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June 2001

**National Synchrotron Light Source**

Brookhaven National Laboratory  
Operated by  
Brookhaven Science Associates  
Upton, NY 11973

Under Contract with the United States Department of Energy  
Contract Number DE-AC02-98CH10886

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# High Gain Harmonic Generation X-ray Free Electron Laser

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*Abstract*

We present the calculation on the performance of a High Gain Harmonic Generation (HGFG) X-ray Free Electron Laser (FEL) based on the high quality electron beam from the proposed Photoinjector Energy Recovery Linac (PERL) at the NSLS. We consider several sets of e-beam parameters. The calculation indicates that it is possible to produce a fully coherent FEL with a wavelength around 10 Angstrom, with a peak power of several GW. The high order harmonics will also be produced with a significant amount of peak power. One further attractive feature is the possibility to produce ultra short radiation pulses of about 10 fs based on such HGFG scheme.

## 1 INTRODUCTION

Free Electron Lasers (FELs) are recognized as the fourth-generation x-ray sources. The proposed Photoinjector Energy Recovery Linac (PERL)<sup>[1]</sup> at the NSLS will provide low emittance,  $\epsilon_n \leq 1 \pi \text{ mm} - \text{mrad}$ , electron bunch at energy up to several  $GeV$ . Such high quality electron bunch will produce high brightness incoherent synchrotron radiation of subpicosecond pulse in the insertion device. Due to the extremely small emittance of the electron bunch, PERL would be a photon source whose brightness is several orders magnitude higher than the currently available light sources. Besides the incoherent light source possibility, the high quality electron bunch from the PERL could also be used to build an x-ray FEL at the NSLS. In this paper, we will investigate such a possibility.

Among the most attractive features of the FEL is the coherence. SASE FEL could not provide full temporal coherence, because of the random start-up noise. In contrast to this, HGFG FEL<sup>[2,3]</sup> is fully coherent temporally. Another attractive feature of the HGFG FEL is the possibility to produce extremely short laser pulse down to  $10 \text{ fs}$ . In the SASE FEL, the final FEL pulse length is determined by the electron bunch, hence in order to produce short light pulse, we need very short electron bunches. Its high qualities are hard to be preserved, when a subpicosecond high density electron bunch is being accelerated and transported along the beam line. For an HGFG FEL, the final pulse length is determined by the initial seed laser pulse length. Hence, if we use an very short seed laser with  $\sigma_t = 10 \text{ fs}$ , the final HGFG FEL will have  $\sigma_t$  around  $10 \text{ fs}$ . All these attractive features inspire us to cascade stages<sup>[4,5]</sup> of HGFG to produce coherent hard x-ray using the high quality electron bunch from PERL.

## 2 FEL SCHEMES

In our calculation, we use undulators with the same FODO cell focusing scheme as in the LCLS. Since the energy in our calculation is  $E = 3 \text{ GeV}$ , the  $\beta$  function is scaled down to  $\lambda_\beta = 2\pi \times 18 \times \frac{3}{14.35} = 23.6 \text{ m}$ . We assume hybrid undulators of Nd-Fe-B type, so according to Halbach's formula<sup>[6]</sup>, the undulator period  $\lambda_w$  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. For all the undulators,  $g$  is restricted not to be smaller than  $6 \text{ mm}$ , considering the collective effects, such as the resistive wall, and the surface roughness wake fields effects. The PERL is designed to use  $1.3 \text{ GHz}$  RF system. Currently, we have two schemes. One is to fill each bucket with a charge of  $Q = 150 \text{ pC}$  per bunch, the other is to fill every third bucket with a charge of  $Q = 450 \text{ pC}$  per bunch. After compression, the final bunch length will be  $\sigma_t = 100 \text{ fs}$ . Hence the peak current  $I_{peak} = \frac{Q}{\sqrt{2\pi}\sigma_t}$  will be in the range of  $600 \sim 1,800 \text{ Amp}$ . The normalized emittance will be less than  $1 \pi \text{ mm} - \text{mrad}$ . In our calculation, we will focus on the nominal case of  $I_{peak} = 1,500 \text{ Amp}$ ,  $\epsilon_n = 1 \pi \text{ mm} - \text{mrad}$ , to produce radiation at  $\lambda_r = 10 \text{ \AA}$ . For comparison, we also consider a low current of  $750 \text{ Amp}$  to produce radiation around  $18 \text{ \AA}$ , and a large current of  $2,500 \text{ Amp}$  to produce radiation around  $10 \text{ \AA}$  or  $18 \text{ \AA}$ , with  $\epsilon_n = 2 \pi \text{ mm} - \text{mrad}$ , considering that all the collective effects in the beam line are more serious for a larger peak current. Radiation at higher order harmonics of  $\lambda_r$  will also exist.

### 2.1 The HGFG FEL Principle

According to the HGFG principle, a seed laser and an electron beam are introduced into a modulator. The wavelength  $\lambda_r$  of the seed laser, the Lorentz factor  $\gamma$  of the electron beam, the undulator parameter  $K$ , and the undulator period  $\lambda_w$  should satisfy the resonant condition,  $\lambda_r = \lambda_w \frac{1+K^2}{2\gamma^2}$ . In such a resonant system, the transverse wiggling of the electron couples to the traverse laser electric field. Hence an energy modulation at the seed laser wavelength scale is built up in the electron beam. Such an energy modulated electron bunch then traverses a dispersion section ( a three dipole chicane ). 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

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rapidly. This coherent emission is further amplified exponentially in the rest of the same undulator or a separate amplifier.

## 2.2 Cascading Stages of HGHG

Commercially available lasers have wavelengths larger than  $2,000\text{\AA}$ , hence to use one step HGHG to go down to x-ray region need extremely high harmonic on the order of thousand. It is hard and lacks stability<sup>[5]</sup>. Hence, we need cascading several stages of HGHG, in each stage, a low harmonic is produced coherently. For the stability consideration, we will not use harmonic higher than 5 in our calculation.

To cascade several stages of HGHG, we need some extra components. Each stage consists of one modulator, a dispersion section, and one radiator. So the physical process in each stage will be the same as in the one stage HGHG<sup>[2,3]</sup>. During the process, the output radiation has disturbed a part of the e-beam, which interacts with the seed. In order to achieve the best efficiency to carry out the next stage of HGHG, we must use a fresh part of the e-beam. There are two methods. The first is to shift the laser (i.e., the output radiation from the previous HGHG stage) toward the front part of the same e-beam, so that the laser will interact with a “fresh” part of the same e-beam. The second is to introduce a new electron bunch for each stage, so that again the laser will interact with a “fresh” bunch. This is the “fresh bunch technique”<sup>[7]</sup>. For the first case, we use a “shifter” to “shift” the laser to the “fresh” part of the same e-beam.

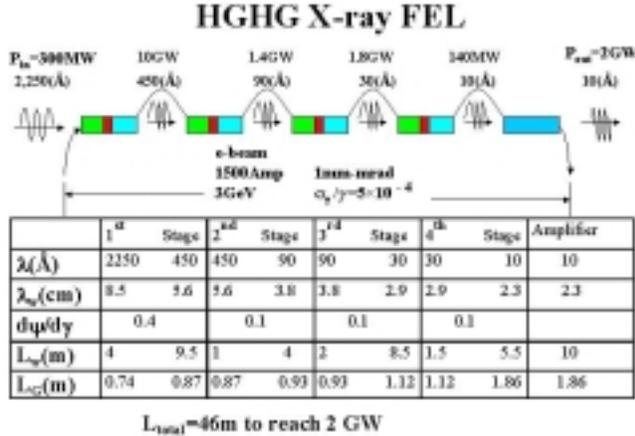


Figure 1: Conceptual layout of the HGHG X-ray FEL and parameters.

We begin with a seed laser at  $2,250\text{\AA}$ . For the cases when the peak current  $I_{peak} = 750\text{ Amp}$  or  $1,500\text{ Amp}$ , we assume the seed laser has a peak power of  $300\text{ MW}$ . For the case of  $I_{peak} = 2,500\text{ Amp}$ , we assume the peak power to be  $180\text{ MW}$ . As we mentioned above, we will focus on the nominal case of Fig. 1, i.e., we will adopt  $I_{peak} = 1,500\text{ Amp}$  and  $P_{in} = 300\text{ MW}$ .

**Nominal Case** Let us now present the details. As illustrated in Fig. 1, we consider a laser with a wavelength of  $2,250\text{\AA}$ , and a peak power of  $P_{in} = 300\text{ MW}$ . The corresponding start-up shot-noise power<sup>[8]</sup> is only about  $P_{noise} \approx 40\text{ W}$ . So, the input seed laser power dominates the shot-noise power. This dominance holds for all seeds into the four stages and the last amplifier. After four stages, we get  $10\text{\AA}$  radiation, which is then amplified to saturation with a peak power around  $2\text{ GW}$  by traversing the last undulator, the amplifier. The parameters for the electron beams, the undulators, and the dispersion sections are given in the table of Fig. 1. Let us first explain the meaning of each parameter in Fig. 1. The numbers on the first row above the schematic system stand for the output power of each stage. The output power of one stage is the input power of the next stage, though diffraction effects on the radiation beam during its travel to the next stage is taken into consideration. We will address this later. The second row stands for the corresponding wavelength of the radiation. The e-beam parameters are printed just below the schematic device. It has an energy of  $E = 3\text{ GeV}$ , a peak current  $I_{pk} = 1,500\text{ Amp}$ , normalized emittance  $\epsilon_n = 1\text{ }\pi\text{ mm} - \text{mrad}$ , and local energy spread  $\frac{\sigma_z}{\gamma} = 5 \times 10^{-4}$ . The local energy spread increase due to the spontaneous radiation<sup>[9]</sup> in the undulators is negligible. For the table, the first row gives the radiation wavelength  $\lambda$ , the second is the undulator period  $\lambda_w$ , the third is the dispersion strength  $\frac{d\psi}{d\gamma}$ , the fourth is the length of the undulators  $L_w$  (modulators, radiators, and the amplifier). The fifth stands for the power e-folding length  $L_G$ , when there is no initial energy modulation in each undulator. The table has five boxes, the first four boxes stand for the four stages, while the last one for the amplifier. In each of these four boxes, the left column gives the parameters for the modulator, while the right column gives those for the radiator. The numbers in the middle, stand for  $\frac{d\psi}{d\gamma}$ , the dispersion strength. Here,  $\psi = (k_r + k_w)z - \omega_r t$  is the pondermotive phase in the radiators. For example, the second box stands for the second stage. The left column in the second box stands for the modulator of the second stage. The table shows that in the modulator the resonant radiation is  $\lambda = 450\text{\AA}$ , the modulator has  $\lambda_w = 5.6\text{ cm}$ ,  $L_w = 1\text{ m}$ , and the corresponding  $L_G = 0.87\text{ m}$ . The right column shows that the radiation in the radiator is  $\lambda = 90\text{\AA}$ , the radiator has  $\lambda_w = 3.8\text{ cm}$ ,  $L_w = 4\text{ m}$ , and the corresponding  $L_G = 0.93\text{ m}$ . The number in the middle stands for  $\frac{d\psi}{d\gamma} = 0.1$ . Similarly for the other boxes, except for the fifth, which stands for the amplifier, so there is no  $\frac{d\psi}{d\gamma}$ . The effect of the global energy spread (or correlated energy spread, in the terminology of certain other workers in this field) is essentially an issue of detuning.

Let us now explore the physics process. Shown in Fig. 1, the  $2,250\text{\AA}$  laser, with a peak power of  $300\text{ MW}$ , together with the  $3\text{ GeV}$  e-beam, are introduced into the modulator of the first stage. The modulator and the radiator are resonant to  $2,250\text{\AA}$  and  $450\text{\AA}$  respectively. The first stage

generates  $450\text{\AA}$  output according to the HGHG principle. To go to next stage, we need a shifter, where the e-beam is magnetically delayed. Hence effectively, the  $450\text{\AA}$  radiation is shifted to the front part of the same e-beam, where the e-beam is still “fresh”. As we mentioned above, the spontaneous radiation effect is negligible. In our example, we assume the output pulse is nearly flat of  $10\text{ fs}$  long and e-beam pulse is nearly a flat pulse longitudinally of  $250\text{ fs}$  long. The  $10\text{ GW}$   $450\text{\AA}$  radiation serves as the seed in the second stage, where the  $450\text{\AA}$  radiation input generates a  $90\text{\AA}$  output with  $1.4\text{ GW}$ . Now, the  $90\text{\AA}$  radiation is the seed for the next stage to be converted to  $18\text{\AA}$ . This process is repeated at the fourth stage and the amplifier except that, there is no HGHG process in the amplifier, where the radiation is amplified exponentially until saturation. Finally, with a total undulator length of about  $46\text{ m}$ , we obtain about  $2\text{ GW}$  radiation at  $10\text{\AA}$ , well into saturation. We emphasize that in the radiator of the fourth stage, there is no exponential growth of the harmonic, but rather, after the coherent emission is finished, the harmonic is introduced to the next stage directly.

The coherent emission from the radiator in the previous stage is a divergent beam with its waist position back in the radiator. Further more, when this coherent emission beam is shifted to a “fresh” part of the same e-beam, the e-beam needs be magnetically delayed, hence the coherent emission light beam gets further divergent due to traveling the distance for delaying the e-beam. In our calculation, we assume that we need magnetically delay the e-beam for  $50\text{ fs}$ , i.e.  $\Delta s = 15\text{ }\mu\text{m}$ . We also assume that the shifter is structured identical to an idealized dispersion section with a length of  $L_s$ . The field is  $B$  when  $0 \leq s \leq \frac{L_s}{4}$  and  $\frac{3L_s}{4} \leq s \leq L_s$ , and  $-B$  when  $\frac{L_s}{4} \leq s \leq \frac{3L_s}{4}$ . Then  $L_s = \left[ \frac{96\Delta s\gamma^2 m^2 c^2}{e_0^2 B^2} \right]^{\frac{1}{3}}$ . So, if we assume  $B = 2\text{ Tesla}$ , then  $L_s = 33\text{ cm}$ . This distance is taken into account in our calculation.

**Alternative cases** Since the optimized parameters of the PERL are still under investigation, here we provide some alternative schemes for comparison.

For the cases when the peak current is high  $I_{peak} = 2,500\text{ Amp}$ , while the normalized emittance is  $\epsilon_n = 2\pi\text{ mm} - \text{mrad}$ . We could follow a similar cascading scheme as what is in Fig. 1, i.e,  $2,250\text{\AA} \rightarrow 450\text{\AA} \rightarrow 90\text{\AA} \rightarrow 30\text{\AA} \rightarrow 10\text{\AA}$ . Or if the final radiation is designed to be at  $\lambda_r = 18\text{\AA}$ . Then the scheme would be  $2,250\text{\AA} \rightarrow 450\text{\AA} \rightarrow 90\text{\AA} \rightarrow 18\text{\AA}$ . For the cases when the peak current is low  $I_{peak} = 750\text{ Amp}$ , while the normalized emittance is  $\epsilon_n = 1\pi\text{ mm} - \text{mrad}$ . The scheme would be  $2,250\text{\AA} \rightarrow 450\text{\AA} \rightarrow 90\text{\AA} \rightarrow 18\text{\AA}$ . The final peak power and the total undulator length of the whole device are listed in Table 1 for comparison.

The Pierce parameters of the FELs at  $10\text{\AA}$  or  $18\text{\AA}$  are around  $\rho \approx 1 \times 10^{-3}$ , hence it sets a requirement for the design of the PERL, i.e. the global relative energy spread should not be larger than  $\frac{\sigma_\gamma}{\gamma} \sim \rho \approx 1 \times 10^{-3}$ .

Table 1: Comparison of the four schemes

$I_{peak}$ <i>Amp</i>	$\epsilon_n$ $\pi\text{ mm} - \text{mrad}$	$L_w$ <i>m</i>	$\lambda_r$ $\text{\AA}$	$P_{out}$ <i>GW</i>
1,500	1	46	10	2
750	1	49	18	1
2,500	2	35	18	4
2,500	2	45	10	1

To meet this requirement, detailed beam dynamics analysis is underway<sup>[10]</sup>.

### 3 CONCLUSION

In conclusion, based on our calculation, it is possible to use the electron beam from the PERL to build an x-ray FEL at the NSLS. Such an HGHG based FEL will have a short pulse length. Further more, such an HGHG FEL pulse will be transform-limited. Besides the high brightness fundamental radiation around  $10\text{\AA}$ , the third harmonic at  $3.3\text{\AA}$  will reach a peak power of tens of *MW*. This makes the harmonic itself<sup>[11]</sup> a bright light source.

### 4 ACKNOWLEDGEMENT

The work is done under the contract *DE – AC02 – 98CH10886* with the US Department of Energy.

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