1 Future Plan of the Photon Factory

1-1 Future Roles of the Photon Factory

We expect that the Photon Factory can maintain its competitive edge as a first rate research facility over the coming 5 ~ 10 years by continued upgrades, such as the modification of the straight sections at the 2.5-GeV PF ring and the development of unique activities utilizing the dedicated single-bunch operation at the 6.5-GeV PF-AR. Nevertheless, the renewal of the light source will become an inevitable necessity in the following decade since the concept, design and hardware of the 2.5- and 6.5-GeV rings cannot but become obsolete and less competitive, after 30 years of operation. We have started discussing with users and accelerator scientists all over Japan the necessity to build a new light source at the Photon Factory. We recognize that the new facility should satisfy two-fold roles as shown in Fig. 1.

One role is that the Photon Factory should have the most advanced experimental facility to offer users the opportunities to carry out the foremost cutting-edge experiments requiring ultimate performance of the light source and the beamlines. To enable those demanding experiments in the future, the ability to provide sub-picosecond X-ray pulses and spatially coherent X-ray beams would be very important. With the present PF-AR, we have so far accomplished time-resolved experiments with 100-ps time resolution to investigate some interesting phenomena in non-equilibrium states of materials. We now recognize some very intriguing photo-induced phase transitions in materials, which are supposed to change the structures within 1 ps. Therefore, sub-picosecond X-ray pulses are now required to understand the electronic and structural changes in atomic scales in these materials. Spatially coherent X-rays are necessary to enable several new experimental techniques including coherent X-ray imaging to investigate the structure of non-crystalline materials. In particular, X-ray photon-correlation spectroscopy using the so-called dynamical speckle patterns can be employed to investigate the fluctuation of domain formations and within domains in materials.

The other role is that we should also have the capabilities to provide abundant support for a large variety of user needs in scientific as well as industrial disciplines with the state-of-the-art experimental instruments and beamlines under user friendly conditions. For example, the focused beam size at the sample position should be of the order of several tens of nm for pursuit of nanoscale structural analyses in extreme conditions such

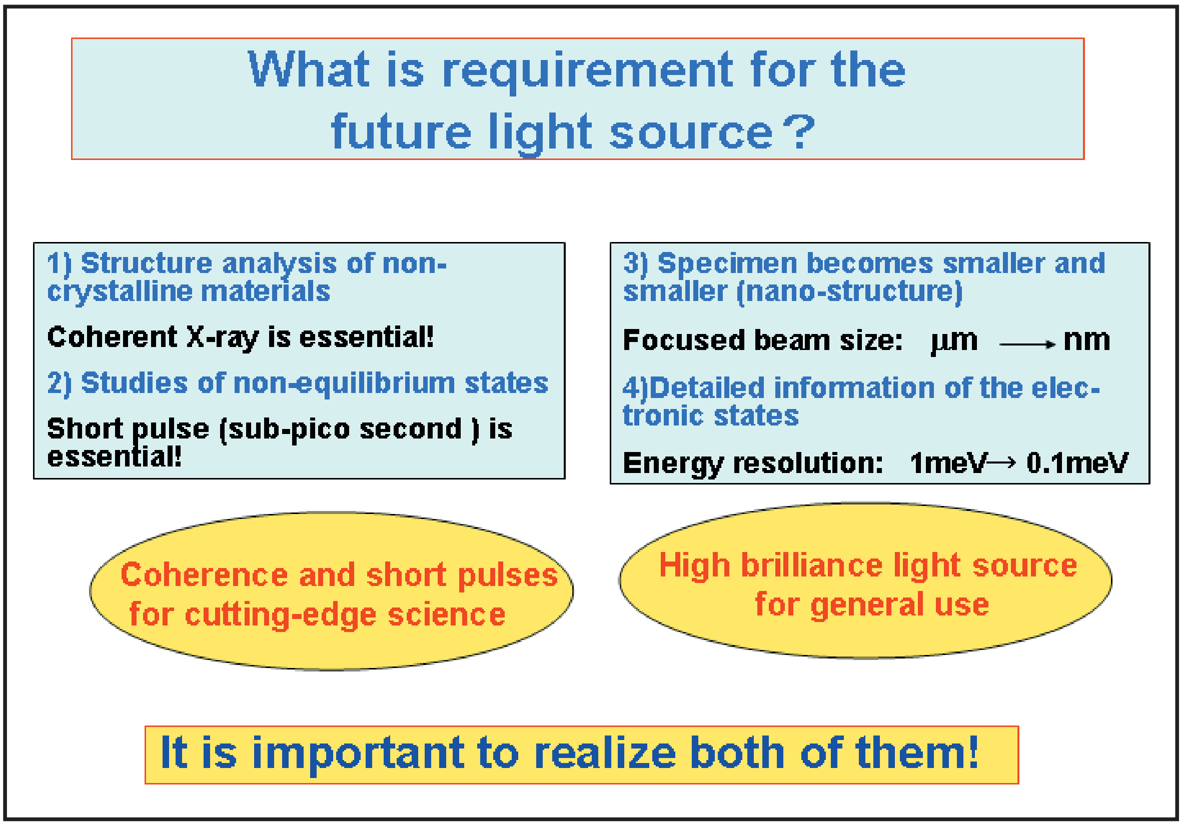

Figure 1
Roles which are needed for the future light source at PF.

Table 1 Desirable specifications for synchrotron radiation emitted from the future light source.

Energy Region	30 eV - 30 keV
Brilliance @ 1 - 10 keV	10^{21} - 10^{23}
	(/s/mrad^2/mm^2/0.1%b.w.)
Coherent Fraction	10 - 20%
Pulse Width	0.1 - 1 ps

as ultra-high pressure. The energy resolution should also be higher than that available at present to investigate fine electronic local structures in materials. To realize such goals, the new light source must produce synchrotron radiation much more brilliant than those of 3rd-generation light sources, and be equipped with a sufficient number of insertion-device beamlines.

The desirable specifications for the synchrotron radiation from the new light source at the Photon Factory are summarized in Table 1. A broad photon-energy region from 30 eV to 30 keV has to be covered by more than 30 insertion-device beamlines to support a large variety of user needs. The brilliance should be about 10^{21}~10^{23} photons/s/mrad^2/mm^2/0.1%b.w. at 1~10 keV. The temporal length of the photon pulses should be of the order of 0.1~1 ps. The coherent fraction in the X-ray region (~10 keV) should be of the order of 10~20%. To achieve such a high coherent fraction, the emittance of the electron beam of the new light source should be equal to or less than the intrinsic emittance of the X-ray photon beam itself which is approximately $\lambda/4\pi$ ~ 10 pmrad. Such a low emittance and short pulse length cannot be achieved by storage rings that operate at equilibrium.

1-2 The Choice of Energy Recovery Linac as the Next-Generation Light Source at the Photon Factory

After a series of internal discussions, we came to the conclusion that the energy recovery linac (ERL) with 5-GeV acceleration energy should be the most suitable candidate to fulfill the above-mentioned specifications, and decided to aim at its realization as the next-generation synchrotron-radiation source. The horizontal emittance and pulse length of the electron beam in linac-based light sources can be improved beyond the limitation in storage rings, by optimizing the performance of the electron gun.

Through our preliminary investigations, the performance of the ERL has been estimated as shown in Figs. 2-4. Figure 2 shows the estimated average brilliance spectra expected from undulators of various period and total lengths on the ERL, that are operated with the parameters summarized in Table 2. Please note that the horizontal emittance of the electron beam is equal to the vertical emittance in ERLs. The brilliance in the X-ray region can be almost 1~2 orders-of-magnitude higher than those of the present-day 3rd-generation storage rings. As shown in Fig. 3, the coherent fraction from a 5-m undulator (λ_u = 16 mm, N = 312) on the 5-GeV ERL is estimated to be higher than 10% at around 10 keV [1]. As a result, the coherent flux from the PF-ERL will be 2 orders higher than the currently available 25-m undulator at SPring-8, as shown in Fig. 4.

These features are compatible with the required specifications listed in Table 1, except for the difficulty to obtain a wide energy-range coverage from VUV to X-rays. As we mention later, it will be necessary to construct a prototype ERL, with an energy of 100~300 MeV, and make progress in the development of several key-components such as a superconducting RF cavity and a low-emittance electron gun system. Therefore, following the test operation of this prototype ERL, it can be converted into a light source for the VUV photon energy region. For example, the expected brilliance spectra from a 5-m undulator on the prototype ERL operated at 300 MeV with the electron beam emittance of 170 pm·rad are also shown in Fig. 2. About 10^{18} photons/s/mrad^2/mm^2/0.1%b.w. can be obtained in the energy range of 30 - 100 eV.

It is worth comparing the ERL to the Self Amplified Spontaneous Emission (SASE) Free Electron Laser

Table 2 Parameters of the target ERL.

Acceleration Energy	5 GeV
Beam Current	100 mA
Emittance (ε_x, ε_y)	10 pm·rad

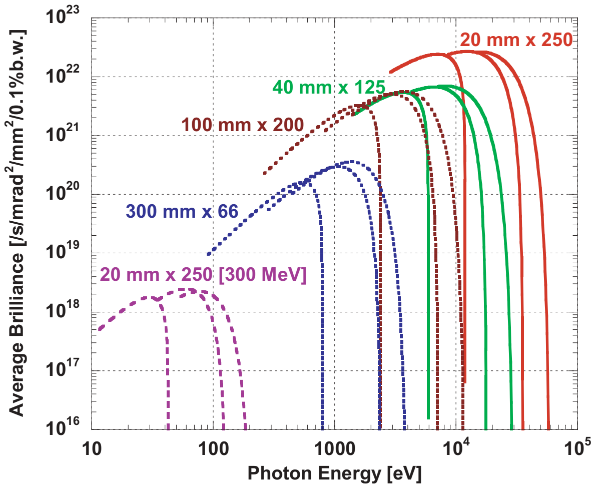

Figure 2
Estimated brilliance spectra from 5-m and 20-m undulators. Solid and dotted lines are calculated for a 5-GeV ERL while dashed lines are for a 300-MeV prototype machine. Length and number of periods for each undulator are denoted in the figure. Only the 1st, 3rd and 5th harmonics are shown.

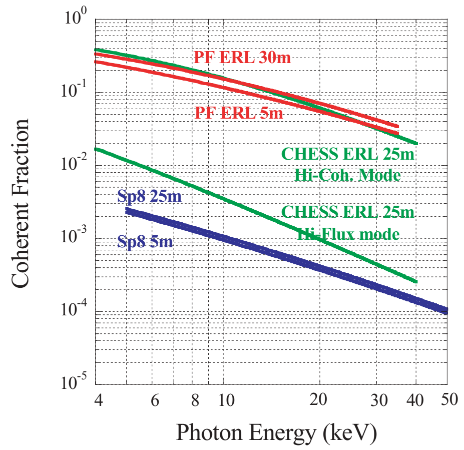

Figure 3
Coherent fraction spectra from the 5-GeV ERL compared with other light sources.

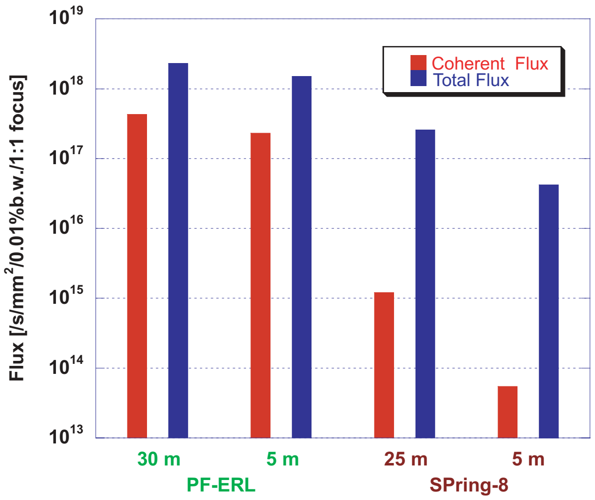

Figure 4
Expected coherent and total fluxes of 8-keV X-rays from the undulators at PF-ERL and SPring-8 under the 1:1 focusing condition.

(FEL). Several projects to construct a SASE-FEL, such as the LCLS at SLAC, the TESLA project at DESY, and the SCSS at RIKEN/SPring-8 are already in progress. The SASE-FEL will provide high peak intensity, ultra-short pulses with low duty cycles of the order of 100 Hz, so that the peak brilliance of the photon beam will reach the order of 10^{33} photons/s/mrad^2/mm^2/0.1%b.w. The ultra-high peak brilliance is one of the most interesting characteristics for the photo-excitation of atoms, molecules and materials. The other essentially new and important characteristic of photons emitted form the SASE-FEL is their extremely high (~100% for FEL)

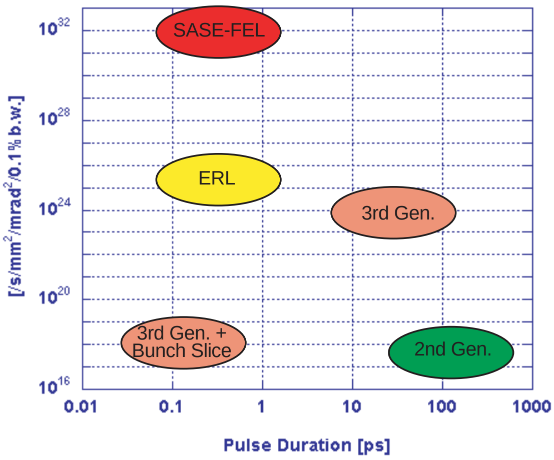

Figure 5
Pulse duration and peak brilliance of the ERL compared with other light sources.

coherent fraction. This attractive feature would undoubtedly provide researchers with an unprecedented probe into the "phase correlation" of the electron wave function. However, it is likely that there will also be a problem with the SASE-FEL, due to the Coulomb explosion of the irradiated materials, making it difficult to be utilized as a "probing light", which has been the most important usage of the 3rd-generation synchrotron-radiation sources. In materials science experiments, it is important to keep well controlled experimental conditions (temperature, pressure, magnetic field, electric field etc.) at the sample to investigate the electronic structures, atomic structures and charge densities with particular experimental conditions. In this respect, the ERL will provide high photon intensity and short photon pulses with a frequency of the order of GHz, so that the peak brilliance will be of the order of 10^{26} photons/s/mrad^2/mm^2/0.1%b.w, which is very much lower than that of a SASE-FEL but higher than that of typical 3rd-generation synchrotron storage rings. Therefore, it should be possible to keep the character of a "probing light" without any Coulomb explosion.

The position of the ERL is shown schematicaly in Fig. 5 concerning the pulse duration and the peak brilliance, compared with the SASE-FEL, the 3rd- and 2nd-generation storage rings.

References

[1] K. Hirano, *Trans. Mater. Res. Soc. Jpn.*, **28** (2003) 43.