DESIGN STUDY FOR A HARD X-RAY GENERATION BY USING HIGH HARMONIC GENERATION FREE ELECTRON LASER

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Abstract

A high harmonic-generation(HHG) free electron laser (FEL) scheme was investigated to produce a hard X-ray light of amplified, longitudinally coherent and short wavelength. For more realistic study, S2E simulation in an accelerator with a beam energy of 6.4 GeV was performed. For the intense output of HHG FEL, we optimized a system that consists of 2 modulators, 2 chicanes and 1 radiator. We show the results on steady-state and time-dependent simulations which can produce output powers, respectively, in a wavelength of 1.03 $\mathring{A}$, 1.96 GW and 2.8 GW in a HHG system of 65 m long.

INTRODUCTION

Free Electron Laser (FEL), which is based on the linear accelerator with the undulator, is one of the candidate of the next generation light source. It can produce the light which has the high longitudinal coherenct with the high power and short wavelength. The performance of the FEL machine can be improved by using the high harmonic-generation (HHG) scheme. The strong advantage of the HHG-FEL is the generation of the short pulse of light with the sharp peak and free tunability of resonant wavelength by changing energy of electron beam and strength of undulator [1, 2, 3]. The designed optics of the HHG-FEL consist of the two modulators, a undulator and two chicanes. The two stage modulators were adopted to produce the light which has a wavelength of 1.03 Å. At the first modulator, the energy modulation was produced by the HHG laser with harmonic condition of the undulator. The wavelength and pulse length of HHG laser are 12.4 nm and 20 fs, respectively. After passing the first modulator, the energy modulation of the bunch was convered to the density modulation at the first chicane. At the second modulator, the energy modulator which is the harmonic number of the first modulator, was produced. It was also converted to the density modulation. Then the wavelength of the radiation of 1.03 $\mathring{A}$ which is produced by the radiator has sharp peak with the short pulse of 40 fs (in full length), in time domain. For the design study and optimization of the optics of HHG-FEL, the betatron function matching of the FODO cell was performed by using the ELEGANT and MAD8 to achieve the high power with a short gain length [4, 5]. We performed the study for optimization of the angle of the chicane, length of the period and number of the poles of the undulators. The optimization of the designed HHG-FEL was performed by using GENESIS to achieve the high power with sharp peak on spectral domain[6].

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TRACKING SIMULATION ON LINAC

For the more accurate design study of HHG-FEL, we used the parameters of electron bunch that were produced by the linear accelerator. It also was required to identify the realistic performance of the designed HHG-FEL. In our calculation, the electron beam was produced by the photocathod RF electron gun. The electron bunch, which has the energy of 135 MeV, normalized emittance of 0.45 μm, energy spread of 0.048 % and bunch charge of 0.2 nC , was accelerated to 6.5 GeV in the linear accelerator, which consists of the S-band RF cavities, the one X-band RF cavity and 2 stage bunch compressor [7]. The layout of the linac is shown by Fig. 1.

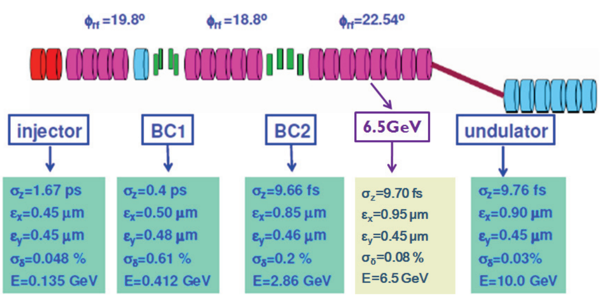

Figure 1: The layout of the linear accelerator that is used by the simulation

The phase of the S-band RF cavities in the first linac which are installed in the up-stream of the first chicane, have the 19.8°. The beam energy was accelerated to 412 MeV. The length of the bunch was compressed by approximately a factor of 4. Then the beam was accelerated to 2.86 GeV by using the second linac. After acceleration, the length of the bunch was compressed by factor of 41 due to the second bunch compressor. And then the beam was accelerated to the 6.5 GeV in the third linac. The beam parameters and slice distribution when the beam energy is 6.5 GeV are given by Table 1 and Fig. 2, respectively.

DESIGN OF HHG-FEL FOR THE HARD X-RAY

To produce the high power hard X-ray radiation, which has the wavelength of 1.03 Å, the designed HHG-FEL adopted the HHG laser with wavelength of 12.4 nm and two modulators which causes the harmonics with order of 10 and 12, respectively. Perturbative harmonic generation

ISBN 978-3-95450-117-5

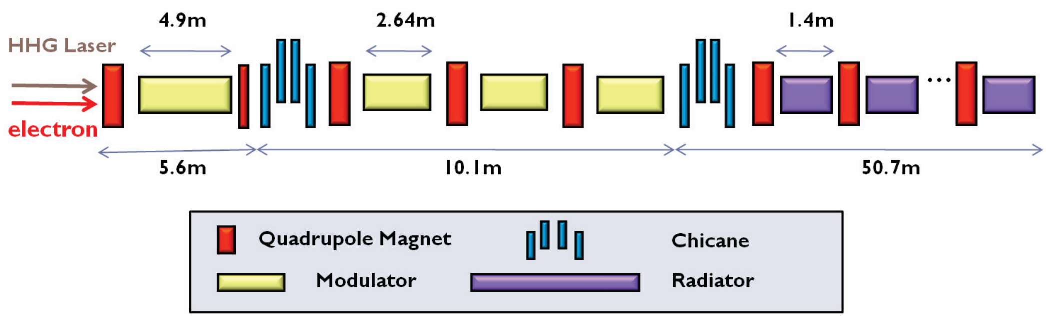

Figure 3: Layout of the hard X-ray HHG-FEL.

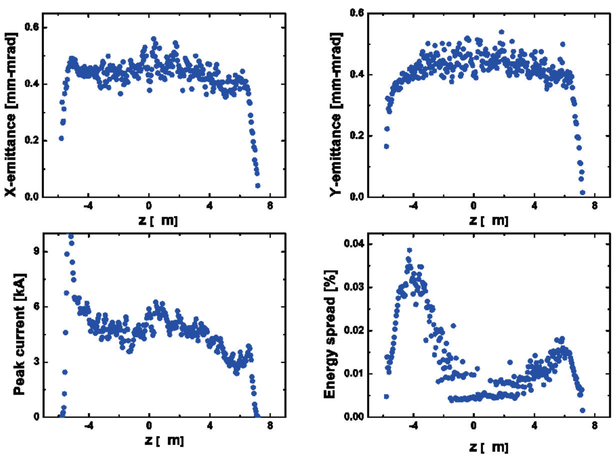

Figure 2: The beam slice distribution at the exit of linac

Table 1: Major linac beam parameters

Parameter	Value
Beam energy	6.5 GeV
Projected energy spread (rms)	0.08 %
Horizontal beam size	20 μm
Vertical beam size	20 μm
Slice horizontal Nor. emittance	0.45 mm·mrad
Slice vertical Nor. emittance	0.45 mm·mrad
Bunch length (rms)	9.7 fs
Peak beam current	6 kA

is a process whereby laser light of frequency ω and photon energy $\hbar\omega$ can be used to generate new frequencies of light. The newly generated frequencies are integer multiples $n\hbar\omega$ of the original light's frequency [8]. Therefore, the scheme of HHG-FEL can reach the shorter wavelength around 1.03 $\AA$ due to the decreaseing of the total harmonic ratio between HHG laser and final radiation at the radiator. The optics of the HHG-FEL is based on the FODO cell. The layout of the designed HHG-FEL is shown by Fig. 3.

The electron bunch was injected to the first modulator with HHG laser which has the wavelength of 12.4 nm, pulse length of 20 fs and peak power of 400 kW. This HHG laser causes growth of the energy spread and the harmonics which satisfied the resonant formula of undulator. This energy modulation was converted to a density modulation by chicane. The density modulated electron beam generates logitudinal high coherent radiation at radiator [9]. To obtain the high power and short pulse with the sharp peak in the spectral domain, the angles of the dipoles in the chicanes and strength of the undulator with length of the undulator period were optimized. Also, the strengths of the quadrupoles which were installed between the undulators were optimized to compensate the growth of the transverse emittance and to obtain the short saturation length in the radiator. The optimum betatron function was calculated by using the analytical formula which is based on 3-D FEL theory [10, 11, 12]. The calculation results of the saturation length and the saturation power in the radiation are shown by Fig. 4.

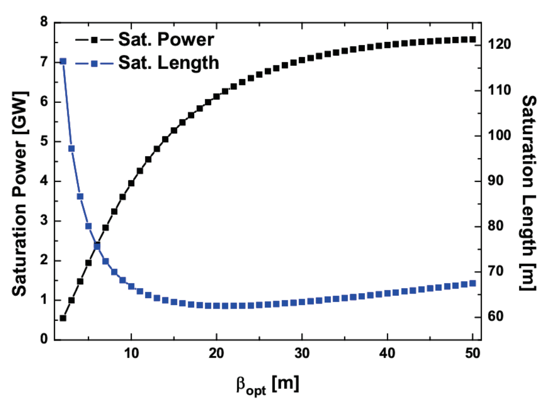

Figure 4: Analytical calculation of the saturation length and power. That are based on the 3-D FEL theory.

As shown by Fig. 4, the optimum betatron function for reducing the saturation length with high power is around 40 m. Based on the this calculation result, the optics function matching was performed on the hole system of the HHG-FEL. In this matching, the maximum strength of quadrupole is 15 T/m. The result is shown by Fig. 5.

ISBN 978-3-95450-117-5

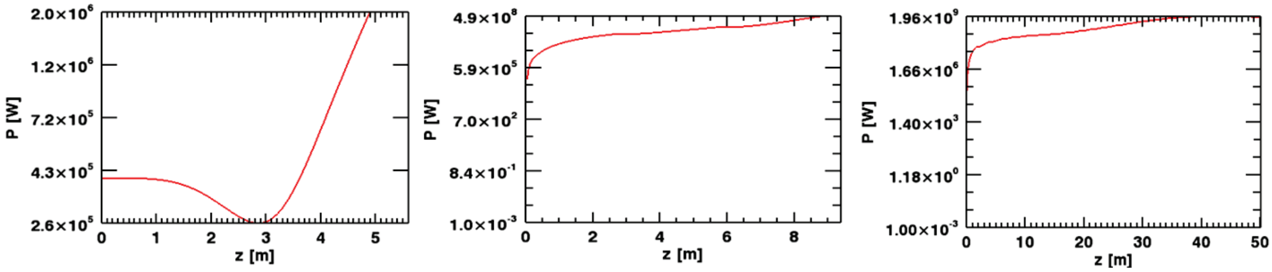

Figure 6: Results of the steady state simulation. The growth of the seed power in the first (left) and second(center) modulator were saturated to 2 MW and 0.5 GW, respectively. The radiation power in the radiator is 1.96 GW (right).

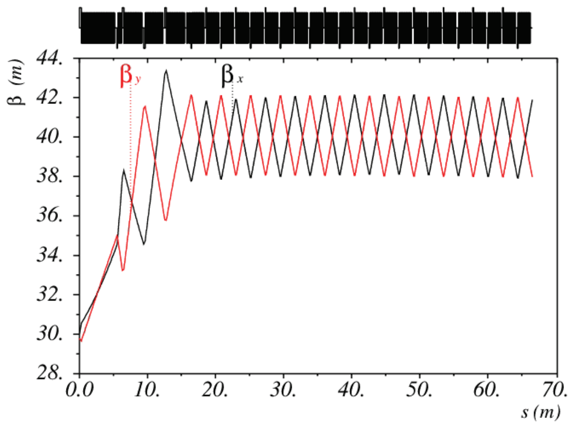

Figure 5: The betatron function in the whole system of the designed HHG-FEL

STEADY STATE SIMULATION

After performing the optics matching in the designed HHG-FEL, this scheme has been simulated by using GENESIS code. In order to allow rapid progress with resonable calculation results in the optimization of the design parameters, steady-state simulation was performed. Steady-state simulations are based on the assumption of an infinite long electron bunch and radiation field with no longitudinal variation of any parameter. The partial derivative with respect to the time drops out of the field equations resulting in the parabolic equation. The longitudinal description can be reduced to a single wavelength with periodic boundary condition in the phase of the macro particles [6]. The results of the optimization of the designed HHG-FEL for the high power are shown by Fig.6. The growths of the seed power in the first modulator and second modulator were observed. The coherent radiation power in the radiator is also amplified exponentially to saturation of 1.96 GW with saturation length of 50 m. The field strength, length of the dipoles and R_{56} in first chicane were determined to 1.5 T, 8 cm and 8.43 μm, respectively. The lengths of the periods of two modulators and radiator were optimized to 7, 4.4 and 2 cm, respectively. The first modulator has one module and second modulator has the three modules. The radiator also have the the twenty-three modules.

TIME DEPENDENT SIMULATION FOR OPTIMIZATION OF THE HHG-FEL

Time dependent simulations have been performed to provide the information regarding spectral and temporal properties of the radiation in designed HHG-FEL including the effect of the shot noise. It also gives the effect of the length of the bunch and distribution of the electrons in the bunch. It causes the decreasing of the radiation power and the shifting of the wavelength. Based on the results of steady state simulation, the opimization was performed. In the opimization of the designed HHG-FEL, the effect of the length of the periods in undulators, number of the modules and R_{56} induced by two chicanes on the spectral profile of the radiation and saturation power were investigated to achieve the high power with sharp peak on spectral domain. In this simulation, the uniform distributed beam was used which has the parameters calulated by tracking simulation of linac. The coherent radiation power and spectral profile with uniform beam distribution are shown by Fig. 7.

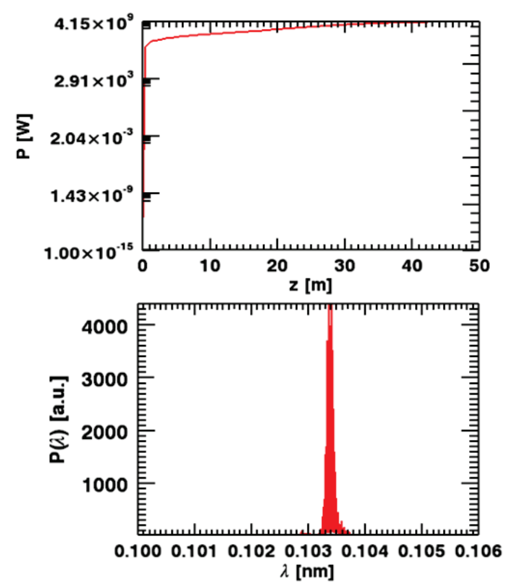

Figure 7: The result of the time dependent simulation with uniform beam distribution.

As shown by Fig. 7, the coherent radiation power is 4.15 GW with the wavelength of 1.03 Å and the 50 m long ra-

ISBN 978-3-95450-117-5

diator. It also has the small bandwidth, $|\Delta\lambda/\lambda|$, around 2.9 $\times 10^{-3}$ on spectral domain. After optimization of the designed HHG-FEL with uniform beam distribution, the beam distribution which is calculated by using the start-to-end simulation of the 6.5 GeV linac was used. It can be determined the realistic performance of the designed HHG-FEL. The coherent radiation power, spectral profile and pulse profile with beam distribution are shown by Fig. 8.

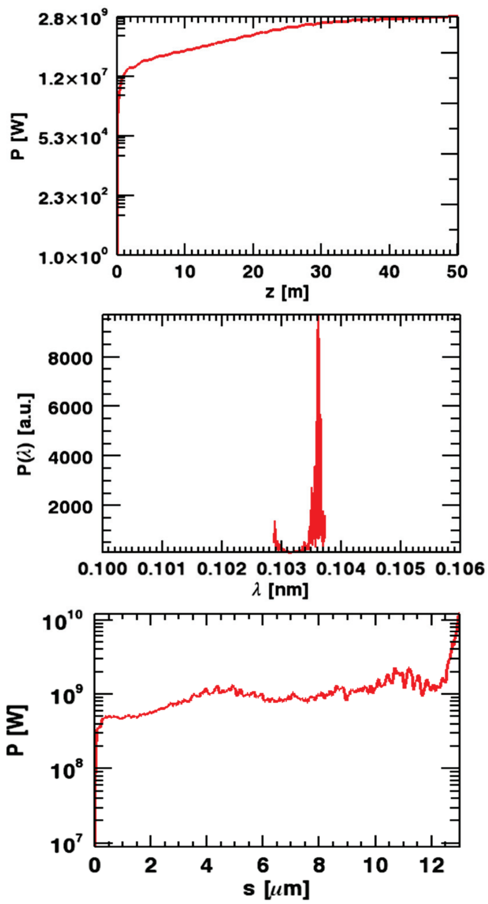

Figure 8: The coherent radiation power, spectral profile and pulse profile by the time dependent simulation.

Due to the fluctuation of the energy spread, current and energy of the bunch, the shifting of the wavelength and the decresing of coherent radiation power were oberserved. It could be compensated by changing of the beam distribution at the exit of linac. The coherent radiation power in the radiator is 2.8 GW. The bandwidth is also increased to 4.8 $\times 10^{-3}$.

CONCLUSION

The design study of HHG-FEL for the hard X-ray generation which has the wavelength of 1.03 $\AA$ with high radiation power and short saturation length was performed. To obtain the realistic beam parameters for the design of HHG-FEL, the start-to-end simulation of the linear accelerator which included the photocathod RF electron gun, injector system, two stage bunch compressor and S-band RF cavities was performed. After optimization of the linac, the beam parameter and the particle distribution at the exit of the linac were defined as the sliced horizontal emittance of 0.45 mm·mrad, vertical emittance of 0.45 mm·mrad, peak current of 6 kA. Based on the tracking simulation of linac, the HHG-FEL was designed to produce the high coherent radiation power with sharp peak on spectial domain. The length of the periods, number of the pole and number of modules on the two modulatior and one radiator were optimized. It is shown that our system shows the results of the optimization which have the wavelength of 1.03 $\AA$, bandwidth of 4.8 $\times 10^{-3}$ and coherent radiation in the chicane power of 2.8 GW. In the near future, we will study the effect of the coherent synchrotron radiation in the chicane which may cause the growth of the energy spread and growth of the horizontal emittance.

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ISBN 978-3-95450-117-5