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Optimization considerations for a SASE free electron laser based on a superconducting undulator

B. Ketenoğlu*, Ö. Yavaş

Department of Engineering Physics, Ankara University, 06100, Tandoğan, Ankara, Turkey

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ABSTRACT

A self amplified spontaneous emission (SASE) free electron laser (FEL) based on a new generation superconducting planar undulator, is optimized. It is shown that the laser wavelength should be down to soft X-rays range (∼2–3 nm) of the spectrum via a dedicated undulator driven by a 1 GeV electron linear accelerator (linac). Numerical calculations and simulation results of the three main performance parameters for SASE operation, namely 1D gain length ($L_{G,1D}$), saturation power (P_{sat}) and saturation length (L_{sat}), are compared and discussed.

1. Introduction

As known, conventional FELs, i.e. FEL oscillator, use two reflection mirrors to confine the laser beam in an optical resonator, which enables the interaction repetition of the electron beam with the radiation inside the undulator resulting a generation of coherent, high power laser. But assuming much more shorter wavelengths, such as VUV, soft X-rays and even X-rays region, no reflecting mirror is available. Considering dedicated wavelengths, in case of a longer undulator is designed without any mirrors, the electron beam injected to the undulator keeps interaction with undulator field and radiation field relatively in a long time, the noise signal is amplified and finally reaches saturation, hence the abbreviation SASE comes out (see Fig. 1).

In recent years, 6.5 nm wavelength via a conventional hybrid with iron planar undulator and 3.5 nm wavelength via an in-vacuum permanent undulator, is achievable by 1 GeV electron beam [1,2]. In following sections, it is shown that the laser wavelength should be down to ∼2–3 nm without increasing the beam energy more than 1 GeV, but modifying the undulator configuration to a new generation superconducting technology.

2. Electron beam specifications to drive SASE undulators

Considering both operating facilities and proposals about 1 GeV beam energy (i.e. FLASH [1], SCSS [2], FERMI@Elettra [3]) as dedicated SASE sources around the World, high current (∼kA), ultra short (∼ps) and low emittance (∼nm) electron beam obtained from an L-band (1.3 GHz) superconducting, or a C-band (5.7 GHz) normal conducting, or evenmore an S-band (3 GHz) normal conducting linac, could serve as a driver for SASE undulators. In this sense, a typical electron beam configuration given in Table 1, should conveniently interact with undulator and radiation fields during the lasing process.

Where, transverse emittance of the beam is calculated by Eq. (1). Furthermore, peak current and beam peak power are obtained by Eqs. (2) and (3), respectively.

$$\varepsilon_{x,y} = \frac{\sigma_{x,y}^2}{\beta_{x,y}} \tag{1}$$

$$I_{peak} = \frac{Q}{t_\mu} \tag{2}$$

$$P_{beam} = E_{beam} I_{peak} \tag{3}$$

3. SASE FEL optimization based on a superconducting undulator

In this section, it is shown that two stand-alone superconducting planar undulator lines with two different gaps (g=0.8 cm and g=1.2 cm) should asynchronously be operated to go down to soft X-rays range (∼2–3 nm) of the spectrum by the same undulator period (λ_u = 1.5 cm) for both. On the other hand, 1 GeV beam energy (see Fig. 2) is sufficient for a dedicated superconducting planar undulator with a gap of 0.8 cm for 3.15 nm wavelength.

Peak magnetic field on axis of the superconducting planar undulator is calculated by Eq. (4), where a is expressed in units of Tesla

* Corresponding author.
E-mail address: bketen@eng.ankara.edu.tr (B. Ketenoğlu).

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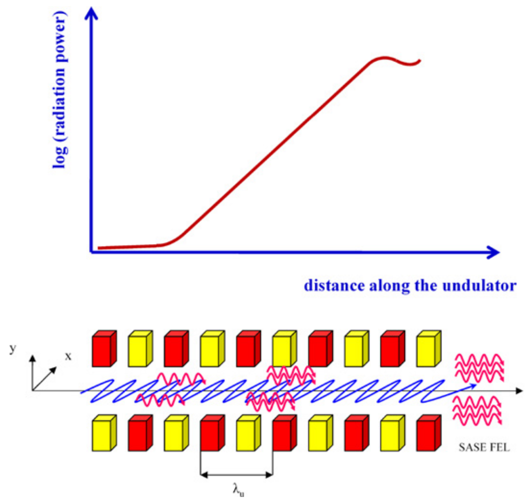

Fig. 1. SASE FEL power saturation along the undulator.

Table 1
Typical 1 GeV electron beam parameters @ undulator entrance.

Parameter	Unit	Value
Electron beam energy, E_{beam}	GeV	1
Bunch charge, Q	nC	1
Transverse emittances, $\varepsilon_{x,y}$	nm	3.2
FWHM bunch length, t_{μ}	ps	0.5
Transverse bunch sizes, $\sigma_{x,y}$	μm	180
Peak current, I_{peak}	kA	2
Beta functions, $\beta_{x,y}$	m	10
Energy spread, $\Delta E/E$	–	2×10^{-4}
Beam peak power, P_{beam}	TW	2

and b and c are dimensionless. In addition, one has to keep the restriction in mind on λ_u for g=0.8 cm: 0.8 cm < λ_u < 3.2 cm [4].

$$B_{peak} = a\exp\left[b\frac{g}{\lambda_u} + c\left(\frac{g}{\lambda_u}\right)^2\right] \tag{4}$$

On the other hand, K parameter of an undulator is calculated by Eq. (5). In general, this parameter is typically less than 3 for undulator magnets, and more than 3 for wigglers.

$$K = 0.934\lambda_u[\text{cm}]B_{peak}[\text{T}] \tag{5}$$

Furthermore, two similar critical parameters which directly effects the quality and the performance of the free electron laser, have to carefully been optimized. First is the q quantity, and the second is Pierce (ρ) parameter, defined in Eqs. (6) and (7) respectively [5]. In Eqs. (6) and (7), γ is the Lorentz factor of the electron beam, J_0 and J_1 are 0th and 1st order Bessel functions.

Table 2
Superconducting planar undulator parameters (g = 0.8 cm).

Parameter	Unit	Value
Undulator gap, g	cm	0.8
Undulator period, λ_u	cm	1.5
Peak magnetic field, B_{peak}	T	0.787
K parameter	–	1.1
Number of undulator periods, N_u	–	1580
Undulator length, L_u	m	23.7

$$q = \left\{\gamma\frac{K^2}{(1+(K^2/2))^2}\left[J_0\left(\frac{K^2/4}{1+(K^2/2)}\right) - J_1\left(\frac{K^2/4}{1+(K^2/2)}\right)\right]^2\right\}^{1/3} \tag{6}$$

$$\rho = \left\{\frac{\gamma(\lambda_{FEL})^2 r_e n_e}{8\pi}\frac{K^2}{(1+(K^2/2))^2}\left[J_0\left(\frac{K^2/4}{1+(K^2/2)}\right) - J_1\left(\frac{K^2/4}{1+(K^2/2)}\right)\right]^2\right\}^{1/3} \tag{7}$$

where, r_e is electron classical radius and n_e is the electron density in a bunch. Finally, wavelength of the laser (λ_{FEL}) is calculated for a planar undulator by Eq. (8).

$$\lambda_{FEL} = \frac{\lambda_u}{2\gamma^2}\left(1+\frac{K^2}{2}\right) \tag{8}$$

Superconducting planar undulator parameters for g = 0.8 cm and λ_u = 1.5 cm optimized based on 1 GeV electron beam (Table 1), are summarized in Table 2. Here below, it is shown that ~3.15 nm wavelength should be achieveable by this configuration.

In Fig. 3, the q quantity is contour-plotted vs undulator period and gap for 1 GeV electron beam and dedicated undulator configuration (Table 2). Additionally, three more parameters, namely 1D and 3D gain lengths and Rayleigh length (L_R), which enable to optimize L_{sat}, are given in Eqs. (9)–(11) respectively, where η is the universal scaling function [6].

$$L_{G,1D} = \frac{\lambda_u}{4\pi\sqrt{3}\rho} \tag{9}$$

$$L_{G,3D} = (1+\eta)L_{G,1D} \tag{10}$$

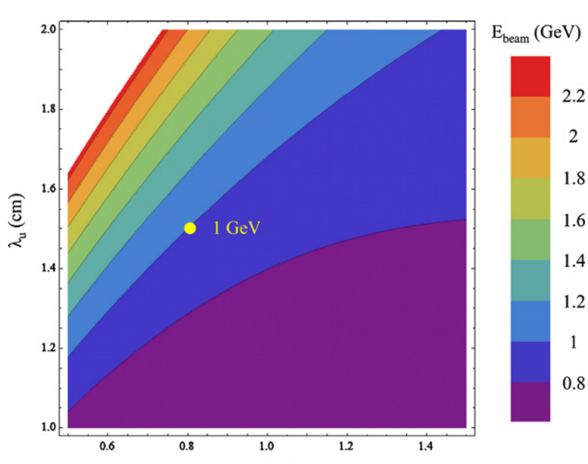

Fig. 2. E_{beam} [GeV] vs λ_u [cm] and g [cm] for 3.15 nm laser wavelength.

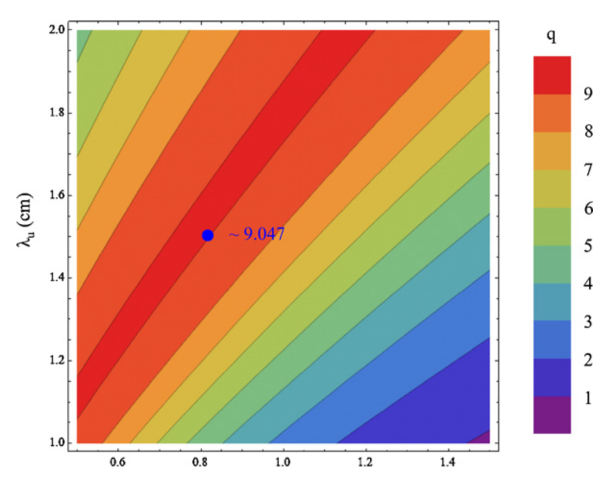

Fig. 3. q quantity vs λ_u [cm] and g [cm] for 1 GeV electron beam.

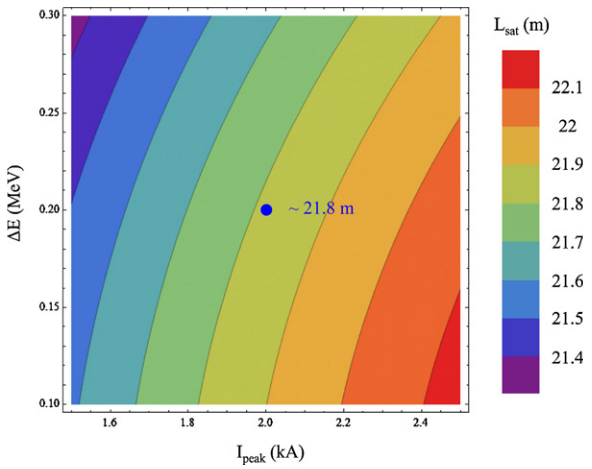

Fig. 4. L_{sat} [m] vs ΔE [MeV] and I_{peak} [kA] for 3.2 nm transverse emittance.

Table 3
SASE FEL parameters based on Tables 1 and 2.

Parameter	Unit	Value
q quantity, q	–	9.047
Pierce parameter, ρ	–	6.327×10^{-4}
1D gain length, $L_{G,1D}$	m	1.089
3D gain length, $L_{G,3D}$	m	2.659
Rayleigh length, L_R	m	129.2
Saturation length, L_{sat}	m	21.8
FEL wavelength, λ_{FEL}	nm	3.15
Saturation power, P_{sat}	GW	1.265
FEL energy, E_{FEL}	keV	0.392
Photons per pulse$^\sharp$	–	1.29×10^{13}
Energy per pulse$^\sharp$	J	8.15×10^{-4}
Peak flux$^\sharp$	photons/s	1.45×10^{25}
Peak brilliance$^\sharp$	photons/s/mm^2/mrad^2/0.1% bw	5.82×10^{30}

$$L_R = \frac{4\pi\sigma_x^2}{\lambda_{FEL}} \tag{11}$$

Furthermore, saturation length of the undulator, which approximately gives the length of the undulator (L_u) is calculated by Eq. (12) and contour-plotted vs energy spread (ΔE [MeV]) and peak current (I_{peak} [kA]) for 3.2 nm transverse emittance in Fig. 4 [6].

$$L_{sat} = L_{G,1D} \ln\left(\frac{9\lambda_{FEL}P_{sat}}{\rho^2 c E_{beam}}\right) \tag{12}$$

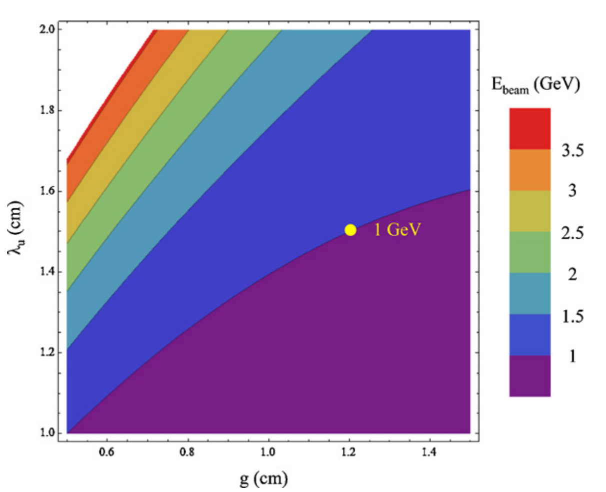

Fig. 5. Contour plot of E_{beam} [GeV] vs λ_u [cm] and g [cm] for 2.18 nm laser wavelength.

Table 4
Superconducting planar undulator parameters (g = 1.2 cm).

Parameter	Unit	Value
Undulator gap, g	cm	1.2
Undulator period, λ_u	cm	1.5
Peak magnetic field, B_{peak}	T	0.344
K parameter	–	0.482
Number of undulator periods, N_u	–	2598
Undulator length, L_u	m	38.9

Table 5
SASE FEL parameters based on Tables 1 and 4.

Parameter	Unit	Value
q quantity, q	–	7.02
Pierce parameter, ρ	–	3.847×10^{-4}
1D gain length, $L_{G,1D}$	m	1.79
3D gain length, $L_{G,3D}$	m	13.82
Rayleigh length, L_R	m	186.2
Saturation length, L_{sat}	m	31.9
FEL wavelength, λ_{FEL}	nm	2.18
Saturation power, P_{sat}	GW	0.769
FEL energy, E_{FEL}	keV	0.565
Photons per pulse$^\sharp$	–	2.37×10^{12}
Energy per pulse$^\sharp$	J	2.15×10^{-4}
Peak flux$^\sharp$	photons/s	4.29×10^{24}
Peak brilliance$^\sharp$	photons/s/mm^2/mrad^2/0.1%bw	3.6×10^{30}

Table 6
Simulation results obtained by SIMPLEX 1.3 code [7] for the dedicated undulator (g = 0.8 cm).

Parameter	Unit	Value
Peak magnetic field, B_{peak}	T	0.788
Pierce parameter, ρ	–	8.117×10^{-4}
1D gain length, $L_{G,1D}$	m	0.85
3D gain length, $L_{G,3D}$	m	1.072
Saturation length, L_{sat}	m	22.6
FEL wavelength, λ_{FEL}	nm	3.15
Saturation power, P_{sat}	GW	1.628
FEL energy, E_{FEL}	keV	0.393

where $P_{sat} \approx \rho P_{beam} = 1.6\rho(L_{G,1D}/L_{G,3D})^2 P_{beam}$. In addition, FEL energy of the fundamental harmonic given in Tables 3 and 5, is calculated by Eq. (13).

$$E_{FEL}[\text{keV}] = \frac{0.947(E_{beam}[\text{GeV}])^2}{\lambda_u[\text{cm}](1+(K^2/2))} \tag{13}$$

In Table 3, SASE FEL parameters are summarized based on dedicated electron beam (Table 1) and undulator (Table 2) configurations. Parameters in Tables 3 and 5 with superscripts above (♯), are obtained by SIMPLEX 1.3 simulation code [7].

Finally, a superconducting planar undulator with a gap of 0.8 cm and a period of 1.5 cm, has been considered to optimize FEL characteristics as yet. From now on, a new superconducting planar undulator with a gap of 1.2 cm keeping the same period of 1.5 cm, will be considered. It is shown in Fig. 5 that, 1 GeV beam energy is sufficient also for a dedicated undulator (g = 1.2 cm and λ_u = 1.5 cm) for 2.18 nm wavelength.

Superconducting planar undulator parameters for g = 1.2 cm and λ_u = 1.5 cm based on 1 GeV electron beam (Table 1), are summarized in Table 4 while keeping the restriction in mind on λ_u for g = 1.2 cm: 1.2 cm < λ_u < 4.8 cm [4].

In Fig. 6 above, q quantity (Eq. (6)) of the laser vs undulator period and gap for 1 GeV electron beam (Table 1), is shown. On the other hand, saturation length (Eq. (12)) of the laser vs energy spread

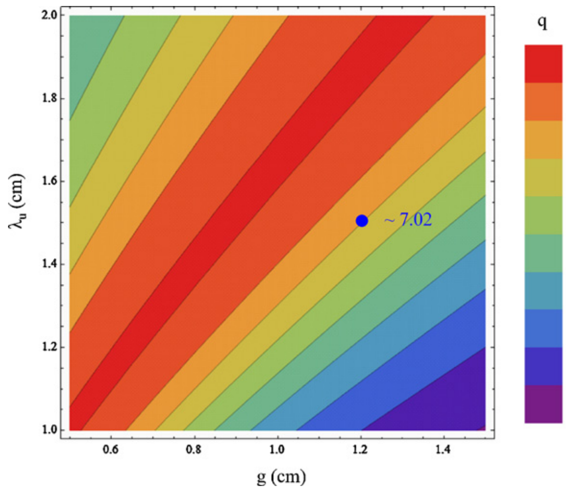

Fig. 6. q quantity vs λ_u [cm] and g [cm] for 1 GeV electron beam.

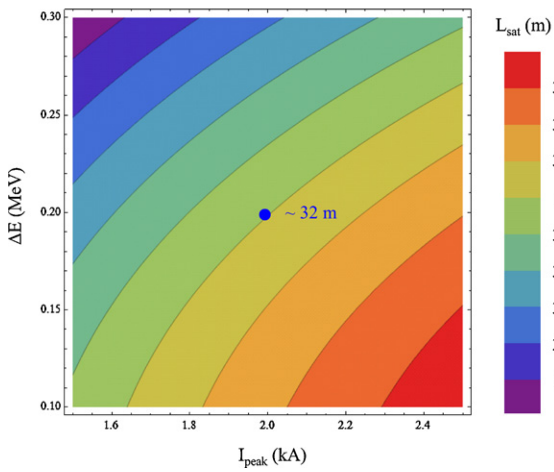

Fig. 7. L_{sat} [m] vs ΔE [MeV] and I_{peak} [kA] for 3.2 nm transverse emittance.

(ΔE [MeV]) & peak current (I_{peak} [kA]) for 3.2 nm transverse emittance, is shown in Fig. 7. Furthermore, SASE FEL parameters based on a dedicated electron beam (Table 1) and undulator (Table 4) configurations, are summarized in Table 5.

In Table 6, it is shown that simulation results obtained by SIMPLEX 1.3 code [7] for the dedicated undulator (g = 0.8 cm), are fairly well consistent with numerical calculations.

4. Conclusion

As mentioned in Section 1, 6.5 nm wavelength via a conventional hybrid with iron planar undulator and 3.5 nm wavelength via an in-vacuum permanent undulator driven by a 1 GeV electron linac, is achievable at the present time [1,2]. In this study, it is shown that the laser wavelength should be down to ∼2–3 nm while keeping the same beam energy (without increasing the energy more than 1 GeV), but modifying the undulator configuration to new generation superconducting technology. Consequently, it is proved that numerical optimizations and simulation results are fairly well consistent for the dedicated superconducting planar undulator with a gap of 0.8 cm.

On the other hand, 1 GeV electron linac of the linac-ring type e^-e^+ collider proposal of the Turkish Accelerator Center (TAC) project [8,9], namely TAC Super Charm Factory, was also planned to be operated as a SASE FEL light source. In this sense, optimization and simulation studies carried out in previous sections, has been considered under technical design studies on 1 GeV SASE FEL proposal [10] of the TAC project since 2006.

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