are valid when storage rings are equipped with wigglers. Although it is possible to make the wiggler long enough to produce 50 W or more the outband power is a factor of 120 to 500 higher (depending on the energy). This violates the requirement that the outband power is not allowed to exceed 500 W.

And, in addition, a similar statement is true for undulators. Even with ridiculous large undulators the ratio inband to outband power cannot be met. As an example at

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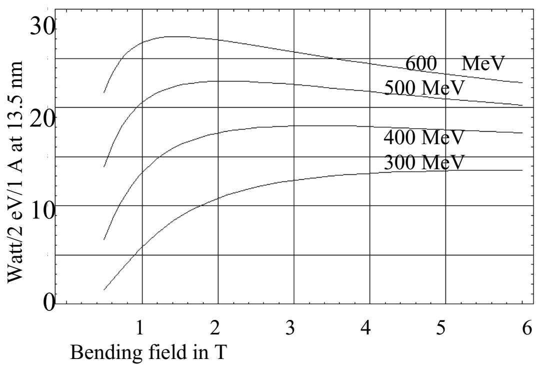

Fig. 1 Maximum power at 13.5 nm from various storage rings collected over the whole circumference. The stored beam is 1 A

0.6 GeV an undulator with a k-value of 2, a period length of 1.24 cm and 100 periods delivers an inband power of 4.7 W. The out of band power is about 150 times larger.

3 FEL SOURCES BASED ON LINACS

In the following only FELs based on the SASE effect are considered [5] for the sake of shortness.

For the classical FEL design (Rayleigh length one-half of the interaction length L) the horizontal and the vertical emittance ε has to fulfil the conditions [6]

$$\varepsilon \le \frac{\lambda_{Phot}}{4\pi}$$

and requires that the horizontal and vertical emittance of the beam has to be smaller than 1.07 nm (λ_{Phot} = wavelength of the photon). In a linac the emittance shrinks with energy (adiabatic damping)

$$\varepsilon = \varepsilon_n / \gamma$$

where ε_n is the so-called normalized emittance. The magnitude of the normalized emittance depends on the gun properties. Assuming a photo-cathode gun ε_n close to 10^{-6} m.rad (depending on current, bunch length etc.) [7] γ has to be 1000 or higher (linac energy about equal or above 500 MeV). Assuming a gradient of 20 MeV/m the linac is 27.5 m (or close to 30 m) long. Linacs with more than 40 MeV/m are available, so that the overall length of the linac is between about 15 m to 30m.

The period length of the undulator λ_u has to fulfil the condition (K= K-value of the undulator)

$$\lambda_{Phot} = \frac{\lambda_u}{2\gamma^2}\left(1+K^2/2\right)$$

For γ = 1000, λ =13.5 nm, $\varepsilon_n = 10^{-4}$ λ_u becomes

$$\lambda_u = \frac{27}{1+\frac{K^2}{2}}[mm]$$

With an assumed K of $\sqrt{2}$ the period length is 13.5 mm. Conventional permanent magnet undulators with a reasonable gapwidth cannot fulfil these conditions. Therefore superconductive undulators [8] are the preferred undulators which allow to operate the FEL with an acceptable gap.

In the following the length of the undulator for a SASE type of undulator is estimated. The gain length L_G is the length in which the FEL power increases by a factor of e. The gain length depends on the power density of the emitted light. The power density is a function of the undulator properties (K-value, period length), the beam properties (peak current, energy, β-functions, emittance, energy spread etc.) and the properties of the optical beam (diffraction). In order to separate the different influences the following parameters are introduced:

$$L_G = \frac{\lambda_u}{4\pi\sqrt{3}\rho\chi S}$$

where ρ is the so called Pierce parameter (the power density of the emtted synchrotronradiation), χ describes the influence of the energy spread and S the influence of the diffraction effects.

For an energy spread of 10^{-4} χ is very close to 1. The dependence of L_G on the beta-function is shown in fig.2.

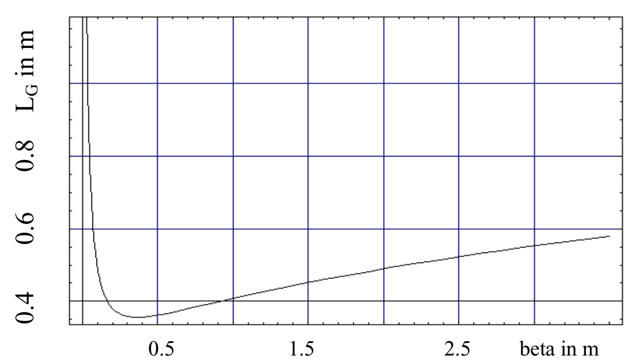

Fig. 2 L_G as a function of β

It is obvious that the gain length depends strongly on the beta-function in the undulator and has a minimum close to a beta-function of 0.4 m. Changing the energy spread from 10^{-4} to e.g. 5.10^{-4} changes χ from 1 to 0.4 (at the minimum) and increases the gain length therefore significantly. Therefore the energy spread is the crucial parameter defining the length of the undulator.

The development of the power along the undulator axis z is described by an exponential law

$$P(z) = P(\beta)e^{z/L_G}$$

until the amplification comes to an end at the saturation length $z_{sat.}$ This is shown in fig. 3. The saturation is calculated for two k-values: k=1.4 and k=2. High k–values reduce the undulator length significantly. This is a strong argument for a superconducting undulator. The peak current in fig. 3 is 200 A. The main parameters are summarized in Table I.

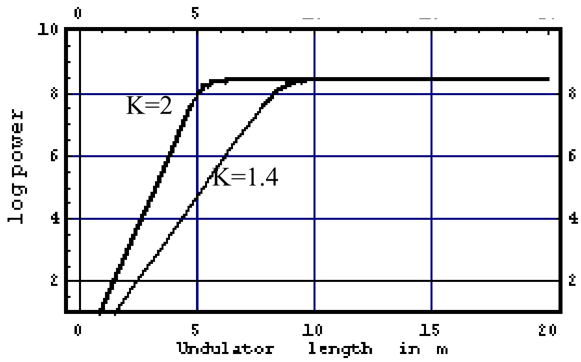

Fig. 3 Power development along the undulator axis for two diffent K-values of the undulator: K =1.4 and 2. β is 0.3 m in both directions

Table I: Main parameters

Beam energy [MeV]	522
Normalized emittance [m]	10^{-6}
Peak current [A]	200
Relative energy spread	10^{-4}
Photon wavelength [nm]	13.5
Average current [µA]	30

The peak power of one pulse is ca. 1.33. 10^8 W. One pulse with an assumed bunch length of 3 psec produces an energy of $\sqrt{2\pi}$ .3.10^{-12} 1.33 10^8 J or about 1 mJ. In order to produce a cw power of 50 W, a pulse repetition rate of 50 kHz is required. The required average current is fairly modest. Working on the basis of a 1.5 GHz linac RF system (bucket repetition of time of 0.67 nsec) the average current is about 30µA.

4 POSSIBLE LAYOUT OF A FEL-SYSTEM FOR 13 5 nm LITHOGRAPHY

A possible layout of a distributed FEL system for micro-lithogaphy is shown in fig.4. The linac is either in a separate building or in the basement of the factory. The beam is brought via isochronous bends to the undulators which emit the radiation. A switchyard system brings the beam to undulators next to the steppers. Afterwards the beam power is recovered or the beam hits a beam stopper.

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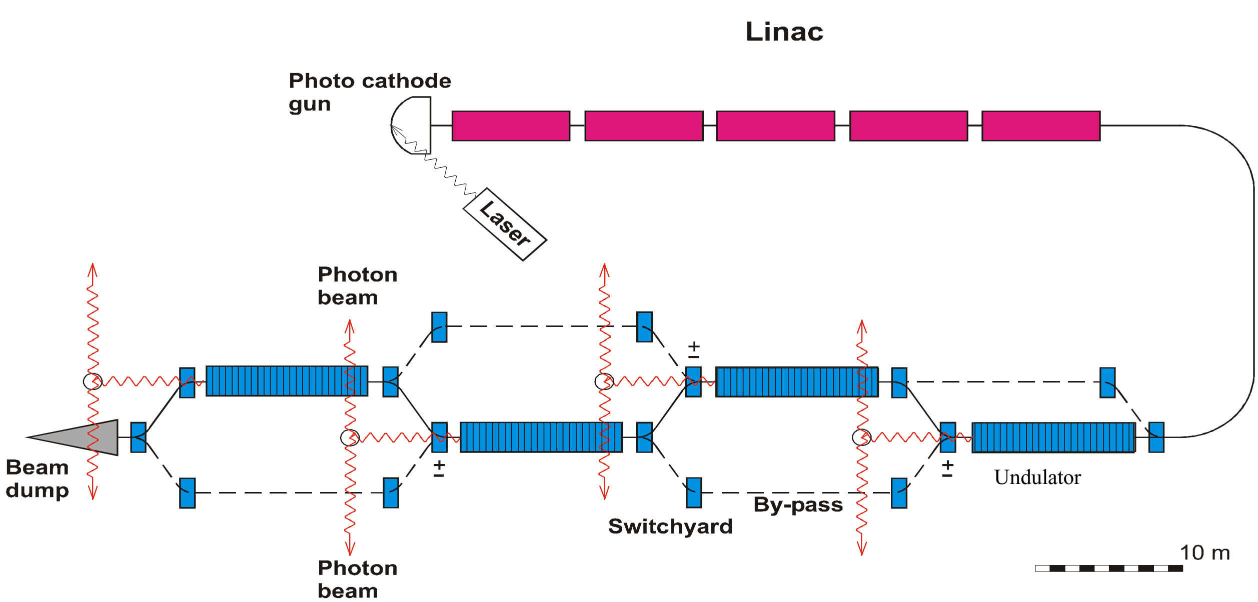

Figure 4: Possible layout of the linac and the distributed undulators next to the steppers. A beam switchyard directs the beam to the requested undulator. Both linac and undulators are in the basement of the building.