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CURRENT AND FUTURE OF STORAGE RING BASED LIGHT SOURCES IN KEK

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Abstract

KEK (High Energy Accelerator Research Organization, Tsukuba, Japan) has two storage-ring light sources. One is Photon Factory (PF). This is the first storage-ring light source in X-ray region in Japan, and the user-run started in 1983. The ring energy is 2.5 GeV, and the emittance has been reduced to 36 nmrad from 460 nmrad through some improvements. Another is Photon Factory Advanced Ring (PF-AR). The ring energy is 6.5 GeV, and the single-bunch operation and hard X-ray are featured. The user-run started in 1987, and the emittance is 293 nmrad. The magnetic lattice is almost the same as the original one. Now we consider the future plans of KEK light sources. One is the fully new facility applying DQBA lattice, named KEK-LS. The circumstance is 571 m, and the emittance is 315 pmrad @ 3 GeV and 500 mA. In parallel with that, two plans of the only replacements of the lattices reusing existing tunnels of PF and PF-AR are considered. For the PF upgrade, only the arc lattice will be replaced with a new lattice employing combined bends, and the emittance will be improved to 8 nmrad from 35 nmrad. For the PF-AR update, fully replacement will be carried out with a new HMBA lattice, and the expected emittance is 520 pmrad @ 3 GeV and 500 mA.

PRESENT STATUS

KEK is one of the biggest laboratory in Japan focusing on Accelerator Science, and has not only the high-energy accelerator for the particle experiments but also light sources for the research such as material science and biology. We have two ring-based light source: Photon Factory (PF) and Photon Factory Advanced Ring (PF-AR).

Photon Factory

PF ring began the user operation in 1982 with the horizontal emittance about 460 nm·rad [1,2]. The emittance reduced to about 128 nm·rad by the low emittance configuration in 1986 [3], and about 36 nm·rad by the high-brilliance reconstruction in 1997 [4]. Before the reconstruction in 1997, the normal cell consists of two bending magnets. After the reconstruction, the normal cell consists of only one bending magnet. The number of the quadrupoles, sextupoles and the normal cells were doubled in order to reduce emittance. By the straight sections upgrade in 2005, the lengths of the existing straight sections were extended and new four straight sections for the in-vacuum insertion device were installed. At present, the insertion devices were installed to the all available straight sections.

Photon Factory Advanced Ring

PF-AR is 6.5 GeV light source dedicated to the single bunch operation. The ring originally constructed as an accumulation ring (AR) for TRISTAN project in 1984. Because KEKB, the successor of TRISTAN adopted the full-energy injection from LINAC, AR becomes PF-AR, the full-time synchrotron radiation facility. The circumference of PF-AR is 377 m with four long straight sections. East and west long straight sections are used for RF cavities. North and south straights are originally used for detector development for TRISTAN. Presently, the insertion device is installed in the north straight section and just small accelerator components in south. Because the original injection and extraction systems are installed to the south half of the ring, the experimental hall for SR users are concentrated only in the north half of the ring. The emittance of the present FODO structure lattice is about 300 nmrad for 6.5 GeV that is about two orders of magnitude worse than those of present advanced SR facilities.

FUTURE PLAN

Now we are planning a construction of a fully-new light source called KEK-LS. This is based on the ESRF-type HMBA (Hybrid Multi Bend Achromat) lattice, and promoted to be constructed in KEK Tsukuba campus. Recently, we improved the design reported in the conceptual design report (CDR) in Oct. 2016 to add the two quadrupole magnets to the short straight section. We call this new lattice DQBA (Double Quadruple Bend Achromat) lattice, and it has more flexibility of the lattice design, better emittance and larger dynamic apertures than the CDR design. In parallel with this, the upgrades for the existing facilities of PF and PF-AR are considered. For the PF upgrade, the limited improvement of the arc part to double the bending magnet and introduce the combined bend will be applied. For the PF-AR upgrade, the full-replacement of the lattice will be carried out employing the flexible DQBA KEK-LS lattice. The scales of the budget and the improvements of the emittance are summarized in Table 1. In the following, the each project is explained in detail.

KEK-LS

KEK-LS is a fourth generation 3.0 GeV light source and promoted to be constructed in KEK Tsukuba campus. We start the lattice design from the example lattice of 3 GeV EBS with 20 cells [5, 6]. Then, the short straight section of 1.2 m was added in order to double the number of the insertion device. We reported this design as CDR [7]. The circumference is about 570 m, and the horizontal natural

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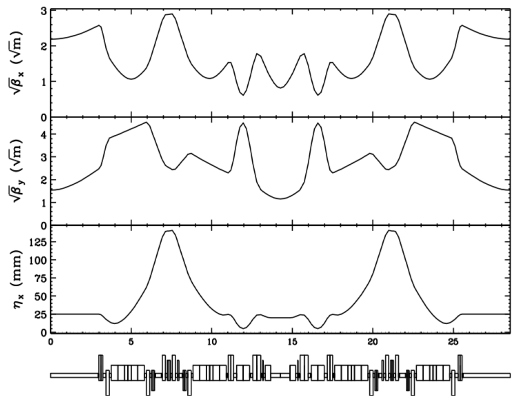
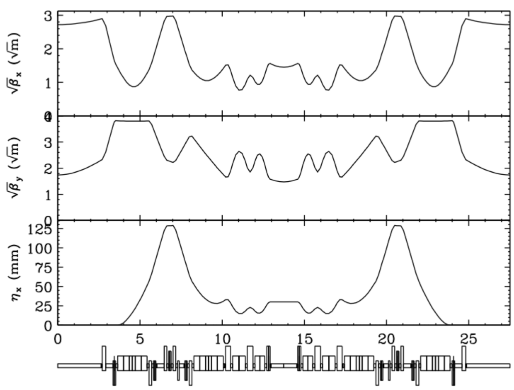
Table 1: Each Budget Scale and Emittance of Ring-Based Future Light Source in KEK

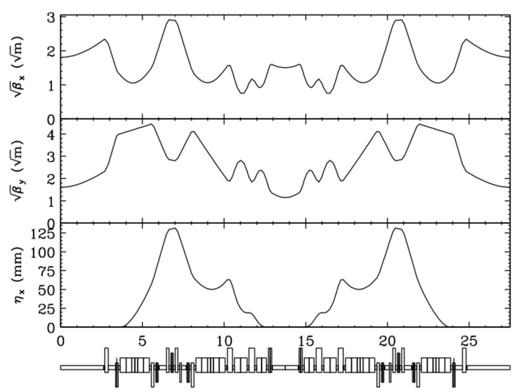
	Rough budget size [million US$]	Current emittance [nm·rad]	Improved emittance [nm·rad]
KEK-LS	300	-	0.315 (CDR ver. with 500 mA)
PF Upgrade	20	35.4	8.073 (with 450 mA)
PF-AR Upgrade	100	295.2	0.520 (with 500 mA)



(a) Present CDR version



(b) 5m section achromat for DQBA



(c) Complete achromat for DQBA

Figure 1: Optics of the normal cell.

Table 2: Parameters of the Ring

	Symbol [Unit]	CDR (a)	New DQBA (b)	(c)
Energy	E [GeV]	3.0		
Cell number	N_s	20		
Circumference	C [m]	570.721		
RF freq.	f_{RF} [MHz]	500.0735096		
Harmonic Number	h	952		
RF voltage	V_{RF} [MV]	2.5		
Beam current	I [mA]	500		
Betatron tune	ν_x	48.58	47.10	
	ν_y	17.62	17.15	
Horizontal emittance (w/o IBS)	[pm·rad]	133	121	253
(effective, 5 m sec., w/o IBS)	[pm·rad]	160		
(effective, short st., w/o IBS)	[pm·rad]	225	204	
(500 mA w/ IBS)	[pm·rad]	315	228	366
Residual dispersion (@ long straight)	[mm]	25	0	0
(@ short straight)	[mm]	20	3	0
Bucket height	$\Delta E/E$ [%]	4.5	4.5	4.0
Energy loss	U_0 [MeV/rev.]	0.30	0.26	0.26
Momentum compaction	α [$\times 10^{-4}$]	2.2	2.4	3.1
Damping time	τ_x [ms]	29.3	21.5	23.4
	τ_y [ms]	38.3	43.1	43.1
	τ_z [ms]	22.6	43.4	37.2
y/x coupling	[%]	2.6	3.5	2.2
Vertical emittance	ε_y [pmrad]	8.2	8.0	8.1
Momentum Aperture	[%]	2.8	4.0	4.0
Horizontal Aperture	[σ_x]	150	200	200
Touschek lifetime	[hour]	2.4	17.0	27.0
Energy spread (0 mA)	σ_E/E [$\times 10^{-4}$]	6.4	7.2	6.7
(500 mA)	σ_E/E [$\times 10^{-4}$]	7.9	9.7	8.5
Bunch length (0 mA)	[mm]	2.7	2.8	2.9
(500 mA)	[mm]	3.3	3.8	3.8

emittance about 133 pm·rad. Since the original example lattice has very small amplitude and momentum dependent tune shifts and results in the large dynamic apertures, the small distortions were accumulated during the lattice studies and the dynamic apertures and lattice flexibility become deteriorated. In order to recover and improve the performance, the two quadrupoles are added to the short straight sections [8]. For this modification, the flexibility of the lattice design, the emittance and the dynamic apertures are improved. The similar lattice was already examined for the DIAMOND II as DTBA [9]. Following this, we call the improved HMBA lattice as DQBA. In this following, we show the shortage of present CDR version lattice and advantage of the DQBA lattice for the KEK-LS.

The parameters of the CDR version lattice is shown in Table 2 and the optics in Figure 1 (a). Firstly, the momentum aperture is about 3 %. For this lifetime, the estimated beam loss is about three times larger than the present PF ring during the hybrid mode (lowest lifetime mode). Though this may be too permissive, the longer lifetime is better. For the second, the insertion device causes the emittance growth [10] because of the low horizontal beta and the residual dispersion at the straight section. While the achromatic long straight section can be realized by about 15 % effective emittance deterioration, the achromat of the short straight section results in the very large emittance. At the short straight section, the residual dispersion is 25 mm and the horizontal beta function 0.66 m. With these parameters, The

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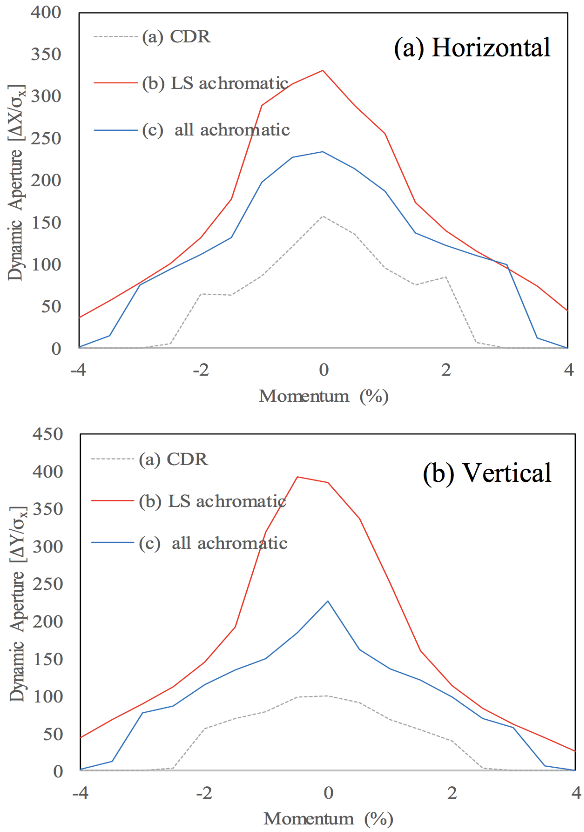

Figure 2: Dynamic aperture for each design of KEK-LS.

short in-vacuum insertion device of 0.6 m length results in the significant emittance growth.

The DQBA option was firstly developed in collaboration with ESRF. It has better emittance and apertures than the CDR version. Figure 1 and Table 2 shows the two cases for DQBA version; the case (b) has the achromatic long straight section with the chromatic short straight section, and for the case (c), both straight sections are completely achromatic. The effective emittance in the Table 2 shows the emittance including the effects of the dispersion function and energy spread. For the case of 500 mA, the effect of intra-beam scattering (IBS) is considered[1]. With larger momentum and horizontal amplitude aperture, the lifetime certainly may be longer for DQBA case than that of CDR case. The dynamic aperture with magnetic errors are shown in Figure 2. The assumed magnetic errors are the Gaussian random magnetic errors of the standard deviation 1 σ for the alignment errors of 50 μm, the magnetic field fluctuation of 0.05 %, and skew rotation of the magnets of 0.1mrad. The results shows the average of 100 random seeds. The systematic magnetic errors like the higher order components of the magnets and the effect of the insertion devices are not included.

[1] Presently, the estimation of Touschek lifetime are very rough, and not calculated by LMA (local momentum acceptance) method. It seems that some important effect is not included and calculated lifetime seems to be too long.

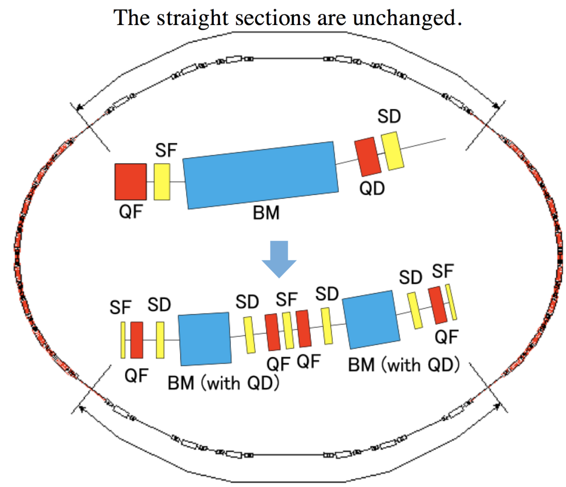

Figure 3: Lattice Modification of PF Upgrade.

For the DQBA cases, the maximum quadrupole magnetic field is about 60 T/m. The minimum magnetic spacing is 12 cm core to core. If we can relax these parameters, it is easier to design the hardware. The precise calculation of lifetime and simulation including more types of errors are required. The quadrupoles are only used to optics change from (b) to (c). The matching of beta function is required to select the optics cell by cell.

PF Upgrade

The present horizontal emittance of the Photon Factory (PF) ring is about 35.4 nm·rad. By the reconstruction of the normal cells at the arc section, the emittance can be reduced to about 8 nm·rad. In this proceedings, the design, optimization and simulation results for the low emittance lattice are shown.

Figure 3 shows the section for the reconstruction. While the straight sections are unchanged, the arcs are reconstructed. Similar to the reconstruction in 1997, the numbers of the normal cells are doubled by replacing the present 1.9 m length bending magnet to the new two short combined function magnets of 0.65 m length. While the horizontal emittance of the present normal cell is about 41 nm·rad, it reduces to 4.6 nm·rad by doubling the cell number. The parameter of the ring is shown in Table 3. Although the chromaticity is not largely increased, the strong chromatic sextupoles by about ten times are required due to the small dispersion function. In order to realize them, the diameter of the magnetic poles of the sextupoles are reduced from 90 mm to about 40 mm.

For the large dynamic aperture, the linear optics of the straight sections are designed to be transparent for the sextupoles. The matching section at the end of the normal cell consists of one bending magnet and no sextupole, and the identical 14 normal cells form the arc section. For the large dynamic aperture, the tune advance of the straight section with the matching sections are adjusted to be integer or the half integer. If the sextupoles are installed to the dispersive

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Table 3: Parameters of the PF Upgrade

	Symbol [Unit]	PF Upgrade
Energy	E [GeV]	2.5
Circumference	C [m]	187.0
Emittance	ε_0 [nm·rad]	8.073
Emittance of Normal Cell	ε_{NC} [nm·rad]	4.561
Energy spread	σ_E/E	1.64×10^{-3}
Momentum compaction	α	4.39×10^{-3}
Betatron tune	ν_x, ν_y	12.1, 6.2
Chromaticity	ξ_x, ξ_y	-17.573, -25.117
Energy loss	U_0 [MeV/rev.]	0.513
Damping time	τ_x, τ_y, τ_z[ms]	3.040, 6.109, 6.171
Revolution freq.	f_{rev} [MHz]	1.60253
RF freq.	f_{RF} [MHz]	500.100
Harmonic Number	h	312
RF voltage	V_{RF} [MV]	1.70
Synchrotron tune	ν_s	-0.009
Bunch length	σ_z [mm]	10.475
Bucket height	$\Delta E/E$ [%]	1.7

section of the long straight section, the total strength of the sextupoles can be largely reduced. The dynamic aperture, however, also largely reduced. Although the error of the tune advance for the transparency is acceptable to some extent, the sextupole component at the long straight sections are unacceptable for the large aperture.

Figure 4 shows the simulated dynamic aperture after the COD correction with the random magnetic errors of the alignment errors of 50 μm, field fluctuation of 0.05 % and rotation of 0.1 mrad. Even with these errors, the dynamic aperture is as wide as that of the present PF ring. At the injection point, the present dynamic aperture is about 24 mm for the ideal case. For the new lattice, β_x is 10.25 m and the horizontal dynamic aperture is about 23 mm with 80 σ aperture. With the worst case of the simulation, it may be about 17 mm with 60 σ aperture. The optics of the straight sections are almost unchanged. The injection scheme and the minimum gap of the in-vacuum undulators can be kept unchanged. The brilliances of the insertion devices are improved by 7-8 times [11].

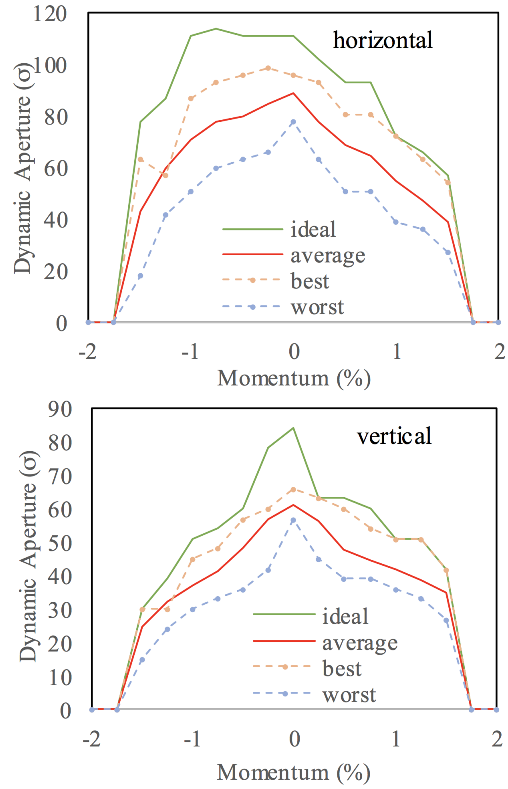

Figure 4: The Dynamic Aperture of PF Upgrade.

PF-AR Upgrade

Photon Factory Advanced Ring (PF-AR) has been operated for users over 30 years from 1987. The lattice and optics are almost not changed from the original one as the TRISTAN booster ring constructed in 1984. The lattice employs FODO structure and the horizontal emittance for the 6.5 GeV user run is about 300 nm·rad. In order to improve the performance of PF-AR dramatically, the full replacement of the accelerator to the ESRF-type HMBA (Hybrid multi bend achromat) lattice is examined. In order to geometrically fit the new lattice to the present PF-AR tunnel, the new ring consists of 12 cells with four long straight sections. The emittance is improved to about 500 pm·rad at 3.0 GeV.

In order to fit the circumference, we determined the cell number 12. We started the design from the ring consisting of the identical 12 normal cells with the circumference of about 330 m and the emittance of about 0.5 nm·rad for 3.0 GeV. We add the short straight section to double the numbers of available insertion devices. In order to fit the ring for the existing accelerator tunnel, we adjusted the length of the straight sections of the symmetrical 12 cells. The required geometrical adjustments are shown in Figure 5.

Assuming the magnetic errors similar to present PF ring as the Gaussian random alignment errors of 50 μm, field fluctuation of 0.05 %, and rotation of 0.1 mrad, the simulated dynamic aperture after COD correction is show in Figure 6. With errors, the momentum aperture is about 3.5 % and

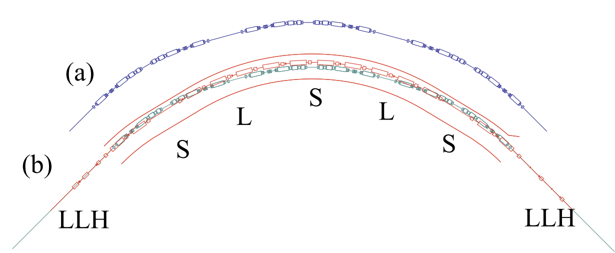

Figure 5: Geometrical adjustment of the long straight section to fit the existing tunnel arc. Figures show the quarter of the ring. The blue figure (a) is the symmetrical ring with twelve identical normal cells for the starting point of the design. The red figure in (b) shows the existing PF-AR lattice of FODO structure and the tunnel wall of the arc section. The green figure shows the new lattice for the replacement. S is the short straight section of 1.68 m, L the arc long straight of 2.7 m. LLH is the very-long straight section that has about 23 m length between two bending magnets at the both sides.

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the horizontal amplitude 150 σ_x. Here, σ_x is the amplitude normalized with the horizontal beam size. The dynamic aperture is large enough to adopt the conventional injection system and the estimated Touschek lifetime is about 5.6 hours. The parameters of PF-AR upgrade are summarized at Table 4.

Table 4: Parameters of the Ring

	Symbol [Unit]	PF-AR Upgrade	
Energy	E [GeV]	3.0	
Cell number	N_s	12	
Circumference	C [m]	374.28	
RF freq.	f_{RF} [MHz]	500	
Harmonic Number	h	544	
Energy loss	U_0 [MeV/rev]	0.4259744	
Momentum compaction	α	5.6715×10^{-4}	
Damping time	τ_x, τ_y, τ_z[ms]	8.365, 17.58, 19.59	
RF voltage	V_{RF} [MV]	2.5	
Bucket height	$\Delta E/E$ [%]	3.58	
Betatron tune	ν_x, ν_y	28.7, 10.2	
Beam current	I_b [mA]	0	500
Horizontal emittance	ε_x [pm·rad]	481.15	520.23
Vertical emittance	ε_y [pm·rad]	-	7.8
y/x coupling	[%]	-	1.5
Touschek lifetime	[hour]	-	5.6
(3.5 % $\sigma_{\Delta p}$, 150 σ_x)			
Energy spread	-	9.79×10^{-4}	1.01×10^{-3}
Bunch length	[mm]	5.21	5.37

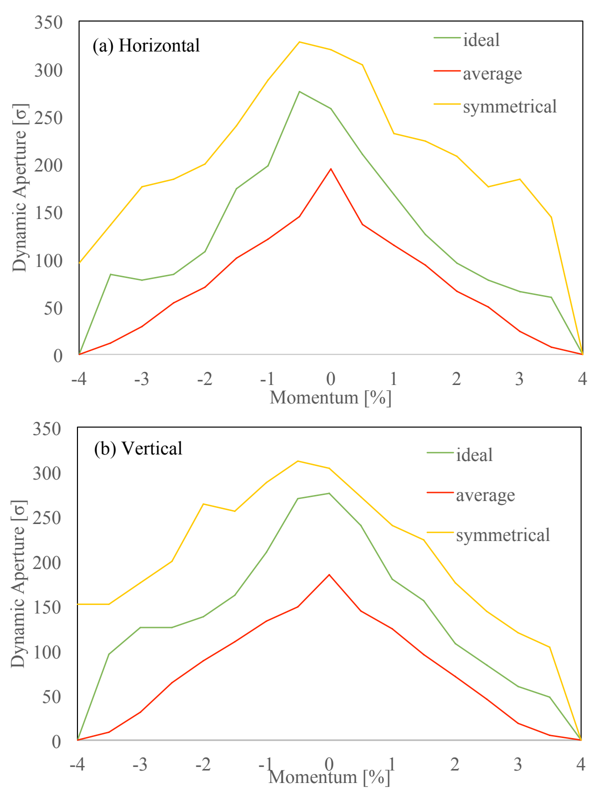

Figure 6: Dynamic aperture with reasonable magnetic errors after COD correction. The line "average" shows the averaged dynamic aperture for 100 random error seeds. The line "ideal" shows the aperture without errors and "symmetrical" for the symmetrical 12 cells case without errors.

SUMMARY

PF and PF-AR have provided user-runs over 30 years. Although some improvements were carried out to reduce the emittance, those international competitive powers are gradually decreasing. HMBA lattice recently appeared is pretty attractive, and we are now promoting a new 4th generation light source of KEK-LS based on the ESRF-type HMBA lattice. This new project is very powerful as an alternative of PF and PF-AR. However, its construction cost are estimated to be 100 million US$ roughly, therefore we are considering other projects with relatively small scale in parallel with KEK-LS project. We will proceed to consider which the best candidate is, comparing the expected qualities and the costs.

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