OVERVIEW OF ENERGY-RECOVERY LINACS

R. Hajima[#] JAEA-ERL, Tokai, Ibaraki 319-1195, Japan

Abstract

Energy-recovery linacs (ERL), which is able to produce a high-power electron beam with high brightness, has been developed for high-power free-electron lasers. Now, ERL is also considered as a future X-ray light source, where coherent X-ray and ultrashort X-ray pulses are realized. In this paper, we overview current R&D status of ERLs in the world, and give a detail description of the ERL light source project in Japan.

INTRODUCTION

An energy-recovery linac (ERL), which is able to generate a high-brightness electron beam with high-average current, has been developed for a driver of high-power free-electron laser. Now, the ERL is expanding its role and contribution to various fields: next-generation X-ray light sources, high-flux gamma-ray sources, colliders for high-energy physics, an electron-cooler for ion beams, etc. World-wide efforts of R&Ds are launching towards such future ERLs.

For an example of ERL, figure 1 shows a 17-MeV ERL-FEL at Japan Atomic Energy Agency (JAEA). The ERL consists of an injector, a merger, a main linac and a return loop. An electron bunch generated by injector is further accelerated by main linac and delivered to the FEL undulator. If we assume a typical conversion efficiency of 1% from the electron energy to the laser energy, the electrons energy of 99% remains unused after the FEL undulator. The energy-recovery is a technique to recycle this unused electron energy to improve the total efficiency of the FEL from the electricity power to the laser power. This recycling of the unused electron energy is possible by decelerating the electrons at the main linac as seen in fig.1. The decelerated electron beam goes to a beam dump. As a result, the energy-recovery technique enable one to accelerate high-power electron beams with small capacity of RF sources.

In the ERL, a fresh electron bunch is injected to a main linac for acceleration at any time, and we can keep an electron beam of small emittance and/or ultrashort pulse duration. This flexible manipulation of transverse and longitudinal dimension of electron bunch is a common feature to linear accelerators, and generation of high-power CW beams is a strong point of storage rings. Thus, the ERL has advantages of linear accelerators and advantages of storage rings simultaneously. Due to these excellent advantages, the energy-recovery linac is now considered as one of the important topics in accelerator science and technology, and a session for ERL has been regularly organized in xPAC since PAC-2003. In this paper, we overview current status of ERLs in the world, and give a detail description of the ERL light source project in Japan.

[#] hajima.ryoichi@jaea.go.jp

HIGH-POWER FELS

From a historical point view, concept of energy-recovery linac was first proposed for an electron collider in 1965, in which electrons are decelerated for energy recovery after passing an interaction point[1]. However, the ERL technology has been developed for high-power free-electron lasers. In 1980s, experimental attempts for increasing FEL power by energy-recovery linacs were conducted at Los Alamos National Laboratory[2] and Stanford University[3]. These early experiments indeed had a certain impact on ERL development, but they revealed the fact at the same time that the ERL requires sophisticated technology of superconducting accelerator. An energy-recovery linac for practical use was first demonstrated at JLAB IR-demo FEL (Thomas Jefferson National Accelerator Facility) [4], which employed CEBAF-type superconducting cavities. Following this first demonstration of ERL-FEL, two ERL-FELs were built in JAERI (Japan Atomic Energy Research Institute) and BINP (Budker Institute of Nuclear Physics).

In JAERI, a research program towards a high-power free-electron laser started in 1987. In the research program, a 17-MeV superconducting linac was developed and a high-power FEL lasing was demonstrated with the linac[5]. For the further enhancement of the FEL power, the linac was modified into an energy-recovery configuration. Design of the ERL started in 1999, and after a construction period, demonstration of ERL was completed in 2002[6]. In order to make best use of energy-recovery, the injector current has been enlarged with keeping the same RF sources for the main linac. The original injector equipped with two 6 kW solid-state amplifiers have been replaced by two 50 kW IOTs, and the repetition rate of the gun pulser has also been doubled from 10 MHz to 20 MHz. The injector beam current of 10 mA is now available (originally 5 mA) [7]. The FEL power has reached to 0.75 kW with an electron beam of 136 kW (17 MeV, 8 mA). The FEL power is now restricted by energy acceptance of the return loop [8].

The ERL at BINP is a unique facility based on a normal conducting accelerator of 12 MeV operating at 180 MHz. An FEL for high-power THz radiation was developed utilizing this ERL. The first lasing of the FEL was achieved in 2003 and laser power of 20 W has been obtained in THz region[9]. They are also constructing the second FEL with a 40-MeV electron beam, which will be the first multi-turn

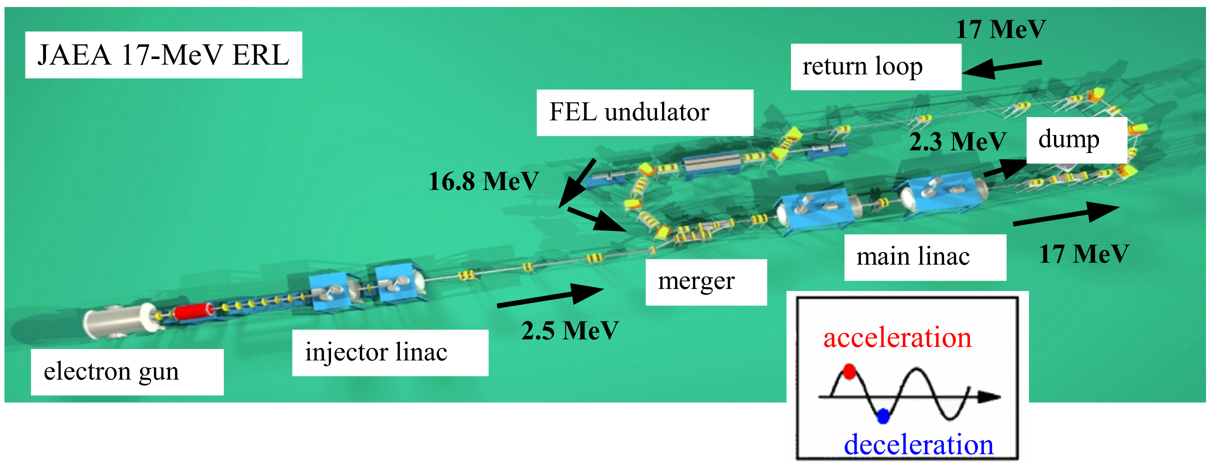

Figure 1: The energy-recovery linac at JAEA.

(4-turn) ERL [10]. These two FELs share the same linac and are installed in a vertical plane and a horizontal plane, respectively.

The IR-demo FEL at JLAB has been upgraded into a 160-MeV ERL, which is called "FEL upgrade". As a result of the upgrade, the electron beam power has been enlarged from 48 MeV, 4.5 mA (IR demo) to 160 MeV, 9.1 mA (FEL upgrade). This enlargement of the beam power has boost up the FEL power [11]. They recently achieved the record of high-power FEL, 14.26 kW at 1.6 μm[12]. Another FEL for UV wavelength is planned to install at the ERL.

From successful operation of these facilities, it has been confirmed that ERL is a suitable device for a high-power FEL. Scalable enlargement of FEL power up to 10 kW level has been clearly demonstrated and further enlargement towards a 100 kW FEL is surely convincing by reinforcement of electron beam power through increasing injector current, increasing electron energy with additional accelerating structures, increasing electron energy with multi-turn configuration.

ERL FOR FUTURE LIGHT SOURCES

The advantages of ERL, high-average current and high-brightness, are also intrinsic properties for future X-ray light sources. The first proposal of ERL light source was given by a group of BINP at the 1st Asian Particle Accelerator Conference, which is "MARS – diffraction limited 4th generation X-ray source"[13]. The term "diffraction limit" means the condition that an electron beam has smaller divergence than the emitted photon beam, and given by $\varepsilon \leq \lambda/4\pi$, where ε is geometrical emittance, λ is radiation wavelength. It is known the geometrical emittance is reduced by linear acceleration, that is adiabatic damping of transverse phase space. If we have an electron beam of normalized emittance $\varepsilon_n = 0.1$ mm-mrad and accelerate the beam to 6 GeV, the beam becomes diffraction limit for hard X-rays of $\lambda = 0.1$ nm.

Diffraction microscopy by using coherent X-rays is now an emerging topic of synchrotron radiation research, because it can be applied to obtain an image of non-crystal material [14]. In an ERL light source with diffraction limited electron beams, the coherent fraction of 10 keV X-ray becomes 20% or more, while the coherent fraction is around 0.1% in the most brilliant beam line of 3rd-generation light sources. Thus, the number of coherent photons in ERL light sources will be increased by two orders of magnitude from existing light sources, and the ERL light sources will promote strongly novel science with coherent X-rays. Figure 2 shows calculated X-ray brilliance for SPring-8 and a future ERL light source, where we assume ERL parameters: electron energy of 6 GeV, geometrical emittance of 8.5 pm, beam current of 100 mA, and electron energy spread of 0.04%. It can be seen the average brilliance is improved by two orders of magnitude in the future ERL light source. This improvement of brilliance corresponds to the increasing of coherent fraction.

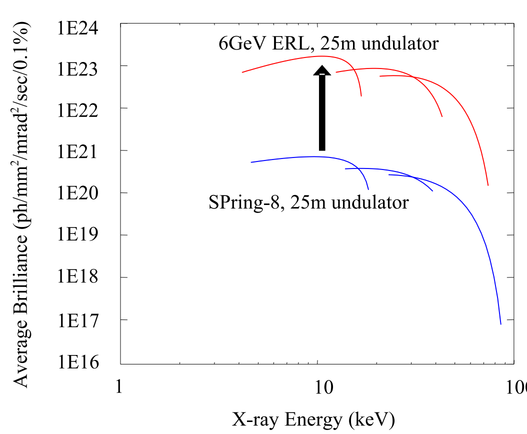

Figure 2: Average X-ray brilliance for SPring-8 and a future 6-GeV ERL.

The ERL light source also drives ultrafast X-ray science by utilizing femtosecond electron bunches, which can be generated from a well-established technique of electron bunch compression in a linac or an arc section.

There are three major R&D activities for future ERL light sources in the world, 4GLS at Daresbury, Cornell ERL, and ERL in Japan. In Daresbury, they propose an ERL light source, 4GLS, which consists of a 800 MeV ERL for undulator radiation, an XUV FEL branch, and a 25-35 MeV ERL-FEL for infrared radiation[15]. Now, a 35 MeV ERL is under construction as a prototype to develop technologies relevant to the future ERL light source. Recently, they obtained the first electron beam from a photocathode DC gun [16].

Cornell university has a plan to built a 5 GeV ERL light source utilizing an existing CESR tunnel. They are developing an injector, which fulfills requirements of the future ERL light source, normalized emittance of 0.1 mm-mrad and average current of 100 mA[17].

The status of ERL light source in Japan is described in the following section.

THE ERL LIGHT SOURCE IN JAPAN

In KEK (High Energy Accelerator Organization), a design study of ERL light source was conducted and a report of the design study was published in March, 2003[18], in which a 2.5-5 GeV ERL was proposed as a successor of 2.5-GeV Photon Factory, a 2nd-generation light source.

The FEL Research Group at JAERI, who developed the 17-MeV ERL-FEL, changed its name to ERL Development Group concurrently with the reorganization of two national institutes in Japan, merging of JAERI and JNC (Japan Nuclear Cycle Development Institute) into JAEA (Japan Atomic Energy Agency) in October, 2005. In the midterm plan of JAEA approved by Japan's government (2005-2009), the ERL group is in charge of development of an electron gun for a future ERL light source as well as operation of the 17-MeV ERL-FEL. They also designed a 6-GeV ERL light source[19].

Encouraged by world-wide increasing demands for next-generation light sources, Japanese Society for Synchrotron Radiation Research (JSSRR) set up an ad-hoc committee to discuss next-generation light sources in Japan. The ad-hoc committee for future light sources was headed by Prof. Yoshiyuki Amemiya (Univ. Tokyo) and involved both light source users and accelerator scientists. They started discussion in March 2005, and after several meetings the committee submitted a recommendation in September 2005[20]. The recommendation was finally approved by JSSRR. In the recommendation, they addressed that next generation light source in Japan should contain both an XFEL as an ultimate light source for astonishing progress in specific science and an advanced ring-shaped light source to promote a cutting-edge science in broad area. The latter part of the recommendation was followed by another JSSRR committee, the ad-hoc committee for advanced ring-shaped light sources headed by Prof. Amemiya (from October 2005 to August 2006). The committee concluded that an energy-recovery linac is a most promising candidate for an advanced ring-shaped light source, which will lead us to innovation of synchrotron radiation research in both its quality and quantity, and national-wide research and development for future ERL light sources should be initiated immediately.

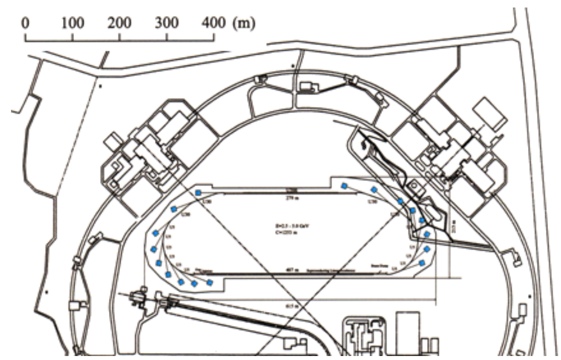

Figure 3: Proposal of a 5-GeV ERL at KEK (Tsukuba campus) presented at the JSSRR public hearing.

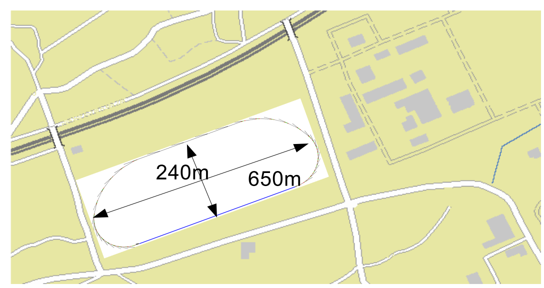

Figure 4: Proposal of a 6-GeV ERL at JAEA (Naka-west campus, former ITER site) presented at the JSSRR public hearing.

During the above critical discussion in JSSRR, they had a public hearing for future light source proposals in Japan. In the hearing at April 12, 2005, four institutes presented their plans, SCSS-XFEL by RIKEN[21], Super-SOR by ISSP[22], 6-GeV ERL by JAEA[19], and KEK presented two plans, 5-GeV ERL[18] and 3-GeV super storage ring. The super storage ring is a storage ring optimized for small emittance, and equipped with crab cavities for generation of femtosecond bunches in a straight section[23], and a set of skewed quadrupoles and a solenoid magnet to generate a round beam in another straight section[24].

In the Photon Factory of KEK, they had discussed the merit of the ERL and the super storage ring in detail. Finally, they concluded that a 5 GeV class ERL should be the most suitable candidate of their future plan to foster cutting-edge experiments, as well as to support a large variety of users' demands from VUV to X-rays[25].

Following the decision of KEK-PF, JAEA and KEK had a negotiation for possible collaboration on the development of ERL technologies, and reached to the agreement for the collaboration. They signed a memorandum of understanding at March 10, 2006. Thereafter, a joint R&D team has been organized for the development of ERL technologies, and the design study of a future ERL light source. The joint team involves members of KEK, JAEA, ISSP, SPring-8, UVSOR. A high-brightness electron gun[26] and superconducting cavities [27] for the future ERL are under development by the joint team. They plan to build a test facility of 60-200 MeV ERL as a prototype of their future ERL light source of 5 GeV class[28].

SUMMARY

We have overviewed the status of energy-recovery linacs for high-power free-electron lasers and future X-ray light sources. The ERL, which produces high-power electron beams with small emittance and ultrashort pulse duration, is a promising device to realize high-power FELs of 10 kW or more and next-generation X-ray light sources with coherent X-rays and ultrashort X-ray pulses. Extensive R&D efforts towards such future ERLs are now conducted in the world. An electron gun for high-average current and small emittance, and a superconducting cavity for high-average current are critical components for future high-power FELs and next-generation X-ray light sources based on the ERL technology. The details of these technological challenges are given by accompanying papers[29].

Adding to the above applications, there are other proposals to make use of ERLs for high-energy physics. An electron cooler for high-energy ion collider is proposed at BNL/RHIC, where a prototype ERL is under development. It is also possible to use ERLs for electron accelerators of electron-ion colliders. Two proposals, eRHIC at BNL and ELIC at JLAB are under consideration. These applications of ERLs for high-energy physics are described in a separate paper[30].

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