High Gain Harmonic Generation UV to DUV Free Electron Lasers at the NSLS

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Abstract

In this paper, we present the calculation on the performance of High Gain Harmonic Generation (HGHG) UV to DUV Free Electron Lasers (FELs) at the NSLS. Based on the beam quality and the available undulators at the NSLS, the calculation shows that it is possible to produce fully coherent DUV FEL down to 500 Angstrom, with a peak power of several hundred Mega Watts. One further attractive feature is the possibility to produce ultra short radiation pulse based on such HGHG scheme.

1 INTRODUCTION

Free Electron Lasers (FELs) possess several excellent features, such as wavelength tunability, high efficiency and high output power. In this paper, we present the possibility of developing UV to DUV FELs at the NSLS based on the HGHG scheme[1,2,3]. Such a proof-of-principle study is an intermediate step to finally reach X-ray FELs.

According to the HGHG principle, a seed laser and an electron beam are introduced into a modulator. The wavelength λ_r of the seed laser, the Lorentz factor γ of the electron beam, the undulator parameter K, and the period λ_w should satisfy the resonant condition, $\lambda_r = \lambda_w \frac{1+\frac{K^2}{2}}{2\gamma^2}$. In such a resonant system, the transverse wiggling of the electron couples to the transverse laser electric field. Hence an energy modulation at the seed laser wavelength is built up in the electron beam. Such energy modulated electron bunch then traverses a dispersion section (a three dipole chicane, or a triple bend achromat). Due to the R_{56} in the dispersion section, the laser-imposed energy modulation leads to microbunching at the seed wavelength. The Fourier spectrum of such microbunched beam has abundant harmonics of the seed laser. Therefore, when this microbunched electron beam is introduced into a radiator, which is resonant to a special harmonic of the seed laser, coherent emission is produced at this resonant harmonic rapidly. This coherent emission is further amplified exponentially.

In the Source Development Lab at the NSLS, the photoinjected linac is expected to provide electron bunches with parameters in Table 1. A tunable titanium-sapphire laser drives the photocathode at $266nm$ (third harmonic of the $Ti^{3+} : Al_2O_3$) and will provide the seed for the HGHG FEL. In our calculation, we assume the laser is tuned to $3,000$ Å with a peak power of about $100\,MW$ to produce UV FEL at $1,000$ Å with a peak power of more than $100\,MW$ by one stage HGHG, and finally a DUV FEL at 500 Å with a peak power of several hundreds of MW by cascading stages of HGHG[4,5].

2 THE SCHEMES

Based on the available undulators and electron beam at the NSLS, we will combine the Mini undulator (as the modulator), and NISUS undulator (as the radiator) to set up the first stage of HGHG, where the $3,000$Å seed laser interacts with an electron beam of $E_0 = 290\,MeV$ to produce $1,000$Å FEL. The pulse length of the seed laser, e.g., $50\,fs$, is much shorter than the electron bunch length, which is on the order of ps. To go one step further, we will add two more stages to go down to 500 Å . The electron beam from the first stage has reached saturation, hence, abundant microbunches at the scale of $1,000$ Å exist. Therefore, if the microbunched electron beam is introduced into a radiator, which is resonant to some harmonic of $1,000$ Å , in our case, the second harmonic, 500 Å , then this harmonic will be coherently emitted. The radiator will be a $2\,m$ long VISA undulator. Then, this coherent emission will be further introduced into another $4\,m$ long VISA undulator resonant at 500 Å as an amplifier. Before entering the VISA amplifier, the electron bunch is magnetically delayed, hence, effectively, the 500 Å radiation pulse is shifted to the front part of the electron bunch. Since the seed laser pulse is much shorter than the electron bunch, the front part of the electron bunch doesn't experience FEL interaction, it is still fresh. In the amplifier, this fresh part of the electron bunch then amplifies the 500 Å coherent emission, coming from the previous radiator, until saturation.

2.1 Undulators and Electron Beam Parameters

The parameters of the electron beam and the undulators are given in Table 1 and Table 2 respectively. Notice that the VISA undulator has permanent parameters, so, the parameters of the NISUS and Mini undulators are adjusted accordingly to meet the resonant conditions. According to Halbach's formula[6], the undulator period λ_w and the undulator parameter K satisfy $K = 3.44 \times 93.4\lambda_w \exp[-5.08\frac{g}{\lambda_w} + 1.54(\frac{g}{\lambda_w})^2]$, where g is the undulator gap. Based on this, we could adjust the gap of the Mini, and the NISUS undulators to meet the resonant condition accordingly.

Table 1: Parameters of the electron beam

γ	I_{peak} kA	$\frac{\sigma_\gamma}{\gamma}$ %	ϵ_n π mm-mrad
568	1	0.15	3

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Table 2: Parameters of the undulators

	Mini	NISUS	VISA
Period λ_w cm	8	3.9	1.8
Gap cm	5	2	0.6
K$_{peak}$	1.69	1.14	1.26
Length m	0.76	10	2 and 4
Focusing scheme	natural	natural	FODO

2.2 *One stage HGHG*

In this one stage HGHG scheme, $1,000$Å FEL will be produced with a peak power around $130MW$, as shown in Fig. 1. Parameters of the FEL are given in Table 3.

Table 3: Parameters of the FELs

Resonant Wavelength Å	3,000	1,000	500
L_G m	0.99	1.14	0.43
Pierce parameter 10^{-3}	5.08	2.54	3.35
Rayleigh range m	1.36	2.66	0.73

To optimize this system, we need first find the right detune in the NISUS undulator to get the minimum power e-folding length L_G. Such optimization gives the best radiation wavelength around $1,004.2$ Å . Then, the radiation wavelength in the modulator is to be chosen as $3 \times 1,004.2 = 3,012.6$ Å . We then optimize the undulator parameter of the modulator to ensure best modulation. This is optimized together with adjusting the strength of the dispersion section. The energy modulation produced in the Mini modulator should dominate the intrinsic local energy spread. This energy modulation increases the effective energy spread, so degrades the exponential growth in the NISUS radiator. Hence in fact, the optimization is an integrated part. Input power and dispersion strength are scanned to optimize energy modulation, hence maximum output.

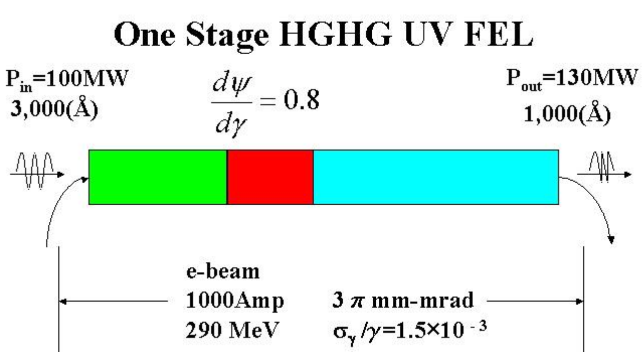

Figure 1: One stage HGHG UV FEL

2.3 *Cascading Stages of HGHG*

To further produce a DUV FEL at 500 Å , we need two more undulators. The electron beam after exiting the NISUS radiator has reached saturation, so there is microbunching at $1,000$ Å wavelength. Based on the same mechanism as in the first stage, now if this microbunched electron beam is introduced into a radiator resonant at some harmonics of the $1,000$ Å , then this harmonic will be coherently emitted. In our case, we use a $2\,m$ long VISA radiator, resonant at the second harmonic of $1,000$ Å , so radiation at 500 Å is coherently emitted. But, the electron bunch from the previous stage has too large energy modulation due to the FEL interaction in the NISUS radiator, it is no longer useful for further exponential growth at 500 Å . Hence a fresh part of the electron bunch is needed in order to reach high saturation power at 500 Å . We use the same type of VISA undulator as the amplifier, only the length is now $4\,m$. The 500 Å coherent emission is now amplified until saturation in the VISA amplifier. Parameters of the FELs are given also in Table 3.

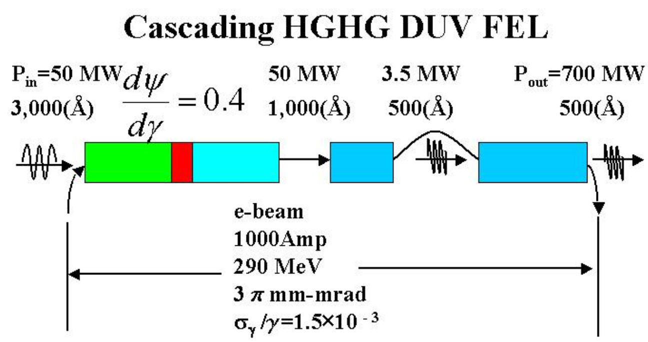

Figure 2: Cascading HGHG DUV FEL

When the coherent emission at 500 Å exits the VIAS radiator, it is in a divergent mode with the waist position at about $0.5m$ back in the VISA radiator. Since we need some distance to magnetically delay the electron bunch, the coherent emission light beam gets further divergent due to traveling this distance. In our calculation, we assume that we need delay the electron bunch $50\,fs$, i.e. $\Delta s = 15\,\mu m$. We also assume that the shifter is constructed identical to an idealized dispersion section with a length of L_s. The field is B when $0 \le s \le \frac{L_s}{4}$ and $\frac{3L_s}{4} \le s \le L_s$, and $-B$ when $\frac{L_s}{4} \le s \le \frac{3L_s}{4}$. Then $L_s = \left[\frac{96\Delta s\gamma^2 m_e^2 c^2}{e_0^2 B^2}\right]^{\frac{1}{3}}$. So, if we assume $B = 1\,Tesla$, then $L_s = 11\,cm$. This distance is taken into account in our calculation. In the undulators, the incoherent synchrotron radiation effects are negligible.

Since the NISUS has no extra focusing, the betatron motion in it is purely due to the natural focusing, with a beta-function of about $\beta_{NISUS} = 6\,m$. In the VISA undulator, there is a strong extra-focusing due to the FODO cell with permanent magnet. The natural focusing of the VISA undulator itself provides $\beta_{VISA}^{Natural} = 2.6\,m$. Superimposing on it is the FODO cell focusing. In the middle plane of the focusing quadrupoles, $\beta_x = 0.8\,m$, and $\beta_y = 0.6\,m$. So, a matching is needed for the prebunched e-beam from the NISUS radiator to get into the VISA radiator.

To optimize the system, we first optimize the VISA amplifier to get minimum power e-folding length L_G, and find the radiation wavelength to be 504.7 Å . This determines the upstream radiation wavelength accordingly. Then we optimize the undulator parameters of the NISUS and Mini undulator, together with the dispersion strength in the dispersion section between the Mini and the NISUS undulators. Once again, we need optimize the system as an integrated part. In the one stage HGHG, we hope to get maximum output from the NISUS radiator. While in the cascading scheme, we want to get maximum output from the VISA amplifier, the quantity we need to optimize is then the bunching factor at 504.7 Å at the entrance of the VISA radiator. As we know, if we want to get maximum output from the NISUS radiator in the one stage scheme, we will optimize the system so that the saturation comes before the end of the NISUS radiator. When the e-beam gets into saturation, the total radiation power will still grow for some amount, but in this process, the particles with higher energy will overpass the lower energy particles, hence debunching. This is to say, the maximum radiation output power point comes after the largest bunching factor point does. In the cascading scheme, we want the largest bunching factor to enter VISA radiator. But the NISUS radiator has a fixed length, we could not cut it at the largest bunching factor point. So, in order that the largest bunching factor point comes right at the end of the NISUS radiator, we could only reduce the dispersion strength in the dispersion section, and reduce the energy modulation produced in the Mini undulator, so that at the exit of the NISUS, the beam is right at the largest bunching factor at 500 Å , though it will not give the maximum radiation output power at $1,000$ Å at the end of the NISUS radiator. Notice in Fig. 1, the final output power could be much larger than $100\,MW$ from the NISUS radiator, while in the cascading scheme, the output power at the end of the NISUS radiator is only about $50\,MW$ to ensure the largest bunching factor into the 500 Å VISA radiator. Also, the $\frac{d\psi}{d\gamma}$ in Fig. 2 is about 0.4, which is smaller than that in Fig. 1 with $\frac{d\psi}{d\gamma} = 0.8$. The input power in Fig. 2 is about $50\,MW$, which is also smaller than that in Fig. 1, with $100\,MW$.

For stability consideration, we design the system so that the maximum radiation peak power of $800\,MW$ comes around $3.5\,m$ in the VISA amplifier. So, the system is well into saturation. Hence the radiation output power drops a little bit at the end of the VISA amplifier to be around $700\,MW$ as shown in Fig. 2. If on the other hand, we want to get the largest output power right at the end of the VISA amplifier, then we could further lower the input power to the Mini modulator to be about $P_{in} = 20\,MW$.

3 SHORT PULSE LENGTH AND TRANSFORM-LIMITED FEL

SASE FEL could provide orders of magnitude shorter pulse than those of the third-generation storage ring sources. This qualitative improvement provides unique opportunities in a breadth of scientific disciplines. Still such FEL pulse length is much longer than the short-pulse optical laser available today. Thus, there is a real desire to match this pulse duration with the FEL, permitting the use of FEL as a structural probe with atomic resolution. In SASE FEL, the FEL pulse is essentially determined by the electron bunch length. But, in HGHG FEL, the FEL pulse length is determined by the seed laser pulse. Further more, SASE FEL could not provide full longitudinal coherence, while due to the full coherence of the seed laser, the HGHG FEL could provide such coherence.

4 CONCLUSION

In conclusion, based on our calculation, it is possible to use the available undulators at the NSLS to set up UV to DUV FELs capable of vacuum ultraviolet operation. Such HGHG based FEL will have a short pulse length around $10\,fs$. Further more, such HGHG FEL pulse will be a transform-limited beam.

5 ACKNOWLEDGEMENT

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6 REFERENCES

[1] L.H. Yu, *Phys. Rev.* **A 44**, 5178(1991).

[2] L.H. Yu, *et al.*, *Science* **289**, 932(2000).

[3] L.H. Yu, *et al.*, this proceedings.

[4] L.H. Yu, *Proceedings of the IFCA Advanced Beam Dynamics Workshop on Future Light Sources*, C.E. Eyberger, Ed., Argonne National Laboratory, Argonne, IL(1999) (URL:http://www.aps.anl.gov/conferences/FLSworkshop /proceedings/papers/wg1-01.pdf).).

[5] Juhao Wu, and Li Hua Yu, *Proc. 22nd International FEL Conference*, Duke University, Durham, NC, August 13-18, (2000), BNL-67732.

[6] K. Halbach, *J. Phys. (Paris) Colloq.* **44**,C1-211(1983).