# STATUS REPORT ON THE KEK PHOTON FACTORY

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*Abstract*

Two synchrotron light sources, the 2.5-GeV Photon Factory (PF) storage ring and the 6.5-GeV PF-AR, are working at the High Energy Accelerator Research Organization (KEK). We first describe the PF storage ring on its present system, operations and the beam performance. We then report the current status of the PF-AR and a future plan of the Photon Factory.

## 1 INTRODUCTION

The Photon Factory storage ring[1] is a 2.5-GeV electron storage ring, which has been working since 1982 as one of the leading synchrotron light sources. An original beam emittance of 460 nm·rad was reduced to 130 nm·rad by optimizing the beam optics in 1987. The ring lattice was largely reconstructed in 1997 to the present one[2-6], which allowed us to achieve a lower emittance of about 30-36 nm·rad. Much hardware and software were replaced together. As a result, both the stability of the synchrotron radiation (SR) and the reliability of the machine have been improved greatly.

A picture of the PF storage ring is shown in Fig. 1. The present layout is shown in Fig. 2. There have been constructed 22 SR beamlines with more than 60 experimental stations. Six insertion devices have been installed in the ring. The PF storage ring is mainly operated with multiple (typically, 280) electron bunches. The beam current during routine operations ranges from 450 to 300 mA. The beam lifetime is about 48 hours at a beam current of 430 mA. The principal parameters of the ring are given in Table 1.

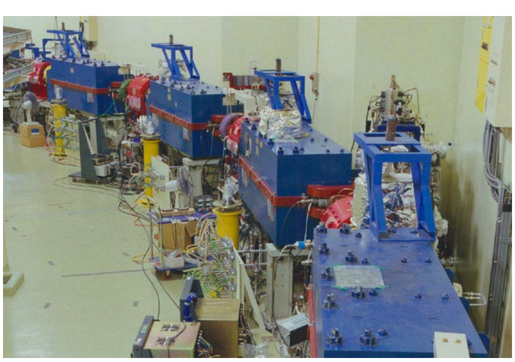

Figure 1: The Photon Factory storage ring.

The other 6.5-GeV light source, the PF-AR[1], was originally called the TRISTAN AR (Accumulator Ring), since it was mainly used for a booster for the TRISTAN $e^+e^-$ collider. Parasitic usage of synchrotron radiation started in 1986. Along with a construction of the KEK B-factory, the AR was converted to a dedicated light source in 1998, and it was renamed to the "PF Advanced Ring for pulse X-rays (PF-AR)".

The PF-AR has been operated at beam energies of 6.5-5.0 GeV. The ring always stores a single-bunch beam of

Table 1: Principal parameters of the PF storage ring.

| | |
|---|---|
| Nominal beam energy | 2.5 GeV |
| Circumference | 187.03 m |
| Natural beam emittance[1)] | 36 nm·rad |
| Betatron tune ($\nu_x$, $\nu_y$) | (9.60, 4.28) |
| RF frequency | 500.1 MHz |
| Harmonic number | 312 |
| Synchrotron tune | 0.014 |

1) Phase advance per FODO-cell: 105 degrees.

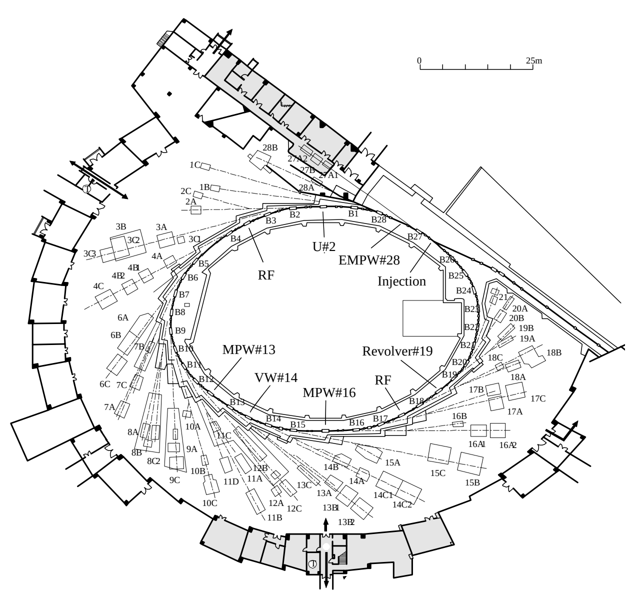


Figure 2: Layout of the Photon Factory storage ring.

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about 40 mA (at maximum), providing unique pulse X-rays for such research as the time-resolved X-ray experiments. In order to achieve longer lifetime and higher beam currents, an upgrading program[7] of the PF-AR started in March, 2001.

## 2 PF STORAGE RING

The PF storage ring is made up of normal FODO-cells and some straight sections. In order to reduce the beam emittance, each FODO-cell was reconstructed to two FODO-cells in 1997. This was carried out by replacing old quadrupole and sextupole magnets in the above sections to thinner and stronger ones, and by installing additional quadrupoles and sextupoles. As a result, a beam emittance of about 30 nm·rad has been achieved, which is about 23% of the one before the reconstruction. The PF storage ring is currently operated at a moderately small emittance of 36 nm·rad under a 105-degrees[b] optics due to such advantages as a large dynamic aperture.

Vacuum ducts in the normal-cell sections, together with some other ones, were replaced in 1997. Ten beamline front ends (for BL-6, 7, 8, 9, 10, 11, 12, 19, 20, and 21) were also upgraded during 1994-1996. The upgraded front-ends[3] can handle higher heat loads from a beam current of up to 1 A.

The following insertion devices have been installed: (i) 60-period long undulator; (ii) 4-way multi-undulator; (iii) 26-period multipole wiggler; (iv) 13-period multipole wiggler; (v) elliptically polarized multipole-wiggler; and (vi) 5-Tesla super-conducting vertical wiggler. Figure 3 shows a summary of the SR spectra, including those from the above insertion devices.

Full energy (2.5 GeV) electron beams are injected from the linac at a repetition frequency of 25 Hz. The kicker magnets for beam injection, as well as their power supplies, were replaced at the beginning of 2000. The new traveling-wave kicker magnets[8] can produce shorter magnetic pulses (pulse width: ~1.3 μs), which is useful to obtain wide acceptance for injected beams. Typical beam-filling rate is 0.8-1.2 mA/s using the above system.

Four damped accelerating cavities[9] produce a total rf-voltage of 1.7 MV. These cavities were developed by collaborating with the University of Tokyo, and were installed during 1997-1998. Harmful higher-order modes can be damped by using microwave absorbers (made of Silicon-Carbide), which were attached in a copper beam pipe.

There are 65 beam position monitors (BPMs) in the ring. We constructed an integrated system for the beam-position measurement and for the global orbit feedback. The vertical beam variations are also monitored with 12 photon beam-position monitors at the beamline front ends.

Both hardware and software for the ring control were fully renewed during 1997-1999. The new system comprises an UNIX server, personal computers or VME-systems for equipment control, and graphical user-interface servers, which are connected through a fast ATM network.

## 3 OPERATION AND PERFORMANCE OF THE PF STORAGE RING

### *3.1 Operation statistics*

A summary of the past operation time is shown in Fig. 4. During last fiscal year (from April, 2000 to March, 2001), the ring was operated for 5464 hours. The scheduled and the net user-times were 4632 and 4455 hours, respectively. Because much effort has been made to improve the reliability, the failure time could be limited to about 1.5% of the total time.

About 8% of the beam time was allocated to a single-bunch operation. About 7% of the beam time was operated at higher energy (3 GeV) and lower beam currents (initially 200 mA).

Figure 5 shows the records of the average beam current and the average duration of one user run. Thanks to the long lifetime, both the high average current and the long duration have been achieved.

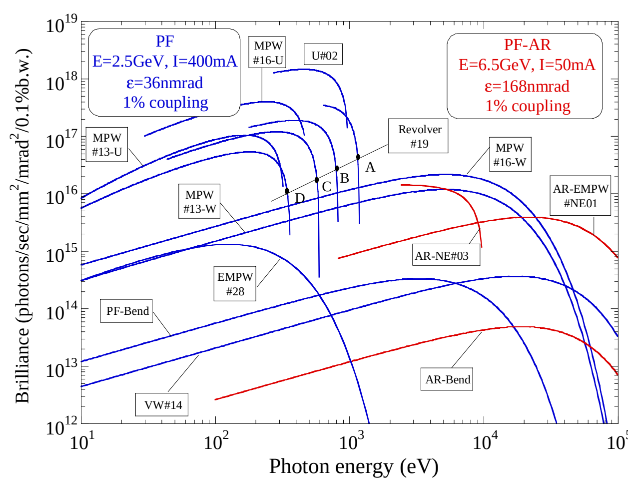


Figure 3: Brilliance of the synchrotron radiation[1].

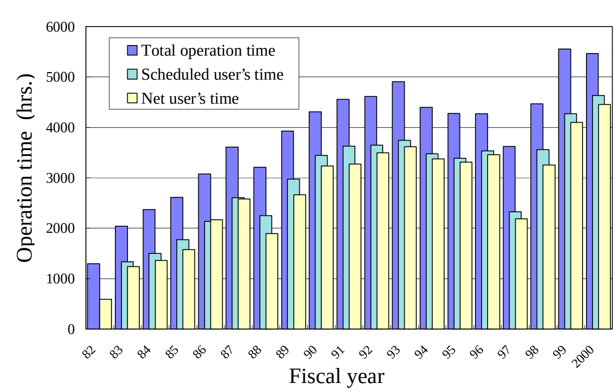


Figure 4: Summary of the operation time of the PF storage ring.

[b] Phase advance per normal FODO cell.

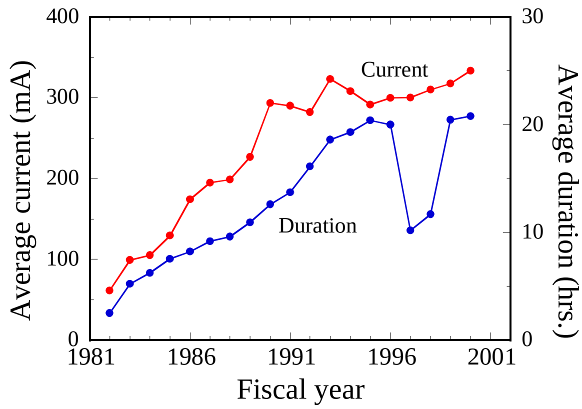


Figure 5: Average beam current (during multibunch user runs) and average duration of one user run.

## 3.2 *Beam emittance and coupling correction*

After the lattice reconstruction, we confirmed the reduction in the beam emittance. In the first measurement [10], a horizontal beam size was measured using a beam-profile monitor with adaptive optics system. Under a 125-degrees optics, the measured beam size agreed well with the one, which was estimated from a design emittance of about 30 nm·rad.

In the second measurement[11], both the horizontal and the vertical beam sizes were measured using an SR interferometer. Under the routine 105-degrees optics, the measured horizontal beam size agreed with the estimated one from a design emittance of about 36 nm·rad. An x-y coupling coefficient was estimated to be about 1.3%.

In order to reduce the vertical beam size further, we corrected the x-y coupling using many skew-quadrupoles [12]. The strengths of these quadrupoles were determined so as to minimize the vertical closed-orbit distortion (COD), which was produced by every horizontal kick. As a result, the vertical beam size would be reduced to about 60% of the uncorrected one. This correction has been used since January, 1999.

## 3.3 *Beam lifetime*

After the low-emittance operation started, the limitation of the beam lifetime due to the Touschek effect became very important. An estimated Touschek lifetime under multibunch operation was comparable to, or shorter than, the beam-gas scattering lifetime. In order to improve the Touschek lifetime, we modulated an rf phase at a frequency of two-times the synchrotron frequency, and induced a longitudinal quadrupole-mode oscillation of the bunches[13]. Using this method, the lifetime was improved by a factor of about two. Note that the similar method was originally applied to such a purpose in ASTRID[14] and BESSY[15].

Figure 6 shows the typical beam current and the beam lifetime during two days. In this example, we re-filled the beam at 9:00 a.m.; after one day, we still had a beam of about 300 mA. The beam lifetime ranged from 45 hours (at 450 mA) to 70 hours (at 300 mA). Thanks to this long lifetime, we need to inject beams only once a day, which is very fine for users to minimize a disturbance. Note that low vacuum pressures also contributed to the long lifetime; an average pressure was about $1.7\times10^{-8}$ Pa at 430 mA.

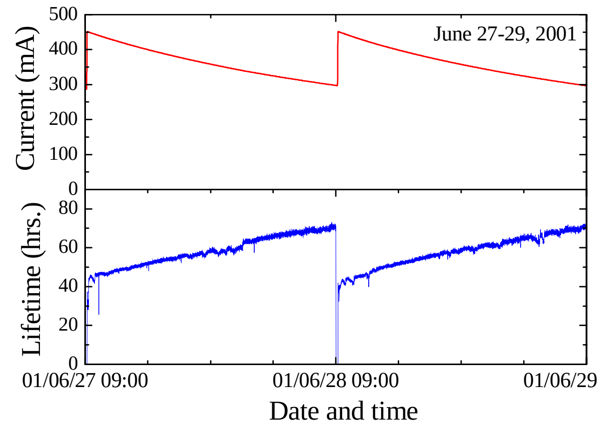


Figure 6: Beam current and beam lifetime during two days.

## 3.4 *Orbit stabilization*

In order to stabilize the vertical beam positions during user runs, the global feedback system[16] is used. This system can measure the closed-orbit distortion (COD) in every 12 ms. Using 28 fast-response correctors, we can correct the vertical beam-position variations at frequencies of up to 0.3 Hz. Routine COD correction after every injection is carried out using separate powerful correctors. An effect of the feedback is demonstrated in Fig. 7. In this example, the vertical orbit drifted more than 100 μm (at maximum) without the feedback, while it remained within a few tens of microns using the feedback.

Another rf-frequency feedback is used to stabilize the horizontal orbit. We change the rf frequency in every minute so as to keep an average horizontal position.

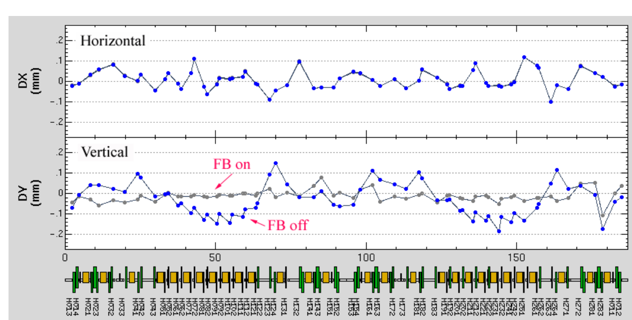


Figure 7: Beam positions with and without the feedback, which were taken 24 hours after the last COD correction.

## 3.5 *Beam instabilities*

Because the damped cavities worked finely, no cavity-induced beam instabilities have been observed during user runs. However, a longitudinal coupled-bunch instability begins to arise at about 20 mA, which should be due to many cavity-like structures in the ring. We found that the phase modulation is also very effective to suppress this longitudinal instability, and are using this method routinely. No transverse coupled-bunch instabilities have been observed during user runs.

In spite of very-low pressures achieved, a vertical instability due to ion trapping arises under some conditions. This instability can be avoided completely by a partial filling (280 bunches among 312 buckets) and by exciting four octupole magnets with a strength ($=B'''l/B\rho$) of -390 $m^{-3}$ each.

### *3.6 Single-bunch operation*

Initial beam current of 70 mA was injected about three times a day. In order to elongate the Touschek lifetime, the x-y coupling was deliberately enlarged. For the pulse SR usage, single-bunch purity is very important. We have been using a selective rf-knockout method[17], by which we could kept the single-bunch purity to be better than $1\times10^{-6}$ during user runs.

### *3.7 Machine study*

Other than starting-up and tuning of the ring, much time has been devoted for accelerator study, for example: (i) investigation of the lower-emittance optics; (ii) study on the longitudinal and transverse quadrupole-mode oscillations[18]; (iii) experimental study on the dynamic aperture[19]; (iv) measurement of a bunch-by-bunch tune difference which was induced by trapped ions[20]; (v) beam-based measurement of alignment errors[21]; (vi) development of new optical beam-monitors[22]; and so on. Such research would produce steady improvement in the machine performance.

## 4 PF-AR

### *4.1 Operations*

The PF-AR has been operated with single electron bunch at beam energies of 6.5-5 GeV, where the 5-GeV operation was arranged for medical applications. The principal parameters of the PF-AR are shown in Table 3. High beam energy and full-time single-bunch operation characterize the PF-AR. There are two beamlines from the insertion devices and the other two from the bending magnets. One of the insertion devices is the first in-vacuum undulator[23] while the other is an elliptically-polarized multipole wiggler[24].

During constructing the KEK B-factory, the PF-AR was shut down from January, 1997 to February, 1998. The PF-AR was recently operated for 4148 hours (in f.y. 1999) and 3699 hours (in f.y. 2000). The beam lifetime was relatively short; about 3 hours at a beam current of 40 mA. To maintain an average current, beams were injected about ten times a day.

Table 3: Principal parameters of the PF-AR.

| | |
|---|---|
| Beam energy for SR usage | 5 - 6.5 GeV |
| Injection energy | 2.5 GeV |
| Circumference | 377.26 m |
| Betatron tune ($\nu_x$, $\nu_y$) | (10.15, 10.23) |
| Beam emittance (at 6.5 GeV) | 294 nm·rad |
| RF frequency | 508.58 MHz |
| Harmonic number | 640 |
| Energy loss per turn | 6.66 MeV |
| Initial current | 40 mA |

### *4.2 Reconstruction status*

Because the PF-AR was not originally designed for the dedicated light source and that much hardware became too old, there have been some problems such as: (i) short lifetime, (ii) less reliability of hardware, (iii) low beam currents, and (iv) a small number of beamlines. In order to improve the above issues, an upgrade program was approved by the government. The budget included about 1.66 billion yen (in f.y. 1999) for upgrading the machine, and about 1.19 billion yen (in f.y. 2000) for constructing a new experimental hall and beamlines. Figure 8 shows a plan view of the PF-AR. Both the ring and the halls are housed under the ground. New north-west experimental hall, two beamlines (NW-2 and NW-12), and a new tapered undulator[25] for the XAFS experiments are under construction.

This program includes the following machine improvements: (i) replacement of the vacuum chambers and pumps; (ii) renewal of some quadrupole and sextupole magnets and installation of new correction magnets; (iii) upgrade in the BPM system; (iv) renewal of the control system to the EPICS-based one; and many other works. The goal of the above upgrade is to obtain a

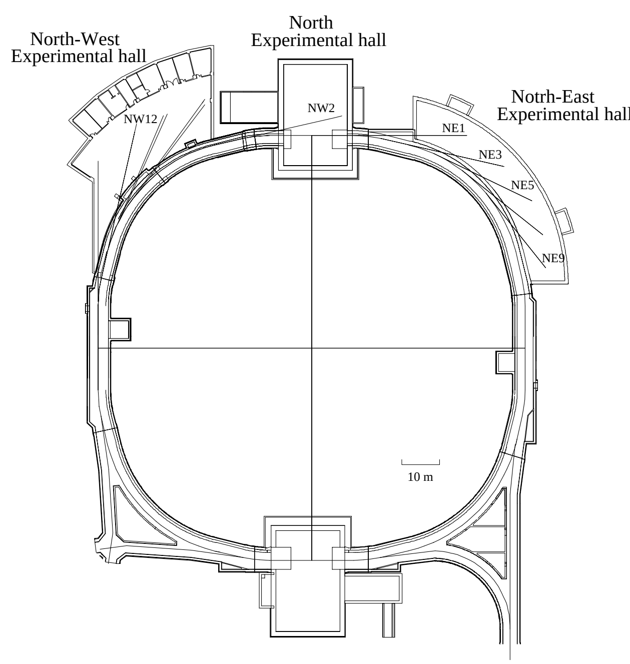


Figure 8: Ground plan of the PF-AR[26].

beam lifetime of more than 10 hours, a beam current of 70-100 mA, and to make the machine reliable. We also plan to reduce the emittance by increasing the phase advance in the normal cells. These reconstruction works are under way during a present shutdown from March to December, 2001.

## 5 FUTURE PLAN

We have made a new upgrade plan[27] for the PF storage ring. This plan aims at making more available space for the insertion devices by reconstructing all straight sections. To this end, the quadrupole magnets in the straight sections will be replaced to thinner and stronger ones, and then, will be moved towards the bending magnets as close as possible. This will result in the following benefits: (i) four 1.5-m sections will be newly produced; (ii) two long-straight sections will be extended from 5 to 9.2 m; and (iii) eight middle-straight sections will be extended from 3.5 to 5-5.7 m.

The beam optics after this upgrade is shown in Fig. 9. The new optics was optimized so as to make the dispersion and the betatron functions as small as possible. The vertical beta-function at the new 1.5-m sections was squeezed to about 1 m, which is compatible with mini-pole undulators. By using the mini-pole undulator[27] under design, it is possible to produce X-ray of 10-keV region. The beam emittance will be reduced from 36 to 27.5 nm·rad under the same phase advance in the normal-cells.

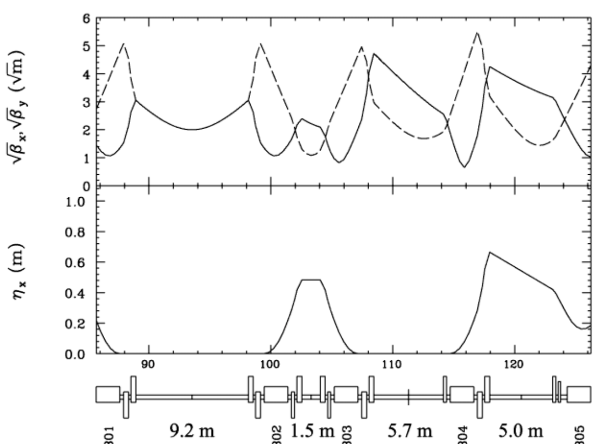


Figure 9: Beam optics in the straight sections after the upgrade.

## 6 CONCLUSIONS

After the upgrade to the low-emittance lattice in 1997, high brilliance, good reliability and excellent stability have been achieved in the 2.5-GeV PF storage ring. A further upgrade plan, which aims at making more space for the insertion devices, is under proposal. The other 6.5-GeV PF-AR is under reconstruction, which aims at longer lifetime, higher currents and better reliability. The recommissioning of the PF-AR is scheduled in January, 2002.

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## REFERENCES

[1] Photon Factory Activity Report 1999, KEK.
[2] M. Katoh and Y. Hori (ed.), KEK Report 92-20 (1993) [in Japanese].
[3] Photon Factory Activity Report 1995, KEK, p. A-4.
[4] M. Katoh *et al.*, J. Synchrotron Rad. **5**, 366 (1998).
[5] M. Katoh *et al.*, APAC'98, p. 271.
[6] M. Katoh *et al.*, EPAC'98, p. 590.
[7] "Design Report on Advanced Ring for Pulse X-rays (PF-AR)", KEK Report 97-2 (1997) [in Japanese].
[8] A. Ueda *et al.*, presented in the PAC'2001.
[9] M. Izawa *et al.*, J. Synchrotron Rad. **5**, 369 (1998).
[10] T. Mitsuhashi *et al.*, APAC'98, p. 698.
[11] M. Katoh and T. Mitsuhashi, PAC'99, p. 2307.
[12] M. Katoh and T. Mitsuhashi, in Proc. of the 12th Symposium on Accelerator Science and Technology, Wako, 1999, p. 403; KEK Preprint 99-79.
[13] S. Sakanaka *et al.*, Phys. Rev. ST Accel. Beams **3**, 050701 (2000).
[14] Yu. Senichev *et al.*, EPAC'98, p. 1339.
[15] P. Kuske, EPAC'98, p. 1297.
[16] T. Obina *et al.*, EPAC'98, p. 1726.
[17] T. Obina *et al.*, PAC'99, p. 2310.
[18] S. Sakanaka *et al.*, presented in the PAC'2001.
[19] Y. Kobayashi and K. Haga, EPAC'2000, p. 1048.
[20] A. Mochihashi *et al.*, Phys. Rev. ST Accel. Beams **4**, 022802 (2001).
[21] T. Honda *et al.*, presented in the PAC'2001.
[22] T. Mitsuhashi, to be published in the *Proc. of DIPAC*, Grenoble, 2001.
[23] S. Yamamoto *et al.*, Rev. Sci. Instrum. **63**, 400 (1992).
[24] S. Yamamoto *et al.*, Phys. Rev. Lett. **62**, 2672 (1989).
[25] S. Yamamoto *et al.*, in preparation.
[26] H. Kawata, Photon Factory News, Vol. 18, No. 4, 2001, p. 9 [in Japanese].
[27] Y. Kobayashi and S. Yamamoto, to be published in the Proc. of SSILS, Shanghai, 2001.