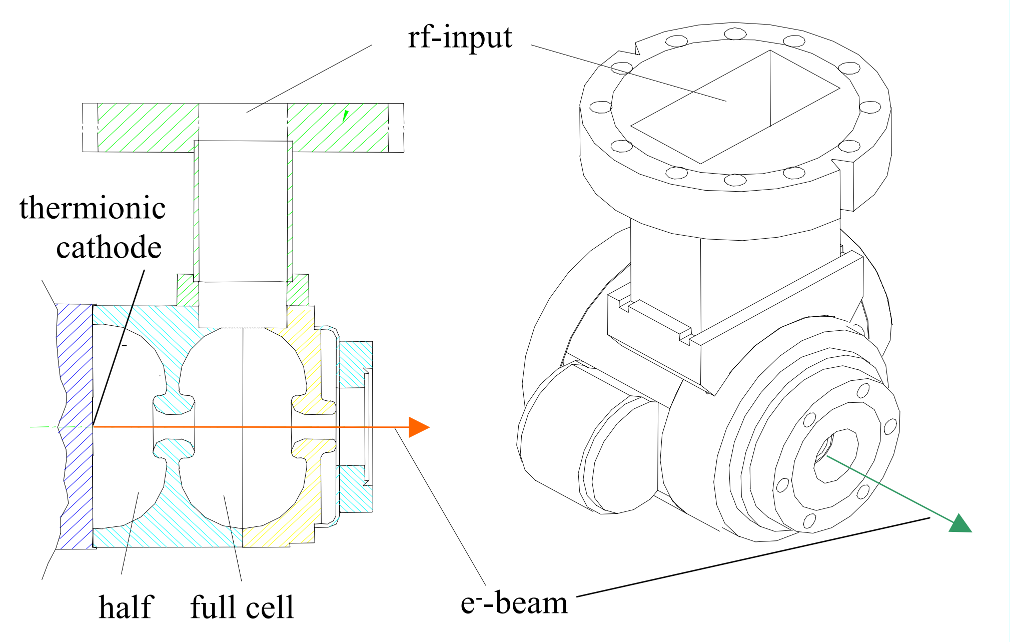
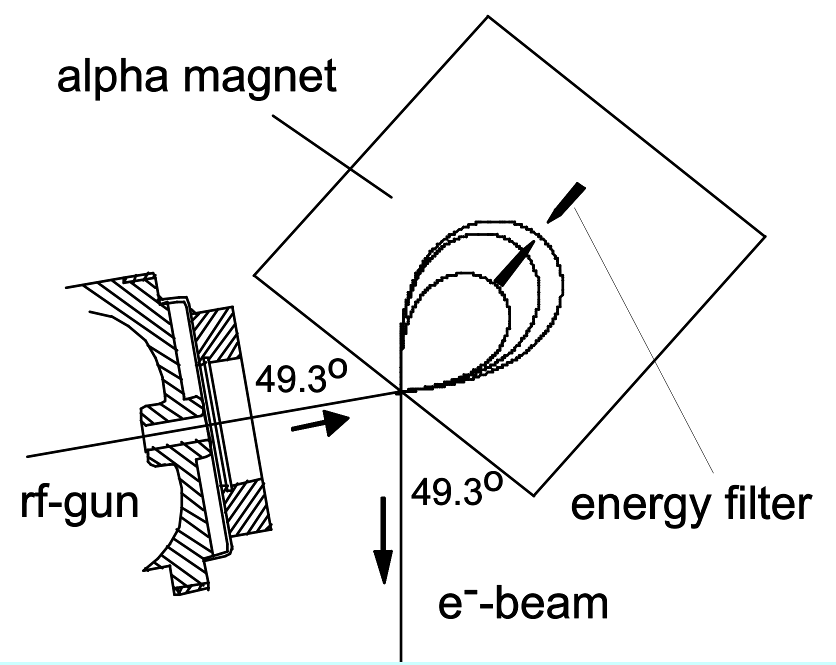
Femto-Second Electron and Radiation Pulses

Helmut Wiedemann, Stanford University

ultra short bunches

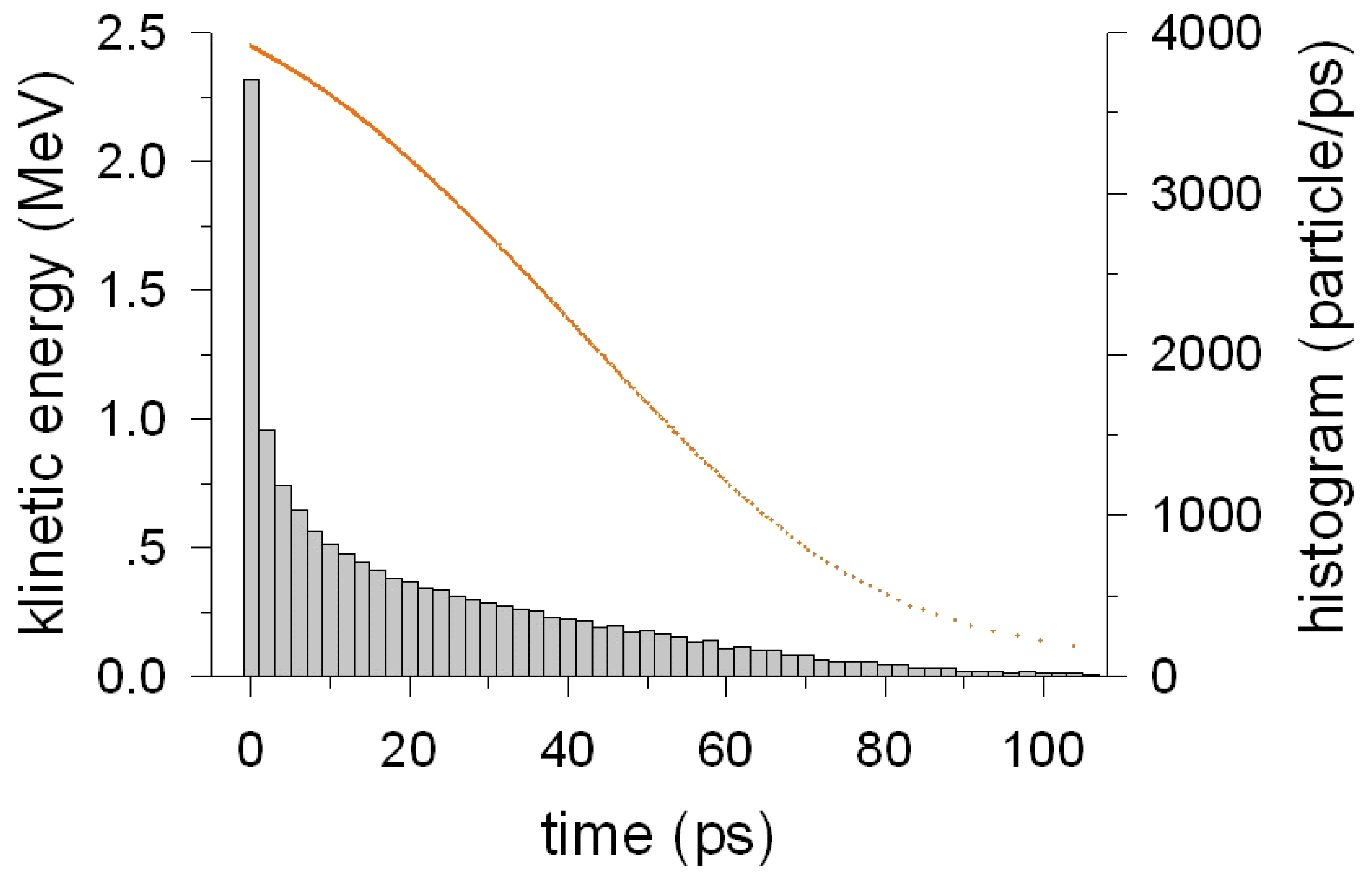


Microwave gun

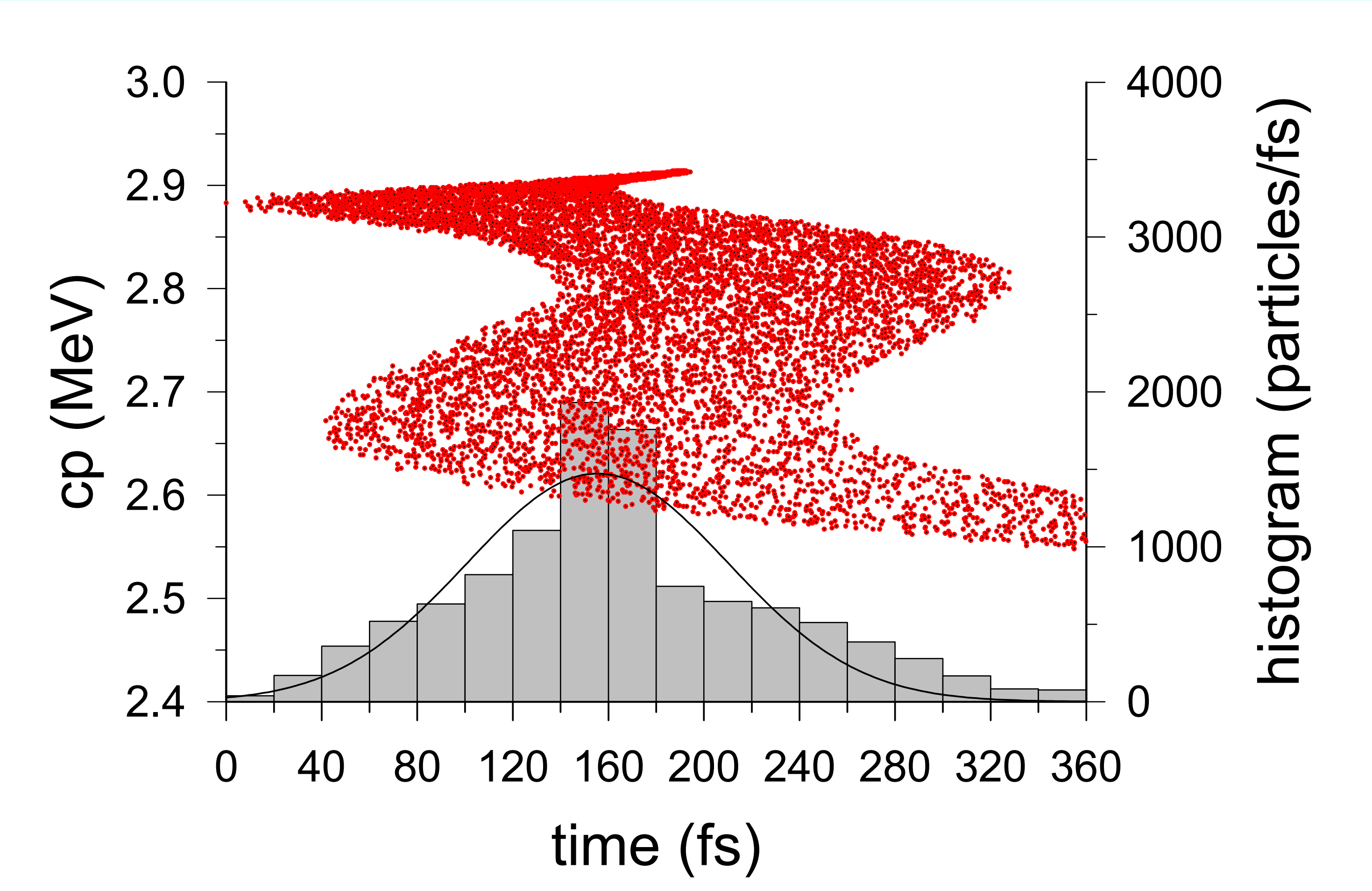


Bunch compression

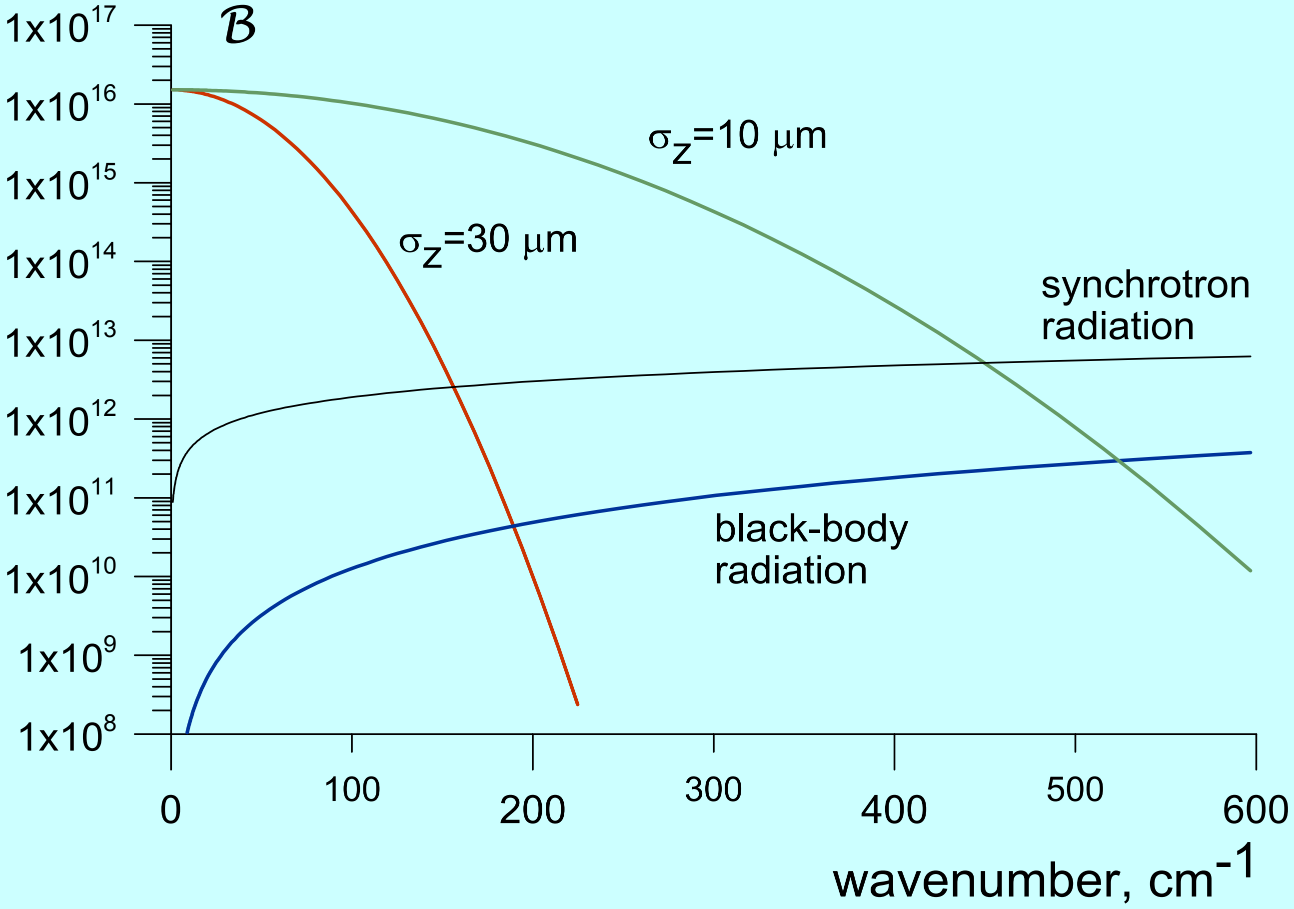
gun exit


klinetic energy (MeV)
2.5
2.0
1.5
1.0
.5
0.0
0
20
40
60
80
100
time (ps)
4000
3000
2000
1000
0
histogram (particle/ps)

compressed bunch



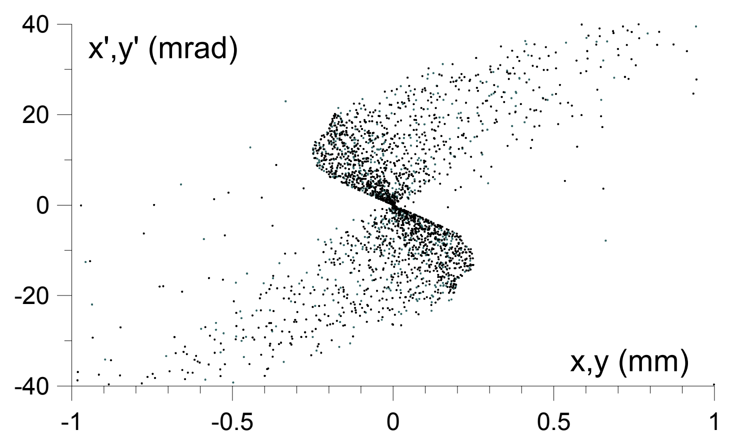
BB-SR-TR



brightness B = photons/s/mm^2/mr^2/100%BW

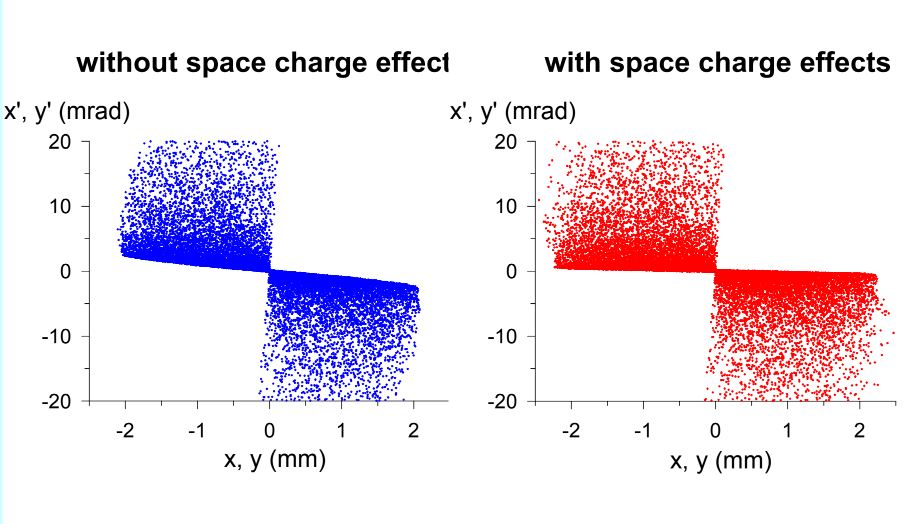
transverse effects

path length dispersion



old gun

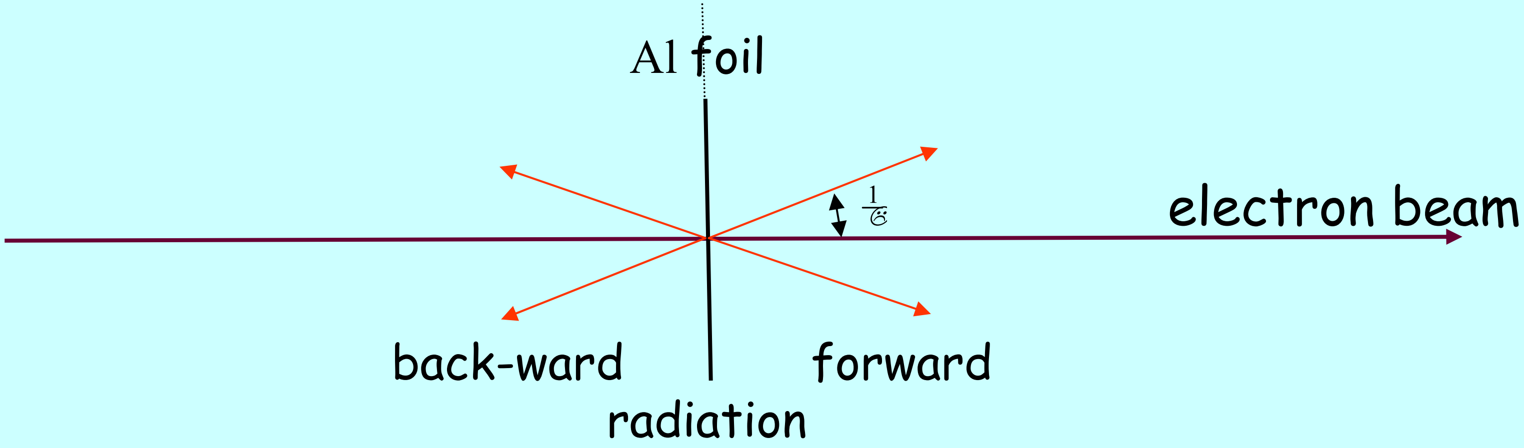
120 fs rms (measured)



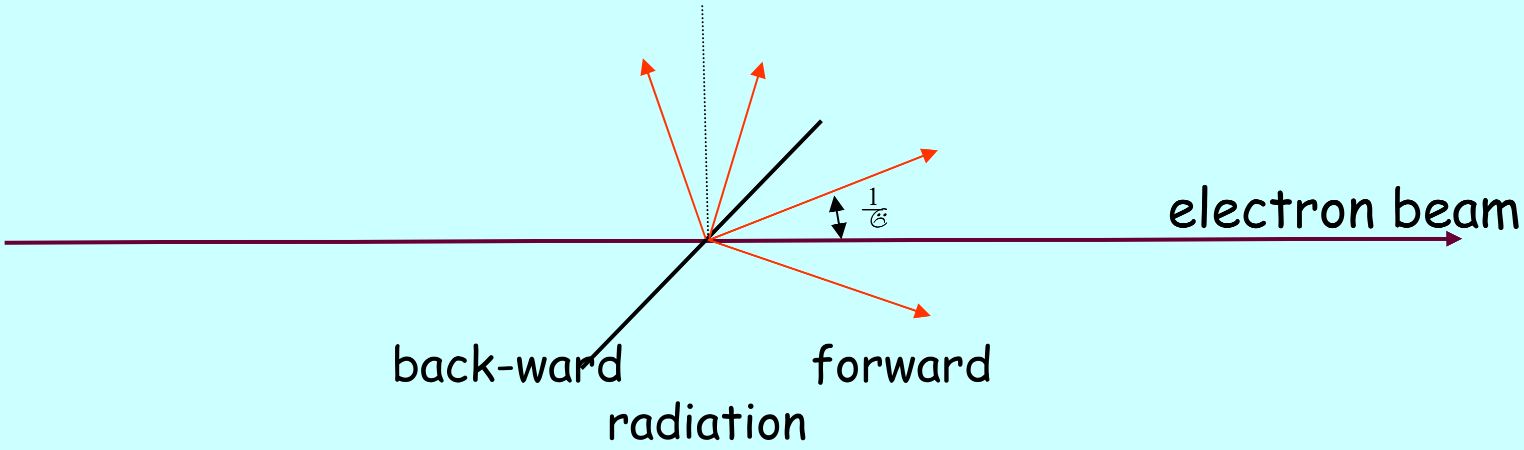
new gun

54 fs rms (simulation)

Transition Radiation



inconvenient to separate electron beam from TR



tilt radiator by 45^0

now, TR can be extracted normal to electron beam through window

TR theory – 1

Poynting vector $\mathbf{S}_r = \frac{c}{4\pi}\left[\frac{4\pi}{\mu_0 c}\right] B^2_{\mathrm{ret}}\,\mathbf{n}$

radiation power $\frac{\mathrm{d}P}{\mathrm{d}t} = \mathbf{S}_r \mathbf{n} R^2_{\mathrm{ret}}$ [illegible] $= \frac{c}{4\pi}\left[\frac{4\pi}{\mu_0 c}\right] R^2_{\mathrm{ret}} B^2_{\mathrm{ret}}$ [illegible]

need some tools:

Fourier transforms

$$B(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} B(\omega)\, e^{-i\omega t}\,\mathrm{d}\omega$$

$$B(\omega) = \int_{-\infty}^{\infty} B(t)\, e^{i\omega t}\,\mathrm{d}t$$

Parceval's theorem

$$\int_{-\infty}^{\infty} B^2(t)\,\mathrm{d}t = \frac{1}{2\pi}\int_{-\infty}^{\infty} B^2(\omega)\,\mathrm{d}\omega$$

TR theory - 2

$$\frac{dW}{dt} = S_r \cdot n R_{ret}^2 \, d\Omega = \frac{c}{4\pi}\left[\frac{4\pi}{\mu_0 c}\right] R_{ret}^2 B_{ret}^2 \, d\Omega$$

$$dW(t) = \frac{c}{4\pi}\left[\frac{4\pi}{\mu_0 c}\right] R_{ret}^2 \, d\Omega \, B_{ret}^2(t) \, dt$$

$$dW(\omega) = \frac{c}{4\pi}\left[\frac{4\pi}{\mu_0 c}\right] R_{ret}^2 \, d\Omega \, \frac{1}{2\pi} B_{ret}^2(\omega) \, d\omega$$

use only $\omega > 0$!

$$B(\omega)?$$

spectrum: $0 \le \omega \le \omega_{plasma}$

our interest is in $\omega \ll \omega_{plasma}$

$B(t) \neq 0$ during time τ only

$e^{i\omega\tau} \approx 1$

$$\boxed{B_{ret}(\omega) = \int_{-\infty}^{\infty} B_{ret}(t) e^{i\omega t} dt \approx \int_{-\tau/2}^{\tau/2} B_{ret}(t) dt}$$

for $\omega \ll \omega_{plasma}$

TR theory - 3

$$B_{\text{ret}}(\omega)? \qquad B_{\text{ret}}(t) = \nabla \times \mathbf{A}_{\text{ret}} = \left\{ \frac{\partial A_z}{\partial y} - \frac{\partial A_y}{\partial z}; \dots \right\}_{t_\text{r} = t - R/c}$$

$$\frac{\partial A_z}{\partial y} = \frac{\partial A_z}{\partial t_\text{r}} \frac{\partial t_\text{r}}{\partial y}; \dots \qquad R^2 = (x - x_\text{r})^2 + (y - y_\text{r})^2 + (z - z_\text{r})^2$$

$$\frac{\partial t_\text{r}}{\partial y} = -\frac{1}{c} \frac{y - y_\text{r}}{R} = \frac{n_y}{c}; \dots$$

n is unit vector from observer to electron

$$\frac{\partial A_z}{\partial y} - \frac{\partial A_y}{\partial z} = \frac{1}{c} \frac{\partial A_z}{\partial t_\text{r}} n_y - \frac{1}{c} \frac{\partial A_y}{\partial t_\text{r}} n_z$$

$$B_{\text{ret}}(t) = \nabla \times \mathbf{A}_{\text{ret}} = \frac{1}{c} \left(\mathbf{n} \times \frac{\partial \mathbf{A}}{\partial t_\text{r}} \right)_\text{r} = \frac{1}{c} \frac{\mathrm{d}}{\mathrm{d}t_\text{r}} (\mathbf{n} \times \mathbf{A})_\text{r}$$

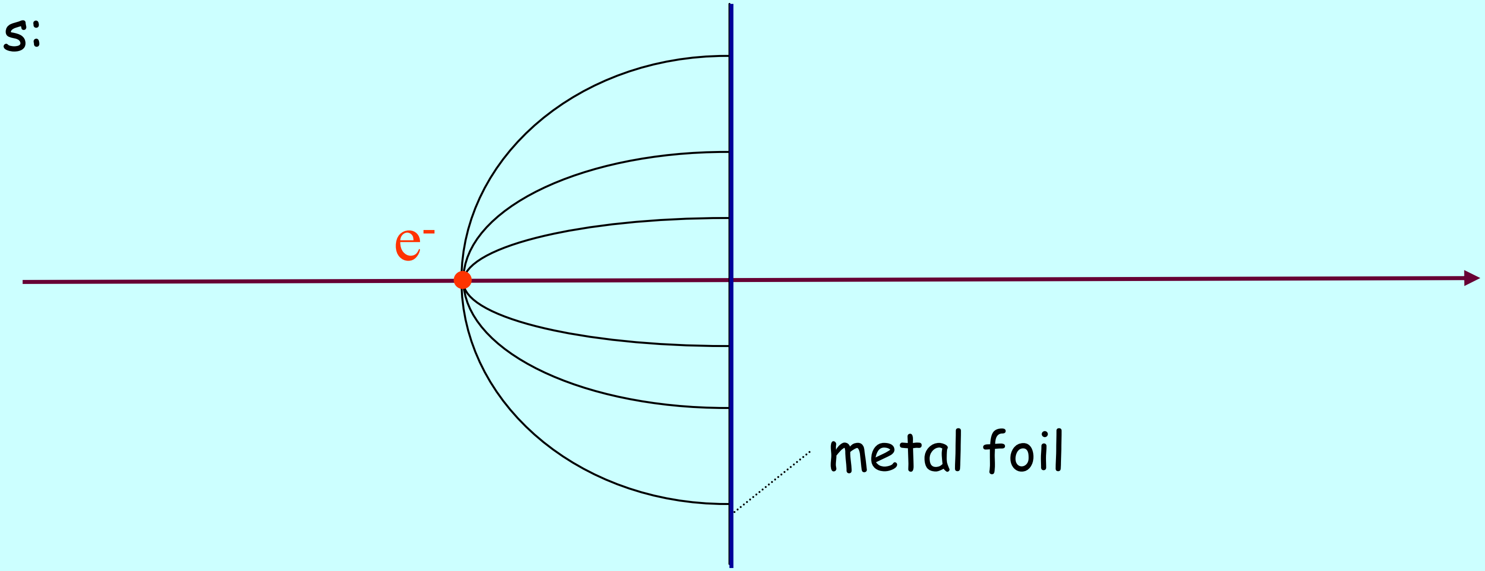
$$\boxed{B_{\text{ret}}(\omega) \propto \int_{-\infty}^{\infty} B_{\text{ret}}(t)\,\mathrm{d}t = \frac{1}{c} (\mathbf{n} \times \mathbf{A})_\text{r} \Big|_{\text{initial}}^{\text{final}}}$$

TR theory - 4

$$\left.\left(\mathbf{A}\right)_r\right|_{\text{initial}}^{\text{final}} \quad ?$$

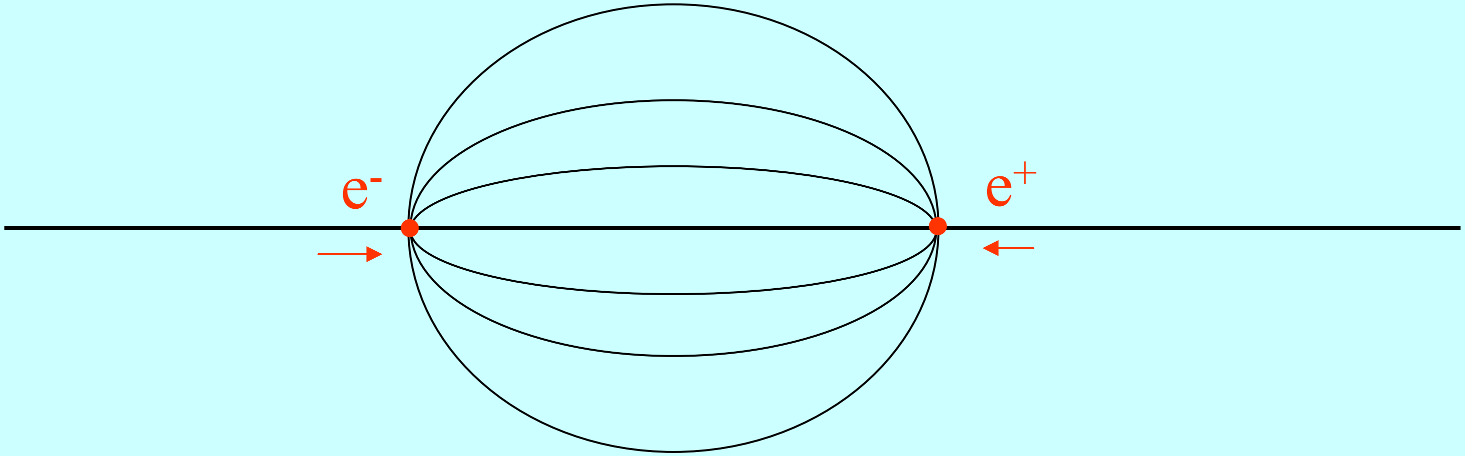
Lienard - Wiechert Potentials $\mathbf{A} = \left.\frac{e\boldsymbol{\beta}}{R(1-\mathbf{n}\boldsymbol{\beta})}\right|_{\text{ret}}$

fields:



field and metal foil can be replaced by head-on moving electron and positron

TR theory - 5



field

$$\mathbf{A} = \underbrace{\left.\frac{e\boldsymbol{\beta}}{R(1-\boldsymbol{\beta}\cdot\mathbf{n})}\right|_{ret}}_{e^-} - \underbrace{\left.\frac{(+e)(+\boldsymbol{\beta})}{R(1+\boldsymbol{\beta}\cdot\mathbf{n})}\right|_{ret}}_{e^+}$$

$$d\mathcal{W}(\omega) = \frac{c}{4\pi}\left[\frac{4\pi}{\mu_0 c}\right] R^2_{ret} \iint \frac{1}{2\pi} B^2_{ret}(\omega)\, d\omega\, d\Omega$$

$$B_{ret}(\omega) = \int_{-\infty}^{\infty} B_{ret}(t)\, e^{i\omega t}\, dt = \frac{1}{c}\left(\hat{\mathbf{n}} \wedge \mathbf{A}\right)_r \Big|_{initial}^{final}$$

TR theory - 6

$$\frac{\mathrm{d}W}{\mathrm{d}\omega\,\mathrm{d}\Omega}=\frac{\cancel{c}}{4\pi}\left[\frac{4\pi}{\mu_0 c}\right]\cancel{R^2}_{\text{ret}}\,\frac{\cancel{2}}{\cancel{2}\pi}\frac{e^2}{c^{\cancel{2}}}\left[\frac{\mathbf{n}\times\boldsymbol{\beta}}{\cancel{R}(1+\boldsymbol{\beta}\cdot\mathbf{n})}+\frac{\mathbf{n}\times\boldsymbol{\beta}}{\cancel{R}(1-\boldsymbol{\beta}\cdot\mathbf{n})}\right]^2_{\text{ret}}$$

with $\boldsymbol{\beta}=\beta\mathbf{z}$

$$\frac{\mathrm{d}W}{\mathrm{d}\omega\,\mathrm{d}\Omega}=\frac{e^2}{4\pi^2 c}\left[\frac{4\pi}{\mu_0 c}\right]\underbrace{(\mathbf{n}\times\mathbf{z})^2}_{\sin^2\theta}\left[\frac{2\beta}{1-\beta^2\underbrace{(\mathbf{n}\,\mathbf{z})^2}_{\cos^2\theta}}\right]^2_{\text{ret}}$$

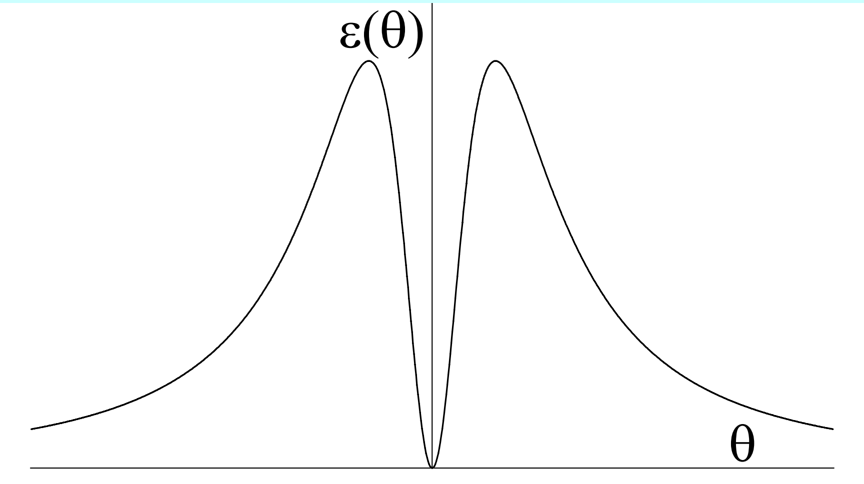
θ observation angle with respect to z

spectral and spatial radiation power distribution of transition radiation

$$\boxed{\frac{\mathrm{d}W}{\mathrm{d}\omega\,\mathrm{d}\Omega}=\frac{r_{\mathrm{c}}mc^2}{\pi^2 c}\,\frac{\beta^2\sin^2\theta}{(1-\beta^2\cos^2\theta)^2}}$$

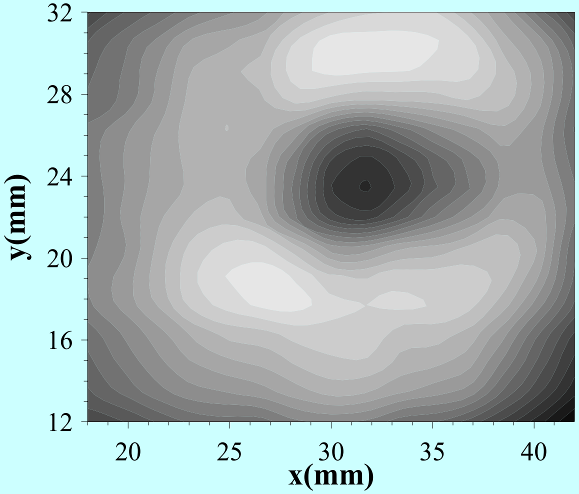
TR radiation distribution

theoretical
radiation distribution



measured
spatial distribution

C. Settakorn, 1998



TR total radiation power

with $\mathrm{d}\Omega = \sin\theta\,\mathrm{d}\theta\,\mathrm{d}\varphi$

$$\frac{\mathrm{d}W}{\mathrm{d}\omega} = \frac{2r_c mc^2}{\pi c}\int_0^{\pi/2}\frac{\beta^2\sin^3\theta}{\left(1-\beta^2\cos^2\theta\right)^2}\,\mathrm{d}\theta$$

$$= \frac{r_c mc^2}{\pi c}\int_{-1}^{1}\frac{\beta^2\left(1-x^2\right)}{\left(1-\beta^2 x^2\right)^2}\,\mathrm{d}x$$

$$= \frac{r_c mc^2}{\pi c}\left(-1+\frac{\left(1+\beta^2\right)\arctan\beta}{\beta}\right)$$

$$= \frac{r_c mc^2}{\pi c}\left(-1+2\ln 2+2\ln\gamma\right)\approx\frac{2r_c mc^2}{\pi c}\ln\gamma$$

spectral TR disribution

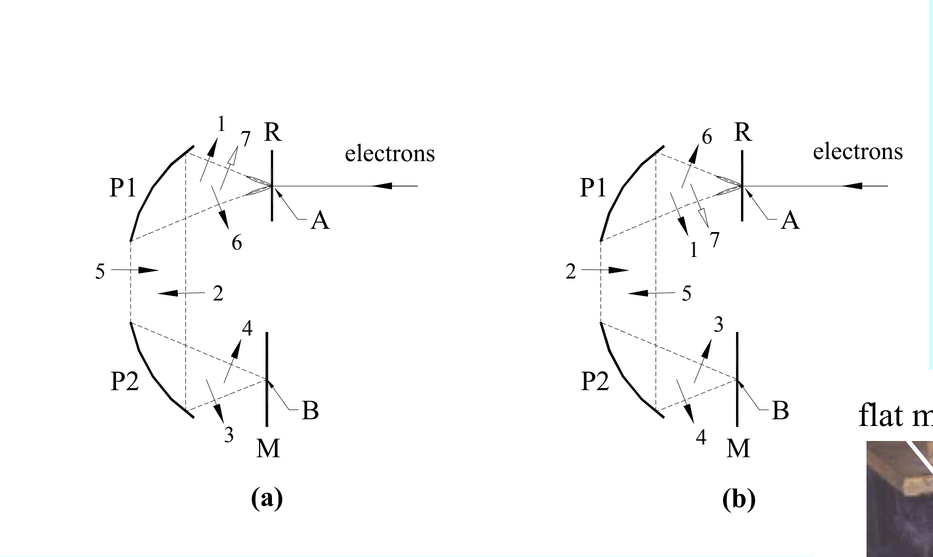
$$\boxed{\frac{\mathrm{d}W}{\mathrm{d}\omega} = \frac{2r_c mc^2}{\pi c}\ln}$$

for $\omega \ll \omega_{\text{plasma}}$

STR

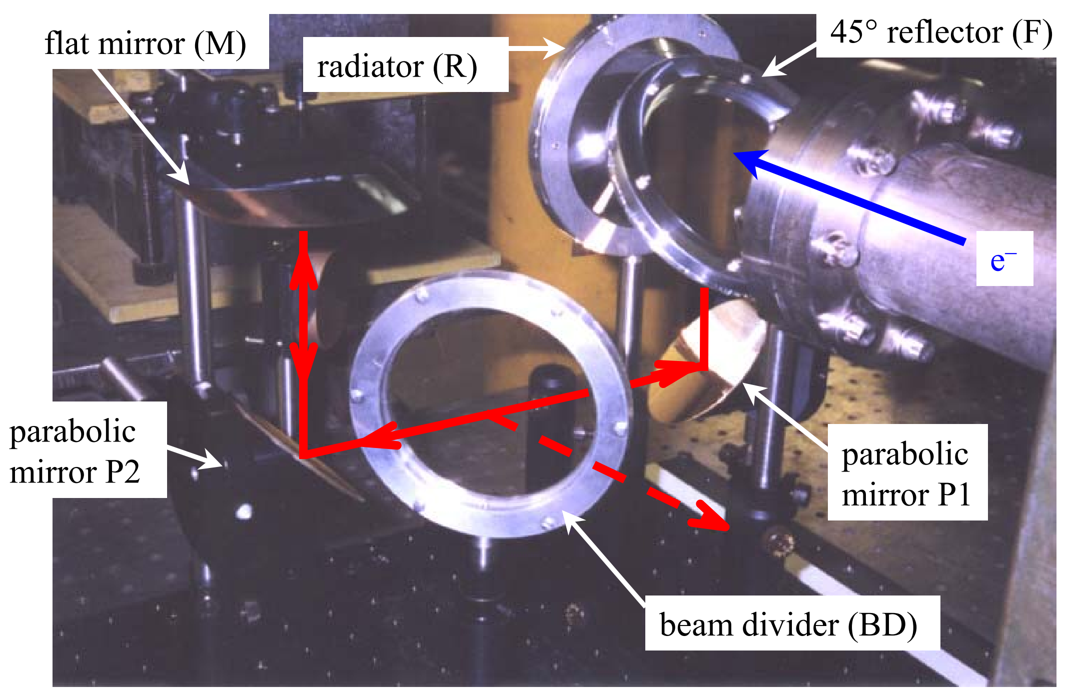
Stimulated Transition Radiation

optical cavity

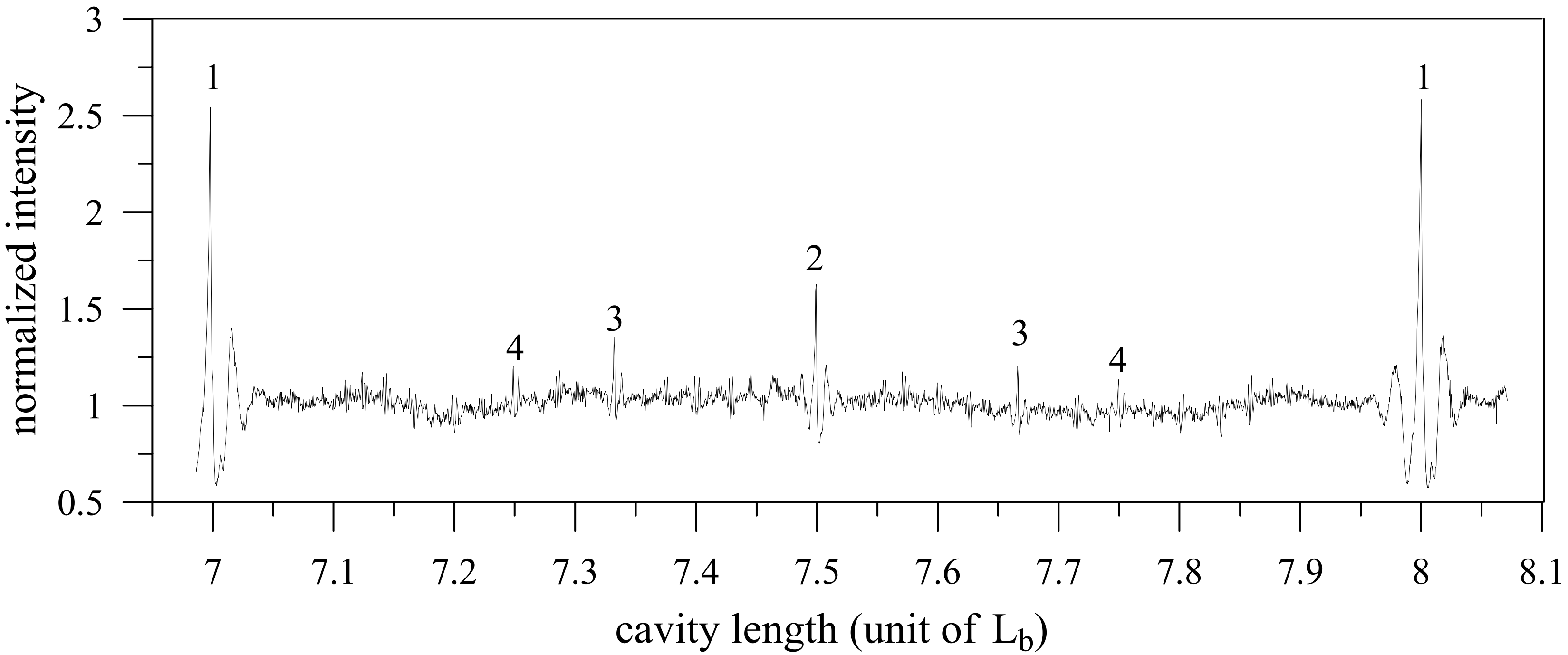


(a) (b)

C. Settakorn

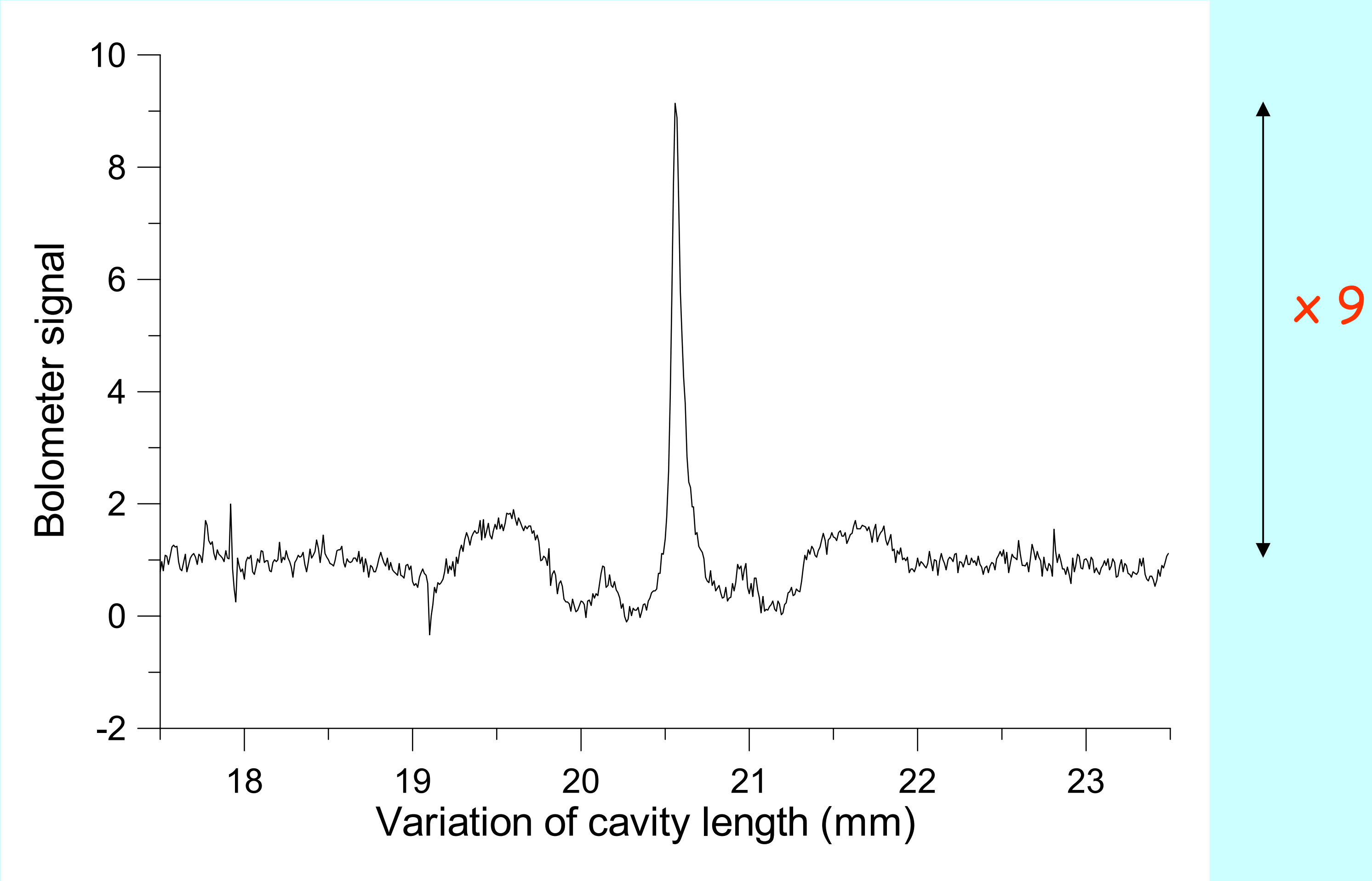


scan



Recorded radiation intensity as a function of optical cavity length (C. Settakorn)

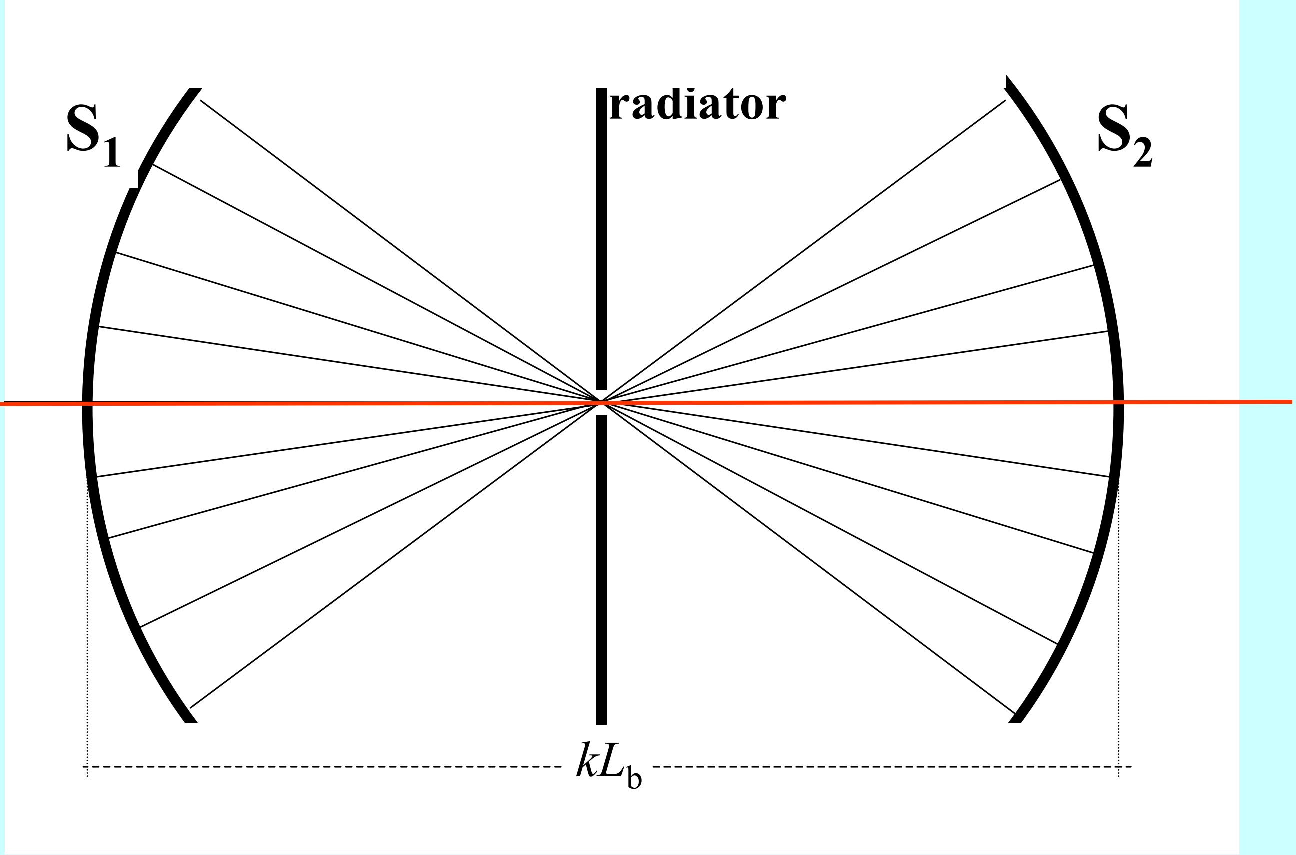
maximum enhancement



Max. enhancement of STR achieved so far (C.Settakorn)

new STR cavity ?

try this one ?



X-rays from Low Energy Electron Beams

types of radiation

- Thomson/Compton Scattering
- Channeling Radiation
- Parametric x-rays
- Smith-Purcell Radiation
- Crystalline Undulator
- Resonant Transition Radiation
- Stimulated Transition Radiation
- ?????

Compton scattering

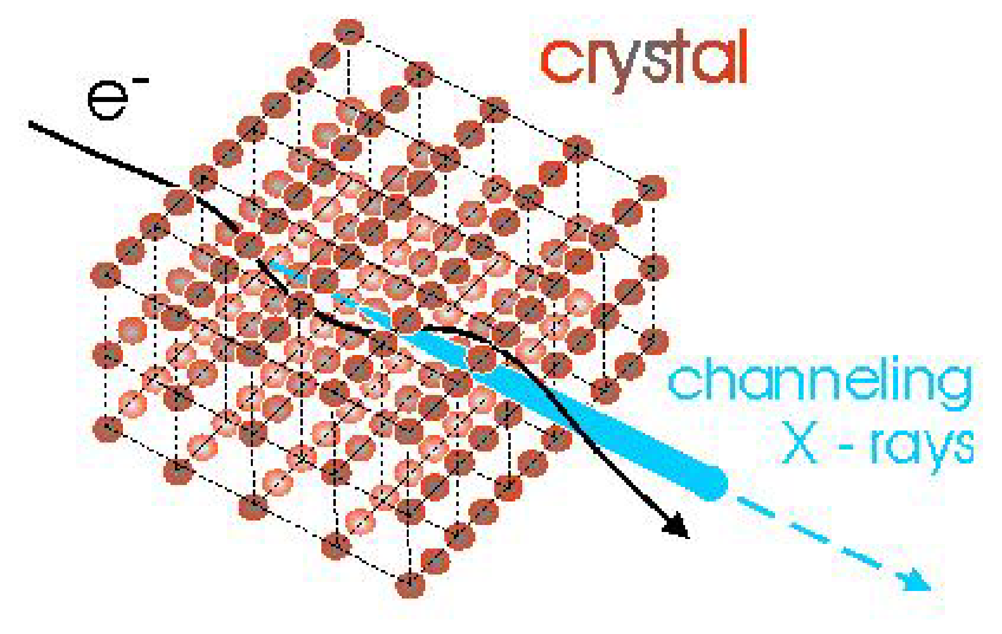
Thomson backscattering

$$\varepsilon_{\mathrm{ph}}(eV) = 4.959\,\frac{\gamma^{2}}{\lambda_{\mathrm{L}}(\mu m)}$$

For 25 MeV electrons:

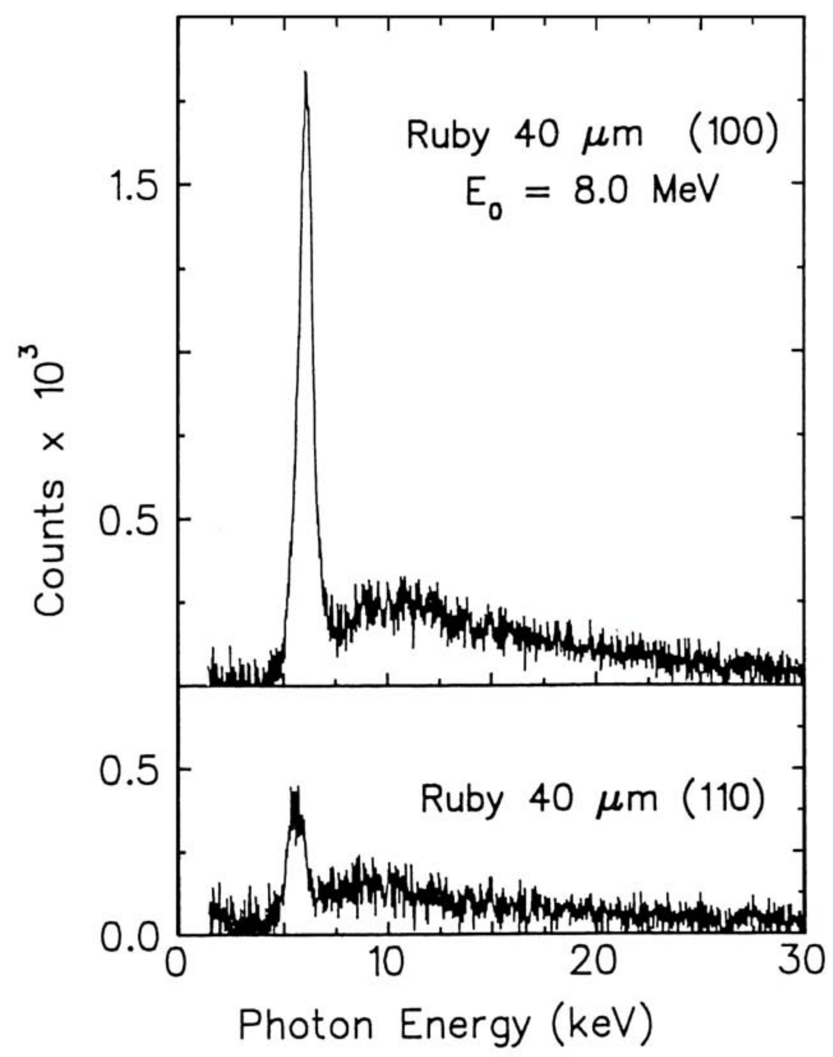
incoming radiation	**backscattered radiation**
coherent FIR, 100 - 1000 μm	12-120 eV
CO_2 Laser, 10μm	1200 eV
Yag Laser, 1μm	12.0 keV

Channeling radiation



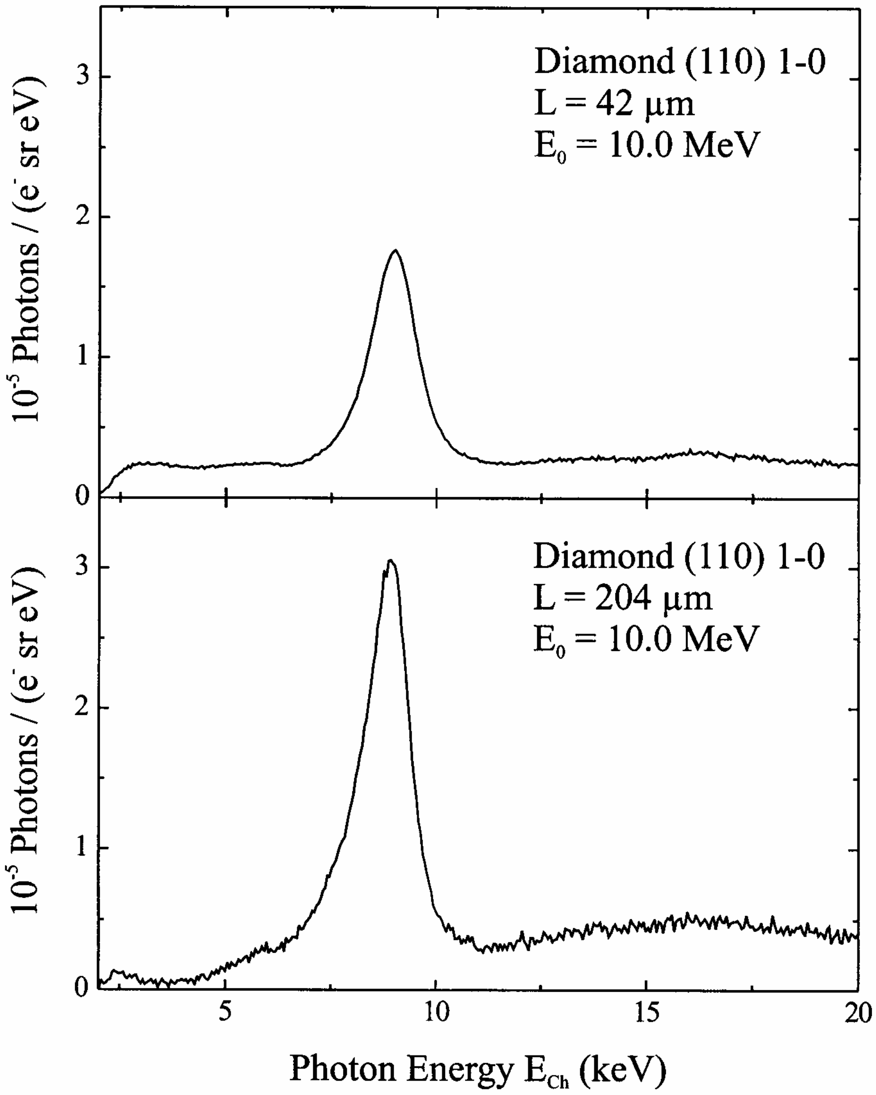
Channeling - 1

Channeling-radiation spectra from 8.0-MeV electrons along the (100) and (110) planes of ruby, obtained at the superconducting linac at Darmstadt [Freudenberger *et al*. NIM B**119** (1996) 123].



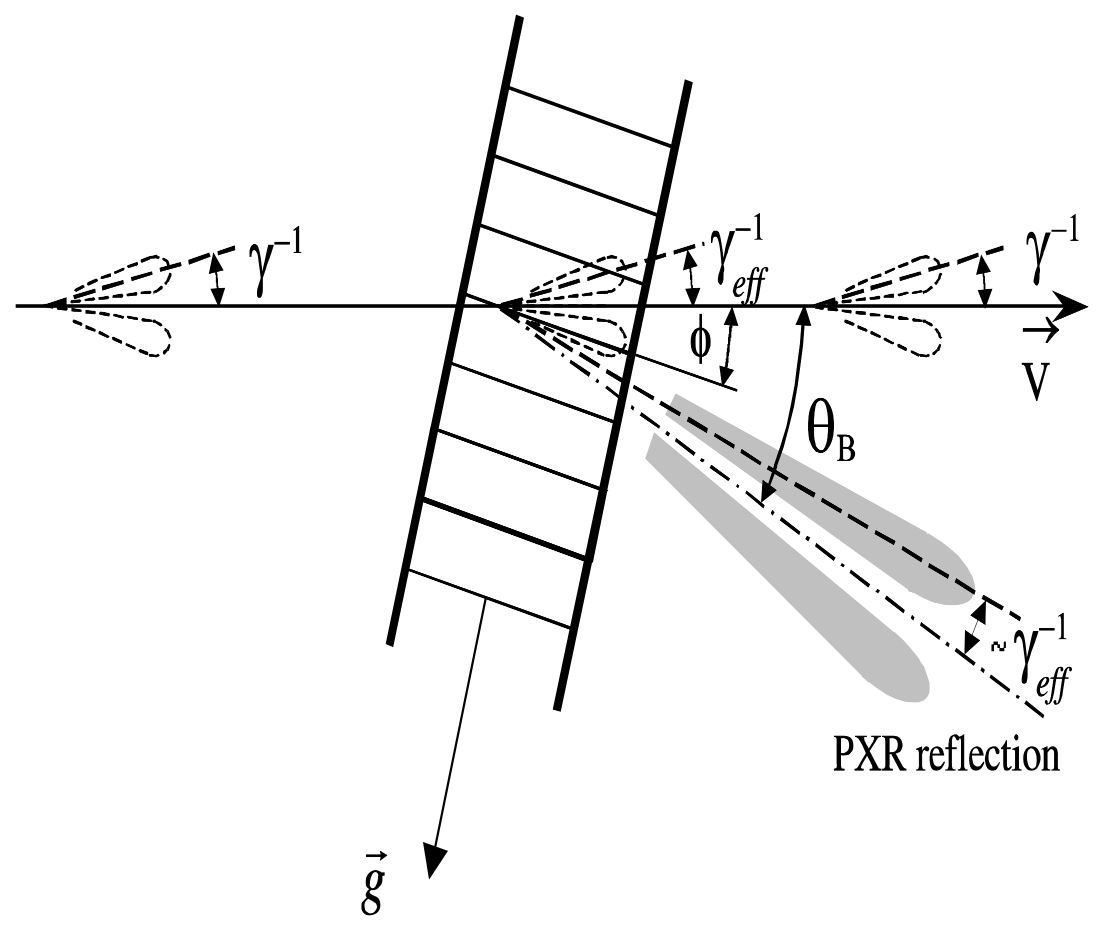
Channeling - 2

Channeling radiation spectra obtained from diamond crystals after substraction of bremsstrahlung background (H. Genz)



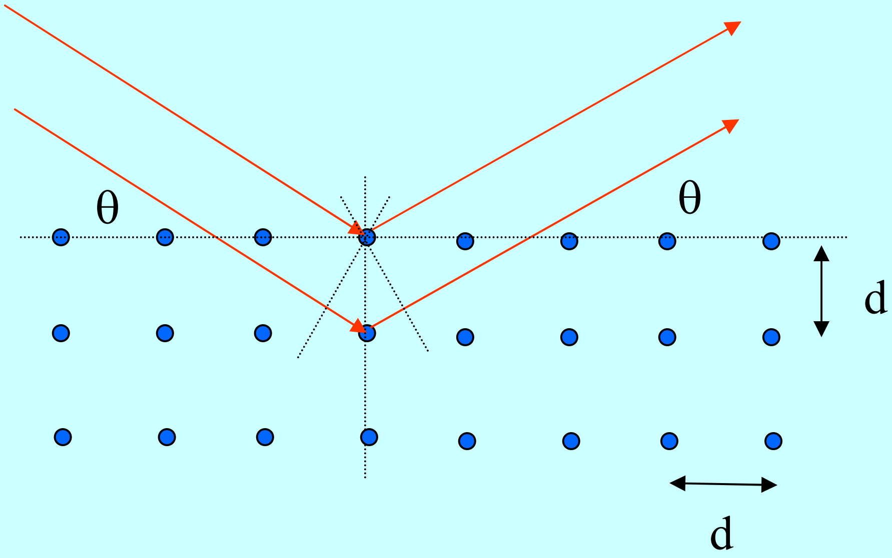
PXR

PXR as diffraction of virtual photons associated with relativistic charged particles
(A. Shchagin)



Photon energy of PXR

PXR is emitted under the Bragg reflection rule



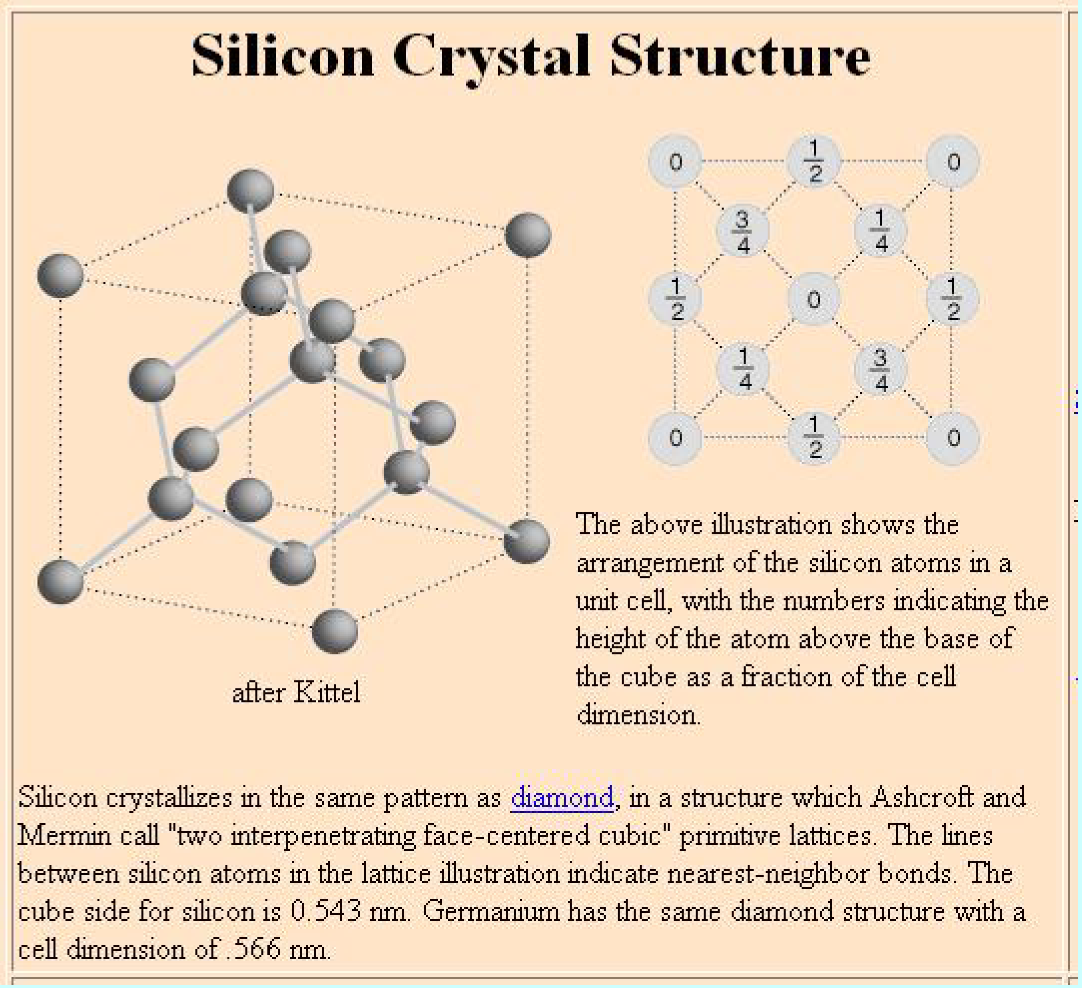
Bragg reflection

$$2d\sin\theta = n\lambda$$

example

$$\left.\begin{array}{l}\text{for Si}\quad d = 1.8\ \text{A}\\ \qquad\quad\ \ \theta = 22.5\ \text{deg}\end{array}\right\}\quad \lambda = 1.4\ \text{A}\quad \text{or}\quad 8.8\ \text{keV}$$

Si crystal



Silicon Crystal Structure

after Kittel

The above illustration shows the arrangement of the silicon atoms in a unit cell, with the numbers indicating the height of the atom above the base of the cube as a fraction of the cell dimension.

Silicon crystallizes in the same pattern as diamond, in a structure which Ashcroft and Mermin call "two interpenetrating face-centered cubic" primitive lattices. The lines between silicon atoms in the lattice illustration indicate nearest-neighbor bonds. The cube side for silicon is 0.543 nm. Germanium has the same diamond structure with a cell dimension of .566 nm.

PXR

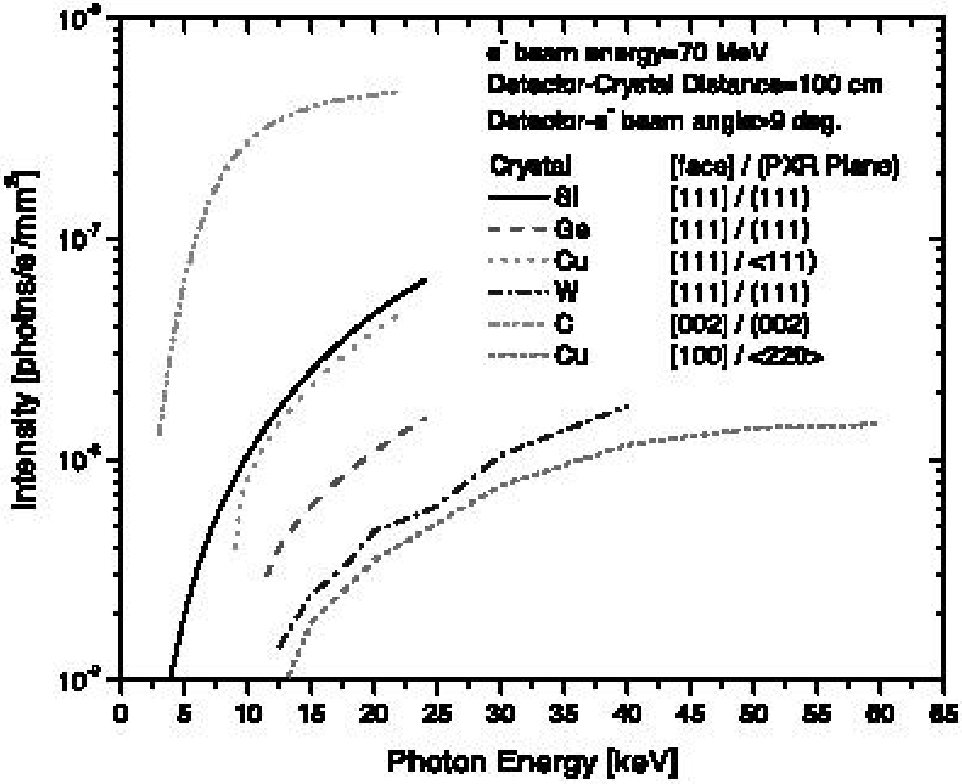
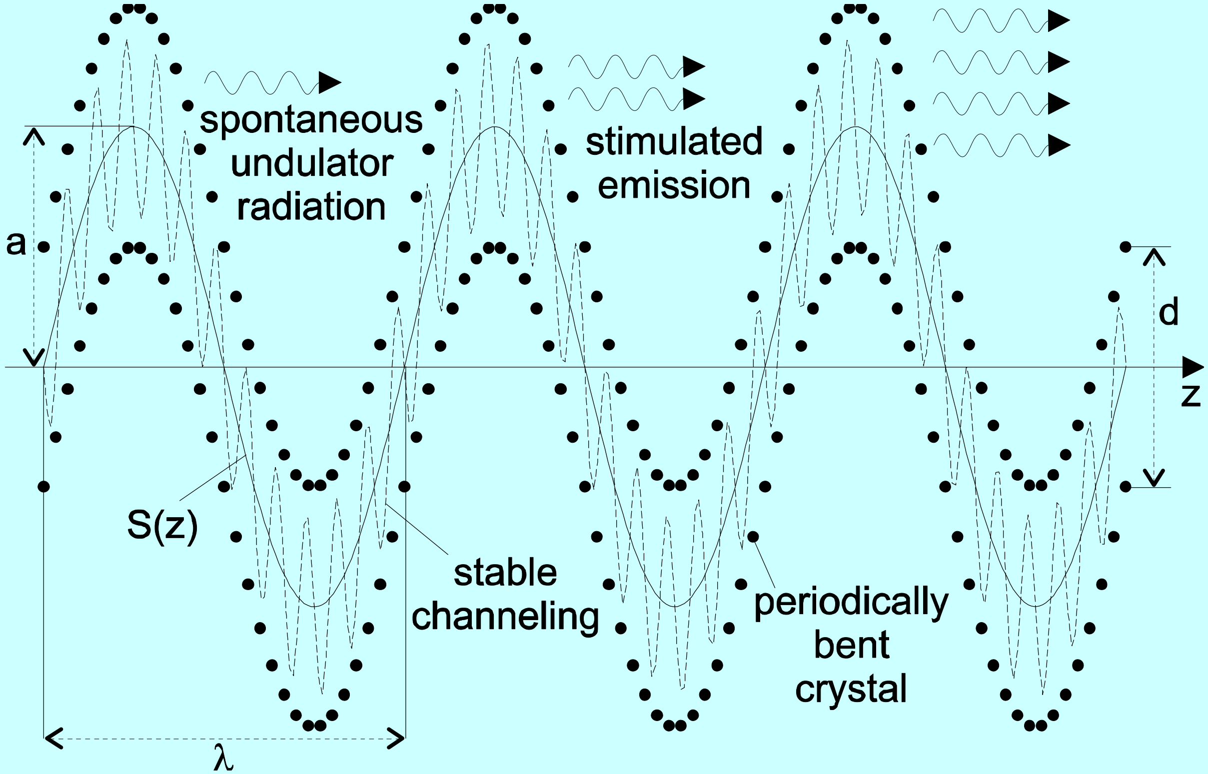


Fig. 1. Calculated X-ray intensities for several 500 μm thick crystal targets for several reflection planes and crystal face planes. The upper energy limit of each case was limited by a requirement of an angle of more than 9 deg between the detector and the electron beam axis.

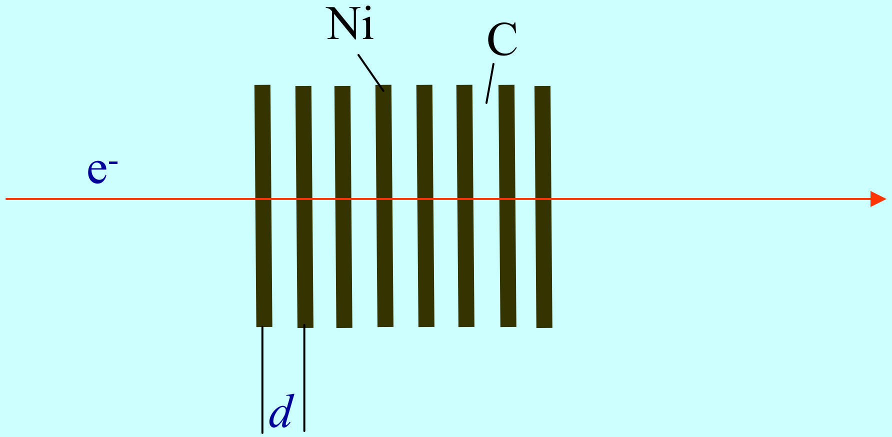
Crystalline undulator



Crystalline undulator (schematic). Vertical scale magnified by 10^4. (Krause et.al.)

Resonant TR-theory

use stack of layered low-Z/high-Z material



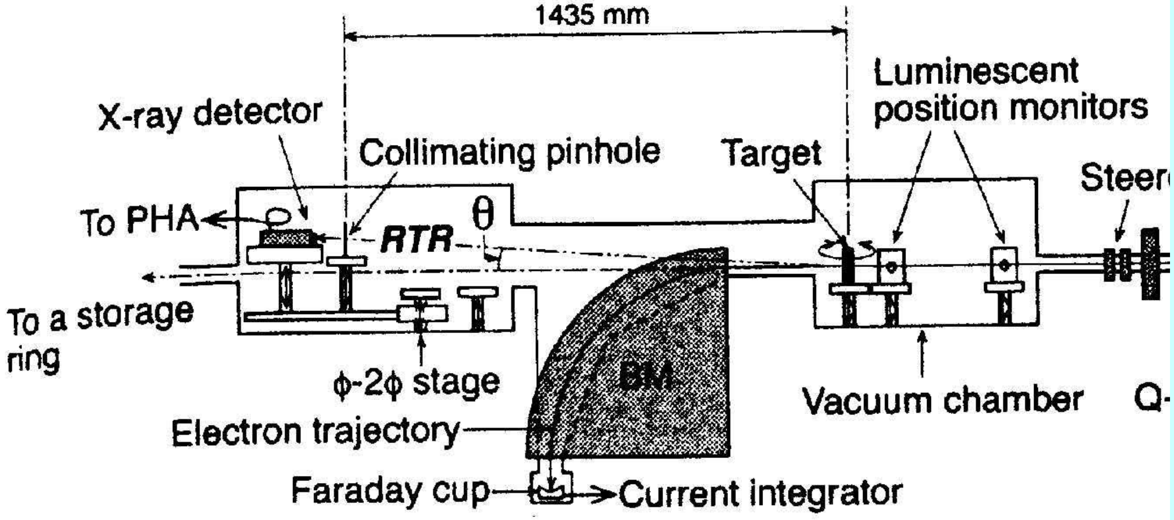
resonance condition in electron frame: d👎 🖫 $\frac{d}{☹}$ 🖫 n 🕆👎

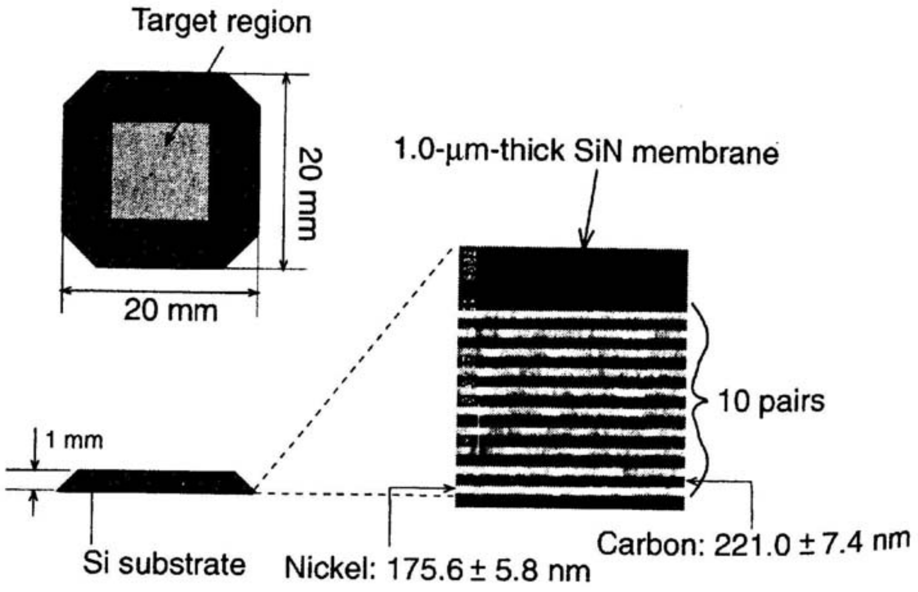
radiation observed in lab frame: 🕆 🖫 $\frac{d}{2☹}$ ⋂ 🖅☹ 🖊 (

for $\lambda = 1$A and E = 20 MeV, we need d = 320 nm

Resonant TR-Ispirian

RTR experimental Setup at the Yerevan Physics Institute

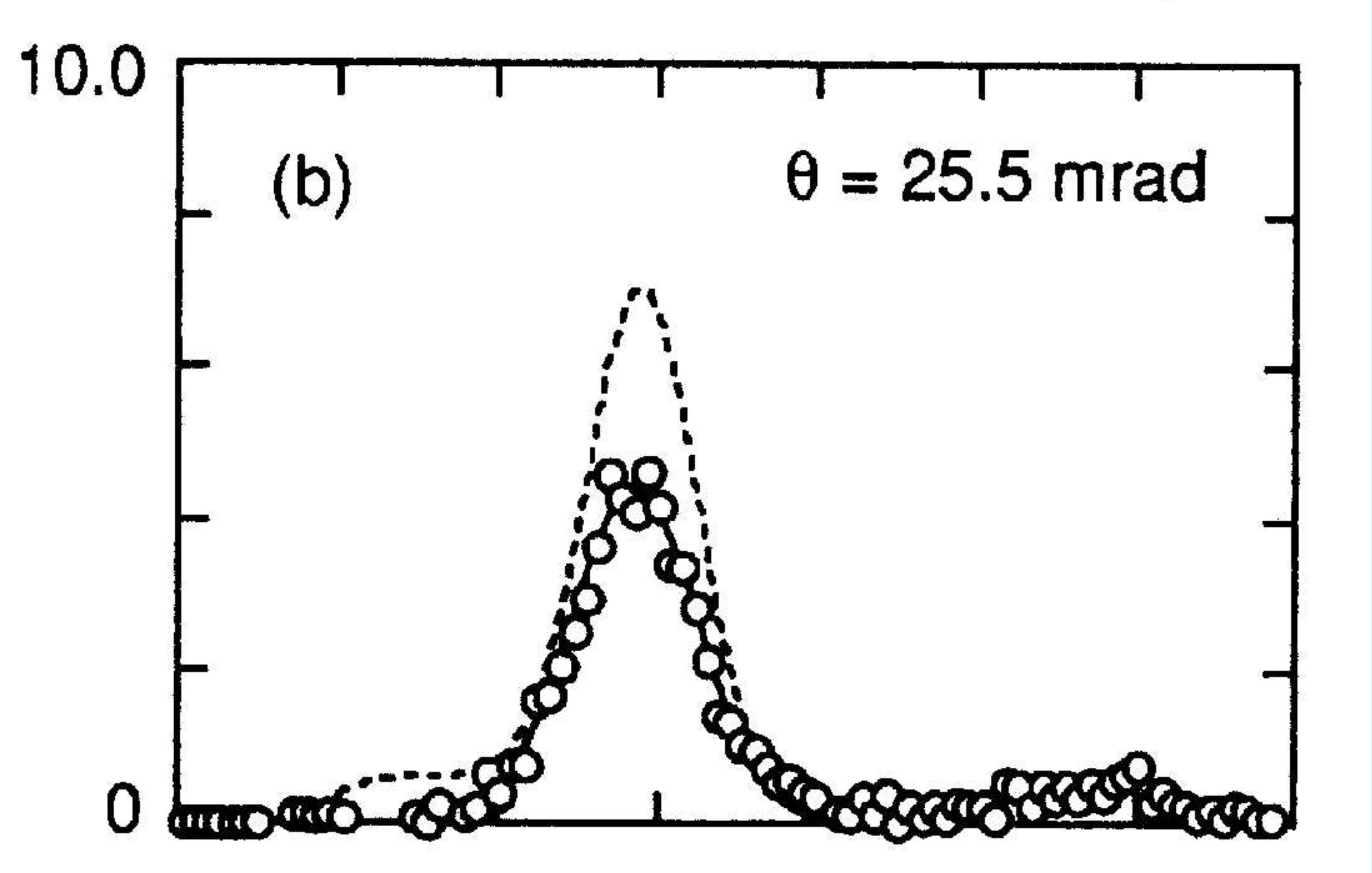




Multi layer radiator

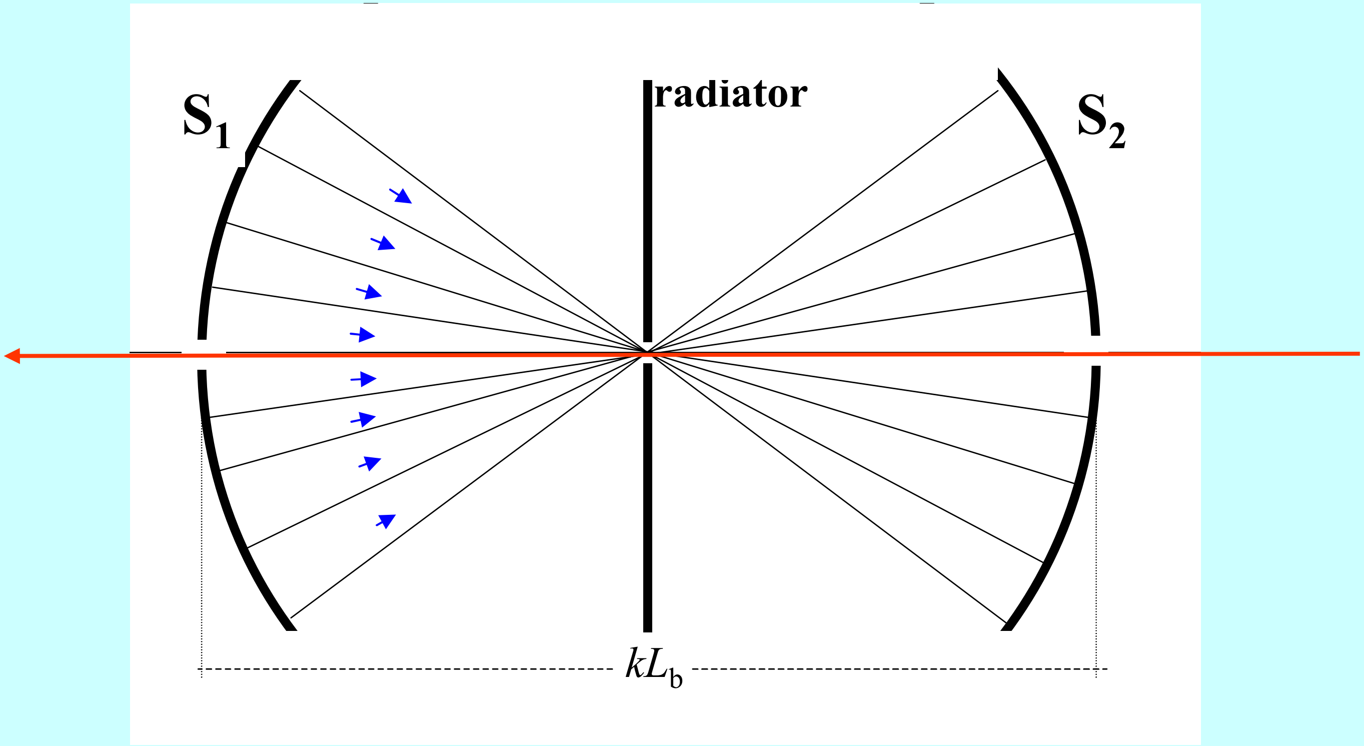
K.A. Ispirian

Resonant TR-Ispirian



0 3000 (eV) 7000

STR

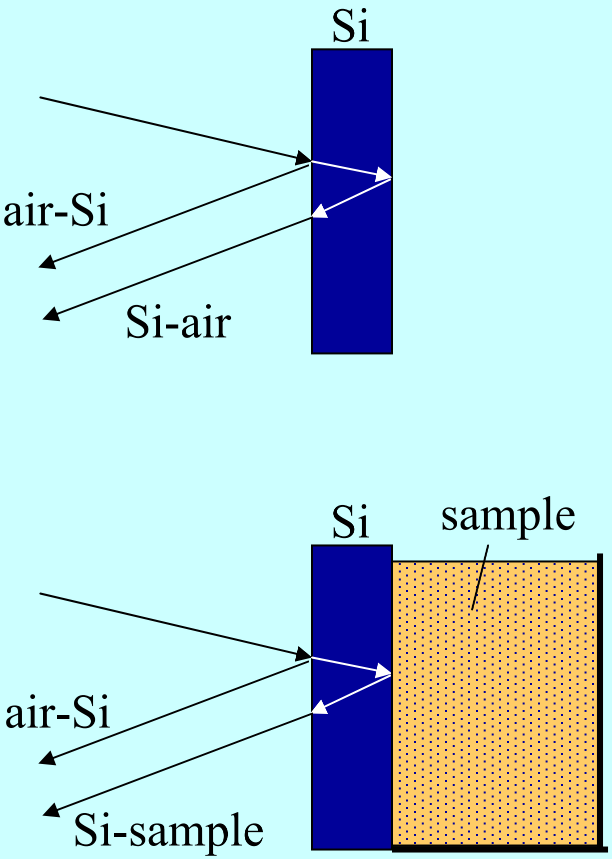


FIR radiation: $50 < \lambda < 1000$ µm

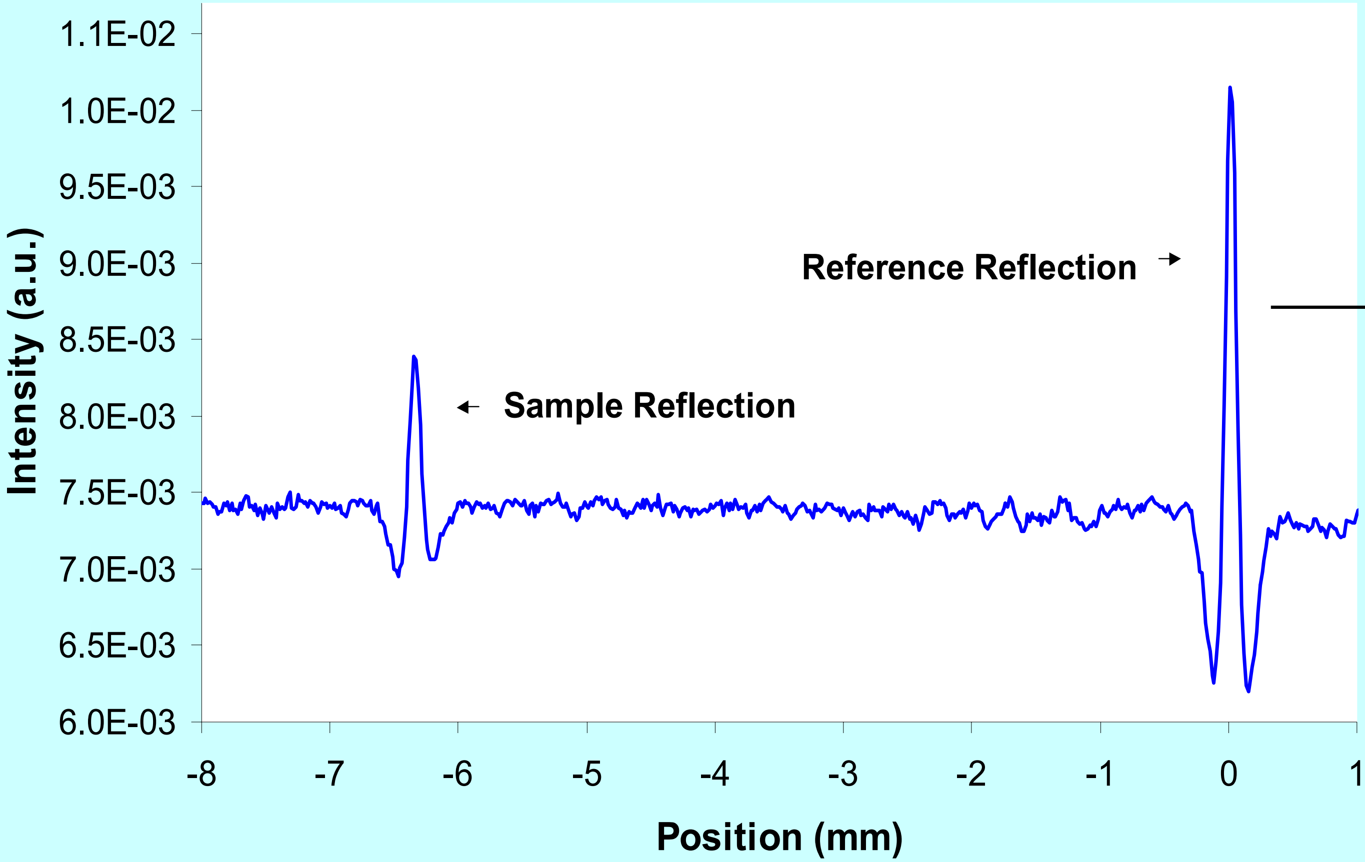
VUV-radiation: 150 eV $< \varepsilon_{ph} < 7$ eV

FIR and Biological Molecules

Dispersive Fourier Transform Spectroscopy



Disp.FourierTransform Spect.



FFT

$n(\nu) + ik(\nu)$

Dynamics

works well for very heavily absorbing liquids

Disp.FourierTransform Spect.-2

Fourier transform of peak 1 $F_{W,O}(\tilde{\nu})$

Fourier transform of peak 2 $F_{W,L}(\tilde{\nu})$

$$\boxed{\frac{F_{W,L}(\tilde{\nu})}{F_{W,O}(\tilde{\nu})} = \frac{\tilde{n}_W - \tilde{n}_L}{\tilde{n}_W + \tilde{n}_L}\,\frac{\tilde{n}_W + 1}{\tilde{n}_W - 1}}$$

$\tilde{n}_W, \tilde{n}_L$ complex refractive indices of window and liquid

Experimentation with calf thymus NaDNA

explore low frequency dynamics of DNA, DNA complexes and proteins

what is the role of low frequency vibrations for biological functions ?

important, because they involve motion of large groups of atoms

conformational transitions like

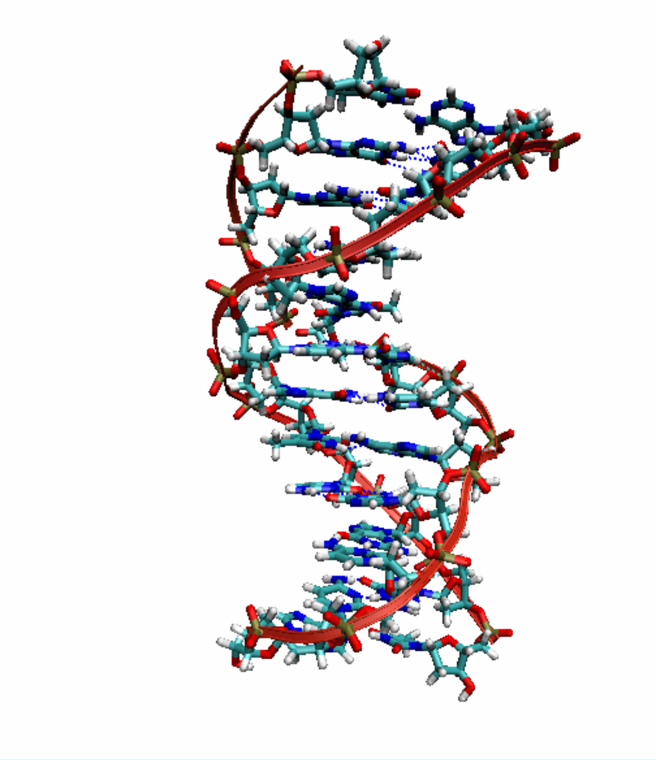
local “melting”: separation of two strands of DNA

transport of molecules and ions through cell membranes by membrane proteins

DNA experiments

Dilute solution samples ~ 1mg/ml

B – form (native state of DNA)



Strand separation

study process of DNA strand separation

in laboratory initiate "melting" by heating, ~ 60 deg C

monitor "melting" with UV absorbance

living cells do not melt their DNA by temperature !

energy for melting becomes available by hydrolysis of ATP into ADP

mechanism unknown !

hypotesis: chemical energy is converted into vibrational energy of interbase hydrogen-stretching modes

study hydrogen-bond-stretching modes of DNA

to test validity of this hypothesis

hydrogen-bond stretching

theory (Prohofsky) indicate mode near 80 cm^{-1}.

observed Raman modes (solid and gel samples) are very broad!

K. Woods, Stanford observed same in solutions, where DNA has no interaction with neighboring DNA molecules

Observed modes are much narrower and better resolved

Only one Raman study of melting has been published so far !

quality very poor and no useful information can be extracted except to state that “feature” vanished upon melting

Initial experiments at Stanford indicate that FIR can produce excellent data about melting

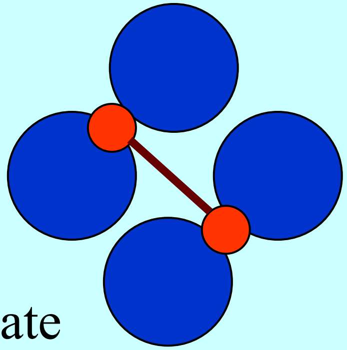
this is of great interest

so far, nobody could follow dynamics of melting

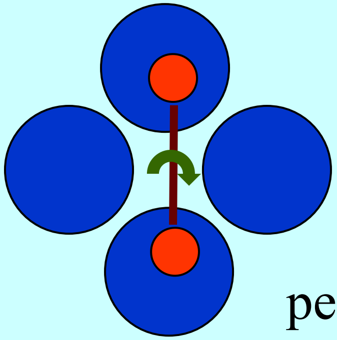
Pump-Probe example

"Direct Observation of Surface Chemistry using Ultrafast Soft X-Ray Pulses", Bauer et.al. PRL **87** (2001) 025501-1

- consider molecular oxygen on a Pt(111) single crystal surface
- photoemission spectroscopy is extremely sensitive to chemical state of surface-adsorbate complex
- excite oxygen molecule by laser pulse
- probe with soft x-ray pulse and photoemission spectroscopy
- determine photo electron energy spectrum by TOF



superoxo-state



peroxo-state

Summary

- femtosecond electron pulses at 10 – 30 MeV provide excellent opportunity to do genuine research
- development and optimization of FIR and x-ray source
- monitor chemical reactions of femto second time scale
- determine spectral complex refractive index for heavily absorbing samples by dispersive FT spectroscopy
- fitting for university based research
- MS and PhD projects