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A Design Study of an FEL–SR at the FELI

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Abstract

A compact, low emittance SR dedicated to both of FEL and SOR is studied. The FEL wave length and small signal gain are estimated using the emittance of the designed lattice. Designing problem of the FEL– SR was also shown, and a 45 deg bending, modified DBA lattice was adopted. The FEL wavelength, small signal gain, and output power are estimated.

1. Introduction

Considering the practical application of the short wave length FEL, two types of facilities are promising: Linac type and SR type. Linac can lase high power FEL, and SR can make cw FELs with narrow spectrum bands. Considering the application of high peak power FEL, the FELI has adopted an S–band linac for its main accelerator system, and succeeded in the lasing at two lasing sections (30 MeV and 70 MeV) for middle and near infrared FEL longer than 1 μm, and has began the application study in the regions of solid state physics and bio–sciences. In addition, we have constructed a high energy (160 MeV) beam line for the lasing of visible and UV FELs with the wavelength of 1.2–0.35 μm and obtained spontaneous emission of 0.5 μm [1]. On the other hand, aiming as a research and application center of FEL in Japan, the FELI has also considered the possibility of the construction of an SR for FEL and has prepared its space. This paper reports a preliminary design study of an SR FEL apparatus suitable for the FELI.

In the design of SRs, the selection of the lattice from various candidates is most important. Most of SR FEL experiments made use of existing machines such as ACO, VEPP–III, TERAS, UV–SOR, and few SRs such as super–ACO, Duke–SR, and NIJI–IV which were designed for FEL lasing. Hence, we compared several achromatic, low emittance lattices for a compact FEL SR suitable for the FELI, and chose a modified DBA lattice with eight 45 deg bending magnets. We applied this lattice to the designed of a 1 GeV SR for the application of SOR to say nothing of FEL.

2. Comparison of lattices

Considering the limit of the available space, we were interested in so called compact rings. In these rings, bending angles are large and corresponding changes of machine functions are also large. Therefore, making of dispersion–free straight sections is inevitable for the reduction of beam diameter in the undulator section. For this reason, we concentrated on achromatic lattice as DBA, TBA, and QBA.

As the small signal gain of FEL rapidly decreases below the diffraction limited wave length, the lasing wave length λ should satisfy the following condition [2].

$\lambda > 2\pi\varepsilon$ (ε:emittance of the electron beam) (1)

Althogh, Einfeld and Plesko [3] and Wiedemann [4] proposed equations for the estimation of emittance, their equations can not be applied to large bending, compact lattices. In general, there is a tendency of $\varepsilon\,[\mathrm{m \cdot rad}] \propto \gamma^2 \theta^{-3}$, where γ =1957E/GeV is the electron energy, θ[rad] the bending angle, respectively. In addition, the lattice of FEL SRs also needs long straight sections for the installations of undulators. Putting these conditions in mind, we compared five achromatic lattices shown in Fig. 1 using MAGIC, and obtained machine functions shown in Fig. 2.

Parameters including the emittance of 1 GeV of these lattices are listed in Table 1. We chose the betatron numbers so as to make the emittance to be minimum, and adopted edge angles so as to reduce the maximum values of vertical betatron functions β_y. The variation of the edge angle does not affect the emittance. Table 1 shows that, there is no remarkable difference between three typical achromatic lattices of DBA, TBA, and QBA.

Considering the diffraction limit of the lasing wave length of eq.(1), we adopted the 2–fold modified DBA lattice shown by Fig.1(e).

Table 1 Comparison of typical compact lattices

Lattice type		DBA	TBA	QBA	DBA	DBA*
Bending angle θ (deg)		90	60	45	45	45
Bending radius ρ (m)		2.3	2.3	2.3	2.3	2.3
Edge angle ε (deg)		0	20	22.5	0	0
Circumference C(m)		41.95	43.46	45.75	68.05	52.46
Long straight sec. L(m)		9.8	9.8	9.8	9.8	9.8
Periodicity N		2	2	2	4	2
Field gradient K・ℓ (1/m)						
(l:Length)	(QC)	0.662	0.866	0.734	1.01	0.800
	(QF)	1.15	1.11	1.04	0.938	1.18
	(QD)	−1.08	−0.990	−0.900	−0.995	−1.14
	(QF1)					0.752
	(QD1)					−0.800
Betatron number	ν_x	2.75	2.75	2.75	3.25	3.25
	ν_y	1.25	1.25	1.25	1.25	1.25
Emittance ε (mm・mrad)		0.90 π	0.65 π	0.76 π	0.29 π	0.37 π
(1 GeV, MAGIC)						
Betatron function	$\beta_{x,c}$(m)	1.06	2.54	2.51	11.8	1.76
(c:straight sec. center)	$\beta_{x,max}$(m)	23.6	12.0	12.1	13.8	15.4
	$\beta_{y,c}$(m)	2.75	0.770	1.32	9.65	2.72
	$\beta_{y,max}$(m)	27.1	77.5	45.8	23.0	27.5

* Modified

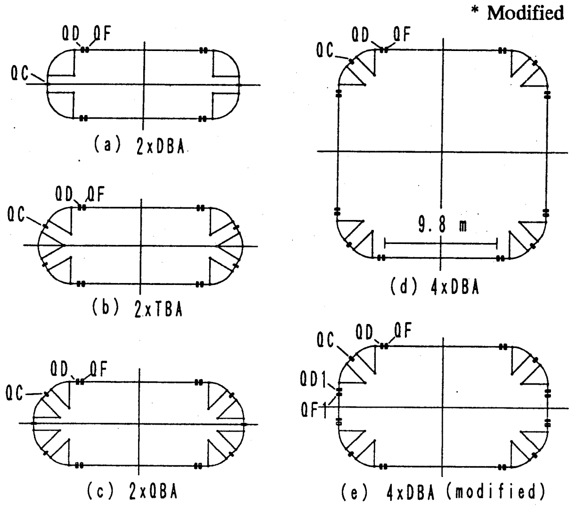

Fig. 1 Achromatic lattices for compact rings

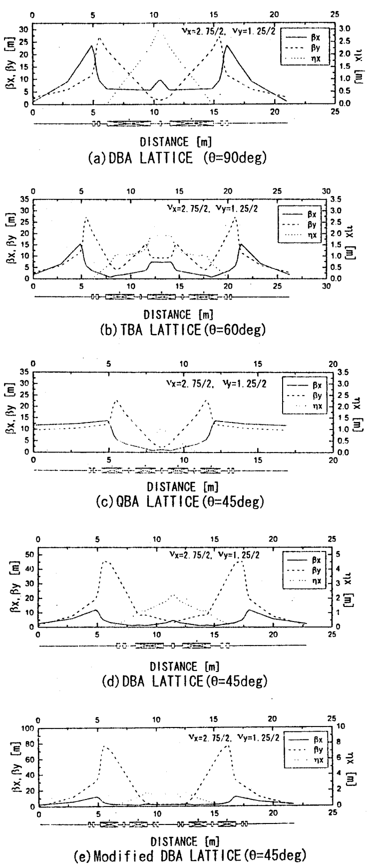

Fig. 2 Machine functions of achromatic lattices

3. Design estimation of an FEL SR

Considering the limit of available space, we modified the lattice of Fig. 1(e) to resemble a race track shape and designed a ring shown in Fig. 3.

Its parameters are listed in Table 2, and the machine functions are shown in Fig. 4. The maximum energy is set to be 1 GeV considering the application of SOR not only FEL. The RF frequency is set to 915 MHz, and its power source is supposed to be Toshiba cw klystron with highest output power of 200 kW. Using this high frequency, we can make short micropulse FELs which are convenient for the basic research of materials. In addition, as the length of optical beam packet is proportional to the square root of the length of electron bunches [5], the time fluency of FEL increases according to the square root of the RF frequency.

Table 2 SR ring parameters

Lattice parameters		
Lattice type		Modified DBA
Beam energy	E_{max}	1 GeV
Injection energy	E_{inj}	160 MeV
Average current	I_{av}	0.5 A (0.3 A*)
Circumference	C	47.21 m
Long straight section	L	8.78 m
Periodicity	N	2
Bending angle	θ	45 deg
Bending radius	ρ	2.3 m
Bending field	B_{max}	1.45 T
Field index	n	0
Edge angle	ε	0 deg
Focusing field gradient	K	5.628 m^{-2}(QF1)
(Length 0.2 m)		-5.369 m^{-2}(QD1)
		4.000 m^{-2}(QC)
		-4.000 m^{-2}(QD1)
		7.344 m^{-2}(QF1)
RF parameters		
Harmonic number	h	144
Frequency	f_{RF}	915 MHz
Tube type		CW Klystron
Acc. Gap Voltage	V_{acc}	100 kV
Machine parameters		
Betatron number	ν_x	3.25
	ν_y	1.25
Momentum compaction	α	0.0804
Emittance	ε	3.60×10^{-7} π m・rad(1 GeV)
Betatron function	$\beta_{x,c}$	1.52 m(straight section center)
	$\beta_{x,max}$	14.2 m
	$\beta_{y,c}$	4.33 m(straight section center)
	$\beta_{y,max}$	21.4 m
Energy spread	$\Delta E/E$	5.3×10^{-4}(1 GeV)
Bunch size	σ_x	0.71(1.46*)mm(1GeV,10% coupling)
(Straight section center)	σ_y	0.38(0.46*)mm(1GeV,10% coupling)
	σ_z	24.7 mm (1 GeV)
Damping time	τ_x	11.1 ms
	τ_y	8.2 ms
	τ_E	3.6 ms
Touschek life time x Beam current		3.2×10^{4} A・s

* used for FEL gain estimation

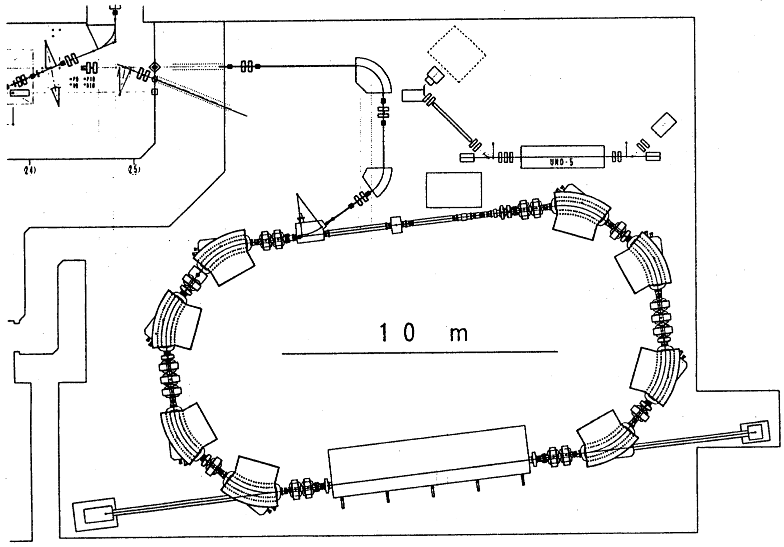

Fig. 3 A layout plan of an FEL-SR at FELI

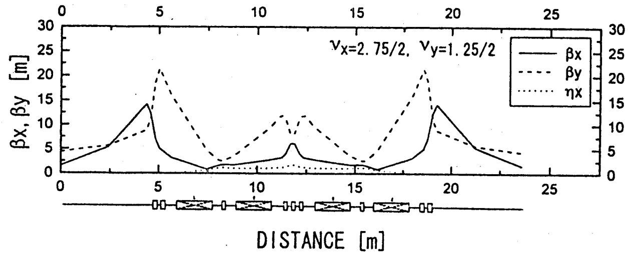

Fig. 4 Machine functions of an FEL-SR

The FEL wave length is given by eq.(2).

$$\lambda = (1+K^2/2)\,\lambda_u\,/2\gamma^2 \qquad (2)$$

Here, λ_u[m] is the period length of the undulator, K=93.4B[T]λ_u[m], where B[T] is the peak value of the undulator magnetic field. The FEL wave length according to the electron beam energy is shown in Fig. 5 with the diffraction limit of eq.(1). Here K is fixed to be $\sqrt{2}$ for simplicity. This value of K makes the small signal gain almost maximum in many cases. Considering that the maximum average FEL out put power is proportional to the synchrotron radiation (so called Renieri's limit)[6] which is proportional to the fourth power of the electron beam energy as eq.(3), the combination of a long period undulator and high energy electron beam is the answer to the demands of high power FEL.

$$P_{max} = (\Delta E/E)_{max} 8.86 \times 10^{-2} E^4 I\,/\rho \qquad (3)$$

Here, $\Delta E/E$ is the energy spread of the ring, I[a] the average current, and ρ[m] the bending radius, respectively. Figure 5 shows that the diffraction limit of $2\pi\varepsilon$ is a very severe restriction to high energy i.e. high output power operation of FEL rings. In this figure, a moderate experimental limit such as $\sqrt{2}\pi\varepsilon$ is also plotted.

The small signal gain of compton regime FEL can be estimated by eq.(4) which uses a trivial arithmetic deformation of the equation presented by Dattoli [7].

$$G_0 = 4.46\times 10^{-3}(K^2/2)\gamma^{-3}[JJ]^2(L_u{}^3/\lambda_u)\cdot c/\{(2\pi f_{RF})(2\pi\,\sigma_x\sigma_y\sigma_z)\}\cdot I\cdot F_f \qquad (4)$$

Here, N_u is the period number of undulator, L_u[m]=$N_u\lambda_u$ [m] is the undulator length, $[JJ]^2=\{J_0(\xi)-J_1(\xi)\}^2$, $\xi=K^2/(4+2K^2)$, f_{RF} is the RF frequency of the accelerating cavity, and $\sigma_x, \sigma_y, \sigma_z$ are horizontal and vertical bunch radius and the half of the bunch length, respectively. The factor $F_f=1/\sqrt{\{(1+w/2\sigma_x)^2+(1+w/2\sigma_y)^2\}}$ is the filling factor [8]. In addition, maximum small signal gain using optical klystron (OK) can be estimated by the following equation [8,9].

$$G_{OK,\,max} = 0.045\ G_0\ /\ \{N_u(\Delta E/E)\} \qquad (5)$$

Using the parameters listed in Table 2, we obtain the small signal gain with various period length according to the electron energy shown in Fig. 6. Here, the undulator length L_u is fixed to be 7 m considering the long straight section of our lattice, and the filling factor is set to be 0.5 which corresponds that the optical waist size coincides with the electron beam diameter, and K is $\sqrt{2}$. This figure shows that the small signal gain is large enough for the small period length of 4 cm, but, for larger period length, the gain decreases due to the decrease of period number. In this case, the use of OK is necessary.

Figures 5 and 6 show that the combination of a small undulator period length and the low electron energy is suitable for the lasing of short wavelength FEL, and the combination of a large period length and the higher electron energy is necessary for high power FELs.

4. Conclusions and discussions

We compared several achromatic lattices and adopted a 45 deg bending, modified DBA lattice as the lattice of a compact, low emittance SR for FEL. We estimated the relations between the electron beam energy, the period length of undulator, FEL wave length, and the small signal gain. Our design needs further revising considering the available space, estimated cost, and application plans.

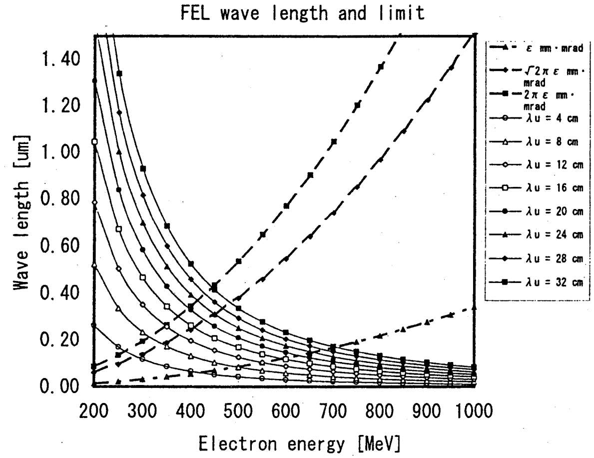

Fig. 5 FEL wavelength (K=$\sqrt{2}$)

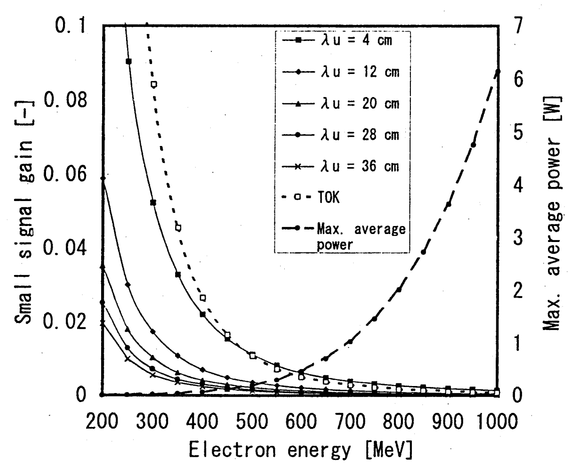

Fig. 6 FEL small signal gain (K=$\sqrt{2}$, F_f=0.5)

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