ELPH, Towards Scientific Research Core Based on Electron Accelerators

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ABSTRACT

ELPH, a research center for ELectron PHoton science, is belongs to a Japanese national university, Tohoku University. We probe substances in the nature with electron and photon beams. Currently three electron accelerators are operational for contributions to scientific research fields such as radiation chemistry, nuclear physics, accelerator science, and related sciences and technologies. In this article, research activities in ELPH are briefly introduced together with describing respective accelerator systems.

INTRODUCTION

The Research Center for Electron Photon Science (ELPH), formerly the Laboratory for Nuclear Science (LNS), was founded in 1966 at the faculty of science, Tohoku University. A large-scale 300 MeV electron linac was completed in 1967, and the 300 MeV linac commenced to provide the beams to not only nuclear physics but also various scientific fields. In addition to relatively higher beam energy for university accelerators, the 300 MeV linac had been operated at a tremendous repetition rate such as 300pps, which is still impressive for the current linac technology. The 300 MeV linac played an important role in the scientific field of nuclear physics and achieved a number of significant results such as a study of giant resonances in deformed nuclei via electron inelastic scattering. Furthermore, a pulsed-neutron beam from a dense target irradiated by the high-power electron beam was developed for solid-state physics, material science and other related fields, by the first director of the laboratory, Dr. Motoharu Kimura. This historical 300 MeV linac no longer exists as major components suffered serious damage due to the Great East Japan Earthquake on March 11, 2011.

Since there was no technical support for the 44-year-old linac, recovering its whole function was impossible. Nowadays superconducting technology has been developed for high average power electron beams, so that a high-repetition normal conducting linac seems to be left behind. This means it may require a huge budget to reconstruct a 300 Hz – 300 MeV linac. Consequently, we have decided to separate major functions of the linac, i.e. production of short-lived radioisotopes (RI) and beam injection into a 1.2 GeV booster synchrotron. Among five 25 MW-klystron modulators, two adequate modulators were recovered as main power sources for a 300 Hz – 60 MeV linac for RI-production. Other usable components and devices in the old linac have been stored for possible malfunctions in near future. A beam transport line into an experimental room where there is a target station for RI-production was also improved by introducing a new dispersive arc and a dispersion-free beam line. The memorial old linac was revived as a linac that can provide an extremely high beam power of 10 kW and is now dedicated to RI production. Accordingly handling of the high-power beam has been greatly improved, so that the stable beam is able to be achieved in a short tuning time. In the meantime a 1.2 GeV booster synchrotron, the so-called STB-ring, was also recovered and reincarnated as a 1.3 GeV booster-storage ring (BST-ring) by introducing high-performance synchrotron tracking power supplies. The BST ring is now able to store the high beam current of more than 100 mA due to replacing quadrupole magnets with novel sextupole-quadrupole combined magnets to cure the head-tail instability. A 90 MeV injector linac was newly constructed in which an originally developed thermionic RF gun was introduced in order to reduce the cost considerably. The role of the old linac is then distributed to the 60 MeV high-power linac and the 90 MeV injector linac, and parallel operation of two linacs is now indeed possible. The alteration of the 300 MeV linac, a symbol of the long history of ELPH and LNS, implies the opening of a new era of the laboratory.

ELPH HIGH-POWER LINAC

Short-lived RI-production and application

Short-lived RI produced by high energy beams from particle accelerators are widely applied in various scientific field. Since detection sensitivity of radioactive isotopes is good, RI is suitable for trace microelements analysis and atomic level structures in materials. Proton-rich radioisotopes are usually produced using hadron machines such as cyclotrons because (p/α, n) and (p/α, 2n) reactions are dominant. On the other hand, the electron beam does not produce RIs directly. Electrons are converted to Bremsstrahlung γ rays by a dense target, and then γ rays induce photo nuclear reactions such as (γ, n) and (γ, p) in the case of E1 giant resonance in nuclei being well excited. Accordingly, the electron linacs can produce different kinds of RIs than do cyclotrons. In order to excite the giant resonance and produce significant amounts of RI, a beam energy of 40 ~ 50 MeV and an average beam power of several kW are required. The 60 MeV linac at ELPH shown in Fig.1, which is a relatively small system with low electricity consumption, satisfies this condition well [1]. In addition, there is a hot-lab equipped for treating large amounts of RIs and for chemical separation as well.

Fig.1: ELPH 60 MeV high-power linac.

Recently radioactive medical isotopes have received much attention in healthcare, both for diagnostics and for cancer treatment. Technetium-99m (^{99m}Tc) is the most popular RI in medical imaging diagnosis. Since ^{99m}Tc decays quickly (half-life is about 16 hours) a patient is exposed to 141 keV γ-rays for a short time. In order to obtain ^{99m}Tc, molybdenum-99 (^{99}Mo) is required as a parent isotope. Several important medical isotopes have been so far produced in nuclear reactors since the 1960's. Nowadays, however, such old reactors seem not to be safe because of huge amount of high-level radioactive waste. We are facing a risk of shortage of medical isotopes. However relatively small electron linacs such as ELPH have potential as alternatives and local production for local consumption might be possible. We have already finished basic research for production of ^{99}Mo via the photoreaction ^{100}Mo(γ, n)^{99}Mo in collaboration with a Japanese medical isotope industry [2], and we concluded that the estimated total cost including a bland-new facility will allow profitable operation. Table 1 shows a summary of short-lived RI supply in 2018 using the ELPH high-power linac.

New ULQ2 beamline challenges proton radius puzzle

A notable feature of the ELPH high-power linac is not only a high beam power but also a high duty factor,

Table I. List of RIs provided to users in 2018.

Radioisotope	Quantity (kBq)
^{99}Mo	44,000
^{43}K	40,480
^{46}Sc	12,000
^{136}Cs	11,280
^{180}Ta	10,000
^{57}Ni	9,050
^{202}Tl	9,000
^{47}Sc	9,000
^{42}K	8,200
^{135m}Ba	4,800
^{88}Zr	2,500
^{57}Co	2,280
^{203}Hg	1,400
^{132}Sc	1,010
^{56}Ni	1,000
Others (14 RIs)	4,860
Total	**170,860**

which is quite important for nuclear physics experiments. In order to keep a constant counting rate in experiments for steady data acquisition, continuous-wave (cw) or cw-like temporal structure of the beam is preferred. The duty factor of the ELPH high-power linac is 1 % as a result of a 3-microsecond macropulse with 300 Hz repetition rate that is, apparently, far from an ideal cw-beam. It is, however, very high for a normal conducting linacs. In 2019, a new beamline, ULQ2, for low energy electron-scattering experiments was completed. The major purpose is to solve the proton radius puzzle by means of precise measurements of electron-proton scattering. The proton charge radius puzzle was suddenly turned into a problem ten years ago, because one measured by the Lamb shift of muonic hydrogen atoms was found to be smaller and greatly outside the error of the previous well-known value [3]. Although the electron-scattering is a classical but reliable method for measuring the charge radius of nuclei, we noticed that the low momentum side of experimental cross section data in old electron-proton scattering experiments is quite insufficient to determine the radius with high accuracy [4]. The ULQ2 beamline has been carefully designed to perform complementary experiments employing electron energies bellow 50 MeV, which will be pursued soon.

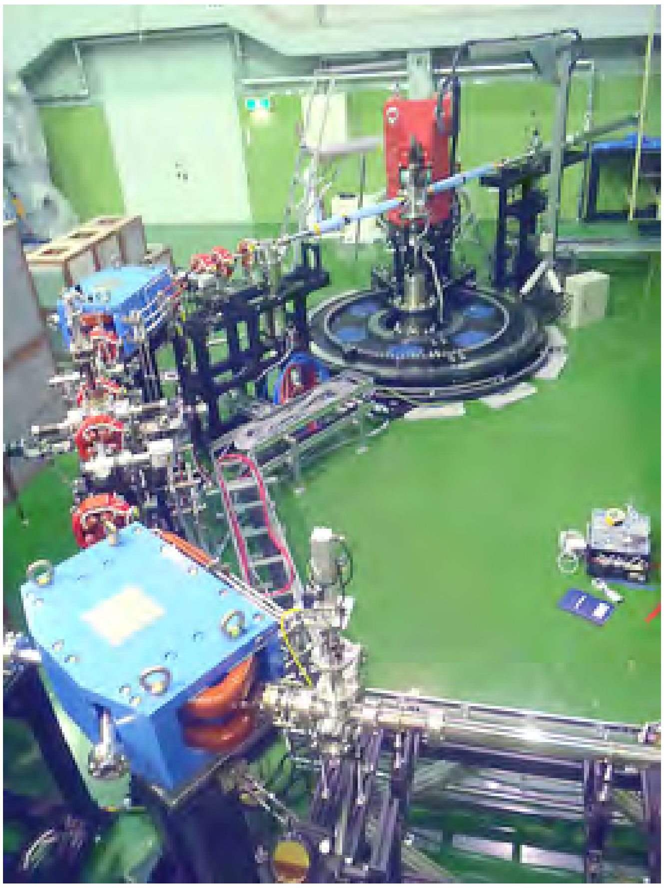

Fig.2: ULQ2 beamline with a compact high-resolution spectrometer (red dipole magnet) installed at a branch of the beam transport line of the ELPH high-power linac.

HADRON PHYSICS WITH NOVEL GAMMA-RAY SOURCE

High-energy photons are one of the powerful tools for nuclear physics, as well as particle physics including detector development. Among some high-energy γ-ray sources currently available in the world, ELPH operates two facilities. At a synchrotron radiation facility, SPring-8, a particular beamline, LEPS2, operated in collaboration with the Research Center for Nuclear Physics, Osaka University, provides high-energy γ-rays up to 2.1 GeV by means of external laser photons for Compton backscattering. Meanwhile the γ-ray source at the ELPH-BST ring is based on Bremsstrahlung from an internal thin-wire target. Scattered electrons in the ring are detected by a plastic counter array (tagging counters) installed in a synchrotron-bending magnet to tag energies of the Bremsstrahlung γ-rays [5, 6]. Currently two beam-lines (the NKS2 beamline and the GeV-γ beamline) are available and both beam-lines cover the energy range from 0.8 GeV to 1.26 GeV. At the GeV-γ beamline, an additional experimental beamline of high-energy positrons, that are created via annihilation of high-energy γ-ray, is also available. After a macro-pulse of 90 MeV electrons is injected into the ring, energy ramping is immediately started. It takes about 1 sec to reach 1.3 GeV, and the target wire is inserted to produce Bremsstrahlung γ-rays. Since a considerable number of scattered electrons go out of the dynamic aperture of the ring, the ring current is quickly decreasing to zero, and then the ring magnets are back to the setting for beam injection. Energy resolution of tagged γ-rays is from 2 to 6 MeV depending on the location of the tagging counter for which the maximum counting rate is $\sim$ 100 MHz. In the actual experiments, the overall counting rate is usually 20 MHz for an initial ring current of 30 mA, which is a compromise between the counting rate and the ring sequence cycle (typically 17 sec). Temporal structure of the γ-ray spill is tuned by the wire position control to be almost flat.

According to quantum chromodynamics (QCD), hadrons made of 3 quarks (*baryons*) or 2 quarks (*mesons*) are held together by the strong force, which are most fundamental particles of the matter. After entering the 21st

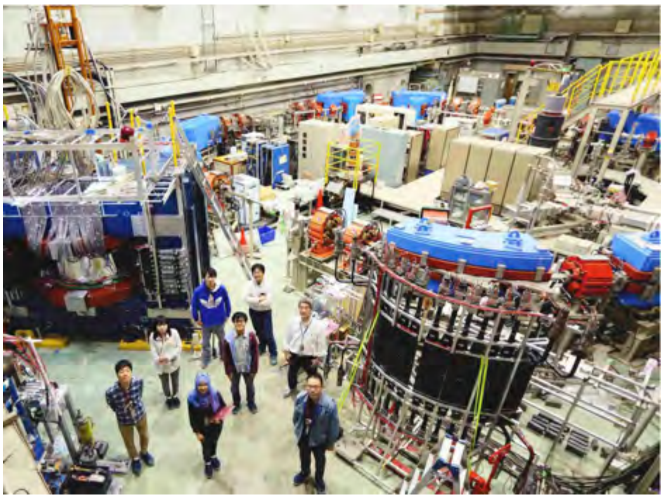

Fig.3: ELPH 1.3 GeV Booster-Storage (BST) ring with a large acceptance spectrometer (left side).

century, some exotic hadrons such as *tetraquark* states and *pentaquark* states were founded experimentally [7, 8]. However, the structures of such exotic hadrons are still open questions. Meanwhile, the most exciting latest result from the ELPH GeV-γ beamline is that three states of the 6-quark baryon (dibaryon) in the photon-deuteron reaction of ($\gamma d \rightarrow \pi^0\pi^0 d$) were discovered [9, 10]. In order to identify whether the 6-quark state is a *hexaquark* or a coupled two-*baryon*, a new research area in hadron physics, dibaryon spectroscopy, has now opened.

FEMTOSECOND ELECTRON PULSE FACILITY

Energy and power used to be highlights of pioneering accelerator performance. Other characteristics such as low emittance, short pulse duration and low energy spread are, however, have received the most attention

Fig.4: 50 MeV t-ACTS, femtosecond electron pulse facility.

among electron accelerators in the last 20 years. X-ray free electron lasers (XFEL) were the very likely stimulating motivation.

Coherent radiation, electromagnetic radiation in which waves have a constant phase relationship, emitted from an electron beam was firstly observed at LNS, former ELPH, in 1989 [11]. Since wavelengths sufficiently shorter than electron bunches are mostly coherent, intensity is proportional to the square of number of electrons. At ELPH, very-short electron beam pulses are available at the t-ACTs facility (test accelerator as coherent terahertz source). t-ACTs consists of an original thermionic radiofrequency (RF) electron gun followed by a 3-m-long accelerating structure and produces an electron bunch length of 80 femtosecond (~25μm) employing a velocity bunching scheme in the accelerator structure [12]. Since the energy range is from 20 to 50 MeV, intense coherent radiation in the terahertz region is able to be produced. At the moment, coherent transition radiation up to 4 THz can be provided for experiments. In addition, a crossed-undulator system is also under development as a variable polarized terahertz source to be used for circular dichroism spectroscopy [13]. As for accelerator science, novel beam diagnostic tools employing coherent radiation such as Cherenkov and Smith-Purcell effects are being developed [14].

FUTURE PROSPECT

Nowadays superconducting radiofrequency (SRF) linacs are paid much attention because of their capability for advanced research in science and technology. In order to extend current research activities at ELPH, and to cultivate cross-fertilization of scientific fields, we have investigated introducing a compact superconducting linac as the inheritor of the present high-power linac. In the 1970's, accelerator projects with niobium (Nb) superconducting cavities were established, and in the 1990's, large scale machines such as CEBAF at Jefferson Lab., etc were successfully operated. Looking at electron SRF machines, Euro-XFEL at DESY has just started to provide photons to users and some other XFEL machines are now under construction. Regarding rather small and compact machines, a 36 MeV SRF linac at the ELBE facility, HZDR has been actively working for multiple purposes such as high-field THz pulse, mid-and far-infrared FEL, positron beam, neutron time-of-flight and Bremsstrahlung γ-ray. Those SRF linacs have been based on 2-K superconducting technology. To maintain a superconducting state in the cavity, a large scale liquid He refrigerator with liquid N thermal shield is required. Those operating cost is, of course, pretty high. However, in 2015, the possibility of 4-K SRF cavity was proposed at Fermilab using high-temperature superconductor [15]. A high-accelerating gradient was demonstrated at 4.2 K by using a Nb_3Sb coated SRF cavity. Although multi-cell coating techniques are still under development, we hopefully expect that high-temperature superconductors will be a promising candidate material for SRF cavities, leading to a great reduction of system size and running cost, which are really significant aspects for university-size accelerator facilities. We have already started to discuss a future accelerator project employing the latest SRF technology, and the expected potential for expansion of the science and technology based on intense electron cw-beams [16].

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