Development of a high-power coherent THz sources and THz-TDS system on the basis of a compact electron linac

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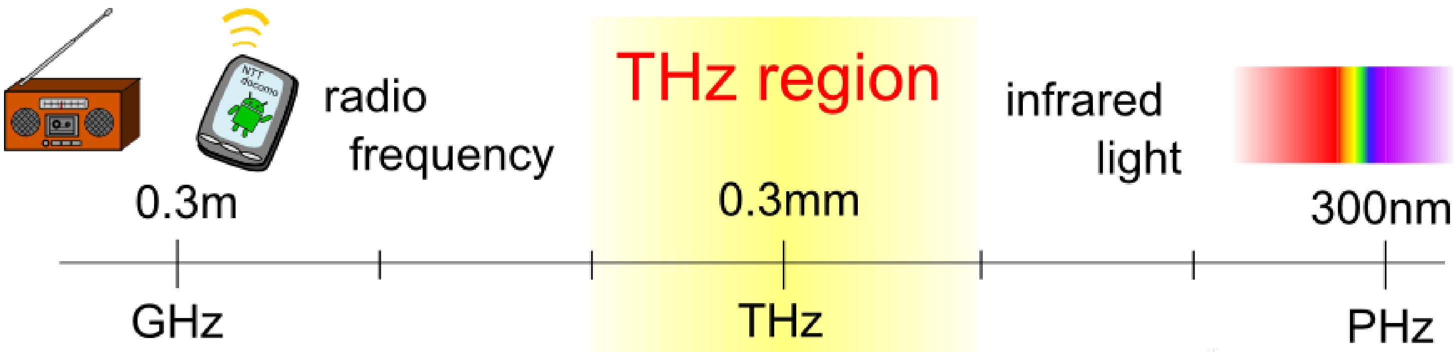
Outline

1. Introduction
   - What's THz?
   - Motivation of our work
2. THz Generation and Application with the Accelerator
   - THz Coherent Radiation
   - THz Imaging and THz-TDS system
3. Experiment
   - S-band Linac at AIST
   - Characteristics of Coherent Transition Radiation
   - Results of THz-TDS System
4. Summary

THz Wave

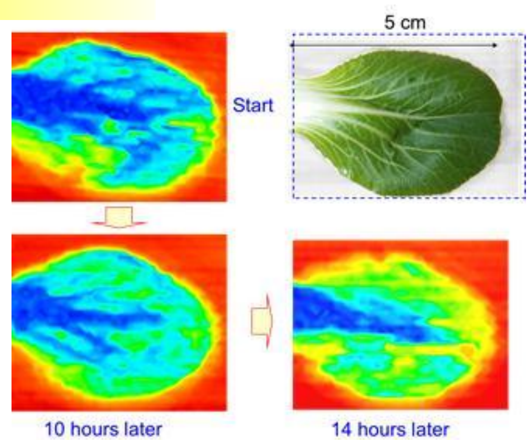
Terahertz wave (THz wave) is electromagnetic wave located between radio frequency and infrared light.

Frequency	0.1 THz ～ 10 THz
Wavelength	3 mm ～ 30 μm



Security

Jefferson Lab.
Science Vol. 297,
2 Aug. 2002



Quality Inspection

AIST
Nucl. Instr. and Meth.Vol. 637,
1 May. 2011

Motivation

Identification of illegal drugs and explosives hidden in envelopes for security field using THz radiation.

Why THz ?

- Explosives and drugs have a characteristic THz spectrum
- THz wave transmits through papers, envelopes and plastics

Our Research

- High power THz source
- Development of spectroscopy system

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THz Coherent Radiation

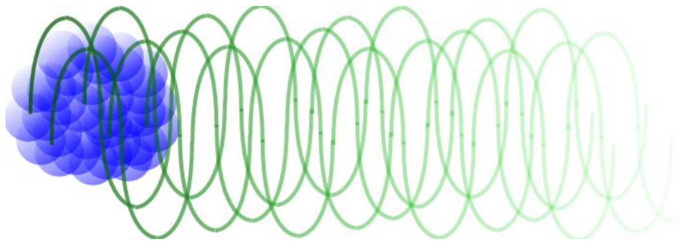
High Power THz Coherent Radiation

⇨ The electron bunch is compressed to less than 1ps with magnetic bunch compressor.

Incoherent Radiation (bunch length＞wavelength)

Electron bunch

$I_{inc} \propto N$



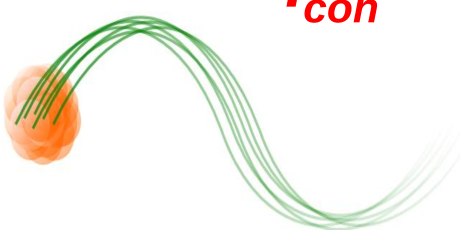
$N = 6 \times 10^9$ @ 1nC

P	:	Intensity of Synchrotron Radiation
N	:	Number of electrons

$\sim \times 10^{9\sim10}$

Coherent Radiation (bunch length＜wavelength)

$I_{coh} \propto N^2$



Intensity

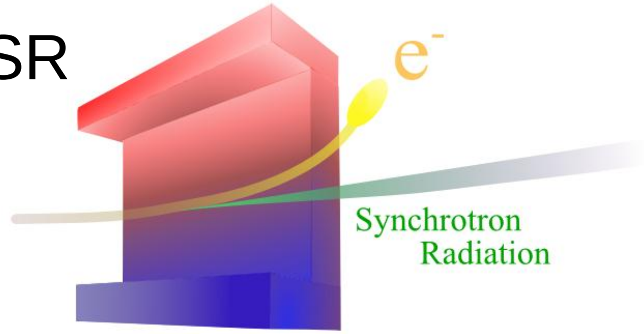
$$I_{coh} = \left(1 + (N-1) f(\omega)\right) I_{inc}(\omega)$$

$f(\omega)$: Form factor

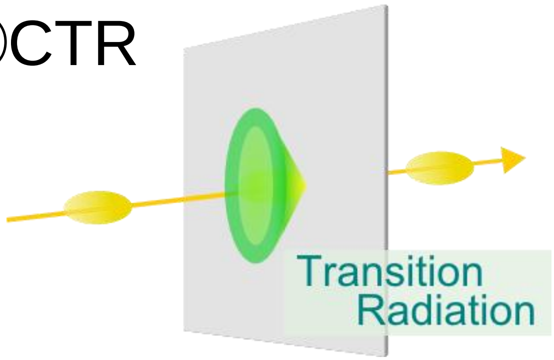
$$f(\omega) = e^{-\frac{(\omega\sigma_z)^2}{2}}$$

Our methods for THz generation

①CSR



②CTR



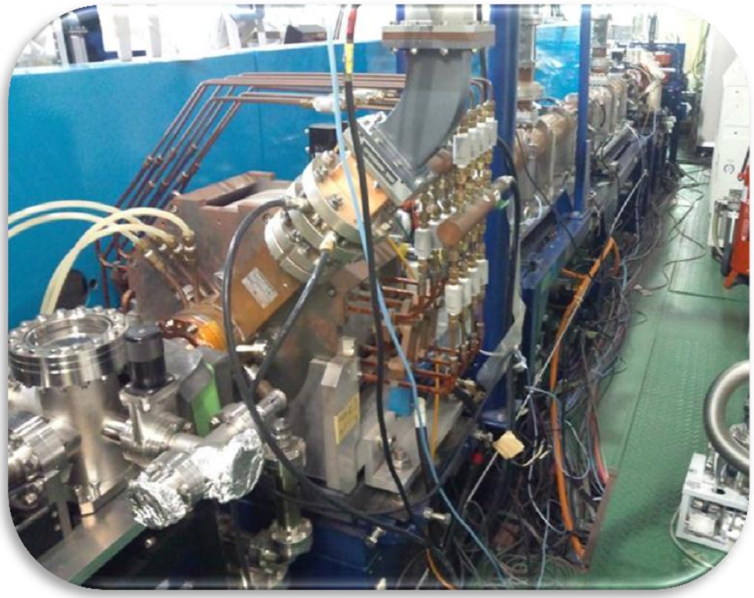
Characteristics of CSR and CTR

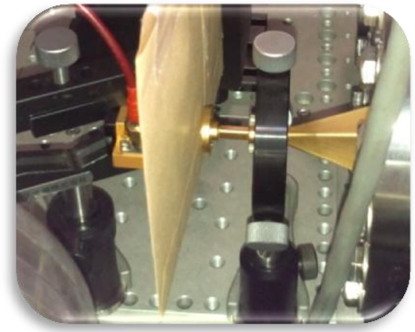
Generation Method	①Coherent Synchrotron Radiation (CSR)	②Coherent Transition Radiation (CTR)
Peak Power	High	High
Source size	Large	Small
Divergence	Large	Small
Polarization	Horizontal	Radial

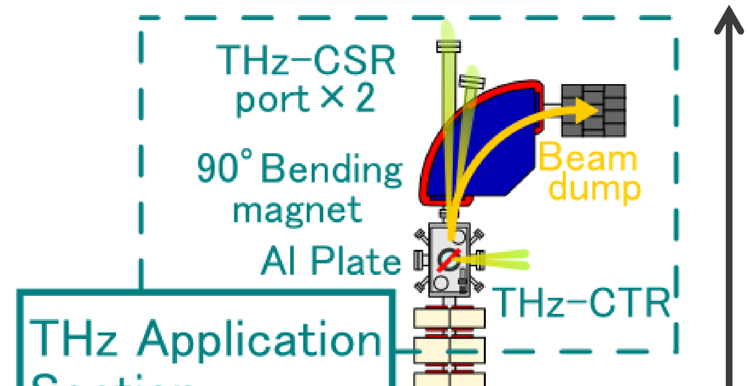
THz Imaging

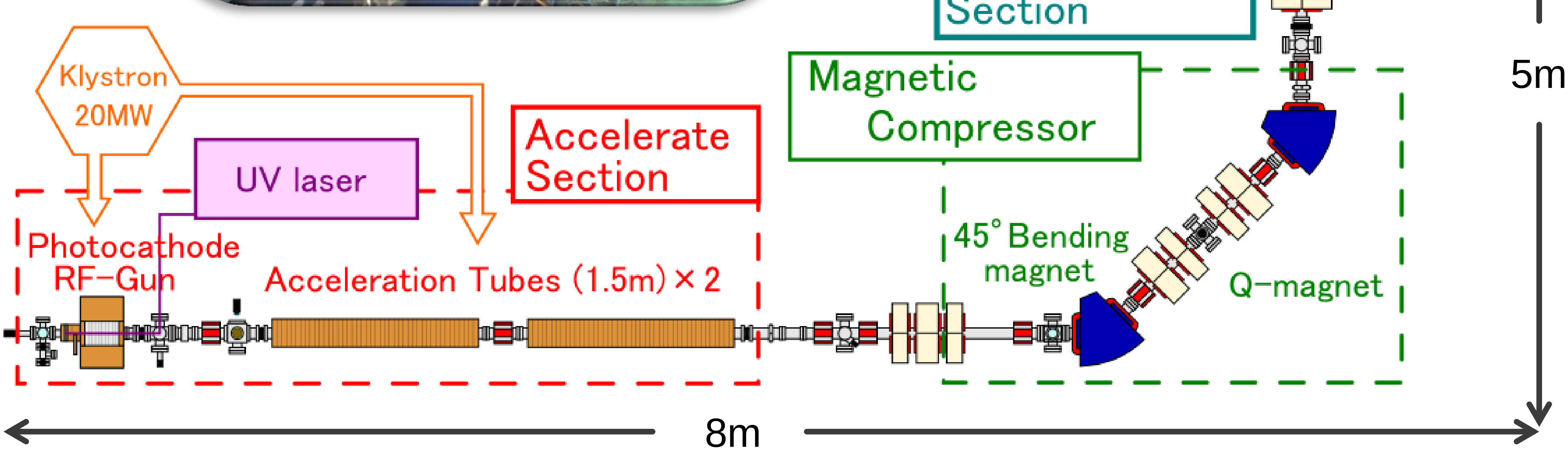
THz-Time Domain Spectroscopy (THz-TDS)

S-band Linac at AIST

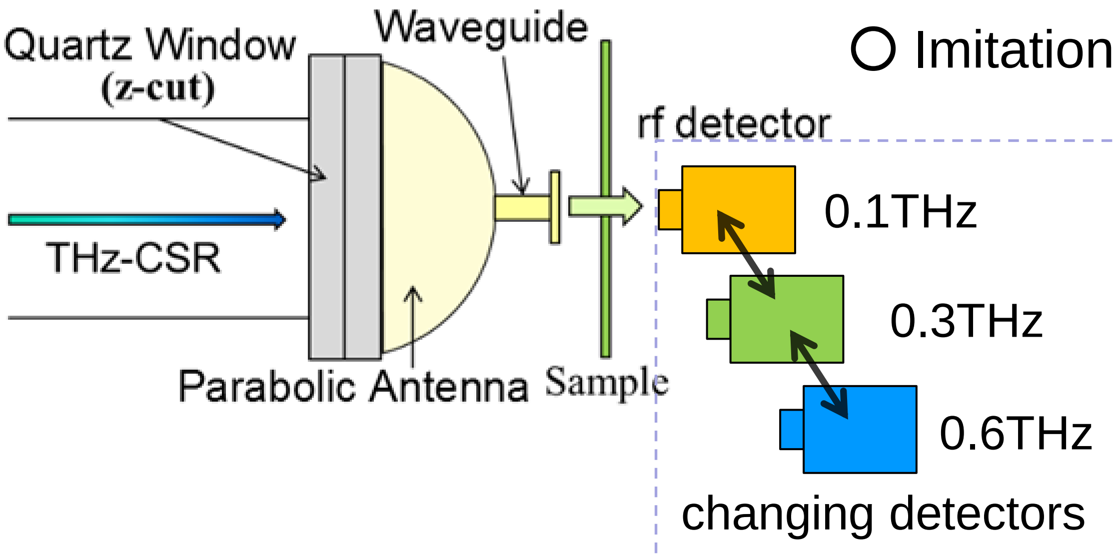




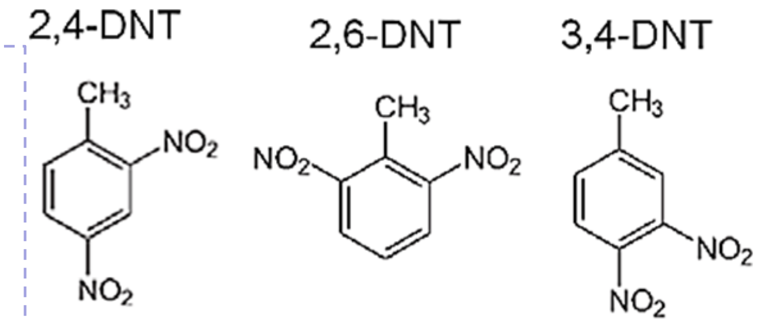


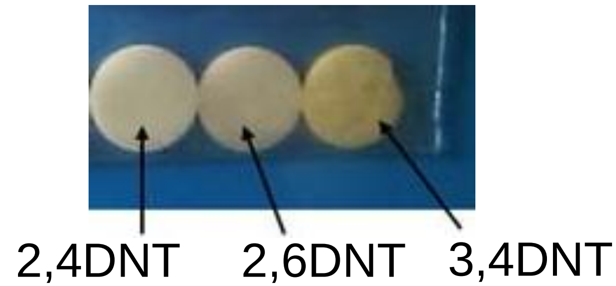


THz Scanning Imaging with CSR

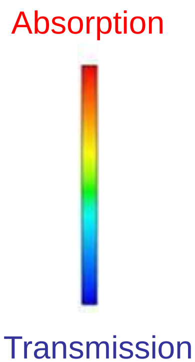


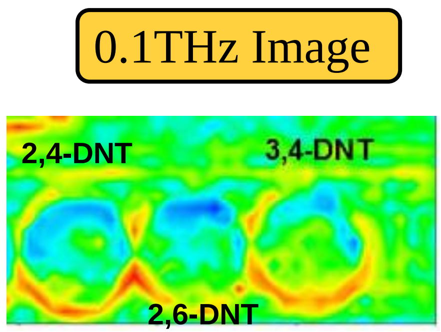
○ Imitation explosive: DNT (DiNitroToluene)

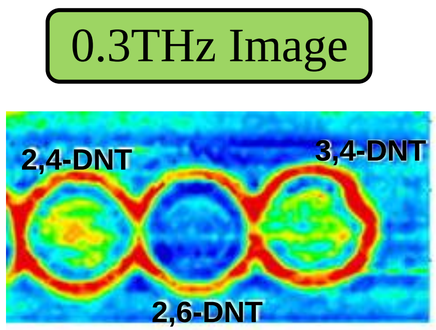


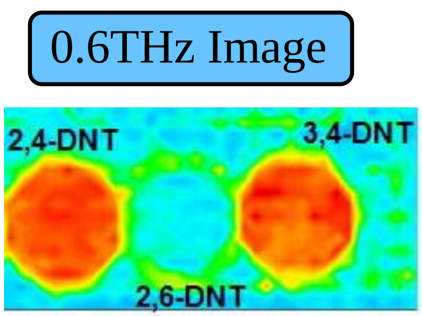


3 color THz Imaging





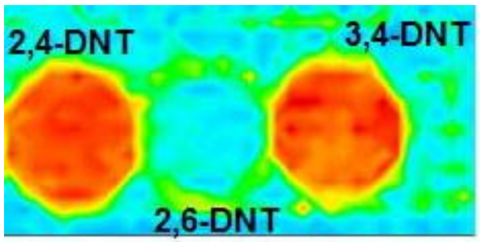


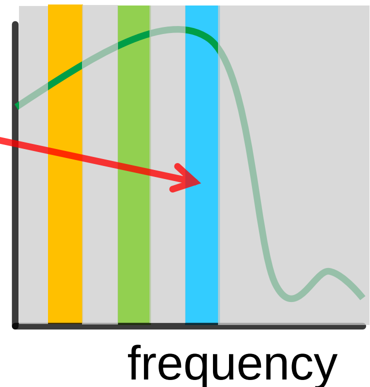


in collaboration with Central Customs Laboratory, Japan

Why do we need the THz TDS System ?
-for identifying materials-

0.6THz Image





3 color THz Imaging with CSR and rf detector

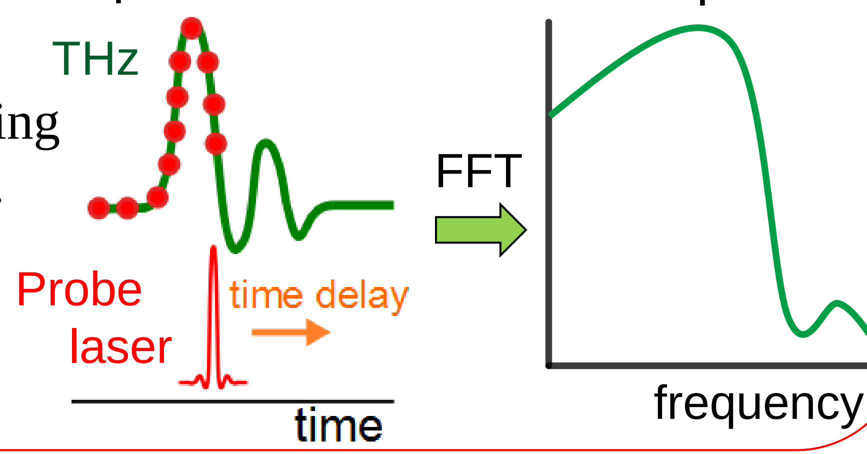
Spectral resolution is limited by rf detector
Central frequency depends on the detector

- Higher spectral resolution
- Extend spectral range

THz-Time Domain Spectroscopy (THz-TDS)

The THz-TDS is based on the EO sampling methods with the pump-probe technique.
The THz spectrum is obtained by Fourier transform of the measured temporal THz waveform.

Temporal Waveform   THz Spectrum



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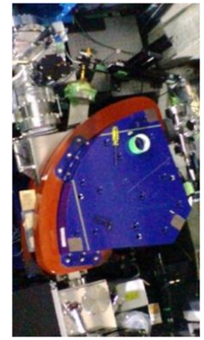
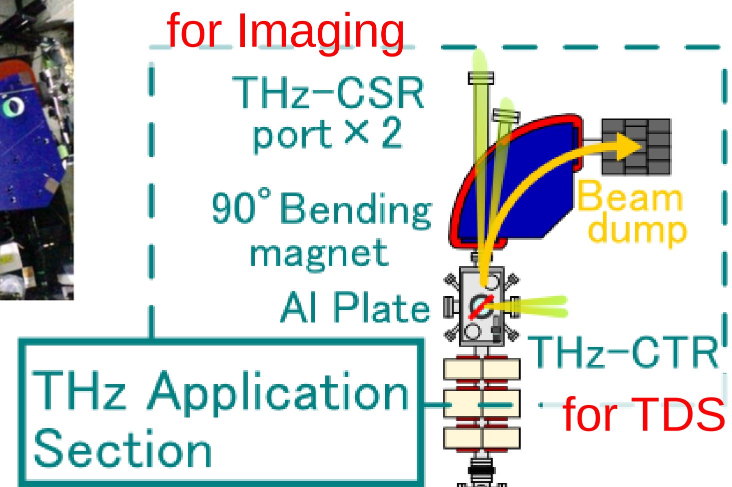
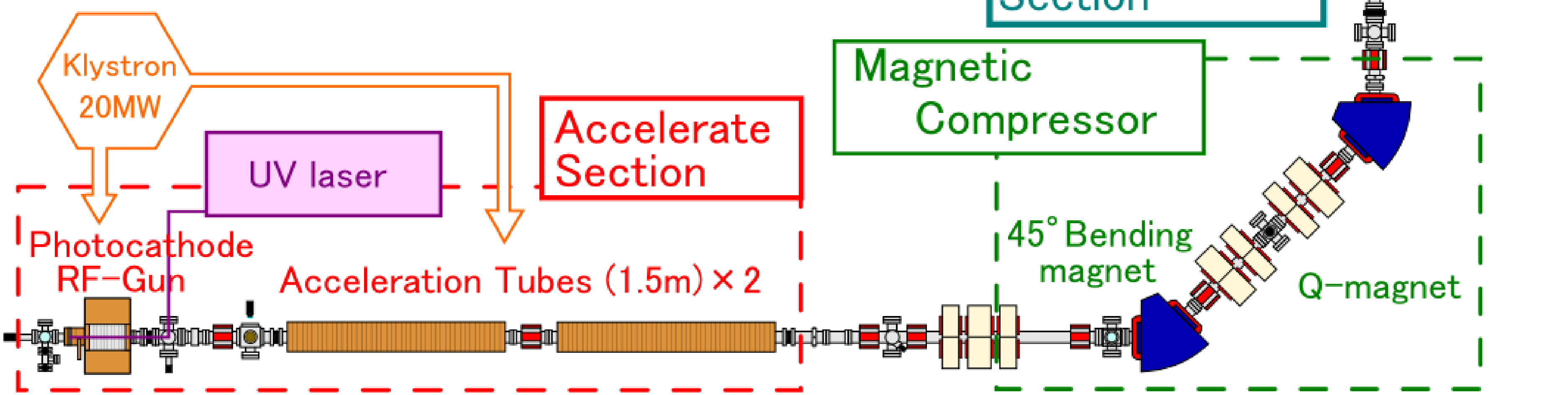
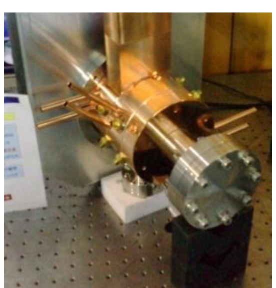
S-band Linac at AIST

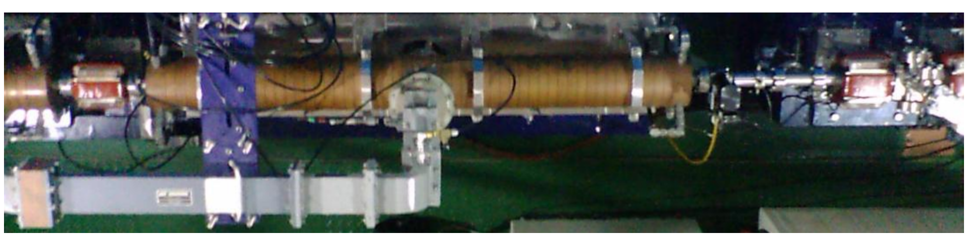
Energy	40MeV
Charge per bunch	1nC
Bunch length	<1ps (estimated 500fs)
Rep. rate	1 - 50Hz



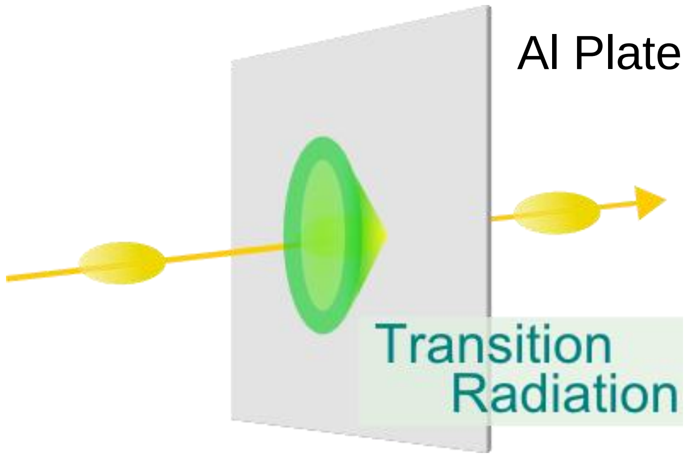






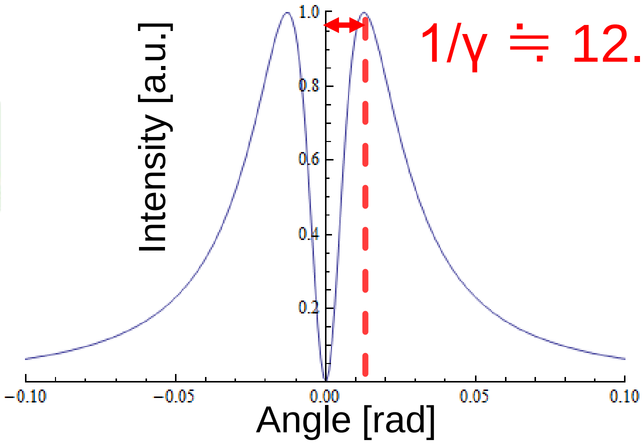


THz-CTR (Coherent Transition Radiation)



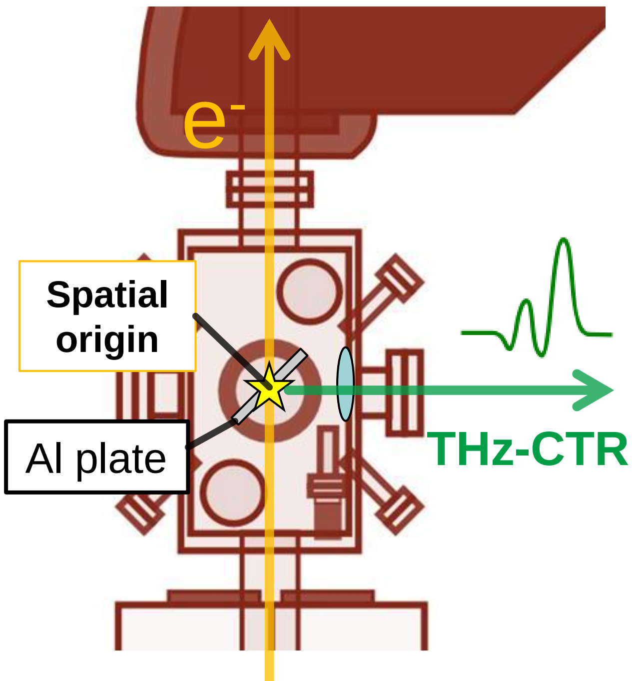
CTR Intensity

$$\frac{e^2}{4\pi^3\varepsilon_0 c}\frac{\beta^2 sin^2\theta}{(1-\beta^2 cos^2\theta)^2}$$



$1/\gamma$ ≒ 12.5mrad @40MeV

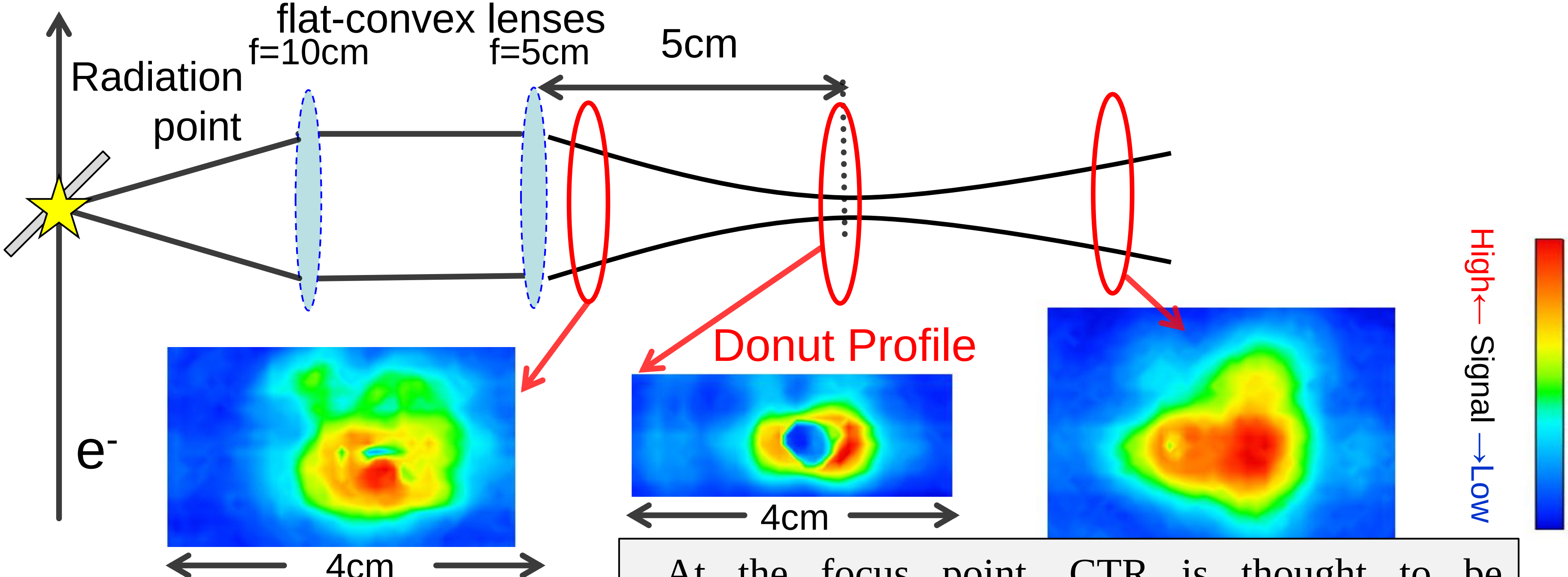
Small divergence comparing with CSR



Merits of CTR Source

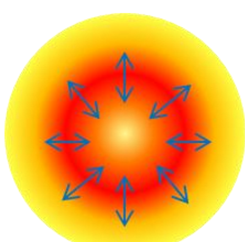
- We can precisely determine the spatial origin and the generation time of the THz-CTR.
- It is easy to synchronize the interaction timing between THz-CTR and probe laser.

THz-CTR Electric Field Profile and Polarization



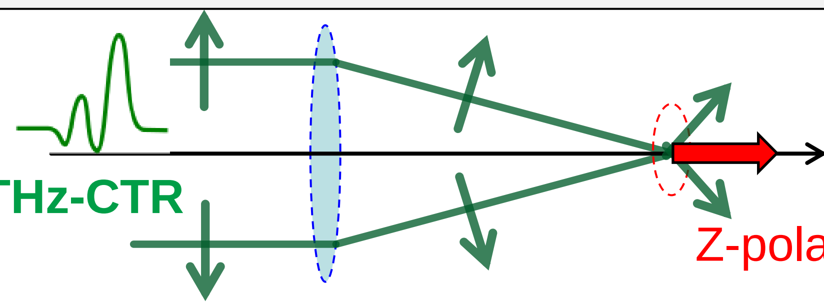
At the focus point, CTR is thought to be longitudinally polarized (called z-pol.), because electronic fields are canceled in transverse direction. (Schottky diode cannot measure the z-pol.)

TR has radial polarization

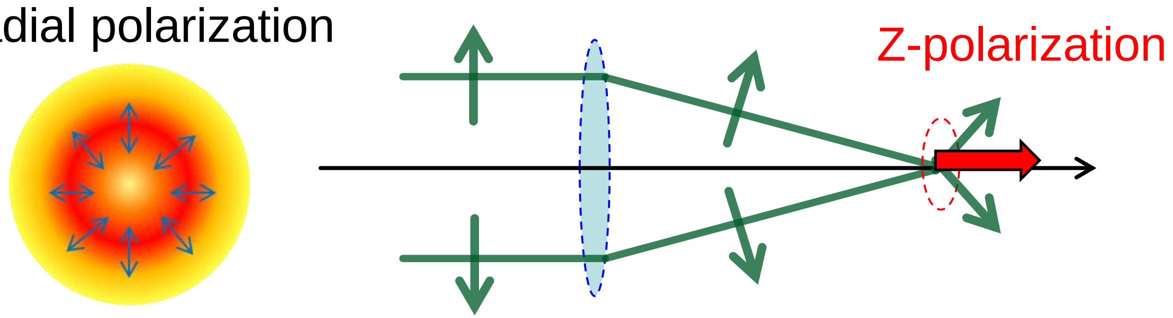


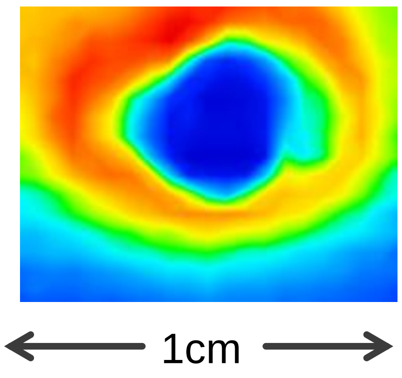
Radial Polarizer

Electric Fields



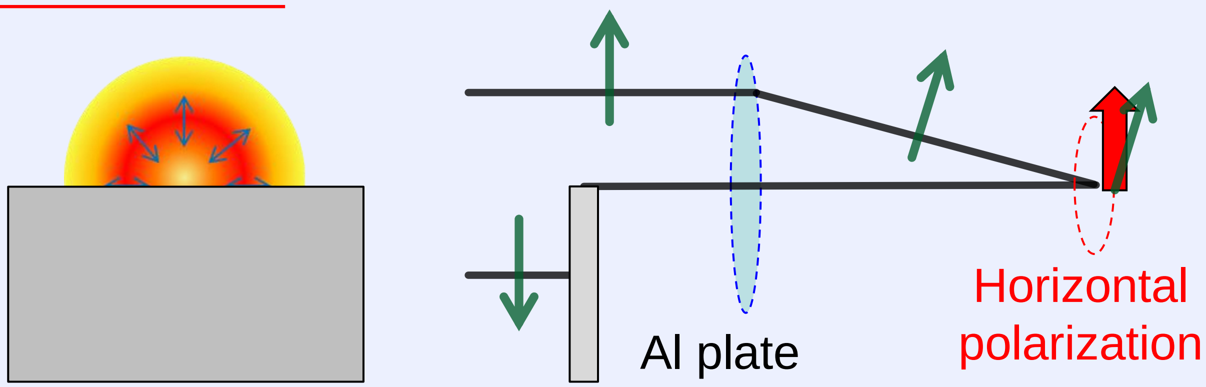
Polarization control of CTR

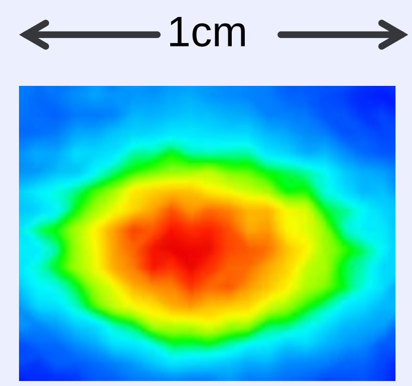




The Z-polarization is not suitable for the EO sampling method

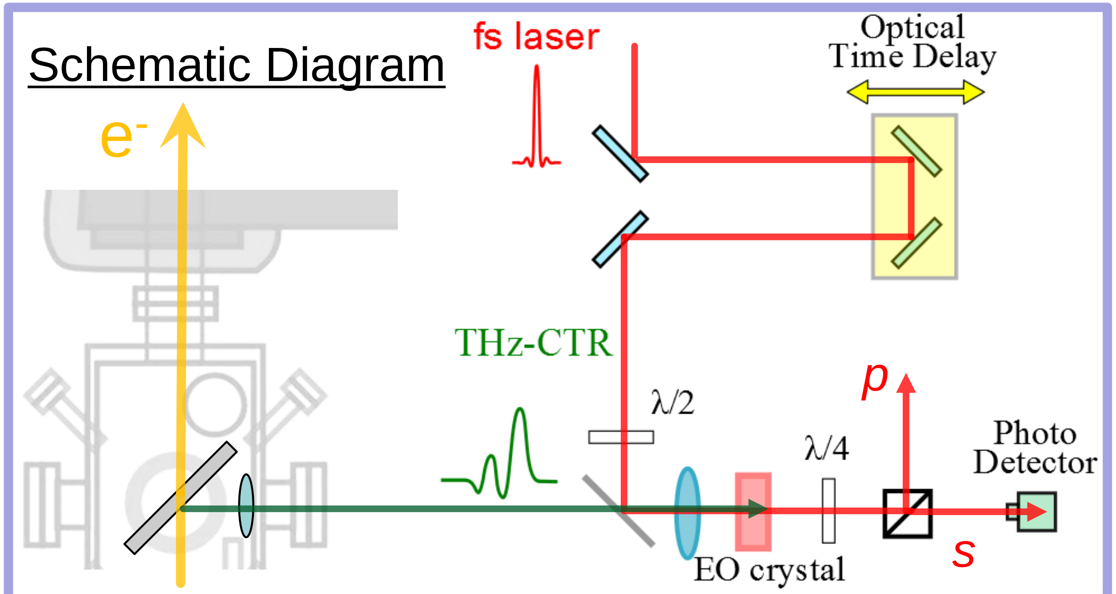
Half Shade

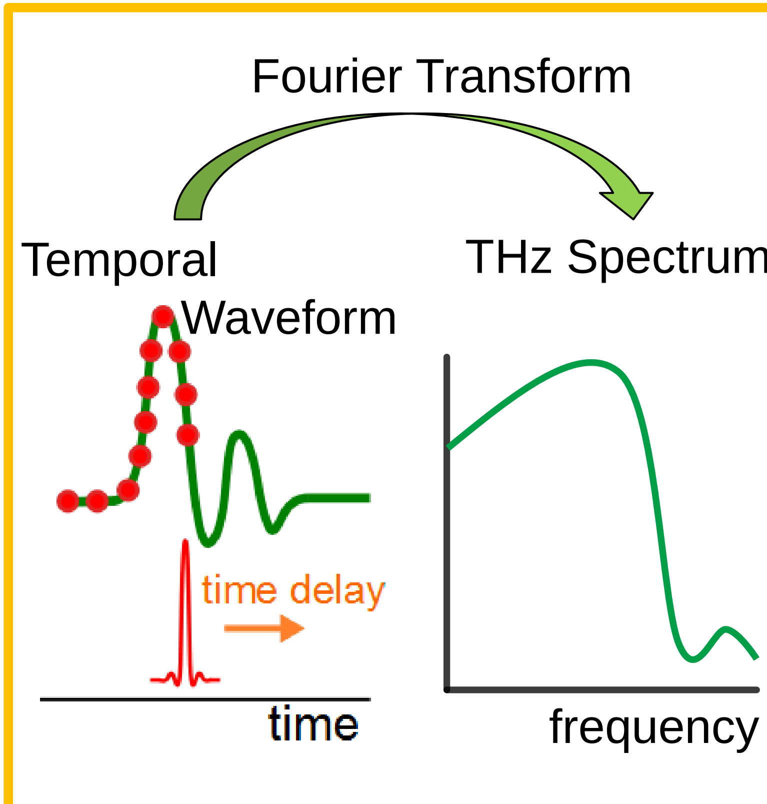




THz-CTR-TDS using EO sampling method

Schematic Diagram





When the THz-CTR and probe laser pass through the EO crystal at the same time, the refractive index of the crystal is changed by the THz electric fields.

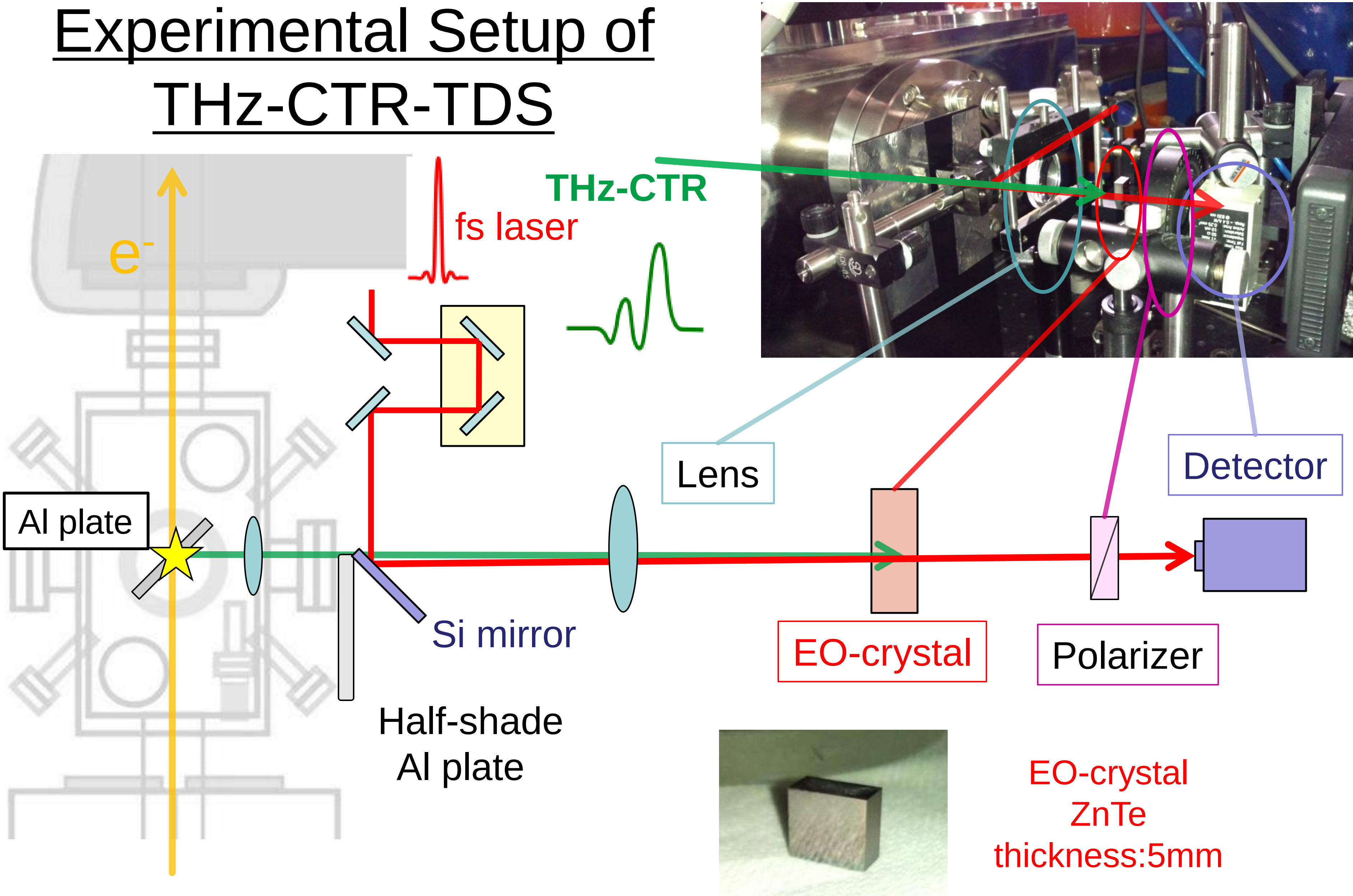
⇒ The polarization of the probe laser is also changed.

We measure the intensity difference between the p- and s-polarization of the probe laser.

⇒ The difference corresponds to the intensity of THz electric field.

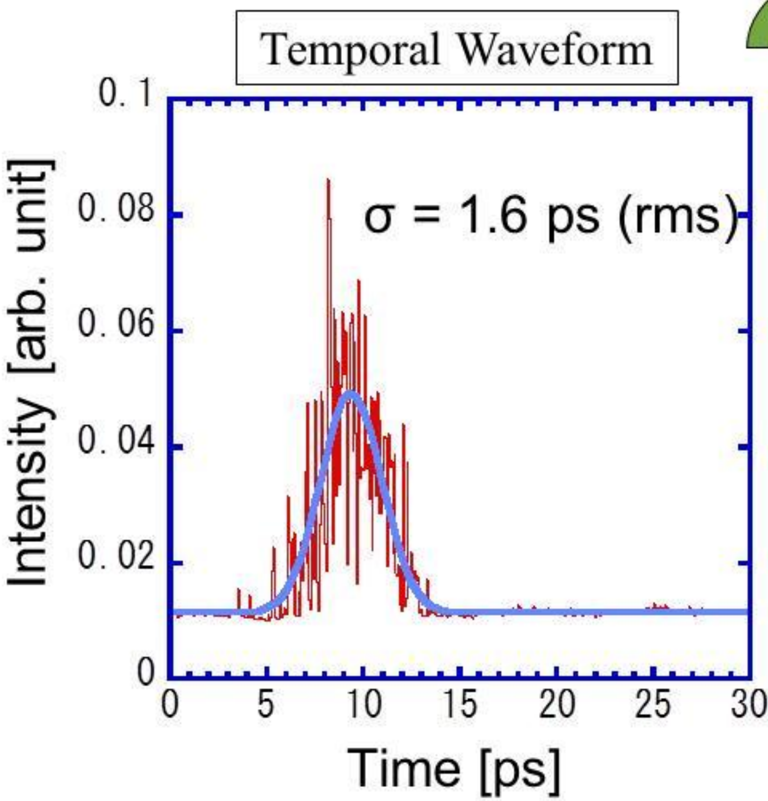
The temporal waveform is obtained with the pump-probe technique and the THz spectrum is calculated by Fourier transform.

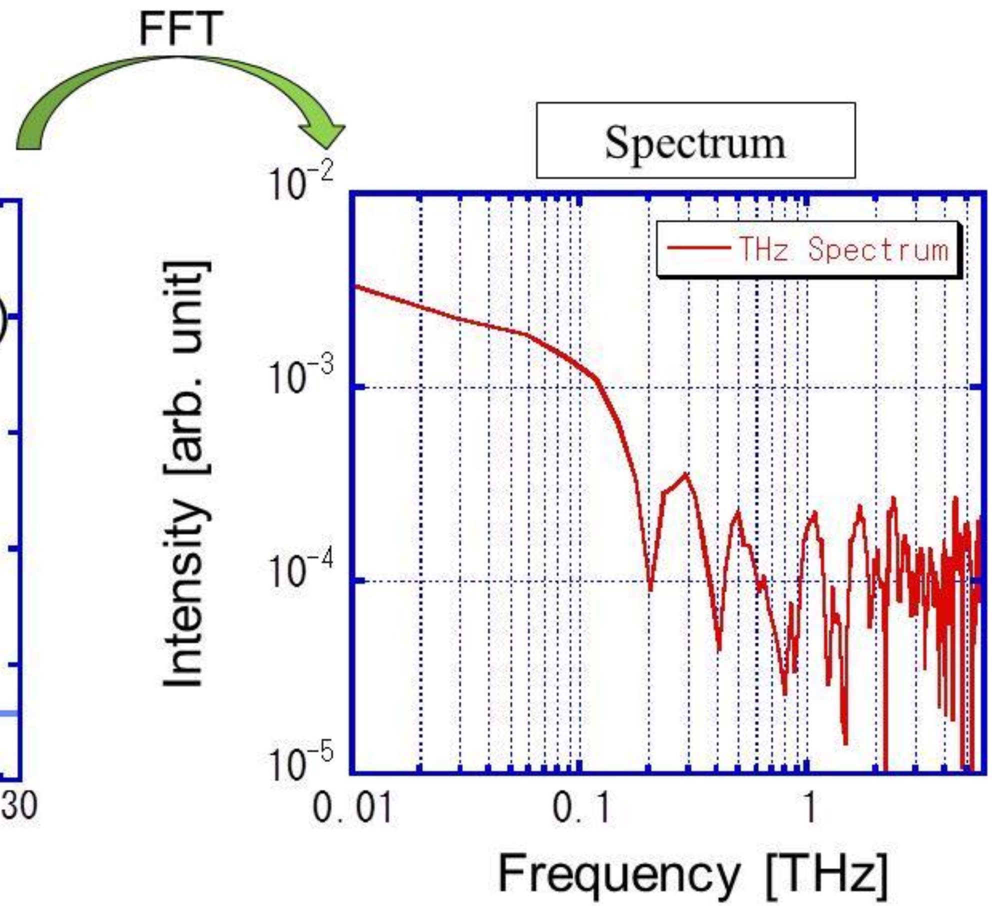
Experimental Setup of THz-CTR-TDS



EO-crystal
ZnTe
thickness:5mm

THz-TDS Result





The THz temporal waveform has been successfully obtained.

The measured THz pulse length has been estimated to be about 1.6 ps (rms).

It is larger than the expected value (= electron bunch length, 0.5 ps)

due to the time jitter between the probe laser and THz pulse and the finite

frequency response of EO crystal depending on its thickness.

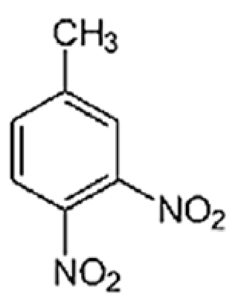
THz-TDS Result

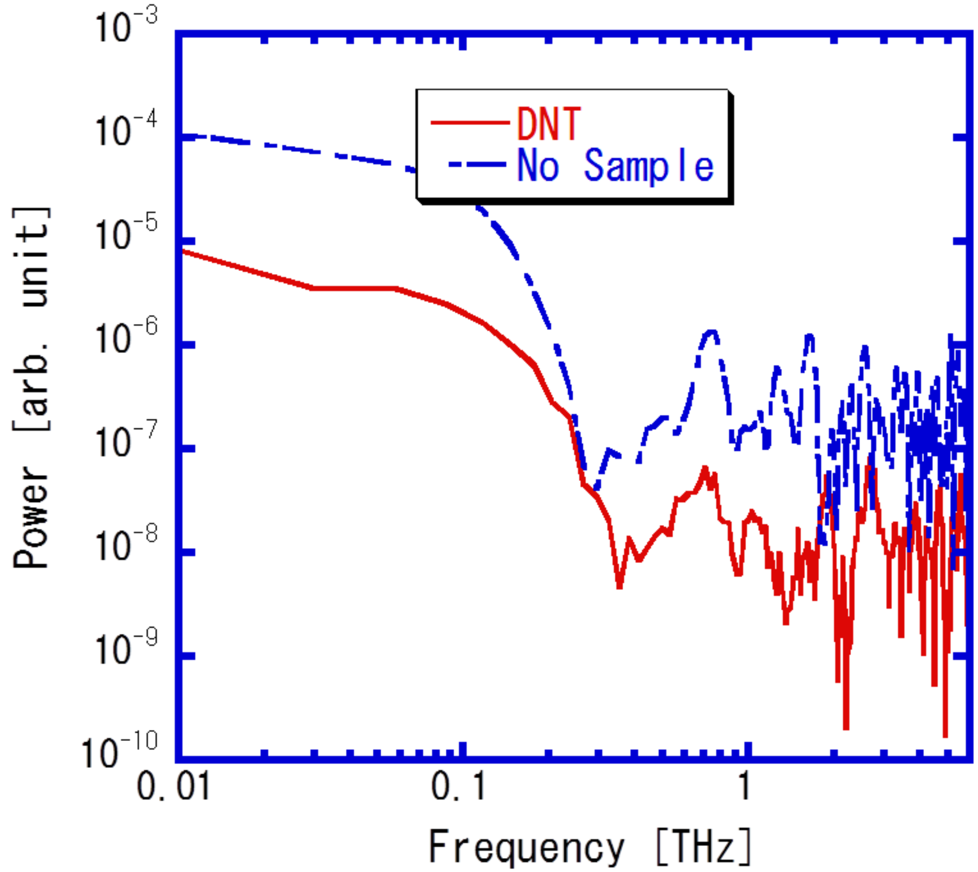
FFT

○ Sample measurement
Imitation explosive:
DNT (DiNitroToluene)

Preliminary Experiment

3,4-DNT





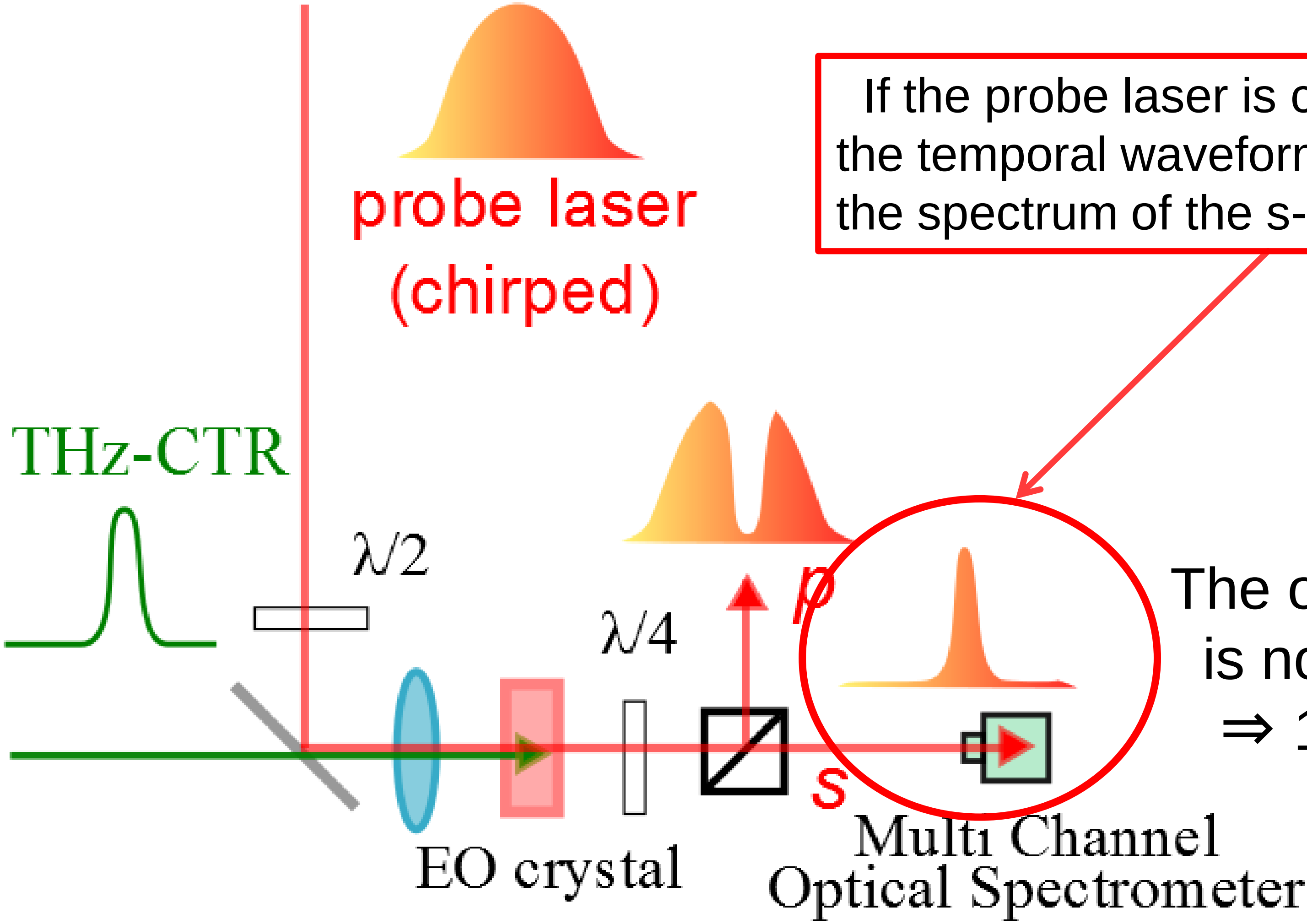
frequency response of EO crystal depending on its thickness.

Summary

- THz radiation has been generated using coherent transition radiation (CTR) with polarization control for THz time domain spectroscopy (THz-TDS) at AIST.
- The THz-CTR-TDS system has been constructed with EO sampling method.
  The THz temporal waveform has been successfully measured with this system.
- In the next step, we will reduce the jitter and optimize the thickness of the EO crystal in order to improve the measurement accuracy of this system and to extend the measured spectral range.
  In near future, we will apply the THz CTR-TDS system to investigation of explosives and illegal drugs.

Thank you for your attention

1shot THz-TDS using chirped probe laser



If the probe laser is chirped, the temporal waveform corresponds to the spectrum of the s-polarized laser.

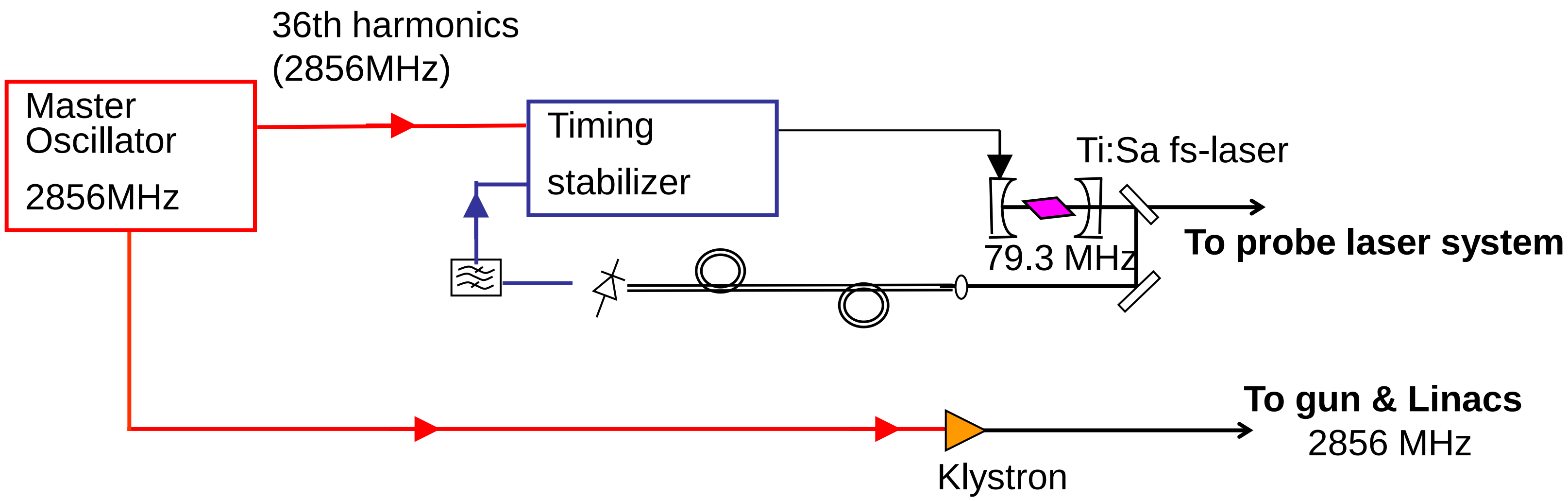
The optical time delay is not necessary.
⇒ 1shot TDS

Timing synchronization system (Low-jitter)

- Probe laser is synchronized to the their mode-lock frequencies (79.3MHz : fundamental).
- Relative timing jitter between the master and the laser is
  - about 1ps (synchronized with fundamental freq. : in this experiment)
  - < 10fs. (synchronized with 36th harmonics freq. :the acceleration frequency (2856MHz))

(F. Sakai, Proceedings of SPIE, 5194, 149-156 (2003)

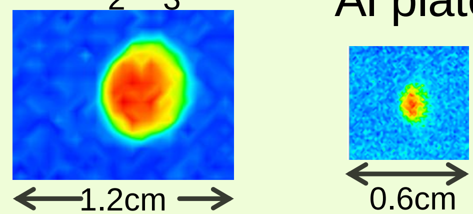
Measured using time domain demodulation technique with the vector signal analyzer by measuring the amplitude monitor and phase noise.

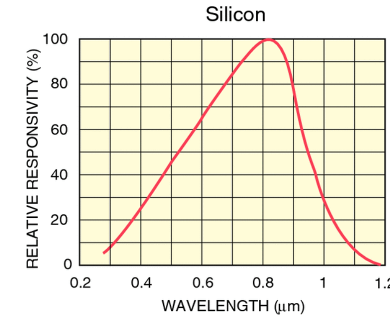


This synchronization system has been accomplished for the 150 fs laser Compton X-ray generation. It is easily to apply to the THz-TDS.

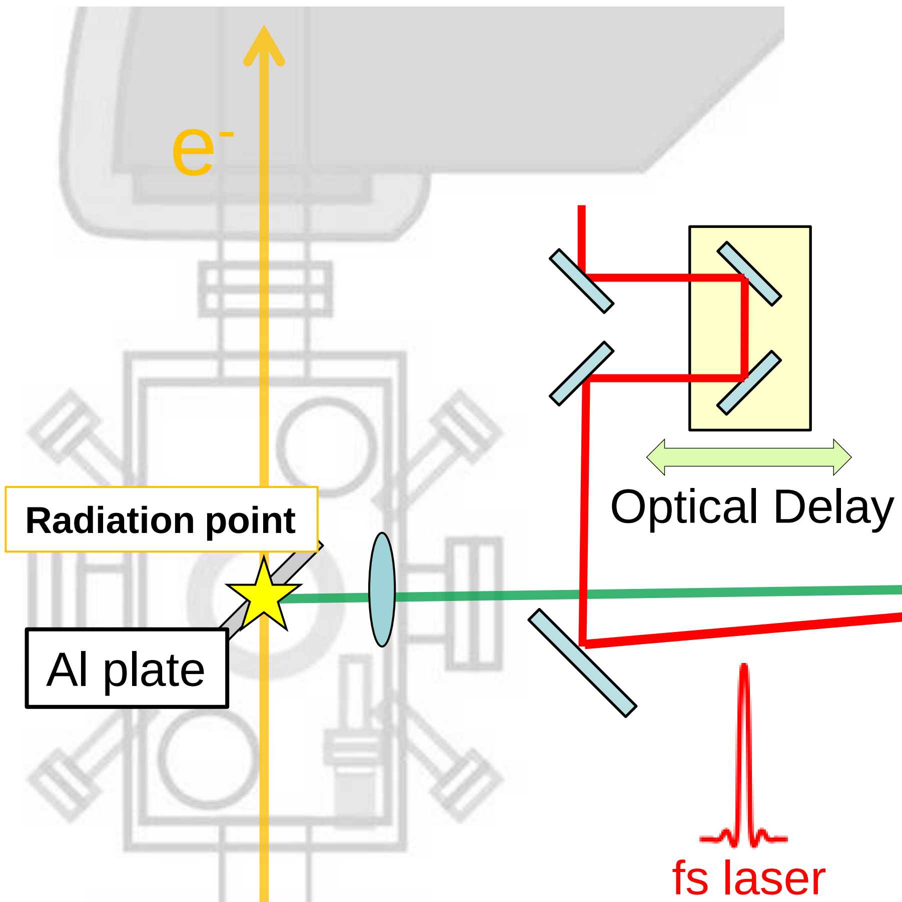
Timing Measurement

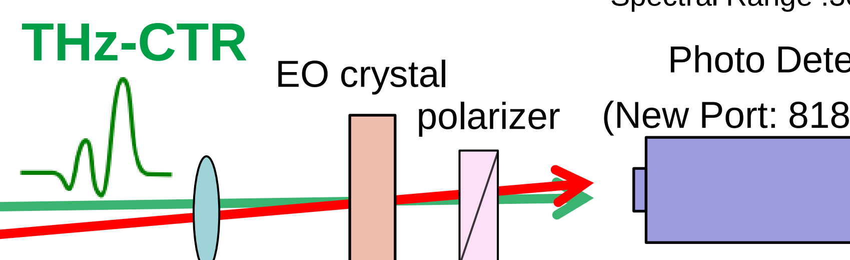
Measuring
OTR (optical TR) profile

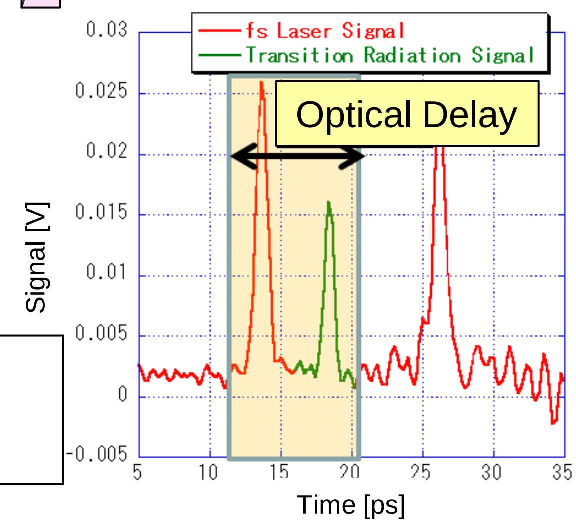




Rise Time : < 300ps
Spectral Range :300-1100nm







It is easily to synchronize the interaction timing between probe laser and THz-CTR.

THz Power-meter(0.1～2THz)

VDI - Erickson Power Meters

The VDI Erickson Power Meter is a calibrated calorimeter-style power meter for 75 GHz to > 2000 GHz applications. The sensor head has a WR10 input and VDI sells a variety of input waveguide tapers for use at high frequencies (see application note). Contact VDI for additional information.

Submillimeter Power Meter Model PM4

- Extremely wide bandwidth
- Excellent input match
- High sensitivity
- RS232 interface

Readout

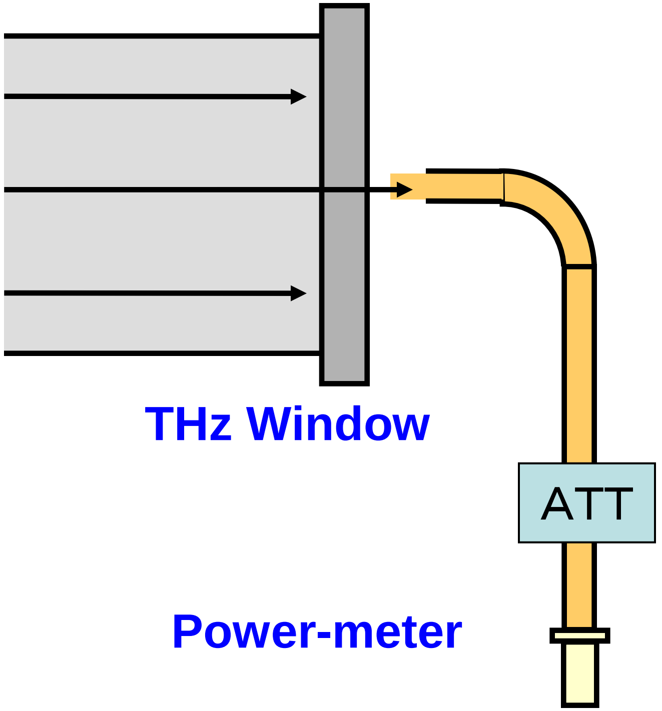
Sensor

Specifications:

- Input is WR10 waveguide (1.25 x 2.5 mm) with UG387 precision flange. Useful frequency response is 75 GHz through the submillimeter range, extending even to the visible.
- Sensor size is 5.1 x 4.8 x 7.6 cm. 1 m cable connects to readout.
- 1KO heater resistor (on the RF load) is used for DC calibration. Internal calibration check on all ranges..
- Maximum VSWR <1.15:1 in 80-110 GHz band.
- Input loss is <0.15 dB at 90 GHz.
- 41/2 digit LED panel meter readout, with 4 power ranges. Maximum input power is 200 mW average.
- Analog output BNC connector on back panel: 0-10V corresponds to 0-full scale meter reading.
- RS232 data output port.
- Calibration factor adjustment of up to ±29.9 dB using digi switches.
- Temperature drift is compensated to <2 μW/°C.
- The sensor has a thermal time constant (1/e) of 6 seconds. For faster response, the load is heated to a nearly constant temperature using a feedback loop. When input power is applied, the heater power is reduced, and the circuit measures the change, which is equivalent to the input power. The loop gain varies with the power to be measured, changing the response time. For highest sensitivity, no feedback is used on the lowest scale.

Typical performance

Scale (FS)	time for 90% response*	RMS noise
200 mW	0.1 s	~3 μW
20 mW	0.15 s	~0.3 μW
2 mW	1.3 s	0.1 μW
200 μW	15 s	0.01 μW



○1-2 nJ/pulse/1mm×2mm

⇒ Peak Power about 1 kW/mm^2 @1.4m point from Source point (THz Beam size at this point : about 20cm)

Theory of EO sampling method using ZnTe crystal

Phase retardation of probe laser ∝ Intensity of THz electric field

Probe transmission of the polarizer $T=(1 + \sin\Gamma/2)$
(Γ is magnitude of induced phase retardation)

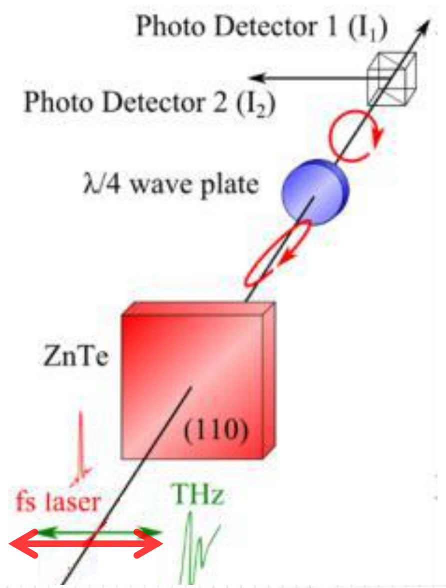
$$\Gamma = \frac{2\pi L}{\lambda} n^3 \gamma_{41} E_{THz} = \frac{\pi E_{THz} L}{V_{\lambda/2}}$$

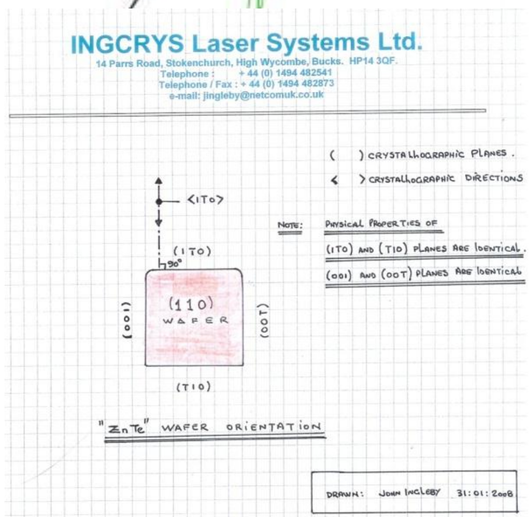
λ: probe wavelength,
L : crystal length
n : probe refractive index
γ_{41} : EO coefficient involved in the Pockels effect
E_{THz} : THz electric field
$V_{\lambda/2}$: half-wave voltage of about 3 kV@800nm

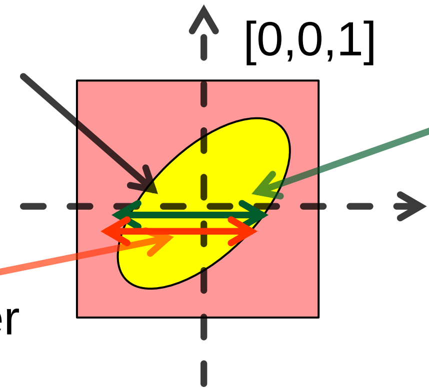
Phase retardation is increased with the crystal length *L.*
But the length is limited by the phase matching and a coherence length between the THz pulse and the probe pulse.

⇨ We should determine the crystal length.

Electro optical (EO) crystal







where φ is the angle between the major ellipse axis *y''* and the *y'* axis. When the phase retardation is largest with Φ=90°, the angle φ is equal to φ=45°, which means that one should set the polarization of the probe beam to be parallel to either *y'* [±1,-+1,0] or *z'* [0,0, ±1] for optimized EO sampling geometry.

phase retardation

Maximum

$$\Gamma = \frac{\Delta I}{I_0} = \frac{2\pi d}{\lambda} n_0^3 r_{41} E_{THz}$$

Q. Chen, M. Tani,* Zhiping Jiang, and X.-C. Zhang. Electro-optic transceivers for terahertz-wave applications Vol. 18, No. 6/June 2001/J. Opt. Soc. Am. B page823

Frequency Response dependence against the thickness of EO crystal

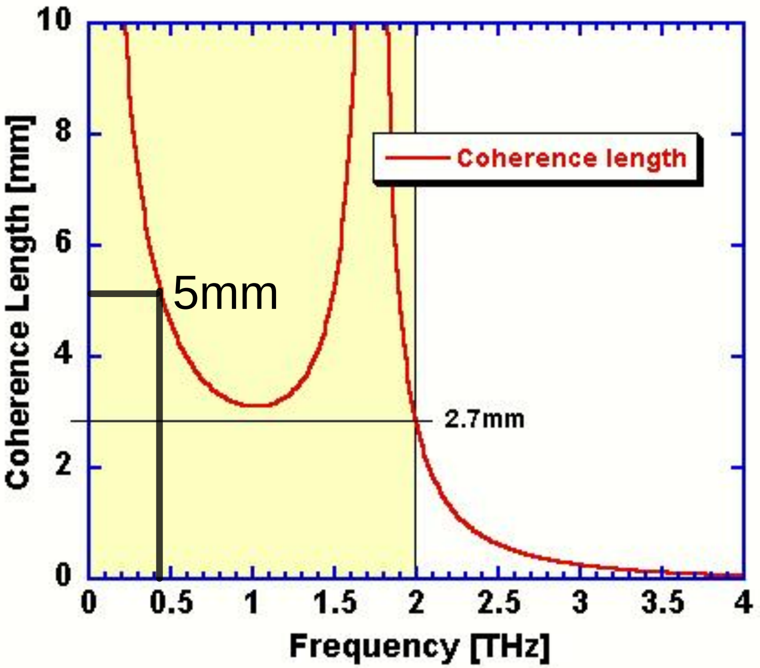
The coherence length *lc* (=$\pi/\Delta k$) is expressed with the dispersion in the optical spectral range by

$$l_c = \frac{\pi c}{\omega_{THz}\left|n - \lambda \frac{dn}{d\lambda} - n_{THz}\right|} = \frac{\pi c}{\omega_{THz}\left|n_{eff} - n_{THz}\right|}$$

c : speed of light
n_{THz} : THz refractive index
n_{eff} : effective refractive index of probe pulse

THz refractive index:

$$n_{THz} = \sqrt{(289.27 - 6f^2)/(29.16 - f^2)}$$

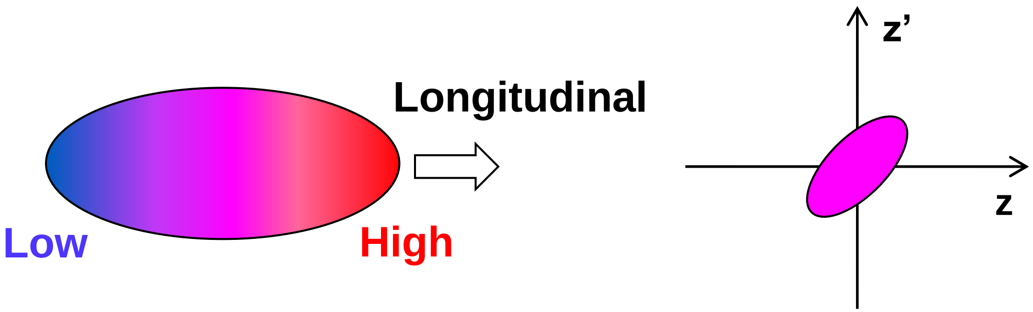


Coherence length of ZnTe crystal as a function of THz frequency

THz: ~ 2THz ⇒ ZnTe crystal length < 2.7 mm

Bunch Compression

The head and tail of the bunch correspond to high-energy and low-energy parts, respectively.

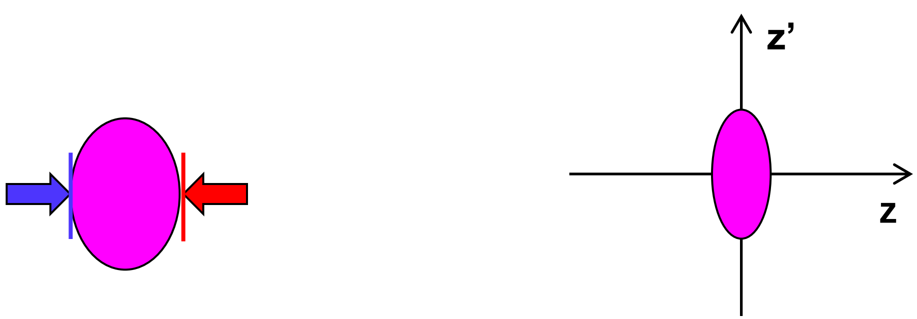


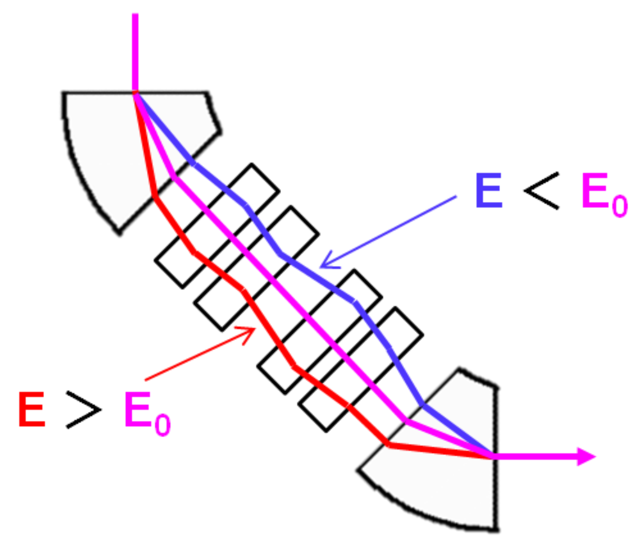
After this section longitudinal

Before

$$z_f = z_0 + R_{56}\left(\frac{\Delta E}{E}\right)$$

The high-energy and low-energy electrons pass along the long path and the short path respectively after optimising magnetic fields of Q-magnets for the bunch compression.

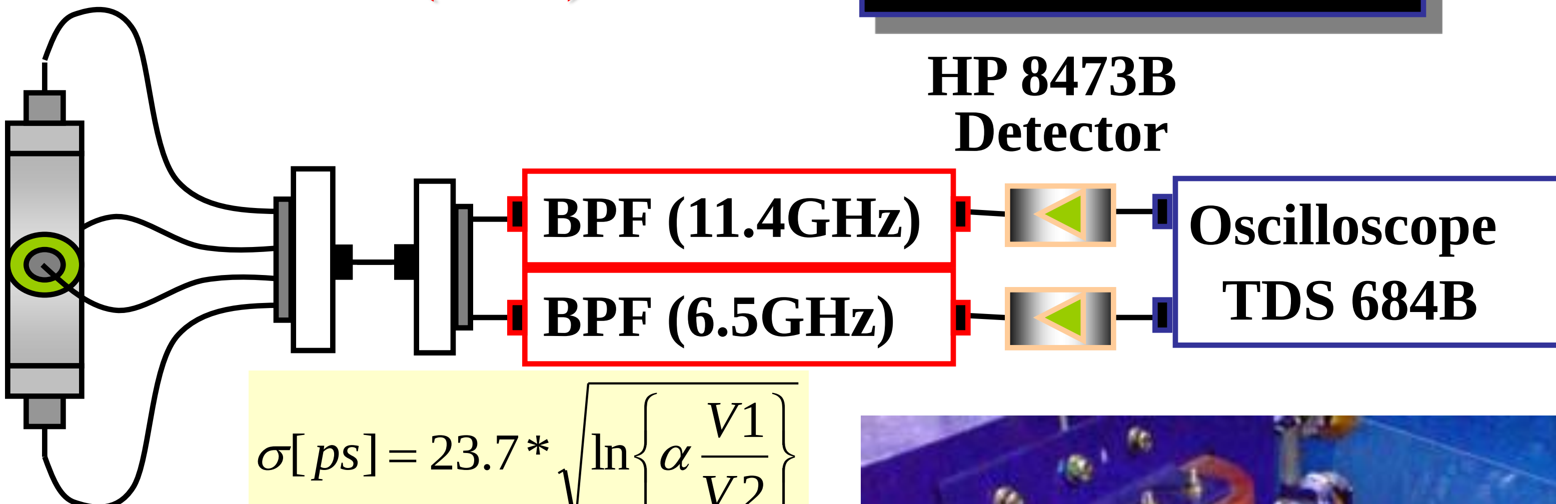




RMS Bunch Length Monitor

Two-frequency analysis technique

Beam Position Monitor (BPM)

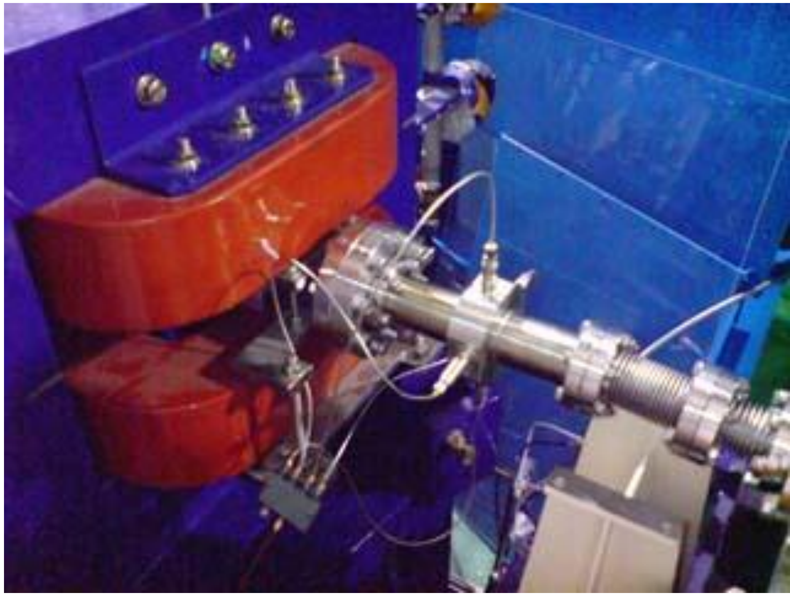


$$\sigma[ps] = 23.7 * \sqrt{\ln\left\{\alpha \frac{V1}{V2}\right\}}$$

$$\sigma_t = \sqrt{\frac{2}{\Delta\omega^2} \ln\left\{\frac{|F_1(\omega_1)|}{|F_2(\omega_2)|}\right\}}$$

$$\Delta\omega^2 = \omega_2^2 - \omega_1^2$$

$$\omega_2 > \omega_1$$



Theoretical THz CSR generation

Synchrotron radiation less than critical frequency ωc is coherently emitted from a ultra short electron bunch (σ_z). Its frequency is expressed by

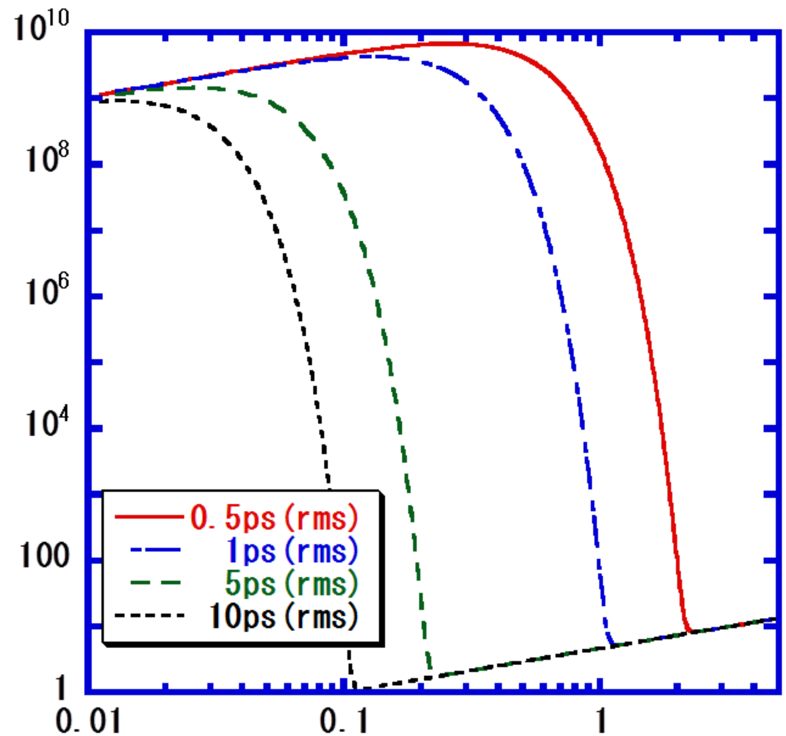
$$\omega_c = \pi c / \sigma_z$$

The total photons (I_{tot}) with both of incoherent and coherent radiation are derived from equations

$$I_{tot} = I_{inc}(1 + (N-1) f(\omega))$$

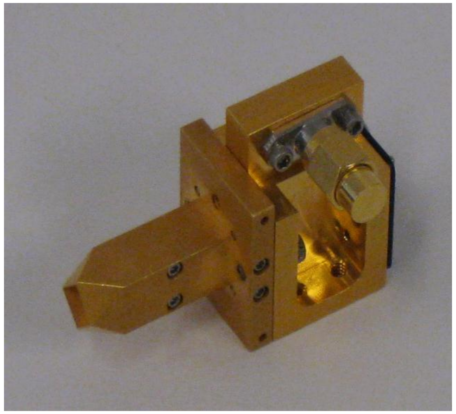
$$f(\omega) = e^{-\frac{(\omega\sigma_z)^2}{2}}$$

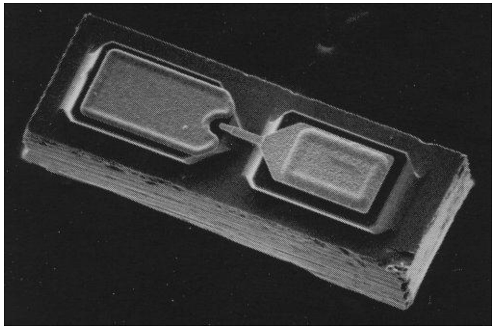
I_{inc} : photos of incoherent radiation
N : number of electrons in the bunch
$f(\omega)$: fourier transform of the longitudinal electron density with Gaussian bunches(σ_z)



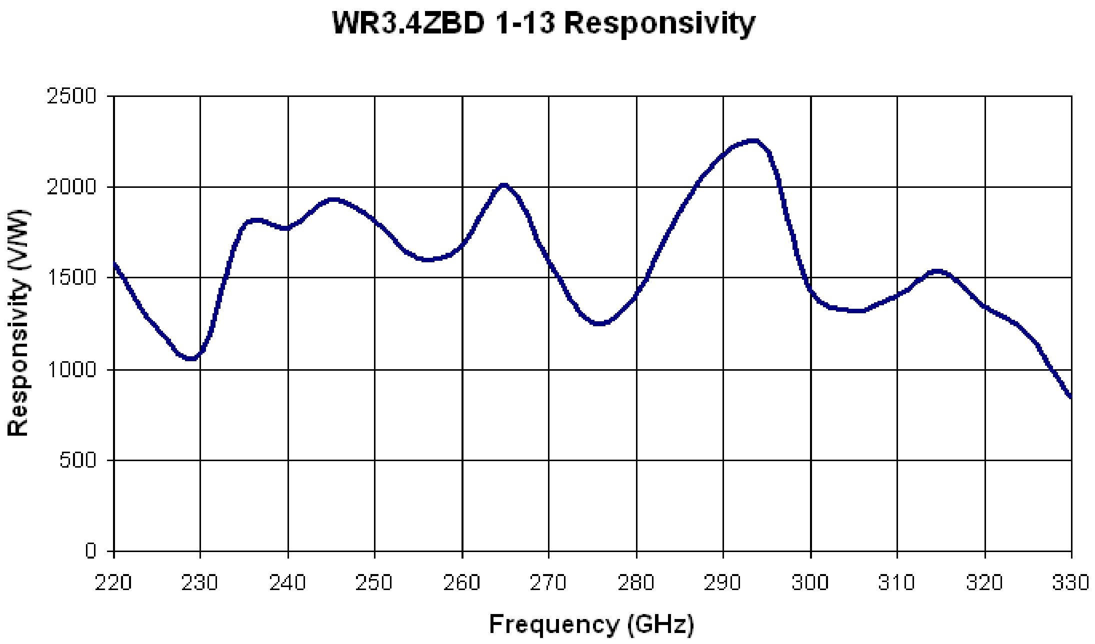
Enhancement factor of CSR as a function of frequency by changing electron rms bunch length (500 fs, 300 fs, 100 fs, Incoherent radiation)

THz Detector（Schottky Diode） Virginia Diodes, Inc.



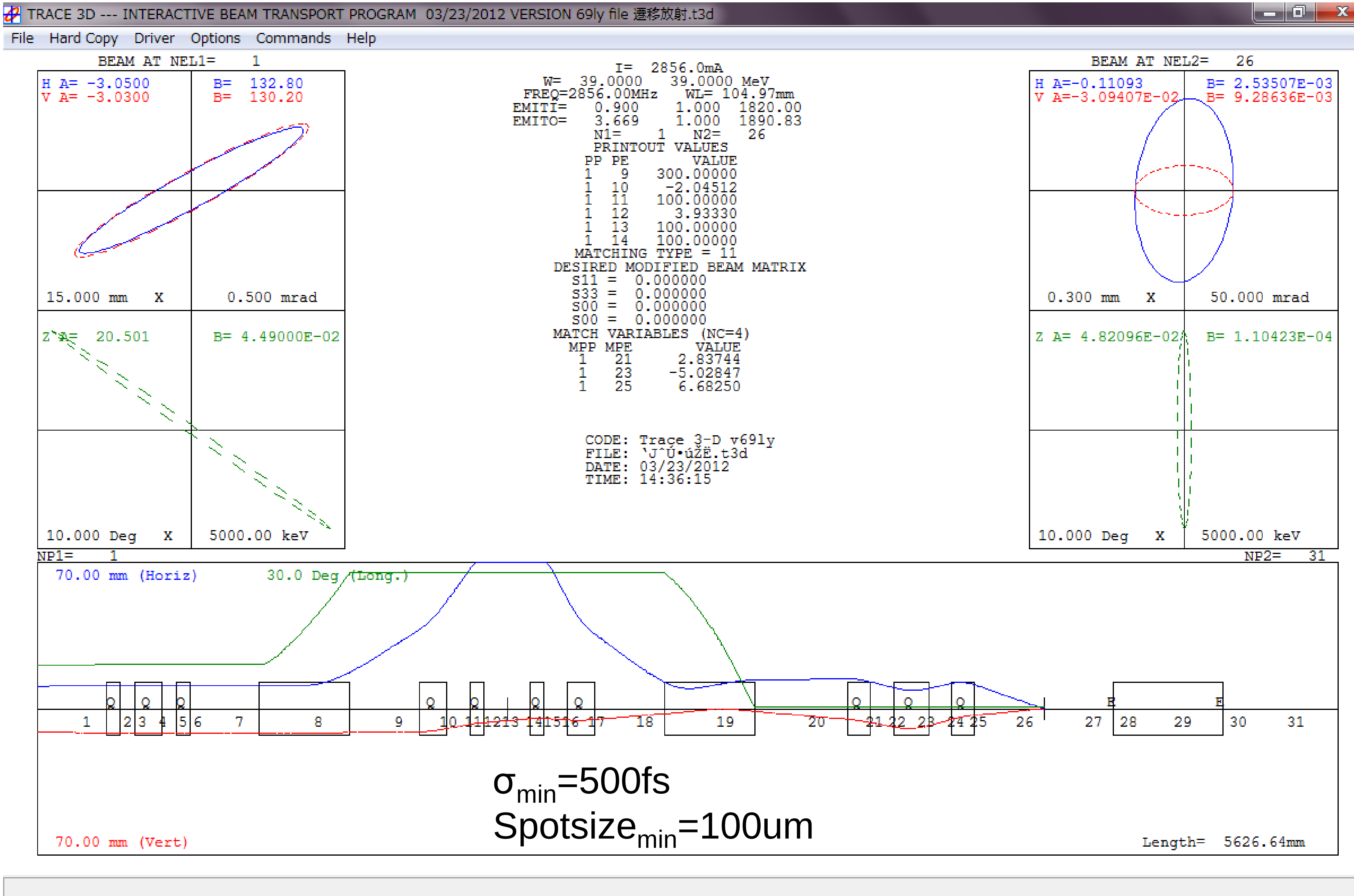


Scanning electron micrograph of a planar Schottky barrier diode. Chip dimensions approximately 180x80x40 μm



Tunerless Design
No bias required
No mechanical tuners
NEP: 1E-11 W/√Hz (typ.)
Responsivity: 1500 V/W (typ.)
Input: WR-3.4 (UG-387/UM)
Output: 2.9mm Coax
Shown with optional horn antenna

Bunch Compression Simulation with TRACE3D



σ_{min}=500fs
Spotsize$_{min}$=100um

Second order, Third order effect

A path length difference for particles with a relative energy deviation δ is given by:

$$\Delta z = \eta\delta = R_{56}\delta + T_{566}\delta^2 + U_{5666}\delta^3 \ldots\ldots$$

η : longitudinal dispersion

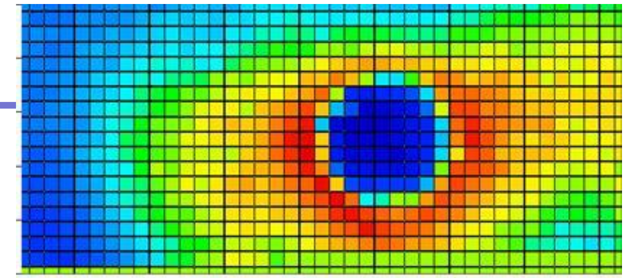
δ : relative energy deviation (= $\Delta E/E$)

R_{56} : linear longitudinal dispersion (leading term for bunch compression)

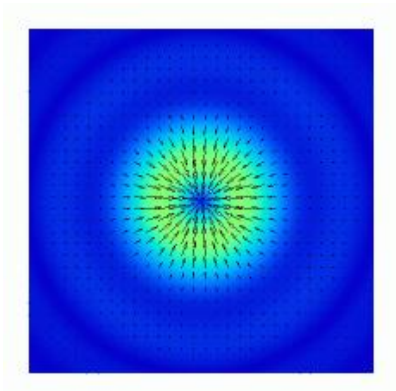
T_{566} : second - order longitudinal dispersion

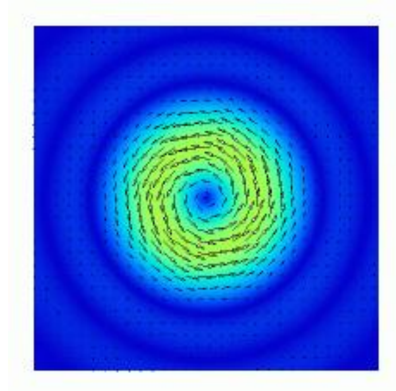
U_{5666} : third - order longitudinal dispersion

Possibility of Donuts profile



①Radial Polarization ②Azimuth Polarization

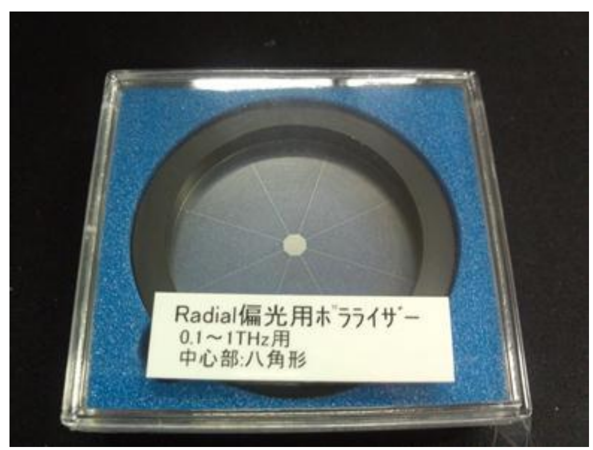




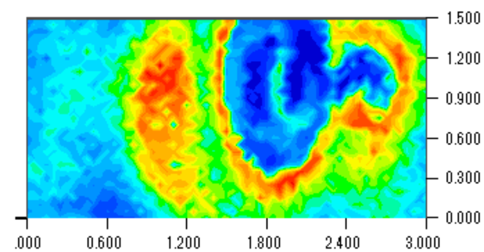
M.Endo, Radial Polarization
http://teamcoil.sp.u-tokai.ac.jp/kenkyu/Resonator/Radial/

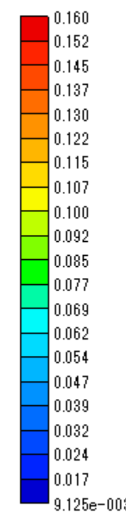
FEASIBILITY TEST OF LASER-INDUCED SCHOTTKY-EFFECT-GATED PHOTOCATHODE RF GUN
Proc. of FEL 2007 (2007) pp.382-385

Radial Polarizer

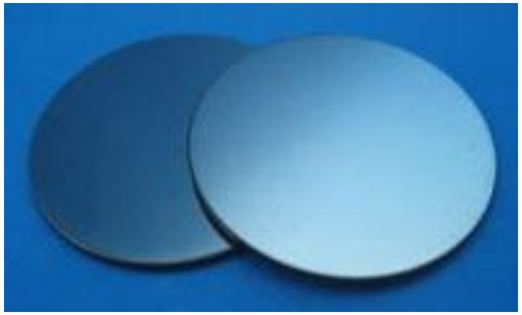


CTR with radial polarizer has also the donuts profile





THz Spectral Splitters



Type	NIR-THz spectral splitter	MIR-THz spectral splitter
Material of substrate	- HRFZ-Si - THz-grade crystal quartz	
Dimensions tolerance, mm	+/-0.25	
Clear aperture, %	90	
Surface quality, scr/dig	60/40	
Surface accuracy, mm	+/-0.01 deviation from ideal plane	
Coating	High-reflection dielectric coating (R>90%) @ 730-860 nm	High-reflection dielectric coating (R>90%) @ 9-11µm
Angle of incidence, arc. grad:	45	

The following THz spectral splitters are available from stock:

No.	Diameter		Thickness
	mm	inches	mm
1	25.4	1.0	1.0

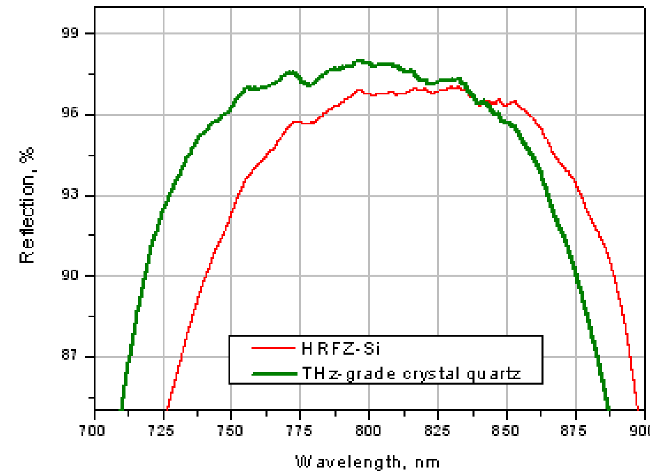


Fig.1 Reflection of NIR-THz spectral splitter (two types of substrate).

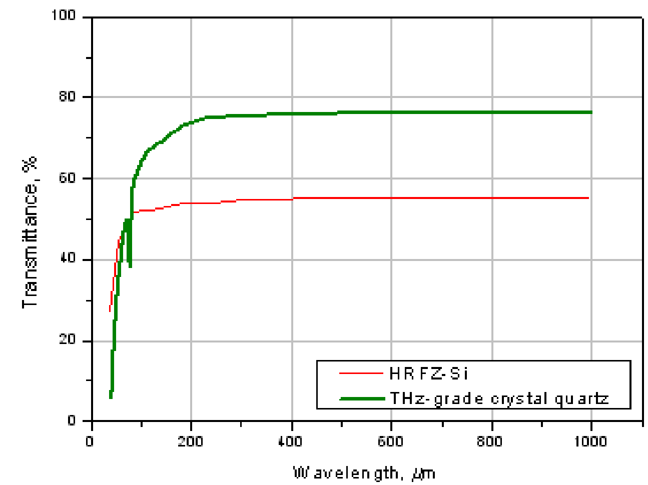
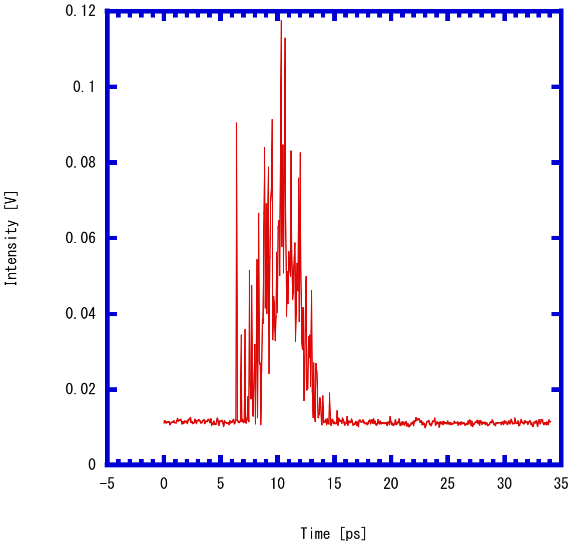
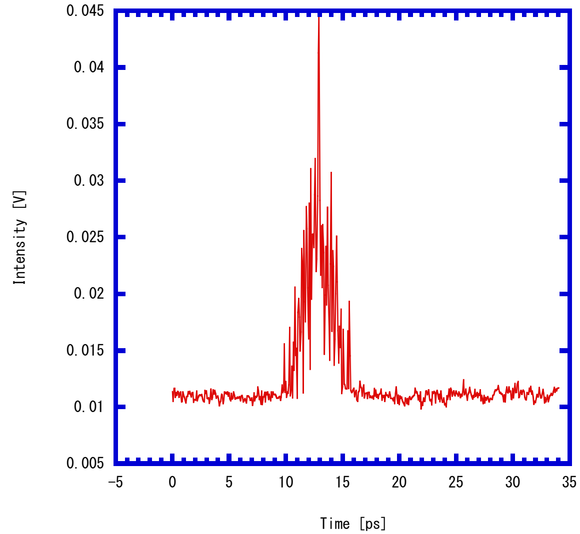


Fig.2 Transmission of NIR-THz spectral splitter (two types of substrate).

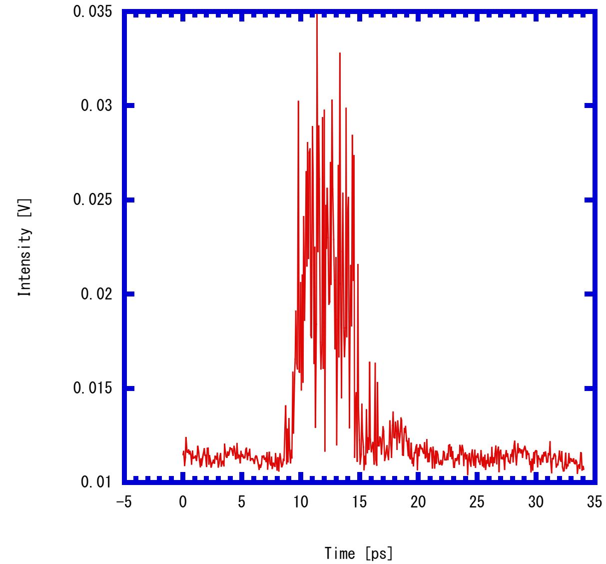
No sample

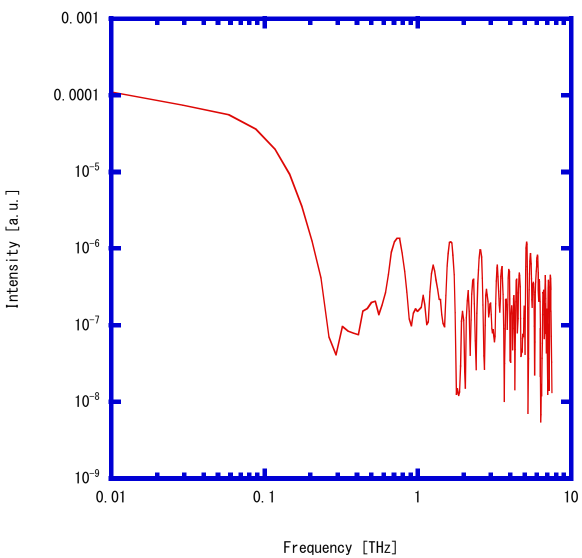


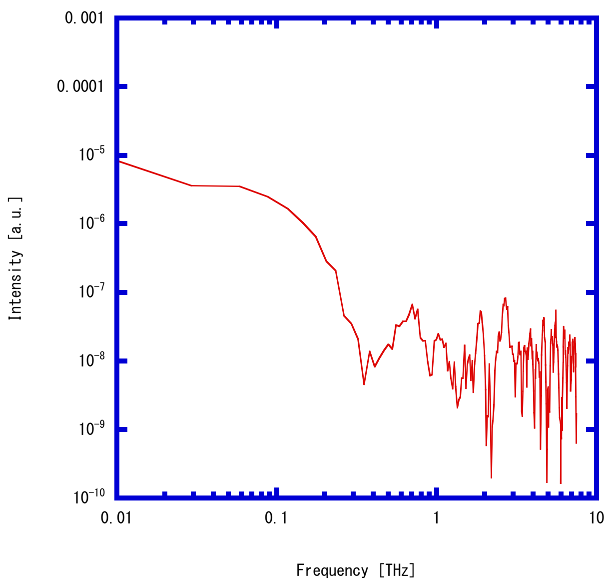
3,4DNT

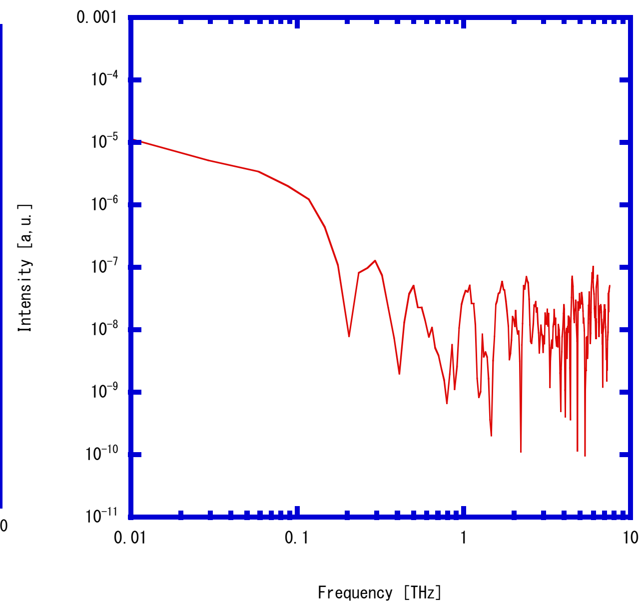


PTFE







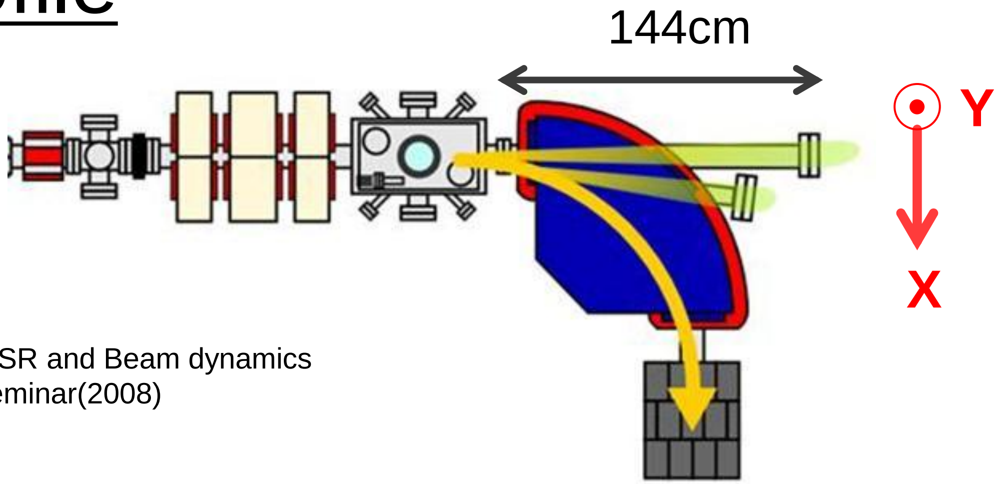


CSR electric field profile

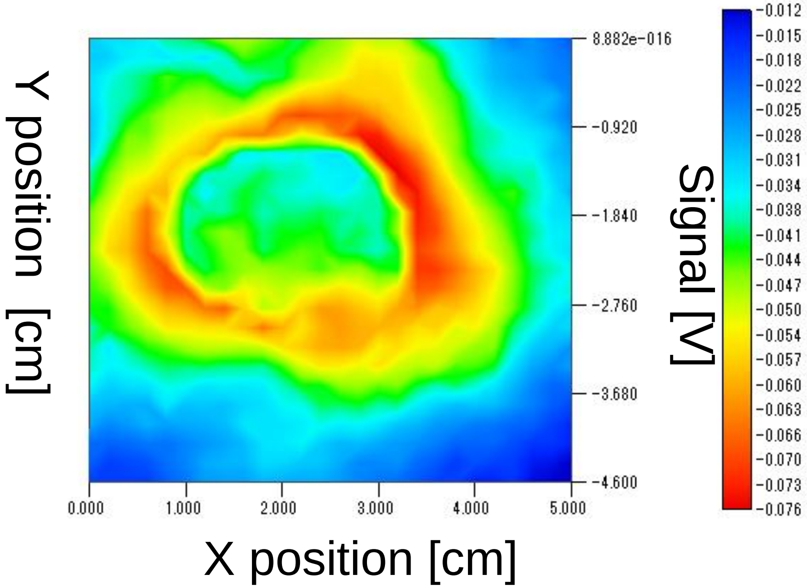
The divergence of THz-CSR

$$< \theta_{\rm rad}^2 >^{1/2} \sim \frac{1}{\gamma}\left(\frac{2\omega_c}{\omega}\right)^{1/3}$$

About 142mrad



From Miho Shimada CSR and Beam dynamics
OHO Seminar(2008)



The size of THz-CSR is about 20 cm
at the THz window. (> the size of beam pipe)

Confirming CSR

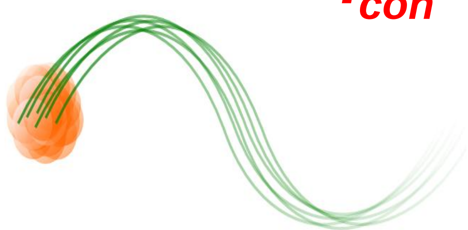
P : Intensity of CSR
C : Charge of the bunch

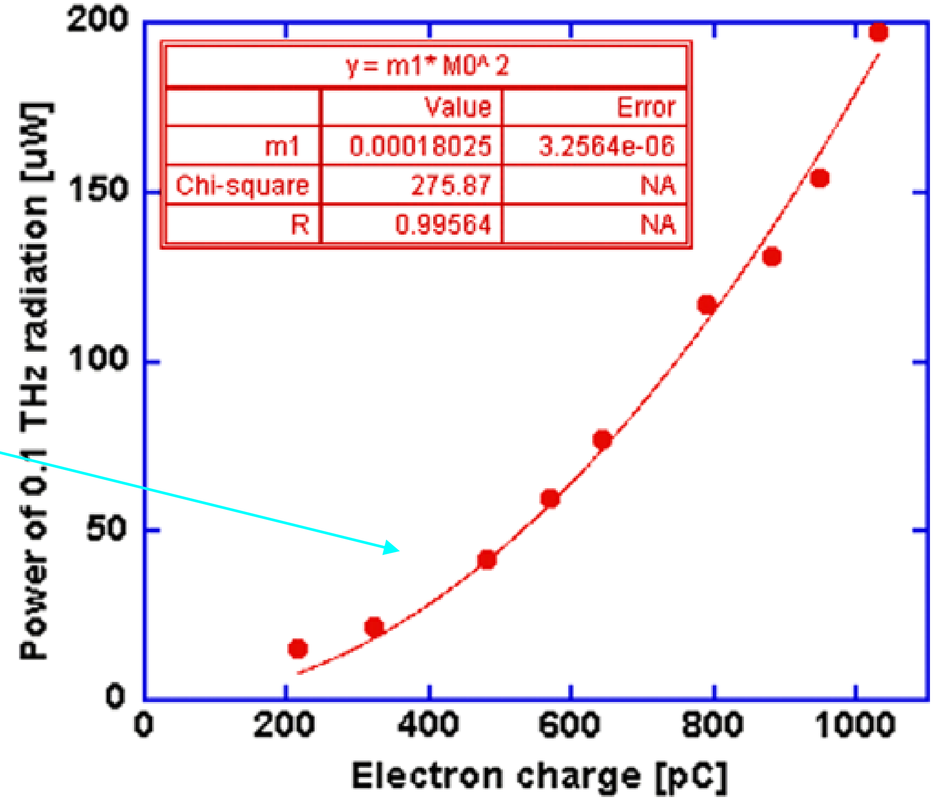
$P \propto C^2$

$C \propto N$

$P \propto N^2$

$I_{coh} \propto N^2$





Electron charge vs Power of 0.1 THz radiation