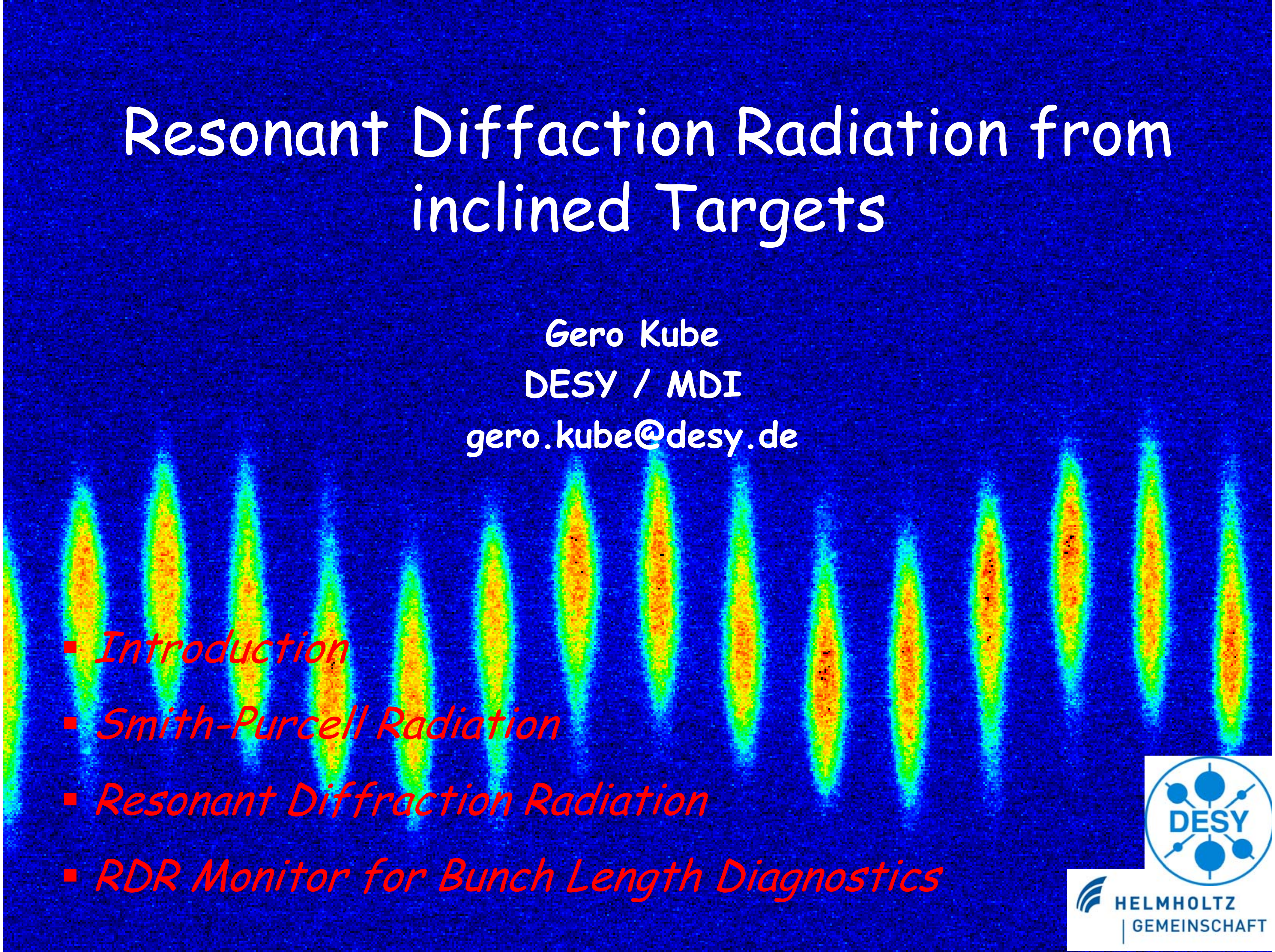


Resonant Diffaction Radiation from inclined Targets

Gero Kube
DESY / MDI
gero.kube@desy.de

- *Introduction*
- *Smith-Purcell Radiation*
- *Resonant Diffraction Radiation*
- *RDR Monitor for Bunch Length Diagnostics*

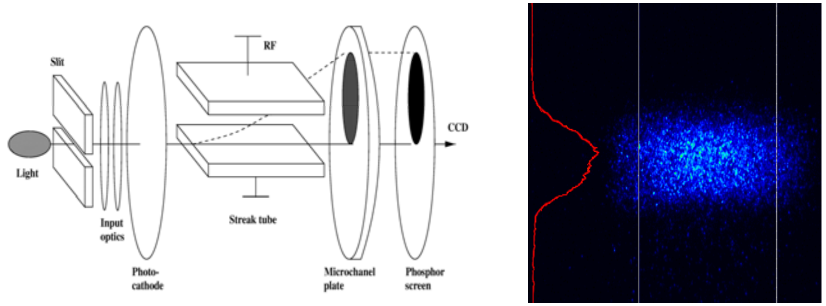
Bunch Length Diagnostics

- purpose

high resolution measurement ↔ machine tuning

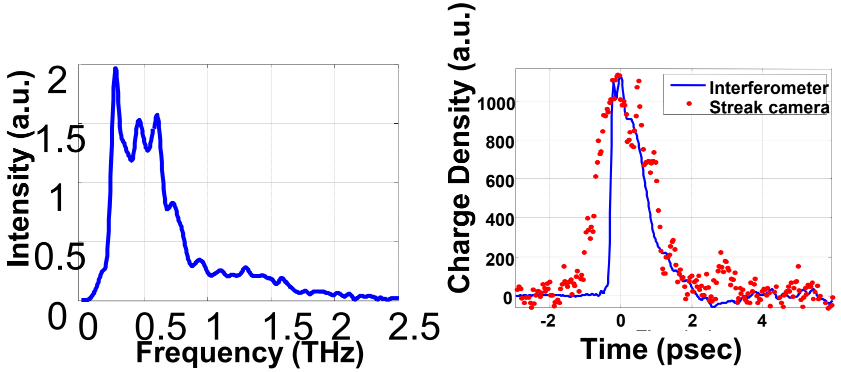
- principles

  - **streak camera**



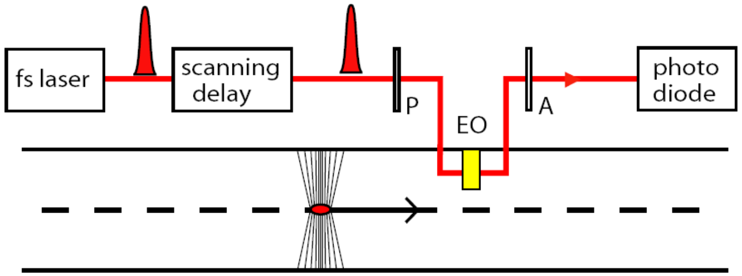
courtesy D.Lipka (DESY)

  - **coherent radiation diagnostics**



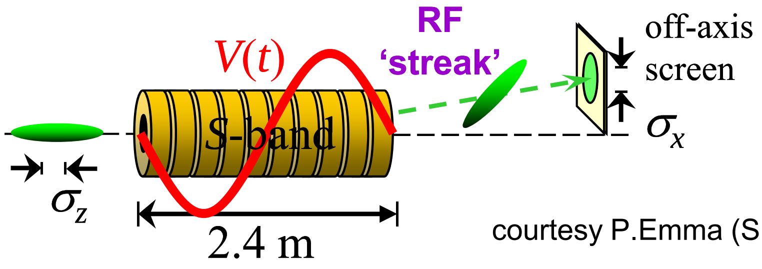
courtesy O.Grimm (DESY)

  - **EO techniques**



courtesy B.Steffen (DESY)

  - **RF techniques**

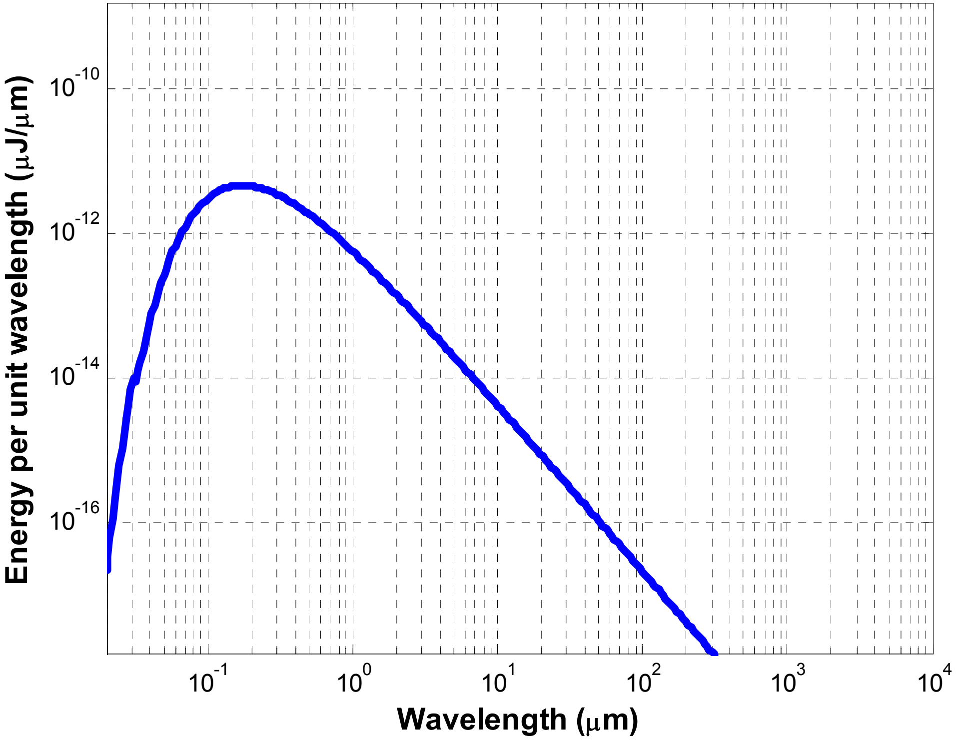


courtesy P.Emma (SLAC)

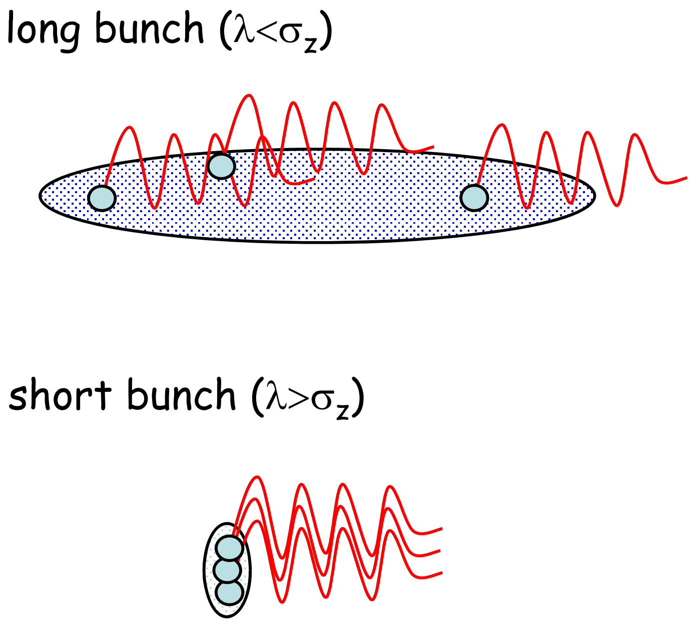
and more …

Basic Principle of CRD

- single electron synchrotron radiation spectrum
    - circular motion, $E = 130$ MeV, $\rho = 1.6$ m



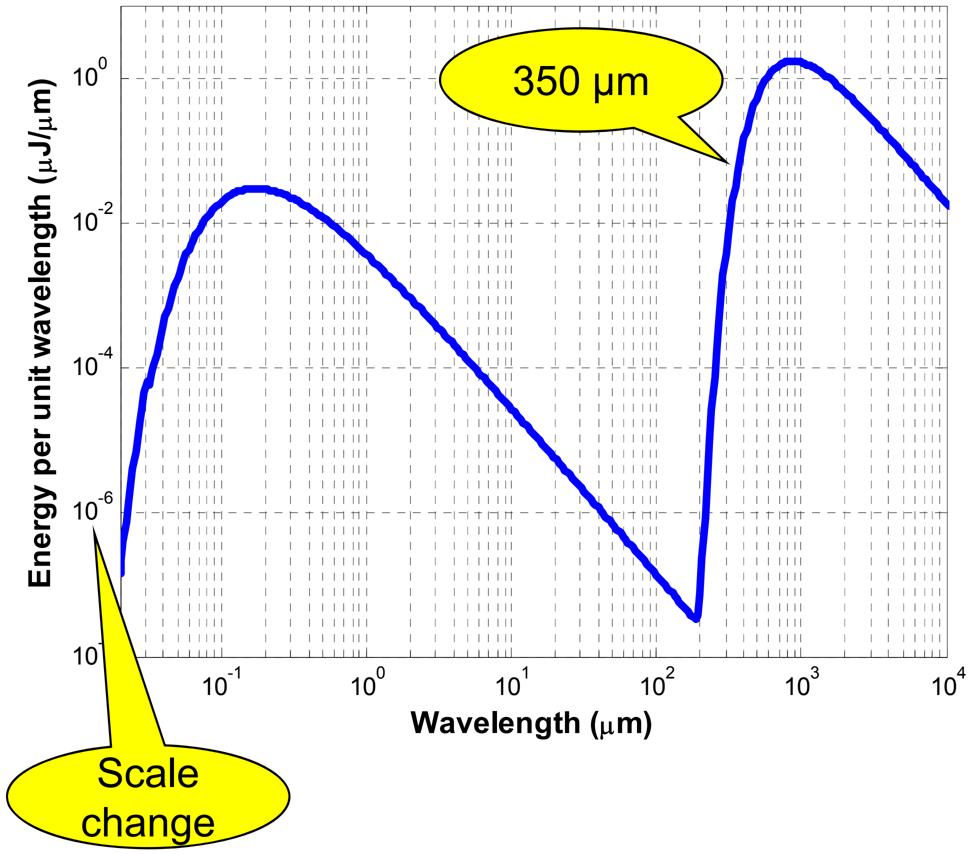
- longitudinal coherence



Courtesy O. Grimm (DESY)

Basic Principle of CRD

- synchrotron radiation spectrum for charge 1 nCb
  - circular motion, E = 130 MeV, ρ = 1.6 m

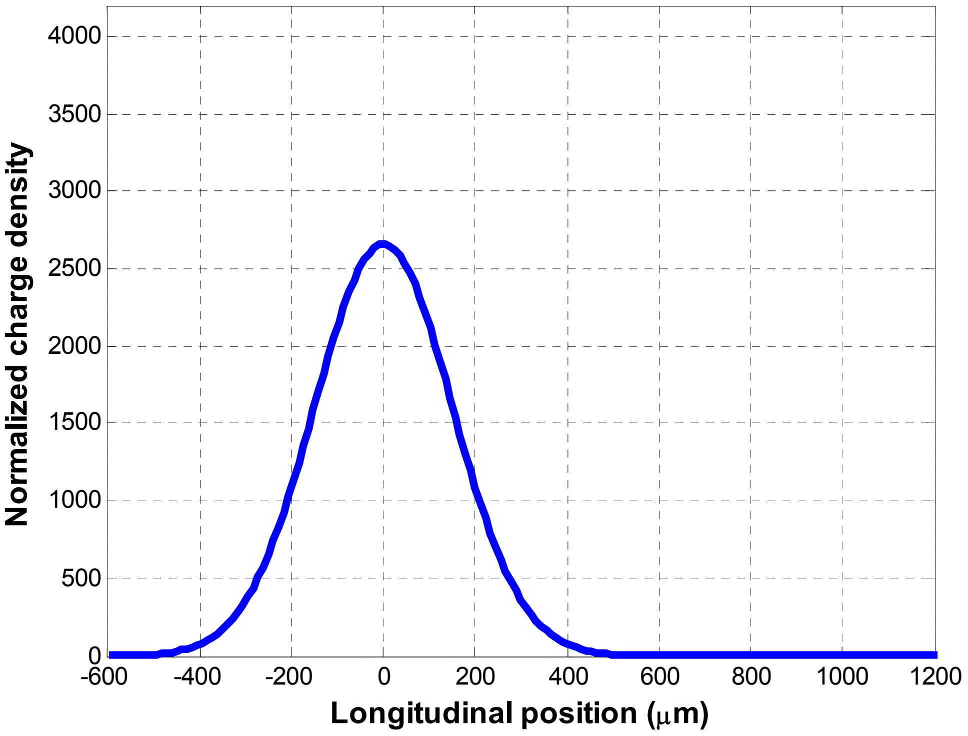


350 µm

Scale change

Gaussian (line) bunch

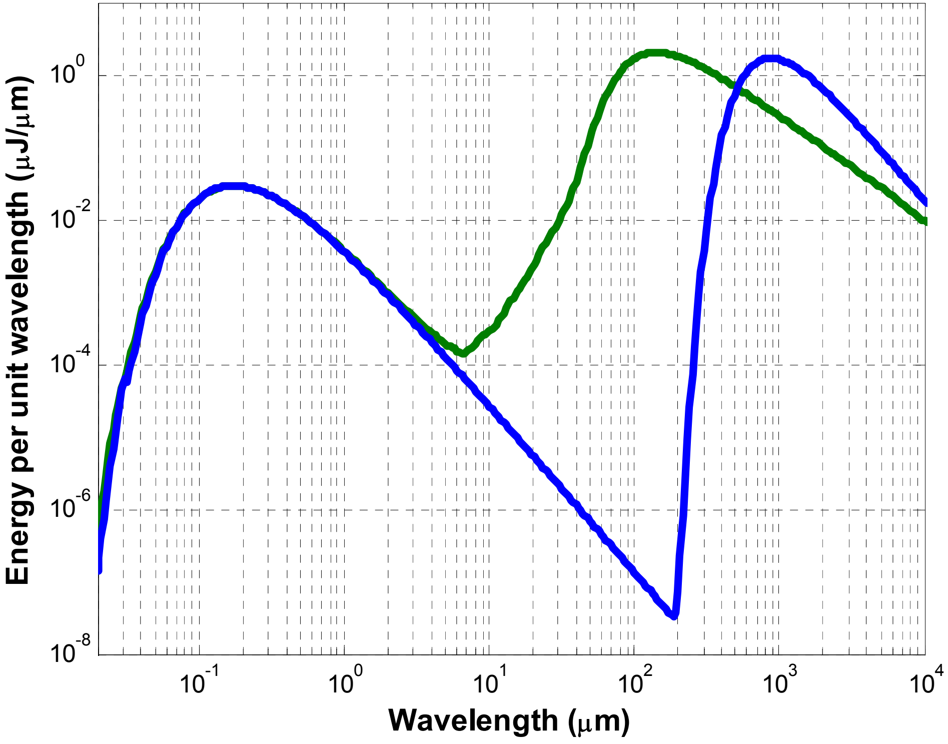
FWHM=350 µm



Courtesy O. Grimm (DESY)

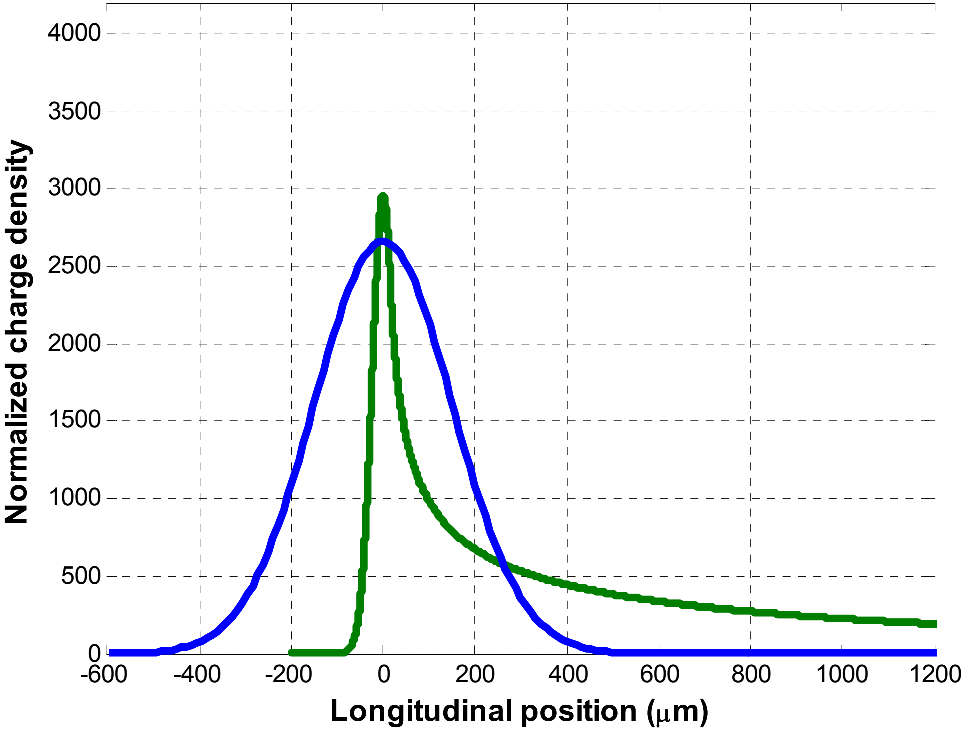
Basic Principle of CRD

- synchrotron radiation spectrum for charge 1 nCb
  - circular motion, E = 130 MeV, ρ = 1.6 m



Spiked bunch

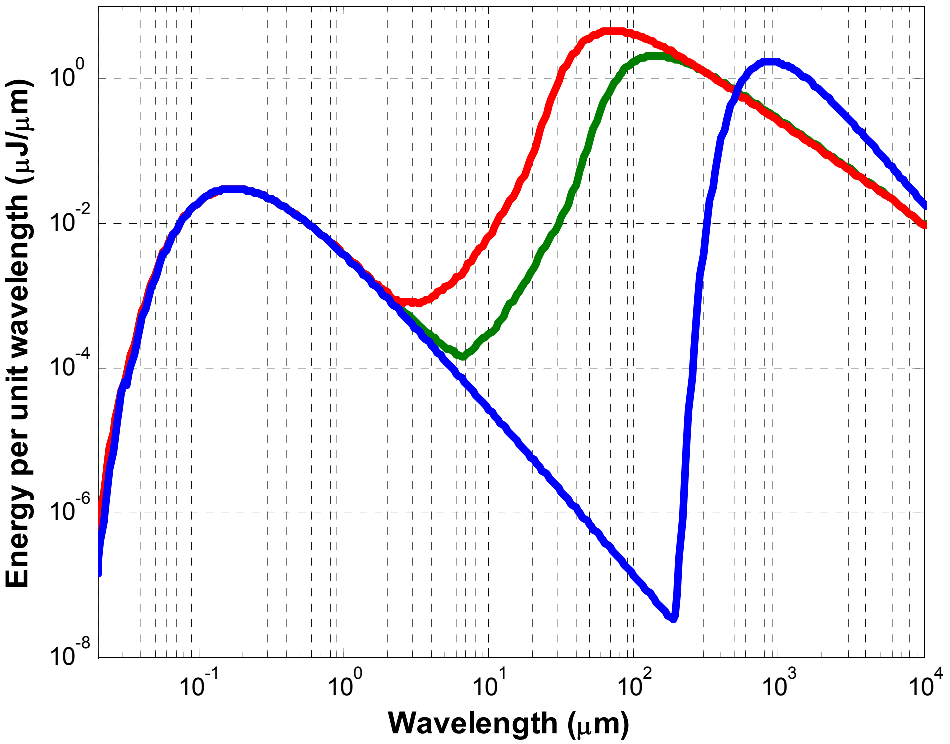
FWHM=70 μm



Courtesy O. Grimm (DESY)

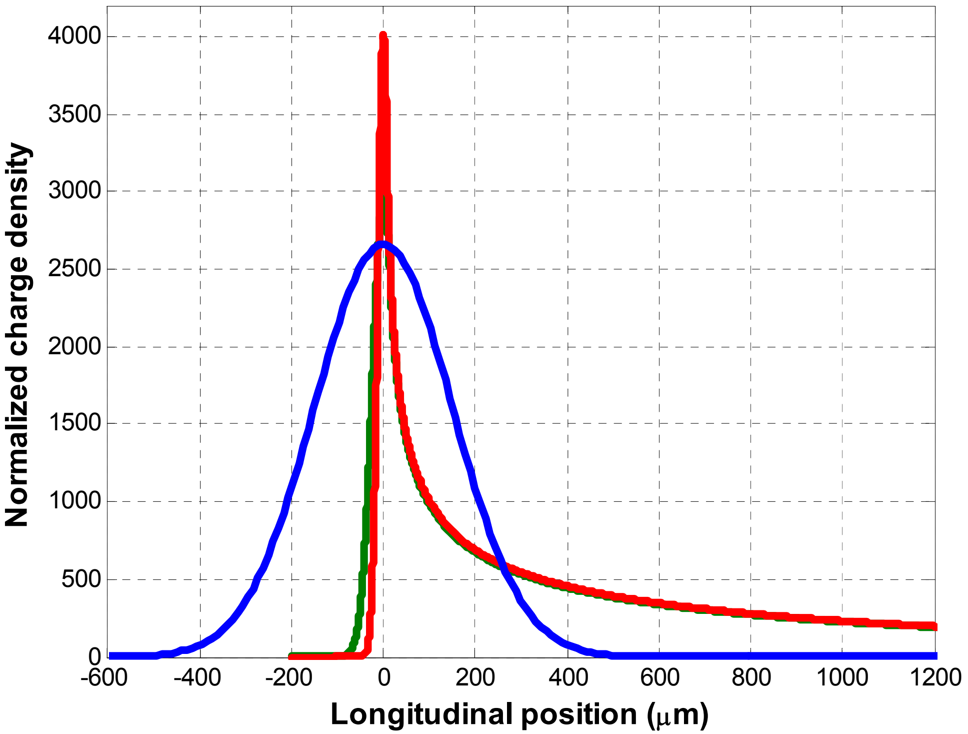
Basic Principle of CRD

- synchrotron radiation spectrum for charge 1 nCb
  - circular motion, E = 130 MeV, ρ = 1.6 m



Spiked bunch

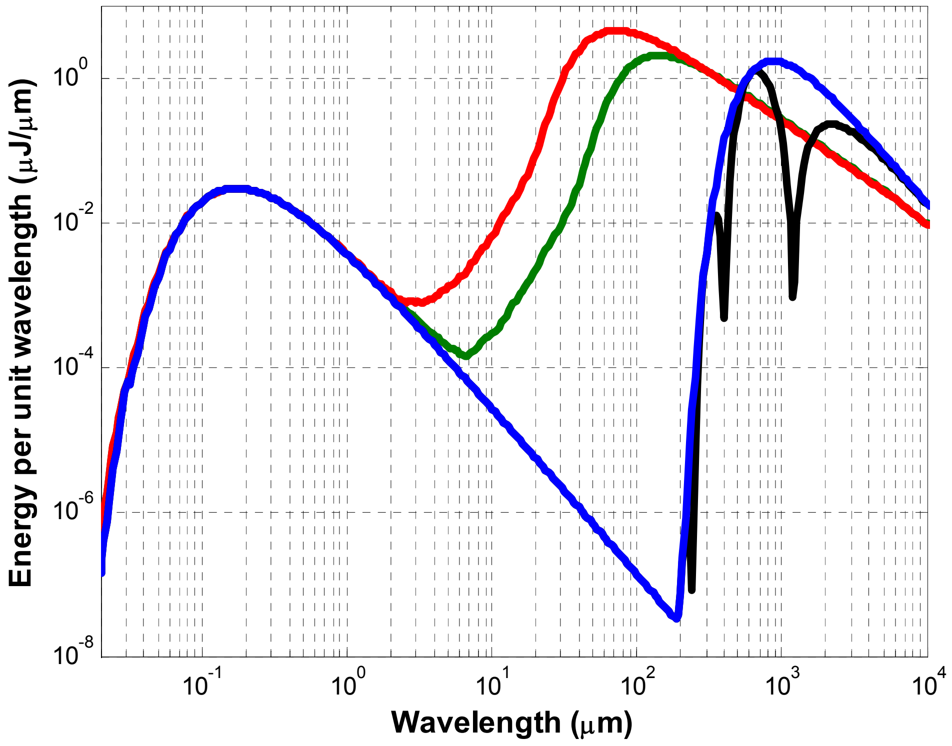
FWHM=40 μm



Courtesy O. Grimm (DESY)

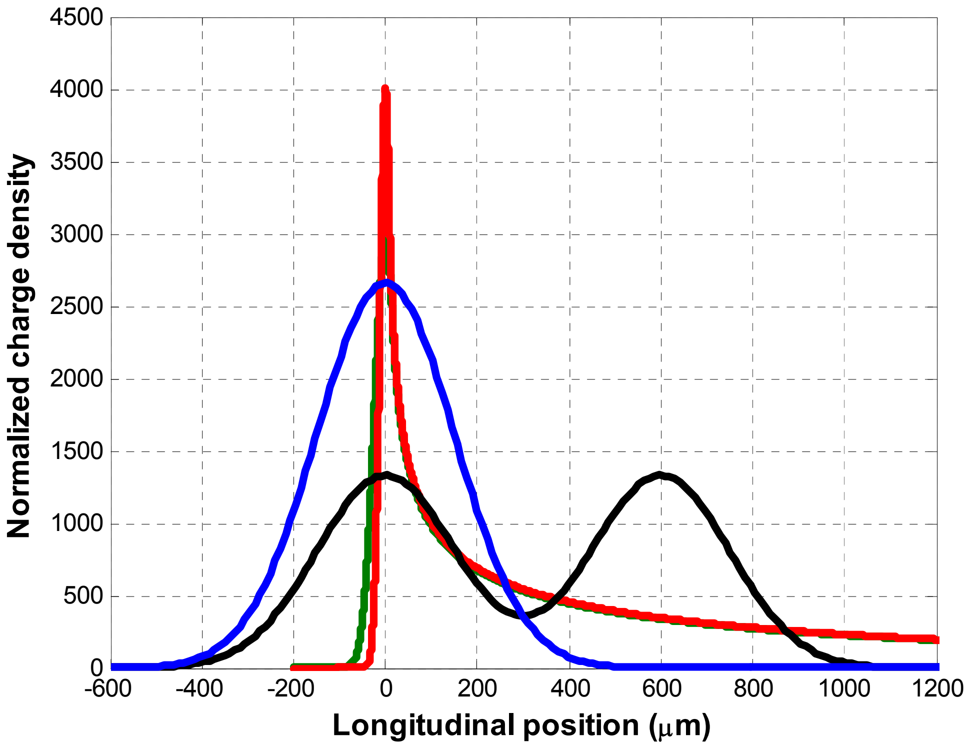
Basic Principle of CRD

- synchrotron radiation spectrum for charge 1 nCb
  - circular motion, E = 130 MeV, ρ = 1.6 m



Double Gaussian Bunch

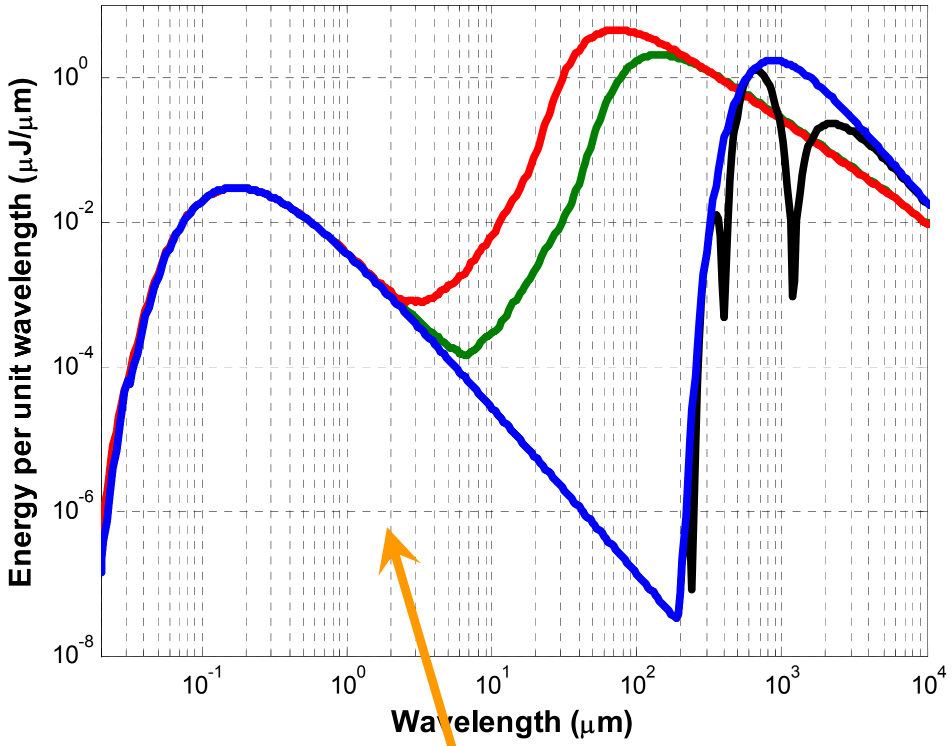
FWHM=350 µm, Δ=600 µm



Courtesy O. Grimm (DESY)

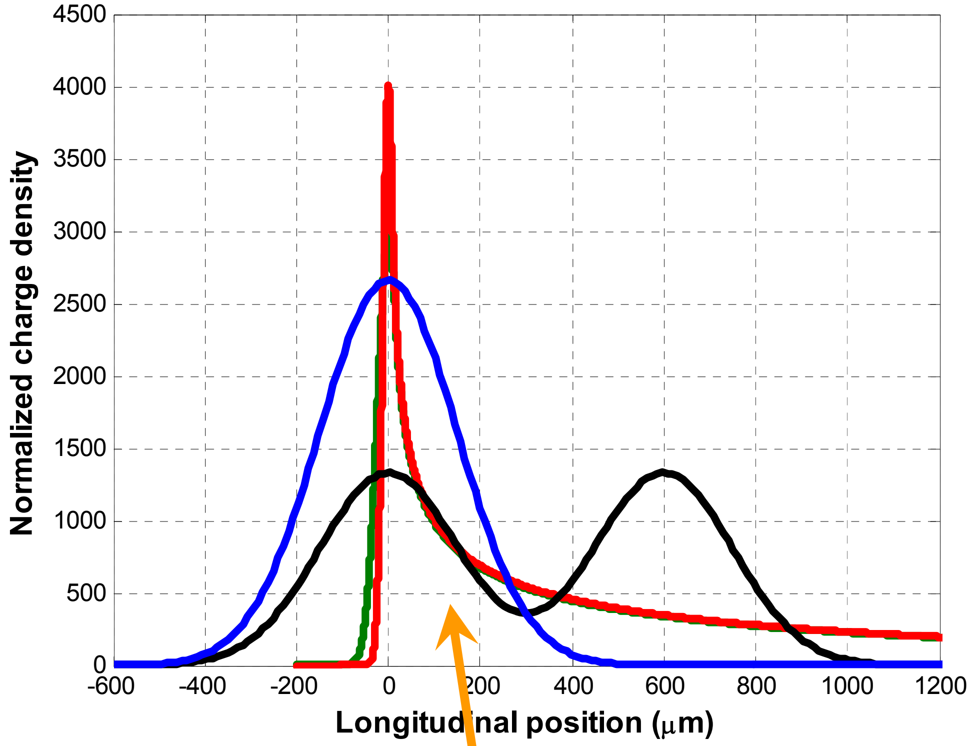
Basic Relation of CRD

Courtesy O. Grimm (DESY)



Double Gaussian Bunch

FWHM=350 μm, Δ=600 μm

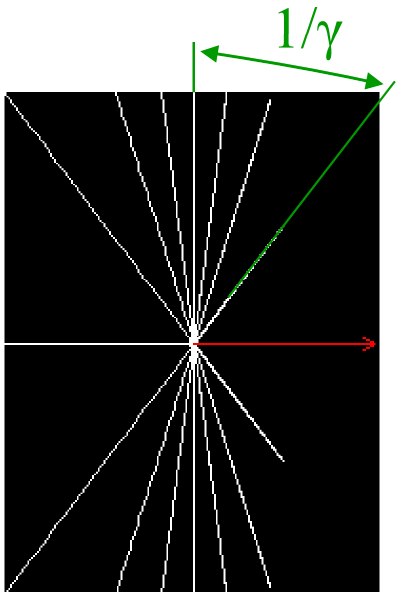


$$\boxed{\frac{\mathrm{d}U}{\mathrm{d}\lambda}} = \left(\frac{\mathrm{d}U}{\mathrm{d}\lambda}\right)_1 \left(N + N(N-1)\left|F(\lambda)\right|^2\right) \quad F(\lambda) = \int \boxed{S(z)e}^{\frac{2\pi \mathrm{i}z}{\lambda}} \mathrm{d}z$$

→ Emission spectrum depends on *longitudinal* charge distribution

Radiation Generation

- radiation generation via particle electromagnetic field



electric field lines
in LAB frame

Lorentz factor

$$\boxed{\gamma = E / m_0 c^2}$$

E : total energy

$m_0 c^2$: rest mass energy

$\gamma \to \infty$: plane wave

- $mc^2 = 0$ MeV : light → „real photon“
- ultra relativistic energies : idealization → „virtual photon“

- exploit analogy between real/virtual photons:

- light reflection/refraction at surface	↔	backward/forward transition radiation (TR)
- light diffraction at edges	↔	diffraction radiation (DR)
- light diffraction at grating	↔	Smith-Purcell radiation

Radiation Source

reminder: coherent radiation diagnostics

- **principle:** bunch length/shape dependent emission spectrum of coherent radiation

single particle spectrum

bunch form factor

$$\frac{dU}{d\lambda} = \boxed{\left(\frac{dU}{d\lambda}\right)_1} \left(N + \boxed{N}(N-1)\left|\boxed{F(\lambda)}\right|^2\right) \qquad \text{with} \qquad \boxed{F(\lambda)} = \int dz\, \boxed{S(z)}\, e^{i\frac{2\pi z}{\lambda}}$$

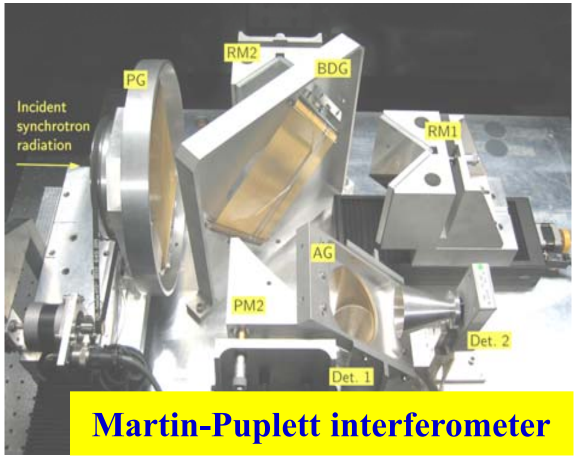
no. of particles per bunch

bunch profile

- spectral decomposition and Fourier transform:
  → bunch length and shape

- transition radiation (TR), diffraction radiation (DR):
  - polychromatic angular disribution

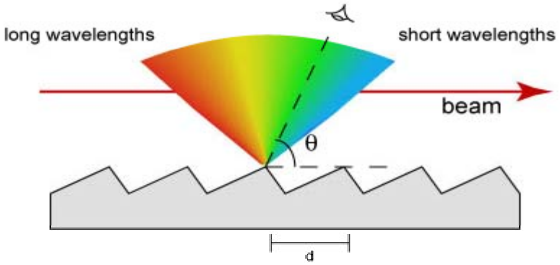
  → spectrometer for decomposition



Martin-Puplett interferometer

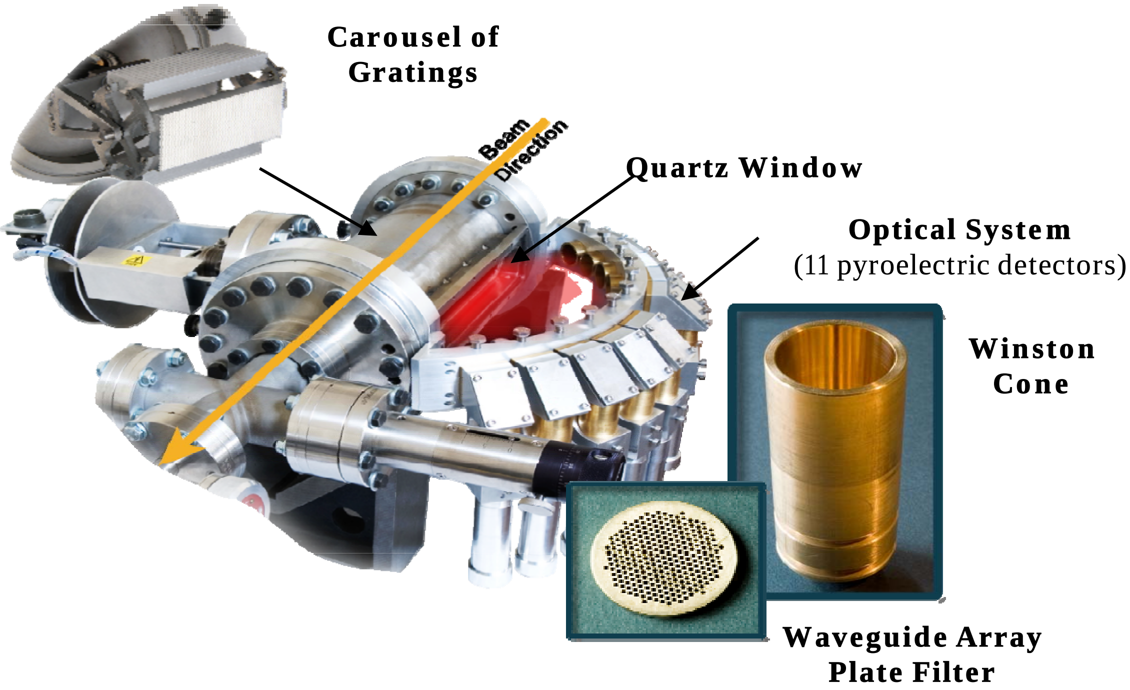
- Smith-Purcell radiation (SPR):
  - (virtual) photon diffraction at 1D Bravais-structure
  - grating provides discrete momenta $p_n = n\, 2\pi\hbar / d$
  - angular distribution wavelength-dependent

  → no additional spectrometer



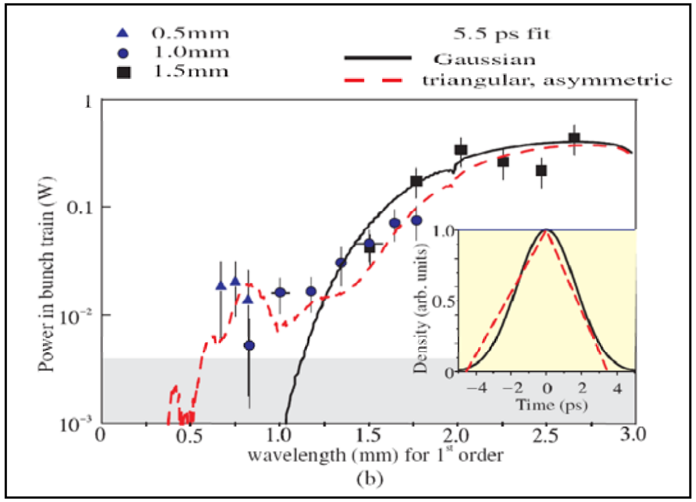
SPR Bunch Length Diagnostics

- bunch length monitor based on Smith-Purcell radiation



Courtesy G. Doucas, V. Blackmore (Oxford)

Measurement at 45 MeV, FELIX



G. Doucas et al., PRST 9 (2006) 092801

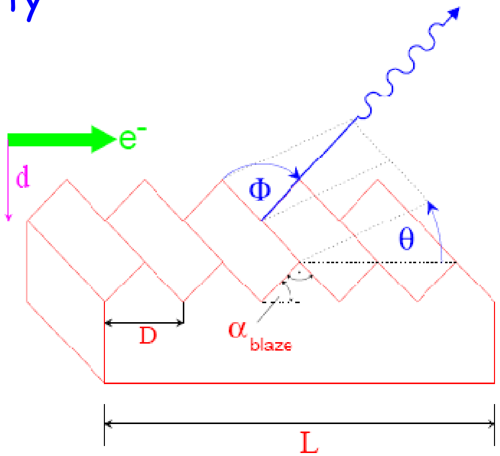
Experiment at 28.5 GeV, SLAC

V.Blackmore et al., PRST 12 (2009) 032803

- critical items
  - number of detectors limits the number of points for reconstruction
    → interferometer: about 200 points
  - influence of the grating structure

Smith-Purcell Radiation

- intensity



$$\frac{d\dot{N}}{d\Omega} = \alpha \cdot n \cdot \frac{I}{e} \cdot \frac{L}{D} \cdot |R_n|^2 \cdot \frac{\sin^2\theta \cdot \sin^2\Phi}{(1/\beta - \cos\theta \cdot \sin\Phi)^2} \cdot e^{-\kappa \cdot d}$$

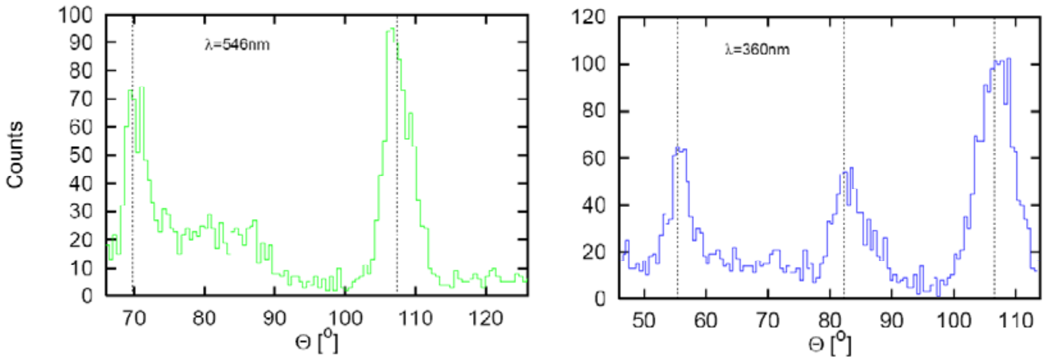
α : fine structure constant
n : diffraction order
I : beam current
e : elementary charge
D : spacing of grooves
L : grating length
d : distance between beam and grating surface
R_n : radiation factor, $R_n = R_n(\gamma, \theta, \Phi, \alpha_{blaze})$
θ, Φ : angle of observation
κ : evanescent scale, $\kappa = h_{int}^{-1} \cdot \sqrt{1 + (\beta\gamma\cos\Phi)^2}$
h_{int} : interaction length

$$\boxed{h_{int} = \frac{\beta\gamma}{4\pi} \cdot \lambda}$$

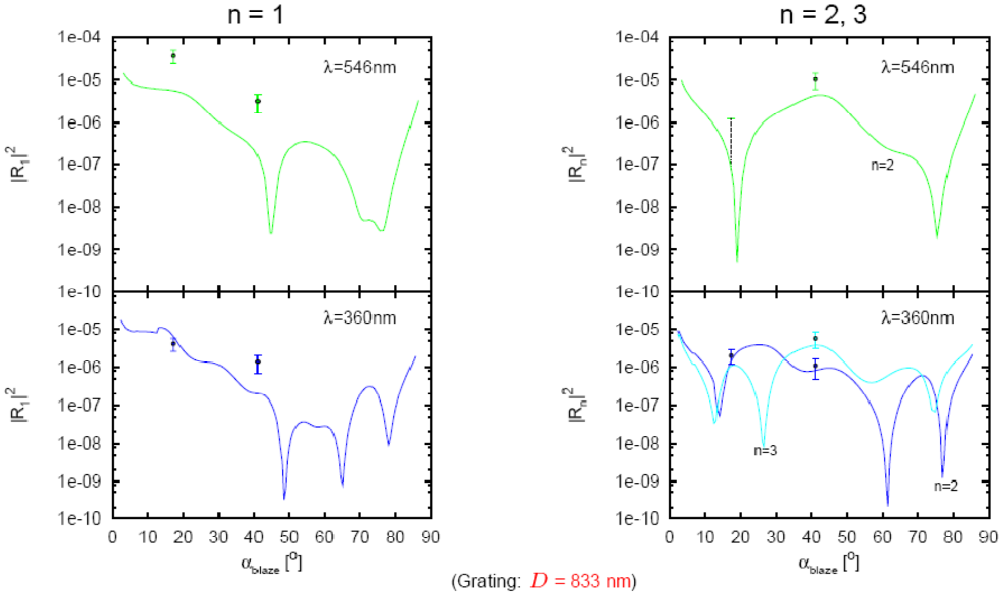
P.M.van den Berg, J.Opt.Soc.Am. 63 (1973) 1588

- coherence condition $\boxed{n\lambda = D\left(1/\beta - \cos\Theta\right)}$

E = 855 MeV, D = 833 nm, α_{blaze} = 41.12°



- radiation factor

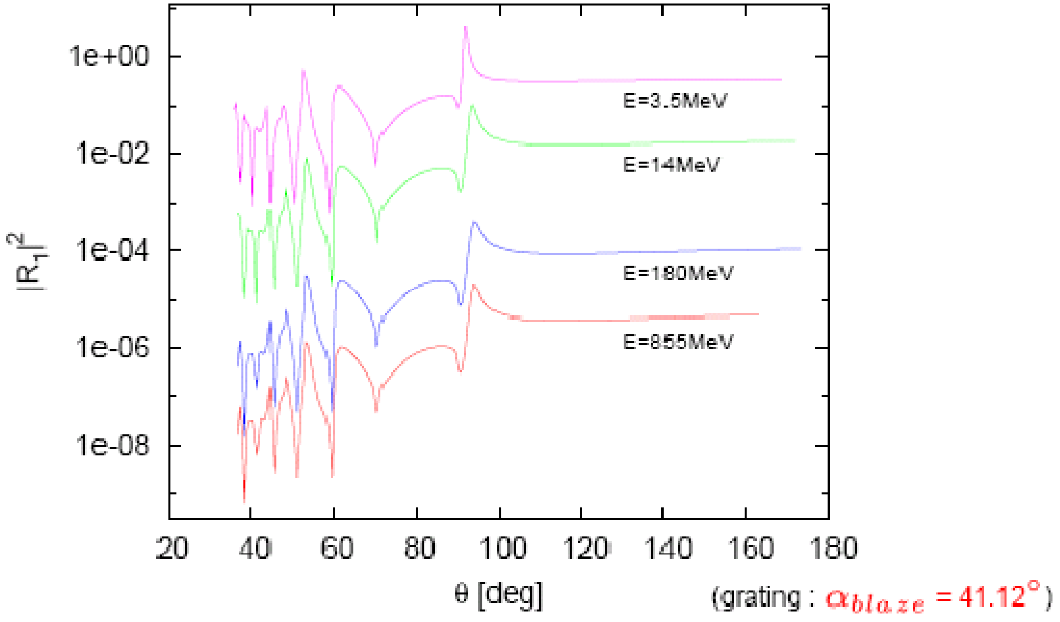


(Grating: D = 833 nm)

G.Kube et al., Phys.Rev. E 65 (2002) 056501

SP Radiation Factors

- radiation factors for blazed gratings



P.M.van den Berg, J.Opt.Soc.Am. 63 (1973) 1588

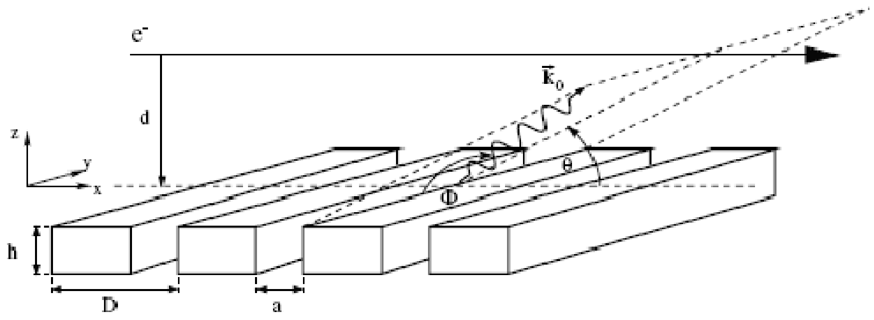
- pronounced resonance structures
  → Wood-Rayleigh anomalies
  (optical grating theories)

- strong modification of $\frac{dU}{d\lambda}$
  → decreased sensitivity on bunch length

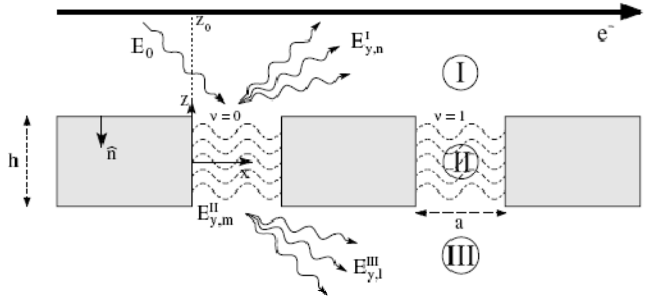
G.Kube, Proc. DIPAC ‘03, Mainz (Germany) 2003, p.40

- volume strip grating

G.Kube, Nucl.Instrum.Meth. B 227 (2005) 180



- solution for reflected and transmitted field
  → modal expansion



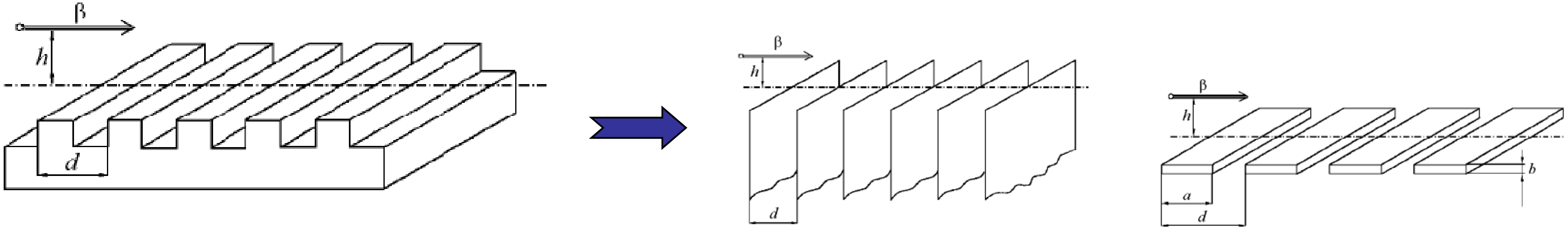
- limit h → 0:
  → influence of resonances to neglect
  → better suited for bunch length diagnostics

SPR and RDR

- Smith-Purcell radiation from periodic stack of diffraction radiators

A.P.Potylitsyn, Nucl.Instrum.Meth. B 145 (1998) 60

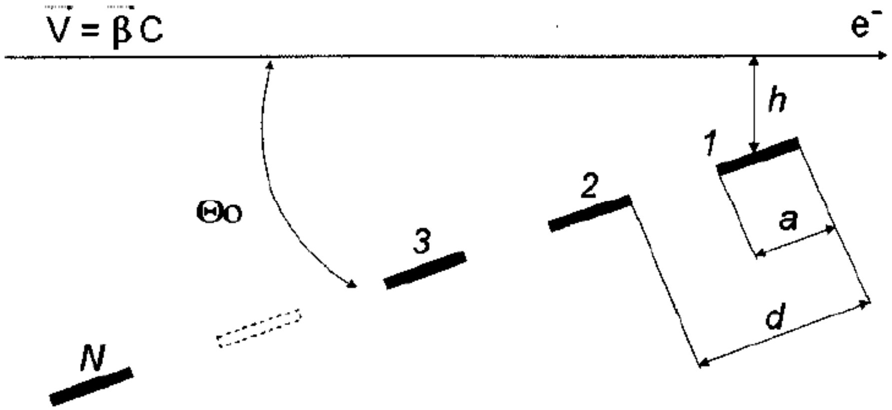
A.P.Potylitsyn and M.N.Strikhanov, Rus.Phys.J. 45 (2002) 905



Resonant Diffraction Radiation

- Resonant diffraction radiation from inclined target

A.P.Potylitsyn, P.V.Karataev and G.A.Naumenko, Phys.Rev. E 61 (2000) 7039



RDR from inclined Targets

… and application for bunch length diagnostics

A.P.Potylitsyn, D.V.Karlovets, G.Kube, Nucl.Instrum.Meth. B 226 (2008) 3781

- critical items
  - number of detectors limits the number of points for reconstruction

    - use of one/two detectors at fixed positions
    - variation of grating inclination angle wrt. beam axis

    → reduced number of detectors has additional advantage:
    sensitivity of each individual detector must be known with high accuracy
    (reconstruction of bunch shape relies on absolute intensities)

  - influence of the grating structure

    - use strip grating instead of reflection grating to avoid resonance structures

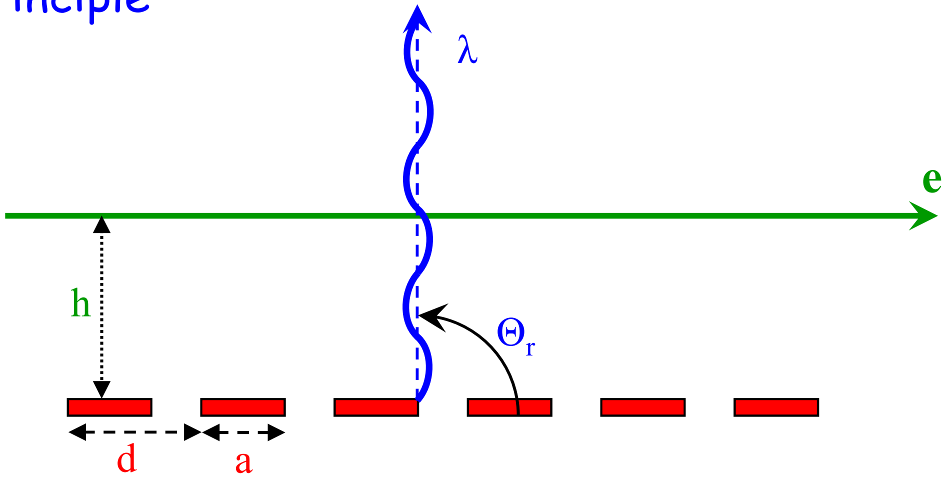
    → strip grating allows to exploit transmitted and reflected radiation at the same time

- proposed DITANET project
  - experiment to be carried out at 100 MeV injector linac of Swiss Light Source (PSI)
  - develop monitor for beam tuning (no high resolution measurements)
  - collaboration between DESY, PSI and Tomsk Polytechnic University (Russia)
  - looking for Experienced Researcher

… still searching for suitable candidate

RDR for Bunch Length Diagnostics

- principle

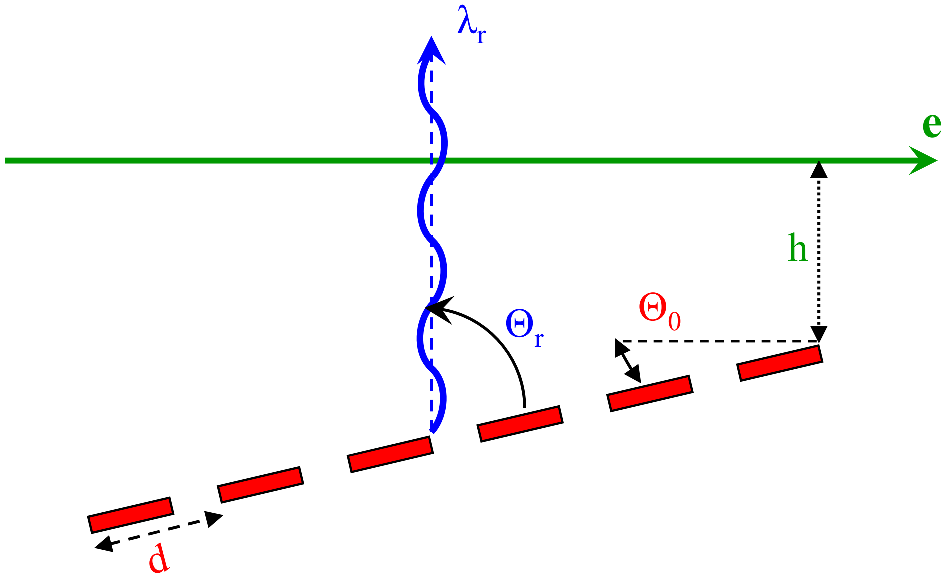


- coherence condition

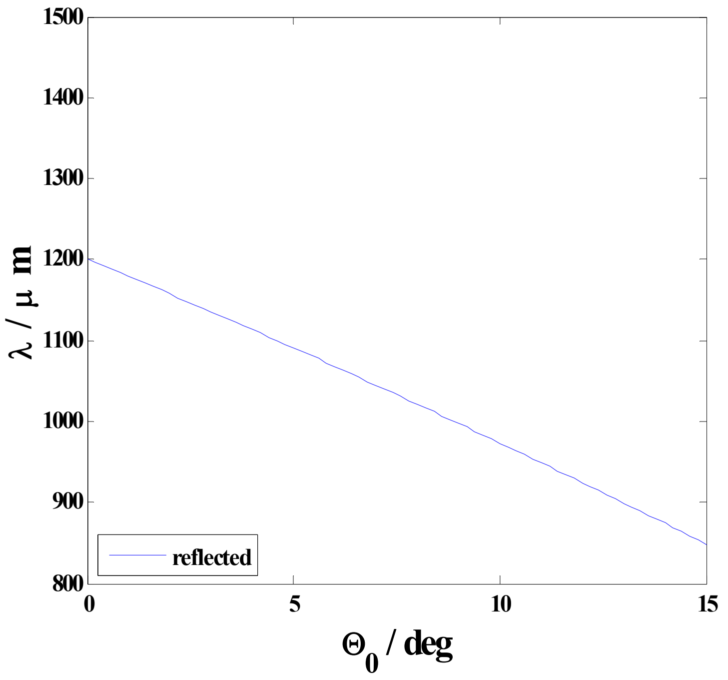
$$n\lambda = d\,(1/\beta - \cos\Theta)$$

RDR for Bunch Length Diagnostics

- principle



- spectral decomposition



n = 1, d = 1.2 mm, γ = 200

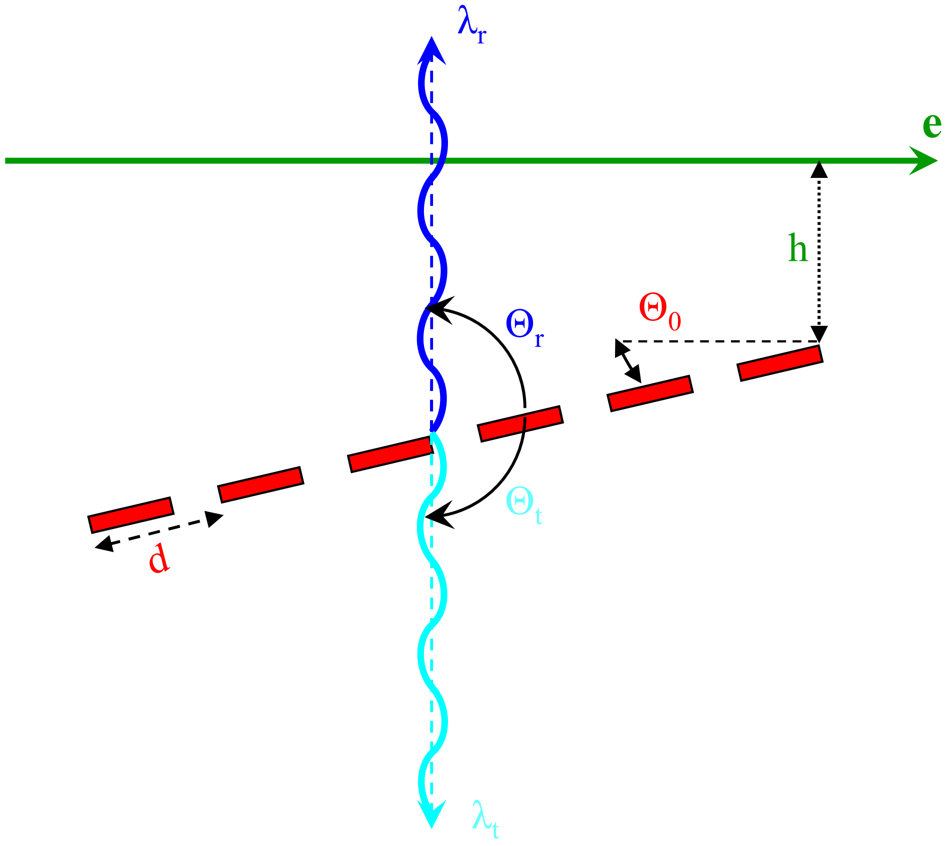
- coherence condition

$$n\lambda = d\left(\cos\Theta_0/\beta - \cos(\Theta - \Theta_0)\right)$$

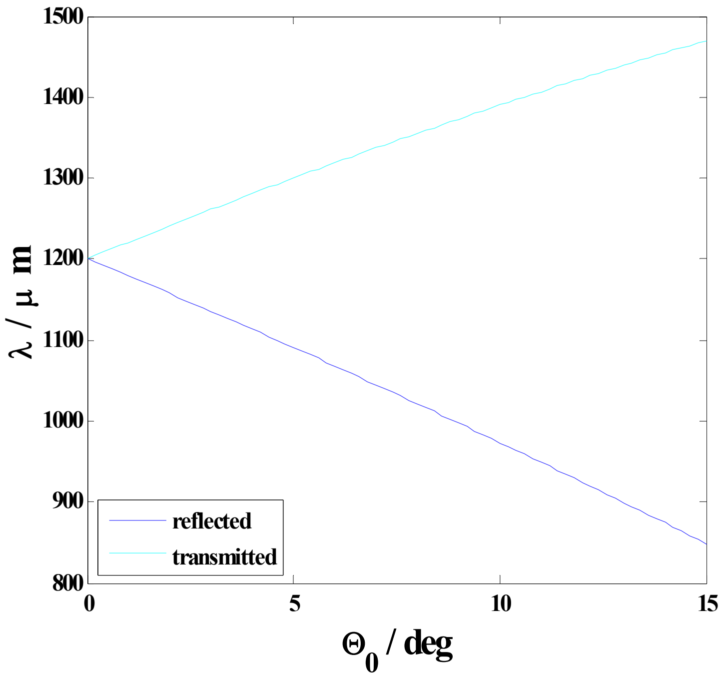
with $\Theta = \Theta_r = +90^\circ$

RDR for Bunch Length Diagnostics

- principle



- spectral decomposition



n = 1, d = 1.2 mm, $\gamma = 200$

- coherence condition

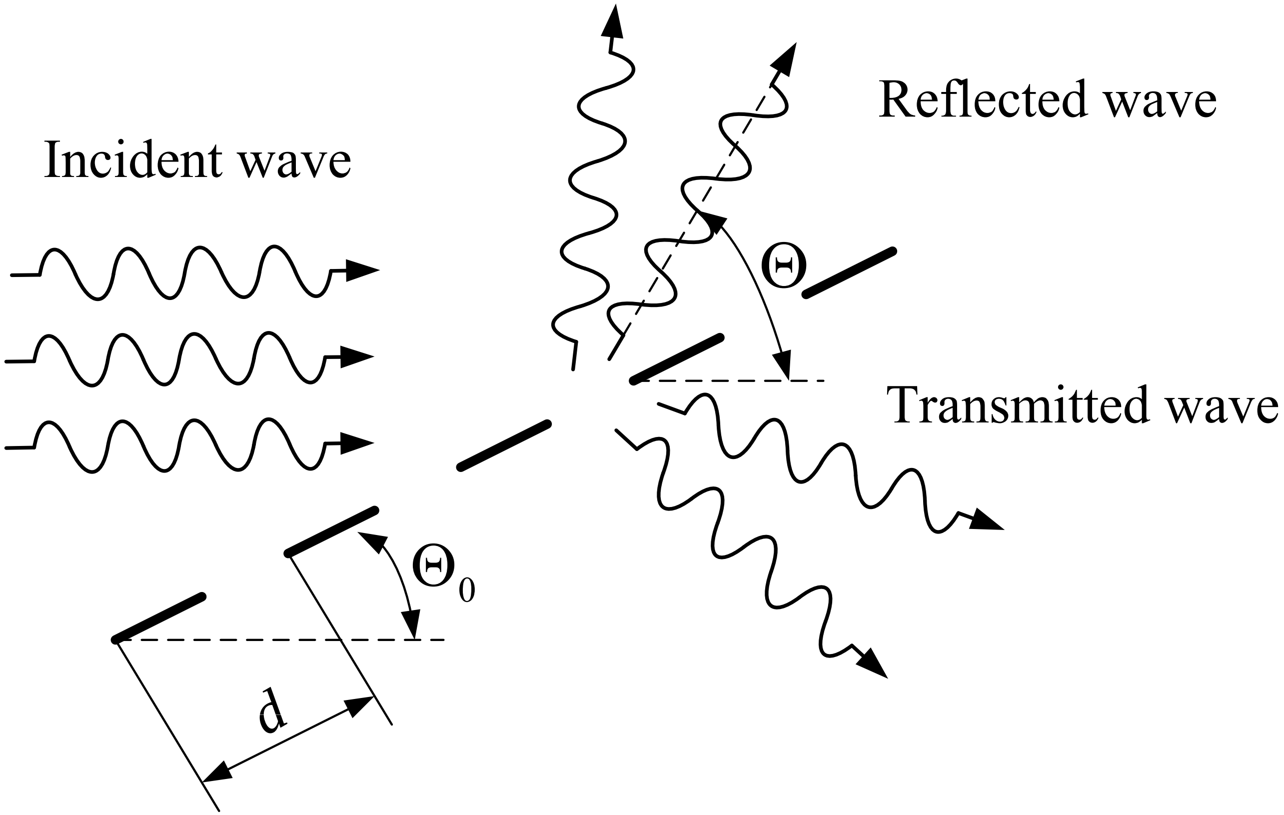
$$\boxed{n\lambda = d\left(\cos\Theta_0/\beta - \cos(\Theta - \Theta_0)\right)}$$

with $\Theta = \Theta_r = +90^\circ$

$\Theta = \Theta_t = -90^\circ$

Optical Analogon

Analogy from classical optics:
semi-transparent grating

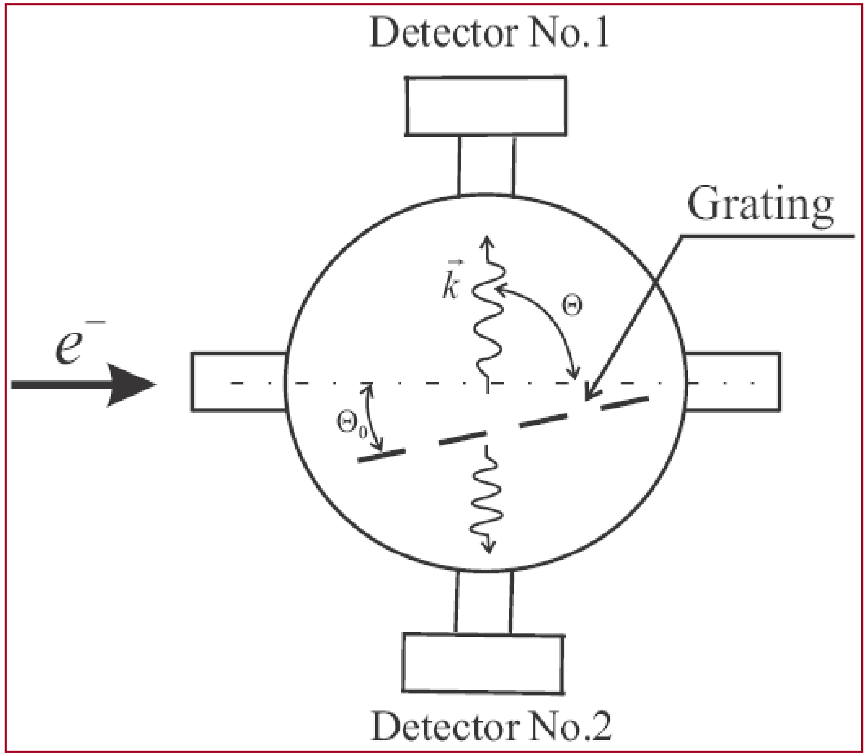


$$\lambda_n = \frac{d}{n}\left(\cos\Theta_0 - \right.$$
$$\left. -\cos(\Theta_0 - \Theta)\right)$$

$$\lambda_n = \frac{d}{n}\left(\cos\Theta_0 - \right.$$
$$\left. -\cos(\Theta_0 + \Theta)\right)$$

Proposed RDR Experiment

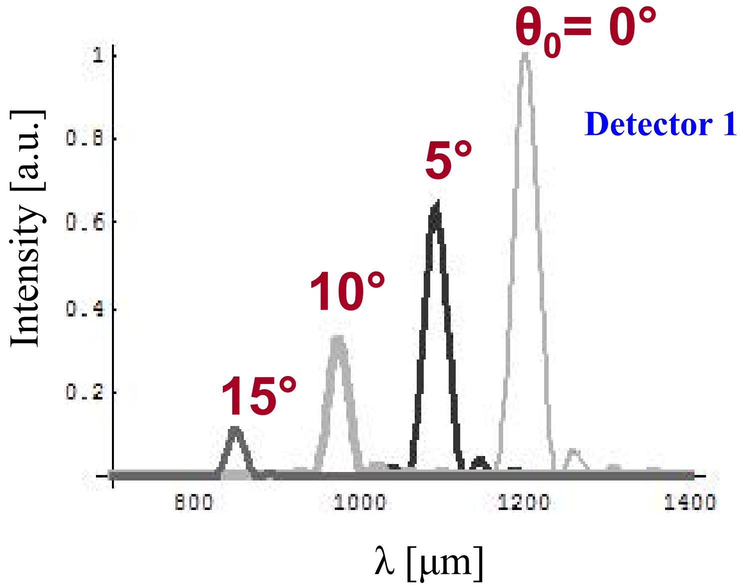
- experimental scheme

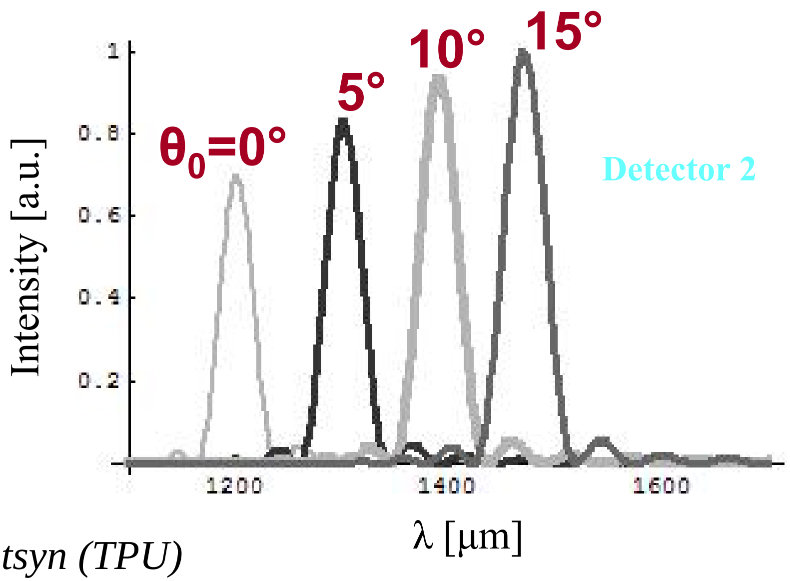


- parameters

grating period	d = 1.2 mm
number of grating strips	N = 30
beam energy	$\gamma = 200$
bunch length (Gaussian)	$\sigma = 0.44$ mm
observation angle	$\Theta = \pm 90°$

- signature

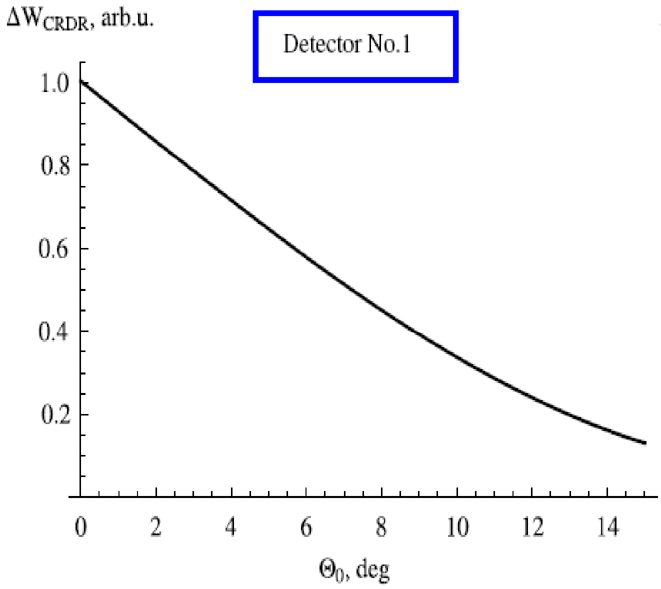


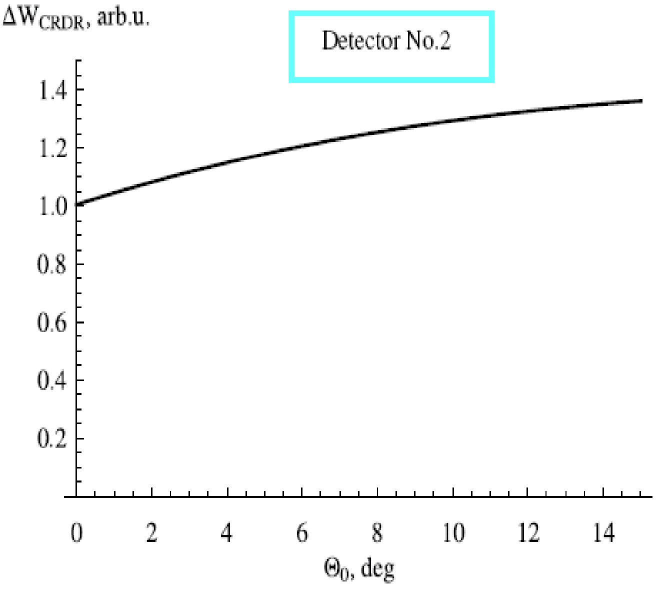


Courtesy A.P. Potylitsyn (TPU)

RDR Intensity Dependence

- intensity dependence





- parameters

grating period	d = 1.2 mm
strip width	a = d/2
number of periods	N = 30
beam energy	$\gamma = 200$
bunch length (Gaussian)	$\sigma = 0.44$ mm
observation angle	$\Theta = \pm 90°$
detector aperture	S = 1 cm^2
distance detector/grating	$r_0 = 1$ m

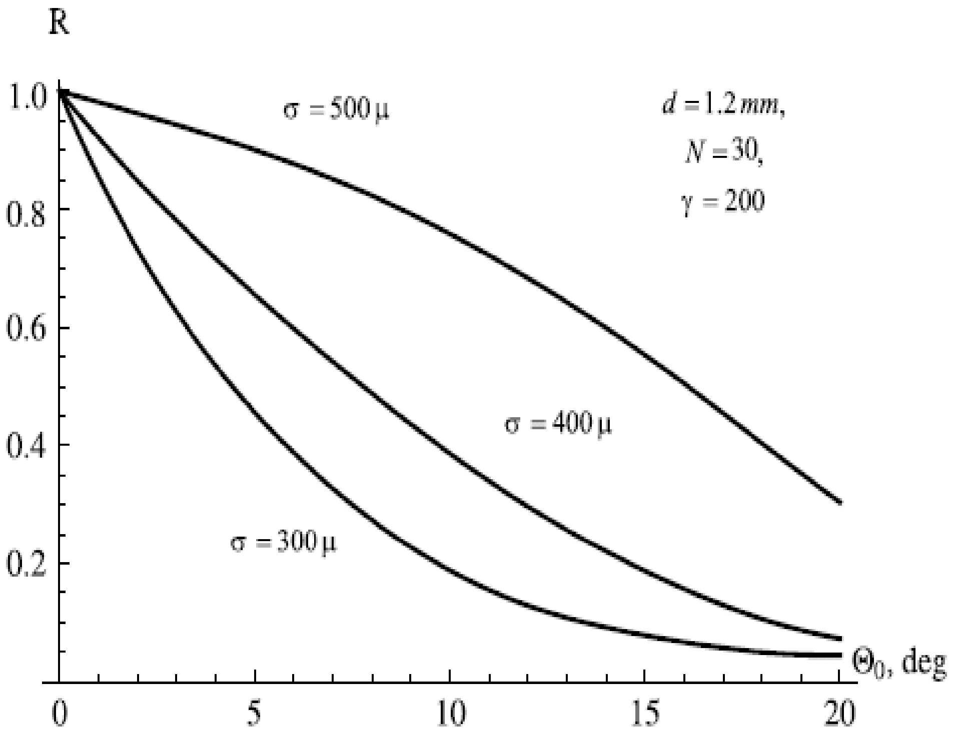
- detector 1: increase of grating tilt angle Θ_0
  - → wavelength shift to smaller λ
  - → reduced contribution of coherent emission
  - → **intensity decrease**

- detector 2: increase of grating tilt angle Θ_0
  - → wavelength shift to larger λ
  - → increased contribution of coherent emission
  - → **intensity increase**

…parameter optimization to increase sensitivity

RDR Signal Ratio

- difficulty
  - knowledge of absolute intensity required
  - spectral response of each individual element must be known to high level of accuracy
- simplification
  - intensity ratio of D1/D2



  - ratio sensitive on beam size variation
  - prerequisite: detectors with flat response

→ **simple monitor for beam tuning**

RDR Power Estimation

- coherent RDR yield for parallel orientation

grating period	$d = 1.2$ mm → $\lambda = 1.2$ mm
strip width	$a = d/2$
number of periods	$N = 30$
tilt angle	$\Theta_0 = 0°$
beam energy	$\gamma = 200$
bunch length (Gaussian)	$\sigma = 0.44$ mm
distance beam/grating	$h = 2$ mm
observation angle	$\Theta = \pm 90°$

$$\frac{dW_{CRDR}}{d\Omega} \approx 3 \cdot 10^{13} \frac{\mathrm{eV}}{\mathrm{sr\ \ bunch}}$$

- measured yield

detector aperture	$S = 1\ \mathrm{cm}^2$
distance detector/grating	$r_0 = 1$ m

$$\Delta W_{CRDR} \approx 0.5 \frac{\mathrm{nJ}}{\mathrm{bunch}}$$

- estimated power level

$$P_{CRDR} \approx \Delta W_{CRDR} / \tau_b$$

τ_b : bunch duration $\approx 2.36\sigma/c \approx 3.5\,\mathrm{psec}$

$$P_{CRDR} \approx 140\,\mathrm{W}$$

→ **high power level even allows use of broadband room-temperature detectors**

G. Naumenko, A. Potylitsyn, G. Kube, O. Grimm, V. Cha, Yu. Popov, Nucl.Instrum.Meth. A 603 (2009) 35

Summary & Conclusion

- coherent radiation as tool for bunch length diagnostics
- Smith-Purcell radiation suitable radiation source
    - dispersive emission process → no additional spectrometer required
    - influence of grating structure → modification of intensity distribution
- Smith-Purcell radiation from flat strip grating
- radiation from inclined target
    - resonant diffraction radiation
- monitor concept for bunch length monitoring based on RDR
    - experimental proof of principle still pending

$\Rightarrow$ END