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Introduction to Terahertz Free Electron Laser

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USTC

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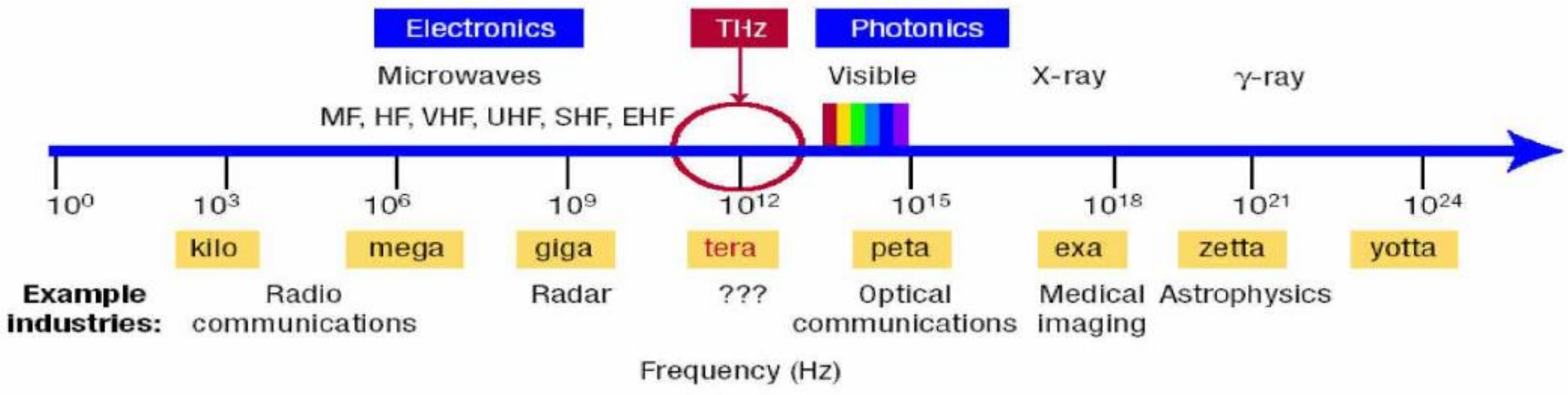
Outline

Outline

What is Terahertz？



- Between microwave and infrared
- Frequency: 0.1-10 THz
- Wavelength: 3-0.03 mm
- Wavenumber: 3.33-333.33 cm-1
- Photo energy: 0.41-41.4 meV
- "Terahertz Gap"

$\lambda = c/f$

$k = 1/\lambda$

$E = h \cdot f$

$h = 6.62606896 \times 10^{-34}$ J s

$h = 4.13566743 \times 10^{-15}$ eV s

Main properties of THz

01 High penetration capability for non-polar materials

02 Reflection at metal surface；Absorption by water, oxide

03 No ionizing radiation effect with low energy photons; Safety for cells and tissues

04 Fingerprint spectrum
Similar energy level with vibration and rotation of most moleculas

05 Large bandwidth, large capacity, high speed

06 Short pulse; coherence; High time and space resolution

Methodologies of Terahertz

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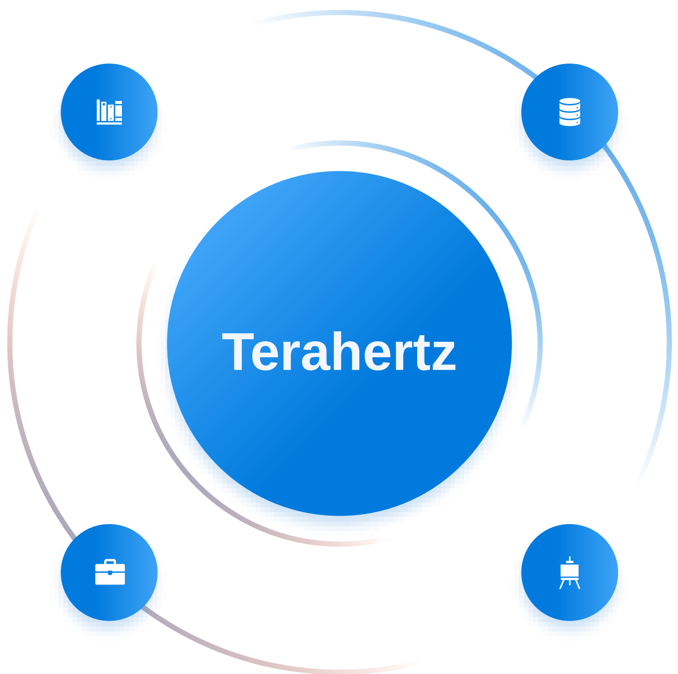
Spectroscopy

Crystalline and non-crystalline solid,
liquid crystal,
polymers,
atom and molecule spectroscopy,
nonlinear spectroscopy, …



Imaging

THz imaging,
near-field THz imaging,
biomedical imaging,
clinical imaging,
tomography,
THz scanning tunnelling microscopy,
security imaging, ….

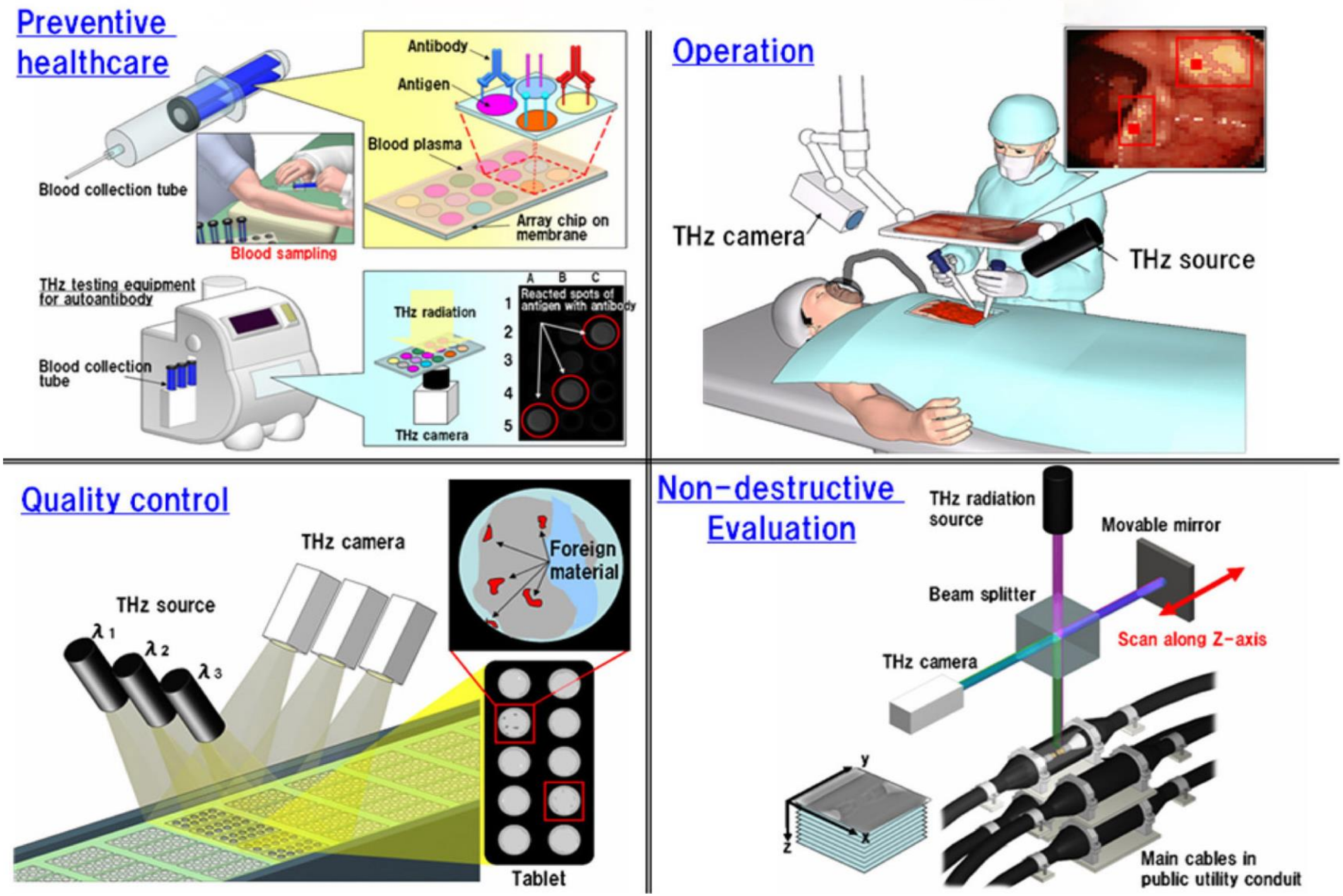
Control

Strong magnetic/electric field,
ultrafast, …

Others

Communication,
metrology,
astronomy, …

Application examples



Application examples

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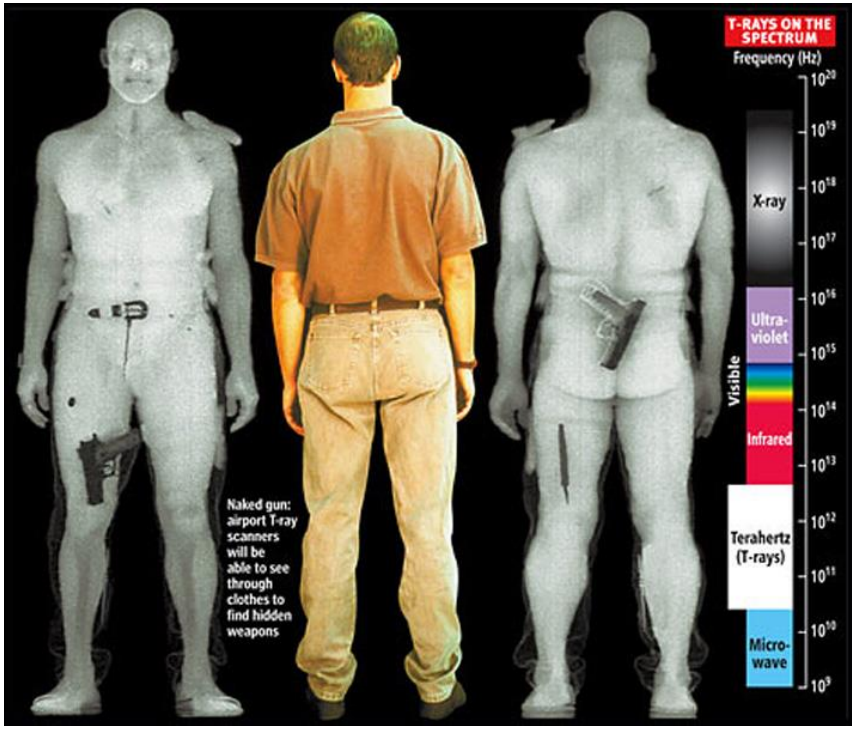
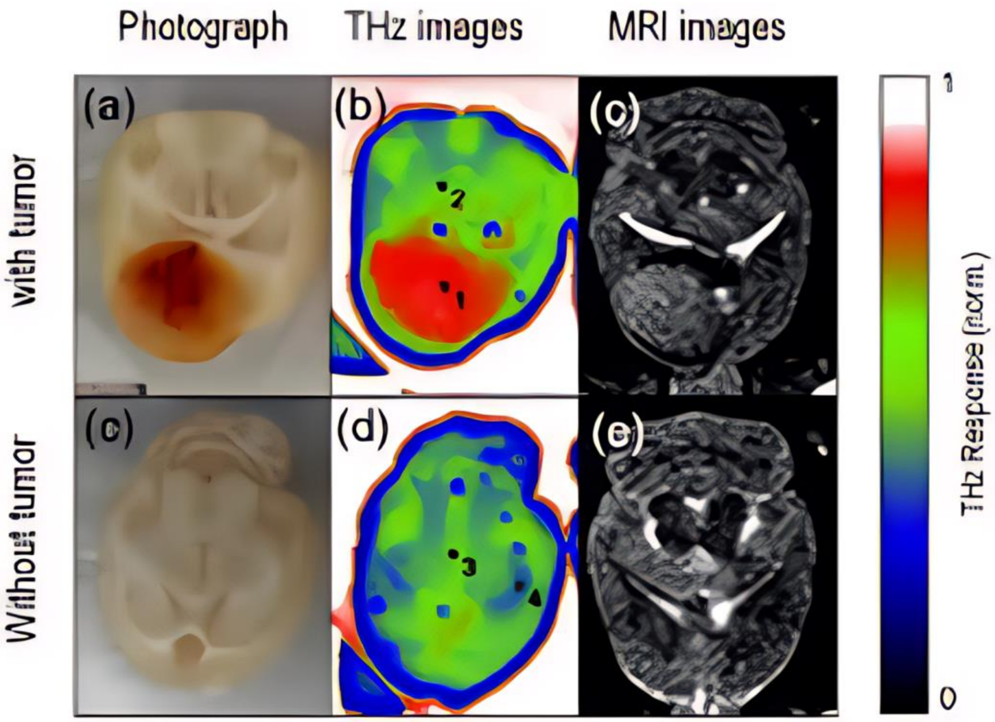
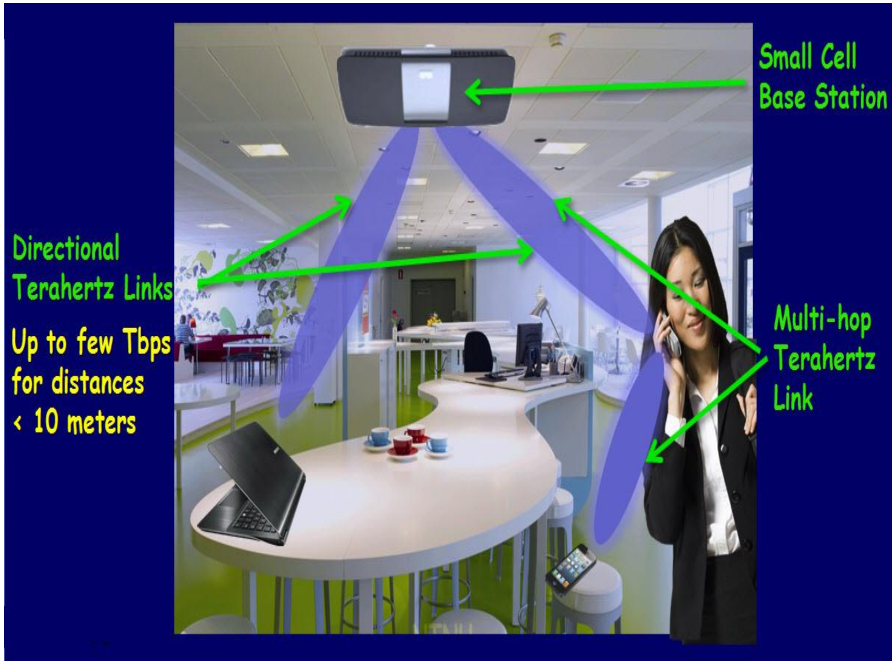


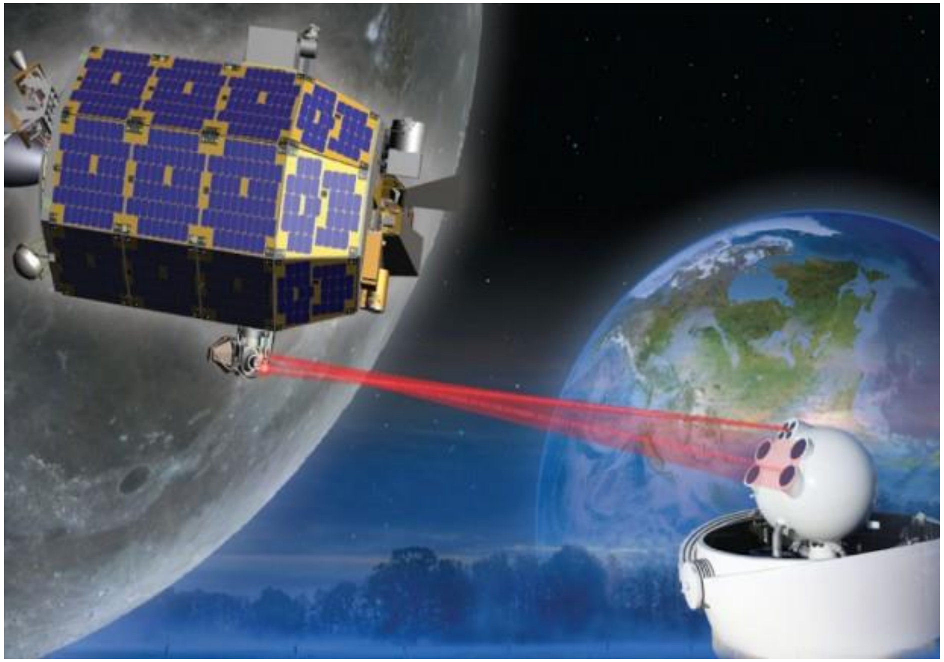


- Harmless to humans
- The imaging is clear

- Cancer detection in living organisms
- The edges are clearly visible

Application examples





- large bandwidth, huge information

→secure communication over short distances

- The THz band has a water window

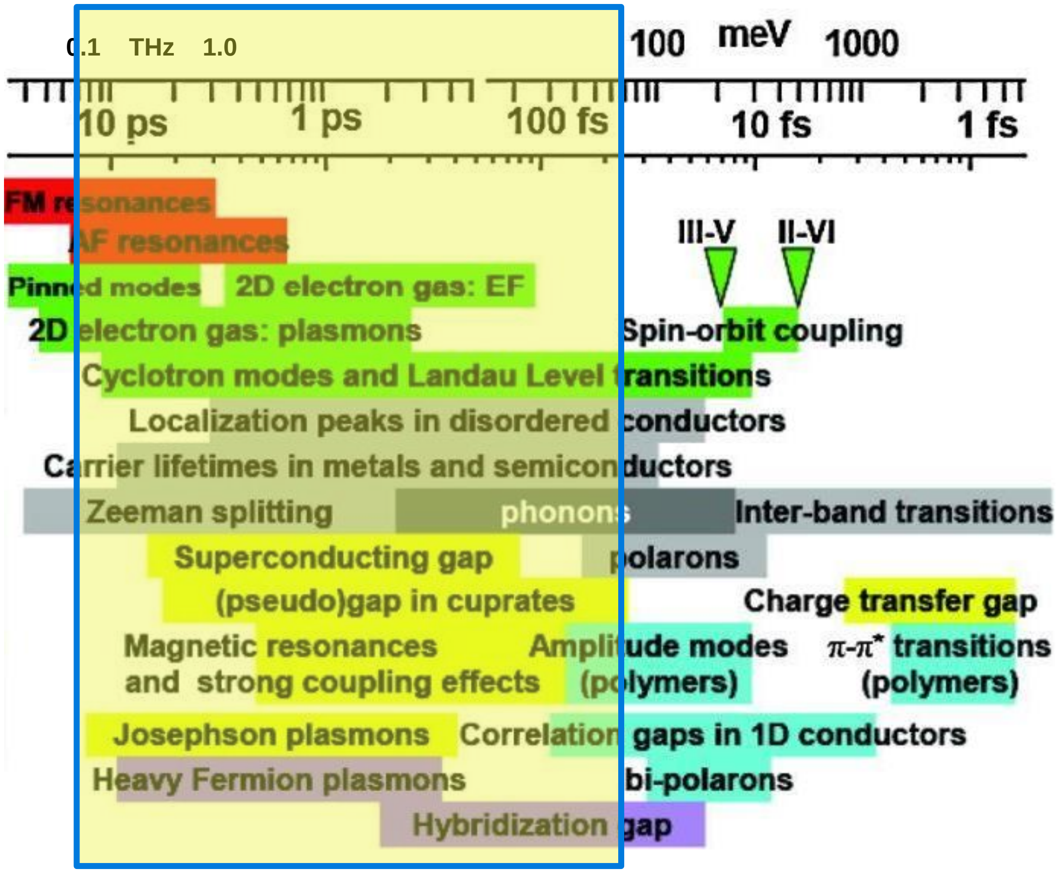
→ground and space communications

Application examples

Quasi-particle is an emergent phenomena that arises from the collective behavior of particles in certain physical systems, such as solids or superconductors.

It behaves like a particle with its own properties, but it is not a fundamental particle like those found in particle physics.

Most of the characteristic energies of quasi-particles are located in the terahertz frequency band, so the correlation with the characteristic physical properties of functional materials is universal!



Objective	Functional materials
Magnetons	Magnetic materials
Migration rate	Semiconductor materials
Band gap	Superconducting materials
Electromagnetic oscillators	Multiferroic material
Plasmons	Metamaterials
…	

Some references

- Terahertz Techniques, Springer Series in Optical Sciences 151
- Principles of Terahertz Sciences and Technologies, Springer
- Terahertz Spectroscopy and imaging, Springer Series in Optical Sciences 171
- Convergence of Terahertz Sciences in Biomedical Systems, Springer
- The 2017 terahertz science and technology roadmap, Journal of Physics D: Applied Physics
- The 2023 Terahertz Science and Technology Roadmap, Journal of Physics D: Applied Physics
- Rev. Mod. Phys., 83, 471(2011)

……

- Twenty years ago, developed countries, such as the United States and Japan, recognized the importance of Terahertz science and technology, which should be an innovative technology in new century.
- In the past 20 years, Terahertz science and technology have made rapid progress, but in my personal opinion, there is still a gap compared to expectations due to THz gap

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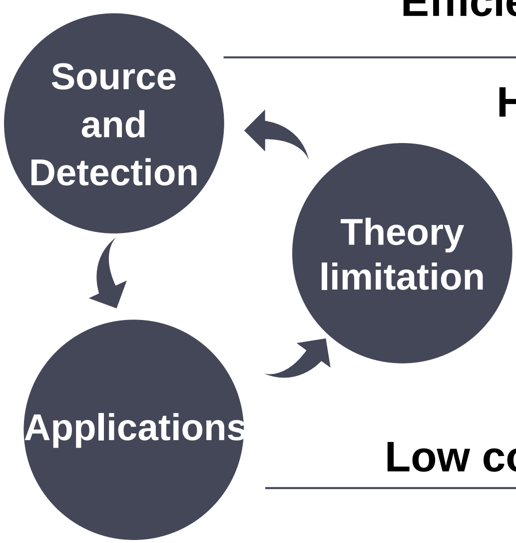
Outline

THz Gap

It's not a natural band gap in the spectrum

It's the special stage limited by technological development



Efficient and stable coherent terahertz generation

Highly sensitive terahertz detection

Insufficient theoretical description: limitations of microwave theory and optical theory

The mechanism of interaction with matter is not well understood

Low conversion rate from theory and experiments to application

THz sources

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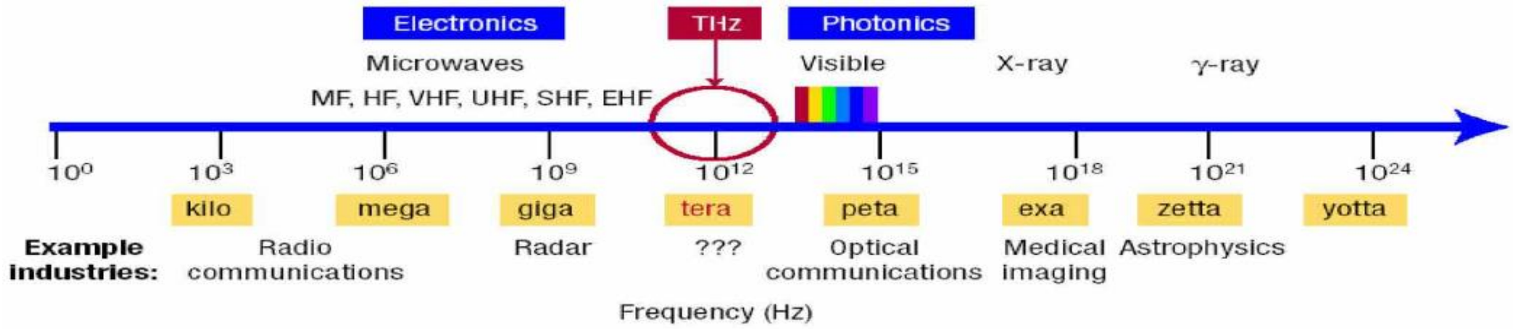
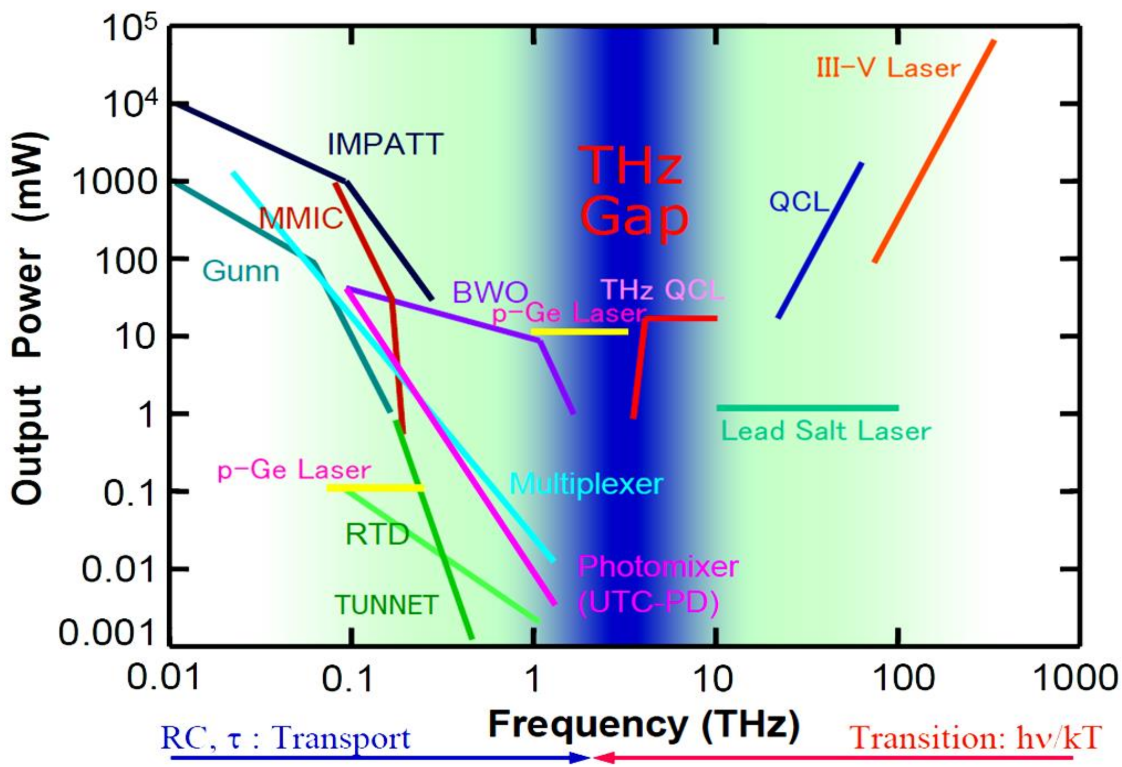


Vacuum electronics technology



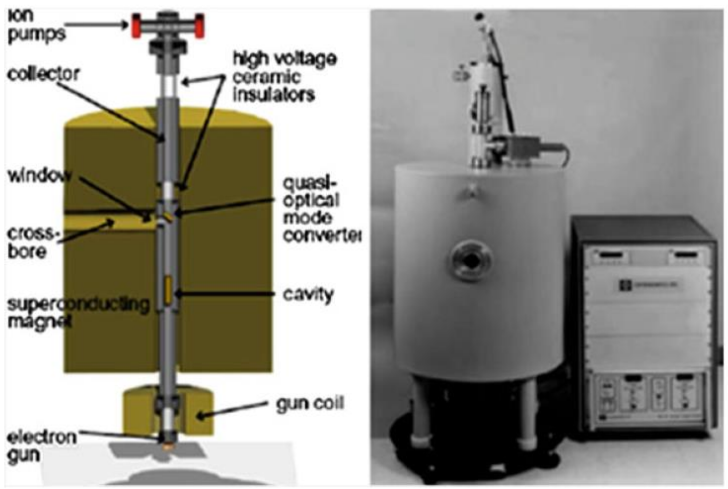
Photonics technology

THz Vacuum Electronic Device

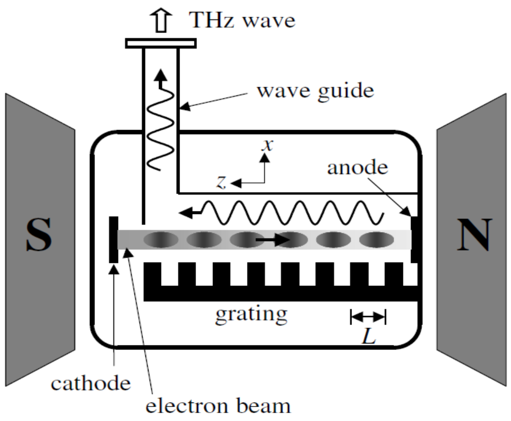
- In a vacuum environment, the electron beam is accelerated through a specific structure (resonant cavity, slow-wave structure). Energy coupling occurs with the electromagnetic field, and the kinetic energy of electrons is transferred to the electromagnetic field, which directly generates or enhances the Terahertz band electromagnetic fields.
- Advantages：**High output power; Good working stability**
- Disadvantages：**Large size and weight; High power consumption; Higher cost; The frequency is limited to the low THz band**
- Application scenarios：radar, Meteorological and environmental remote sensing, Long-range terahertz communication, Security imaging, Industrial material defect detection, Deep space exploration, Nuclear industry testing

Typical THz VEDs

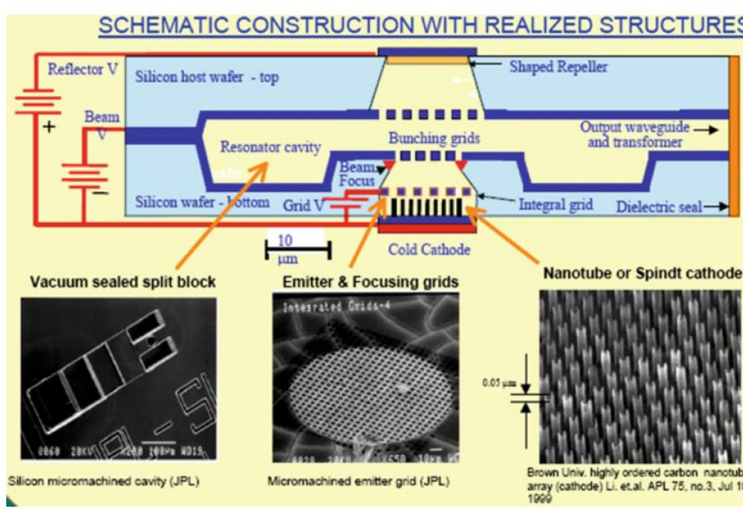
Klystrons:
THz nano-reflex klystron,
Multi-cavity sheet beam klystron,…



Travelling Wave Tubes(TWTs)/
Backward Wave Oscillator (BWOs)：
Straight-edge connected planar helix TWTs,
Folded waveguide and coupled cavity TWT/BWO,
Staggered double vane arrays TWT



Gyrotrons:
DNP-NMR Gyrotrons,
THz Gyrotrons,…



Typical THz VEDs

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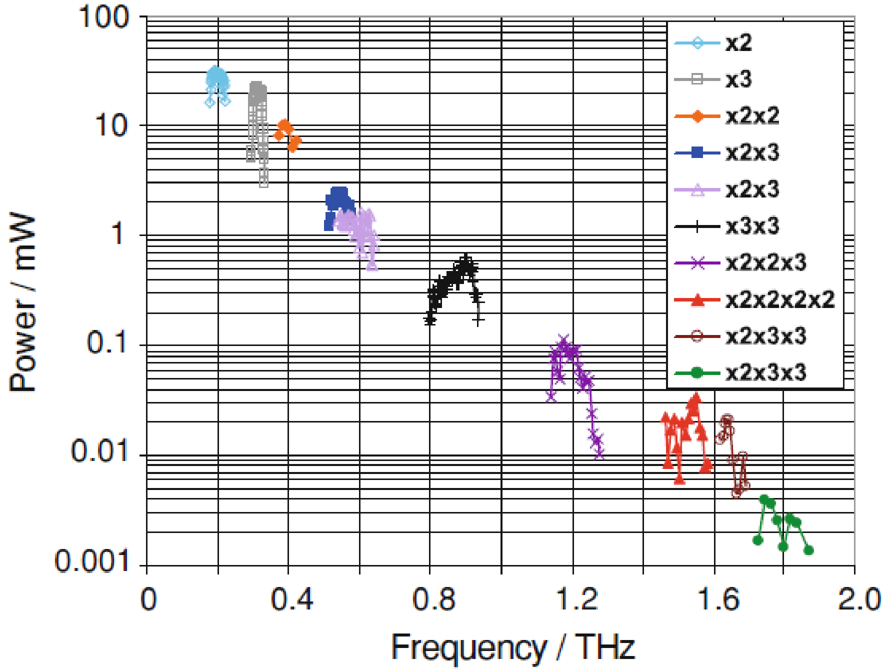
Microwave Frequency Multipliers, based on Gunn diodes and impact ionization avalanche transit-time diodes, IMPATT



New type:
dielectric Cherenkov radiation sources,
multi-beam devices using photonic crystal resonators,
Metamaterial-embedded THz VEDs

Broadband THz

- **Photo-conductive antenna**, a terahertz generator based on the photoelectric effect of semiconductors. Fast laser irradiation excites carriers, the carrier accelerates to produce a transient current, then produces a broadband terahertz pulse. **Saturation power limit; Efficiency limitations.**
- **Photo-rectification, femtosecond lasers** act on second-order nonlinear crystals(for example, lithium niobate, Zinc telluride), the broadband spectral component of the pulse undergoes differential frequency oscillation in the medium and produces terahertz waves. **Damage threshold; Efficiency limitations**
- **Photo-dember emitters**, ultrashort laser pulses irradiate semiconductors to form transient carrier gradients, its asymmetric diffusion forms a transient electric dipole moment, produces terahertz waves
- **Parametric amplification**, a process that utilizes energy transfer in a nonlinear medium, the energy from the pump light is transferred to the signal light. Including optical rectification, differential frequency generation, and Optical Parametric Oscillation(OPO)
- **Terahertz generation in air**(plasma) . **High damage threshold; High efficiency**

Laser-based THz sources

Narrowband THz

- **Photo mixing,** two lasers with a slight difference in center frequency are introduced into materials with high second-order nonlinear optical coefficients(for examples, GaAs、$LiNbO_3$), sum and differential frequency signals will be generated when the laser interacts in a nonlinear material. The difference frequency signal may be THz wave determined by source laser frequency.

- **Difference frequency generation,** its core is based on second-order nonlinear optical effects. When two beams of pump light with similar frequencies are incident into a nonlinear medium, due to response through the second-order polarization of the medium, a terahertz wave with a frequency of the difference between the optical frequencies of the two pumps is produced

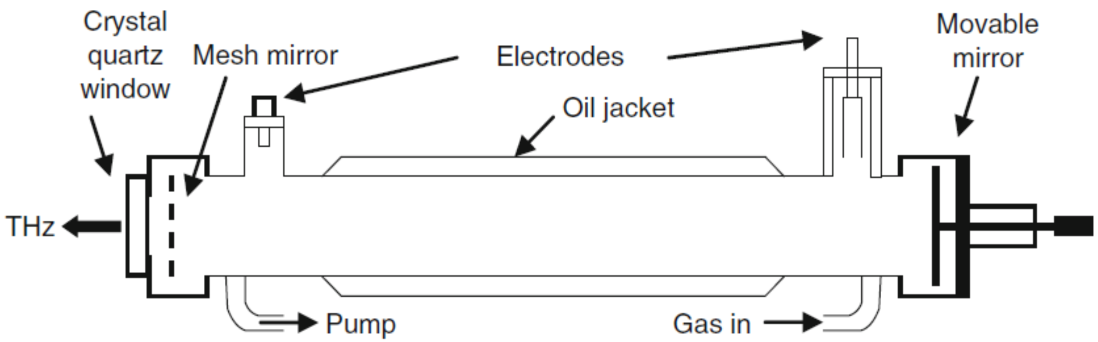
- **Narrowband Terahertz generation in quasi-phase-matching crystals**(Phase Matching with tilted optical pulses in Lithium Niobate)

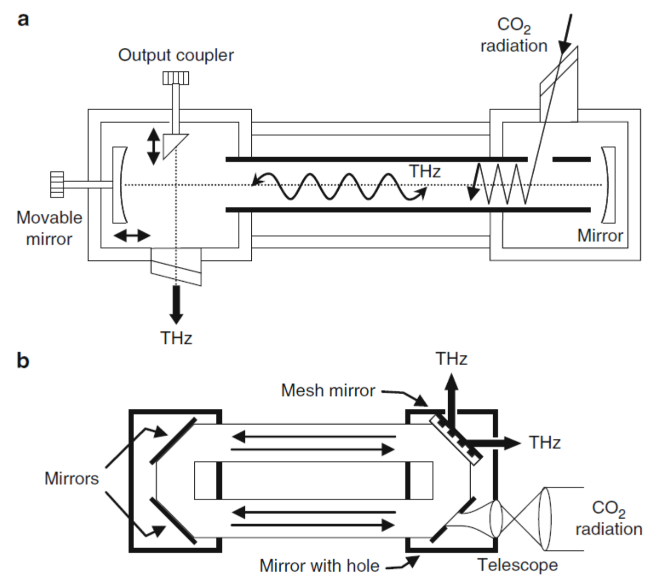
THz lasers

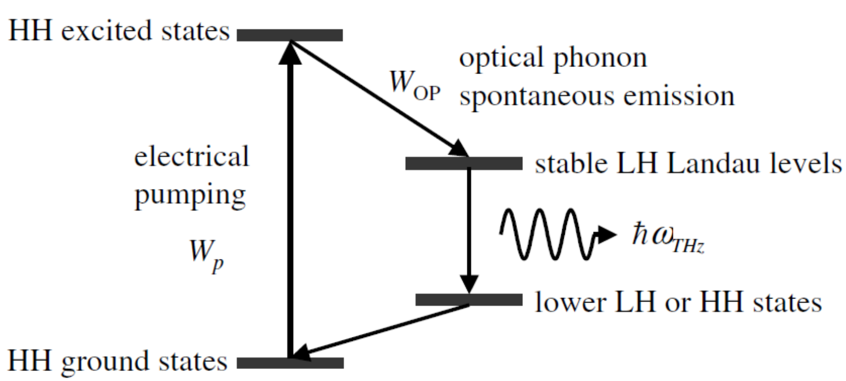
Narrowband THz

- **Gas Lasers:** The principle of terahertz gas laser is that the light pump excites the rotational energy level transition of gas molecules, realizes the reversal of the number of particles, and produces terahertz laser through stimulated radiation and resonant amplification. Including electrically excited gas lasers, optically excited gas lasers
- **Quantum cascade laser:** electron transition between bands based on semiconductor-coupled quantum well (non-traditional p-n junction composite luminescence), a single electron can generate multiple photons through a cascading structure, achieving high power output
- **P-type Germanium lasers**

Schematic diagrams







Non-accelerator THz sources

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- Improve performance(THz spectrum, power, repetition frequency, electric field) with rapidly progress of

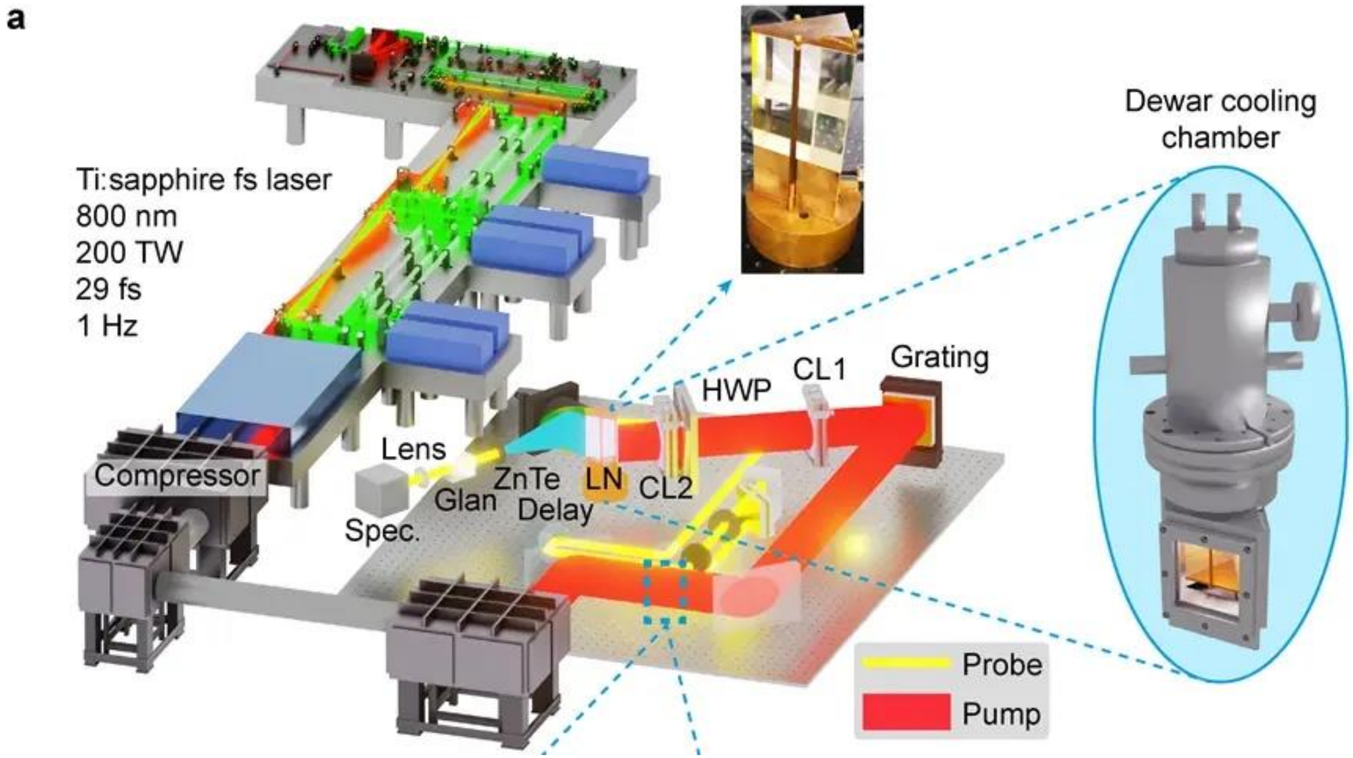
  picosecond and femtosecond laser technologies,

  high repetition laser technologies,

  functional materials technologies,

  …
- In most cases, their relatively low cost and small scale, are more suitable as laboratory instruments

Photo rectification



Pulse energy 13.9mJ,
Converting efficiency 1.2%
Peak electric field 7.5 MV/cm

Ref: Generation of 13.9mJ Terahertz radiation from lithium Niobate material, Advanced Materials

Accelerator-based THz sources

Broadband THz

- **Transition radiation**, a type of electromagnetic radiation that occurs when a charged particle, such as an electron, passes through a boundary between two media with different dielectric constants or conductivities.
- **Diffraction radiation**, an electromagnetic phenomenon that occurs when a charged particle moves near an edge or aperture of an ideally conducting screen in a vacuum. Diffraction of the particle's self-field by the obstacle, governed by electromagnetic wave diffraction principles (e.g., Huygens-Fresnel theory and Kirchhoff's diffraction formula)
- **Synchrotron radiation**, electromagnetic radiation emitted when charged particles, such as electrons, are accelerated radially in a magnetic field at velocities close to the speed of light.
- **Edge radiation**, a specific type of electromagnetic radiation emitted when relativistic charged particles interact with magnetic field geometry. The abrupt variation in the magnetic field or material boundaries can lead to enhanced radiation emission
- **Cherenkov radiation**, a charged particle moves through a transparent medium at velocity v exceeding the speed of light in that medium ($v > c/n$)

Accelerator-based THz sources

Narrowband THz

- **Undulator radiation**, electromagnetic radiation emitted by charged particles (typically electrons) when they are forced to oscillate periodically through a spatially varying magnetic field in a device called an undulator. This periodic motion causes the particles to emit radiation with specific characteristics, such as high brightness, polarization, and tunable wavelength, depending on the undulator's magnetic field strength and the particle energy
- **Smith-Purcell radiation**, as charged particles pass near the grating, they disturb the electromagnetic fields near its surface. The periodic structure of the grating diffracts or "scatters" this disturbance, converting the kinetic energy of the moving charges into emitted photons
- **FEL radiation,** is a type of laser that generates coherent electromagnetic radiation by utilizing relativistic free electrons as the lasing medium, rather than bound electrons in atoms or molecules

Accelerator based THz sources

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- **Storage ring-based THz sources:**
low alpha operation mode, laser-slicing technique,
controllable microbunching process, laser-modulated electron beam …

- **Normal conducting linac based THz sources:**
transition radiation， undulator radiation…
Compressing bunch length to enhance radiation, such as velocity compression, magnetic compression,…

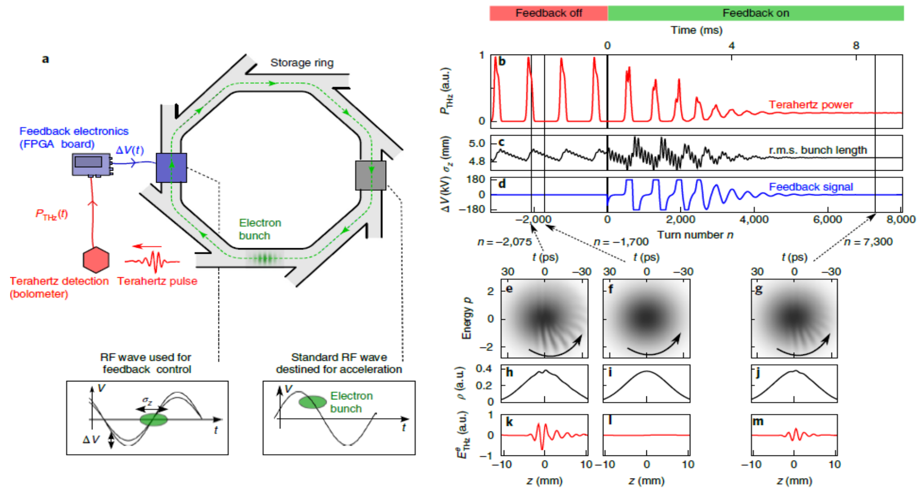
- **Superconducting linac based THz sources**, similar to NC driven THz sources, but with higher repetition rate, resulting high average power

- **Energy recovery linac based THz sources:**
superconducting ERL or normal conducting ERL increase converting efficiency and enhance average power.

Storage ring based THz sources

Limitations of low α mode:

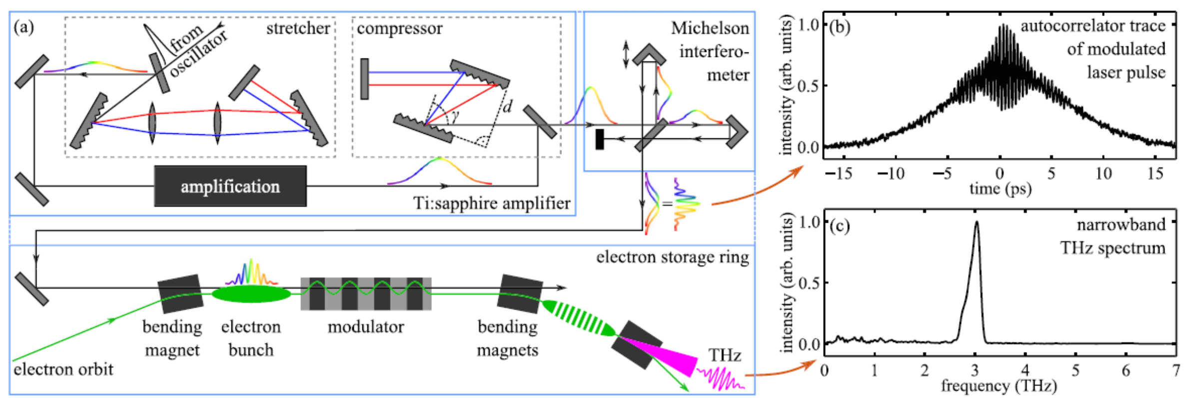
- Spectrum
- Peak power
- Compatibility with other experimental stations



[Ref: Stable coherent terahertz synchrotron radiation from controlled relativistic electron bunches, Nature physics]

New ideas:

- Controllable microbunching process with feedback
- Laser-modulated electron beam
- …



[Ref: Continuously tunable narrowband pulses in the THz gap from laser-modulated electron bunches in a storage ring, PRAB]

SLAC-FACET

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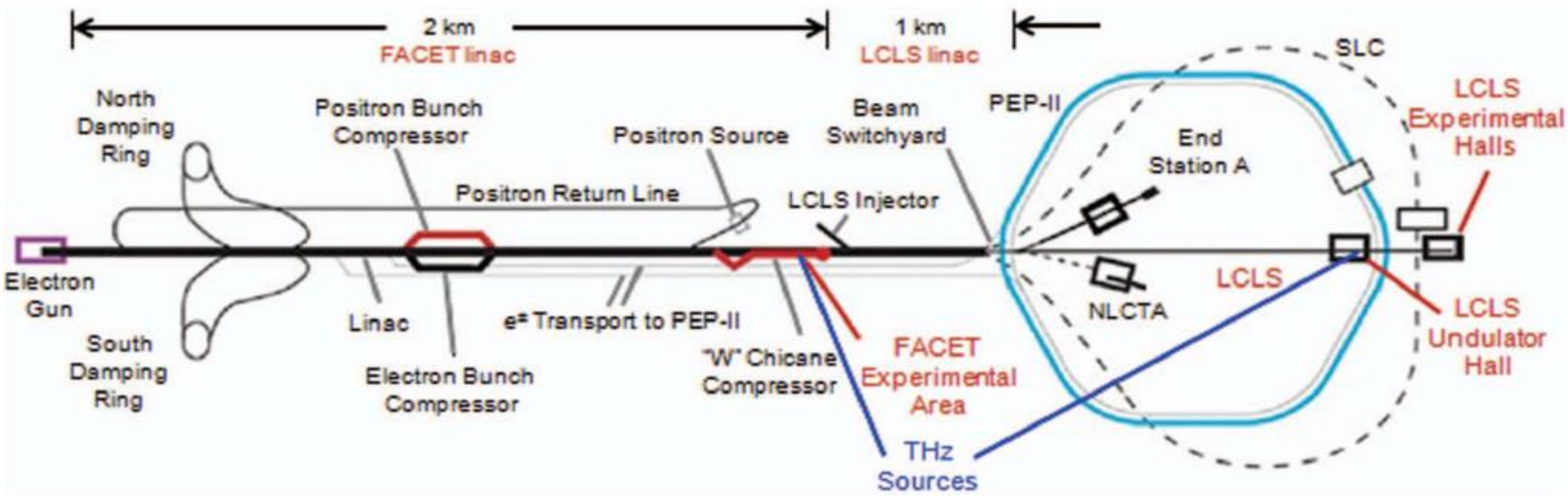
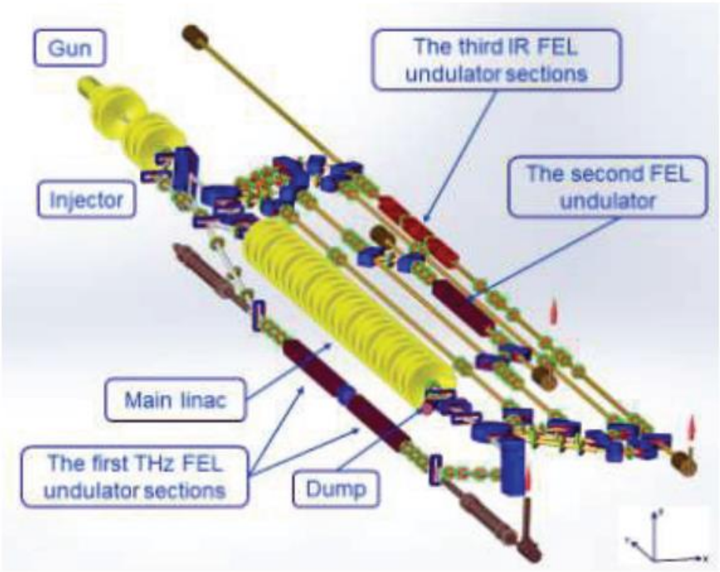
FACET: Facility for Advanced Accelerator Experimental Test

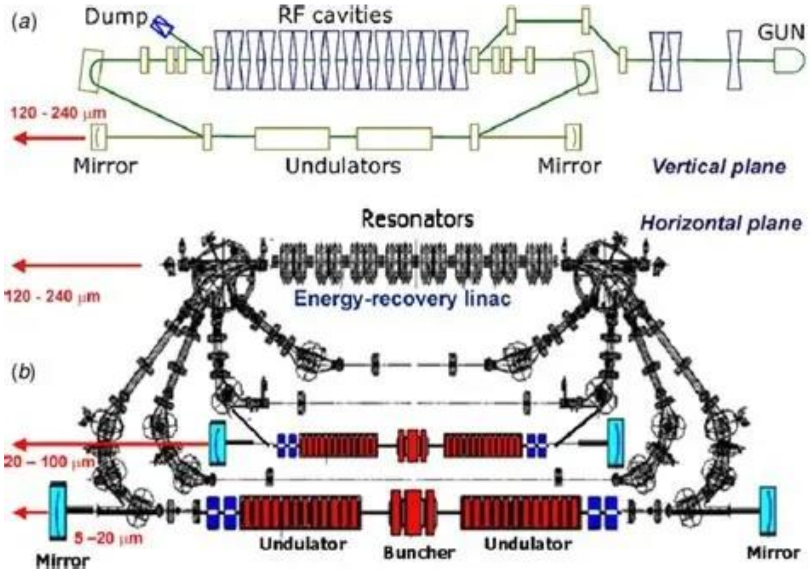
- Beam energy : ~20 GeV
- Coherent transition radiation from two 1-um-thick Ti foils
- Energy: ~ 0.5mJ
- Bunch length: ~25 fs
- Spectrum: ~1THz
- Electric fields: ~ 6MV/cm



Ref: Intense terahertz pulses from SLAC electron beams using coherent transition radiation., Rev. Sci. Instum
FACET The New User Facility at SLAC, Christine Clarke

Novosobirsk THz FEL

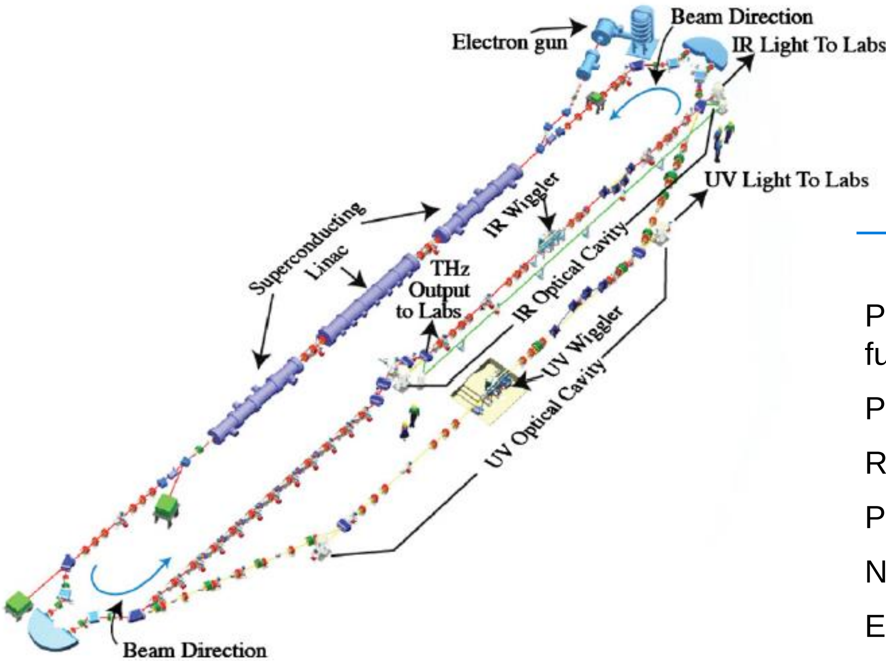




- ➢ Room-temperature RF cavity-based energy recovery linac, 187MHz
- ➢ Spectral range: 90-240 um, 37-80 um, 5-20 um
- ➢ Average power: 100 W order

Ref: The Novosibirsk Free Electron Laser-unique source of terahertz and infrared coherent radiation, Physics Procedia

The Jefferson IR-FEL



	IR-FEL	UV-FEL
Photon energy range of fundamental (eV)	0.1-1.4	1-3.4
Photon energy per pulse (uJ)	100	20
Repetition rate (MHz)	4.678-74.85	4.678-74.85
Photon pulse length (FWHM)	100 fs-2 ps	100 fs-2 ps
Nominal pulse bandwidth (%)	1	<1
Electron beam energy (MeV)	80-140	80-140
Charge per electron bunch (pC)	135	60

- Superconducting RF cavity-based energy recovery linac (100MeV, 10mA)
- MHz repetition rate
- 10kW order radiation power at IR

Ref: The VUV/IR/THz free electron laser program at Jefferson Lab, NIMA
Progress at the Jefferson laboratory FEL, PAC09

C(hinese)T(erahertz)FEL

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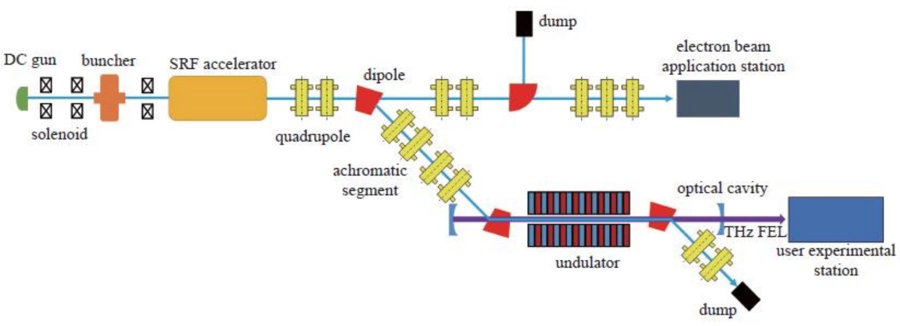
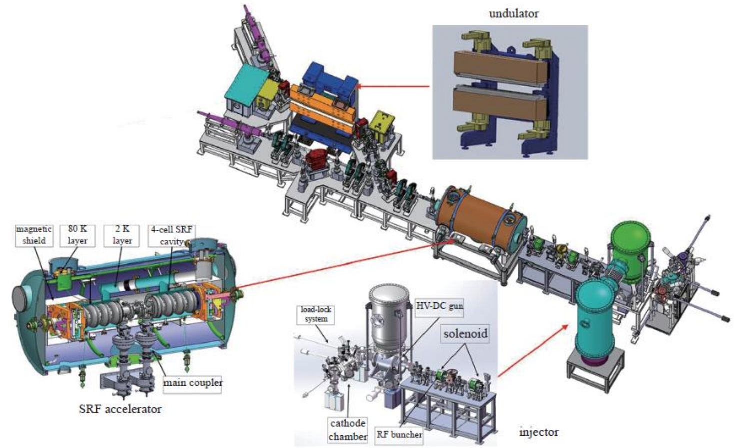




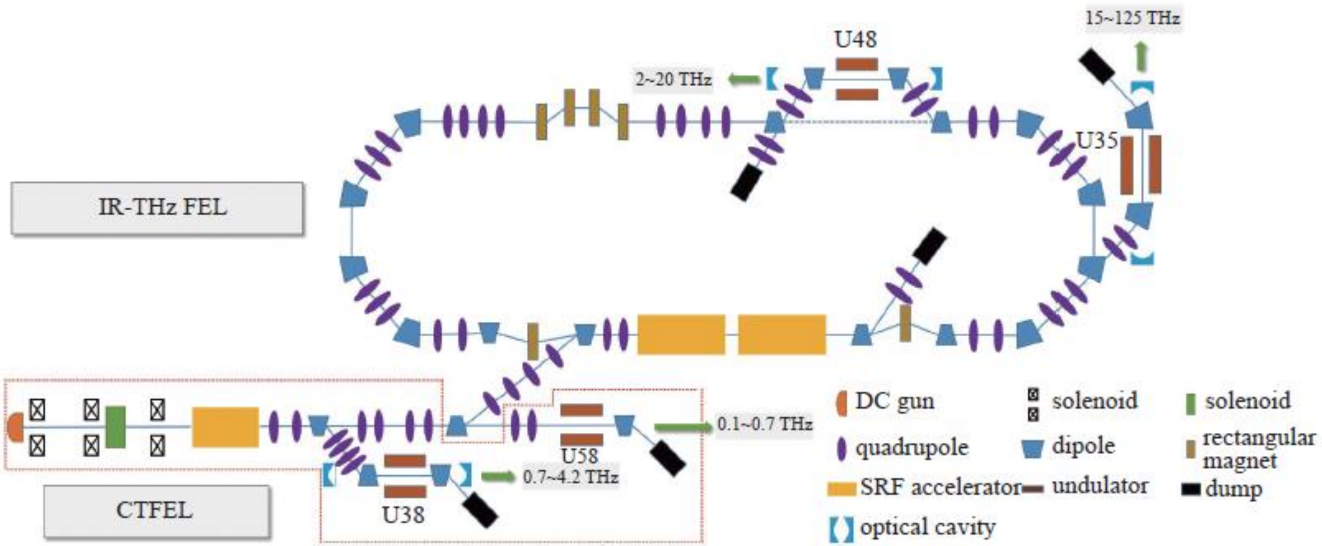
injector parameter	value	SRF accelerator parameter	value	undulator parameter	value
laser wavelength/nm	532	working frequency/GHz	1.3	number of periods	42
repetition rate/MHz	54.167	working temperature/K	2	period length/mm	38
gun voltage/kV	320	effective field gradient/(MV/m)	10	gap range/mm	18～32
bunch length/ps	～12	amplitude stability	0.03%	optical cavity length/mm	2769
beam current/mA	1～5	phase stability/(°)	0.06	curvature radius/mm	2218

parameters	values
THz FEL frequency range/THz	0.67～4.2
bandwidth/%	～2
macro-pulse average power/W	10～60
macro-pulse repetition rate/Hz	1/5/10/20
macro-pulse length/ms	0.3～8
micro-pulse length/ps	<10
micro-pulse repetition rate/MHz	54.17
peak power/MW	>0.1
minimum beam size/mm	<1
polarization direction/%	>99 (horizontal)
super-radiation frequency range/THz	0.1～0.7
super-radiation electric field/(MV/cm)	～1

The superconducting linac based THz-FEL

- Spectral range
- High repetition
- High average power

CTFEL-upgrade

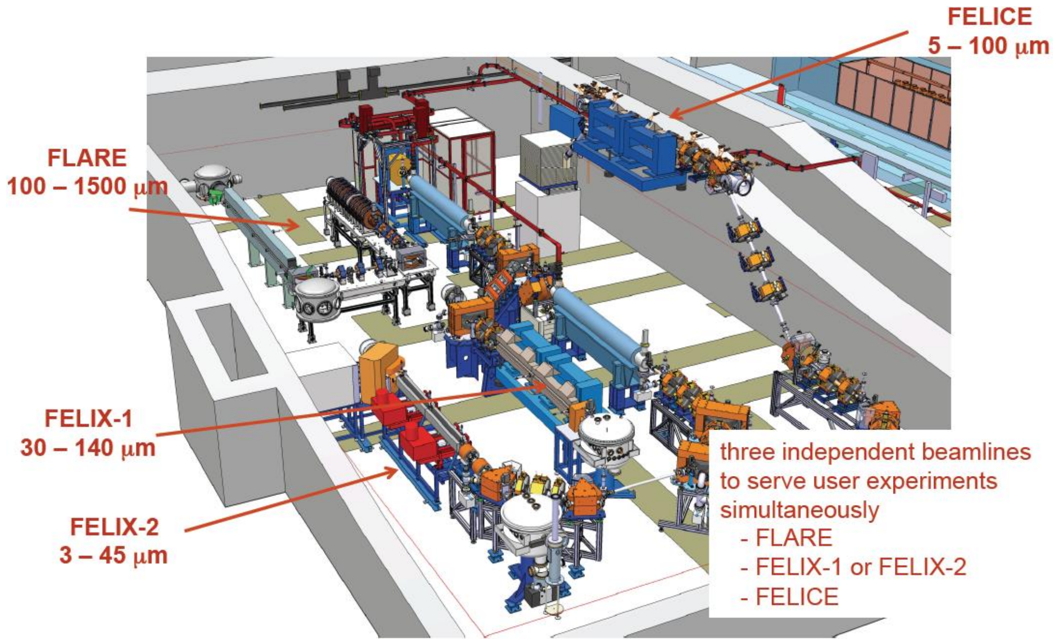


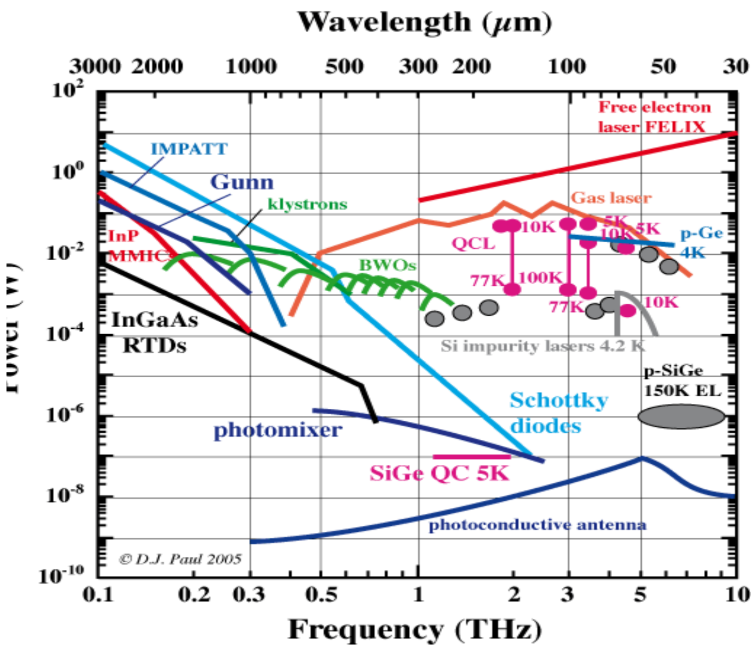
electron beams		IR-THz FEL	
maximum energy/MeV	50	frequency range/THz	0.1～125
energy spread/%	＜0.3 (FWHM)	wavelength range/μm	2.4～3000
normalized emittance @100 pC/μm	＜15	pulse length/ps	0.5～20
bunch charge/pC	50～100	maximum macro-pulse power/W	＞100

- Extension of spectrum to infrared
- Enhancement of average power
- Potential of energy recovery operation

Ref: Status and upgrade plan of CAEP THz-FEL facility, High Power Lasers and Particle Beams

FELIX/FELICE/FLARE





Room temperature linac based IR-THz FEL

- FELIX: 15-50 MeV, 20uJ/100mJ/100MW
- FLARE: 10-15 MeV,5uJ/100mJ/10MW
- FELICE: 18-50 MeV, 1mJ/5GW

Ref: Introduction to the infrared and THz user facility FELIX, Britta Redlich

Brief summary

- So far, Terahertz source technologies have made significant progress, manifest in the terahertz coverage band, average power, peak power, ultra-fast, etc.
- Fruitful results have been achieved in various research and application fields
- VED sources based on a low-energy electron beam, Terahertz sources based on laser technology, Terahertz lasers…

- The terahertz sources based on the accelerator still have many advantages: spectral coverage, peak power/average power, ultra-fast, spectral tuning capability, reliability, etc.
- A number of terahertz source user facilities were built, especially on large-scale light sources
- Many THz sources based on low energy accelerator were operated for special application fields
- Its scale and cost limit its wide application, and miniaturization is an urgent need

An example

- A desktop THz Free Electron Laser scheme from Korea
- Oscillator FEL with waveguide
- Microtron as driver

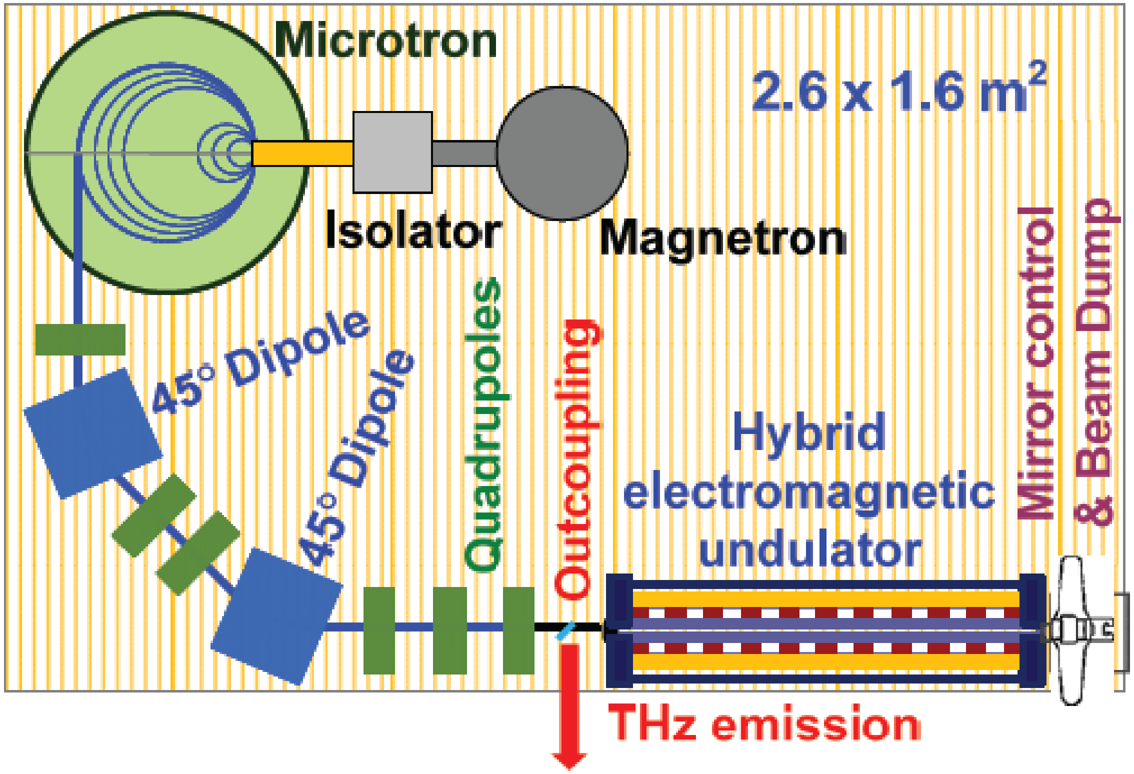


Figure 1: Schematic top view of the FEL.

Ref: A compact THz FEL at KAERI: the project and the status, FEL2017

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Outline

01 THz and its applications

02 THz sources

03 Principle of THz FEL

04 THz facilities in USTC

05 Summary

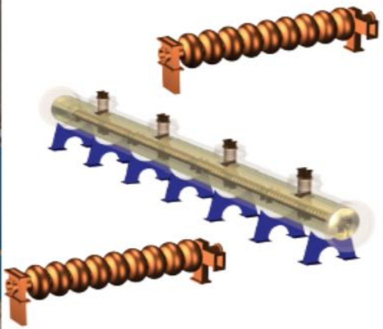
What is Free Electron Laser?

FEL: an energy transformer,
from wall plug power to photons

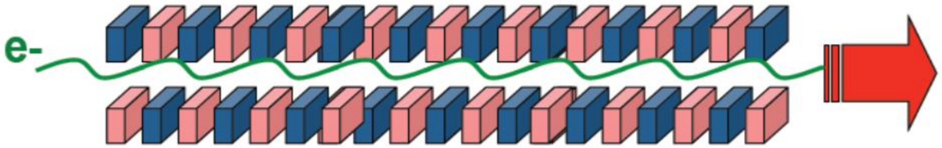
Wall Plug

Pulsed Power Modulator

RF Klystron



RF Electron Accelerator



"Stimulated Emission of Light in an Undulator"
IR, Optical or Xray Electron Decelerator

Unlike general lasers, such as solid-state lasers, gas-lasers, the working medium of FEL is 'free electrons', especially ultra-relativistic electron beam

Comparisons

Conventional Laser

Light amplification by Stimulated Emission of Radiation

Electrons in bound states – discrete energy levels

Waste heat in medium ejected at speed of Sound

→Limited tunability, Limited Power

Free Electron Laser

Light amplification by Synchronized Electron Retardation

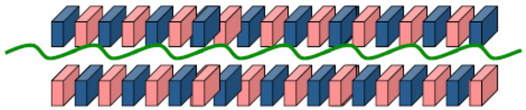
Electrons free – continuum of energy levels

Waste heat in electron beam ejected at speed of Light

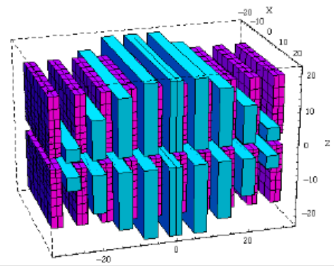
→Continuous tunability, High Power

Undulators

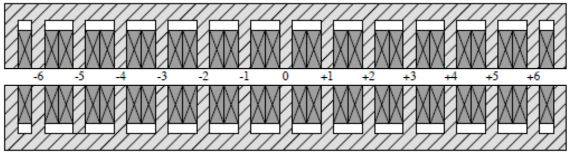
- Pure Permanent Magnet (PM)



- PM+ Metal Poles Hybrid



- Electromagnetic



Three types of undulators

- Pure SmCo5: $B_0[T] = -1.55\,\mathrm{Exp}[-\pi g/\lambda_u]$
- Hybrid: $B_0[T] = 0.95\,a\,\mathrm{Exp}[-g/\lambda_u(b - c\,g/\lambda_u)]$

where a, b and c are given in the table above for two types of materials when $0.07 \le g/\lambda_u \le 0.7$.

Parameter	SmCo5	NdFeB
a	3.33	3.44
b	5.47	5.08
C	1.8	1.54

Empirical formula for estimation of magnetic field

Undulator Strength Parameter, $K = 0.934\,\lambda_u\,[cm]\,B_0[T]$

When K » 1, it is named wiggler. Its radiation properties is different.

Ref: Undulator radiation, J.B.Murphy & J.Wu

Undulator radiation

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Radiation wavelength

$$\lambda = \lambda u\,(1 + K^2/2)/2\gamma^2$$

Linewidth

$$\frac{\Delta\lambda}{\lambda} = -2\frac{\Delta\gamma}{\gamma} + \frac{2K^2}{1+K^2}\frac{\Delta K}{K} + \frac{\gamma^2\theta_e^2}{1+K^2}$$

$\triangle\lambda/\lambda \approx 1/Nu$

Spectral distribution in forward direction

$$\frac{d^2I}{d\omega d\Omega} = \frac{e^2\omega^2K^2N_U^2}{c\omega_U^2\gamma^2}\sum_{n=-\infty}^{\infty}\left[J_n^2(s) + \left(\frac{\gamma\theta}{K} - \frac{n}{s}\right)^2 J_n^2(s)\right] \times \left(\frac{\sin\Delta_n(\theta)}{\Delta_n(\theta)}\right)^2$$

$$\frac{d^2I_n}{d\omega d\Omega} = r_e mcN_U^2\gamma^2\frac{K^2n^2}{(1+K^2/2)^2}F_n(K)\left(\frac{\sin\Delta_n}{\Delta_n}\right)^2$$

Radiation Power

$$\mathrm{P[W]} = 7.26\mathrm{E}^2[\mathrm{GeV}]\mathrm{I[Amp]NuK}^2/\lambda\mathrm{u[cm]}$$

Ref: The physics of x-ray free electron lasers, Review of modern physics

Principle of coherent radiation

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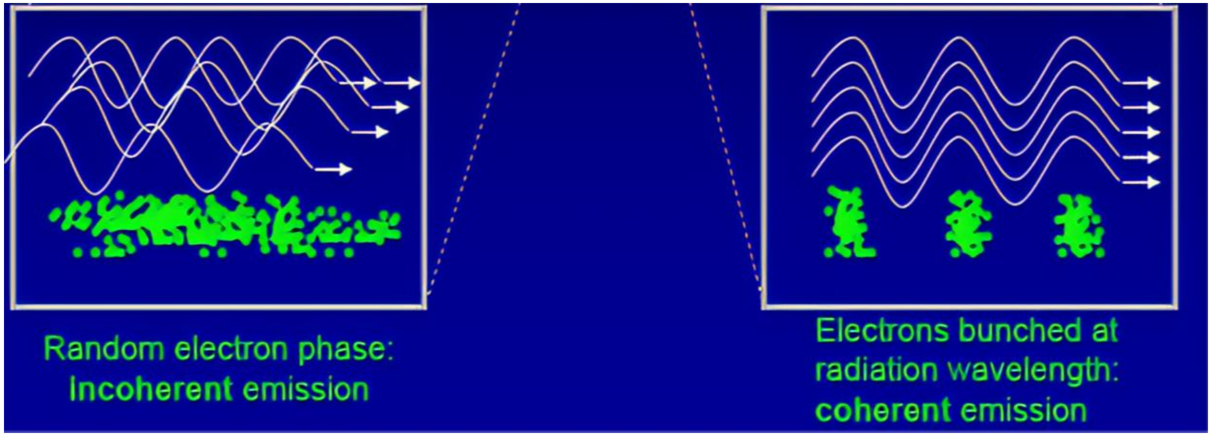
Total radiation

$$I_N \propto I_1 \left(N + \sum_{\substack{i=1 \\ i \neq j}}^{N} \sum_{j=1}^{N} \mathrm{Exp}\left[-i\vec{k} \cdot (\vec{r}_i - \vec{r}_j) \right] \right) = I_{Inc} + I_{Coh}$$

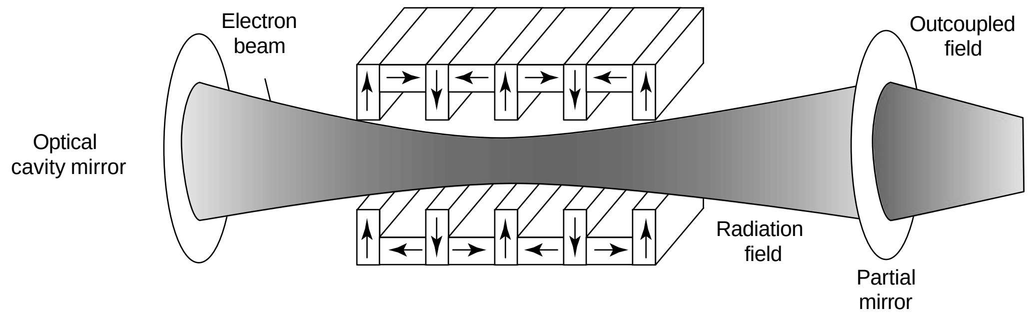


Bunching factor

$$B(\omega) = \frac{1}{N_e} \sum_{n=1}^{N_e} e^{-i\omega z_{0n}/c}$$

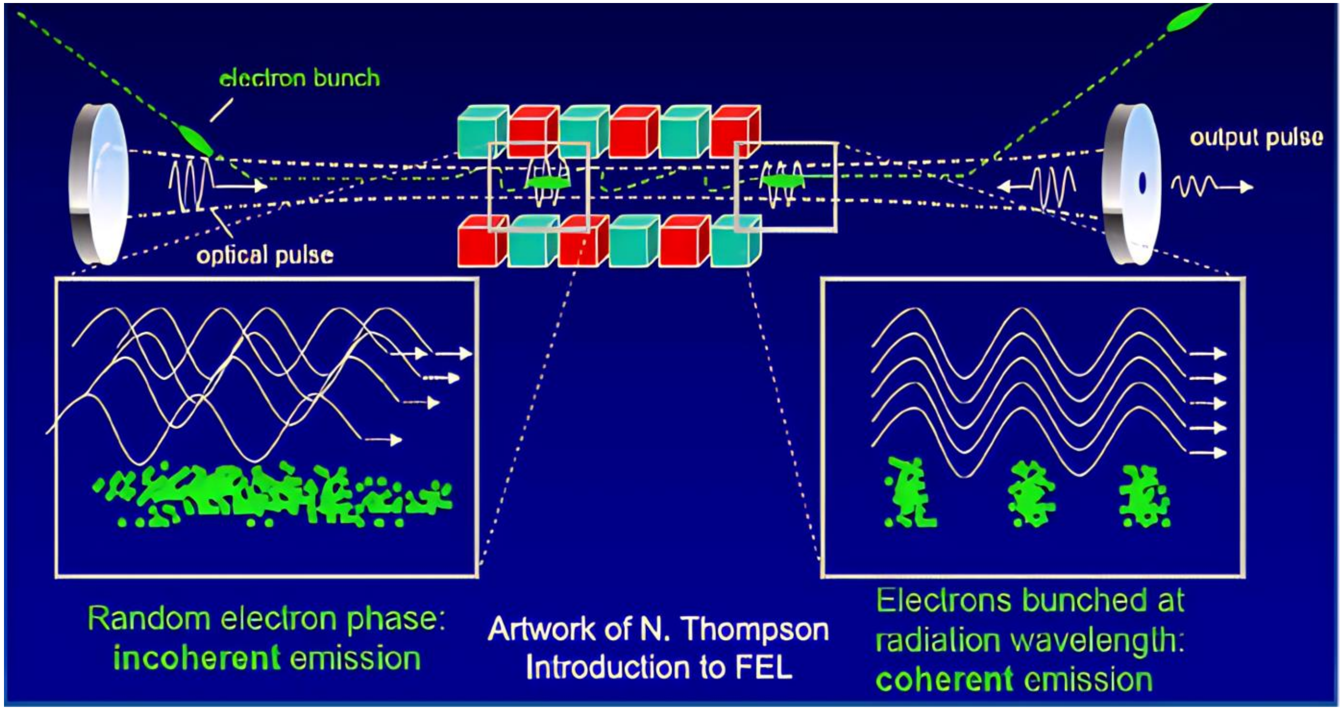
- The coherent radiation is very powerful when high charge bunch with effective bunching.
- Bunching process: Oscillator-FEL, SASE-FEL, Pre-bunched FEL

Review of oscillator THz-FEL



- Oscillator FEL uses a combination of low current electron beam and an optical cavity to trap the optical pulse in several passes through the undulator. Each pass involves a new electron bunch interaction with the optical field and undergoing microbunching at the end of the undulator.
- The optical intensity grows by a small amount (low gain) in each pass with an amplification factor of $1+g_{ss}$， g_{ss} is proportional to the cube of number of undulator period, N_w
- At high intensity, the electrons rotate in phase space and absorb light near the end of the undulator, and the large signal gain is reduced compared to g_{ss}. Saturation occurs when gain is equal to total cavity losses.
- Oscillator FEL's extraction efficiency is approximately one divided by $2.4N_w$.

Ref: Introduction to Free Electron Lasers, Neil Thompson



- FEL power builds up from noise to saturation in N passes inside an optical cavity.
- In the N_{th} pass, a fresh bunch of randomly distributed electrons interacts with the optical beam and develops microbunching with period λ

Small Signal Gain

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$$g_{ss} = \frac{2\pi N_w^3}{\gamma^3}\left(\frac{[JJ]a_w\lambda_w}{r_b}\right)^2\left(\frac{I}{I_A}\right)$$

$$\lambda = \lambda u\,(1 + K^2/2)/2\,\gamma^2$$

N_w, number of undulator periods,

γ , relative energy factor,

[JJ] reduction factor of FEL interaction in a planar undulator,

a_w, dimensionless undulator parameters,

λ_w, undulator period,

r_b, electron beam radius (usually smaller than optical beam)

I, peak beam current,

I_A, Alfven current, 17kA,

amplification factor $P_{out}/P_{in}=1+g_{ss}$

Small signal gain should be higher than total round trip losses.

With dimensionless FEL (Pierce) parameter

$$\rho = \frac{1}{2\gamma}\left(\frac{[JJ]a_w}{\sigma k_w}\right)^{\frac{2}{3}}\left(\frac{I}{I_A}\right)^{\frac{1}{3}}$$

The small signal gain can be rewritten as:

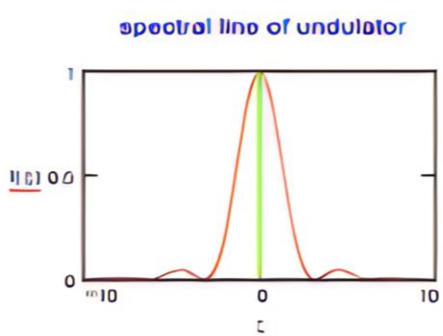
$$g_{ss} = 2(2\pi N_w \rho)^3$$

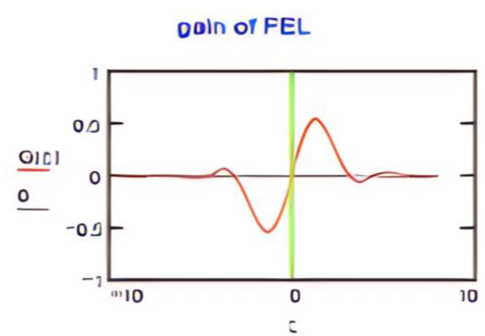
A_w and γ can be tuned to vary radiation wavelength

Madey Theory

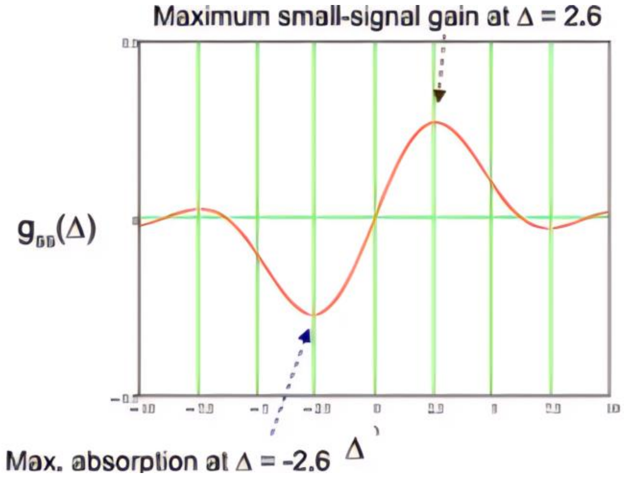
$$G(\xi)=-\frac{\pi e^2K^2N_w^3\lambda_w^2n_e}{4\varepsilon_0 m_e c^2\eta_r^3}\cdot\frac{d}{d\xi}\left(\frac{\sin^2\xi}{\xi^2}\right)\ with\ \xi=\pi N_b\frac{\omega-\omega_\ell}{\omega\ell}$$

- Madey theorem: the FEL gain curves is obtained by taking the negative derivative of the line-shape curve of undulator radiation
- Madey's theorem mainly reveals the internal **relationship between stimulated radiation and spontaneous radiation**
- The stimulated radiation gain is directly proportional to the derivative of the spontaneous radiation spectrum
- Energy conversion efficiency or gain





Maximum gain and efficiency

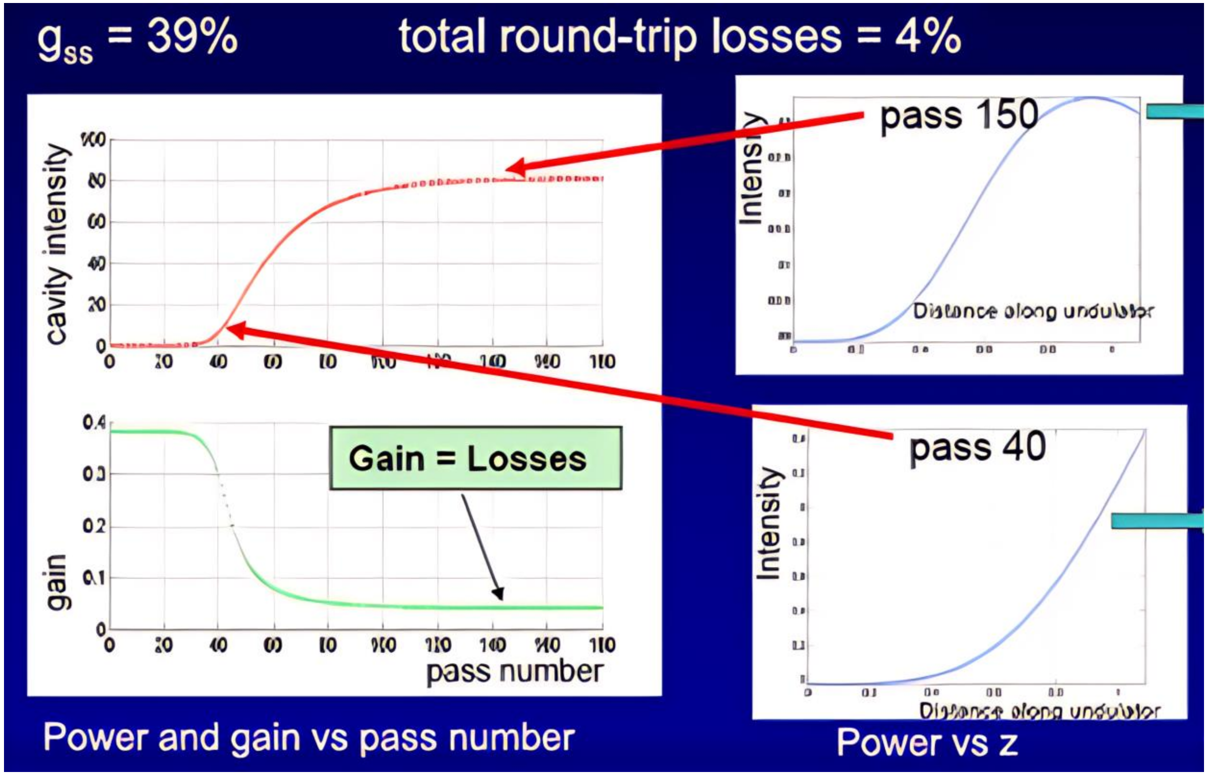


Energy detuning $\Delta = 4\pi N_{\mathrm{w}}\left(\frac{\Delta E}{E}\right) = 2\pi N_{\mathrm{w}}\left(\frac{\Delta\lambda}{\lambda}\right), \Delta_{max} = 2.6$

- For maximum gain, energy detuning (electron beam energy minus FEL resonance energy) should be slightly positive.
- Conversely, at a fixed beam energy, the lasing wavelength is longer than the resonance wavelength

Efficiency $\eta = \frac{P_{FEL}}{P_{c-b\,\mathrm{eam}}} = \frac{1}{2.4N_w}$

Typical power grow curves



As the optical intensity increase, the large signal gain decrease until FEL gain is equal to the total cavity losses and FEL power saturates.

At pass 50, intracavity power increases with z^3

At pass 150, the power at undulator exit is decreased due to over-bunching

Saturation

- For zero cavity loss, intensity would increase indefinitely
- In practice, several loss mechanisms: diffraction(especially for THz range), absorption, outcoupling
- Power loss is proportional to cavity intensity
- Finite extraction efficiency
- When gain is equals to cavity loss, no more growth, SATURATION

Outcoupling

Various methods for getting the light out of the cavity:

- hole in mirror, partially transmitting mirror, Brewster Plate, Scraper Mirror, …
- Hole in mirror is used in most cases.
- Broadband, simple; Outcoupling fraction changes with wavelength; mode distortion

$P_{out}=(1-R_{out})(1-A)P_{cav}$

Outcoupling R_{out} should be reasonable

Absorption A must be very low

Usually intracavity power is higher, $P_{out}/(1-R_{out})$

Resonator design

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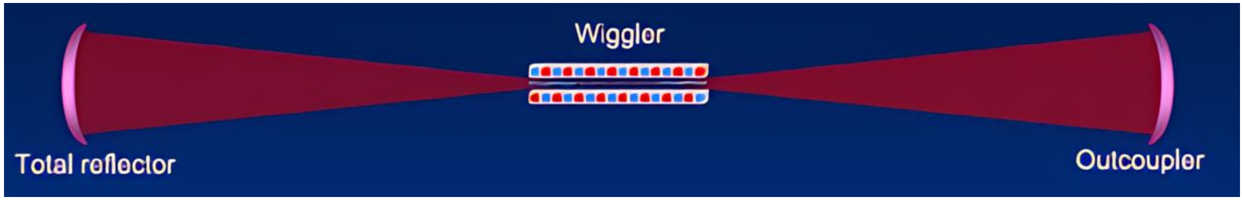
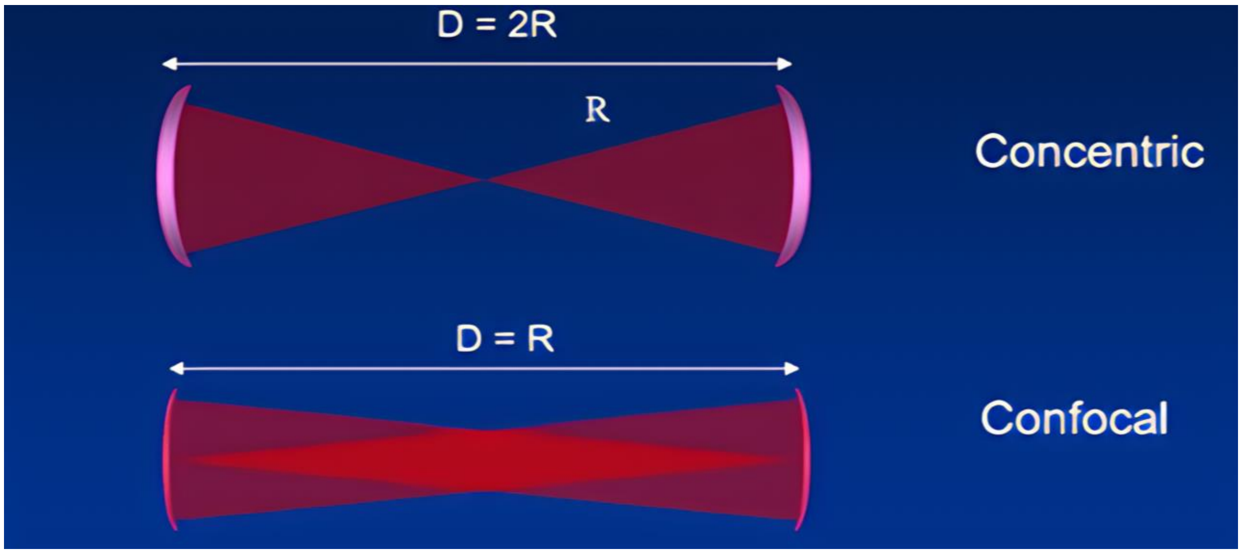
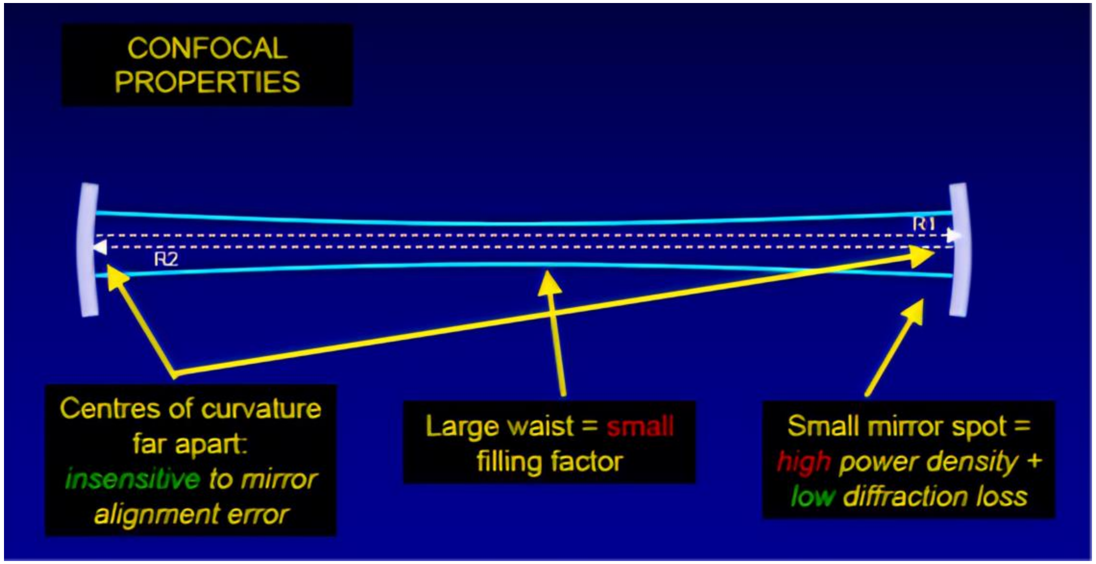
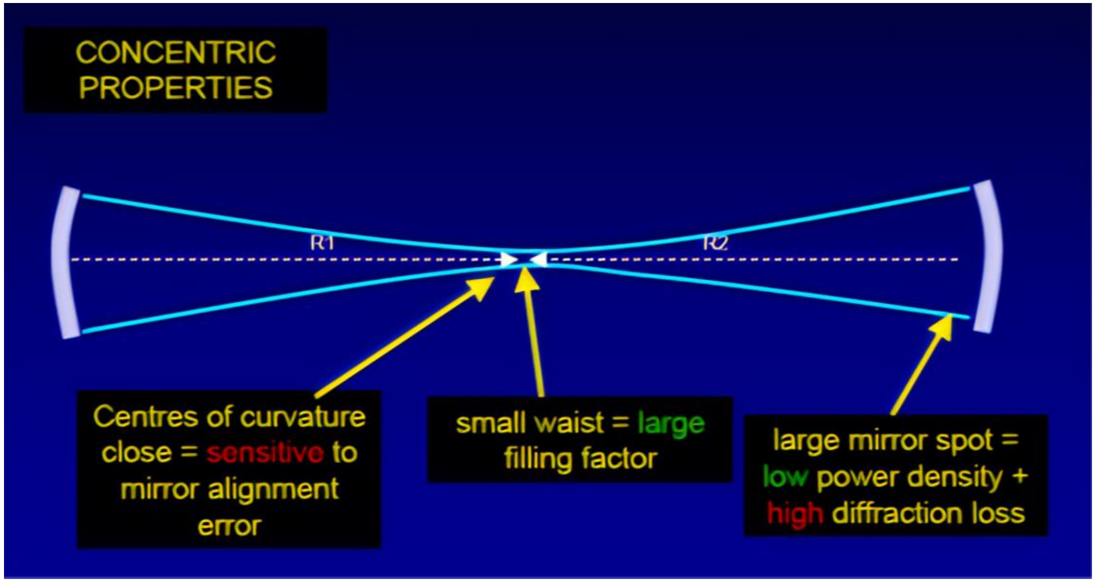




- The optical resonator consists of two concave mirrors with radii of curvatures R1 and R2. The mirrors are separated by a distance D
- Cavity length: the round-trip time should be matched with electron bunch separation, usually it is difficult to achieve small cavity length due to beamline elements
- Concentric and Confocal

Different properties





Concentric resonator is preferred, due to

- large spot size at mirrors small spot size at waist
- released thermal effects
- effective interaction between electron beams and optical fields

Stability

Analog to beam optics, the trace of round-trip transfer matrix M

$$|\mathrm{Trace}(M)| < 2$$

Stability condition

$$0 < g_1 g_2 < 1, g_1 = 1 - \frac{D}{R_1}, g_2 = 1 - \frac{D}{R_2}$$

For symmetric resonator

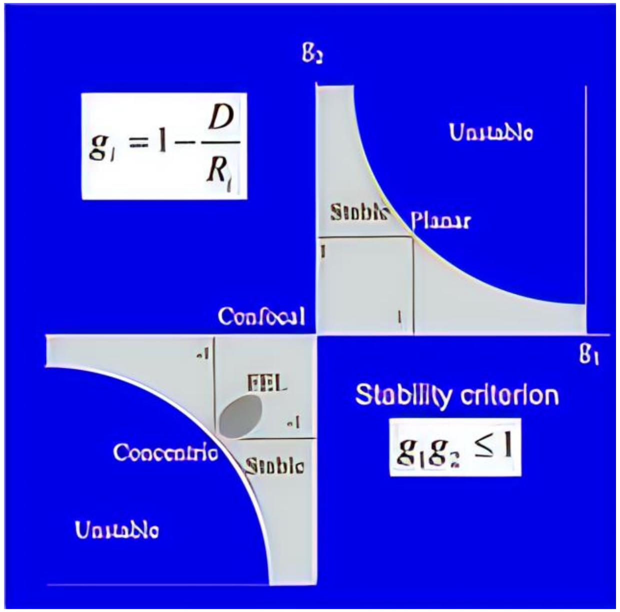
$$g_1 = g_2 = g$$

Rayleigh length

$$z_R = R\sqrt{\frac{1+g}{1-g}}$$

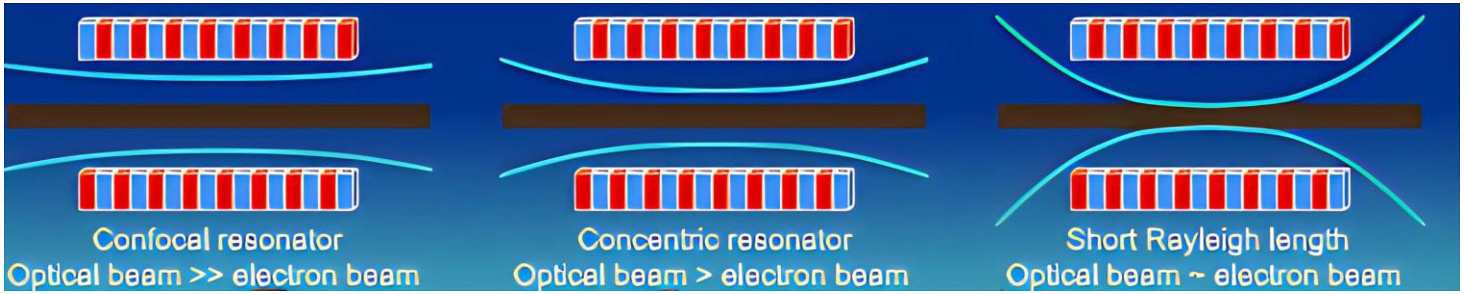
Gaussian mode area at waist

$$\Sigma_0 = D\lambda\sqrt{\frac{1+g}{4(1-g)}}$$



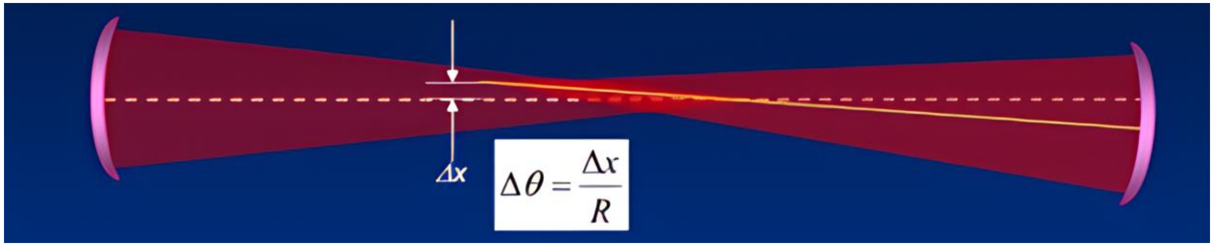
Optimized Rayleigh length

At undulator center	$\Sigma_0 \sim R\lambda\sqrt{\frac{1+g}{2}}$
At undulator exit	$\frac{\Sigma_w}{\Sigma_0} = 1 + \left(\frac{L_w}{2z_R}\right)^2$
At mirrors	$\frac{\Sigma_R}{\Sigma_0} = \frac{2}{1+g}$



- Optical mode diameters at the undulator entrance and exit should be smaller than aperture limitation of vacuum tube
- Effective interaction between electron beam and optical field through whole undulators

Angular sensitivity of near-concentric resonators



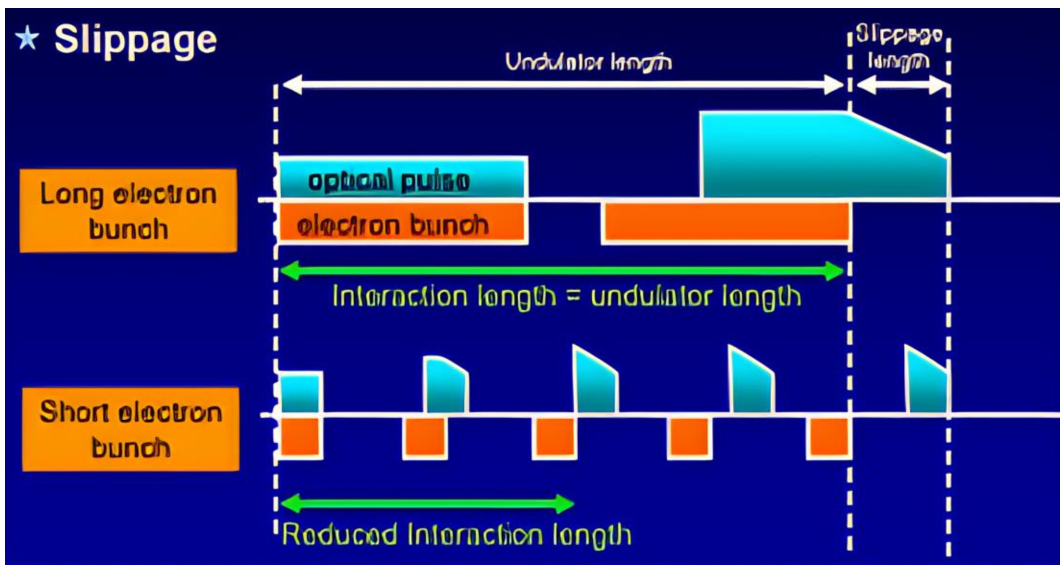
Angular sensitivity for symmetric resonator

$$\Delta\theta = \sqrt{\frac{\lambda}{\pi D}(1-g)^{\frac{1}{4}}(1+g)^{\frac{3}{4}}} \qquad \Delta\theta \approx \sqrt{\frac{\sqrt{2}\lambda}{\pi D}x^{\frac{3}{4}}}$$

For THz range, it is not particularly demanding requirements (~μrads)

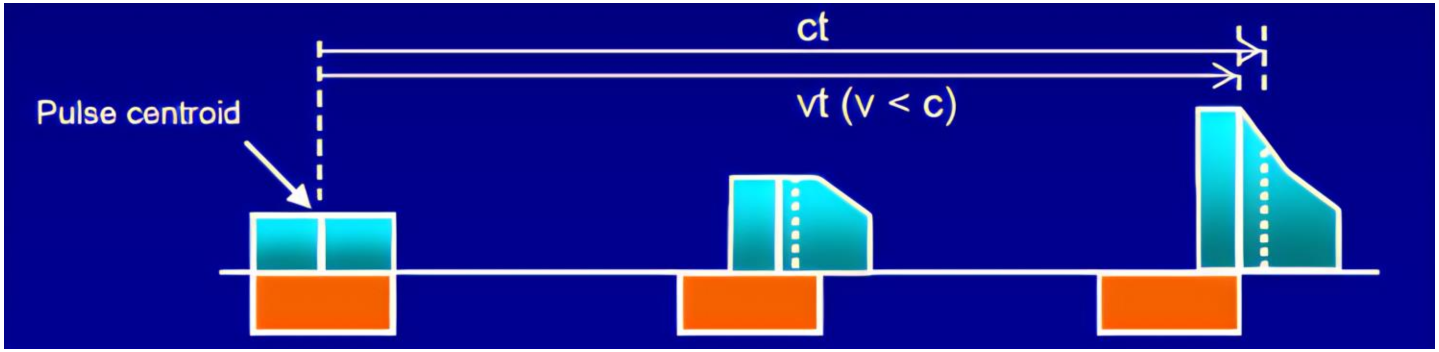
Un-desired effects: Slippage

- Resonance condition: electrons slip back by one radiation wavelength per undulator period
- Slippage per undulator traverse = N_u times wavelength, $N_u*\lambda$ is slippage length
- For **short electron bunch** or **long wavelength**, slippage length ~ bunch length, will results in effective interaction length reduced and gain degraded.



Un-desired effects: Lethargy

The electrons slip back over the optical pulse, bunching increases, the maximum emission occurs at the end of undulator where bunching is strongest.
Optical pulse peaks at rear and centroid of pulse has velocity < c, synchronism between pulses and electron bunch on next pass is not perfect



Lethargy can be reduced by cavity length detuning
But as intensity increase, the back of pulse saturates first, then rest of pulse saturates, returning centroid velocity to c
Different detuning is necessary for gain optimization and power optimization

Other effects: beam emittance, beam energy spread,…

Parameters optimization

- Electron beam parameters: energy, peak current, emittance, energy spread, bunch length
- Undulator parameters: K, number of period, period length
- Resonator parameters: length, mirror radius of curvature

- Considering : resonance condition, small signal gain, beam quality, slippage and lethargy

- Usually, a long enough undulator to allow sufficient interaction
- A good peak current and tightly focused electron beam to provide high charge density
- A small optical cross section to provide high E field
- Slippage and lethargy should pay attentions for THz-FEL

- Simulation code (for example, Genesis+OPC) and Intelligence algorithms can be used to make complex parameter optimization.

Taper undulator, zero slippage waveguide, desynchronization of cavity length… can be used to improve THz-FEL performance

Review of high gain THz-FEL

Self-Amplified Spontaneous Emission

- SASE FEL uses a combination of high current electron beam and a long undulator to reach saturation in a single pass.
- SASE starts up from the random positions of electrons in the bunch, i.e. noise.
- The initial interaction is linear, that is electrons outside the separatrix interaction with the optical field become bunched and amplify the optical field.
- SASE power grows exponentially(exponential gain) along the undulator with the power gain length.
- At higher intensity, the electrons becomes nonlinear. Saturation occurs when the over-bunched electrons at the bottom at the bucket rotate upward. SASE extraction efficiency is approximately the same as the gain coefficient ρ.
- SASE FEL is fully coherent transversely and only partially coherent longitudinally.
- Shot-to-shot energy fluctuations are large in the exponential gain region.

Ref. Linac-based Free Electron Lases, JOTG Rossbach

SASE physics summary

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FEL parameter	$\rho = \{(a_u/4\gamma)(\Omega_P/\omega_u)JJ\}^{2/3}$
	where $\omega_u = 2\pi c/\lambda_u, \Omega_P =$ *beam plasma frequency*
Power gain length (Exponential growth rate)	$L_G = \lambda_H/2\pi\rho$
Saturation power	$P \sim \rho I_{beam} E$
Undulator saturation length	$L_{sat} \sim 10L_G \sim \lambda_W/\rho$
Line width	$\sim 1/N_W \sim \rho$
Cooperation length	$L_c = \lambda_r/4\pi\rho$
Number of spikes	$M = L_{bunch}/2\pi L_c$

Three dimensional effects

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M.Xie's parameterization is used to calculate 3D gain length, based on the 1D gain length results.
The result is longer than 1D gain length due 3D effects.

$$L_{3D} = L_{1D}(1 + \Lambda)$$

$$\Lambda = 0.45\eta_d^{0.57} + 0.55\eta_\varepsilon^{1.6} + 3\eta_\gamma^2 + 0.35\eta_\varepsilon^{2.9}\eta_\gamma^{2.4} + 51\eta_d^{0.95}\eta_\gamma^3 + 0.62\eta_d^{0.99}\eta_\varepsilon^{1.1} + 5.3\eta_d^{0.76}\eta_\varepsilon^{2.3}\eta_\gamma^{2.7} + 120\eta_d^{2.1}\eta_\varepsilon^{2.9}\eta_\gamma^{2.8} + 3.7\eta_d^{0.43}\eta_\varepsilon\eta_\gamma$$

Diffraction

$$\eta_d = \frac{L_{1D}}{Z_R}$$

Emittance

$$\eta_\varepsilon = \left(\frac{L_{1D}4\pi}{\beta_b\gamma\lambda}\right)\varepsilon_n$$

Energy spread

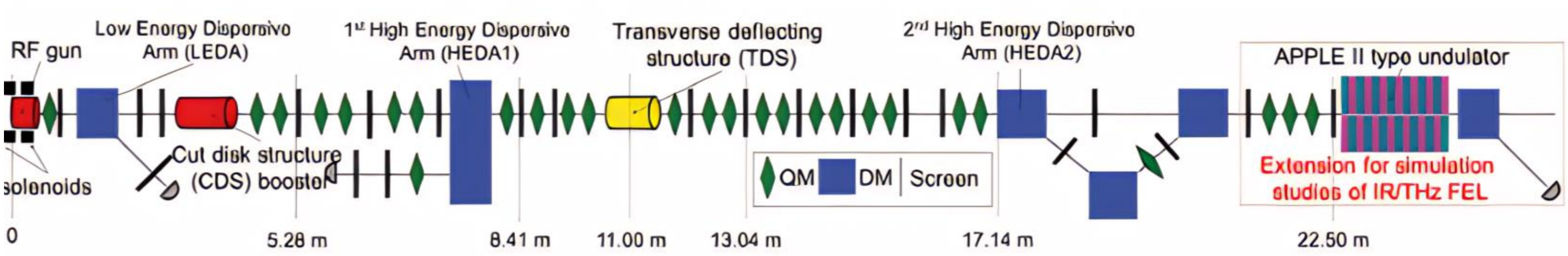
$$\eta_\gamma = \left(\frac{L_{1D}4\pi}{\lambda_w}\right)\frac{\delta\gamma}{\gamma}$$

Beam quality

$$\varepsilon \le \frac{\lambda}{4\pi} \qquad \sigma_E/E < \rho$$

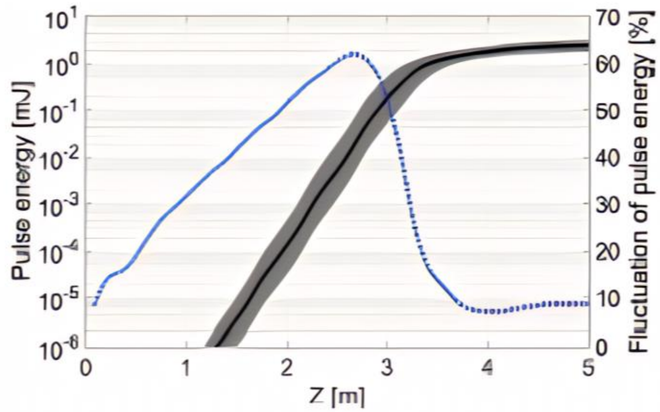
PITZ: SASE THz FEL

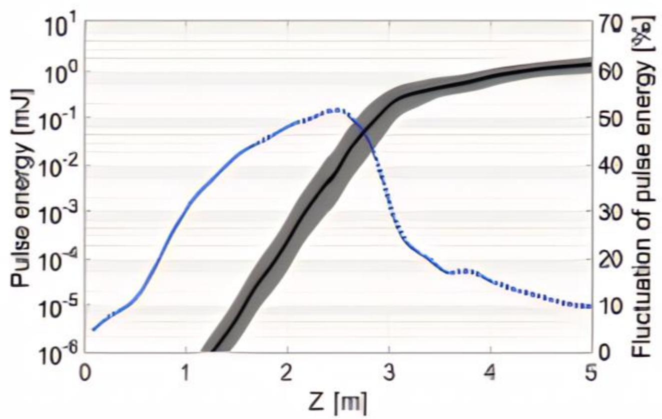
The Photo Injector Test facility at DESY, Zeuthen site
High brightness electron sources for linac-based FEL
Prototype demonstration for pump-probe experiments at the European XFEL.

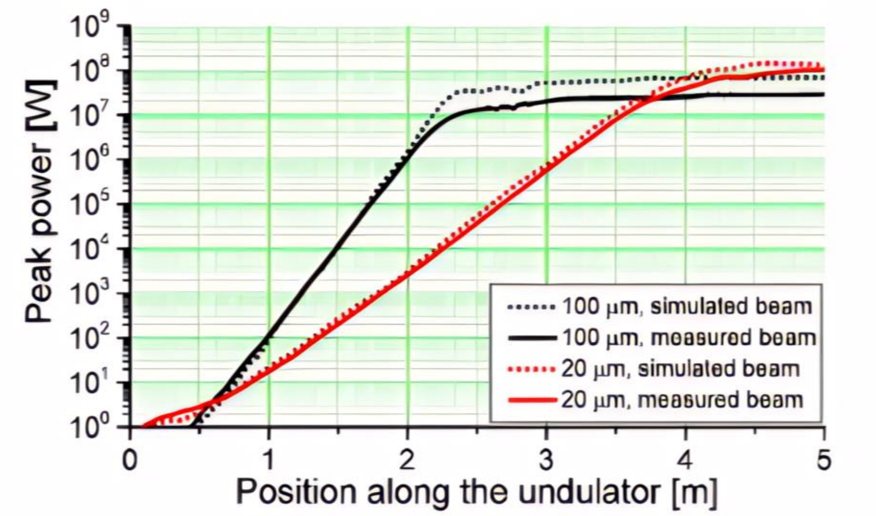


Parameter	Sim.5	Meas.
Bunch charge [nC]	4.0	4.0
Average momentum [MeV/c]	15.1	15.2
Momentum spread [keV/c]	134.7	50.9
Average slice momentum spread [keV/c]	6.2	28.5
Projected &n,x[um]	7.9	7.1
Projected &n,y [um]	7.6	11.1
Average slice &n,x [um]	3.1	10.9
Average slice &n.y[um]	3.1	-
Peak current [A]	195	183
Bunch length [mm]	2.0	3.0

PITZ: SASE THz FEL

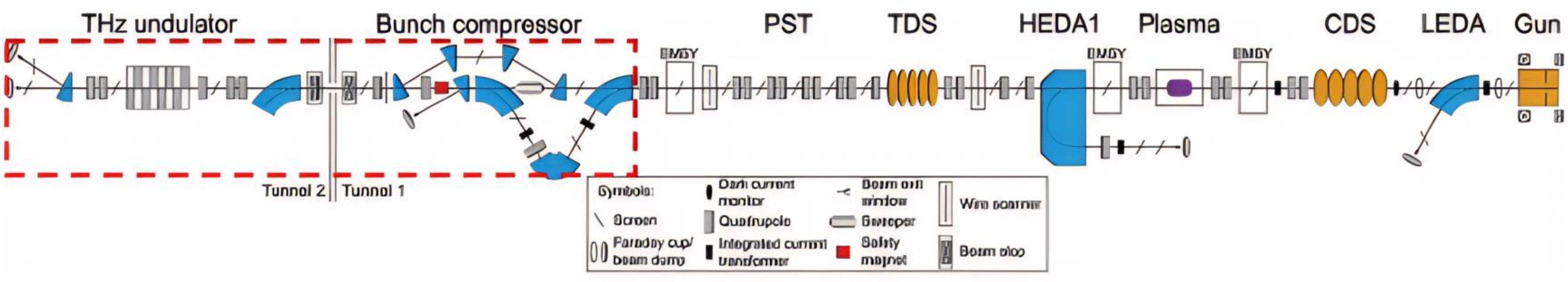






	Psat [MW]	Lsat[m]	Esat[p]]
100 um, sim.beam	67	3.74	650
100 um, meas.beam	29	4.16	390
20 um, sim.beam	143	4.60	570
20 um, meas.beam	101	4.92	480

PITZ: SASE THz FEL



- Purpose: tunable THz source prototype for pump-probe experiments at the European XFEL.
- The first lasing at a center wavelength of 100 μm was observed in the summer of 2022.
- The lasing of the narrowband THz source was achieved using an electron beam with an energy of ~17 MeV and a bunch charge up to several nC.
- Optimization of beam transport and matching resulted in the measurement of THz radiation with a pulse energy of tens of μJ, measured with pyroelectric detectors.

Ref: PITZ team, Commissioning status of the THz FEL at PITZ, Simulation and experiments on THz FEL at PITZ, THz SASEFEL based on high brightness photo injector PITZ: lasing at a wavelength of 100 um,…

Review of pre-bunched THz-FEL

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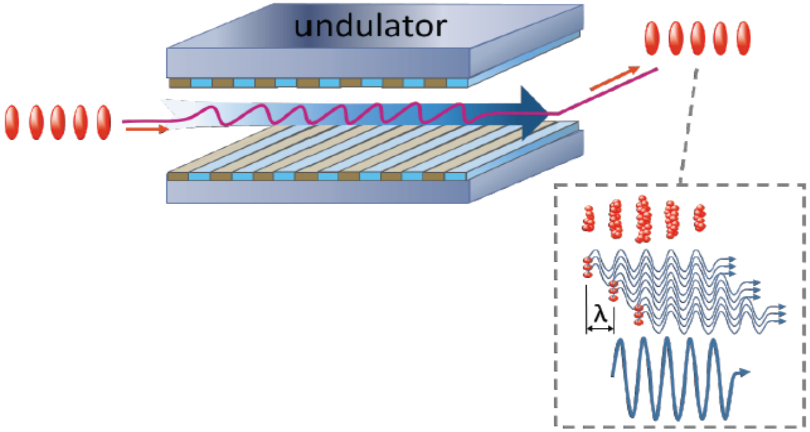
- Unlike Oscillator FEL and SASE FEL, where the micro-bunch structures were formed in radiation process due to interaction between electron beam and optical field, the micro-bunch structures were preformed before entrance to radiators by artificial methods. The THz frequency information in micro-bunches will enhance coherent THz radiation significantly.
- **Without optical cavity**
- **Short undulator**
- More preferred to compact THz sources



Example: Comb-like lasers

Coherent radiation power

$$\left(\frac{d^2W}{d\omega d\Omega}\right)_N = N_e^2 B_f^2(\omega)\left(\frac{d^2W}{d\omega d\Omega}\right)_1$$

Form factor for Gaussian bunch

$$b(f) = \exp[-(2\pi f\sigma_z)^2/2]$$

Bunch trains produced by comb laser

$$I_e(t) = I_0 e^{-t^2/(2\sigma_M^2)} \sum_{m=-\infty}^{\infty} e^{-(t-2m\pi/\omega_b)^2/(2\sigma_\mu^2)}$$

Bunching factor

$$B_f(\omega) = \frac{\sum_{m=-\infty}^{\infty} e^{-m^2\sigma_\mu^2\omega_b^2/2} \times e^{-\sigma_M^2(\omega-m\omega_b)^2/2}}{\sum_{m=-\infty}^{\infty} e^{-m^2(\sigma_\mu^2+\sigma_M^2)\omega_b^2/2}}$$

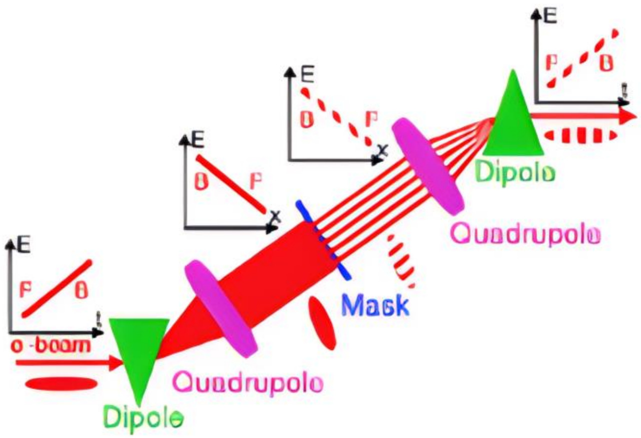
Radiation from helical undulator

$$\left(\frac{d^2W}{d\omega d\Omega}\right)_1 = \frac{e^2N_u^2\gamma^2}{2\pi}\eta\frac{a_u^2}{(1+a_u^2+\gamma^2\theta^2)^2} \times \left\{\frac{\sin[N_u\pi(\omega/\omega_r-1)]}{N_u\pi(\omega/\omega_r-1)}\right\}^2,$$

Ref: Desktop megawatt super radiant free-electron laser at terahertz frequencies, Applied physics letters

Methods of bunch train production

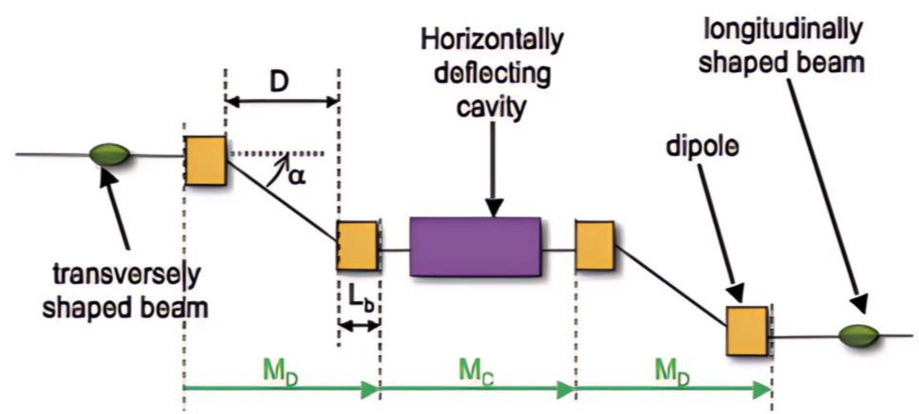
Transformation of transverse space modulation to longitudinal density modulation



Electron bunch with linear E-t correction
In the middle of dispersion section, electron transverse position are correlated with energy, then with longitudinal position. A multiple slit is used to produce transverse modulated electron bunch. At the exit of dispersion section, the longitudinal density modulated is produced.

$$z = -\frac{\xi}{\eta}x_0 - \frac{L\xi - \eta^2}{\eta}x_0' \qquad \delta = -\frac{1}{\eta}x_0 - \frac{L}{\eta}x_0',$$

Entrance of dispersion section: transversely shaped electron bunch
Middle of dispersion section: deflecting cavity, different kick at different longitudinal position
Exit of dispersion section: longitudinal density modulation electron bunch



Ref: Tunable sub-picosecond electron bunch train generation using a transverse to longitudinal phase space exchange technique, PRL

Direct modulation on photocathode

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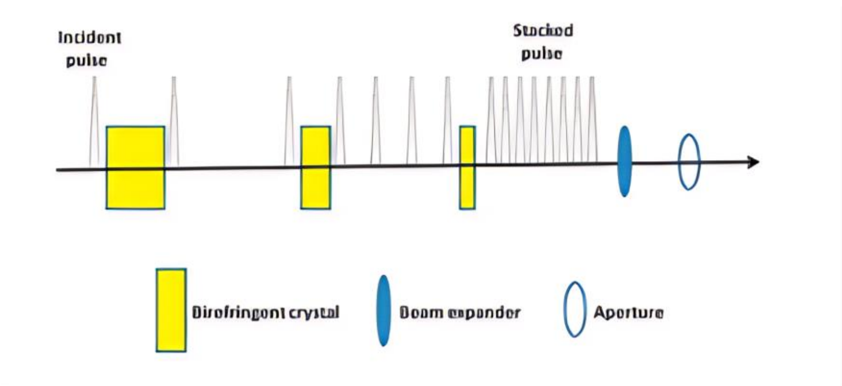
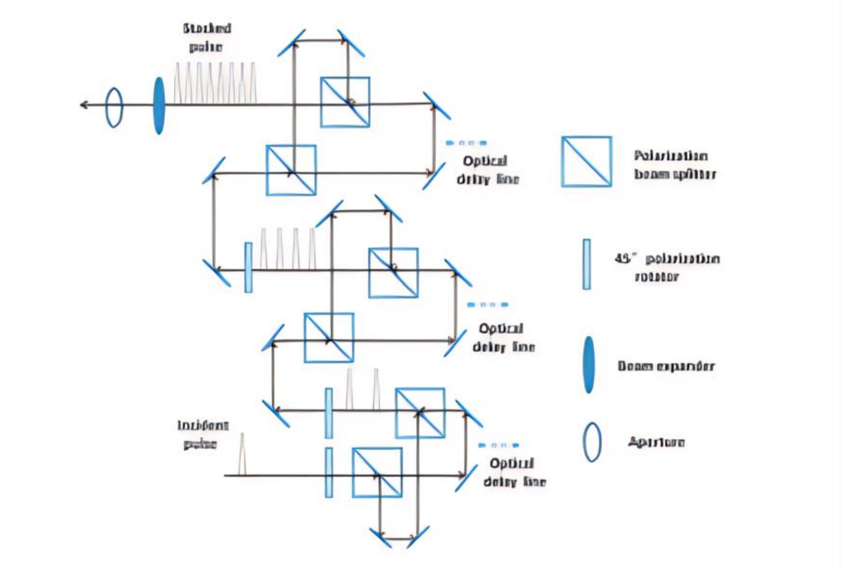
Pulse stacking method

- Using α-BBO crystal with different thickness. The optical axis is parallel to the crystal surface and perpendicular/parallel to the incident surface: the o-light and e-light have the same direction but different velocities,
- Using polarizing beam splitter plus delay loop



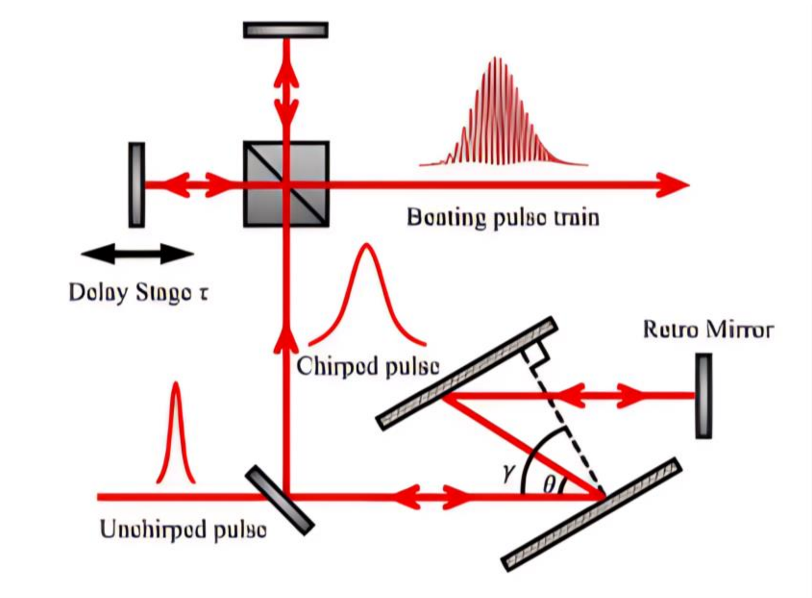


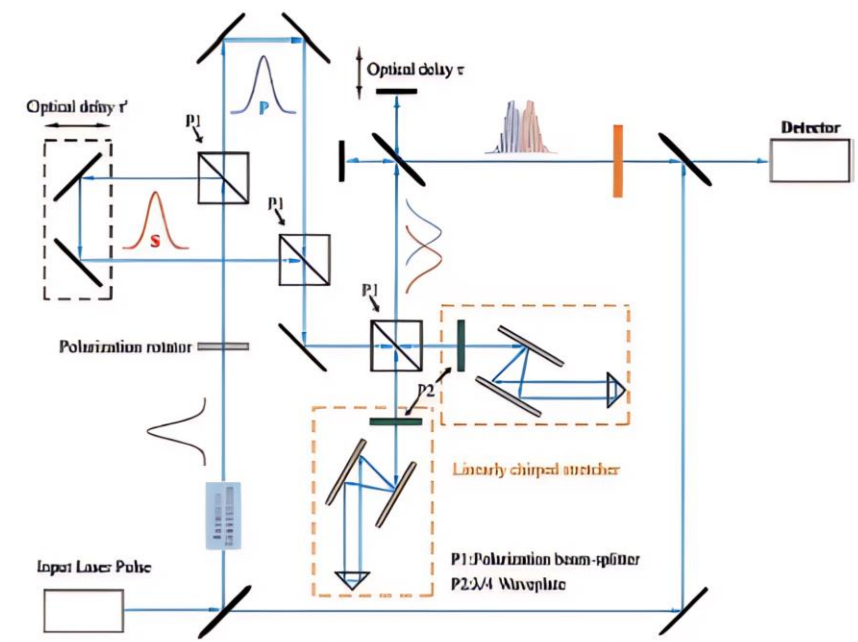
Ref: Generation of pre-bunched electron beams in photocathode RF gun for THz-FEL super-radiation, NIMA

Direct modulation on photocathode

Laser pulse beating technology

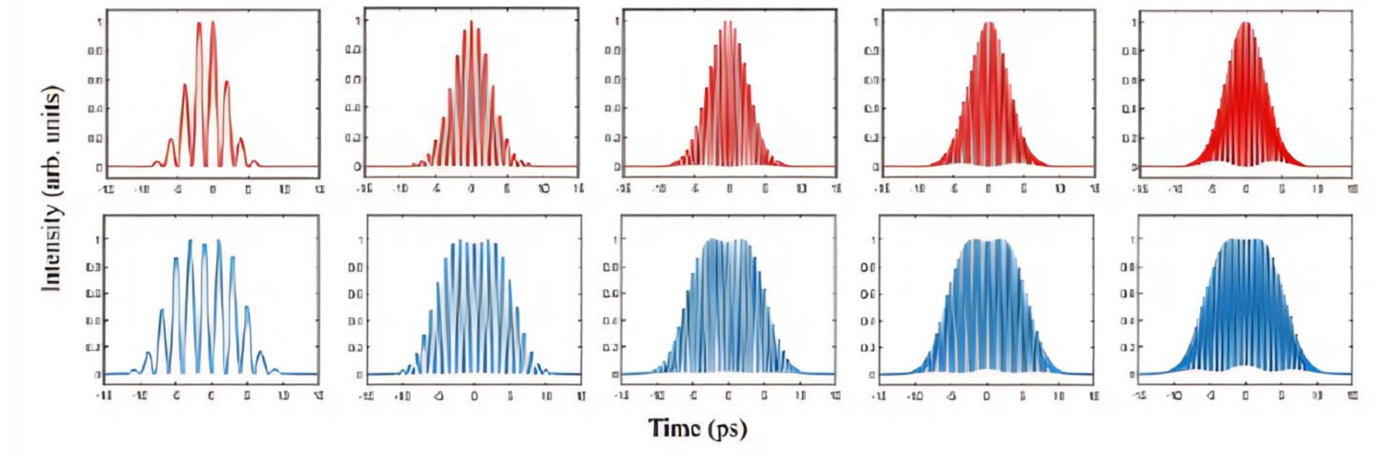
- ➢ Chirped laser pulse beating plus delay loop
- ➢ Double chirped laser pulse beating plus delay loop

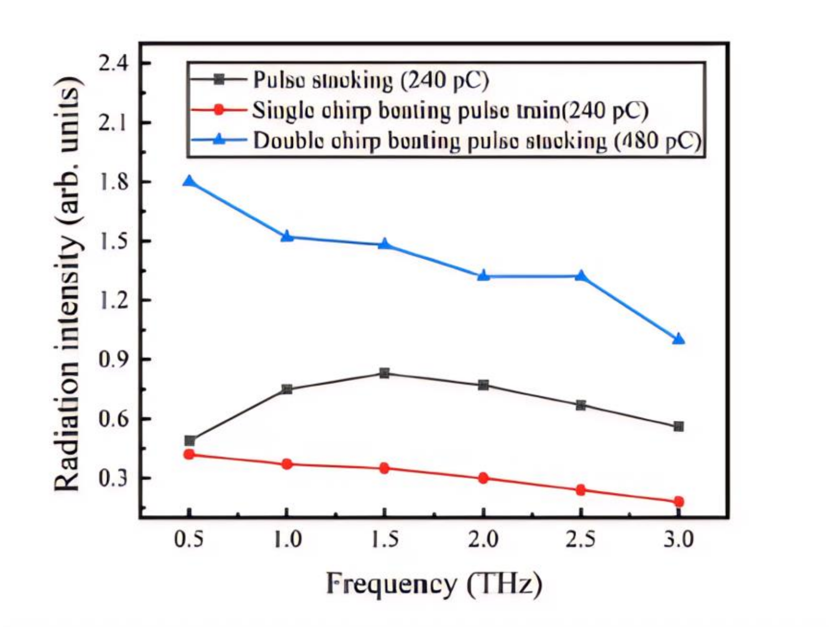




Ref: Pre-bunched Terahertz Coherent Radiation Source Based on Photocathode RF Gun, Wang Wenxing

Comparison with other methods





Two color THz pulses

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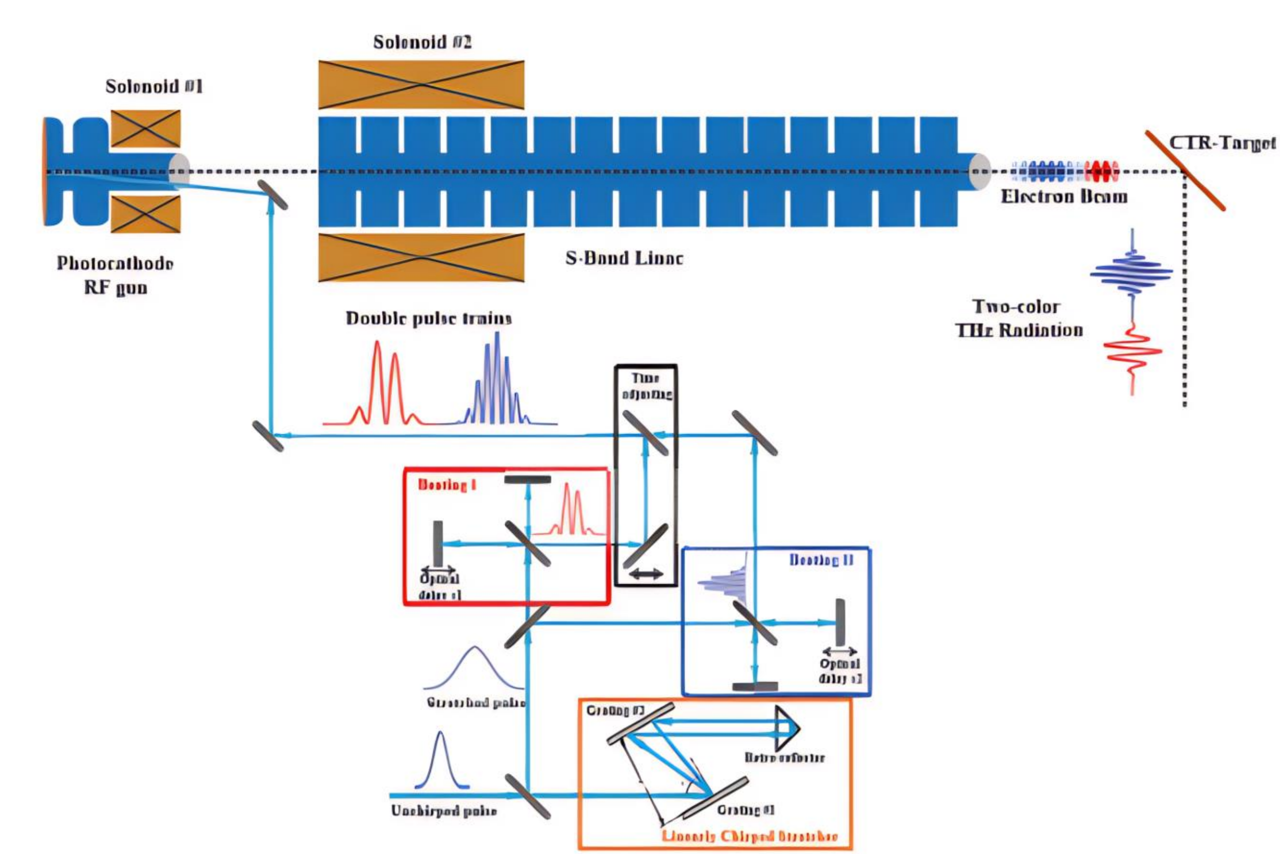
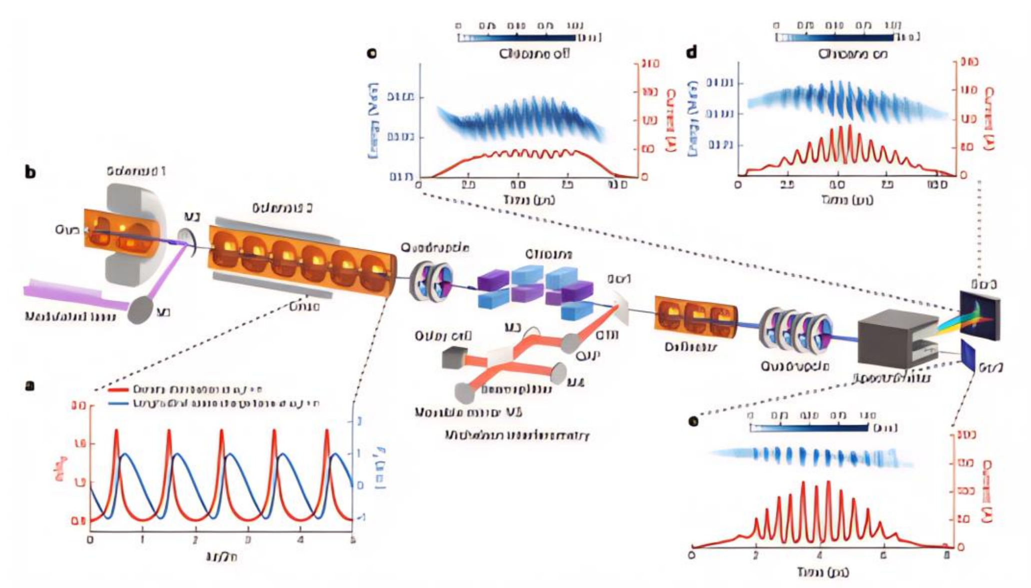


Ref: Generation of two Terahertz radiation pulses with continuously tunable frequency and time delay, IPAC2019

Improvement of tunability



Parameter	Value	Unit
Beam charge	200	PC
Beam energy	27-34	MeV
Bunching tunability	1-10	THz
Measured bunching factor	0.15-0.35	
Measured bunching bandwidth	-9.3%	

Using α-BBO crystal to produce electron bunch train with fixed bunch separation, then using tunable energy chirp along electron bunch and dispersion section to adjust the separation of bunch trains, finally the central frequency of THz radiation is tunable

Ref: Widely tunable electron bunch trains for the generation of high power narrowband 1-10THz radiation, Nature Photonics

THz wave from laser-modulated electron beam

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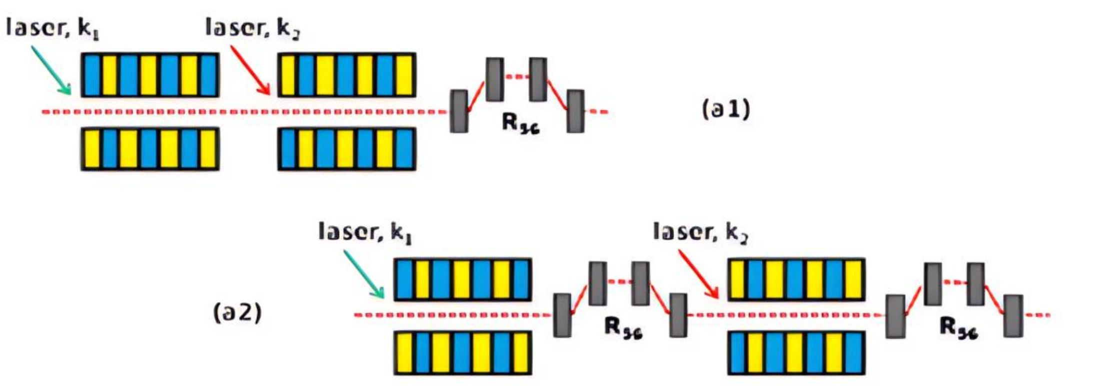
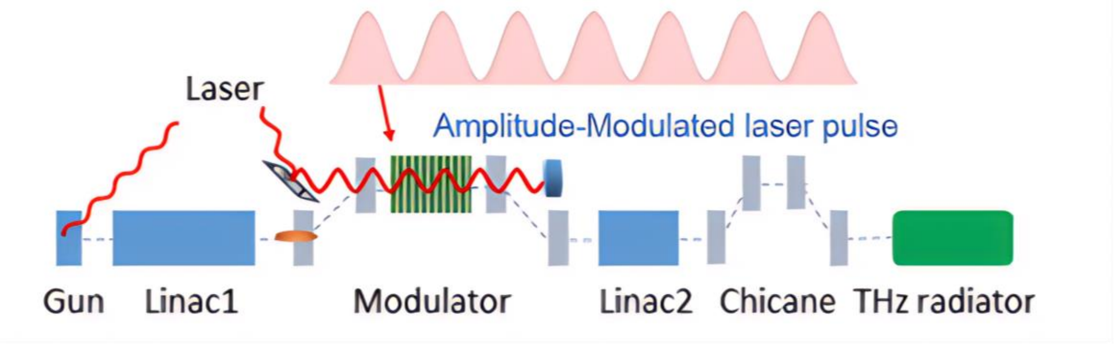
- Energy modulation is produced in modulator with a strong lasers or other methods (wakefield, plasmas).
- Then converts to density modulation after passing dispersion section with carefully optimized R_{56} and electron bunch train were formed.
- The coherent radiation is radiated when it passes the undulators.



Several schemes for density modulated electron beam production

Ref: Enhanced tunable narrow-band THz emission from laser-modulated electron beams, PRAB
Continuously tunable narrowband pulses in the THz gap from laser-modulated electron bunches in a storage ring, PRAB
Echo-enabled tunable terahertz radiation generation with a laser modulated relativistic electron beam, PRAB

Numerical example



The final bunching frequency is determined by initial modulation frequency and beam compression factor

$$|k_1 R_{56} \bar{\sigma}| \approx 1.75$$

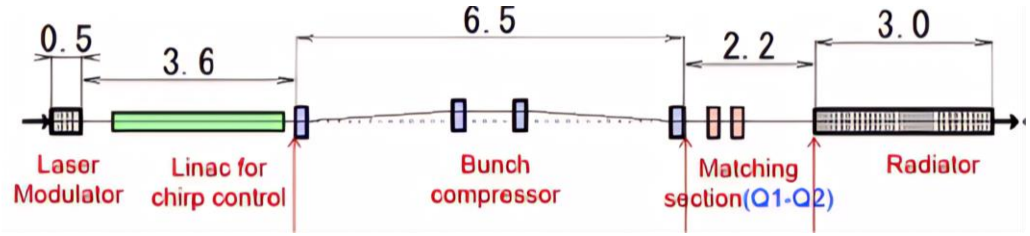
Keeping above optimum condition, energy chirp controlled by linac and laser power are used to control compression factor and obtain target bunching frequency.

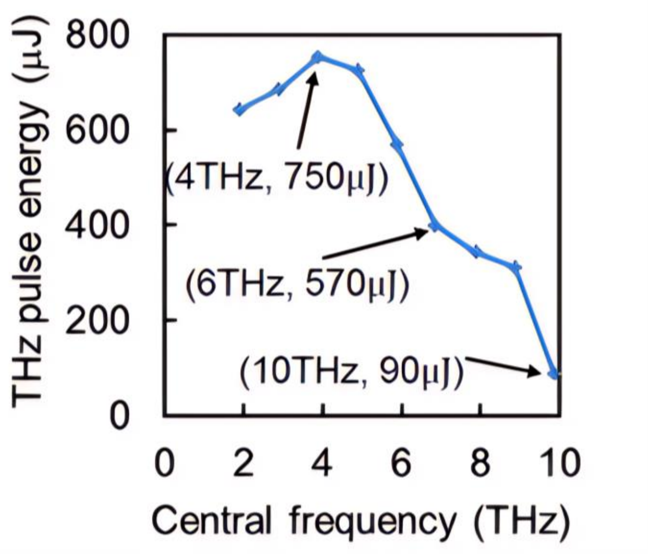
Ref: Generation of high power, tunable Terahertz radiation from laser interaction with a relativistic electron beam, Zhen Zhang and Zhirong Huang, IPAC2018

Compact accelerator, ~ 50MeV; Modulated laser, 800 nm

Laser- electron interaction through 3rf harmonic(for a planar undulator with fundamental resonant wavelength 2.4um)

E-beam charge	1 nC
Beam energy	50 MeV
RMS beam size	0.2 mm
Bunch length (flattop)	10 ps
Modulator	
Undulator period	2.5 cm
Peak field/ K value	0.56 T /1.29
Undulator length/period	0.25 m / 10
Laser wavelength	800 nm
Laser RMS spot size	0.5 mm
Laser stacking separation	0.5 ps (2 THz)
Laser peak power	100 MW

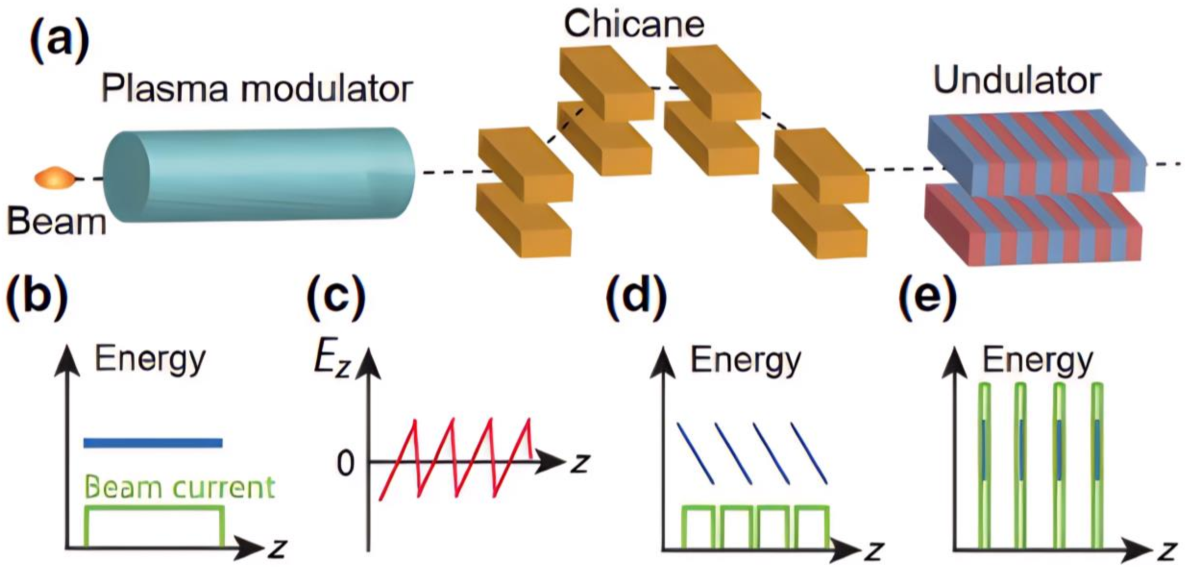




$\lambda_w = 10cm \quad N_w = 30$
$Q = 1nC \quad I = 100A \quad E = 50MeV$
$P_L = 100MW$

- Relatively low beam energy, moderate requirements on lasers and electron beam, more compact layout
- High THz pulse energy, good tunability

Energy modulation from wake



Proposal: passing through plasma and interacting with self-excited nonlinear plasma wake, beam gains ‘sawtooth’ energy modulation. After dispersion section, it is converted in density modulation.
High bunching factor

Ref: Generation of tunable 10-mJ-level Terahertz pulses through nonlinear plasma wakefield modulation, Physical Review Applied

Brief summary

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- The accelerator-driven THz Free Electron Laser has been developed rapidly with its **excellent frequency coverage and tuning capabilities, excellent peak power and average power**
- The development of accelerator technology and the improvement of accelerator performance have promoted the performance improvement of THz Free Electron Laser , such as high average power and miniaturization.
- The development of the THz Free Electron Laser principle, in addition to the classic low-gain oscillator THz-FEL, SASE type high-gain THz-FEL, pre-bunched THz-FEL (including direct laser modulation on the photocathode, electron beam density modulation converting from energy modulation from laser), seeded THz-FEL amplifier,…

- But, in most cases, due to scale and cost, THz-FEL is used as a laboratory-scale instrument rather than a desktop instrument like traditional lasers

Outline

FELiChEM: Specialized facility for Energy chemistry

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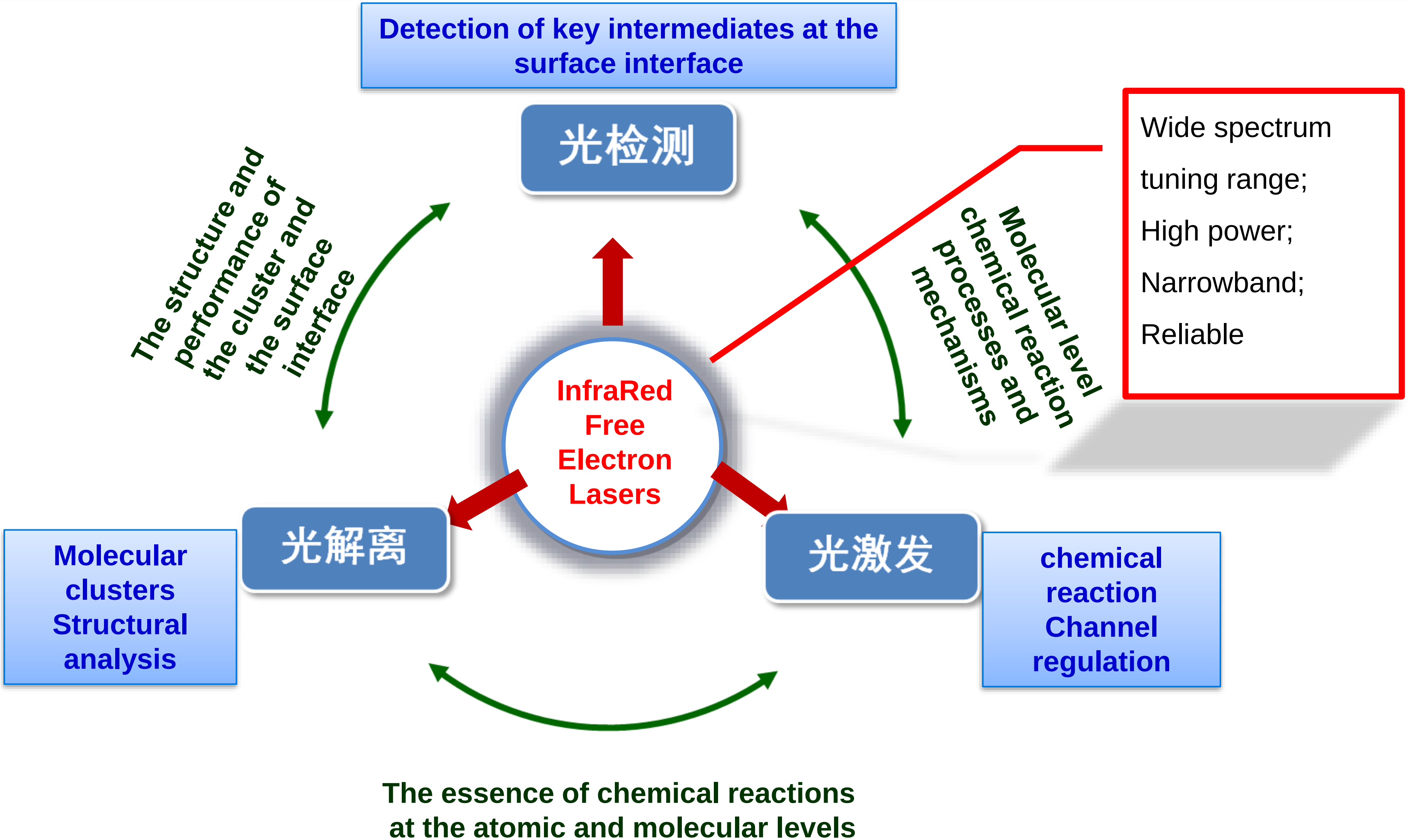

IRFEL: light source of FELiChEM

Major scientific instrument projects of the
National Natural Science Foundation of China

Requirements for IRFEL

- Spectral range: mid infrared to THz, 120-1.5THz/ 2.5um-200um
- High power for macro bunch and micro bunch
- repetition frequency of micro bunch is adjustable, 238,119,59.5MHz
- In existing shielded tunnels …

Experimental station:

- Photo dissociation-high pulse energy
- Photo excitation-high pulse energy
- Photo detection- stability, tuning ability, synchronization, bandwidth

The 3D drawing

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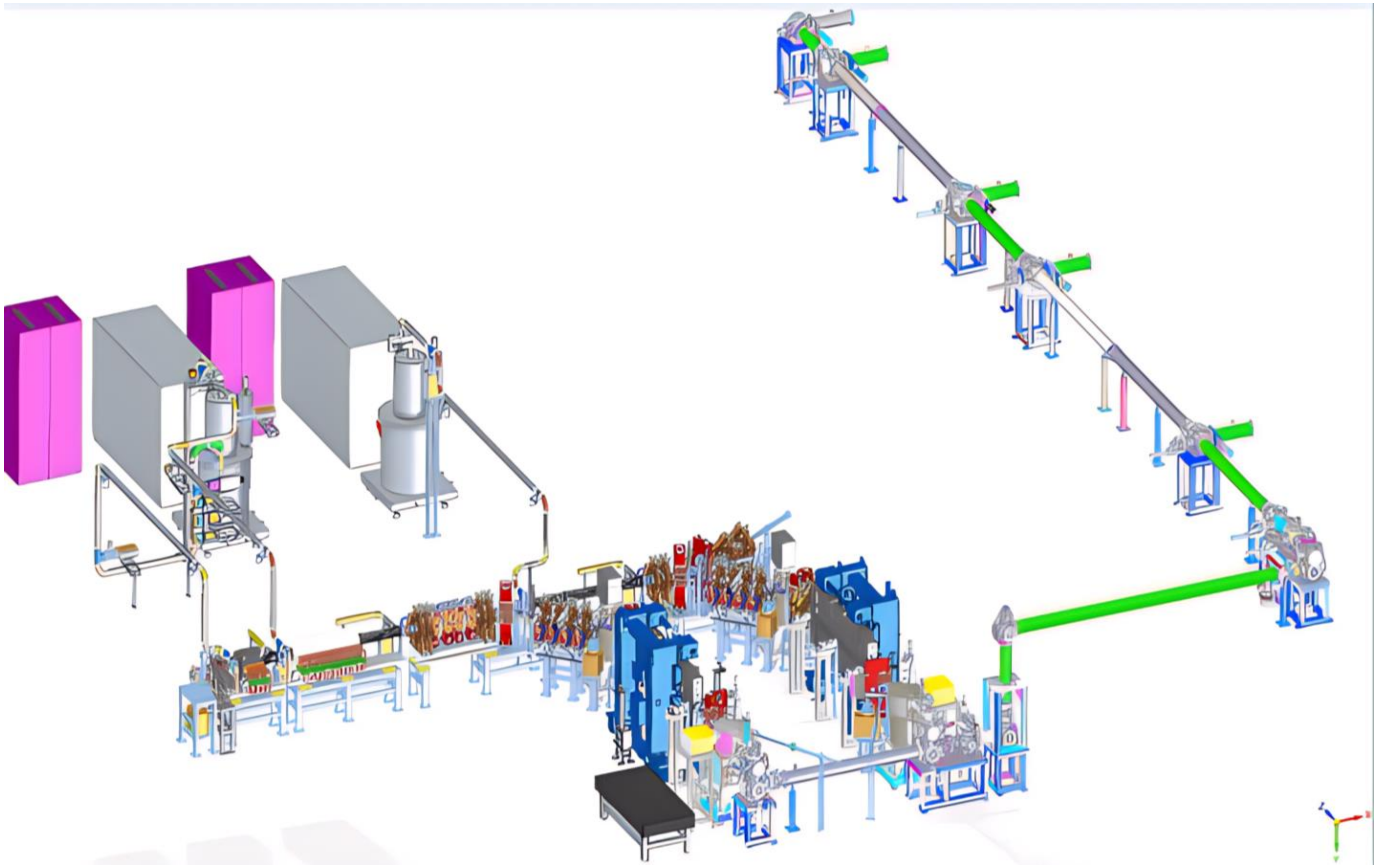

Three types experiments

- Photo dissociation
- Photo excitation
- Photo detection(Surface-interface spectra, spatial resolution spectra, temporal resolution spectra)

Six beamline
Five for experiments
One for on-line diagnostics

Technical route and schemes

Oscillator THz FEL

- Excellent performance: radiation power, bandwidth, tunability
- Relatively compact layout
- Moderate cost
- Mature technologies: driven electron accelerator, resonators, undulators,…

Driven electron accelerators:

- Linear accelerators: good beam quality, energy tunability
- NC travelling wave accelerating tube: low cost, mature technology
- Grid-controlled thermal cathode electron gun: low cost, high charge, good reliability and repeatability; special gate-control power supply to achieve high repetition frequency of micro-bunch
- Repetition frequency of macro-bunch is limited by Klystron and constant-temperature water system

It is difficult to cover 1.5-120THz in one resonator——two oscillators are used

Question: parameters optimization of resonators and linac

Used formula in design

Resoant wavelength	$\lambda_s = \frac{\lambda_u}{2\gamma_0^2}(1+K^2/2)$
Small signal gain	$g_{ss} = 0.54\sqrt{3}\pi^2 N_u^2 \frac{1}{\gamma}\frac{a_u^2}{1+a_u^2}\frac{I_p}{I_A}[JJ]$
Correction for 3D effect	$G = f_{\sigma_\gamma} f_{\varepsilon_y} f_{\mu_c} g_{ss}$
Undulator magnetic field	$B_0 = ae^{-\frac{g}{\lambda_u}(\mathrm{b}-\mathrm{c}\frac{g}{\lambda_u})}, \quad \begin{cases} a = 0.55B_r + 2.835 \\ b = -1.95B_r + 7.225, \\ c = -1.3B_r + 2.97 \end{cases} \quad 0.07 \le \frac{g}{\lambda_u} \le 0.7$
Undulator parameters	$K = 0.934\lambda_u[\mathrm{cm}]B_0[\mathrm{T}]$

Initial optimization starting point：small signal gain

Purpose: continuously tuning range, when electron energy is fixed, the wavelength is varied by adjusting K

at different wavelength, the K should be not too small considering small gain

Used formula in design

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Cavity length Lc should be matched with micro-bunch separation, curvature of mirrors

Stability factor of cavity

$$g_1 g_2 = (1 - \frac{L_c}{R_{c1}})(1 - \frac{L_c}{R_{c2}})$$

Rayleigh length

$$Z_R = \frac{\sqrt{(R_{c1} - L_c)(R_{c2} - L_c)(R_{c1} + R_{c2} - L_c)L_c}}{R_{c1} + R_{c2} - 2L_c} \overset{R_{c1}=R_{c2}}{=} \frac{\sqrt{(2R_c - L_c)L_c}}{2}$$

Beam waist

$$\omega_0 = \sqrt{\frac{\lambda_s Z_R}{\pi}}$$

$$\omega(z) = \omega_0 \sqrt{1 + \frac{z^2}{Z_R^2}} = \sqrt{\frac{\lambda_s}{\pi}} \sqrt{Z_R + \frac{z^2}{Z_R}}$$

Divergence of far-field

$$\theta_f = \frac{\lambda_s}{\pi \omega_0}$$

Design parameters-MIR

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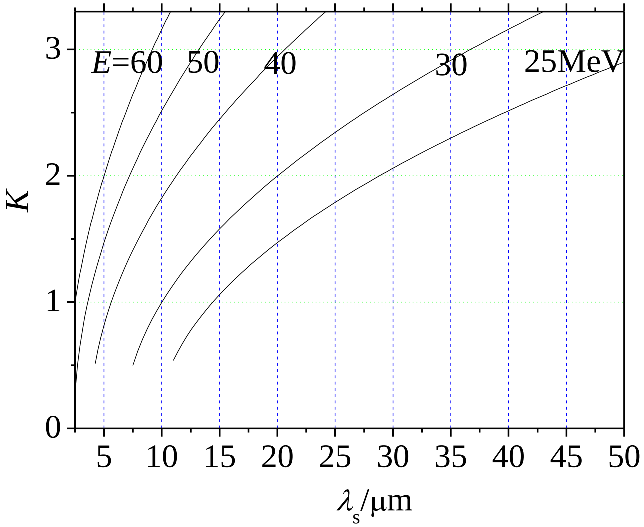
Oscillator parameters

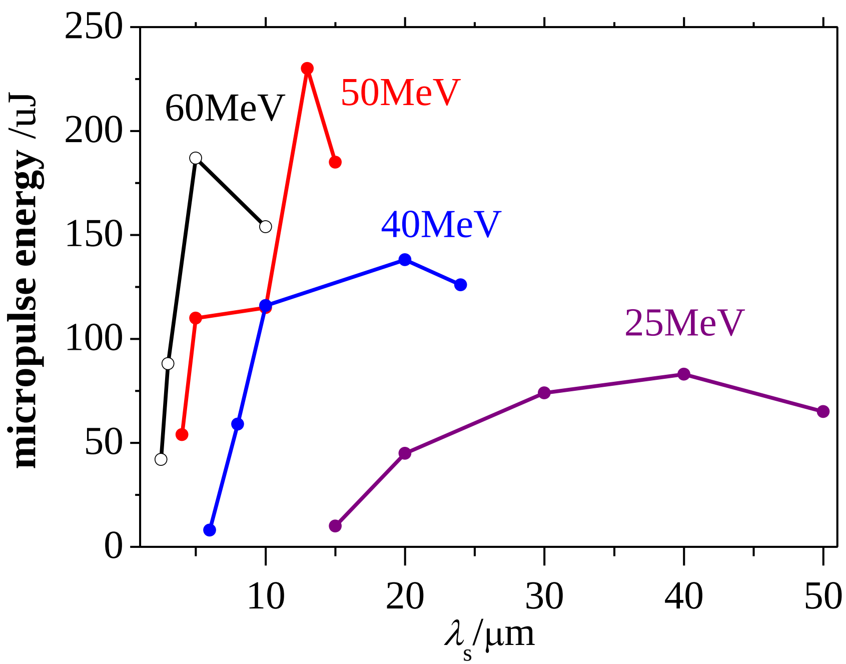
Cavity length	5.04 m
Curvature of mirror	2.756 m
Outcoupling hole	1.0，1.5，2.5，3.5 mm
Reyleigh length	0.77 m
Stability factor	0.69
Beam waist	0.78-3.5 mm
Spot size at mirrors	9-42 mm
divergence	1.02-4.55 mrad

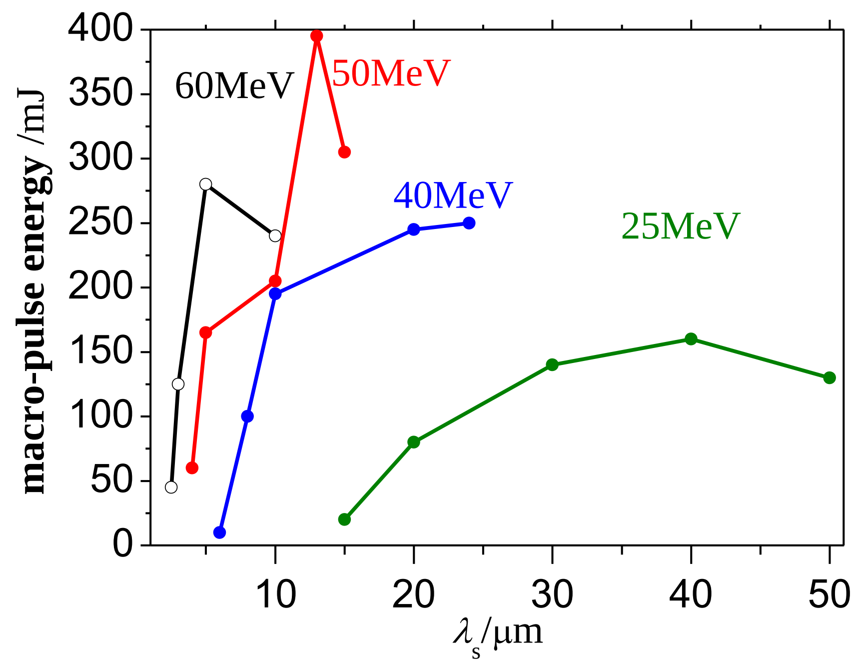
Undulator parameters

Period length	46 mm
Period number	50
Minimum gap	16 mm
Undulator K	0.5-3.2
Peak magnetic field	0.1-0.72 T



Simulation results





Choosing 4 beam energy, the radiation pulse energies were simulated tuning undulator parameters

Error effects

- Electron beam：beam emittance, beam energy spread, beam energy shift, beam alignment

- Undulators：first and second integral of magnetic field, phase error, peak to peak magnetic field error

- Resonator：cavity length，curvature of mirror, reflectivity of mirror, alignmet of mirrors

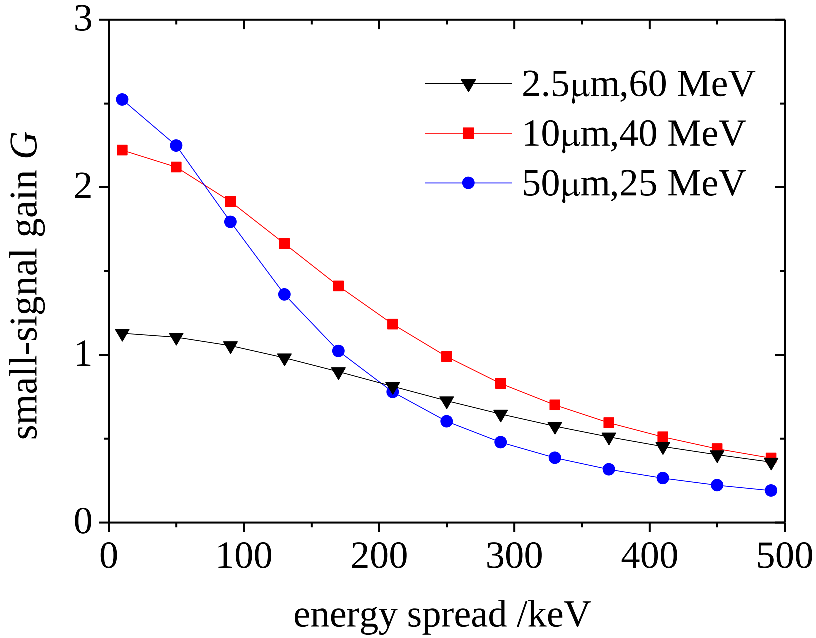
- Analytical formula：small signal formula

- Numerical simulation：GENESIS+OPC simulation

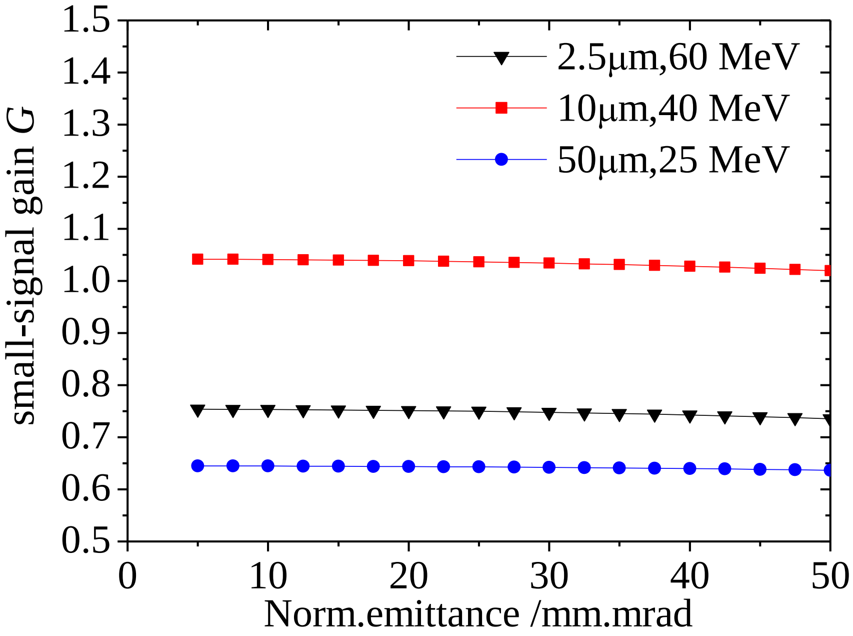
Error effects

Requirement for energy spread $$\frac{\Delta\gamma}{\gamma} < \frac{1}{4N_u}$$

Requirement for transverse emittance $$\varepsilon_{x,n} < \frac{\gamma\lambda_s}{4\pi}$$

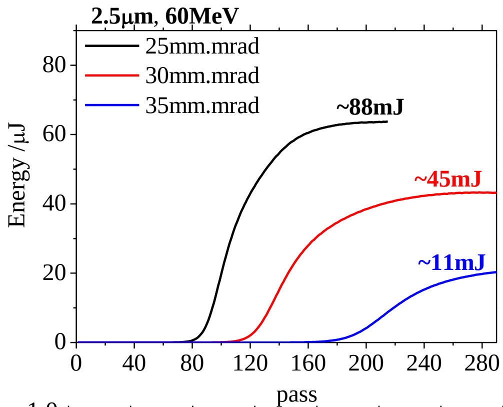


Small signal vs. energy spread

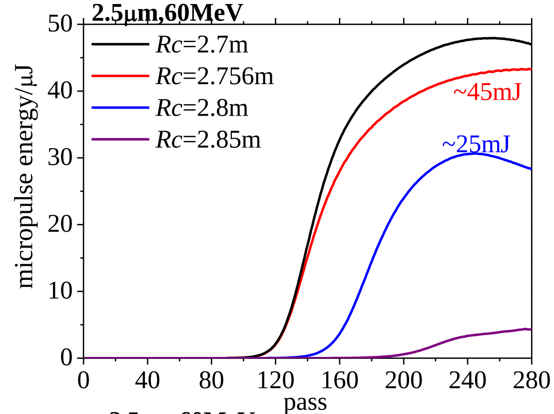


Small signal vs. normalized emittance

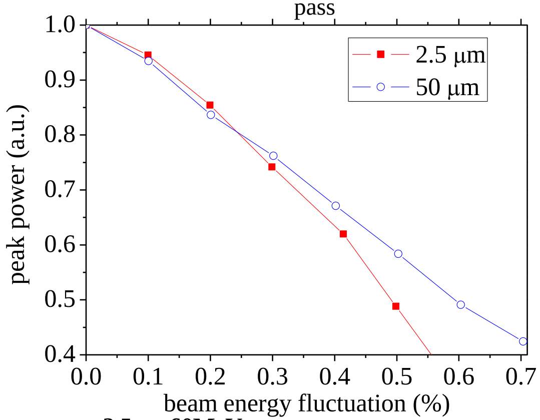
Error effects



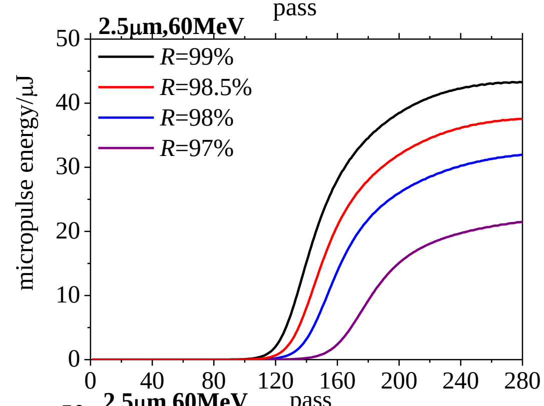
Beam emittance



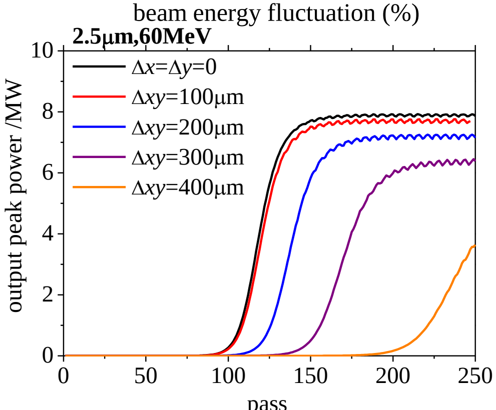
Curvature of mirror



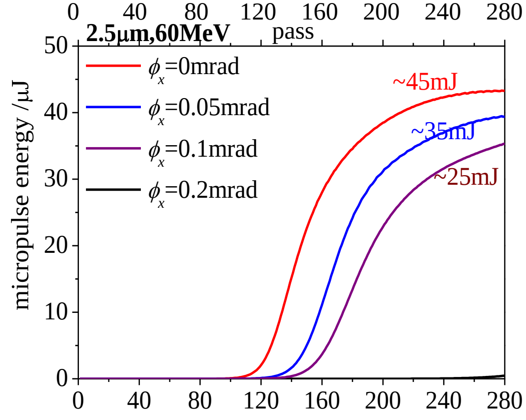
Beam energy



Reflectivity of mirror



Beam alignment



Tilt angle of mirror

Design parameters-FIR

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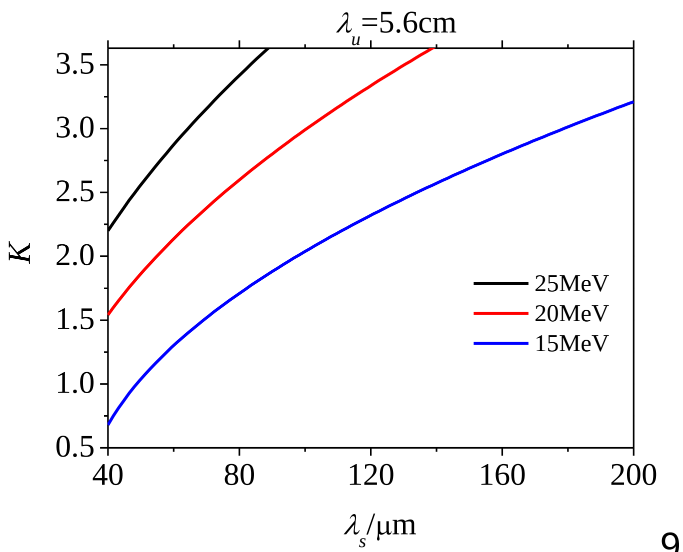
Resonator parameters

Cavity length /Lc	5.04 m
Curvature of mirror	3.018 m
Outcoupling hole	1.0，2.0，4.0 mm
Reyleigh length	1.12 m（Lu /2）
Stability factor /g2	0.45
Beam waist /w0	3.77-8.44 mm
Spot size at mirror	32-72 mm
Divergence angle	3.37-7.54 mrad

Undulator parameters

Period length	56 mm
Period number	40
Minimum gap	20 mm
Undulator K	0.5-3.6
Peak magnetic field/B0	0.12-0.7 T



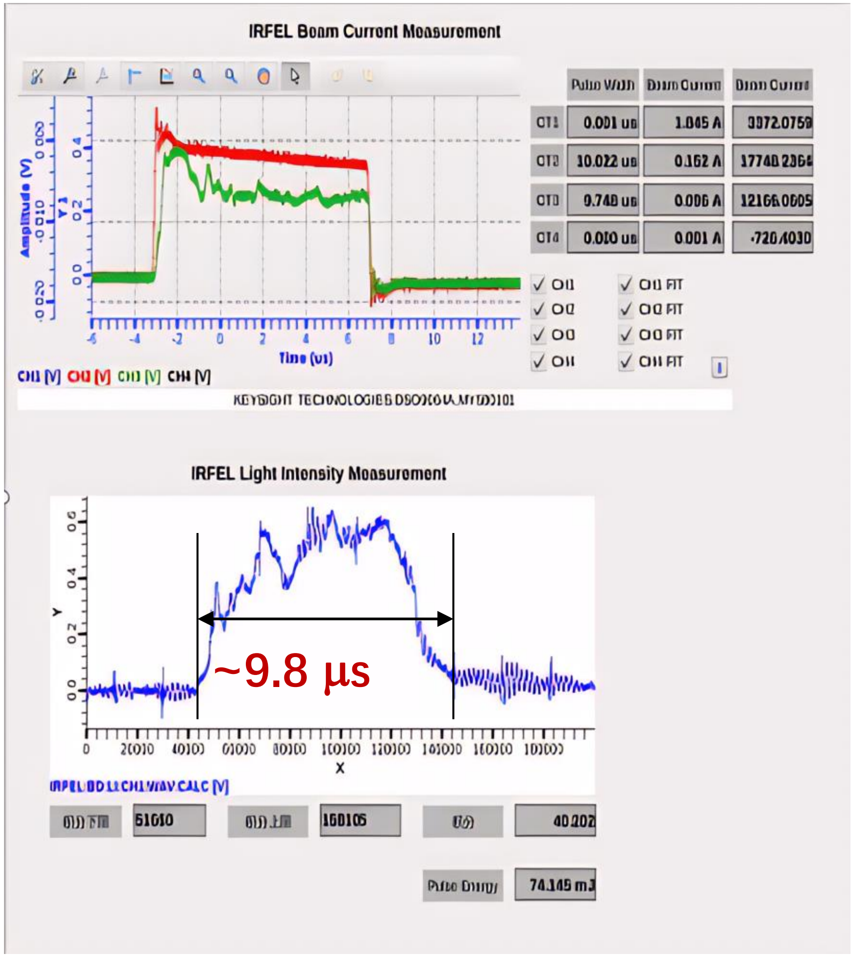
Design parameters of FEL

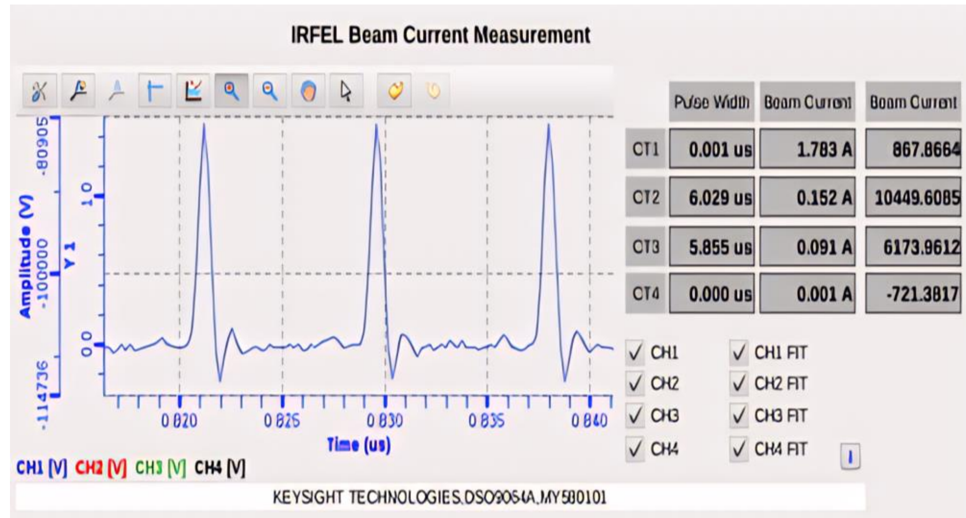
FEL rariation		
Wavelength		2.5-50 um， 40-200 um
Polarization		Horizontal linear polarization
Bandwidth		0.3%-3%
Time structure		Macro-bunch + micro-bunch
Macro-bunch	Length	5-10 ms
	Pulse energy	10-100 mJ
	Repetition frequency	20 Hz
Micro-bunch	Length	5-10 ps
	Pulse energy	5-100 uJ
	Peak power	1-10 MW
	Repetition frequency	476， 238， 119， 59.5… MHz

Parameters of e linac

Electron energy/*E*		Max: 60 MeV
Energy spread/ D*E*		<240 keV
Normalized emittance		<30 mm·mrad
Micro-bunch	Charge /*Q*	~1 nC
	Peak current/*Ip*	>95 A
	Length	2-5 ps
	Repetition frequency	476，238，119，59.5… MHz
Macro-bunch	Length	Max：13 ms
	Mean current	<300 mA (beam loading limitation)
	Repetition frequency	20 Hz

Time structure of IRFEL





The repetition rate of micropulses in macro pulses is 119MHz
Micro pulse width ~2ps

Macro pulse repetition rate 10Hz
Macro pulse maximum width 10μs

Measured energy at endstation

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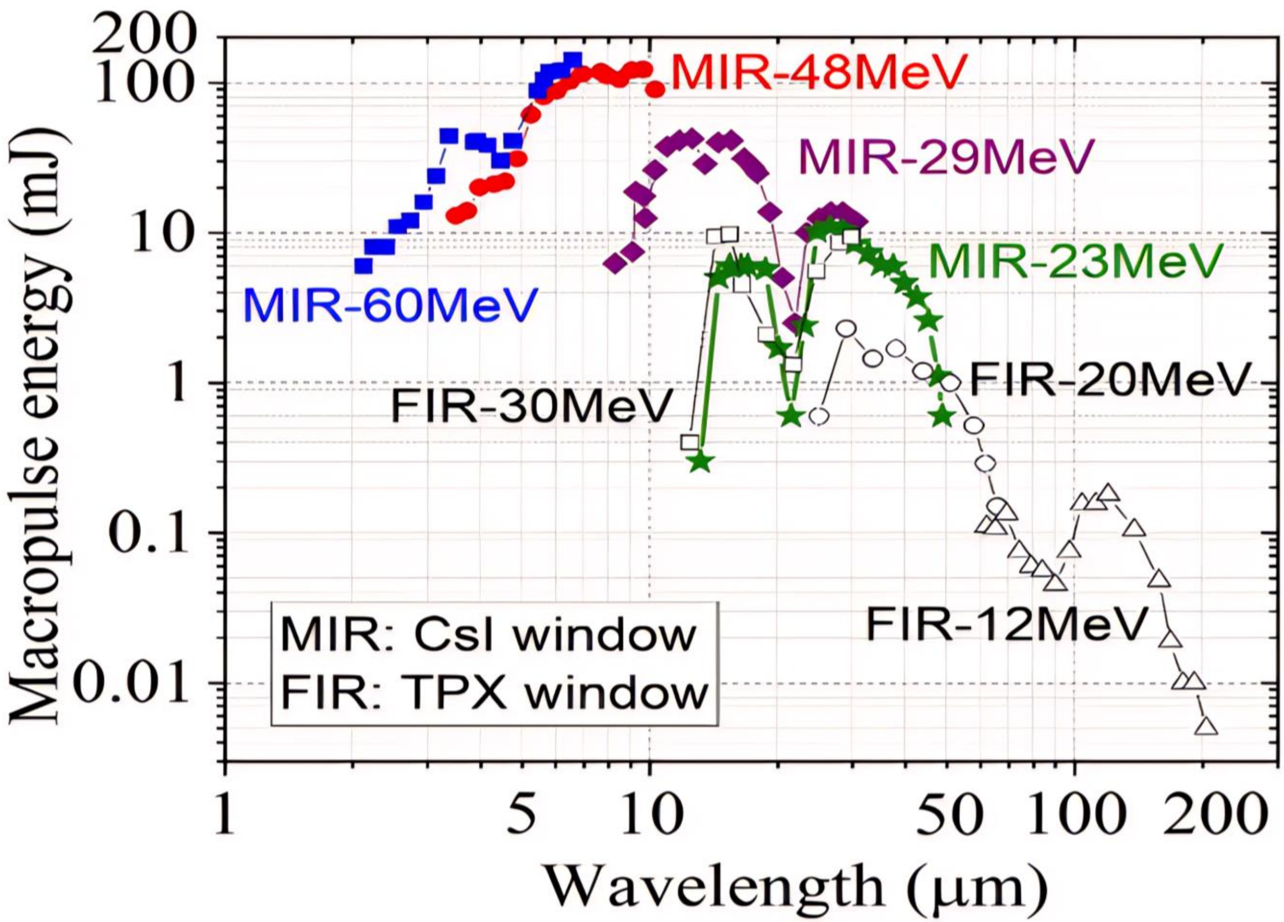
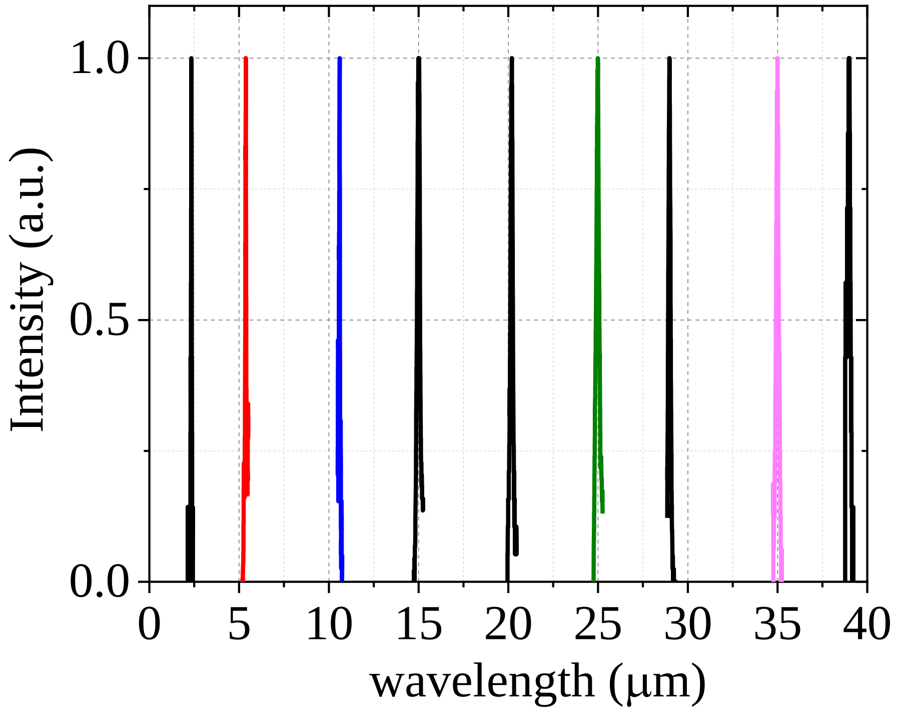


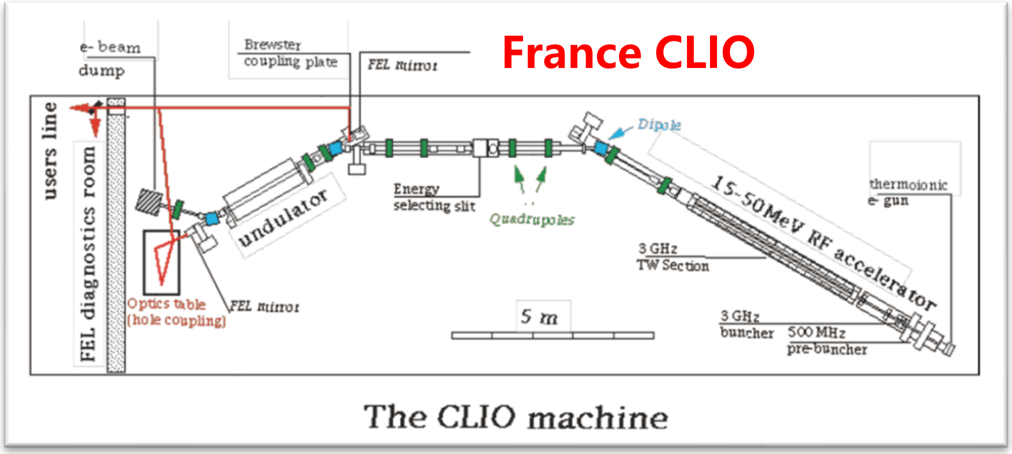
MIR performance is better, at long wavelength is weaker

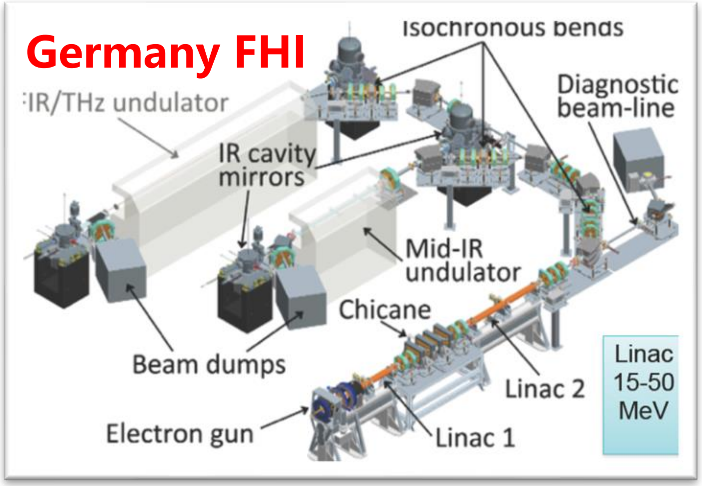
There is bandgap in tuning curve, where the radiation energy is lower than neighborhood



Bandwidth at different wavelength：~1%

Similar facilities in the world





Main parameters

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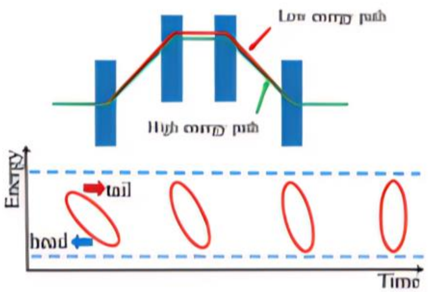
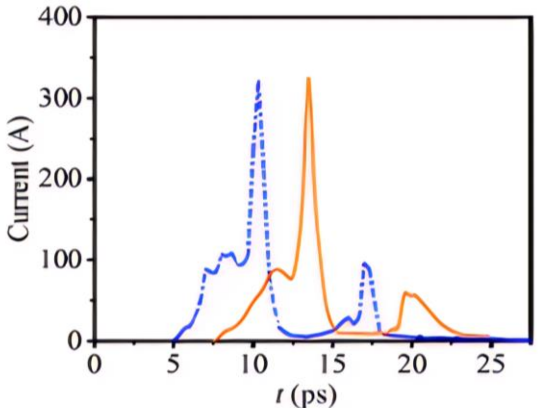
	FELIX	CLIO	FHI	FELiChEM
Radiation wavelength	3-45 um 30-150 um	3-150 um	4-50 um 40-500 um	2.0-50 um 20-200 um
Electron energy	15-50 MeV	10-50 MeV	15-50 MeV	15-60 MeV
Micropulse length(RMS)	0.2-10 ps	0.2-6 ps	1-5 ps	~2ps
Macropulse length Repetition frequency	<10 ms 5/10 Hz	10 ms 6.25-25 Hz	10-15 ms 10/20 Hz	1-10 ms 1-20 Hz
Micropulse energy	1-40 uJ	10-100 uJ	10-20 uJ	< 200 uJ
Macro pulse energy	1-200 mJ	9-90 mJ	0.1-100 mJ	< 200 mJ
Radiated bandwidth	0.2-5%	0.2-2 %	0.3-5%	0.2~3 %
tunability	200-300%	250%	-	~300%

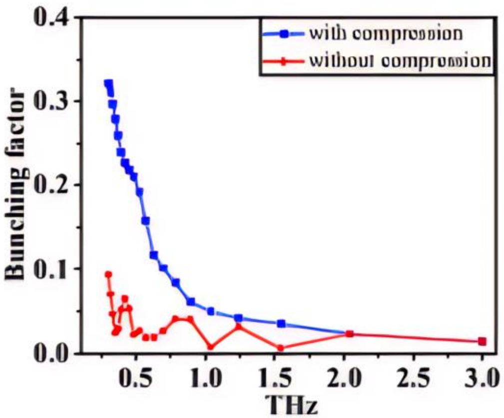
Super radiance

To improve the performance in low THz range,
a super-radiance mode was proposed.

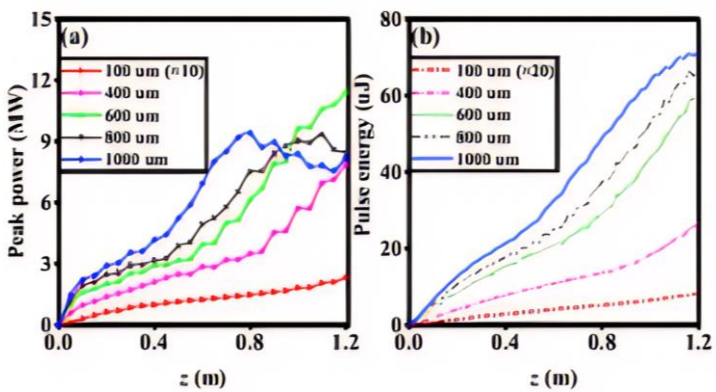


Electron bunch compression by chicane





Bunching factor comparison



Radiation power growth along undulators

Ref: Design of a megawatt super-radiant terahertz source for FELiChEM, Journal of Instrumentation

NFZ-FEL: pre-bunched THz facility

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Scientific motive: measurement of quasiparticles
Quasi-particles: exist in a crystalline fractional multiparticle system, have characteristic energy, momentum, magnitude, and characteristic motion time. It is directly related to the physical properties and functions of quantum materials, SC materials,

Name	Sence	Ref	energy, space scale, time scale,muti phycial fields relevant
Polar vortex	由晶格中原子位移极化形成的准粒子，是纳米铁电材料中的典型拓扑结构	Nature 592, 376 2021 Nature 530, 198 2016	5 nm, 0.3–0.4 THz, 10s ps
Magnetic S. Mingzi	二维材料中的手性自旋结构	Nat Comm 12, 185 2021 Nat. Phys. 16, 541 2020 Nature 564, 95 2018	Low temperature, 10s nm, 10s ps
Magnetic polarizer	是磁子和声子之间的杂化激发	PRL 125, 217201 2020 Nature 578, 70 2020 Science 368, 160 2020	Strong magnetic field, 0.1-0.5 THz
Plasma excitons	光的电场与电子相互作用产生的一个具有拓扑等离子体自旋结构的准粒子	Nature 588, 616 2020	100s nm, THz, ns-fs
polaron	在物质中被离子包围的移动的带电准粒子	PRL 125, 126401 2020 Science 364, 1079 2019	Low T, THz, ps
Magnetic exciton	电子在材料中自旋的相干激发	Science 361, 794 2018	Low T, magnetic field, THz
Majorana Fermizi	与自身反粒子相等的准粒子，某些超导体中以中间间隙状态出现	PRL 126, 090502 2021 Science 367, 64 2020 Nature 549, 492 2017 PRL 116, 257003 2016	Low T, magnetic field, 10s nm
Cooper e-answer	声子作用下自旋相反动量相反的电子成对束缚,0电阻运动	Nat Phys 9, 220 2013	THz, 10s nm, Low T, Magnetic field

The requirement for THz sources

- Spectrum : THz range, try to cover whole THz range
- Narrowband : for energy resolution
- Broadband and high electric field: for control by electric field
- Ultrashort pulse: 10s fs – 10s ps, for dynamic process measurement
- Environment with high magnetic field, low temperature
- …

NFZ-THz FEL, partially meets scientific needs due to limited costs and infrastructure conditions

- Narrow-band THz source: pre-bunched THz FEL
- Broad-band THz source: fs laser-based THz source, photoconductive antenna

NFZ-FEL: pre-bunched THz facility

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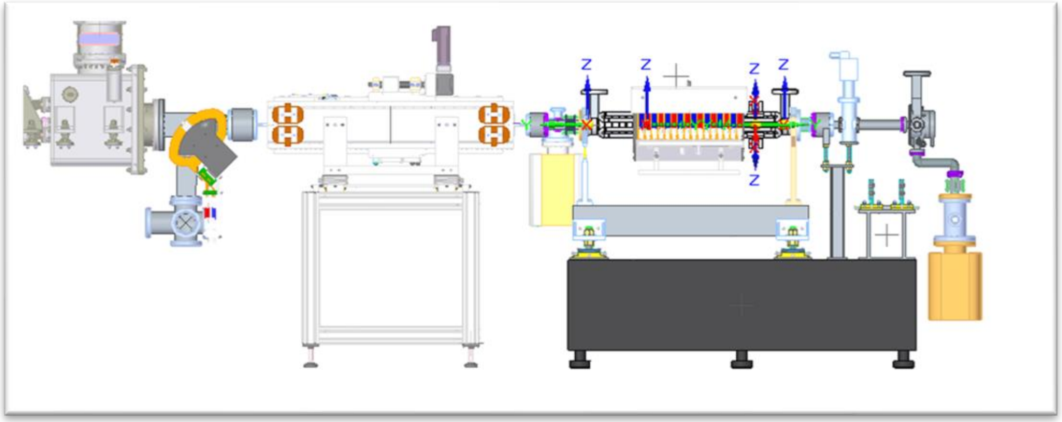
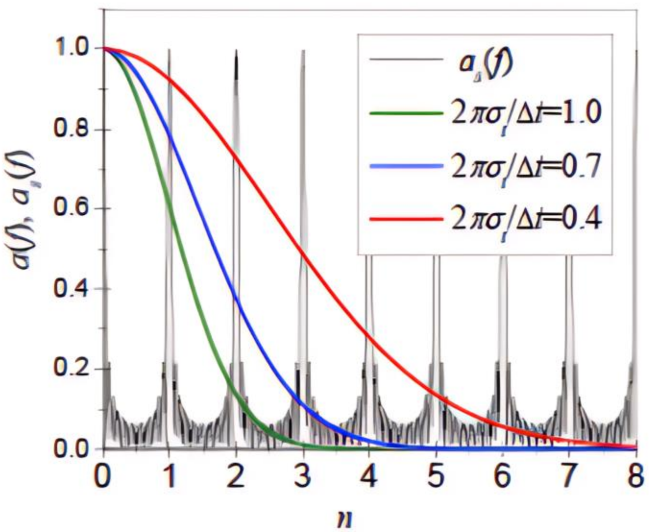
Parameters		Design values
Spectra		0.5-5 THz
Beam energy		10~18 MeV
Number of micro-bunch		16
Separation of micro-bunch		0.33-2 ps
Charge of micro-bunch		5~15 pC
Fundamental harmonics	Resonant frequency	0.5~3.0 THz
Fundamental harmonics	Peak power	0.1-7 MW
Fundamental harmonics	Pulse energy	4-30 uJ
Second harmonics	Resonant frequency	3~5 THz
Second harmonics	Peak power	0.1-0.6 MW
Second harmonics	Pulse energy	0.5-3.8 uJ



Copper based photocathode electron gun
A 1m long traveling wave tube
A fixed gap undulators
A beam dump
A coated Al mirror reflects THz radiation out of shield tunnel

Due to overlap of micro pulse of laser, it is difficult to achieve high THz using fundamental harmonics radiation



Bunching factor of electron bunch train

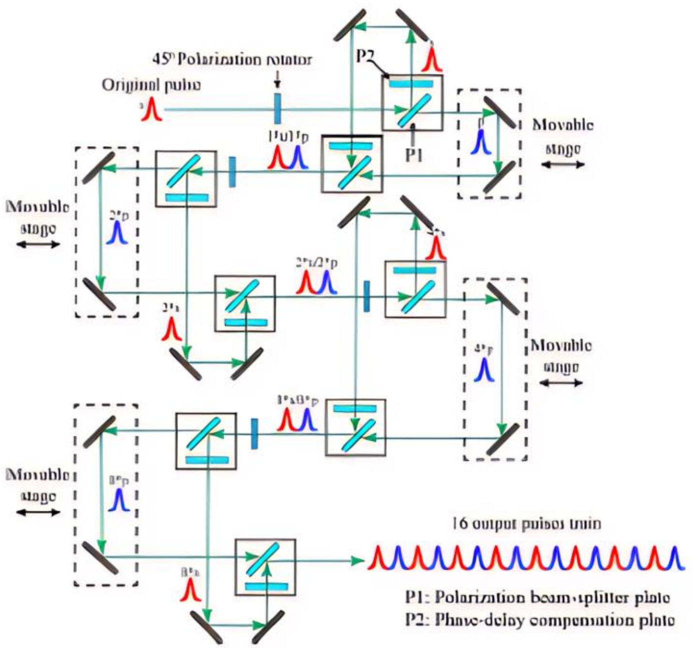
$$b(f) = \frac{1}{N_b}\left|\frac{\sin \pi N_b f \Delta t}{\sin \pi f \Delta t}\right| \exp\left[-\frac{(2\pi f \sigma_t)^2}{2}\right]$$

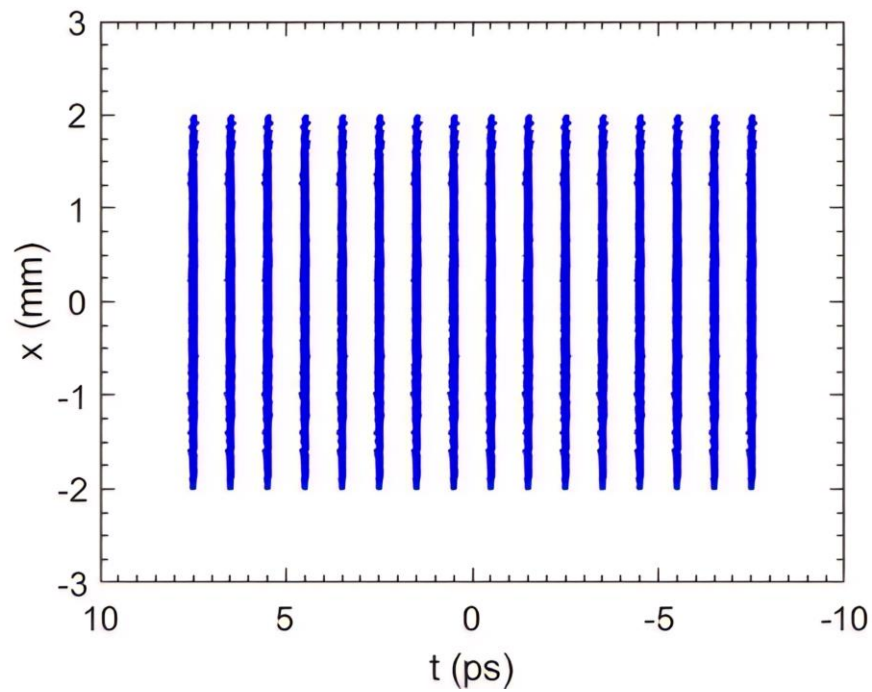
Spectral properties of coherent undulator radiation

$$\left(\frac{dW}{d\omega}\right)_N \propto \mathrm{sinc}^2\left[\frac{\pi N_u \Delta\omega}{\omega_0}\right]\left|\frac{\sin N_b \frac{\omega \Delta t}{2}}{\sin \frac{\omega \Delta t}{2}}\right|^2 \exp^2\left[-\frac{(\omega\sigma_t)^2}{2}\right]$$

The third term represents the form factor of single Gaussian bunch and is slowly varied with frequency..
The second term represents the form factor of electron bunch train and is narrowband, $1/N_b$
The first term represents the property of undulator radiation and is narrowband also, $1/N_u$

Simulation results

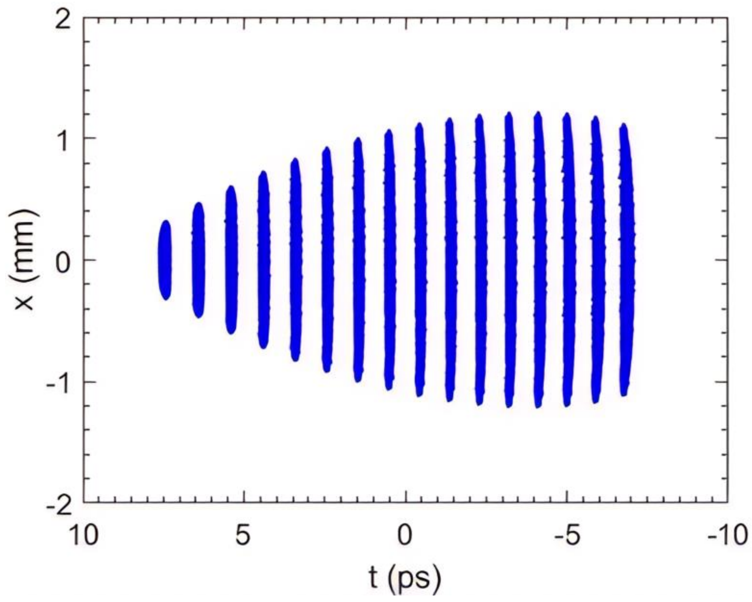




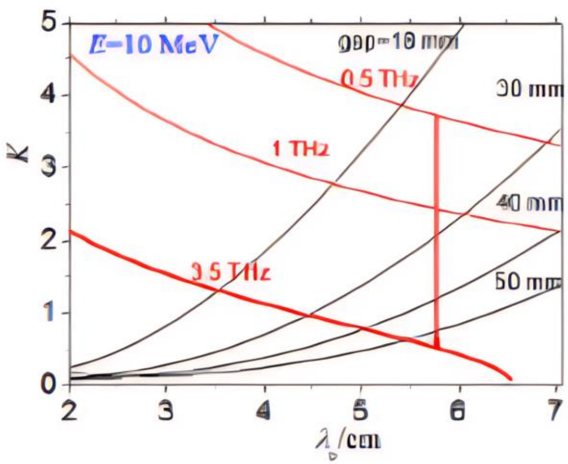
Uniform 16 micro pulses of laser produced by polarized splitting optical loop

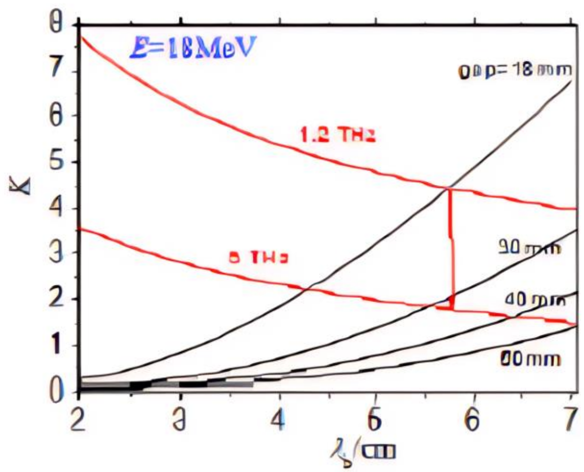
Electron bunch trains at photocathode

Simulation results



Electron bunch trains at entrance of undulator





Two operation beam energy point, varying K to achieve tunable spectral range 0.5-5THz

Simulated bunching factor

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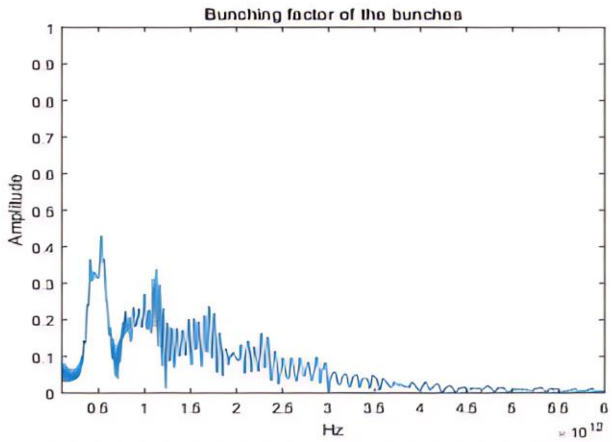
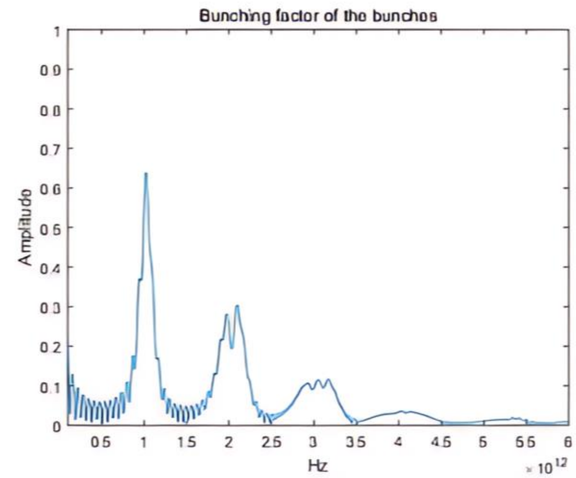
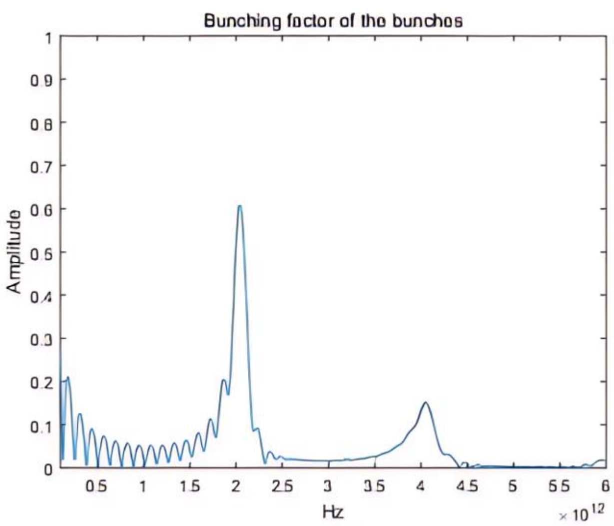


.5THz

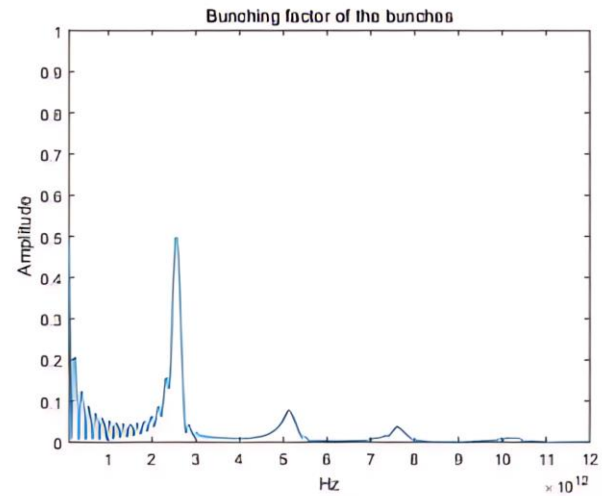
1.0THz





.0THz

2.5THz



Main design parameters

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Linac parameters

	values
energy	8-18MeV
Beam size(rms)	0.5mm
Number of micro bunch	16
Charge of micro bunch	5-15pC
Pulse length	~100fs
Pulse seperation	0.3ps-2.0ps

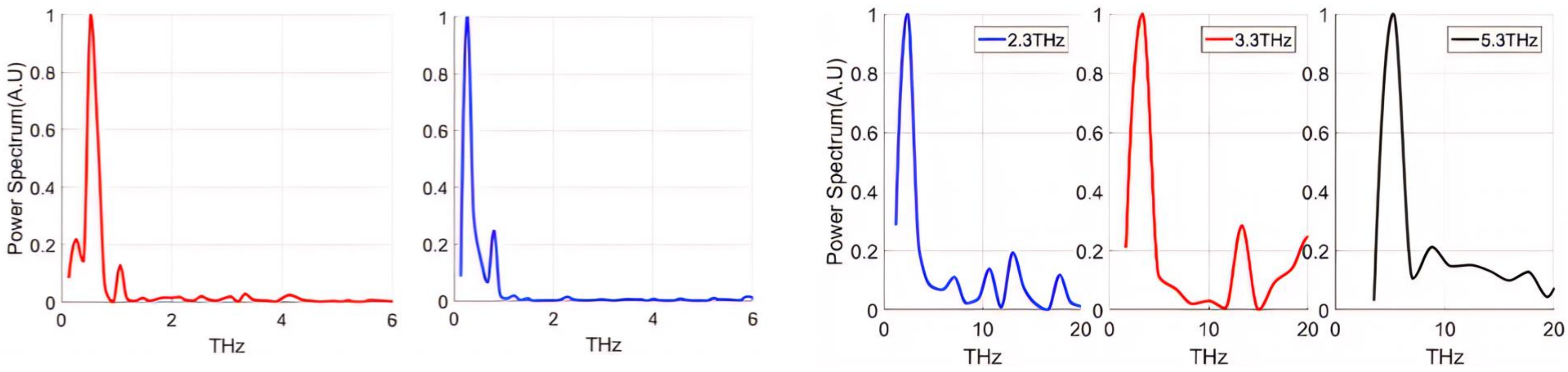
Undulator parameters

Period length	54 mm
Period number	20
Field at axis	0.1-0.66 T
K	0.5-3.83

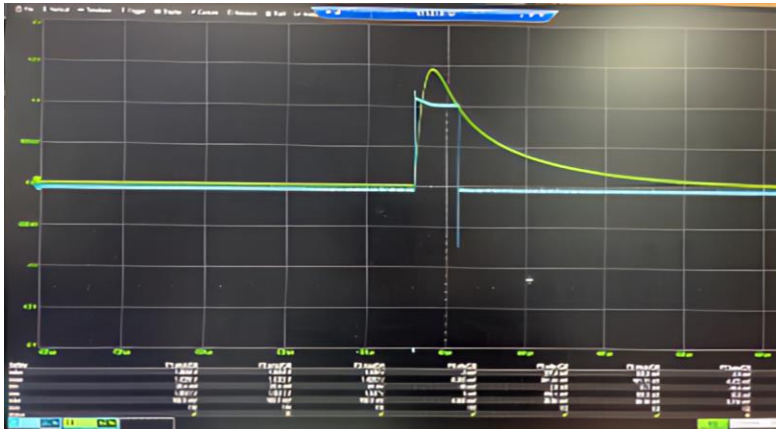
Radiation properties

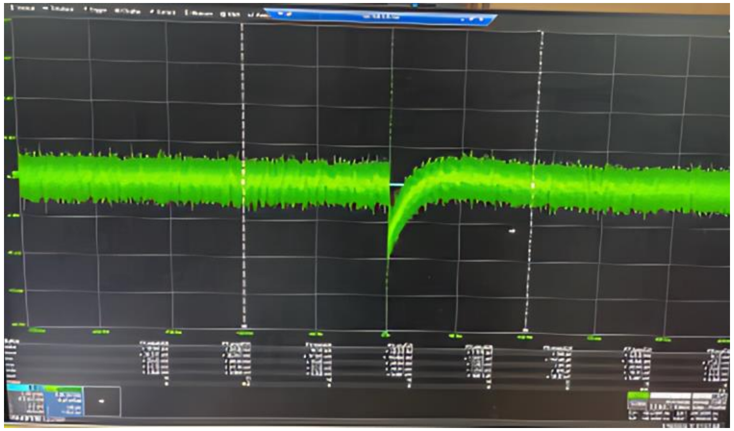
Central frequency （THz）	At exit of undulator			
	Peak power （MW）	Pulse energy （uJ）	Pulse length （ps）	Band width
0.50	0.165	4.01	72	19.8 %
1.0	1.07	18.03	36	8.5%
2.5	2.97	18.18	14.4	4.6%
3.0	7.00	31.01	12	5.2%
3.0	0.61	3.83	17.3	6.8%
4.0	0.256	1.21	13	6.2%
5.0	0.11	0.54	10.4	9.4%

Measured results



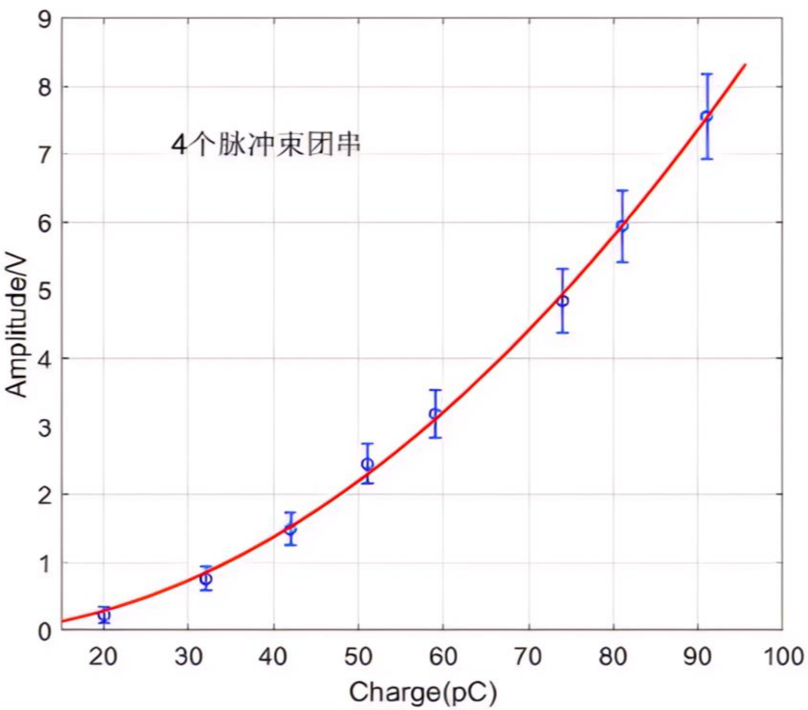
Spectrum measure by Fabry-Perrot interferometer

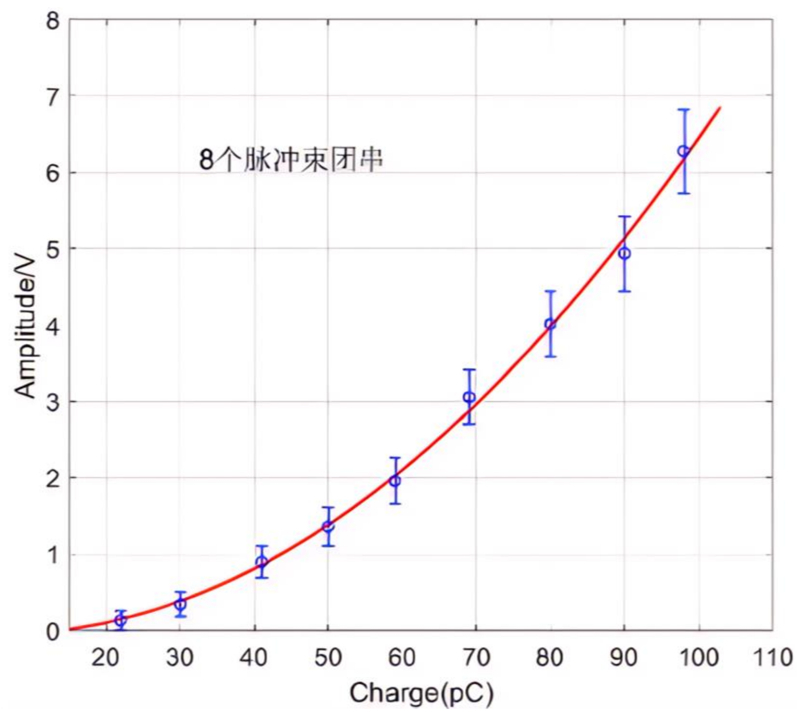




THz signal measured by Bolometer and Galey cell

Super radiance



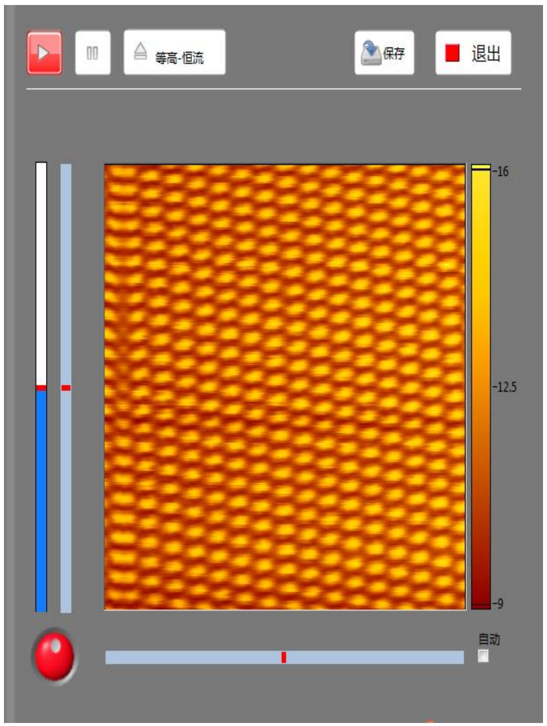


Under 4 micro bunch and 8 micro bunch case, the radiation intensity shows nearly square relationship with bunch charge and demonstrates the super radiance.

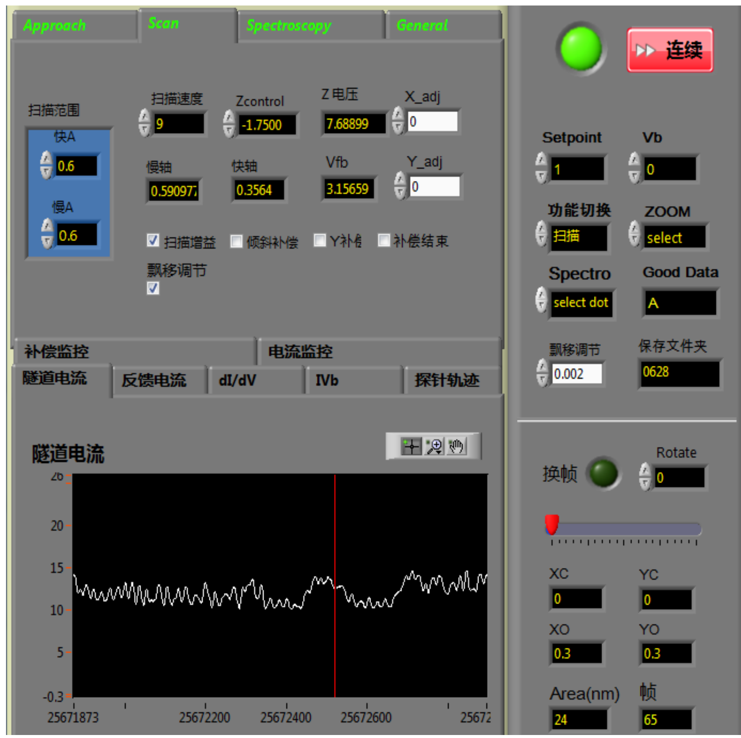
An example of measurement

Atomic image of materials

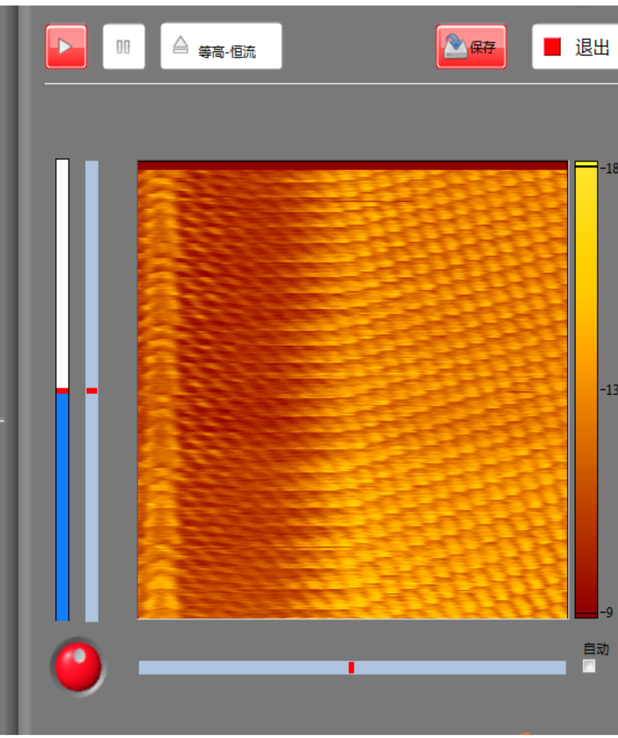
Without THz
With DC bias



Tunneling current with THz
10^6 than DC case



The measured image
with THz



With THz, the transient signal far exceeds the traditional, means more sensitive.
Except for surface, it is possible to detect body structure

Limitations

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Several shortcomings were displayed in operation of NFZ-FEL

- The spectrum: 0.5-5THz, with increase of frequency, the radiation energy is lower due to limitation of laser pulse length
- The repetition frequency is 10Hz due to cooling water system and laser system. The experimental efficiency is lower, and the requirement to THz source stability is very stringent.
- The transfer efficiency of THz light to experimental station is lower due to existing tunnel limitation.

USTS: a new THz facility based on accelerators

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A new THz facility was proposed
USTS: Ultrafast Strong electric field Terahertz Sources
(under construction)

To meet the measurement requirements of quantum functional materials, several improvement are expected:

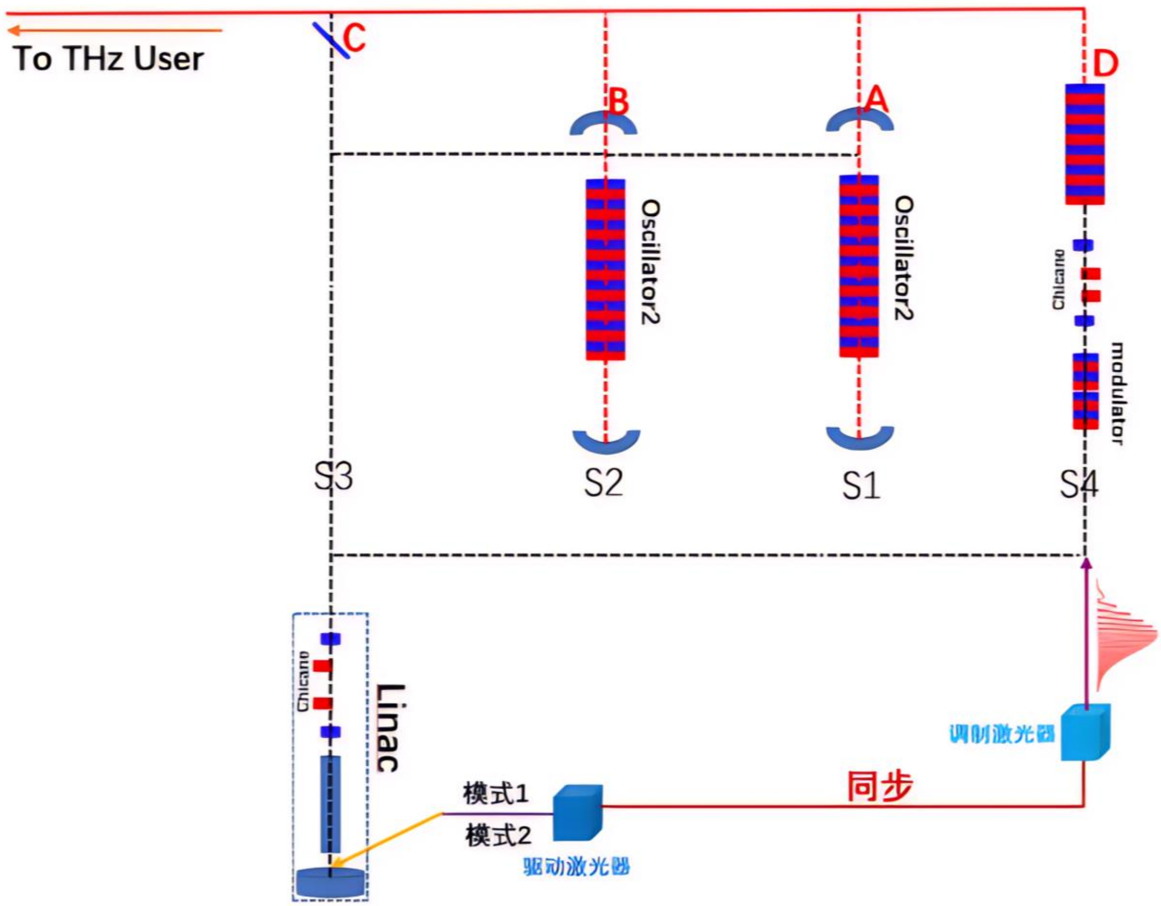
- Spectrum: 0.1-10 THz, can be extended to higher
- Ultrashort pulse length, < 100fs, to detect the ultrafast process
- Higher electric field, > 1MV/cm， to analyze the nonlinear effects

- As a user facility, USTS should be reliable, and has good tunability to satisfy different user requirements. The scale and cost should be acceptable.
- Accelerator based THz sources: high peak/average power, broadband/narrowband, complete THz spectrum, timing structure, …

The layout of USTS

Station 1: THz near-field scanning tunnel microscopy

Station 2: THz spectrometer(pump-probe experiments, THz as pump source or detector)



Driven linear electron accelerator

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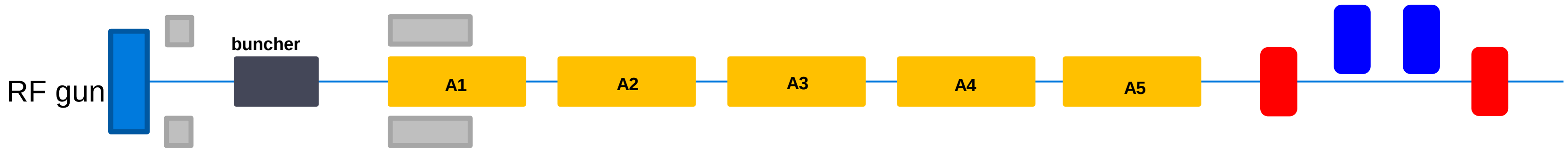
Linac(2856MHz）



- Ca_2Te Photocathode gun with high quantum efficiency is used to decrease beam loss in the bunching process and enhance synchronization between THz source and other laser systems.
- Normal conducting accelerating techniques are used to control facility scale and cost
- Standing wave accelerating tube and high duty cycle klystron, which is usually used in irradiation, are used to enhance average beam intensity
- Velocity bunching and magnetic compression are used to adjust micro bunch length
- In oscillator FEL operation mode, only three accelerating sections are used, in other operation mode, all accelerating sections will be used and the maximum beam energy is about 65 MeV

Different oscillator type

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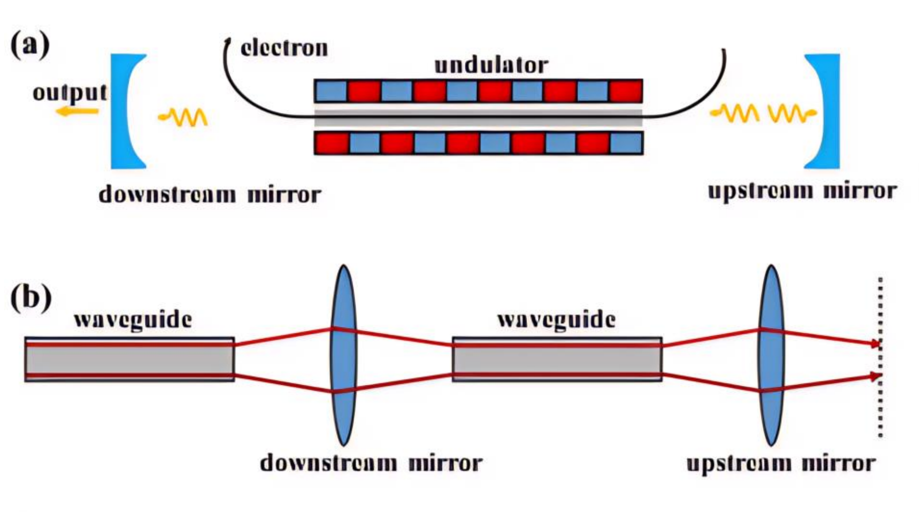
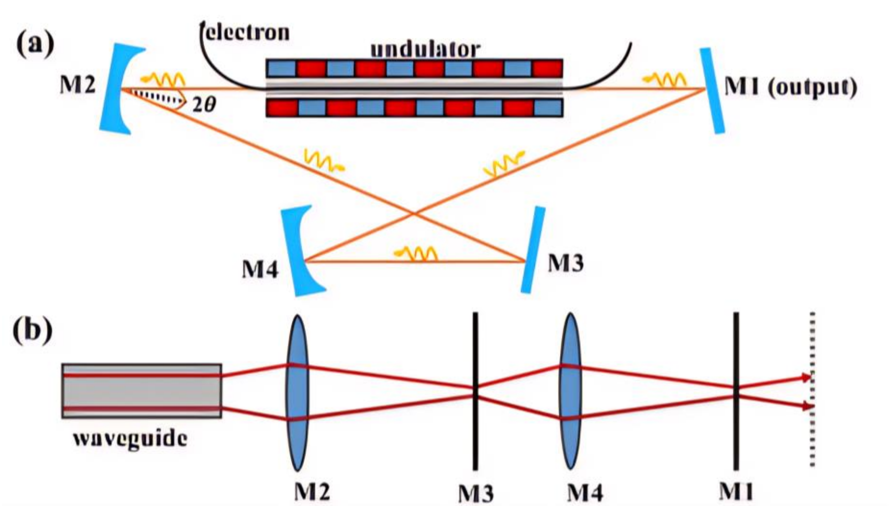


For high THz oscillator FEL, 2 mirrors oscillator with rectangular waveguide is used again

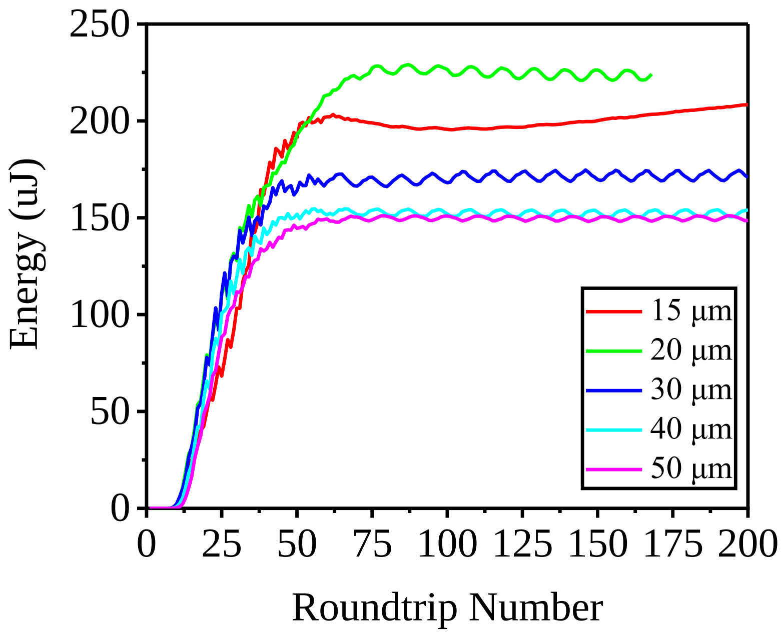


For low THz oscillator FEL, 4 mirrors oscillator with rectangular waveguide is used:
control optical beam size at critical position to decrease truncation loss and weaken diffraction effect

high THz Oscillator

Parameter	Value	Remark
Electron energy	35 MeV	Covering 15-50 um
RMS K value	1.22-2.72	
Micro-pulse charge	800 pC	
Normalized Emittance	~2 mm·mrad	
Micro-pulse length	~3.0 ps (rms)	
Peak current	106.38 A	800/(3.0*sqrt(2*pi))
Energy spread	~130 keV (rms)	
Macro-pulse length	~10 μs	

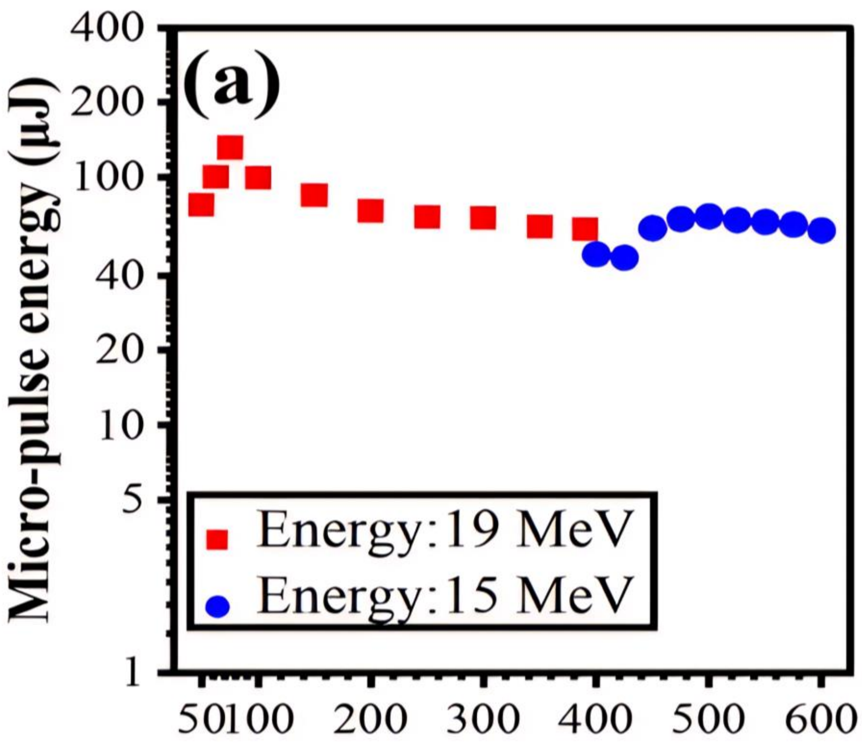
Time evolution of radiation energy

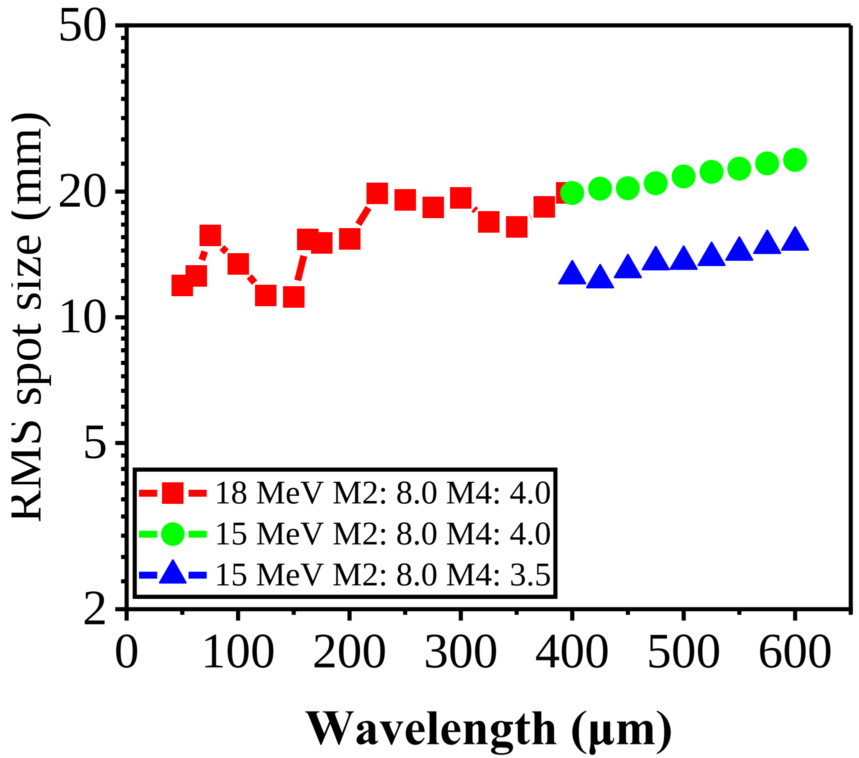


Micro pulse energy at different resonant wavelength

If micro pulse charge is higher, the pulse energy will higher

Low THz Oscillator





Mirco-pulse energy of low THz FEL: using 4 mirrors oscillator, the pulse energy is increased two orders, bandgap in spectrum is eliminated
Rms spot size before outcoupling hole: size change is decreased

Oscillator THz FEL

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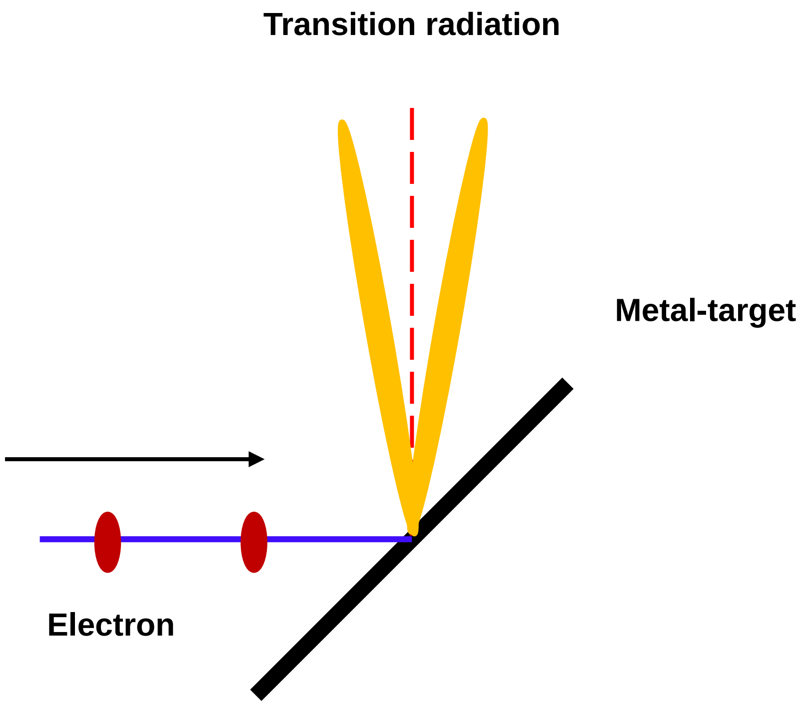
Pulse time structure

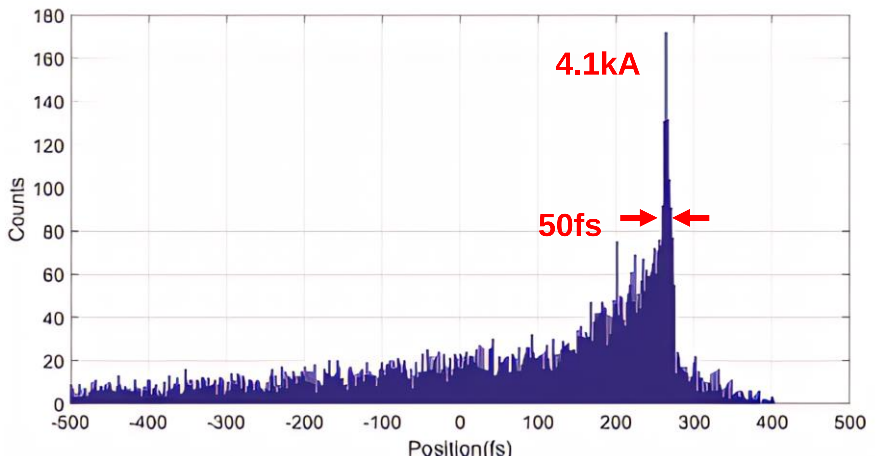
Repetition frequency of micro-bunch	28.56 MHz
Repetition frequency of macro-bunch	500 Hz(max)
Micro bunch numbers	**300*500 = 150k**

Radiation properties at experimental station considering 50~70% transfer efficiency

	High THz	Low THz
Spectrum	15-50μm，~1%-3% (bandwidth)	50–600μm，~1%-3% (bandwidth)
Micro-pulse length	~3ps	~10ps
Micro-pulse energy	>100μJ	>20μJ
Macro-pulse length	~10μs	~10μs
Peak power	33MW	2MW
Average power	>10W	>3W

Coherent transition radiation

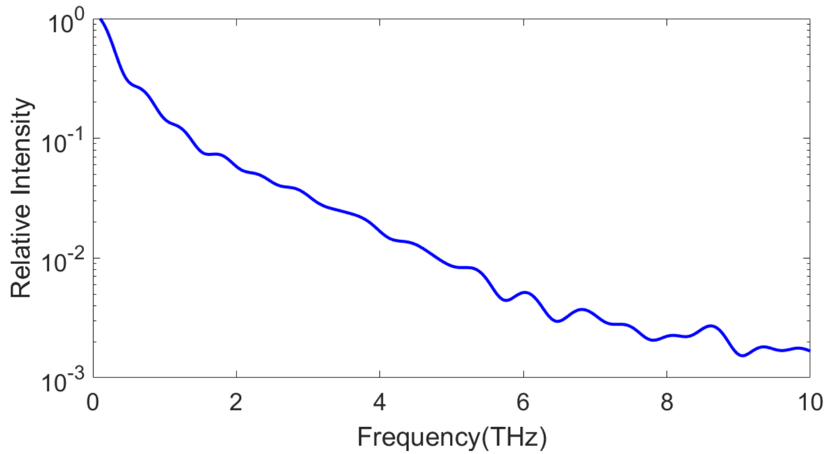




45 deg thin Al or Ti foil
Backward transition radiation is used

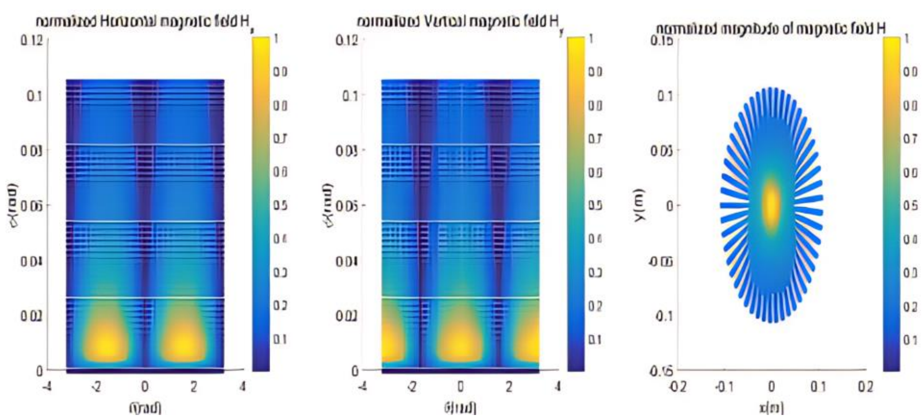
Velocity compression + magnetic compression
FWHM of electron bunch is less than 50fs

Coherent transition radiation



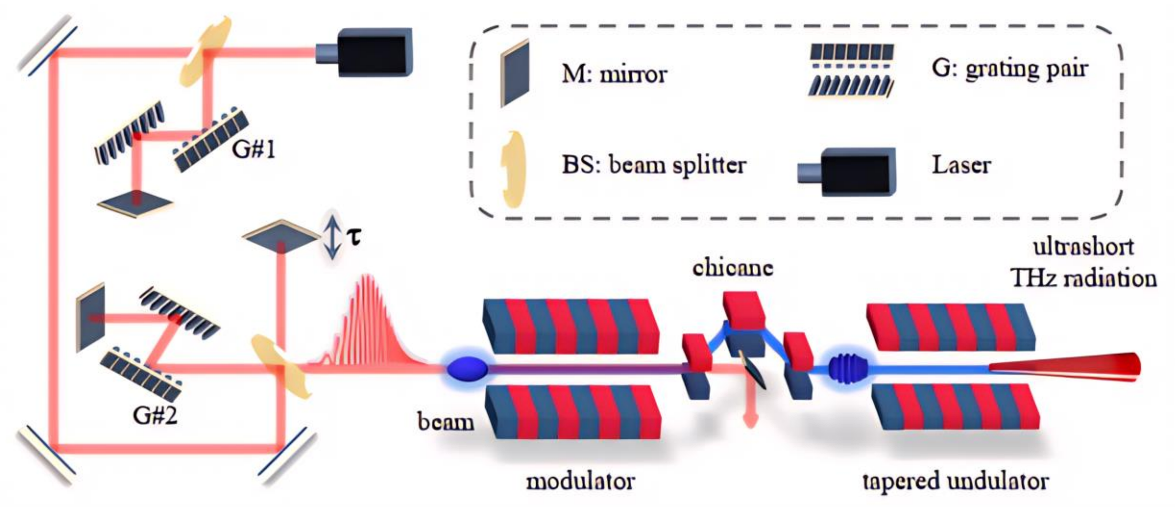
THz radiation spectrum from source, relevant with electron bunch length and target size

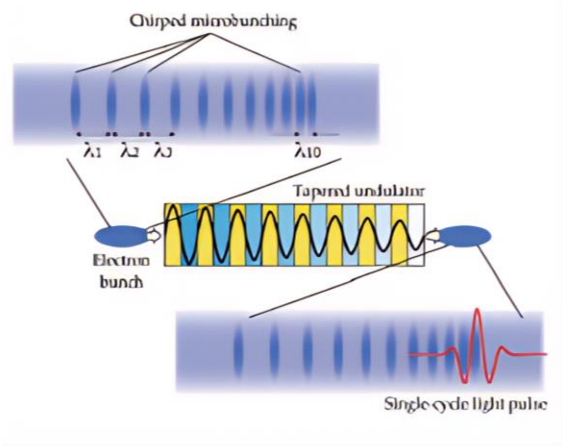
At the experimental station, the spectrum is limited by optical transfer line, and the lower THz will weak due to diffraction effects.

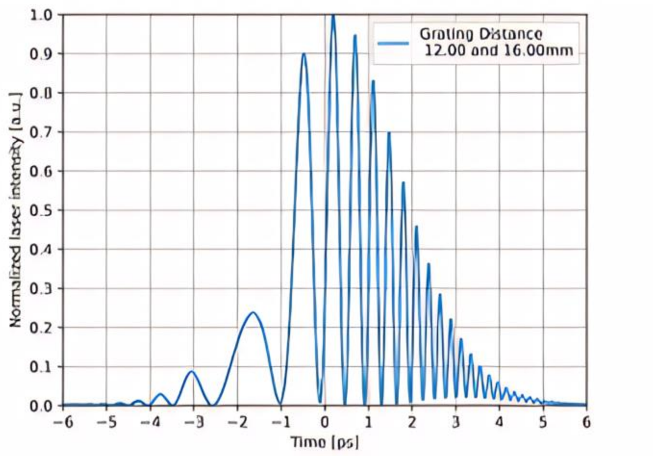


The spatial distribution of transition radiation

Laser modulated electron beam







- **800nm laser modulated electron beam in short modulator**
- **Double chirped laser pulse beating system**
- **Chirped rate is adjusted by parallel grating**
- **Delay time is adjusted by electronic control delay line**
- **After chicane, density modulated electron beam**

Coherent radiation

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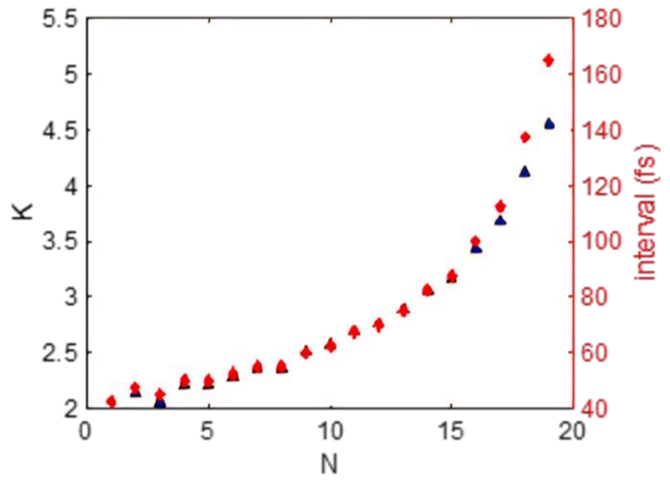
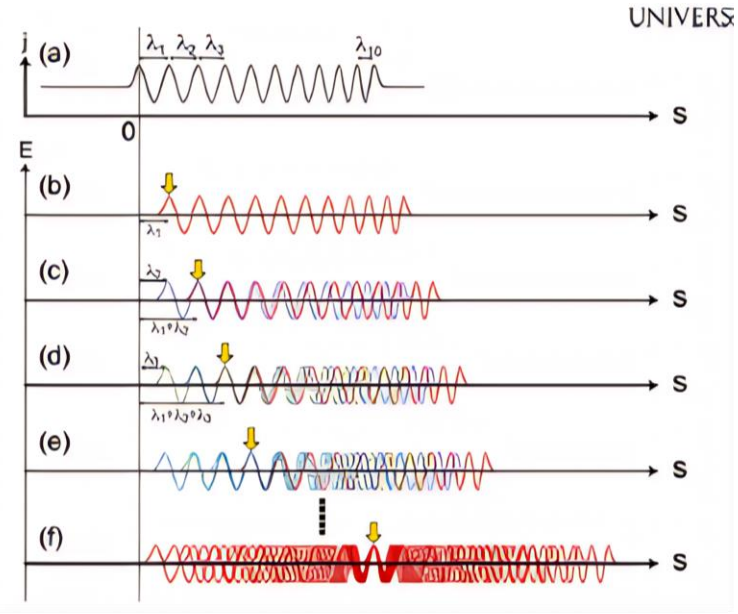
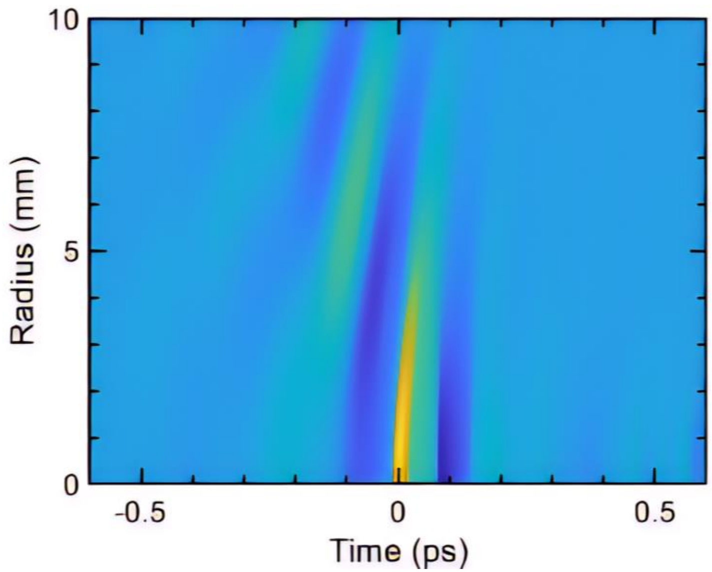


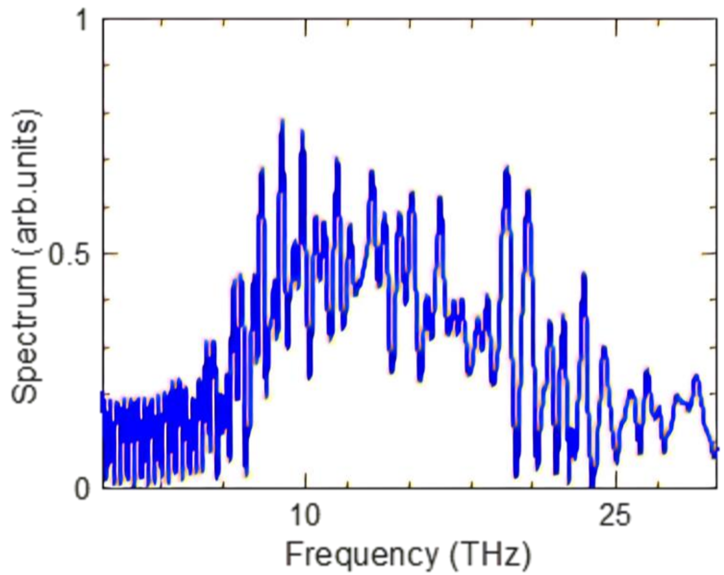
Longitudinally tapered undulator, the K is matched to density modulated electron beam



Passing tapered undulator, the laser modulated electron beam will radiate coherently at THz range.

Sub-cycle THz pulse





The FWHM is about 40fs, the peak electric field is about 30MV/m, the waist about 3mm, the spectra is between 6-20THz, the peak electric field is above 1MV/cm after focusing.

Summary

Ultrafast Strong field Terahertz

Source(USTS)

- Broadband and narrow band THz sources
- Coverage spectral: 0.1-20THz
- Electric field: >1 MV/cm
- Ultrafast pulse: < 100fs (~ps for oscillator THz FEL)
- Repetition rate: 500Hz
- Synchronization: < 50fs

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Outline

Summary

The Terahertz FEL has the unique advantages

- wide spectral coverage
- high peak power/high average power
- Narrow bandwidth
- good tuning ability
- Good reliability

- The integration of THz source with large scale scientific facilities, such as Strong Magnetic Field facility, X-ray FEL, Synchrotron Radiation Facilities, will creates new scientific research opportunities.

Summary

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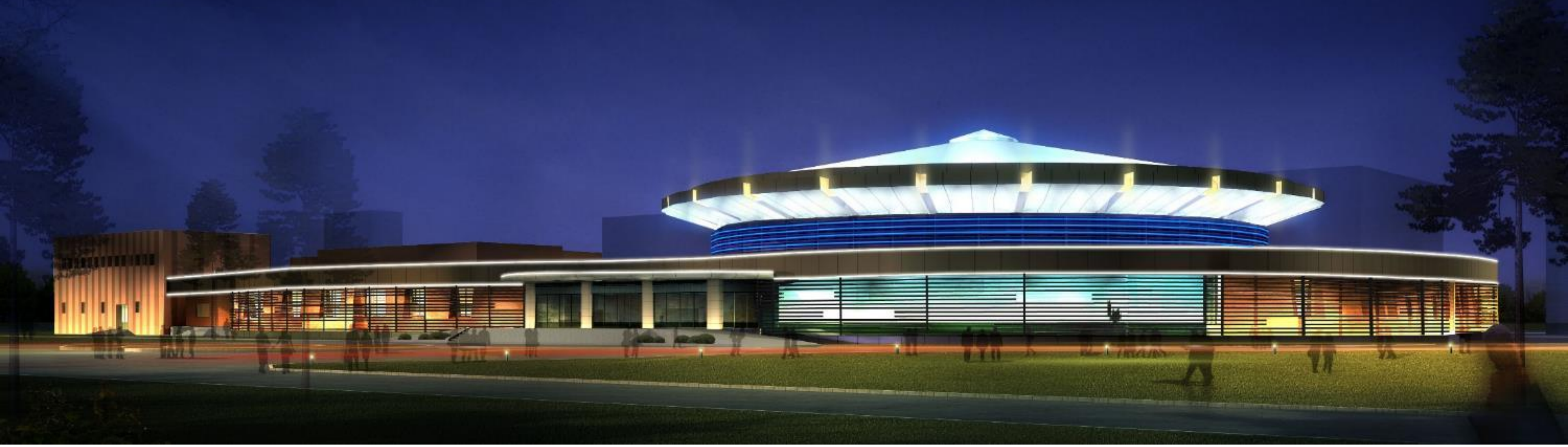
Several disadvantages limit the wide application of accelerator-based Terahertz sources：

- low efficiency
- large scale
- high cost
- special radiation protection requirements

- Compact, high-performance accelerator-driven desktop source
- New theory and techniques, such as using tapered undulator to enhance efficiency

Thanks for your attention！



Performance of non-acceletator THz sources

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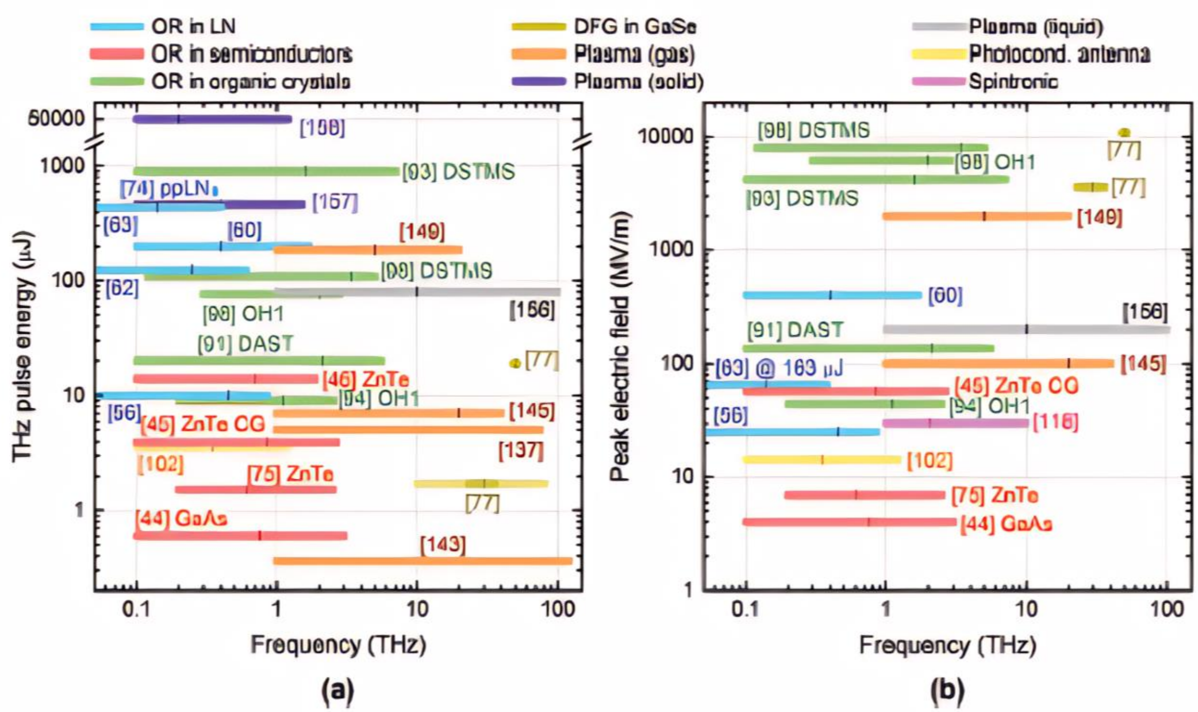
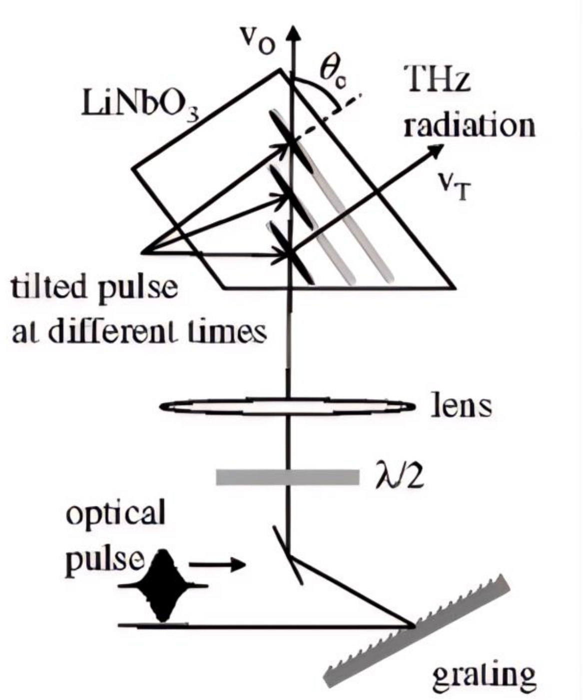


Maximum:
~10 mJ

Maximum:
~10MV/cm


v_O
θ_c
THz
radiation
$LiNbO_3$
v_T
tilted pulse
at different times
lens
λ/2
optical
pulse
grating

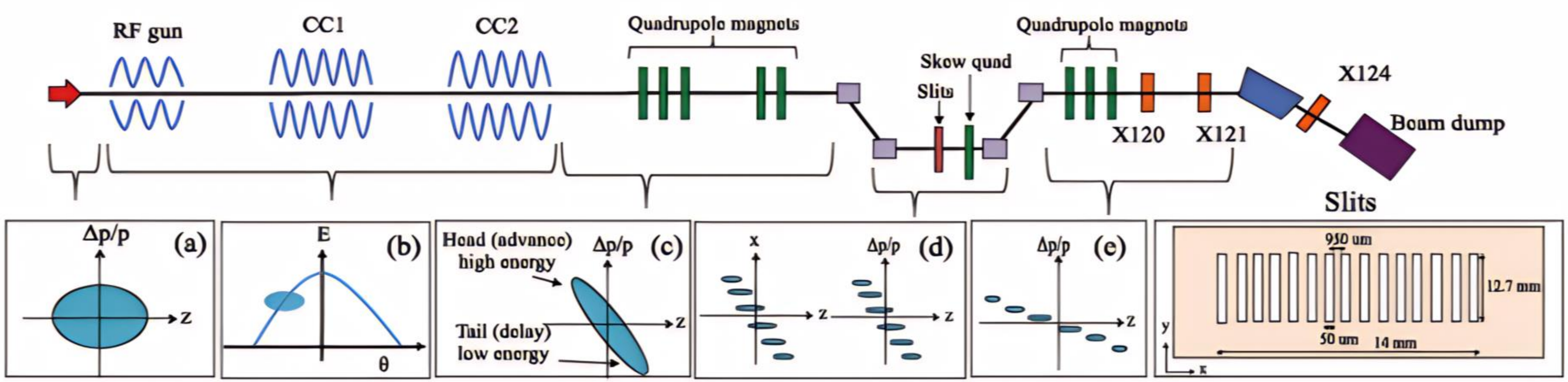
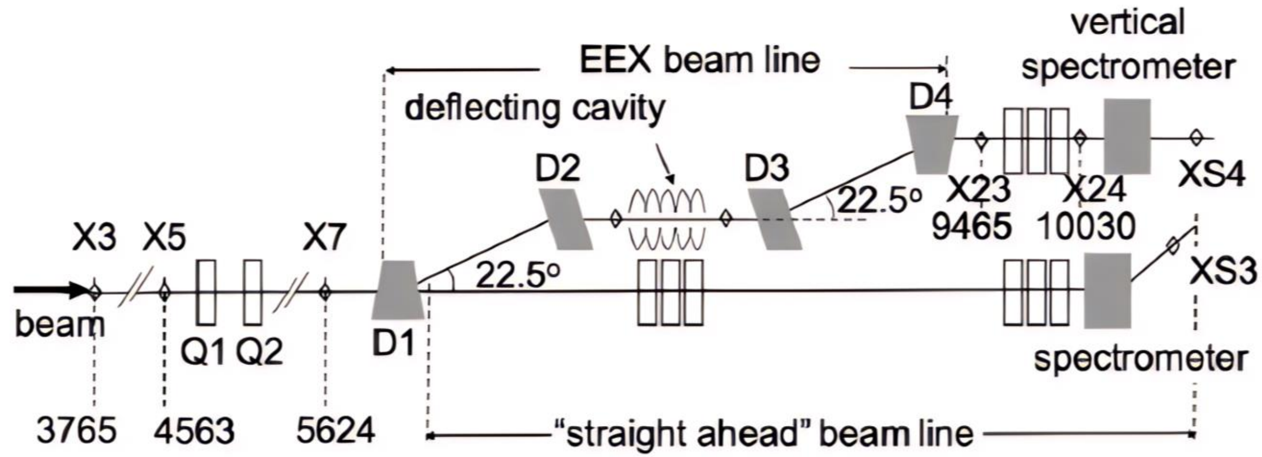


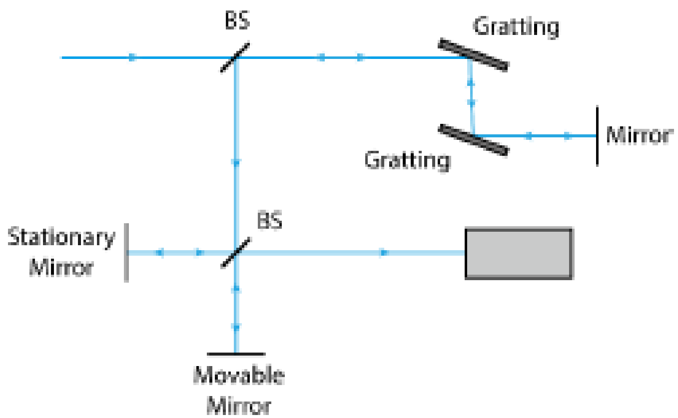
Figure 1: Layout of the FAST injector and phase spaces of an electron beam at each place.

Ref: Micro bunched beam production at fast for narrow band THz generation using a slit mask, IPAC2018



$$z = -\frac{\xi}{\eta}x_0 - \frac{L\xi - \eta^2}{\eta}x_0' \; \delta = -\frac{1}{\eta}x_0 - \frac{L}{\eta}x_0'$$

Ref: Tunable sub-picosecond electron bunch train generation using a transverse to longitudinal phase space exchange technique, PRL



Chirped pulse beating

$$E_{in}(t) = E_0 \cdot \exp\left[\left(\frac{t}{\sigma}\right)^2 - i\omega_0 t\right]$$

$$\Phi(\omega) = \Phi(\omega_0) + \tau_0(\omega - \omega_0) + \frac{(\omega - \omega_0)^2}{2\mu} + \beta(\omega - \omega_0)^3 + \ldots .$$

Phase including GVD and TOD

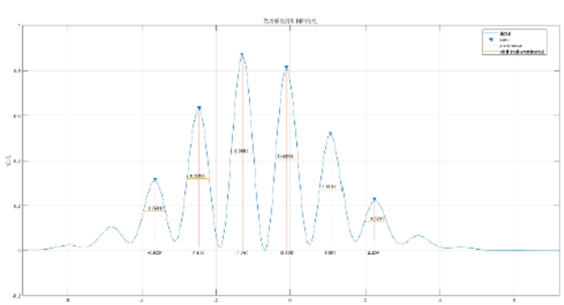
$$\cong E_0\left(\frac{\sigma}{\sigma_n}\right)^{1/2} \exp\left\{\frac{-t^2}{\sigma_n{}^2}\left[1 - i\left(\frac{\sigma_n}{\sigma}\right)\right]\right\} \times \exp\{i[\Phi_0 - \omega_0(t + \tau_0) - \pi/4]\},$$

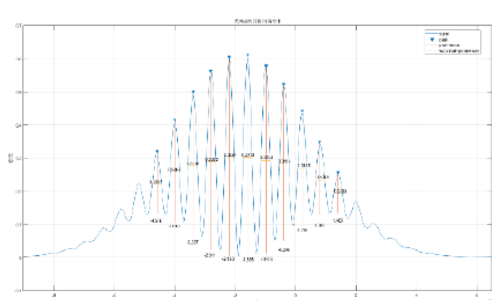
Chirp spread

$$I(t) = \left|E_+\left(t + \frac{\tau}{2}\right) + E_-\left(t - \frac{\tau}{2}\right)\right|^2$$

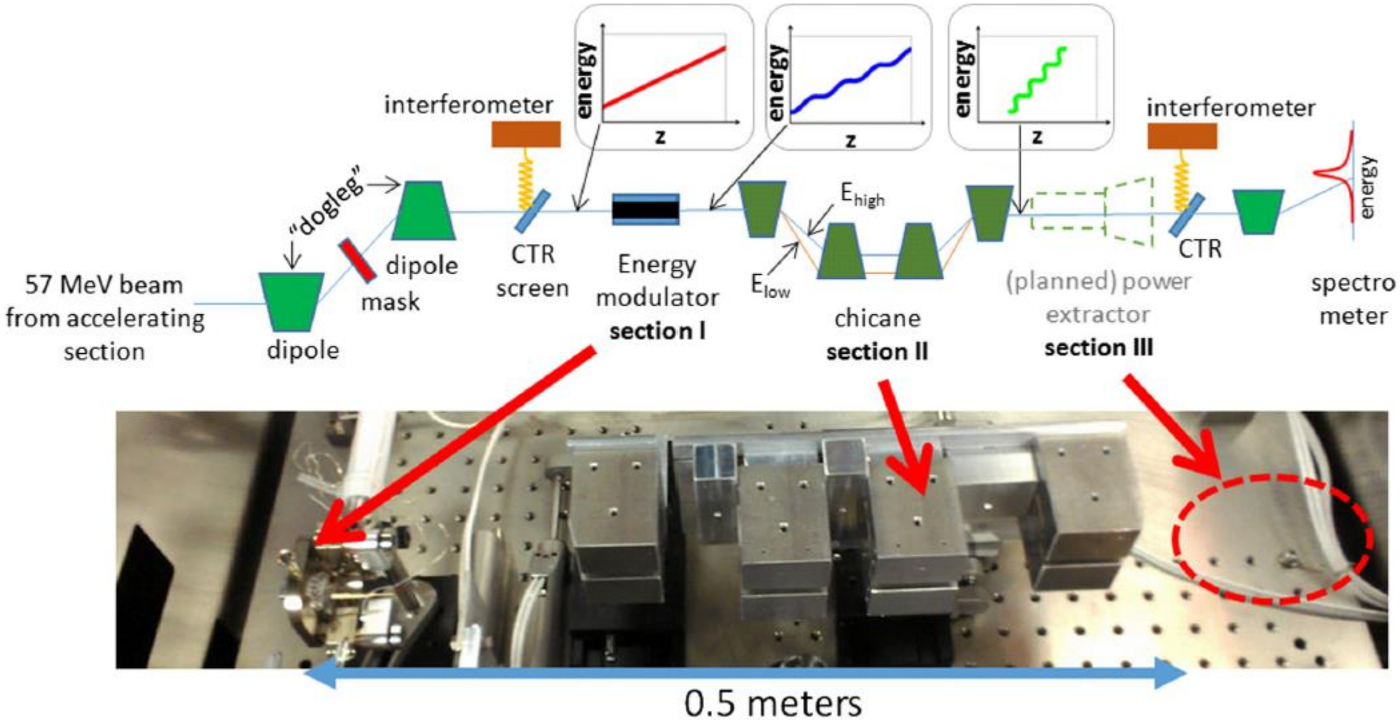
$$= I^+(t) + I^-(t) + E_0{}^2\left(\frac{\sigma}{\sigma_n}\right) \times \exp(-2t^2/\sigma_n{}^2)\exp(-\tau^2/2\sigma_n{}^2) \times \cos\left(\frac{2t\tau}{\sigma_n\sigma} + \omega_0\tau\right).$$

Beating wave

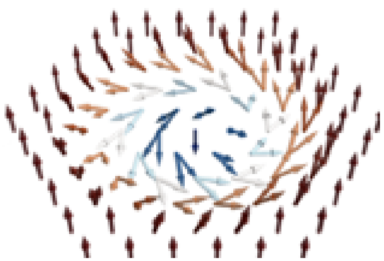


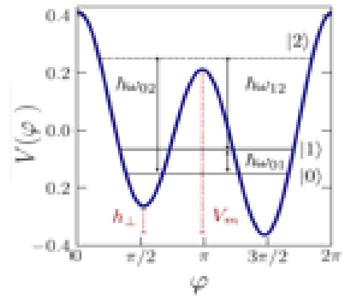


One numerical case



Ref: Sub picosecond bunch train production for a tunable mJ level THz source, PRL





量子态斯格明子第一激发态跃迁频率

量子态斯格明子能级间跃迁频率

Qubit类型	磁场	外场调控	ω_{01} (GHz)	ω_{12} (THz)
Z方向磁化(S_z)	8.9 mT	电场：108 mV/μm	25.6	0.31
旋度(Helicity)	445 mT	电场：296 mV/μm	14.9	0.33
	445 mT	磁场梯度：1.73 mT/nm	2.1	0.33

磁场 | 磁场调控 | 微波场 | THz 波段