SASE FEL at SDUV-FEL*

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Abstract

A SASE experiment has been done at SDUV-FEL(Shanghai deep ultra-violet free electron laser source), a $130 \sim 140MeV$, 50A,normalized emittance $8\mu m.rad$ and local energy spread 0.1% electron beam passes through six section undulators, each one with length 1.5m, period 2.5cm and parameter $K \sim 1.40$. The spontaneous radiation and exponential growth are observed at $328nm$ and $385nm$, and the fine structure SASE spectrum also is measured.

INTRODUCTION

Free electron laser(FEL) is recognized as one potential candidate for the next generation high-brightness x-ray sources. Both the theory and experiments have indicated that the FEL can provide an intense tunable coherent radiation with wavelength from $1000\AA$ to hard X-ray regime [1]. This kind of ultrashort wavelength light has widespread applications in a wide research fields: such as in atomic and molecular physics, condensed matter physics, material physics, high energy physics, chemistry, structural biology, and medical diagnostics, etc. As the advances in ultrashort and high power laser technology are improved in recently 20 years, and the mature accelerator technology which can provide high quality (short pulse, small emittance and small energy spread, etc) electron sources, it is possible to design a high power and high brightness coherent deep ultra-violet free electron laser source. SASE (self amplified spontaneous emission) operation, HGHG (high gain harmonic generation) operation and Echo(Echo-enhanced Harmonic Generation) FEL operation schemes have been considered in the design of SDUV-FEL. The optimization wavelength for three FEL schemes can cover the deep ultra-violet region about $150 \sim 650nm$.

SASE OPERATION IN SDUV-FEL

The SASE scheme of SDUV-FEL consists of a 4MeV photoinjector driven by a laser with wavelength 1047 nm, a 160MeV S-band linear accelerator, a four-magnet bunch compressor and a 9m planar undulator system, see Fig. 1. The bunch compressor is shown in Fig. 2, with compression ratio $2 \sim 3$, bend angle $7^\circ \sim 14^\circ$ and maximum $R_{56} \sim 100mm$. The undulator system(hybrid/Nd-Fe-B type) has 6 sections, each one has length $1.5m$, period

Figure 1: The tunnel of SDUV-FEL

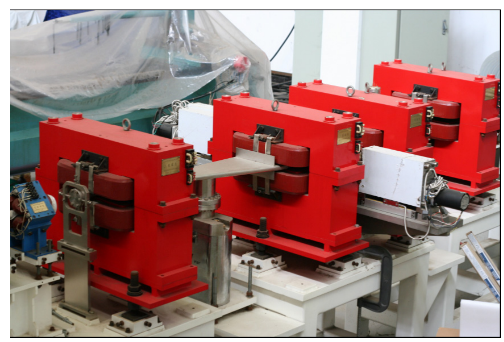

Figure 2: Bunch compressor of SDUV-FEL

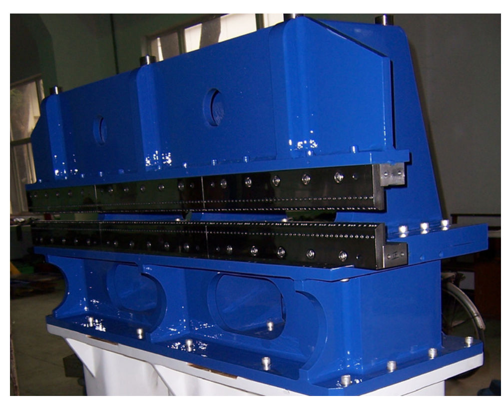

Figure 3: Undulator in SASE FEL operation

$\lambda_u = 2.5cm$, fixed gap $g = 10mm$, strength $K \sim 1.40$, and peak field $B_0 = 0.60T$, see Fig. 3 and Table 1. The segment scheme is shown in Fig. 4. Optic structure for the electron beam is composed by nine quadrupoles and the six undulators. Envelop function β of beam oscillation in the undulators is limited in regime $\beta = 1 \sim 4m$,

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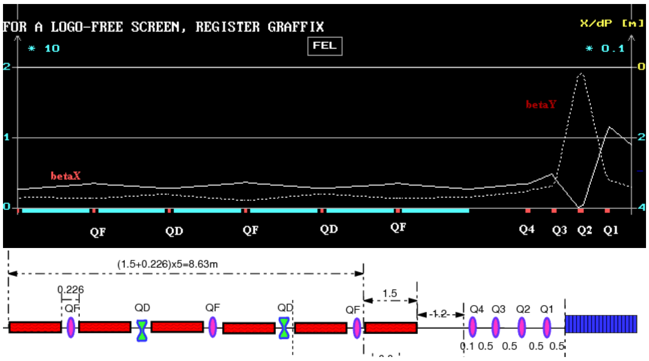

Figure 4: Segments and electron beam optic structure

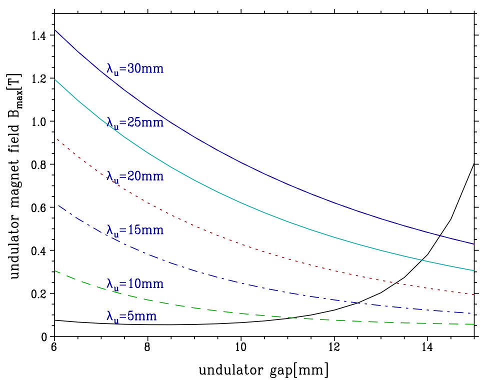

Figure 5: Peak magnetic field vs gap for undulator

see Fig. 4. Parameters for SASE FEL scheme are listed in Table 1. The electron beam provided by the linac has energy $E \leq 160MeV$, pulse length $\sim 10psec$, normalized emittance $\varepsilon_N = 4 \sim 10\mu m.rad$, local energy spread $\sigma_\gamma \leq 0.1\%$ and peak current $I_p \leq 400A$.

Table 1: Parameters for SASE operation at SDUV-FEL

electron beam	
electron energy $E_0[MeV]$	$100 \sim 160$
pulse length[psec]	10
local energy spread $\sigma_\gamma[\%]$	≤ 0.1
normalized emittance $\varepsilon_N[\mu m.rad]$	$4 \sim 10$
peak current $I_p[A]$	≤ 400
Pierce parameter $\rho[0.1\%]$	$1 \sim 5$
undulator	
period $\lambda_u[cm]$	2.5
gap $g[cm]$	1.0
strength parameter K	1.40
peak magnetic field B_0[T]	0.60
section length $z[m]$	1.5
section number	6
$\beta[m]$	$1 \sim 4$
SASE radiation	
radiation wavelength[nm]	$250 \sim 650$
normalized emittance $\gamma_0\varepsilon_\gamma[mm.mrad]$	$6 \sim 10$

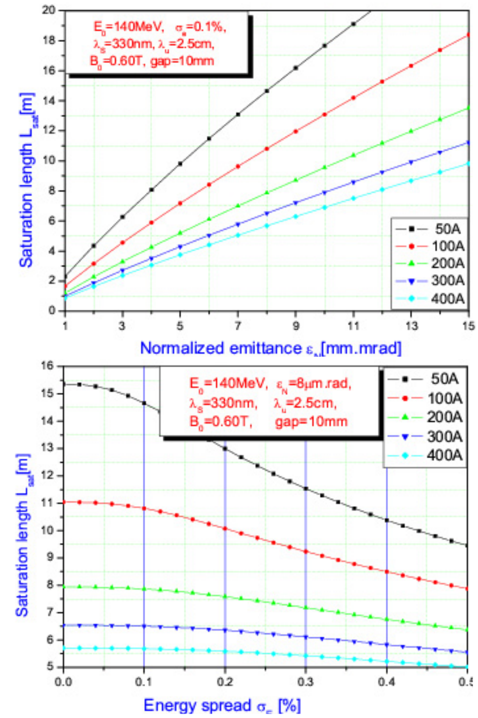

Figure 6: Saturation length L_{sat} vs I_p, ε_N and σ_γ.

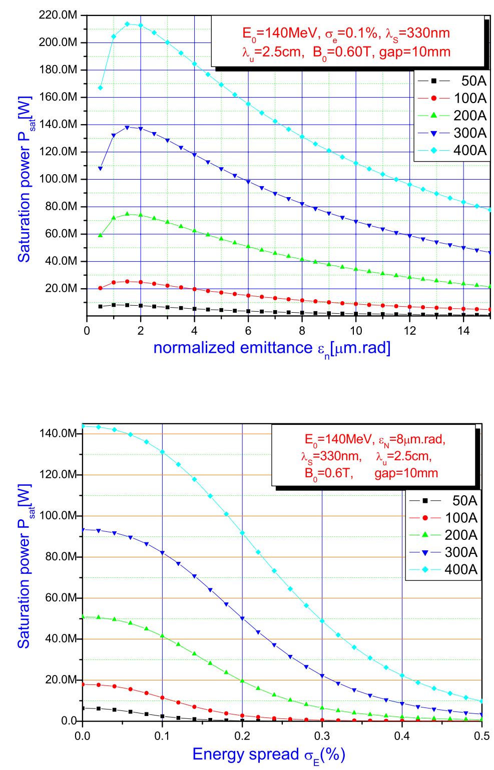

Figure 7: Saturation length P_{sat} vs I_p, ε_N and σ_γ.

OPTIMIZATION

The strength parameter K of undulator with period λ_u is defined by its peak magnetic field B_0, $K = \frac{eB_0\lambda_u}{2\pi mc^2} \approx 0.934\lambda_u[cm]B_0[T]$. For the Nd-Fe-B type hybrid undulator at SDUV-FEL SASE scheme, its peak field B_0, pe-

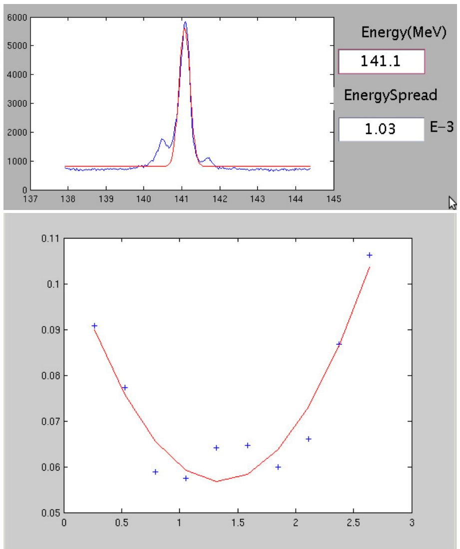

Figure 8: Electron energy $141MeV$, energy spread 0.1% and normalized emittance $\sim 8\mu m.rad$ are measured.

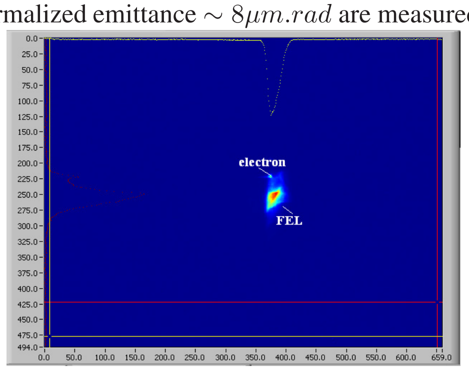

Figure 9: Transverse profiles of electron beam and SASE light measured by OTR. Electron beam is offset from the light pulse by one bending magnet.

riod λ_u and gap g are related by the Halbach formula [2]: $B_0[T] = 3.649\lambda_u[cm]\exp\{-5.068g/\lambda_u + 1.52(g/\lambda_u)^2\}$, where g is the undulator gap. In our design, the paramerers of undulator are selected $B_0 = 0.60T$, $K = 1.40$, $\lambda_u = 2.5cm$ and $g = 10mm$, see Fig 5.

When an electron beam with energy γ passes through the undulator, it emits a radiation with resonance wavelength $\lambda r = \lambda_u(1+a_u^2)/2\gamma^2$, where $a_u = K$ for helical undulator and $K/\sqrt{2}$ for planar undulator. The initial random spontaneous radiation induces a longitudinal density modulation in the beam at λ_r scale, and the microbunching structure in the beam is produced. The radiation emitted from one microbunch is coherent, and this leads to the radiation intensity exponential growth[3, 4, 5, 6]: $P \propto e^{z/L_g}$, where L_g the power gain length. Following the electron beam losing its energy(its energy spread increases) as the emitting photons, the resonant frequency will be outside of the FEL bandwidth, so that the radiation power tends to saturation, and saturation length $L_{sat} \approx 20L_g$.

In high gain FEL, there is one important scaling dimen-

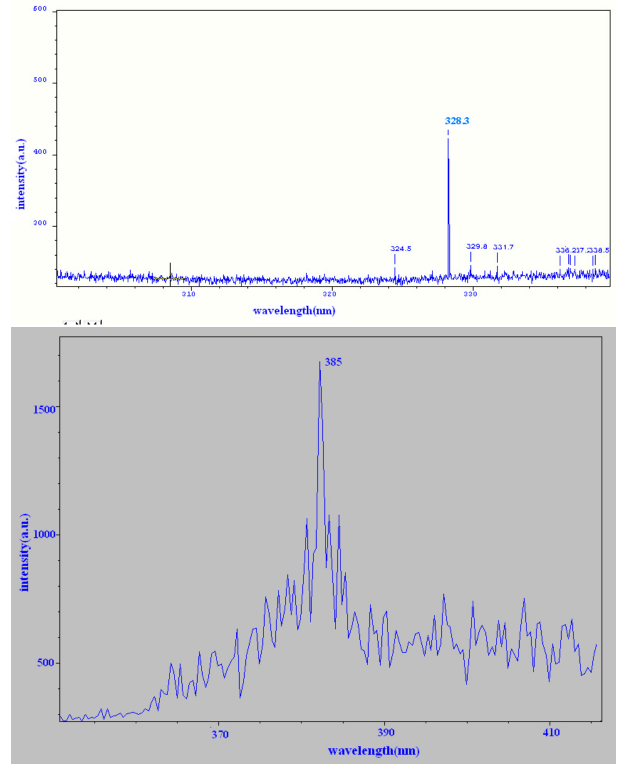

Figure 10: SASE spectrum signals at 328nm for $140MeV$ case and the fine structure at $385nm$ for $130MeV$ case were observed.

sionless Pierce parameter ρ [6], defined as

$$\rho = \left[\left(\frac{I_p}{I_A}\right)\left(\frac{\lambda_u a_u[JJ]}{2\pi\sigma_x}\right)^2\left(\frac{1}{2\gamma}\right)^3\right]^{1/3}, \qquad (1)$$

where $I_A = 17kA$ the Alfven current, $[JJ] = 1$ for helical undulator and $[JJ] = J_0(\xi) - J_1(\xi)$ for planar undulator, $\xi = a_u^2/2(1 + a_u^2)$, and σ_x electron beam size, J the Bessel function. The Pierce parameter ρ will decide the SASE FEL output efficiency, saturation power and gain length. For 1D model case, $P_{sat} = \rho P_{beam}$ and $L_g = \lambda_u/4\pi\sqrt{3}\rho$. Here power of the beam is given by $P_{beam}[TW] = E_0[GeV]I_p[kA]$. Spectrum bandwidth of SASE radiation is also affected by ρ, i.e. $\Delta\lambda r/\lambda_r \approx 2\rho$. For an optimized SASE FEL, the electron beam is required an excellent quality: small emittence($\varepsilon_N \leq \gamma\varepsilon_r$) and small energy spread($\sigma_\gamma \leq \rho$), where $\varepsilon_r = \lambda_r/4\pi$ is the emittance of the radiation. At the SASE scheme of SDUV-FEL, $\rho = 0.1 \sim 0.5\%$, $\gamma_0\varepsilon_\gamma = 6 \sim 10\mu m.rad$, see Table 1.

The saturation gain length and power vs the beam current, emittance and energy spread for $140MeV$ case are given in Fig. 6 and Fig. 7. For SDUV-FEL case, the experiment result is restricted by its electron beam, especially by its peak current and emittance. Unfortunately, at current status, the linac machine can only steadily provide the beam with peak current $I_p \leq 50A$. From Fig. 6 one can see that the relevant saturation gain length $L_{sat} \geq 15m$. Then the SASE output power P can not saturate at the end of

9m undulators for present low beam current case, and olny appear the exponential growth.

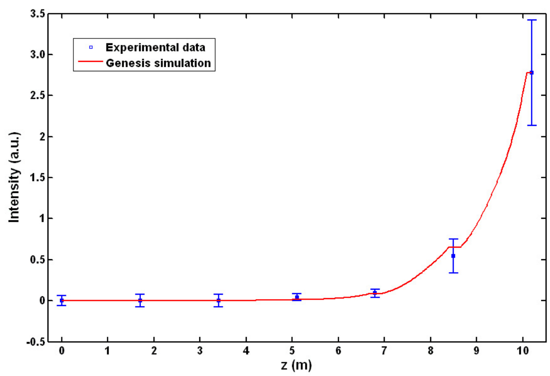

Figure 11: Exponential growth of SASE radiation intensity along undulator length(for $\sim 140MeV$, 328 nm case, and drift sections included here).

EXPERIMENTAL RESULTS

The beam energy, emittance and energy spread have been measured nearby $141MeV$ with peak current $50A(\rho = 0.15\%)$, which are shown in Fig. 8. The energy spread σ_γ is about 0.1%, normalized emittamce ε_N is about $8\mu m.rad$. After the beam passes through the six undulators, the beam and SASE radiation are observed by OTR, and their transverse profiles are shown in Fig. 9. Electron beam is offset from the light pulse by one bending magnet in here. The spot size of radiation is larger than the one of electron beam. This case is induced by the divergent angle of FEL and collimation accuracy of electron beam when it passes through the long undulators. The spectrum of SASE radiation at $328nm$ and $385nm$ are observed, as shown in Fig. 10. Here the classical SASE spectrum can be seen from the fine structure $385nm$ case(the scale is too large in the $328nm$ case, only one signal line is shown). The radiation intensity of SASE increases along undulator length is measured for $140MeV$ case in Fig. 11, it is in accord with the simulation given by genesis code. After the initial random spontaneous radiation, the exponential growth appears.

CONCLUSIONS

The SASE operation at SDUV-FEL is introduced. The radiation of SASE FEL are observed, and the exponential growth of SASE radiation intensity along undulator length is measured.

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