DESIGN OF A COMPACT X-RAY FREE ELECTRON LASER*

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Abstract

A compact hard X-ray FEL facility is proposed based on self-amplified spontaneous emission (SASE) scheme, which is aiming at generating 0.1nm coherent intense hard X-ray laser with the total facility length around 600m. To reach this goal, low emittance S-band photo cathode injector, high gradient C-band linear accelerator and short period cryogenic undulator are used. Simulation results show that 0.1nm coherent hard X-ray FEL with peak power up to 10GW can be generated from a 70-m-long undulator when the slice emittance of the electron beam is lower than 0.4mm-mrad. The energy of the electron beam is only 6.4GeV which is available in accelerator length of 230m with the help of 40MV/m C-band rf system. This paper describes the physic design of this compact hard X-ray FEL facility.

INTRODUCTION

Significant progress has been made in recent years in the development of X-ray FEL. Many X-ray FEL projects worldwide have either been proposed or currently under constructions [1]. XFEL can produce coherent X-ray with high brightness and ultra fast time structures which will enable scientists in physics, chemistry, biology and medicine to study nature down to the atomic level at a time-scale that fits this resolution. Because of its unique performance, XFEL is complement to the 3rd generation light source like the Shanghai Synchrotron Radiation Facility (SSRF) [2]. However, this magnificent facility will not be as easily accessible as the 3rd generation light sources, because of its large scale and only very few users can be served simultaneously. For example, the first hard X-ray FELs, the European X-ray Free electron Laser Project (EXFEL) [3] and the Linac Coherent Light Source (LCLS) [4] are 2-3 km long facilities. It is a natural attempt to find the possibility of reducing the size of an XFEL machine to a reasonably modest size without degrading the radiation quality. With the development of low-emittance beam injector, short period undulator and high-gradient accelerating structure, the compact machine has already become a new direction in the X-ray FEL design. A well known example is the Spring-8 Compact SASE Source (SCSS) [5] which is expected to get 0.1nm hard X-ray with the total facility length about 750m, and the SwissFEL at Paul Scherrer Institute (PSI) is also aiming at generating coherent hard X-ray with the facility length around 700m [6].

The following three key technologies are crucial to the compact XFELs:

- Low-emittance beam injector;
- High performance linac with gradient >40MV/m;
- Cryogenic permanent magnet in-vacuum undulator.

LAYOUT AND MAIN PARAMETERS

General Layout

The fundamental radiation wavelength of an undulator is given by

$$\lambda_s = \frac{\lambda_u}{2\gamma^2}\left(1+K^2/2\right),\ K = 0.934 B_u \lambda_u \qquad (1)$$

Where λ_u is the undulator period, γ is the Lorentz factor of the beam energy, K is the undulator parameter, and B_u is the peak magnetic field of the undulator. Either a short-period undulator or a high-energy beam can provide short-wavelength radiation. A short-period undulator is preferred for a compact FEL machine. It is important to keep a reasonably large K to obtain a short

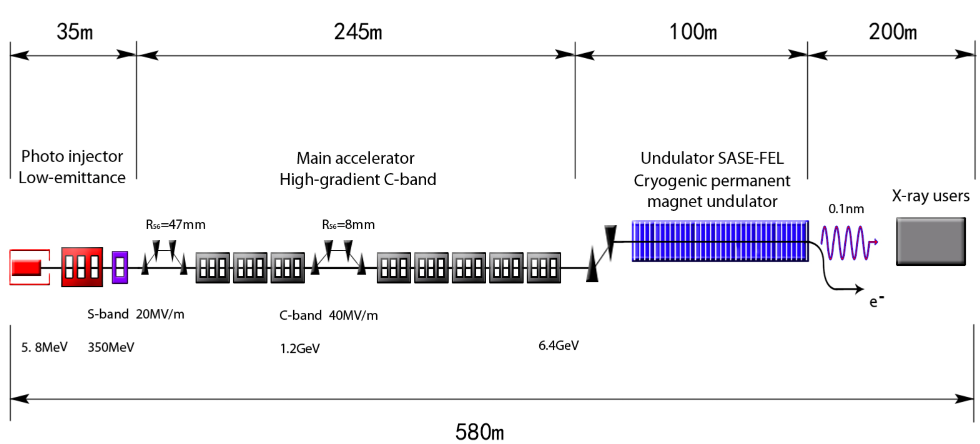

Figure 1: Layout of the compact hard X-ray FEL at SSRF.

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saturation length. A cryogenic in-vacuum undulator can meet this requirement. To futher reduce the whole facility length, we employ C-band linear accelerator which can provide 40 MV/m accelerating gradient, and a beam energy of 6.4 GeV is available in accelerator length of 245m. Including the injector length of 35m, the undulator and the dogleg length of nearly 100m, the X-ray beam line of 200m, the total facility length becomes 580m, which fits the available space at SSRF campus.

Figure. 1 shows the machine layout of the design. The main parameters are summarized in table 1. It should be point out that the parameters in table 1 are still a tentative, and still need to be optimized.

Table 1: Main Parameters

Electron beam parameters	
Energy/GeV	6.4
Peak current/kA	3
Bunch charge/pC	200
Normalized slice emittance/mm-mrad	0.4
RMS slice energy spread	0.01%
Full bunch length/fs	30
Undulator parameters	
Period/cm	1.6
Segment length/m	4.8
Full undulator length	70
Peak undulator field/T	0.93
K	1.4
Gap/mm	6
Average β -function/m	20
FEL parameters	
Radiation wavelength/nm	0.1
FEL parameter ρ	3.41×10^{-4}
Peak coherent power/GW	10
Peak brightness/ photons/(mm mrad)^2/s/0.1% bandwidth	2×10^{33}
Pulse repetition rate (Max.)/Hz	60
3D gain length/m	2.156
Saturation length/m	50

LCLS-type Photo Injector

Figure. 2 shows 3D gain length according to normalized emittance, which are calculated according to M. Xie [7]. Due to the small periodic length of an undulator, the FEL gain length of our design is smaller than LCLS and EXFEL when the normalized emittance can be controlled under 0.7mm-mrad. This is why a low emittance gun is needed when designing low beam energy XFEL. A beam emittance of 1-1.2 mm mrad has been a widely used number for a photo-cathode RF gun design. However, the slice emittance of the LCLS photo injector was measured to be 0.4 mm-mrad with 250pC charge which is a practical result for future compact hard XFEL design. Our design adopts the LCLS-type 1.6 cell photocathode RF gun. The single bunch charge is about 200pC.

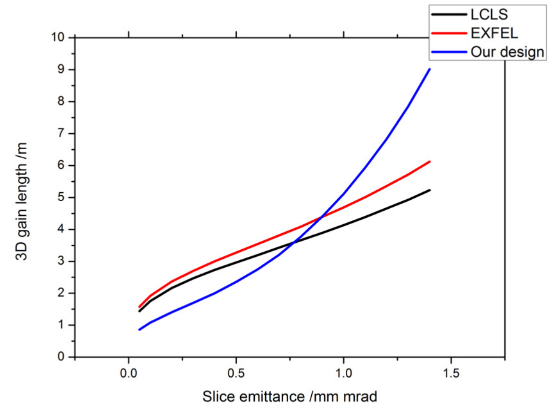

Figure 2: 3D gain length according to normalized emittance.

C-band Linear Accelerator

The operating rf frequency of C-band linear accelerator is 5712 MHz, which is twice as the conventional S-band frequency 2856 MHz. Because the shunt-impedance of the rf accelerating structure becomes higher at higher frequency, C-band system can provide higher accelerating gradient than the conventional S-band system. The accelerating gradient of the KEKB C-band injector linac is 42MV/m, and the recent performance of the C-band module is recorded an average field gradient of 45MV/m [8]. We choose the field gradient of 40MV/m in our design.

Cryogenic Permanent Magnet Undulator

A short period undulator is very attractive for compact X-ray FEL facilities. In order to pursue shorter periodicity, further improvement of the magnetic performance is needed. One method is reducing the gap of the in-vacuum undualtor, which will definitely increase the wake field effects that may badly degrade the performance of FEL. Cryogenic permanent magnet undulator (CPMU) is a more attractive mature technology which can improve the magnetic field performance of the existing in-vacuum undulator by roughly 30% by cooling down the permanent magnets to cryogenic temperature. Our design adopt hybrid CPMU that uses NdFeB permanent magnets and soft iron blocks [9].

On the axis the CPMU field can be calculated by using the formula,

$$\mathrm{B} = a\cdot\exp\left(\frac{g}{\lambda_u}(b + c\frac{g}{\lambda_u})\right) \qquad (2)$$

Where g is the magnet gap, λ_u is the period of the undulator, $a = 8.62703, b = -8.1857, c = 5.9718$. This formula can be used when $0.1 < g/\lambda_u < 1.0$. Here we choose the electron beam energy of 6.4GeV and the undulator gap should be 6mm.

S2E SIMULATION

The performance of a FEL depends crucially on the electron beam parameters. Since analytically calculations can only give an estimate of the expected performance, the numerical start to end simulation is necessary to account for various aspects of beam dynamics during the progress. The performance of the photocathode injector has been simulated first with PARMELA [10]. Then the electron beam was tracked through magnetic bunch compressor and the main accelerator which consist of S-band and C-band accelerating structures with help of ELEGANT [11] taking into account of the coherent synchrotron radiation (CSR) and the space charge effect. The SASE FEL process in the undulator was simulated with GENESIS1.3 [12] based on the output of ELEGANT.

We performed the simulations with PARMELA from the cathode to the end of the photo-injector using 10^5 macro-particles. The bunch length is about 10 ps, the peak current is close to 25 A, and the global normalized emittance is about 0.33mm-mrad.

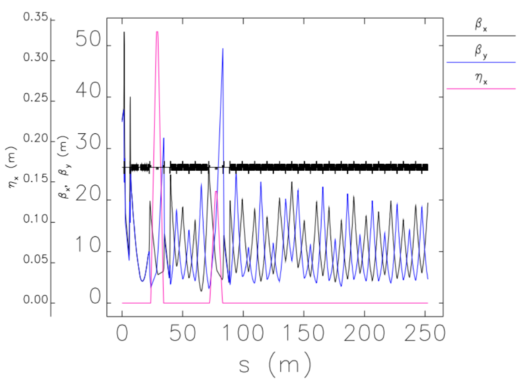

Figure 3: Optimized beta-function of the linac.

At the entrance to the main linac, the output distribution of macro-particles is converted into the input distribution for ELEGANT. Then the electron beam is tracked through the S-band linac, magnetic bunch compressors and C-band linac. The optimized beta-function of the linac is shown in figure 3 and the parameters for the beam at the entrance to the undulator are presented in figure 4,

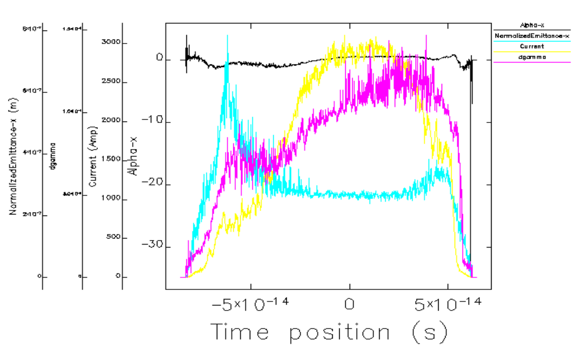

Figure 4: Normalized emittance (cyan), alpha-x (black), slice energy spread (magenta), and current distribution (yellow) along bunch upstream of the undulator.

from which one can find that the peak current is compressed to over 2500A, the beam energy is 6.4GeV and the slice emittance is lower than 0.4mm-mrad.

The optimization of undulator parameters is conducted using 3D code GENESIS1.3 and the FEL simulation results are summarized in Figure 5. The saturation length is about 50m. The peak power of the 0.1nm radiation is over 10GW at 70m undulator length. The bandwidth of spectrum is about 0.08% at saturation.

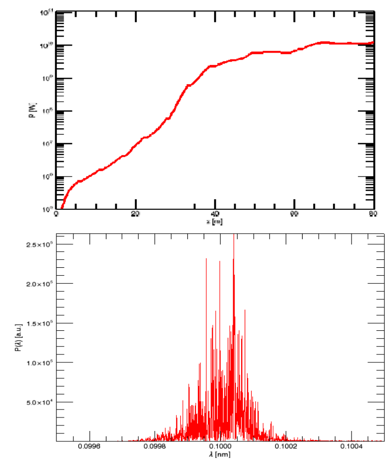

Figure 5: Radiation power along the undulator length (left) and FEL spectrum at saturation (right).

CONCLUSION

The design of a compact X-ray FEL facility has been described. The design shows that with the state-of-the-art electron gun, accelerator and undulator technology, 0.1 nm coherent hard X-ray FEL with peak power up to 10 GW can be generated while the scale and cost of the hard X-ray facility can be substantially reduced. The total length of the facility in this design is around 600m.

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