RECENT PROGRESS IN THE ENERGY RECOVERY LINAC PROJECT IN JAPAN

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Abstract

Future synchrotron light source using a 5-GeV energy recovery linac (ERL) is under proposal by our Japanese collaboration team, and we are conducting R&D efforts for that. We are developing high-brightness DC photocathode guns, two types of cryomodules for both injector and main superconducting (SC) linacs, and 1.3 GHz high CW-power rf sources. We are also constructing the Compact ERL (cERL) for demonstrating the recirculation of low-emittance, high-current beams using above-mentioned critical technologies.

ERL PROJECT IN JAPAN

Energy recovery linacs are expected to bring innovation to the synchrotron-radiation (SR) science [1]. Our Japanese collaboration team is proposing to construct a 5-GeV ERL at KEK as a future project of the KEK Photon Factory [2]. Goals of the 5-GeV ERL are shown in Table 1. We aim at achieving normalized beam emittances (both in horizontal and vertical planes) of 0.1 mm·mrad at an average beam current of 10 mA (high coherence mode), and those of 1 mm·mrad at a beam current of 100 mA (high flux mode). The ERL will also produce ultra-short beam pulses having pulse lengths of less than 100 fs (rms) with bunch charges of higher than 77 pC at a typical repetition frequency of about 1 MHz. The ERL is also expected to deliver high-brightness electron beams to an X-ray free-electron laser oscillator (X-FELO) [3] that is a very promising option [4] for our ERL project.

In order to save both construction cost and space, we are currently considering a 2-loop ERL configuration. Figure 1 shows our idea which can make the ERL and X-FELO compatible. Under an ERL mode, beams are accelerated twice through a 2.5-GeV SC linac, 5-GeV beams are used for the SR experiments, and they are decelerated twice and dumped. Under the other recirculating-linac mode, we change a path length of an outer loop by a half rf-wavelength by introducing an orbit bump. Then, beams are accelerated three times through the SC linac, yielding 7.5-GeV beams used for the X-FELO. The higher beam energy is favorable for obtaining higher FEL gain. Since an average beam current required for the X-FELO is relatively low (typically 20 μA under 20 pC/bunch with a bunch repetition of about 1 MHz), 7.5-GeV beams are immediately dumped after they are utilized. In principle, a hybrid operation of these two modes is possible by switching the pulsed bump at a repetition frequency of about 1 MHz as shown in Fig. 2.

Table 1: Goals of 5-GeV ERL and Compact ERL in Japan

Parameter	5 GeV ERL	Compact ERL
Beam energy	5 GeV	35 - 245 MeV
Average current	10 - 100 mA	10 - 100 mA
Normalized emittance	0.1 - 1 mm·mrad	0.1 - 1 mm·mrad

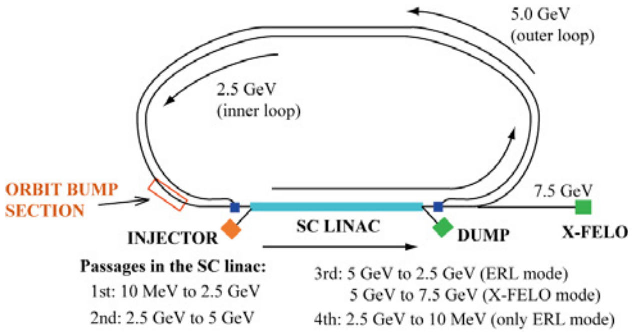

Figure 1: A convertible configuration of a 2-loop ERL and a recirculating linac.

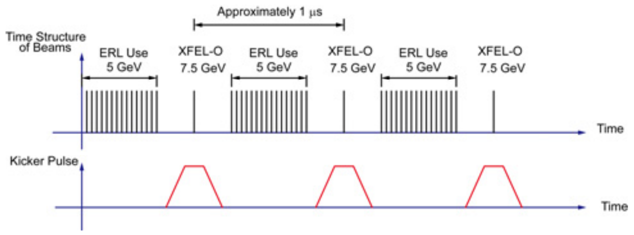

Figure 2: Hybrid operation of ERL/recirculating-linac.

R&D EFFORT FOR THE ERL PROJECT

We are conducting active R&D efforts for the ERL project since 2006. The latest results are briefly reported.

High-Brightness DC Photocathode Gun

The ERL project requires a high-brightness electron gun which can produce beams of 100 mA (10 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 current of 10 mA (100 mA in future). A schematic drawing of the 500-kV gun is shown in Fig. 3. In order to prevent any damage to a ceramic insulator due to emitted electrons from a support-rod electrode, this gun is equipped with a segmented ceramic insulator having guard-ring electrodes. As we expected, this gun could successfully be 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 [5]. Detail status of this gun is reported in [6].

Following the above-mentioned development, we decided to construct another 500-kV gun at a KEK site. The purpose of the second gun is to provide an opportunity for further development of the gun technology after one of them has been installed in the Compact ERL. For the second gun, we also employed titanium chamber having low outgassing 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 assemble.

Basic research for the photocathode is also underway [7].

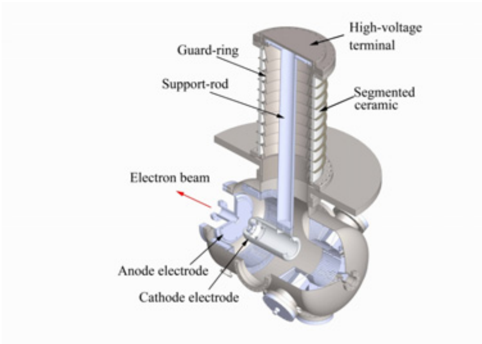

Figure 3: A schematic drawing of a 500-kV, 10-mA photocathode gun which was constructed at JAEA.

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 the initial stage of the Compact ERL. We have currently assembled a 100-mW fiber-laser system that comprised of 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]. We have so far developed a 10-W fiber preamplifier using an Yb-doped photonic crystal fiber, and succeeded in demonstrating the second harmonic generation of the amplified laser by a conversion efficiency of 48%.

SC Cavities for the Injector [10]

To pre-accelerate 100-mA beams from 0.5 MeV to 10 MeV (or 5 MeV at cERL), we use three 2-cell SC cavities. Goals for an 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. The latest cavity (No. 2) has two input-coupler ports and five loop-type HOM couplers which have an improved design from those of TESLA-type ones. Under a vertical test, this cavity achieved an accelerating gradient of 41 MV/m without connecting HOM pickups. Vertical tests with connecting HOM pickups are underway.

We have also produced two prototype input couplers, and are conducting high-power tests. At present, these couplers were successfully conditioned with rf pulses having a peak power of 130 kW, pulse widths of 1 sec, and a repetition frequency of 0.2 Hz (average power: 26 kW). Design of a cryomodule which can house three 2-cell cavities is also underway.

SC Cavities for the 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 fix problems during the cavity fabrication or processing. We have also developed an input coupler for the main-linac cavities [13,14]. After some R&D efforts, we succeeded in feeding an rf power of up to 27 kW. An HOM-absorber assembly, which is used under low temperature of about 80K, is under development [15]. We are designing a cryomodule [16] which houses two 9-cell cavities, input couplers, and HOM-absorber assemblies. This cryomodule is to be finished in FY2011.

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 FY2009. 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, as well as developed a 35-kW (CW) klystron, used for the main linac.

A digital low-level RF system is also under development [18]. Our tentative goals for the amplitude and phase stability are 0.1% (rms) and 0.1 degrees (rms), respectively. A micro-TCA system, having a new FPGA board with four 16-bit ADCs and four 16-bit DACs, was adopted.

THE COMPACT ERL

To demonstrate the production and recirculation of ultra-low emittance beams using our R&D products, we are constructing the Compact ERL (cERL) in the East Counter Hall at KEK. The first goal of the cERL is to generate and recirculate low-emittance (normalized emittance: 1 mm·mrad) beams of 10 mA (CW) at a beam energy of 35 MeV. To this end, we will construct a 5-MeV injector linac, a main linac having two 9-cell cavities in a single cryostat, and a single return loop until FY2012. Recent design studies on the cERL are reported in [19,20].

Due to supplemental budgets in FY 2008 and 2009, we have prepared much infrastructure such as: 1) refurbishment of the East Counter Hall together with clearing old proton beamlines and concrete shields, 2) renewal of cooling water system which can supply pure water flow of approximately 2600 liters/min with a cooling capacity of about 1900 kW, 3) electric substation which can supply electric power of up to 4.1 MW. We have also installed a liquid-helium refrigerator system which comprises a refrigerator having a cooling capacity of 600 W at 4K, a 3000-liter Dewar, two 2K cold boxes, and a pumping system. The refrigerator system is now under test. We have also installed a clean room for assembling cryomodules and a part of the rf system. Figure 4 shows a picture taken in the East Counter Hall.

After achieving the first goal, we plan to upgrade the cERL step by step; the future plan includes raising the beam current up to 100 mA, installation of additional cavities in the main linac, and installing the second return loop. Figure 5 shows our planned full layout of the cERL having double return loops.

Figure 4: East Counter Hall after the refurbishment.

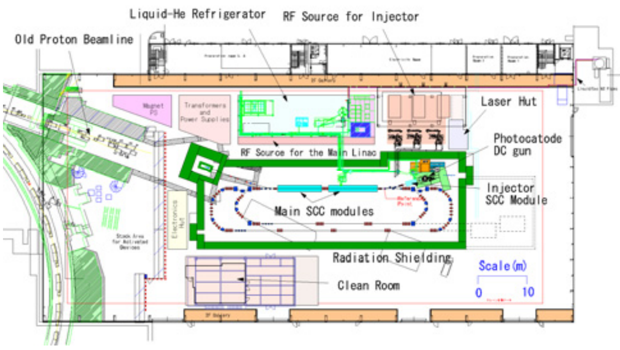

Figure 5: Planned full layout of the Compact ERL.

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