

## Quantum Radiation Energy Research Section

H. Ohgaki, Professor  
 T. Kii, Associate Professor  
 H. Zen, Assistant Professor  
 Jordi Cravioto Caballero, Program-Specific Assistant Professor

## 1. Introduction

Coherent-radiation energy with a wide wavelength tunability and a high power is an indispensable tool for exploiting cutting-edge science. The research in this section aims at generating and application of 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 study field wider wavelength region, a coherent A compact THz source, high Tc undulator for X-ray generation, and Laser Compton Gamma-ray (LCS) for isotope imaging have been carried out. Transdisciplinary research on renewable energy has also been promoted through international collaborations.

## 2. Free-electron Laser

FEL is a next generation light source because of its wide wavelength tunability where the conventional lasers cannot reach, potential high efficiency, and high peak power. However, the system is usually much larger and the cost is higher than conventional lasers. We are going to overcome these difficulties by exploiting an RF (radio-frequency) gun, a high Tc undulator, etc.

### 2.1 KU-FEL

The target wavelength of KU-FEL is MIR (Mid infra-red) regime, from 5 to 20  $\mu\text{m}$ , with high-power and tunability for basic researches 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, and a 1.8-m undulator and a 5-m optical resonator. The FEL device now can cover the wavelength range from 3.4 to 28  $\mu\text{m}$ . The maximum macro-pulse energy which can provide is around 40 mJ in a 2- $\mu\text{s}$  macro-pulse at the wavelength of 4.9  $\mu\text{m}$ . The FEL is routinely operated and opened for internal and external users.

Another topic of KU-FEL development is introduction of photo-cathode RF gun, which enables to generate higher peak power and wider tunable range MIR-FEL. Development of a UV-laser system for illuminating photo-cathode has been completed under collaboration with Dr. R. Kuroda, Researcher of AIST. In FY2014, we have achieved FEL lasing with photo-

electron beam generated from LaB<sub>6</sub> cathode. In FY2018, the laser system has been upgraded under the Q-LEAP project organized by MEXT. This upgrade increases the macro-pulse duration of the photocathode operation. Under the photocathode operation, the world highest extraction efficiency of the oscillator-type FEL has been achieved.

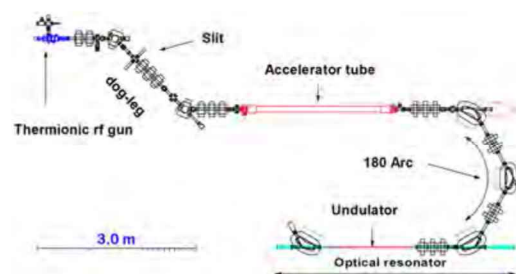


Fig. 1 Schematic drawing of the KU-FEL

### 2.2 THz Coherent Undulator Radiation Source

A new compact terahertz coherent undulator radiation source (THz-CUR) has been constructed. It consists of a 1.6-cell RF-gun, a solenoid magnet, a magnetic chicane bunch compressor, a triplet quadrupole magnet, a planar undulator, and a laser system for photocathode. Schematic view of the proposed system is shown in Fig 2. In this device, short electron bunches are generated by the photocathode RF gun and the bunch compressor. The electron bunches are injected to the undulator and intense coherent undulator radiation can be generated.

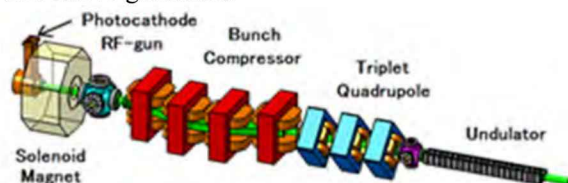


Fig. 2 3D image of THz coherent undulator radiation source.

The 1.6 cell RF gun used for the THz-CUR was replaced with an energy chirping cell attached RF gun for improving its performance under collaboration with Dr. Sakaue, Tokyo University. The gun utilizes a velocity bunching scheme for generating ultra-short electron bunch. A commissioning experiment has been done and the saturation of THz peak power due to the

space charge effect can be successfully suppressed.

The polarization control method of the THz-CUR has been developed under collaboration with Dr. Kashiwagi, Tohoku University. The polarization state of the THz-CUR can be easily controlled from linear to left-handed circular and right-handed circular without significant power loss.

### 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 JFY2020, 14 external user groups used KU-FEL.

### 3. Bulk HTSC Staggered Array Undulator

An undulator with strong magnetic field will play an important role in future synchrotron light sources and FELs. We have developing a new undulator which consists of stacked bulk high critical temperature superconductors array and a solenoid magnet. As a next prototype of this type of undulator, we have developed new prototype consists of a new solenoid whose maximum field was 6 T and GM cryocooler. Periodic magnetic field using bulk  $MgB_2$  array was demonstrated and better field uniformity than that of REBCO array was observed as shown in fig. 3.

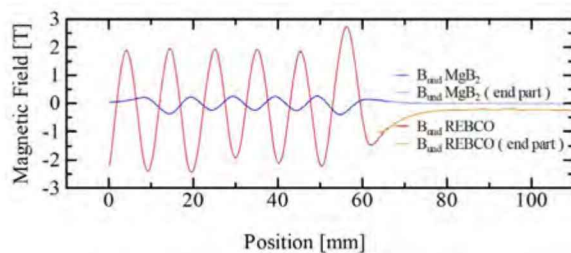


Fig. 3 Undulator field using the  $MgB_2$  array and the REBCO array were demonstrated. Although the measured field amplitude of the  $MgB_2$  array was smaller than that of the REBCO, the field uniformity for the  $MgB_2$  array was better than that of the REBCO.

### 4. Isotope Imaging for Nuclear Safety and Security

A Nuclear Resonance Fluorescence (NRF) method is a powerful tool for an isotope selective

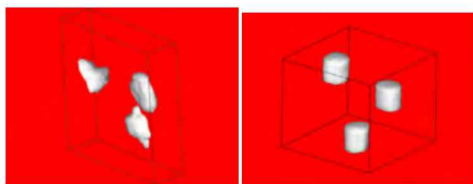


Fig. 4 Original isotope selective 3D image (left) and the fusion visualization image (right).

imaging. In 2021, we improved the image quality of the isotope selective 3D image by using a fusion visualization technique in combination with the NRF based rough CT image which provides the isotope distribution and a gamma-ray CT image which gives a high-resolution image of the CT target. A proof-of-principle experiment has been carried out at BLIU LCS beamline in UVSOR. The image quality of the original isotope ( $^{208}Pb$ ) selective 3D image (Fig.4 left) was dramatically improved by the fusion visualization technique, as shown in Fig. 4 right.

### 5. Social aspects of energy use

Electrification projects using renewables are essential to achieve SDG7. These projects can positively influence poverty eradication and community development. Our group investigates the effects of electrification on quality of life in rural contexts of ASEAN by comparing the process and outcomes of different electrification systems (Fig. 5).



Fig. 5 Rural electrification survey sites 2016-2022

In urban contexts of ASEAN, our group also conducts analyses on household roles in connection with efficient appliance purchasing using survey data and quantitative methods. Finally, in the context of Latin America, we also study geographical and socio-cultural characterizations of household energy services.

### Acknowledgment

All our research work have been supported by the KAKENHI, Q-LEAP(MEXT), JASTIP(JST), UVSOR Collaboration Research, The Heiwa Nakajima Foundation, The Murata Foundation, Hitachi Zaidan, CSEAS DASU (Kyoto University), and the Laboratory for Complex Energy Processes Collaboration Research (IAE).

## Collaboration Works

大垣英明, University of Malaya (マレーシア), 倉田奨励基金:「Before and After 手法による東南アジアにおける非電化地区への再生可能エネルギー導入の住民生活に与える影響に関する研究」

大垣英明, 森井孝, 片平正人, 野平俊之, モンゴル国立大学, インドネシア大学, フィリピン大学ディリマン校, ベトナム国家大学ハノイ校, ラオス国立大学, 王立ブノンペン大学, アジア新興国産天然資源を由来とする機能性物質創生のための高度分析研究拠点の形成

大垣英明, NSTDA (タイ), JASTIP「日 ASEAN 科学技術イノベーション共同研究拠点—持続可能開発研究の推進」

大垣英明, University of Malaya (マレーシア), JASTIP-net

大垣英明, Cravioto Jordi, University of Malaya (マレーシア), Fundamental Research Grant Scheme (マレーシア)

## Financial Support

### 1. Grant-in-Aid for Scientific Research

大垣英明, 基盤研究(B), F-LCS レーザーコンプトン散乱 $\gamma$ 線による同位体イメージングの高度化に関する研究

大垣英明, 基盤研究(B), LCS-NRF による同位体 3D イメージング法の基盤確立 (繰越し)

紀井俊輝, 基盤研究(A), 新材料 Mg B 2 と超伝導電流流体解析による新型アンジュレータ精密磁場制御法の確立 (繰越し)

Cravioto Jordi, 基盤研究(B), 包括的 QoL 評価法の確立: 東南アジアの僻地電化における幸福度と不公平

Cravioto Jordi, 若手研究, Comparative studies of culturally-based characterisation of energy services (期間延長)

### 2. Others

大垣英明, 国立大学法人東京大学, 「先端レーザーイノベーション拠点「次世代アト秒レーザー光源と先端計測技術の開発」部門」「自由電子レーザーで駆動する高繰り返しアト秒光源のための基礎基盤技術の研究」

大垣英明, 科学技術振興機構, サトウキビ収穫廃棄

物の統合バイオリファインリー

大垣英明, 科学技術振興機構, 日 ASEAN 科学技術イノベーション共同研究拠点—持続可能開発研究の推進—

大垣英明, 日本学術振興会研究拠点形成事業(B), アジア新興国産天然資源を由来とする機能性物質創生のための高度分析研究拠点の形成

大垣英明, 国立大学改革強化推進補助金, ICT を利用したハイブリッド型による国内外フィールドワーク・実習教材の開発

大垣英明, 理化学研究所, 次世代アンジュレータのための高温超伝導体の評価研究

Cravioto Jordi, (公財) 村田学術振興財団, QoL 評価法の提案: 東南アジアの僻地電化における幸福度とエネルギーの評価

## Publications

A. Khaled, H. Zen, H. Ohgaki, T. Kii, T. Hayakawa, T. Shizuma, M. Katoh, Y. Taira, M. Fujimoto, H. Toyoka-wa, Fusion Visualization Technique to Improve a Three-Dimensional Isotope-Selective CT Image Based on Nuclear Resonance Fluorescence with a Gamma-CT Image, Applied Sciences, 11, 24, 11866, 2021

H. Negm, H. Zen, H. Ohgaki, Comprehensive simulation study on CT isotope imaging beyond the experiment on the 208Pb based on nuclear resonance fluorescence, Journal of Nuclear Science and Technology, 2022

N. Sei, H. Zen, H. Ohgaki, Peak Shift of Coherent Edge Radiation Spectrum Depending on Radio Frequency Field Phase of Accelerator, Applied Sciences, 12, 2, 626, 2022

Y. Tanaka, M. Hashida, C. Hosokawa, H. Zen, T. Nagashima, N. Ozaki, S. Inoue, S. Sakabe, Mid-infrared free electron laser induced periodic surface structures on semiconductors, Laser Applications in Microelectronic and Optoelectronic Manufacturing (LAMOM) XXVI, 11673, 116730U, 2021

全炳俊, 紀井俊輝, 大垣英明, 京都大学小型中赤外自由電子レーザー施設の開発とその利用展開, 放射光, 34, 3, 144-151, 2021

全炳俊, 共振器型赤外自由電子レーザーの引き出し効率とその向上, 加速器, 18, 2, 54-62, 2021

全炳俊, 第 8 回研究奨励賞受賞論文紹介 中赤外自由電子レーザーの高性能化とその利用推進, 日本赤外線学会誌, 31, 2, 99-101, 2022

Shizuma, H. Toyokawa, M. Fujimoto, Y. Taira, M. Katoh, Three-Dimensional Nondestructive Isotope-Selective Tomographic Imaging of 208Pb Distribution via Nuclear Resonance Fluorescence, Applied Sciences, 11, 8, 3415, 2021

R. Garcia-Ochoa, D.I. Avila-Ortega, J. Cravioto, The Geography of unequal access to energy services in Mexican households, Terra Digitalis, 5, 1, 1, 7, 2021

J. Cravioto, E. Yamasue, D.Q. Nguyen, T.D. Huy, Benefits of a regional co-processing scheme: The case of steel/iron and cement industries in Vietnam, Laos, and Cambodia, *Journal of Cleaner Production*, 312, 127702, 2021

J. Cravioto, A. Mosqueda, Local Culture and Urban Retrofit: Reflections on Policy and Preferences for Wall and Roof Materials, *Frontiers in Sustainable Cities*, 3, 63, 2021

R. Akasegawa, H. Zen, K. Hachiya, K. Yoshida, T. Goto, T. Sagawa, H. Ohgaki, Mode-selective excitation of an infrared-inactive phonon mode in diamond using mid-infrared free electron laser, *Japanese Journal of Applied Physics*, 60, 10, 102001, 2021

H. Zen, H. Ohgaki, Study of the origin of the complex beam profile of a hole-coupled free electron laser oscillator, *Journal of the Optical Society of America A-Optics Image Science and Vision*, 38, 11, 1656, 1661, 2021

## Presentations

H. Zen, H. Ohgaki, R. Hajima, Record High Extraction Efficiency of Free Electron Laser Oscillator, *IPAC2021*, Online, 2021.5.28

全炳俊, 中赤外自由電子レーザーの高性能化とその利用推進, 日本赤外線学会第 89 回定例研究会, Online, 2021.6.4

K. Ali, H. Ohgaki, H. Zen, T. Kii, T. Hayakawa, T. Shi-zuma, H. Toyokawa, Y. Taira, M. Fujimoto, M. Katoh, Proposal study for the fused visualization technique of 3D NRF-CT and a high-resolution gamma-CT image, 3rd International Conference on Nuclear Photonics (NP2020), Online, 2021.6.9

T. Hayakawa, H. Zen, K. Kawase, M. Fujimoto, T. Shi-zuma, J. K. Koga, R. Hajima, T. Kii, H. Ohgaki, M. Katoh, Delbruck scattering using linearly polarized gamma-rays generated by laser Compton scattering at UVSOR-III, 3rd International Conference on Nuclear Photonics (NP2020), Online, 2021.6.9

Anugerah Yuka Asmara, AR. Rohman Taufik Hidayat, H. Ohgaki, T. Mitsufoji, J. Cravioto Caballero, Utilization of Solar and Wind Energy to Increase Quality of Life for Rural Communities in Blora Regency - Indonesia: From Triple Helix to Quadruple Helix, 5th International Conference on Planning in the Era of Uncertainty, "Rural Urban Connectivity, Online, 2021.7.19

J. Cravioto, On The Use of Hard Data in Energy-Related Research from Social Science and Humanities, 未踏科学研究ユニット報告会 2021, Online, 2021.7.24

Jordi Cravioto, 大垣英明, Mark Napao, Joseph Quinones, Household lighting and quality of life in rural Philippines: the effect of PV lamps use in non-electrified communities of Tanay, 第 40 回エネルギー・資源学会研究発表会, Online, 2021.8.3

Chansatya Meas, 大垣英明, Jordi Cravioto, Gender Inequality in Renewable Energy Policy, 第 40 回エネルギー・資源学会研究発表会, Online, 2021.8.3

全炳俊, 常伝導加速器を用いた共振器型赤外自由電子レーザーの引き出し効率向上に関する研究, 第 18 回日本加速器学会年会, Online, 2021.8.11

宮島司, 全炳俊, 高富俊和, 福田将史, 梶田駿汰, 島田美帆, 大垣英明, 羽島良一, 高効率極短 FEL パルス生成のための 1.6 セル高周波電子銃の開発, 第 18 回日本加速器学会年会, Online, 2021.8.11

全炳俊, 大垣英明, 羽島良一, 京都大学小型中赤外自由電子レーザーからの数サイクルパルス発生とその計測, 第 18 回日本加速器学会年会, Online, 2021.8.12

全炳俊, 紀井俊輝, 大垣英明, 京都大学自由電子レーザー施設の現状, 第 18 回日本加速器学会年会, Online, 2021.8.12

B.J.Y. Hnin, H. Zen, R. Akasegawa, K. Hachiya, K. Yoshida, H. Ohgaki, Mode-Selective Phonon Excitation Of SrTiO<sub>3</sub> By MIR-FEL With Anti-Stokes Hyper Raman Scattering Spectroscopy, *IRMMW-THz2021*, Online, 2021.9.2

全炳俊, 自由電子レーザー引き出し効率のリアルタイム計測に向けた二次電子放出型電荷分布モニタ開発, 日本原子力学会 2021 年秋の大会, Online, 2021.9.8

K. Ali, H. Ohgaki, H. Zen, T. Kii, T. Hayakawa, T. Shi-zuma, H. Toyokawa, M. Katoh, M. Fujimoto, Y. Taira, Fused CT imaging technique to improve 3D isotope-selective NRF-CT image, 日本原子力学会 2021 年秋の大会, Online, 2021.9.8

J.Y.H. Bo, H. Zen, R. Akasegawa, K. Hachiya, K. Yoshida, H. Ohgaki, Anti-Stokes Hyper-Raman Scattering Spectroscopy of Strontium Titanate for Mode-Selective Phonon Excitation Using Mid-Infrared Free Electron Laser, 第 30 回 (2021 年度) 日本赤外線学会研究発表会, Online, 2021.10.21

清紀弘, 小川博嗣, 早川恭史, 境武志, 住友洋介, 田中俊成, 早川建, 高橋由美子, 野上杏子, 山添亮, 木下耀, 大谷昭仁, 川島雄介, 金田隆, 全炳俊, 大垣英明, 高強度コヒーレントエッジ放射光源の開発及び利用研究, 第 30 回 (2021 年度) 日本赤外線学会研究発表会, Online, 2021.10.22

K. Ali, Y. Ogino, T. Sakamoto, C. Meas, T. Sakabe, A.Eladl, O. Eladl, J. Cravioto, K. Mukai, C. Qu, H. Ohgaki, S. Konishi, Alternative strategies for the carbon-neutral transition to advance renewable energy supply in specific Japanese manufacturing sectors, 2021 Ajou - Kyoto - Zhejiang Joint Symposium on Energy Science, Online, 2021.11.29

- K. Ali, Non-destructive Inspection for the hidden isotopes using Laser Compton scattering gamma rays, 2021 Ajou – Kyoto – Zhejiang Joint Symposium on Energy Science, Online, 2021.11.29
- R. Akasegawa, H. Zen, K. Yoshida, K. Hachiya, T. Goto, T. Sagawa, H. Ohgaki, Selective phonon-mode excitation with mid-infrared freeelectron laser probed by hyper-Raman scattering spectroscopy, 2021 Ajou – Kyoto – Zhejiang Joint Symposium on Energy Science, Online, 2021.11.29
- H. Ohgaki, Global Energy Situation and Carbon Neutral Strategy in Japan, AUN/SEED-Net Joint Regional Conferences in Transportation, Energy and Mechanical Manufacturing Engineering, Online, 2021.12.10
- H. Ohgaki, Realizing Sustainable Carbon Neutral Society 5.0, Japan case: The 6th Strategic Energy Plan & McKinsey Report, International Multidisciplinary Symposium on Contemporary Global Issues 2021, Kumamoto, 2021.12.11
- J.Y.H. Bo, Hyper-Raman scattering spectroscopy of the phonons of Strontium Titanate, 2nd Japan ASEAN Collaboration Education Program (JACEP) Research Forum and Workshop, Online, 2021.12.20
- H. Ohgaki, Present Status of KU-FEL and Application of MIR-FEL, PCELL/CMU Meeting, Chiang Mai University, 2021.12.27
- 全炳俊, 大垣英明, 羽島良一, KU-FEL高効率発振時のパルス構造測定, 第 35 回放射光学会年会放射光科学合同シンポジウム, オンライン開催, 2022.1.8
- "J. Cravioto, L. Seniorita, S.M.G. Dumlaio, K-K. Krishna-Murthy, C. Qu, H. Ohgaki, Household roles and efficient appliances purchasing in Indonesia and The Philippines, 第 38 回エネルギーシステム・経済・環境コンファレンス, オンライン開催, 2022.1.25
- C. Meas, J. Cravioto, H. Ohgaki, Women's Leadership in Energy Transition: Cambodia's Perspectives, 第 38 回エネルギーシステム・経済・環境コンファレンス, オンライン開催, 2022.1.26
- J. Cravioto, Household roles and efficient appliances purchasing in urban Indonesia and The Philippines, DASU2021 年度年度末ワークショップ, オンライン開催, 2022.3.2
- H. Ohgaki, WP5: Briefing of WP5 2021 JFY, -Asia WP5 Group Workshop Integrated Biorefinery of Sugarcane Trash, Online, 2022.3.8
- Ju Yoon Hnin Bo, Hyper-Raman Scattering Spectroscopy of Selective Phonon Excitation of Strontium Titanate Using Mid-Infrared Free Electron Laser, 第 28 回 FEL と High-Power Radiation 研究会, Online, 2022.3.9
- 全炳俊, 移設先直線部における UVSOR-FEL の再立ち上げと Intracavity Laser Compton Scattering によるガンマ線発生, 第 28 回 FEL と High-Power Radiation 研究会, Online, 2022.3.10
- Zhao Yuhao, Simulation of a new Photocathode RF Gun in KU-FEL, 第 28 回 FEL と High-Power Radiation 研究会, Online, 2022.3.10
- 羽島良一, 全炳俊, 大垣英明, 長波長赤外 FEL パルスによるガスの放電発光, 日本物理学会第 77 回年次大会, オンライン開催, 2022.3.15
- 柏木茂, 全炳俊, 坂上和之, 光共振器を用いたアンジュレータ超放射の電場重畳による高強度 THz パルス発生, 日本物理学会第 77 回年次大会, オンライン開催, 2022.3.16
- 紀井俊輝, バルク超伝導体アンジュレータにおけるバルクソーティングによるピーク磁場強度調整, 日本物理学会第 77 回年次大会, オンライン開催, 2022.3.16
- H. Ohgaki, Current biogas-to electricity status, pilot case and funding opportunities, BIO-GAS-TO-ELECTRICITY FOCUS GROUP DISCUSSION (FGD) IN ASEAN, オンライン開催, 2022.3.17
- 全炳俊, 電子ビームからの超放射, 日本物理学会第 77 回年次大会, オンライン開催, 2022.3.19
- H. Ohgaki, Socioeconomic analysis of the integrated process, e-ASIA Workshop Integrated Biorefinery of Sugarcane Trash, Online, 2022.3.30