第31回放射線利用総合シンポジウム

京都大学中赤外自由電子レーザー施設の現状と将来展望

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Brief History of KU-FEL

1995: 吉川潔教授がFEL研究を開始
1998: 山崎鉄夫教授がFEL施設の建設を開始
　　　4.5-cell thermionic RF-gunからビーム発生
2002: 40 MeV リニアック完成@化研
2004: FEL建屋の改築
2006: 1.6mアンジュレータ設置
2008: FEL 発振
　　　THz光源開発開始
2011: 1.8mアンジュレータ移設、ZE共同研究拠点開始
2013: THz光源建設開始
2016: THz光発生

Contents

- Introduction
- Present Status of MIR-FEL
- Present Status of THz-CUR
- Summary

Introduction

長波長領域の光源を目指して2台の電子加速器を開発

- **MIR-FEL (named as KU-FEL, 3.4 – 26 μm)**
  - For users and light source development
  - Opened for user experiments from 2009.
  - ZE collaborative research opened since 2011.
  - First Lasing with Photocathode operation (2014).

- **THz-FEL (0.2-0.6 THz)**
  - Light source development
  - First e-Beam in 2015.
  - Coherent transition radiation observation in 2016.
  - First light from an undulator in August 2016.

Facility Layout

Currently Available Laser Sources:

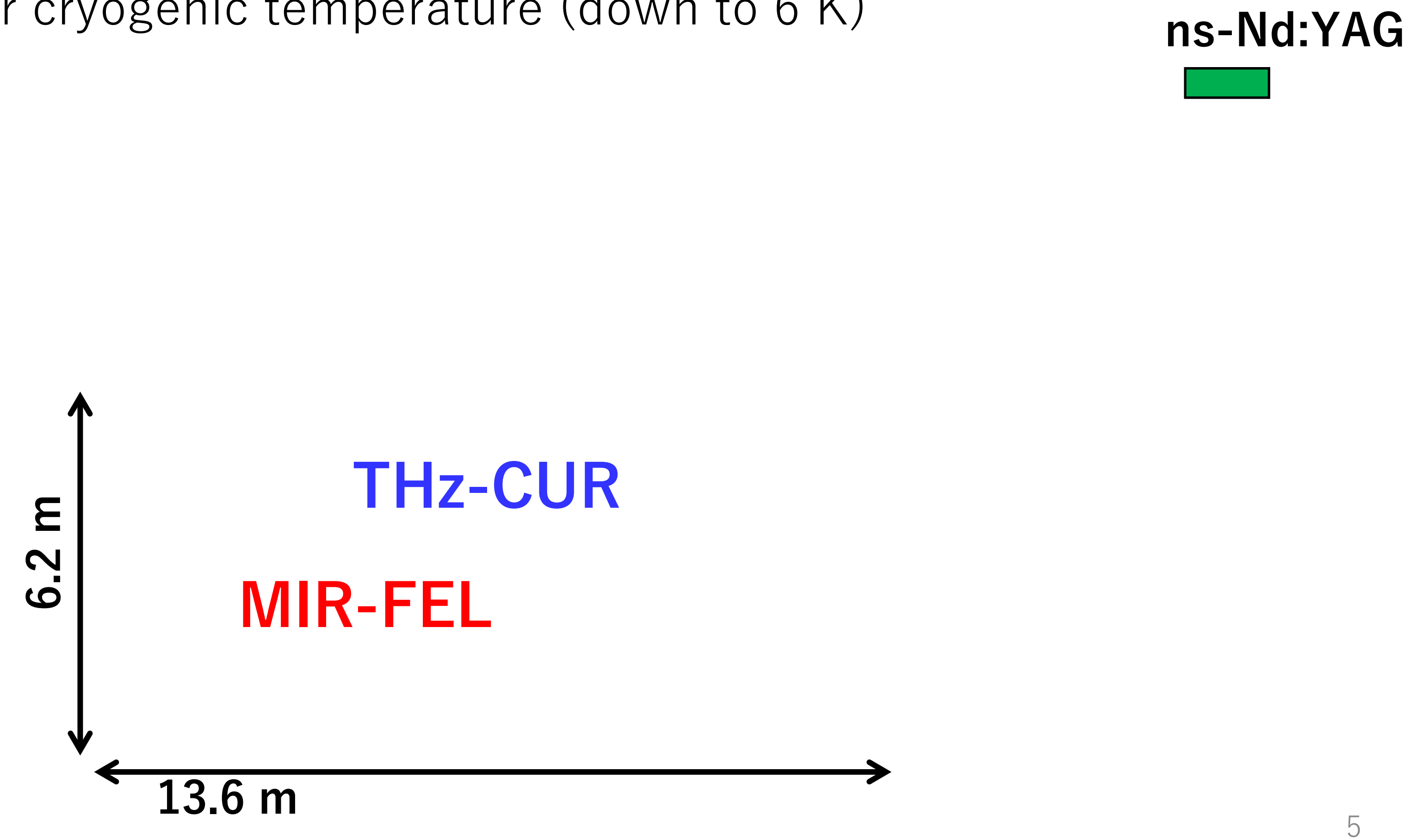
MIR-FEL, **THz-CUR**, ps-Nd:YAG, ns-Nd:YAG+OPO(0.41-2.3μm)

User Stations:

#1 : MIR-FEL Diagnostics & Simple Irradiation

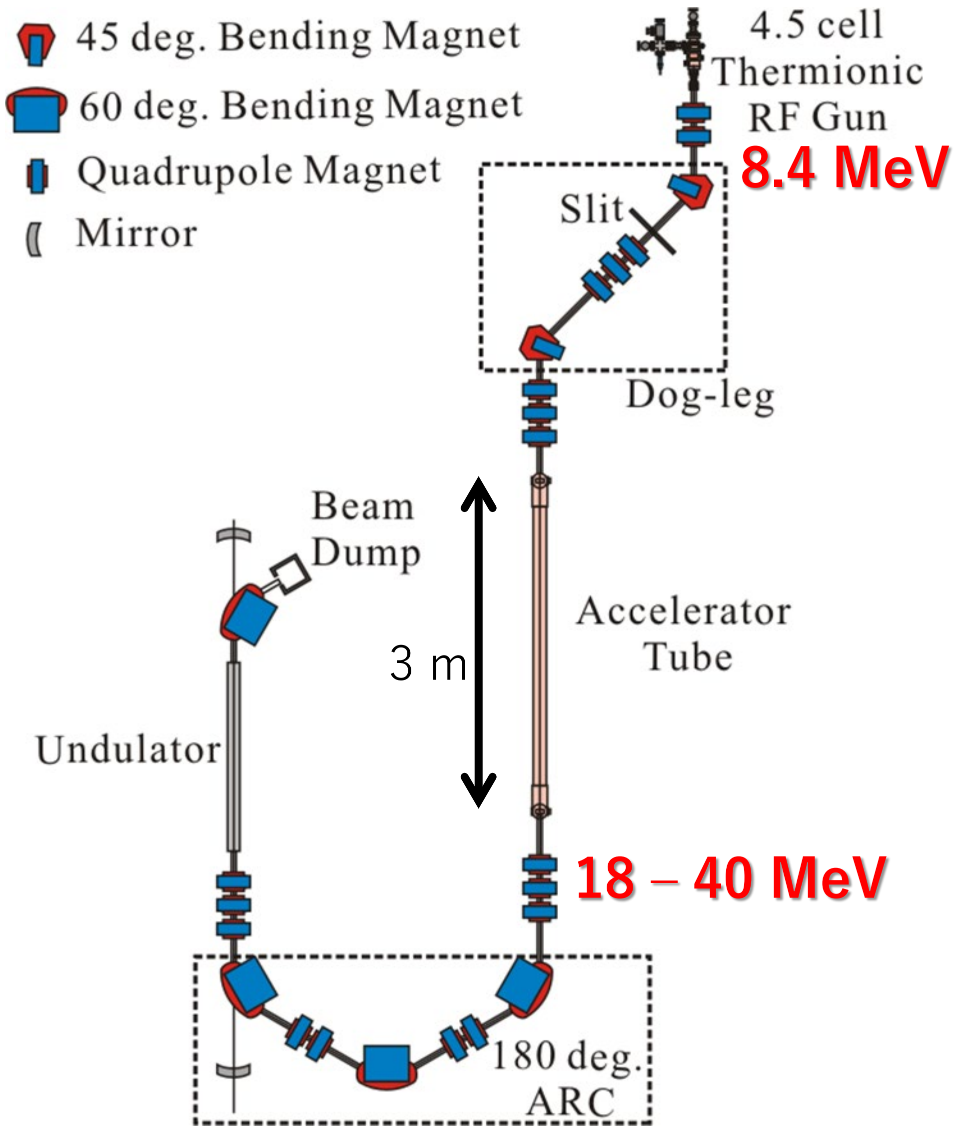
#2 : Pump-Probe (ps, ns) under cryogenic temperature (down to 6 K)

#3 : Multipurpose



Contents

MIR-FEL in Kyoto Univ. – KU-FEL –



RF Gun as the electron source
➔Compact Accelerator
➔Reduce Total Cost

Thermionic cathode & RF acceleration
➔3-GHz e-bunch with 7 us length
➔3-GHz FEL with 2 us length

Electron bunch compression
➔ Sub-picosecond Electron Beam
➔ Sub-picosecond MIR-FEL Beam

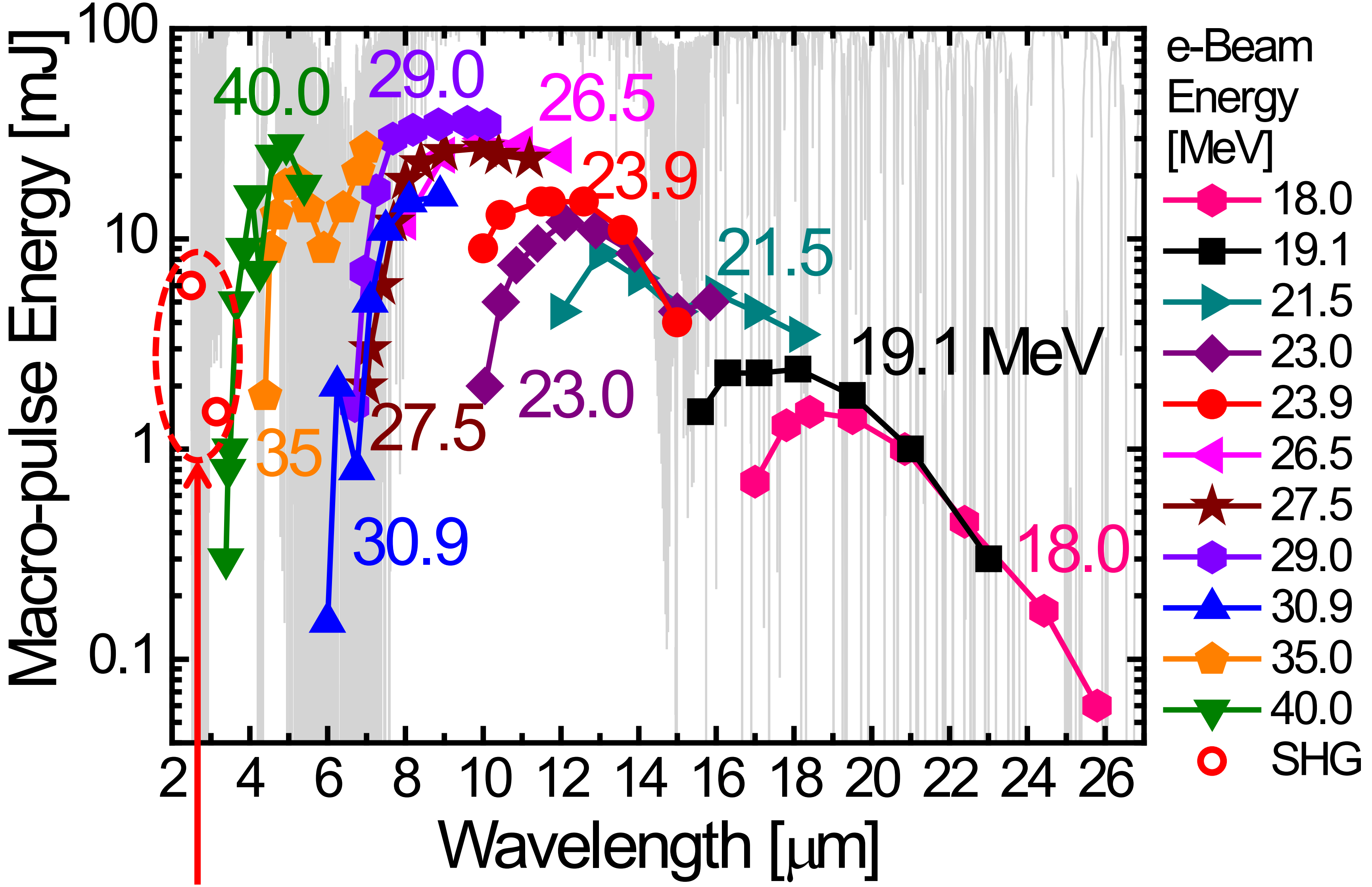
Laser induced electron emission in Gun
Photocathode Operation
➔ 29 MHz e-bunch with 7 us length
➔ 29 MHz FEL with 3.5 us length,
higher peak power than Thermionic

Performance of MIR-FEL

RF Gun Operation Mode	Thermionic	Photocathode
Wavelength Range	3.4 – 26 μm	To be determined
Max. Macro-pulse Energy*	41.8 mJ @4.9 μm	4.5 mJ @11 μm
Typ. Macro-pulse Duration	2 μs	3.5 μs
Micro-pulse Repetition Rate	2856 MHz	29.75 MHz
Max. Micro-pulse Energy*	7.3 μJ @4.9 μm	~40 μJ @11 μm
Micro-pulse Duration*	~0.3 ps @11 μm	~0.2 ps @11 μm
Typ. Bandwidth*	3%-FWHM	~6%-FWHM
Max. Extraction Efficiency	5.5% @11.6 μm [23]	9.4% @11 μm [24]

*Observed at user station 1 (after 12 m transport).

Macro-pulse Energy (Thermionic Operation)

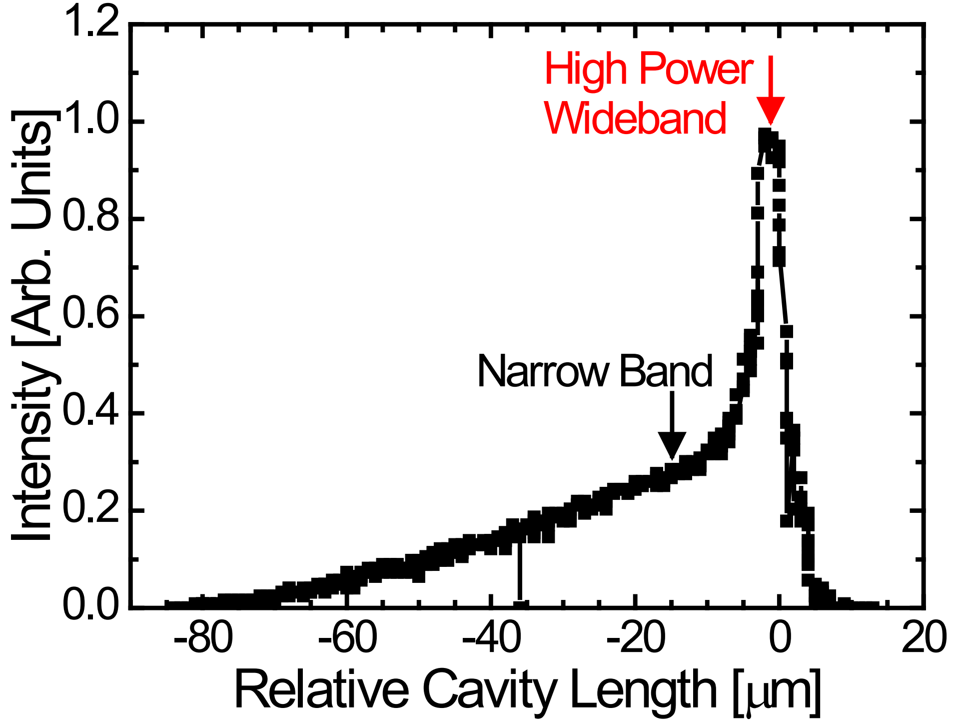


SHG with $ZnGeP_2$ (θ = 48.8 deg., ϕ = 0 deg., 3photon Ltd.)

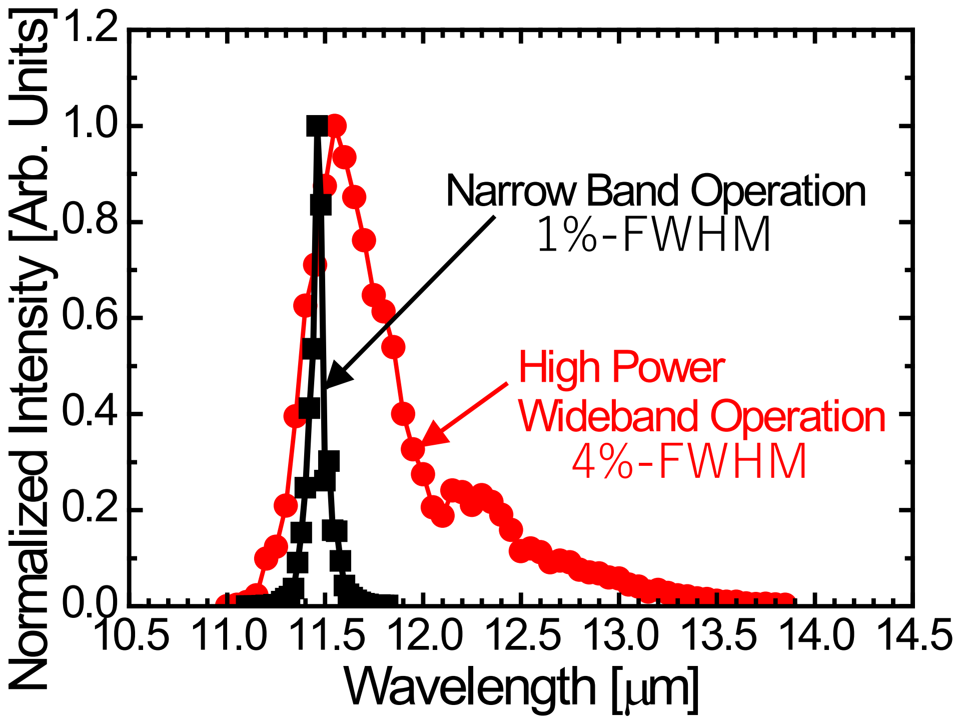
Two operation modes

By slight change of the optical cavity length, FEL lasing condition can be switched from high power wideband operation to narrow band operation.

Intensity V.S. Optical cavity length



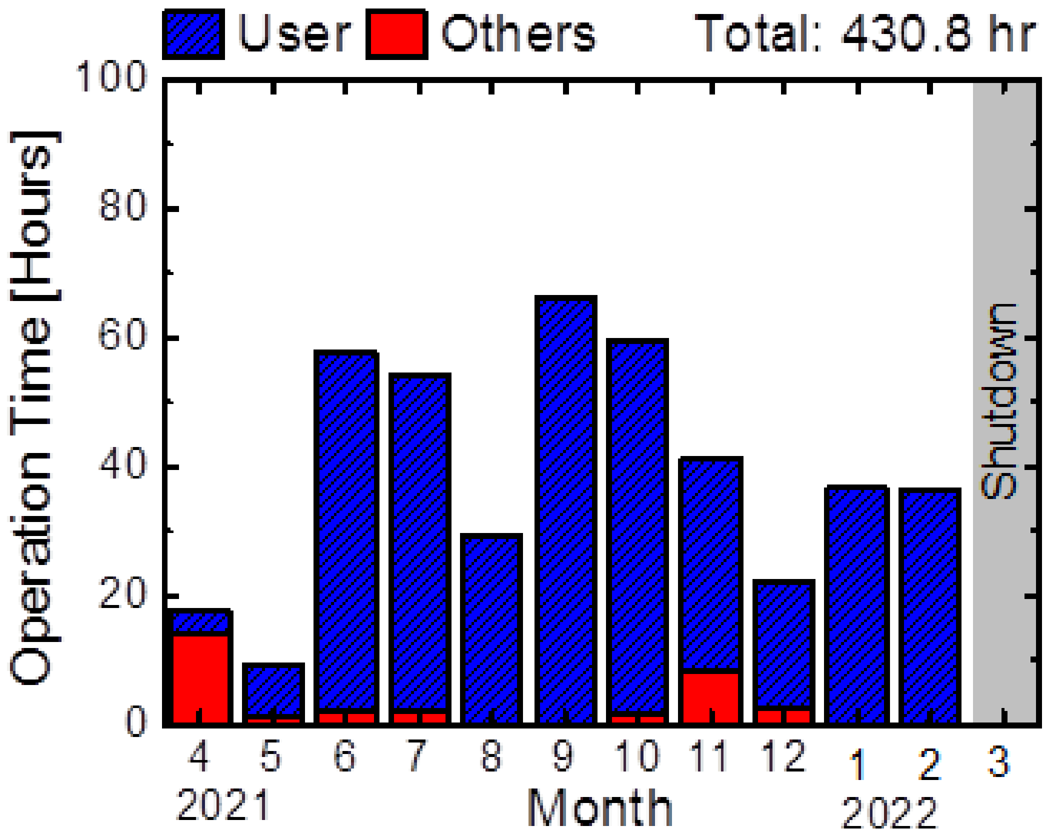
Wavelength Spectrum

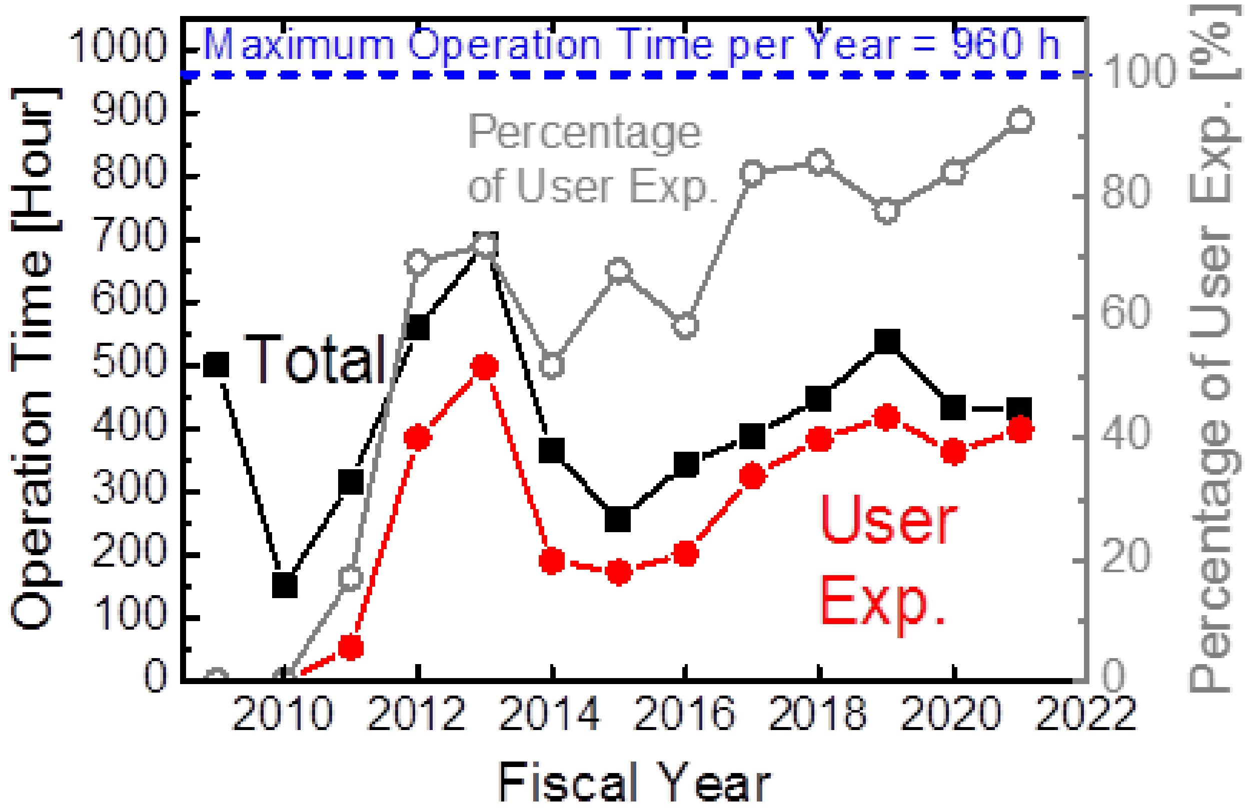


High power operation: wideband (➔short pulse), highest peak power

Narrow band operation: narrow band (➔ long pulse), lower peak power

Operation Time in FY2021





- There was shutdown of KU-FEL in March 2022 for radiation facility upgrade
    - beam power 40W => 60W, added a photocathode RF gun
- More than 90% of operation time was used for user experiments.

光源開発：Q-LEAP Project

- A research group for FEL-HHG demonstration has been constructed.

 (4 Institutes: QST, Nihon Univ., KEK, and Kyoto Univ., 10 researchers)

- In Nov. 2018, our group was got funding support from MEXT, Japan.
- The project name is “Research on the basic technology for high repetition rate attosecond light sources driven by Free Electron Laser,” which is a part of MEXT Q-LEAP program.
- The funding period is 10 years in maximum.

2018-2023: Development of basic technologies

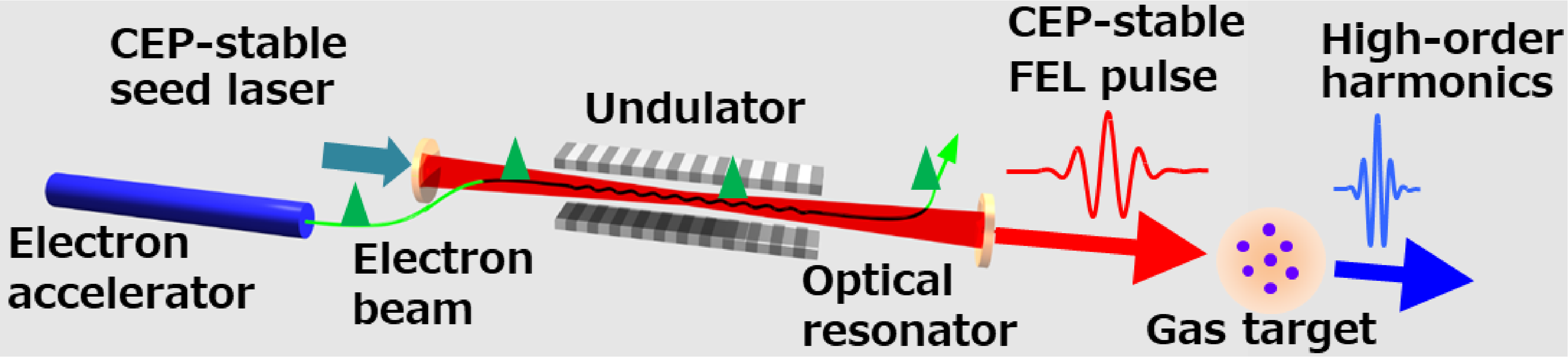
↓

2024-2027: Proof-of-Concept experiment of FEL-HHG

- Two existing MIR-FEL facility, KU-FEL and LEBRA-FEL have been used in this project.

光源開発：Q-LEAP Project

FEL-HHG：中赤外FELで駆動する高次高調波アト秒光源

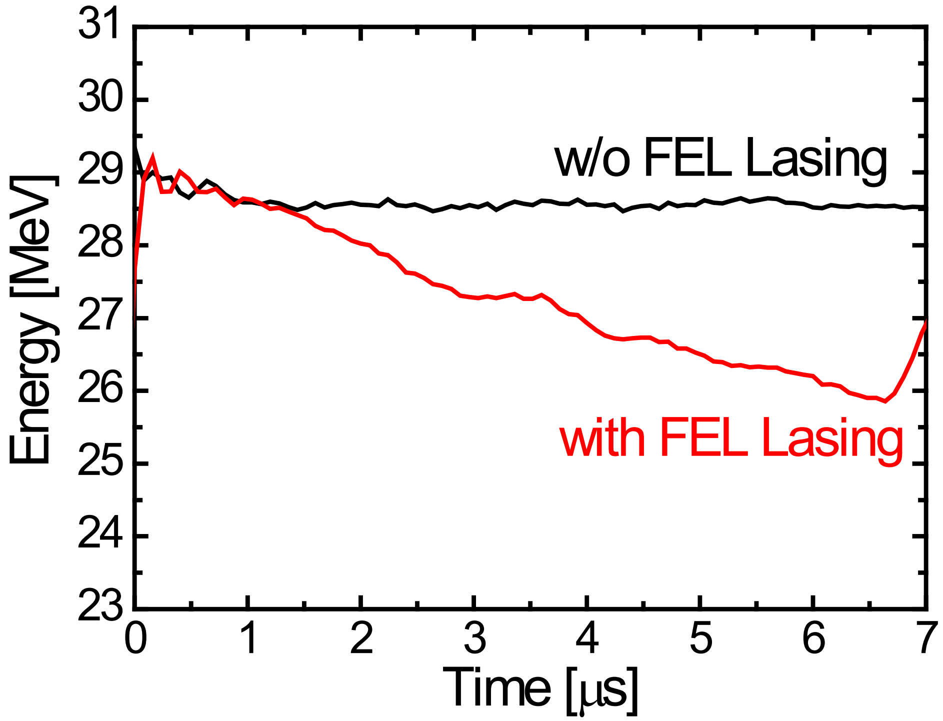


- 共振器型中赤外FELから超短パルス中赤外レーザを発生させ、ガスターゲットに集光。HHGによりアト秒パルスを発生。
- 2018年度からプロジェクトスタート。
- 量研・日大・KEK・京大が参画。
- 京大は共振器型中赤外FELからHHG駆動に十分な高強度超短パルスレーザを発生させるための基礎基盤技術の開発がメイントピック。

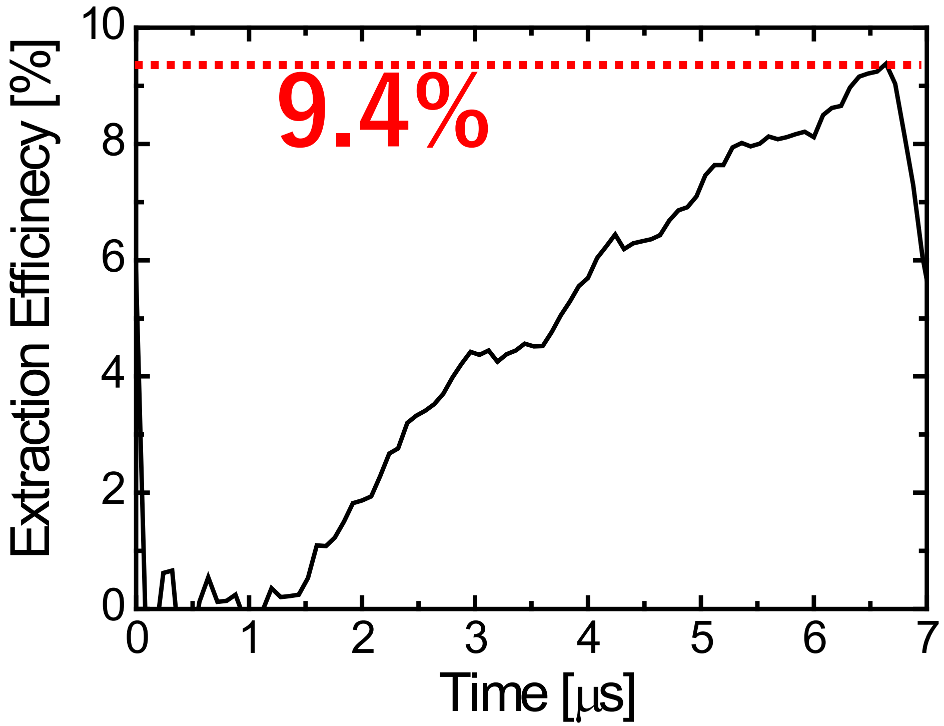
Variation of Average Energy and Extraction Efficiency

H. Zen et al., Appl. Phys. Express 13, 102007 (2020)

Variation of average energy



Extraction Efficiency



- Evaluate the average energy from measured energy distribution.
- Relative energy variation for FEL ON and OFF corresponds to the extraction efficiency
- Max extraction efficiency : 9.4%
- **Record high efficiency comparable to the JAERI-FEL even with a NC accelerator.**

(The highest efficiency before this work was 9%@2002 JAERI-FEL w/SC accelerator)

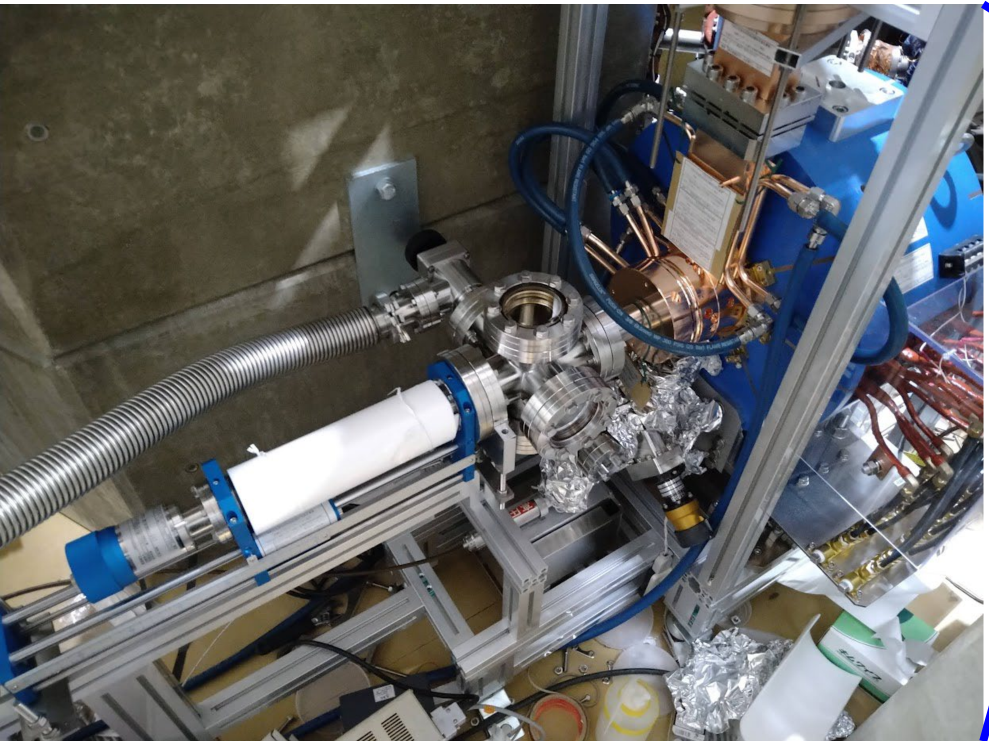
N. Nishimori et al., NIM-A 483, 134 (2002).

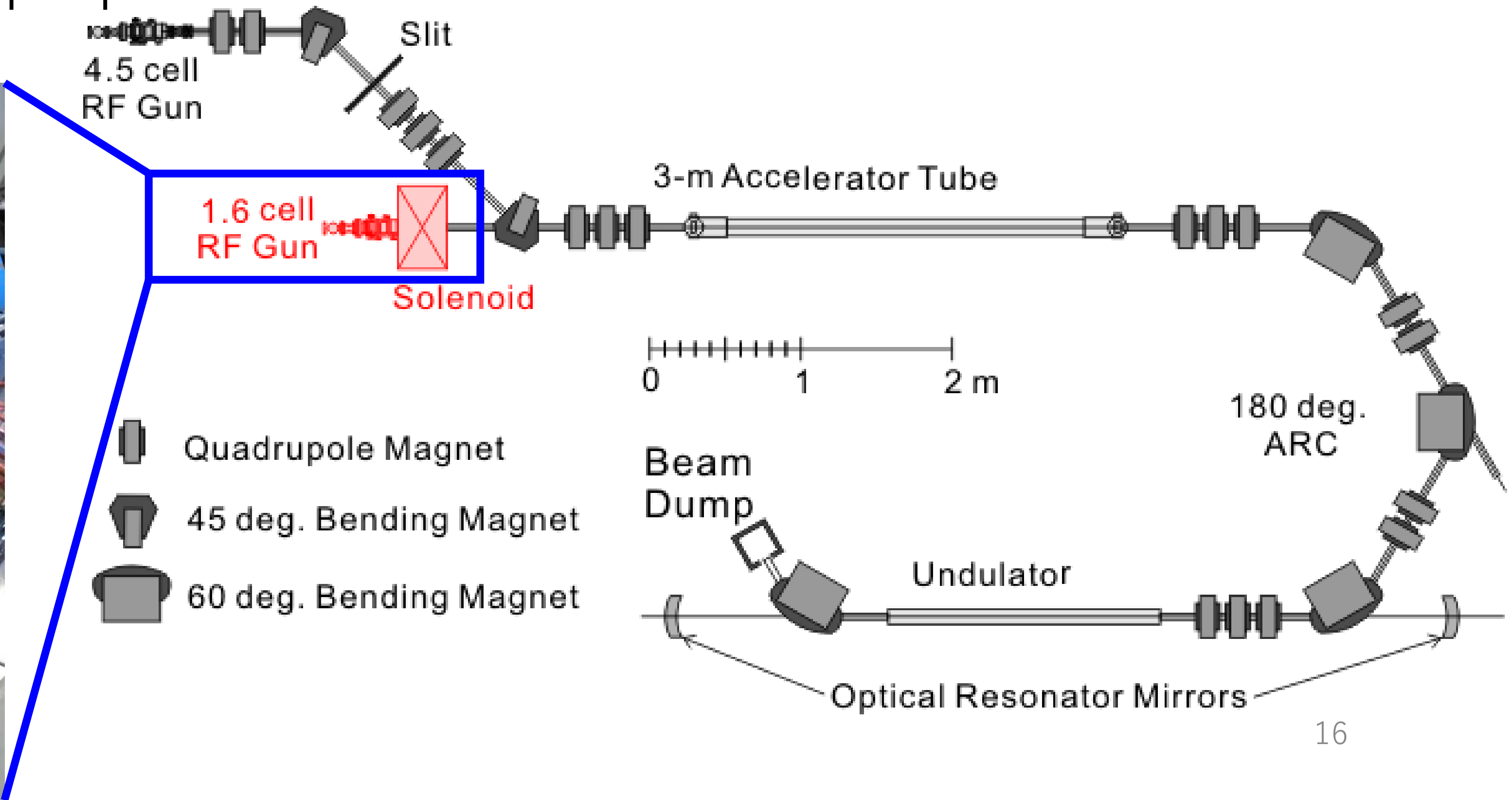
Next Step

- Dedicated 1.6 cell photocathode RF gun will be installed to KU-FEL for increasing the e-bunch charge up to 1 nC.
- The gun has been fabricated under collaboration with KEK.
- Other components are under preparation.

Performance Expectation

Q: 0.2 nC ➔ 1 nC
η: 9% ➔ 20%
E: 0.1 mJ ➔ 1 mJ
P: 0.5 GW ➔ 13 GW





ZE Joint Research（2022）: Light Source

1	Tohoku University: Generation of high intensity THz pulse by superimposing of undulator superradiance
2	QST: Gas Ionization with Ultrafast Intense Long-Wavelength Infrared Pulses
3	AIST: Study of temporal evolution of amplified coherent edge radiation during free-electron laser oscillations

ZE Joint Research（2022）：Biology

4	KEK: Structure control of persistent materials by molecular vibrational excitation
5	Nihon University: Analyses of Electroretinograms from Crayfish's Compound Eyes Evoked by KU-FEL Irradiation-2: Fast and Late Reaction
6	Nihon University: Effect of FEL irradiation on the efficiency of carbon dioxide fixation in bacterial cells
7	KEK: Research on enzyme-free structural alteration of glycan by infrared free electron laser
8	Gunma University: Contribution of infrared laser irradiation to diabetes-related pancreatic dysfunctions

ZE Joint Research（2022）: Material

9	Kyoto University: Application of mode-selective phonon-excitation method in semiconductors of energy functionality with mid- infrared free-electron laser
10	Kyoto University: Surface Processing of SiC Achieved by Combination of Phonon Excitation using FEL and Electrochemistry
11	Kyoto University: In-situ measurement of periodic nanostructures on semiconductor surface induced by mid-infrared free electron lasers
12	Yamagata University: Mid-infrared spectroscopy of Zintl-phase NaMgX (X=Bi,Sb) using Free-electron laser
13	Tsukuba University: Control of humidity sorption in porous molecular crystal by intense infrared rays
14	Chaing Mai University: Study of solvation structure and dynamics of room-temperature ionic liquids using MIR free-electron laser

ZE Joint Research（2022）：Processing

15	Kumamoto IRI: Counting the number of mode-selectively excited phonon by observation of anti-Stokes/Stokes Raman scattering
16	Tokyo University of Science: Analysis of processing mechanisum in high polymer material by using infrared free electron laser
17	Tokyo University of Science: Fabrication of functional organic thin films using infrared free electron pulsed laser deposition method
18	Kyoto University: Luminescent nanoporous diamond formed by anodization
19	Tohoku University: Study on emission process and evaluation of light outputs for novel scintillation materials using the one electron beam

Mode-Selective Phonon Excitation

Phonons

- Strong correlated electron system
- Control of material properties

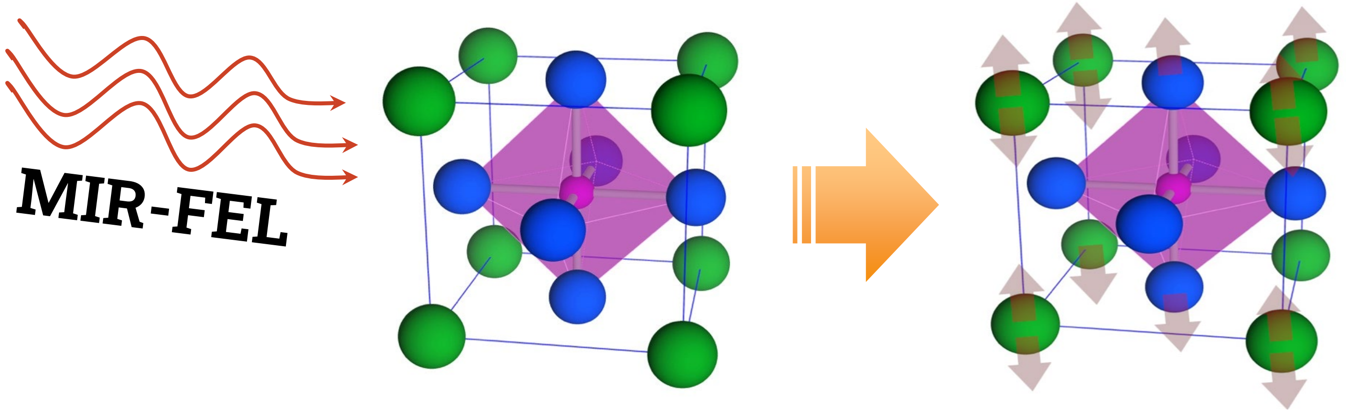
(Mn-O vibrational mode of $Pr_{0.7}Ca_{0.3}MnO_3$ - metal-insulator transition phenomenon (Rini et al.) , magnetism of $La_{0.5}Sr_{1.5}MnO_4$ (Forst et al))

Mode-Selective Phonon Excitation (MSPE)

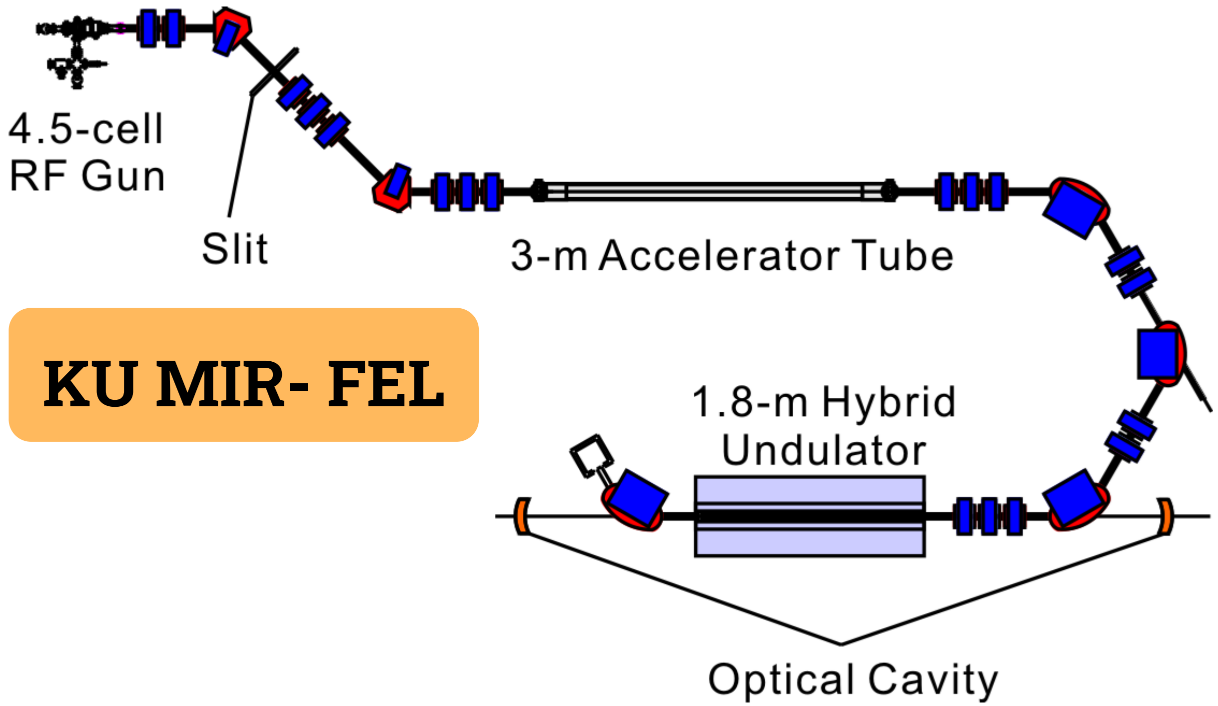
Through coherent phonon excitation by ultra-short pulse laser

Through direct excitation by mid-infrared (MIR) laser

Mode Selective Phonon Excitation (MSPE) Using KU MIR-FEL

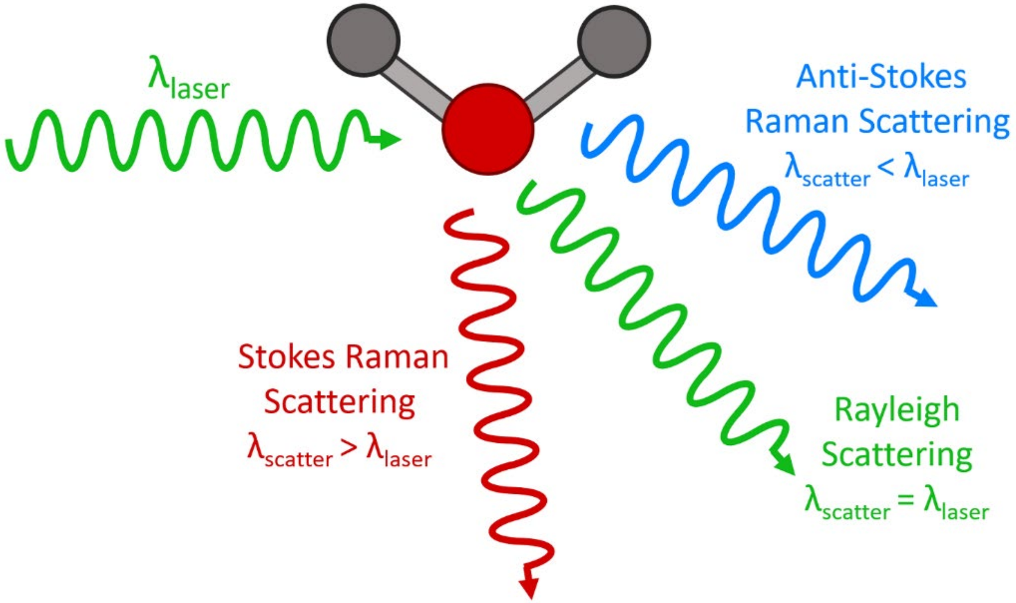


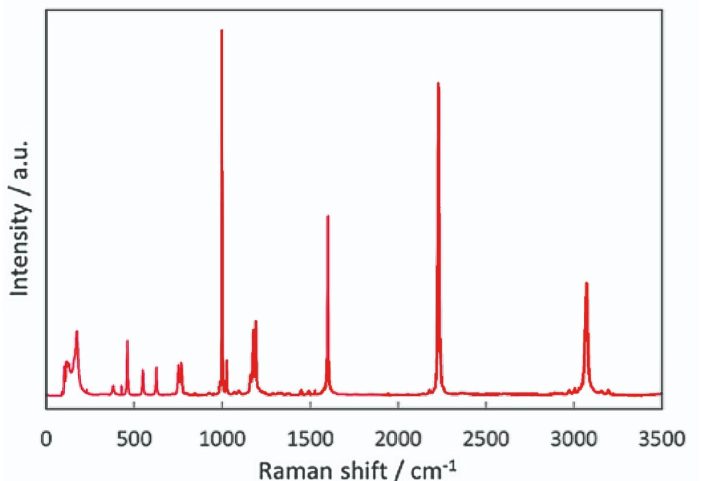
- Straightforward
- Short pulse width
- High laser power
- Wide tunability
  (3.4 to 26 µm - KU FEL)



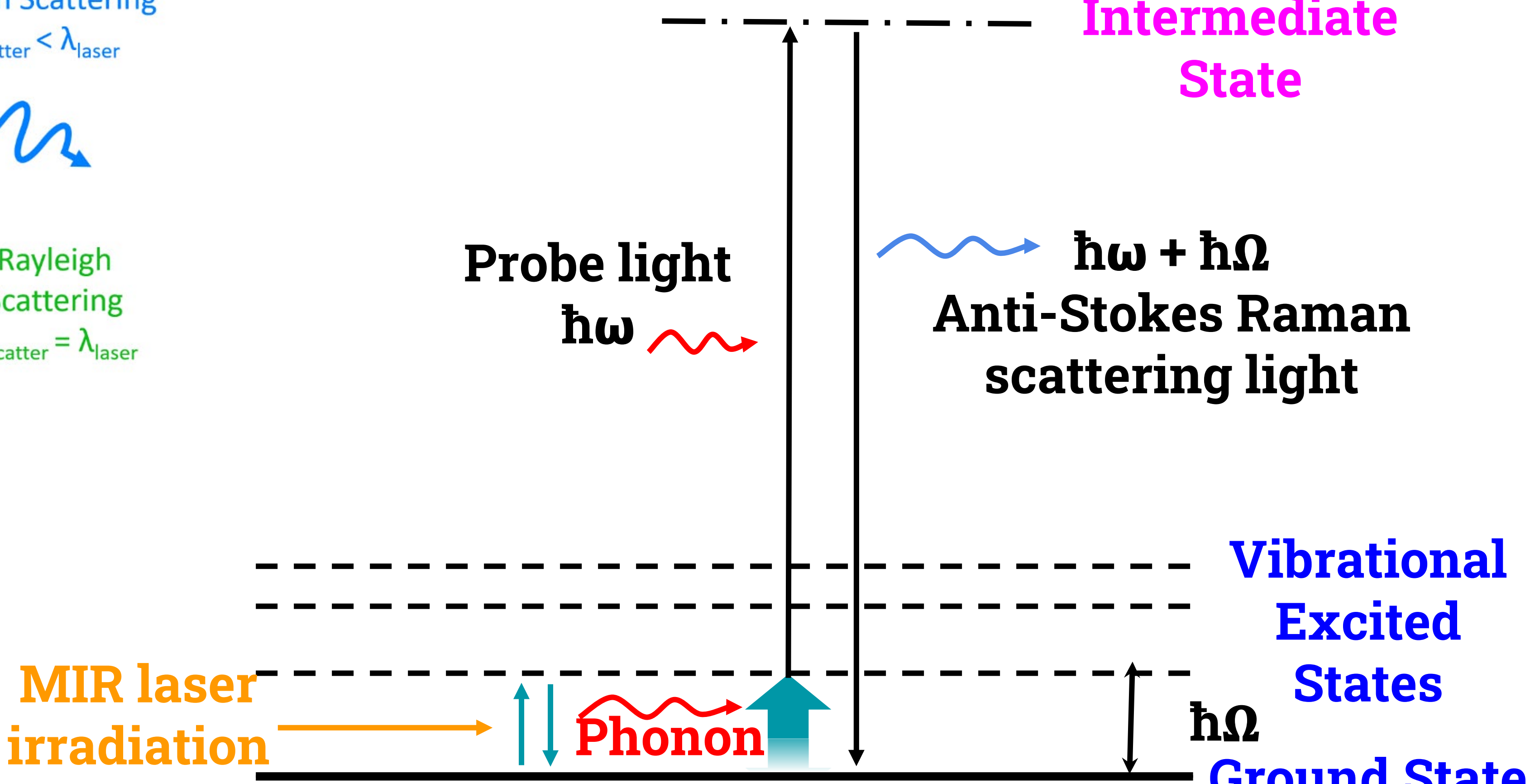
Mode Selective Phonon Excitation (MSPE) Using MIR-FEL

Raman Scattering



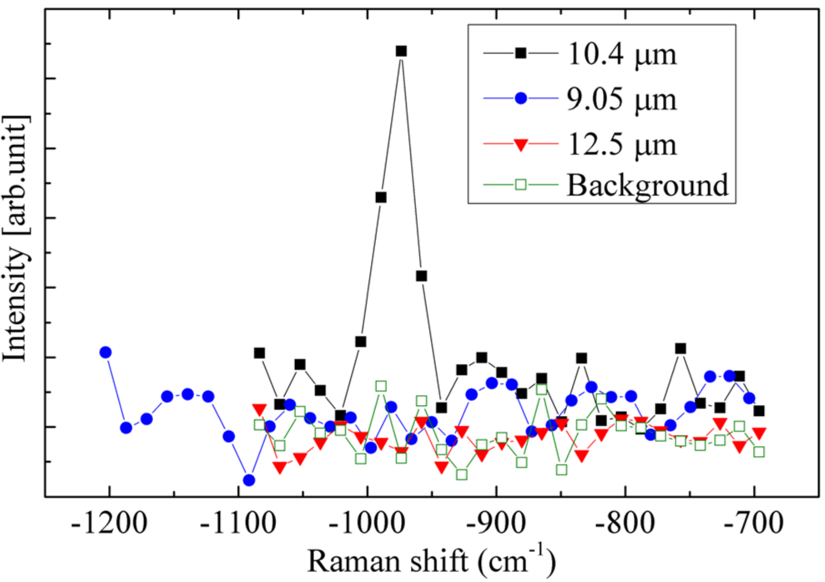


Observation of MSPE through anti-Stokes Raman Scattering Spectroscopy



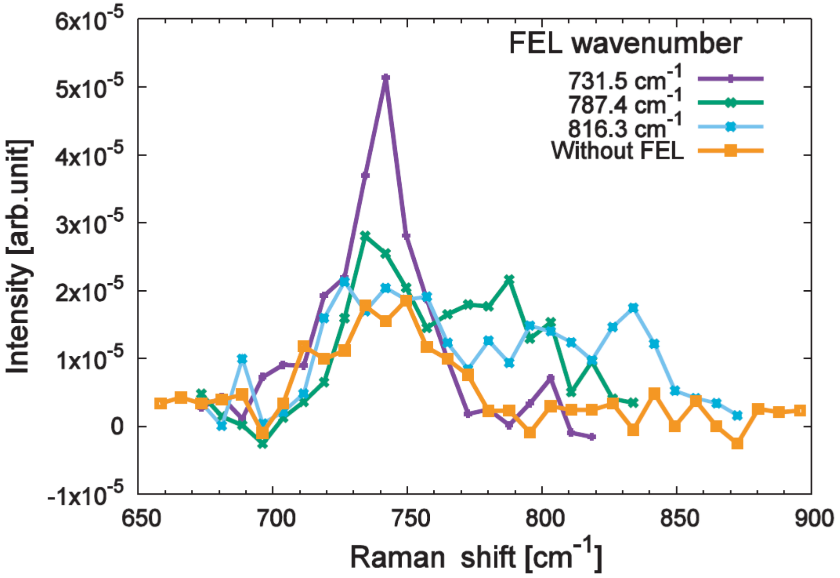
Anti-Stokes Raman Scattering

Mode Selective Phonon Excitation (MSPE) Using MIR-FEL



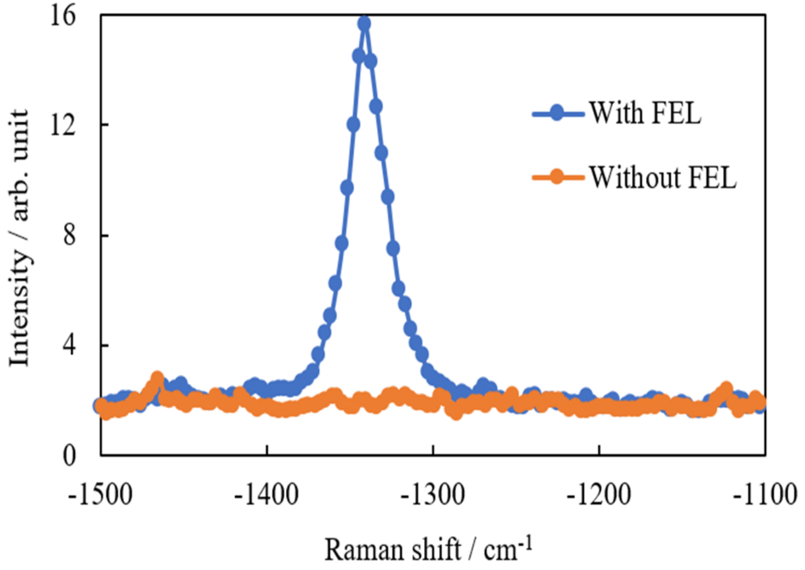
Raman active FLO(0) mode of 6H-SiC

(K. Yoshida et al.)



Raman active A_1 (LO) mode of GaN

(M. Kagaya et al.)



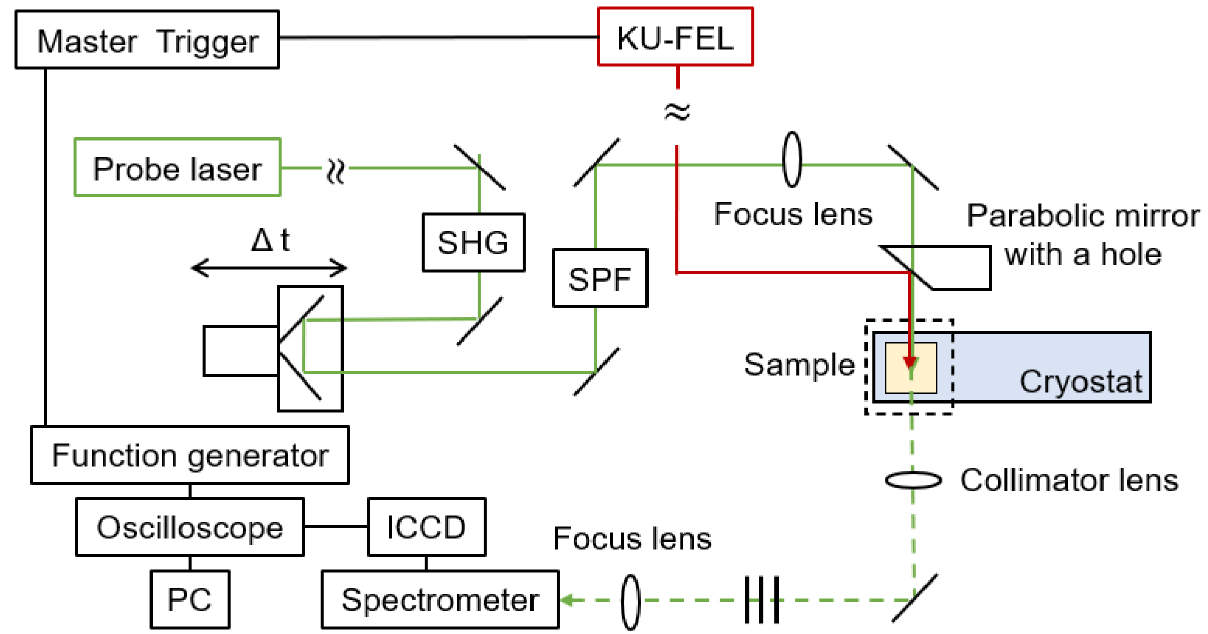
Raman active but infrared inactive T_{2g} mode of diamond

(R. Akasegawa et al.)

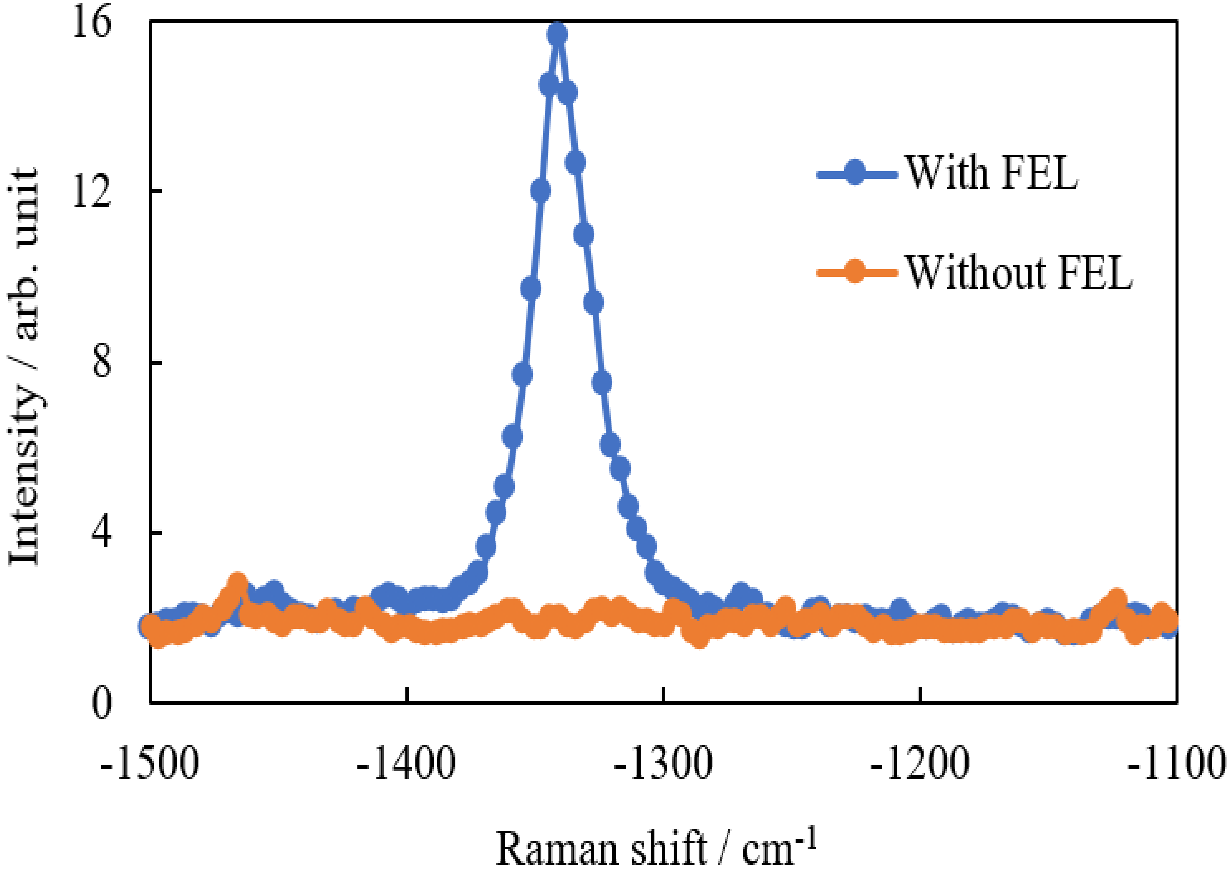
What about Raman <u>inactive</u> phonon modes?

Mode-selective excitation of an infrared-inactive phonon mode in diamond using mid-infrared free electron laser

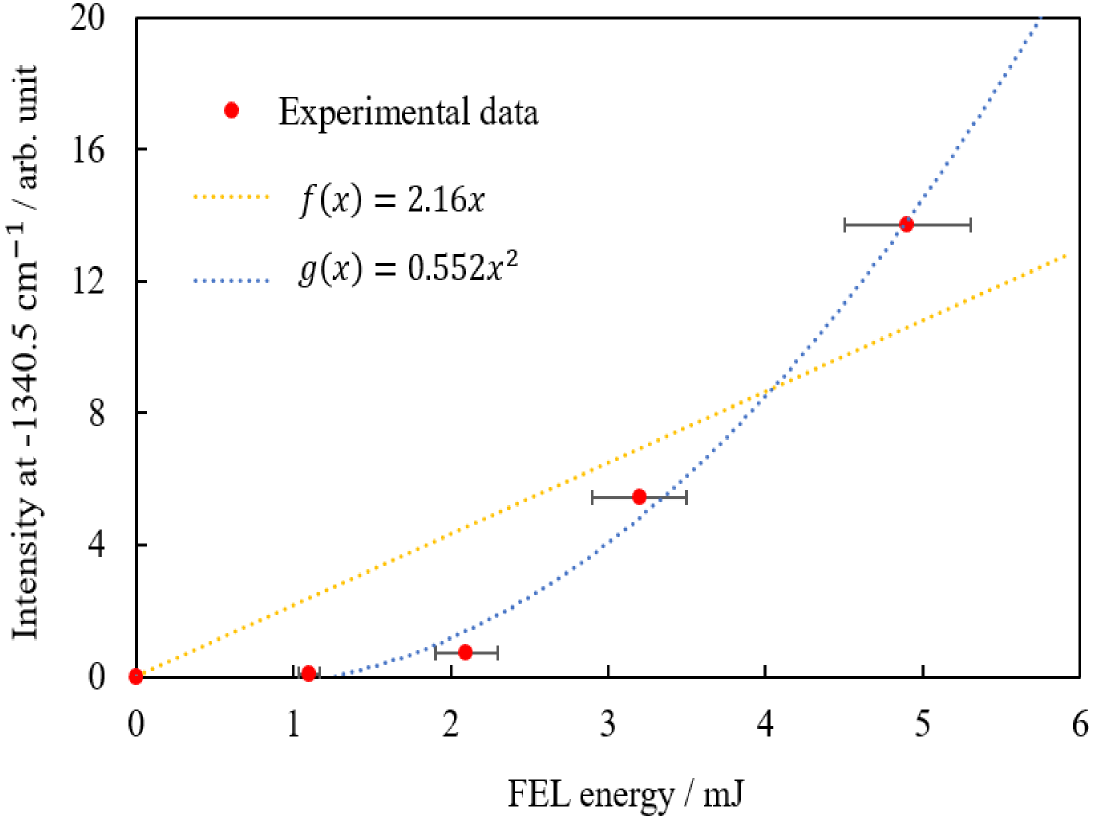
- Selective excitation of the **infrared-inactive** T_{2g} mode (1332 cm^{-1}) in the single crystal diamond by two-photon excitation
- Anti-Stokes Raman scattering light: -1339 cm^{-1}
- MIR-FEL : 666 cm^{-1}



Direct observation of two-photon excitation



Evidence of two-photon excitation

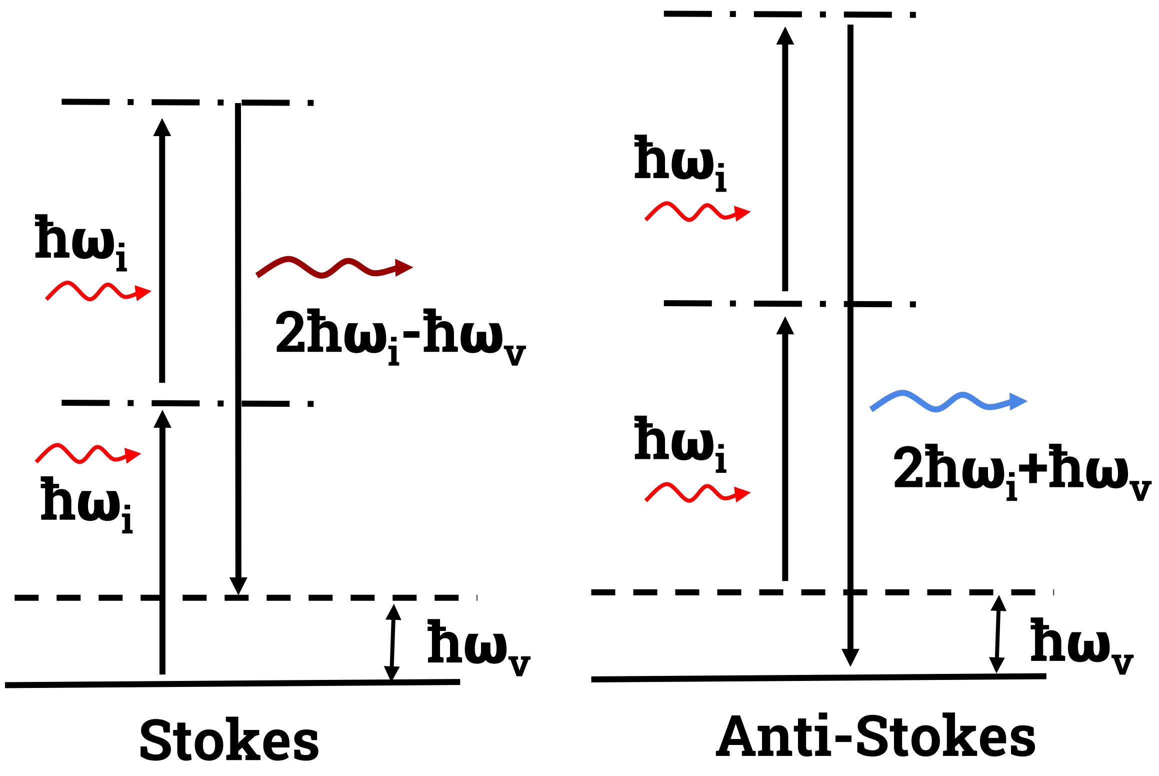


Raman inactive modes

Hyper-Raman scattering spectroscopy

- Hold different selection rule
- IR active modes are always hyper-Raman active
- Mutual exclusive with Raman spectroscopy for centrosymmetric crystals

$$\hbar\omega_{HRS} = 2\hbar\omega_i \pm \hbar\omega_v$$



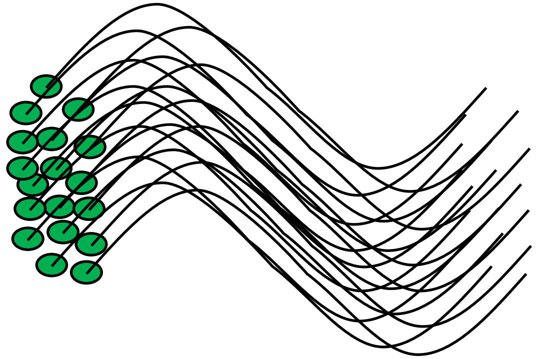
Issues on KU-FEL

- **Aging in accelerator component**
  - RF power generator: switching devices have lifetimes, but no replacement => changed (from KEK)
  - HV capacitors: must be replaced…
- **Radiation Safety**
  - Researchers were always exposed (0.1 mSv/m)
- **Operation and maintenance**
  - Totally depend on the one specialist
  - Electricity charge…: try to get rich user groups

Contents

Coherent Undulator Radiation (CUR)

Coherent Radiation



Electron pulse length < Radiation wavelength

All the radiation emitted from each electron can be coherently summed up.

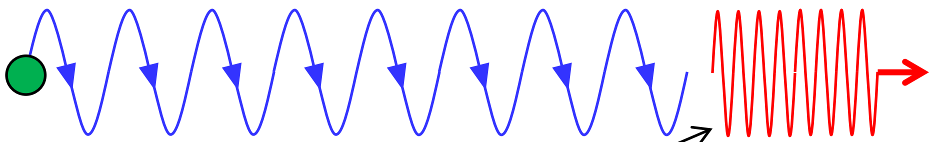
$$P_{coh} \propto N^2 = P_{incoh} \times N$$

N: Number of electron in bunch (> 10^8)

Undulator Radiation

Electron makes wiggling motion in <u>a pair of magnet array</u>.

Undulator



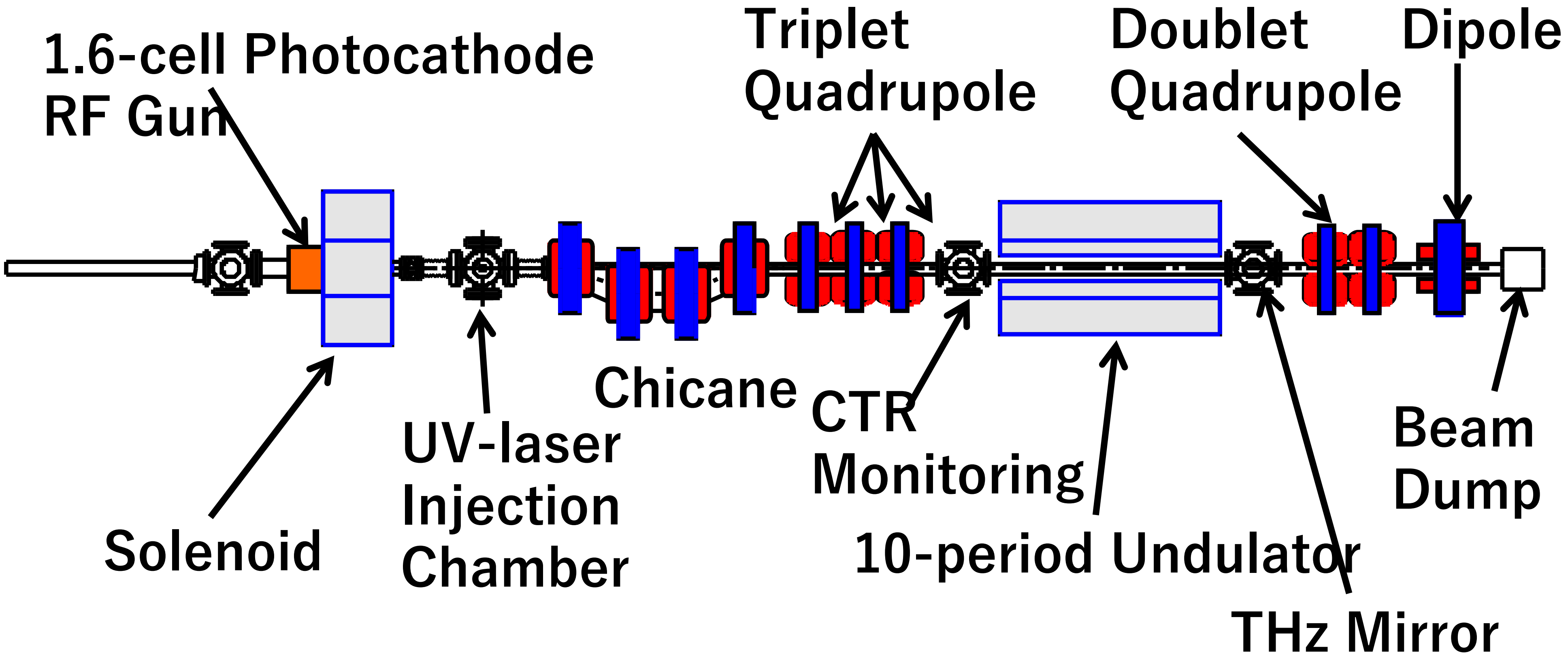
We can generate quasi-monochromatic radiation, so-called undulator radiation.
The wavelength can be continuously tuned.

Coherent Undulator Radiation

- Intense
- Quasi-monochromatic
- Wavelength Tunable

THz Radiation can be generated.

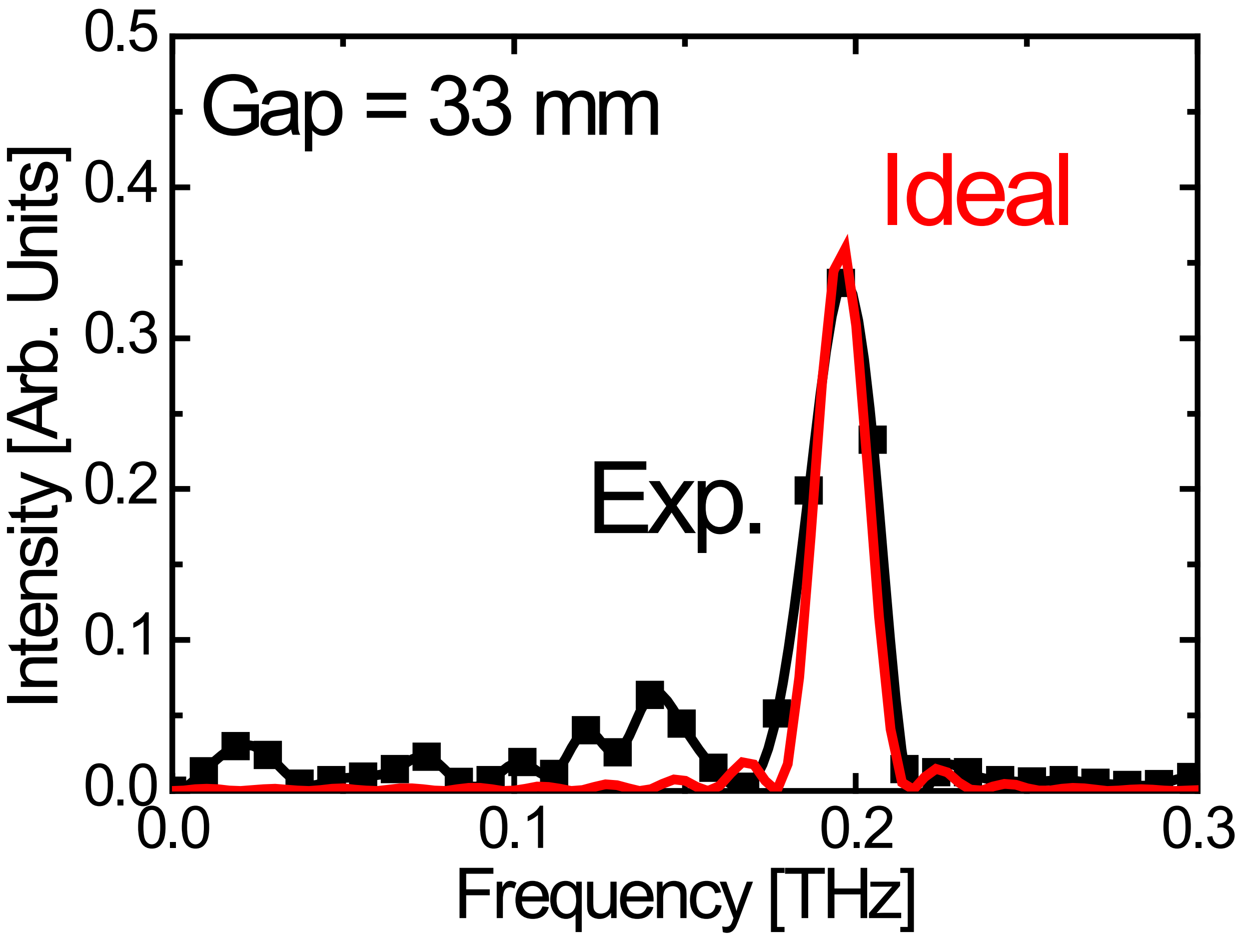
THz-CUR Source at Kyoto University



- One of the smallest configuration of THz-CUR.
- Short e-bunch is generated by RF gun and chicane bunch compressor.
- Compressed e-bunch is injected to undulator and generate THz radiation.
- First light at Aug. 2016.
- Basic characteristics has been measured.

Typical Spectrum of THz-CUR

Frequency spectrum was measured by a self-made Michelson Interferometer.



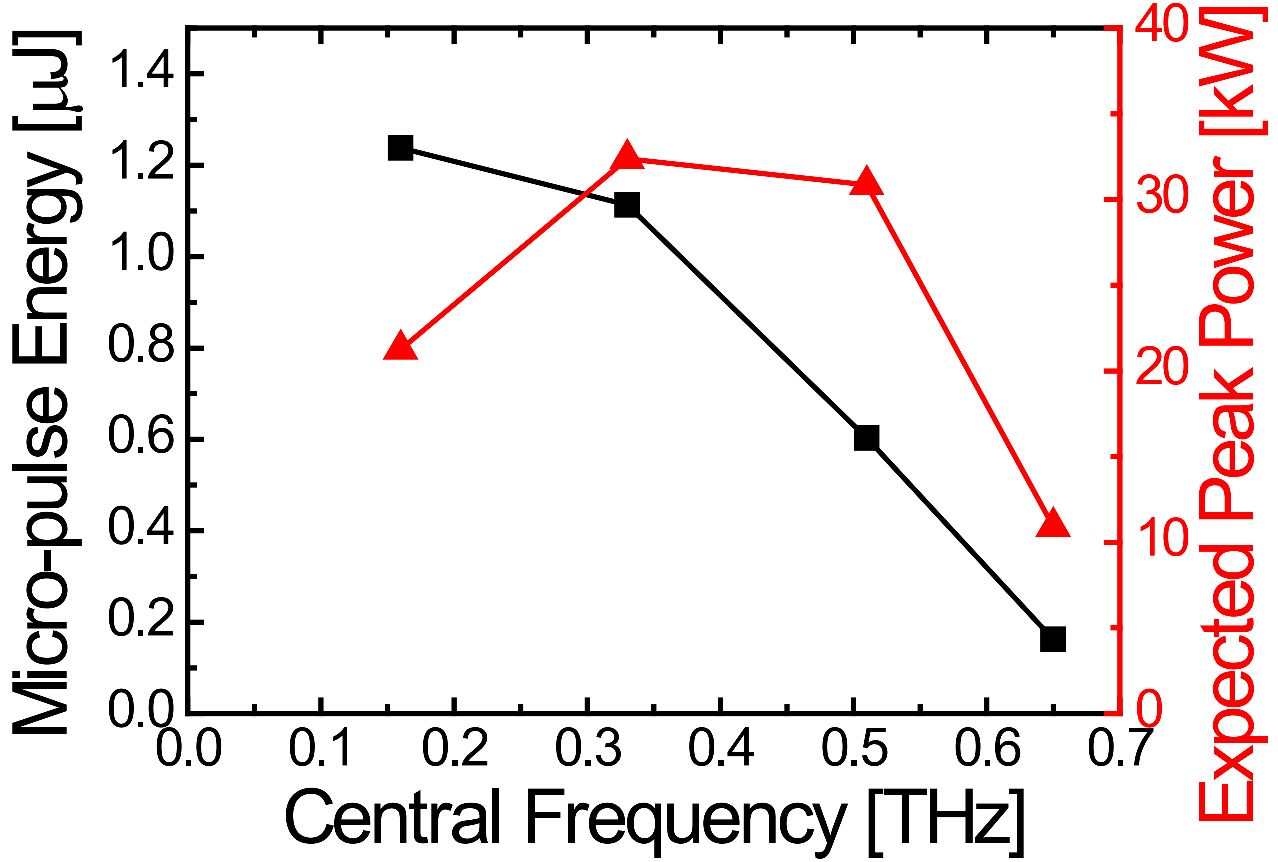
The spectrum of THz-CUR is almost same with the ideal 10-cycle radiation.

➔The pulse duration can be expected as 10-cycle.

The central frequency can be tuned from 160 to 650 GHz.

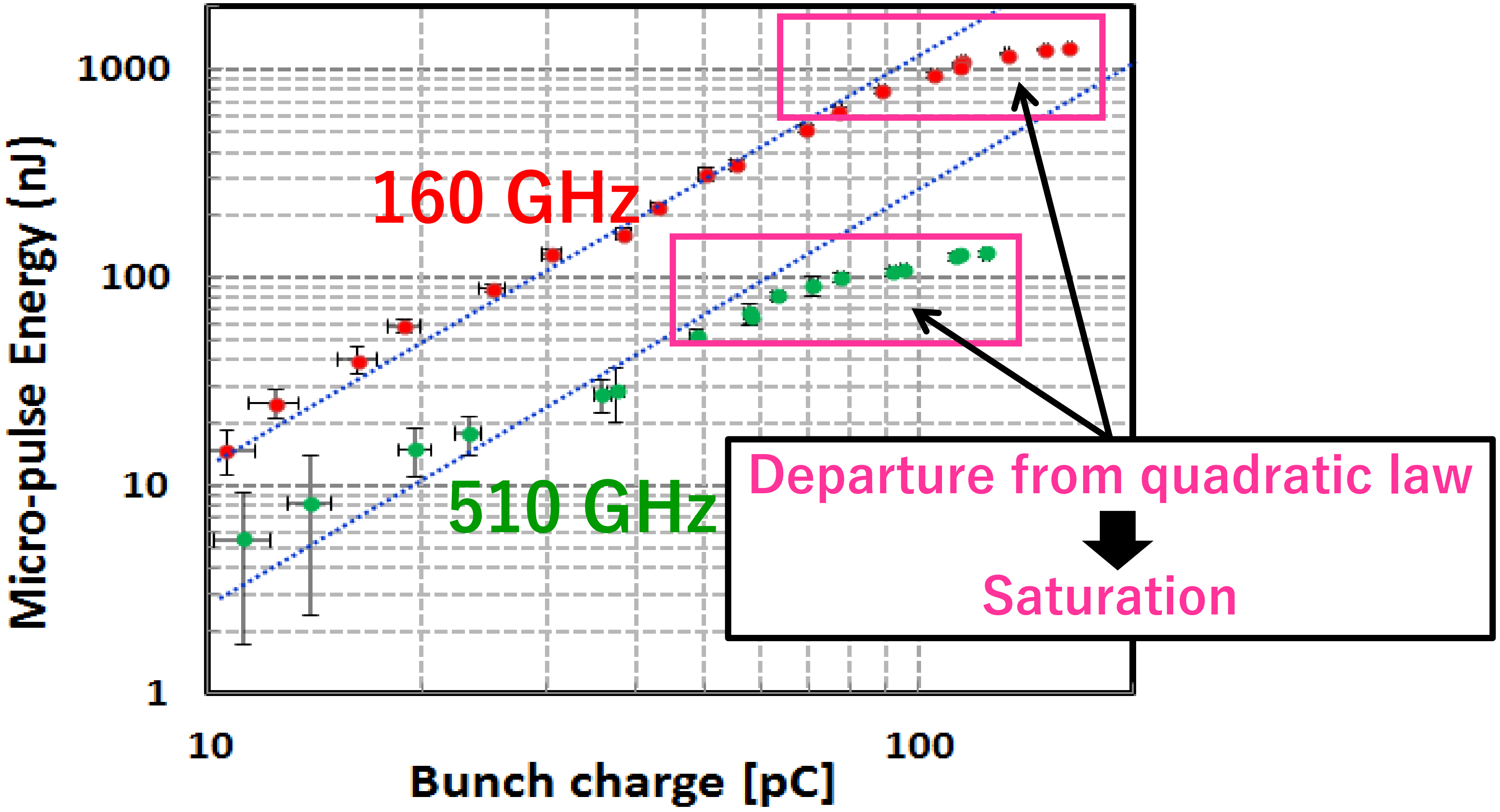
Performance of THz-CUR

THz detector (THz10, Sensor-und Lasertechnik) calibrated at PTB was used.
The peak power was calculated with assumption of 10 cycle radiation.



The highest micro-pulse energy was 1.2 μJ @160 GHz.
The highest expected peak power was around 30 kW @330 GHz.

Saturation Phenomena



Since the low energy electron beam, space charge effect makes electron bunch length long at the high charge condition. ➔ **Saturation of THz-CUR**

Summary

Present status of two accelerator based infrared light sources at Kyoto Univ. are reported.

- **MIR-FEL**
  - Tunable range: 3.4 – 26 μm
  - Highest macro-pulse energy: 30 mJ @5 μm
  - Two operation condition
    - Wideband (~4%-FWHM), High Power, Short Pulse
    - Narrow band (~1%-FWHM), Lower Power, Longer Pulse
- **THz-CUR**
  - Tunable range: 0.16 – 0.65 THz
  - Highest macro-pulse energy: 1.2 mJ @160 GHz
  - Highest peak power: ~30 kW @330 GHz
  - Saturation phenomena was observed at high charge condition

    ➔Saturation should be avoided to have higher peak power.

先端研究施設・設備・機器の整備・共用

第6期科学技術基本計画を見据えた課題・検討事項（たたき台）では、先端研究施設・設備・機器の整備・共用として

- ＜国としての戦略的な整備＞共用プラットフォーム（数億～数十億円規模の最先端研究施設・設備）
- ＜各機関の組織としての整備＞新共用（数百万～数億円規模の研究設備・機器）

に区分記述。

後者では「ラボから組織へ」として機器・人材・資金・情報の集約

大学・法人間での広域的な連携の促進

＝＞施設の共用化、集約・連携が今後加速

まとめ

- 「京都大学中赤外自由電子レーザー施設の現状と将来展望」
- 中赤外自由電子レーザー施設として定常的に運用＋装置開発・性能向上
- Zero-Emission Energy共同利用・共同研究拠点
- 施設維持や将来への投資