SECTION XIII

ACCELERATOR APPLICATIONS

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GENERATION OF HIGHLY BRILLIANT RADIATION

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Abstract The Photon Factory ring has been studied on its characteristics and improved to get stable and brilliant synchrotron radiation. During its operation for seven years, the brilliance of synchrotron radiation has been increased by order of two to four depending on the photon energy region. There were many problems to be solved to get highly brilliant synchrotron radiation. This paper describes the causes of problems and the process how to eliminate the causes.

INTRODUCTION

Since later period of 1950, high-energy electron circular accelerators have been used as synchrotron radiation (SR) sources. In the early days of SR utilization, electron synchrotrons were the main source of SR and , then, electron-positron storage rings were coming up to the important SR source because they produced strong and stable SR. During these period, these accelerators were constructed and used only for the high energy physics and the SR users were parasites of these accelerators. Although SR generated from storage rings were enough powerful for the SR usage, the SR light axis moved largely, so that, in the extreme case, a certain user could not get any data for one week. The reason was that high energy physicists always changed energy of the storage ring and wanted to get higher luminosity at the electron-positron colliding section. The operators of the storage ring must inevitably change current of quadrupole- and sextupole-magnets. Because there is no guarantee that the closed orbit goes through the exact centers of quadrupole- and sextupole-magnets, this operation mode gave a certain distortion of the electron closed orbit. This closed orbit distortion does not give any inconvenience to the high energy physics experiments because electron and positron are antimatters to each other so that they can always collide even if the closed orbit is largely shifted from the designed position. This is the reason why many electron storage rings dedicated to the SR usage have been commissioned.

In the beginning of 1970, the energy of the dedicated rings was rather low so that users could use SR in the VUV region. Since 1981, when Daresbury has commissioned the 2 GeV electron ring, other three rings which are dedicated to SR usage in the X-ray region has being commissioned by and by. They are the 2.5 GeV PF ring, the 2.5 GeV

NSLS ring and the 1.8 GeV DCI ring. In such a way, SR users can use SR in any wave length region which are useful for research works of wide fields in the material science.

In the course of research works using SR, many users felt that highly brilliant radiation will able to open new fields of material science. Notifying this fact, accelerator physicists have improved SR rings to get much brilliant radiation by increasing stored current, inserting undulators or wigglers and applying a certain low-emittance lattice to rings. As a whole, the brilliance of SR has been increased with a growth rate of thousand times per ten years. This rapid pace will be continued through remaining twenty century, because SR rings which have ring energy ranging from 6 to 8 GeV and have their horizontal emittances less than 10 nm rad have been constructing or designing.[1,2,3] Furthermore, high energy colliding rings shall be converted to SR dedicated rings reducing ring energy and, inevitable, decreasing their horizontal emittances. Stanford group had tried the 7 GeV operation of PEP and get the horizontal emittance of about 5 nm rad though the stored current was very low.[4] This paper describes the process how the Photon Factory (PF) ring at the National Laboratory for High Energy Physics has been increased the brilliance of SR.

OUTLINE OF PF-RING

The PF ring is a 2.5 GeV electron storage ring dedicated to SR usage.[5] The main parameters of the ring are listed in Table 1. In March, 1982, after four years construction period, the PF ring succeeded in its trial operation. From July of the same year, the user's run started. Until March, 1987, when the lattice of the ring changed to a low-emittance mode, the ring had been operated in the normal-emittance mode with the horizontal emittance of 400 nm rad. During the ring had been operating in the normal-emittance mode, the ring itself had been studied and improved in the following way. In the first year of ring commissioning, fifty percent of the ring operation time was allocated

TABLE 1 Main parameter of the ring

Energy	2.5 GeV	(1.6 GeV to 3 GeV)
Injection	2.5 GeV Linac	(positron/electron)
Stored current	350 mA	(max. 500 mA)
Emittance	130 mm rad (horizontal)	~ 2 nm rad (vertical)
Circumference	187 m	(bending radius 8.66 m)
RF frequency	500 MHz	(harmonic number 312)
Beam lifetime	32 hrs at 200 mA	
SR channels	20 for SR experiment, 3 for beam diagnosis	

to the machine study. The percentage had been reduced year by year and reached to twenty percent in 1986 and this value has been continued until now. All accerelators in KEK must be shutdown every August through September to save electric power and to get back pay from the electricity company for the cooperation of saving electric power in summer time. During these summer shutdowns, the ring has been improved on the base of the machine studies. As the result, the ring has got a longer lifetime, stored higher current and being stable. Details are described in each section.

LOW-EMITTANCE LATTICE

During the summer shutdown in 1986, four quadrupole magnets newly fabricated were installed in the ring at each point where the normal-cell section ends and the insertion section begins. Furthermore, all of the power supplies for quadrupole magnets were reinforced. Table 2 shows parameters of the low-emittance and the normal-emittance mode. Details of the low-emittance lattice was reported in "Photon Factory Activity Report 1987".

TABLE 2 Parameters of the low-and the normal-emittance mode

	normal	low
Betatron number		
horizontal	5.40	8.38
vertical	4.16	3.14
Momentum compaction	0.037	0.015
Chromaticity		
horizontal	-6.8	-15.8
vertical	-4.7	-8.6
Emittance (nm·rad)		
horizontal	404	127
vertical	~ 6	~ 2

The commissioning of the low-emittance mode succeeded on February 3, 1987. The brilliance of SR increased by three to twenty times depending on SR channels compared with that in the normal-emittance mode. However, after three days operation, the low-emittance mode must be stopped and again the ring was operated in the normal mode. It was because that the diurnal drifting motion of the closed orbit in the vertical direction reached 0.6 mm and, in addition, an irregular movement of about 0.1 mm was found. In such a situation, SR users could not take fine data. One month later, the ring was equipped with a feedback system and the users were enjoying bright SR from the low-emittance mode.[6] There still remained a small closed orbit distortion, a new feedback system has been developing. The cause of the movement of the closed orbit will be described in later.

INSERTION DEVICES

The Photon Factory has six insertion devices in the PF ring and one in the 6 GeV Accumulation Ring which is the injector of the 30 GeV electron-positron collider, TRISTAN.[7] Their characteristics are listed in Table 3. The first insertion device is an undulator #2 which was installed in the ring in February, 1983, and the brilliance at the photon energy of the first harmonic, 0.4 KeV, is higher by 1000 times compared with that of bending magnets. The second one is a vertical wiggler which consists of a superconducting magnet with three poles generating the magnetic field strength of 5 T and was installed in July, 1983. This wiggler generates SR having vertically polarized electric field which is very useful for precision experiments and is supplying brilliant X-ray in the energy region of 20 KeV.

After commissioning of the low-emittance mode, it came up to be possible to install a vacuum chamber having a narrow gap in the vertical direction. Then, a multipole wiggler (MPW) which is made of permanent magnets having the magnetic gap of 19 mm and generating the field strength of 1.5 T was installed.[8,9] At the photon energy of 6.2 KeV, this MPW generates highly brilliant SR as is seen in Table 3.

Most interesting insertion device is an EMPW which generates elliptically polarized SR. The EMPW has horizontal- and vertical-magnetic field alternatively, but the each field strength is different so that the electron orbit is a distorted spiral. This distortion

TABLE 3 Insertion devices

The photon energy range, the photon energy of the first harmonic (E_1), the critical energy of bending magnet or wiggler (Ec) and brilliance (B) (photons/S·mm^2·mrad^2·0.1% band width) are calculated values when the stored current is 250 mA for the 2.5 GeV ring (6 devices) and 50 mA for the 6 GeV Accumulation Ring (one device EMPW#NE1)
U: undulator. MPW: multipole wiggler. -W: wiggler region. -U: undulator region, VW: superconducting vertical wiggler. Revolver: four undulators are installed. EMPW: elliptically polarized multipole wiggler. λu: period length. N: number of period. Gz magnetic gap in the vertical direction. Bz: magnetic field strength

Name		λu cm	N	Gz cm	Bz T	Energy range KeV	E_1/Ec KeV	B
Bending Mag.						< 30	4.0	2.1E13
U#02		6.0	60	2.8	0.3	0.4 ~ 3	0.40	3.7E16
MPW#13	-W	18.0	13	2.7	1.5	< 70	6.2	4.4E14
	-U					0.03 ~ 1	0.22	2.0E15
VW#14				5.0	5.0	< 100	20.8	1.6E13
MPW#16	-W	12.0	26	1.9	1.5	< 70	6.2	1.8E15
	-U					0.03 ~ 1	0.33	9.4E15
Revolver		5.0	46	3.0	0.28		0.64	1.3E16
#19		7.2	32		0.41	0.007	0.18	7.3E15
		10.0	23		0.53	~ 1.1	0.044	2.5E15
		16.4	14		0.62		0.007	4.2E14
EMPW	-W	16.0	12	3.0	1.0	< 15	4.2	1.8E14
#28	-U					0.04 ~ 0.35	0.18	4.0E15
EMPW	-W	16.0	21	3.0	1.0	< 100	24	9.1E13
#NE1	-U					0.2 ~ 2	1.1	3.5E15

makes strong components of higher harmonics of SR so that the brilliant circular-polarized SR can be generated in the region of the high photon energy. In October, 1988, the EMPW was installed in the Accumulation Ring and the first experiment was done at the photon energy of 40 KeV.[10]

STORED CURRENT AND BEAM LIFETIME

The average brilliance of SR used by an experiment is proportional to the average stored current and to the net user time. This means that the high initial stored current and the long beam lifetime give the highly brilliant SR to users. The PF ring has a good vacuum pressure of several times 10^{-11} torr when there is no stored current. Then, the vacuum pressure is proportional to the stored current. This gives a simple relation between the stored current (I) and the beam lifetime(τ), that is, $I\tau$ is constant.[11] Figure 1 shows the improvement of the ring about $I\tau$ and now the value is 6.5 ampere-hours. The maximum

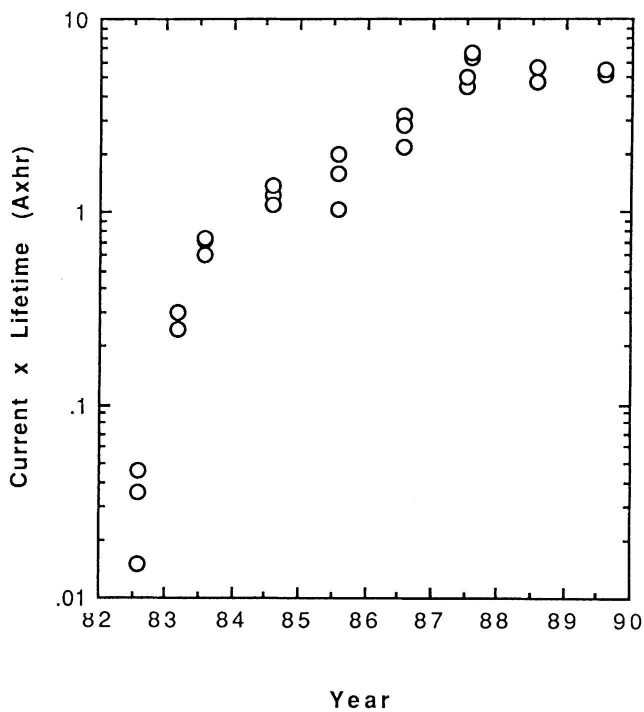

FIGURE 1 The progress of the beam lifetime. When the base pressure of ring vacuum is good, the product of the stored current and the beam lifetime has a constant value depending on the status of the vacuum chamber wall.

initial current is 500 mA, but in such a high current, the beam size becomes larger and the brilliance is saturated. So, in the normal operation, the initial current is limited to 350 mA. With this value and the injection twice a day, the average current is now over 200 mA as is seen in Figure 2.

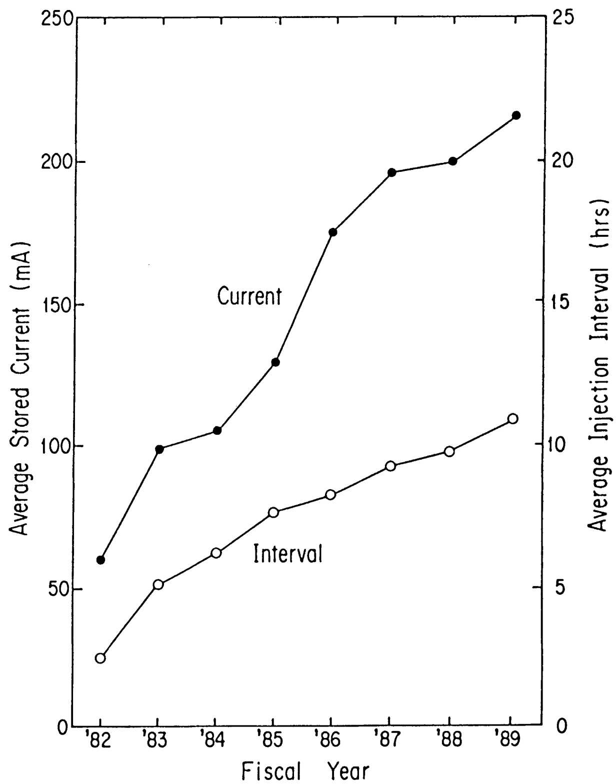

FIGURE 2 Average stored current in the user time through one year and average interval of injection

BEAM INSTABILITY IN THE LOW-EMITTANCE MODE

In the operation using the normal-emittance lattice, many beam instabilities were observed. They are: two-beam instability caused by ions which are generated by ionization of residual gases collided by electrons and trapped in the electron beam . Head-Tail instability caused by the minus value of the natural chromaticity. Two horizontal coupled-bunch instabilities caused by higher order mode resonances of RF cavities, 830 MHz and 1070 MHz. The longitudinal coupled-bunch instability caused by 758 MHz resonance of cavities. They were cured by using sextupole- and octupole-magnets, controlling temperature of cavity cooling water, remaining one-third of RF buckets empty. Details are described in "Photon Factory Activity Report. No.1 ~ No.6".

When the lattice was changed to the low-emittance mode, again the longitudinal coupled-bunch instability appeared. There is no beam loss, but this instability gives the density modulation to bunched beams with the frequency of about 200 Hz and the increment of the beam size at high stored current. In the normal-emittance mode, this instability was suppressed by inserting damping-couplers into each cavity. It was suggested that in the low-emittance mode the Landau damping caused by the non-linear phase oscillation is not effective in the low-emittance mode. Then, the damping-couplers were taken off from cavities and the ports from which the couplers were inserted were covered with blank flanges. Adjusting the length of each flange, which was inserted in each cavity, the longitudinal coupled-bunch instability was completely eliminated.[12]

CLOSED ORBIT DISTORTION

In the low-emittance mode, it was found that the closed orbit distortion caused by misalignment of magnets became more sensitive than that in the normal-emittance mode. Users worried about the large shift of the SR axis in the vertical direction because the diurnal shift was reached 1 mm at the point 12 m apart from the SR source point. The cause of this shift was investigated by measuring the outdoor temperature and weather in the relationship with the drifting motion of the SR axis. It was found that expansion and shrinkage of the roof of the Light Source Building give distortions to the floor of the building and make misalignments of the ring magnets and of experimental apparatus. This cause was also confirmed by the computer simulation done by Shimizu Kensetsu, a building company. Why such a rigid

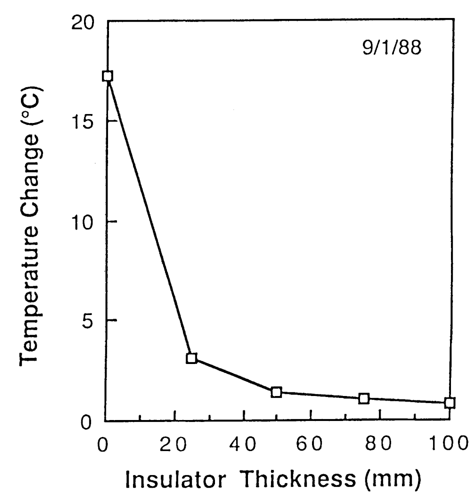

FIGURE 3 The diurnal change of the average temperature of the building roof when the roof was covered with insulators made of urethane foam.

building was designed. It was thought that there are many ground vibrations generated by heavy cars moving around the building and these vibrations propagate to the floor of the building to make a vibrating SR axis if the rigid massive building does not absorb vibrations as a whole.

To stabilize the building, an interesting experiment was done. Two meter square thermal-insulators made of urethane foam with various thickness were put on the roof of the building and the diurnal change of the average temperature of the roof under the insulators was measured. The result is shown in Figure 3 and it was concluded that 50

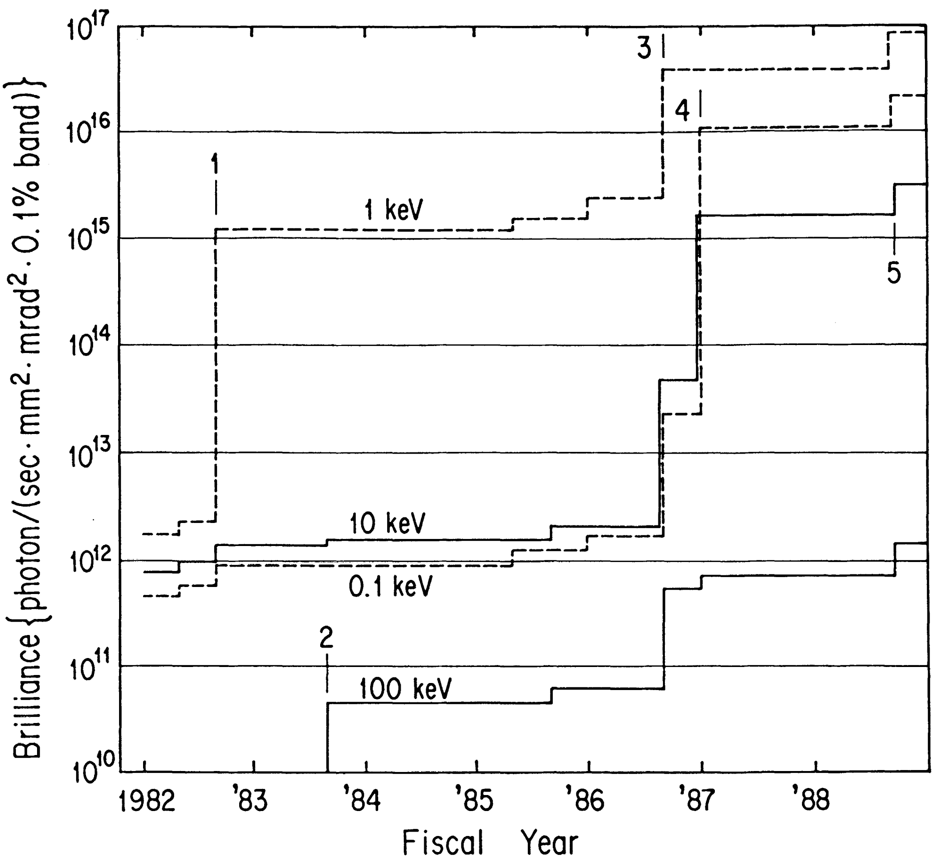

FIGURE 4 The progress of the brilliance of SR generated from the PF ring in each photon-energy region. Numbers in the figure mean: 1, The undulator U#2 was installed. 2, The superconducting vertical wiggler was commissioned. 3, The ring lattice was changed into the low-emittance mode. 4, The multipole wiggler MPW#16 was installed. 5, The initial stored current reached to 500 mA from 350 mA.

mm urethane foam is enough to stabilize the temperature of the roof. The whole roof of the building will be convered with 50 mm urethane foam in the end of this year.

CONCLUDING REMARK

The PF ring has been continuously improved to get brilliant and stable SR as can be seen in Figure 4. The SR brilliance has been increased by order of two to four depending the photon energy region for seven years. However there were many problems to be solved to get highly brilliant SR. Next generation rings dedicated to SR aim to generate much more brilliant SR. The experience at the PF ring seems to be contributed for the successful constructions of coming rings.

The author would like to express his thanks to the PF ring crew. They had constructed the ring and have brought-up the ring with their restless activities.

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