FEL ACTIVITIES IN JAPAN

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Abstract

Outline is presented of activities on free-electron lasers (FELs) in Japan with a stress on shorter-wavelength region. Oscillation of the FELs has been achieved on 3 storage rings, 4 normal-conducting linacs, and a superconducting linac. There are a few FEL projects with the purpose of supplying the FELs to users, in which one is working. The ASE (amplified spontaneous emission) lasing with high-energy electron beam and long undulator is in the stage of design work. In the millimeter wavelength region, (self) amplification has been achieved at several facilities by the use of induction linacs and pulselines.

1 INTRODUCTION

Free-electron laser (FEL) is now receiving great attention in Japan due to its feasibility of high peak power, wide tunability, etc. FEL projects in Japan cover quite a wide range of wavelength from millimeter to ultraviolet (UV) and possibly vacuum ultraviolet (VUV) as seen from Fig. 1 which shows the FEL projects in Japan in terms of laser wavelength and electron energy. Each symbol denotes the kind of accelerator used The numerical values are not precise, because the FEL wavelength is widely tunable and the goal is subject to change. The solid symbol means that the lasing has been achieved in oscillation mode. Refer to the text for the acronyms of the institutes. Fig. 2 shows the location of the FEL projects. There are a few projects of ASE (amplified spontaneous emission) by the use of high-energy electron beam from RF linear accelerators (RF linacs). However the projects are in the stage of basic feasibility study, and not shown in Figs. 1 and 2.

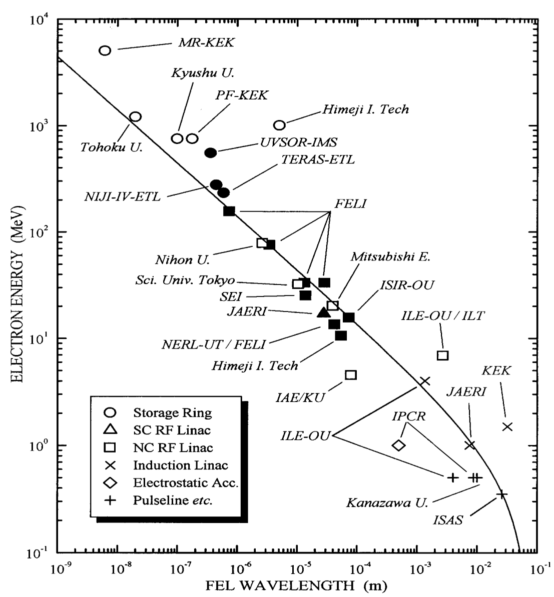

Figure 1 FEL projects in Japan.

2 STORAGE-RING FEL'S (SRFELS)

The quality of an electron beam in a storage ring is excellent, and the SRFEL is suitable for oscillation in shorter-wavelength region

2.1 Electrotechnical Laboratory (ETL)

The SRFEL project at the ETL began in 1985 on the storage ring TERAS dedicated to generation and use of synchrotron radiation, when an OK (optical klystron) was introduced in the ring. Basic studies on the optical cavity, electron-beam quality, were carried out [1]. The FEL gain was measured in 1989, and oscillation in the visible wavelength region was achieved in 1991 [2]. All of the above were the first in Asia.

However, the straight section was so short that the FEL gain was insufficient for shorter-wavelength FEL. A compact racetrack-type storage ring NIJI-IV, which is the first storage ring in the world dedicated to the FELs, was constructed (Fig. 3), and the first storage of the electron beam was achieved in 1991. A 6.3-m OK [3] was installed in 1992 in one of the long straight sections, and the first lasing in the visible region was achieved [4]. Since then, the ring was modified to realize a lower-emittance mode, and a lasing in UV region (350 nm) was achieved in 1994 [5]. There still remained instabilities of the stored beam. The coupled-bunch instability was suppressed by a feedback system, and the head-tail instability was recently suppressed by adding four

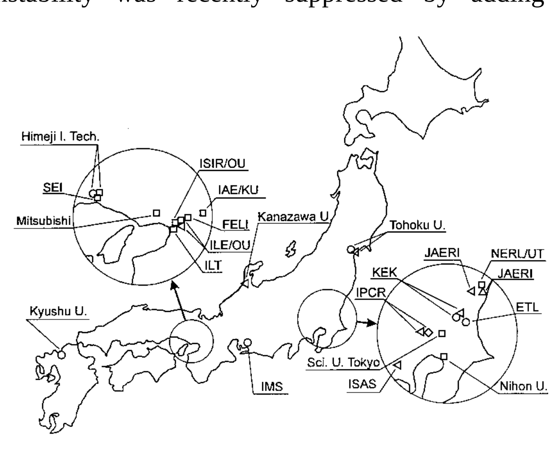

Figure 2 A map of FEL projects in. Japan.

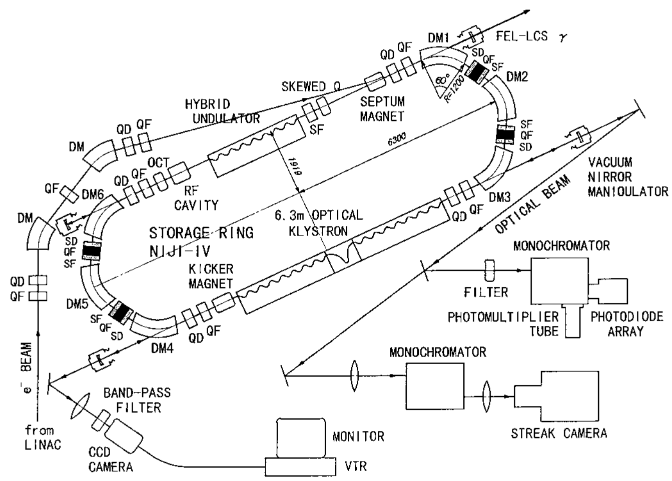

Figure 3 Schematic view of the NIJI-IV FEL system.

compact sextupole-magnet sets. As a result, oscillation at around 300 nm was achieved in 1998 [6].

As to the optical cavity, surface degradation of dielectric multilayer mirrors due to exposure to UV and/or VUV radiation was restored by an oxygen-plasma treatment for the first time in the world [7]. Furthermore, the degradation was almost completely recovered by annealing after the above treatment.

2.2 Institute of Molecular Science (IMS)

On the 750-MeV storage ring UVSOR for research into molecular science, the first lasing at 430 - 480 nm was achieved in 1992 with 500-MeV electron beam and a planar OK after a gain measurement [8]. A third harmonic RF cavity was then installed in order to obtain higher electron density, and a lasing in UV region (300 nm) was observed in 1993 [9]. The macro- and micro-temporal structure of the lasing was studied intensively by the use of a streak camera with a dual sweep.

They constructed a helical OK [10] shown in Fig. 4 to raise the FEL gain and avoid the mirror degradation due to higher-harmonic radiation. Lasing at 239 - 243 nm was achieved in 1996 with the OK and a higher electron energy of 600 MeV, [11]. This is the shortest FEL wavelength ever achieved in the world, though quite close to 240 nm obtained on the storage ring VEPP-3 at the Budker Institute in Russia [12].

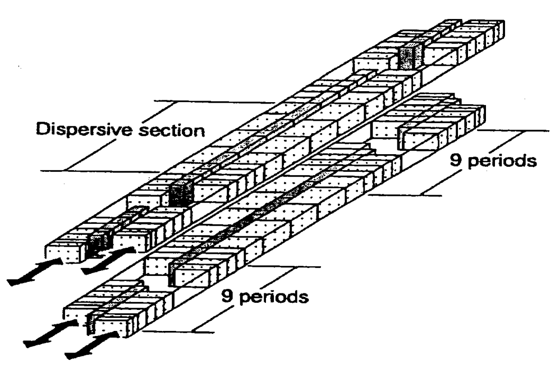

Figure 4 Schematic view of the helical undulator of the IMS [10].

2.3 Other SRFELs

Some SRFELs are planned at the KEK (High Energy Accelerator Research Organization). Spontaneous-emission spectra have been measured at 177 nm with the electron-beam energy of 750 MeV in the PF (Photon Factory). Shorter-wavelength FELs are planned on the PF and the MR (modified main ring) also. At the Tohoku University, some FELs are proposed [13] on the existing stretcher-booster ring of 0.3 - 1.2 GeV and a new 1.5-GeV storage ring being proposed. The FEL wavelength will cover the range from visible to 20 nm. At the Himeji Institute of Technology (HIT), a quasi-isochronous ring called new SUBARU is now being constructed. The injector will be the linac for the SPring-8. FELs of 0.2 - 10 μm with high average power is being designed [14]. A 1.3-GeV storage ring and a high-gain single-pass FEL with a pulsed and detachable bypass straight section were proposed at the Kyushu University. Unfortunately, there is no funding yet.

3 NORMAL-CONDUCTING RF-LINAC FELS

Normal-conducting RF linac is the most popular accelerator throughout the world. The beam quality is moderately good and high-energy beam is easily obtained.

3.1 Nuclear Engineering Research Laboratory of University of Tokyo (NERL-TU) /Free Electron Laser Research Institute (FELI)

The first lasing with RF linac in Japan was achieved at the NERL-TU in 1993 in cooperation with the FELI.[15]. The linac, which had been used for pulse radiolysis, was modified by adding a high-brightness electron gun and a double prebuncher. The wavelength was 42.8 μm with the electron-beam energy of 13.4 MeV.

3.2 Free Electron Laser Research Institute Inc. (FELI)

The FELI is a consortium company established in 1991 financially supported (over 8 billion Japanese yen) by the Japan Key Technology Center (70 %) and 13 corporations (30 %). The purpose of the project was to construct a FEL facility and share the FEL to applications. It is the only one users' facility in Japan. The facility shown in Fig. 5 consists of an S-band 165-MeV linac with a thermionic gun and 6-MeV injector, 4

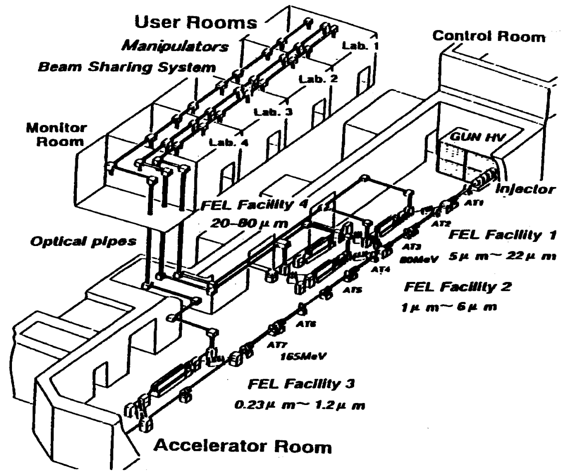

Figure 5 Bird's-eye view of the FELI facility.

undulators, and 4 experimental rooms and ample experimental equipment. The most salient feature of the linac is its macropulse length of 20 μs supported by RF sources of 24-μs macropulse with high stability.

The first lasing at 5 - 7 μm with the FEL-1 was achieved in 1994 [16], and the lasing with the FEL-2 [16] and 3 [17] in 1995. The wavelength of 287 nm achieved here with electron-beam of 155 MeV is the shortest in the world with RF linac. The lasing with the FEL-4 at 18 - 40 μm was achieved in 1997 [18]. The FELs are used by many groups for many fields of application such as semiconductor physics, medical science, bio-science, and isotope separation [19].

3.3 The Institute of Scientific and Industrial Research of Osaka University (ISIR/OU)

The first lasing was achieved in 1994 at the wavelength range of 32 - 40 μm [20] on an L-band linac. Since then, most of the FEL system except the linac has been remodeled with attention to avoid diffraction loss of the laser to be extended to longer wavelengths. The plan view of the FEL system is shown in Fig. 6. Lasing at 21 - 126 mm was observed recently with the electron-beam energy of 14 - 17 MeV [21]. The wavelength of 126 μm is the longest in the word with RF linac.

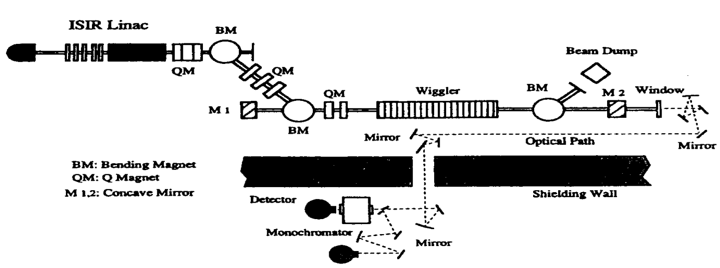

Figure 6 Plan view of the OU/ISIR facility.

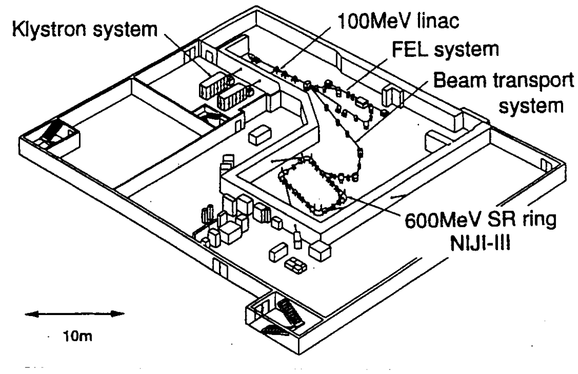

Figure 7 Bird's-eye view of the Harima Research Laboratory of SEI.

3.4 Sumitomo Electric Industries, Ltd. (SEI)

A compact superconducting storage ring NIJI-III originally constructed in cooperation with the ETL, is in operation at the Harima Research Laboratories (Fig. 6) of the SEI, and it is used for microfabrication of devices, and so on. The injector of the ring is an S-band and 100-MeV normal-conducting linac, which is also used for research into the FEL. An FEL oscillation at 14 μm was observed on the system with the electron energy of 25 MeV [22]. It was the first lasing of a FEL on the linac used as an injector of a storage ring.

3.5 Himeji Institute of Technology

A FEL system with an S-band 6-MeV and a photocathode made of LaB_6 has been constructed at the Himeji Institute of Technology as a preparation for the SRFEL planned on the new SUBARU described in *2.3*. The first lasing was observed at the wavelength region of 65 - 75 μm in 1996 [23].

3.6 Other Normal-Conducting RF-Linac FELs

An amplification of coherent synchrotron radiation at 2.73 mm was observed at the Institute of Laser Technology (ILT) in corporation with the Institute of Laser Engineering of Osaka University (ILE-OU) [24]. The electron beam was generated by the same linac as in *3.5.*. A FEL system is being constructed at the Nihon University with the purpose of lasing in the UV region [25]. Commissioning of the system is now going on. At the Institute of Advanced Energy of Kyoto University (IAE/KU), a FEL at around 80 μm with an electron beam from a RF gun with 4+1/2 cavities and a staggered-array undulator is being prepared. Basic studies on high-brightness electron beam and laser-electron interaction are also going on. Fig. 8 shows an example of the results of computer simulation on the behavior of electron beam in the RF gun, which shows the effect of

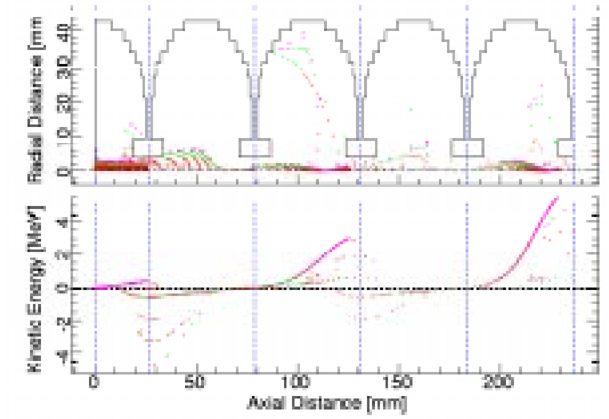

Figure 8 Snapshot of RF fields, electron positions, and kinetic energies in a RF gun

backstreaming of electrons [26]. A new project of Users' facility of infrared FEL on a RF linac has just started at the Science University of Tokyo. The tentative goal is the FEL of 5 - 16 μm with electron-beam of 32 MeV. A FEL experiments at the Mitsubishi Electric, Co. used to be carried out on a 20-MeV linac, but there are no news recently. Feasibility studies on the ASE FELs have been begun at the Accelerator Test Facility of KEK and SPring-8. Electron-beam quality in a long undulator is the most important key issue.

4 SUPERCONDUCTING RF-LINAC FELS

Superconducting (SC) linac is characterized by high efficiency because there is no power loss at the wall of the accelerating tube. A SC linac and a FEL system is now in operation at the JAERI (Japan Atomic Energy Research Institute). A lasing of a FEL at 28 mm with electron-beam energy of 17 MeV was observed in 1997 [27], and stable oscillation was achieved close to the end of the same year [28]. FELs of high-average power at shorter wavelengths with a recirculation of the electron beam and application of the FEL are their ultimate goal.

5 INDUCTION-LINAC AND PULSELINE FELS

These accelerators are characterized by high current

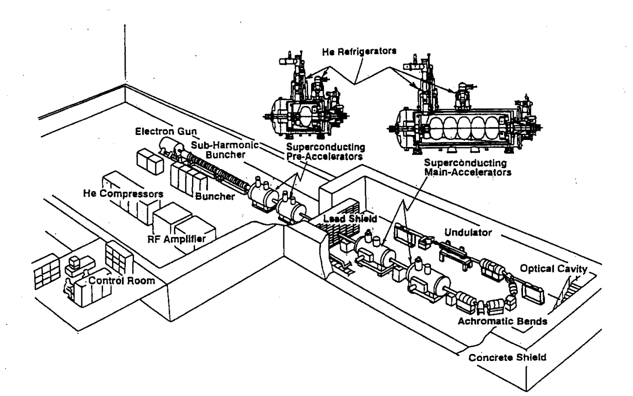

Figure 9 Bird's-eye view of the JAERI SC-linac FEL system.

of the order of kA and rather low energy. The electron beam is often called REB.

At the ILE-OU, ASE experiments were carried out at about 1.36 mm with a 4-MeV and 200-A REB from an induction linac [29]. At the KEK, amplified FEL peak power of 100 MW was obtained with a 1.5-MeV electron beam, and input power from a 9.4-GHz magnetron. [30]. The purpose was to use it for a RF source of a two-beam accelerator. The above two projects seem to have been shut down. Research on millimeter-wave FEL for tokamac heating with a focusing undulator was carried out at the JAERI with 1-MeV electron beam. A superradiant emission at around 40 GHz was obtained [31]. At the ISAS (Institute of Space and Astronautical Science), a compact circular FEL was developed, and an ASE of 10.5 - 50 GHz was obtained. [32]. A cold REB was developed at IPCR (institute of Physical and Chemical Research) with a pioneering Zn photocathode [33] and electrostatic acceleration, and a small-signal FEL gain was measured at about 34.4 GHz. The project was, unfortunately, shut down. A unique Smith-Purcell type FEL was developed at the Tohoku University, and the lasers of 2.5 - 13 mm are used for spectroscopy [34].

6 GENERATION OF QUASI-MONOCHROMATIC PHOTON BEAM BY LASER COMPTON BACKSCATTERING

quasi-monochromatic photon beam is generated from backscattering of laser light from relativistic electron beam (LCS, laser Compton scattering). A few systems with conventional lasers are already working [35]. Use of a SRFEL is quite advantageous because the filling factor is excellent and the electron beam can be reused. This kind of research has been begun on the NIJI-IV/ ETL [36] and the UVSOR/IMS [37] in Japan. A is that a large portion of the stored electron beam is lost due to the energy loss from the interaction. A lower-energy FEL-LCS system is planned at the ETL, and intermittent injection is intended at the IMS.

7 CONCLUSIONS

Recent progress in the field of FEL in Japan has been remarkable, and many new projects are going to start. Though most of the FEL research used to be carried out parasitically on accelerators for other purposes, accelerators dedicated to FELs have become popular after the NIJI-IV. The future FELs will be rather big users' facilities in which the problem of cost is moderate, compact and economical FEL systems aiming at commercial use, and also compact systems built at (graduate) universities for education.

It is interesting to note that though FELs have become possible by the development of accelerator technology from the necessity of high-energy physics, now the progress of FELs is inversely stimulating the accelerator community, because quite high-brightness electron beam is necessary for high-quality FELs.

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