Superradiant THz Free Electron Laser at NSRRC

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線型加速器小組

Outline

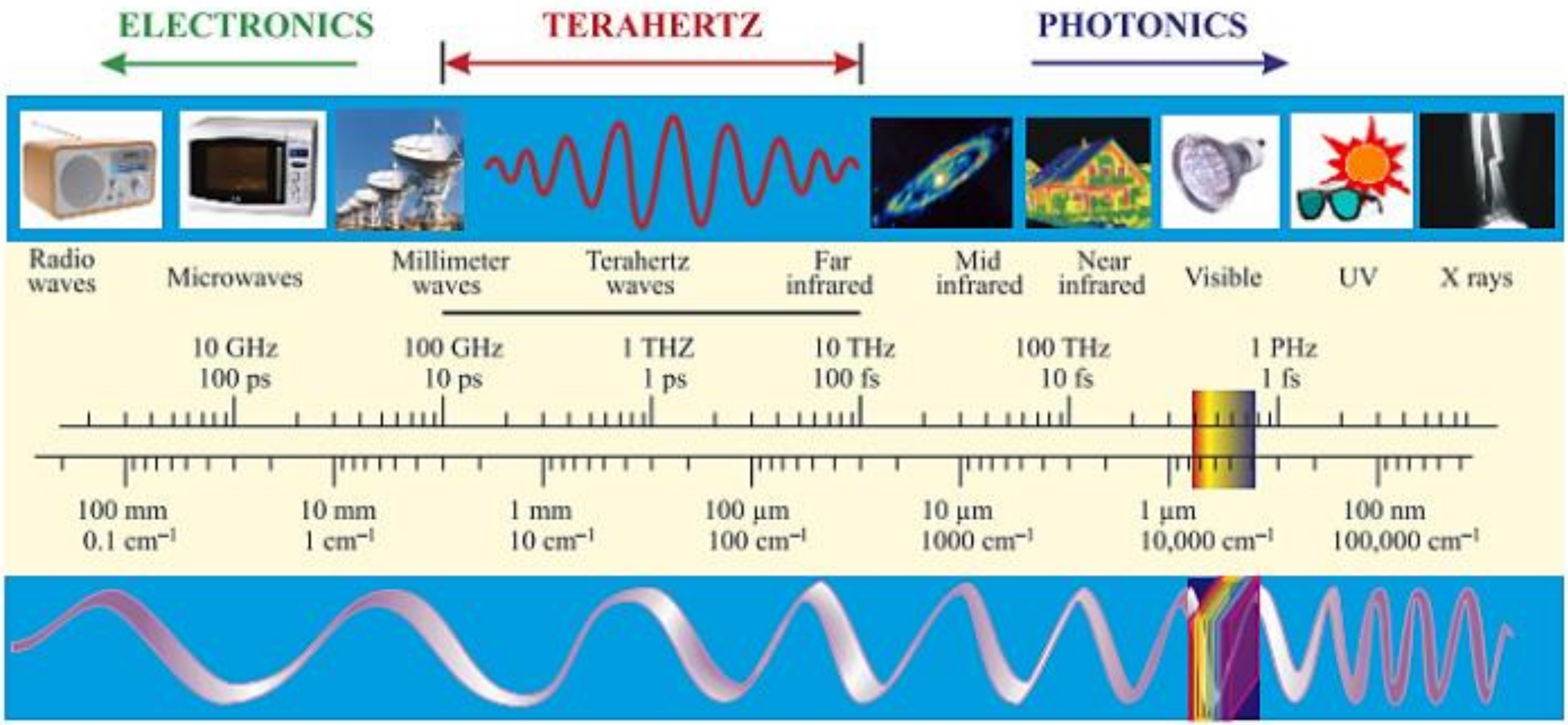
I. Introduction of THz sources

II. Development of superradiant THz FEL at NSRRC

III. Experimental results of coherent THz sources

IV. Summary

What is the Terahertz (THz) Wave?

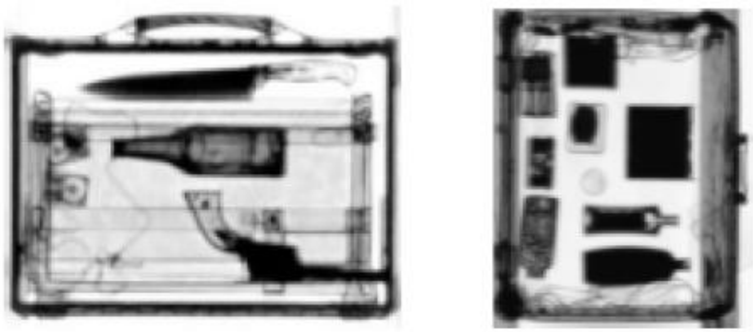


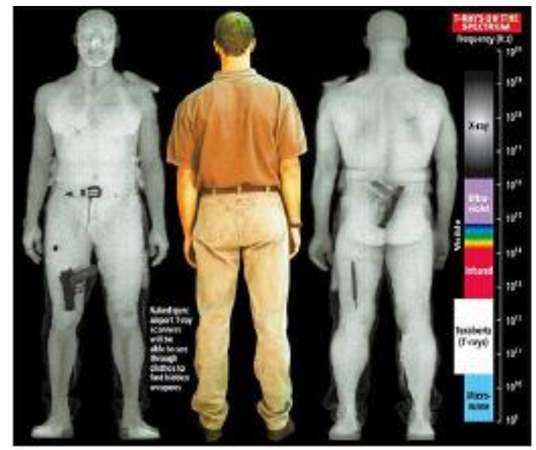
Terahertz wave (THz or T-ray), which is electromagnetic radiation in a frequency interval from 0.1 to 10 THz (3 mm to 30 μm), lies a frequency range with rich science but limited technology.

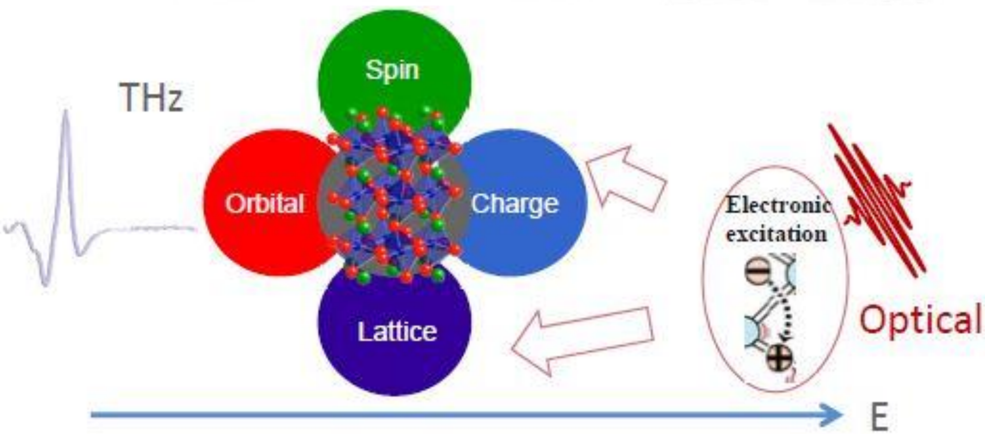
1 THz = 300 μm = 1 ps = 33 cm^{-1}

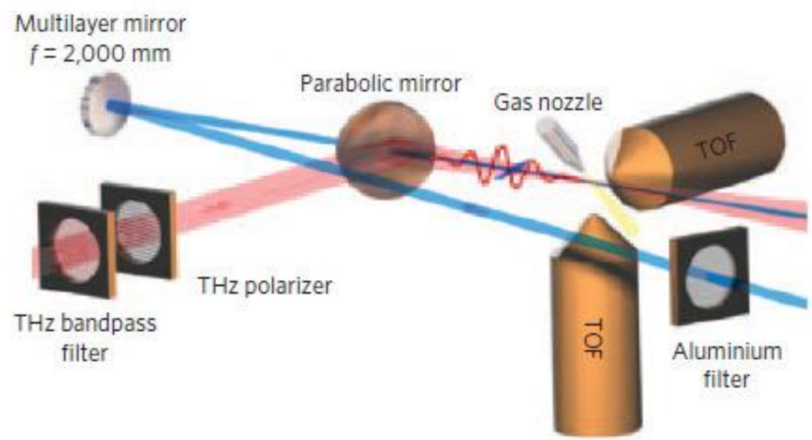
Applications of THz Radiations

- 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)







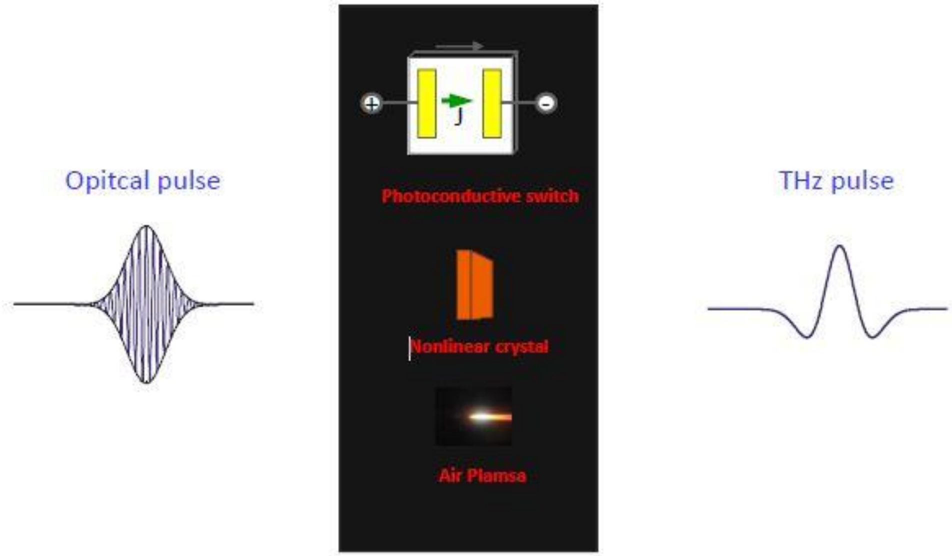


U. Frühling et. al., Nat. Photon. (2009)

Overview of Available THz Sources

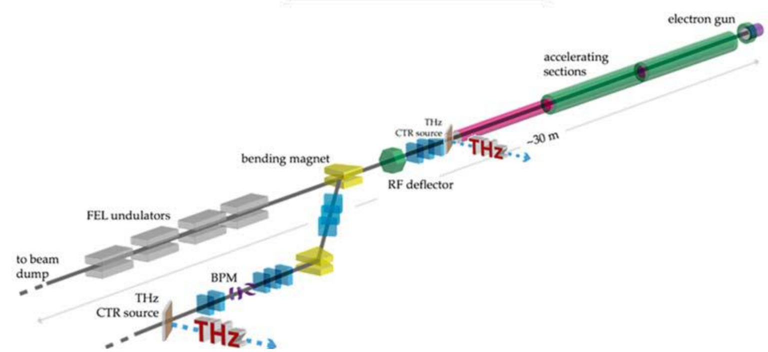
➢ laser based

- Photoconductive switch (antenna)
- Nonlinear crystal
  – optical rectification (OR)
  – difference frequency generation (DFG)
- Gas or air plasma



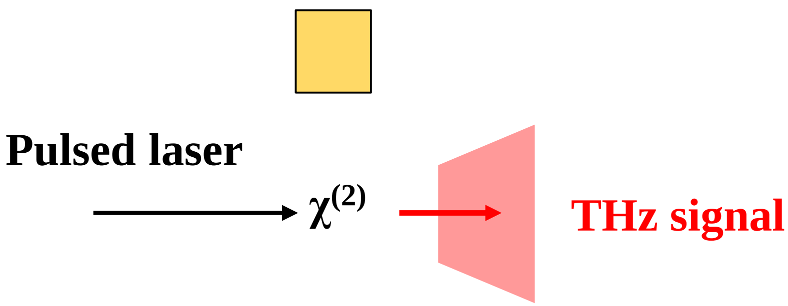
➢ accelerator based

- 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



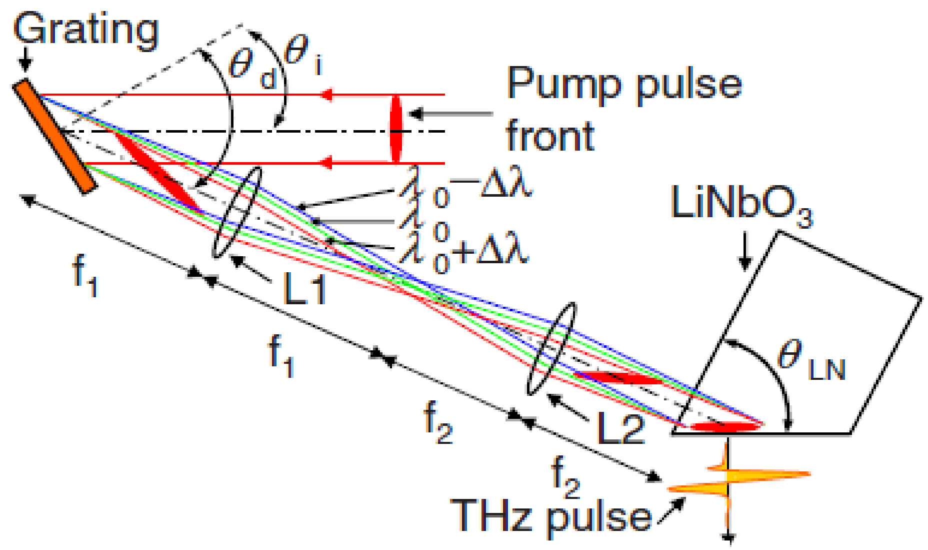
Laser-Based Intense THz Sources

Optical rectification

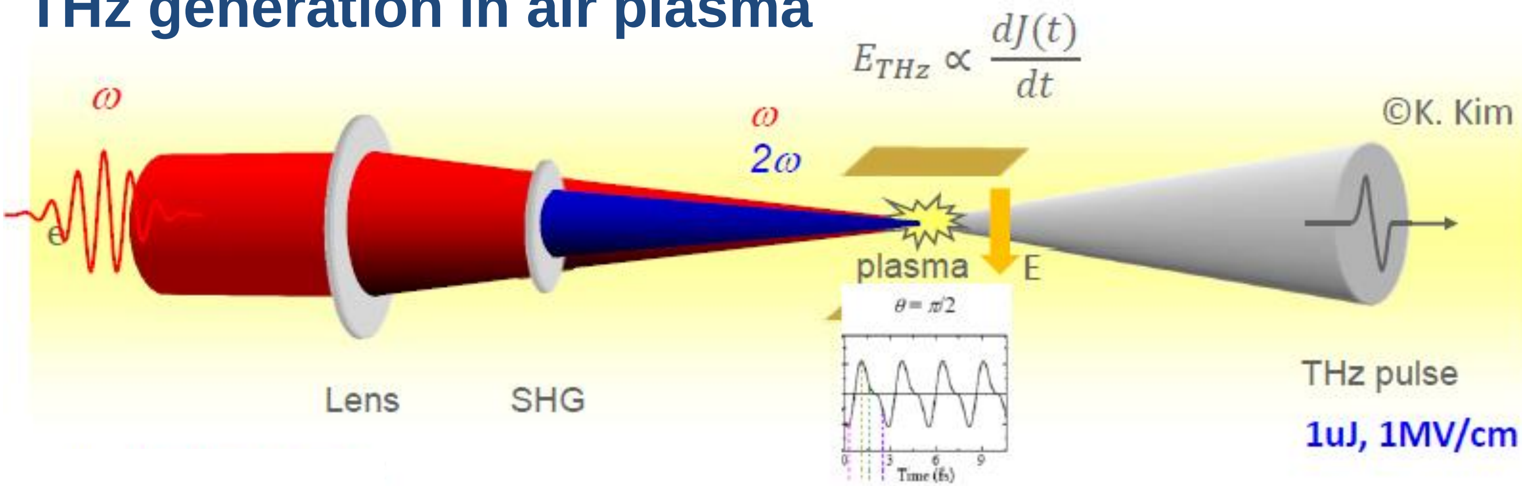


ZnTe, $LiNbO_3$ etc….

Tilted Pulse Front technique

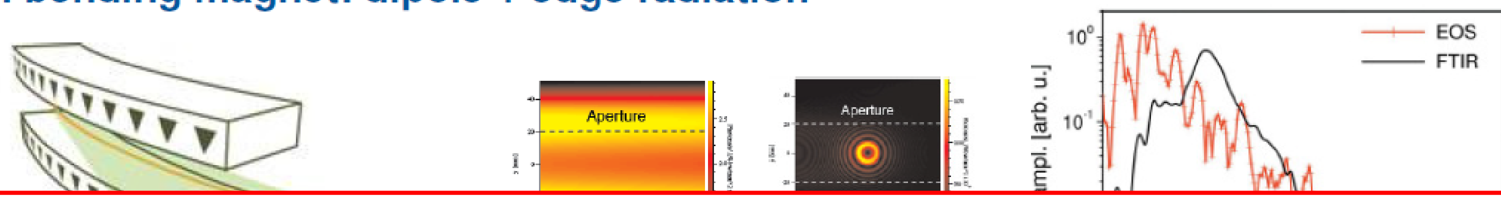


THz generation in air plasma



Accelerator-Based Coherent THz Sources

1. bending magnet: dipole + edge radiation



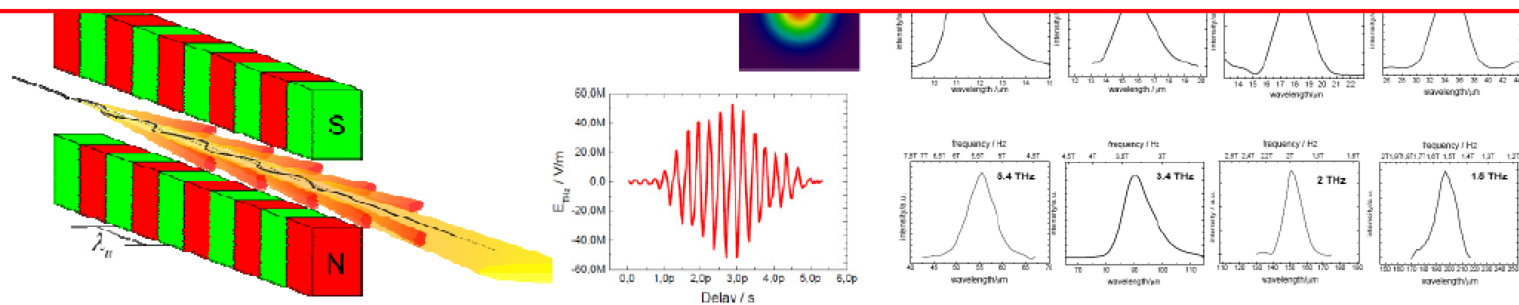
Source type: "super-radiant" sources

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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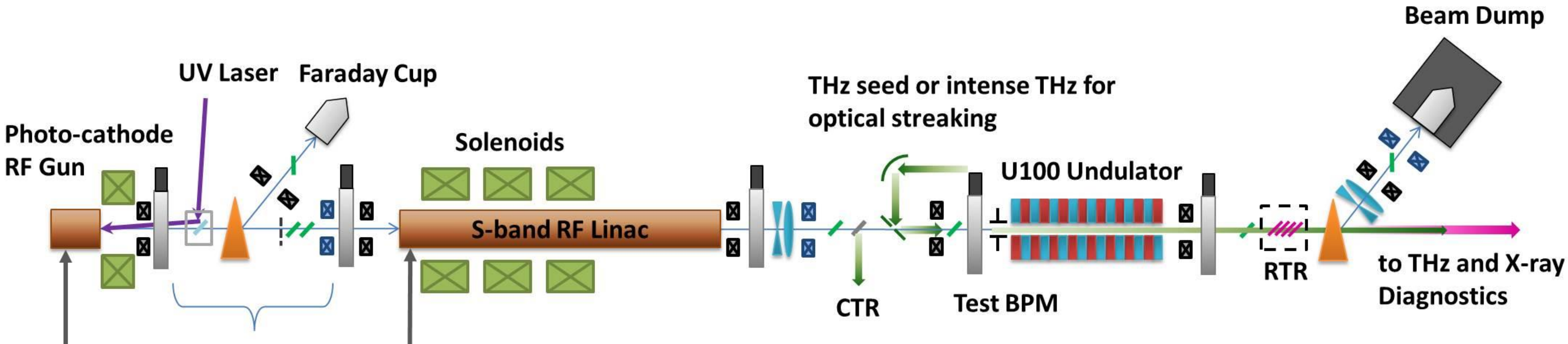
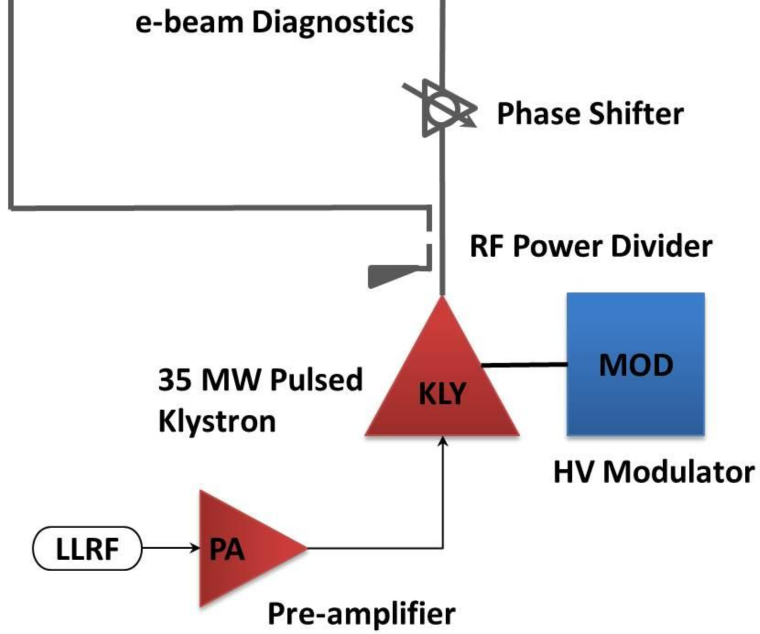
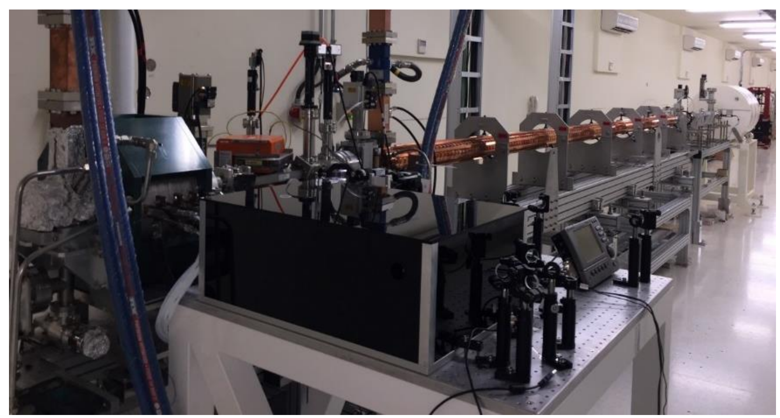
The NSRRC Photo-injector – an Test Accelerator for Light Source Development

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



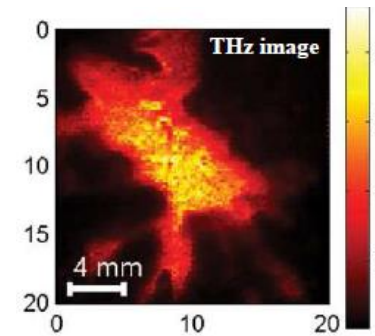
Pursue of High Brightness Electron Beam

➢ **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

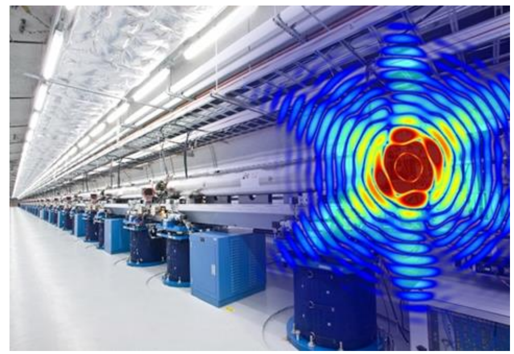


THz image of tumor of breast cancer.
[ref] P.C. Ashworth et al., Opt. Express 17 (2009) 12444; A.J. Fitzgeld et al., Radiology, 239 (2006) 533.

✓ **Key issue of injector design:**

1. beam production 2. bunch compression

3. transport and preserve high brightness beam



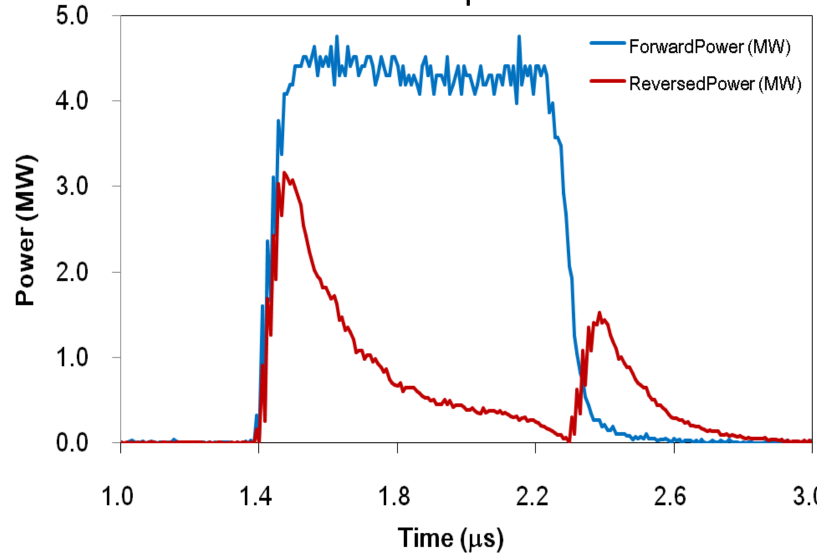
The LCLS and a diffraction pattern of a single mini virus particle.
[ref] http://xray.bmc.uu.se/hajdu/

Photocathode RF Gun

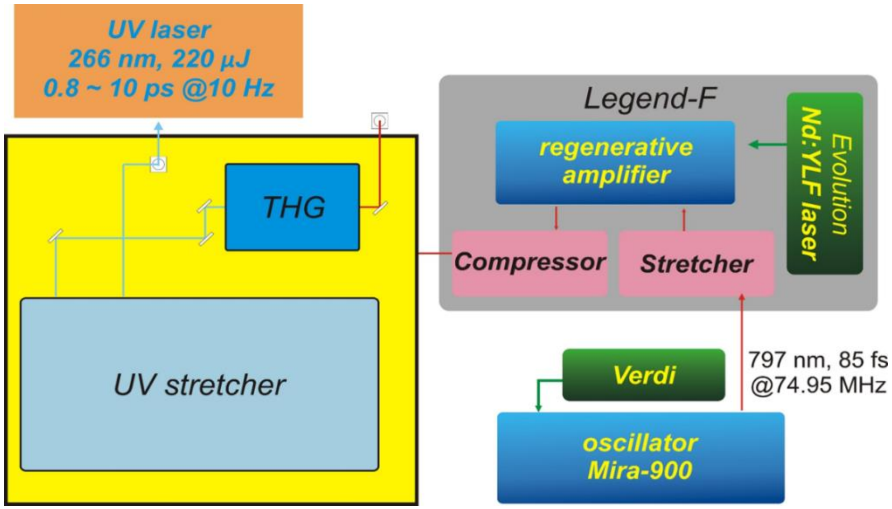
- Design is based on the 1.6 cell s-band rf gun developed at BNL DUV FEL.
- Copper (Cu) photo-cathode
- Operating at temperature 55°C , vacuum < 5 x 10^{-8} mbar
- UV drive laser

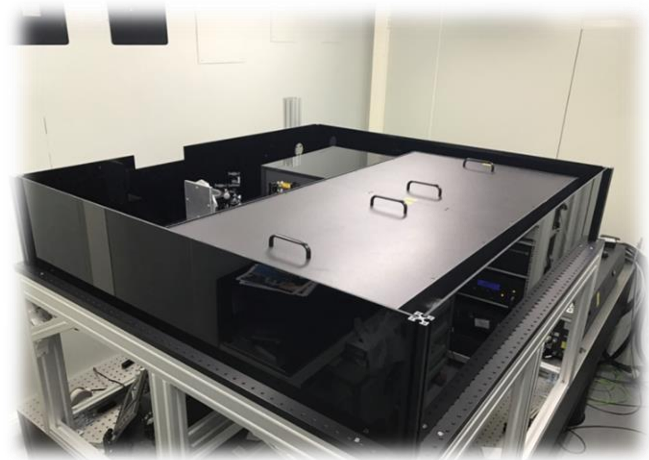
Parameter	Value
Frequency	2.99822 GHz (@55°C)
Q_0	~8000
Coupling coefficient	0.7
Peak field at the cathode	58 MV/m
Beam energy after gun	2.8 MeV
UV laser pulse duration	3 ps
Cathode quantum efficiency	~1 x 10^{-5}

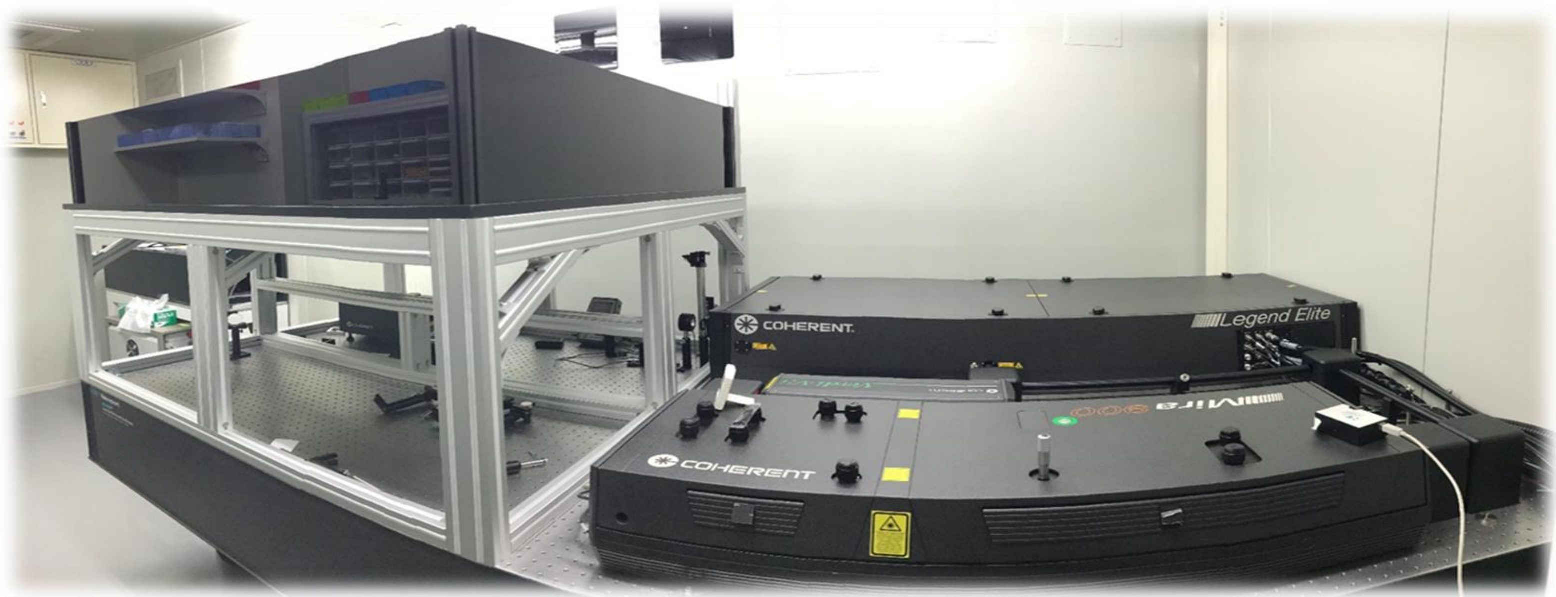
Forward and reverse power of the Gun



Drive Laser for the Photocathode RF Gun



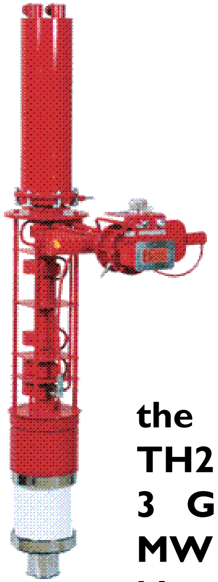




Pulse Klystron System for the Photo-injector

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

Inside the oil tank



the Thales TH2100A 3 GHz, 35 MW pulsed klystron

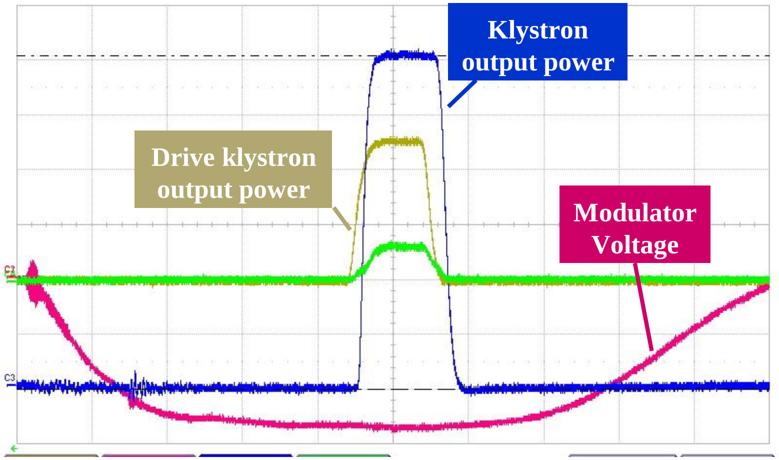
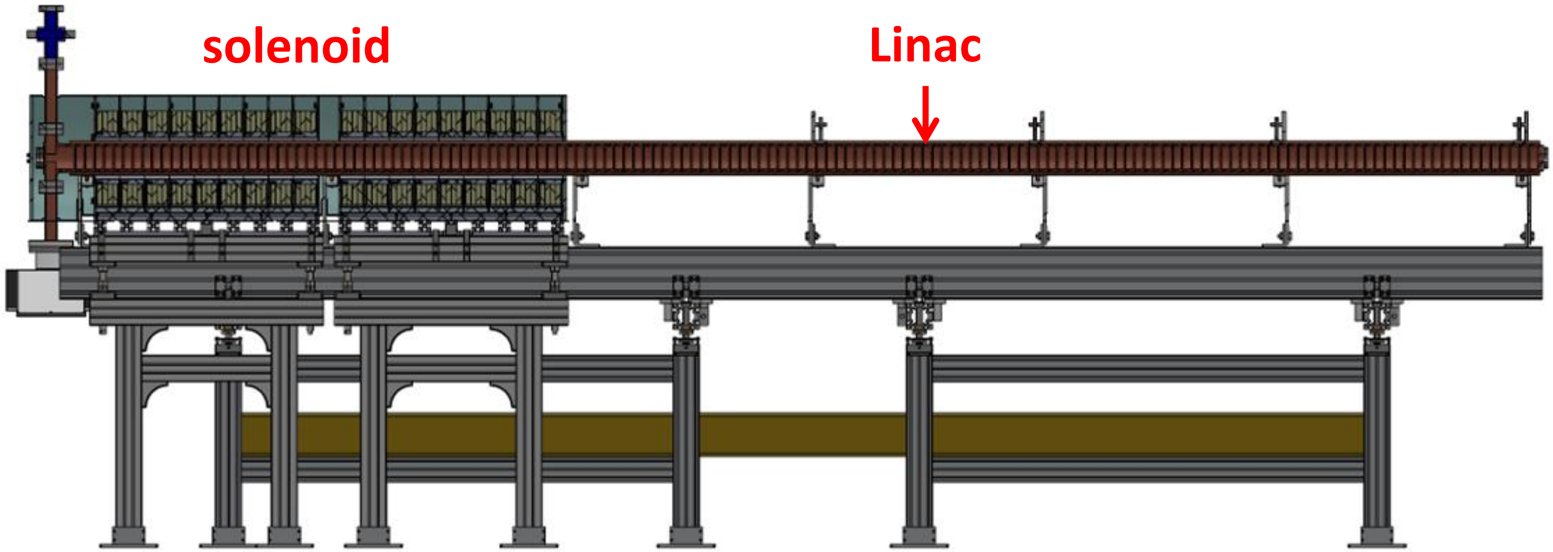


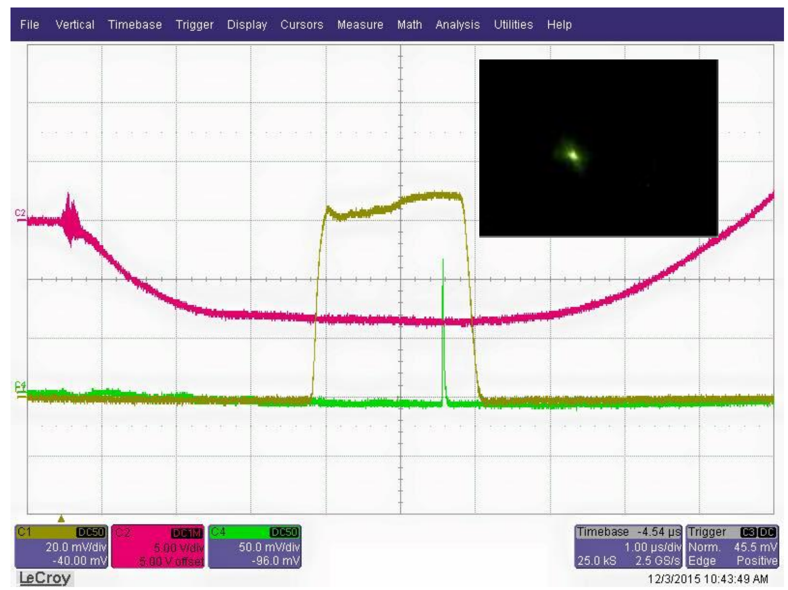
Photo-injector Linac and Focusing Solenoid



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

Commissioning of the NSRRC Photo-injector System

Parameters of the photo-injector system	
Laser pulse width (ps)	3
Laser energy (µJ)	60
Power to RF gun (MW)	4.5
Power to Linac (MW)	12
Beam energy (MeV)	62
Beam charge (pC)	460
Repetition rate (Hz)	10



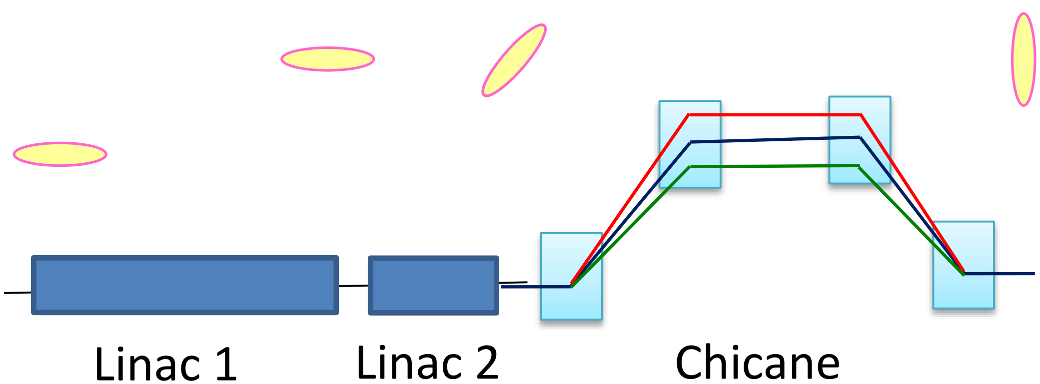
Bunch Compression Scheme

➢ 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…

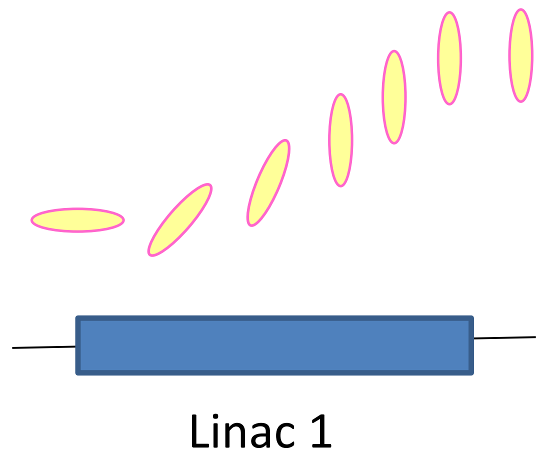


➢ Velocity Bunching

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

< Issue >

- nonlinearilty
- emittance compensation…

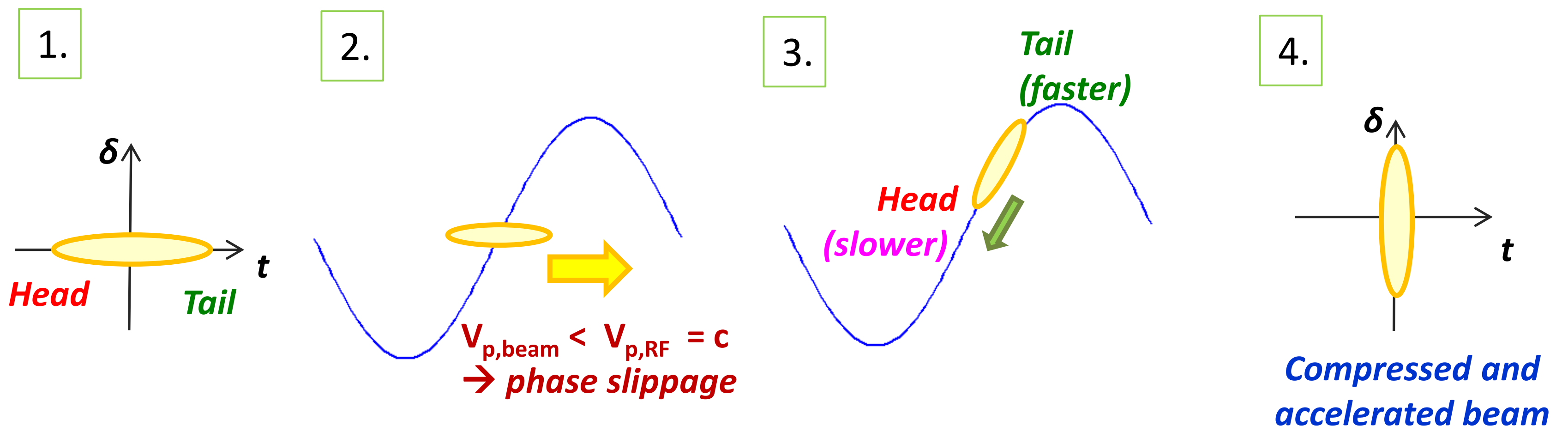


Velocity Bunching in an Accelerator

- 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. Injected the beam 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

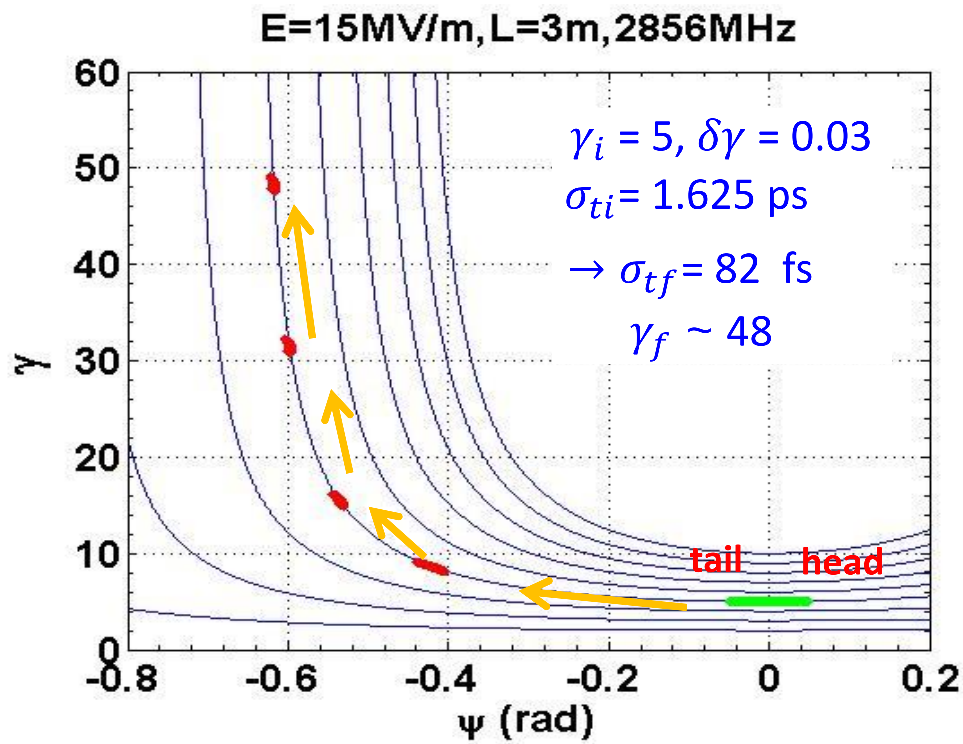


Velocity Bunching in an Accelerator

Velocity Bunching

→ **the deformation of longitudinal phase space during phase slippage**

→ **bunch is compressed and accelerated simultaneously through the accelerating structure**

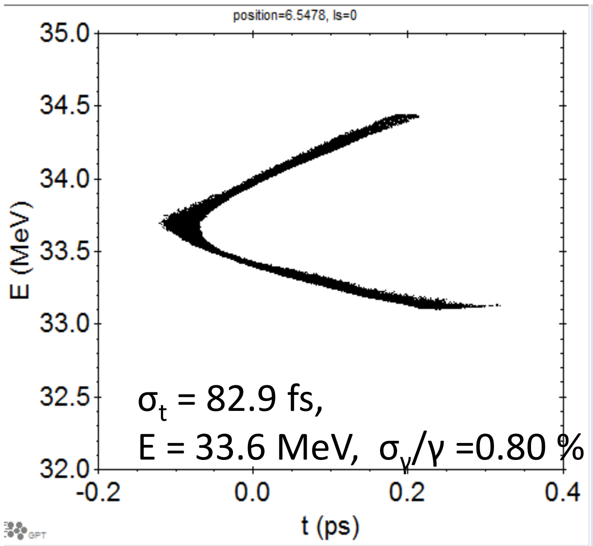


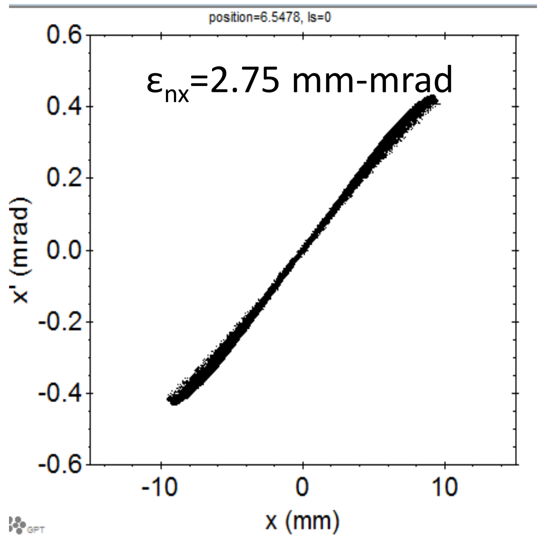
$$V = \beta c = c\sqrt{1 - \frac{1}{\gamma^2}}$$

- 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).

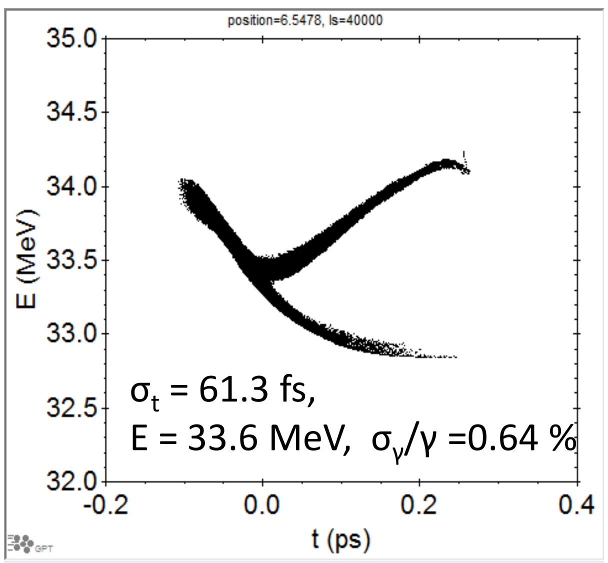
Ultrashort Bunch by Velocity Bunching

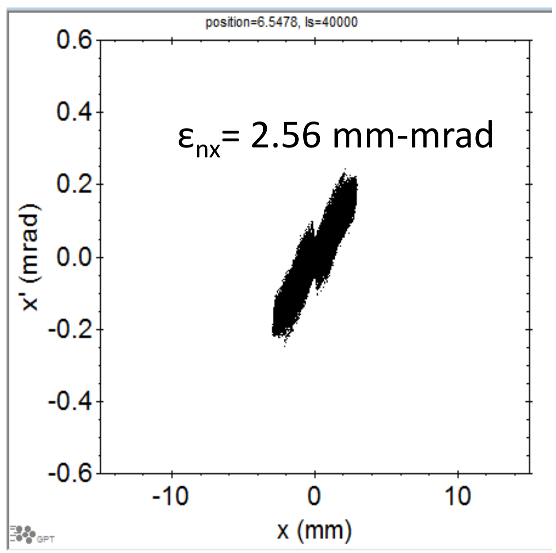
Phase space at L_0 Exit   w/o linac solenoid





Phase space at L_0 Exit   with linac solenoid





- Gun condition

Ep = 65MV/m,

Dp=10 deg, Bp = 1300 Gauss

- Laser condition (uniform)

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

Q = 100 pC

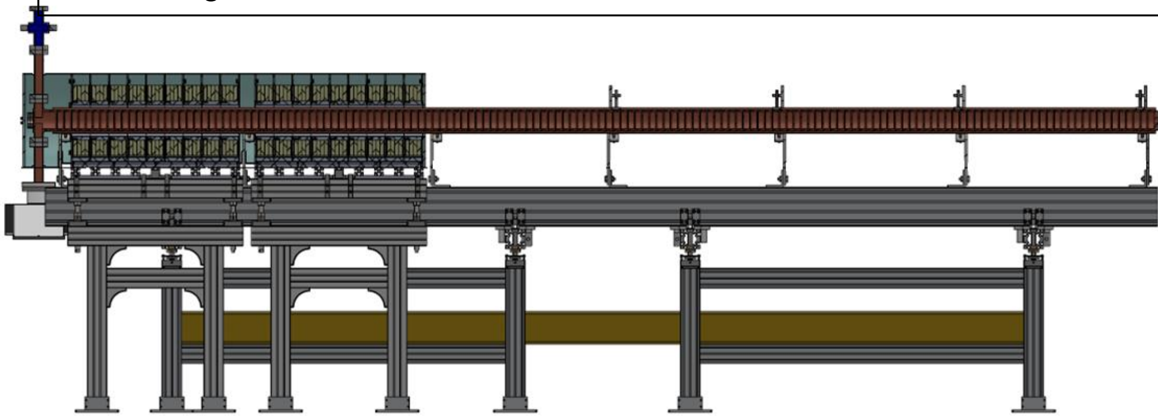
- LINAC L_0 condition

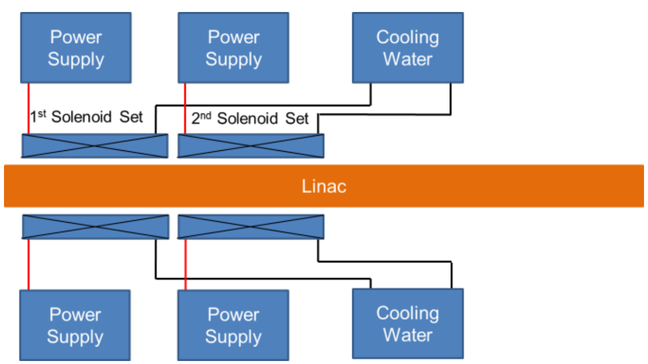
Ep = 15 MV/m,

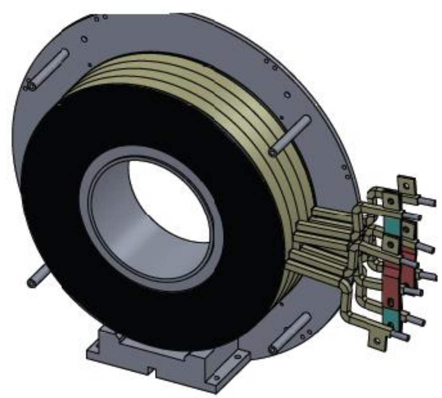
Bs = 502 Gauss, 3 m long solenoid

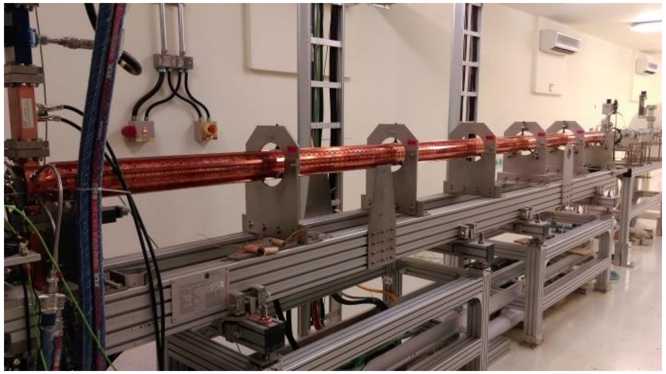
Linac Focusing Solenoid

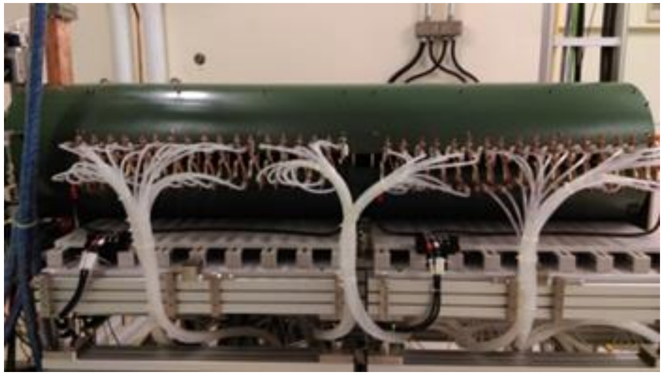
Operating Frequency	2997.9 MHz @ 40 °C
Type	DESY-type const. gradient disk-loaded structure (DESY Linac II)
Operating Mode	$2\pi/3$
Eff. Shunt Impedance	> 52 MΩ/m
Accelerating Gradient	> 11 MeV/m
Total Length	5.2 m











Accelerator-Based Coherent THz Radiation

radiated power

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

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

N: electron number

$f(\omega)$: bunch form factor

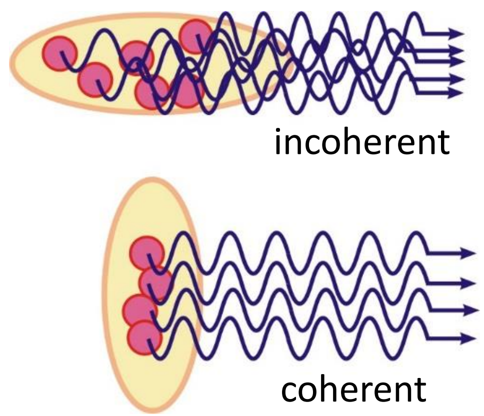
$$f(\omega) = \left| \int e^{ik\hat{n}\cdot\vec{r}} S(\vec{r}) d^3 r \right|^2$$

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

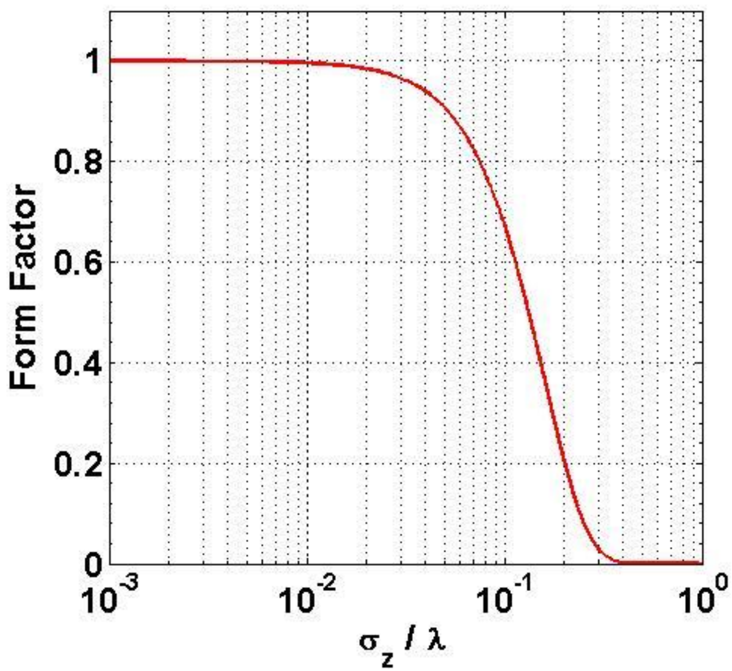
for a Gaussian bunch

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

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)



bunch length σ_z << wavelength λ



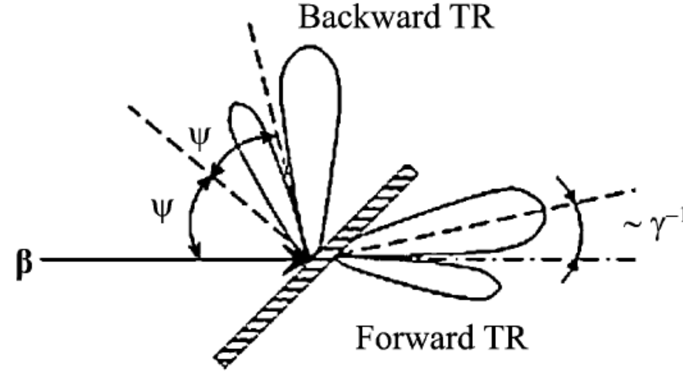
Coherent Transition Radiation

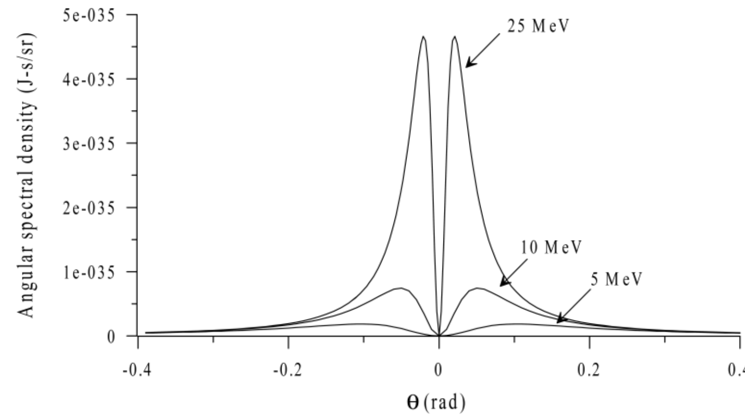
- Transition radiation (TR) is emitted when a charged particle passes through the boundary of two media with different dielectric constant. Forward TR and backward TR occur simultaneously.
- Spectral angular distribution of the emitted TR is given by

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

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 $\theta \sim {}^1/_\gamma$.



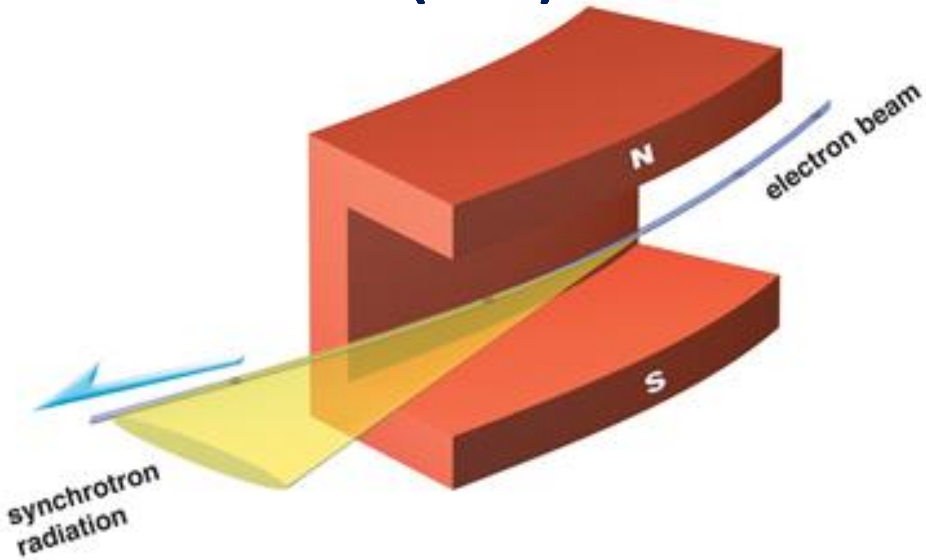


- When the wavelength of the radiation becomes larger than the bunch length, the radiation becomes "COHERENT". ($\lambda \gg \rho_z$)
- Measurements of the radiation spectrum give the information about the bunch length.

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

Coherent Undualtor Radiation

coherent synchrotron radiation (CSR)

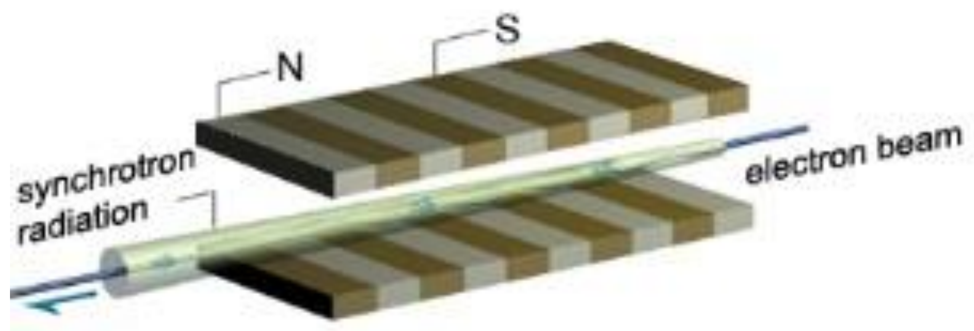


critical energy

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

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

coherent undulator radiation (CUR)



radiation wavelength

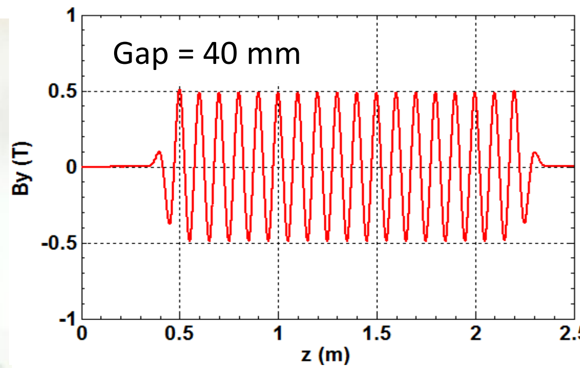
$$\lambda = \frac{\lambda_u}{2\gamma^2}(1 + \frac{K^2}{2} + \gamma^2\theta^2)$$

λ_u: undulator period

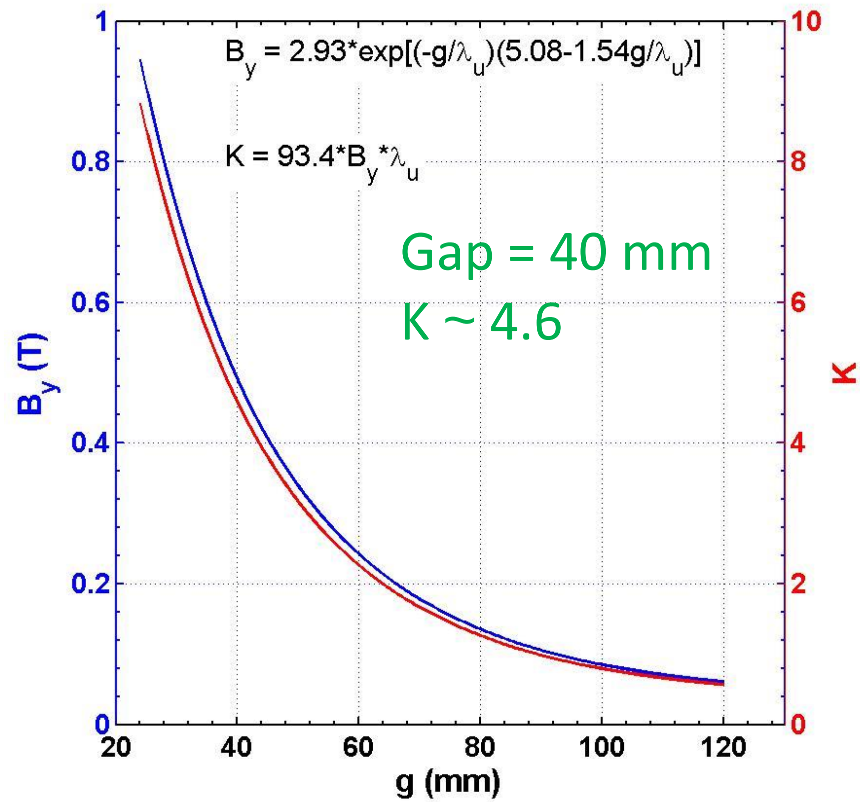
K: undulator strength

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

NSRRC U100 Undulator

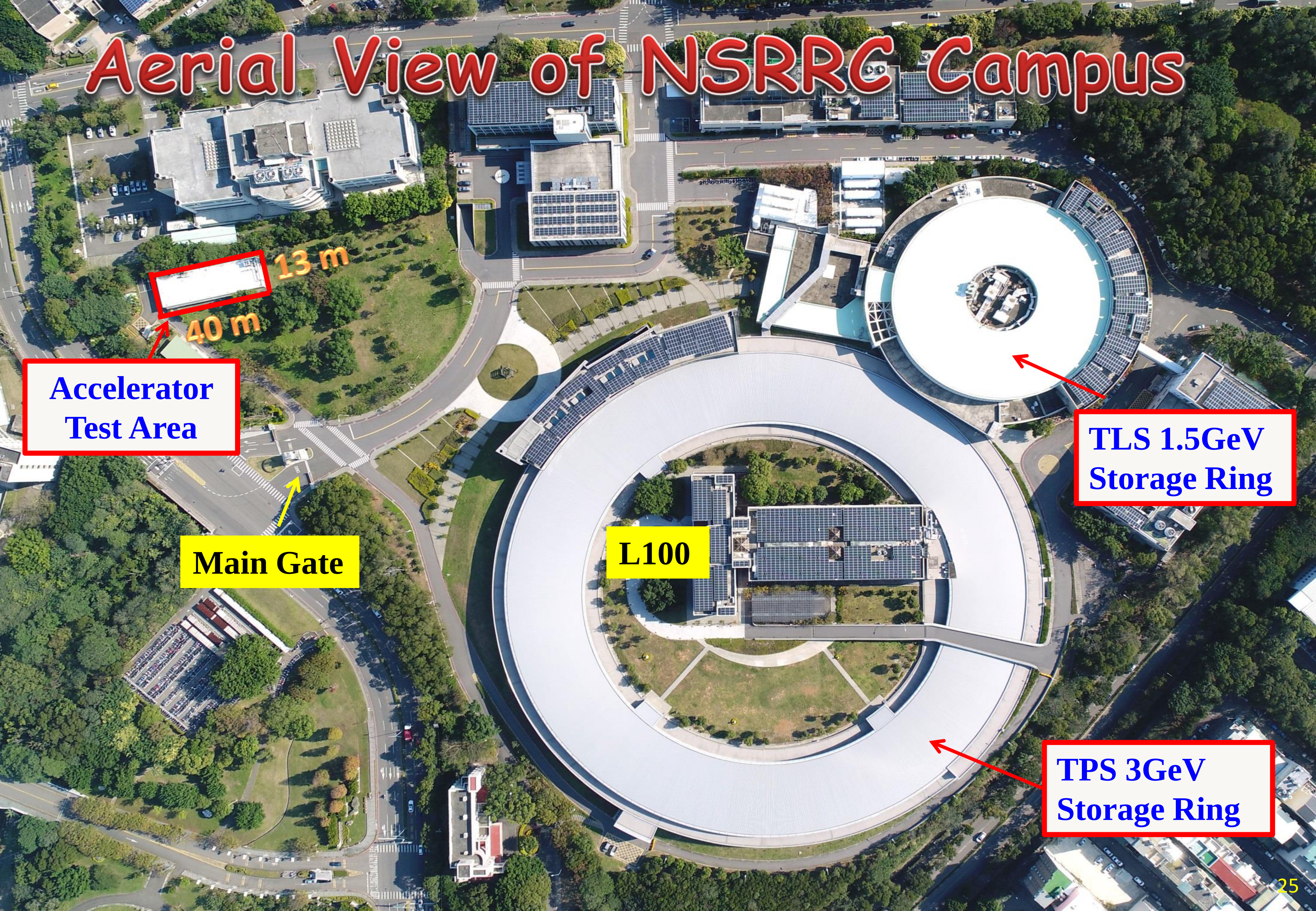


	U100
λ (mm)	100
N_{period}	18
L (m)	2.2
a_w	1.02
gap (mm)	24
B_y (T)	0.945
Ky_{max}	8.8



The U100 undulator built by the NSRRC magnet group more than 20 years ago is used for THz CUR Expt. (also called the THz superradiant FEL or pre-bunched THz FEL)

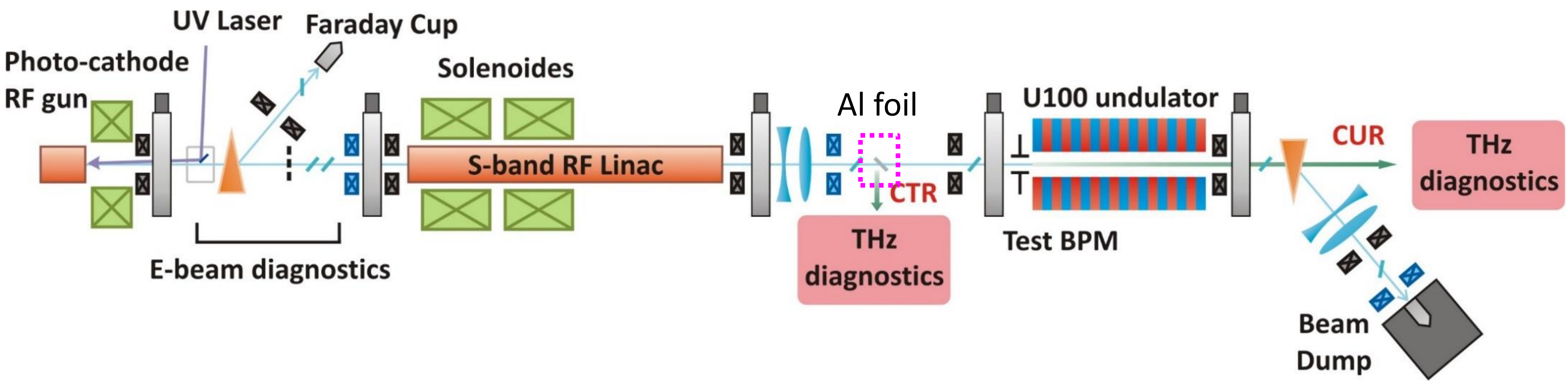
Aerial View of NSRRC Campus



The Accelerator Test Area

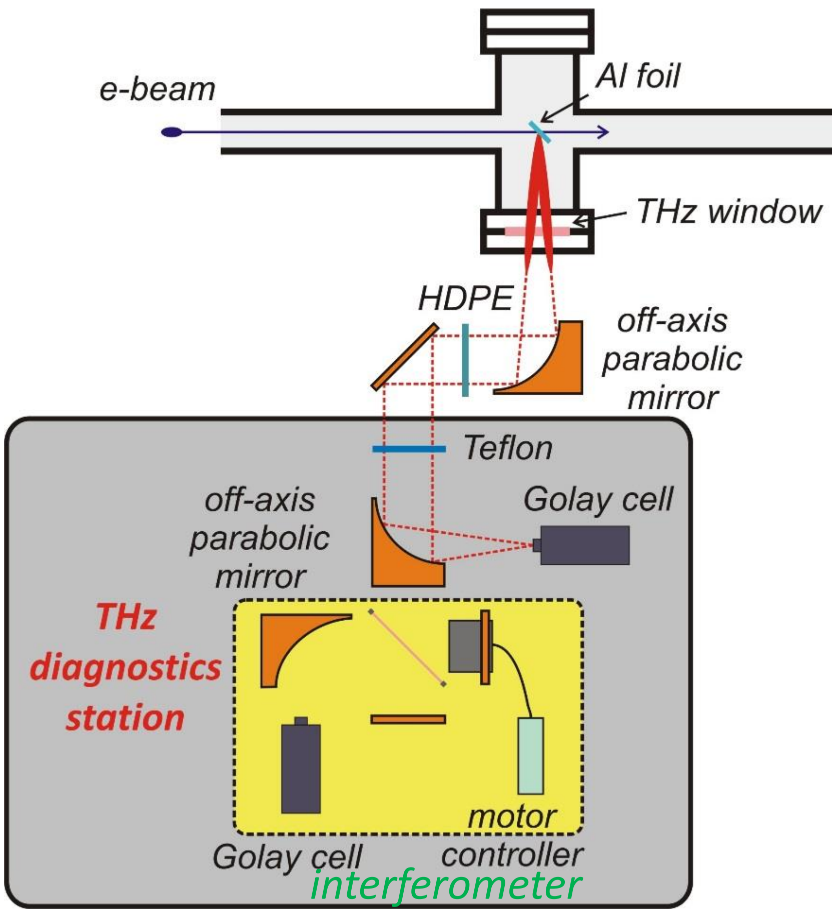
- First operation of the photo-cathode RF gun in 2013 at the TLS Booster.
- Construction of the photoinjector system at the Accelerator Test Area since 2014.
- In 2015 the 90 MeV photoinjector is in operation.
- Demonstration of generation of coherent THz sources in 2017.

Layout of the Coherent THz Radiation Sources

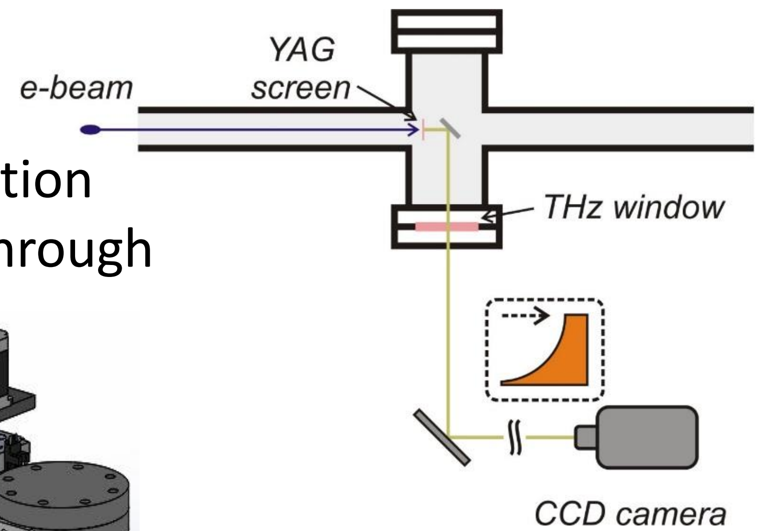


Setup of THz CTR Measurement

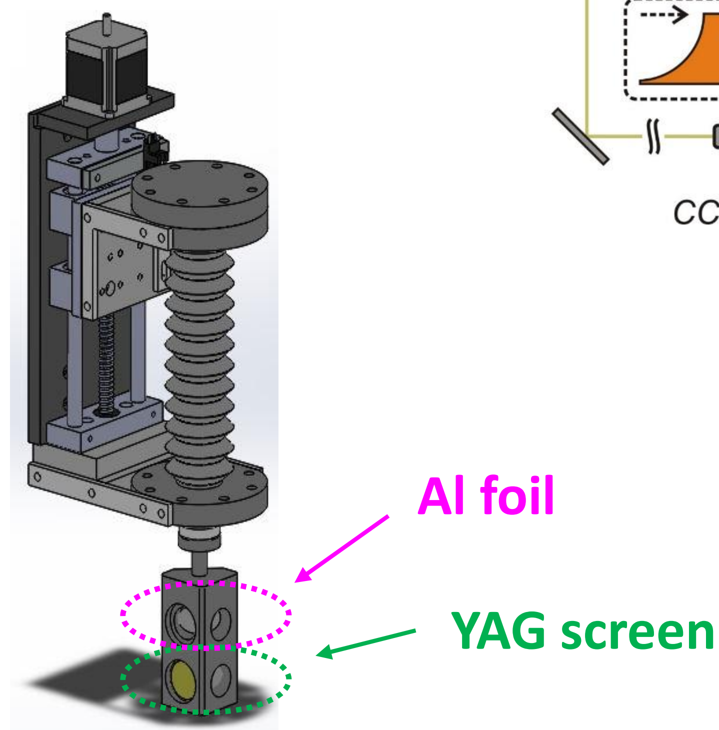
THz power



YAG screen image



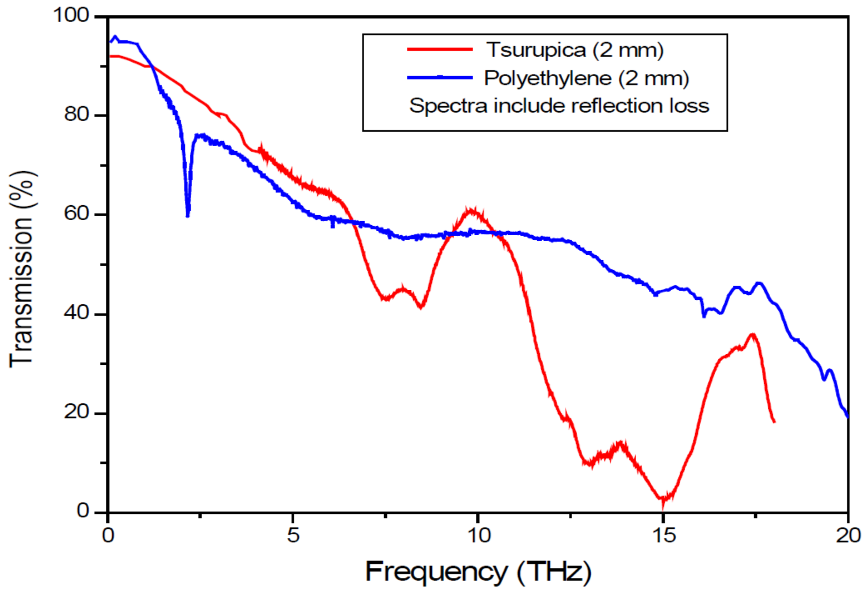
motion feedthrough



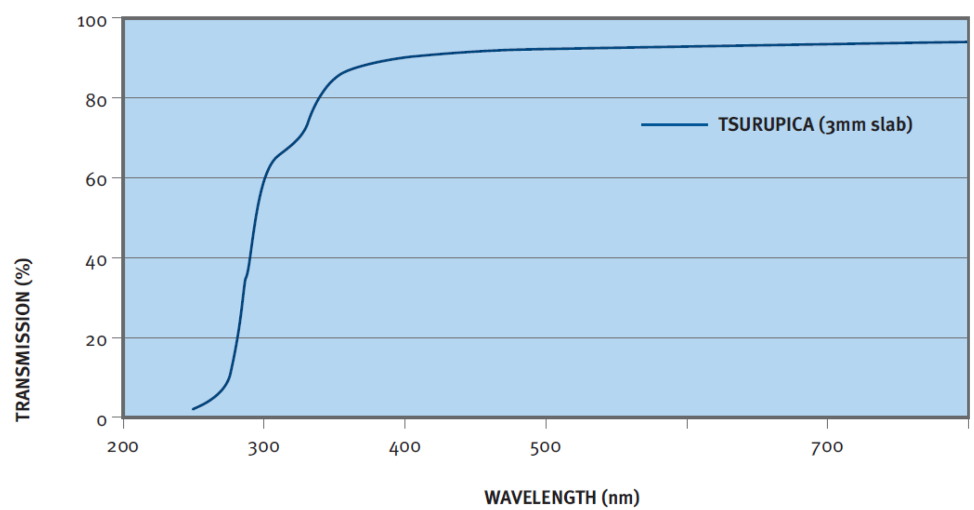
THz Material – Tsurupica

– 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

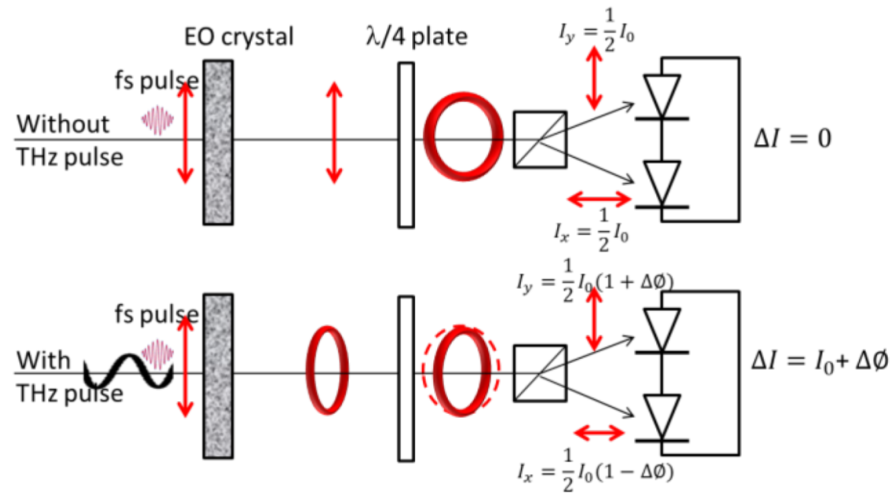


Ref: http://www.mtinstruments.com/downloads/THz%20Lenses%20and%20Windows%20Datasheet.pdf
http://phluxi.com/P91-2-002r4.pdf

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)

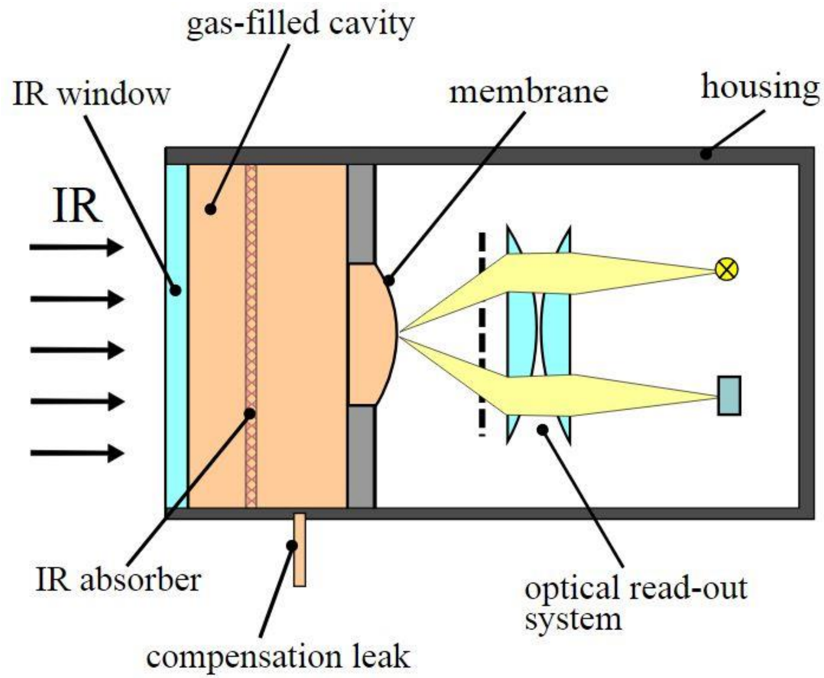


bolometer

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

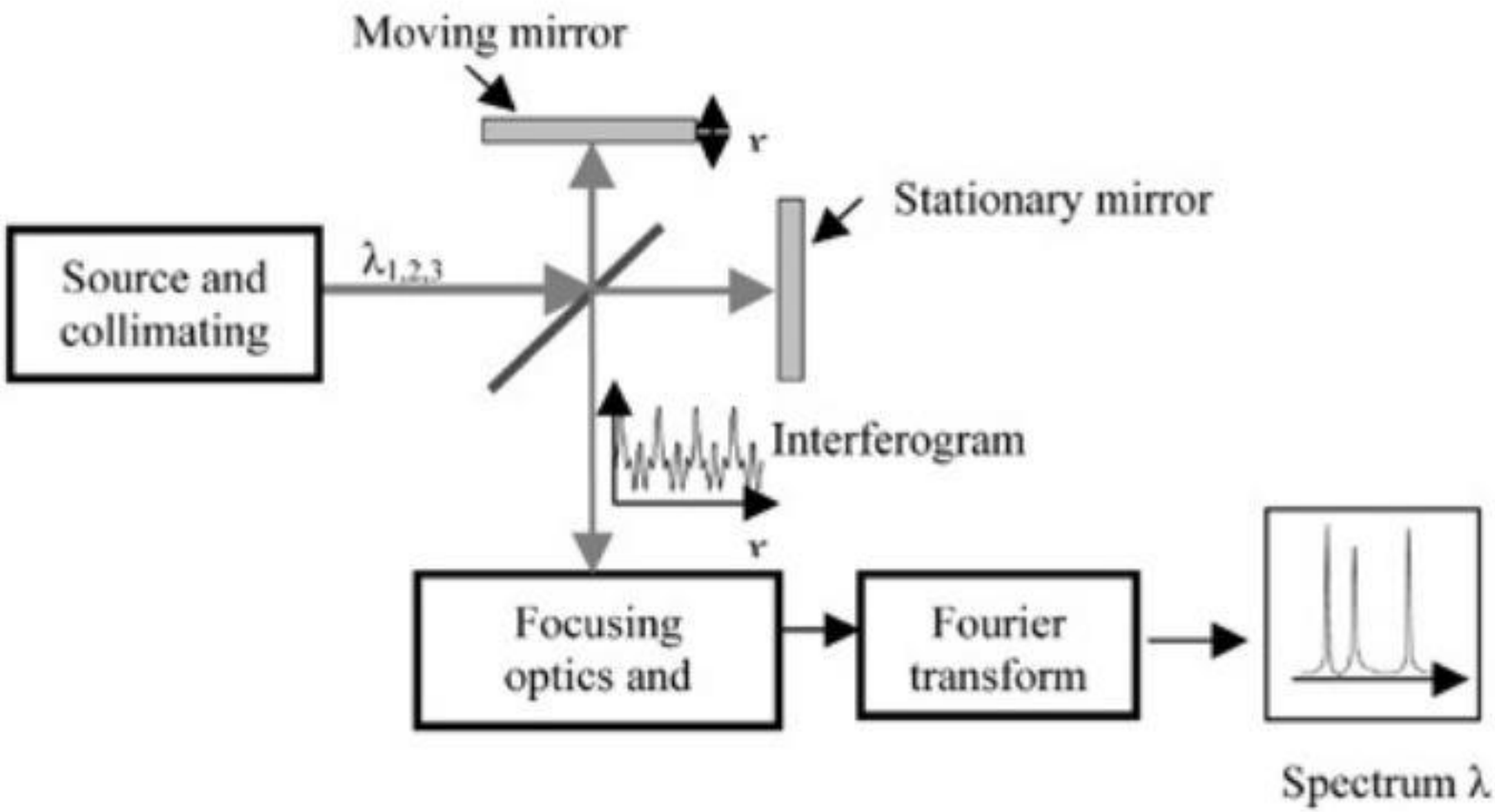
THz Power Measurement – Golay Cell Detector

- 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

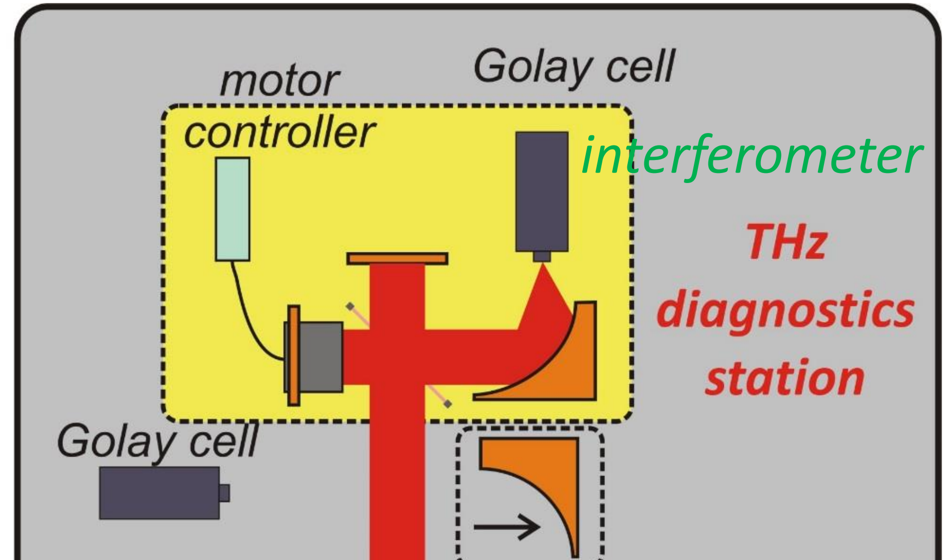


- THz spectrum can be obtained from the interferogram via fast Fourier transform.

Setup of THz CUR Measurement

THz diagnostics station

THz spectrum



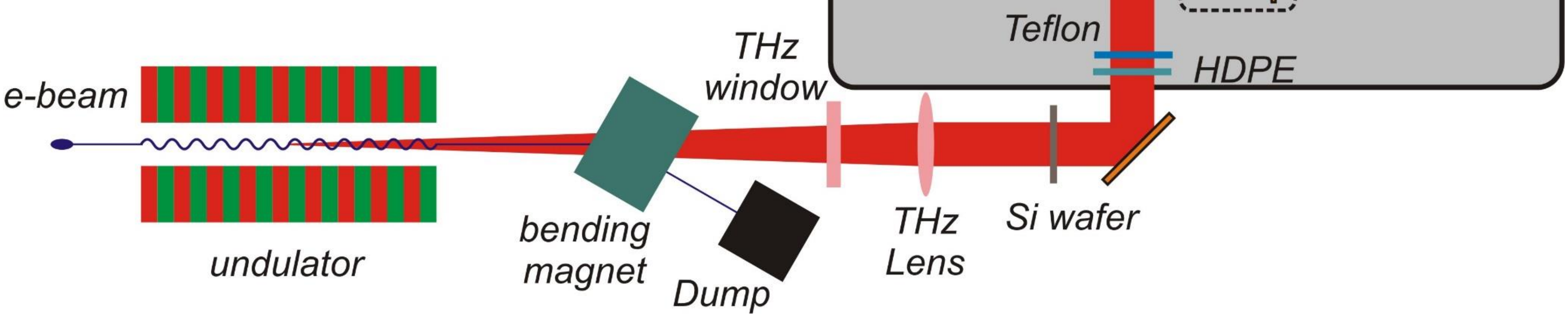
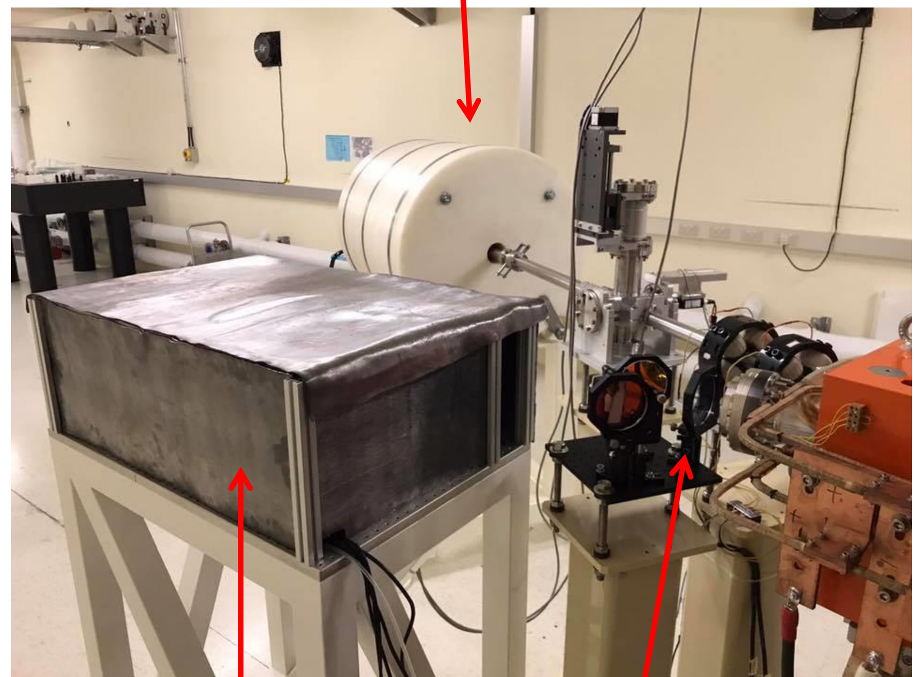


Photo of THz Diagnostics Station

THz interferometer

beam dump



THz detector
(Golay cell)

Pb sheet

Tsurupica
lens

Outline

I. Introduction of intense THz sources

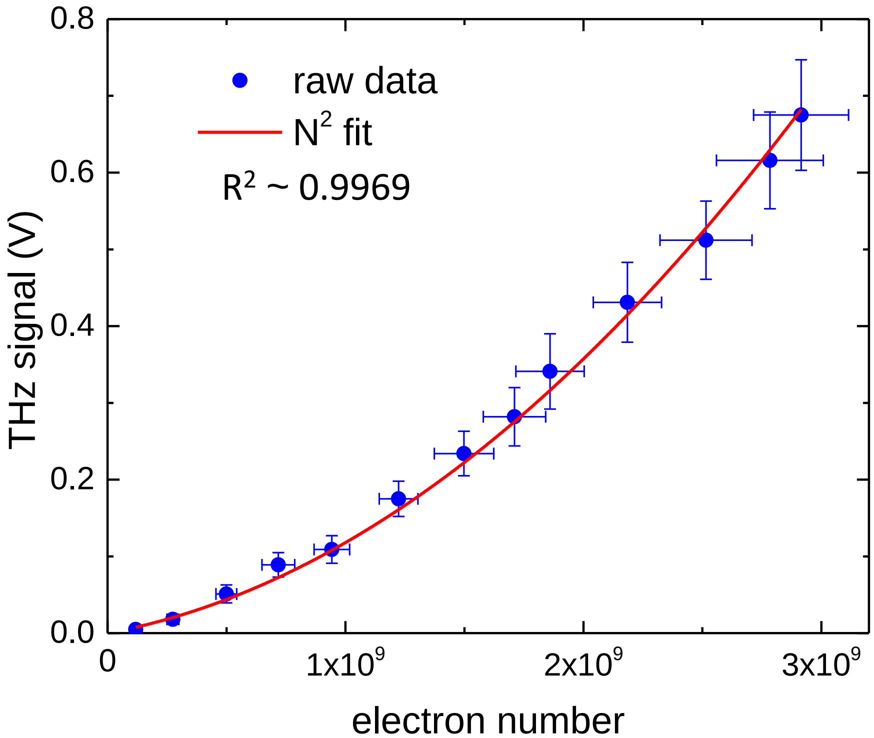
II. Development of superradiant THz FEL at NSRRC

III. Experimental results of coherent THz sources

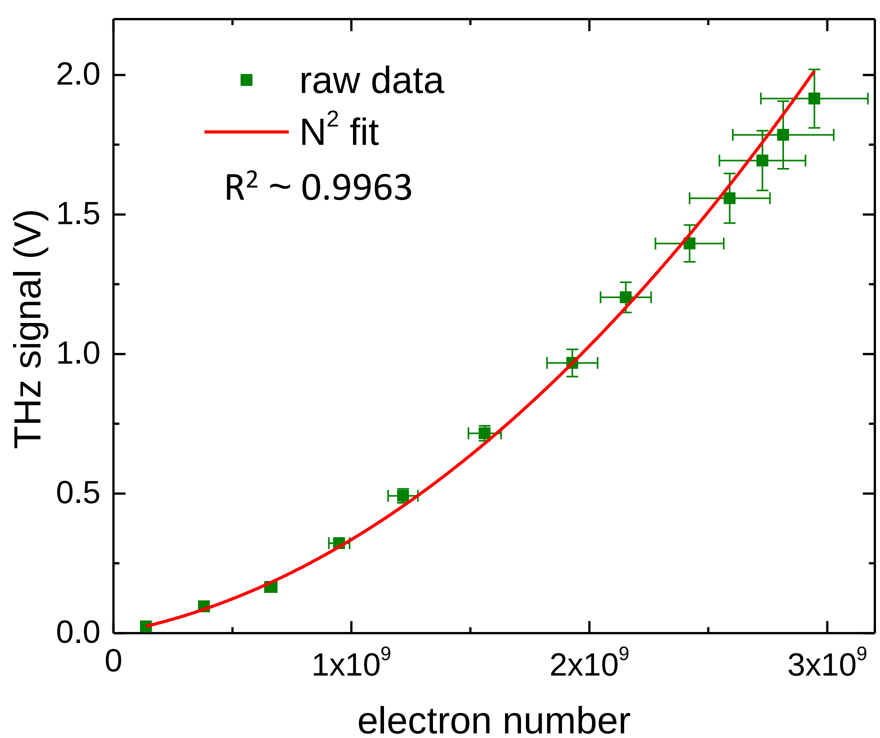
IV. Summary

THz Signal vs. Electron Number

coherent transition radiation



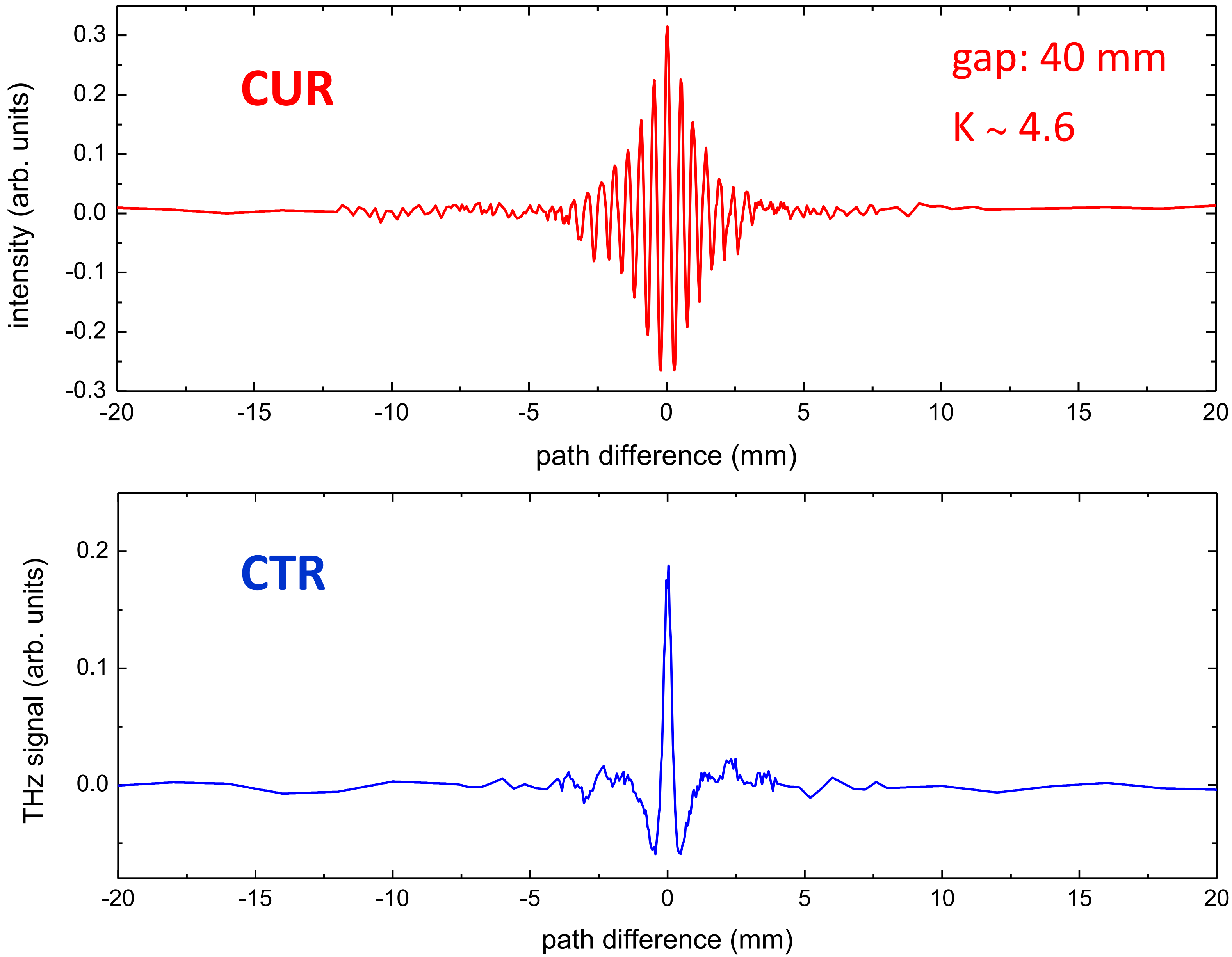
coherent undulator radiation



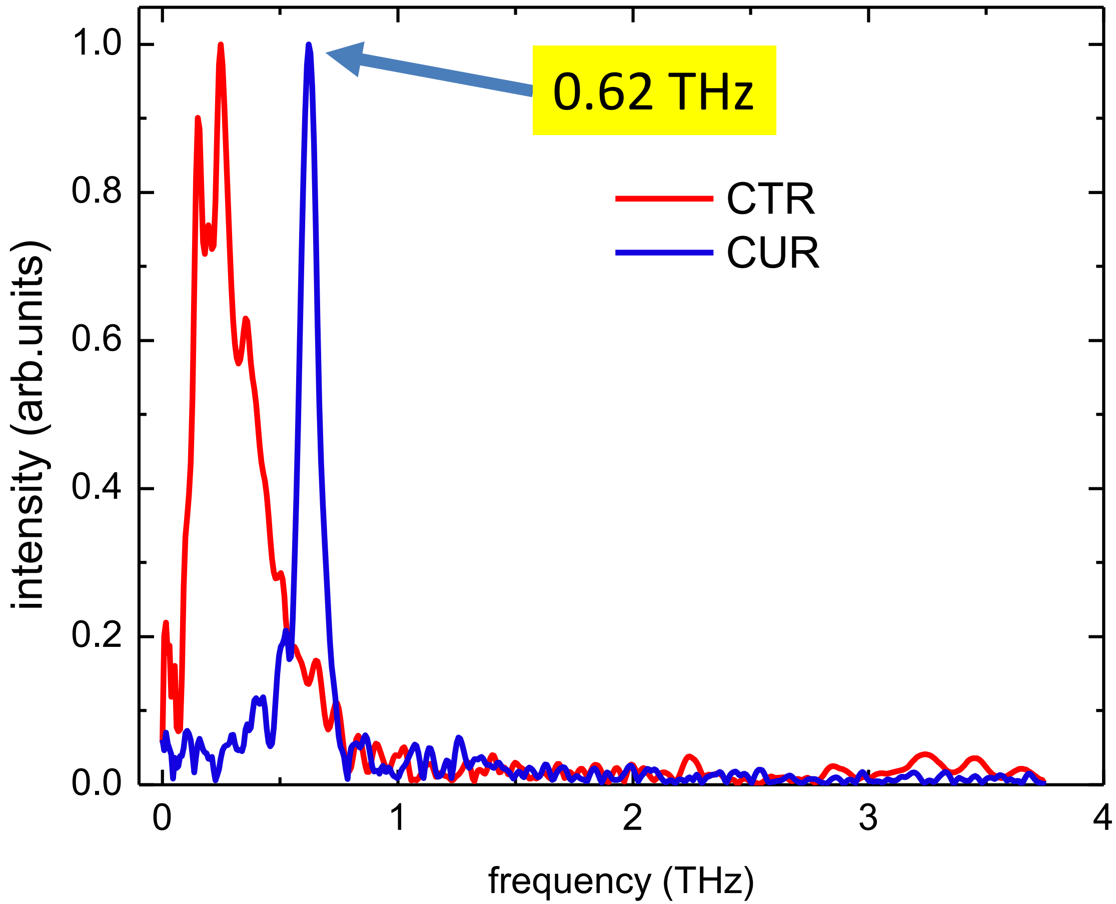
- As expected, quadratic dependence of the THz output signal on the electron number is observed for both CTR and CUR.

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

Measured Interferogram of THz Sources

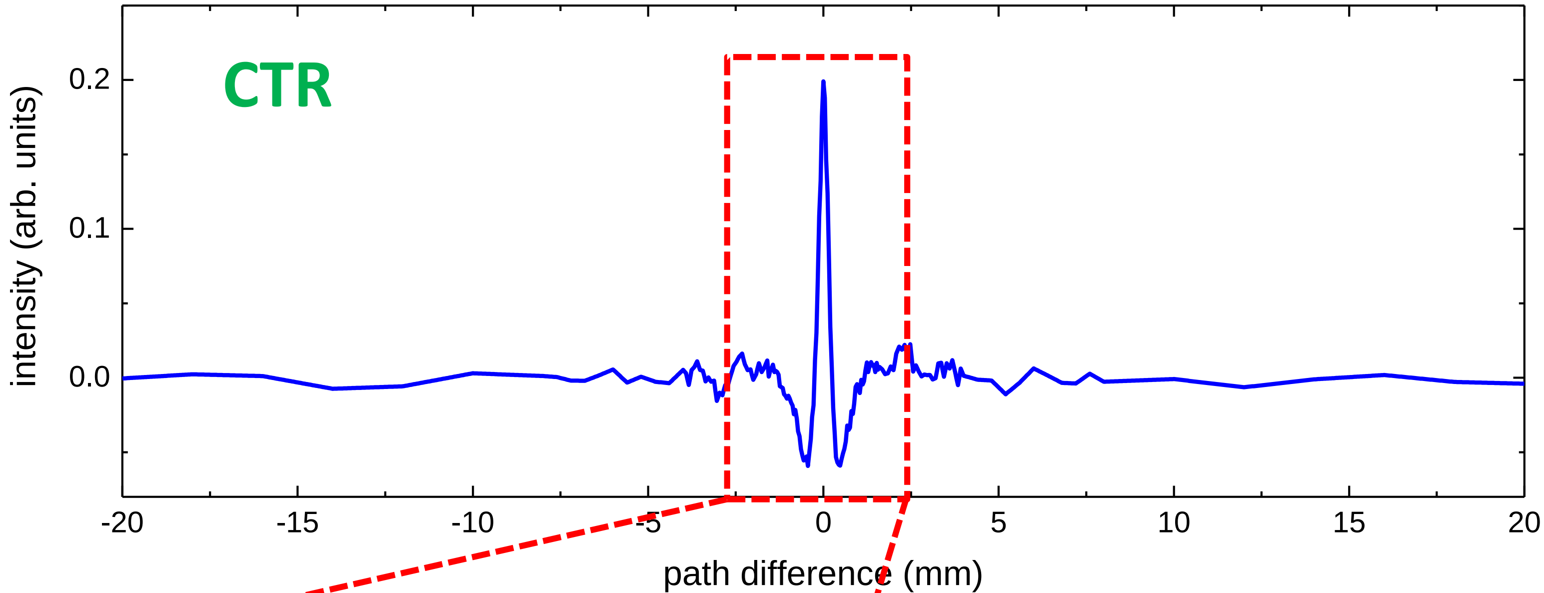


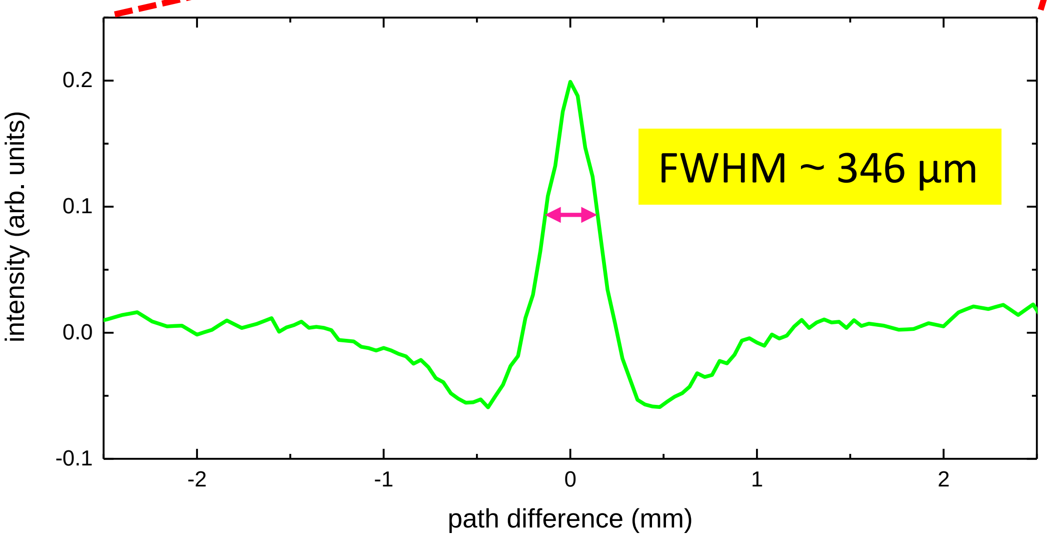
THz Spectrum



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

Retrieved the Electron Bunch Length





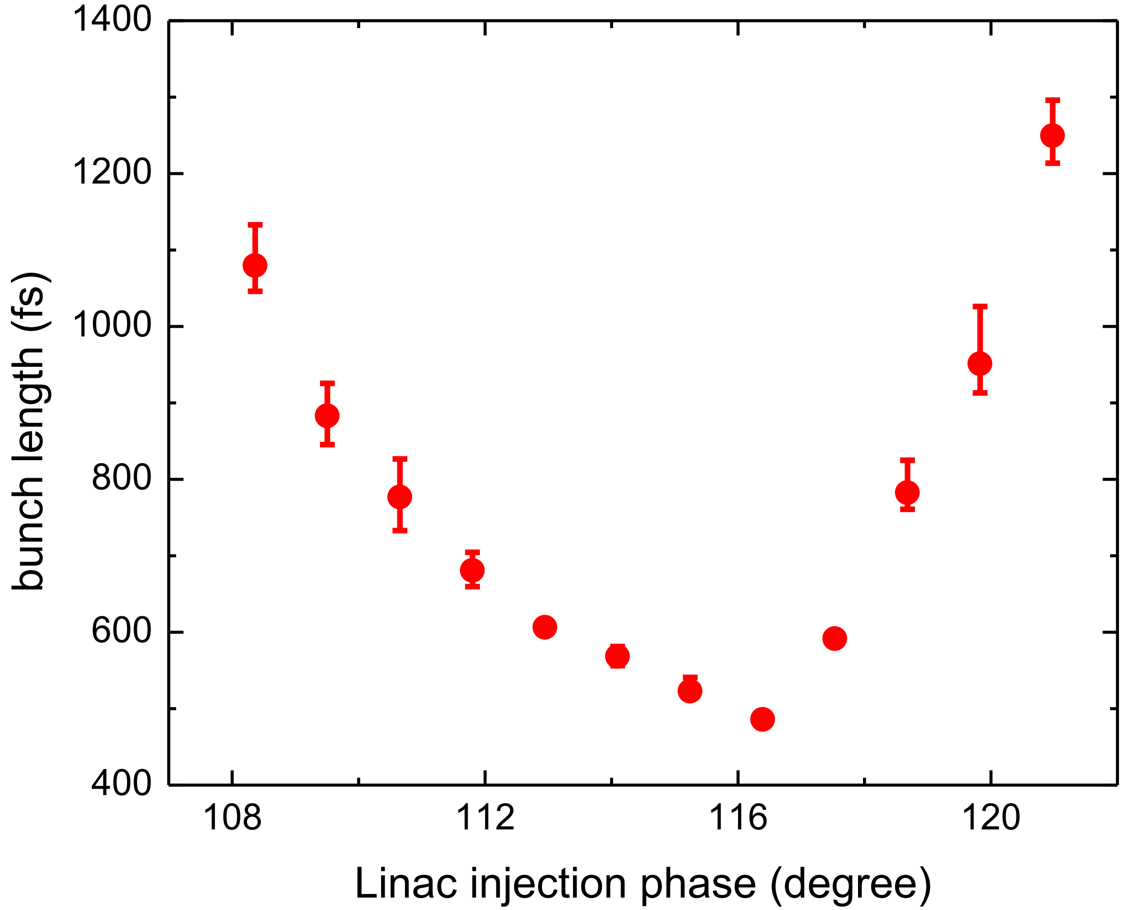
- assume Gaussian distribution

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

  bunch length σ_z ~ 147 μm = 490 fs

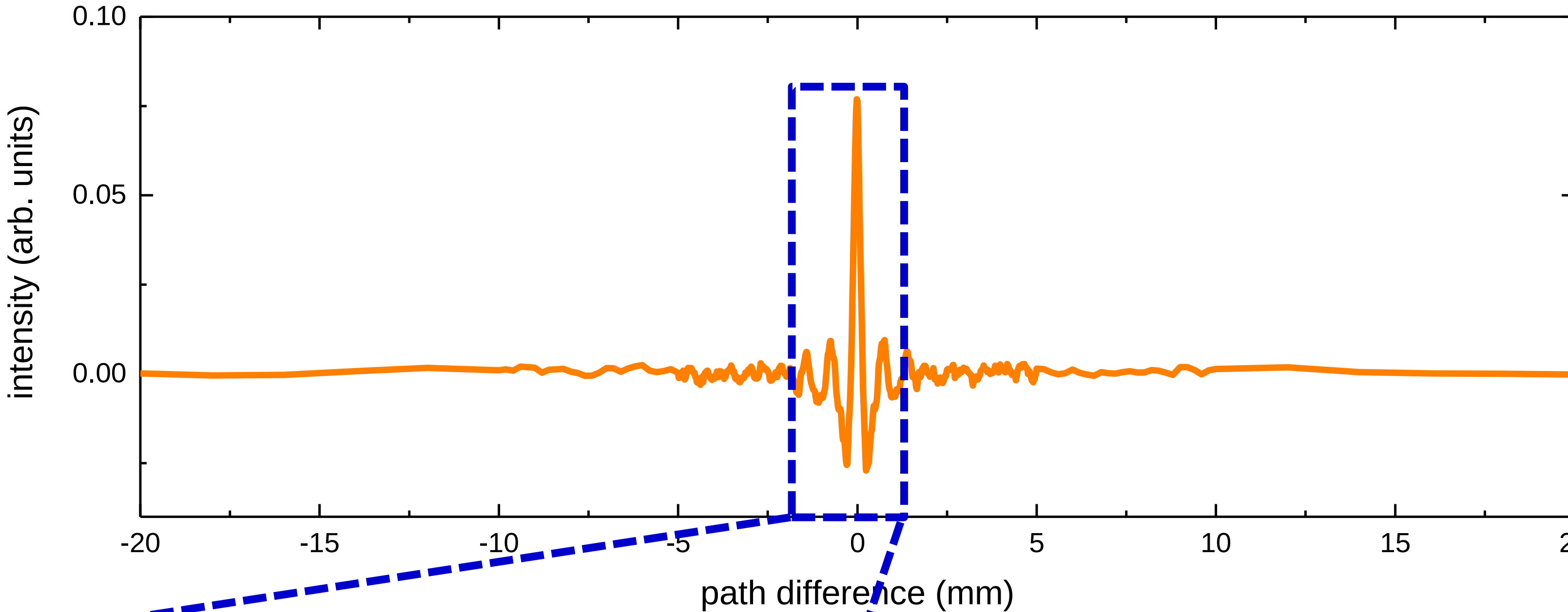
- The measured bunch length is longer than that of simulation. This may cause by the lower linac field used in the experiment.

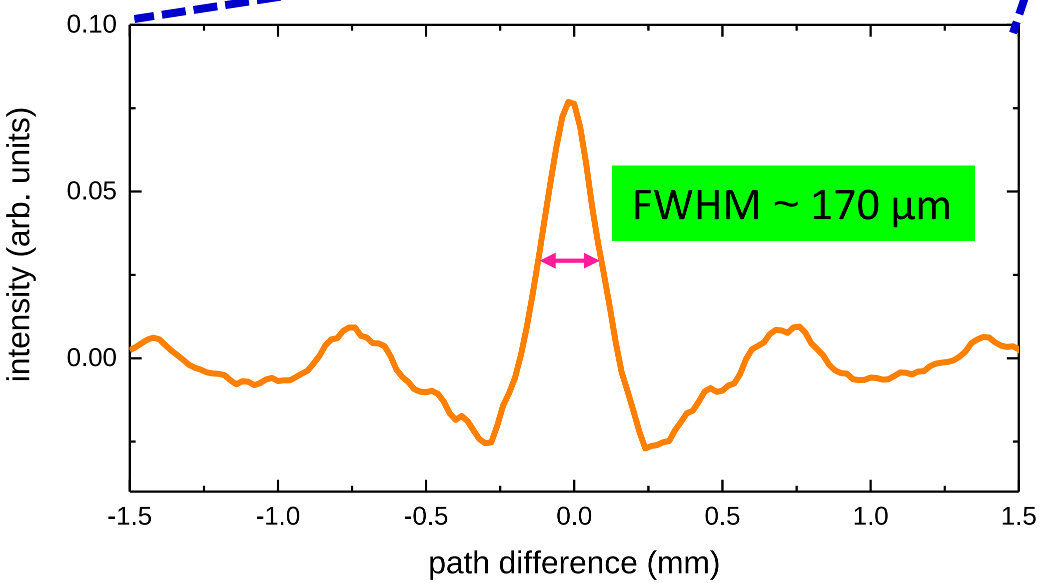
Linac Injection Phase vs. Bunch Length



- 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

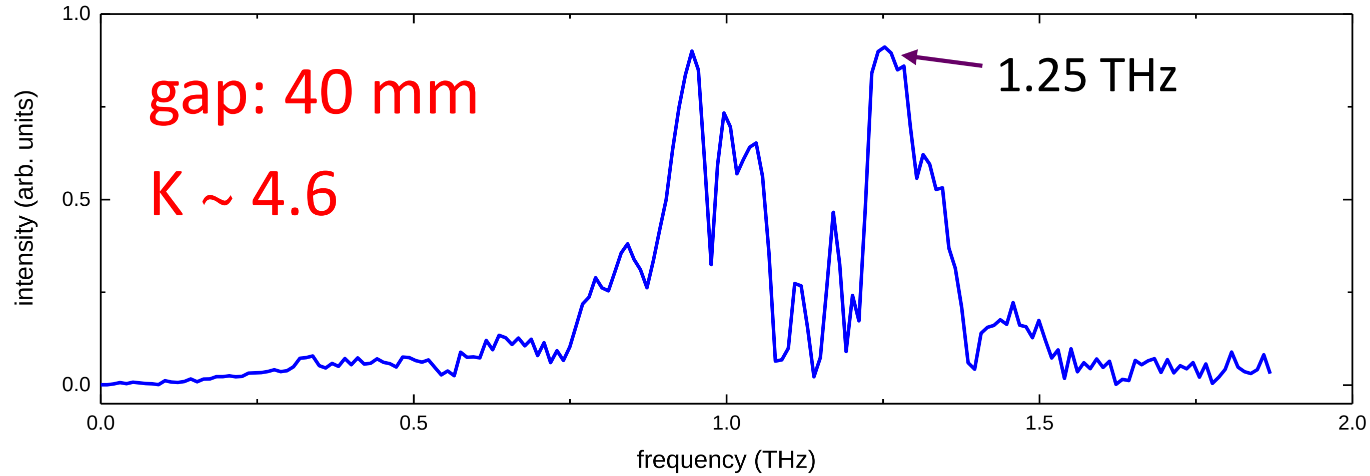
FWHM = $2\sqrt{2ln2}\sigma_z$

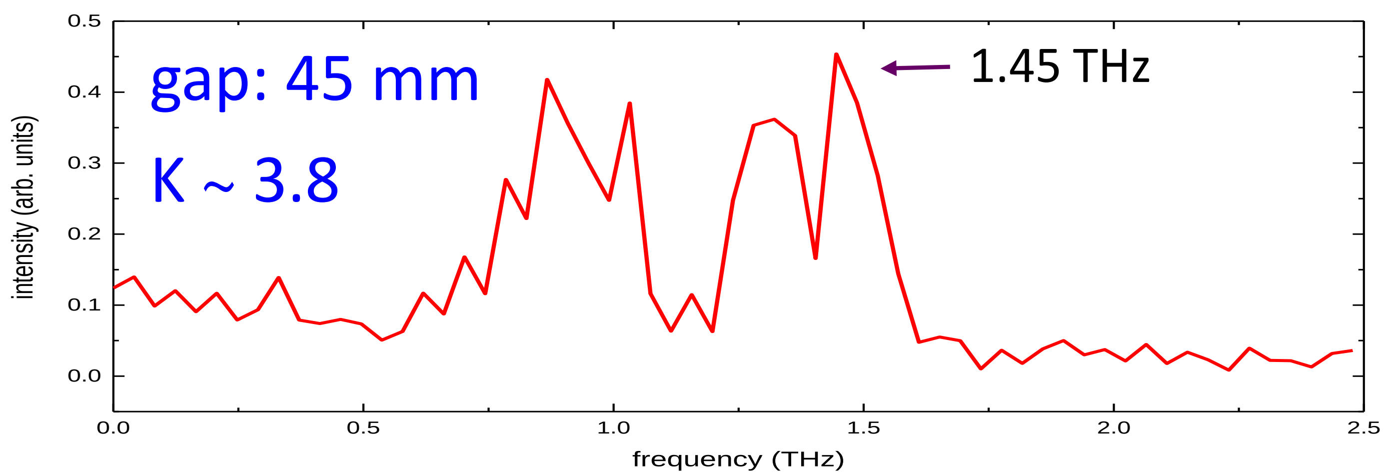
σ_z ~ 72 µm = 240 fs

- The compressed bunch length becomes shorter from 490 to 240 fs when the linac field increased from 9.8 to 13.8 MV/m.

CUR Spectra with Different U100 Gaps

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





Performance of Coherent THz Sources

parameters	2018		2021	
	CTR	CUR	CTR	CUR
electron charge (pC)	210	280	210	530
beam energy (MeV)	17.7		25.1	
Linac field (MV/m)	9.8		13.8	
bunch length (fs, rms)	490		240	
Undulator strength K	--	4.6	--	4.6
central frequency (THz)	--	0.62	--	1.26
bandwidth	--	15%	--	11%
THz energy (μJ)	6.7	18.4	3.4	20.7

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.

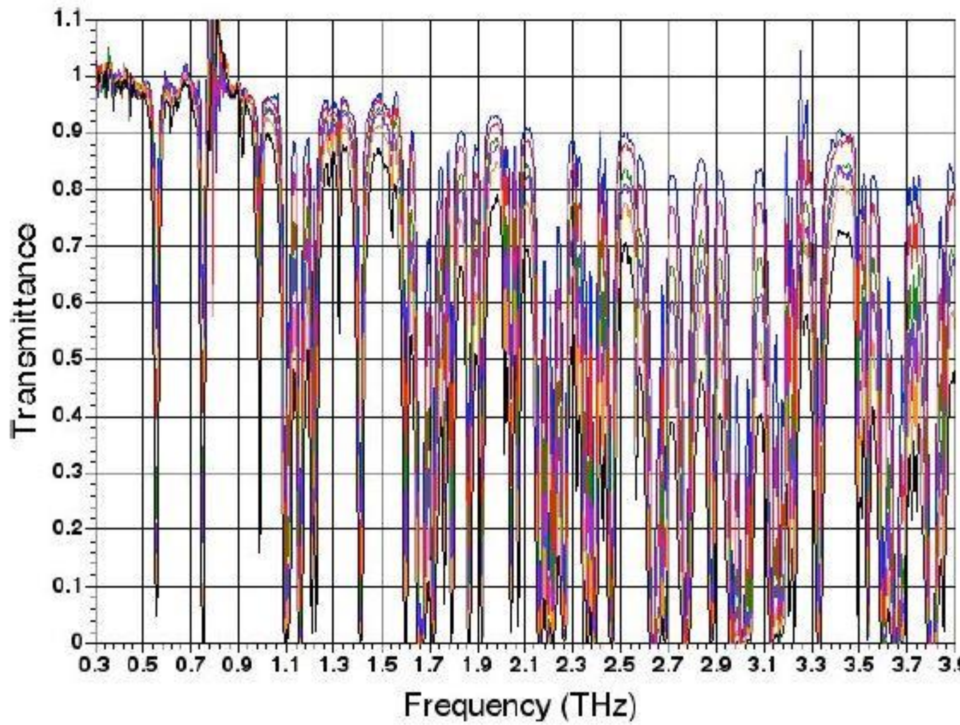
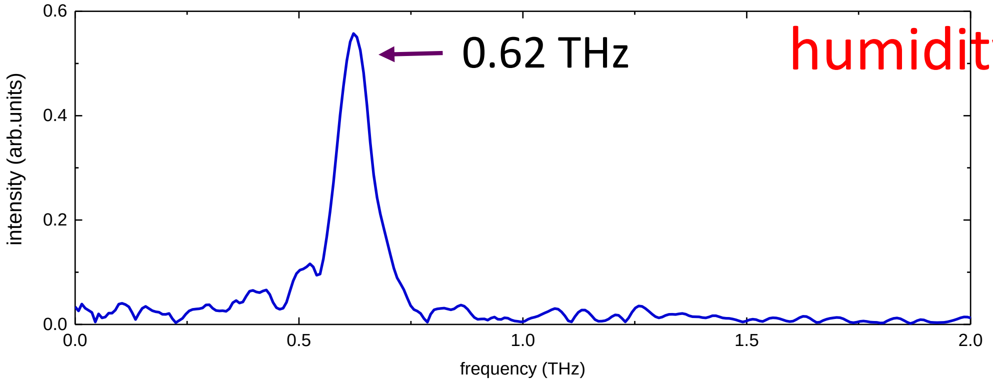


Figure 1. Measured atmospheric THz transmission at different levels of relative humidity. Blue, red, green, purple, orange, and black lines correspond to 6%, 12%, 22%, 26%, 40%, and 52% RH, respectively.

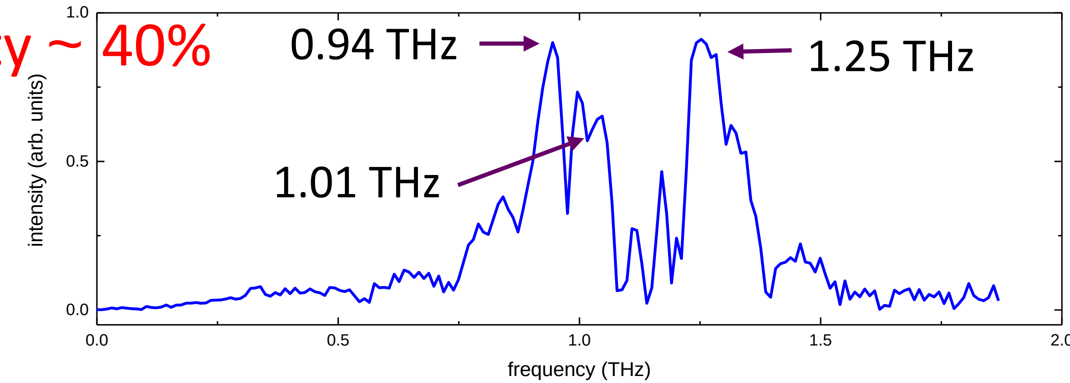
CUR Spectra

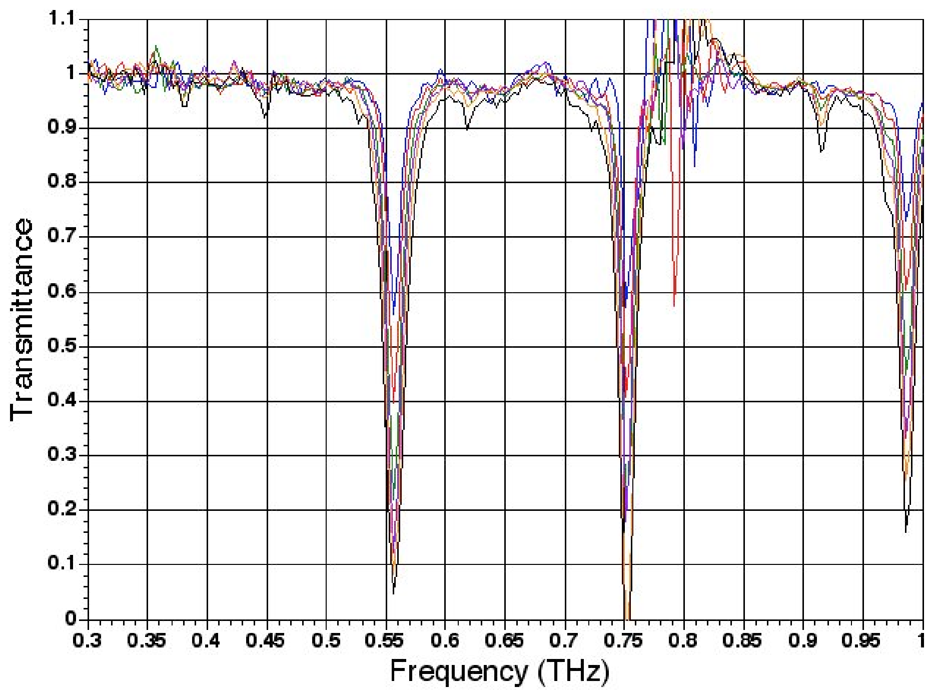
2018

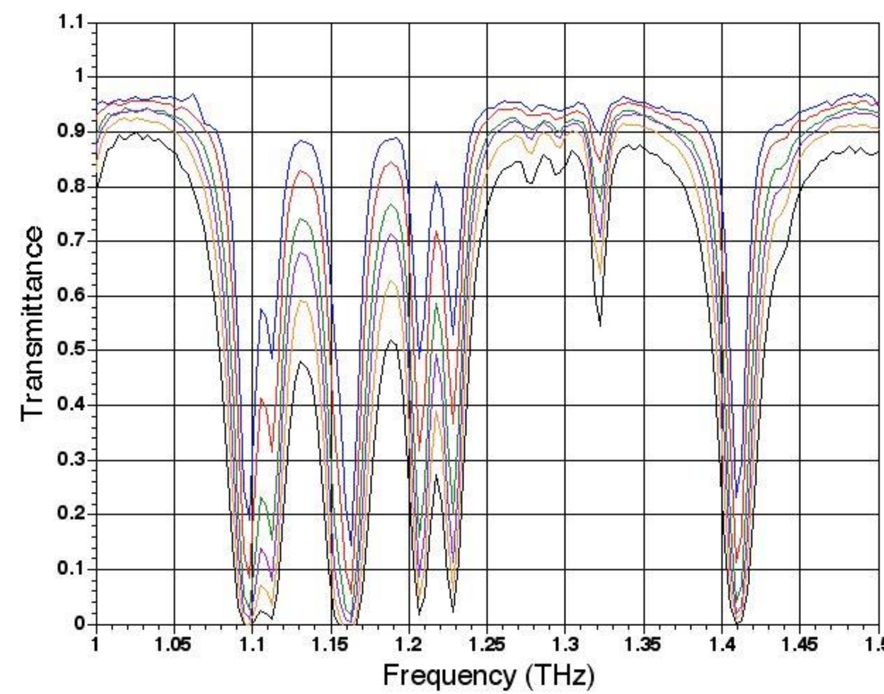


humidity ~ 40%

2021



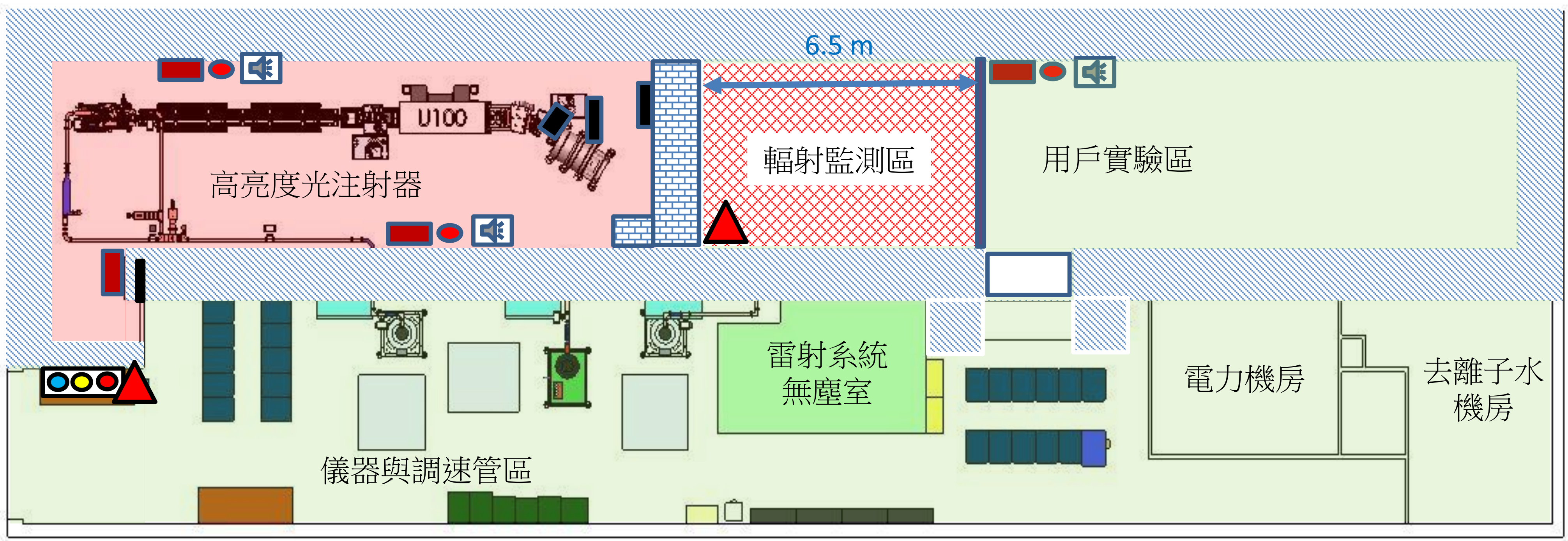




Summary

- Accelerator-based coherent THz sources has been studied to demonstrate the capability of the NSRRC high brightness photo-injector.
- Narrow-band THz coherent undulator radiation can be generated from a U100 planar undulator. The central frequency of THz CUR is 1.25 THz with bandwidth of 11%.
- From the coherent transition radiation and interferometer, currently the electron bunch length can be compressed to 240 fs (rms) by velocity bunching. This technique can be applied to measure the bunch length after the bunch compressor in the free electron laser.
- Improvement of the performance of THz CUR and CTR sources will be continued.
- The THz user facility at NSRRC is under constructing.

THz User Facility @ NSRRC



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Thank You