Infrared Free-Electron Lasers as a Bridge between Accelerator Science, Particle Physics, and Astrophysics

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CHIANG MAI UNIVERSITY

FACULTY OF SCIENCE
CHIANG MAI UNIVERSITY

PARTICLE ACCELERATORS AND LASER TECHNOLOGY RESEARCH GROUP

Chiang Mai University

- Located in Chiang Mai Province
- Founded in 1964
- 1st Provincial University in Thailand
- Comprehensive University
  - Health Sciences
  - Science & Technology
  - Social Sciences
- 26 Faculties, 2 Research Institutes
- 1 Science and Technology Park

Students & Staffs

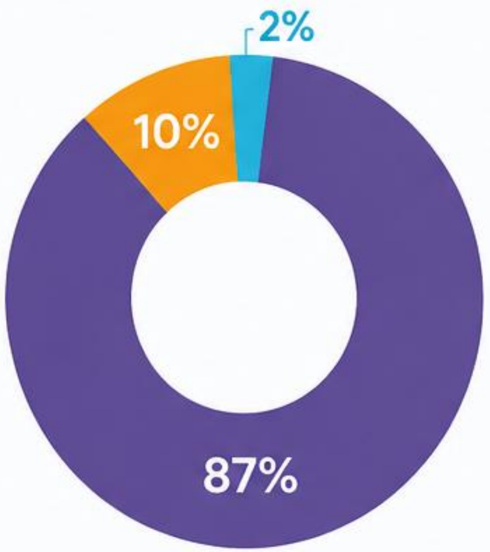
37,174
Total Thai Students

2,461
Total International Students

13,646
Total Staff

	Thai	International
Academic staff	2,750	94
Supporting staff	10,770	32
Total	**13,520**	**126**

Thai Students by Degree Level

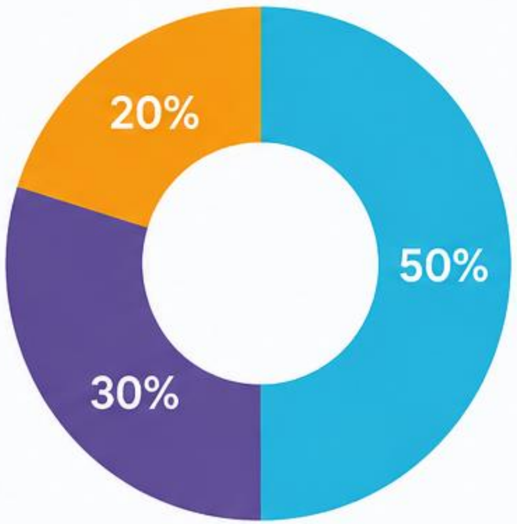


- Doctoral 2%
- Master 10%
- Bachelor 87%

Non-Degree ≈ 0.3%
Graduate Diploma ≈ 0.3%
Higher Graduate Diploma ≈ 0.3%

**as of April 6, 2026*

International Students by Degree Level



- Bachelor 50%
- Master 30%
- Doctoral 20%

Non-Degree ≈ 0.04%

**as of April 6, 2026*

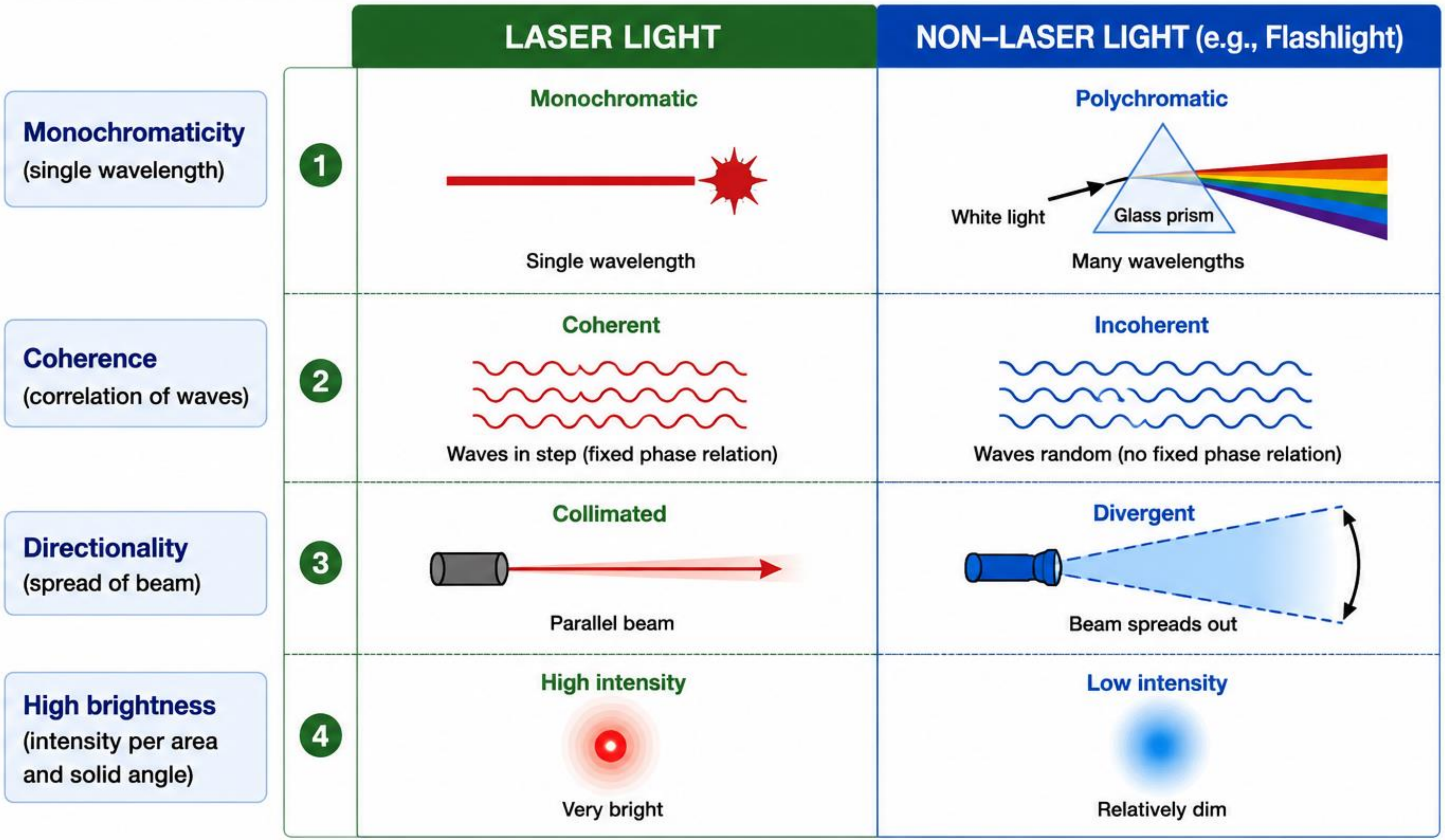
Outline

Outline

01 Introduction of Free-electron Lasers (FELs)

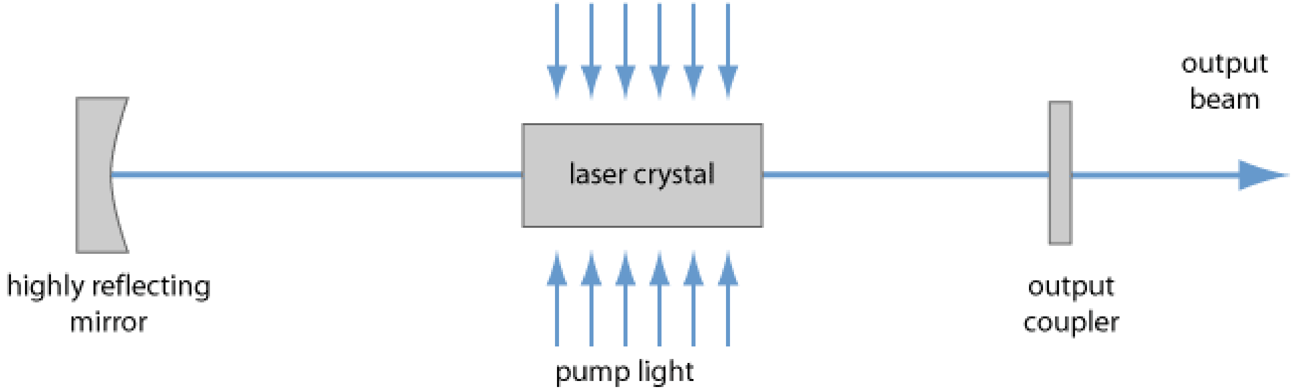
- What are FELs ?
- Why they matter compared with conventional lasers?

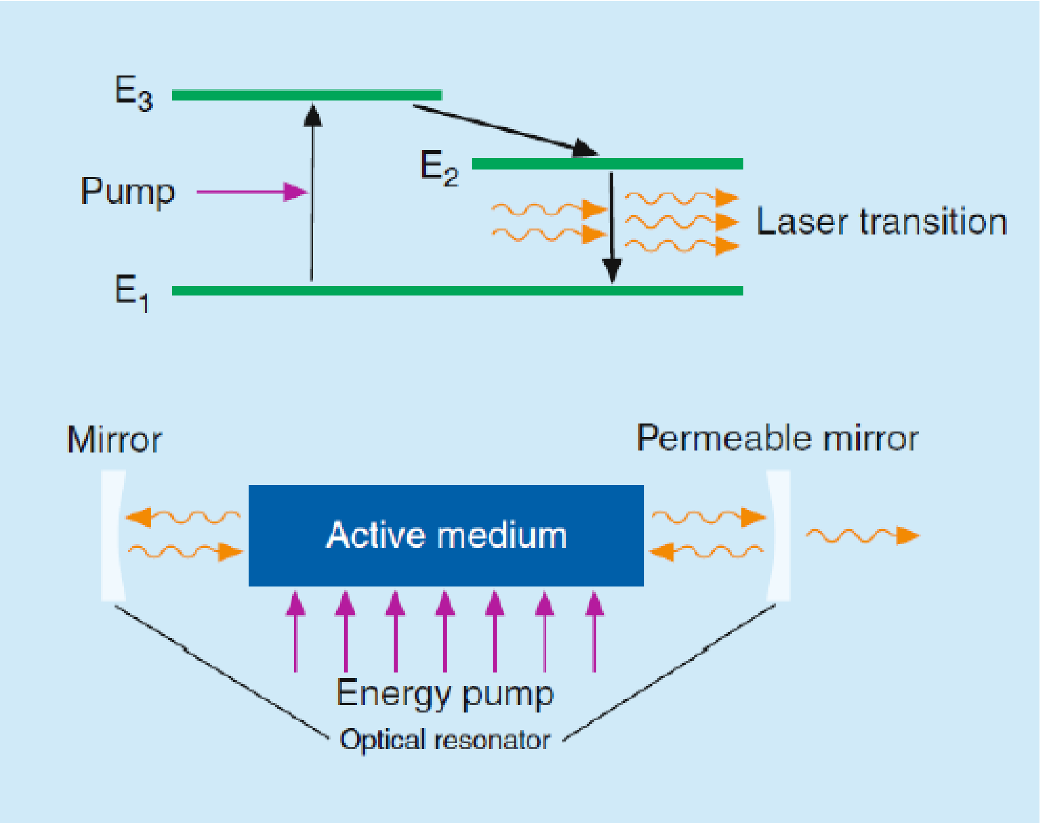
Laser (Light Amplification by Stimulated Emission of Radiation)



Bound-electron Lasers

Conventional "bound-electron lasers" produce light with a specific wavelength by exciting electrons within atoms (or molecules) to jump between atomic energy levels





Source: P. Schmüser, et al. "Free-electron lasers in the ultraviolet and X-ray regime." Springer Tracts in Modern Physics 258 (2014).

Laser components

1. Gain medium: atoms
2. Energy pump (to create population inversion)
3. Optical resonator

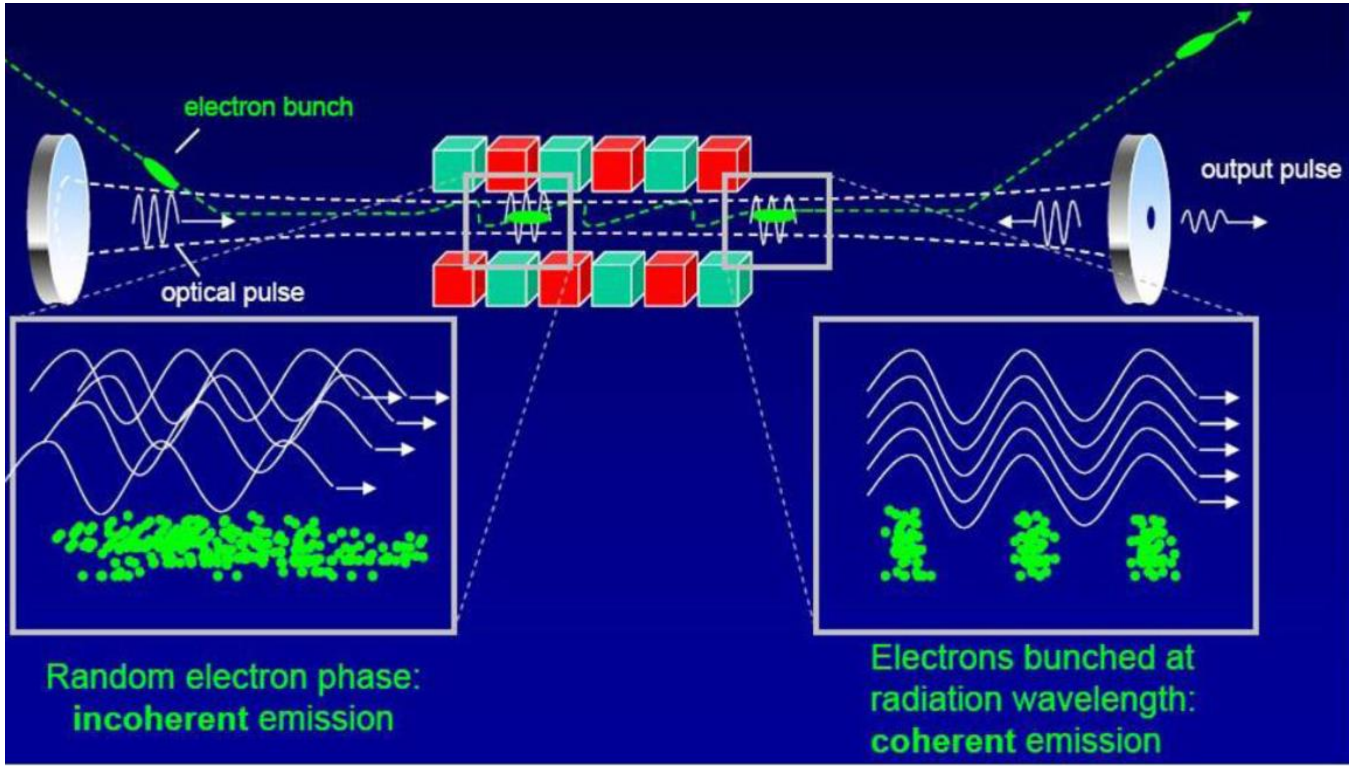
Photons are interacted with atoms in 3 ways

1. Absorption of radiation
2. Spontaneous emission
3. Stimulated emission

Free-electron Laser (FEL)

FEL is produced from relativistic electron beam

- ➢ Electrons oscillate in undulator and emit radiation
- ➢ Radiation bunches electrons into microbunches
- ➢ Microbunched electrons emit intense coherent light



Source: www.astec.stfc.ac.uk/Pages/ALICE-free-electron-laser.aspx

FEL components

- Electron source
- Accelerator
- Undulator (wiggler)
- Electron beam transport & diagnostics
- Radiation output system

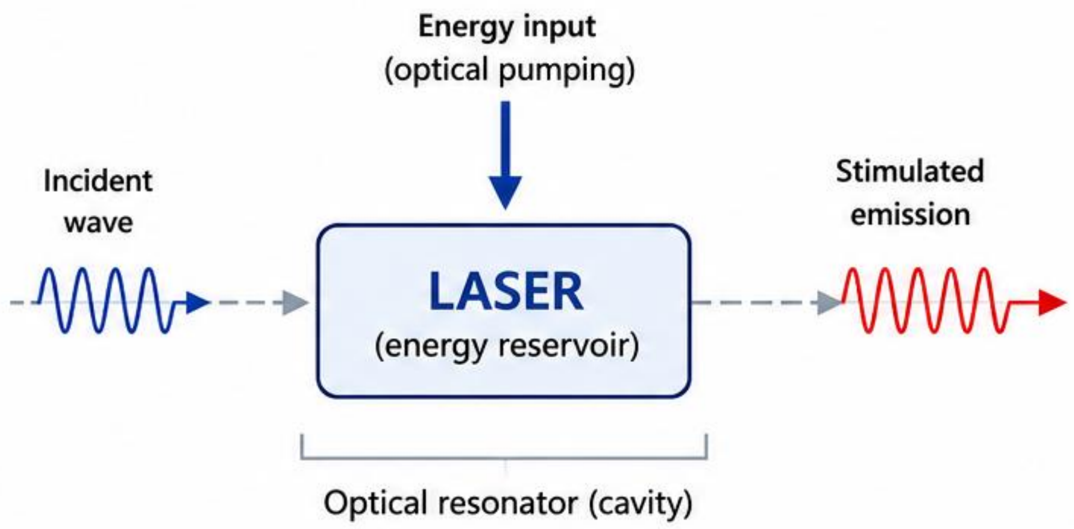
FEL mechanism

1. Spontaneous emission
2. Microbunching
3. Coherent emission
4. Optical amplification
5. Saturation

Comparison

Conventional Lasers

- **Quantized energy levels** (atomic/molecular)
- **Energy pump** creates population inversion
- **Stimulated emission** of radiation
- **Optical resonator** (cavity with mirrors)

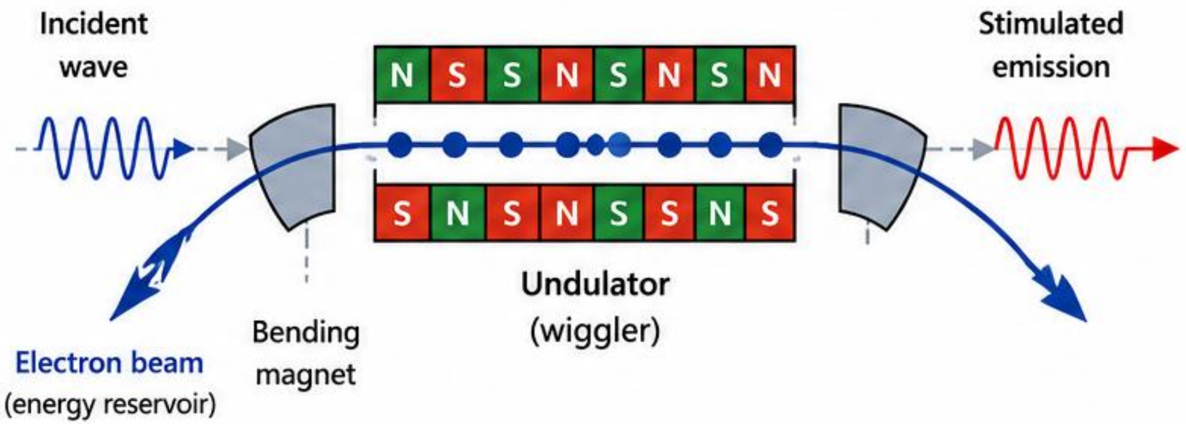


Key point

Energy is stored in the medium (energy reservoir).

Free-Electron Lasers (FELs)

- **Electron energy** **not quantized**
- **Energy source:** **kinetic energy of electron beam**
- **Stimulated emission** of radiation
- **Optical resonator** or **SASE** (self-amplified spontaneous emission)



Key point

The **electron beam** itself **provides** the **energy**.

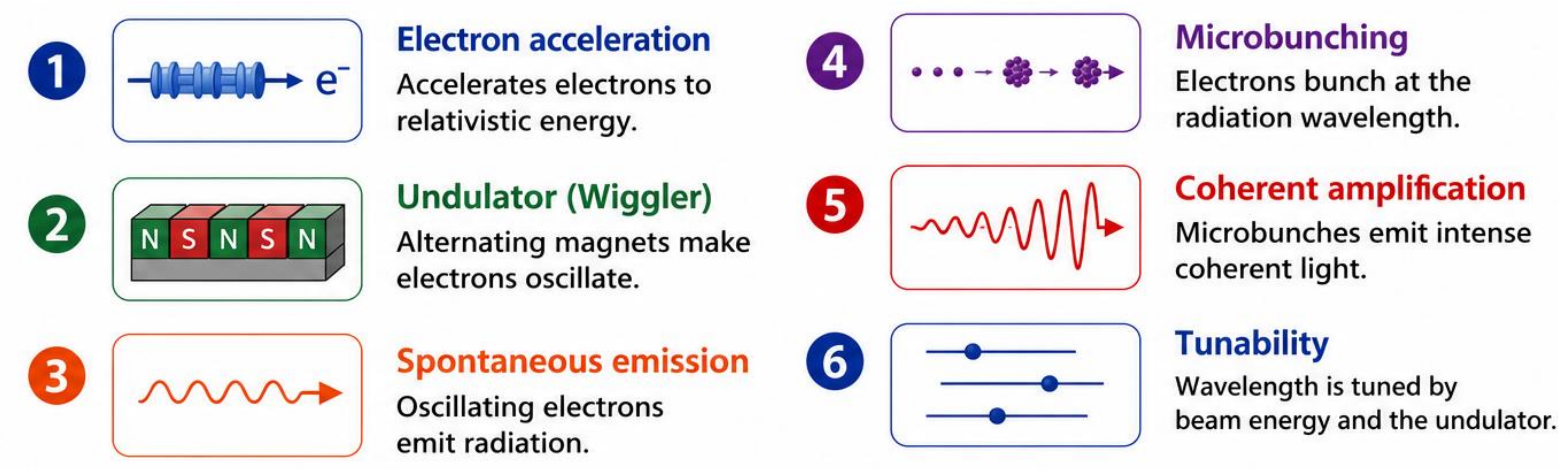
Outline

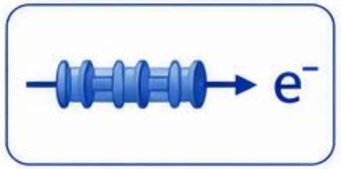
02 Fundamentals of FELs

How do FELs works?

Advantages over conventional light sources

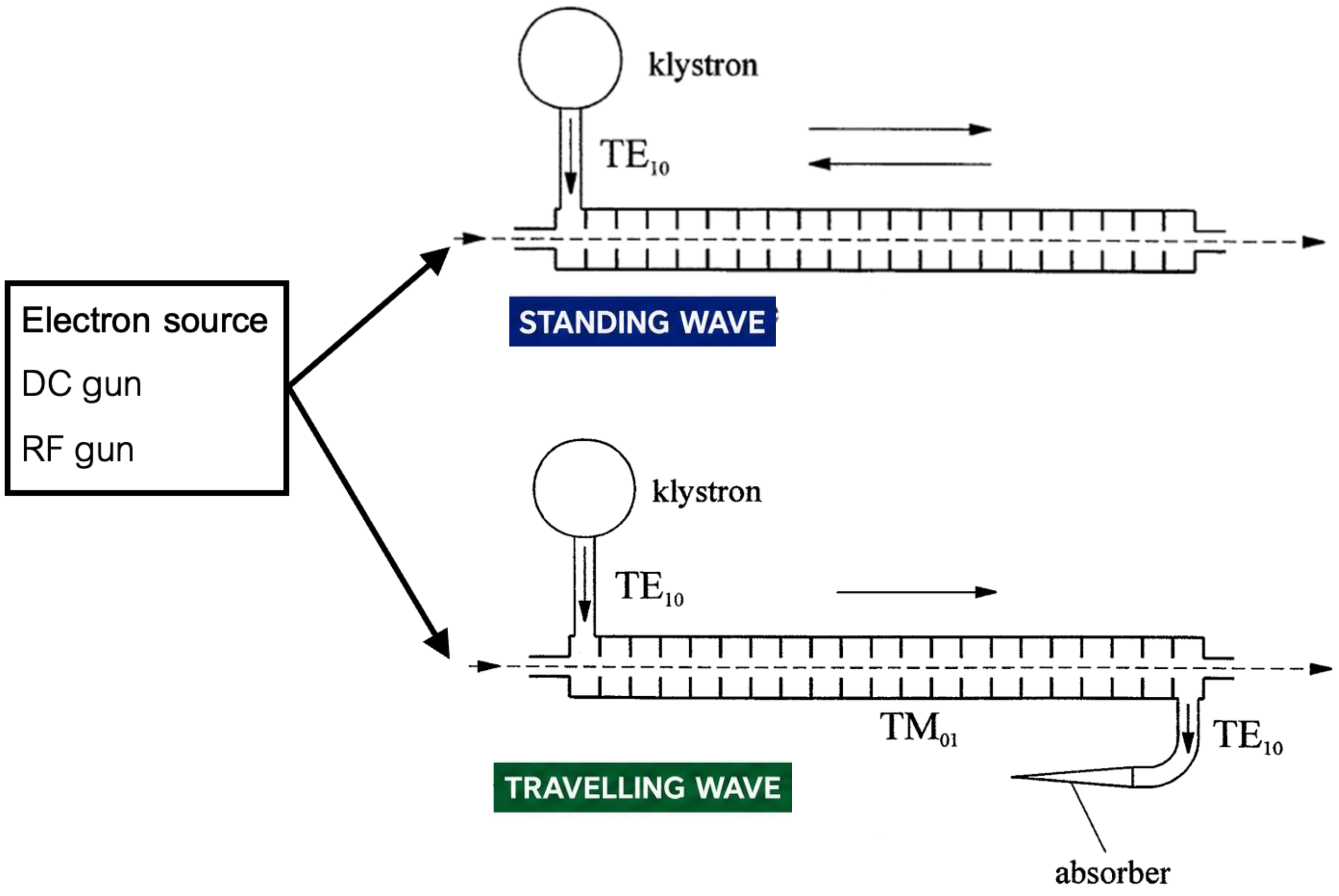
How do FELs work?





Electron acceleration

Accelerates electrons to relativistic energy.



- RF energy forms a standing wave inside the cavity
- No RF power extraction
- Used mainly as an RF amplifier at a fixed frequency

- RF energy propagates as a traveling wave
- RF power is extracted through an output coupler and absorbed in an external load
- Wide bandwidth, used for high-power applications

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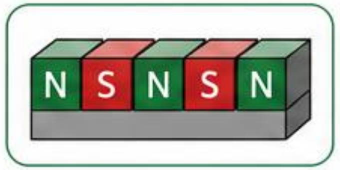
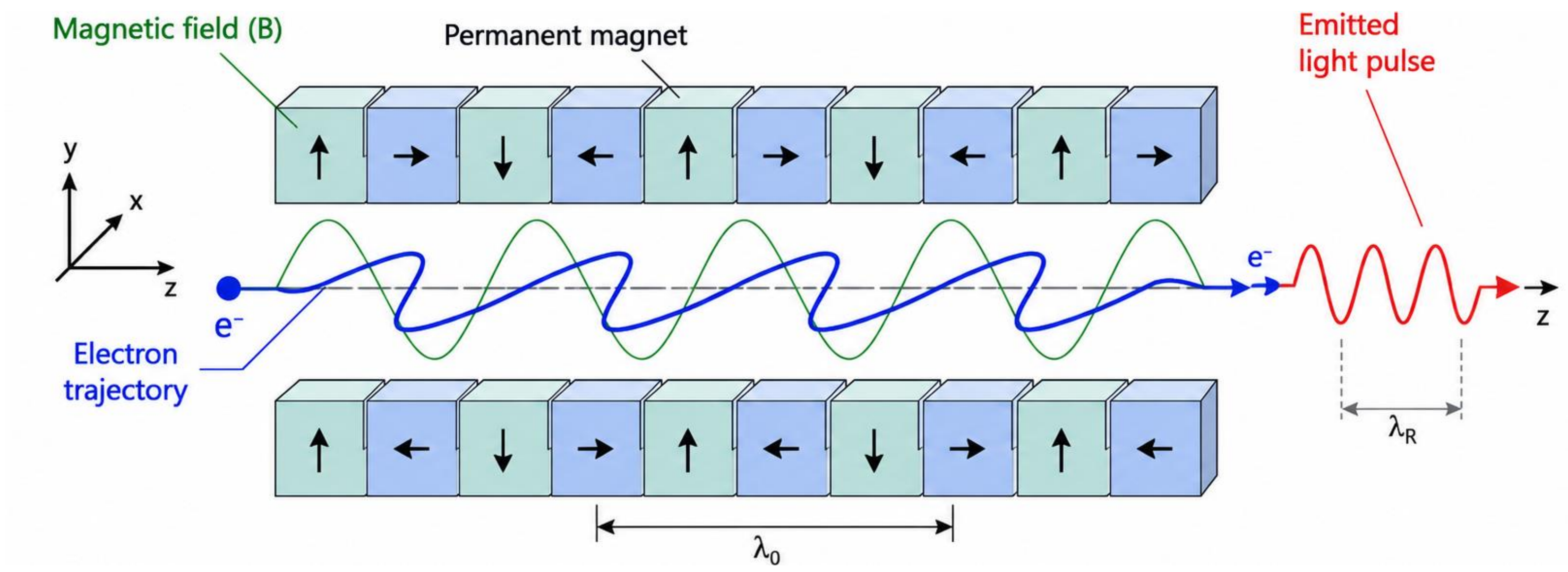
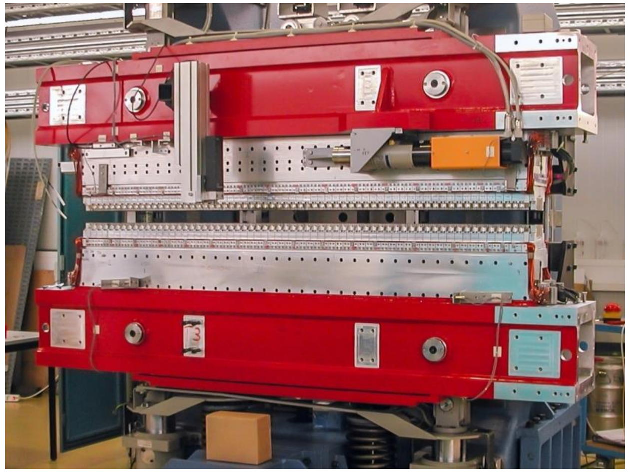


Undulator (Wiggler)

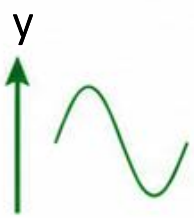
Alternating magnets make electrons oscillate.





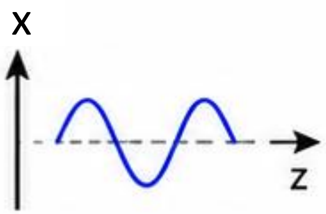
Magnetic field (B)

- Alternating vertical field generated by the permanent magnets.



Electron trajectory

- Electrons oscillate in the horizontal direction while moving forward along z.



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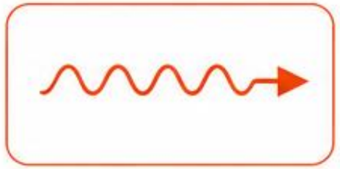
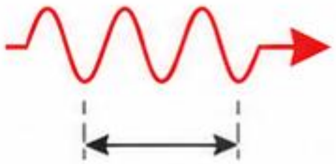


Spontaneous emission

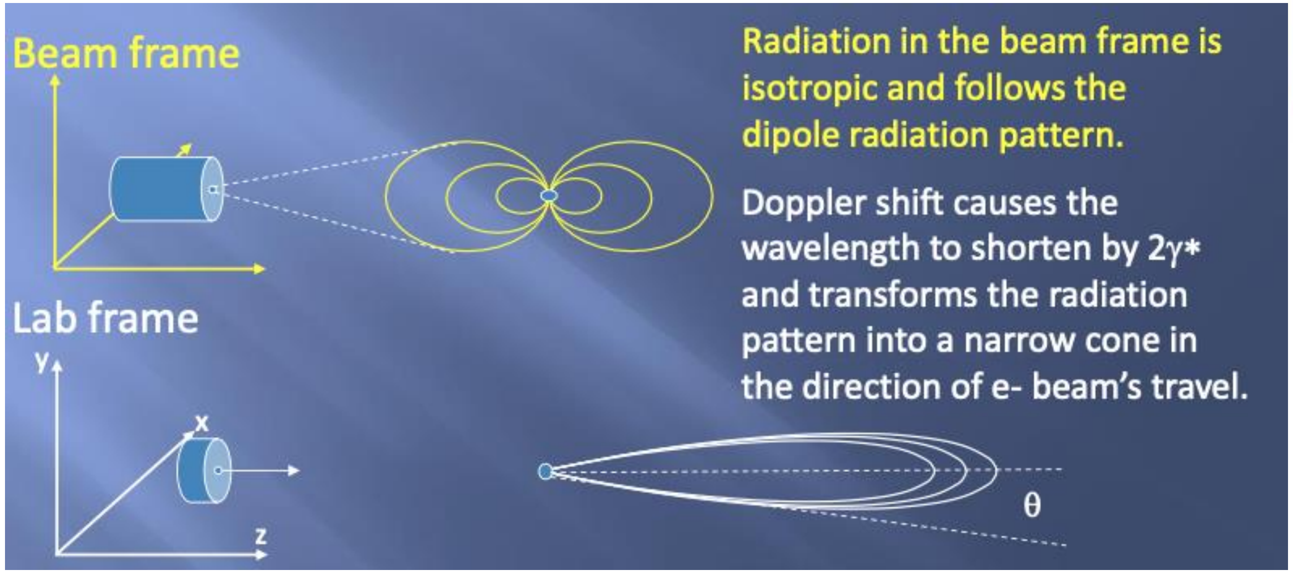
Oscillating electrons emit radiation.

Emitted light

- The oscillating electrons emit electromagnetic radiation in the forward (z) direction.



λ = radiation wavelength

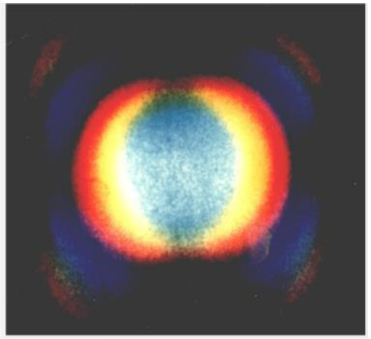


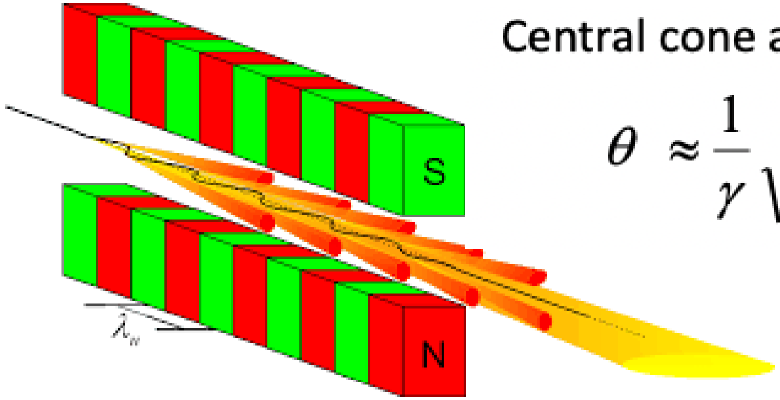
Resonance wavelength

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

λ : radiation wavelength λ_u : undulator period

γ : relativistic factor K : undulator parameter θ : angle





Central cone angles

$$\theta \approx \frac{1}{\gamma}\sqrt{\frac{1}{N_u}}$$

Solid angle

$$\Delta\Omega \approx \frac{\pi}{\gamma^2}\frac{1}{N_u}$$

Undulator parameter

$$K = \frac{eB_0\lambda_u}{2\pi m_0 c}$$

B_0 : peak magnetic field

e : electron charge m_0 : electron rest mass

c : speed of light

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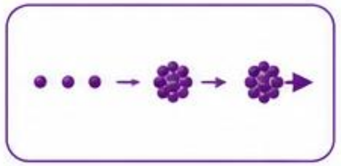
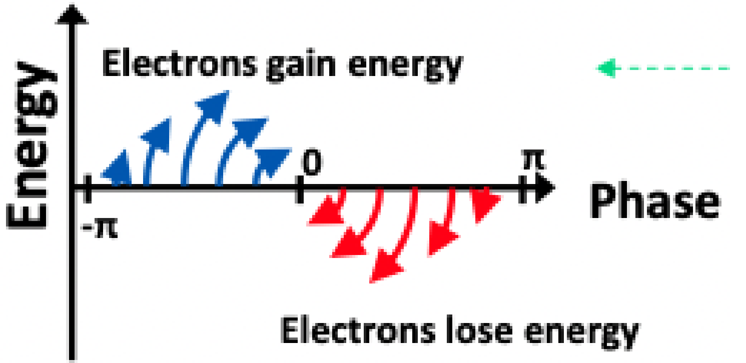


Microbunching

Electrons bunch at the radiation wavelength.

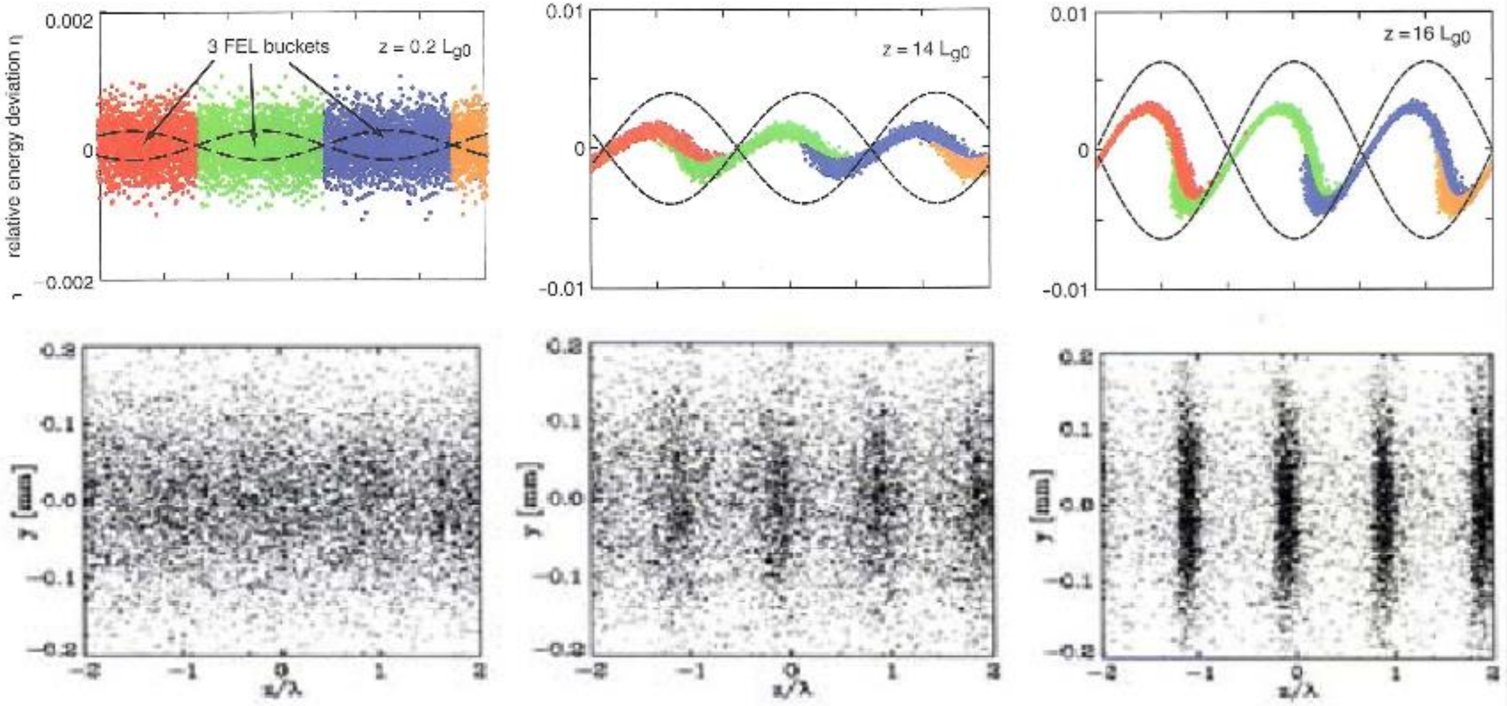
Energy modulation



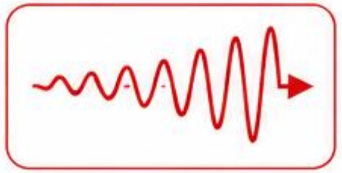
Resonance wavelength

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

Density modulation (bunching with period of resonant wavelength)

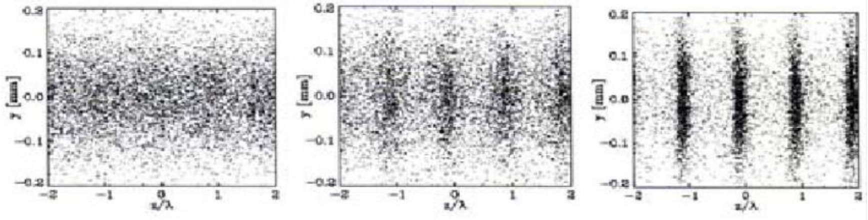


At entrance to the undulator | Exponential gain regime | Saturation(maximum bunching)



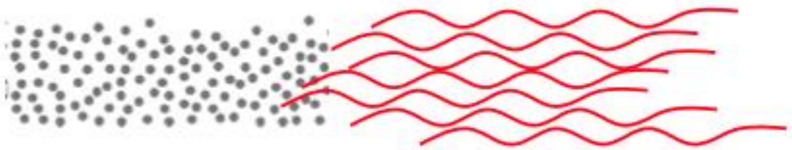
Coherent amplification

Microbunches emit intense coherent light.



At entrance to the undulator | Exponential gain regime | Saturation(maximum bunching)

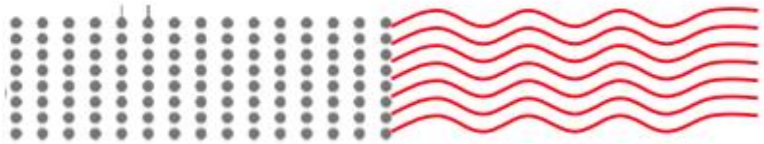
Unbunched beam



Incoherent undulator radiation

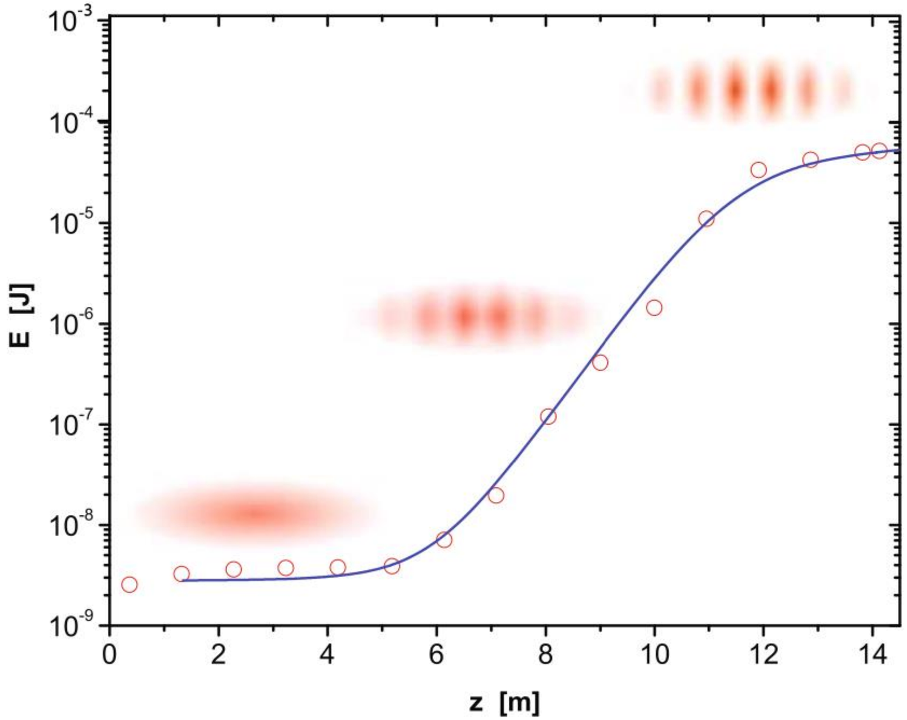
$$E \propto \sqrt{N_e} \qquad I \propto N_e$$

Bunched beam



Coherent bunched beam radiation

$$E \propto N_e \qquad I \propto N_e^2$$



$$N_c \approx 10^6 \quad \Rightarrow \quad P_{FEL} = 10^6 P_{undulator}$$

6

Tunability

Wavelength is tuned by beam energy and the undulator.

Higher electron energy (γ) ➡ shorter wavelength

Resonance wavelength

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

λ : radiation wavelength λ_u : undulator period

γ : relativistic factor K : undulator parameter θ : angle

Undulator parameter

$$K = \frac{eB_0\lambda_u}{2\pi m_0 c}$$

B_0 : peak magnetic field

e : electron charge m_0 : electron rest mass

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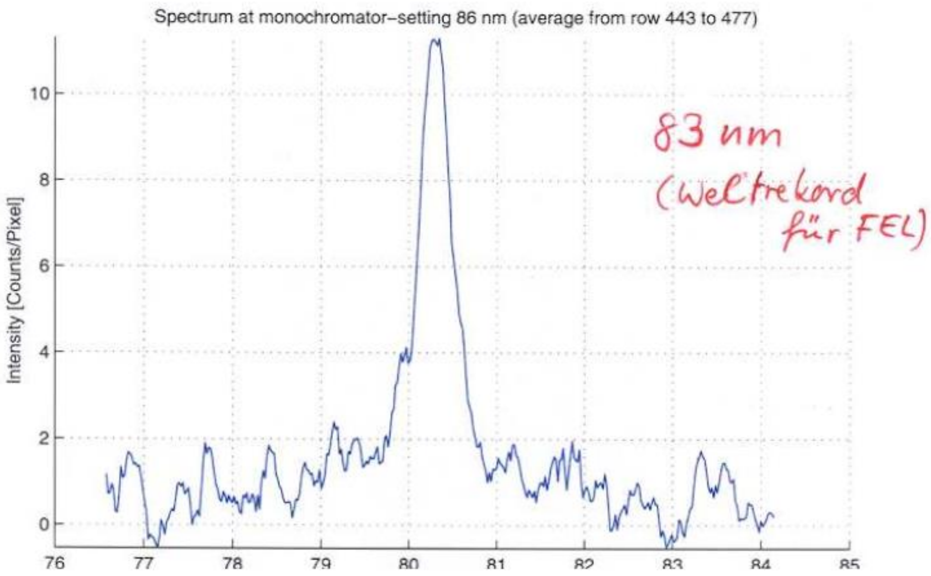
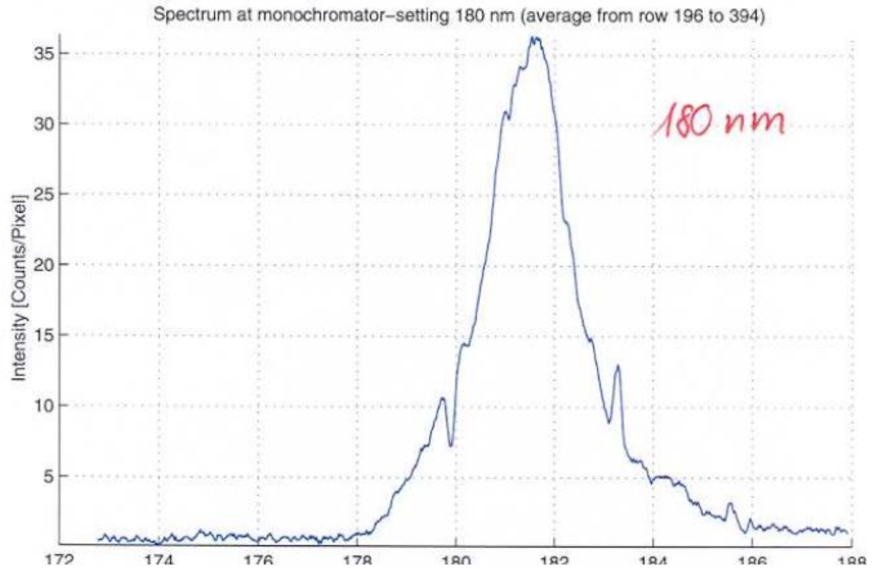




Source: P. Schmueser, Lecture “Free Electron Lasers”, University of Hamburg

Advantages of FELs

Broad Tunability

Wavelength adjustment by changing electron beam energy or magnetic field.

High Peak Power

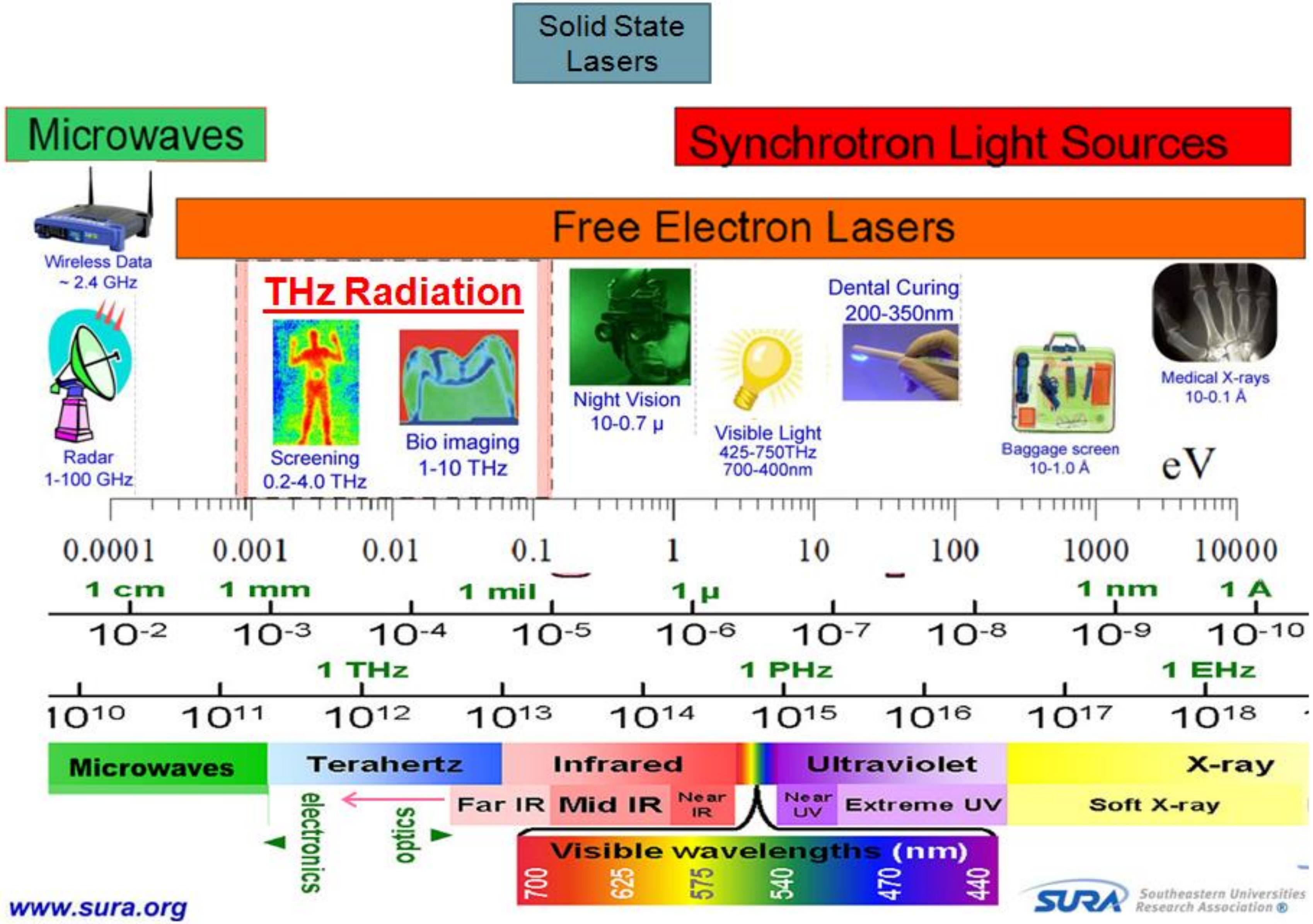
MW-GW levels of peak power enables study of multi-photon processes.

Short Pulse Duration

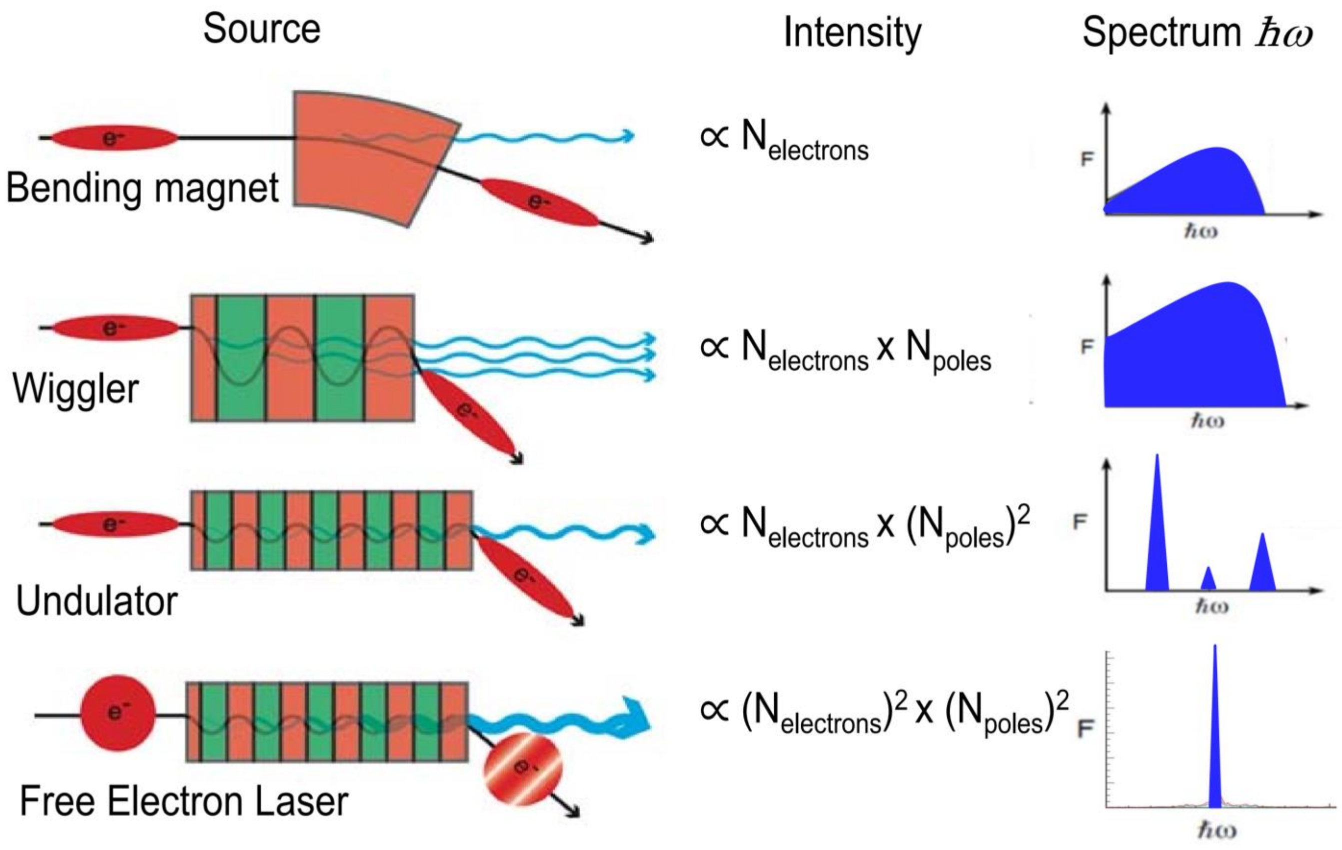
FEL pulses with fs/ps scale are suitable for high-resolution time-resolved spectroscopy.

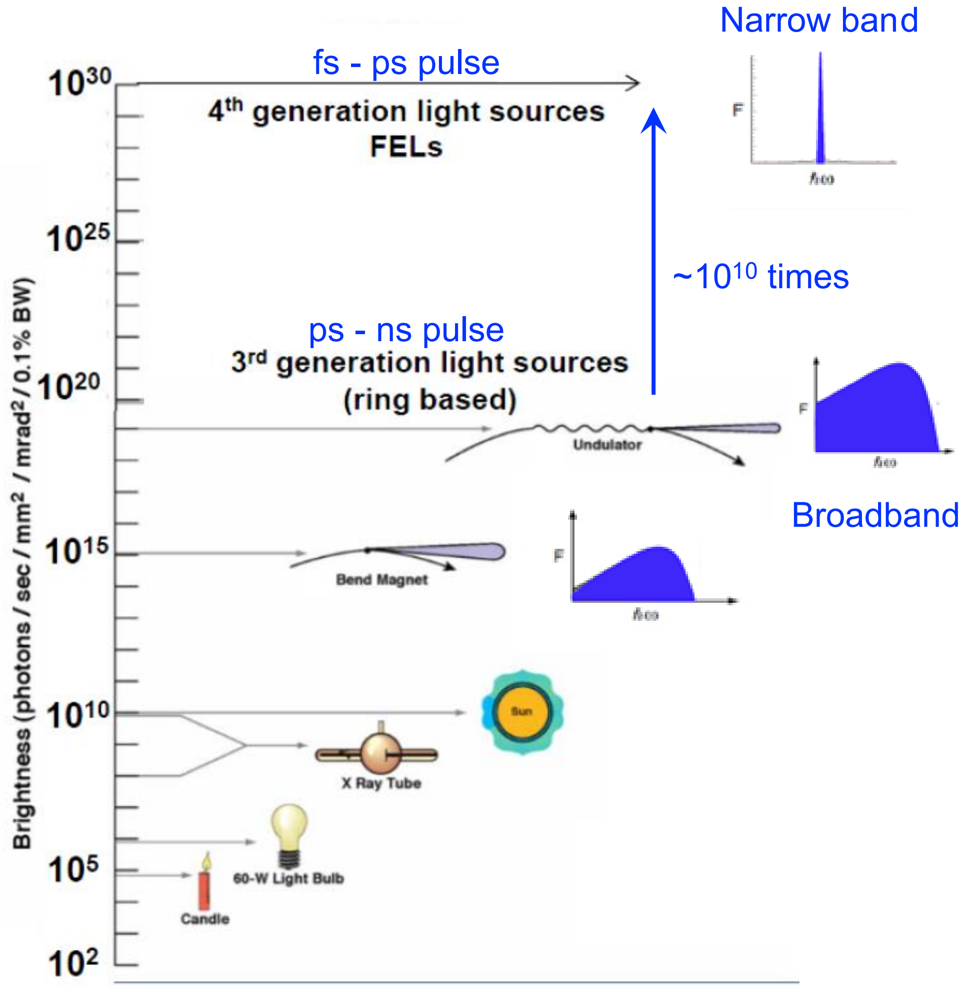
Feature	Conventional lasers	Free-electron lasers
Tunability	Narrow / Discrete lines	Broad / Continuous
Peak power	Low (mW to W)	Ultra-high (MW to GW)
Gain medium	Crystal / Gas / Semiconductor	Relativistic electron beam
Wavelength range	Limited by energy bandgap	THz to X-ray

Advantages of FELs: Light Sources



Advantages of FELs: Synchrotron vs. FEL





Source: T. Shea, Overview of Beam Diagnostics, USPAS09, Albuquerque NM, June 23-26, 2009

Outline

03 Particle Physics ↔ Accelerator Science ↔ FELs

- Accelerator Science: The foundation of FELs
- Common technologies: Particle Physics ↔ FELs
- Skills transfer: Particle Physics → Photon Science

Accelerator Science : Foundation of FELs

FEL performance is determined by electron-beam quality before the undulator.

Key accelerator requirements

- High-brightness electron beam
- Low emittance and small energy spread
- Precise timing, RF stability, and diagnostics
- Beam matching to the undulator

Main message

Without accelerator science, FELs cannot exist.

Improving beam quality directly improves FEL intensity, bandwidth, and stability.

Electron beam quality is built and optimized through each accelerator stage

Electron Source

Generates electrons with high brightness and low emittance.

→

RF Acceleration

Accelerates electrons while controlling energy spread and stability.

→

Bunch Compression

Shortens the bunch length to increase peak current and brightness.

→

Beam Transport

Preserves beam quality while delivering the beam to the undulator.

→

Undulator

Electrons emit coherent light through interaction with the undulator.

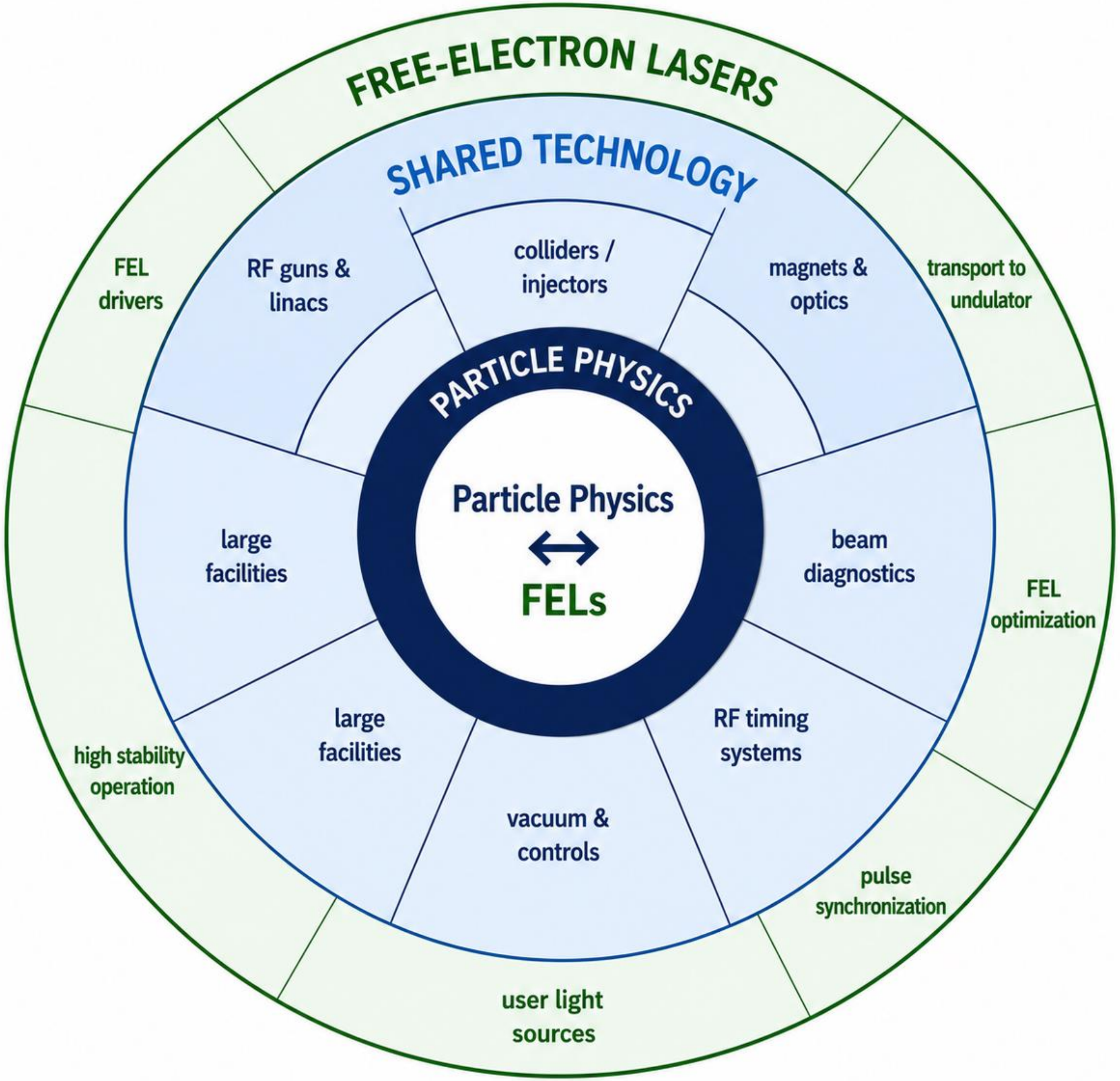
→

Radiation

High-quality electron beam produces bright, coherent radiation.

Common Technologies: Particle Physics ↔ FELs

Accelerator technologies support both high-energy & photon-science facilities.



Skills Transfer: From Particle Physics to Photon Science

Particle Physics
↓
Accelerator Physics
↓
Free-Electron Lasers
↓
Photon Science

Beam dynamics
Understanding and controlling particle beams

RF cavities
Design, operation, and optimization of RF systems

Magnets
Design and operation of accelerator magnets

Vacuum systems
Vacuum technology for high-performance accelerators

Diagnostics
Beam measurement and instrumentation techniques

Timing & controls
Synchronization, control systems, and feedback

Technology developed for fundamental physics becomes a platform for photon science.

Examples: DESY, SLAC, KEK, PSI

Outline

04 Scientific Applications of FELs

FEL configurations

X-FELs key properties

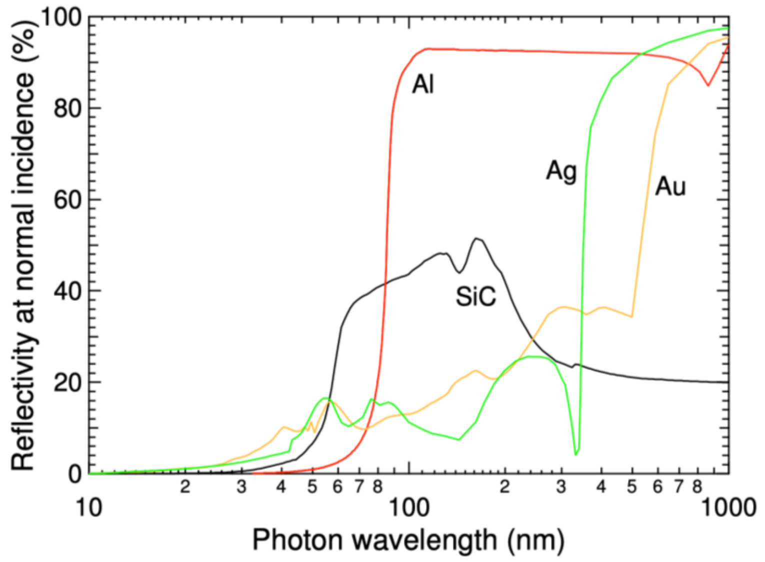
IR/THz-FELs key properties

IR/THz-FEL applications: Material sciences

- Material sciences, Biology & Chemistry, Astrophysics

FEL Configurations

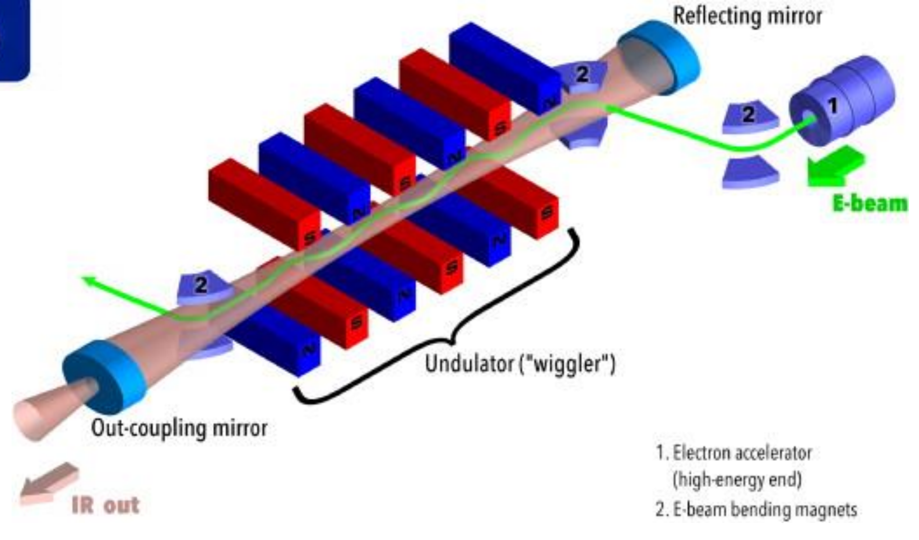
- **1977:** First FEL oscillator @ Stanford University (43 MeV, 3.4 µm IR)
- Optical cavity is not possible for wavelengths <100 nm.



LOW-GAIN FEL (Oscillator)

Oscillator

(Undulator + Optical cavity)

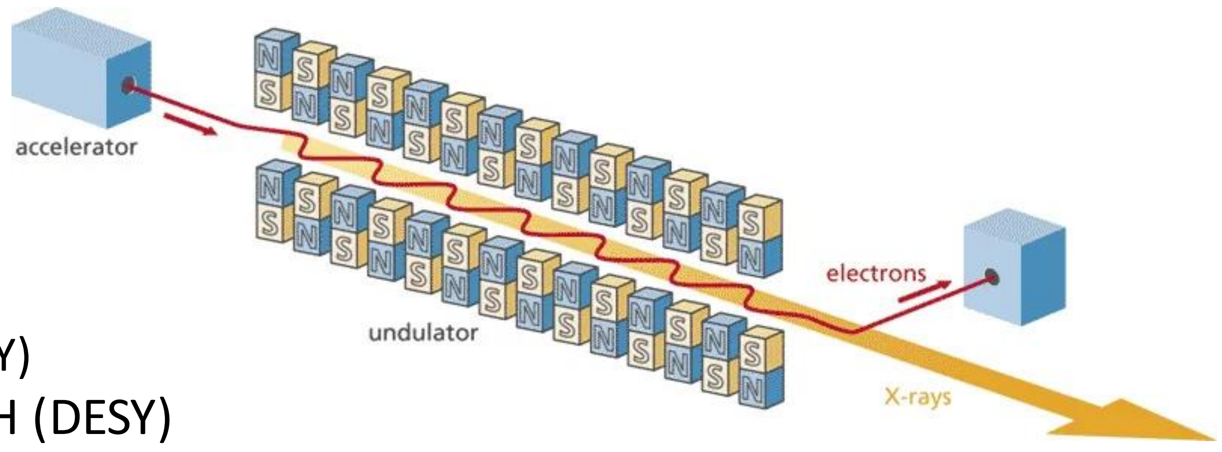


Source: www.sciencedirect.com/topics/engineering/free-electron

HIGH-GAIN FEL (SASE)

SASE (Self-Amplified Spontaneous Emission)

Long undulator

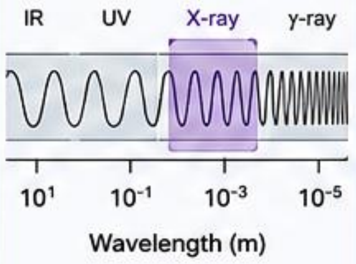


- **2000:** First VUV FEL @ TESLA Test Facility or TTF (DESY)
- **2005:** First XUV & soft X-ray FEL user facility @ FLASH (DESY)
- **2009:** First hard X-FEL @ LCLS (SLAC, Stanford)

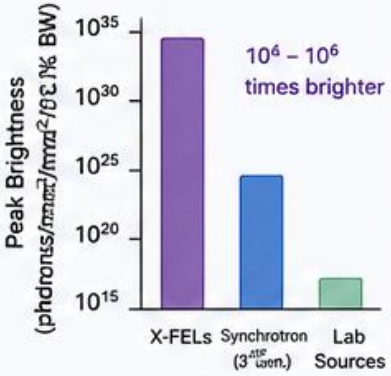
Source: www.psi.ch/en/swissfel/how-it-works

X-FELs Key Properties

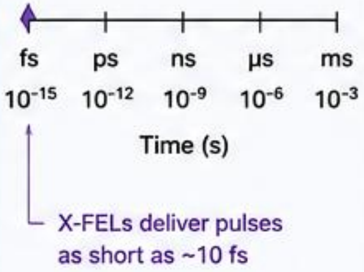
1. Wavelength
Tunable from soft to hard X-rays (~0.1 – 25 keV)



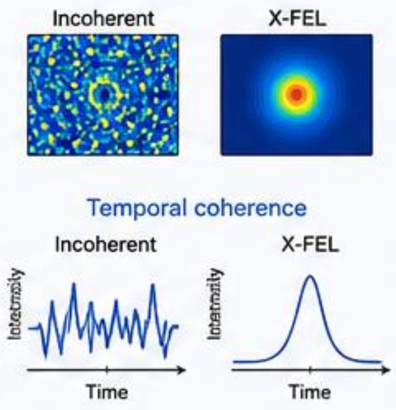
2. Peak Brightness
Up to 10^{33}–10^{35} photons/s/mm²/mrad²/ 0.1% BW



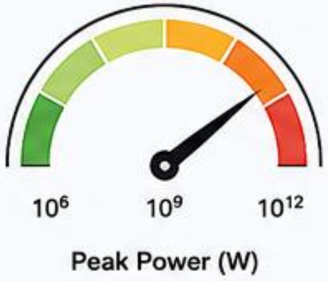
3. Pulse Duration
Ultrashort pulses in the femtosecond regime



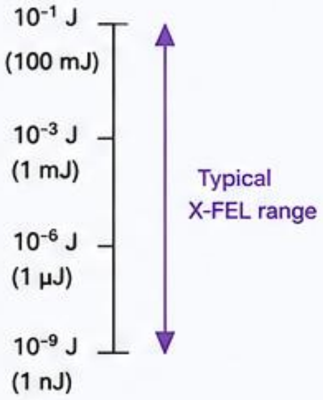
4. Coherence
Highly coherent in space and time



5. High Peak Power
Gigawatt (10^{9} W) to terawatt (10^{12} W) peak power



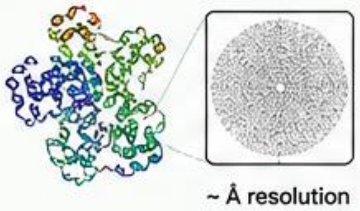
6. Pulse Energy
Microjoule (μJ) to millijoule (mJ) per pulse



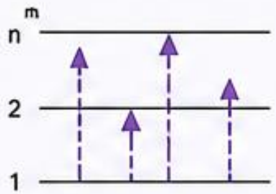
Advantages of X-FELs

1. Ultrafast time resolution
Femtosecond pulses enable "movie" imaging of atomic and electronic dynamics.

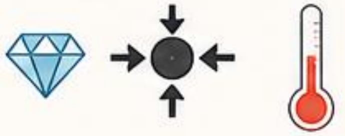
2. Atomic-scale imaging
Coherent, short-wavelength X-rays achieve Ångström (10^{-10} m) resolution.



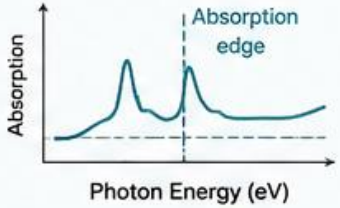
3. Non-linear X-ray science
Extremely high peak intensity allows observation of non-linear and multi-photon processes.



4. Access to extreme states
Enables studies of matter under extreme conditions (pressure, temperature, density).

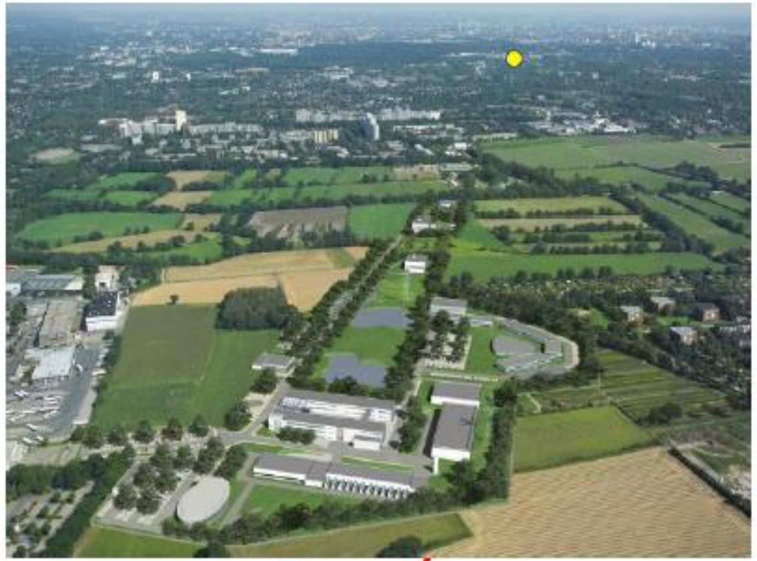


5. Element specificity
Tunable photon energy allows element-selective (chemical-specific) investigations.



6. Versatility
Wide range of applications across physics, chemistry, materials, biology, and medicine.

Examples of X-FEL Facilities



- European XFEL. Germany (λ ~ 0.1-1.6 nm)
- FLASH @ DESY, Germany (λ ~ 0.1-7 nm)
- SPARC, Italy (λ ~ 0.6-40 nm)
- FERMI @ Elettra, Italy (λ ~ 1 0-100 nm)
- SwissFEL, Switzerland (λ ~ 0.1-7 nm)

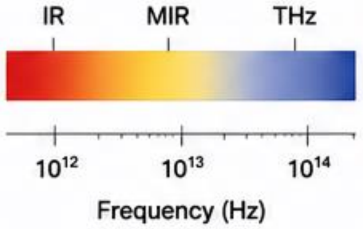
- LCLS FEL @ SLAC, USA
  (λ ~ 0.15-1.5 nm)
- HGHG FEL @ NSLS, BNL, USA
  (λ ~ 193 nm)

- SACLA XFEL @ Spring-8, Japan
  (λ > 0.1 nm)
- Shanghai FEL
- Pohang XFEL

IR-THz FELs Key Properties

1. Wavelength Range

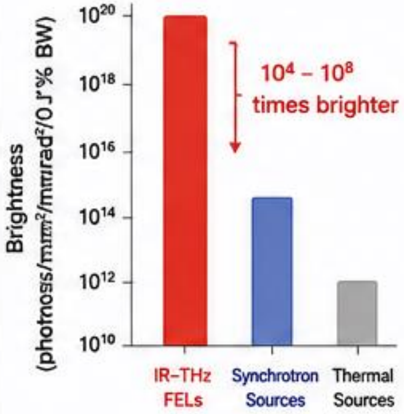
Covers the infrared to terahertz region



Wavelength:
~ 1 µm – 3 mm
(0.1 – 300 THz)

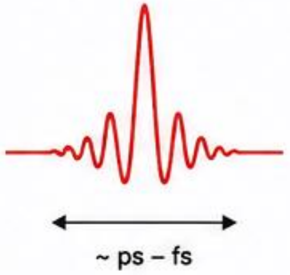
2. High Brightness

High brightness far beyond thermal and synchrotron sources



3. Ultrafast Pulses

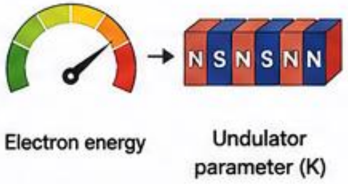
Ultrashort pulse duration enables time-resolved measurements



Typical pulse duration:
~ 1 ps – 100 fs

4. Tunability

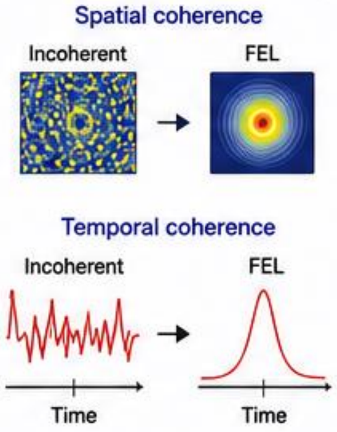
Wavelength continuously tunable by adjusting electron beam energy and undulator



Wide and continuous tuning

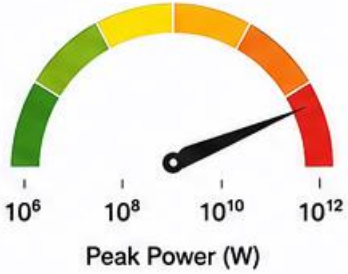
5. High Coherence

High spatial and temporal coherence for precise experiments



6. High Peak Power

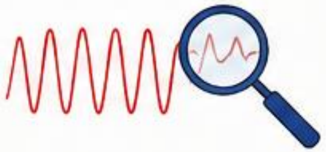
High peak power in a wide mid-IR to THz range



Up to GW peak power in many systems

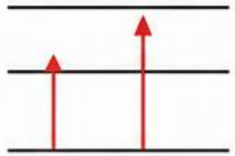
Advantages of IR-THz FELs

1. Access to Unique Spectral Region



Bridges the gap between lasers (IR) and microwaves, providing unique photon energies for many materials and biological systems.

2. Probes Low-Energy Excitations

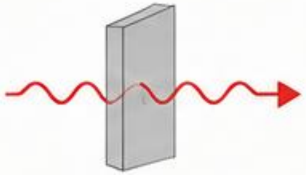


Ideal for studying vibrational, rotational, lattice, and collective excitations in matter.

3. Time-Resolved Studies

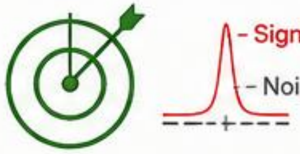
Ultrafast pulses enable observation of dynamics in real time on ps–fs timescales.

4. Non-Destructive & Penetrating



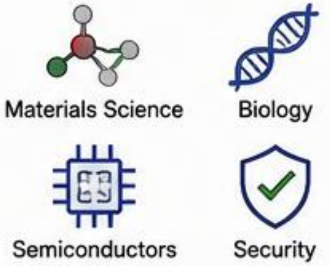
THz and mid-IR radiation penetrate many materials without damaging samples, suitable for in-situ studies.

5. High Sensitivity & Coherence



High brightness and coherence provide excellent signal-to-noise ratio for weak or subtle phenomena.

6. Broad Applications



Applicable to materials, chemistry, biology, medicine, semiconductors, and security screening.

Motivation & Importance of IR/THz FELs

- **Enabling access to nonlinear light–matter experiments**

Driving Strong Fields

IR/THz FELs produce strong electric fields (>100 kV/cm), driving systems beyond linear response.

Coherent Control of Solids

High-intensity pulses can drive and control collective modes, such as in superconductors and magnetic materials.

Investigating Strongly Correlated Electrons

IR/THz FELs manipulate crystal lattices and electronic properties, enabling control of material properties.

- **Need for ultrafast light sources in science**

Capturing Transient States

Ultrafast pulses allow real-time observation of atomic and molecular motion on ps/fs timescales.

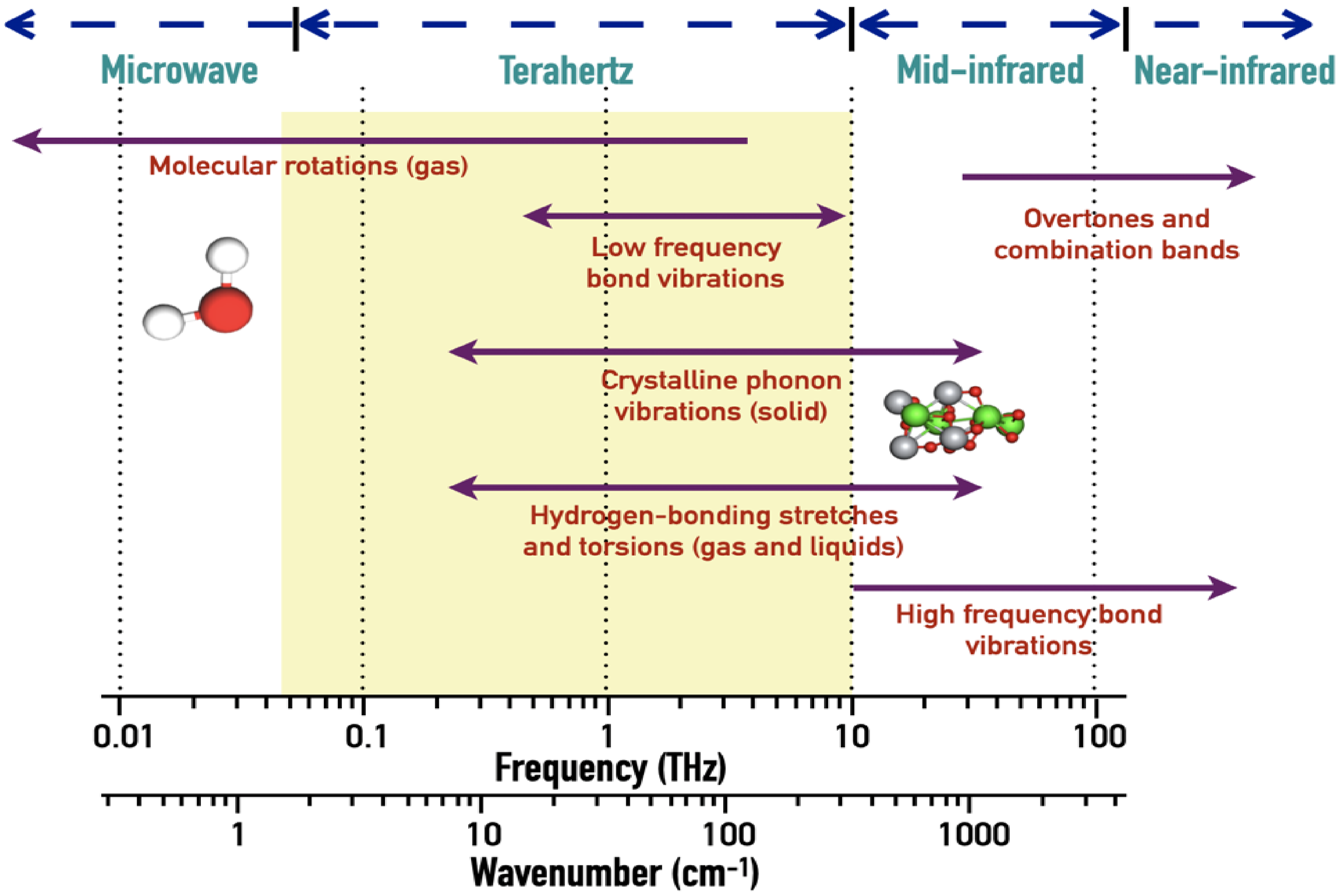
Understanding Fundamental Quanta

Energy of THz/MIR aligns with energy scales of excitations, *e.g.* lattice phonons, superconducting gaps, spin dynamics.

Non-equilibrium Physics

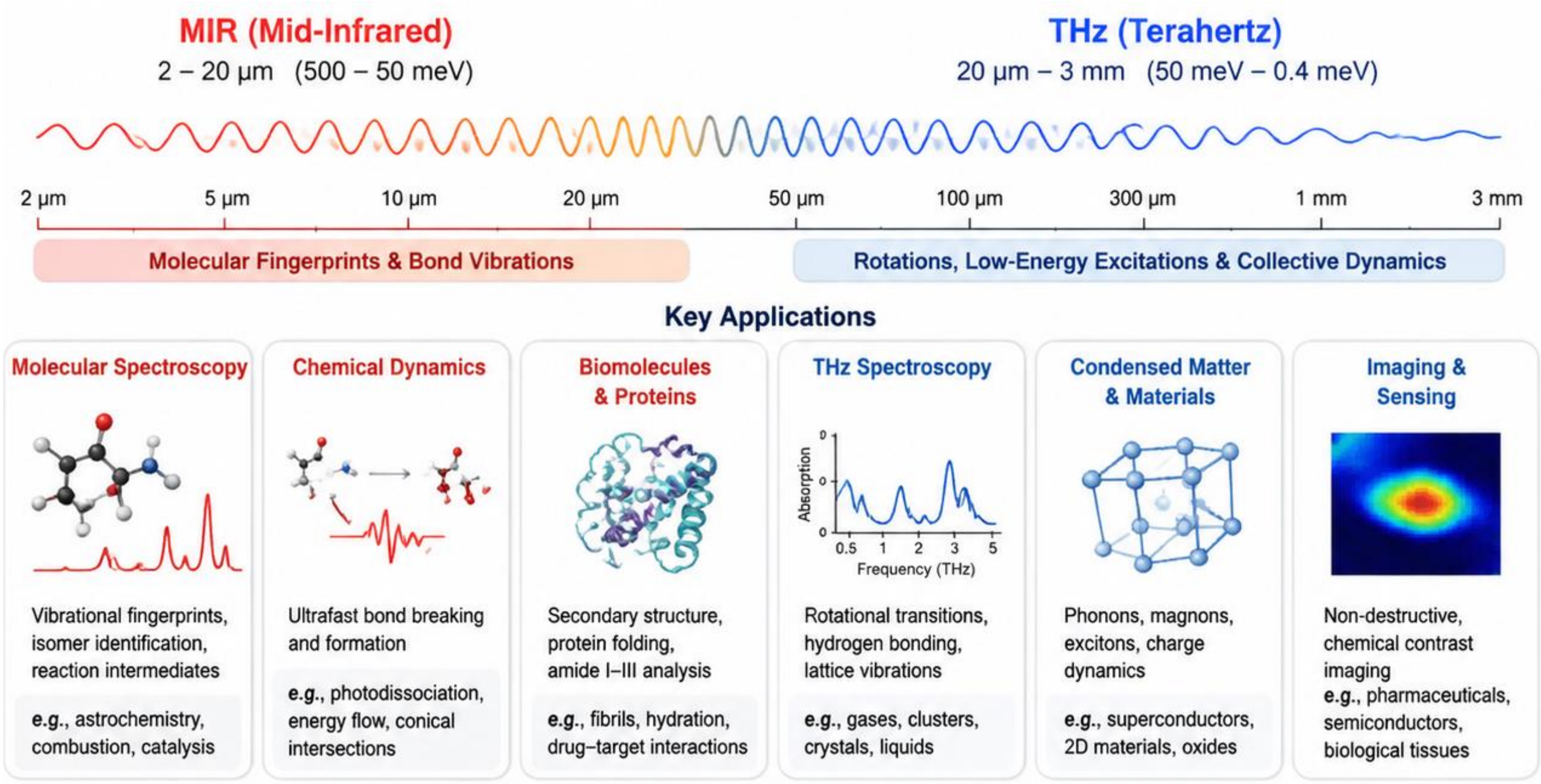
Exciting systems away from equilibrium to reveal hidden phases of matter.

Importance of IR/THz Radiation



Modified from E. Pickwell, V. P. Wallace , Journal of Physics D: Applied Physic 39, 2006

Key Applications of IR/THz Radiation



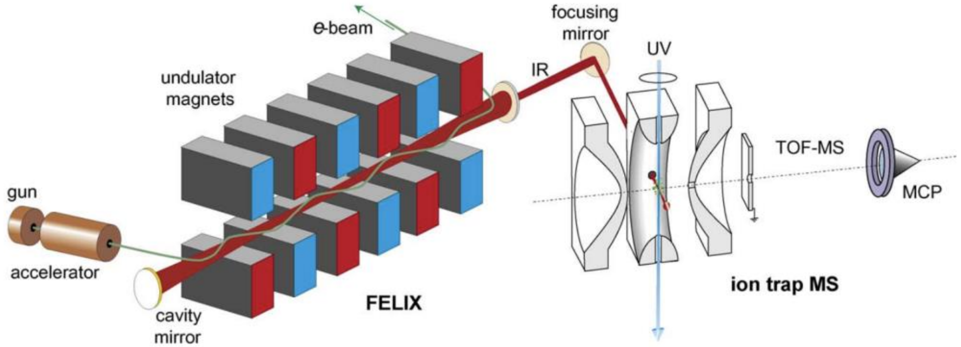
MIR FEL Applications: Molecular Vibrational Fingerprints

Methodology: Structural characterization of mass-selected ions in trap

Result: Experimental vibrational "fingerprint" compared with DFT calculations for structure determination

- **This technique allows detailed studies of molecular vibrations and chemical structures**

- **Gas-phase infrared multiple photon dissociation (IRMPD) spectroscopy of mass-selected molecular ions**



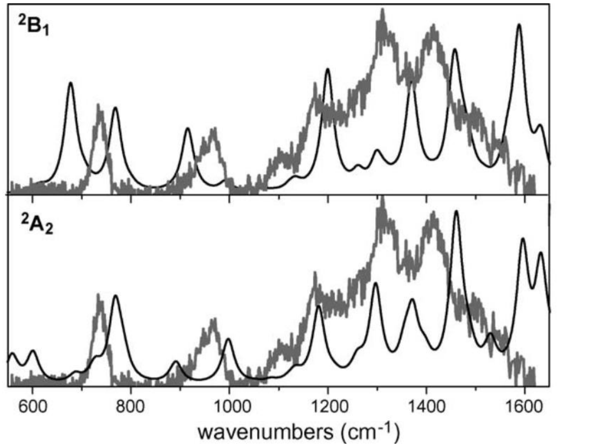
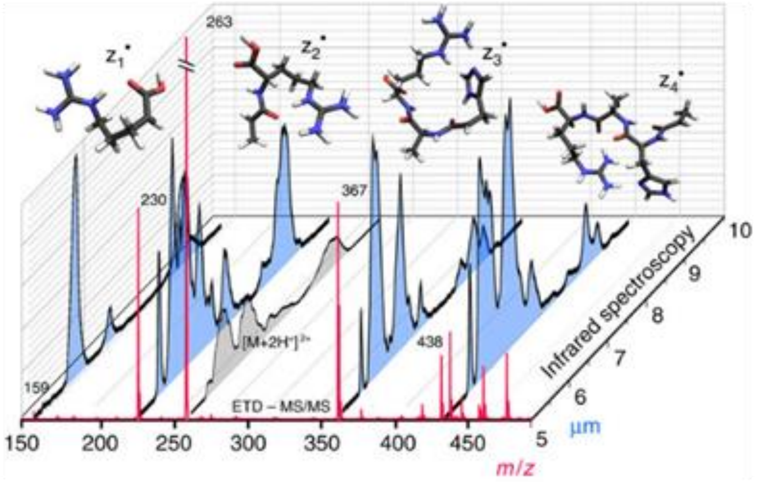


Fig. 5. IRMPD spectrum of cationic triphenylene compared with B3LYP/D95(d,p) calculated spectra for the two structures distorted to C_{2v} symmetry: the $^2B_1$ minimum energy structure and the $^2A_2$ saddle point structure.

J. Oomens *et al.*, *Int. J. Mass Spectrom.* 254 (2006) 1–19.

- **Structural Identification of Electron Transfer Dissociation Products in Mass Spectrometry using Infrared Ion Spectroscopy**

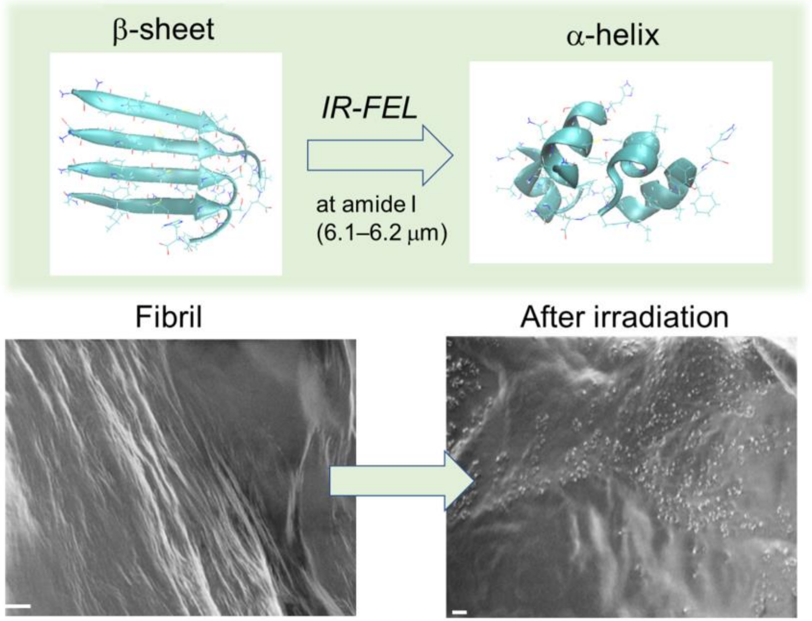
J. Martens *et al.*, *Nat. Commun.* ***7*** (2016) 11754.

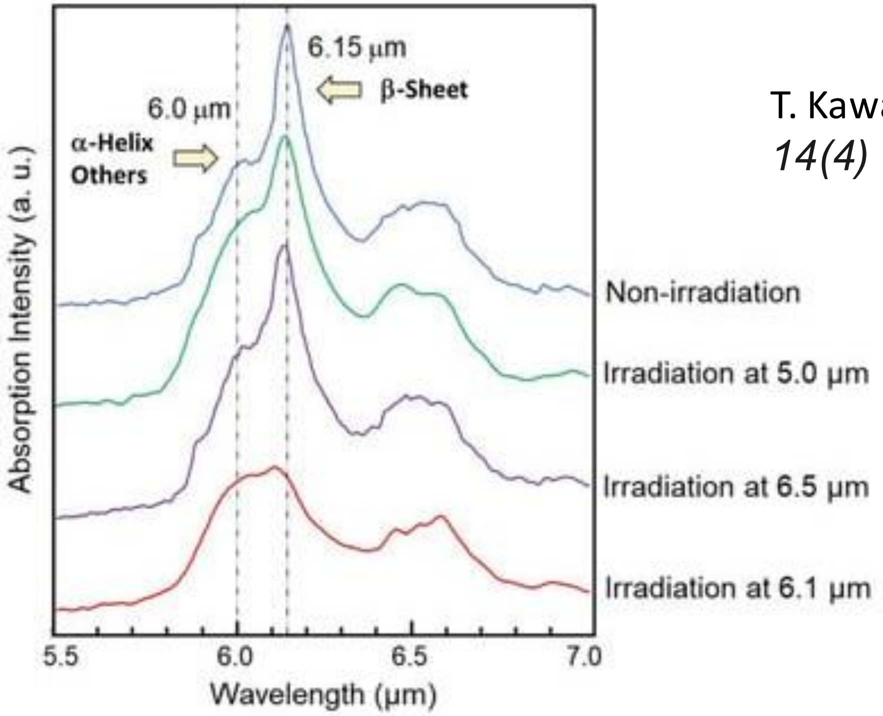


MIR FEL Applications: Dissociation of Protein Fibrils

Structural transformation: from stable, stacked ***β*-sheet** structure (amyloid fibrils) into ***α*-helix**

Mechanism: This change is triggered by IR-FEL irradiation tuned to the **amide I band** (6.1 - 6.2 **μ**m), which targets the vibration of peptide bonds.





T. Kawasaki *et al.*, *Int J Mol Sci 14(4) (2023)* 3686.

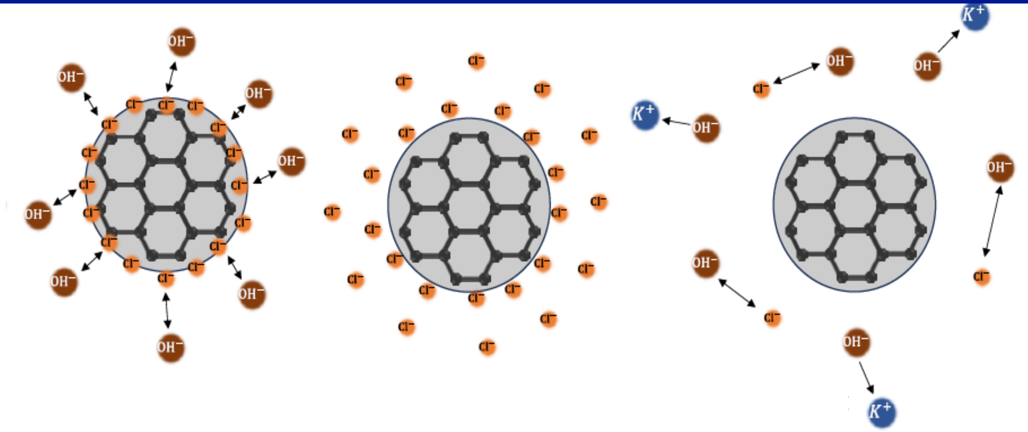
Morphological change

- **Fibril (before irradiation):** Long, fibrous strands (typical of Alzheimer's disease-related aggregates)
- **After Irradiation:** Fibrous structure has been disrupted and broken down into smaller, non-fibrillar particles.

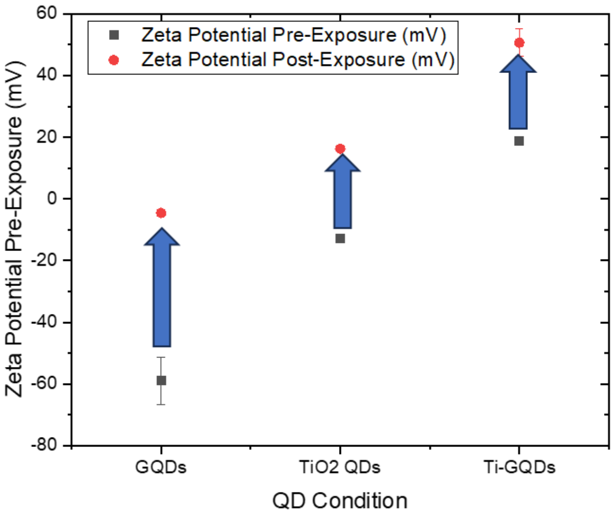
➢ **This application illustrates how MIR-FELs can manipulate biomolecular structures, offering potential for biomedical research**

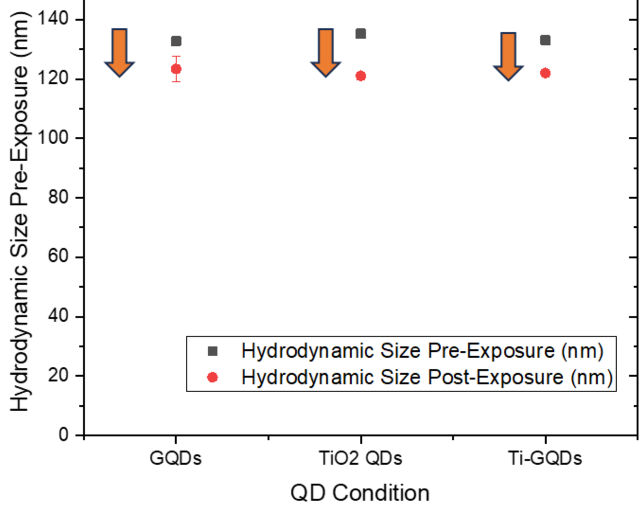
MIR FEL Applications: Ion Reorganization

FEL Exposure on Quantum dots (QDs)



- Implications
  - No pH change
    - OH^-/H^+ balance intact after exposure
  - 10 nm reduction in DLS
    - Tighter ion binds after exposure
  - 30-50 mV positive shift on Zeta Potential
    - Ion species change during bombardment
    - This was semi-permanent
  - Application → Passivation change of QDs without chemical alteration through FEL!
  - This can be used to tailor charge balances when QDs are applied in applications



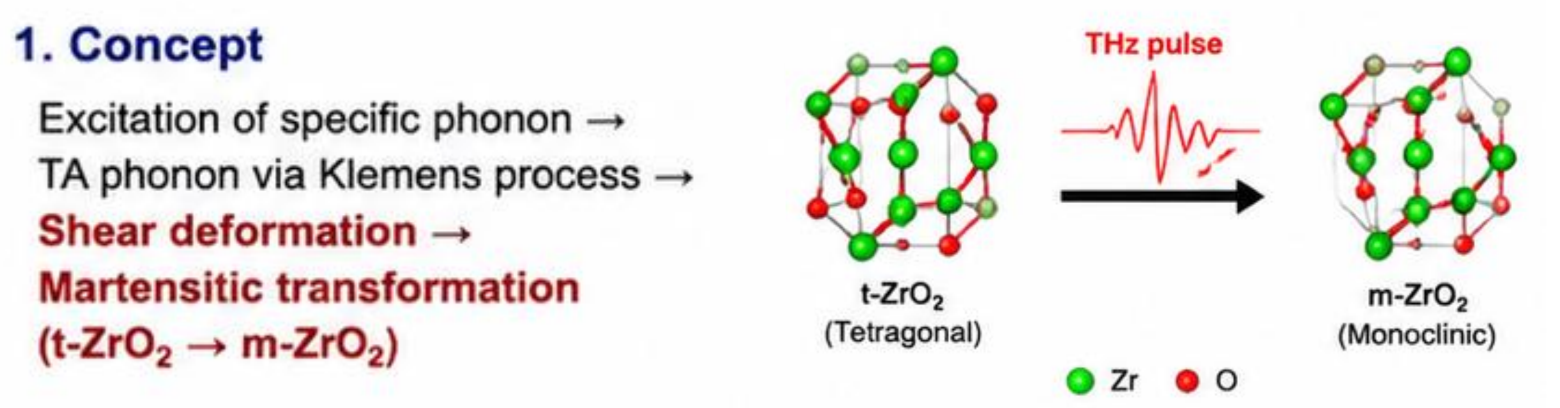


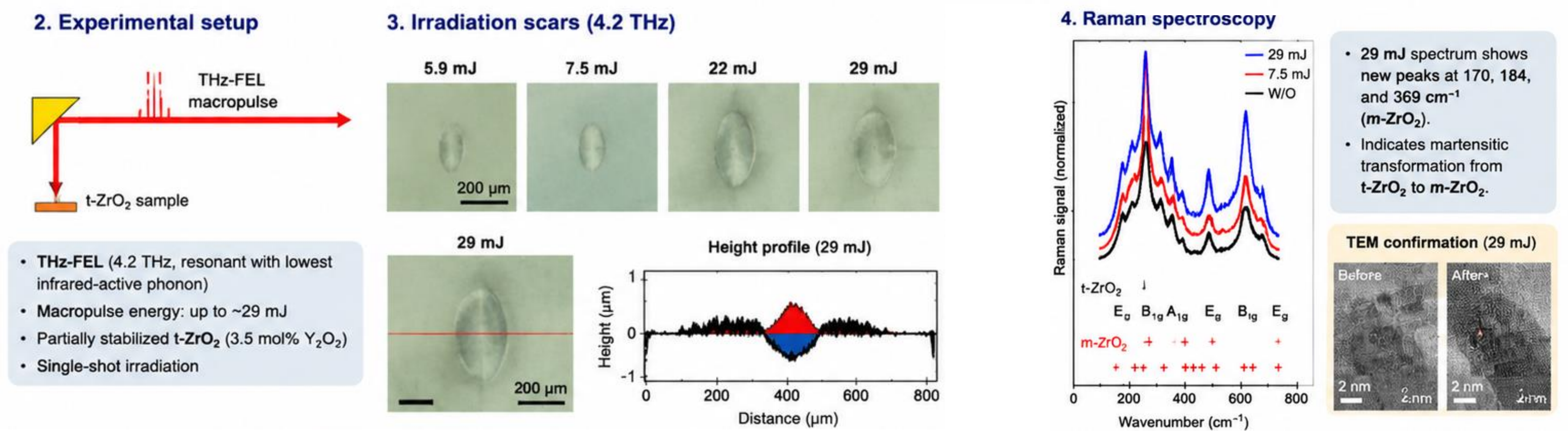
Source: S. Sucharitakul, *et al. Nanomaterials* **15** (2025) 1543

THz FEL Applications: Material Control

“Terahertz-induced martensitic transformation in partially stabilized zirconia”

M. Nagai *et al.*, *Communications Physics* **6** (2023) 88.

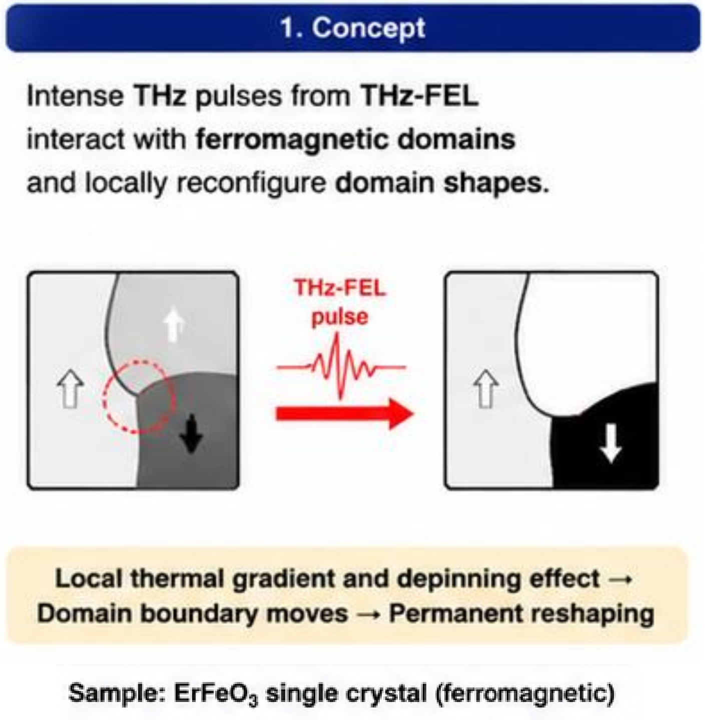


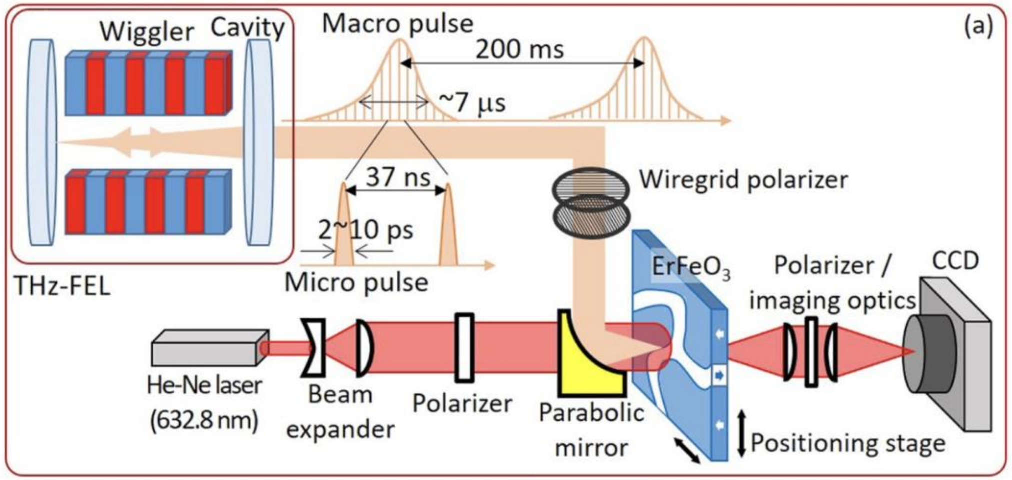


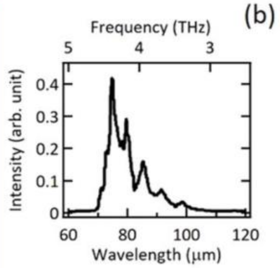
➢ **This demonstrates the potential of THz FELs for ultrafast, non-equilibrium control of materials, enabling studies of phase transitions, strain engineering, and lattice dynamics.**

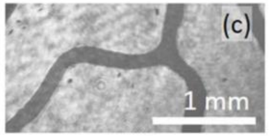
THz-FEL Applications: Magnetic Domain Control

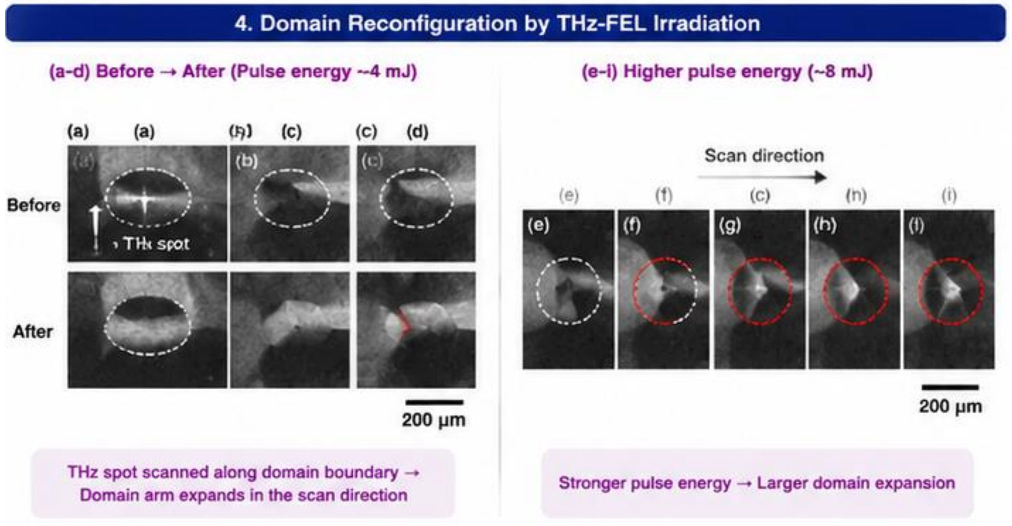
"Reconfiguration of magnetic domain structures of ErFeO3 by intense terahertz free electron laser Pulses"











➢ **This demonstrates the potential of THz FELs for ultrafast spin manipulation and THz spintronic applications, providing a tool for studying thermally induced spin dynamics in solids.**

THz-FEL Applications: High-Sensitivity Spectral Imaging

"Spatially Resolved Spectral Imaging by A THz-FEL"

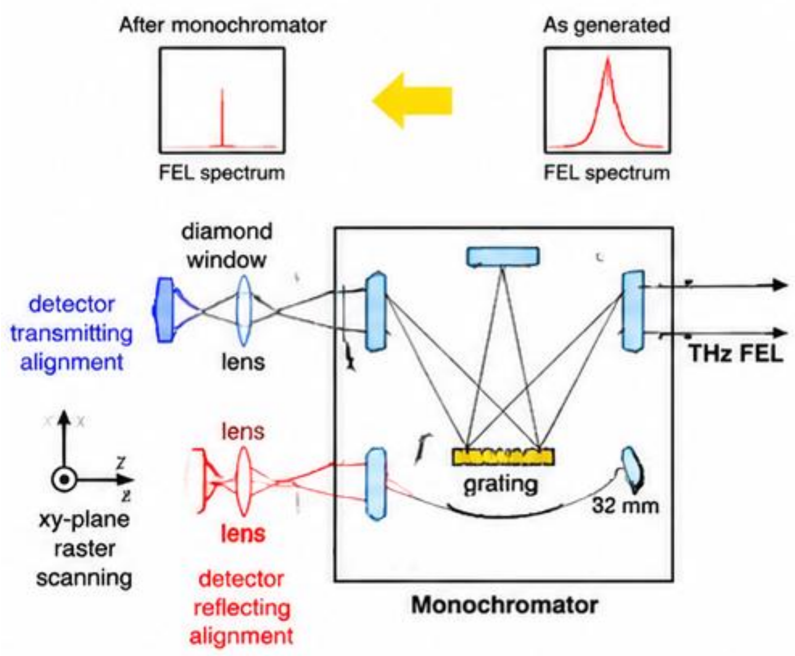
1. THz-FEL Pulse Structure

- Macro-pulse (≈ 4 μs) contains many micro-pulses
- Micro-pulse interval: 9.2 ns (108 MHz mode)
- Sub-harmonic micro-pulse option: 37 ns (27 MHz mode)
- Each micro-pulse has high peak power up to 10 mJ/macro-pulse (27 MHz mode)

2. THz-FEL Spectra

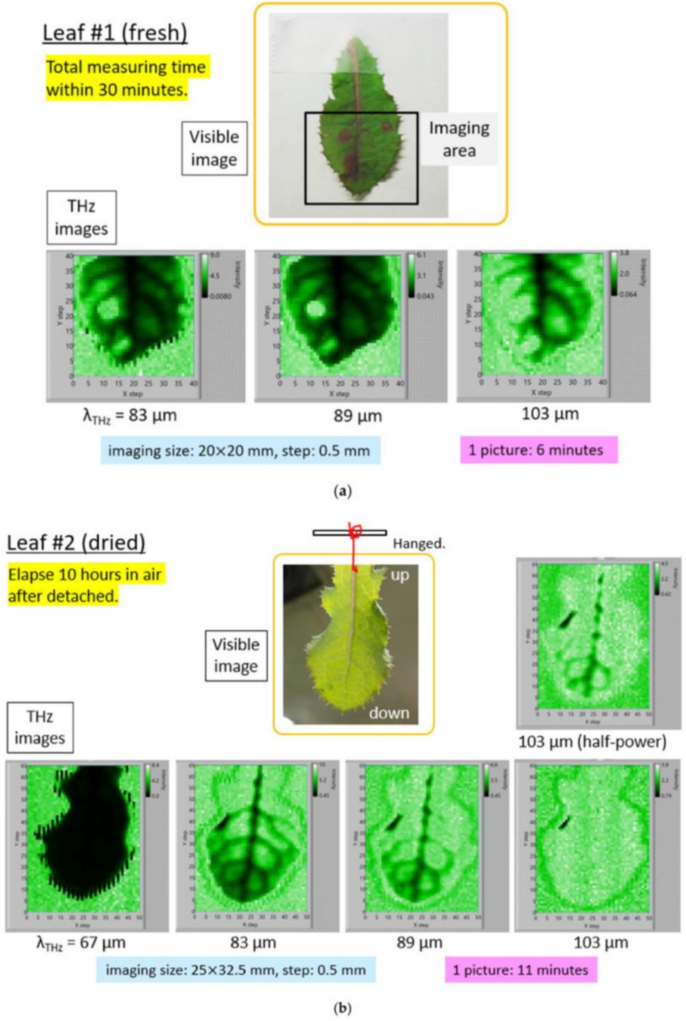
- Wavelength tunable by undulator gap
- Monochromatic in each mode
- Approx. bandwidth: 3% (108 MHz), 10% (27 MHz)

3. Spectral Imaging Setup



➢ **THz FELs provide quasi-monochromatic, high-intensity pulses, allowing faster study of non-linear imaging phenomena,**

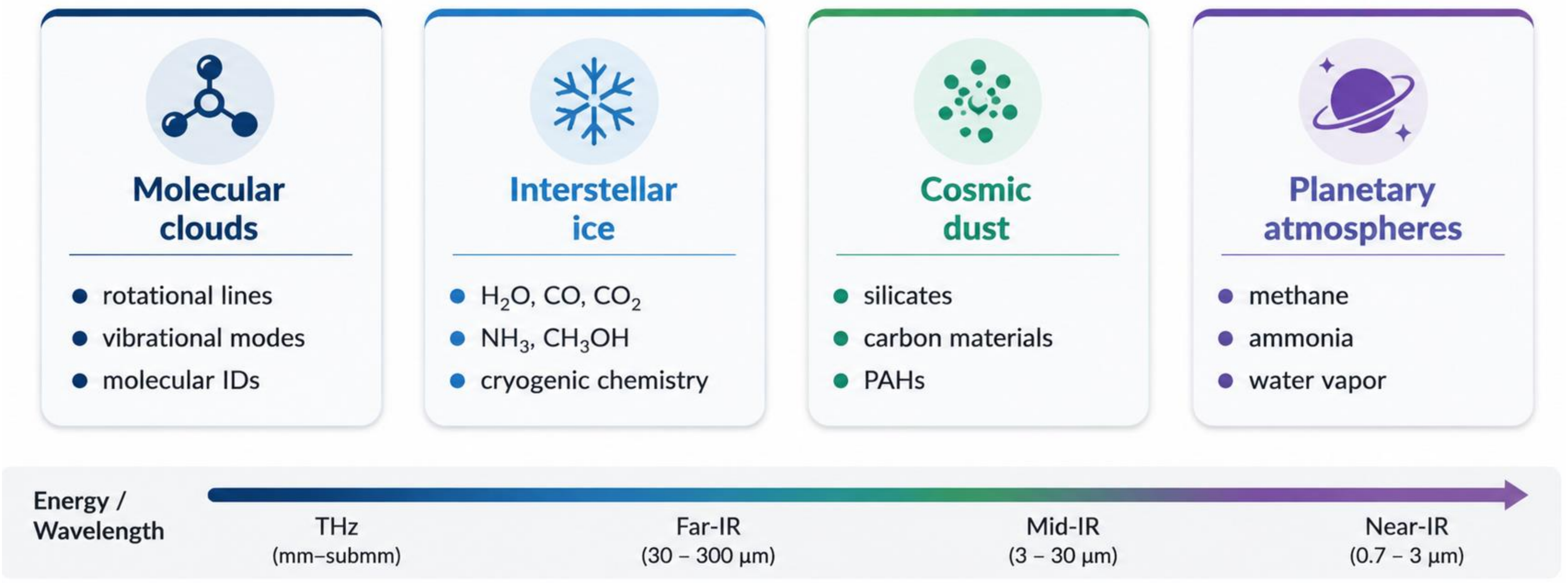
➢ **Provides detailed chemical mapping, and biological imaging.**



A. Irizawa, *et. al.*, *Condens. Matter* 5 (2020) 38.

How IR/THz FELs Contribute to Astrophysics?

IR/THz radiation probes the same energy scale as molecular vibrations, rotations, phonons, and ice chemistry.



APPLICATIONS OF INFRARED AND TERAHERTZ (THz/F-IR) RADIATION IN ASTROPHYSICS

From: The Role of Terahertz and Far-IR Spectroscopy in Understanding the Formation and Evolution of Interstellar Prebiotic Molecules
Mifsud et al., Frontiers in Astronomy and Space Sciences, 2021

OBSERVATIONAL APPLICATIONS

Detecting and characterizing molecules in space

Molecular Identification
Rotational and vibrational spectral lines in the THz/F-IR enable unambiguous detection of interstellar molecules.

Physical Conditions
Line intensities and profiles constrain temperature, density, column density, and kinematics of astrophysical sources.

Chemical Inventory
Surveys with facilities such as ALMA, SOFIA, and Herschel reveal the molecular richness of diverse astronomical regions.

LABORATORY ASTROCHEMISTRY

Reproducing and studying interstellar environments

Example: FELIX-LISA end-station for THz/F-IR irradiation and in-situ measurements.

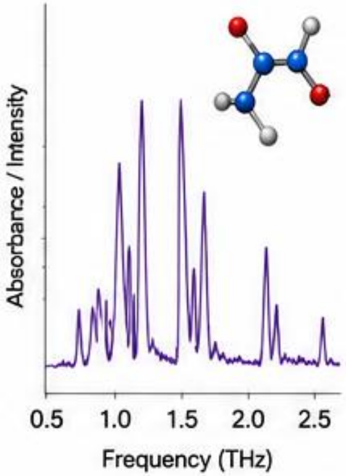
Ice Analogue Studies
Ices (e.g., H_2O, CO, CO_2, CH_3OH, NH_3 mixtures) are prepared at 10–20 K to simulate interstellar grain mantles.

Irradiation & Processing
IR/THz photons drive photolysis, photodesorption, and chemical reactions in ices and on surfaces.

In-Situ Diagnostics
THz/F-IR spectroscopy monitors structural and compositional changes in ices in real time.

MOLECULAR STRUCTURE & INTERACTIONS

Probing the nature of complex molecules



Rotational Transitions
THz spectroscopy measures pure rotational transitions, revealing molecular geometry and dipole moment.

Intermolecular Interactions
Low-frequency lattice modes diagnose hydrogen bonding, clustering, and ice structure.

Isotopologues & Conformers
Sensitive to isotopic substitution and different conformations of astrophysical molecules.

CHEMICAL EVOLUTION ACROSS ASTROPHYSICAL ENVIRONMENTS

Tracing the pathways from simple to complex molecules

Diffuse Clouds (10^2–10^3 cm^{-3})

Atoms, ions, simple molecules (e.g., H, C^+, CH, OH)
THz/F-IR: detect key ions and small molecules

→

Dense Clouds (10^4–10^6 cm^{-3})

Molecules freeze on grains, ice mantle formation
THz/F-IR: probe ice composition and structure

→

Star-Forming Regions (10^6–10^8 cm^{-3})

Ices processed by UV/IR, cosmic rays, shocks
THz/F-IR: probw ice processing and desorption products

→

Pratoplanetary Disks (10^6–10^{12} cm^{-3})

Complex organic molecules in gas and ices
THz/F-IR: detect COMs and molecular inventories

→

Protontary Systems (10^0–10^6 cm^{-3})

Delivery to planets/comets, prebiotic chemistry
THz/F-IR: link chemistry to the origin of life

THz/F-IR observations and laboratory studies provide critical constraints on the formation and evolution of prebiotic molecules throughout the life cycle of matter in the universe.

KEY MOLECULES & SCIENTIFIC IMPACT

Enabling the origins of life studies

Important Molecular Families

- **Simple molecules:**
  H_2O, CO, CO_2, NH_3, CH_4
- **Ions & radicals:**
  OH^+, H_2O^+, CH^+, C^+, etc.
- **Complex organics (COMs):**
  CH_3OH, HCOOH, CH_3CN, amino acids, nucleobases
- **PAHs and fullerenes**

Scientific Impact

Prebiotic Chemistry
Identifies and tracks molecules relevant to the origin of life.

Astrochemical Models
Provides essential data to test and refine chemical models.

Future Missions
Supports interpretation of current and next-generation space observatories.

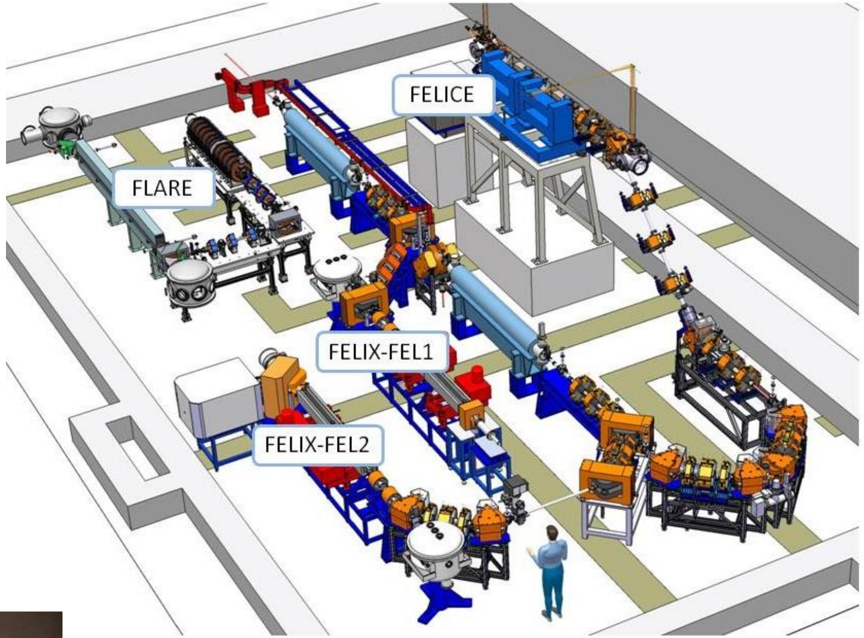
Outline

05 IR/THz FEL Facilities

Global benchmark facilities

CMU MIR/THz FEL facility

Examples: FELIX Laboratory (The Netherlands)



Global benchmark in wide-range MIR, FIR, THz tuning

- **4 multi-laser stations:** FELIX-1, FELIX-2, FELICE, FLARE to cover comprehensive spectra
- **Large tuning span:** MIR - THz (3 - 1500 μm)
- **Astrophysics:** Integrated with end-stations to examine deep-space molecular ice chemistry
- **Applications:** Molecular and solid-state research

Examples: FELBE & TELBE (HZDR, Germany)

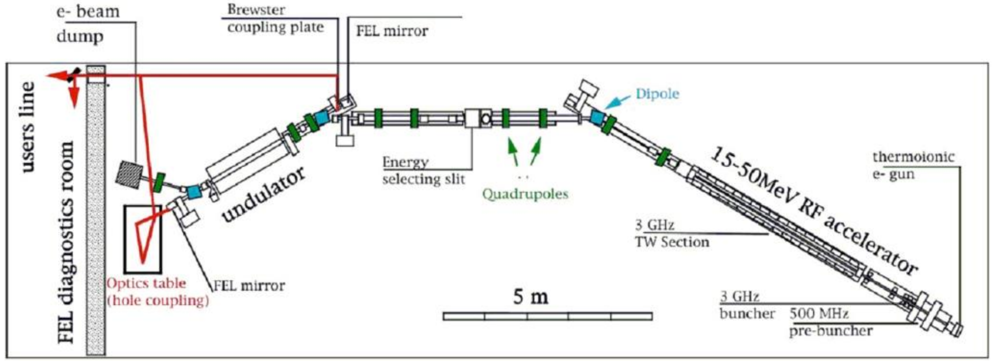
Global benchmark in superconducting repetition rate

- **ELBE superconducting linear accelerator**: drives both continuous-pulse IR emissions (FELBE) and coherent super-radiant THz waves (TELBE)
- Creates ultra-fast, high-average-power radiation at high pulse rates up to 13 MHz
- **Tuning span:** MIR to FIR (4 -250 μm) and THz spectral ranges
- **Applications:** pump-probe experiments for solid-state physics, magnetism, and superconductor research

Examples: Precision Spectroscopy Hosts

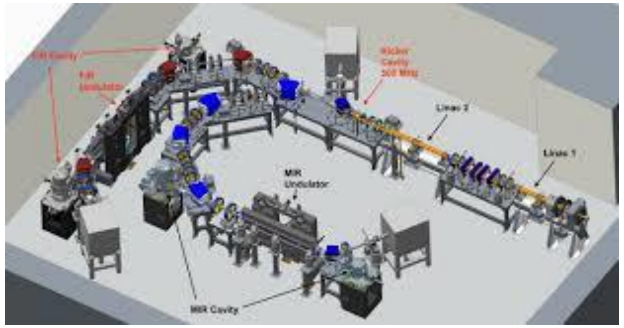
CLIO (Orsay, France)

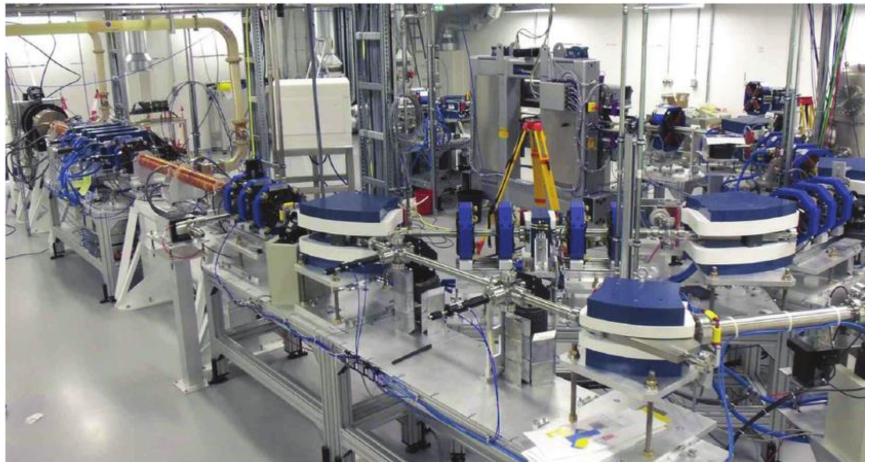
- Operates on a warm linac
- MIR (3 to 120 µm)
- **Applications:** physical chemistry, material and biophysics research, vibrational molecular spectroscopy



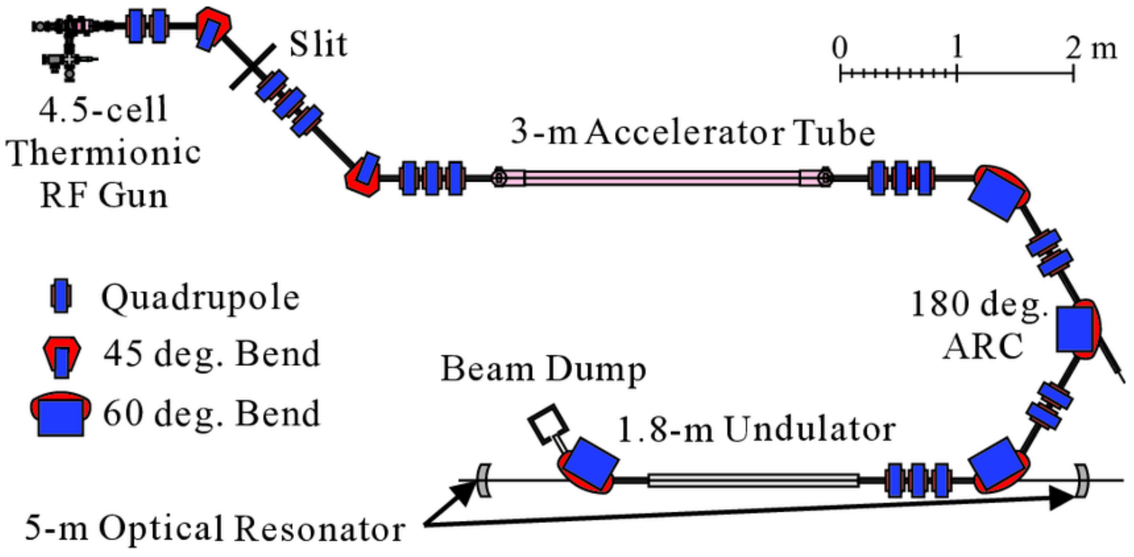
FHI FEL (Berlin, Germany)

- Operates on a warm linac
- MIR/FIR (3 to 165 µm)
- **Applications:** gas-phase spectroscopy, surface science, physical chemistry, complex molecular clusters



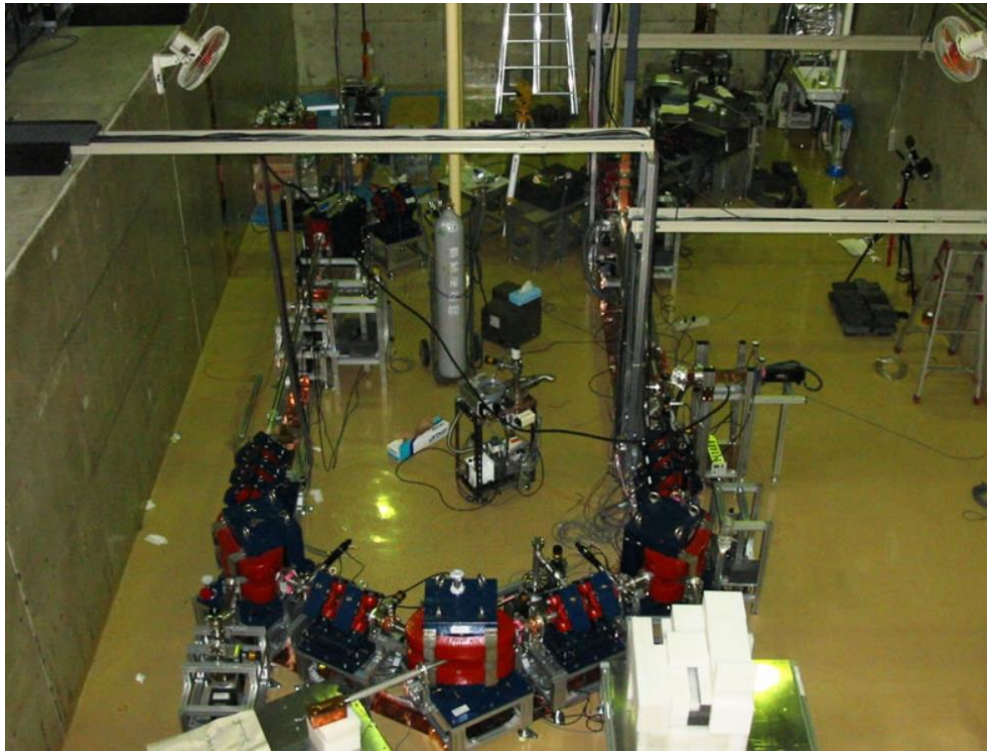


Examples: KU-FEL (Kyoto, Japan)



Global MIR-FEL benchmark

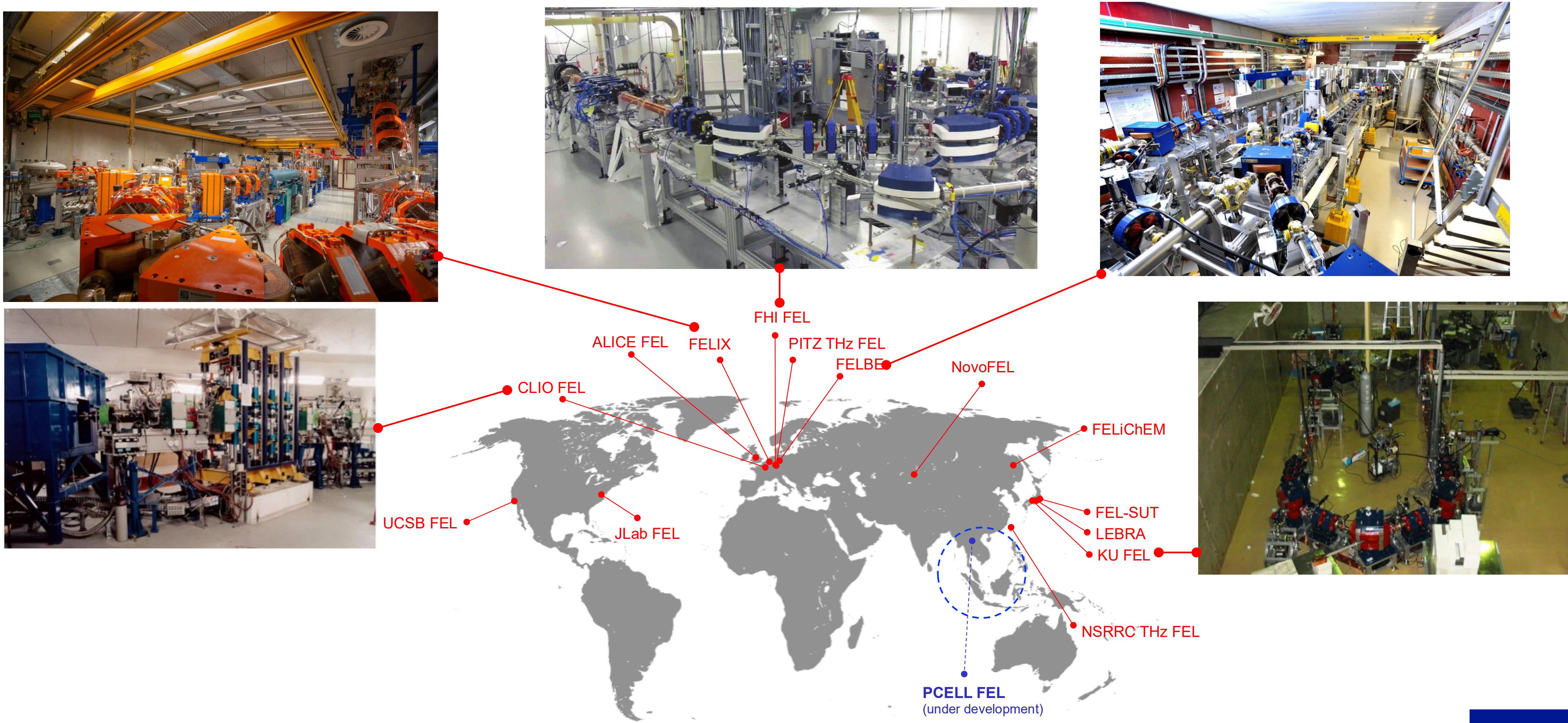
- Achieved **9.4% extraction efficiency**, far exceeding typical 1-5% limitations of traditional oscillator FELs
- Ultra-intense MIR pulses (~100 µJ micropulse energy)
- **Tuning span:** MIR (3.4 to 26 µm) and THz (0.16 – 0.6 THz)
- **Applications:** physical ablation, non-linear optical spectroscopy, polysaccharide and biopolymer science



Facility Comparison

Facility Name	Country	Wavelength Range (µm)	Repetition Rate	Primary Specialization
FELIX	Netherlands	3 – 1,500 µm	25 MHz / 1 GHz	Molecular science, solid-state physics
FELBE	Germany	4 – 250 µm	13 MHz (Continuous)	Ultrafast pump-probe dynamics, condensed matter, semiconductors
CLIO	France	3 – 120 µm	62.5 MHz	Vibrational physical chemistry
FHI FEL	Germany	3 – 165 µm	1st Dual-Color (500 MHz)	Surface science, gas-phase & cluster spectroscopy, molecular cluster spectroscopy
KU FEL	Japan	3.4 – 26 µm	2,856 MHz	Physical ablation, non-linear optical spectroscopy

IR-THz FEL Facility Worldwide



CMU Research Group

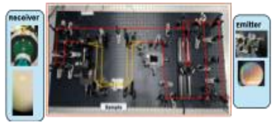
PARTICLE ACCELERATORS AND LASER TECHNOLOGY RESEARCH GROUP

Plasma and Beam Physics Facility

1 Electron Linear Accelerator & IR/THz FELs

2 Ultrashort-pulsed Laser and Advanced Spectroscopy Platforms

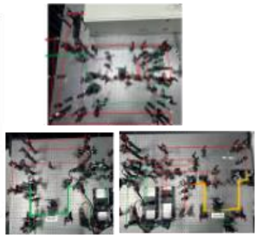
Femtosecond laser system



THz time-domain spectroscopy

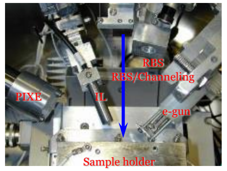
MIR/THz FEL irradiation station

THz-FTIR & Astrochemistry station



Time-resolved THz spectroscopy

3 Ion Beam Facility

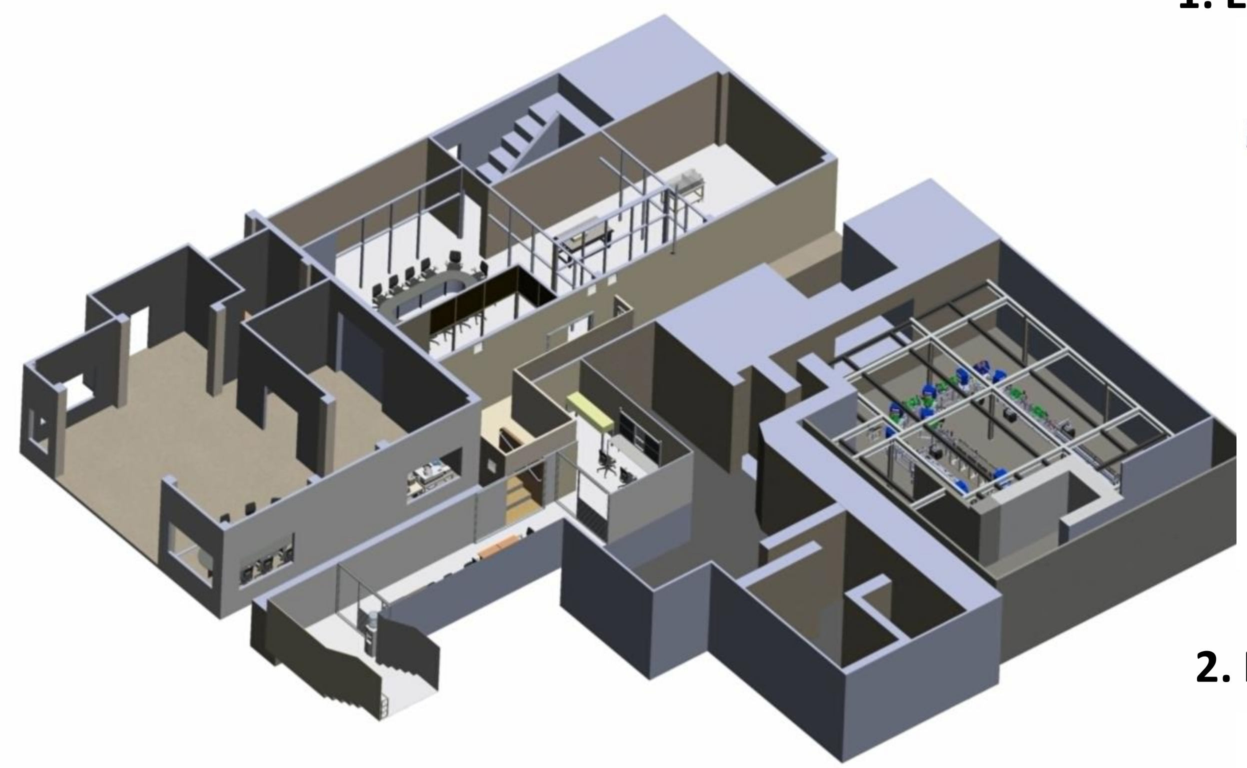


1. **Electron linac** for MIR/THz free-electron lasers, electron beam irradiation and accelerator-based technologies
2. **Ultrashort-pulsed laser and advanced spectroscopy platforms** for frontier research and users applications in materials science, biology, chemistry, agriculture, astrochemistry, etc.
3. **Ion beam tandem & implanters** for applications in gemstones, agriculture, semiconductors, materials science etc.
4. **Collaborative research with domestic & international collaboration**

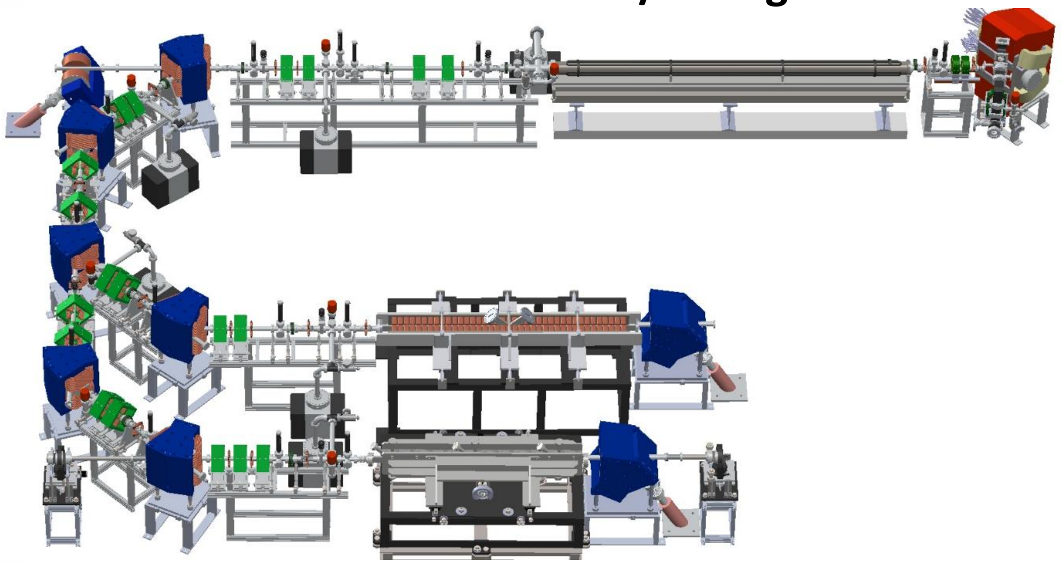
4 Examples of Collaborative Research

- **MIR FEL:** Kyoto University
- **THz FEL:** DESY, Tohoku University
- **Sextupole magnet prototype for FCC-ee:** CERN
- **Muon Research:** RIKEN

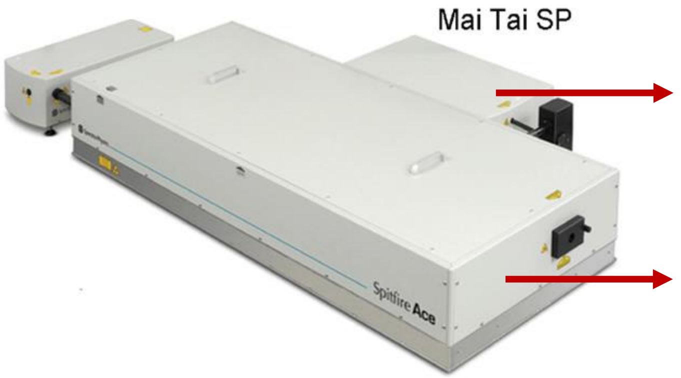
Infrared-THz FEL and Ultrashort Laser Facility



1. Electron beam accelerator & MIR/THz light sources



2. Femtosecond laser-based light sources



Central theme: **Two advanced light sources can both reveal ultrafast material behavior and actively tailor material properties.**

IR/THz FEL Facility @ CMU

PARTICLE ACCELERATORS AND LASER TECHNOLOGY RESEARCH GROUP

Homemade accelerator components with help from collaborators

Stanford University

KYOTO UNIVERSITY FOUNDED 1897 KYOTO JAPAN

TOHOKU UNIVERSITY

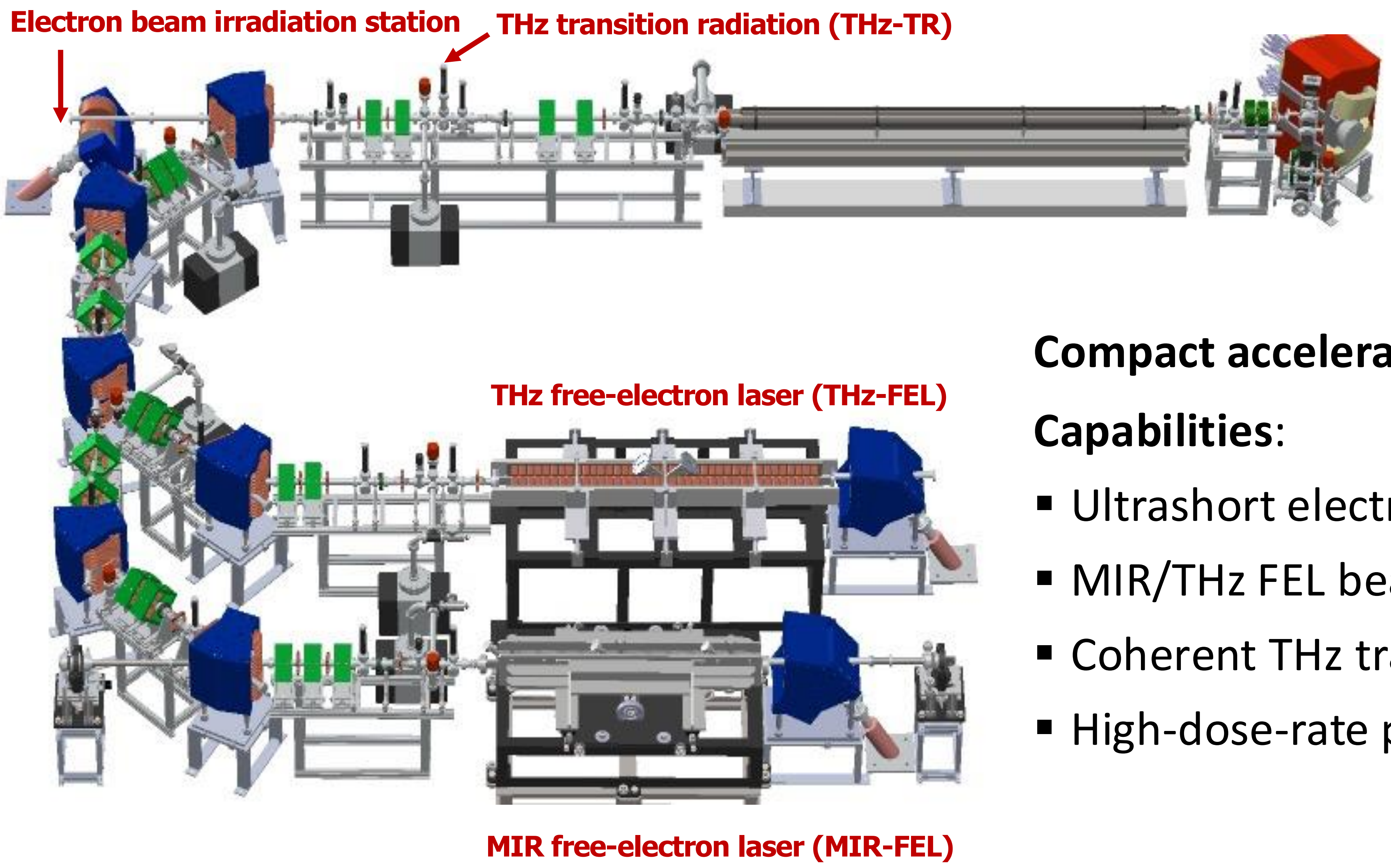
DESY.

NSRRC

NARIT

THAI SYNCHROTRON NATIONAL LAB

Accelerator & Light Sources



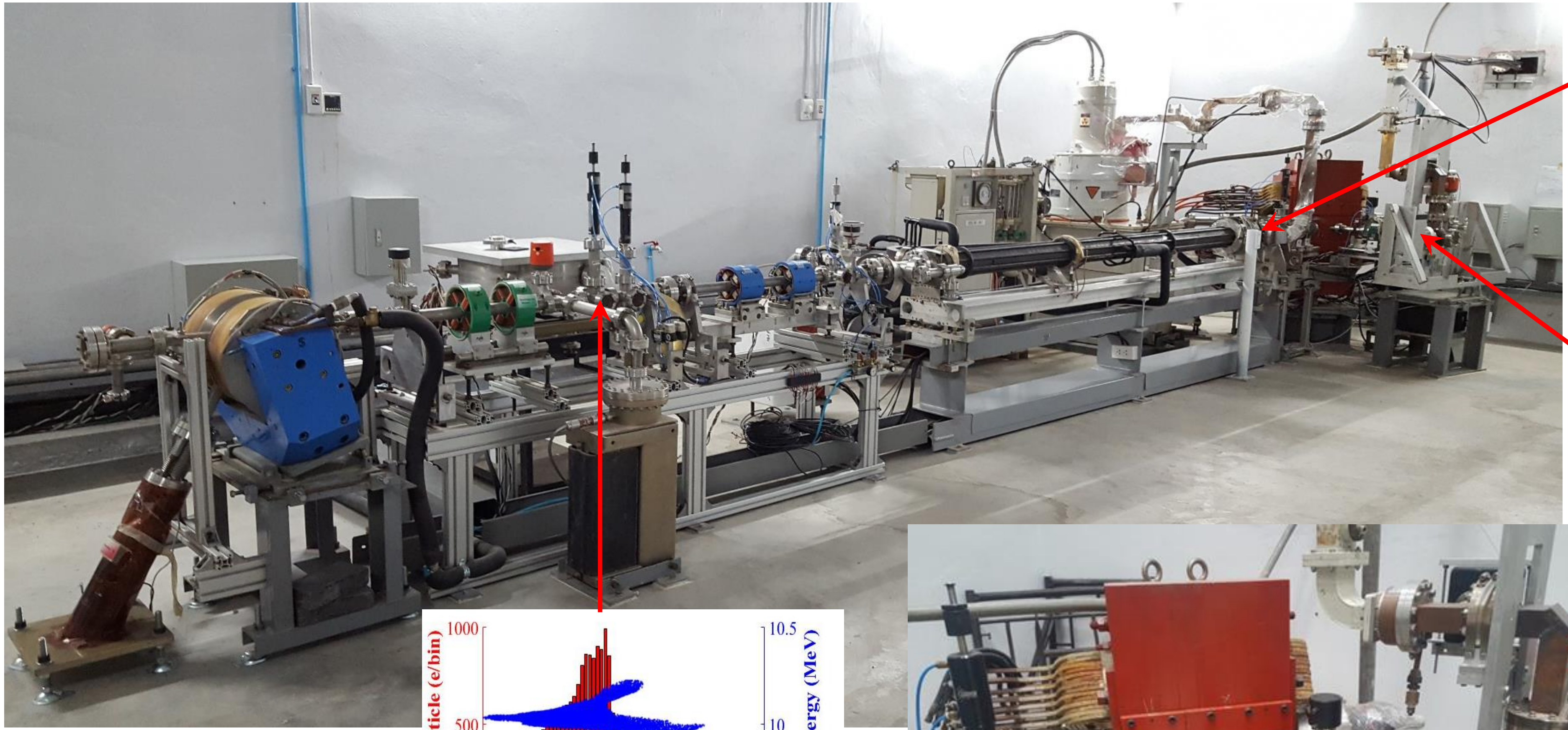
Compact accelerator: 25 MeV (max.)

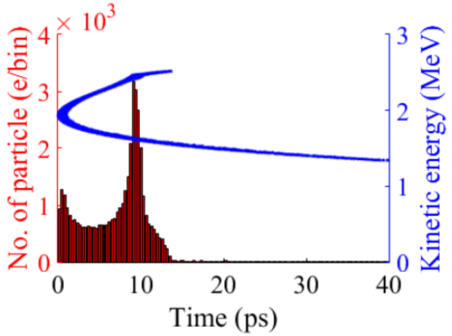
Capabilities:

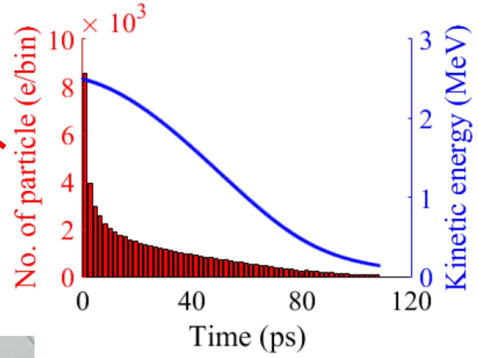
- Ultrashort electron bunches
- MIR/THz FEL beamlines
- Coherent THz transition radiation
- High-dose-rate pulsed electron beams

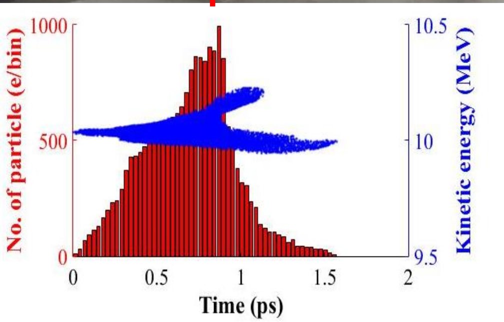
Accelerator System

Accelerator system was developed for generation of fs electron bunches (~200 fs).



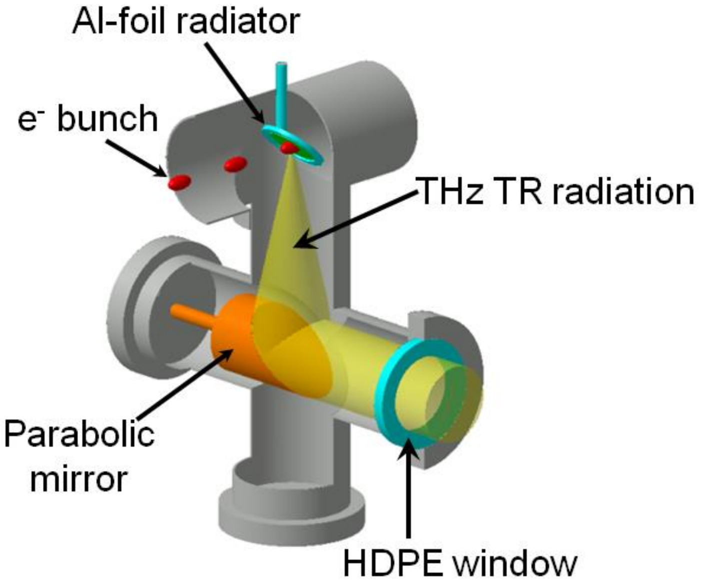


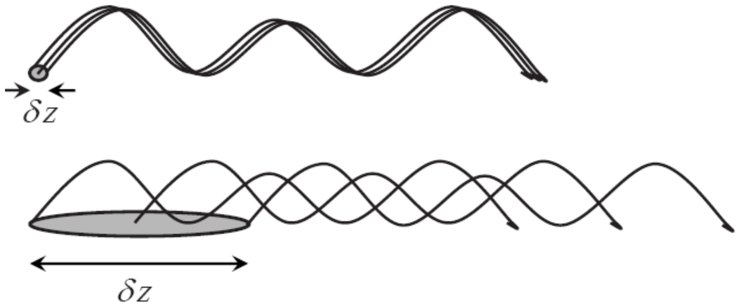




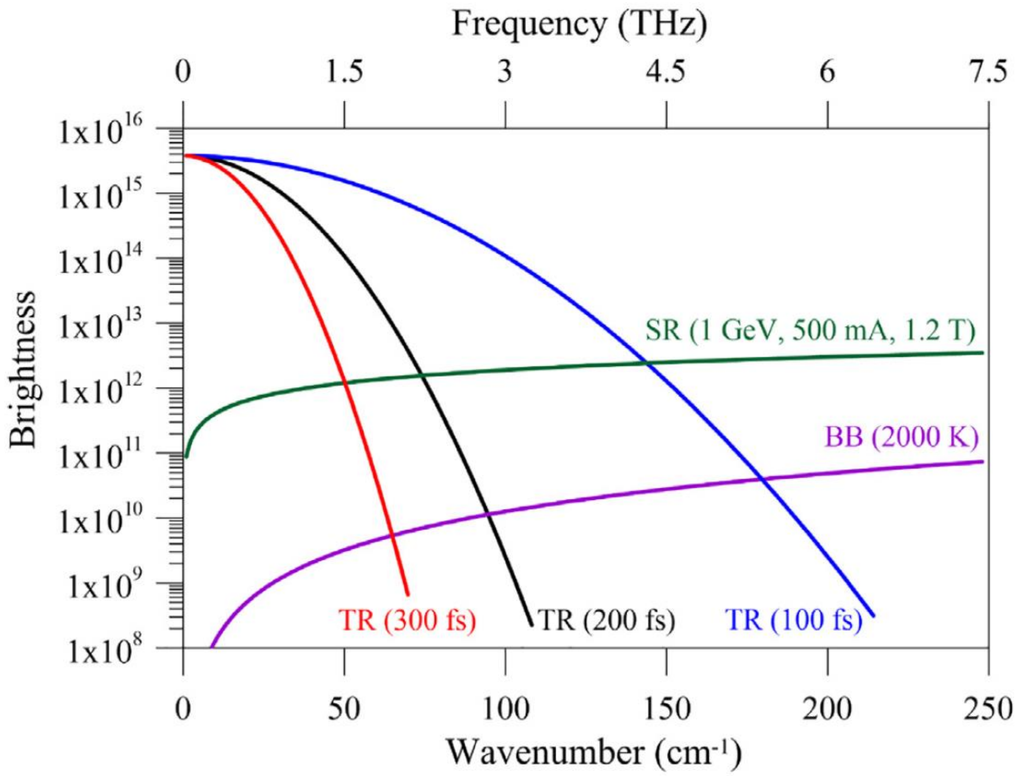
THz Transition Radiation (THz-TR)

fs electron bunches are used to generate coherent THz-TR





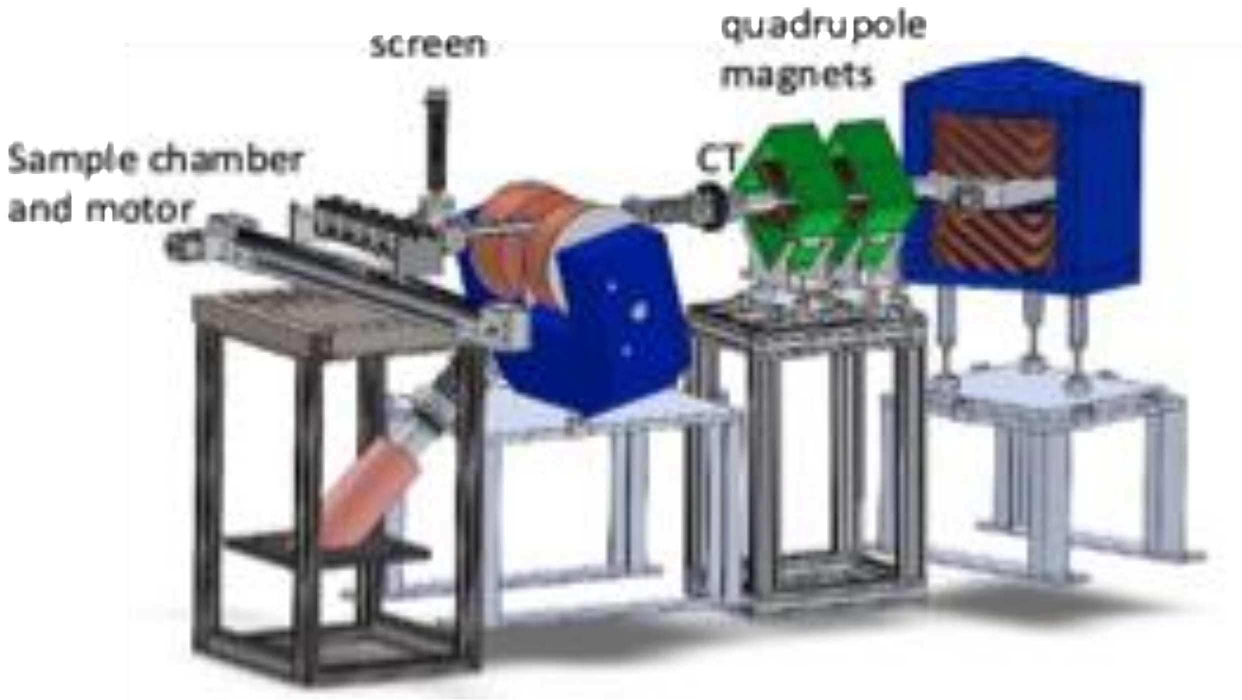
$$\frac{d^2I}{d\omega\, d\Omega} = [N[1-f(\omega)] + N^2 f(\omega)]$$



Broadband, coherent & intense THz radiation

Beam energy (design)	22 MeV
Electron bunch charge	60 pC
Electron rms bunch length	200 – 300 fs
Radiation wavelength	150 – 1000 μm
Radiation frequency	0.3 - 2.5 THz
Pulse energy	0.17 – 0.25 μJ
Peak power	0.9 – 1.5 MW

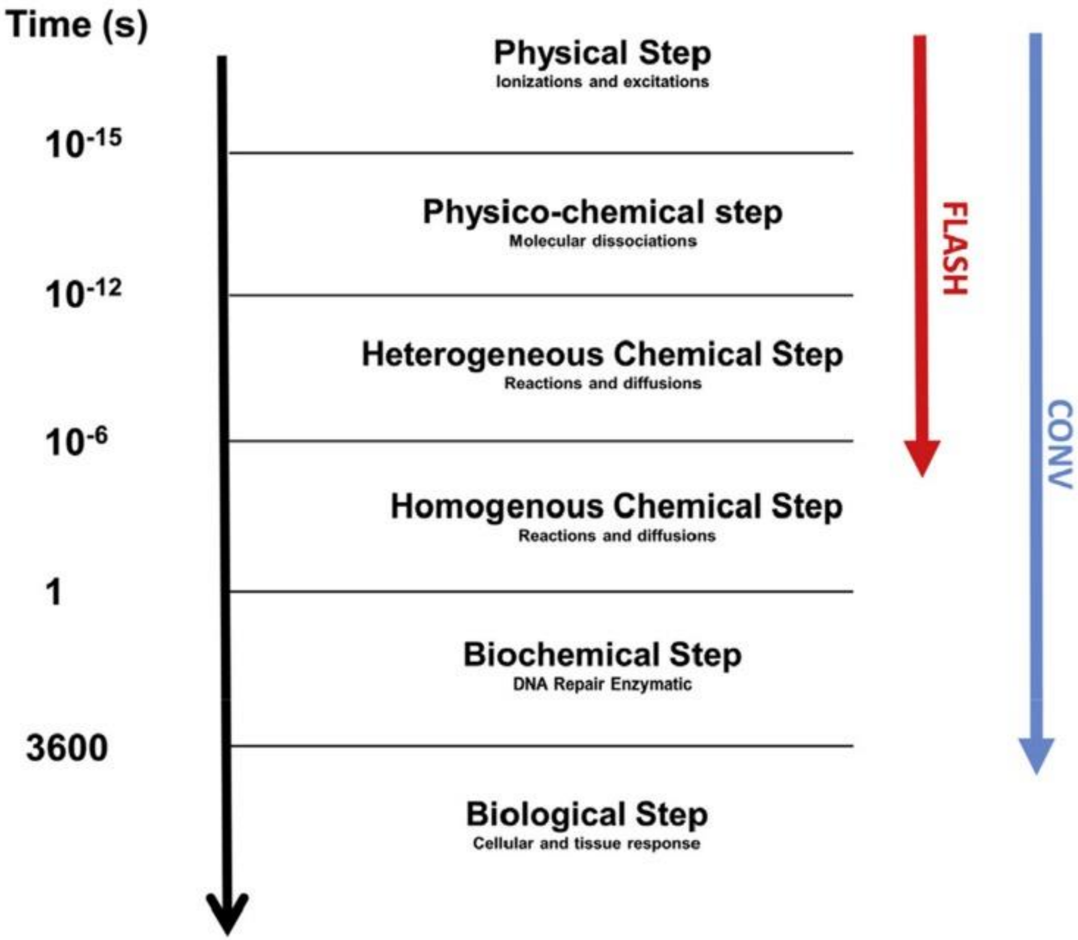
Electron Beam Irradiation Station



Specifications:

- Beam energy: 6 - 25 MeV
- Beam pulse length: 1 - 5 microsecond
- Electron dose: up to ~40 Gy/s
- Repetition rate: 10 Hz
- Irradiation environment: in-air
- Electron dose and beam size can be adjusted

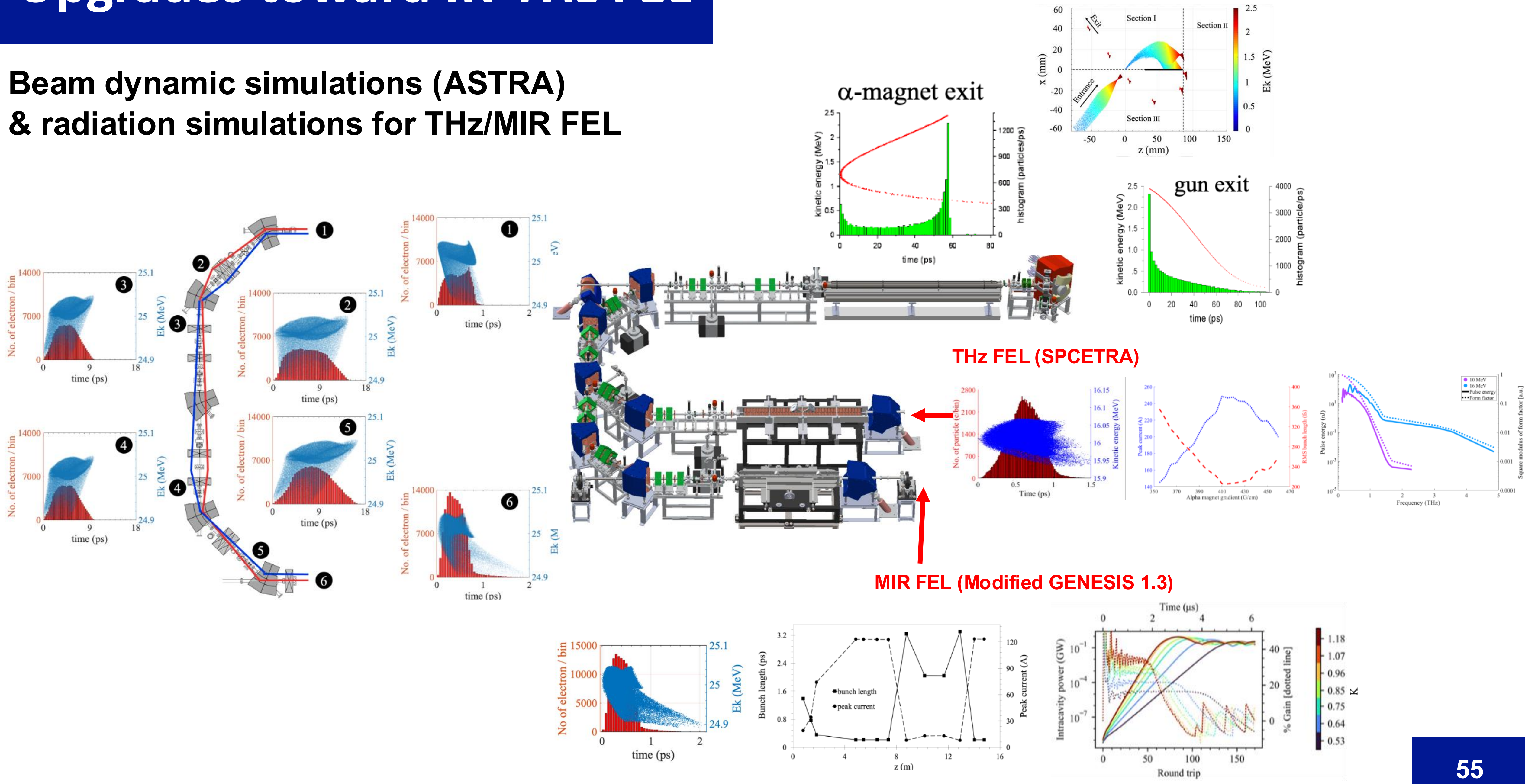
FLASH radiotherapy involves the ultra-fast delivery of radiotherapy at dose rates several orders of magnitude higher than conventional radiotherapy.



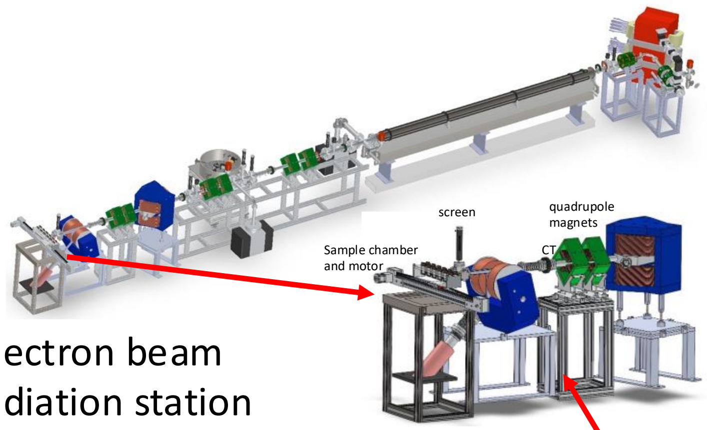
Chronology of events occurring after irradiation in biological tissue.

Upgrades toward IR-THz FEL

Beam dynamic simulations (ASTRA)
& radiation simulations for THz/MIR FEL

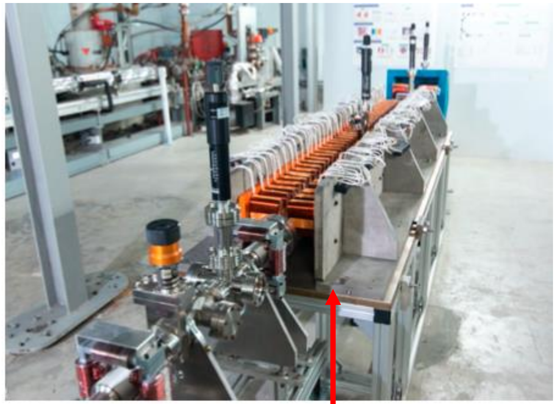


Upgraded Facility

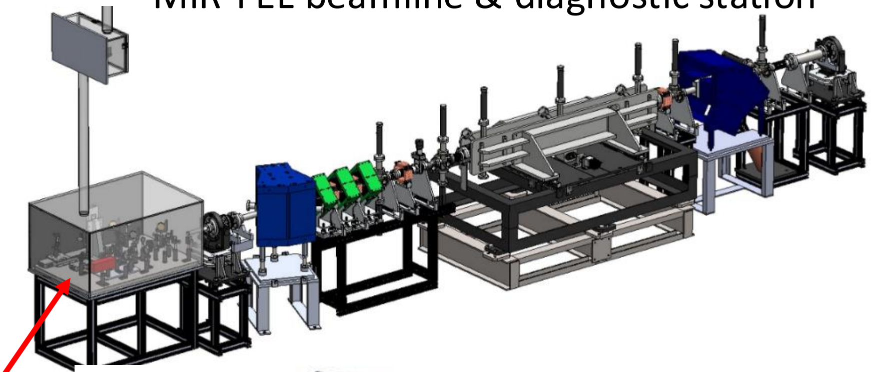


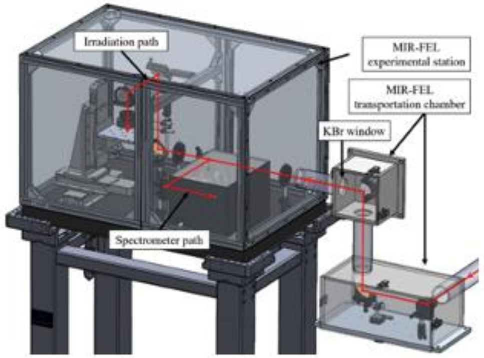
Electron beam irradiation station

THz-FEL beamline

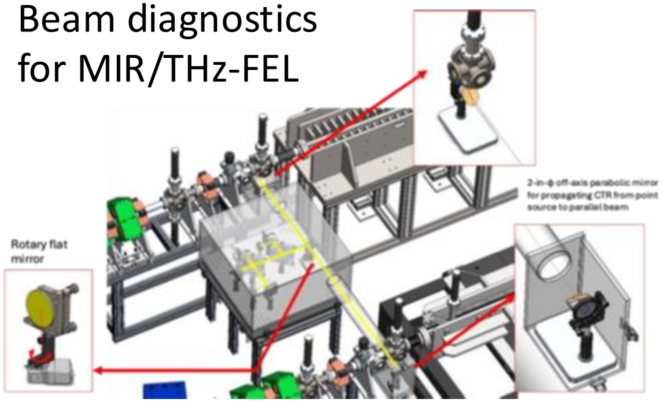


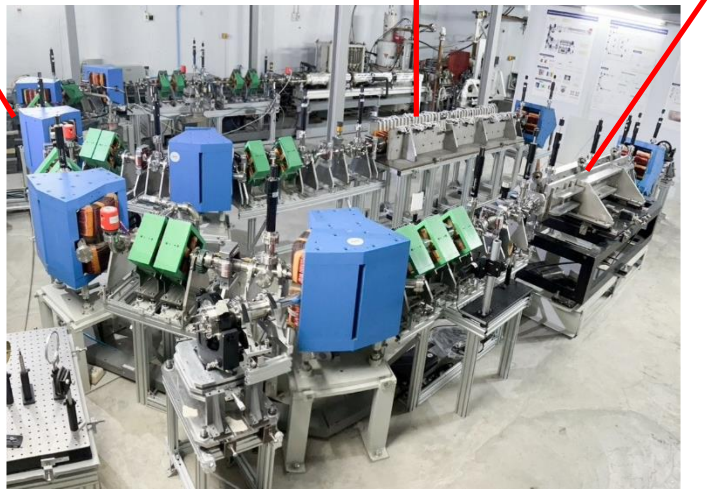
MIR-FEL beamline & diagnostic station



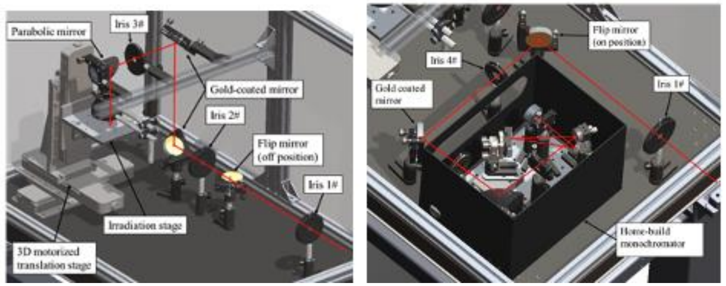


Beam diagnostics for MIR/THz-FEL





Electron accelerator & MIR/THz FEL beamlines



MIR/THz-FEL experimental station

IR-THz FEL Parameters

1. MIR-FEL (Mid-Infrared Free-Electron Laser)

Oscillator FEL light source in the mid-infrared region

Parameter	MIR-FEL
Wavelength range (μm)	9.98 – 11.85 μm
Pulse duration	0.3 – 0.6 ps
Pulse energy	0.12 – 0.54 μJ
Peak power	0.15 – 1.15 MW
Repetition rate	10 Hz
Electron Beam Parameters (MIR-FEL)	
Electron energy	22 – 25 MeV
Charge per bunch	10 – 50 pC
Bunch length (FWHM)	~ 200 fs
Repetition rate	10 Hz

2. THz-FEL (Terahertz Free-Electron Laser)

THz FEL based on
Coherent Undulator Radiation

Parameter	THz-FEL
Frequency range	1 – 3 THz
Pulse duration	200 – 300 fs
Pulse energy	0.07 μJ
Peak power	0.7 MW (at 1 THz)
Repetition rate	10 Hz
Electron Beam Parameters (THz-FEL)	
Electron energy	10 – 16 MeV
Charge per bunch	50 pC
Bunch length (FWHM)	200 – 300 fs
Repetition rate	10 Hz

Two complementary light sources

FEL IR–THz Free-Electron Laser

- Tunable and coherent IR–THz radiation
- High-field excitation of vibrational / phonon modes
- Suitable for selective spectroscopy and materials modification
- Accelerator-based source with flexible pulse parameters

spectral selectivity | coherence | modification

fs Femtosecond laser system

- Ultrafast pump and probe pulses
- Optical excitation and nonlinear optical measurements
- Time-domain access to transient states
- Synchronization with THz / IR probing schemes

temporal resolution | pump–probe | nonlinear optics

+

synergy

Motivation : Femtosecond laser

Advantages

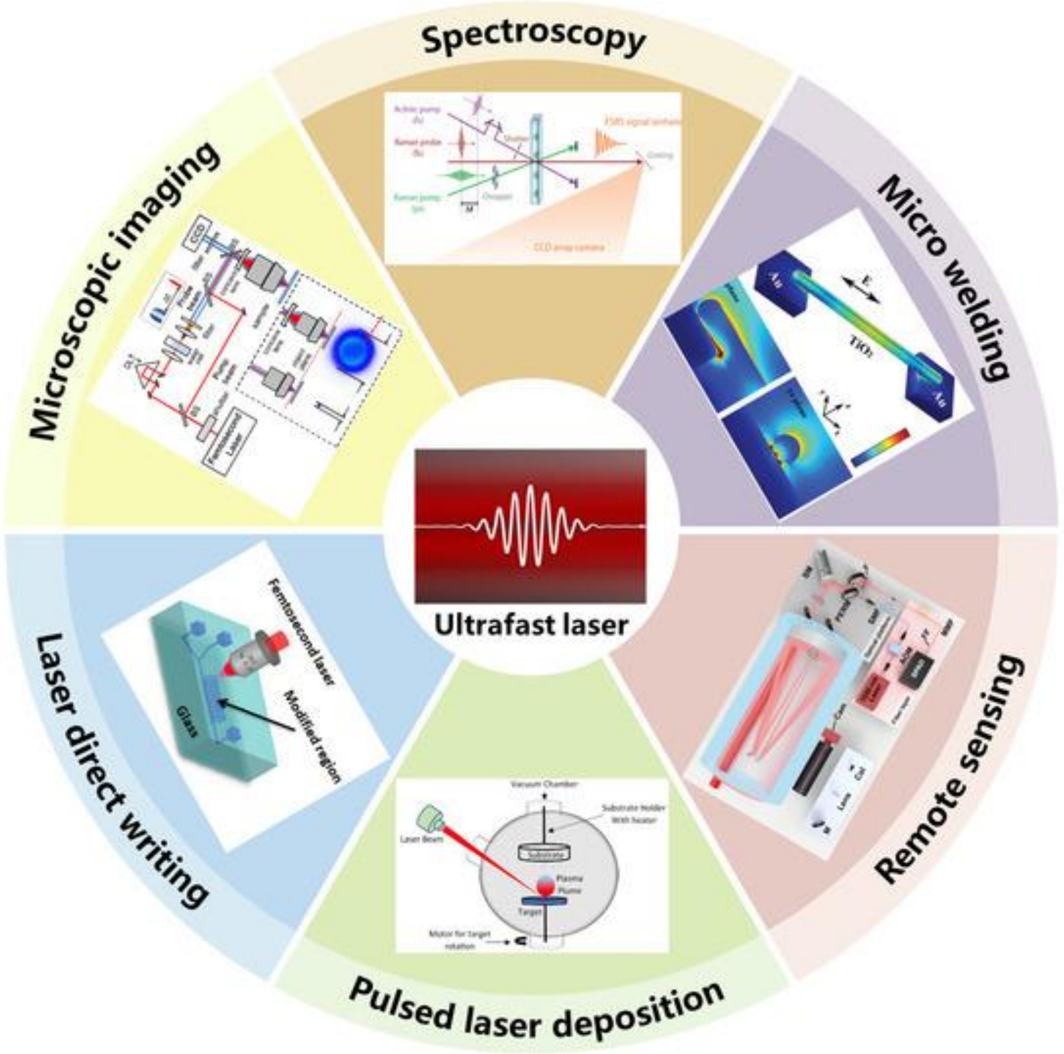
fs time resolution
Capture ultrafast carrier, exciton, phonon, and spin dynamics

High peak intensity
(1 µJ / 100 fs ≈ 10 MW with mW average power)

Access nonlinear optics and strong-field excitation regimes

Low thermal diffusion
Localize energy deposition and reduce heat-affected zones

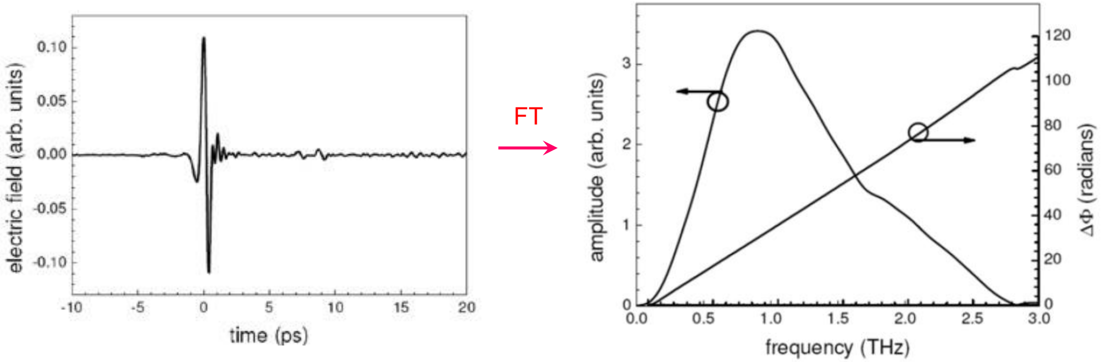
Broad compatibility
Combine with THz-TDS, pump-probe, microscopy, spectroscopy

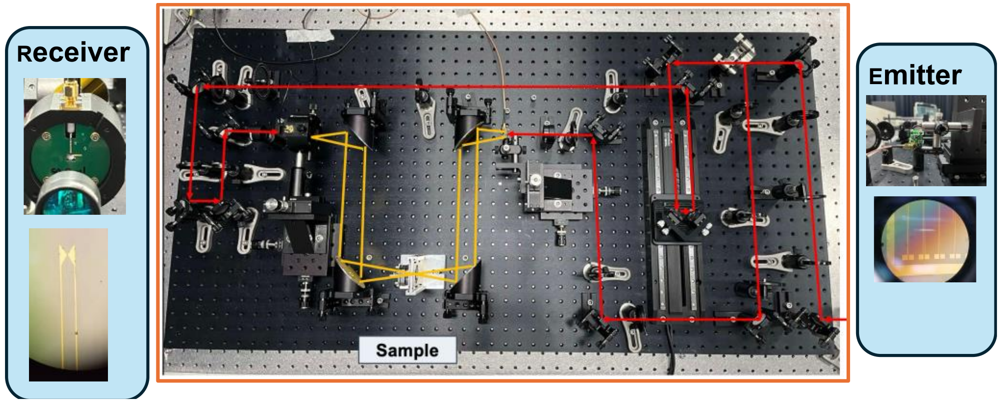


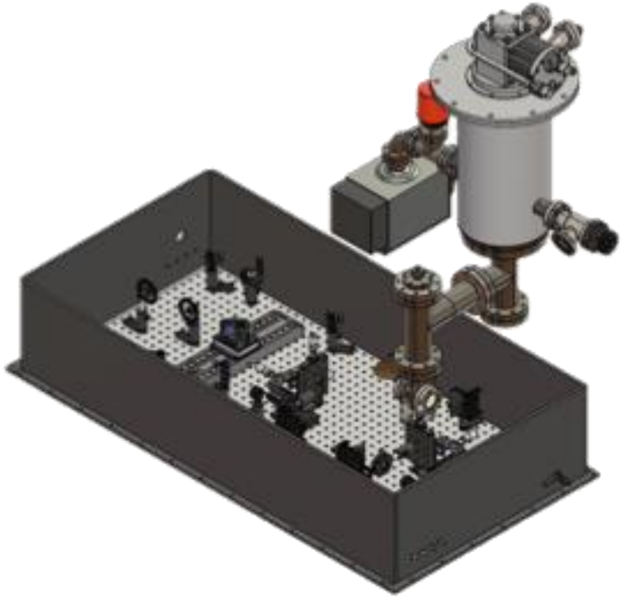
Source: S. Niu et al., *Photonics*, 11(9) (2024) 857

THz Time-domain Spectroscopy (THz TDS)

- Provide both electric field amplitude and phase
- Characterize complex optical properties of materials



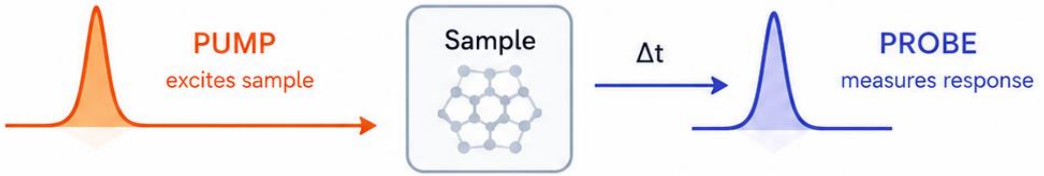




Parameter	Specification
fs laser	• Wavelength: 780 nm – 800 nm • Pulse width: 25 fs – 100 fs • Rep. Rate: 84 MHz • Average Power: 650 mW – 1 W
THz emitter	Photoconductive Antenna (PCA)
THz detector	Photoconductive Antenna (PCA)
Maximum scan range	1470 ps
Operation mode	Transmission
Spectral range	0.05 – 2.5 THz
Spectral resolution	0.68 GHz (at maximum scan range)
Operating temperature	20 °C – 30 °C
Future upgrade	measuring at cryogenic temperature

Time-resolved THz spectroscopy

1. **Optical-pump / Optical-probe (1-color pump-probe)**
2. **Optical-pump / THz-probe (2-color pump-probe)**



PUMP PULSES

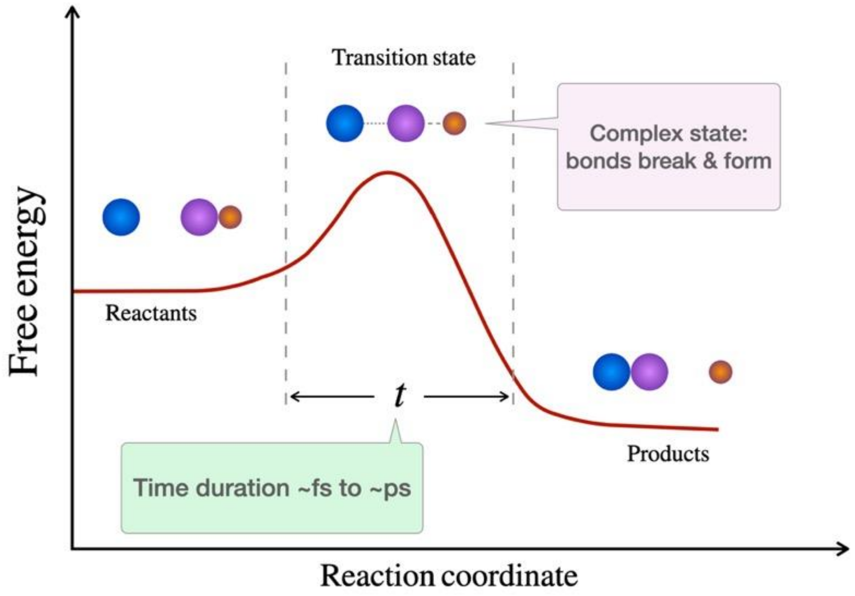
Generated by Non-collinear Optical Parametric Amplification (NOPA)

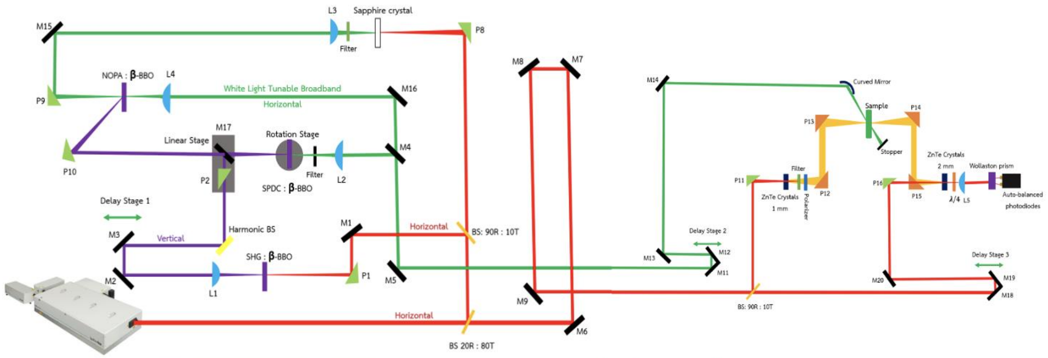
Wavelength:	500–700 nm
Center wavelength:	586 nm
Pulse duration:	100 fs
Pulse energy:	0.005–0.01 mJ
Repetition rate:	1 kHz

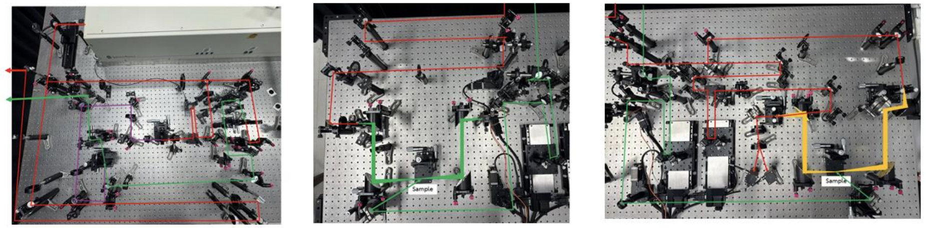
PROBE PULSES

Generated by Difference Frequency Generation (DFG)

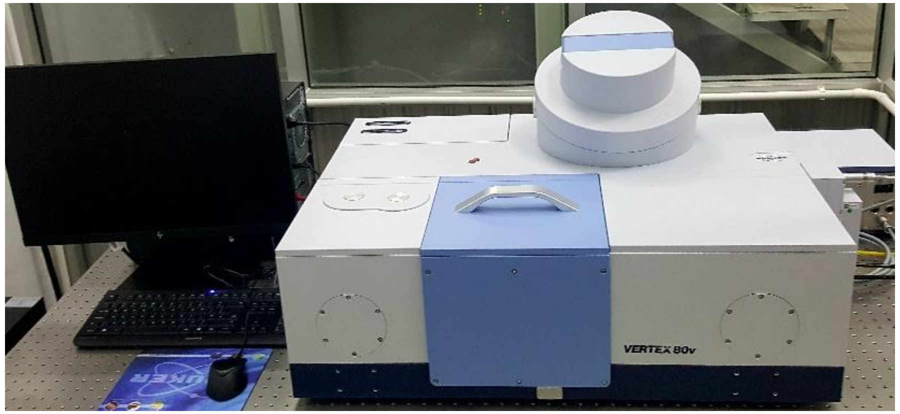
Frequency range:	0.1–3 THz
Pulse duration:	1 ps
Pulse energy:	0.005–0.01 μJ
Repetition rate:	1 kHz
Time resolution:	100 fs

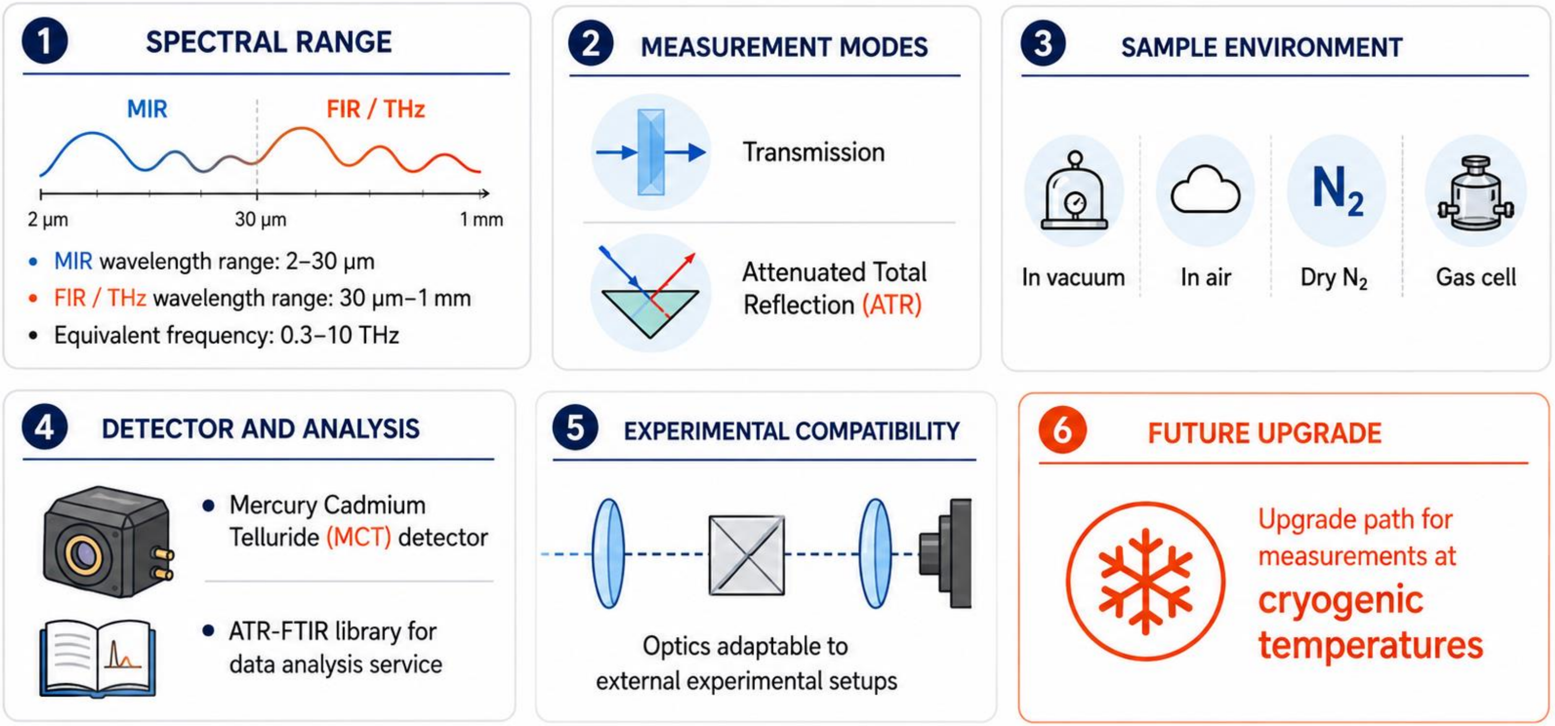


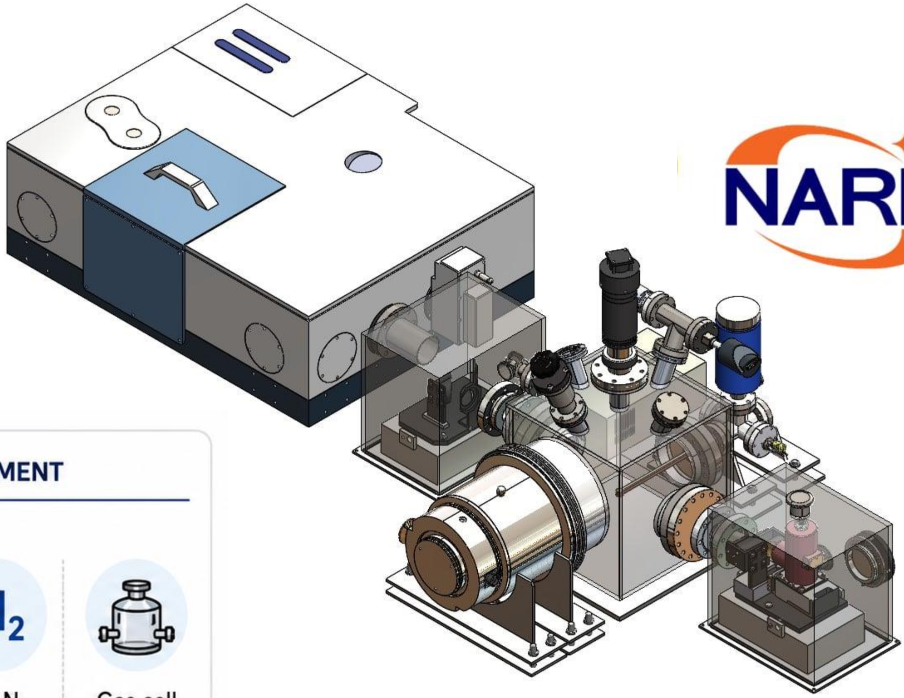




Bench-top Stations : THz-FTIR Spectrometer





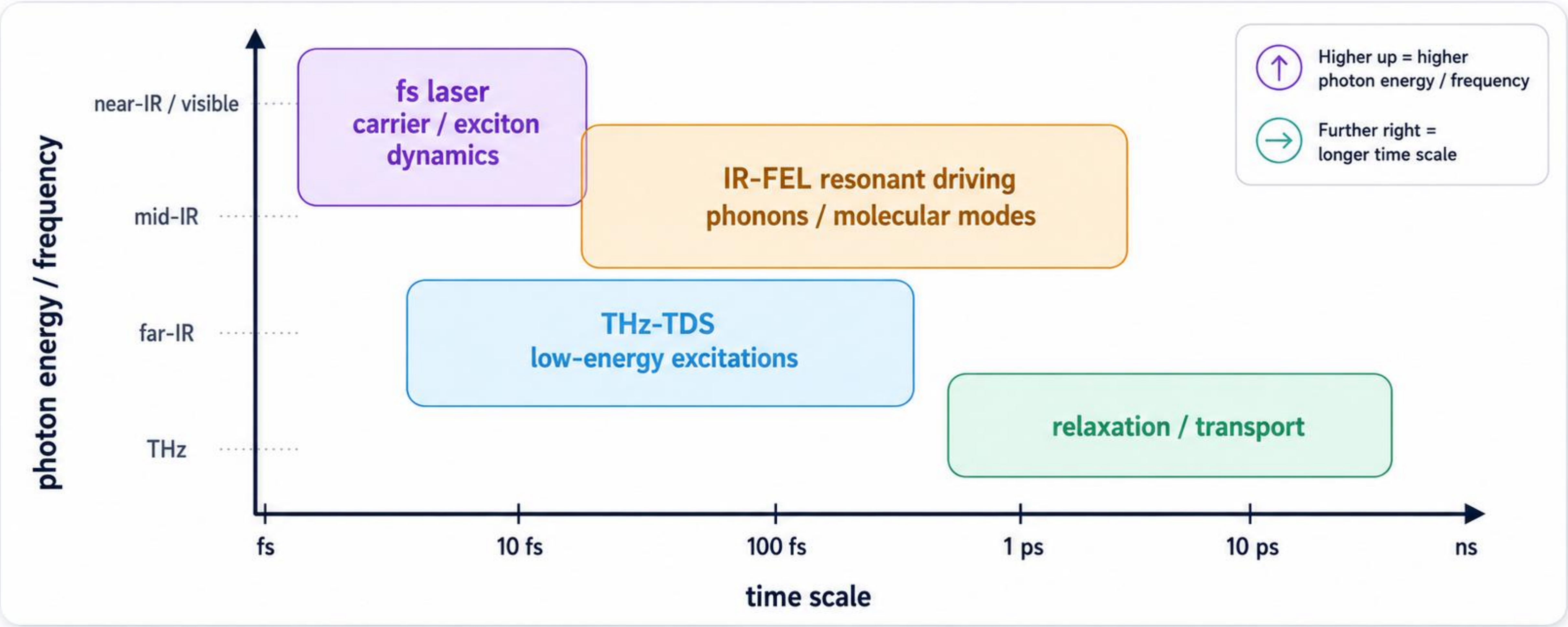


Astrochemistry station:

- Space-like condition in chamber
- Study the original of life in interstellar medium

The useful measurement space

IR–THz FELs add spectral selectivity; femtosecond lasers add temporal selectivity.



Shared Facility @ CMU

PELL — PARTICLE ACCELERATORS AND LASER TECHNOLOGY RESEARCH GROUP

Vision: Shared research infrastructure for users and hub for accelerator-based science

Mission: Establishment of electron accelerator and IR FEL laboratory for frontier research, applications, innovation, and human resource development.

Goals:
- Materials Science
- Biotechnology
- Energy Materials & Storage
- Quantum & Low-Dimensional Materials
- Industrial Products

Advanced Research Platform for Accelerator and Photon Science

Accelerator-based Infrastructure

- Electron beam irradiation & FLASH study
- MIR/THz FEL irradiation
- THz CTR research
- Linear & non-linear transient spectroscopy

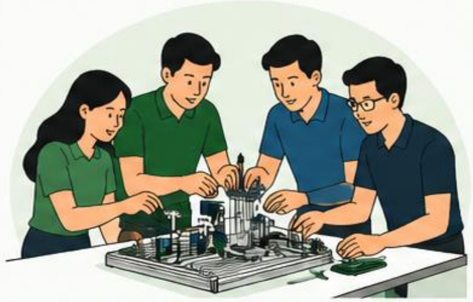
Ultrashort Laser & Spectroscopic Infrastructure

- THz time-domain spectroscopy
- Visible/THz/UV Time-resolved spectroscopy
- Femtosecond laser stereolithography
- FTIR spectroscopy with customized research setup
- Cryocooler setup with temperature control

Pilot Applications:
- THz Emitter/Detector
- Solar Cell & Storage
- Astro-chemistry
- DNA/Cell
- Complex Liquids
- Agriculture

Human Development: Education & Training

Learn-by-building approach for students



- Students learn by designing, building, and testing real systems, bridging theory and practice.
- Encourages creativity, problem-solving, and critical thinking.
- Builds confidence and ownership through hands-on experience.

Hands-on training: design → modeling → construction → experiments

Design	Modeling	Construction	Experiments
Conceptual design and specifications	Simulation and modeling to optimize performance	Build and integrate components and systems	Test, validate, and analyze experimental results

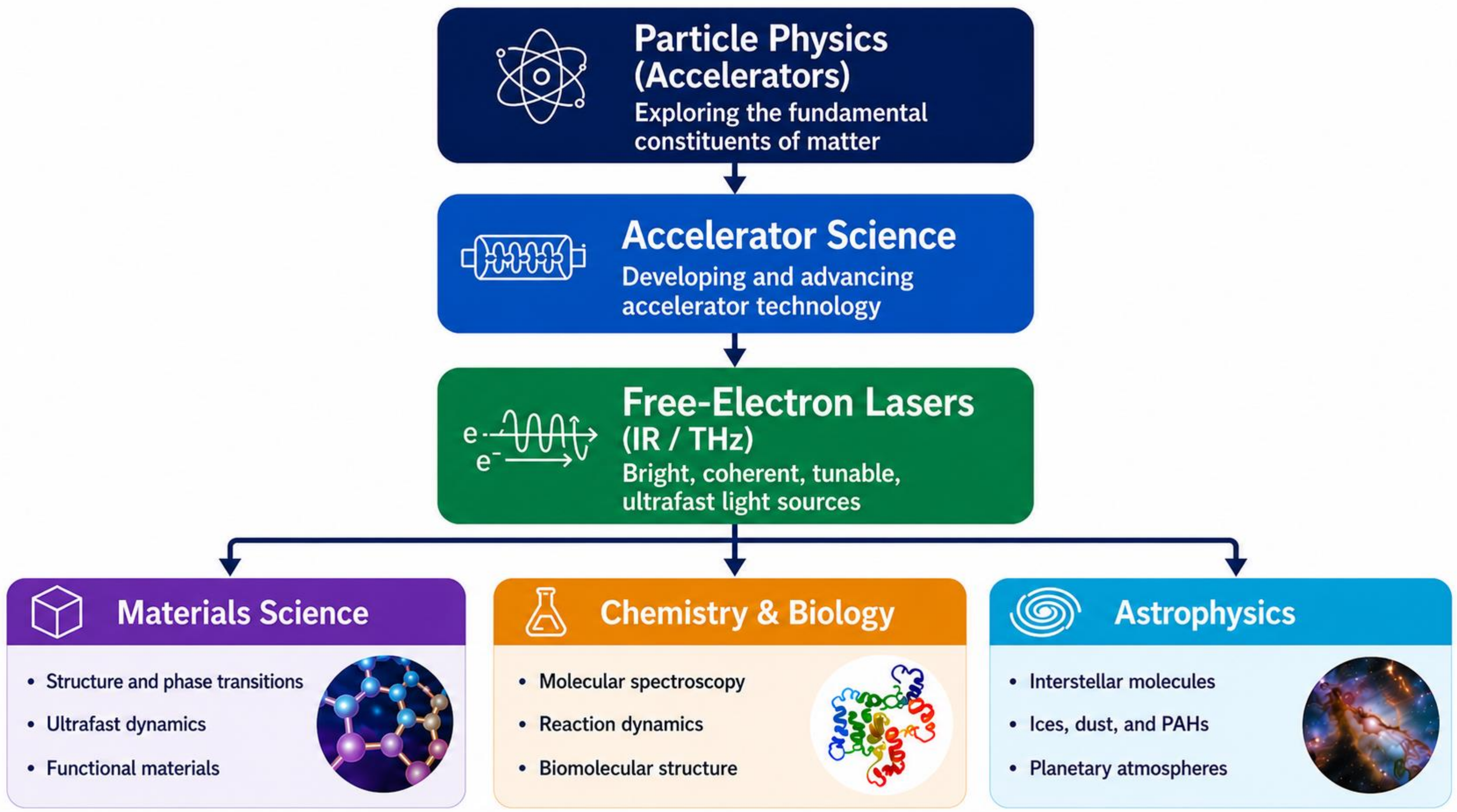
Develop practical skills and a deep understanding of real-world research and engineering.

Early-career researcher involvement

- Engage and empower early-career researchers through real-world research experience and mentorship.
- Promote leadership, collaboration, and interdisciplinary skills.
- Strengthen the next generation of scientists, engineers, and innovators.

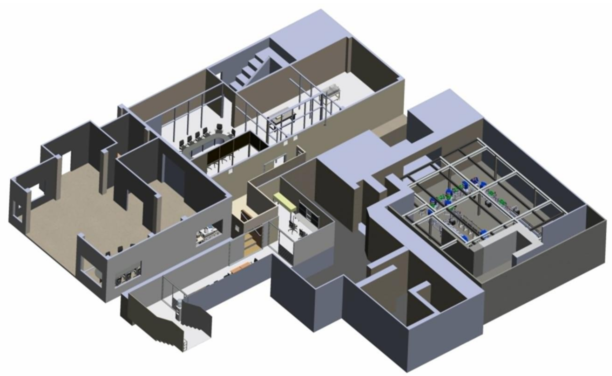
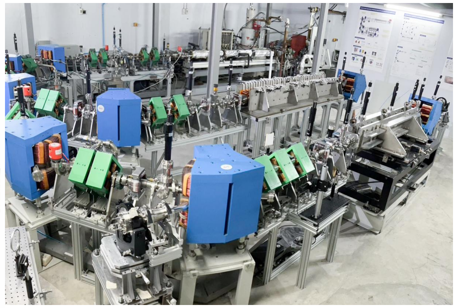
Investing in people through practical training and research involvement builds a strong foundation for innovation, sustainability, and national progress.

06 Conclusion: Accelerator Technology → Many Scientific Frontiers

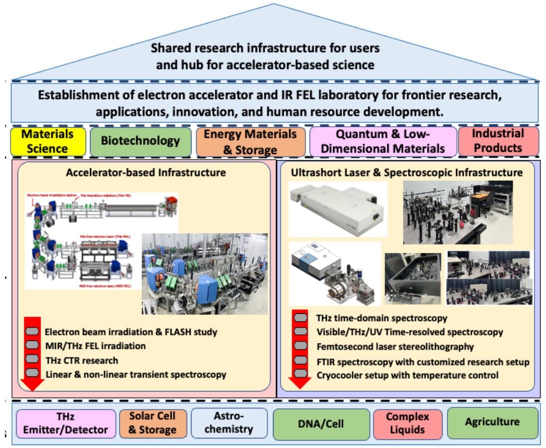


CMU Conclusion

Integrated facility & collaboration network

IR–THz FEL + ultrashort laser facility



Shared facility + domestic/international partners

Two complementary light sources to investigate, control, and tailor materials at ultrafast and molecular scales.

1 Accelerator — 25 MeV compact electron accelerator for MIR/THz FELs, THz-TR, and high-dose-rate pulsed electron beams.

2 Fs laser — THz-FTIR, THz-TDS, and time-resolved spectroscopy provide amplitude, phase, and fs–ps dynamics.

3 Apply — Shared platform supports materials, biology, chemistry, agriculture, astrochemistry, and user collaboration.

Characterize → Understand → Modify → Verify

Acknowledgements & Thank you for your attention

nxpo
Office of National Higher Education Science Research and Innovation Policy Council

สกสว

รวพ.
สำนักงานเร่งรัดการวิจัยและนวัตกรรม
เพื่อเพิ่มความสามารถการแข่งขันและการพัฒนาพื้นที่
(องค์การมหาชน)

PMU-B

วช.
NRCT

Particle Accelerators
HUB OF TALENTS

PARTICLE ACCELERATORS
AND
LASER TECHNOLOGY
RESEARCH GROUP