

Quantum Radiation Energy Research Section

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1. Introduction

Coherent-radiation energy with a wide wavelength tunability and a high power is an indispensable tool for exploiting cutting-edge energy science. The research in this section aims at generating and applying new quantum-radiation energy. Free-electron laser (FEL) is one of such radiation. We have been developing a mid-infrared FEL, KU-FEL. To extend the study field wider wavelength region, a coherent compact THz source, and Laser Compton Gamma-ray (LCS) for isotope imaging have been carried out. Transdisciplinary research on renewable energy implementation, especially in rural areas in ASEAN, has also been promoted through international collaborations.

2. Free-electron Laser

FEL is a next-generation light source because of its very wide wavelength tunability, potential high efficiency, and high peak power. We have been developing several new approaches to improve our FEL system and application research under a collaboration research program.

2.1 KU-FEL

The target wavelength of KU-FEL is the MIR (Mid infra-red) regime, from 5 to 20 μm , with high-power and wide tunability for basic research on energy materials. Figure 1 shows a schematic drawing of the KU-FEL system. The KU-FEL consists of a 4.5-cell thermionic RF gun, a 3-m travelling wave accelerator tube, a beam transport system, a 1.8-m undulator and a 5-m optical resonator. The FEL device can now cover the wavelength range from 3.4 to 28 μm . The maximum macro-pulse energy that can be provided is around 80 mJ in a 2- μs macro-pulse at the wavelength of 8.5 μm . The FEL is routinely operated and opened for internal and external users.

For increasing the peak power of the KU-FEL, the photocathode operation of the 4.5-cell thermionic RF gun has been established. Under the photocathode operation, the micro-pulse energy of 100 μJ and the world's highest extraction efficiency (9.4%) of the oscillator-type FEL has been achieved. Then, the micro-pulse duration was shortened to 150 fs (~ 4.2 cycles at 11 μm). In addition, nonlinear compression of 8.6- μm FEL pulse was achieved, and the pulse duration was compressed from 146 to 106 fs (from 5.1 to 3.7 cycles) by passing through a 30-mm thick Ge plate.

For further increase of the peak power of KU-FEL, a new 1.6-cell RF gun has been installed at the upstream side of the accelerator tube. By using the new RF gun, the highest micro-pulse energy at 5 mm got 2.4 times as high as that obtained by the 4.5-cell RF gun.

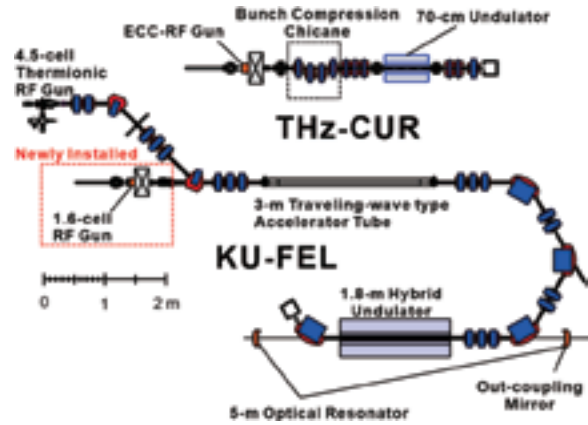


Fig. 1 Schematic drawing of the KU-FEL and THz-CUR

2.2 THz Coherent Undulator Radiation Source

A compact terahertz coherent undulator radiation source (THz-CUR in Fig. 1) has been constructed. It consists of an Energy-Chirping-Cell-attached (ECC) RF-gun, a solenoid magnet, a magnetic chicane bunch compressor, a triplet quadrupole magnet, a planar undulator, and a laser system for photocathode. In this device, short electron bunches are generated by the ECC RF gun and the bunch compressor. Intense coherent undulator radiation can be generated from short electron bunches.

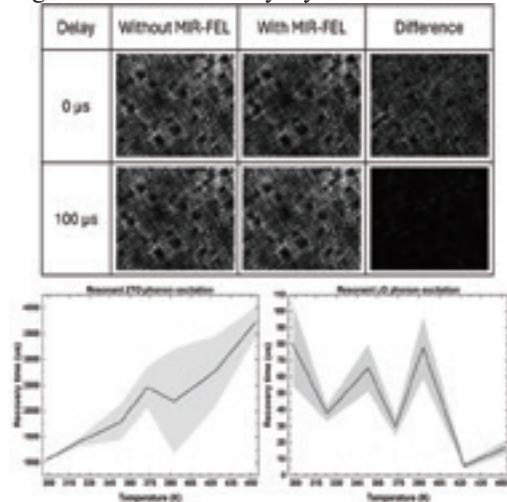
Recently, an optical cavity has been installed for demonstrating the pre-bunched FEL oscillator scheme in collaboration with Dr. Sakaue's group in Tokyo University. Coherent stacking of the coherent undulator radiations has been achieved.

2.3 Application of MIR-FEL and THz-CUR

Many application researches of MIR-FEL and THz-CUR have been performed under the Joint Usage/Research Center for Zero Emission Energy Research of our Institute. In FY2025, 16 external user groups used KU-FEL.

One of the many applications achieved using MIR-FEL is selective phonon excitation. In strongly correlated systems, it is beneficial to understand the role of each phonon mode on the material properties. Due to the widely tunable wavelength range of MIR-FEL, many phonon modes in the mid-infrared region are accessible. Selective excitations of Raman active phonon modes (LO mode of 6H-SiC, A_1 (LO) mode of GaN), Raman inactive mode (LO3 mode of SrTiO₃), and even, infrared inactive mode (T_{2g} of single crystal diamond) have been successfully observed through pump-probe experiments. Most recently, resonant excitations of the 2TO and LO phonon modes in NiO were performed at various temperatures (298 K to 523 K), and changes in the antiferromagnetic domain pattern over time were observed. The domain images, captured using magneto-optical birefringence microscopy, were analyzed using the Structural Similarity Index Measure (SSIM) image metric. Distinct recovery dynamics have been observed, where 2TO phonon excitation induced domain changes that persisted on the millisecond timescale with thermally retarded recovery, whereas LO phonon excitation resulted in microsecond timescale recovery, which accelerated with increasing temperature.

Fig. 2 Distinct recovery dynamics of 2TO and LO



phonon-driven antiferromagnetic domain pattern changes in Nickel Oxide

3. Isotope Imaging for Nuclear Safety and Security

A multi-isotope imaging method has been developed at BL1U beamline in UVSOR, Institute of Molecular Science. We succeeded in obtaining a 3D isotope image of ²⁰⁸Pb embedded in an aluminum cylinder. However, a quantitative evaluation of the specific isotope has not been achieved yet because of the high spatial dependence of the Laser Compton Gamma-ray beam. We proposed generating a flat spatial distribution with a beam size of a few mm in diameter, called a flat-LCS gamma-ray beam. The abundance of a natural lead sample has been tried by using the flat-LCS gamma-ray beam in UVSOR. Enriched ²⁰⁸Pb

rods of 6.2 mm thickness and a natural lead plate of 6 mm thickness were irradiated by normal LCS and flat-LCS gamma-ray beams. The NRF gamma-rays emitted from the witness ²⁰⁸Pb target were measured with two Ge detectors. The evaluation of the abundance of natural lead is evaluated to be 58.6% (LCS) and 58.7% (flat-LCS), which is a slightly high value from the standard abundance of natural lead, 52.4%. We are trying to find the reason for this discrepancy.

4. Social aspects of energy use

In Southeast Asia, significant progress has been made toward universal electrification, yet around 35 million people still lack access today. Much of the research on electrification challenges has focused on Africa and South Asia, often emphasizing economic, technological, and institutional factors while overlooking social dimensions. Since 2016, our group has examined the social impacts of electrification projects from a quality-of-life perspective, assessing changes in living conditions and social disparities across different contexts in Southeast Asia (Fig. 3). Using mixed methods from the social sciences, our findings show that renewable electrification can reduce reliance on expensive energy options while improving educational opportunities and social interactions. However, challenges remain, including limited livelihood improvements, the risk of reinforcing pre-existing inequalities, and issues related to system capacity and waste management. In parallel, we are expanding this work through research on energy justice and sustainable energy transitions, including analyses of the Water-Energy-Food (WEF) nexus in Madagascar and studies on clean cooking transitions in vulnerable communities.



Fig. 3 Rural electrification fieldwork locations 2016-2025

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Collaboration Works

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大垣英明, 京都大学研究連携基盤, フィールドワークとデータサイエンスを融合した超学際研究ユニット

Jordi Cravioto, 京都大学研究連携基盤, フィールドワークとデータサイエンスを融合した超学際研究ユニット

Financial Support

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