ISSUES WITH DIAGNOSTIC SYSTEMS IN ELECTRON ACCELERATORS
&&
KEK LUCX - THZ PROGRAM: OVERVIEW AND PROSPECTS

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Indo-Japan school on Advanced Accelerators of Ions and Electrons

16 February 2015

General preface

- It is impossible to draw any "objective picture" without going into some degree of details.
- From the other hand , details should not take us away from the main direction.

- In this two lectures I will try to melt together two commonly separated, but co-dependent topics on electron beam diagnostics and radiation generation.

General preface

- These two topics will be related to:
  - EM radiation generated by electron beam in a THz frequency range.
  - Necessary electron beam condition control and hence diagnostics to establish efficient THz generation.
- Explanation will be started from basic introduction to the electron beam diagnostics and theoretical review of EM radiation simulation.
- At last I will present systematic approach to development of a compact high-brightness THz source.

Preface

- **“Accelerator is just as good as its diagnostics.”**
- Beam diagnostics is an essential constituent of any accelerator. These systems are our organs of sense that let us perceive what properties a beam has and how it behaves in an accelerator. Without diagnostics, we would blindly grope around in the dark and the achievement of a beam for physics-use would be a matter of sheer luck.

H. Koziol, CERN

- “People who are really serious about **software** should make their own **hardware**.” A. Kay, UCLA
- **“A machine is as good as its diagnostics and its algorithms.”**

General review

- Accelerator performance depends critically on the ability to carefully measure and control the properties of the accelerated particle beams.
- This reflects in part the increasingly difficult demands for high beam currents, smaller beam emittances, and the tighter tolerances placed on these parameters (e.g. position stability) in modern accelerators.
- A good understanding of diagnostics (in present and future accelerators) is therefore essential for achieving the required performance.
- A beam diagnostic consists of the measurement device associated electronics and processing hardware.
- “Beam Diagnostics and Applications”, A. Hofmann (BIW 98)

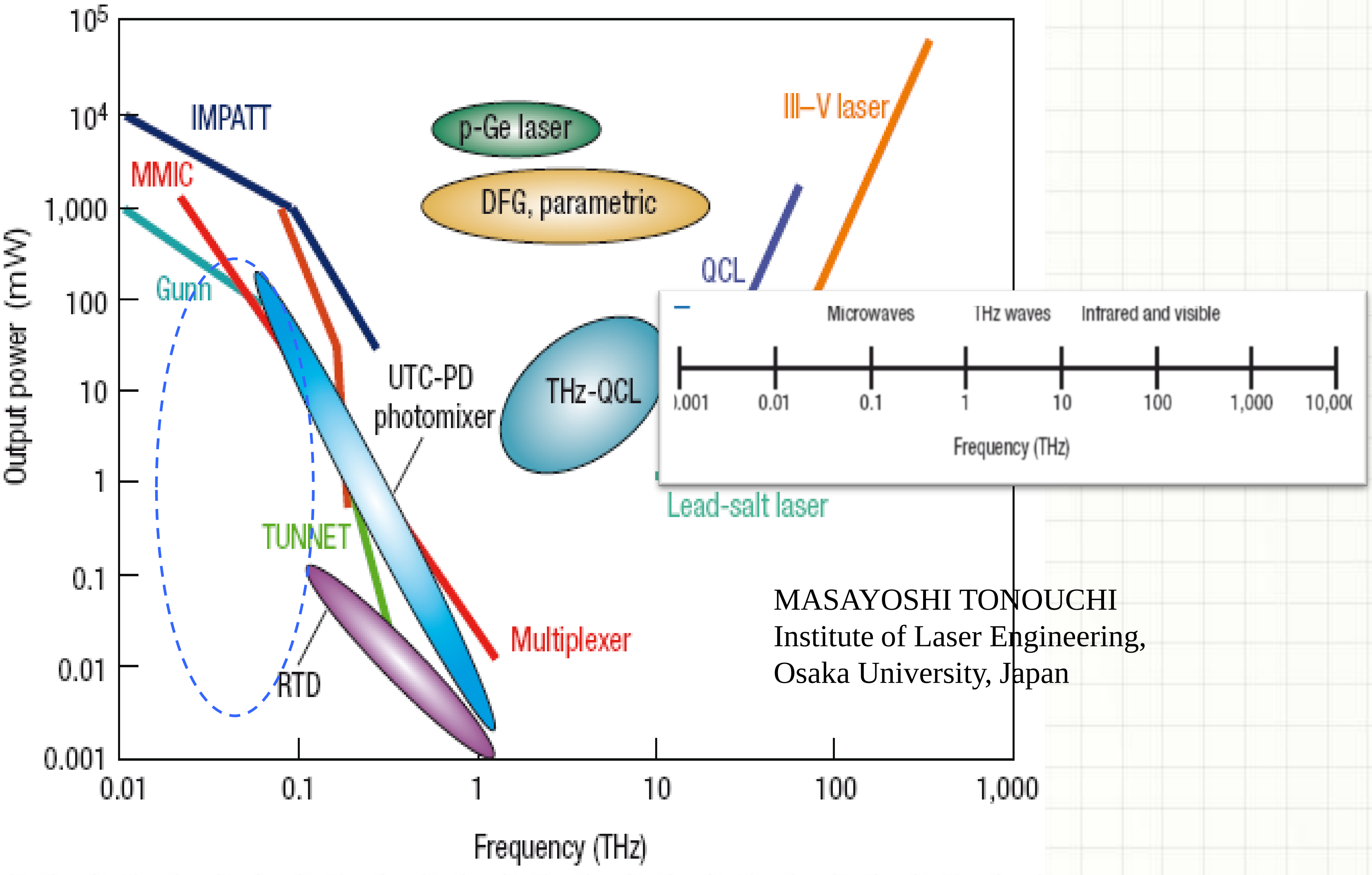
Why it is a big deal?

- Good knowledge of accelerators, general physics and technologies needed.
- Quite different technologies are used, based on various physics processes.
- Each task and each technology calls for an expert.
- Applicability (in term of a reliable results) of various diagnostics types greatly depends on machine type, particles types and beam parameters.
- Well established techniques are not always applied.
- Quick, remotely controlled, on-line, non-destructive, multifunction and possibly single-shot measurements needed.
- Accelerator development goes parallel to diagnostics development.

Preface

- There are no “standard solutions” per se.
  - And that is what gives freedom but generates problems.
- Most of the equipment is highly specialized and never designed to be a part of something bigger.
- The overall complex performance most of the time depends on integration rather than on each component availability.
  - It is quite similar to “Industrial revolution” problems

Preface

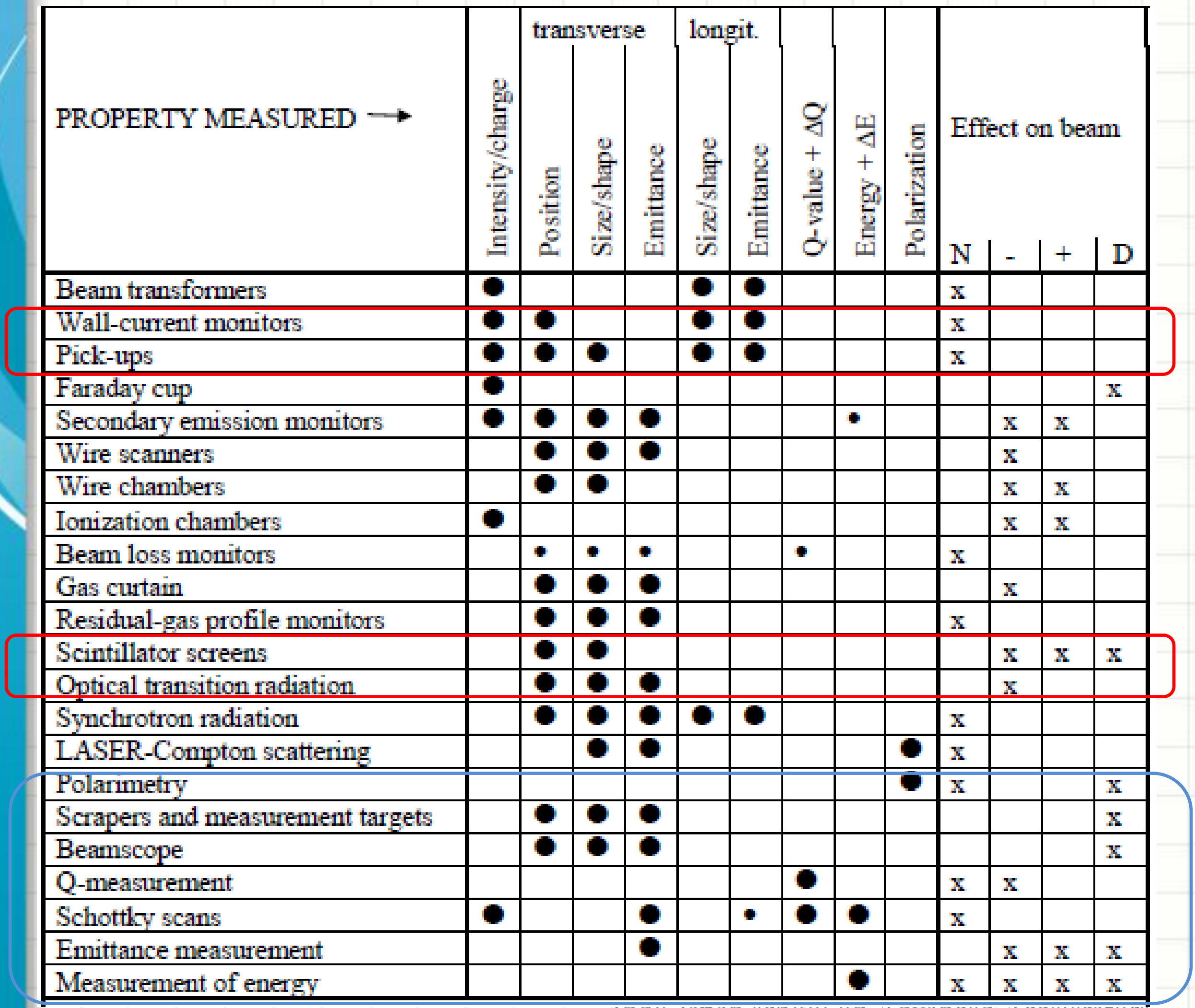


MASAYOSHI TONOUCHI
Institute of Laser Engineering,
Osaka University, Japan

Compact linear accelerator diagnostics

- Electron beam diagnostics
  - Primary:
    - Charge -> **ICT**
    - Position -> **BPMs**
    - Transverse profile -> **Screens** (also gives position)
  - Derivatives:
    - Energy -> Screen in the dispersive region
    - Emittance -> Q-scan & Screen or 4-5 Screens in a drift space
    - Longitudinal profile -> Deflecting cavity
- THz (and any other coherent radiation)
  - Spectrum
    - **Interferometry**
    - Filters or detector array
  - Pulse duration, micro-bunch spacing
    - Interferometry
- X-rays (target positioning with respect to e-beam)
  - Intensity

Diagnostic devices and beam properties measured



PROPERTY MEASURED →		transverse			longit.					Effect on beam			
	Intensity/charge	Position	Size/shape	Emittance	Size/shape	Emittance	Q-value + ΔQ	Energy + ΔE	Polarization	N	-	+	D
Beam transformers	●				●	●				x			
Wall-current monitors	●	●			●	●				x			
Pick-ups	●	●	●		●	●				x			
Faraday cup	●												x
Secondary emission monitors	●	●	●	●				•			x	x	
Wire scanners		●	●	●							x		
Wire chambers		●	●								x	x	
Ionization chambers	●										x	x	
Beam loss monitors		•	•	•			•			x			
Gas curtain		●	●	●							x		
Residual-gas profile monitors		●	●	●						x			
Scintillator screens		●	●								x	x	x
Optical transition radiation		●	●	●							x		
Synchrotron radiation		●	●	●	●	●				x			
LASER-Compton scattering			●	●					●	x			
Polarimetry									●	x			x
Scrapers and measurement targets		●	●	●									x
Beamscope		●	●	●									x
Q-measurement							●			x	x		
Schottky scans	●			●		•	●	●		x			
Emittance measurement				●							x	x	x
Measurement of energy								●		x	x	x	x

Effect on beam:

- “N” – none
- “-” – negligible
- “+” – perturbing
- “D” – destructive

- “●” – primary purpose
- “•” – indirect use

Outline

- To establish stable THz generation we have to:
  - Monitor beam position (BPMs)
  - Monitor beam charge (CTs)
  - Monitor beam profile (Screens)
  - **Choose "effective" generation way (Radiation type).**
- To confirm THz generation and further tune beam parameters we have to:
  - THz radiation intensity distribution (Detectors)
  - Measure bunch length (a few possibilities)
  - THz radiation power spectrum (Interferometer , …)

ISSUES WITH DIAGNOSTIC SYSTEMS IN ELECTRON ACCELERATORS (RELATED TO THZ GENERATION)

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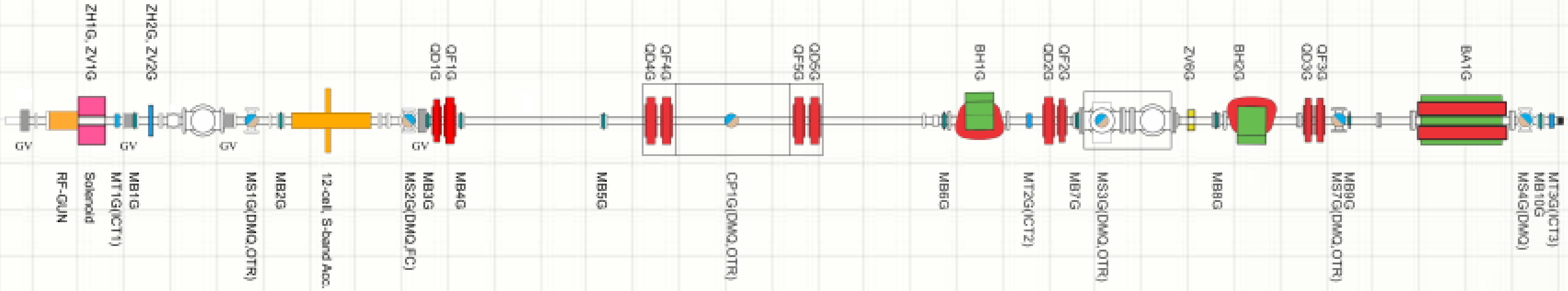
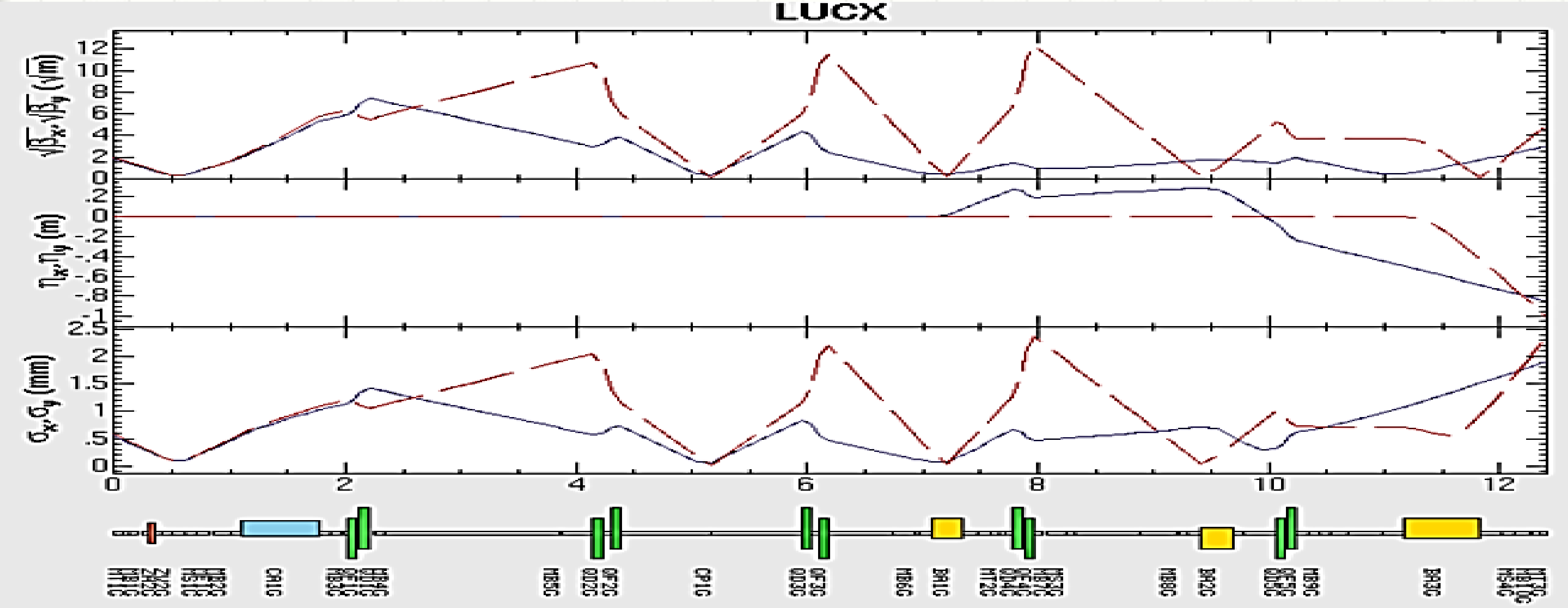
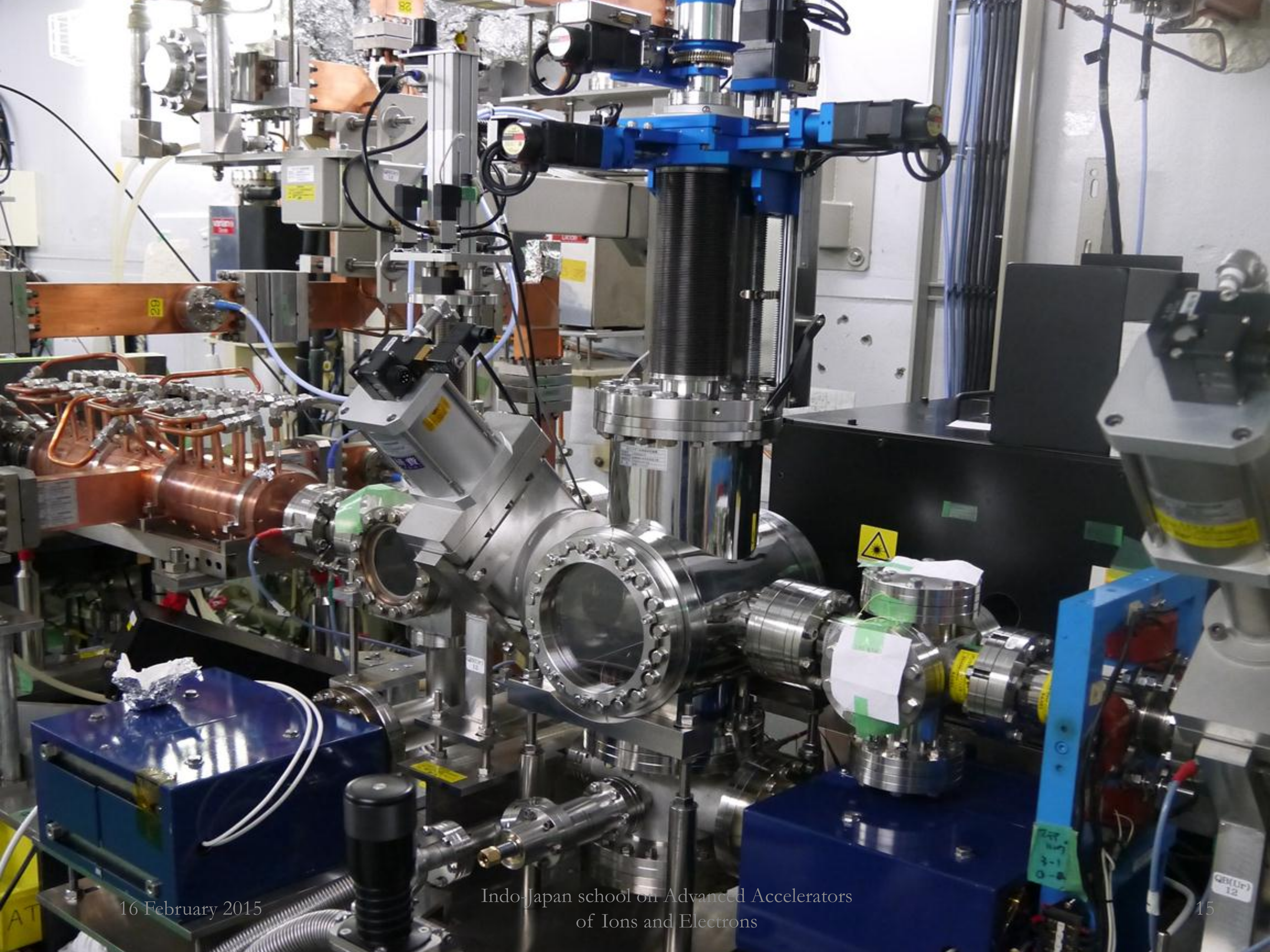
LUCX beamline



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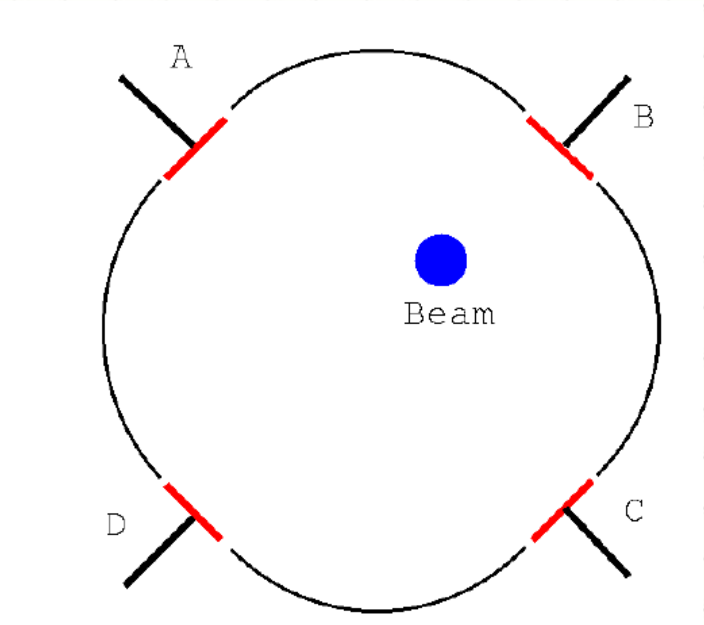
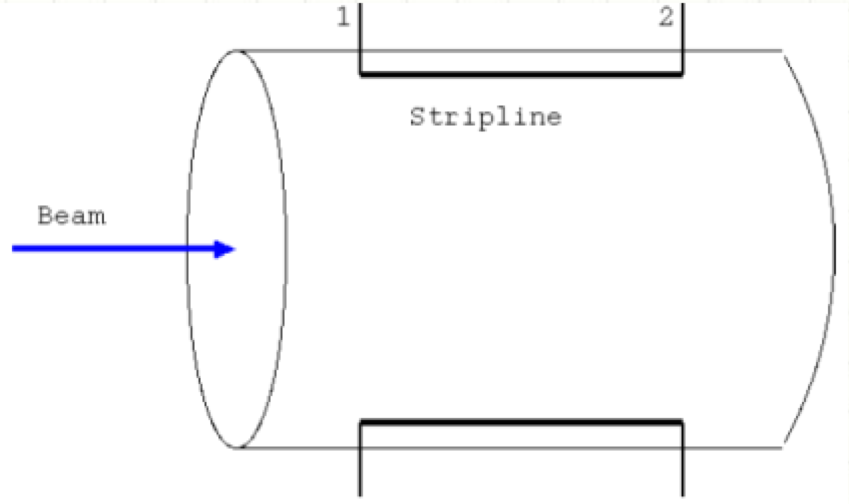
QB(Ur)
12

Beam Position Monitors (BPMs)

- Used in high intensity machines with short bunches and Synchrotron light sources.
- The BPM consists of four metal buttons on the inside of the accelerator structure, connected to wires that extend outside the structure and are grounded.
- The entire apparatus is electrically isolated from the accelerator structure itself.
- The information from the four buttons can be used to measure the number of electrons in the bunch and determine the position of the bunch.
- Buttons are used frequently in synchrotron light sources are a variant of the capacitive monitor.
- Picks up the wall currents at several positions
- Huge dynamic range but poor resolution ~10um (typ.)

Beam Position Monitors (BPMs)





$$x = k_x \frac{(A+D)-(B+C)}{A+B+C+D}$$

$$k_x = k_y = R / \sqrt{2}$$

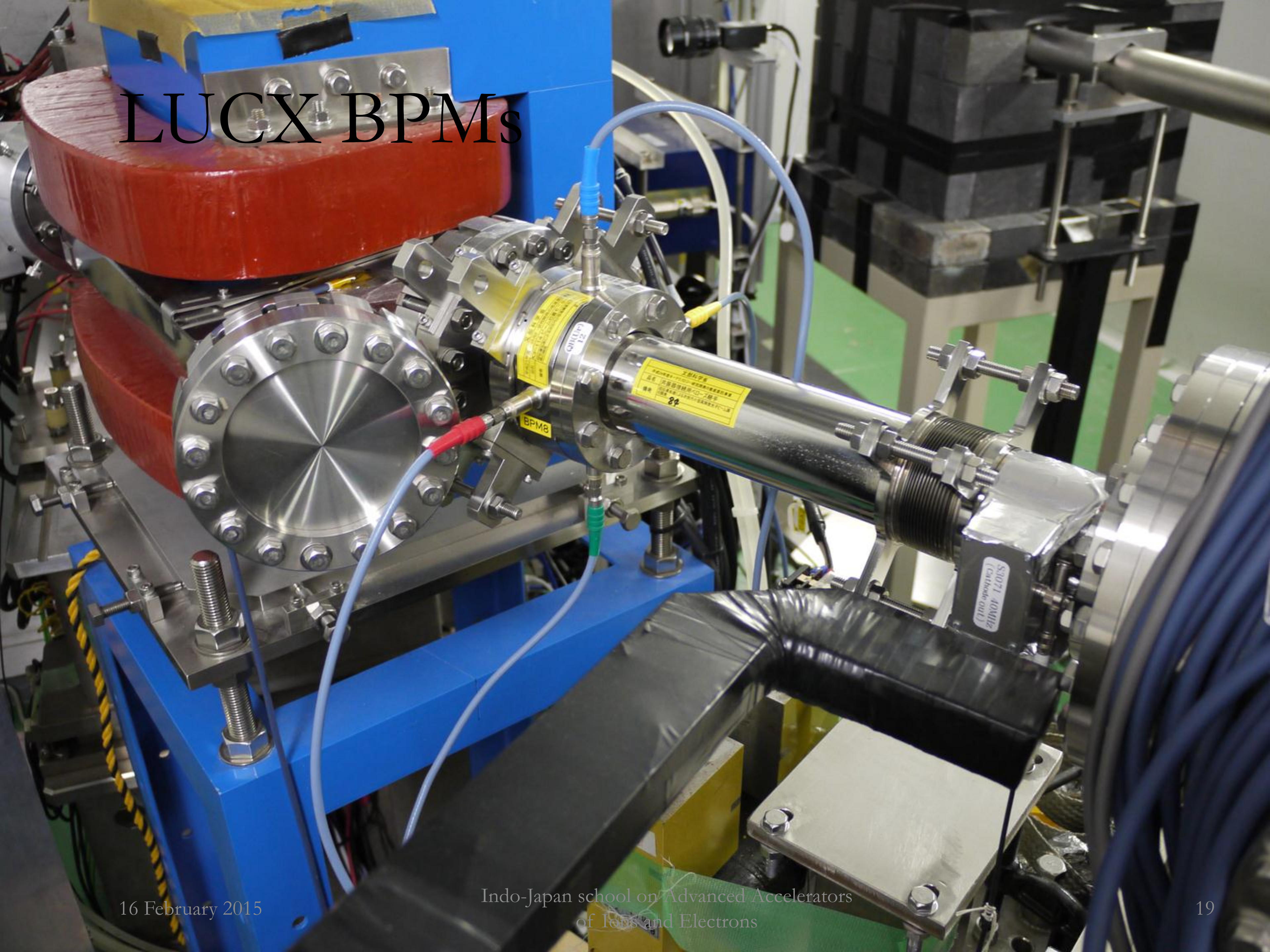
$$y = k_y \frac{(A+B)-(C+D)}{A+B+C+D}$$

Stripline BPM

- Stripline has 4 strips running along the axes of beam, parallel to the vacuum chamber wall.
- The length of the strip is usually longer than the characteristic bunch length and equal to quarter wavelength of fundamental RF.
- The electromagnetic field of the beam induces signal on the strip line.
- The amplitude of signal is a function of its solid angle subtended on the beam and distance of the conductor from the beam.
- Two ends of the stripline are taken out of the chamber. These are called upstream and downstream ports respectively with reference to the beam direction.
- Better resolution <10um

Much better for a short bunches

LUCX BPMs



Current transformers

- Simple design
- Of-the-shelf availability
- Fast response
- Femtosecond bunch generates good signal

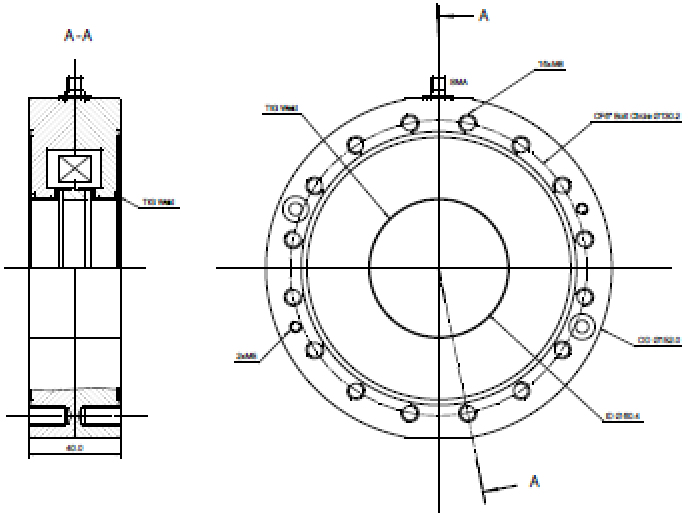


Figure 1. Mechanical drawing of an In-flange.FCT-UHV

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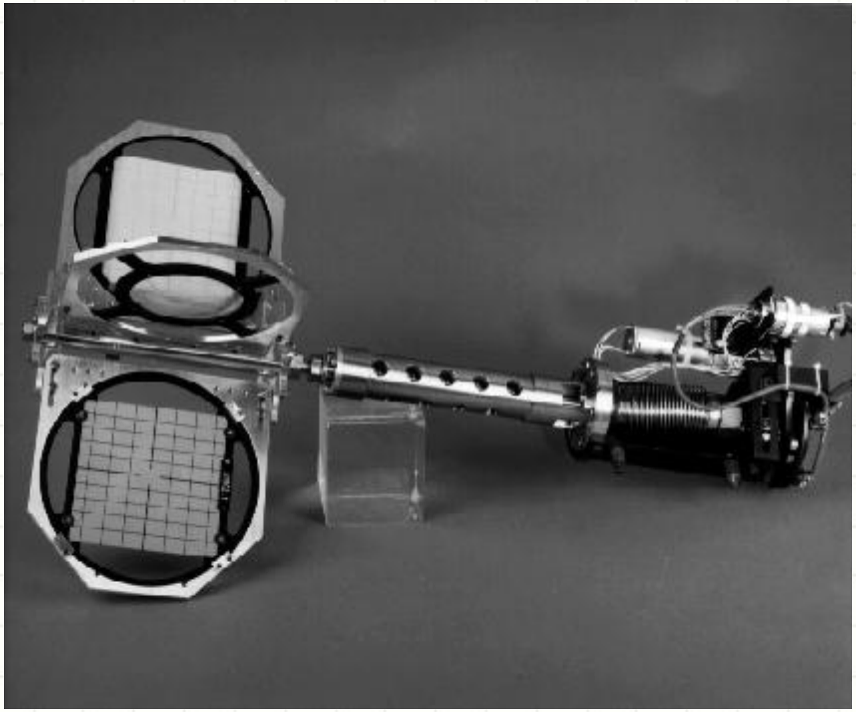
Screen monitors

- Incoherent light monitors
  - Luminescent screens
  - Optical Transition Radiation (OTR) monitor
  - Optical Diffraction Radiation (ODR) monitor
  - Cherenkov radiation monitors
- Coherent light monitors
  - Coherent Transition Radiation (CTR)
  - Coherent Diffraction Radiation (CDR)
  - Coherent Cherenkov Radiation (CChR)
  - Coherent Resonant Diffraction Radiation (so-called Smith-Purcell radiation, CSPR)

Luminescent screens

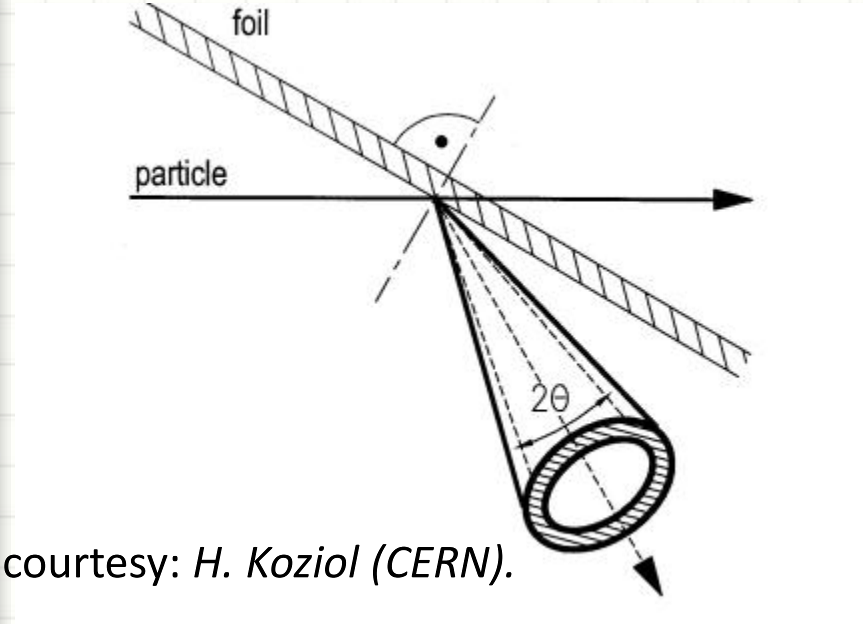


courtesy: *Gérard Burtin (CERN).*

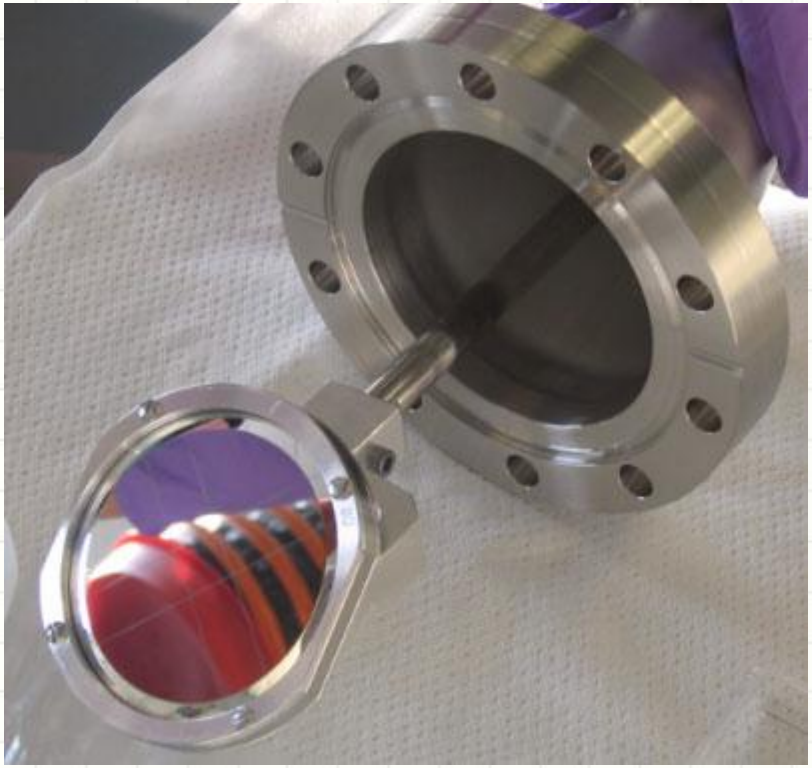
- When a beam passes through a luminescent screen, part of the deposited energy results in excited electrostatic states in the material from which a light emission at a defined wavelength will follow.
- The light emission originates in impurity inclusions, the so-called activators, in most of the used materials.
- They allow a direct observation of the beam position and shape on a TV monitor.
- They are necessarily single-pass monitors.
- Not very accurate

Beam Profile Monitors (Screens)

V.L. Ginzburg and I.M. Frank, Zh. Eksp. Teor. Fiz. 16 (1946) 15.



courtesy: *H. Koziol (CERN).*

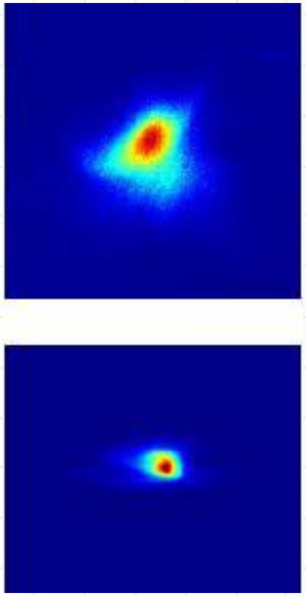


- Profile, roll
- Position
- Charge
- Energy
- Energy spread

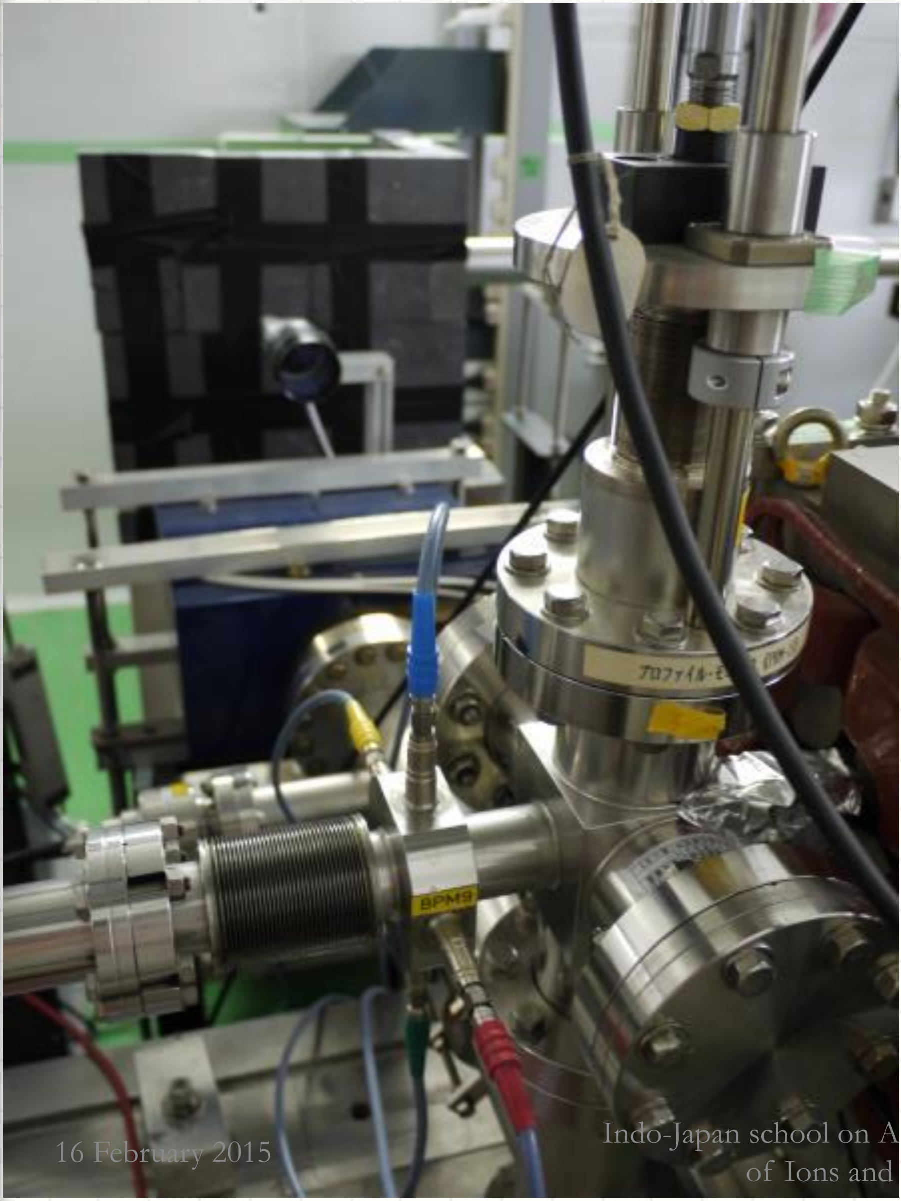
For Bunch length or Bunch profile one have to take into account transverse beam size.

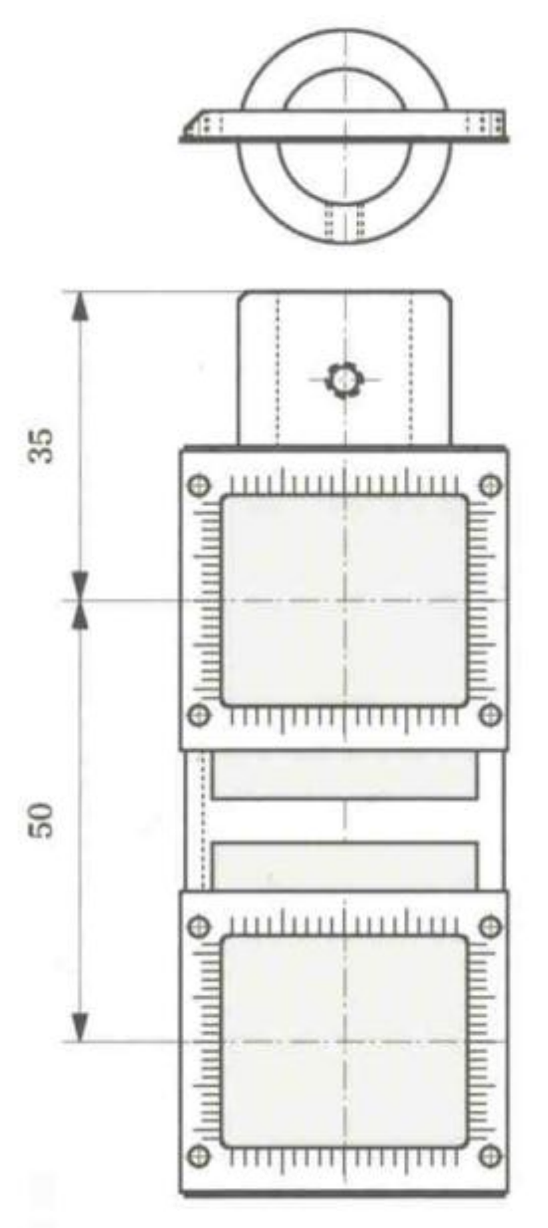
OTR monitors

- Optical Transition radiation occurs when a charged particle crosses the boundary between two media with different dielectric constants.
- According to the characteristics of transition radiation, if the electron beam incidence to the boundary at 45° the transition radiation appears at 90° to the electron beam direction.
- Wide wavelength range OTR can be used for transverse beam profile measurements.
- Silicon screens + Ag or Al coating.
- Often beams are far from Gaussian especially in LINACs.
- Camera must be protected from radiation requiring a complex optical lines.
- Filters are needed to avoid saturating the camera.

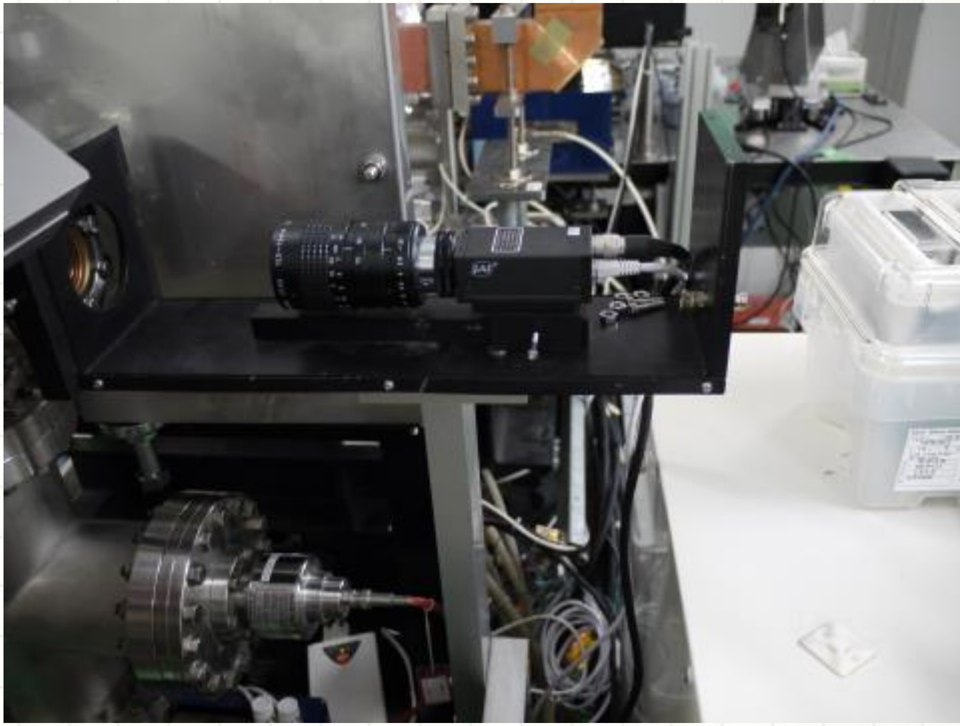


LUCX Screens



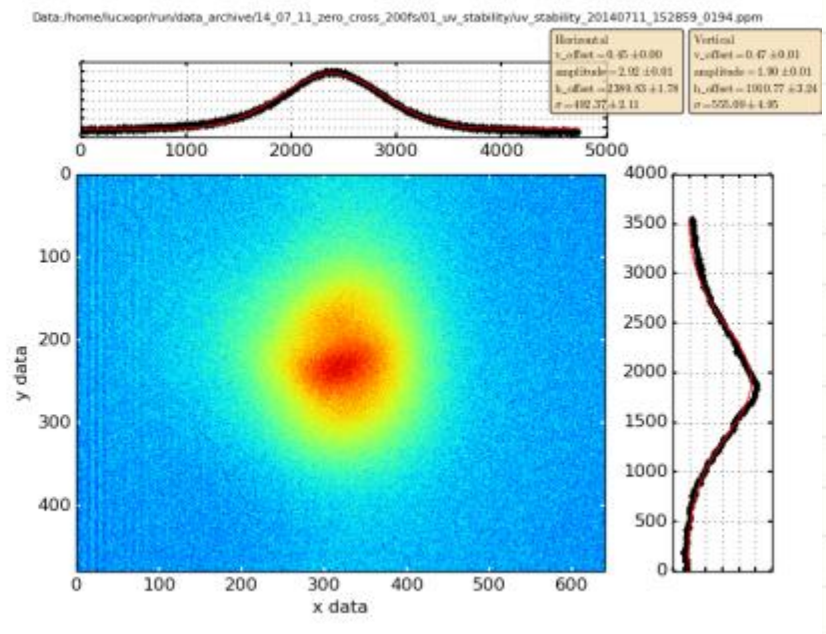


LUCX Screens

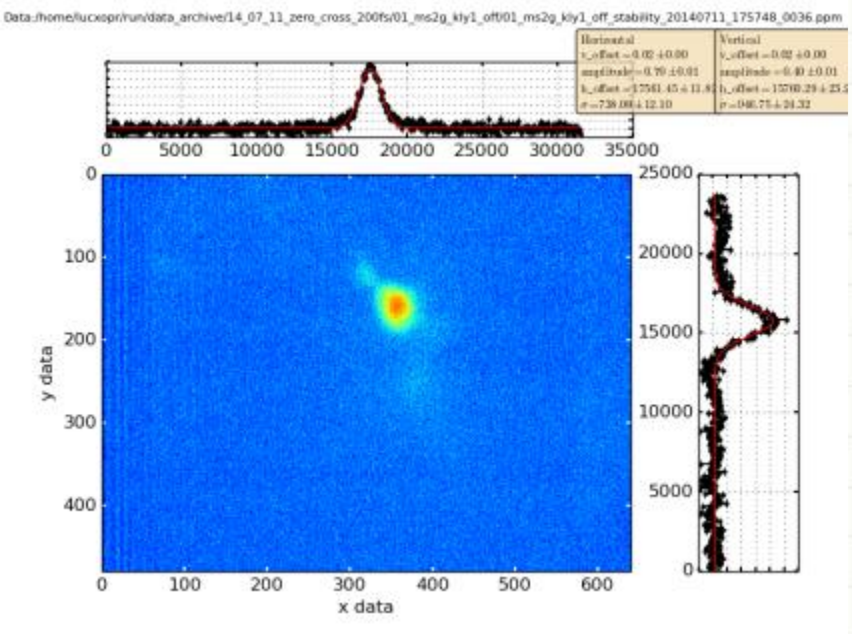


fs e-beam generation

UV



e-beam



Types of radiation

Electromagnetic radiation generated by charged particles can be divided into two categories:

- Bremsstrahlung (gas, plasma); radiation of hard photons due to acceleration (synchrotron radiation, undulator rad., channeling rad., etc.)
- Polarization radiation (radiation of soft photons; acceleration is not required (Vavilov-Cherenkov rad., Transition rad., etc.);)

Polarization Radiation (PR)

- Microscopically, PR arises as a result of the dynamical polarization of the atomic electron shells by the particle's field. PR may dominate over the "ordinary" bremsstrahlung (Amusia, et al., 1976) especially in relativistic case and for heavy particles or ions.
- Macroscopic treatment of PR began from works on
  - Vavilov-**Cherenkov radiation**, VChR (Cherenkov, 1934; Tamm, Frank, 1937),
  - **Transition radiation**, TR (Ginzburg, Frank, 1945),
  - **Difraction radiation**, DR (Bobrinev, Braginsky, 1958; Dnestrovsky, Kostomarov, 1959),
  - **Smith-Purcell radiation**, SPR (Smith, Purcell, 1953),
  - and this is not the end of the list...

Nowadays status of PR

Today PR has a wide range of applications: from detectors in high-energy physics, proposals of the beam diagnostics for accelerators to the new tunable radiation sources for industry, medicine and biology.

The modern applications of PR requires
the adequate methods of calculations!

What the reality-based models should describe?

- Finite permittivity $\varepsilon(\omega) = \varepsilon' + i\varepsilon''$ of a target. Such a model should describe metals as well as dielectrics, photonic crystals, etc. As a result, it should be applicable from the very long waves to the X-rays.
- Real geometrical sizes of a target (screen, grating, cylinder, etc.)
- Real distance to the detector: not only wave zone, but the pre-wave
- zone and the near-field zone as well.
- Such a model should be derived from the first principles, so that one could point out the regions of applicability for the solutions found.

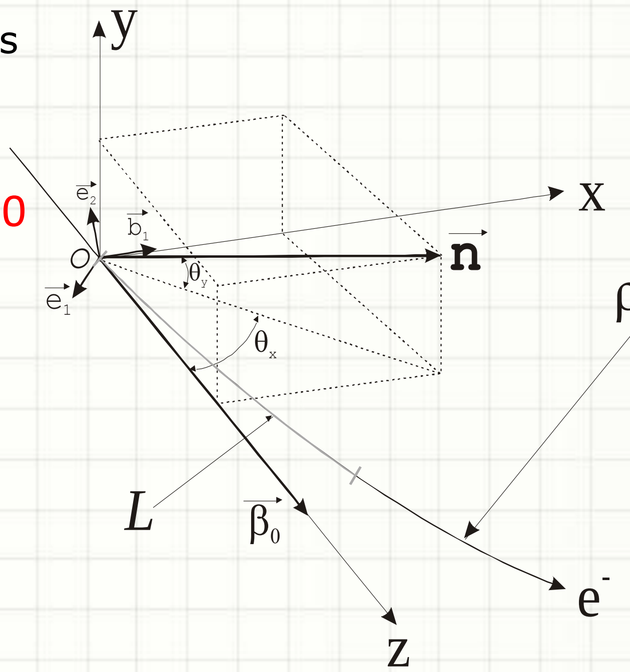
Theory of Coherent Synchrotron radiation

Radiative power of CSR emitted by a bunch of electrons

$$P = \frac{dP}{d\omega}\left[N + N\cdot(N-1)\cdot F(\sigma_z,\lambda)\right]$$

J.S. Nodvick and D.S. Saxon, Phys. Rev., 96, (1954), 180

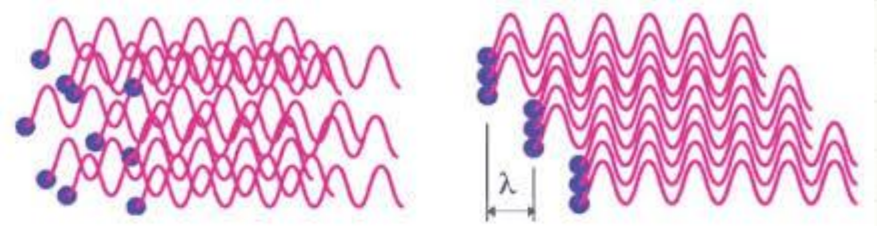
$$F(\sigma_z,\lambda) = \left|\int_{-\infty}^{\infty}\frac{1}{\sqrt{2\pi\sigma_z^2}}\cdot\exp\left(\frac{-z^2}{2\cdot\sigma_z^2}\right)\cdot\exp\left(i\cdot 2\pi\cdot\frac{z}{\lambda}\right)dz\right|^2 = \exp[-4(\pi\sigma_z/\lambda)^2]$$



Fourier transform of the electric field of a moving charge
(so-called Lienard-Wiechert potentials for a moving charge)

$$\vec{E} = \frac{e}{4\pi\varepsilon_0\sqrt{2\pi}}\cdot\int_0^L\left(\frac{\vec{n}\times\left[\vec{n}-\vec{\beta}\right]\times\dot{\vec{\beta}}}{\left(1-\vec{n}\cdot\vec{\beta}\right)^2}\right)\times\exp\left[i\omega\left(t+\frac{R}{c}\right)\right]dt$$

$$\vec{n} = \{\sin\theta_x\cdot\cos\theta_y, \sin\theta_y, \cos\theta_x\cdot\cos\theta_y\} \qquad \vec{\beta} = \beta\cdot\{\sin\tfrac{L}{\rho}, 0, \cos\tfrac{L}{\rho}\}$$



$$\exp\left[i\omega\left(1+\frac{R}{t}\right)\right] = \exp\left[i\cdot\varphi\right] = \cos\varphi + i\cdot\sin\varphi$$

$$\vec{b}_1 = \{1,0,0\} \qquad \vec{e}_1 = \vec{e}_2\times\vec{n} \qquad \vec{e}_2 = \vec{b}_1\times\vec{n}$$

$$\varphi = \omega\left(t+\frac{R}{c}\right) = \frac{2\pi L}{\lambda}\cdot\left(1-\vec{n}\cdot\vec{\beta}\right) = \frac{2\pi L}{\lambda}\cdot\left(1-\cos\theta_y\cdot\cos\left(\theta_x-\tfrac{L}{\rho}\right)\right)$$

$$E_{Hor} = \vec{E}\cdot\vec{e}_1 \qquad E_{Ver} = \vec{E}\cdot\vec{e}_2$$

Theory of Coherent Synchrotron radiation

$$\frac{d^2 P_{Hor}}{d\Omega d\omega} = 4\pi \left| E_{Hor} \right|^2$$

$$\frac{d^2 P_{Ver}}{d\Omega d\omega} = 4\pi \left| E_{Ver} \right|^2$$

$$\frac{dP}{d\omega}_{Hor} = \int_{-\frac{\Delta\theta_x}{2}}^{\frac{\Delta\theta_x}{2}} \int_{-\frac{\Delta\theta_y}{2}}^{\frac{\Delta\theta_y}{2}} \frac{d^2 P}{d\Omega d\omega}_{Hor} d\theta_x d\theta_y$$

$$\frac{dP}{d\omega}_{Ver} = \int_{-\frac{\Delta\theta_x}{2}}^{\frac{\Delta\theta_x}{2}} \int_{-\frac{\Delta\theta_y}{2}}^{\frac{\Delta\theta_y}{2}} \frac{d^2 P}{d\Omega d\omega}_{Ver} d\theta_x d\theta_y$$

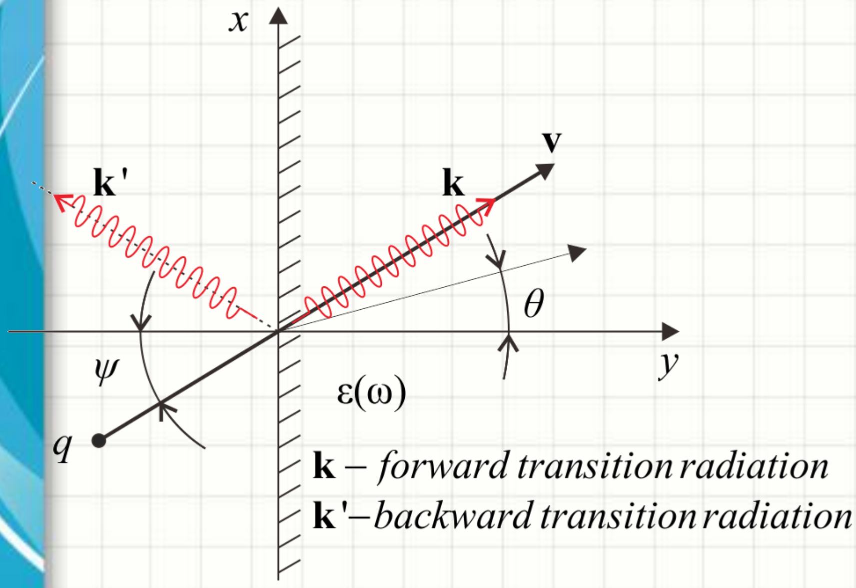
$$\frac{dP_{Hor}^{Coh}}{d\omega} = \frac{dP_{Hor}}{d\omega} \cdot \left[N + N \cdot (N-1) \cdot F(\sigma_z, \lambda) \right]$$

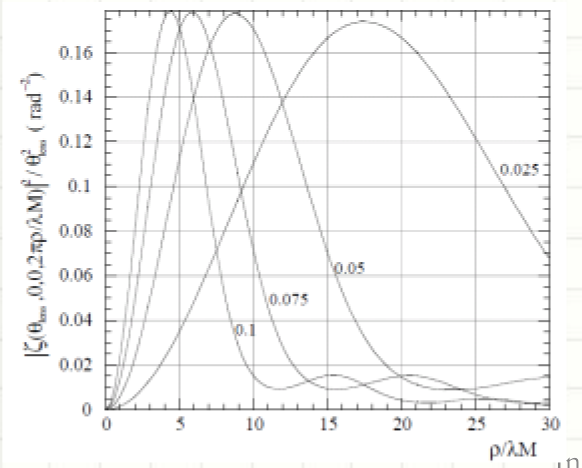
$$\frac{dP_{Ver}^{Coh}}{d\omega} = \frac{dP_{Ver}}{d\omega} \cdot \left[N + N \cdot (N-1) \cdot F(\sigma_z, \lambda) \right]$$

$$P_{Hor}^{Coh}(\sigma_z) = \int_{\lambda_1}^{\lambda_2} \frac{dP_{Hor}}{d\omega} \cdot \left[N + N \cdot (N-1) \cdot F(\sigma_z, \lambda) \right] \cdot \frac{2\pi}{\lambda^2} d\lambda$$

$$P_{Ver}^{Coh}(\sigma_z) = \int_{\lambda_1}^{\lambda_2} \frac{dP_{Ver}}{d\omega} \cdot \left[N + N \cdot (N-1) \cdot F(\sigma_z, \lambda) \right] \cdot \frac{2\pi}{\lambda^2} d\lambda$$

Transition Radiation (TR)





Transition radiation （TR） is a form of electromagnetic radiation emitted when a charged particle passes through inhomogeneous media, such as a boundary between two different media.

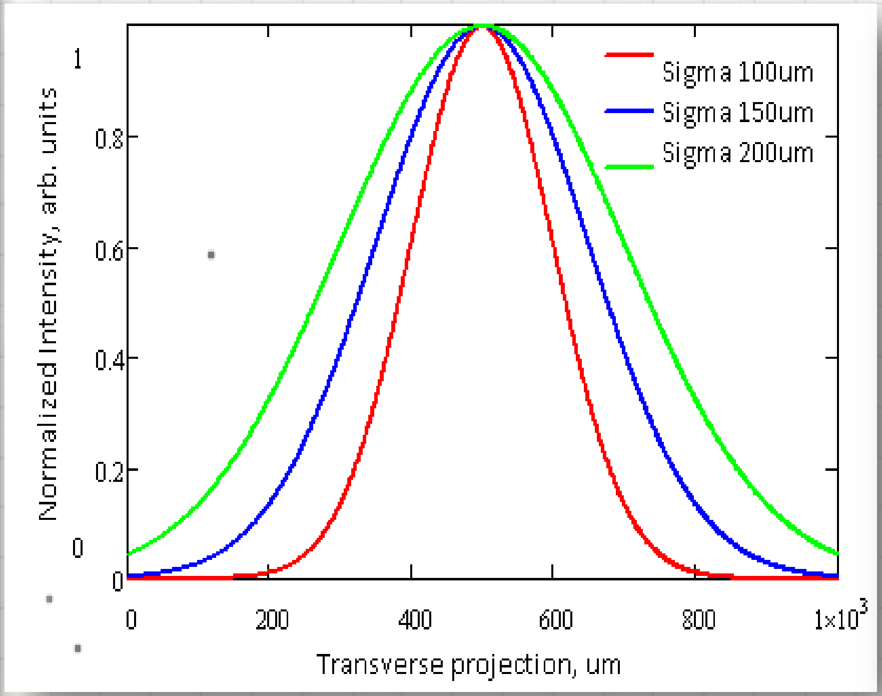
For the case of oblique incidence on a plane the method of images will be used

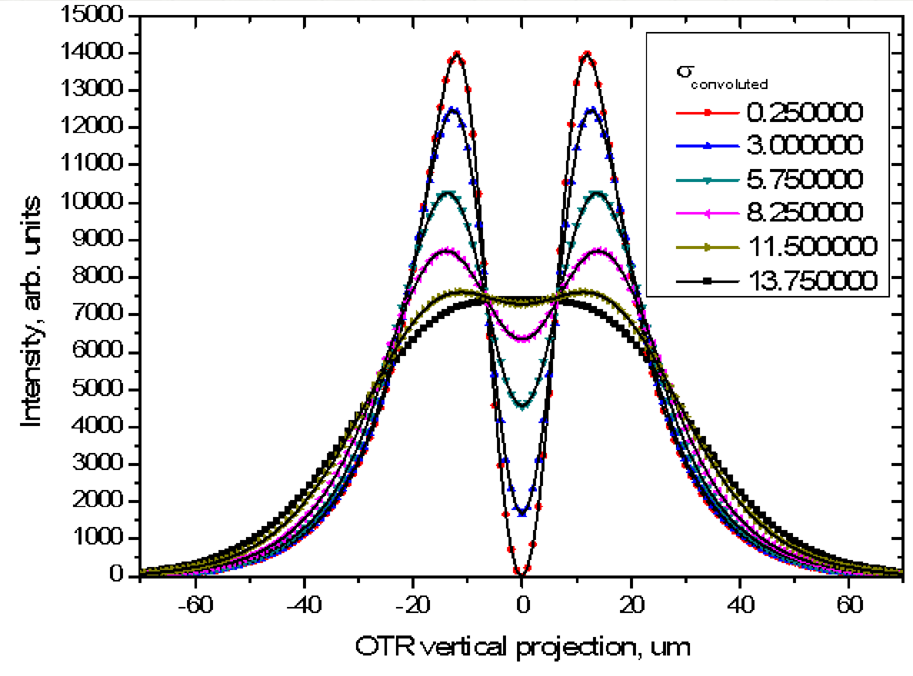
M. Castellano and V. A. Verzilov, PRST-AB **1**, 062801 (1998)

Beam size effect on OTR

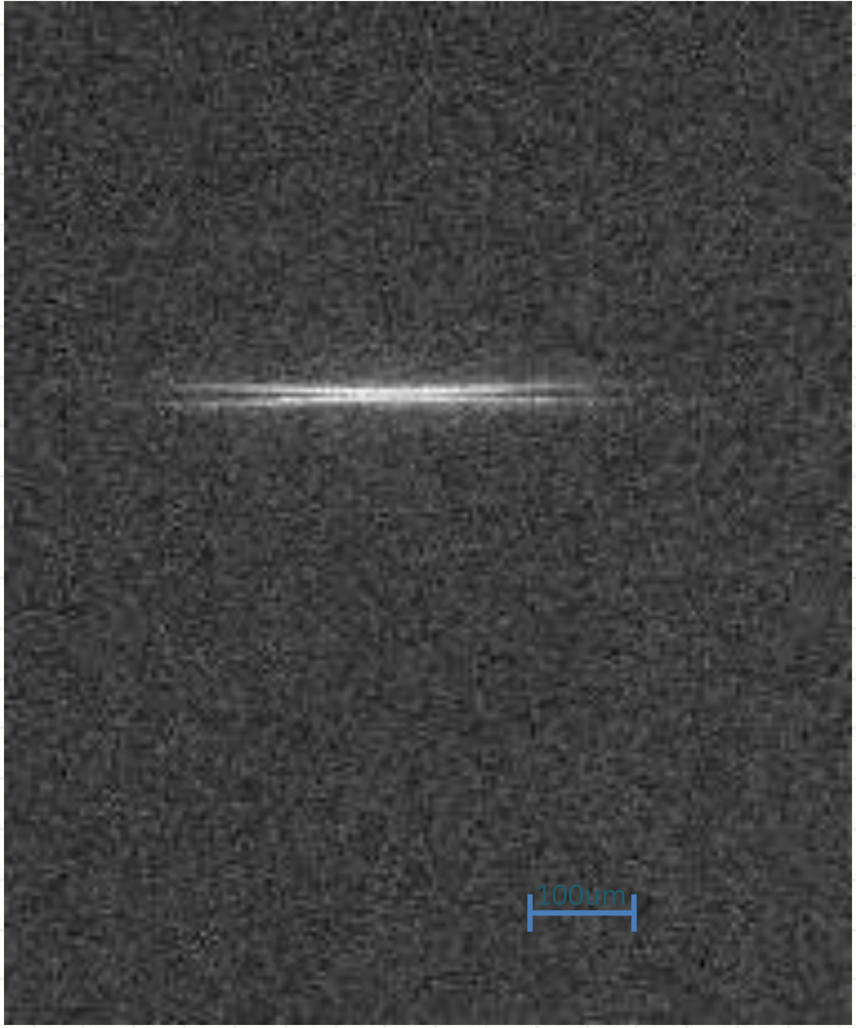
"Usual" OTR image

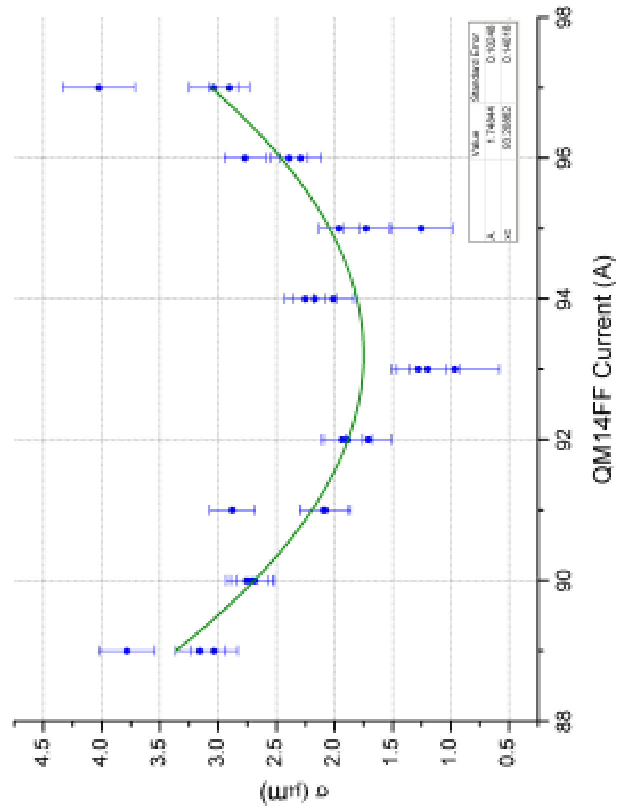
OTR vertical polarization component, for sigma < ~15* um





OTR image and most recent Quadrupole scan.

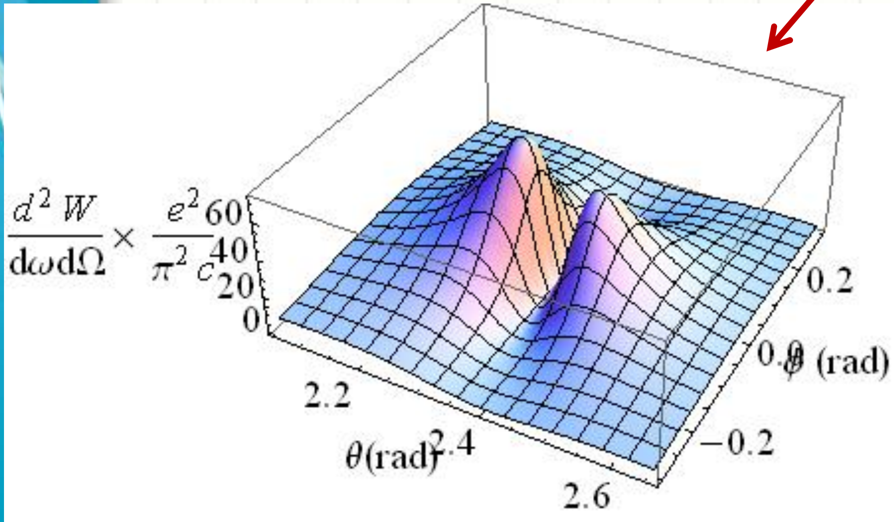


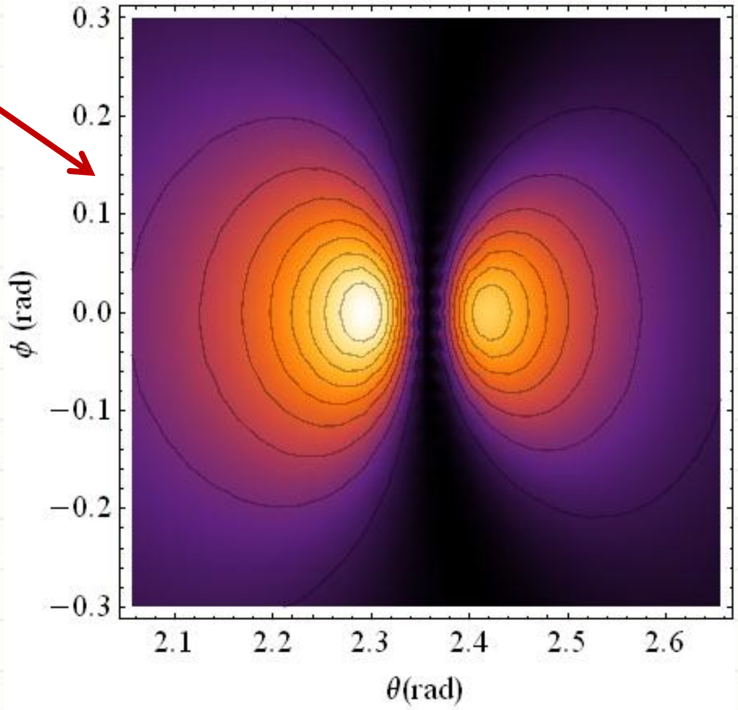


Backward TR (horizontal polarization)

$$\frac{dW^{\parallel}}{d\omega d\Omega} = \frac{e^2\beta^2}{\pi^2 c}\cos^2\psi\left[\frac{\sin\theta-\beta\cos\phi\sin\psi}{(1-\beta\sin\theta\cos\phi\sin\psi)^2-\beta^2\cos^2\theta\cos^2\psi}\right]^2$$

$\gamma = 16$

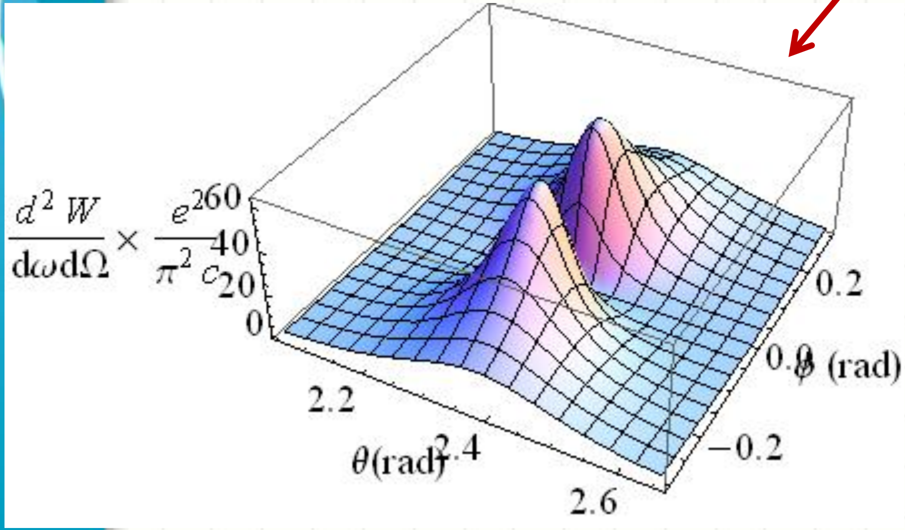


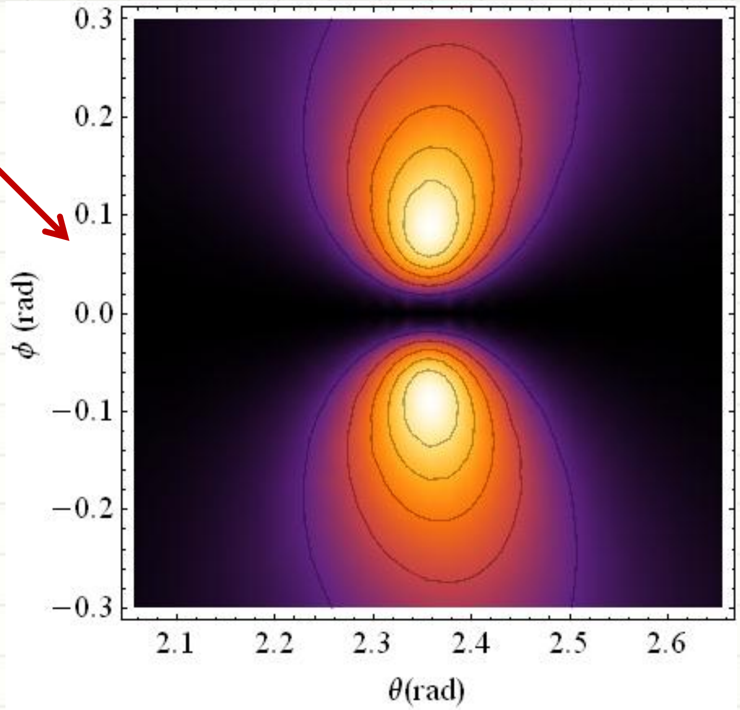


Backward TR (vertical polarization)

$$\frac{dW^{\perp}}{d\omega d\Omega} = \frac{e^2\beta^2}{\pi^2 c}\cos^2\psi \left[\frac{\beta\cos\theta\sin\phi\sin\psi}{(1-\beta\sin\theta\cos\phi\sin\psi)^2 - \beta^2\cos^2\theta\cos^2\psi}\right]^2$$

$\gamma = 16$

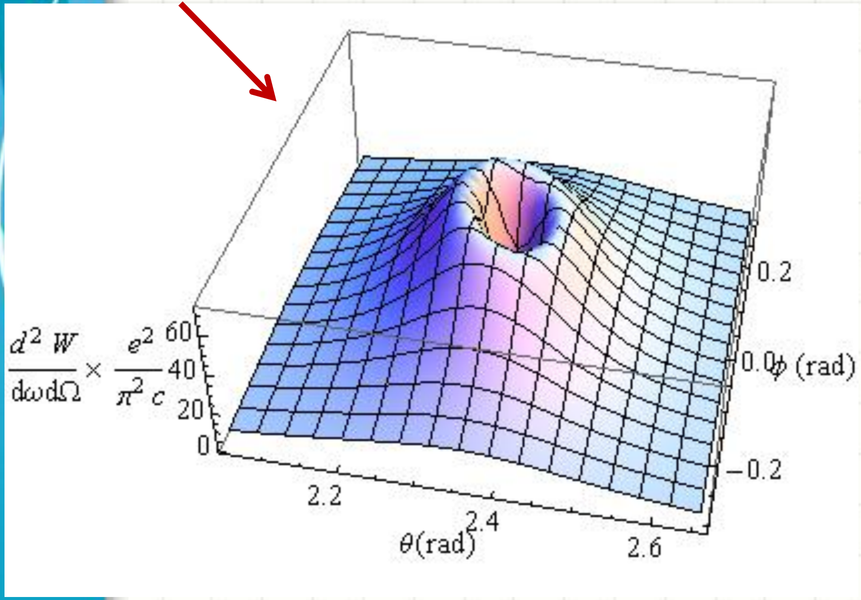


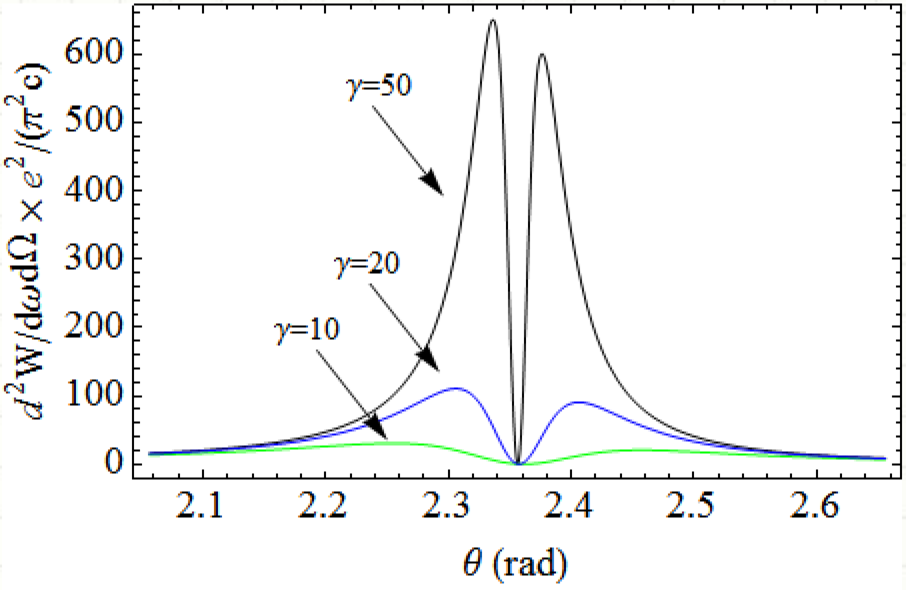


Backward TR

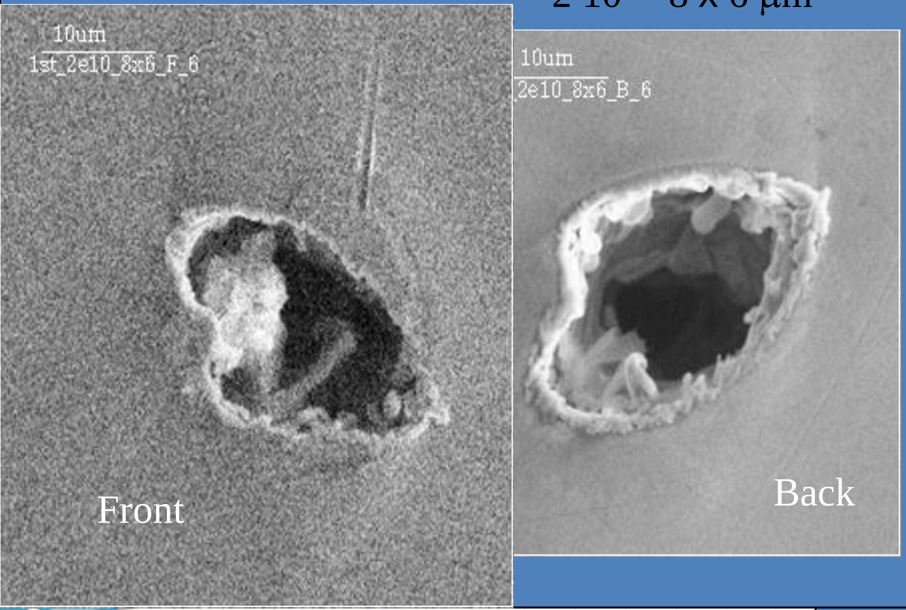
$$\frac{dW}{d\omega d\Omega} = \frac{dW^{\parallel}}{d\omega d\Omega} + \frac{dW^{\perp}}{d\omega d\Omega}$$

$\gamma = 16$

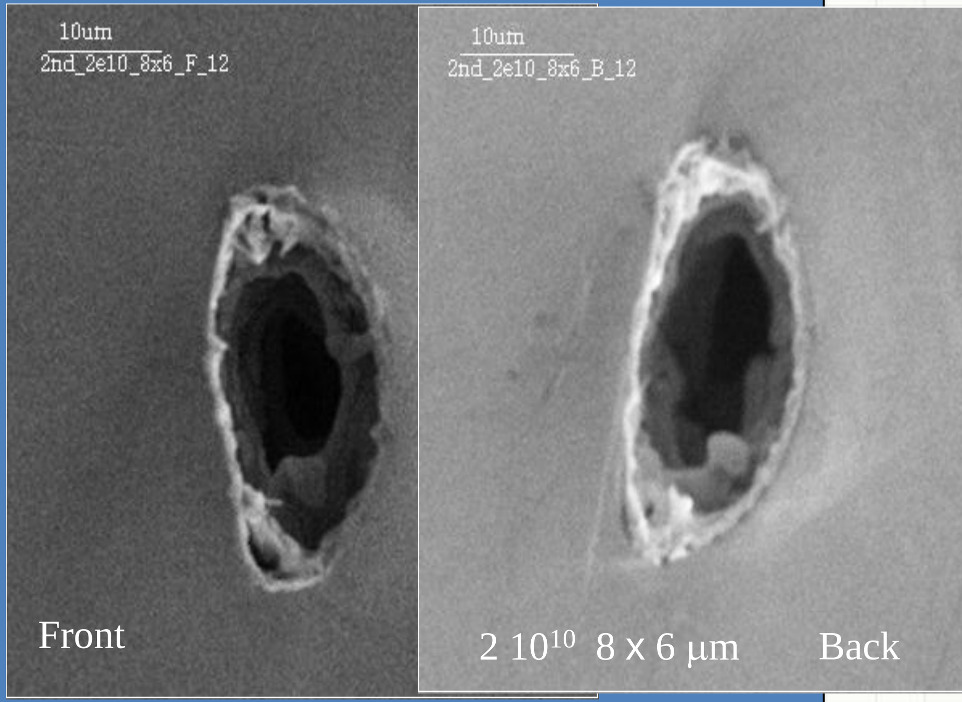




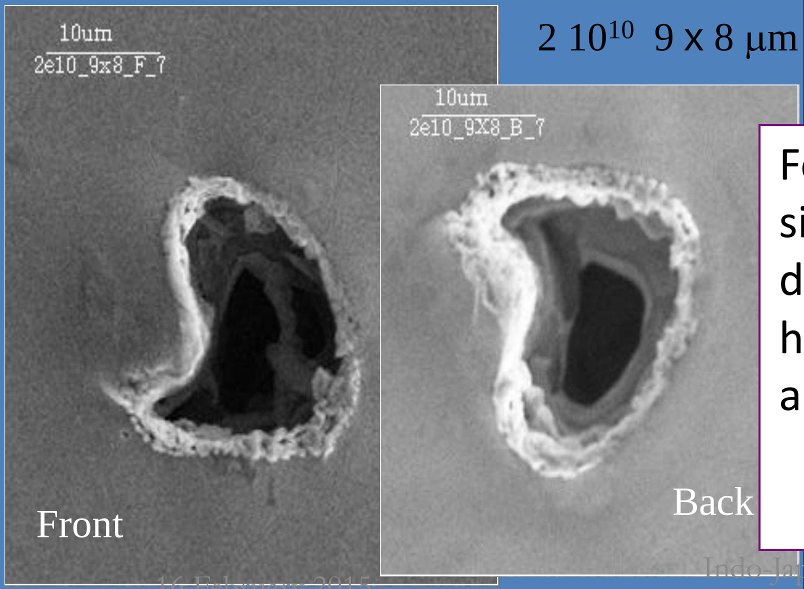
FFTB Single Pulse Damage Coupon Test - front and back side - same scale



2 10^{10} 8 x 6 μm

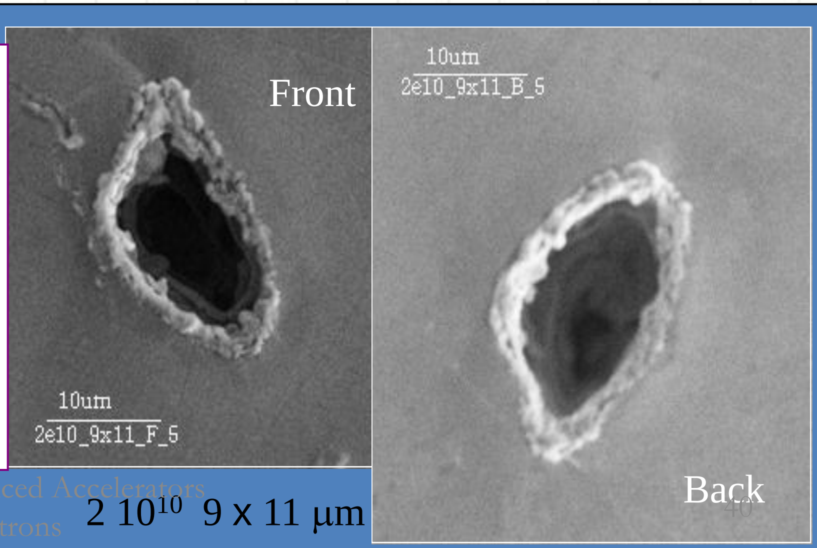


2 10^{10} 8 x 6 μm



2 10^{10} 9 x 8 μm

Four pairs of single pulse damage holes→ front and back



2 10^{10} 9 x 11 μm

TR/CTR Spectrum

$$dW^{\|}(\omega) = \frac{e^2\beta^2}{\pi^2 c}\cos^2\psi\left[\frac{\sin\theta - \beta\cos\phi\sin\psi}{(1-\beta\sin\theta\cos\phi\sin\psi)^2 - \beta^2\cos^2\theta\cos^2\psi}\right]^2 d\omega d\Omega$$

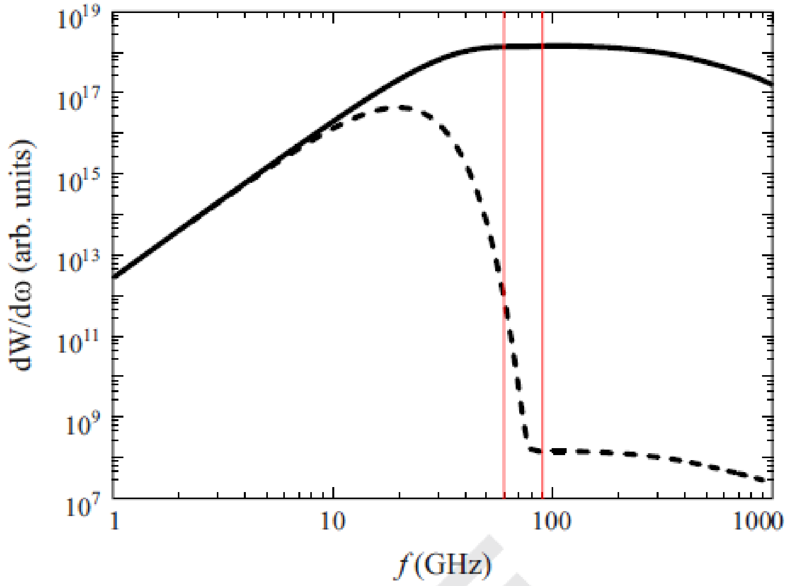
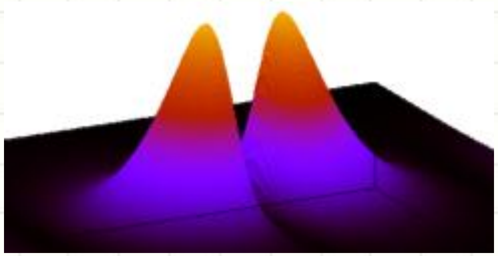
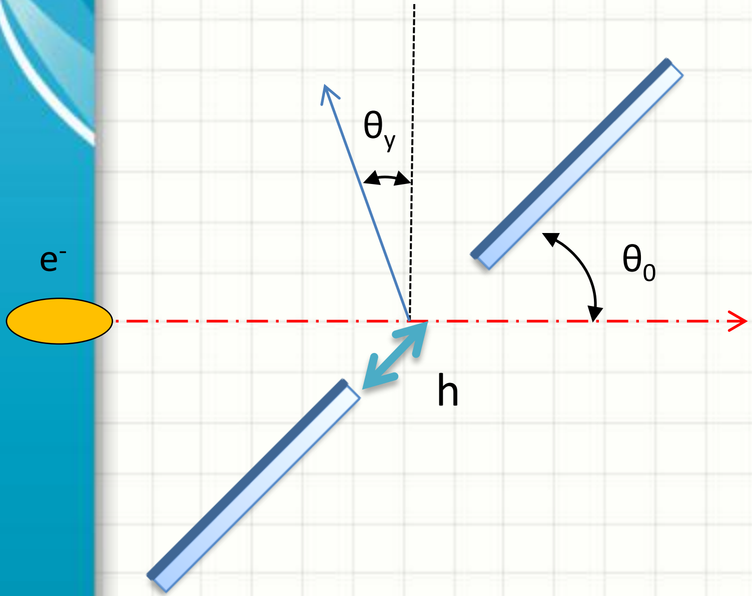


Fig. 3. CDR spectrum calculated for two bunch lengths of 3 mm (dashed line) and 0.03 mm (solid line). The red area shows SBD detector sensitivity range ($b=50$ mm, $a=3$ mm, $\gamma=80$, $N=10^{10}$ e/bunch). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

Diffraction Radiation



DR Angular distribution



Principle:

1. Electron bunch moves through a high precision co-planar slit in a conducting screen (Si + Al coating).
2. Electric field of the electron bunch polarizes atoms of the screen surface.
3. DR is emitted in two directions:
   - along the particle trajectory "Forward Diffraction Radiation" (FDR)
   - In the direction of specular reflection "Backward Diffraction Radiation" (BDR)

Impact parameter:

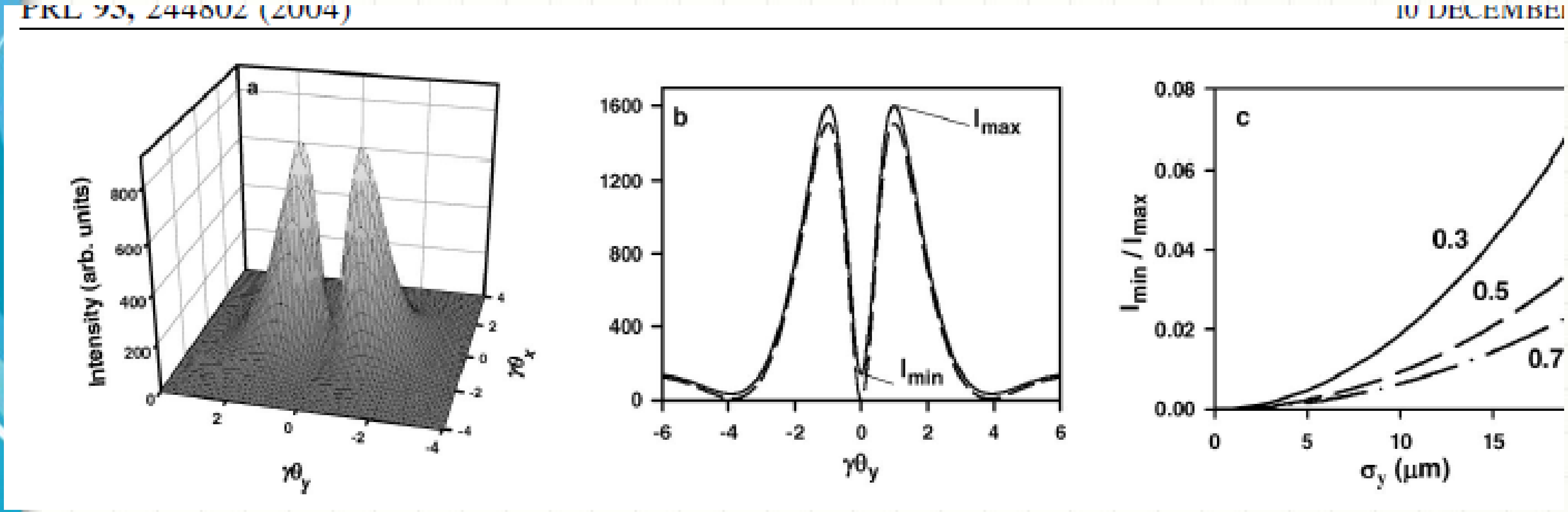
$$h \le \frac{\gamma\lambda}{2\pi}$$

Generally:

DR intensity ⇧ as slit size ⇩

Vertical Beam Size Measurement using the Optical Diffraction Radiation (ODR) model + Projected Vertical Polarisation Component (PVPC)

P. Karataev et al.



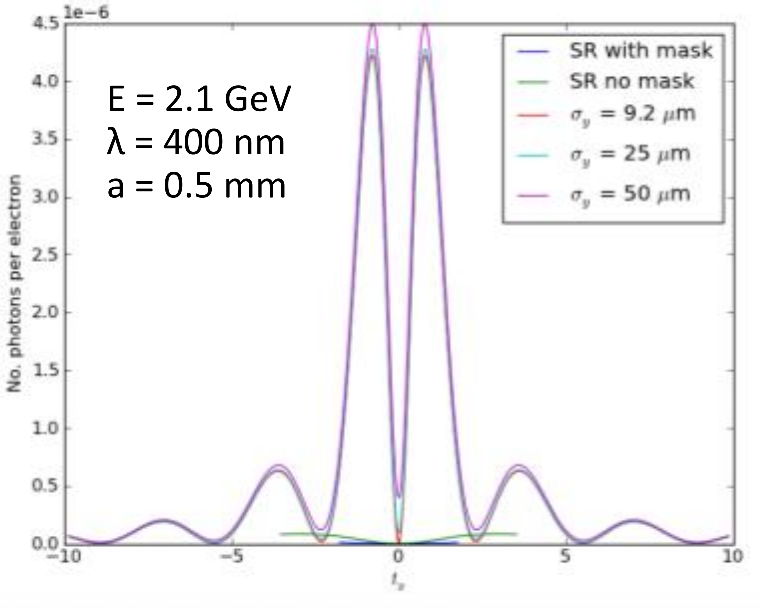
Vertical polarisation component of 3-dimensional (θ_x, θ_y, Intensity) DR angular distribution.

PVPC is obtained by integrating over θ_x to collect more photons.

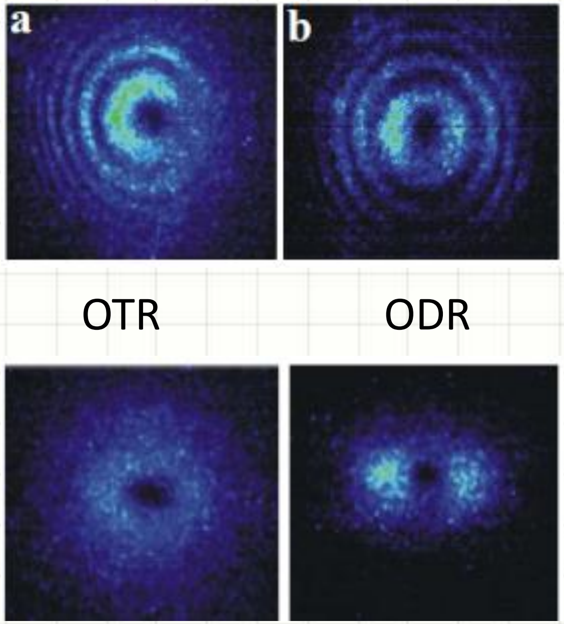
Visibility (I_{min}/I_{max}) of the PVPC is sensitive to vertical beam size σ_y.

Synchrotron Radiation (SR)

Source of background	Contribution
SR from beamline optics	High
Camera noise	Low
Residual background	



SR + DR interference



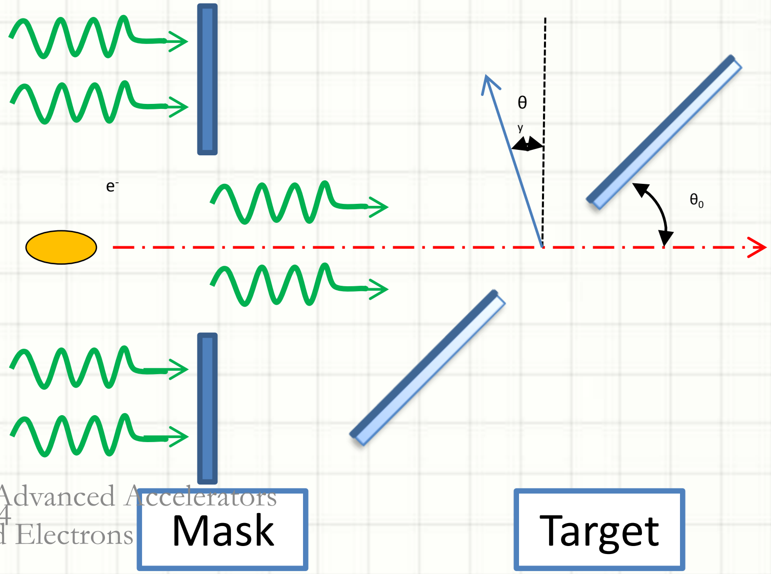
OTR

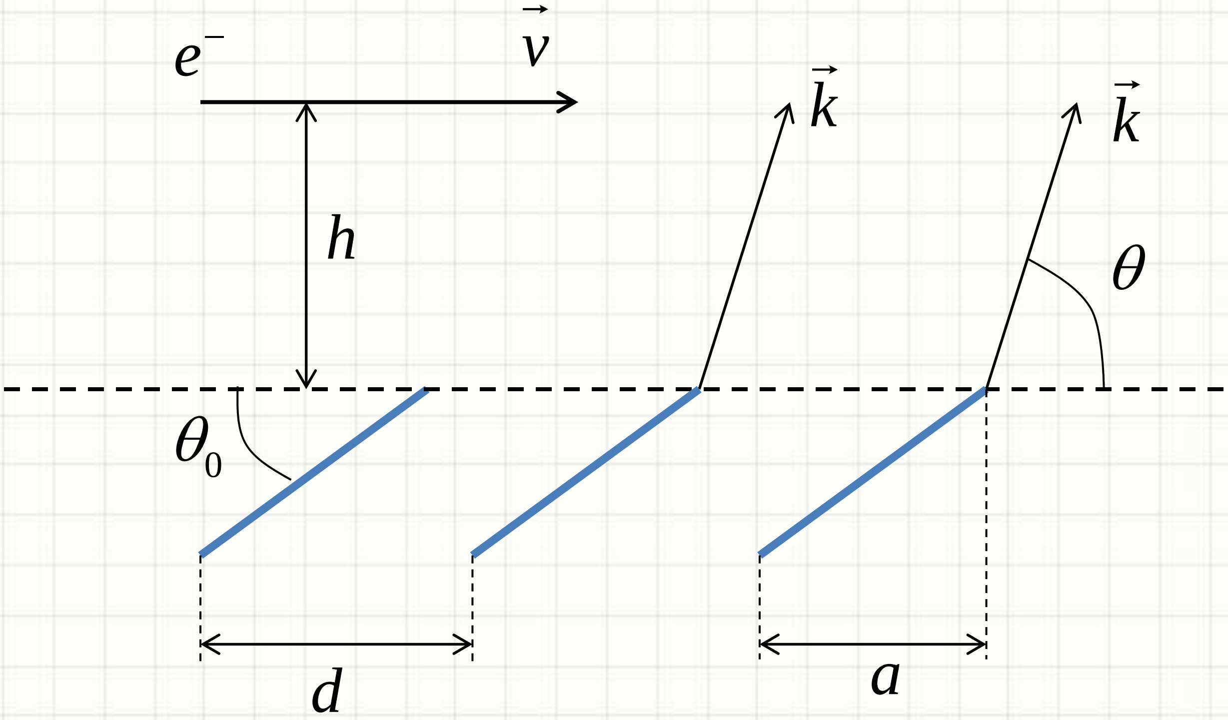
ODR

SR suppression

P. Karataev et al., Proc. of EPAC 2004, THPLT067

Use a mask upstream of target to suppress SR contribution.





- **Propagation of power**

$$q = 2q_0$$

- **Interference factor of the grating**

$$l_n = \frac{d}{n}\left(\frac{1}{b} - \cos q\right)$$

- **Structural factor of the grating**

$$ratio = {}^{d}\!/_{a}$$

Theoretical model

Smith – Purcell effect as resonant diffraction radiation, A.P. Potylitsyn, NIM B 145 (1998) 60 – 66.

Approximations used in the model:

- **Far-field approximation:**
  - **In mm-wavelength range and for some cases of SPR this approximation is not applicable;**
- **Infinitely thin strips:**
  - **Shadowing of the strips by each other is not taken into consideration**
- **Ideal conductor;**
- **Infinite strip length;**
- **Strip width must be much larger than the wavelength.**

$$\frac{d^2W_{RDR}}{d\omega d\Omega} = \frac{d^2W_{semiplane}}{d\omega d\Omega} F_{cell} F_N$$

Radiation distribution from a semiplane

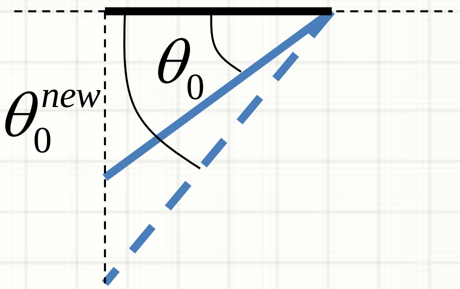
Strip (cell) geometry factor

Interference factor

$$F_{cell} = 4\exp\left[-2\chi\right]\left(\sinh^2\chi + \sin^2\frac{\Delta\varphi}{2}\right)$$

$$\chi = \frac{\pi\left(a/\cos\theta_0\right)\sin\theta_0}{\gamma\lambda}\sqrt{1+\gamma^2\theta_x^2}$$

$$\Delta\varphi = \frac{2\pi\left(a/\cos\theta_0\right)}{\lambda}\left[\cos\left(\theta_y-\theta_0\right) - \frac{\cos\theta_0}{\beta}\right]$$



$$\theta_x = 0; \theta_y = 2\theta_0$$

Direction of the mirror reflection from a strip.

Optimization of the strip tilt angle

θ_x =0 deg;

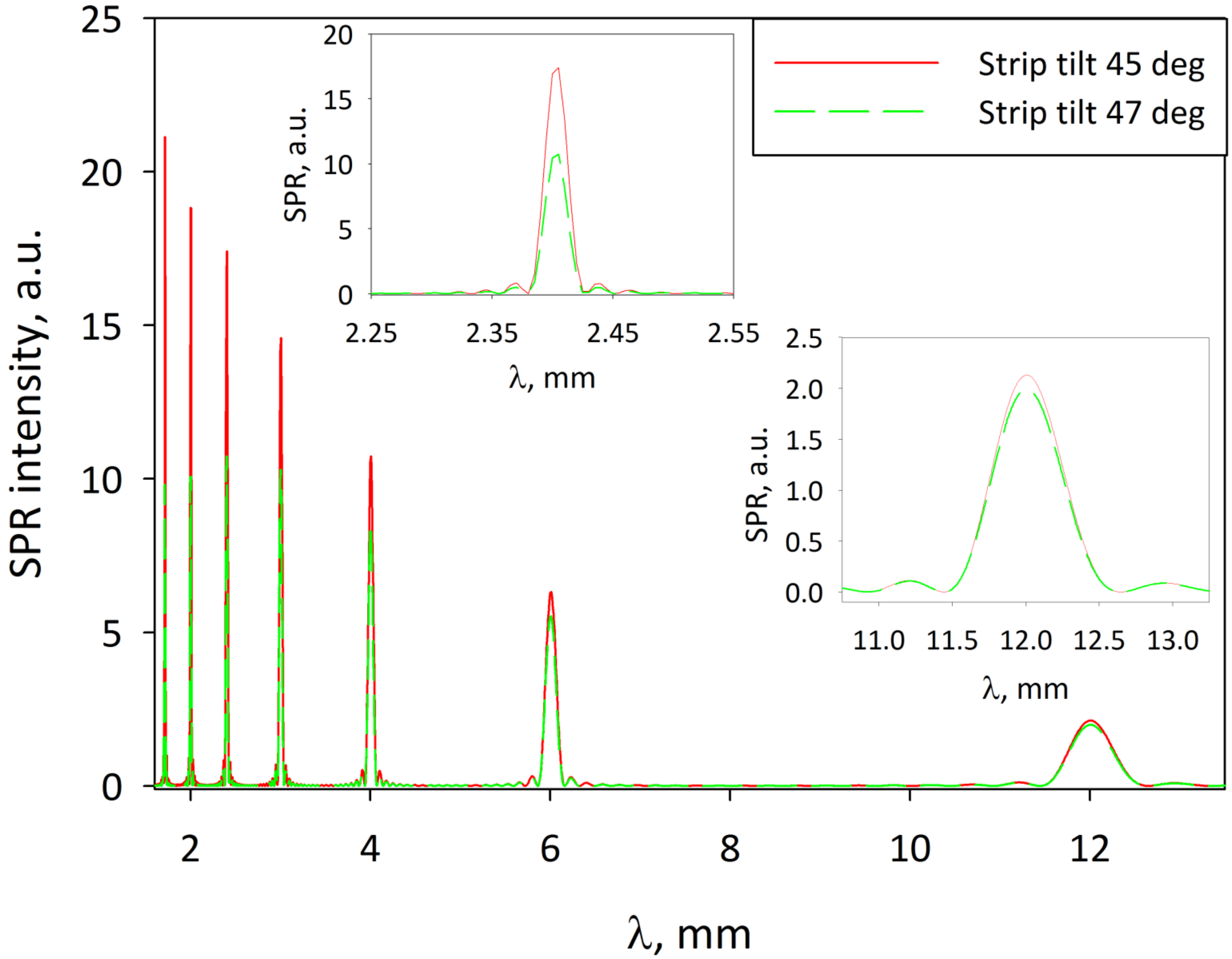
θ_y =90 deg;

γ=20;

h=0.15 mm;

a=d=12 mm;

N=20



TR Form-Factor

For a Gaussian bunch with transverse distribution

$$g(x,y)=\frac{1}{2\pi\sigma_\rho^2}\exp\left[-\frac{(x^2+y^2)}{2\sigma_\rho^2}\right]$$

and the longitudinal distribution

$$h(z)=\frac{1}{\sqrt{2\pi}\sigma_z}\exp\left[-\frac{z^2}{2\sigma_z^2}\right]$$

the form factor for TR has view:

$$\boxed{f(k)=\exp\left[-\left(\left[k\sigma_\rho\sin\theta\right]^2+\left[\frac{k\sigma_z}{\beta}\right]^2\right)\right]}$$

where k – wave number, θ – observed angle, β –the velocity of electron in the units of speed of light

From Factor summary

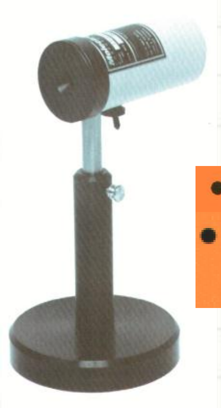
So as we can see form factor for TR dependents on:

- angle of observation;
  - energy of electron beam
  - backward TR or forward TR
  - oblique angle of target
- transverse size of bunch;
- longitudinal size of bunch.

Outline

- To establish stable THz generation we have to:
  - Monitor beam position (BPMs)
  - Monitor beam charge (CTs)
  - Monitor beam profile (Screens)
  - **Choose "effective" generation way (Radiation type).**
- To confirm THz generation and further tune beam parameters we have to:
  - THz radiation intensity distribution (Detectors)
  - Measure bunch length (a few possibilities)
  - THz radiation power spectrum (Interferometer , …)

Pyroelectric detector



Molectron
DETECTOR INCORPORATED

- 5 nanosecond rise time
- Broad spectral response - .001μ to 1000μ

MICROTECH
instruments, inc.

Optimal modulation frequency	10-30 Hz (see calibration curve on the next page)
Noise equivalent power at 20 Hz modulation	10^{-8} W/Hz $^{-0.5}$
Operating Spectral Range	0.1-3.0 THz (with filter) 0.02-20 THz (without filter)

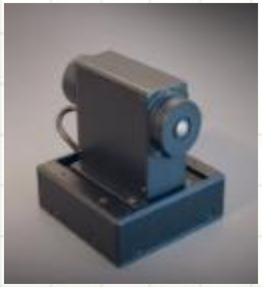
Bolometer

IRLabs
Infrared Laboratories

Si Bolometer	**Features** • Spectral Range: 2μm < λ < 3000μm • Operating Temperature: 0.3 to 4.2 K • Close to 100% efficiency for λ < 200μm • Discrete and Array configurations

Time Constant (Not measured for each detector)
~ 1 microsecond (depending on conditions of measurement)

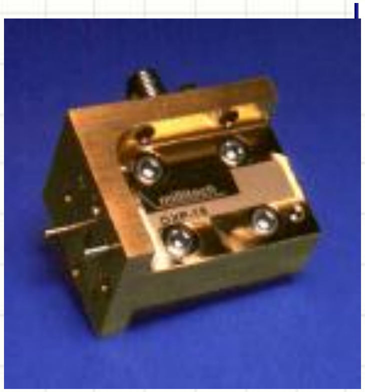
Golay cell detector



MICROTECH
instruments, inc.

Responsivity at 12.5 Hz modulation, V/W	10^4 - 10^5 V/W
Sensitivity at 12.5 Hz modulation, W/Hz$^{1/2}$	10^{-10} W/Hz$^{1/2}$
Maximum modulation frequency	50 Hz
Dynamic range	100 nm - 1 mW

Rectifier-type detector



VDI Virginia Diodes, Inc.

millitech

QUINSTAR TECHNOLOGY, INC.

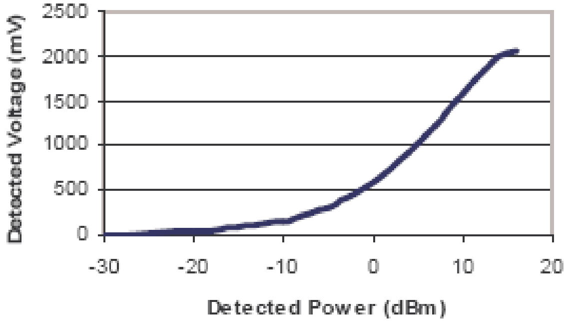
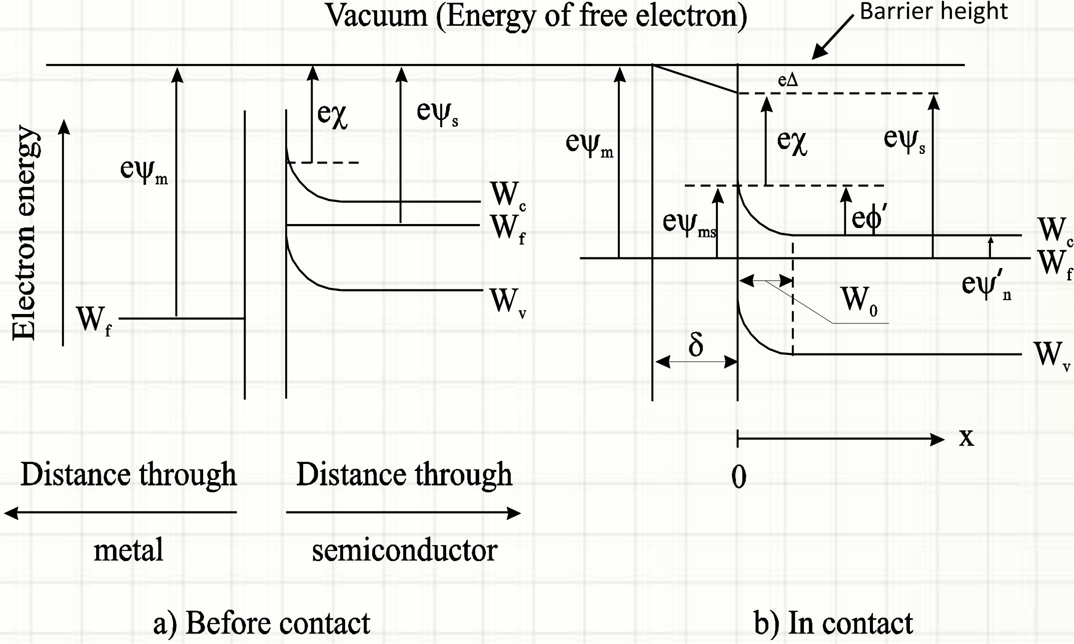


Figure 1.

Energy-level diagram of metal and semiconductor before and after contact.



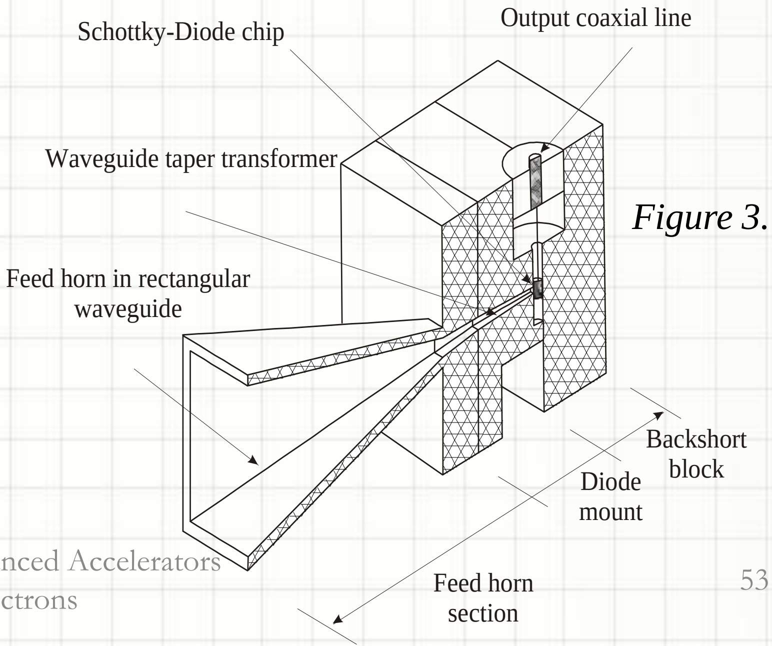


Figure 3.

By its nature, such device has a very short response time.
This detector provides an output voltage which is directly proportional to the incoming RF power without needing any external dc bias.
Detectors have a flat frequency response.

Bunch length measurements

- Direct time-of-flight measurements
  - Streak camera (Profile reconstruction, Single Shot, Expensive, Space-charge limited)
  - Deflecting cavity (Same as above)
  - Cavity-BPM (preliminary) (RMS relative length change, Calibration?)
- Electro-optical methods
  - Profile reconstruction, Single shot
  - http://www-library.desy.de/preparch/desy/thesis/desy-thesis-11-017.pdf
- Methods based on coherent spectrum
  - Spectral measurements
    - Longer wavelengths
    - Lack of broadband detectors
    - Care is needed (absolute calibrations, linearity, spectral response)
  - Bunch profile reconstruction
    - Complicated mathematics
    - Dependence on radiation generation mechanism

Coherent Radiation Spectrum

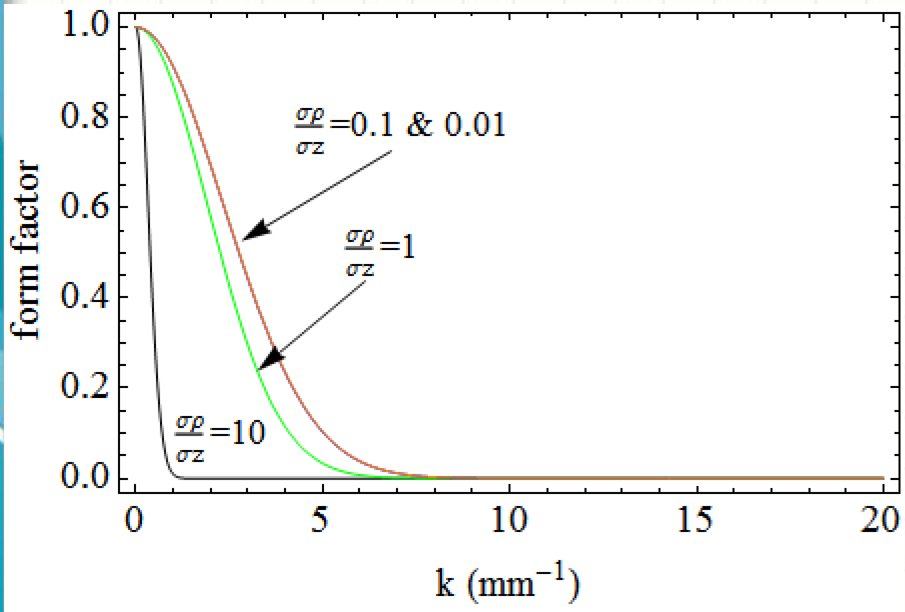
$$I_{coh}(\omega) = N \cdot I_e(\omega) \cdot [1 + (N-1) f(\omega)]$$

where N – number of electron in bunch, I_e – spectrum of radiation generated by one electron, $f(\omega)$ – form factor;

$$f(\omega) = \int e^{ik\mathbf{nr}} S(\mathbf{r}) dr^3$$

$S(\mathbf{r})$ – probability density for the electrons at the position $\mathbf{r}$ from the bunch center

Study of Coherent TR Spectral Distribution for Different ratio



Parameter of calculation:

- $\gamma = 16;$
- Oblique angle is $\frac{\pi}{4}$;
- Backward TR is observed.

When ratio σ_ρ/σ_z is 0.1 or less form factor for TR doesn't changed

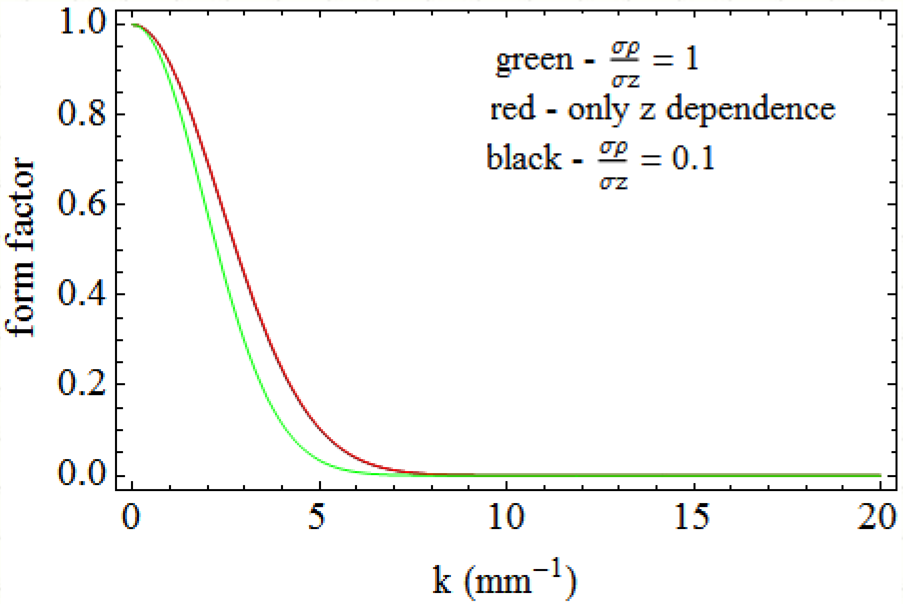
Comparison

For a Gaussian bunch with distribution

$$h(z) = \frac{1}{\sqrt{2\pi\sigma_z}} \exp\left[-\frac{z^2}{2\sigma_z^2} \right]$$

the form factor is

$$f(k) = \exp[-(k\sigma_z)^2]$$



Parameter of calculation:

- $\gamma = 16$;
- Oblique angle is $\frac{\pi}{4}$;
- Backward TR is observed.

If is not differences for value of   less then 0.1 as the fist approximation we can use only longitudinal form factor.

Outline

- To establish stable THz generation we have to:
  - Monitor beam position (BPMs)
  - Monitor beam charge (CTs)
  - Monitor beam profile (Screens)
  - **Choose "effective" generation way (Radiation type).**
- To confirm THz generation and further tune beam parameters we have to:
  - THz radiation intensity distribution (Detectors)
  - Measure bunch length (a few possibilities)
  - **THz radiation power spectrum (Interferometer , …)**

Terahertz Spectrometer for LUCX

(The terahertz spectral range roughly extends from 100 GHz to 10 THz)

- KEK LUCX THz program calls for construction of the Terahertz Spectrometer for systematic and robust measurements.
- Spectral and spatial THz radiation measurements are crucial for THz sources development.
- The coherent radiation spectrum information can be used for longitudinal beam size diagnostic and may be used for bunch profile reconstruction (for example Kramers-Kronig analysis).

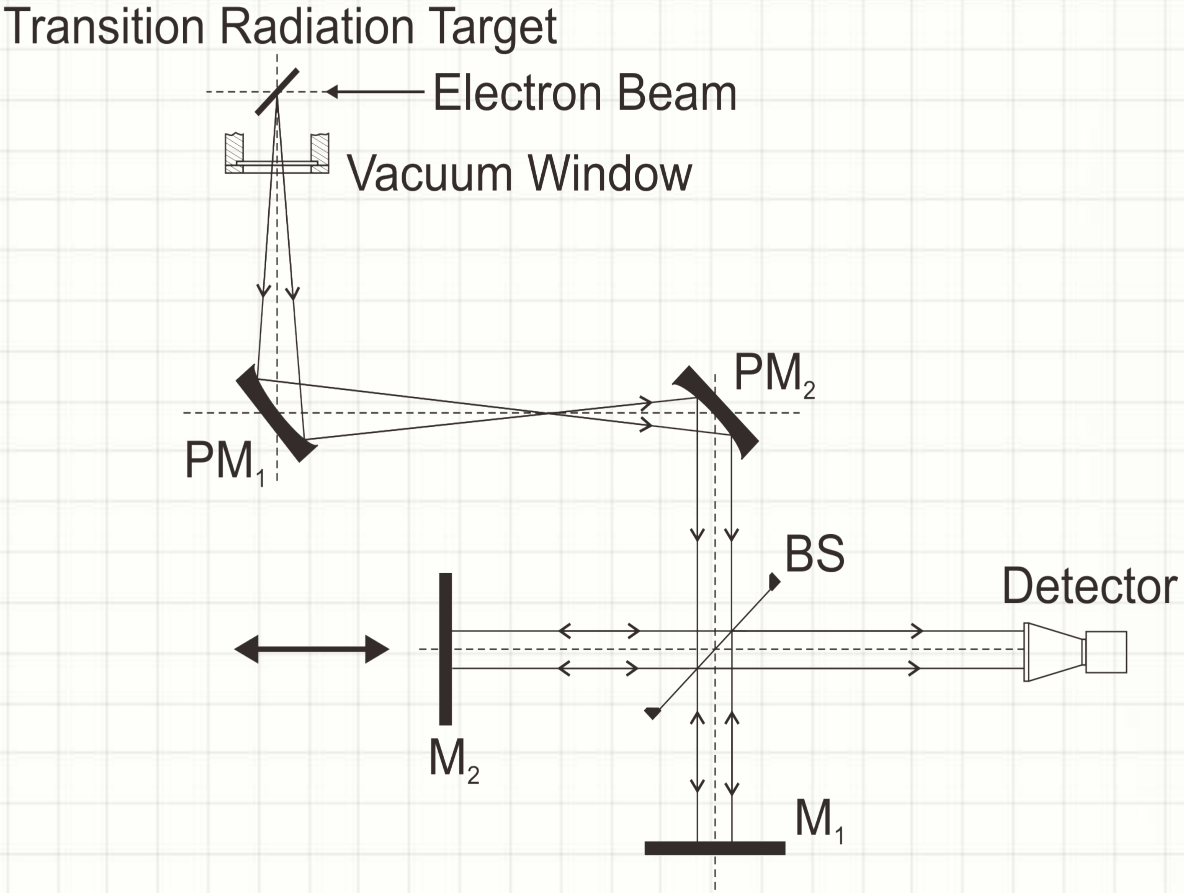
Kramers-Kronig Analysis

$$\hat{f}(\omega) = \int_0^\infty \rho(z)\exp[i\frac{\omega z}{c}dz] \equiv \sqrt{f(\omega)}\exp[i\psi(\omega)]$$

$$\psi(\omega) = -\frac{2\omega}{\pi}\int_0^\infty \frac{\ln[\sqrt{f(x)}/\sqrt{f(\omega)}]}{x2-\omega 2}dx$$

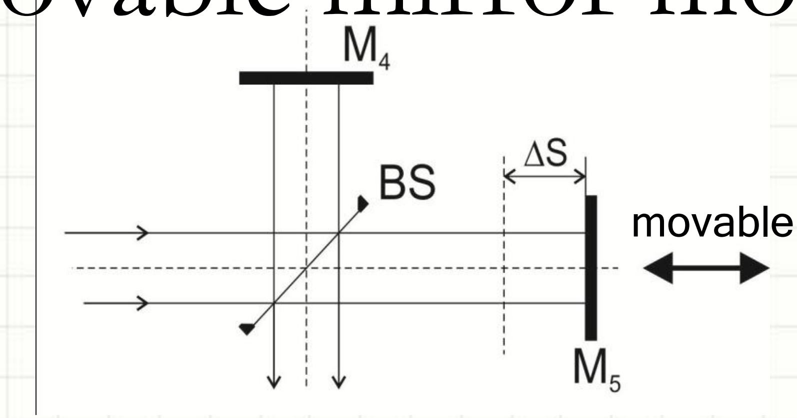
$$\rho(z) = \frac{1}{\pi c}\int_0^\infty \sqrt{f(\omega)}\cos\left(\psi(\omega)-\frac{\omega z}{c}\right)d\omega$$

Michelson Interferometer



Layout of Michelson Interferometer

Movable mirror motion accuracy



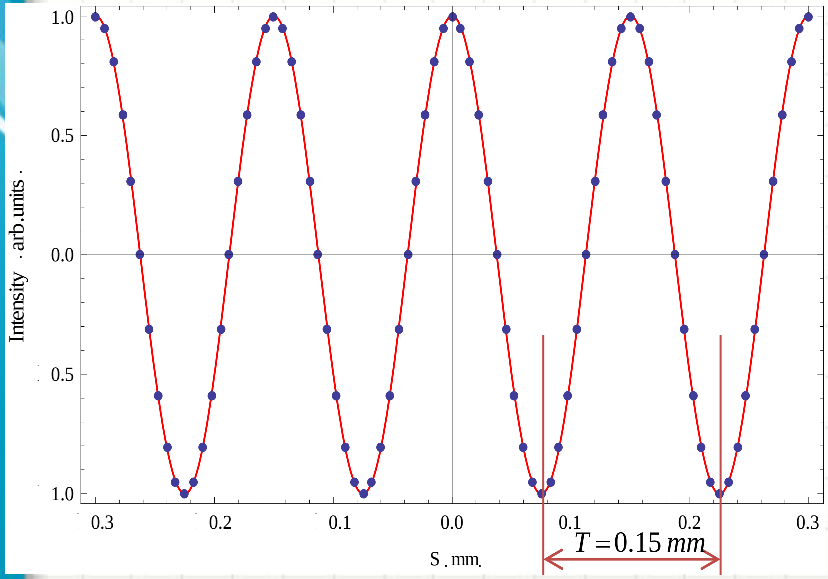
to detector

Michelson Interferometer

$$I_{total} = I(1+\cos[\frac{4\pi\cdot\Delta s}{\lambda}])$$

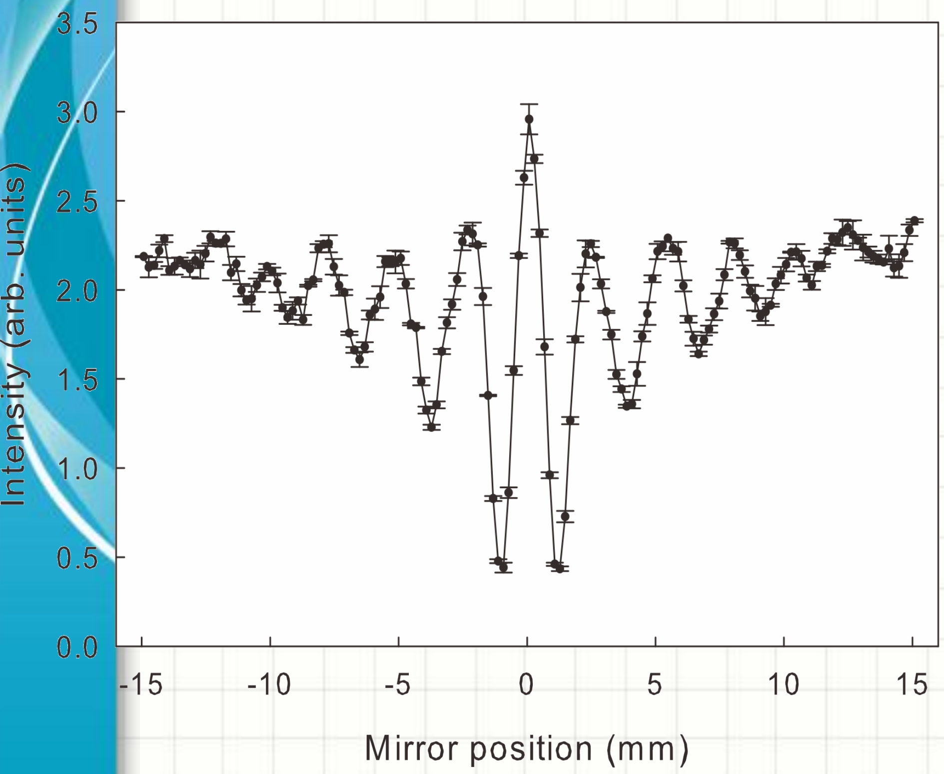
$T = \frac{2\cdot\Delta S}{\lambda}$ – period of cosines;

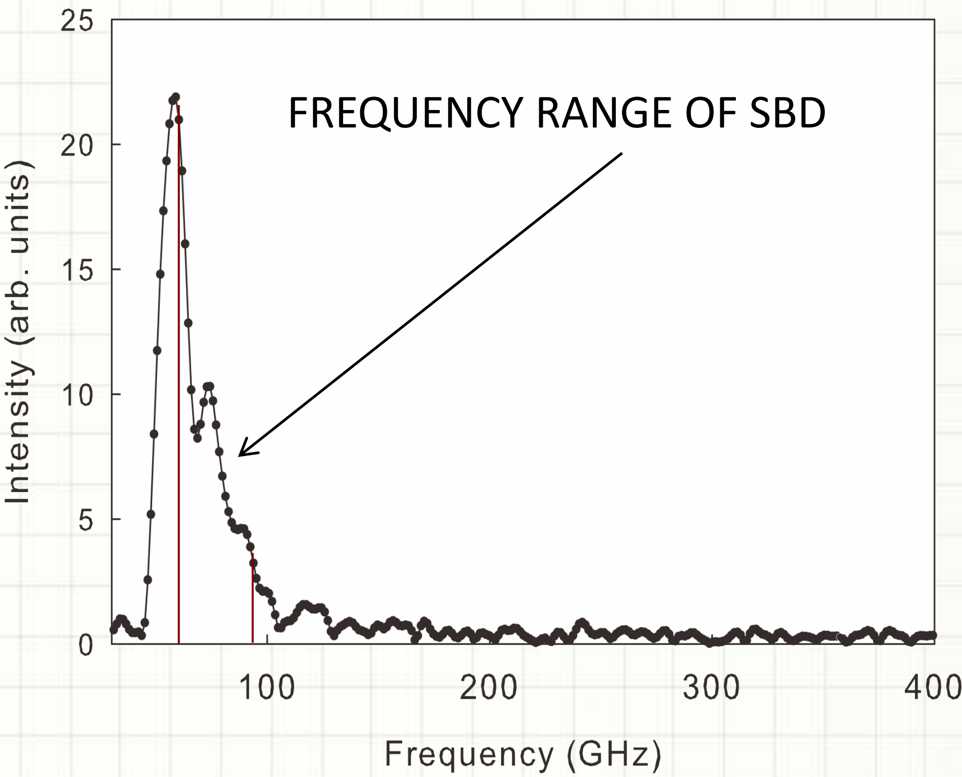
For $\nu = 1\text{THz} \Rightarrow \lambda = 0.3\text{ mm}$



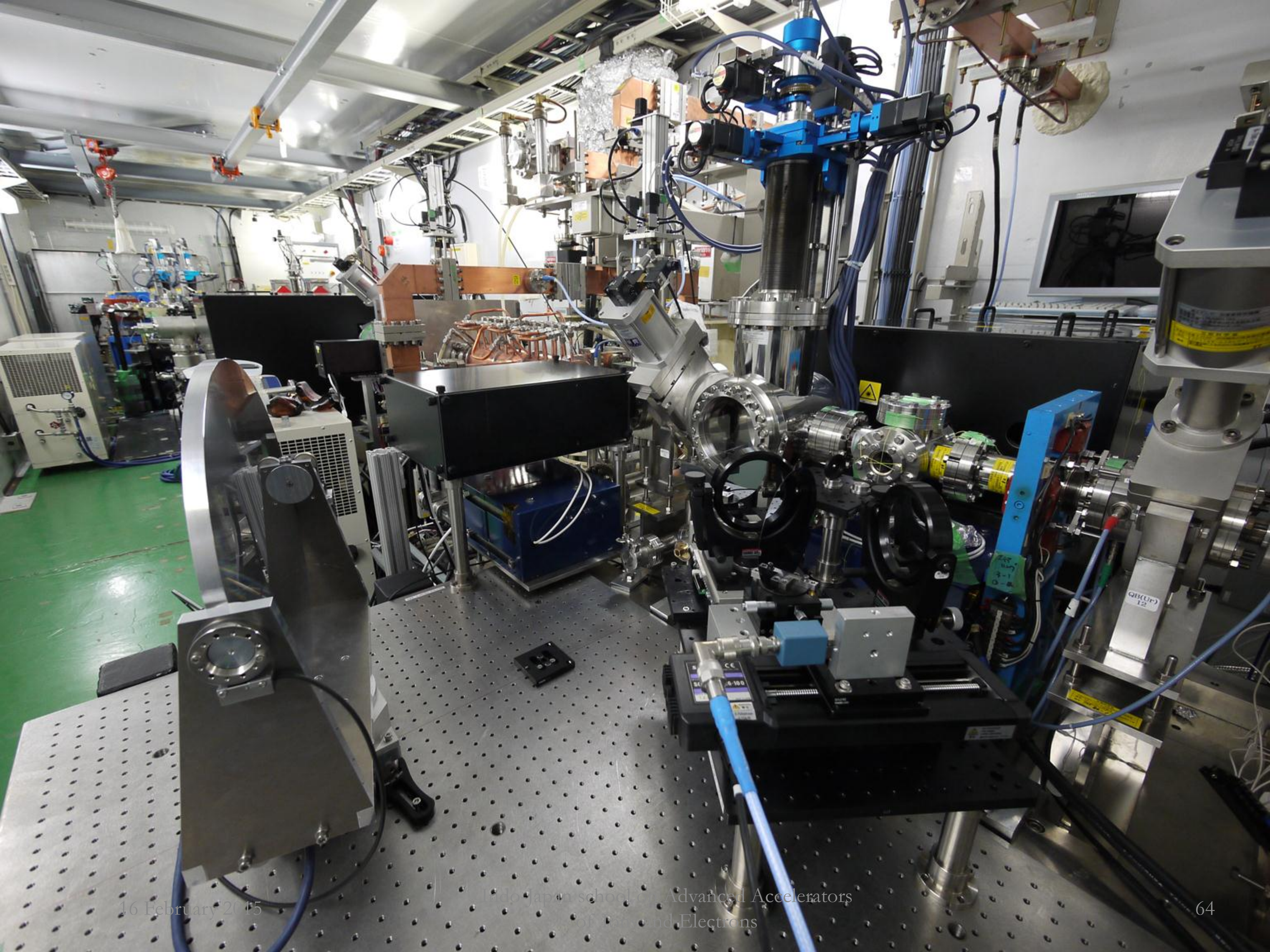
For good approximation ~20 experimental data point per autocorrelation period will be needed, so for ν=1THz the mirror M$_5$ should be moved with the step of 7.5μm.

Autocorrelation dependence measured by SBD

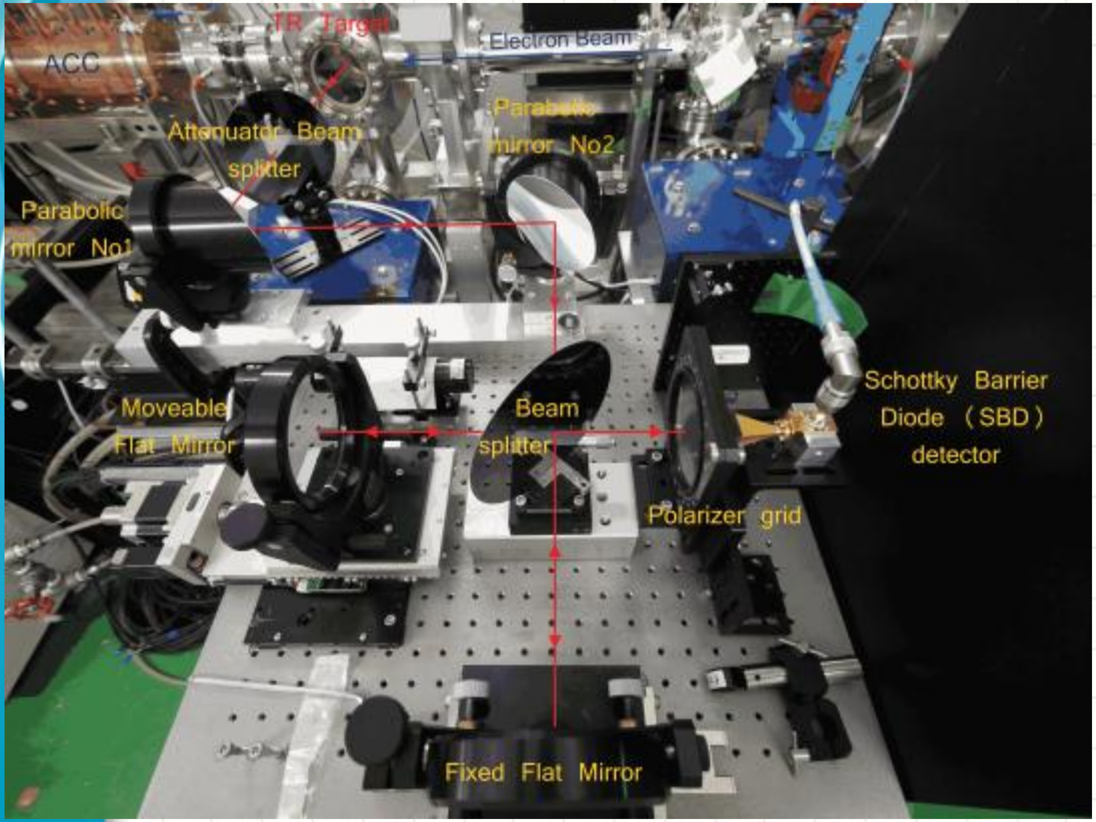


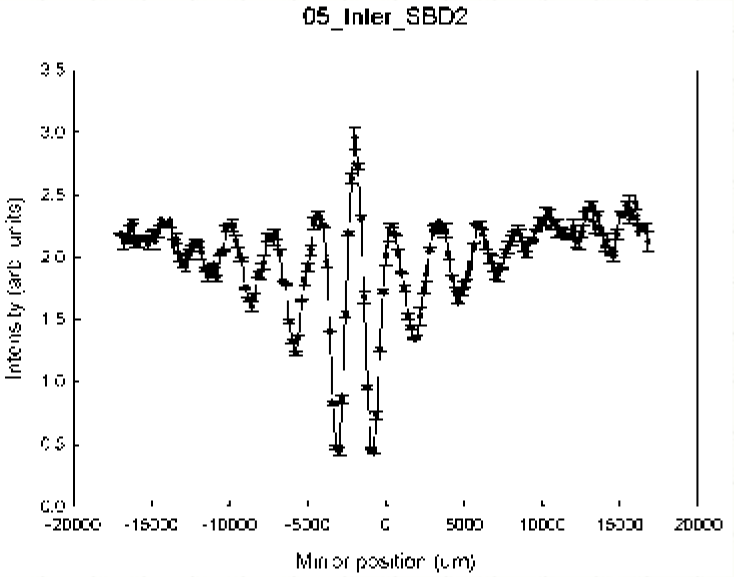

FREQUENCY RANGE OF SBD

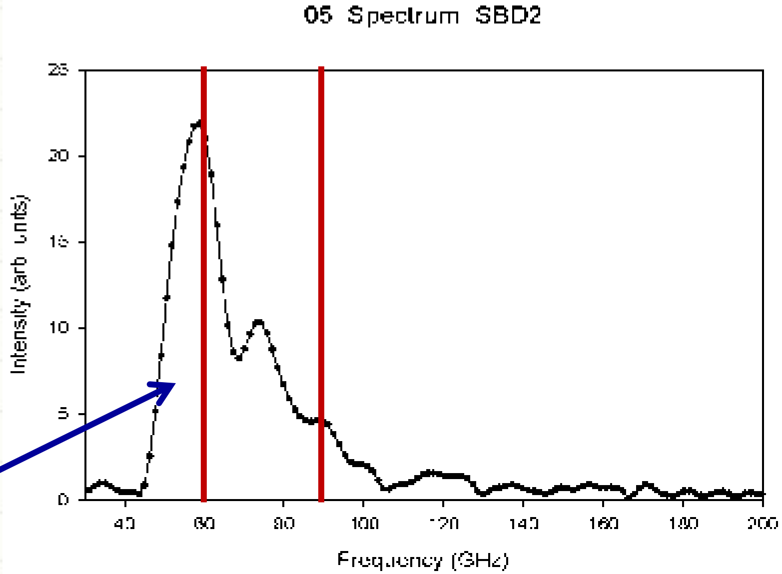
There is not enough information about real coherent radiation spectra.
Reconstructed spectra shows only SBD spectral response.
Most certainly we need better SBD calibration.



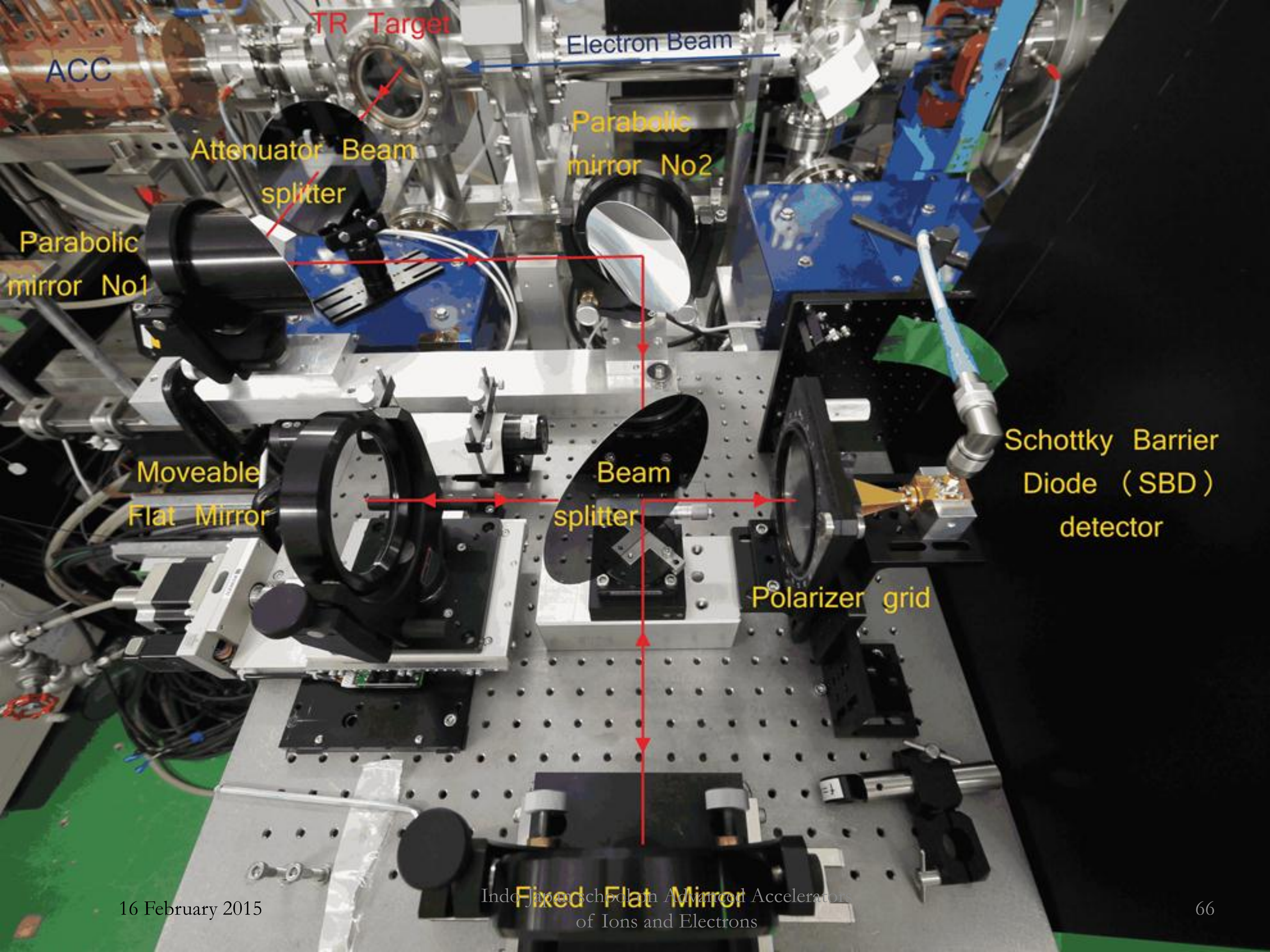
LUCX Experiment





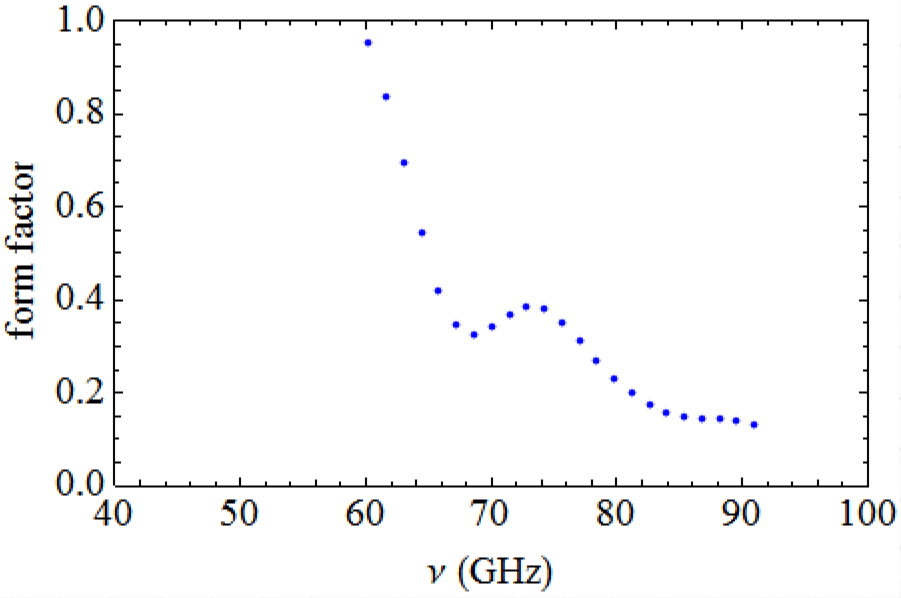


SBD frequency range 60-90 GHz


TR Target
ACC
Electron Beam
Attenuator
Beam splitter
Parabolic mirror No2
Parabolic mirror No1
Moveable Flat Mirror
Beam splitter
Schottky Barrier Diode （SBD） detector
Polarizer grid
Fixed Flat Mirror

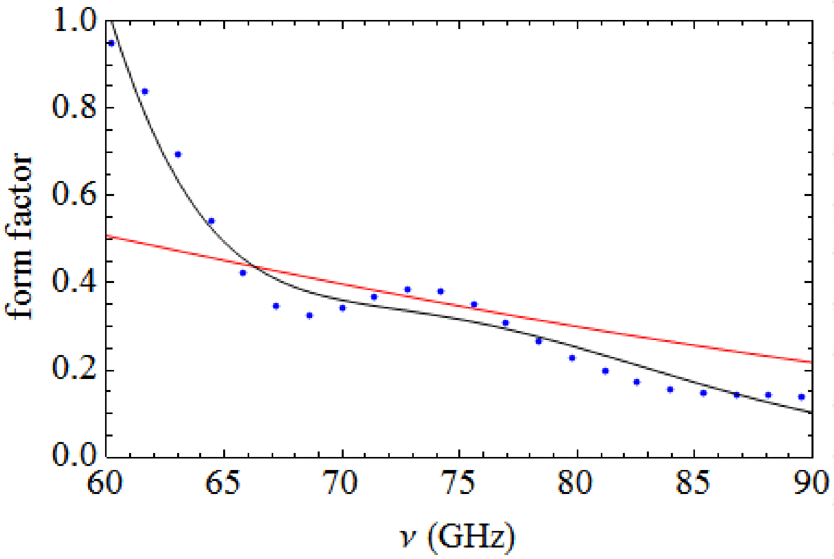
Form Factor Reconstruction

What part of form factor did we measure?

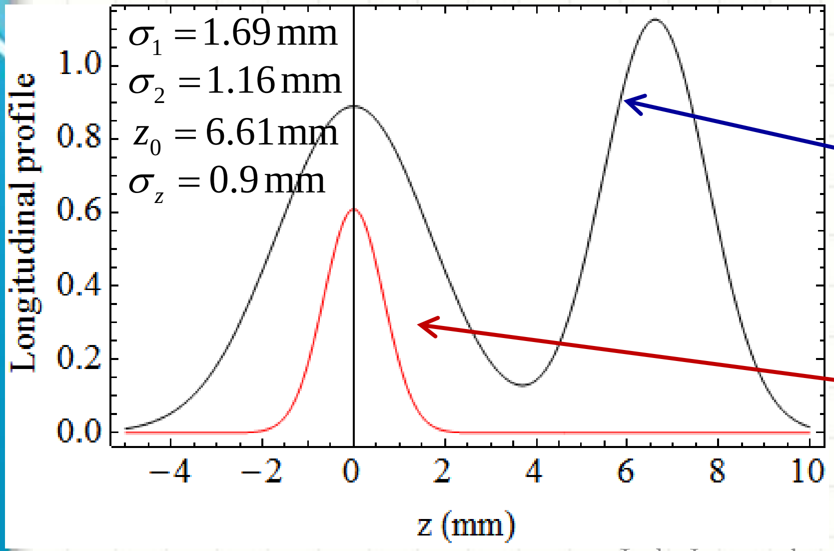


We don’t know normalized coefficient and need more information!

Example No1 (all coherent threshold)



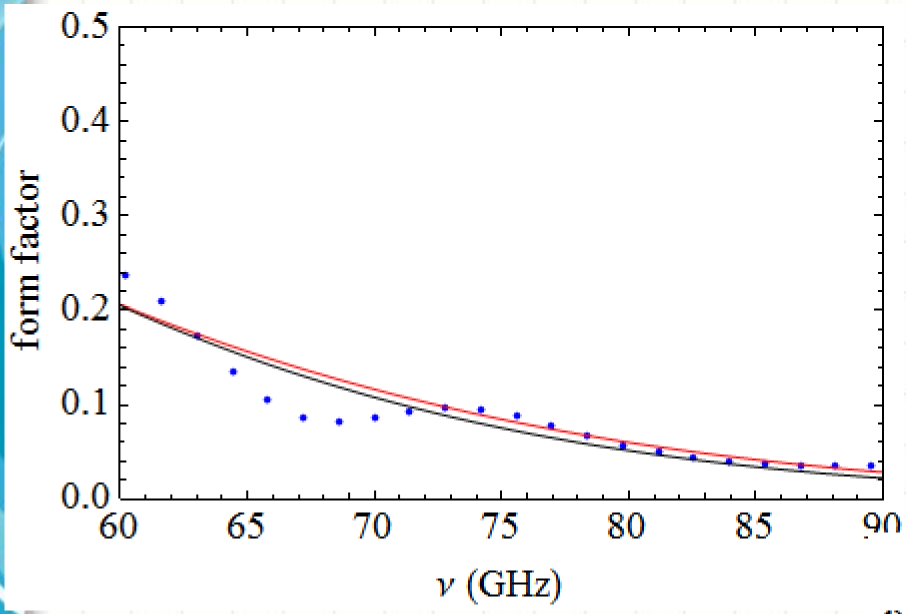
dots – experimental data
red curve – gauss fit
black curve – double gauss fit



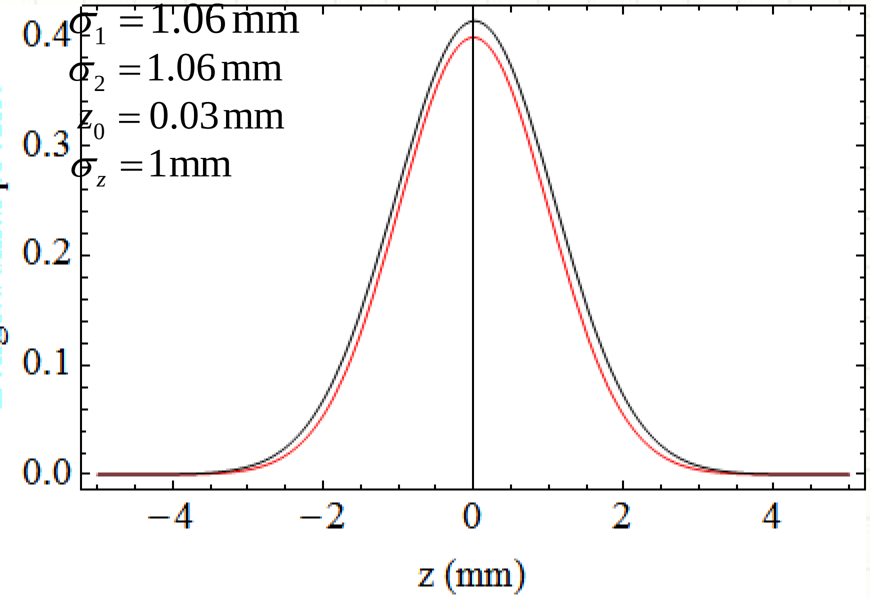
$$\rho(z) = A\frac{1}{\sqrt{2\pi}\sigma_1}\exp\left[-\frac{z^2}{2\sigma_1^2}\right] + B\frac{1}{\sqrt{2\pi}\sigma_2}\exp\left[-\frac{(z-z_0)^2}{2\sigma_2^2}\right]$$

$$\rho(z) = \frac{1}{\sqrt{2\pi}\sigma_z}\exp[-\frac{z^2}{2\sigma_z^2}]$$

Example No2 (initial part of coherent threshold)



dots – experimental data
red curve – gauss fit
black curve – double gauss fit



Summary:

- To use Kramers-Kronig method one should know more data of Coherent Radiation Spectrum
- Deflected Cavity allows to check reconstruction analysis

Summary

- To establish stable THz generation we have to:
  - Monitor beam position (BPMs)
  - Monitor beam charge (CTs)
  - Monitor beam profile (Screens)
  - **Choose "effective" generation way (Radiation type).**
- To confirm THz generation and further tune beam parameters we have to:
  - THz radiation intensity distribution (Detectors)
  - Measure bunch length (a few possibilities)
  - THz radiation power spectrum (Interferometer , …)

Materials

- In this presentation I used materials from:
  - M. Shevelev (KEK)
  - A. Konkov (TPU)
  - P. Karataev (RHUL)
  - L. Bobb (RHUL, Diamond)

THANK YOU FOR YOUR ATTENTION