6. FUTURE PROSPECT

6.1 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 modifications of the straight sections at the 2.5-GeV 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 regarding 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 in order to offer the users the opportunities to carry out the foremost cutting edge experiments requiring ultimate performances of the light source and the beamlines. To accommodate those demanding experiments in the future, we think that the ability to provide sub-ps 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 that there are some very interesting photo-induced phase transitions in materials, which apparently change the structures within 1 ps. Therefore, sub-ps X-ray pulses are now needed to understand the atomic and electronic structural changes 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 forma-

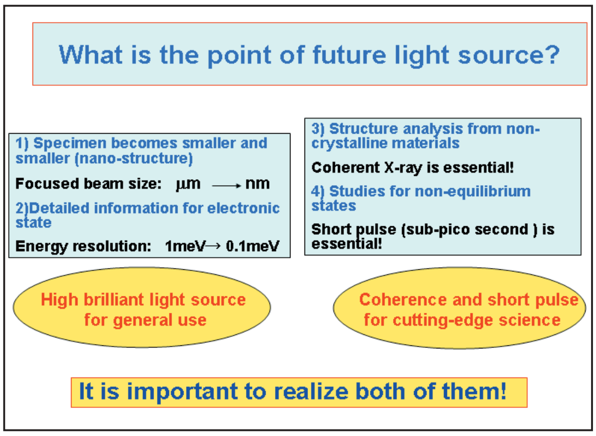


Figure 1
Roles which are needed at the future light source at PF.

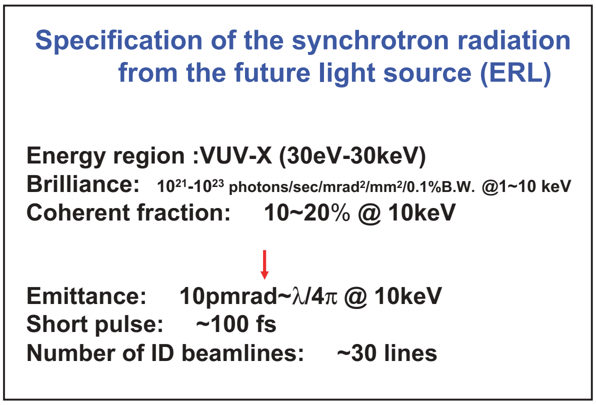


Figure 2
Required specifications of the synchrotron radiation from the future light source. These are expected to be realized by ERL.

tions in materials.

The other role is that we should also have the capabilities to provide abundant support to a large variety of user needs in scientific as well as industrial disciplines with the state-of-the-art experimental instruments and beamlines under very user friendly conditions. For example, the focused beam size at the sample position should be of the order of several tens of nm and also, the energy resolution should be higher than that of the present 3rd generation synchrotron radiation light source for the pursuit of nanoscale structural analysis in extreme conditions such as ultra-high pressure, and to investigate fine electronic local structures in materials. In order to realize such goals, the new light source must produce much more brilliant synchrotron radiation than that of 3rd generation light source with a sufficient number of insertion device beamlines.

The specifications for the synchrotron radiation from the new light source of the Photon Factory can be summarized as in Fig. 2. A broad photon energy region from 30 eV to 30 keV has to be covered 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 coherent fraction in the X-ray region (~10 keV) should be higher than 10~20%. In order 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 itself which is approximately $\lambda/4\pi$ ~ 10 pmrad. The length of the photon pulses should be of the order of 0.1~1 ps. More than 30 insertion device beamlines are needed.

6.2 Choice of Energy Recovery Linac as the Next Generation Light Source of the Photon Factory

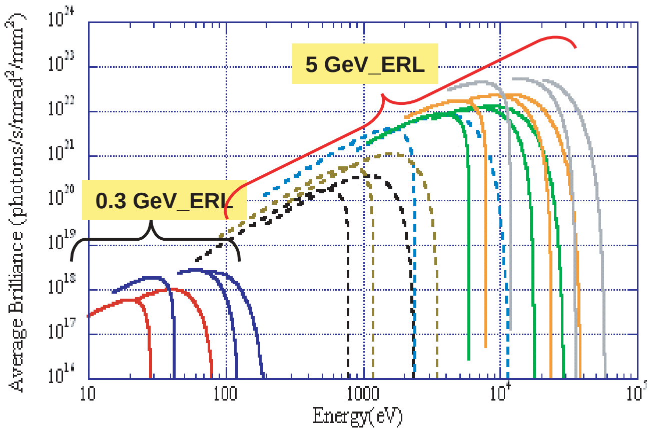
After a series of internal discussions, we came to the conclusion that the energy recovery linac (ERL) should be the most suitable candidate to fulfill the above specifications, and decided to aim at its realization as the next generation synchrotron radiation source. It is worth mentioning about the difference in characteristics comparing the ERL to the SASE-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 ultra-high intensity, ultra-short pulses of photons with low duty cycles of the order of 100 Hz, so that the peak brilliance of the photon 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 photoexcitation of atoms and materials. 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 in order to investigate the electronic structures, atomic structures and charge densities with particular experimental conditions. In this respect, the ERL will provide high 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 "probing light" without any coulomb explosion. Furthermore, the average brilliance will be one or two orders of magnitude higher than that of present 3rd generation storage rings and the expected pulse width should be about 0.1~1 ps, which is almost two orders of magnitude less than that of present 3rd generation storage rings. The emittance of the electron beam can be approximately 10 pmrad with the acceleration energy of 5 GeV, so that coherent X-rays can be obtained. These features are compatible with the required specifications shown in Fig. 2, except for the difficulty to obtain wide energy range coverage from VUV to X-rays. As mentioned later, it will be necessary to construct a prototype ERL, with the energy of 100~300 MeV, and make progress in the development of several key-components such as the super-conducting RF cavity, and a low emittance electron gun system. Therefore, after the test operation of the prototype ERL, it can be converted into a light source for the VUV photon energy region. Fig. 3 shows the estimated average brilliance from ERLs, that are operated at the acceleration energies of 5 GeV and 300 MeV at the current of 100 mA, from 5 m length insertion devices. As shown in this figure, the estimated average brilliance spectra are almost 1~2 orders of magnitude higher than those of the present 3rd generation storage rings.

6.3 Expected Scientific Cases in the PF-ERL

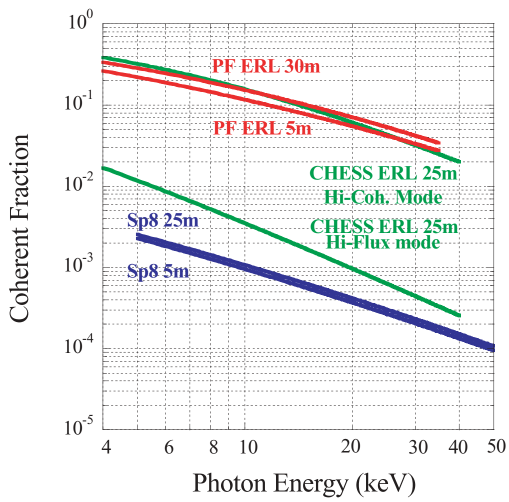
As described in the preceding sections, the ERL can provide photon beams which much more intense, brilliant, coherent and shorter pulses than beams from 3rd generation storage rings. The excellent scientific cases for the PF-ERL are shown in Fig. 4.

6-3-1 Scientific subjects opened by short pulses

The electron bunch length in the ERL can be much shorter than that of an electron storage ring. A typical bunch length is about 1 ps and it can be shortened further to 0.1 ps with a bunch compression system at the accelerator. This feature is one of the outstanding qualities of the ERL light source. Sub-ps time-resolved measurements in X-ray diffraction, photo-emission



It is possible to cover the energy range from VUV to X-ray by using 5GeV ERL and 0.3GeV ERL.



Coherent fraction expected from ERL. It is possible to achieve 10-20% at the energy about 10keV.

Figure 3
Brilliance and coherent fraction spectra from two ERLs whose operational energies are 0.3 and 5 GeV, respectively.

spectroscopy, small angle scattering, X-ray absorption fine structure (XAFS) and magnetic circular dichroism (MCD) and so on will provide us with various interesting information about the non-equilibrium dynamics of matters. Fig. 5 shows the summary of such time domain science with synchrotron radiation. In atomic and molecular science, one of the interesting time domain experiments would be the molecular alignment and structural deformation with an intense optical laser field. Such a phenomenon can be investigated by time resolved measurements using electron-ion coincidence spectroscopy. The time-resolved MCD and PEEM methods have brought us information about the magnetization dynamics of magnetic devices. The sub-ps time resolution of the ERL will give us further information about the dynamics of spin precession relaxation and so on. Time resolved XAFS will give us information about the dynamics of charge transfer, electronic state, and local structure during chemical reactions, especially, photo-chemical reactions such as photocatalysis. Time resolved X-ray diffraction and small angle scattering will give us information about the dynamics of the structural changes for various reactions such as photo-induced phase transition, chemical reaction at polymer, and biological systems.

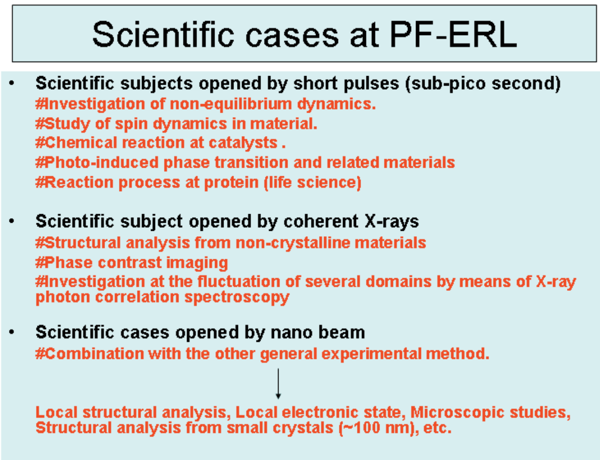


Figure 4
Summary of the outstanding scientific cases at the PF-ERL.

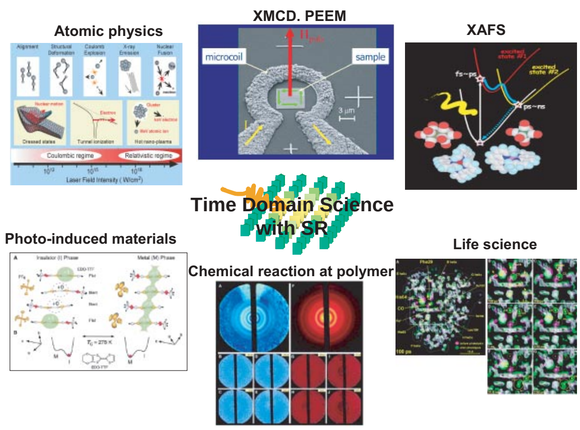


Figure 5
Summary of time domain sciences with a sub-ps time resolution.

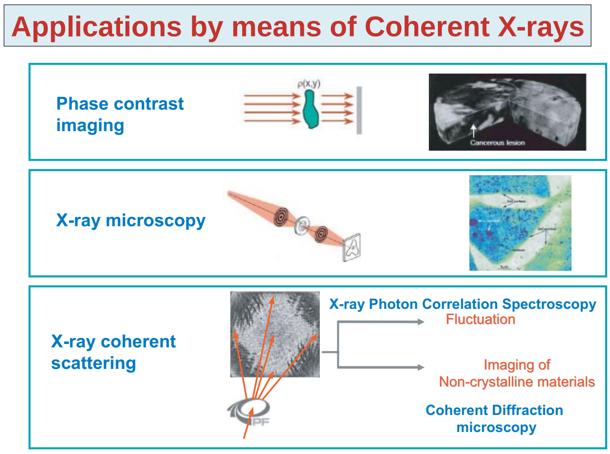


Figure 6
Typical scientific subjects which will be opened by coherent X-rays.

6-3-2 Scientific subjects opened by coherent X-rays

The ERL will provide X-rays with much higher coherence compared to the 3rd generation storage rings and almost two orders of the magnitude more coherent flux than rings such as SPring-8. Fig. 6 shows some typical new scientific subjects that will be opened by coherent X-rays. One is the applications of phase contrast imaging and microscopy. The highly coherent X-rays would reduce the exposure time by orders of magnitude and also improve both resolution and contrast. This will open new possibilities of flash imaging studies of soft matters such as biological tissues. The next are scientific subjects related to X-ray coherent scattering such as coherent diffraction microscopy and X-ray photon correlation spectroscopy. The former might be one of the most exciting technological developments by the usage of coherent X-rays, because it might become possible to study the structure of some biological matter and other non-crystalline materials. For example, the dynamic speckle patterns can be studied to give us information about the fluctuation of domain formation in materials near the phase transition temperature. This technique can also be applied to the investigation of vibration modes in biological systems. The other scientific subject is related to diffraction-limited focusing, which will open several applications of high-intensity nano-beams such as microscopy, micro-diffraction, and micro-analysis to investigate local atomic structures and/or local electronic structures. These applications spread over various scientific fields and some typical examples will present in the next section.

6-3-3 Scientific subjects opened by nano beams

The coherent synchrotron radiation from the ERL can be focused down to the diffraction limit, i.e. several tens of nm in diameter. Various new research areas can be opened by the availability of this nano-beam. X-ray diffraction with nano-beams will enable local atomic structural analysis for nano-materials, fine mosaic materials and very small sub-µm crystals. For example, in the area of the macro-molecule structural analysis, the highly intense beam with the diameter of several hundred nm will make it possible to solve the structure of a crystal whose diameter is just sub μm, and cannot be studied with a present 3rd generation storage ring. This achievement will make it possible to accomplish the structural analysis of large complexes and membrane proteins important for biological science. The extremely small beam size will also enable us to investigate structures under ultra-high pressure environments that can be realized only within a very small volume of the diamond anvil cells. This should promote a drastic progress of Earth-planetary science. Photo-electron emission spectroscopy with nano-beams will also give us information on local electronic structures of interesting nano-materials.

6.4 Technical Investigations of ERL and Problems to be Solved

As described in detail in the preceding sections, we have chosen the ERL of 5 GeV as the future light source of the Photon Factory. In order to realize this ERL, the development of many components would be necessary and investigation of the beam dynamics is also essential. These include the recovery of the energy stored in the RF cavities, the stability of the beam, conservation of normalized emittance etc. Accordingly, we have a plan to construct a proto-type ERL of 150-300 MeV class to substantiate the principle of the ERL in several years.

6-4-1 Preliminary Design Study on PF-ERL

Feasibility studies of the ERL have been continued at the KEK Photon Factory and Accelerator for Laboratory for several years and the "Study Report on the Future Light Source at the Photon Factory — Energy Recovery Linac and Science Case — (in Japanese)" was published in March, 2003. A plan view of the ERL proposed in this report is shown in Fig. 7 and its principal parameters are tabulated on Table 1. The detailed

Table 1 Principal Parameters of the ERL proposed in 2003.

Beam energy	2.5-5 GeV
Injection energy	10 MeV
Circumference	1253 m
Maximum current	100 mA
Normalized emittance	0.1 mm.mrad
Energy spread	5×10^{-5}
Bunch length	1-0.1 ps
Acceleration frequency	1.3 GHz
Acceleration gradient	10-20 MeV/m

structure of the PF-ERL as the future light source, however, has not been decided yet. It will be determined as the construction and the demonstration of the 150-300 MeV class ERL prototype proceed during the next several years.

ERLs are different from usual storage rings in that the transverse emittance is not determined by the balance of the quantum excitation and the radiation damping but instead determined by the "adiabatic damping". Specifically, the excitation of the transverse motion due to the SR emission is negligibly small in the ring where the electrons pass through only once, and the normalized emittance of the beam emitted from the electron gun is conserved if no growth of the emittance occurs in the route including the pre-accelerator, main acceleration structures, arcs etc. The beam must be accelerated up to its final energy at once in such a ring and must be dumped every time after circulating the ring once. Therefore, a high field superconducting linac is essential for this kind of a ring. Furthermore, because the beam energy of several GeV is required as discussed below, the total power of the beam is tremendous and the energy must be withdrawn from the beam back to the linac. This is the reason why this kind of a ring is called "Energy Recovery Linac". We expect to develop an electron gun with the normalized emittance of 0.1 mm.mrad in a few years. The figure is not unrealistic in the case of small emission current. If the electron beam

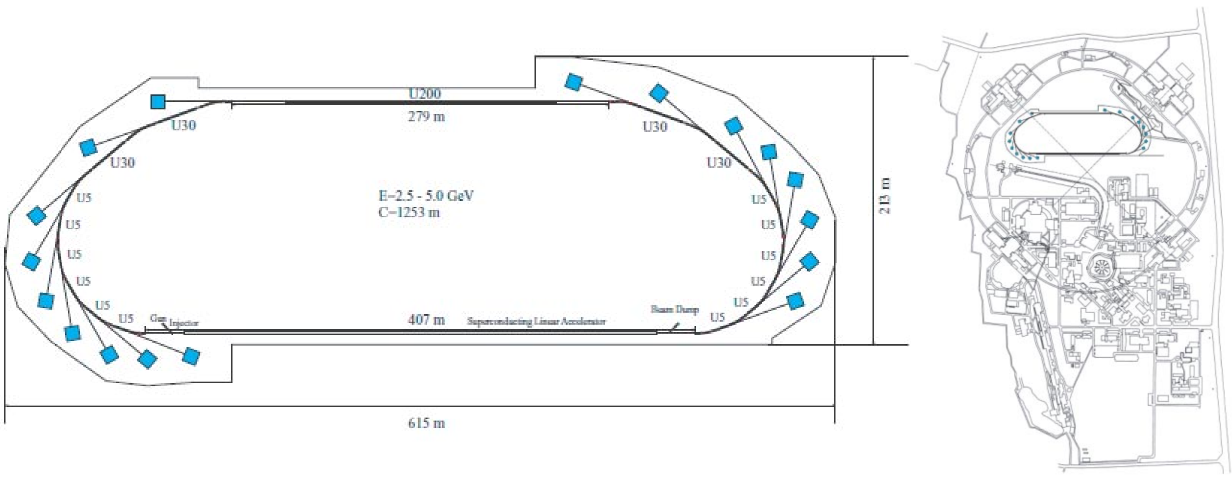


Figure 7
Plan view of the ERL proposed in March, 2003, whose energy 2.5-5 GeV with the circumference of 1253 m.

from such a gun can be accelerated up to 5 GeV (γ =10000) without any emittance growth, the emittance of 10 pm.rad at 5 GeV can be achieved. This value fulfills the condition for the diffraction limit in the X-ray region as discussed in the preceding sections.

In the case of usual storage rings, the bunch (time) length is limited by the balance of quantum excitation and radiation damping, and range from several tens of ps to several hundreds of ps. It is almost impossible to obtain light pulses with lengths less than 1 ps at a reasonable beam current (e.g. a few mA). On the other hand, in the case of ERLs, short electron bunches from a gun can be transported without elongation. In addition, they can be compressed further in the longitudinal direction, and it does not seem to be difficult to obtain light pulses with lengths less than 1 ps. Thus the condition for the light pulse length discussed above can also be satisfied.

6-4-2 Prototype ERL

As mentioned above, we are convinced that the ERL should be the most suitable choice for the future light source at the Photon Factory. However, there are a myriad of technical issues to be resolved before the construction of this kind of light source can become possible. Some of them are listed below.

1) Effects that spoil energy recovery.
2) Instabilities that spoil conservation of normalized emittance.
3) Effects that elongate the bunches.
4) Effects of the so-called coherent synchrotron radiation.
5) "Beam gymnastics" in longitudinal phase space.
6) Achievable acceleration gradient.
7) Technical issues on the superconducting acceleration structure
8) Development of an electron gun with the required conditions
etc.

In order to resolve these issues and investigate the beam dynamics, we plan to construct an ERL prototype machine. As shown in Fig. 8, the experimental hall for cold neutron science on the Tsukuba campus will be available for the prototype. Although its area of 43 m × 19.2 m is not entirely satisfactory for our eventual purpose, it is sufficient for the construction of a 150-200 MeV class ERL in it. Moreover, there is a building for a cryogenic system near the hall. Although part of the cryogenic system is also moving to the Tokai campus, we expect that the rest of it and the building can be used for our purpose. According to the provisional layout of the prototype in the hall, a straight section with a length of about 25 m should be available for a superconducting linac. The maximum energy obtained by the linac depends on the capacity of the cryogenic system. We expect an energy of 150-200 MeV. When a powerful cryogenic system (kW class at 2 K) becomes available, the prototype can be converted into a practi-

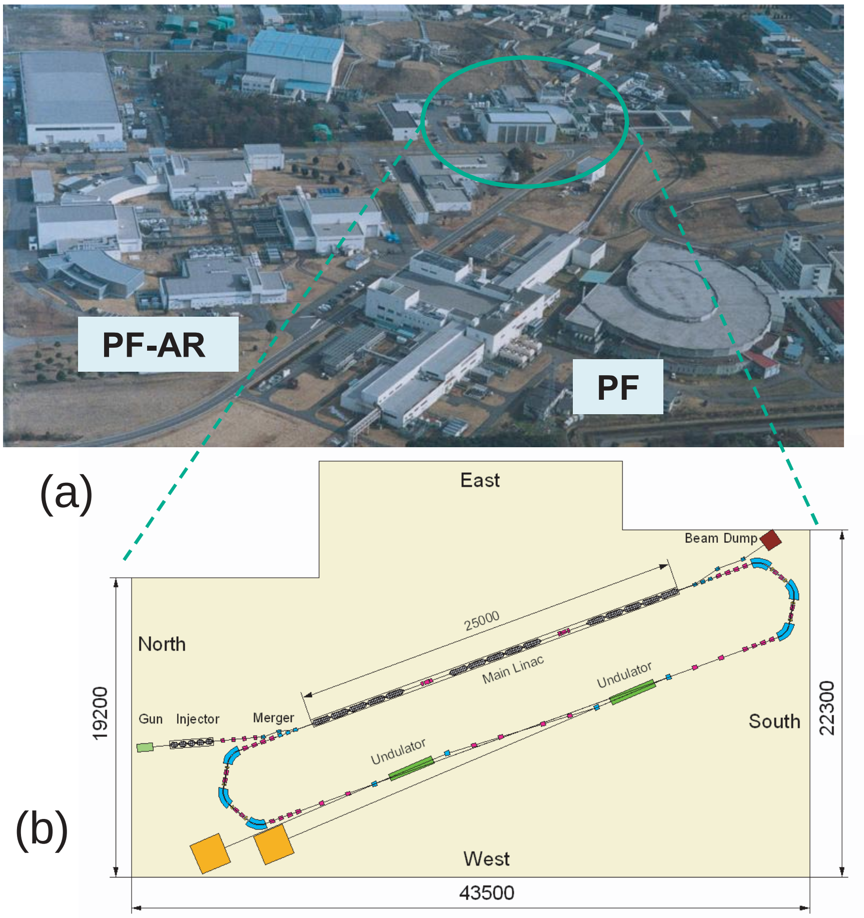


Figure 8
(a) Building which will be used for construction on the prototype ERL.
(b) Schematic drawing of the prototype ERL with a straight section for a superconducting linac, whose length will be about 25 m.

cal light source in the VUV region. In this case, insertion devices will be installed in the other straight section.

6.5 Time Schedule to Realize the PF-ERL

We have just started organizing an R&D group consisting of PF staff members and Accelerator Laboratory members of KEK. We aim to design, construct and test a 200 MeV prototype accelerator during the years 2006-2009 and then hope to start the construction of the main 5 GeV class ERL machine from 2010. In addition to the Photon Factory staff members, the Accelerator Laboratory of KEK is now officially involved in this project. We have also starting collaboration with JAEA (previously JAERI) group which is also proposing the construction of an energy recovery linac. The official organization of the ERL Project Office at KEK will start at the beginning of April in 2006. As the first step, we have started a design study of a prototype ERL of 200 MeV. We hope to complete the construction of this prototype ERL by the end of FY 2008 and gain operational experience in 2009. The tentative time schedule of the ERL project is shown in Fig. 9.

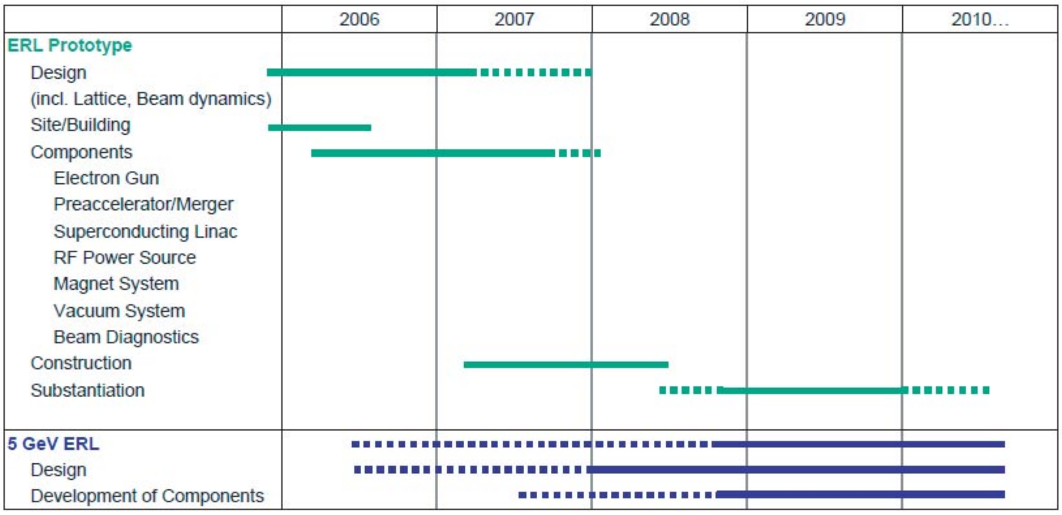


Figure 9
Tentative time schedule for the PF-ERL project.