國家同步輻射研究中心
National Synchrotron Radiation Research Center

2026 自由電子雷射冬季課程
Winter School on Free Electron Lasers

Superradiant THz FEL at NSRRC

周明昌

國家同步輻射研究中心

線型加速器小組

Outline

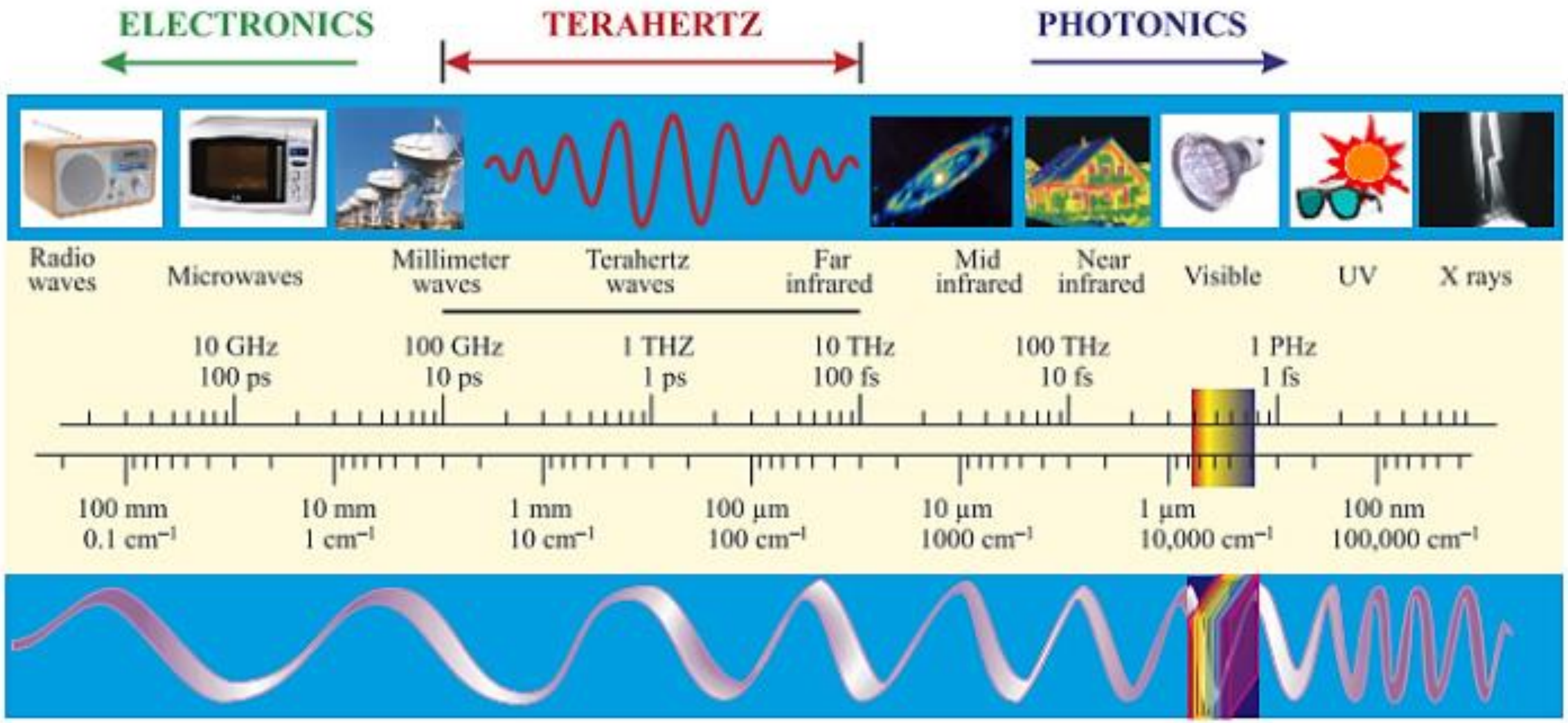
I. Introduction of THz sources

II. Development of superradiant THz FEL at NSRRC

- NSRRC high-brightness photo-injector system
- Superradiant THz free electron laser

III. NSRRC THz user facility

What is the Terahertz (THz) Wave?

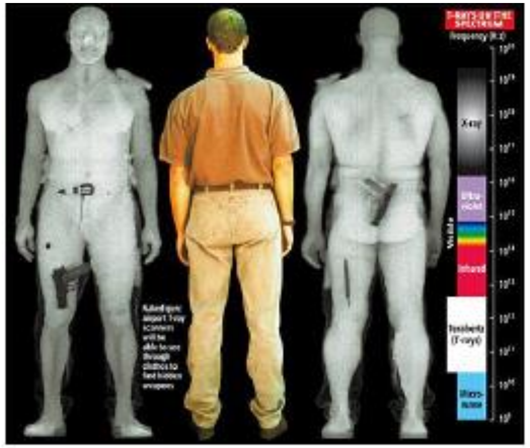


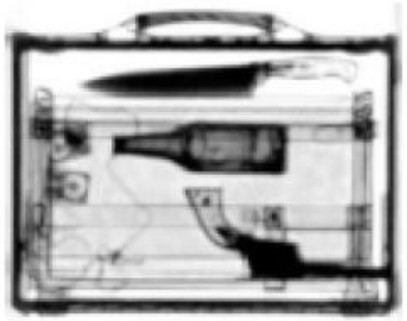
Terahertz wave (THz or T-ray), which is electromagnetic radiation in a frequency interval from 0.1 to 10 THz (3 mm to 30 μm), lies a frequency range with rich science but limited technology.

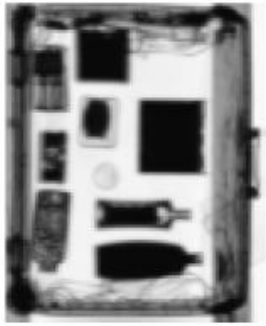
1 THz = 300 μm = 1 ps = 33 cm^{-1}

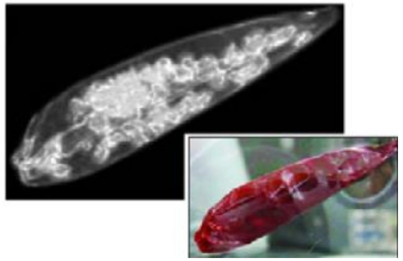
Applications of THz Radiations

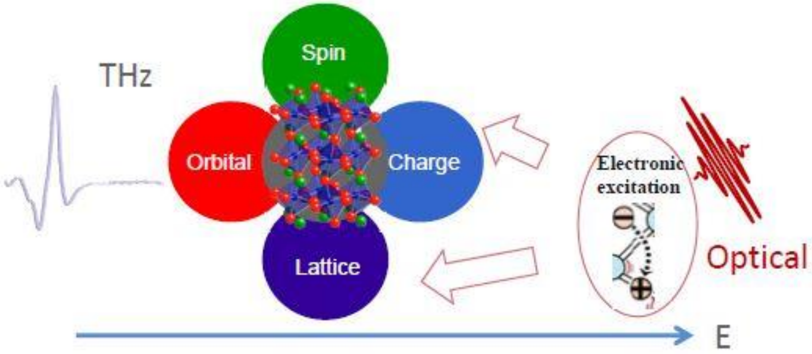
- medical imaging; security technologies; communication; pharmaceuticals
  - THz radiation enables imaging capabilities complementary to X-ray imaging
- THz/optical pump probe; THz/x-ray pump probe
  - THz pulse can drive nonlinear response in matter
- Manipulate and control material properties
  - ultrashort, coherent light with Ep > 100 kV/cm is required)

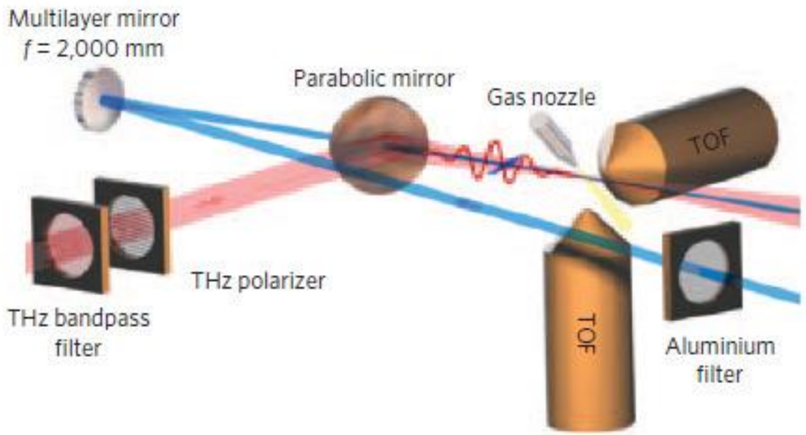








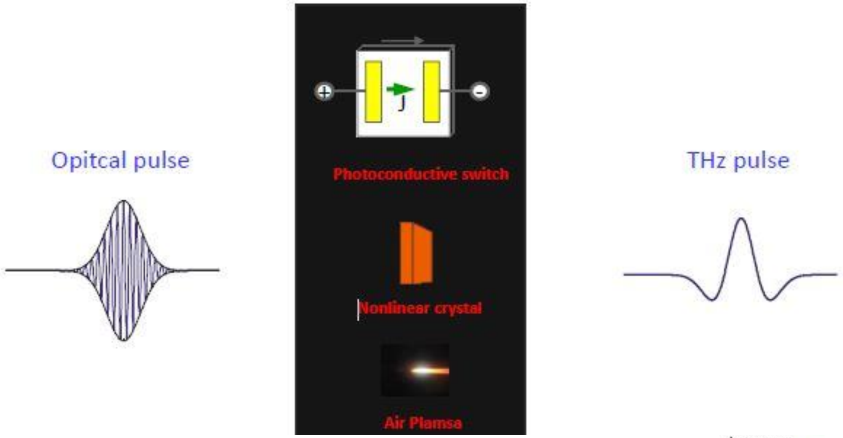


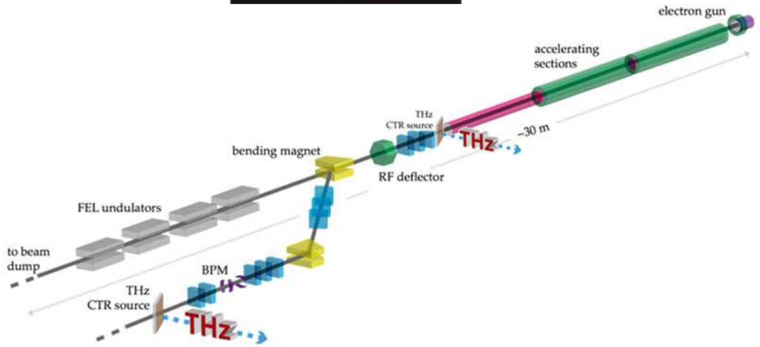


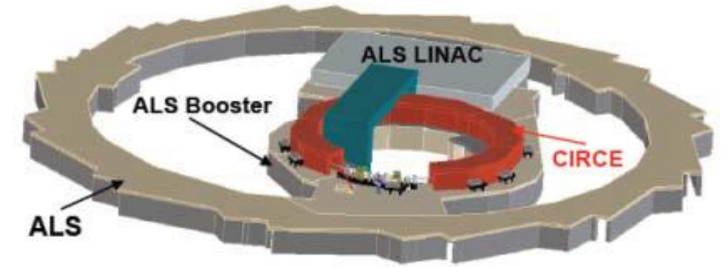
Ref: U. Frühling et. al., Nat. Photon. (2009)

Overview of Available THz Sources

- **laser based**
  - Photoconductive switch (antenna)
  - Nonlinear crystal
    - optical rectification (OR)
    - difference frequency generation (DFG)
  - Gas or air plasma
- **accelerator based**
  - **Single-pass accelerator based**
    - coherent undulator radiation (CUR)
    - coherent transition radiation (CTR)
    - cherenkov radiation
    - smith-purcell radiation
    - free electron laser
  - **Storage-ring based**
    - coherent synchrotron radiation
    - low alpha mode

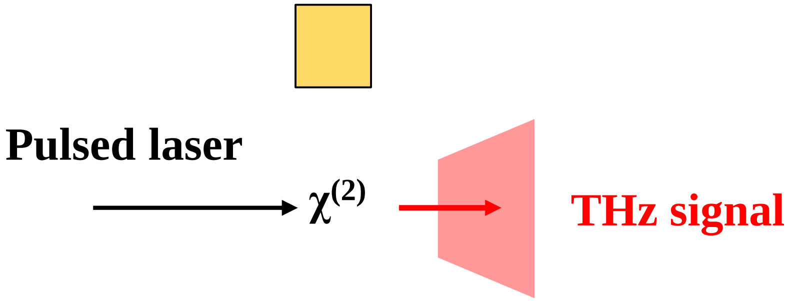






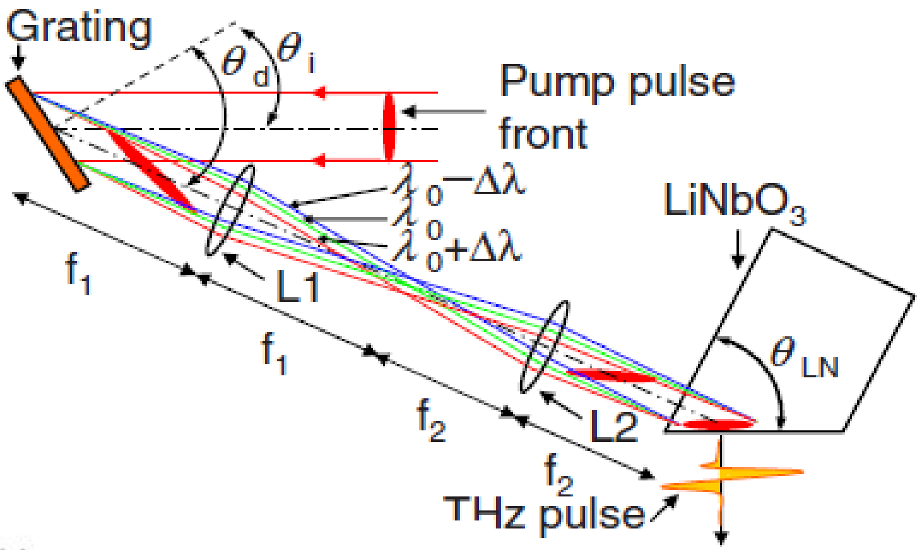
Laser-Based Intense THz Sources

Optical rectification

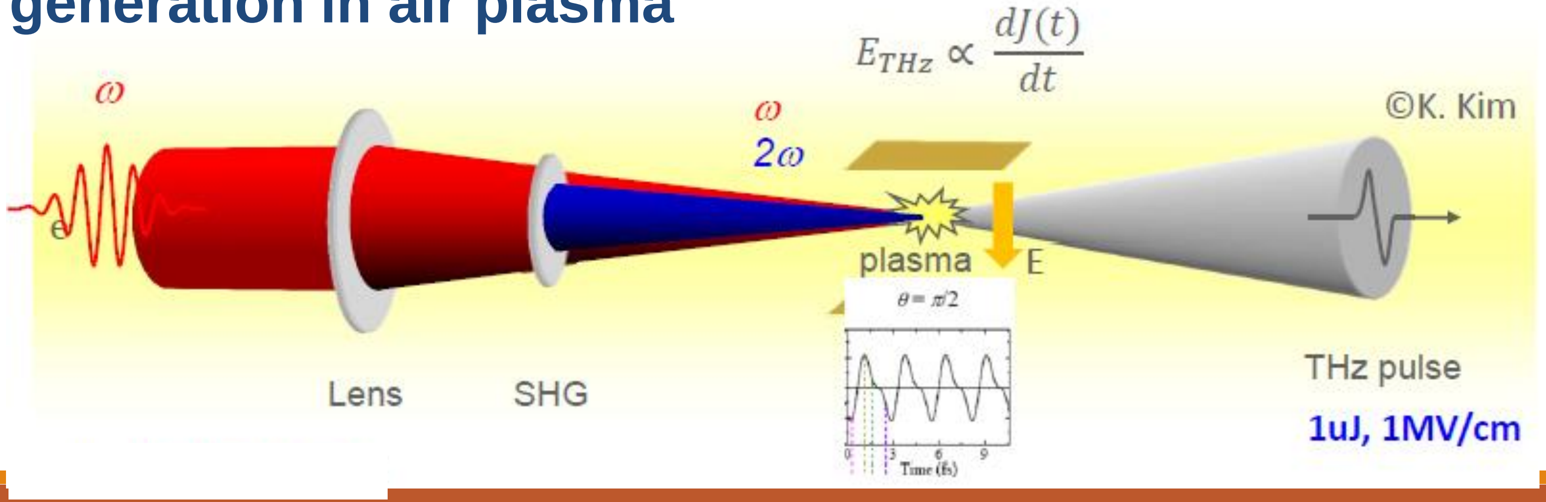


ZnTe, $LiNbO_3$ etc….

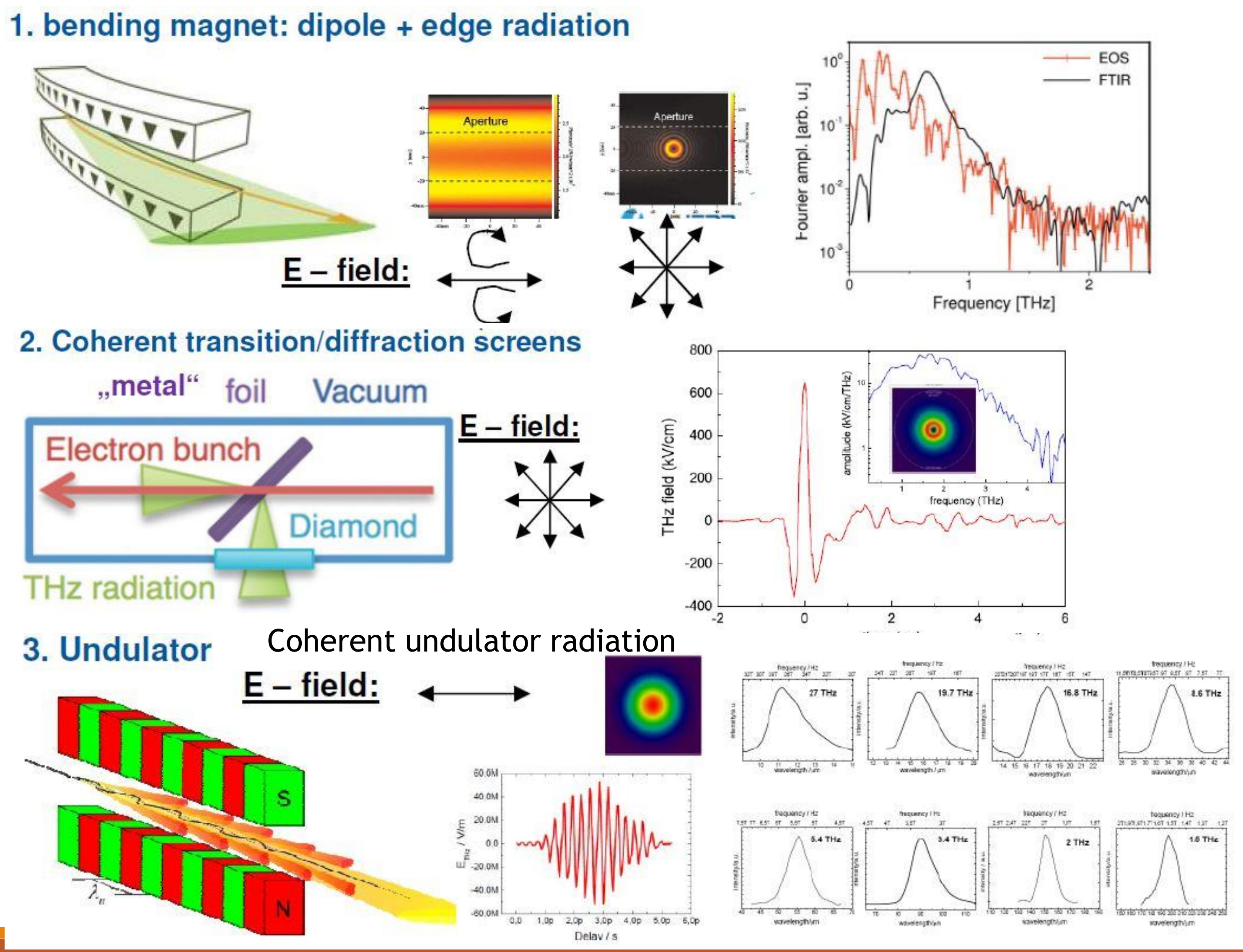
Tilted Pulse Front technique



THz generation in air plasma



Accelerator-Based Coherent THz Sources



Source type: "super-radiant" sources

Overall properties:

- Pulse energy: up to mJ regime (in principle massively scalable!)
- Spectral bandwidth: tunable narrow bandwidth or broad spectral bandwidth
- Repetition rate: few Hz to MHz (depending on rep. rate of accelerator)

Typical application:

Nonlinear dynamics, diagnostics (electron bunch/X-rays), THz control

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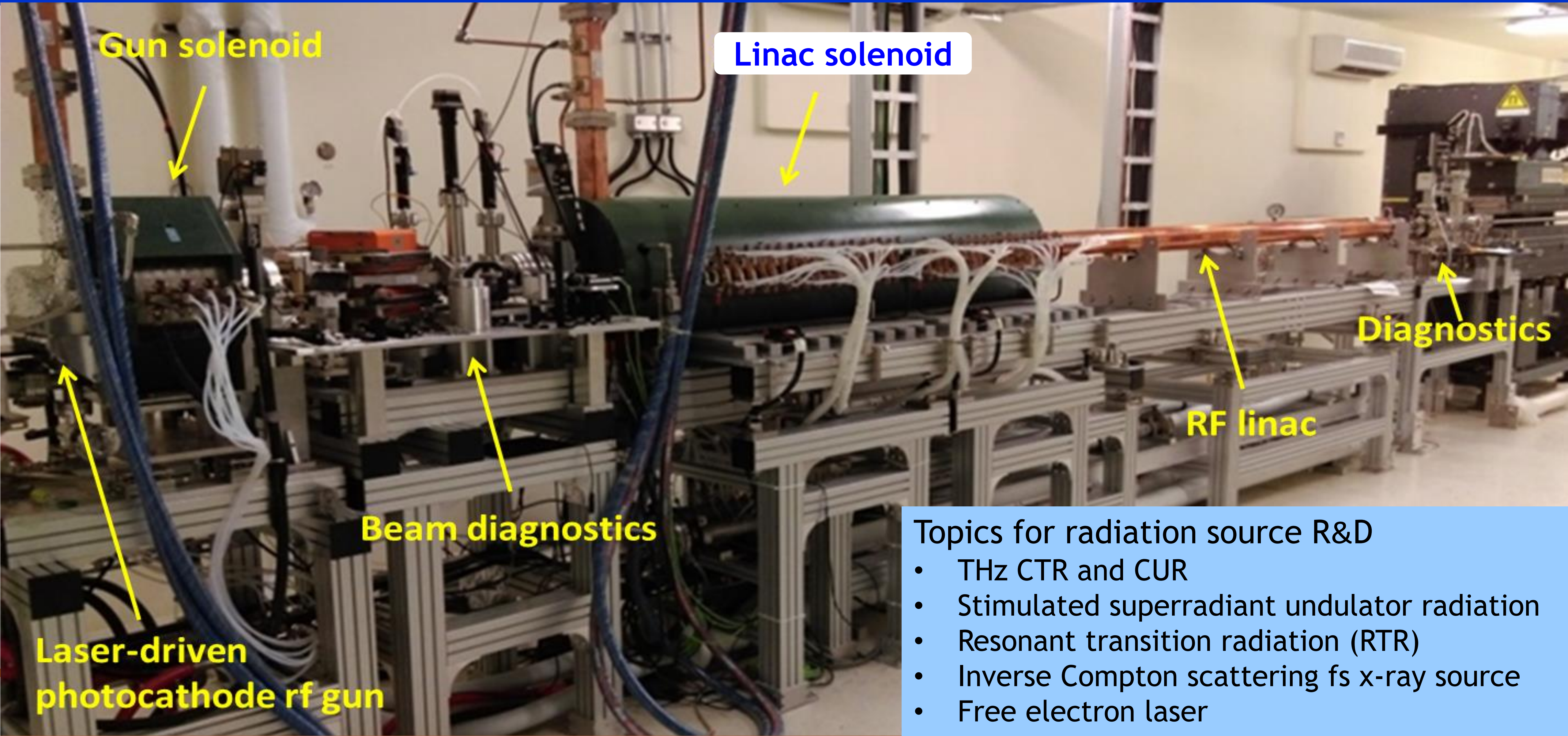
NSRRC high-brightness Photo-injector System - a Test Accelerator for Light Source Development



Topics for radiation source R&D

- THz CTR and CUR
- Stimulated superradiant undulator radiation
- Resonant transition radiation (RTR)
- Inverse Compton scattering fs x-ray source
- Free electron laser

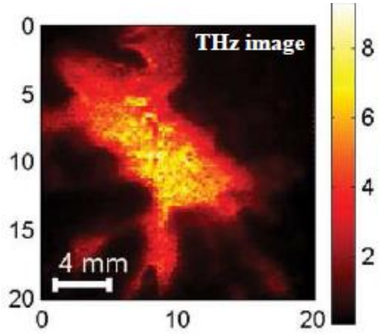
Production of High Brightness Electron Beam

- **high brightness electron beam → high brilliant light sources**
  (short electron bunch, high charge, and low emittance)

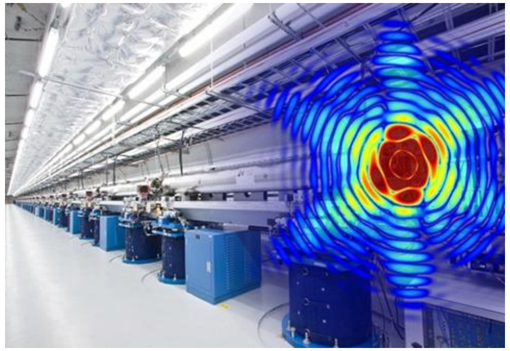
$$B = \frac{q}{\varepsilon_{n,x}\varepsilon_{n,y}\sigma_t\left(\sigma_\gamma / \gamma\right)}$$

- **Free electron laser (FEL)**
- B ~ 10^{14}-10^{16} A/m^2 is required to drive short wavelength SASE FEL
  (I_p > several hundreds of A, ε_n< 1 μm)
- **THz Coherent synchrotron radiation (CSR),**
- **THz Coherent transition radiation (CTR)**
- short electron bunch relative to radiation wavelength
  → sufficient form factor to enhance CR

✓ **Key issue of injector design:**
1. beam production 2. bunch compression
3. transport and preserve high brightness beam



THz image of tumor of breast cancer. [ref] P.C. Ashworth et al., Opt. Express 17 (2009) 12444; A.J. Fitzgeld et al., Radiology, 239 (2006) 533.



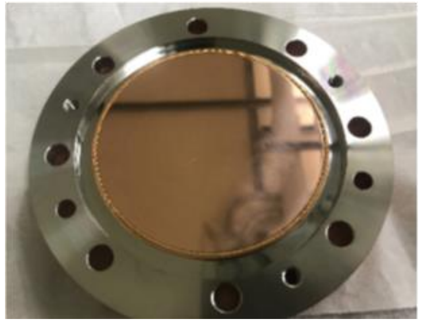
The LCLS and a diffraction pattern of a single mini virus particle. [ref] http://xray.bmc.uu.se/hajdu/

Photocathode RF Gun

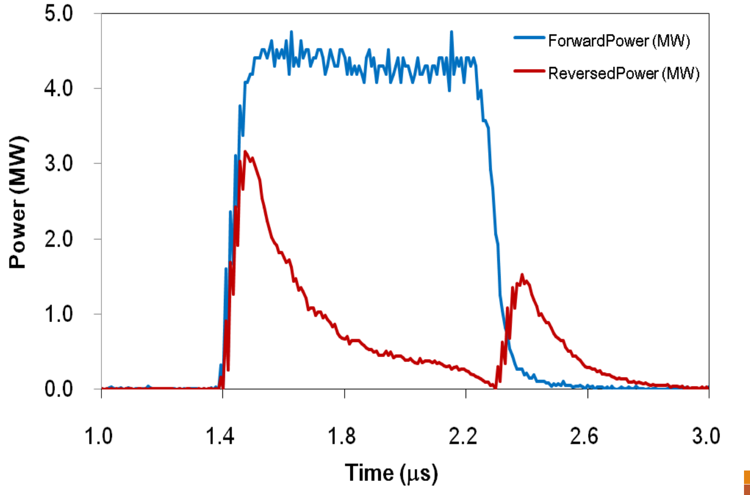
- Design is based on the 1.6 cell s-band rf gun developed at BNL DUV FEL.
- Copper (Cu) photo-cathode
- Operating at temperature 55°C , vacuum < 5 x 10^{-8} mbar

Parameter	Value
Frequency	2.99822 GHz (@55°C)
Q_0	~8000
Coupling coefficient	0.7
Peak field at the cathode	55 MV/m
Beam energy after gun	2.5 MeV
UV laser pulse duration	3 ps
Cathode quantum efficiency	~1 x 10^{-5}

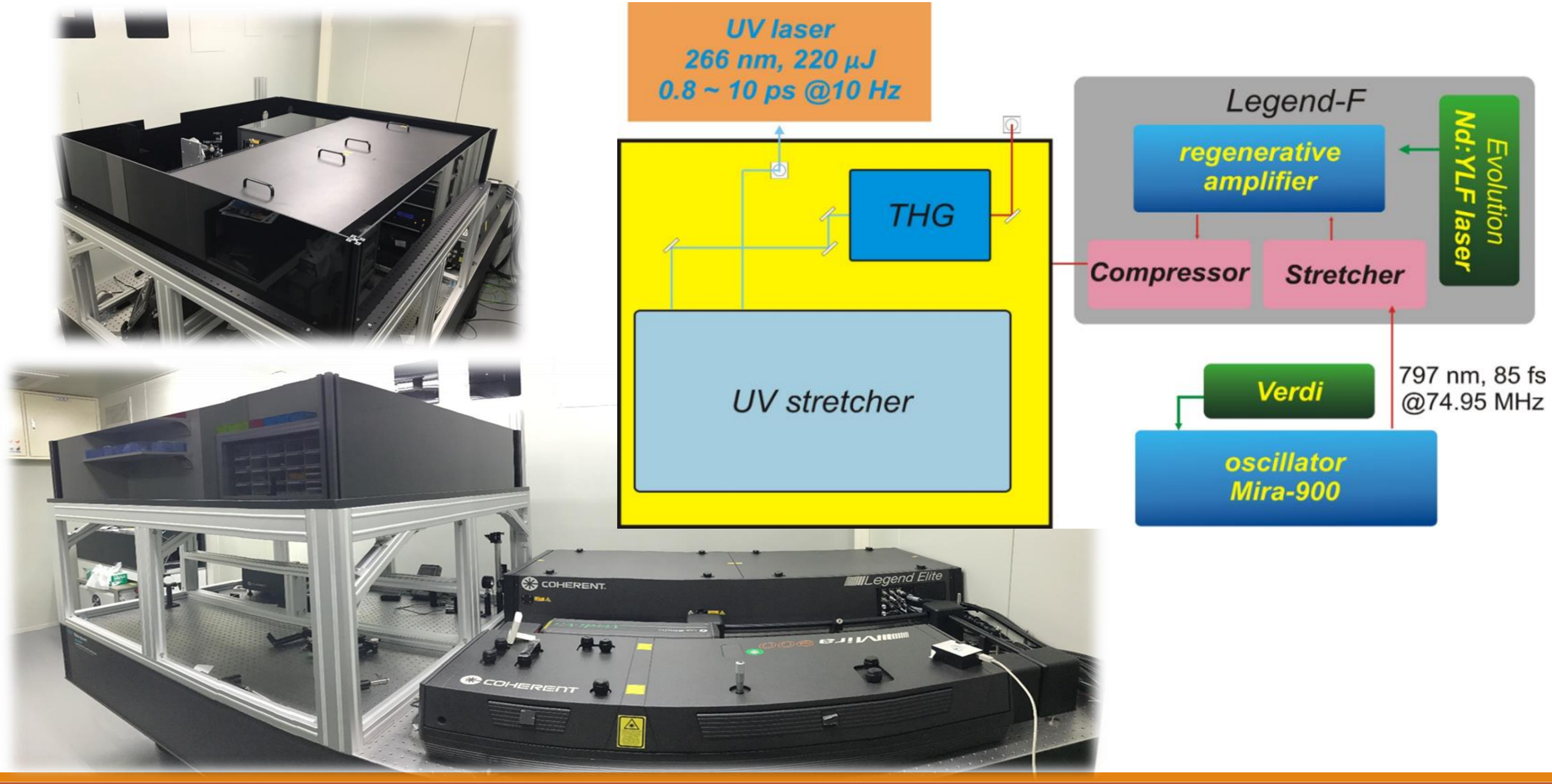
Cu cathode



Forward and reverse power of the Gun

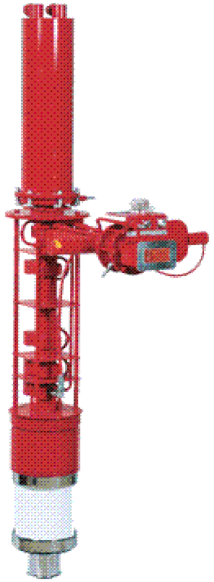


Drive Laser for the Photocathode RF Gun



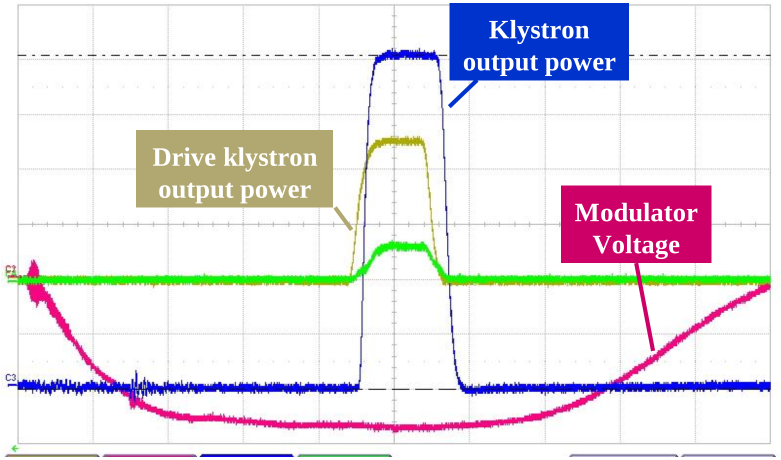
Pulsed Klystron System for the Photo-injector

Inside the oil tank



the Thales TH2100A
3 GHz, 35 MW pulsed
klystron

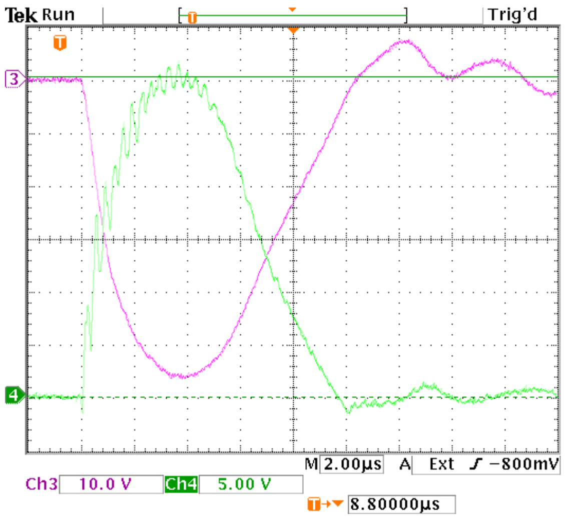
The Thales TH2100A in focusing magnet with X-ray shielding. The background is a 80 MW home-made line-type modulator.



Canon Pulsed Klystron System

Canon E37310A klystron

Canon klystron	
Klystron voltage (kV)	281
Klystron current (A)	307
Output power (MW)	35
Pulse width (μs)	2

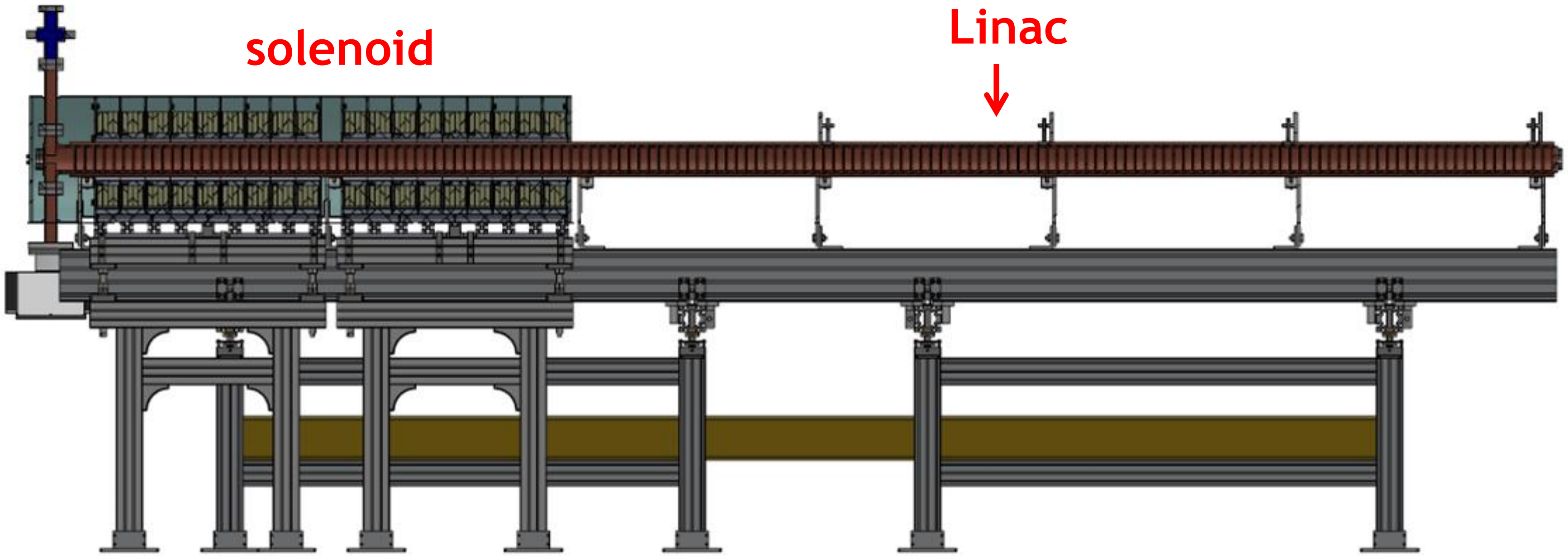


- The Thales klystron system was replaced by that of the Canon company to offer higher rf power in 2020.

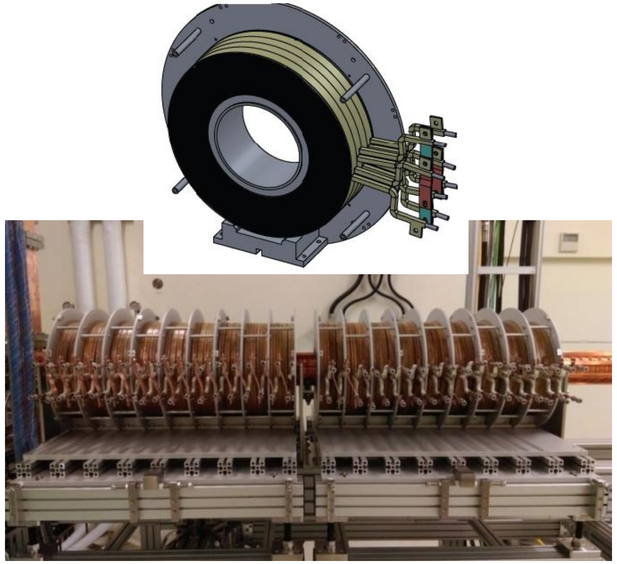
Homemade line-type Modulator	
9 sections PFN network	
PFN voltage, max (kV)	40
PFN character impedance (Ω)	2.8
PFN capacitance (μF)	0.1 x 9
Pulse width @ 50 % (μs)	6.5
Repetition rate (Hz)	10

Homemade Modulator

Photo-injector Linac and Focusing Solenoid



Homemade solenoid



- 2998 MHz, DESY-type 156-cell copper, constant gradient
- accelerating gradient >11 MV/m, total length: 5.2 m
- Linac solenoid for more beam size and emittance control!

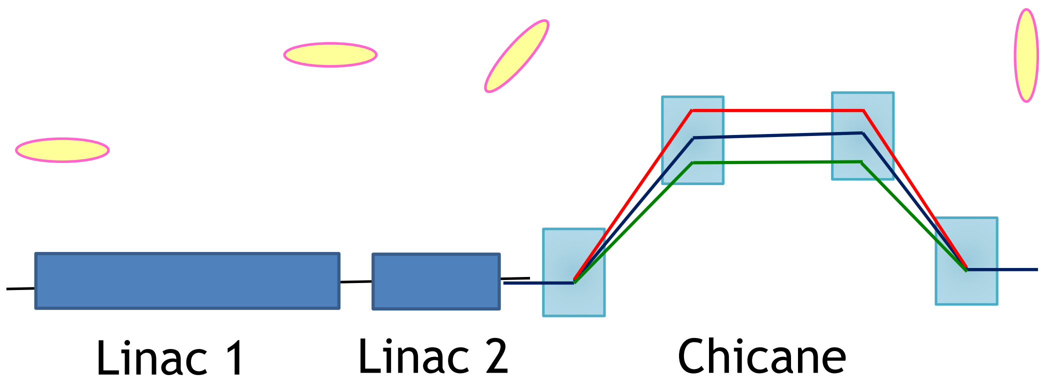
Bunch Compression Scheme

➢ Magnetic Bunching

- Step 1. RF chirp
- Step 2. dispersive section
- space for two-stage process
- wide range of adopted beam energy

< Issue >

- nonlineartity
- emittance degradation…

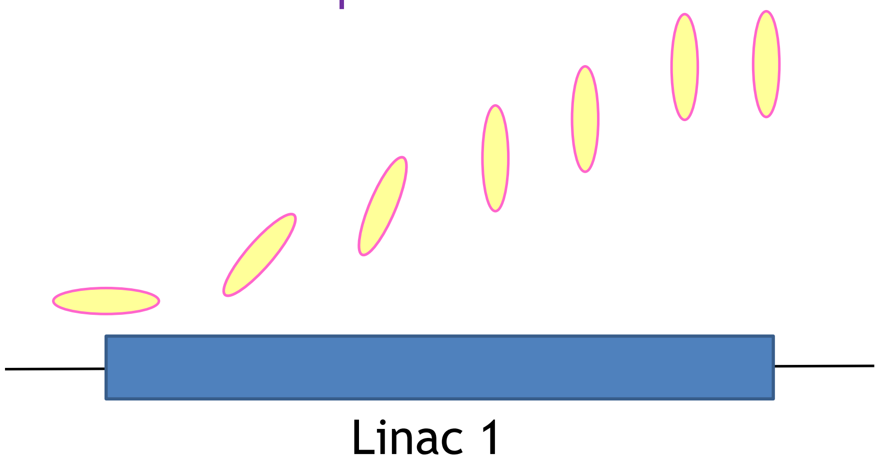


➢ Velocity Bunching

- 1 step in accelerating structure:
  acceleration + compression
- compact and simple operation
- suitable for low energy beam

< Issue >

- nonlineartity
- emittance compensation…

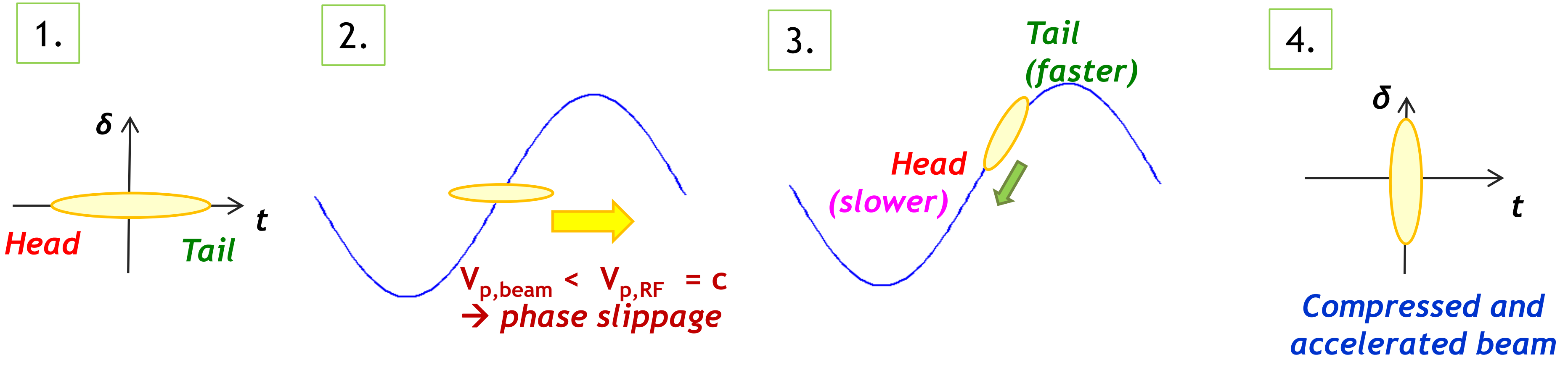


RF Bunch Compression in an Accelerator - Velocity Bunching

- Proposed by Prof. Serafini and Ferrario in 2001 for photoinjector system.
- **DUV-FEL facility at BNL, SPARC in INFN-LNF, PLEADES facility at LLNL, FLASH in DESY**

1. **Beam injection near the rf zero crossing phase**
2. **Phase slippage due to velocity difference between electron beam and rf field**
3. **Rotation of longitudinal phase space**
4. **Compression and acceleration simultaneously in the accelerating structure**

➢ **Velocity difference of energy modulated beam → velocity bunching**

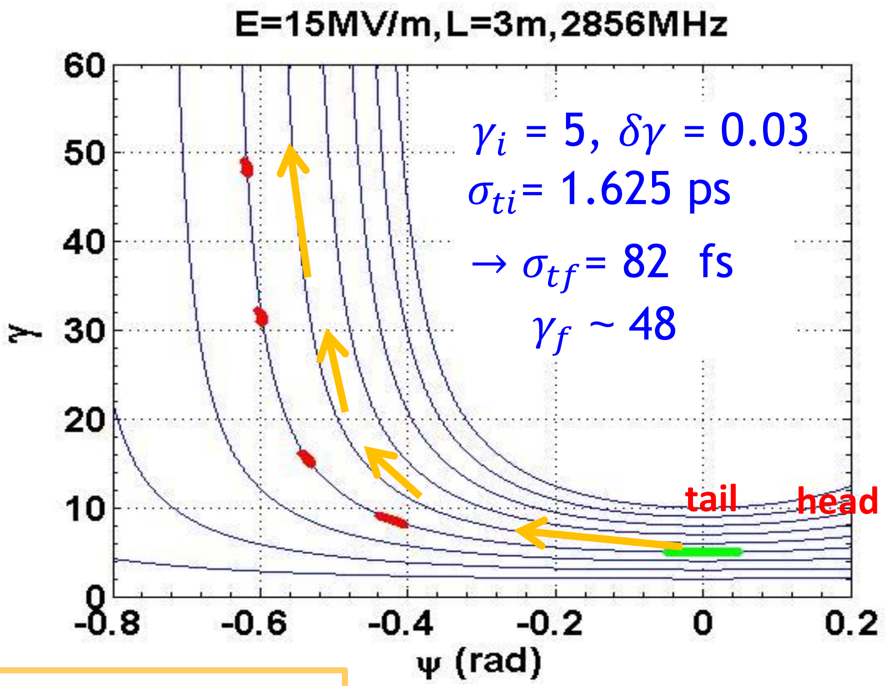


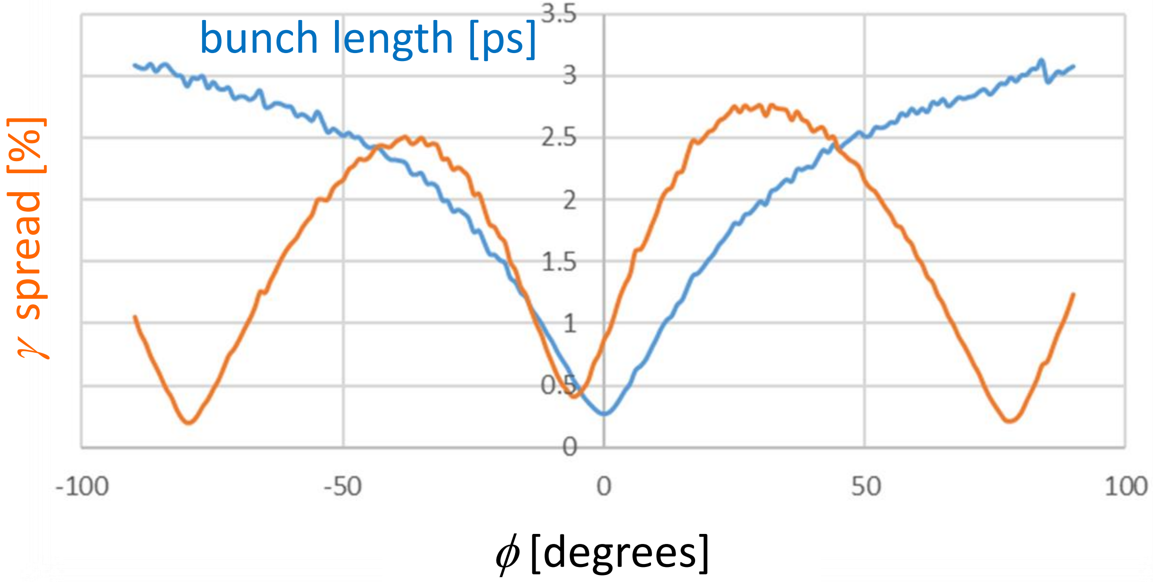
Velocity Bunching in an Accelerator

Velocity Bunching

→ the deformation of longitudinal phase space during phase slippage

→ bunch is compressed and accelerated simultaneously through the accelerating structure



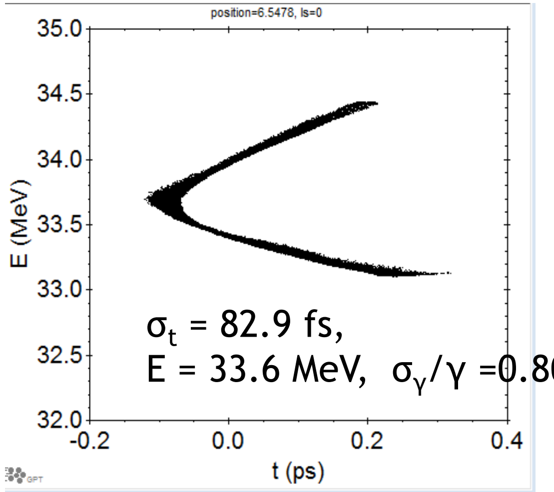


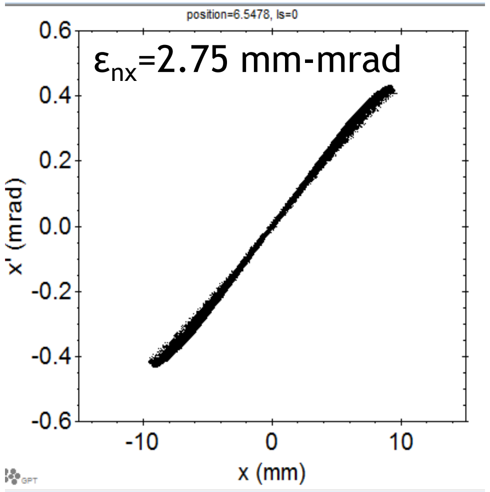
$$V = \beta c = c\sqrt{1 - \frac{1}{\gamma^2}}$$

- For high energy beam (γ >> 1, β~1), the particle velocity is saturated to c. There is no velocity difference between electron beam and rf field. It means this scheme works only for low energy beam (β<1).

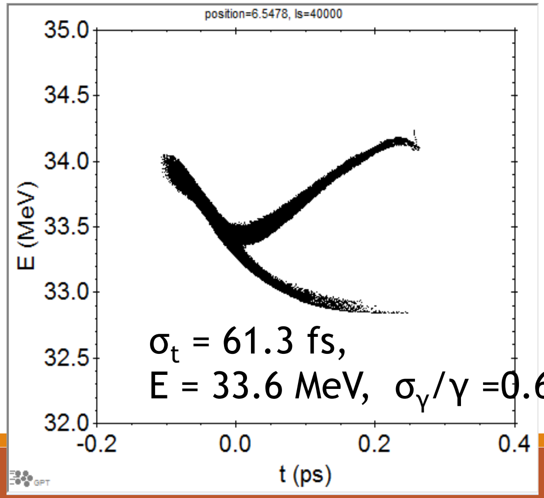
Ultrashort Bunch by Velocity Bunching

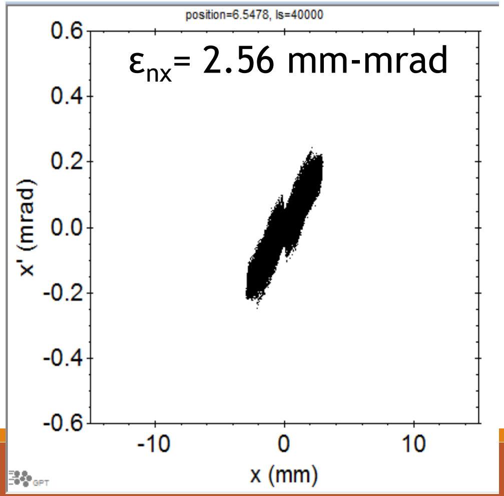
Phase space at L_0 Exit w/o linac solenoid





Phase space at L_0 Exit with linac solenoid





Gun condition

Ep = 65 MV/m,

Dp=10 deg, Bp = 1300 Gauss

Laser condition (uniform)

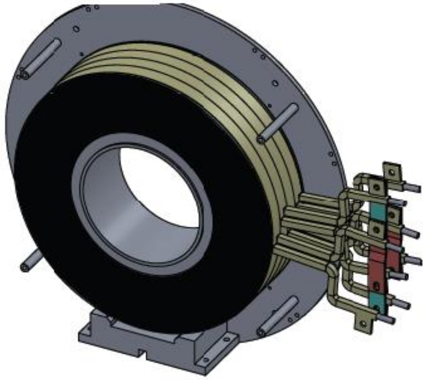
T_{FWHM}=3 ps, r = 1.0 mm,

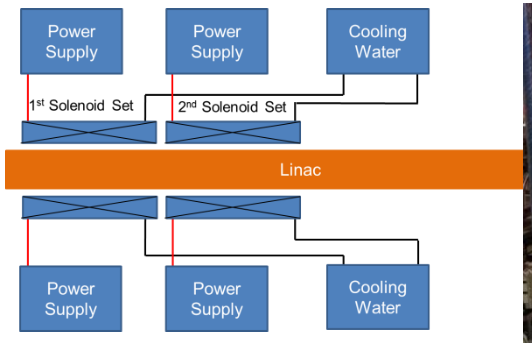
Q = 100 pC

LINAC L_0 condition

Ep = 15 MV/m,

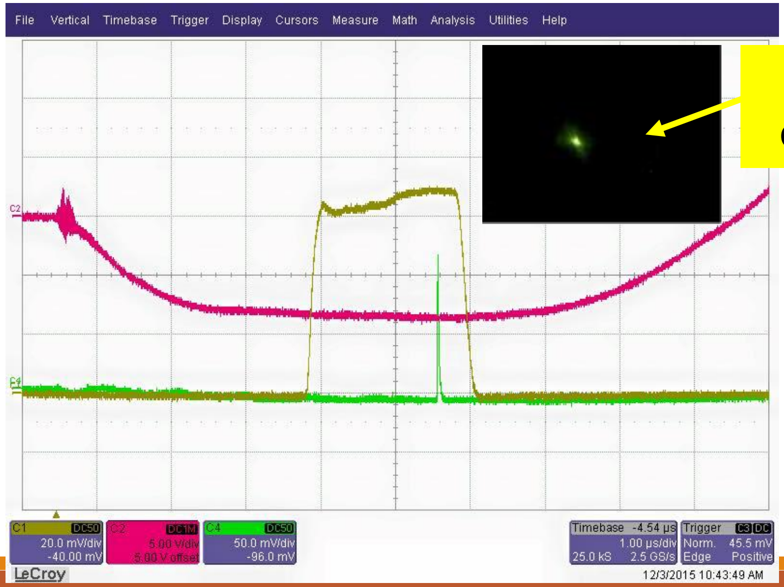
Bs = 502 Gauss, 3 m long solenoid





Commissioning of the High-brightness Photo-injector System

subsystem	Parameters	
RF Gun	Peak field	50 MV/m
	Electron energy	2.5 MeV
Laser	Laser pulse length (FWHM)	3 ps
	UV energy	110 μJ (@cathode)
Linac	E field gradient	12.5 MV/m
Electron beam	Electron Energy	60 MeV
	Bunch charge	Up to 600 pC
	Bunch length (rms)	240 fs
	Repetition rate	10 Hz



The first beam observed in 2015

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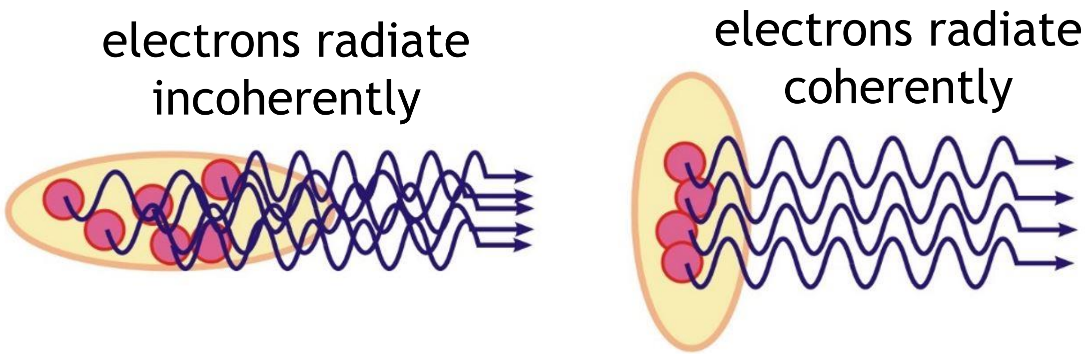
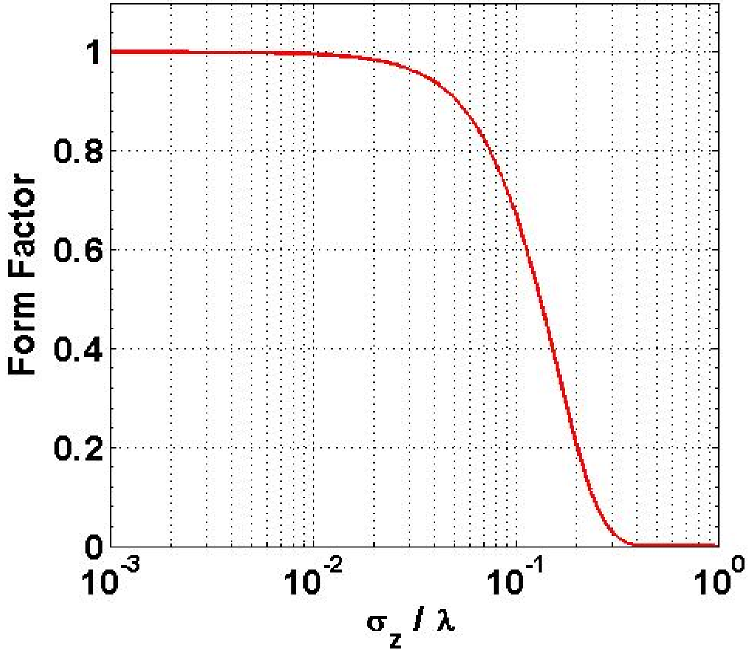
Accelerator-Based Coherent Radiations



bunch length σ_z << radiated wavelength λ



radiation power from a bunch of electrons

$$P(\omega) = P_0(\omega)[\underbrace{N(1 - f(\omega))}_{\text{incoherent}} + \underbrace{N^2 f(\omega)}_{\text{coherent}}]$$

$P_0(\omega)$: radiated power from a single electron

N: electron number

$f(\omega)$: bunch form factor

$$f(\omega) = \left| \int e^{ik\hat{n}\cdot\vec{r}} S(\vec{r}) d^3 r \right|^2$$

$S(\vec{r})$: 3D particle distribution

for a Gaussian bunch

$$f(\omega) = |exp(-2\pi^2 \sigma_z^2 / \lambda^2)|^2$$

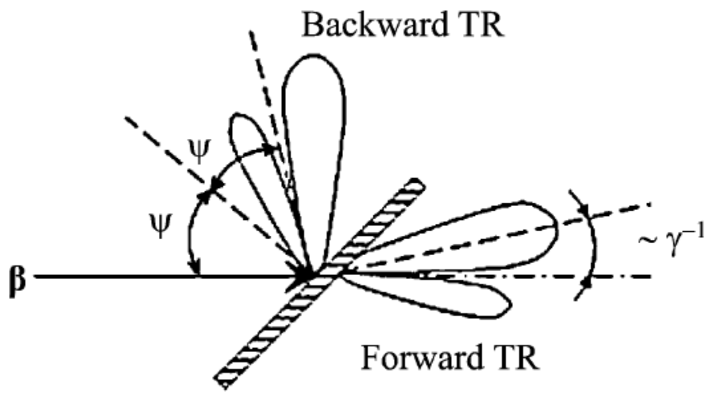
The power of coherent radiation will be about N^2 times larger than that of one electron.
(~ 10^{17} times enhancement for 100 pC bunch)

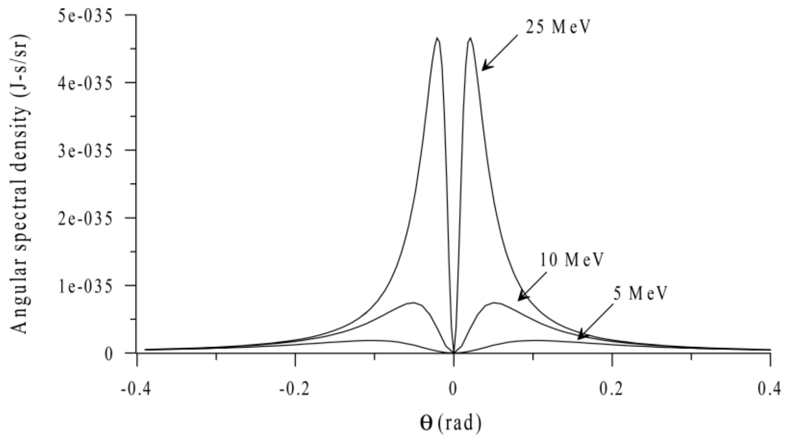
Coherent Transition Radiation

- Transition radiation (TR) is emitted when a charged particle passes through the boundary of two media with different dielectric constant. Forward TR and backward TR occur simultaneously.
- Spectral angular distribution of the emitted TR is given by

$$\frac{dW}{d\omega d\Omega} = \frac{e^2\beta^2 \sin^2 \theta}{\pi^2 c(1-\beta^2 \sin^2 \theta)^2}$$

θ is the emission angle with respect to the electron beam axis.



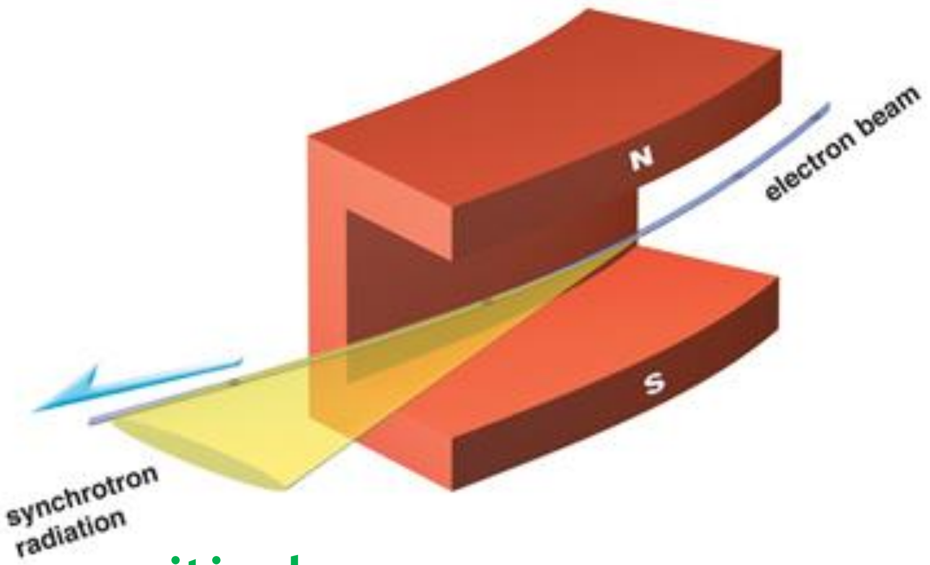


- The radiation intensity increases from zero in the forward direction to a broad peak at an angle $\theta \sim {}^{1}/_{\gamma}$
- When the wavelength of the radiation becomes larger than the bunch length, the radiation becomes "COHERENT". ($\lambda \gg \rho_z$)
- Measurements of the radiation spectrum give the information about the bunch length.

Ref: C.S. Thongbai and T. Vilaithong, Nucl. Instr. And Meth. A. 581 (2007) 874

Coherent Undualtor Radiation

Coherent Synchrotron Radiation (CSR)

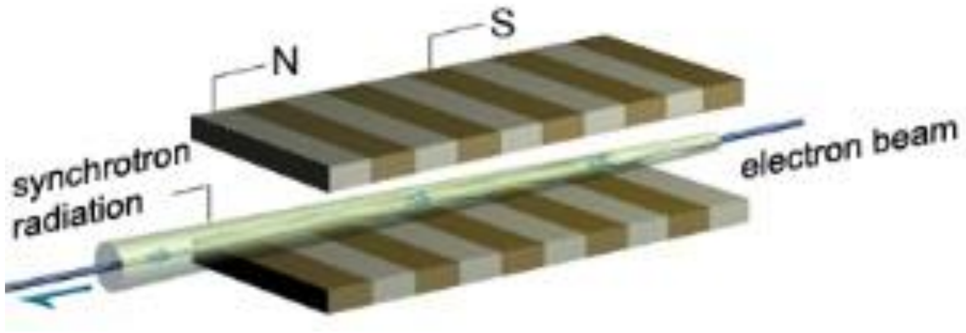


critical energy

$$\varepsilon_c[keV] = \hbar\omega_c = \frac{3\hbar c\gamma^3}{2\rho}$$

$$= 2.218\frac{E^3[GeV]}{\rho[m]}$$

Coherent Undulator Radiation (CUR) Superradiant Free Electron Laser



radiation wavelength

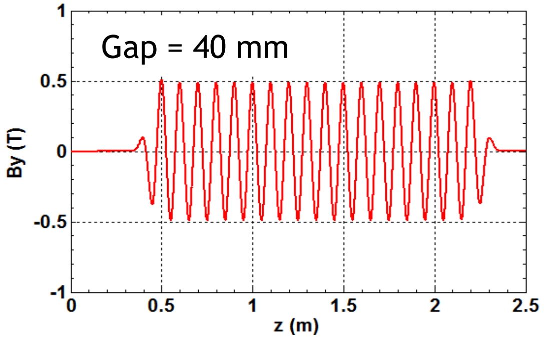
$$\lambda = \frac{\lambda_u}{2\gamma^2}(1 + \frac{K^2}{2} + \gamma^2\theta^2)$$

λ_u: undulator period

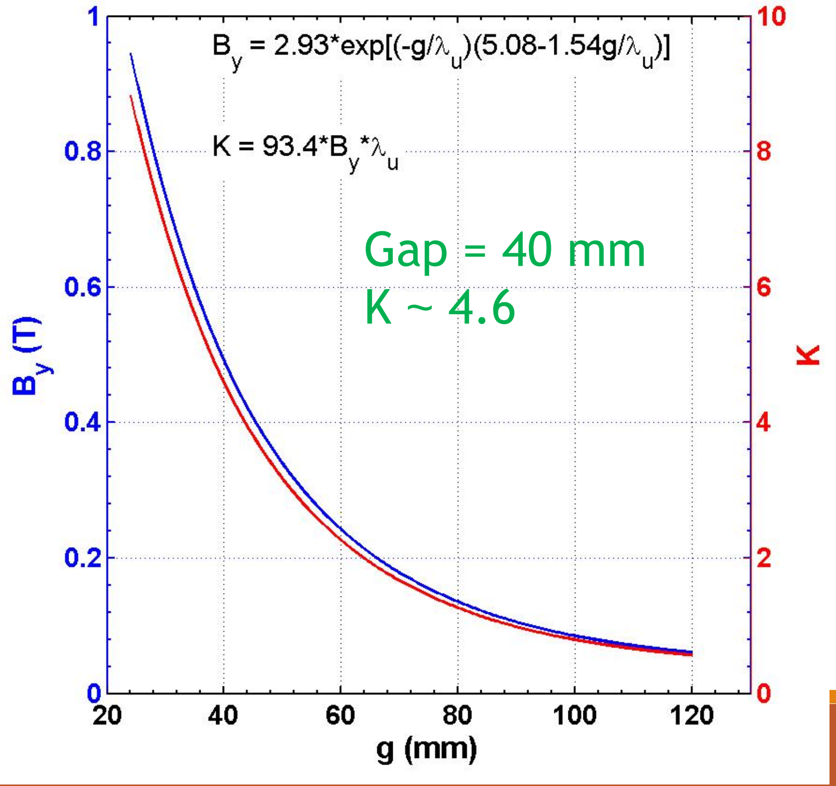
K: undulator strength

$K = 0.9337\hat{B}\ [T]\ \lambda_u\ [cm]$

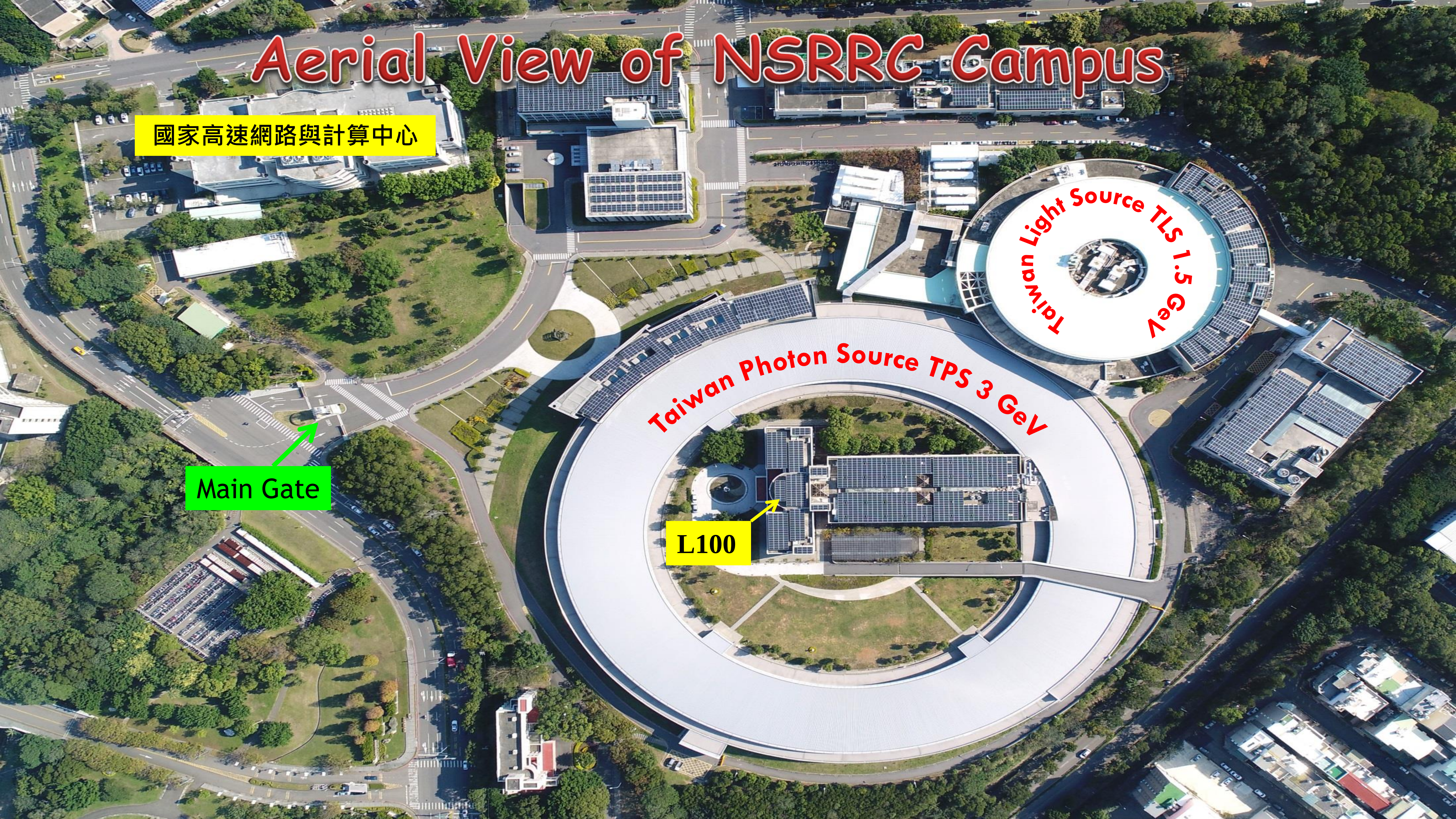
NSRRC U100 undulator



	U100
λ (mm)	100
N_{period}	18
L (m)	2.2
a_w	1.02
gap (mm)	24
B_y (T)	0.945
Ky_{max}	8.8



The U100 undulator built by the NSRRC magnet group more than 25 years ago is used for the superradiant THz FEL (pre-bunched THz FEL).

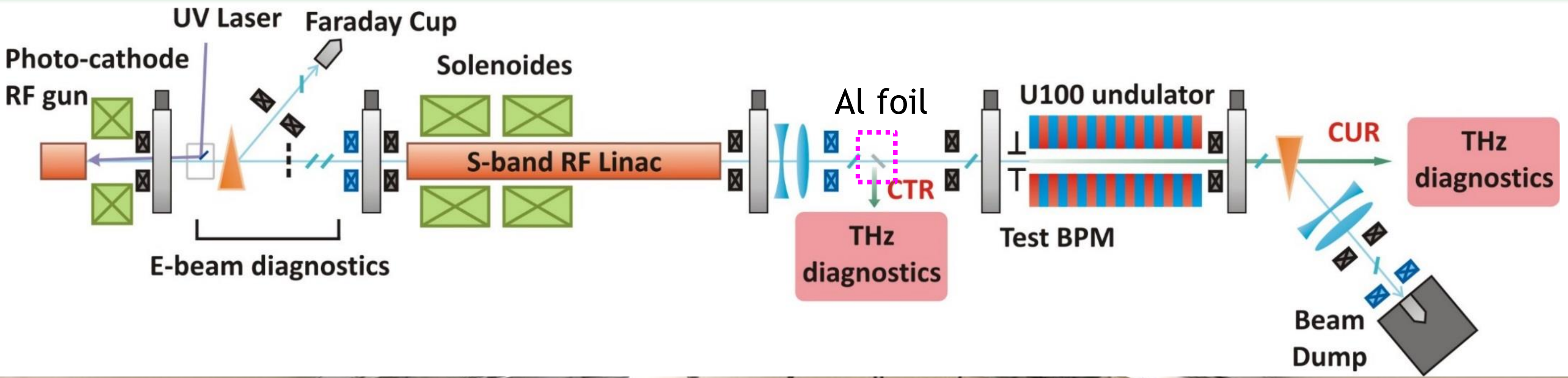

Aerial View of NSRRC Campus
國家高速網路與計算中心
Taiwan Light Source TLS 1.5 GeV
Taiwan Photon Source TPS 3 GeV
Main Gate
L100

Location of NSRRC THz User Facility

Accelerator Test Area

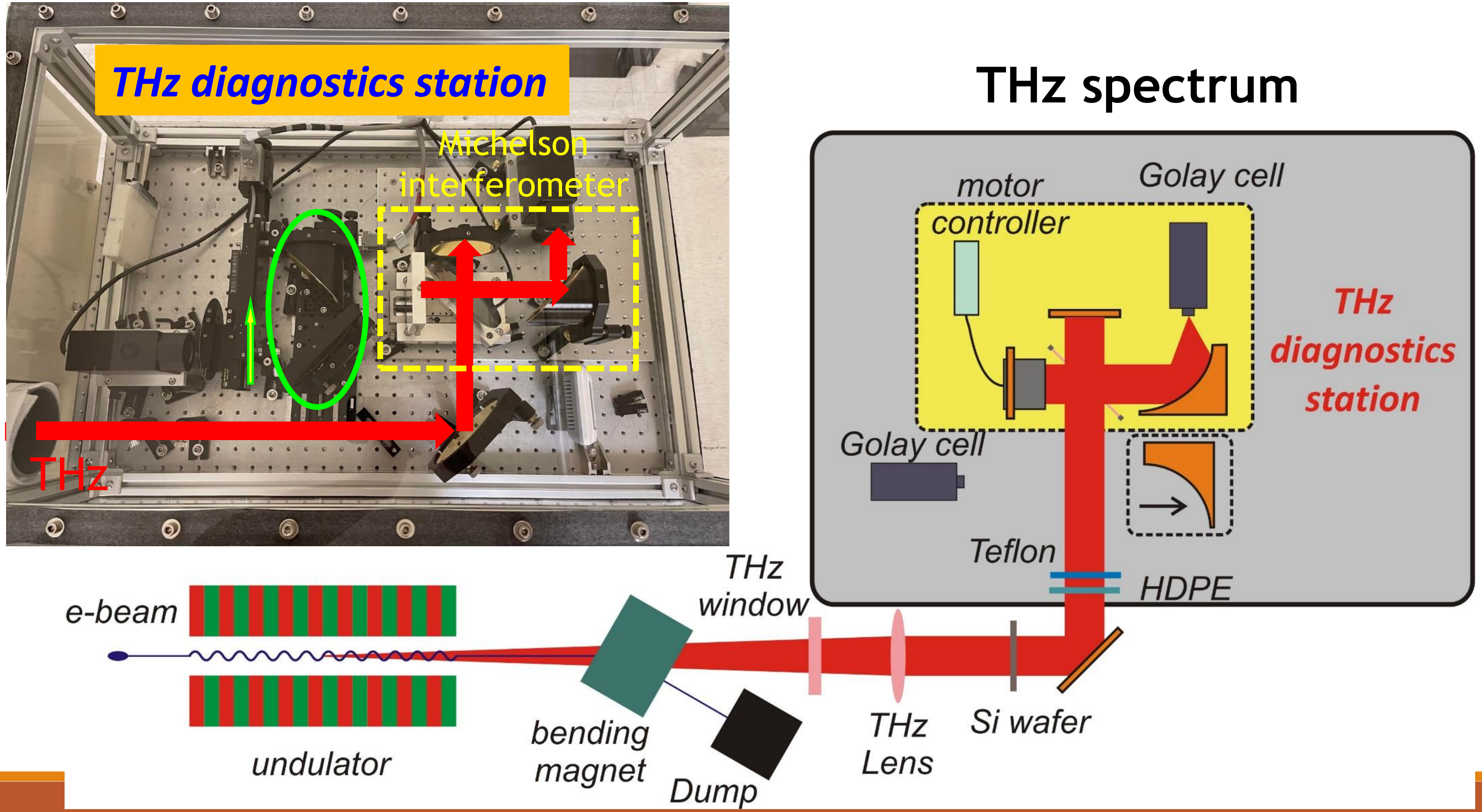
- First operation of the photo-cathode RF gun in 2013 at the TLS Booster.
- Construction of the photoinjector system at the Accelerator Test Area since 2014.
- In 2015 the 60 MeV photoinjector is in operation.
- Demonstration of generation of coherent THz sources in 2017.

Layout of the Coherent THz Radiation Sources

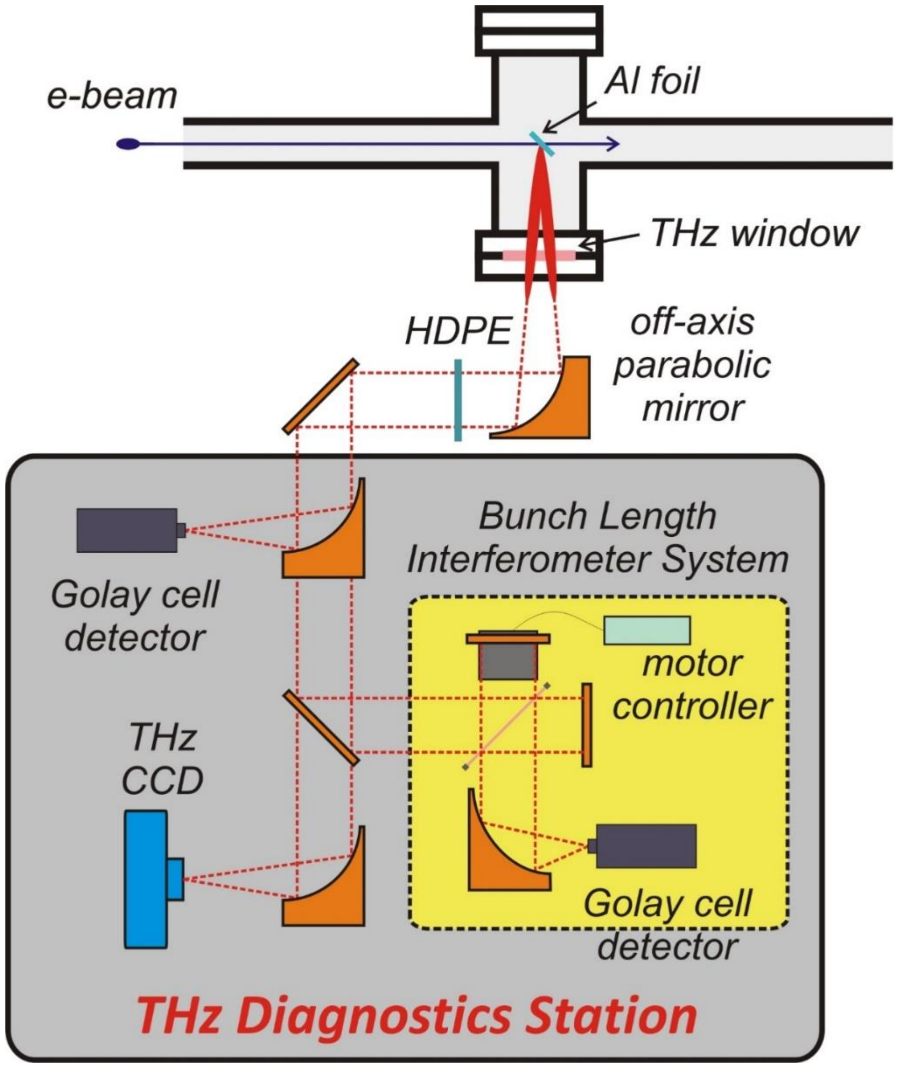


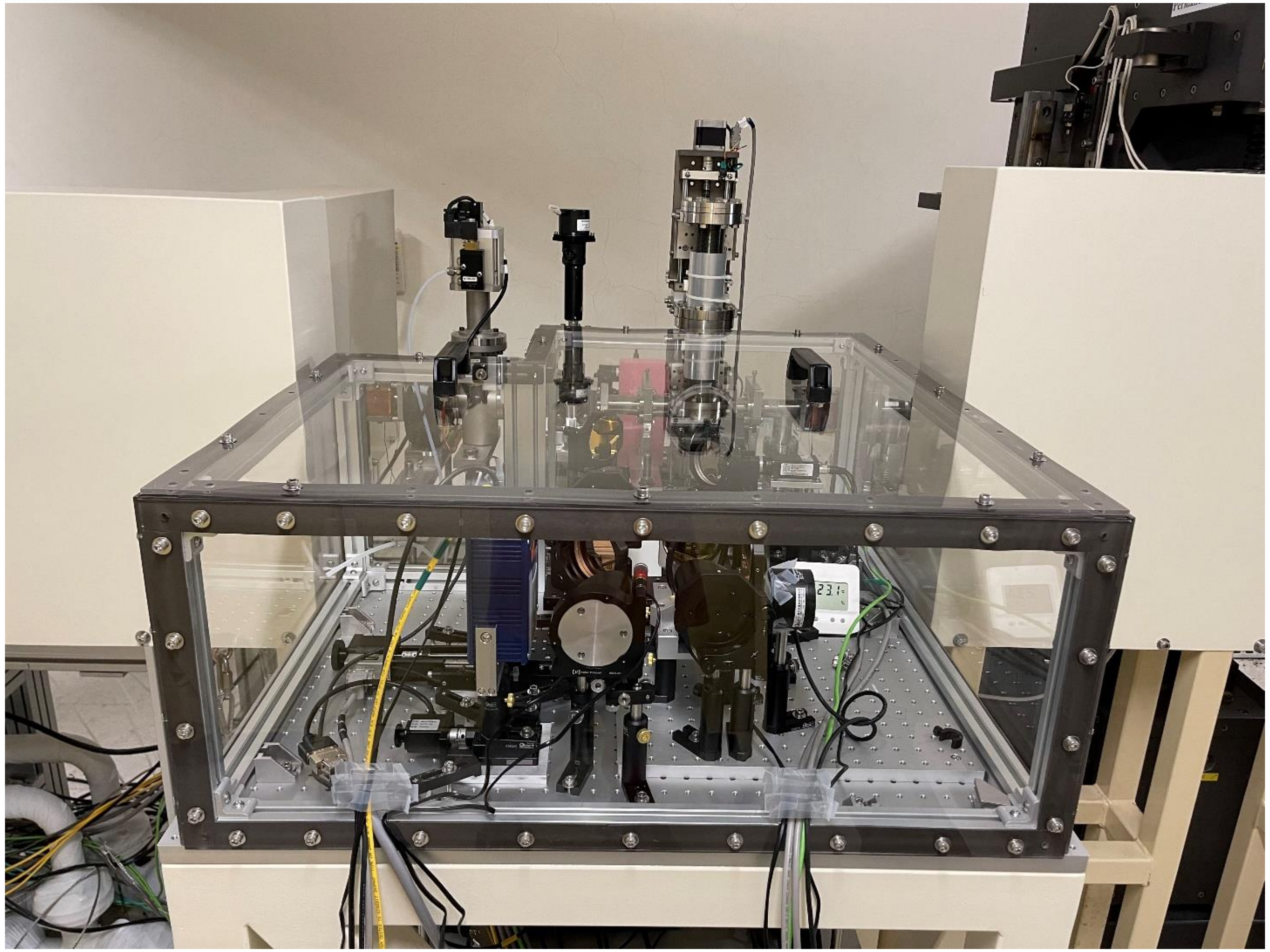
panoramic view

Output Diagnostics for Superradiant THz FEL



Setup of THz CTR Measurement



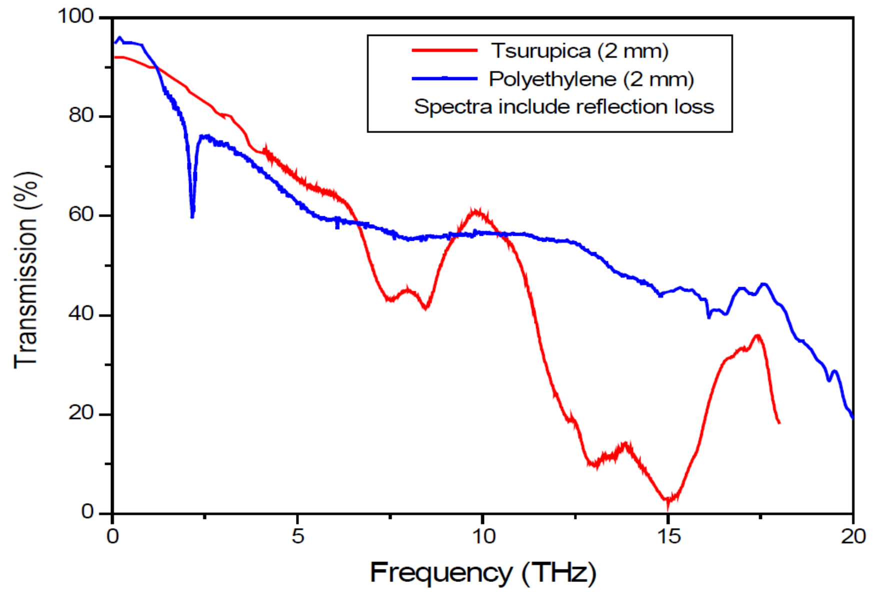


Measurements of the CTR interferogram give the information about the bunch length.

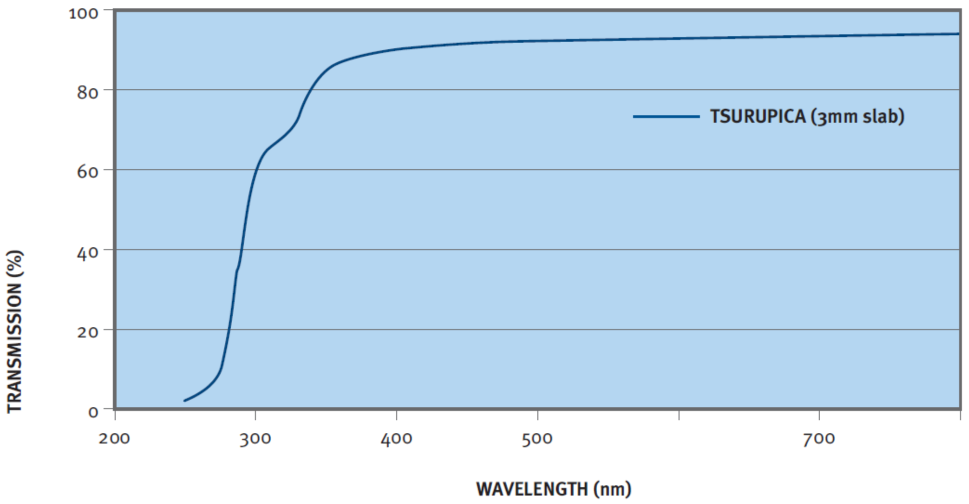
THz Material - Tsurupica

- has extremely higher transmission and lower absorption at the wavelength of VIS and THz than conventional material such as polyethylene.
- is made of transparent material and has the same refractive index at both THz region and visible wavelength. So the beam propagation of invisible THz wave can be visualized and traceable by He-Ne laser.
- is invented by Tera-Photonics Research Team Photo-Dynamics Research Center at RIKEN.

transmission spectrum in the THz range



transmission spectrum in the visible range

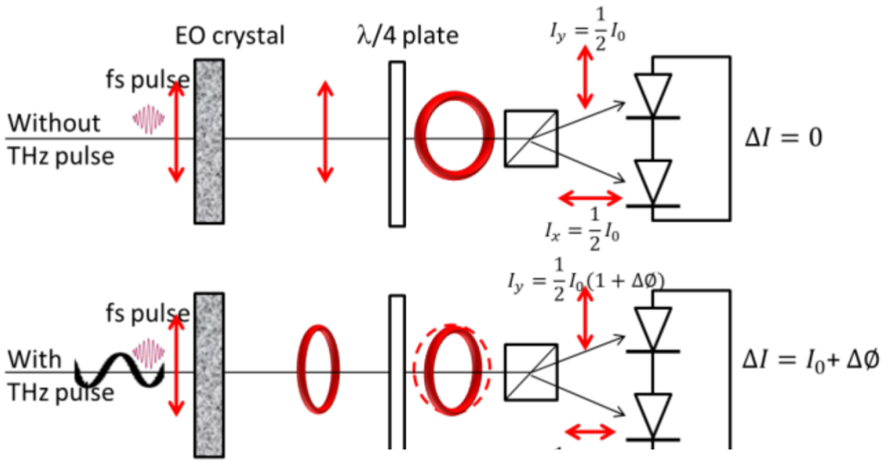


Ref: *http://www.mtinstruments.com/downloads/THz%20Lenses%20and%20Windows%20Datasheet.pdf*
http://phluxi.com/P91-2-002r4.pdf

THz Detection Technology

Technology	Attribute based
Photoconductive antenna detector	Electromagnetic field
Electro-optical sampling	Electromagnetic field
Glow discharge detector	Electromagnetic field
Surface plasmon detector	Electromagnetic field
Golay detector	Thermal effect
Bolometer	Thermal effect
Thermoelectric detector	Thermal effect
Pyroelectric detector	Thermal effect
Barrier detector	Photonic property

Electro-optical sampling (EOS)

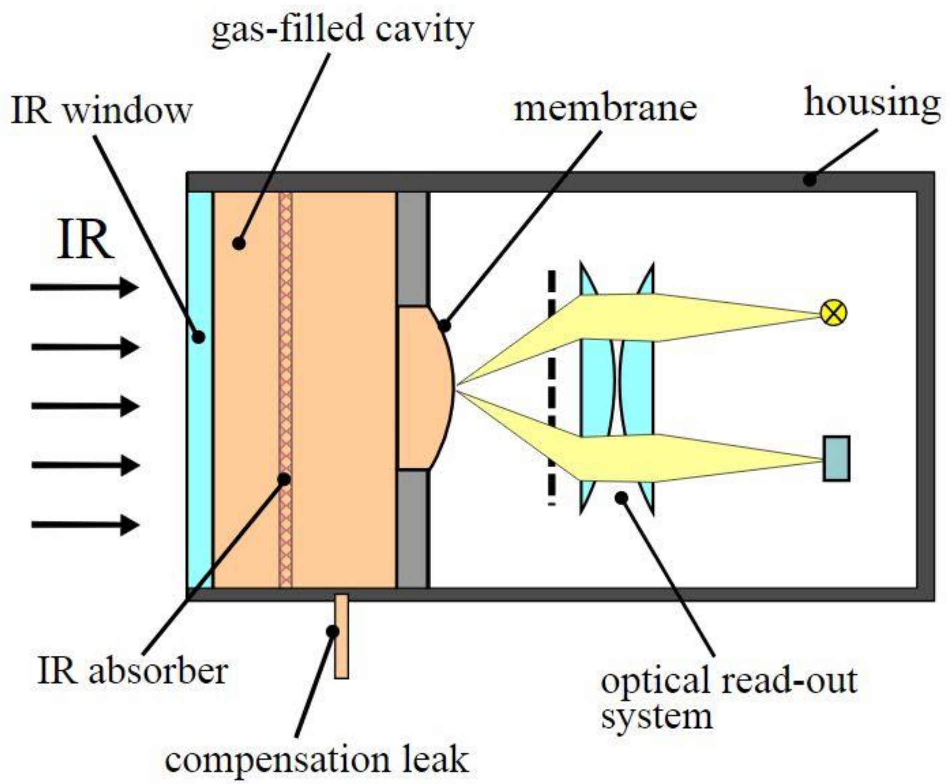


bolometer

Ref: *J. Li and J. Li, Electrical Science & Engineering 2, 11 (2020)*

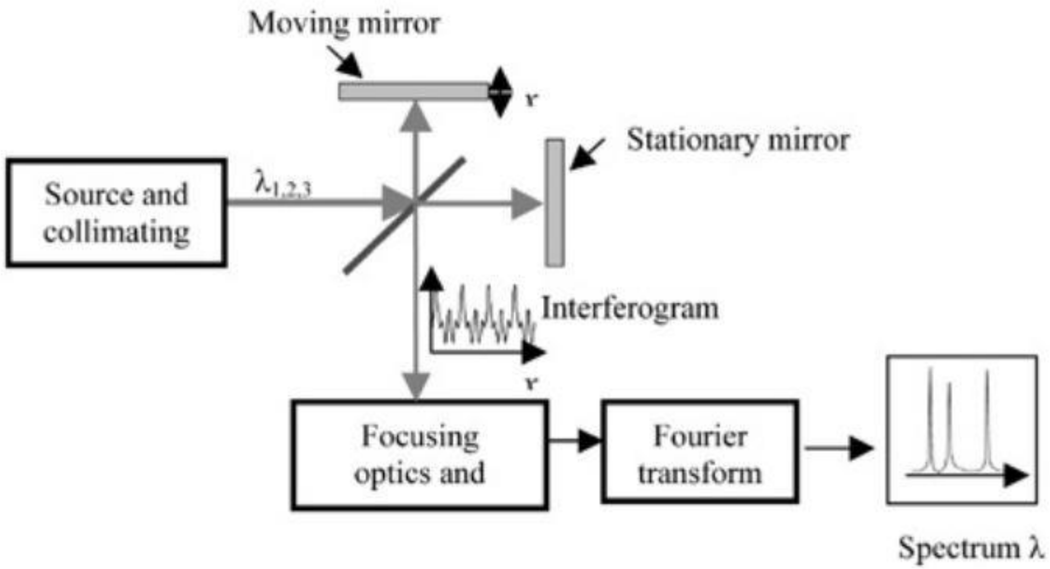
THz Power Measurement – Golay Cell Detector

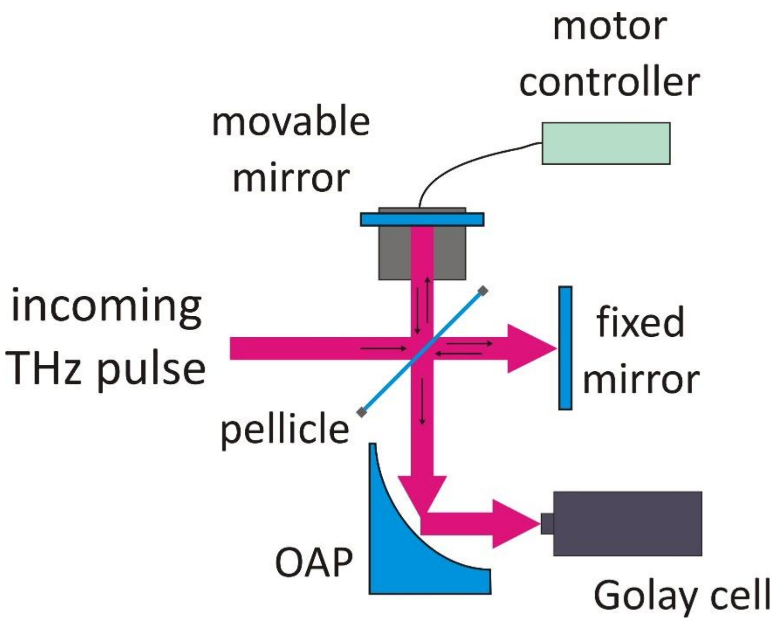
- The Golay cell detector is a type of opto-acoustic detector mainly used for infrared spectroscopy.
- It consists of a gas-filled enclosure with an infrared absorbing material and a flexible diaphragm or membrane closed by a rigid blackened metal plate.
- When infrared radiation is absorbed, it heats the gas, causing it to expand. The resulting increase in pressure deforms the membrane.
- Light reflected off the membrane is detected by a photodiode, and motion of the membrane produces a change in the signal on the photodiode.



THz Spectrum - Interferometer

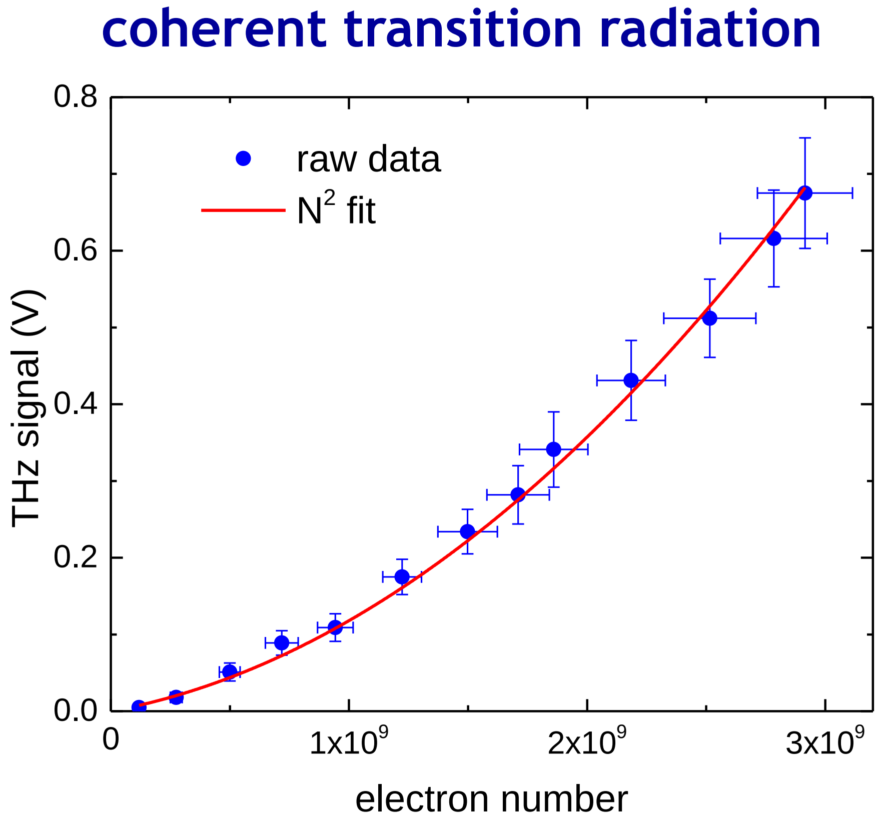
Michelson interferometer

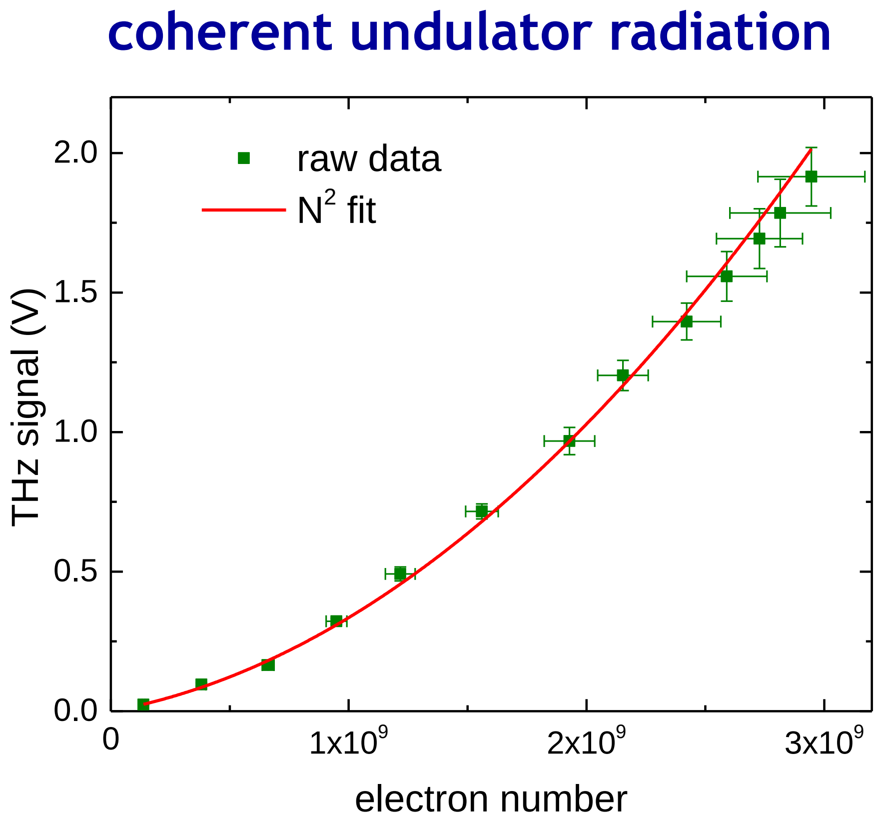




- The incoming coherent THz radiation initially splits at the beamsplitter. The transmitted component reflected by a fixed mirror and then recombined with the other initially reflected component which has subsequently been reflected off the movable mirror mounted on the translation stage. Then the combined radiation can be focused onto the detector by a focusing optics. The path-length difference between the two arms can be varied by moving the translation stage and then the interferogram can be measured.
- THz spectrum can be obtained from the interferogram via Fourier transform.

THz Signal vs. Electron Number

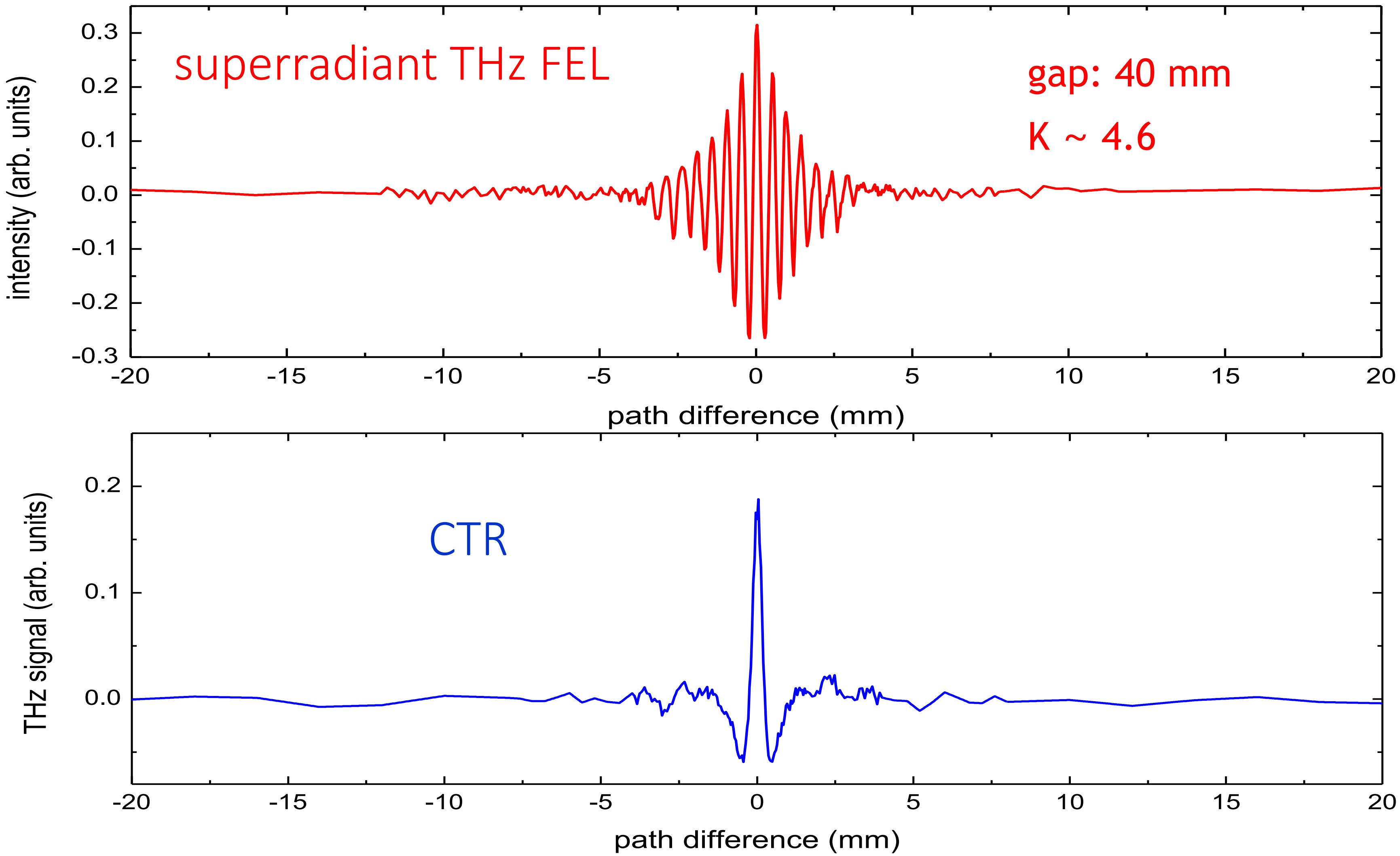




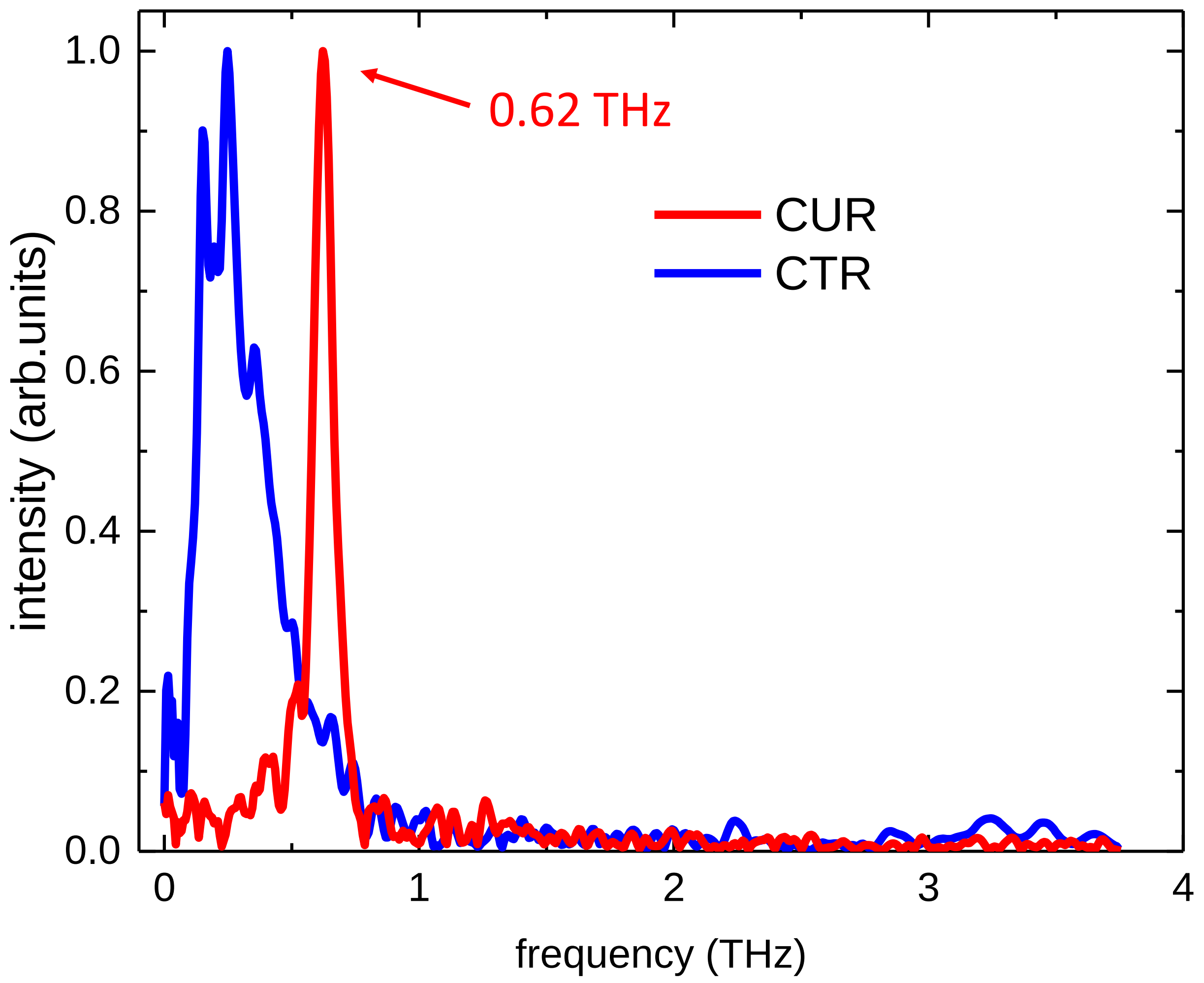
- As expected, quadratic dependence of the THz output signal on the electron number is observed for both CTR and CUR.

$$P(\omega) = P_0(\omega)[N(1 - f(\omega)) + N^2 f(\omega)]$$

Interferograms of Superradiant THz FEL and CTR

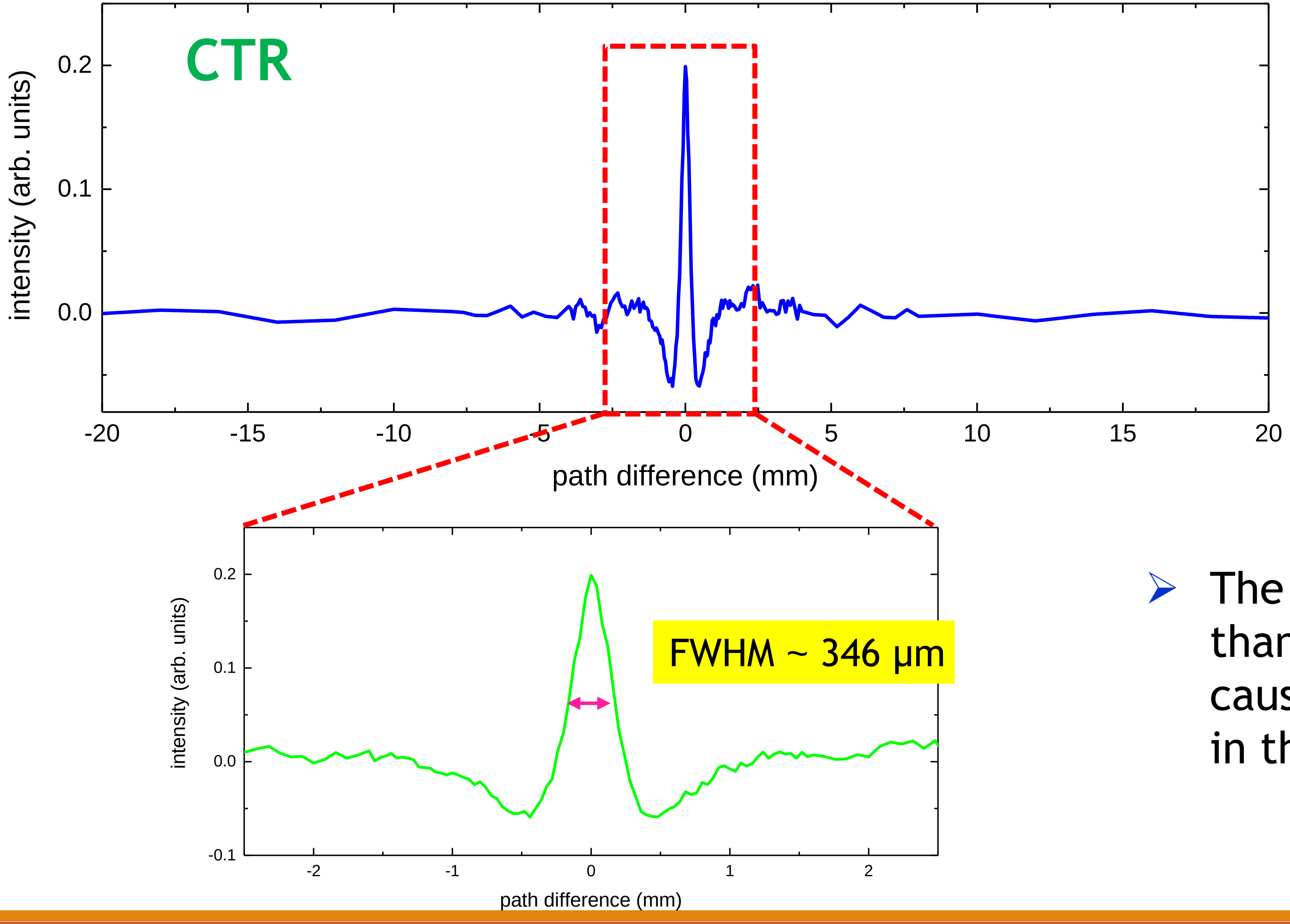


THz Spectrum - 2018



- In contrast, the superradiant FEL spectrum is narrow band but the CTR spectrum is not so broad.
- The central frequency of superradiant FEL is measured to be 0.62 THz, corresponding to the electron beam energy of 17.7 MeV.

Retrieved the Electron Bunch Length - 2018



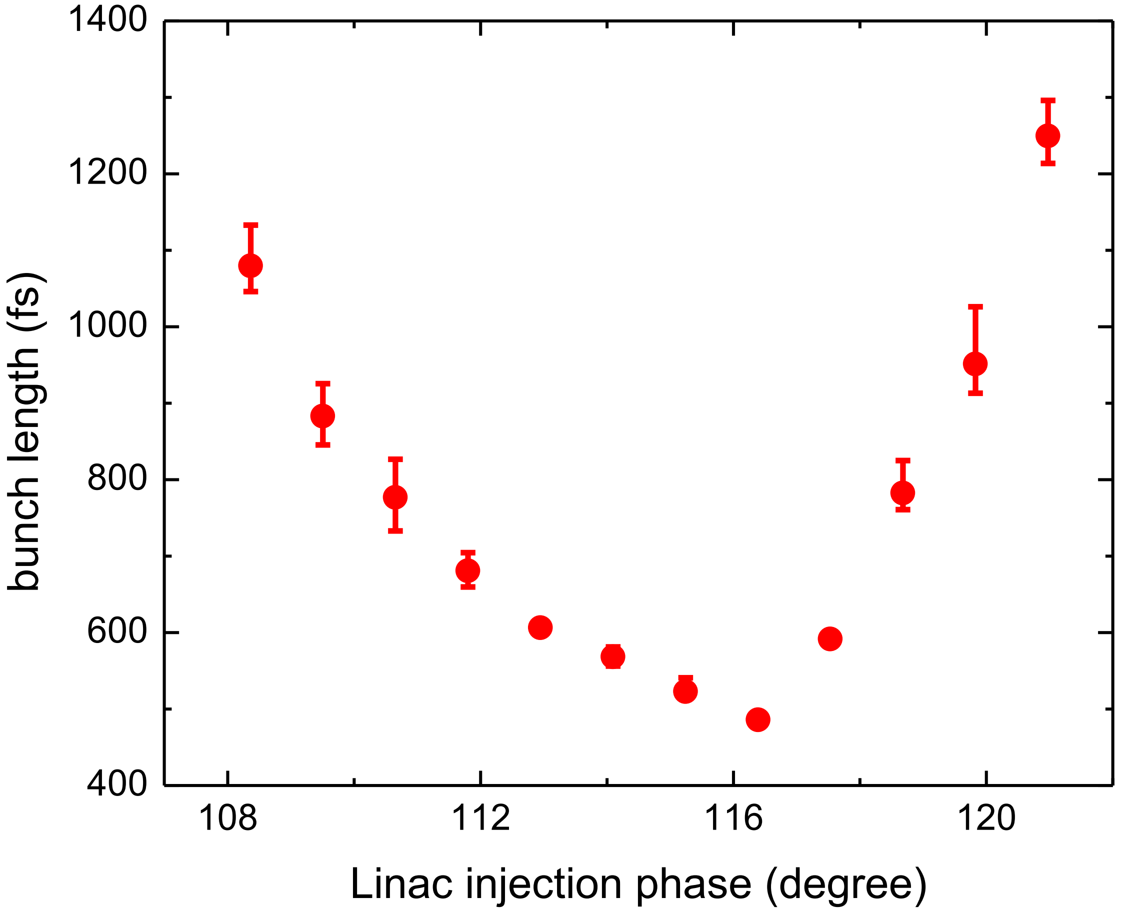
- assume Gaussian distribution

  FWHM = $2\sqrt{2ln2}\sigma_z$

  bunch length σ_z ~ 147 μm = 490 fs

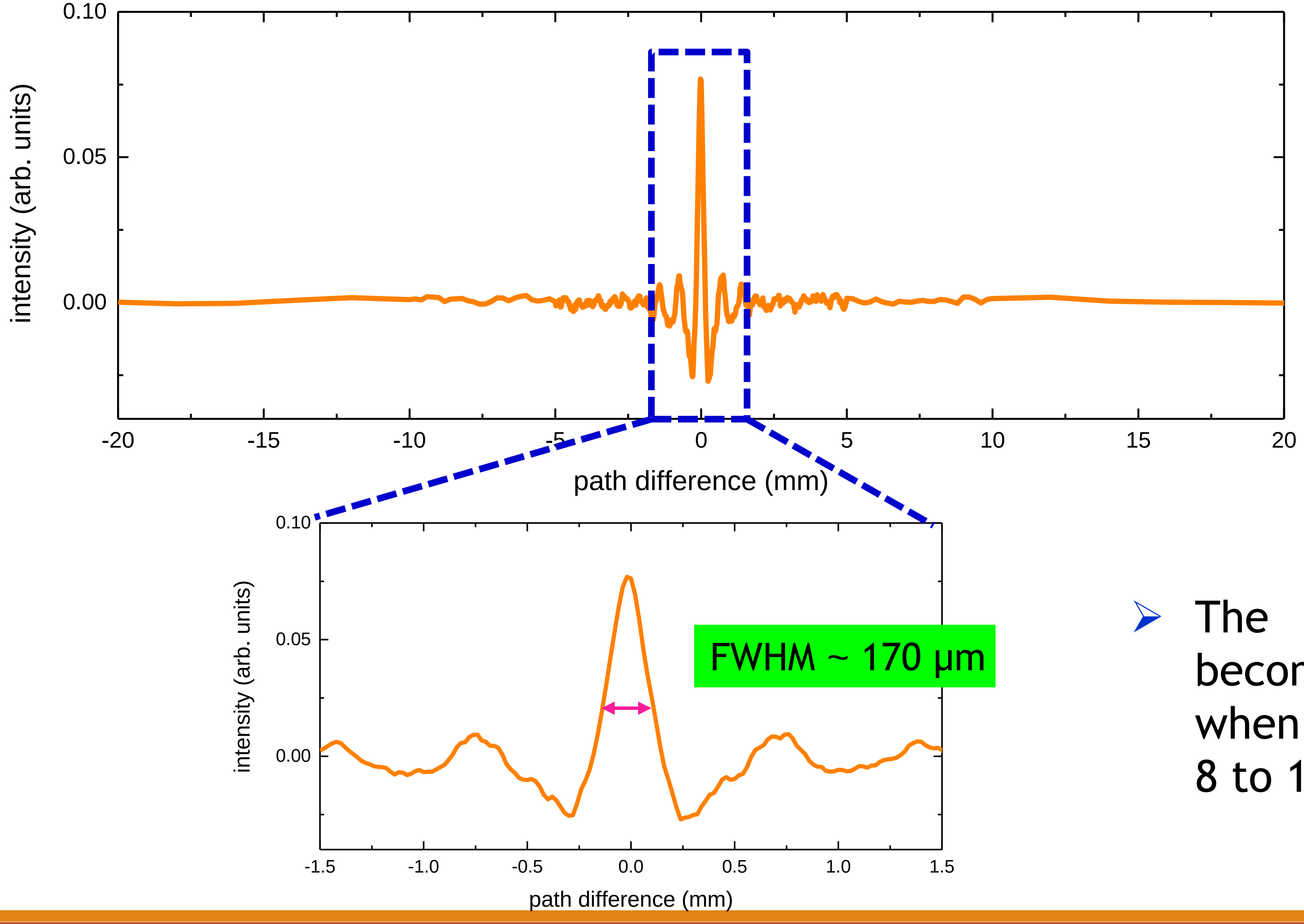
- The measured bunch length is longer than that of simulation. This may cause by the lower linac field used in the experiment.

Linac Injection Phase vs. Bunch Length



- The result shows that electron bunches in the linac can be accelerated and compressed simultaneously by velocity bunching.

Shorter Bunch Length Achieved with Higher Linac Field



- assume Gaussian distribution

  FWHM = $2\sqrt{2ln2}\sigma_z$

  bunch length σ_z ~ 72 µm = 240 fs

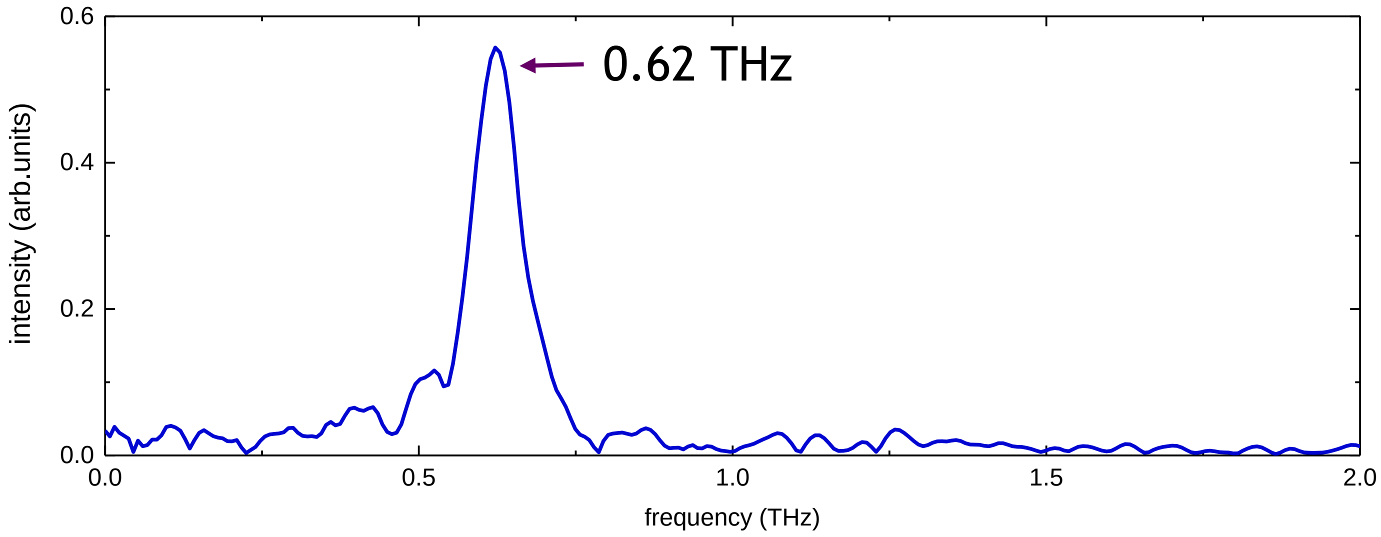
- The compressed bunch length becomes shorter from 490 to 240 fs when the linac field increased from 8 to 12.5 MV/m.

CUR Spectra after upgrade

2018

linac field: 8 MV/m

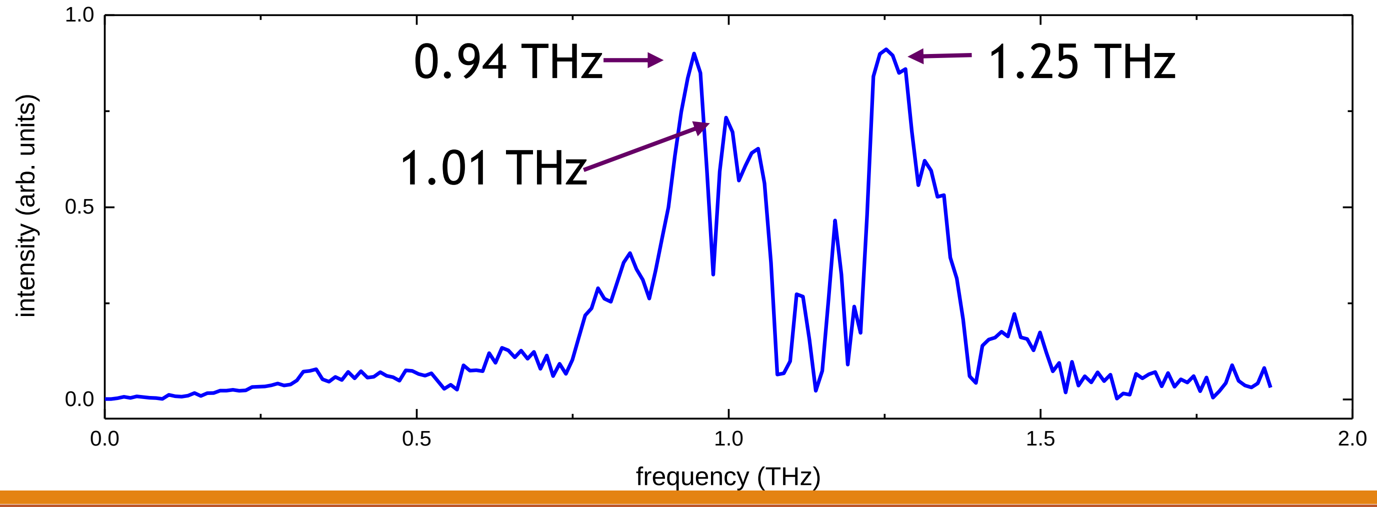
bunch length: 490 fs rms



2021

linac field: 12.5 MV/m

bunch length: 240 fs rms



CUR Spectra with Different U100 Gaps

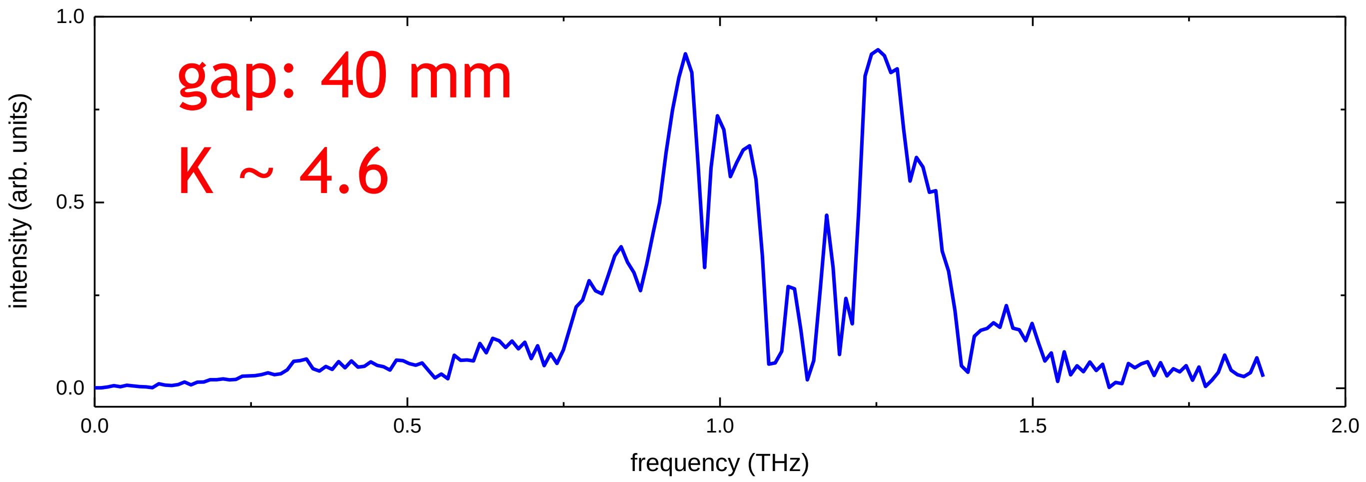
radiation wavelength

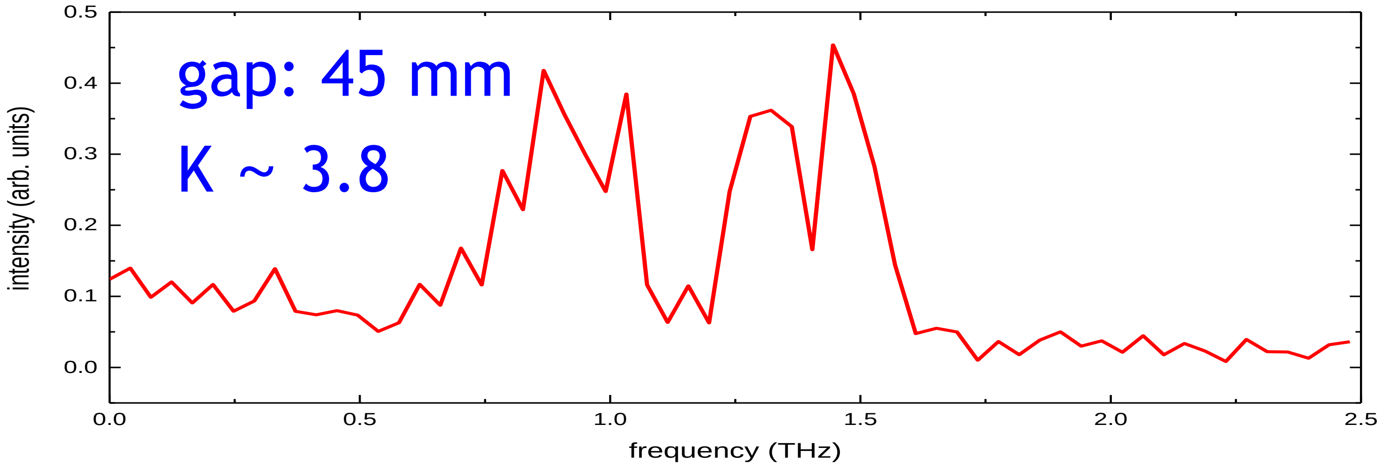
$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

λ_u: undulator period

K: undulator strength

$K = 0.9337\hat{B}\ [T]\ \lambda_u\ [cm]$



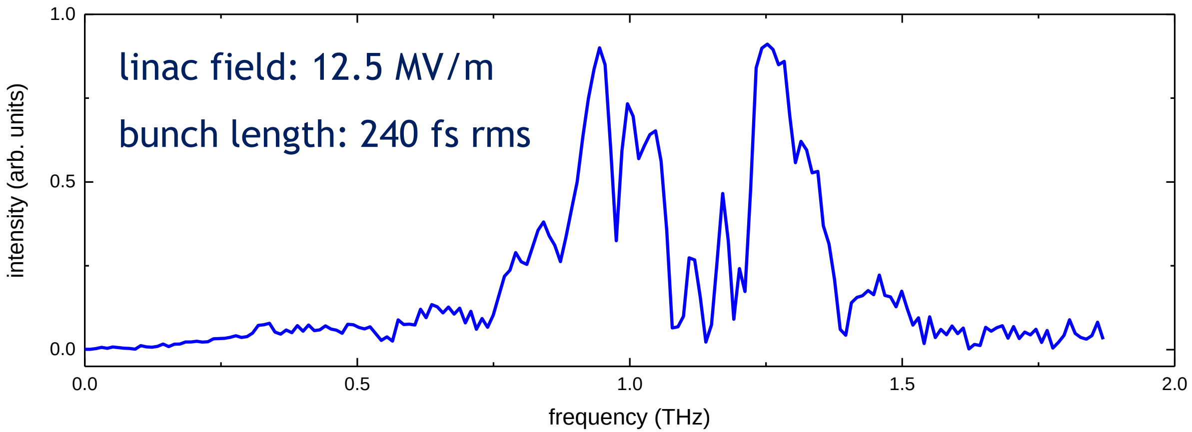


THz Laboratory Measurements of Atmospheric Absorption Between 6% and 52% Relative Humidity (Sept. 2006)

Abstract

Atmospheric transmissions of terahertz radiation were measured over 0.3 – 3.9 THz spectral range at sea-level over 1.7 m path length for relative humidity values ranging from 6% to 52%. Absorption coefficient values were calculated as a function of relative humidity, for the atmospheric windows in this region.

- Water vapor absorption has a serious impact on THz light sources.



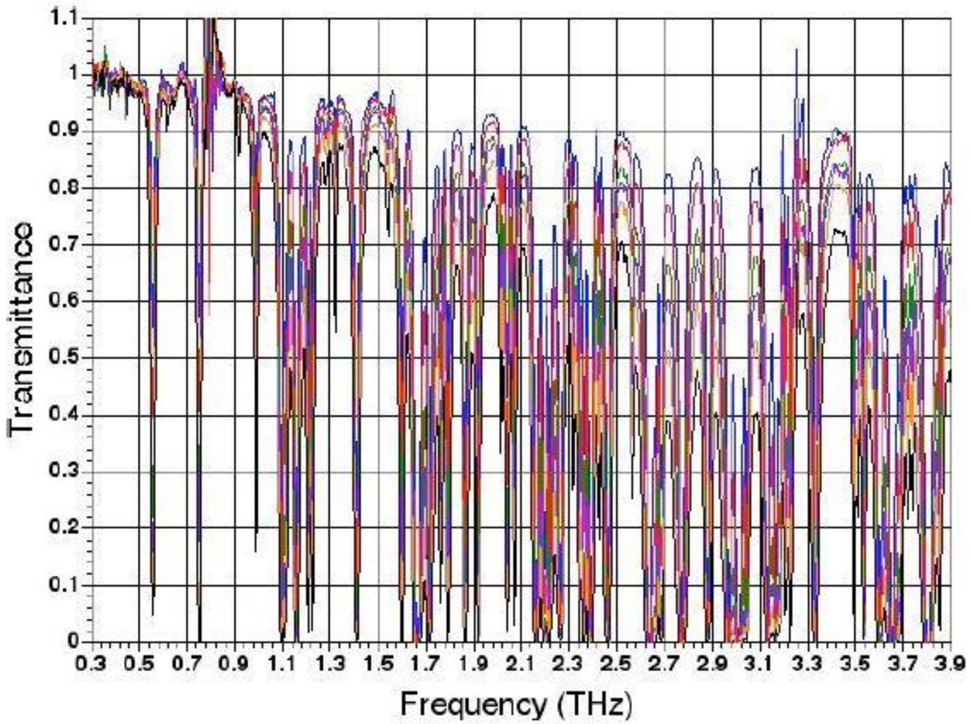
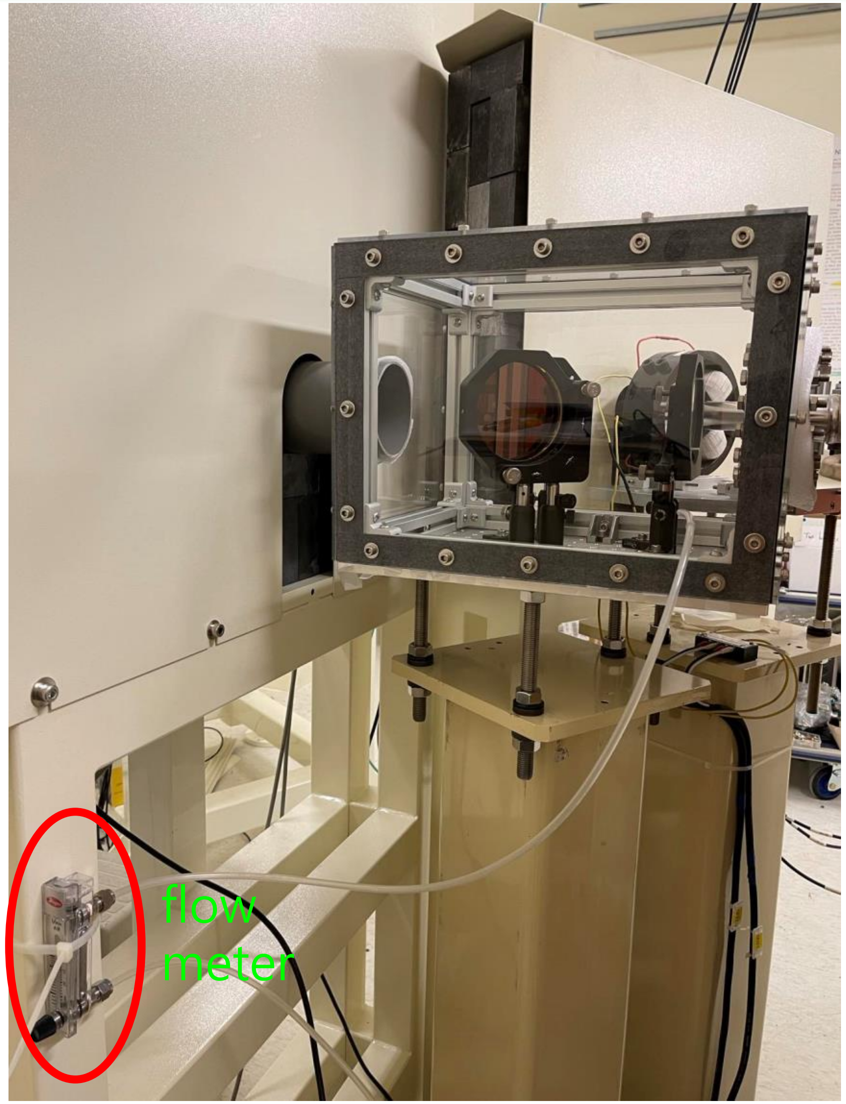
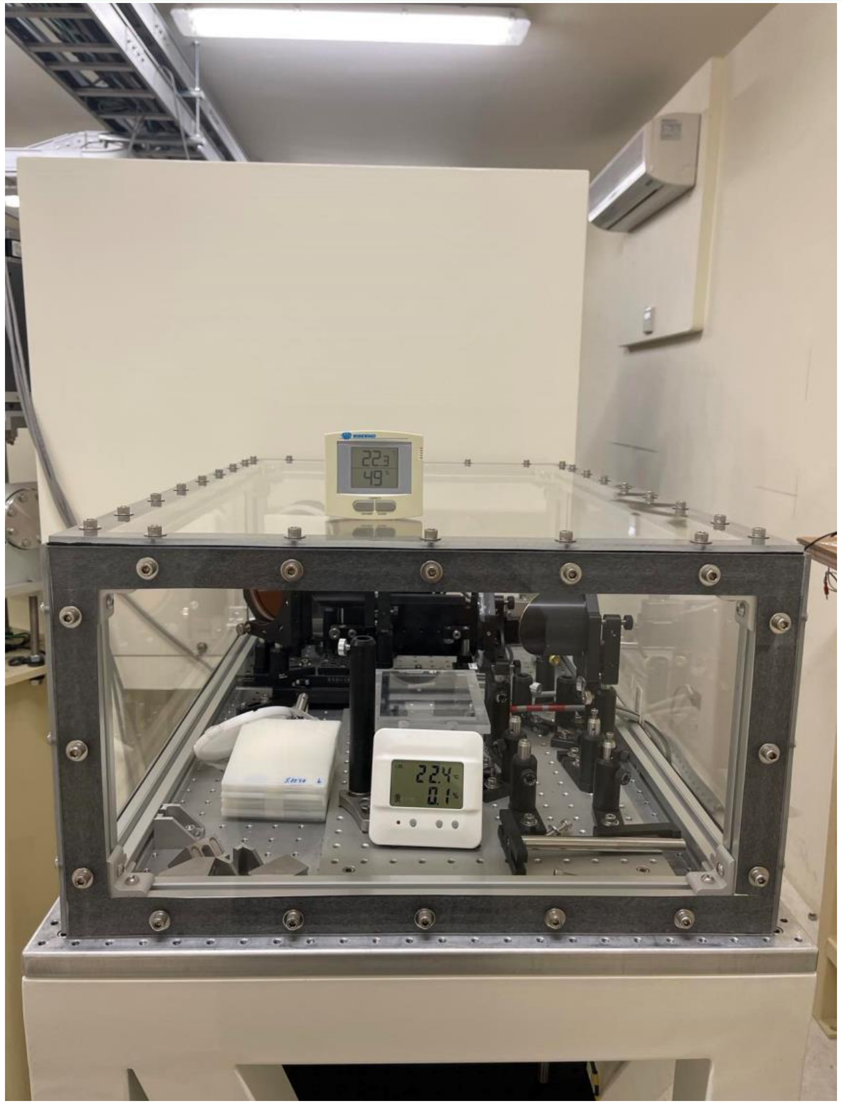


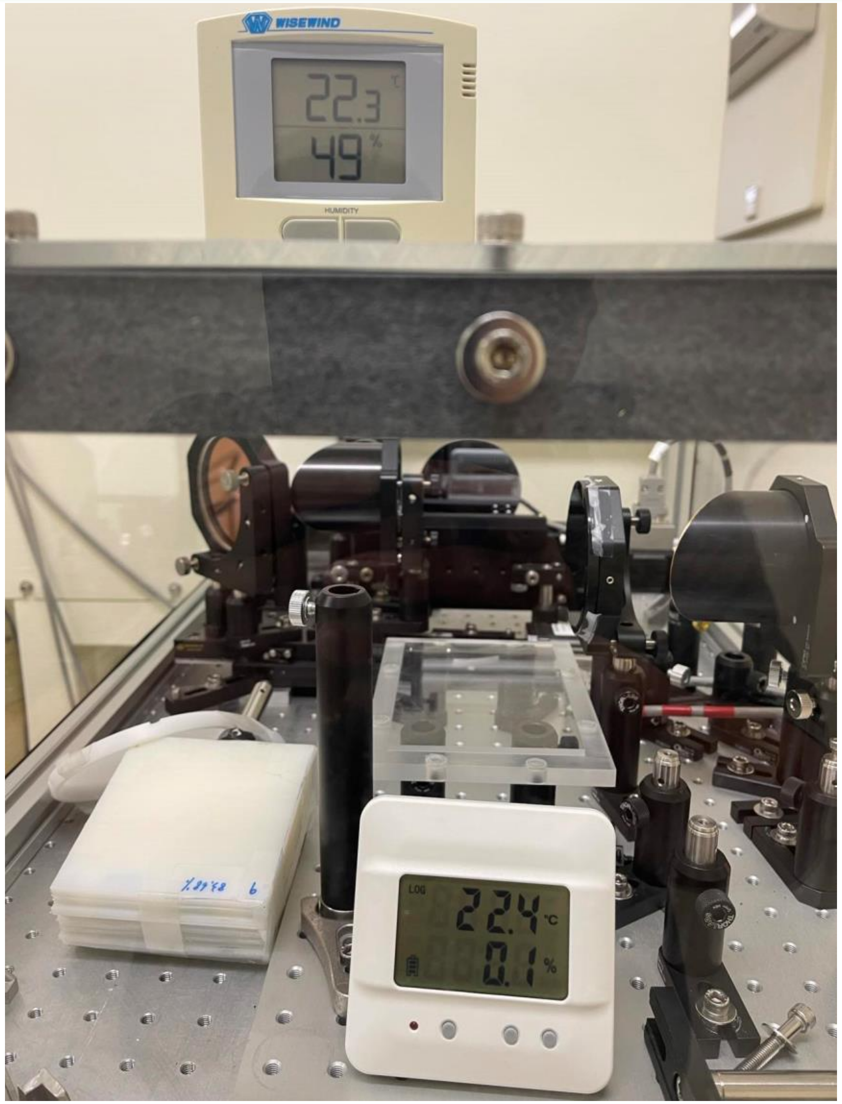
Figure 1. Measured atmospheric THz transmission at different levels of relative humidity. Blue, red, green, purple, orange, and black lines correspond to 6%, 12%, 22%, 26%, 40%, and 52% RH, respectively.

Ref: A. A. Danylov, J. Waldman, internal STL Report (Sept 2006).

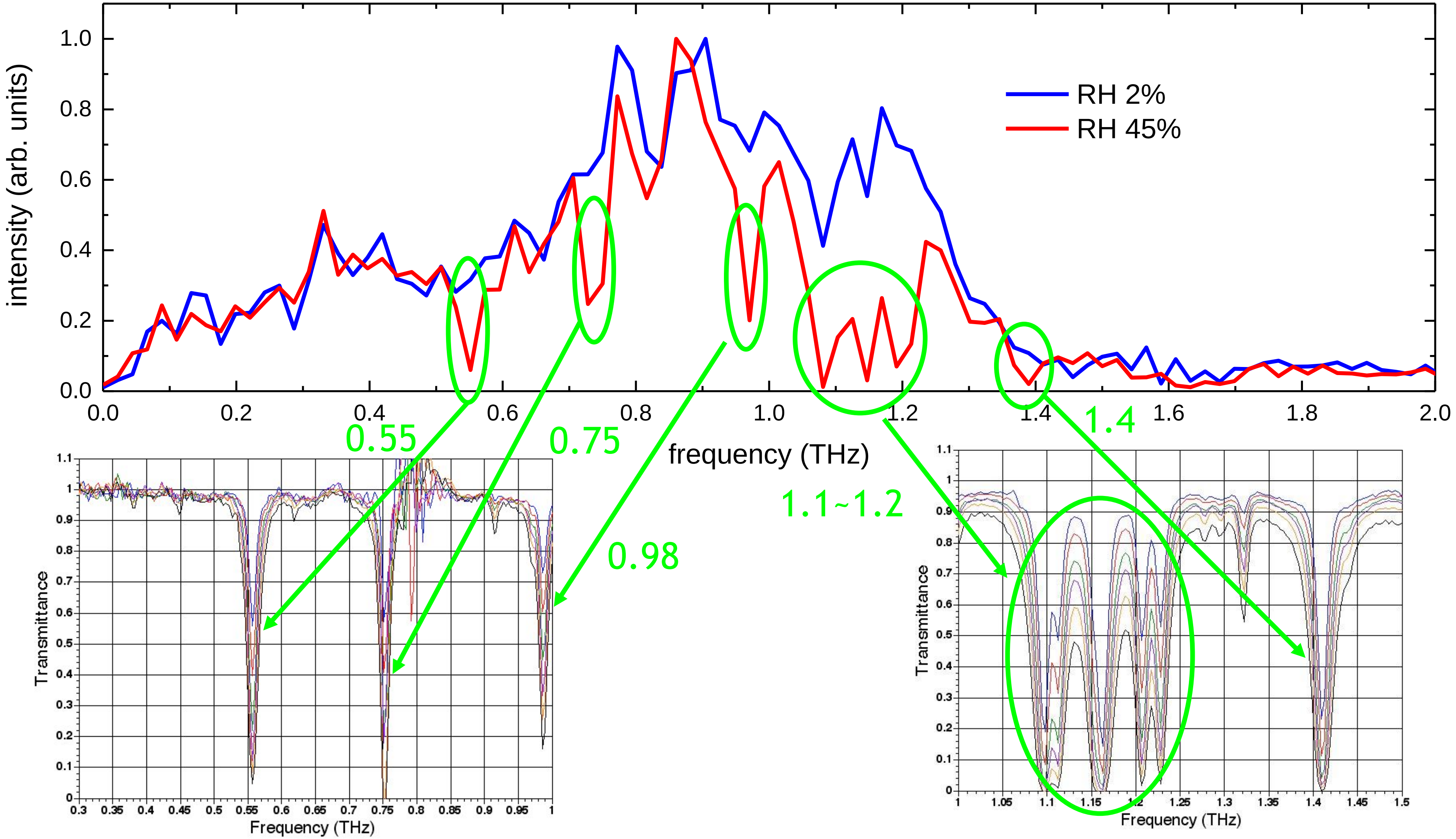
THz Diagnostics Station with Purging Dry Air







CUR Spectra after Purging Dry Air



Performance of NSRRC Coherent THz Sources

Parameters	CTR	Superradiant FEL
electron charge (pC)	210	250
beam energy (MeV)	25	
Linac field (MV/m)	12.5	
THz frequency (THz)	--	0.6 ~ 1.4
THz bandwidth	--	15%
THz energy (μJ)	2	20
THz Pulse duration	300 fs	18 ps
THz Peak power (MW)	6.6	1.1
THz Peak field (kV/cm)	400	163

Outline

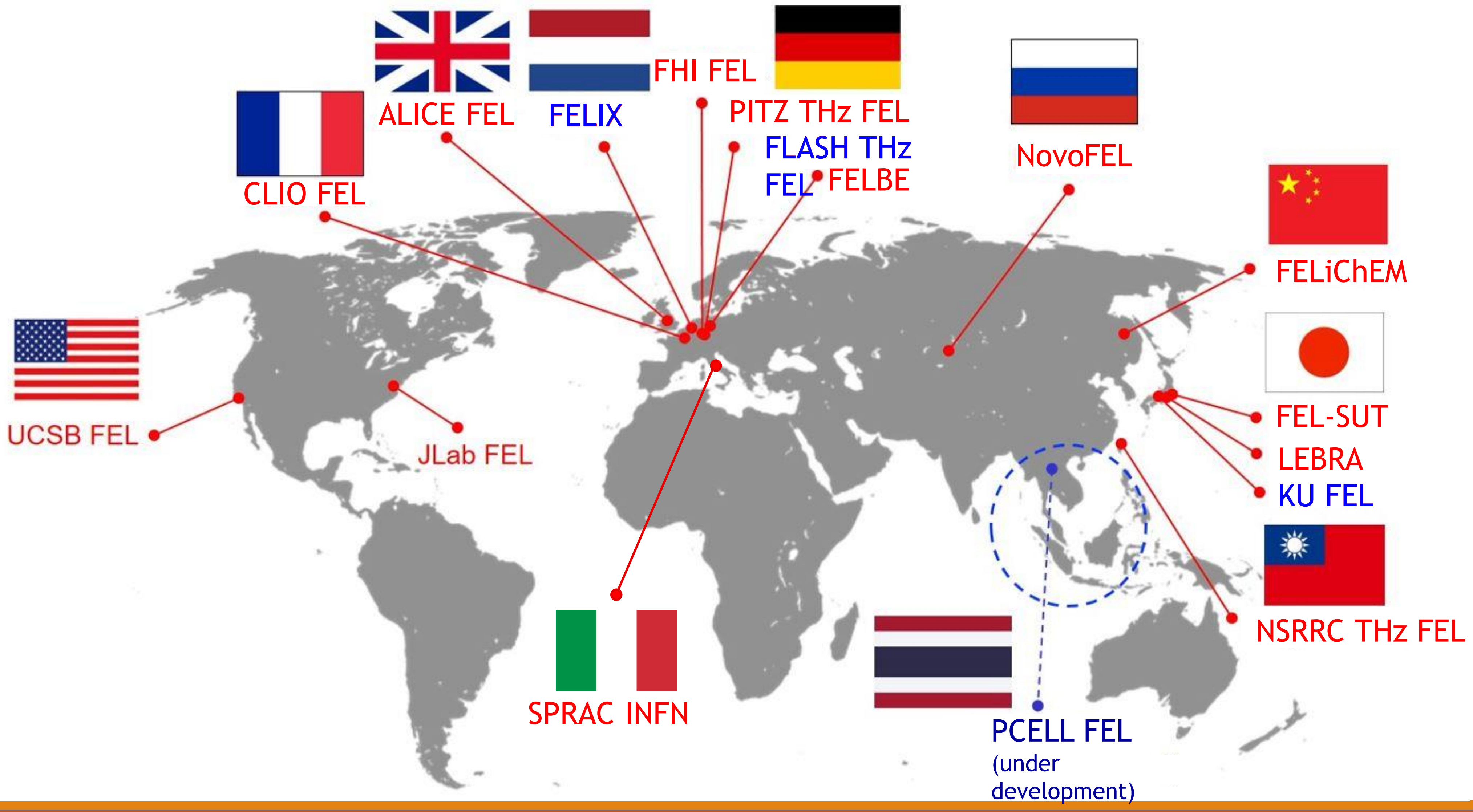
I. Introduction of THz sources

II. Development of superradiant THz FEL at NSRRC

- NSRRC high-brightness photo-injector system
- Superradiant THz free electron laser

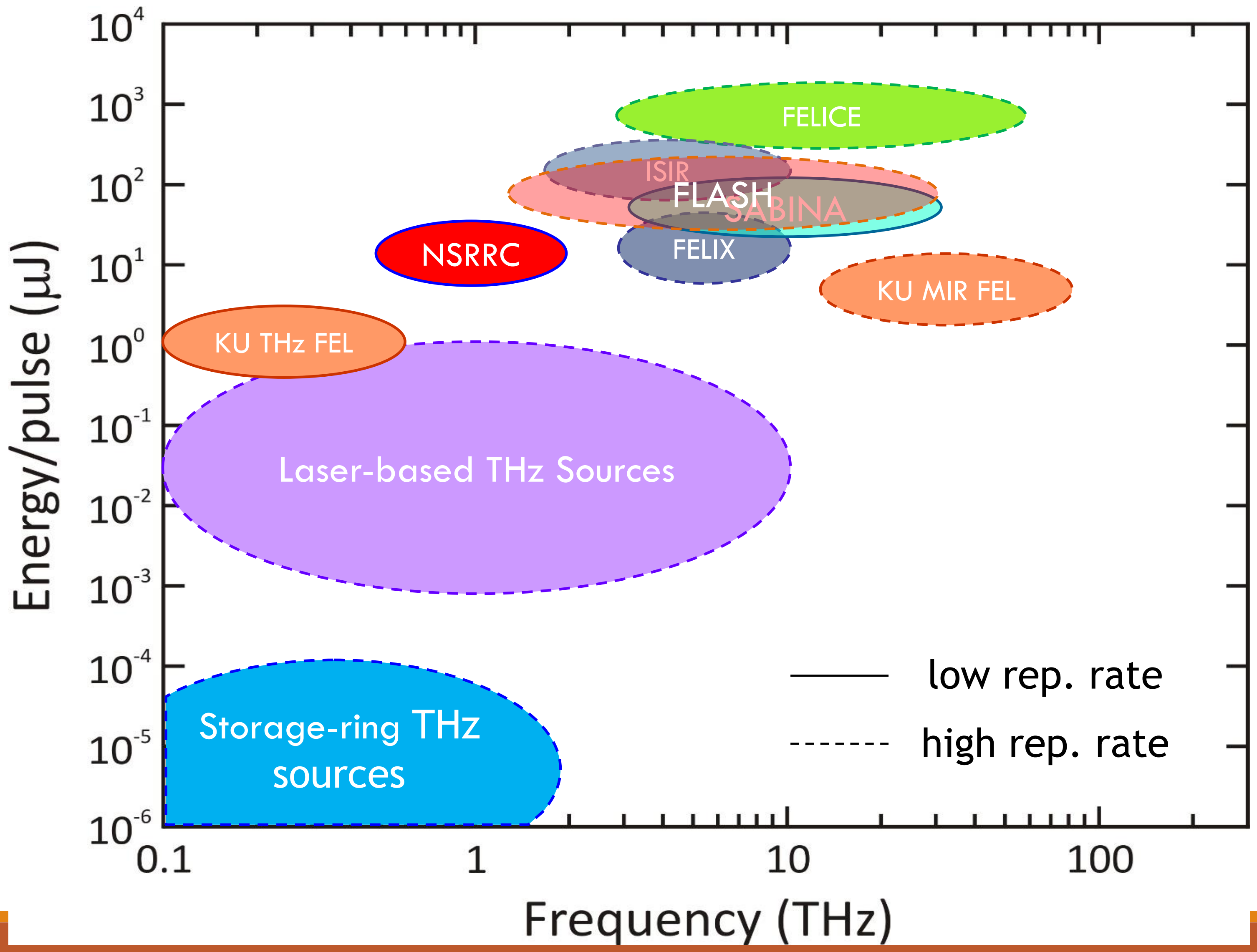
III. NSRRC THz user facility

Infrared/THz Free Electron Laser Facility Worldwide

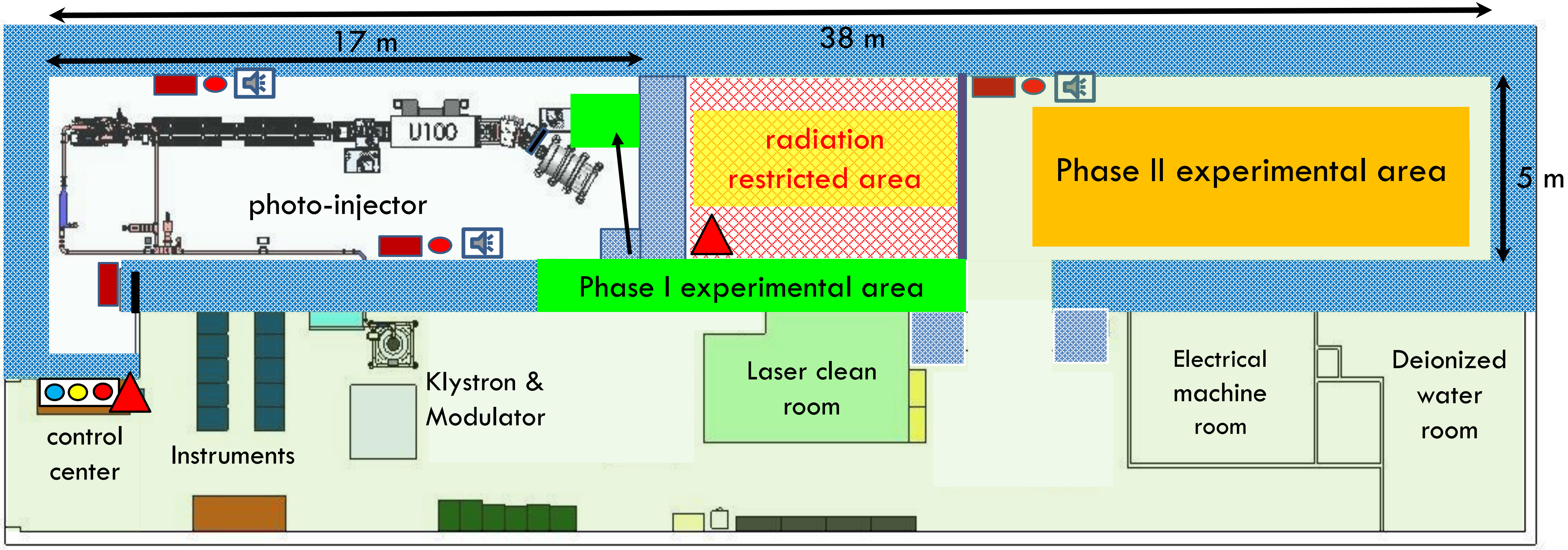


Ref: Courtesy of Prof. Sakhorn

Comparison of Exiting THz Sources for Users



NSRRC THz User Facility



- The Accelerator Test Area was transformed into the THz user facility since 2022. It is planned to be two stages for user experiments.
- In Phase I, the user experiment is conducted inside the accelerator tunnel.
- In Phase II, a THz beamline is under design for maintaining the quality of the THz FEL and can be transported to the rear space of the tunnel for user experiments.

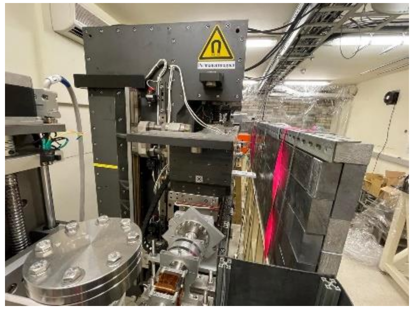
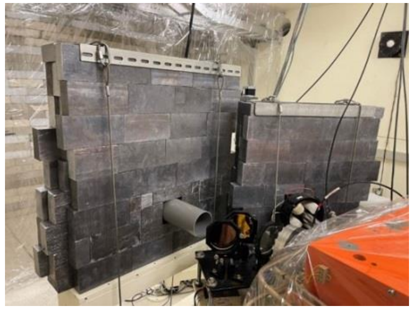
Radiation Safety

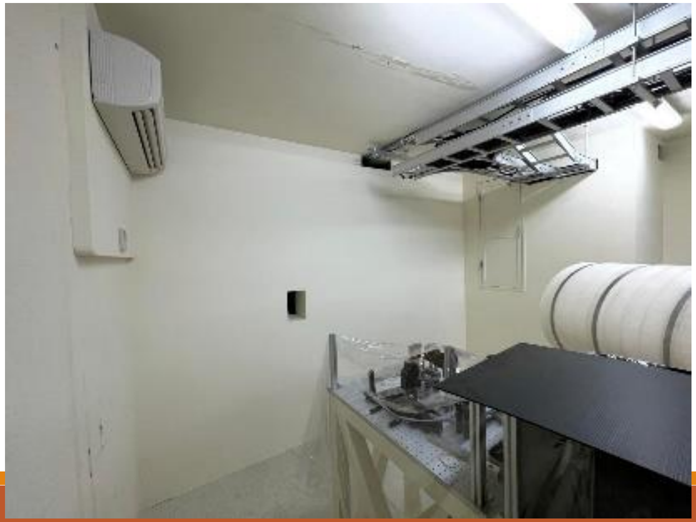











可發生游離輻射設備許可證

設字第100921號

第1頁 共2頁

設施經營者：財團法人國家同步輻射研究中心

地址：新竹市科學園區新安路101號

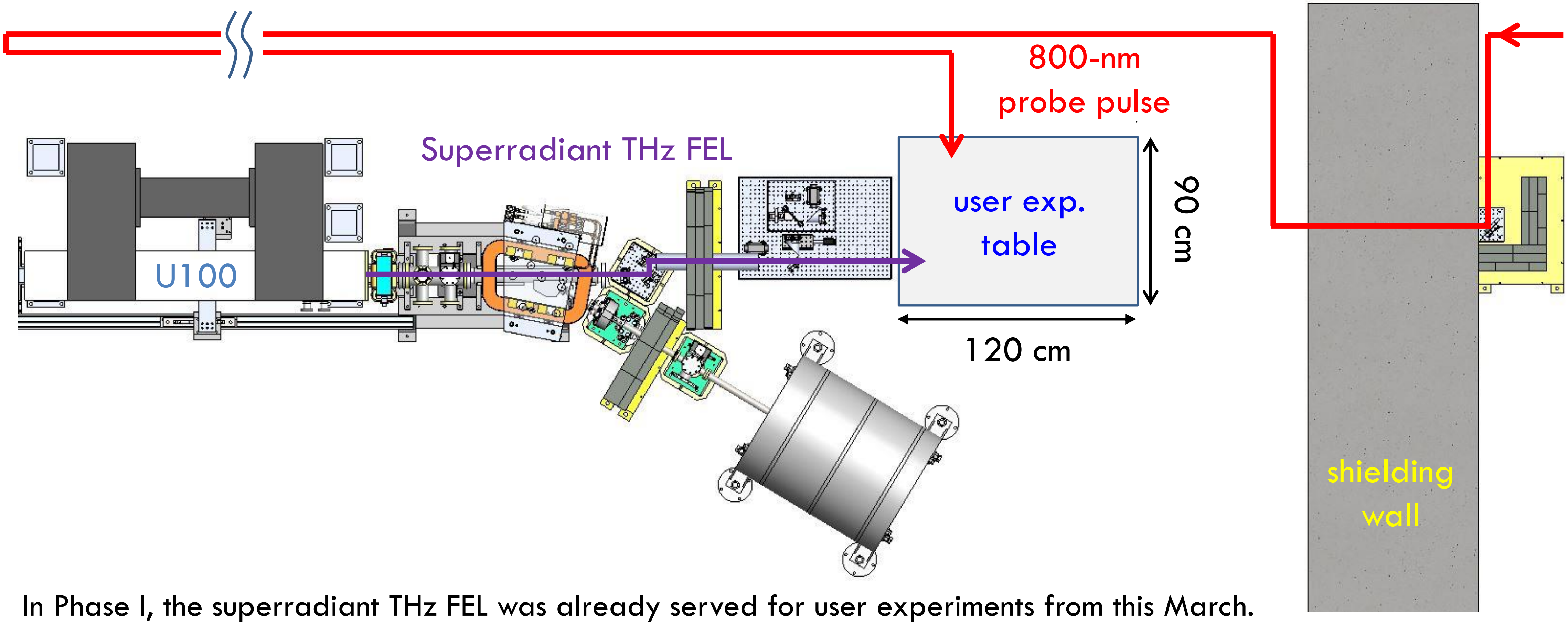
執照狀態：使用
設備名稱：直線加速器
廠　　牌：NSRRC自行組裝
數　　量：1
型　　號：THz光源
序　　號：
放置地點：THz光源（直線型加速器測試區）

頒證依據：依游離輻射防護法第十九條之規定發給證書
原發證日期：112年12月22日
有效期限：117年12月11日
附註：如附頁

核能安全委員會
主任委員

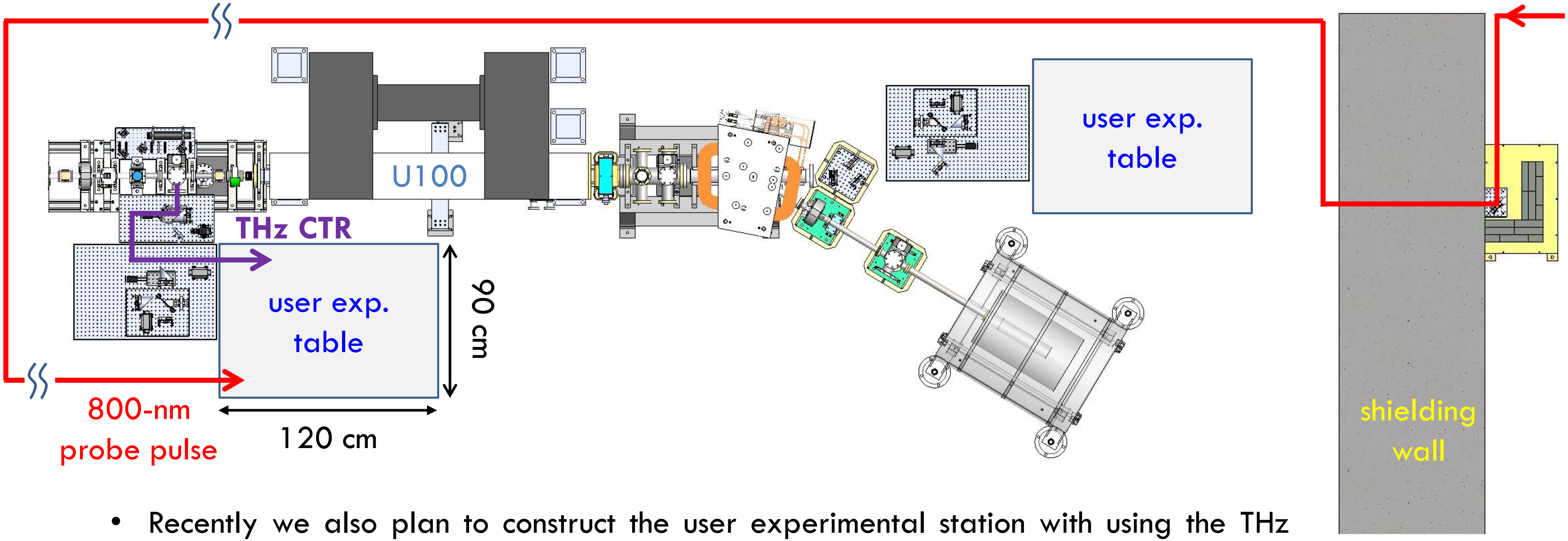
中華民國112年12月28日

Phase I User Experiment by Using Superradiant THz FEL



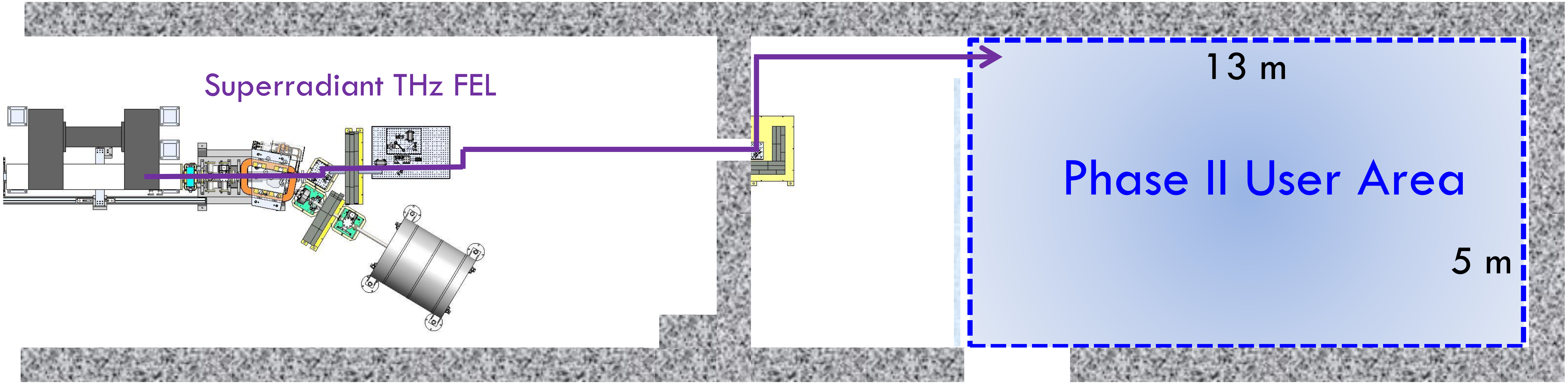
- In Phase I, the superradiant THz FEL was already served for user experiments from this March.
- A 100-fs, 800-nm laser pulse from the photocathode drive laser system is used as the probe pulse for the user experiment.

Phase I User Experiment by Using THz CTR



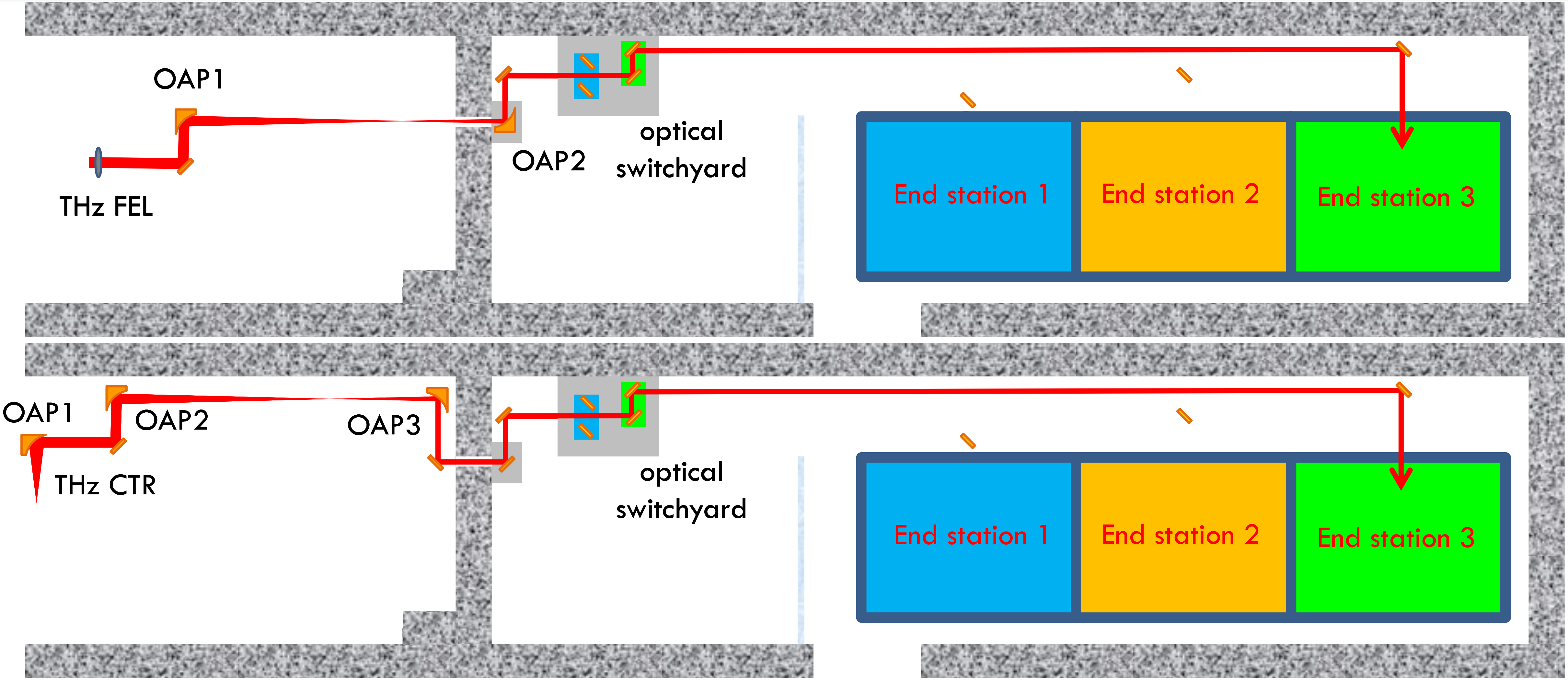
- Recently we also plan to construct the user experimental station with using the THz CTR, which provides shorter THz pulse.

Phase II User Experimental Area



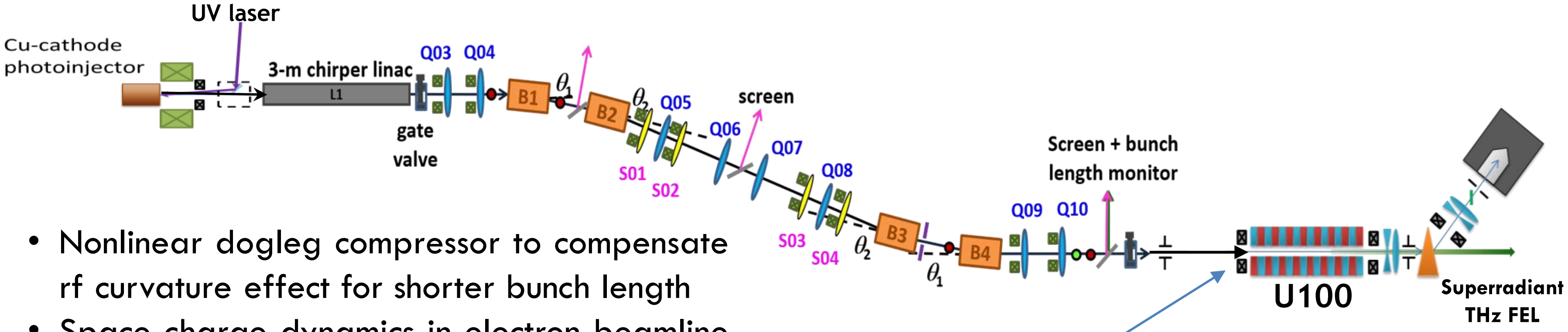
- In Phase II, a THz beamline, maintaining the quality of the THz sources, is under design to transport the THz FEL and THz CTR to the rear space of the tunnel with an experimental area of 13-meter long and 5-meter wide.

Phase II User End Stations



- An optical switchyard will be considered for directing the THz FEL and CTR to different end stations.
- For Phase II, multifunctional user end stations with different scientific research purposes will be expected to build for users.

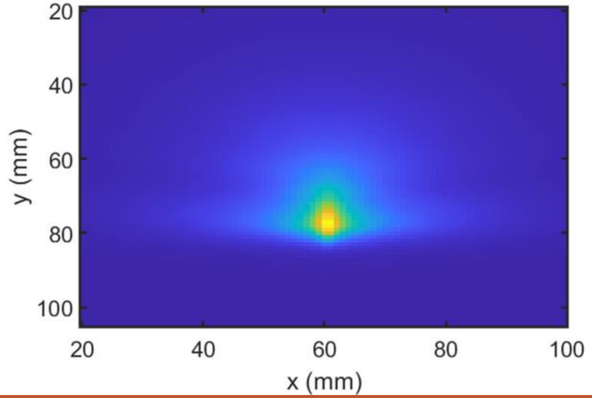
Enhanced Superradiant THz FEL by Magnetic Bunch Compressor



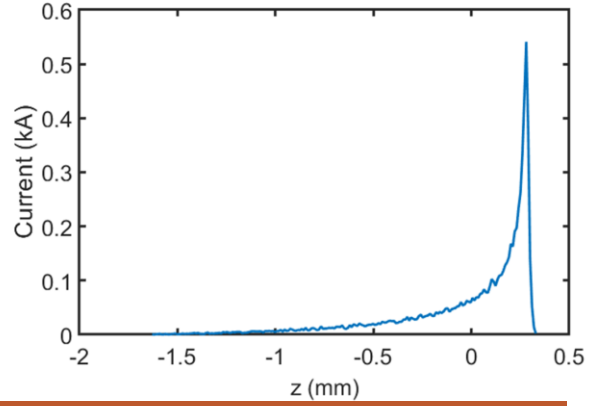
Design Parameters	
Beam energy [MeV]	40
Bunch charge [nC]	0.25
Bunch length [µm]	250
Peak current [A]	500
Transverse emittance [mm-mrad]	3.0
Beam sizes [mm]	1.9/1.2
Energy spread [%]	3.5
Undulator period [cm]	10
Undulator period number	18
Undulator coefficient	4.6

- Nonlinear dogleg compressor to compensate rf curvature effect for shorter bunch length
- Space charge dynamics in electron beamline is simulated by IMPACT-T
- Superradiant THz FEL simulation is done by PUFFIN

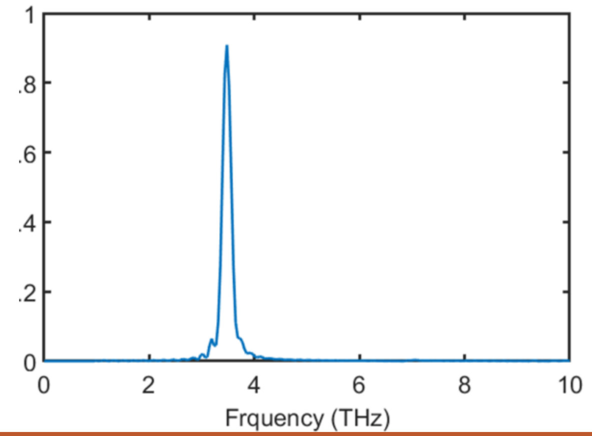
Radiation Profile @ 3 THz



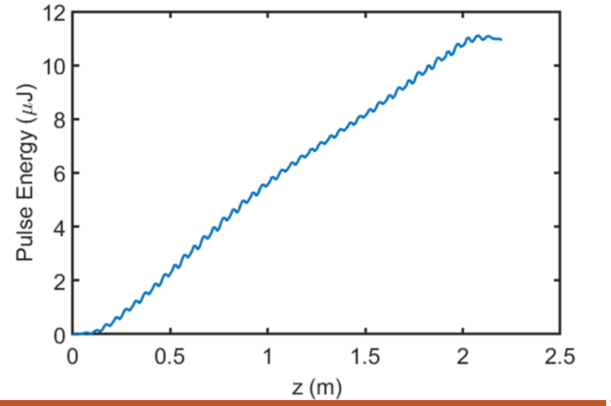
Current Distribution @ Undulator Entrance



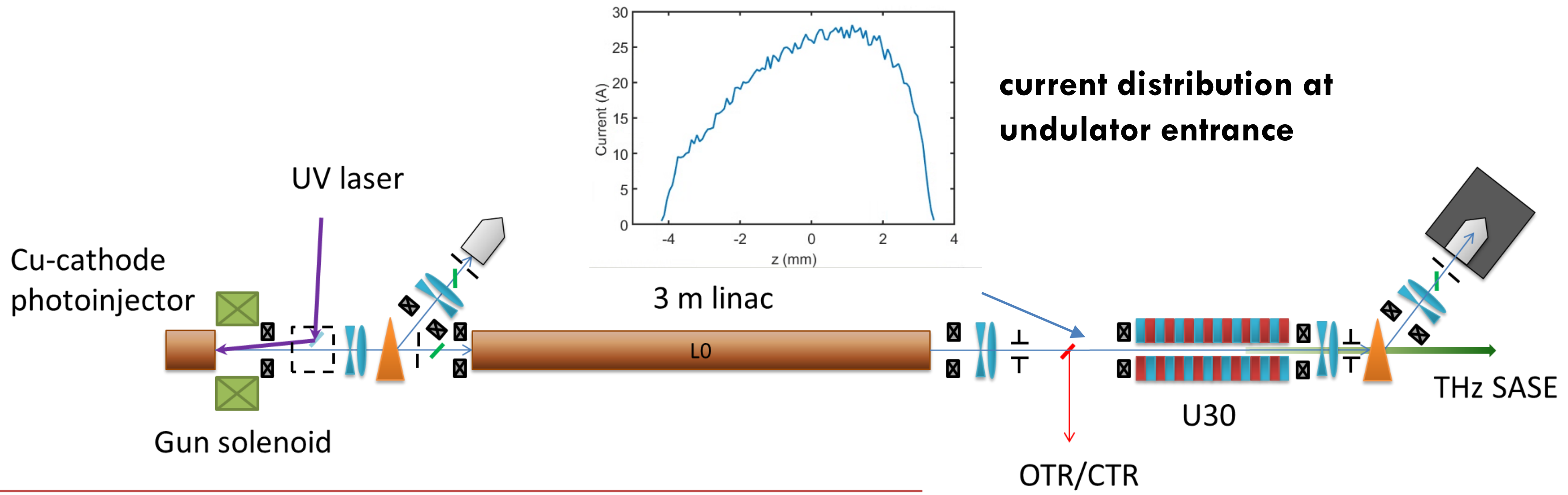
Radiation Spectrum



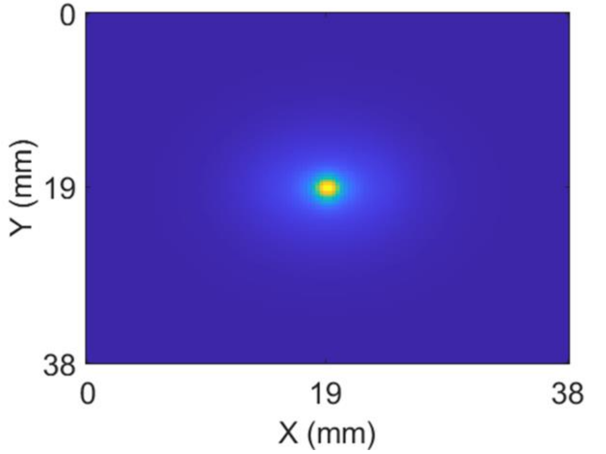
Pulse energy evolution along undulator



Self-Amplification of Spontaneous Emission (SASE) FEL beyond 3 THz

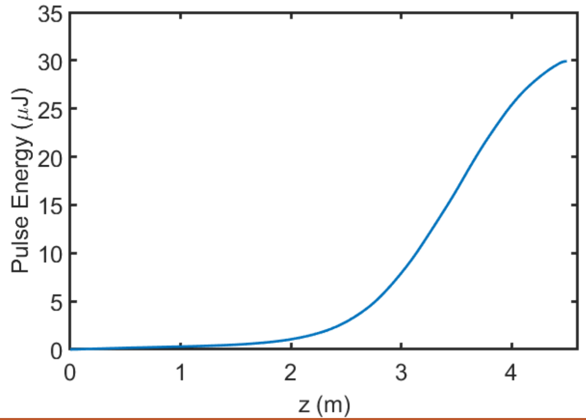


Output radiation profile @ 10 THz

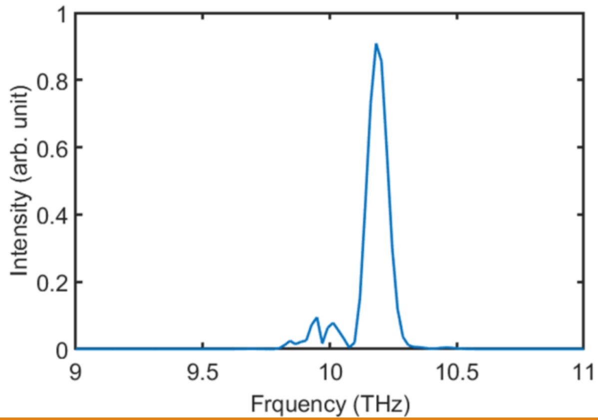


Design Parameters	
Beam energy [MeV]	25
Bunch charge [nC]	0.5
Bunch length [mm]	1.75
Peak current [A]	50
Slice transverse emittance [mm-mrad]	2.0
Slice energy spread [%]	0.1
Undulator period [cm]	3
Undulator period number	150
Undulator coefficient	1.0 – 3.0

Pulse energy evolution along undulator



Radiation Spectrum



國家同步輻射研究中心
National Synchrotron Radiation Research Center

Thank you !