1 The ERL Project

1-1 Introduction

The energy recovery linac (ERL) being developed at KEK has a great potential to open a new era in materials science. By illuminating a specimen with a short-pulse, coherent nanometer-sized X-ray beam, scientists can conduct nondestructive measurements of rapidly evolving dynamical materials and organisms with nanometer spatial resolution. This would benefit researches in materials, life, chemical, and environmental sciences. Research studies on high-speed communication devices, catalysts for hydrogen energy systems, drug discovery, cellular imaging, and efficient light energy utilization are considered as promising targets of the applications of ERL.

The mission of ERL Project Office, established at KEK on April 1, 2006, is to direct the ERL Project Team. The ERL Project Team, which currently includes several working groups, designs and develops key components of the ERL. Accelerator scientists from KEK, JAEA, ISSP, UVSOR, SPring-8, AIST, Hiroshima University, and Nagoya University are the core members of the team. The office also plays a major role in collaborating with other ERL projects around the world. For example, the Cornell Laboratory for Accelerator-based Sciences and Education (CLASSE) at Cornell University and KEK signed an MoU in March 2007. Such collaborations are summarized in Fig. 1.

Because there is no GeV-class ERL in the world, it is necessary to construct an ERL test facility (compact ERL (cERL) with energy of 35–200 MeV) that can be used for developing several critical accelerator components such as a high-brilliance DC photocathode electron gun and superconducting cavities for the injector and main accelerator. From 2006 to 2008, we concentrated on the design and development of such an ERL and its components. The conceptual design report (CDR) [1] for the cERL was published in March 2008.

During fiscal year 2009 (FY 2009), we started the construction of the cERL at the East Counter Hall in KEK campus. Although the East Counter Hall had been used for nuclear physics experiments, these activities have been relocated at J-PARC. All the radiation shielding blocks in the Hall for these experiments were removed and the electric power and cooling water supply systems were renewed in 2009. A liquid helium cryogenic system and part of a RF power sources were located in place, and a clean room for the fabrications of the superconducting cavities and vacuum systems were constructed in the East Counter Hall. We have started fabricating critical accelerator components such as DC electron gun and super conduction cavities for the injector and main linac of the cERL. This work is described in full detail in the next session.

Following the recommendations from the scientific advisory committee of the ERL (chaired by Prof. Kazumichi Namikawa of Tokyo Gakugei University), ERL Science Workshop was held on July 9 – 11, 2009 (Fig. 2). The workshop was focused on the scientific applications of the ERL, and the following four areas were identified as the key research areas.

1) Femtosecond science
2) Local structures in disordered materials
3) Hierarchical structure of materials in space and time domains
4) Advanced X-ray optical instrumentations

The workshop summarized that ERL has a great potential to realize a lot of promising scientific subjects as follows. ERL provides unique opportunities to explore extremely wide time domains from milliseconds to

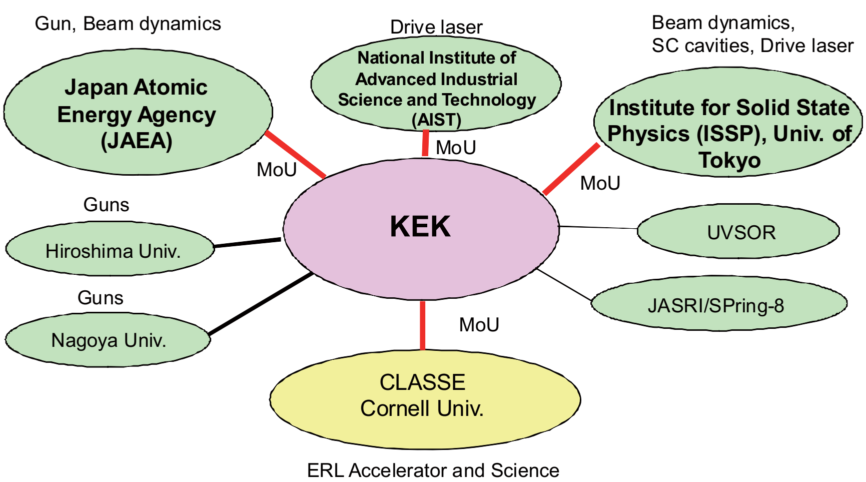

Figure 1
Collaboration to make a progress on the ERL project.

Figure 2
A photograph at the occasion of the ERL science workshop at 9 – 11 July of 2009.

Figure 3
Speakers of the half-day seminar for XFEL-O at 21st of December 2009.

femtoseconds. As for the local structures in disordered materials, nanometer spatial resolution will provide unique functional information of non-periodic systems such as surface/interface, electric double layers, and spintronic devices. Highly brilliant coherent x-rays with relatively high repetition rate (1.3 GHz) will shed light on hierarchical structure in material including biological samples from slow dynamics to nanosecond time domains and from subnanometer to millimeter spatial domains. The X-ray free electron laser oscillator (XFEL-O) [2] is the most remarkable and challenging instrumentation proposed at the workshop, and participants of this workshop mentioned that “XFEL-O should not be considered as just an option but as one of targets of the KEK-ERL.” The proceedings were published [3] and are downloadable at the following Web link (http://ccdb4fs.kek.jp/tiff/2009/0925/0925004.pdf).

On the basis of the above-mentioned summaries, we organized a half-day seminar on XFEL-O with Dr. Kwang-Je Kim of APS/ANL (the pioneer of the XFEL-O), Dr. Jun-ichiro Mizuki and Dr. Nobuyuki Nishimori of JAEA on December 21, 2009 (Fig. 3). The presentation files are also available at the following Web page (http:///pfwww.kek.jp/ERLoffice/topics/XFELseminar.html).

REFERENCES

[1] R. Hajima, N. Nakamura, S. Sakanaka, and Y. Kobayashi (eds.), *KEK Report* **2007-7**/*JAEA-Research* **2008-032** (in Japanese).
[2] K.-J. Kim, Y. Shvyd'ko and S. Reiche, *Phys. Rev. Lett.,* **100** (2008) 244802.
[3] H. Kawata, S. Adachi, K. Amemiya, H. Nakao and K. Hirano (ed), *KEK Proceedings* **2009-4** (2009) (in Japanese).

1-2 Progress in 2009

ERL project to develop 5-GeV class ERL

The progress in 2009 mainly focused on the development of the accelerator components for the cERL. An elegant design concept of 5GeV class ERL and 7.5GeV class XFEL-O are shown in Fig. 4 [4], which consists of a 2-loop configuration to realize the operations of 5-GeV class ERL and 7.5-GeV class XFEL-O. The design concept also enables to save both cost and space. Under ERL operation mode, electron beams are accelerated twice through a 2.5-GeV superconducting (SC) linac, and consequently, 5-GeV electron beams are used for SR experiments. They are decelerated twice and dumped. Under the 7.5-GeV XFEL-O mode, a path length of an outer loop is changed by a half rf-wavelength by introducing an additional orbit bump. The beams are then accelerated three times through the SC linac, yielding 7.5-GeV beams for the XFEL-O. The higher beam energy is favorable for obtaining higher FEL gain. Since an average beam current required for the XFEL-O is relatively low (typically 20 μA under 20 pC/bunch with a bunch repetition of about 1 MHz), 7.5-GeV beams are dumped immediately after they are

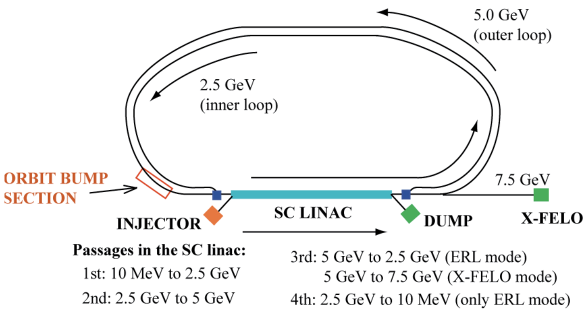

Figure 4
A configuration of a 2-loop ERL and a recirculating linac (After ref. 4).

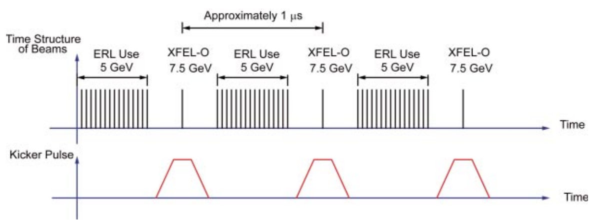

Figure 5
Hybrid operation of ERL/recirculating linac (After ref. 4).

utilized. Figure 5 shows a hybrid operation of these two modes [4], which is realized by switching the pulsed bump at a repetition frequency of about 1 MHz.

Construction of Compact ERL (cERL)

In order to demonstrate ultra-low emittance beams using our accelerator components, we are constructing the cERL in the East Counter Hall at KEK as previously mentioned. The first goal of the cERL is to demonstrate the ERL operation of low-emittance (normalized emittance: 1 mm•mrad) beams of 10 mA (CW) at a beam energy of 35 MeV. To this end, we construct a 5-MeV injector linac, a main linac having two 9-cell cavities in a single cryostat, and a single return loop by the end of FY 2012. The design studies on the cERL have already been reported [5, 6]. Once the first goal is achieved, we plan to upgrade the cERL step by step. Future plans include raising the beam current up to 100 mA, installation of additional cavities in the main linac, and installation of the second return loop. Figure 6 shows our final layout of the cERL having double return loops. During 2009, we developed the infrastructure as follows: (1) refurbishment of the East Counter Hall together with clearing old proton beam lines and concrete shieldings, (2) renewal of cooling water system that can supply pure water flow of approximately 2600 liters/min with a cooling capacity of about 1900 kW, (3) electric substation that can supply electric power of up to 4.1 MW, (4) a liquid-helium refrigerator system that consists of a refrigerator having a cooling capacity of 600 W at 4K, a 3000-liters Dewar, two 2K cold boxes, and a pumping system, and (5) a clean room for assembling cryomodules and a part of the super-conducting cavities. Figure 7 shows a photograph taken in the East Counter Hall at the end of FY 2009.

REFERENCES

[4] S. Sakanaka et al., *Proc. IPAC* (2009) 2338.

[5] N. Nakamura, R. Hajima, K. Harada, Y. Kobayashi, S. Sakanaka and M. Shimada, *Proc. IPAC* (2009)2314.
N. Nakamura, R. Hajima, Y. Kobayashi, T. Miyajima, S. Sakanaka and M. Shimada, *Proc. IPAC* (2009)2317.
N. Nakamura and K. Harada, *Proc. IPAC* (2009)2320.

[6] T. Miyajima, J.G. Hwang and E.-S. Kim, *Proc. IPAC* (2009), 2332.

Figure 7
A picture of the East counter Hall at the end of the fiscal year of 2009 (After ref. 4).

1-3 R&D Efforts for ERL Project

High-Brightness DC Photocathode Gun

The ERL project requires a high-brightness electron gun that can produce beams of 10 mA (100 mA) with a normalized emittance of 1 mm·mrad (0.1 mm·mrad). For this purpose, we are developing a DC photocathode gun having a gun voltage of 500 kV with a beam cur-

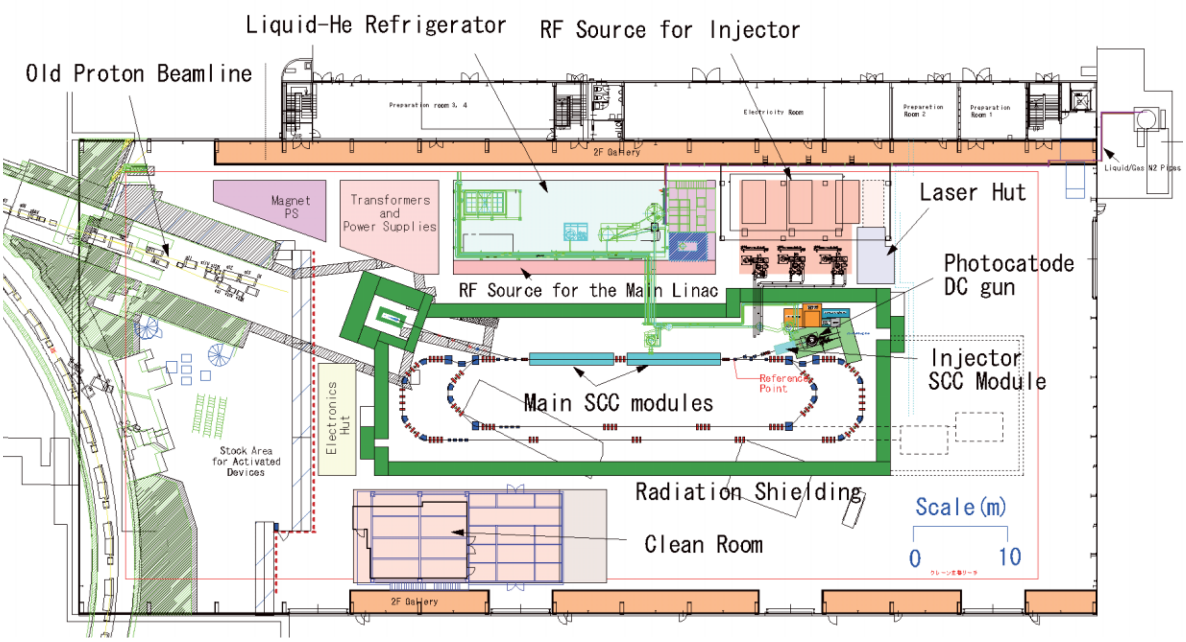

Figure 6
Planned full layout of the Compact ERL (After ref. 4).

rent of 10 mA (100 mA in future) in collaboration with JAEA, Hiroshima University, and Nagoya University. A schematic drawing of the 500 kV gun is shown in Fig. 8. This gun is equipped with a segmented ceramic insulator having guard-ring electrodes in order to prevent any damage to a ceramic insulator due to emitted electrons from a support-rod electrode. As we expected, the gun was successfully conditioned up to a very-high voltage of 550 kV, followed by a long-time holding test for 8 h at a high voltage of 500 kV as shown in Fig. 9. Detailed status of this gun is reported in [7]. We also decided to construct another 500-kV gun at KEK site. The purpose of the second gun is to provide an opportunity for further development of the gun technology once one of them has been installed in the cERL. For the second gun, we employed a titanium chamber having low out-gassing rate and segmented insulators. The second gun can also serve as a backup for the first gun, and to this end, the insulators were designed to be compatible with those of the first gun. The vacuum components of the second gun are under assembly.

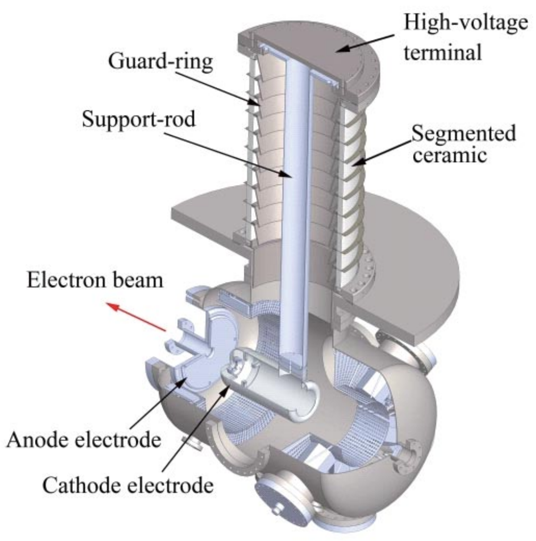

Figure 8
A schematic drawing of a 500-kV DC electron gun which was constructed in JAEA (After ref. 4).

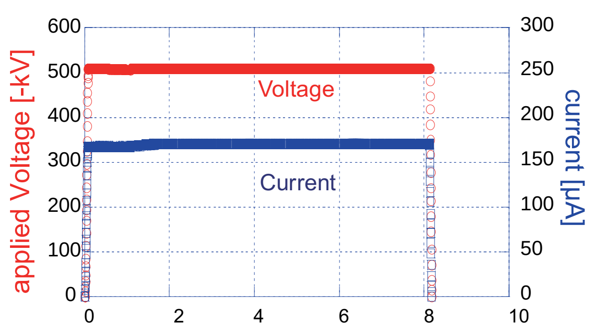

Figure 9
Results of a long-time holding test for 8 h at a generator voltage of 510 kV (After ref. 7).

Drive Lasers

A drive laser for the photocathode gun should produce laser pulses having a repetition frequency of 1.3 GHz, an average power of 15 W (for a beam current of 100 mA by assuming quantum efficiency of 1.5%) at a typical wavelength of 530 nm. We are preparing two lasers. One of them will produce an average laser power of 1.5 W at 530 nm, which is used for the gun test facility [8] as well as for an initial commissioning of the cERL. We have currently assembled a 100-mW fiber-laser system comprising commercial products such as a 1.3-GHz laser oscillator and a fiber amplifier. This system will be boosted up to 1.5 W.

We are also developing an advanced Yb-fiber laser system for higher (15 W) power with tunable wavelength [9] in collaboration with AIST and ISSP. We have so far developed a 10-W fiber preamplifier using an Yb-doped photonic crystal fiber, and we have also succeeded in demonstrating the second harmonic generation of the amplified laser by a conversion efficiency of 48%.

SC Cavities for the Injector [10]

In order to pre-accelerate 100-mA electron beams from 0.5 MeV to 10 MeV (or 5 MeV at cERL), we use three 2-cell SC cavities. The targeted accelerating gradient and a transmission power through each coupler are 14.5 MV/m and 170 kW, respectively. We have produced two prototype 2-cell cavities, as shown in Fig. 10(a). The latest cavity (No. 2) has two input-coupler ports and five loop-type HOM couplers, which have an improved design from those of the TESLA-type. Under a vertical test, this cavity achieved an accelerating gradient of 41 MV/m without connecting HOM pickups, as shown in Fig. 10(b). Vertical tests with connecting HOM pickups are underway.

We have also produced two prototype input couplers and started high-power tests. At present, these couplers were successfully conditioned with rf pulses having a peak power of 130 kW, pulse widths of 1 s, and a repetition frequency of 0.2 Hz (average power: 26 kW). The design of a cryomodule, which can house three 2-cell cavities, is also underway and will be installed in KEK during 2011.

SC Cavities for Main Linac

A cryomodule having two 9-cell SC cavities for the main linac is under development. We carried out vertical tests on two prototype cavities [11]. Since the field gradient of our prototype cavities was limited to be less than 17 MV/m so far, we developed an X-ray mapping system [12], and we are trying to solve problems during the cavity fabrication or processing. We have also developed an input coupler for the main-linac cavities [13, 14] and have succeeded in feeding an RF power of up to 27 kW. An HOM-absorber assembly, which is used under low temperature of about 80 K, is under development [15]. We are designing a cryomodule [16] that houses two 9-cell cavities, input couplers, and HOM-

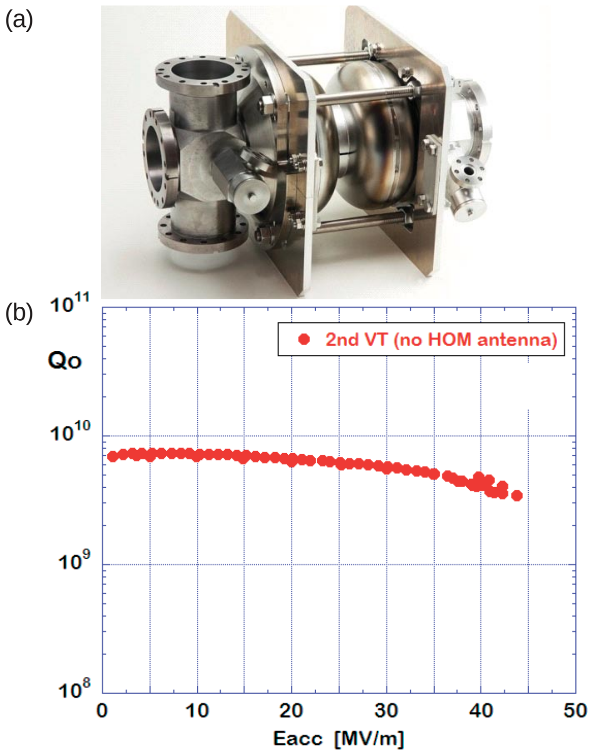

Figure 10
(a) A picture of the prototype 2-cell cavity for injector, and (b) a result of a vertical test which shows the achievement of 41 MV/m accelerating gradient.

absorber assemblies, as shown in Fig. 11. This cryomodule is to be finished during FY 2011.

RF Sources

RF sources [17] for the cERL have been developed since 2007. A 1.3-GHz, 300-kW (CW) klystron for the injector was developed in FY 2009, as shown in Fig. 12. This klystron (Toshiba E37750) achieved an output power of 305 kW with 63% efficiency at a voltage of 49.5 KV and a beam current of 9.75 A. Key waveguide components, such as a 150 kW circulator, were also developed. Using this klystron, we constructed a high-power test station for input couplers. We also purchased an IOT and also developed a 35-kW (CW) klystron used for the main linac. A digital low-level RF system is also under development [18]. Our tentative targets for the amplitude and phase stability are 0.1% (rms) and 0.1 degrees (rms), respectively.

Schedule

The schedule of the construction of cERL is shown in Fig. 13. Fabrication of the accelerator components will be carried out from 2010 to the middle of 2012. We will start the tests of each accelerator components as soon as possible after installation, and then, we will start beam operations at the end of FY 2012 at 35-MeV accelerated energy. The beam test will provide critical and essential information on whether further improvement of the components is necessary and also on the drawbacks of the design of the 5-GeV ERL.

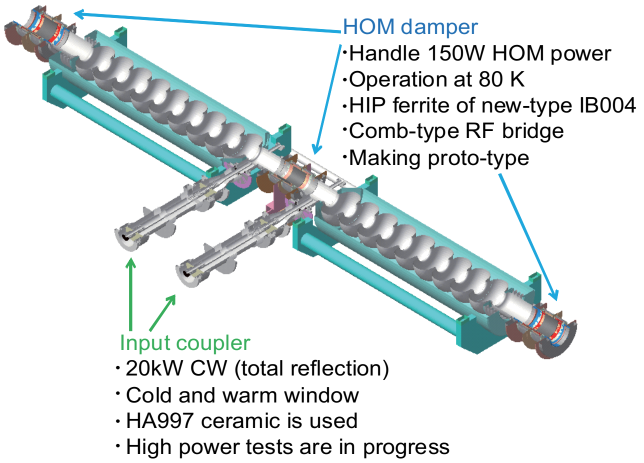

Figure 11
Drawing of a cryomodule for main SC cavities for the main linac which houses two 9-cell cavities, input couplers, and HOM-absorber assemblies.

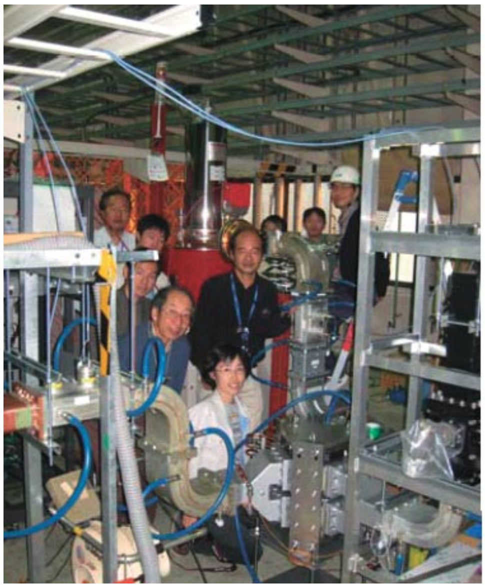

Figure 12
Members to develop a 1.3-GHz 300-kW (CW) klystron for the injector.

REFERENCES

[7] R. Nagai, R. Hajima, N. Nishimori, T. Muto, M. Yamamoto, Y. Honda, T. Miyajima H. Iijima, M. Kuriki, M. Kuwahara, S. Okumi and T. Nakanishi., *Rev. Sci. Instrum.,* **81** (2010) 033304.
R. Nagai, R. Hajima, N. Nishimori, Y.Honda T. Miyajima, T. Muto, M. Yamamoto, H. Iijima, M. Kuriki, M. Kuwahara, T. Nakanishi and S. Okumi, *Proc. IPAC* (2009) 2341.
[8] T. Miyajima et al., *Proc. IPAC* (2009) 2355.
[9] I. Ito, N. Nakamura, Y. Honda, Y. Kobayashi, K. Torizuka and D. Yoshitomi, *Proc. IPAC* (2009) 2141.
[10] S. Noguchi, E. Kato, M. Satoh, T. Shishido, K. Watanabe and Y. Yamamoto, *Proc. IPAC* (2009) 2944.
[11] K. Umemori, T. Furuya, H. Sakai, T. Takahashi, M. Sawamura and K. Shinoe, *Proc. IPAC* (2009)2956.
[12] H. Sakai, T. Furya, S. Sakanaka, T. Takahashi K. Umemori, M. Sawamura and K. Shinoe, *Proc. IPAC* (2009) 2950.
[13] H. Sakai, T. Furuya, S. Sakanaka, T. Takahashi, K. Umemori, A. Ishi, N. Nakamura, K. Shinoe and M. Sawamura, *Proc. IPAC* (2009) 2953.
[14] K. Umemori, T. Furuya, H. Sakai, M. Sawamura and K.

Shinoe, *Proc. IPAC* (2009) 2959.
[15] M. Sawamura, T. Furuya, H. Sakai, K. Umemori and K. Shinoe, *Proc. IPAC* (2009) 2344.
[16] T. Furuya, K. Hara, K. Hosoyama, Y. Kojima, H. Nakai, K. Nakanishi, H. Sasaki, K. Umemori, M. Sawamura and K. Shinoe., *Proc. IPAC* (2009) 2923.
[17] S. Fukuda, M. Akemoto, D.A. Arakawa, H. Honma, H. Katagiri, S. Matsumoto, T. Matsumoto, S. Michizono T. Miura, H. Nakajima, K. Nakao, S. Sakanaka, T. Shidara, T. Takahashi, Y.Yano and M.Yoshida , *Proc. IPAC* (2009) 3981.
[18] T. Miura, A. Akiyama, D.A. Arakawa, S. Fukuda, H. Katagiri, T. Matsumoto, S. Michizono, J.-I. Odagiri and Y. Yano, *Proc. IPAC* (2009) 1440.

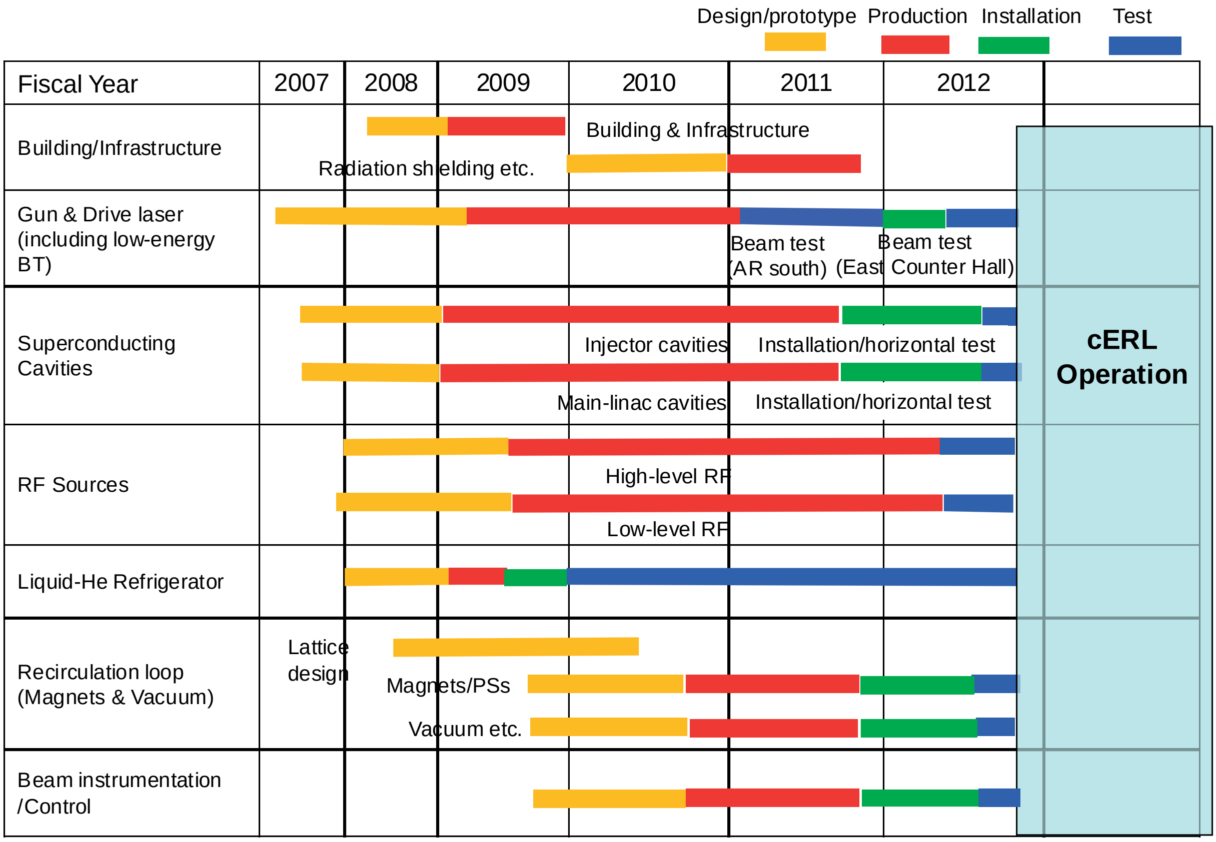

Figure 13
Time schedule of the construction of cERL.