STUDY ON A FREE ELECTRON LASER AT A SPRING-8 LONG STRAGHT SECTION

T. Nakamura, M. Hara, H. Tanaka
RIKEN-JAERI SPring-8 Project Team
Hirosawa 2-1, Wako-shi, Saitama, JAPAN

Introduction

SPring-8, a 8-GeV synchrotron light source, consists of cascaded accelerators of a linac, a booster synchrotron and a low emittance storage ring.

The storage ring has four long straight sections of the length 30m.

We studied on the performance of a free electron laser (FEL) at the one of these straight sections.

The wave length of the FEL in this study is set to be 4nm which is of the ionization energy of K-shell of carbon atoms.

Parameters of the Storage Ring for an FEL

The storage ring has two lattce parameters.

One is a normal lattice for a usual low emittance operation of the storage ring, and the other one, which we call "detuned" lattice, is for comissioning of the storage ring and has higher momentum-compaction factor and higher emittance than the normal lattice [1].

We studied the FEL on these two lattices and also in the case with damping wigglers which reduce emittance and increase the energy spread as

$$\frac{\sigma_{\epsilon w}^2}{\sigma_{\epsilon 0}^2} = \frac{1+\frac{\sqrt{2}\pi^2 N_W R_0^2 K^3}{\lambda_W^2\gamma^3}}{1+\frac{\pi N_W R_0 K^2}{\lambda_W \gamma^2}} \tag{1}$$

$$\frac{\epsilon_{xw}}{\epsilon_{x0}} = \frac{1}{1+\frac{\pi N_W R_0 K^2}{\lambda_W \gamma^2}} \tag{2}$$

where R_0 is the bending radius and the other symbols are of usual definition of wiggler parameters [2].

To keep the energy spread low, the damping wigglers period set to as low as keeping high K value.

With these damping wigglers, the energy spread is 1.6 times increased while the emittance is 0.23 times decreased.

These damping wigglers assumed to be installed in the other three long straight sections and the parameters are listed in Table 1.

The emittance in the detuned lattice is so high that we consider only the case with damping wigglers for the detuned lattice.

The parameters of these lattices with and without damping wigglers are listed in Table 2.

The emittances of a electron beam for each transverse direction should be lower than the emittance of photons radiated from electrons in the beam.

For an FEL of wave length λ, this condition is written as $\epsilon < \frac{\lambda}{2\pi}$ and this value is 0.64 nm-rad for wave length 4nm.

Table 1: Damping Wigglers

Kw	4.0
Bw	1.1 T
Period	4.0 cm
Length	90.0 m

Table 2: The Storage Ring Parameters and Tthreshold Current of Bunch Lengtheninig

	Lattice		
	Normal		Detune
Damping Wiggers	OFF	ON	ON
Energy [GeV]		3	
Eergy Spread(σ_γ/γ)	0.00041	0.00065	0.0006
Momentum-Compaction Factor	0.000146	0.000146	0.0011:
Emittance (x,y)[nm-rad]	0.5	0.1	1.3
$I_{th,BL}$ (naturalσ_γ)	15 A	50 A	330 A
$I_{th,BL}$ (1.5$\times$ natural σ_γ)	34 A	112 A	742 A

In the case of full-coupling operation which can reduce the horizontal emittancae while increase vertical one, the natural transverse emittance of the storage ring for each transverse dimension at the energy 8-GeV are 3.5 nm-rad without damping wigglers and 2.4 nm-rad with damping wigglers. These values are higher than required.

To get the smaller emittance, the electron beam energy is set to 3 GeV. The lower energy also enhances the interaction of the electron and a laser beam.

At 3 GeV in the normal lattice, the emittance is 0.5 nm-rad without damping wigglers and 0.1 nm-rad with damping wigglers and those values are small enough for the FEL.

But in the detuned lattice, even with damping wigglers, the emittance is 1.3 nm-rad and still higher than required value.

Peak Current Estimation

To get higher gain and power of an FEL, higher peak current is also required.

The single-bunch peak current in the storage rings are estimated with the code ZAP and is limited by longitudinal bunch-lengthening instabilities.

We assume the longitudianl impedance of the storage ring to be

$$\left|\frac{Z_{\parallel}}{n}\right| = 1\Omega \tag{3}$$

. This is target value of next generation synchrotron light sources.

Transverse impedace is caliculated in ZAP from the longutudinal impedace with the relation [3]

$$|Z_{\perp}| = \frac{2R}{b^2}\left|\frac{Z_{\parallel}}{n}\right| \tag{4}$$

where b and R are the chamber radius and the average radius respectively. and in this case, b is 0.02m and R is 228 m. . In the nominal operation of the storage ring, the chamber radius is not constant and tapered transitions of vacuum chambers, which connect narrow gap insertion device sections where $b \sim 0.005\ m$ and normal sections where $b \sim 0.02\ m$, are main sources of the transverse impedance of the storage ring.

So, the size of the vacuum chambers at the insertion device sections should be enlarged at the FEL operation with variable gap chambers or so to reduce the tapering angle at the transitions to attain the value derived with equation (4).

With this transverse impedance, the threshold current of transverse instabilities calculated with ZAP is more than a thouthand Ampares.

With the value 1 mm of the bunch length σ_l of the storage ring at 3 GeV, the effective longitudinal impedance calculated with SPEAR scaling

$$\left|\frac{Z_{\parallel}}{n}\right|_{eff} = \left|\frac{Z_{\parallel}}{n}\right|\left(\frac{\sigma_l}{b}\right)^{1.68} \tag{5}$$

is 6.5 $m\Omega$. This value is smaller than the free-space longitudinal impedace

$$\left|\frac{Z_{\parallel}}{n}\right| = 300\frac{b}{R} \tag{6}$$

which is 26 $m\Omega$ in our case.

So we adopt the value of the free-space impedance for the effective impedance of the storage ring.

Bunch-lenghtening is due to the increase of the energy spread caused by a longitudinal microwave instability. If peak current of a bunch reachs to this threshold of this instabilty, the increase of the peak current is stopped and the energy spread begins to increase as the increase of the charge in the bunch.

For usual usage of the storage ring as a light source, bunch-lengthening effect is not so serious problem but for this FEL, this energy spread heavily reduces the performance of the FEL.

Its threshold current is

$$I_{th,BL} = \frac{2\pi\alpha(E/e)}{|Z_{\parallel}/n|_{eff}}\left(\frac{\sigma_\gamma}{\gamma}\right)^2 \tag{7}$$

Because the nominal lattice parameters is for low emittance, the momentum-compaction factor is rather small, the peak current is 15 A without the damping wigglers and 50 A with them.

The detuned mode have much higher value of the momentum-compaction factor so that the peak current is reached to 300A for the detuned mode.

These values are much smaller than threshold current of transverse instablilities.

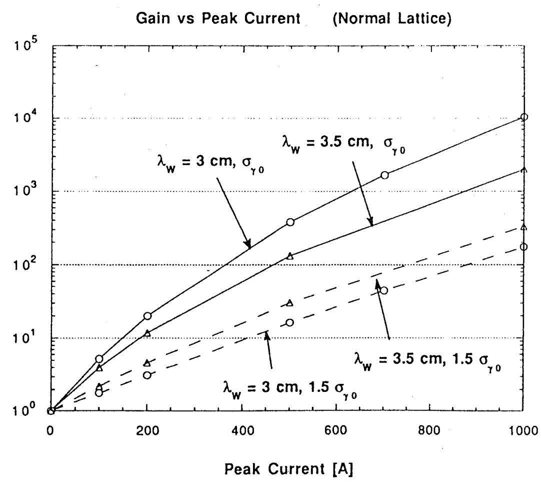

Figure 1: Gain vs Peak Current for Normal Lattice without Damping Wigglers with two different energy spread, $\sigma_{\gamma 0}$(natural energy spread) and 1.5 $\sigma_{\gamma 0}$.

Table 3: FEL Wiggler

Period	3 cm	3.5 cm
Kw	4.0	3.7
Matched β	14.2 m	17.7 m
Length	30.0 m	
	x,y equal focusing	

The FEL Simulation

Three-dimensional simulation of the FEL is performed with the code ELFIN.

ELFIN is developed by one of the authors, T. Nakamura and treats the coupled equations consists of the partial differential equation of FEL field and the Lorents equations of electrons, and solves them on discritized transverse space with FFT and Particle-In-Cell method. This simulation was done for an amplifier configuration and we only got the gain of the FEL. But the calculated gain can be used to study on the feasibility of SASE. The results of the simulation are in -.

The wiggler parameters for the simulation is listed Table 3. The equal focusing with paraboric pole face scheme is assumed and its focusing strength is $\frac{\pi K}{\lambda_W \gamma}$. The electron beam size is matched to the beta function of this focusing of the wiggler to maintain its size in the wiggler.

The input laser field is focused to the center of the wiggler of waist size 0.15mm and input power is 10 watt.

Conclusion

With the current below the estimated bunch-lengtheninig threshold, the gain of the FEL of wave length of 4nm is rather small to get enough SASE power.

In this bunch-lengthening limited region, The detuned lattice has the higher momentum-compaction factor but has the higher emittance so that the gain with the detuned

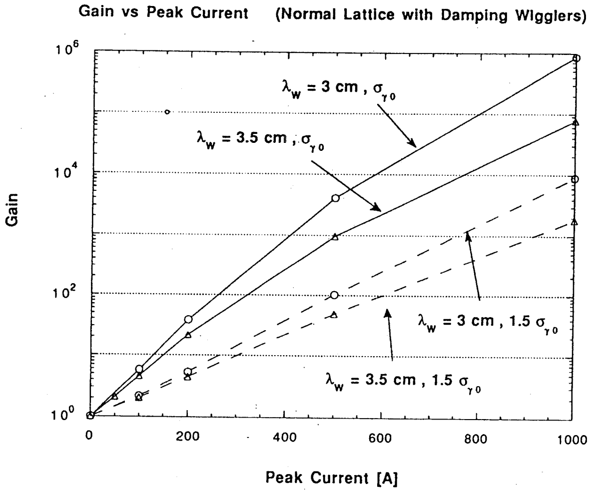

Figure 2: Gain vs Peak Current for Normal Lattice with Damping Wigglers with two different energy spread, $\sigma_{\gamma 0}$(natural energy spread) and 1.5 $\sigma_{\gamma 0}$.

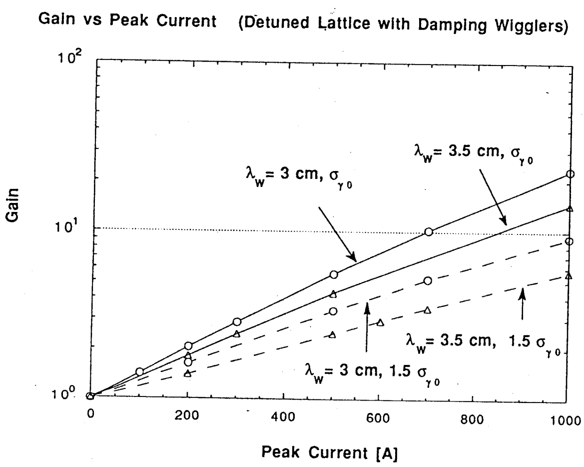

Figure 3: Gain vs Peak Current for Detuned Lattice with Damping Wigglers with two different energy spread, $\sigma_{\gamma 0}$(natural energy spread) and 1.5 $\sigma_{\gamma 0}$.

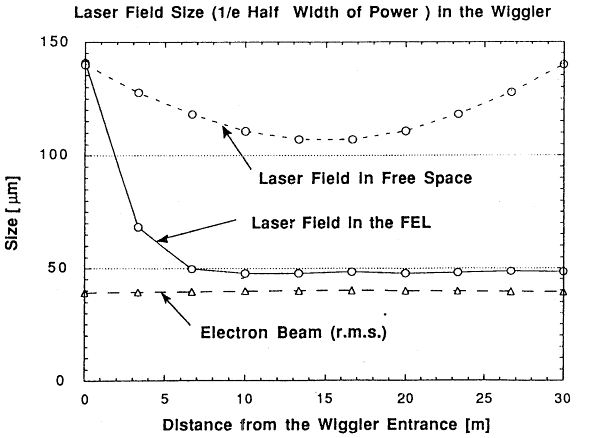

Figure 4: Laser field size in the FEL wiggler in the case with the normal lattice with damping wigglers of peak current 1000A and $\lambda_W = 3.0$ cm

lattice is not so different from the normal lattice though the threshold current have almost one order higher value.

And because the value of the energy spread is in ciritical region for this FEL shownin the figures, the increase of the threshould current with higher energy spread is also not so effective.

But if we could obtain higher peak current over 500A without bunch-lengthening, the gain of FEL is high enough to cause SASE and the effect of gain optical guiding. With this guiding effect, the laser field have almost the same size of the electron beam all the way in the wiggler and this localization of the laser field enhances the interaction between the elctron beam and the laser field.

Hence smaller emittance is better to get such high FEL gain.

but the alignmennt of the electron beam and the laser beam in the wiggler is still difficult problem because those have small size of tens of micro meters. as shown .

Further study on the bunch-lenghening effect is requied for precise estimation of the dependence of the energy spread to the peak current.

The study with simulations with the green-function of the logitudinal wake force is required and the numerical derivation of such green-function caused by various components of the storage ring are also now in progress at RIKEN.

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References

[1] "SPring-8 PROJECT Part 1 Facility Design",JAERI-RIKEN SPring-8 Project Team,1990

[2] A.S.Fisher, et.al "A 40-Å FEL on the PEP Storage Ring",SSRL ACD Note 87 (1990).

[3] M.S. Zisman, S.Shattopadhyay, and J.J. Bisognano, "ZAP User's Manual", LBL-21270,1986.