Constructing the world's top-performing x-ray laser beam

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The year 2011 marked the first successful amplification of an x-ray free electron laser beam at the RIKEN SPring-8 Angstrom Compact Free Electron Laser (SACLA) facility. Later that year, Hitoshi Tanaka led the facility to its peak operation, producing a stable x-ray laser beam with a wavelength of 0.63 ångströms—the world's shortest. X-ray lasers such as SACLA permit researchers to directly observe microscopic structures, as well as molecules or atoms that move at extremely high speeds.

A 'dream light'

Researchers at SPring-8 (Super Photon Ring-8 GeV), a large-scale synchrotron radiation facility based at the RIKEN Harima Institute, analyze the structure of atomic-scale objects, such as proteins, using x-ray radiation. This requires the crystallization of samples, a process that is difficult to apply to the membrane proteins that are often important targets for drug discovery.

Alternatively, the structure of atomic-scale objects can be observed with coherent light—in which the peaks and dips are in phase—without requiring samples to be crystallized. Laser beams emit coherent light but until recently were believed to produce oscillations only in the infrared, visible or ultraviolet light ranges. A laser that could emit light in the x-ray spectrum—with the extremely short wavelength of approximately 1 ångström (Å)—was considered to be a 'dream light.'

The first conceptual designs for an x-ray free electron laser (XFEL), or an x-ray laser beam, were proposed in the 1980s. Within decades, projects to build XFEL facilities were planned in the United States, Europe and at RIKEN in Japan.

Eventually in 2009, researchers in the United States constructed the world's first x-ray laser in an XFEL facility—an improvement of an existing accelerator. Then, in June 2011, SACLA (SPring-8 Angstrom Compact Free Electron Laser)—RIKEN's own XFEL—successfully amplified an x-ray laser beam.

In an XFEL, a high-quality electron beam produced by an electron gun is accelerated using a linear accelerator and compressed with a bunch compressor. The high-density, high-energy electron beam is then made to snake through undulators to generate an intense light beam, which later interacts with another electron beam to produce an x-ray laser (Fig.1).

With a total length of 700 meters, the RIKEN SACLA facility is much smaller than the XFEL facilities in the United States or Europe, which are about 2 and 3.4 kilometers long, respectively. In spite of its compact dimensions, SACLA produces a stable x-ray laser beam with the world's shortest wavelength. SACLA's success did not come easily, however; the researchers who worked on its development faced a series of technical challenges.

Compressing the electron beam

RIKEN was able to create the highly compact SACLA facility by standardizing

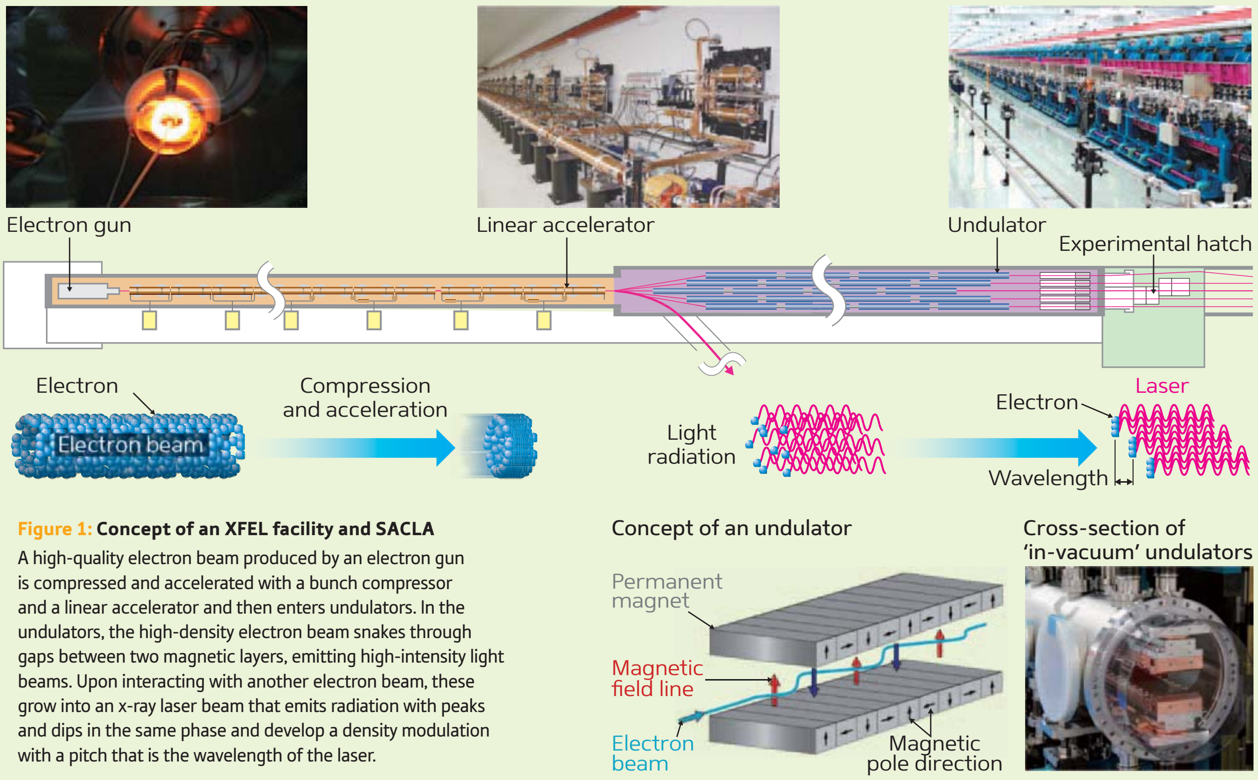

Figure 1: Concept of an XFEL facility and SACLA
A high-quality electron beam produced by an electron gun is compressed and accelerated with a bunch compressor and a linear accelerator and then enters undulators. In the undulators, the high-density electron beam snakes through gaps between two magnetic layers, emitting high-intensity light beams. Upon interacting with another electron beam, these grow into an x-ray laser beam that emits radiation with peaks and dips in the same phase and develop a density modulation with a pitch that is the wavelength of the laser.

and improving the performance of SPring-8's in-vacuum type undulators. Within an undulator, an electron beam is made to snake through a gap between two layers of alternately arranged north and south magnetic poles. Conventionally, two layers of magnetic poles are placed outside the vacuum vessel through which the electron beam is designed to pass.

However, when two layers of magnets, each consisting of north and south poles separated by a shorter fixed pitch, are placed close to the electron beam, these in-vacuum type undulators allow the electron beam to snake through them over a shorter distance, producing an x-ray laser beam with a shorter wavelength—even when the electron beam's energy is low. Using this approach, RIKEN was able to shorten the undulators, and correspondingly, the linear accelerator. The overall XFEL facility was further downsized by using a C-band accelerator, which accelerates the electron beam more efficiently.

RIKEN then developed an electron gun to improve the quality of the electron beam and offset lower levels of energy and acceleration. Composed of a heated single-crystal cerium hexaboride cathode, the electron gun produced a high-quality electron beam in which the electrons were uniformly distributed within the cylindrical shape.

The beam met the quality standards demanded of SACLA, but in order to verify whether it could actually produce an x-ray laser, in 2005 RIKEN began construction of the SPring-8 Compact SASE Source (SCSS), a prototype accelerator of 60 meters in length, and a precursor to SACLA.

Tanaka, director of the XFEL Research and Development Division, was chosen to lead the project because of his experience conducting research into the stabilization and densification of electron beams at SPring-8. A major challenge in developing the SCSS was how to compress the electrons to 300 times their original density, without compromising the electron beam's initial quality.

"Some people advised me not to accept the offer because the SCSS was technically too difficult to complete. But the task did not seem impossible to me," Tanaka recalls.

Assessing feasibility

Construction of SACLA began in April 2006. Compared to the SCSS x-ray laser's oscillator wavelength of 490 Å, the target wavelength for SACLA was set at around 1 Å. In order to achieve this, the electron beam would have to be compressed up to 3,000 fold—ten times more than what was required for the SCSS.

At the time, researchers thought that in order to produce such a high-density electron beam, equipment of a correspondingly high accuracy and stability would need to be procured. "There is a limit to the accuracy of equipment. A simple evaluation predicted that it would not be feasible to construct a facility that could produce a stable electron beam compressed 3,000 fold using current technology," says Tanaka. "In spite of the successful construction of the laser oscillator in the SCSS, laser oscillation in the x-ray band was considered to be difficult by all researchers. Therefore, we decided to run a simulation to find out what level of accuracy or stability would be required of the associated equipment."

The simulation revealed that the accuracy or stability required for the

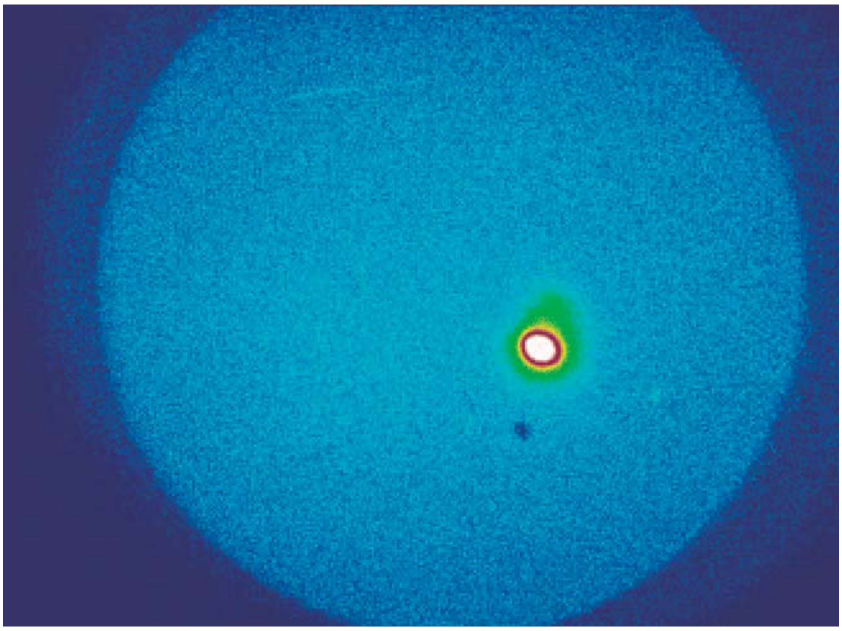

Figure 2: X-ray laser beam produced by SACLA
An x-ray laser beam is positioned at the white portion indicated by the small red circle near the center.

equipment in SACLA to function was almost the same as that required for the equipment in the US XFEL facility, where the compression ratio was about one-tenth of that in SACLA.

An electron beam is compressed in four stages, as Tanaka describes. "In the first stage, the speed of the electrons is adjusted along the direction of their forward movement. As with traffic during periods of congestion, we can compress an electron beam by creating a situation in which faster electrons at the back can catch up with slower electrons at the front. The simulation showed that an error in the compression process in the first stage would not contribute to an increase in the error after the compressed electrons passed through the subsequent compression stages. In this way, we began to see the light at the end of the tunnel in our quest to produce a stable x-ray laser."

A series of problems

By January 2011, SACLA was almost complete, and it was decided that beam tuning would begin in February. The first major problem faced by the researchers was the occurrence of anomalous light emissions that made observing the electron beam's condition impossible. "To diagnose the condition of a compressed electron beam, we observe its spatial distribution by forcing it to strike a thin metal film. However, it is not possible to diagnose its condition if the signal from the electron beam is hidden by anomalous light emissions," explains Tanaka.

"Anomalous light emissions were also a major issue for the US XFEL facility," he continues. "However, since the electron gun used in SACLA differed to the one used in the United States, we had underestimated the probability of there being any such emissions. Furthermore, experiments conducted with the SCSS to confirm the occurrence of anomalous light emissions under various operating conditions did not observe any such emissions."

Unfortunately, Tanaka and his team's conclusions did not hold up: anomalous light emissions were indeed present. "We held urgent meetings to discuss ideas for countermeasures and quickly created an observation system that could spatially separate any anomalous light emissions from the signal."

The team eventually solved the problem and continued with beam tuning, but the quality of the electron beam displayed on the monitor did not improve. "As we searched for the cause, I recalled an error that we had experienced with the monitor in an earlier experiment. We calibrated the monitor and finally succeeded in evaluating the quality of the electron beam correctly."

The final challenge faced by Tanaka and his team was to arrange the undulators in rows with an accuracy of 0.004 millimeters per 100 meters. "The technique used at the US XFEL facility—according to their report—was to analyze the observed data on the trajectory of the electron beam as it passed through the undulators and then to adjust the position of the undulators and ancillary devices. We were not satisfied with their method of analysis and came up with another idea," admits Tanaka. "We knew that electron beams follow the same trajectory when the undulators and their ancillary devices are arranged in rows, even if the beams are of different energies. Therefore, we decided to observe the trajectory of electron beams with different energies and adjust the position of the undulators and ancillary devices so that the beams would follow the same trajectory. Using this approach, we succeeded in arranging the undulators in straight rows."

As a precautionary measure, the team also observed the light radiation emitted from the electron beams, and found them not to be in perfectly straight rows. "In our first approach, we used data on the center of gravity of an electron beam. But later we noticed that an actual electron beam does not have a completely axisymmetric distribution and that the distribution can change slightly whenever the energy of the electron beam varies," points out Tanaka. "Therefore, we decided to change our approach by using light radiation instead of an electron beam to rearrange the undulators in straight rows. As we were the first to attempt this approach, we were able to set the undulators in perfectly straight rows to within the required accuracy, a fact that was verified by our subsequent success with laser amplification." Correspondingly, on 7 June 2011, the team finally managed to produce an x-ray laser with a wavelength of 1.2 Å (Fig. 2).

Producing the world's shortest wavelength

The researchers continued to tune the beam in SACLA to intensify the x-ray laser and stabilize its wavelength and intensity. "We adjusted the position of the electron beam to pass precisely through the center of the linear accelerator's acceleration tube and prevent the quality of the electron beam from deteriorating but regularly came across new locations where the beam would go off-center," continues Tanaka.

"Feeling that something was wrong, we examined these locations and discovered that eight of the acceleration tubes had significant curves in them, despite their having been straight when measured at the factory before shipment."

Tanaka later learned that curvature had been caused by packaging problems at the factory: the tubes were squeezed into boxes without sufficient space and eventually molded into their newly bent shapes.

The SACLA x-ray laser eventually succeeded in producing the world's shortest wavelength of 0.63 Å—almost half of the 1.2 Å achieved by the US XFEL facility. The SACLA facility opened to external users in March 2012, and the facility has been inundated with requests for experiments ever since. In addition, researchers in the United States are considering adopting the stabilization technique used by SACLA in the construction of their second XFEL facility.

Tanaka is aware of SACLA's low stability in comparison to SPring-8. For instance, the intensity of SACLA's x-ray laser tends to shift slightly when the facility is operated continuously, he explains. "Although we can use an advanced control program to automatically restore the intensity, we are actually correcting the deviation manually because we want our operating staff to understand the characteristics of the instability and to use their accumulated knowledge to investigate its cause. In this way, we hope to eliminate the factors of instability one by one in pursuit of ultimate stability."

Toward the observation of physical and chemical phenomena at the atomic scale

A main feature of the x-ray laser developed at SACLA is that the laser is emitted in a series of extremely short pulses, each with an emitting time of 10 femtoseconds. The light pulses should enable the observation of atoms or molecules that move at extremely high speeds when undergoing a dynamic process such as a chemical reaction, phase transition or structural deformation. "Unfortunately, the light in its current form does not allow us to continuously observe these phenomena because it is extremely strong and instantaneously destroys the samples," notes Tanaka. For now, samples must instead be measured at different stages of a reaction and the data then organized into chronological order.

"If we could directly observe and accurately reproduce the process of a phenomenon when matter fulfills a function, the results would produce enormous benefits for the whole of science. Drastically increasing the coherence of the x-ray radiation produced by the SPring-8 synchrotron radiation facility would allow us to continuously observe samples at the atomic scale without destroying the samples," says Tanaka. "I would really like to be able to measure the same samples with SPring-8 and with SACLA, but even in SPring-8, a top-performing facility with the world's highest level of brightness, coherent light accounts for only 0.1% of the x-ray light radiated."

A breakthrough in 2012 changed the situation. "European researchers published the design for equipment capable of increasing the proportion of coherent light in light radiation by combining multiple approaches that had not previously been used."

In May 2013, the RIKEN SPring-8 Center set up the Diffraction Limited Synchrotron Radiation Design Group, and Tanaka assumed the position of group director. "We aim to drastically increase the coherence of light radiation from SPring-8 by integrating our own ideas into the design published by the European researchers." Researchers at the SACLA facility also have plans to add more x-ray laser beam lines to the one currently available for measurements, as well as to further decrease the size of the facility.

"We will be able to add up to five x-ray beam lines," claims Tanaka. "Whereas in SPring-8, the light radiation from an electron beam that moves along the ring and the resultant 62 beam lines can all be used for simultaneous measurements, in the XFEL facility the number of beam lines is limited by its structure. This is why we focused on making the facility more compact," he explains.

"And if the overall length of the facility were to be further reduced to less than 100 meters by extending the technology developed at SACLA, we could even construct an XFEL facility at a campus or company's premises. This would offer many more researchers the opportunity to use an x-ray laser beam for their experiments."

ABOUT THE RESEARCHER

Hitoshi Tanaka was born in Tokyo in 1957 and was awarded his master's degree from the Interdisciplinary Graduate School of Science and Engineering of the Tokyo Institute of Technology. After working at the Atomic Energy Division of JGC Corporation, the RIKEN Cyclotron Laboratory, the Accelerator Division of the Japan Synchrotron Radiation Research Institute and the RIKEN XFEL Project Head Office, Tanaka joined the RIKEN XFEL Research and Development Division as divisional director in April 2011. Since May 2013, he has concurrently led the Diffraction Limited Synchrotron Radiation Design Group as group director.