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RIKEN-JASRI Joint-Project for SPring-8 XFEL
Accelerator Group
Group Director, Dr. Tsumoru Shintake

Successful lasing of the X-ray Free Electron Laser (XFEL) prototype.

Completion of the electron beam generation technology for the future XFEL.

Main points

- Key technologies of national importance. A leading step in the worldwide race for the development of the X-ray Free Electron Laser (XFEL).
- Completion of the electron beam source and of the accelerator: the world highest performances with unique innovative Japanese technology.
- Contribution to the development of the technology for imaging, measurement and utilization, in a new wavelength region for the next light source.

Executive summary

On June 20th, the electrons generated and accelerated by the prototype accelerator for the future X-ray Free Electron Laser (XFEL) lased successfully. The prototype accelerator (Fig.1) is a realization of the "RIKEN-JASRI Joint-Project for the SPring-8 XFEL" (Director, Toichi SAKATA), a joint promotion organization of the Institute of Physical and Chemical Research (RIKEN, President Ryoji NOYORI) and the Japan Synchrotron Radiation Research Institute (JASRI, Director General Akira KIRA).

Lasers are presently an active field of research in optical science, with examples such as the blue diode laser proposed for data storage or the excimer laser used in eye surgery to correct defective eyesight. Since the XFEL attracted attention as "the dream light source" to obtain wavelengths in the X-ray region, an intense worldwide R&D effort has been underway.

An X-FEL lases when a very high quality electron beam passes between rows of carefully arranged magnets, the so-called undulator. The group lead by Tsumoru SHINTAKE has developed a new "electron gun" and a high accelerating efficiency
"C-band accelerator" which succeeded in giving a very high quality electron beam with an emittance*2 of 3πmm · mrad. As it passed through an "in-vacuum undulator" - a device developed primarily at SPring-8*4 -, the electron beam lased at a wavelength of 49nm with a 110kW maximum output power.

The construction of the X-FEL will start in 2006 on the SPring-8 site: with a total length of 800m it will be possible to accelerate the electrons up to an energy of 8GeV. Completed in 2010 it aims at the first X-ray lasing in the world. When compared to similar projects overseas, it is expected to have better performances, with a more compact design and for less than half the cost, thanks to its highly efficient electron gun and C-band accelerator, as well as to the in-vacuum undulator. The successful completion and lasing of the X-FEL prototype shows that Japan is a step ahead in the development of a laser in the X-ray region.

Thanks to the XFEL, new Science will bloom in wide range of fields, such as the development of new drugs through the structure analysis of membrane proteins which are at present difficult to study, or in nanotechnology with the creation of new functional materials.

1. Background
The discovery of X-rays and synchrotron radiation and the invention of the laser have opened the way to new Science and Technology, while contributing to the development of industry. X-rays, for example, are used for medical examination in hospitals, while lasers are found in many applications, from CD players (semiconductor lasers) to eye surgery (excimer lasers). In the same way, SPring-8, the largest and most powerful synchrotron radiation facility in the world, has produced numerous results in fields such as material or life science, as well as in industrial applications.

Laser and synchrotron radiation sources are complementary tools with different characteristics: while the synchrotron radiation produced by SPring-8 is very bright (i.e. has a high brilliance) and covers a broad wavelength ranges (mainly from hard X-rays to vacuum ultraviolet rays), laser light is brighter but at specific wavelengths only, the photons being emitted in a coherent beam. Now that SPring-8 has been completed, the operation of a laser in the X-ray region is eagerly expected.

2. Research approach
(1) Realising a laser without a mirror.
Conventional laser sources use a medium (gas or solid) and an external stimulation (electrical or optical) to generate light. Here, the research group concentrated on the
so-called "Free Electron Laser" method to realise a short wavelength laser. In a Free Electron Laser, the electrons are not bound to a medium (hence the name): The electron beam is the medium. A mirror is put at both ends of an undulator\(^1\) and, as the light emitted by the electrons traveling through the undulator goes back and forth between the mirrors, lasing is achieved through the interaction of the electrons and the light. However, since no mirror can reflect efficiently short wavelength X-rays, it is not possible to obtain laser light in the X-ray region with this method. The breakthrough came at the beginning of the nineties: instead of having many reflections between the mirrors to obtain resonance and then lasing, it was proposed to obtained lasing in a single pass, without reflection (Fig. 2). In other words, lasing can be obtained by increasing the length of the undulator up to the distance covered by the multiple reflections: this is the so-called Self Amplified Spontaneous Emission or SASE principle.

(2) A highly effective and compact accelerator 100% "made in Japan": the C-band accelerator.

The construction of a 60m long prototype accelerator started at the beginning of 2005 as a proof experiment. In order to achieve lasing with a high peak power in a short wavelength region within such a short distance, an accelerator with a high acceleration efficiency was needed. The C-band (i.e. working at 5712M\(^3\)Hz) accelerator proposed by T. Shintake in 1992 was chosen as the best candidate: working at a frequency twice the frequency of the microwave traditionally used for acceleration, it has a high energy acceleration efficiency (30 MeV/m). In other words, with an efficiency twice that of conventional accelerators, it is possible to accelerate the electron beam with half the length needed with conventional accelerators. The successful development and the ultimate performances of the C-band accelerator, are the result of more than 10 years of R&D by the group lead by T. Shintake with the collaboration of numerous Japanese companies (Fig. 3). This includes the R&D done on the high precision processing of the high purity copper "acceleration tube", as well the "klystron" and the "pulse power supply" which provide the high frequency needed for acceleration.

(3) The source of a high quality beam: An ultra-high voltage electron gun with a world record.

To achieve self-amplification over a short length, it is necessary to have a high quality (i.e. low emittance\(^2\)) and high current electron beam. Stability (in position, timing, size, charge, etc.) is also of prime importance. All of these are parameters determined by the electron source: this is why the SPring-8 XFEL project team opted for a novel
thermionic-gun over the conventional laser-driven electron-gun used in accelerators. A single crystal of \( \text{"CeB}_6\) is used as the electron source (cathode). While standard cathodes need only to be heated at about 900°C, it is necessary to heat the \( \text{CeB}_6\) crystal at the ultra-high temperature of 1450°C. However at such temperatures, conventional filament heaters can burn off and therefore cannot be used. A heater had to be developed from graphite, a material mechanically and chemically stable at high temperature (Fig. 4). The emittance of the electron beam generated by RIKEN's original electron-gun reached a world-record of \(1.1\pi \text{ mm} \cdot \text{mrad}\).

(4) A leading light source: the in-vacuum undulator.
As for the electron gun and the C-band accelerator, the undulator is also result of in-house developments. In the in-vacuum undulator (Fig. 8) the magnet rows are placed inside the vacuum chamber: while this has the advantage to enables the undulator gap to be close down to a very narrow height, this requires an extremely high level of technological know-how (high vacuum, compensation of magnetic forces, etc.). Developed by H. Kitamura and his group, the in-vacuum undulator is extensively used at SPring-8 and as been adopted by various synchrotron radiation facilities in the world: the Pohang Light Source in Korea, the Paul Scherrer Institute in Switzerland, the ESRF in France, etc.
The undulator used in the XFEL prototype accelerator contributes to the downsizing of the whole facility: working at a smaller magnetic gap, the period of the undulator can reduced down to 15mm, one-third that of previous devices. Considering its performance and effectiveness, it is the smallest undulator in the world: the high-level of its performance has been demonstrated with the accelerator prototype.

(5) Installing the equipment with a high precision: alignment technology.
Beam trajectory control and alignment are two of the most challenging issues in SASE FEL accelerators. If all these first-rate equipments (gun, accelerator, undulator, etc.) are not installed with a high precision, the accelerator cannot work. The prototype accelerator benefited from SPring-8 expertise in high accuracy beam alignment and beam orbit control technology: the experience gained by T. Ishikawa's group during the construction of numerous beamlines at SPring-8, including the longest one in the world (1 km), have contributed greatly to this project.
A new support stand based on cordierite (a magnesium-aluminum silicate used as an insulator in power lines) has also been developed. Cordierite was selected for its low heat expansion coefficient (1/20th that of iron) which insures a very good stability. A floor
A grinding machine, "Yuka to Kensaku", has also been developed by T. Shintake, in order to install each support stand horizontally: the grinding flatness achieved by this machine is about $10\mu m^2$ (Fig. 5). Thanks to all these efforts, the straight line error is within $50\mu m$.

3. Results
After starting the test operation of the prototype machine, the electron beam generated by the electron gun, passed through the undulator for the first time on November 25th, 2005. Thanks to a thorough beam tuning, a high quality electron beam with an emittance of $3\pi mm \cdot mrad$, a charge of $0.25nC$, and a pulse width $1ps$ can be stably generated and accelerated: this is a big step toward the realization of the XFEL. The lasing capability of the prototype accelerator was demonstrated when the electron beam was injected into the undulator: the beam lased at wavelength of $49nm$ with a maximum output power of $110kW$ (Fig. 6-1). This wavelength is the 2nd shortest in the world, following the $13nm$ observed at DESY (Deutsches Elektronen-Synchrotron, Germany) FEL in April 2006.

4. The Future: Perspectives
Because of its short wavelength, its coherency and its high brilliance, the XFEL can be used in various research areas. For example, the structure of many proteins of the cellular membrane, which play an important role in medicine and life science and which have attracted attention as target for new drugs, is not well understood. And while X-ray structure analysis requires the crystallization of the protein, most membrane proteins are difficult to crystallize. However thanks to its high brilliance and coherence, the XFEL should be able to solve even a single molecule of protein, without having to crystallize it. The race for the development of an XFEL has been intensifying worldwide with projects at SLAC (Stanford Linear Accelerator Center) in the U.S. and DESY in Germany. In Japan, the XFEL has now been authorized as one of the key technologies of national importance in the 3rd Science and Technology Basic Plan and it is promoted as a national project. The total length of the XFEL (Fig. 7) to be built on the SPring-8 site by 2010, is approximately $800m$, its maximum acceleration energy is $8GeV$, and its lasing wavelength is $0.06nm$.

Thanks to the skills and experience of its researchers, the facility planned by the RIKEN-JASRI Joint Project for the SPring-8 XFEL will be the most compact in the world, with a cost and a total length less than half of those of Europe and the United-States. It is also, with DESY, one of the only two light sources in the world which has succeeded in operating a SASE laser. In other words, this shows that Japan is one of the most
likely candidates to make the XFEL dream come true. Once completed, the plan is to use the prototype accelerator and the XFEL as shared facilities just as SPring-8. The prototype machine will not only be used for the research and development required for the completion of the XFEL, but also for various studies which are expected to take advantage of its high coherence and moderate intensity. It is expected to contribute, for example, to the development of photocatalysis, or to the development of high sensitivity analysis methods, with the selective excitation of specific material. The prototype accelerator is also expected to lead to breakthroughs in photonic science through the application of optic-communication technology in a wavelength range that has not been used up to now.

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Additional explanations

*1 Undulator
A device made of two rows (up and down) of magnetic poles with alternate N and S polarity. An electron moving between the rows will "zigzag" with a small periodicity and emit a bright light at a specific wavelength. SPring-8, RIKEN's large synchrotron radiation facility, is the world pioneer in the practical application of in-vacuum undulators. It has built the so-called long in-vacuum undulator with a total length of 27m, which generates world top-level synchrotron radiation.

*2 Emittance
One of the parameters which expresses the character of an electronic beam. A large value means that the beam spreads spatially easily. On the contrary, if the value of the emittance is small, the beam is sharp and is said to be of good quality.

*3 Pico, Nano, Micro, Kilo, Mega, Giga
Prefix p (pico) denotes $10^{-12}$, n (nano) denotes $10^{-9}$, μ (micro) denotes $10^{-6}$, k (kilo) denotes $10^3$, M (mega) denotes $10^6$, G (Giga) denotes $10^9$,
When the trajectory of an electron traveling at almost the speed of light is bent by a magnetic field, the electron emits an electromagnetic wave in its direction of propagation. This electromagnetic wave is called "synchrotron radiation". When the electron energy is high and the change of direction is large, the radiation includes light of short wavelength, such as X-rays. There is three large synchrotron radiation facilities of the third generation, namely SPring-8, APS (United States), and the ESRF (France). In SPring-8 (electron energy: 8GeV), synchrotron radiation can be obtained in a broad wavelength region such as far-infrared rays, visible rays, vacuum ultraviolet rays, soft X-rays and hard X-rays. It is utilized as shared facility by national and international users in fields, such as material science, geoscience, life science, environmental science, and industrial research.

Fig. 1: The X-ray Free Electron Laser (XFEL) prototype accelerator tunnel. View from the electron gun side (left) along the beam trajectory.
Fig. 2: Outline of the Free Electron Laser.

Fig. 3: The C-band accelerator. Inset: the klystron in front and the tank of the modulator power supply (silver color box) at the back.
Fig. 4: The low emittance electron gun.
Fig. 5: "Yuka to Kensaku" performing floor grinding. As shown in the inset, the grinded surface is rectangular.
Fig. 6-1: Electron beam profile. Since it is measured with a fluorescent screen, the actual beam size is in fact smaller.
Fig. 6-2: Spectrum. At the wavelength of 49nm, the light emitted is 6000 times stronger than the spontaneous undulator radiation.
Fig. 6-3: Peak power as a function of the electron charge. The peak power increases exponentially with the electron charge, showing the lasing effect.
Fig. 7: Yellow: the Accelerator and Beamline R&D building in which the prototype machine has been installed. Red: Artist view of the 8 GeV XFEL now under construction by the RIKEN-JASRI Joint-Project for the SPring-8 XFEL.
Fig. 8: In-vacuum undulator. The magnets rows are installed in the vacuum chamber (the silver colored cylinder).