# 13.5-nm FREE-ELECTRON LASER FOR EUV LITHOGRAPHY

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*Abstract*

Lithography over the last years has been actively used to produce more compact and powerful computers. The dimensions of the microchips still require shorter wavelengths of light to enhance future 'nano' scale production. It is envisaged that 193 nm lithography is beginning to reach its limit. Extreme Ultraviolet (EUV) lithography of 13.5 nm wavelength could provide a solution for the next step of miniaturization, however presently no light source exists with sufficient average power and (especially) brightness. We report here results of a study, showing the feasibility of a FEL EUV source driven by a multi-turn superconducting energy-recovery linac (ERL). The proposed 40×20 m$^2$ facility will be located underground for radiation safety purposes. Using MW-scale consumption from the power grid, it is estimated to provide 5 kW of average EUV power. We elaborate in some detail the SASE option, which is presently technically feasible, however regenerative-amplifier option should be also kept in mind. The proposed design is based on a short-period (2-3 cm) undulator. The corresponding electron beam energy is about 0.6-0.8 GeV. The proposed accelerator consists of photoinjector, booster, and a multi-turn ERL.

## INTRODUCTION

The use of a high-gain FEL for the EUV lithography was proposed nearly a decade ago [1]. Here we try to make some improvements of this approach. In particular, the use of the new scheme of the multi-turn ERL [2, 3] decreases the facility sizes and makes possible better control of beam dynamics, matching the ERL beam parameters with the FEL requirements (see, e. g., [4]). The last circumstance allows decreasing of the undulator length. Moreover, further decrease of the necessary peak current may be achieved by the use of a regenerative amplifier FEL [5]. The corresponding scheme is discussed also.

## THE ELECTRON ENERGY

To define the necessary electron energy $E = \gamma mc^2$ we use two equations. The first one is the undulator radiation wavelength

$$\lambda = \frac{d}{2\gamma^2}\left(1+\frac{K^2}{2}\right), \qquad (1)$$

where $d$ is the undulator period, and

$$K = e \cdot B_0 \cdot d \,/\, (2 \cdot \pi \cdot m\, c^2)$$

(in SGS system, used in this article) is the undulator deflection parameter, proportional to the undulator field amplitude $B_0$. The second equation connects the undulator field amplitude $B_0$ with the magnet material coercivity $H_c$. For a planar hybrid undulator, $B_0$. may be estimated as

$$B_0 \approx H_c \frac{\sin(\pi \cdot t/d)}{\sinh(\pi \cdot g/d)}, \qquad (2)$$

where $t$ is the thickness of the permanent magnet blocks (typically, $t \approx d/3$, and we take this value below) and $g$ is the undulator gap. Some authors prefer to use the Halbach equation [6] instead of Eq. (2), but it gives very similar results for short-period undulators [7, 8].

Now, assuming K about 1.5 (higher $K$ values do not increase the FEL gain significantly), the gap $g$ = 1 cm, and $H_c$=13 kOe (typical for NdFeB permanent magnets), Eq. (2) yields undulator period $d$ = 2.0-2.5 cm. Then Eq. (1) yields electron energies $E$=500-750 MeV.

For such energies the characteristic normalized rms emittance accepts values $\gamma \cdot \lambda/(4\pi) \sim$ 1.0-1.6 μm (γ=1000-1500, λ = 13.5nm) . Such values are achievable for charge per bunch less than 1 nC.

The natural vertical focusing of the undulator is described by the matched beta function $\beta_u = \sqrt{2}\, E/(eB_0) \approx 5$ m. This value exceeds significantly the expected gain length 1–2 m (see below). Therefore additional focusing is desirable. The simplest lattice scheme is FODO. Energy $E$, undulator parameter $K$ and natural equal-focusing $\beta$-function are given at Fig. 2.

## THE SEPARATED-TRACKS ERL

During the commissioning of the first two-orbit ERL [9] and its FEL several problems appeared. As the result of this operation experience, the new multi-turn ERL configuration was proposed [2, 3]. The main idea was to separate accelerated and decelerated beams. It may be achieved using splitted accelerating structure, as it was done at CEBAF at JLab (USA).

The scheme for ERL with separated accelerated and decelerated beams is shown in Fig. 1. Electrons with injection energy $E_0$ passes through each RF accelerating section RF1 and RF2 twice, obtaining energy $E_0 + 4\Delta E$. After that, the beam is used in the FEL undulator and enters the RF sections for deceleration. The last orbit length is chosen to tune the the electrons' phase to deceleration.. Then, after the first deceleration in RF2 electrons have energy $E_0 + 3\Delta E$, which differs from

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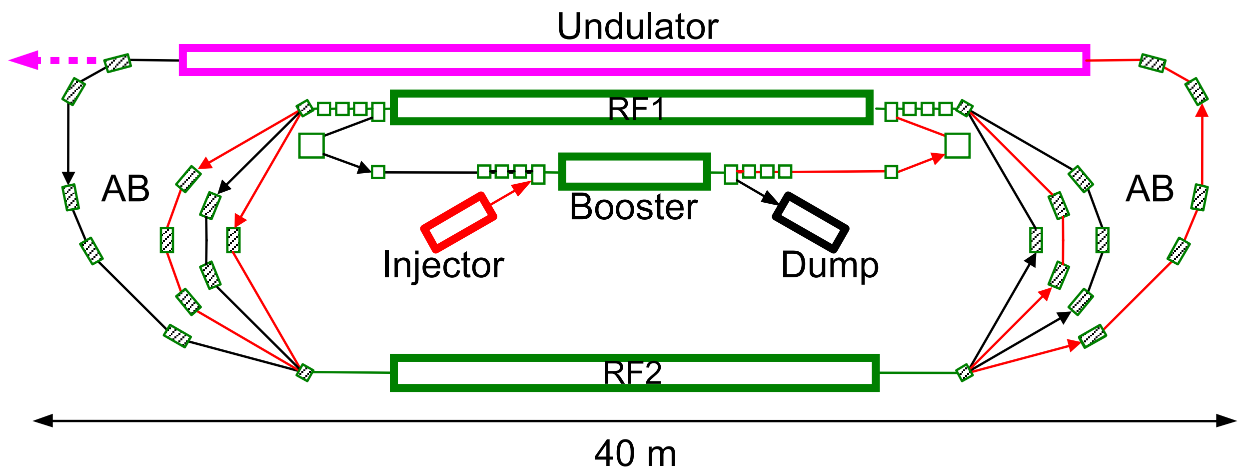


Figure 1: The scheme of ERL with FEL. RF1 and RF2 – RF accelerating structures, AB – achromatic bends. Red arrows – accelerating “fresh” beam, black arrows – decelerating used beam.

energies $E_0 + 2\Delta E$ and $E_0 + 4\Delta E$ of accelerated beams. Then separating magnet directs the decelerated beam to the appropriate arc. During further deceleration, electron energy differs from other beam energies by not less than $\Delta E$. It makes possible to have only one beam at each arc. Therefore one can adjust each arc length, optics, and trajectory steering independently.

The optical requirements for accelerating and decelerating beam lines are very different. As beam delivery system for FEL, the ERL must assure emittance conservation and optimal bunching during acceleration. However, during deceleration maximum energy acceptance with longitudinal “gymnastics” is required. Beam diagnostics also is simplified for separated beams. Splitting of RF system decreases also the length of sections with multiple beams, making easier the focusing problem.

The full arc flexibility makes possible to obtain femtosecond electron bunches in multi-turn ERLs and use them to generate femtosecond x-ray and terahertz pulses.

The size of the ERL, shown in Fig. 1, corresponds to the required electron energy of up to 750 MeV. The maximum energy gain $\Delta E$ per one linac is about 180 MeV. The cascade injection with energies 40 MeV (booster ERL) and 8 MeV (injector) is used.

## THE FEL

The full outer size of the installation was chosen to be 40 m. Then the undulator size is forced to be about 30 m. For the SASE FEL it corresponds to twenty times shorter gain length $L_g$ = 1.5 m. The electron energy spread $\Delta\gamma$ must be less than $d/4\pi L_g \approx 1\cdot 10^{-3}$ [10].

The focusing of the long undulator may be characterized by the average beta function $\bar{\beta}$. Its optimal value is near the gain length. For the simplest case of the FODO lattice the minimum value of $\bar{\beta}$ is the double distance between the quadrupoles. Therefore it is not easy to combine such strong focusing with the undulator field.

Therefore one can try to use the natural undulator focusing, “redistributed” to the horizontal betatron oscillations by weak focusing quadrupoles, as it was demonstrated at the first multisegment SASE FEL LEUTL [11]. In this case $\bar{\beta} = \sqrt{2}\beta_u \approx 7$ m. As $\bar{\beta} \gg L_g$ for low enough energy spread and emittance one can use the simple expression for the gain length [10]

$$L_g = \frac{d}{4\pi\sqrt{3}\rho}, \tag{3}$$

where

$$\rho = \frac{1}{\gamma}\left(\frac{I}{I_A}\frac{K^2 d^2}{64\pi^2\varepsilon\bar{\beta}}\right)^{1/3}\left[J_0\left(\frac{K^2}{4+2K^2}\right) - J_1\left(\frac{K^2}{4+2K^2}\right)\right]^{2/3} \tag{4}$$

($I_A = mc^3/e \approx 17$ kA is the Alfven current, $\varepsilon$ is the transverse rms emittance, $J$ are the Bessel functions) to obtain the lower estimate of required peak current .

For better accuracy we used parametric formula of M. Xie [12]. The results are shown at Fig.3. For the normalized emittance $\varepsilon\gamma = 10^{-6}$ m and energy spread $\Delta\gamma = 10^{-4}$ , the peak current of 150 A is enough to reach the saturation.

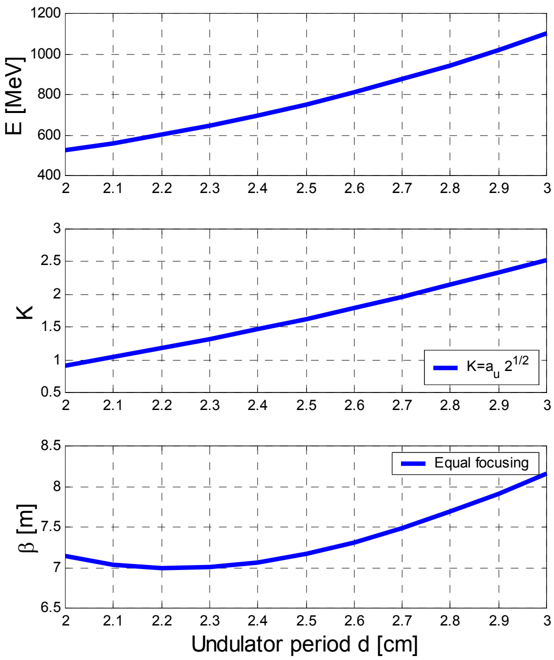


Figure 2: Elecron energy $E$, undulator parameter $K$ and equal-focusing $\beta$-function as functions of the undulator period $d$. $H_C$=13kOe, the undulator gap $g$=1 cm.

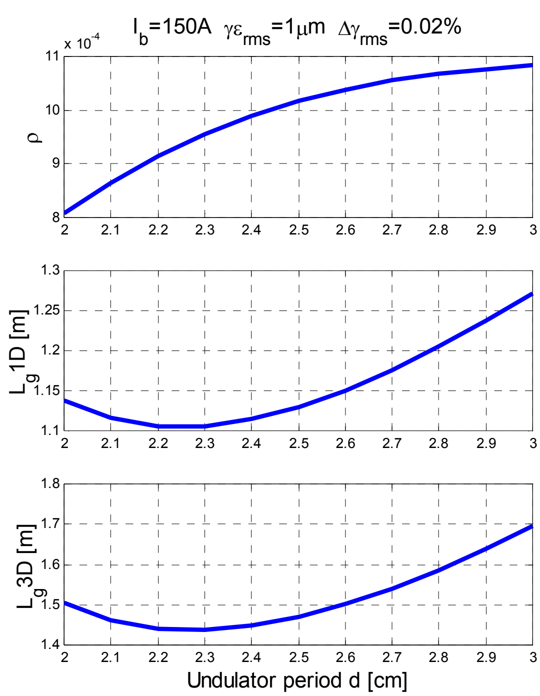


Figure 3: The Pierce parameter ρ, one-dimensional gain length $L_g$1D and actual gain length $L_g$3D as functions of the undulator period $d$. $L_g$3D was calculated according to parametric formula [12].

## THE AVERAGE CURRENT

The FEL efficiency is about [12] $d/4\pi L_g \approx 1\cdot10^{-3}$. Therefore for the 5 kW average power one needs the beam average current about 10 mA. Such average current was already reached at the JLab FEL ERL [13]. It indicates, that proper optics is capable to suppress the instabilities at such currents. Choosing a modest value 0.1 nC for the charge per bunch, one gets repetition frequency of 100 MHz, reasonable for photo-cathodes' driving lasers. It should be also mentioned that recent JLab proposal [13] for 10-100 eV-photons FEL has by obvious reasons some similarity to our proposal.

## THE REGENERATIVE AMPLIFIER FEL

Further improvement of radiation parameters and decrease of the required peak current may be obtained using the regenerative amplifier FEL [5]. The regenerative amplifier has more narrow and stable radiation spectrum compared to the SASE case and allows for shorter (7-10 $L_g$) undulator section. To eliminate the problem of partially transparent mirror, one can use the electron outcoupling technique [14]. In this case the coherent radiation from the last section of the long undulator is used for feedback. This can be achieved in two ways [15]. Both schemes are shown in Fig. 4.

The first method uses achromatic bend before the last undulator section. In this case, the radiation may be deflected from the main undulator axis, as shown in Fig.4, top.

The second method (tapering) uses the last undulator section with shorter period or lower field amplitude. Then, according to Eq. (1) the wavelength of radiation in the forward direction is shorter. Therefore the coherent radiation of the microbunched beam has a hollow angular distribution and can be re-circulated using a hollow mirror (Fig.4, bottom). The optimal period of the initial part of the main undulator may also be shorter than the regular value. Therefore we plan to perform detail calculations for this option.

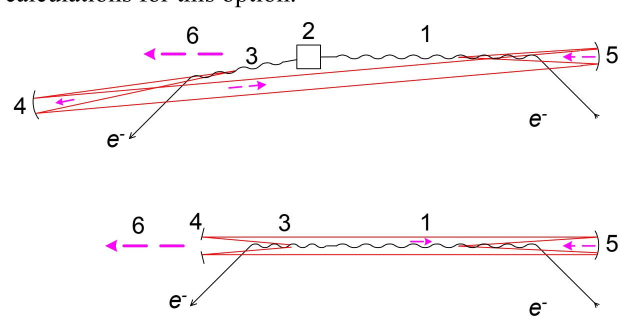


Figure 4: Two schemes of the regenerative amplifier FEL exploiting electron outcoupling technique. Top: with e-beam bending. Bottom: with tapering. 1 – main undulator, 2 – achromatic bend, 3 – last undulator section, 4 and 5 – mirrors, 6 – radiation from the main undulator. Radiation used for feedback is shown by red lines and small violet arrows.

## CONCLUSION

Thus, we have shown, that the use of multi-pass ERL allows building rather compact soft x-ray (or EUV, as it is called in industry) FEL for the industrial lithography. Relatively low required peak current value reduces the coherent synchrotron radiation and other sources of the beam quality degradation. Relatively low average current and the advanced ERL magnetic system prevent instabilities. The use of the regenerative amplifier FEL scheme may further improve the radiation parameters.

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