Coherent Radiation Diagnostics for Short Bunches

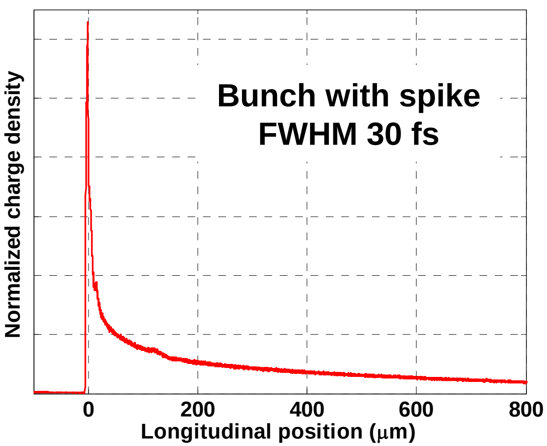
Bunch length measurement in the frequency domain

Oliver Grimm

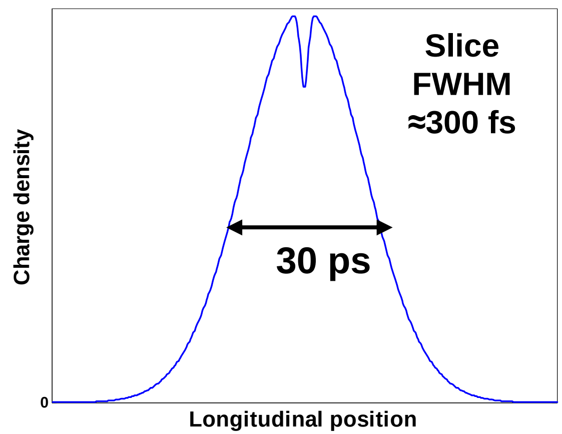
PAC, Albuquerque
28 June 2007

The **longitudinal charge distribution** is an important parameter for machine operation…

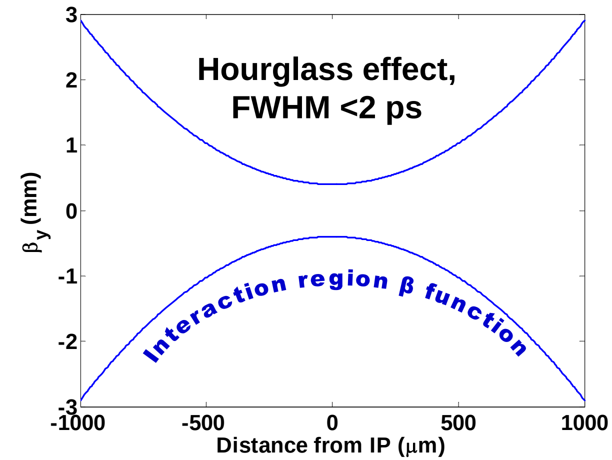
FEL



Bunch slicing

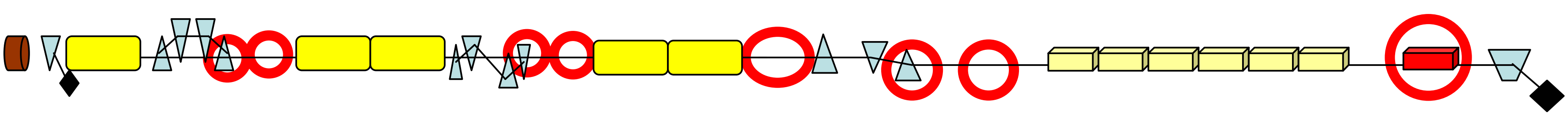


Linear collider



… and **difficult to measure** (non-destructively) for short and/or complicated bunches.

Example for CRD at FLASH (FEL at DESY)

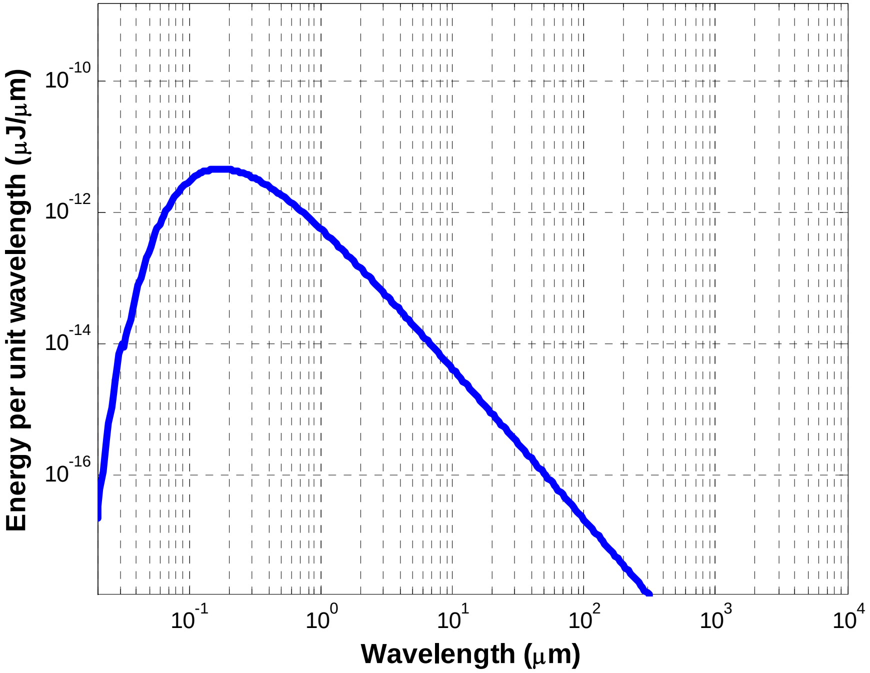


…also used at ALS, ANKA, BESSY, JAERI, NewSubaru, LCLS, SLS, UVSOR-II, ,…

Illustration of basic principle of CRD

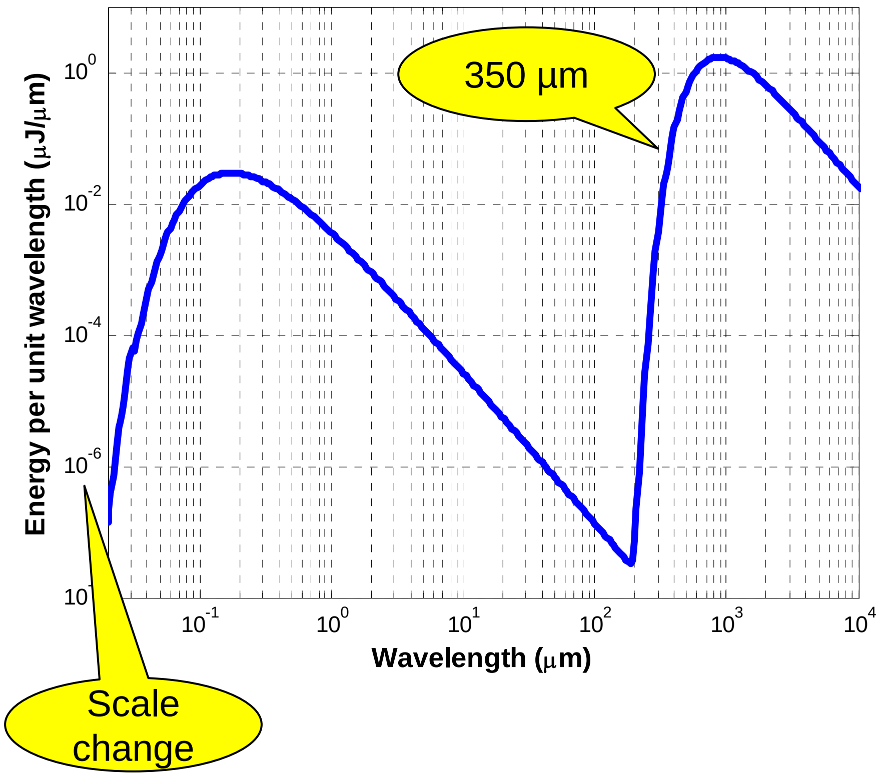
Single electron synchrotron radiation spectrum

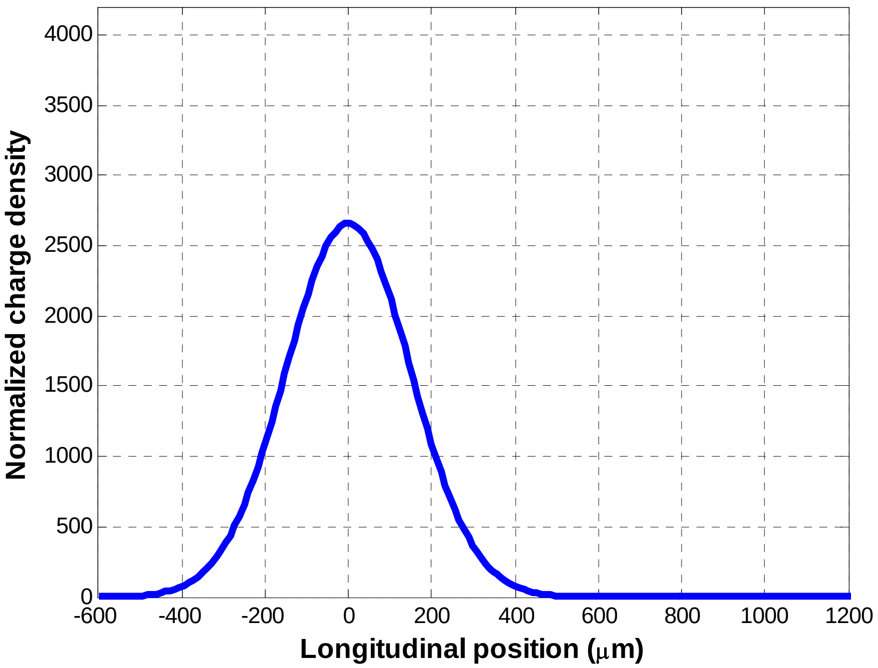
Circular motion, 130 MeV, R=1.6 m



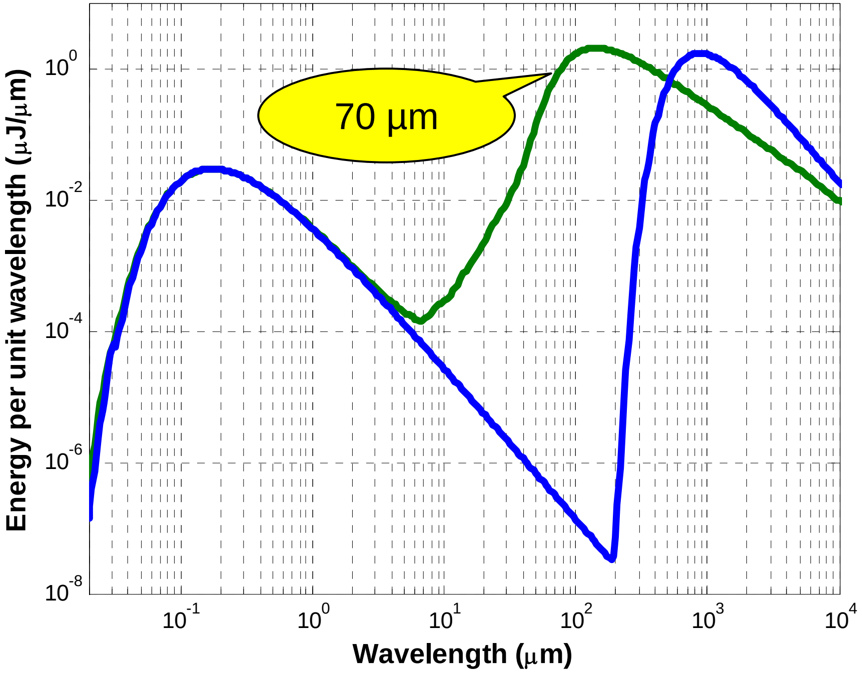
Gaussian (line) bunch

FWHM=350 µm



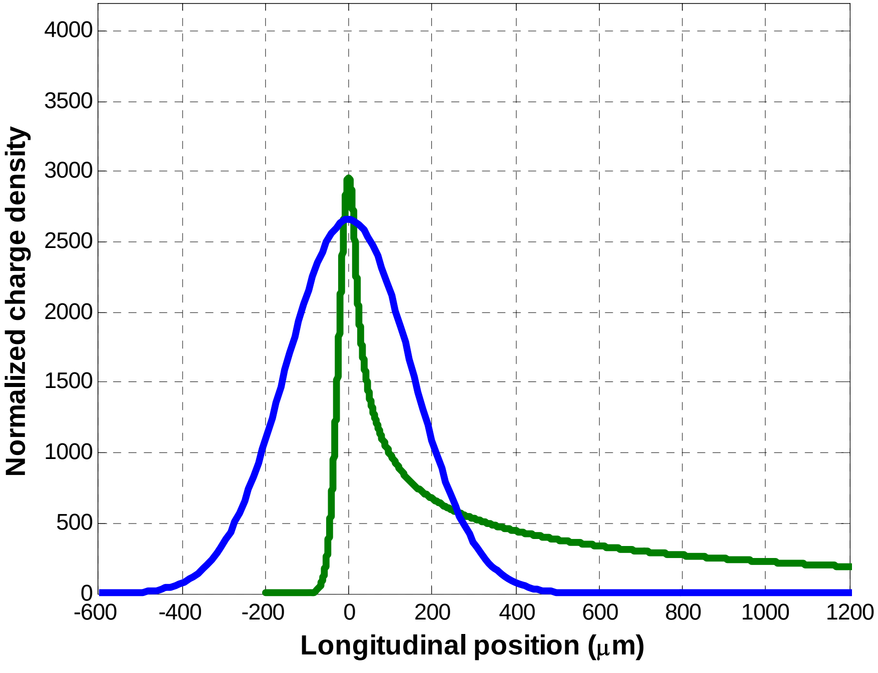


Charge 1 nC



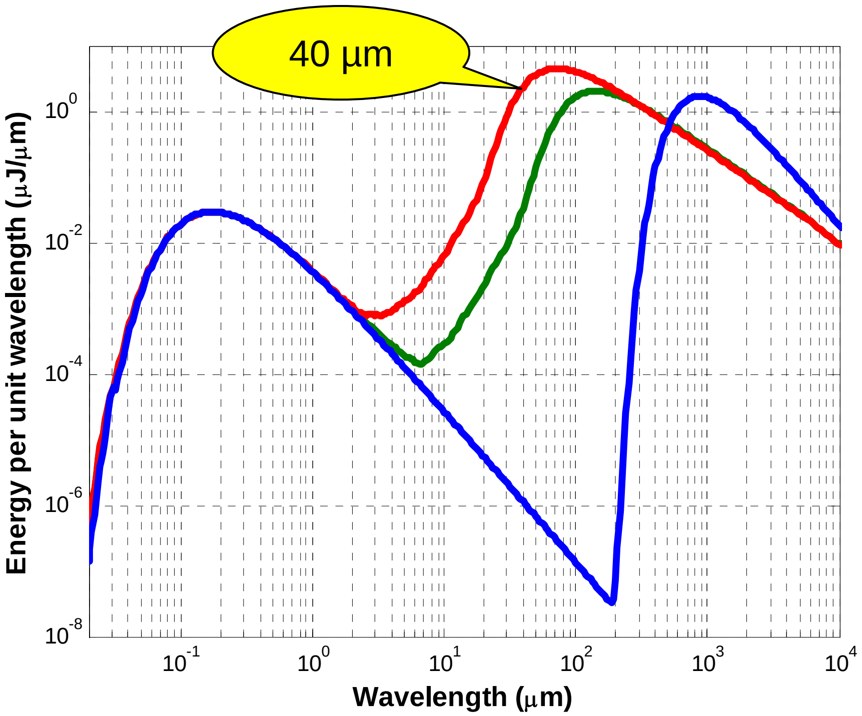
Spiked bunch

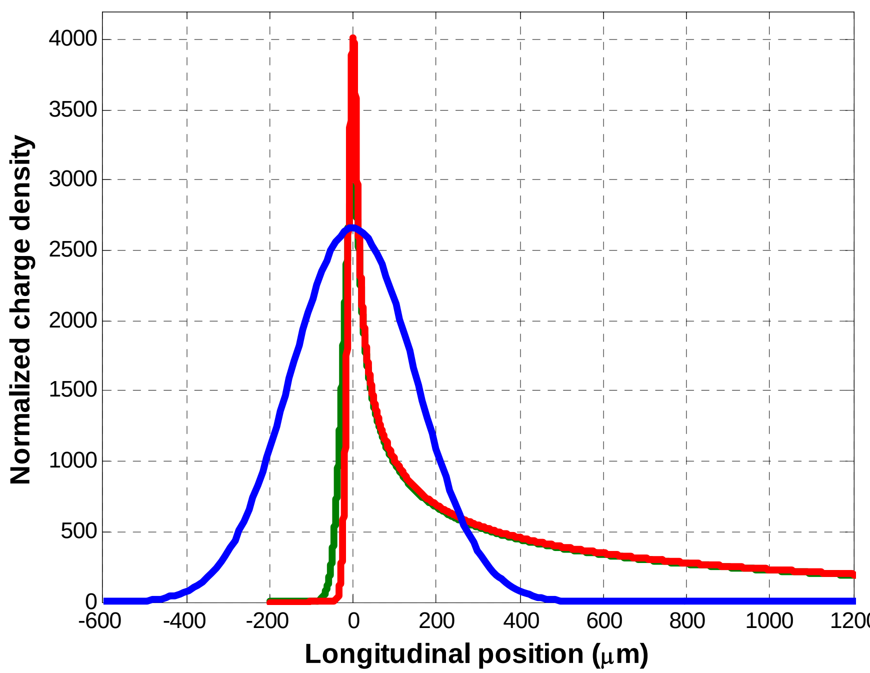
FWHM=70 µm



Spiked bunch

FWHM=40 µm

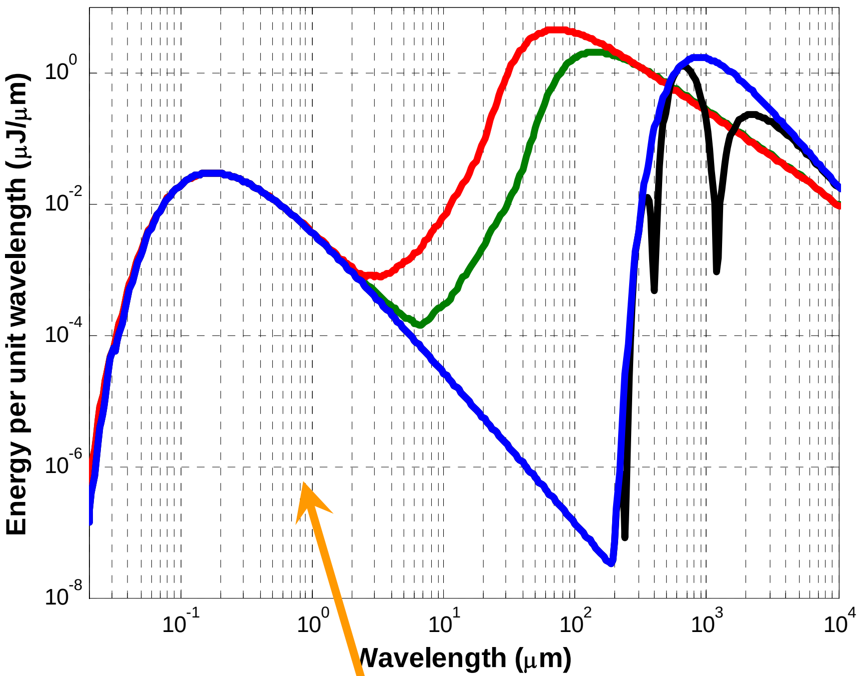




Basic relation of CRD

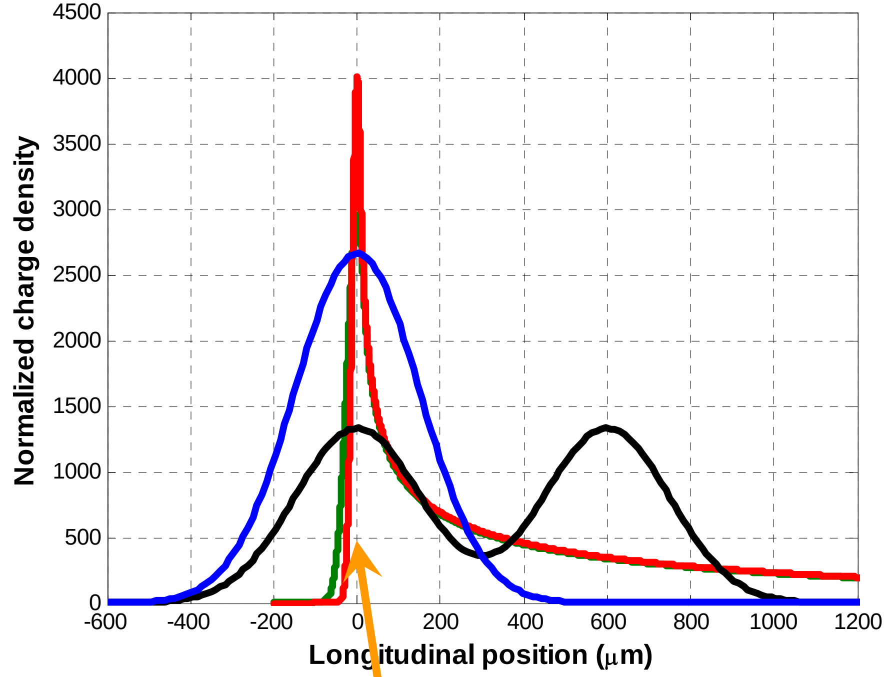
Emission spectrum depends on *longitudinal* charge distribution.

Transverse effects exist, not covered



Double Gaussian Bunch

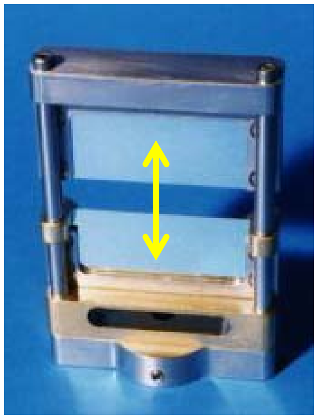
FWHM=350 μm, Δ=600 μm

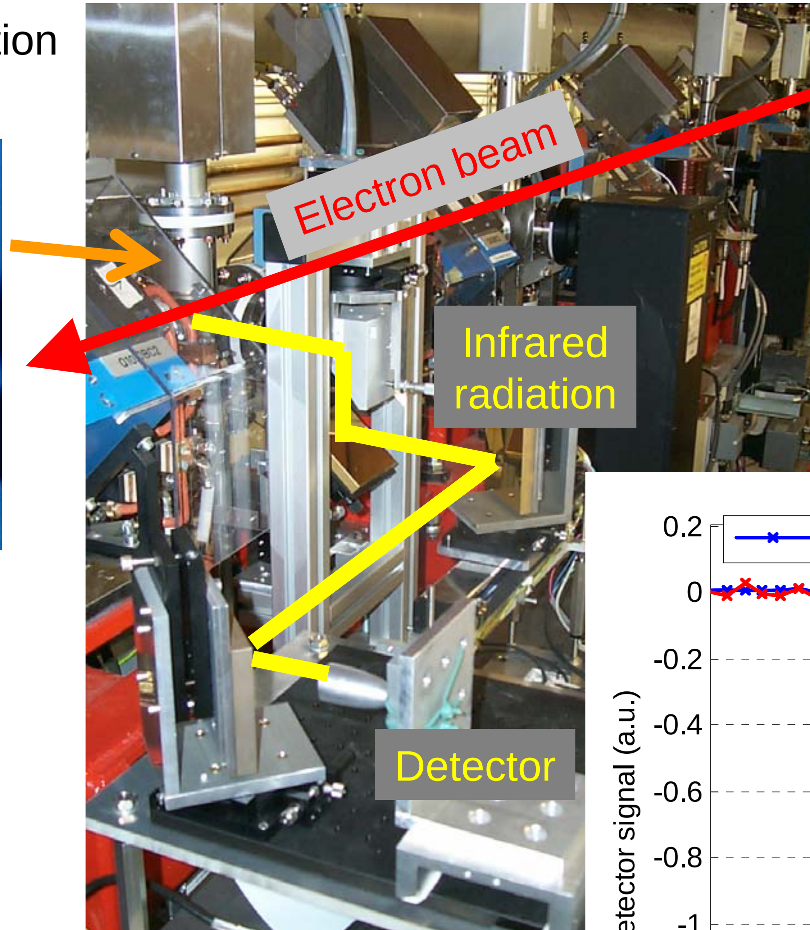


$$\frac{\mathrm{d}U}{\mathrm{d}\lambda} = \left(\frac{\mathrm{d}U}{\mathrm{d}\lambda}\right)_1 \left(N + N(N-1)\left|F(\lambda)\right|^2\right) \quad F(\lambda) = \int S(z) e^{\frac{2\pi i z}{\lambda}} \mathrm{d}z$$

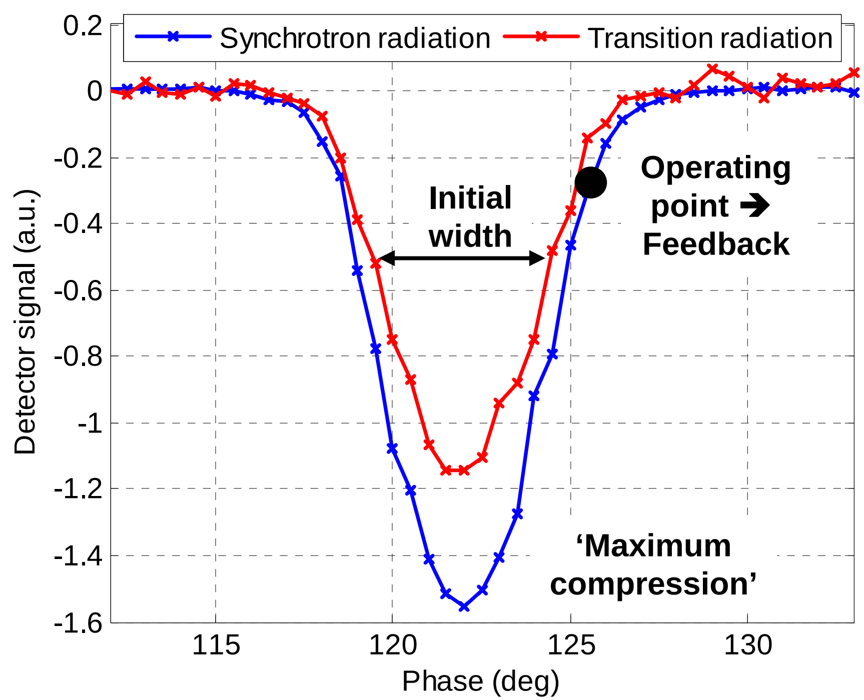
Bunch compression monitor

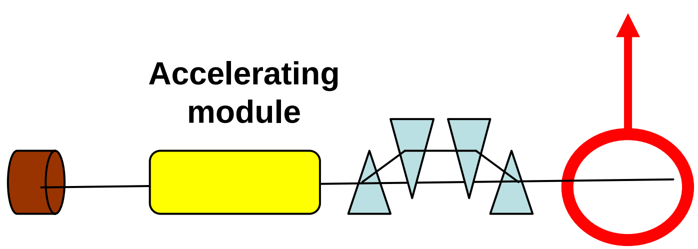
Transition/Diffraction Radiator



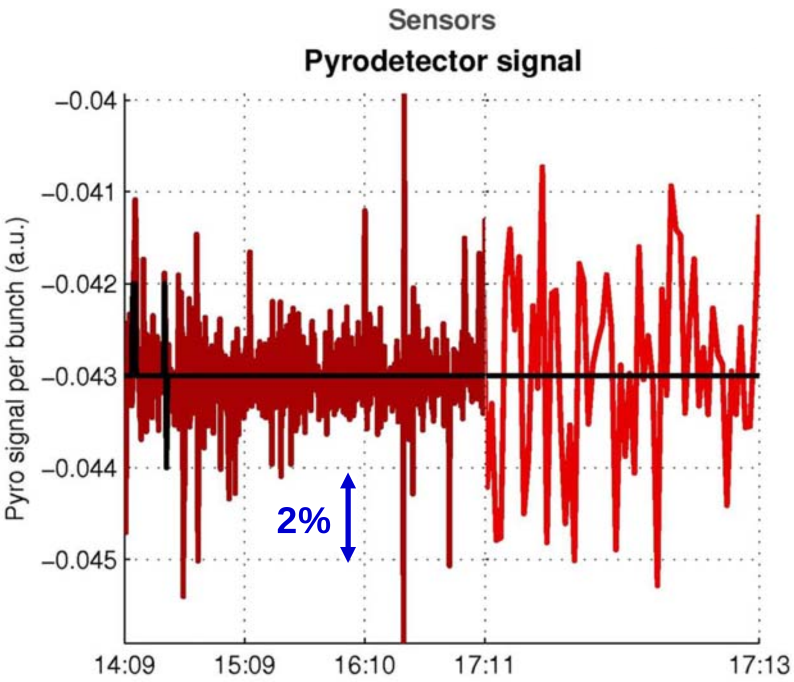


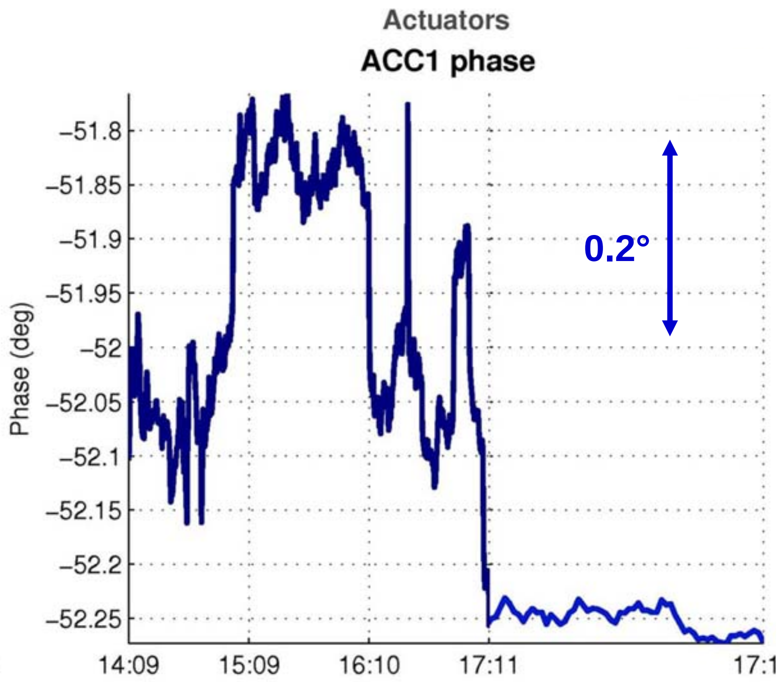
Phase/compression scan



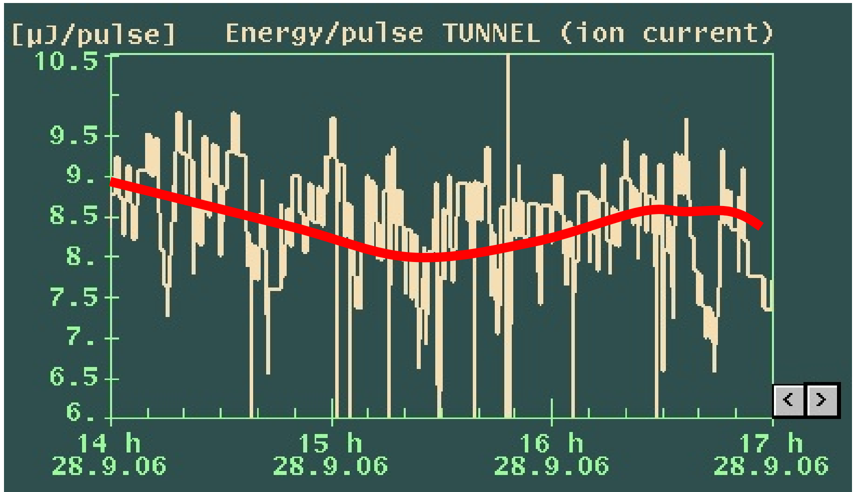


Compression monitor feedback on phase

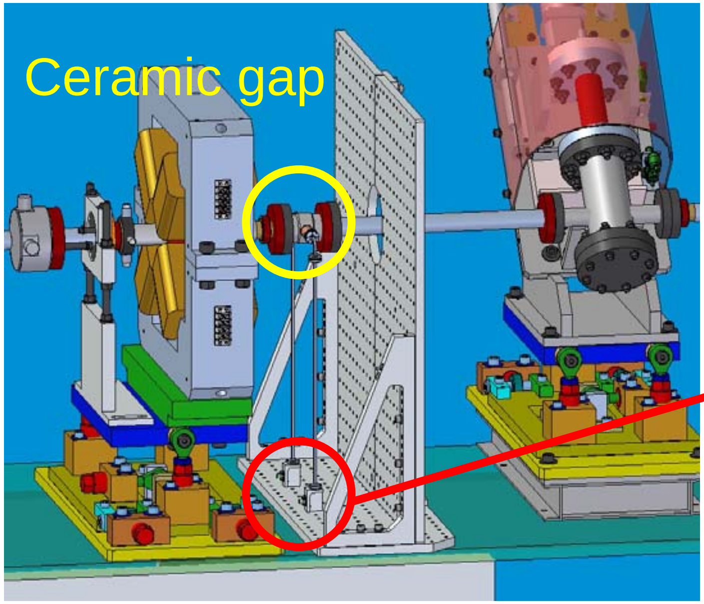


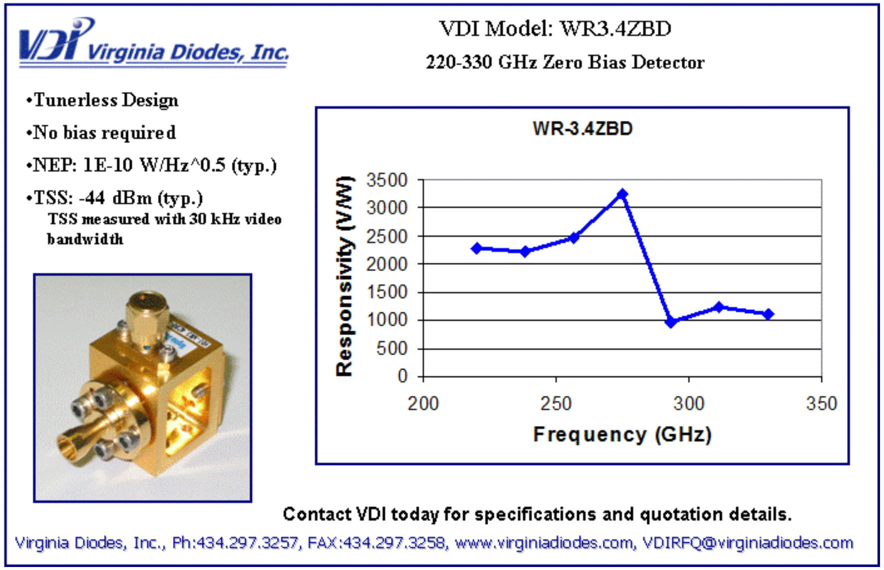


SASE intensity

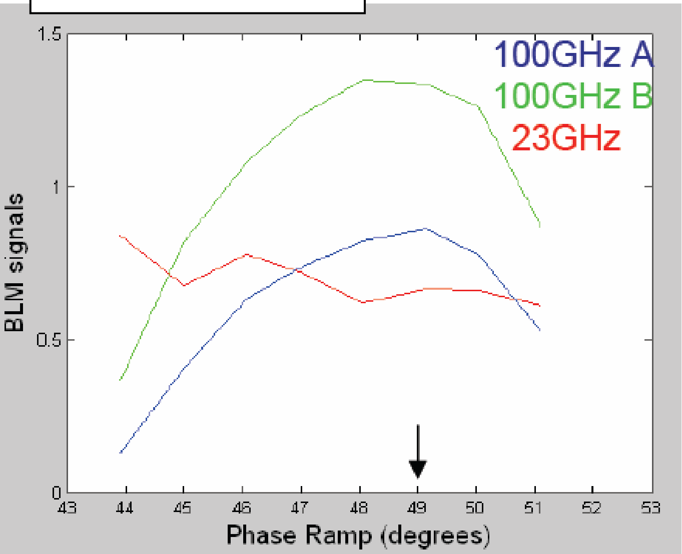


Diode detector as bunch compression monitor





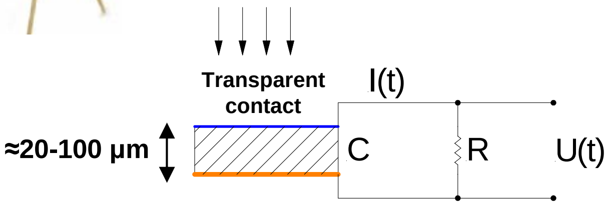
Phase scan



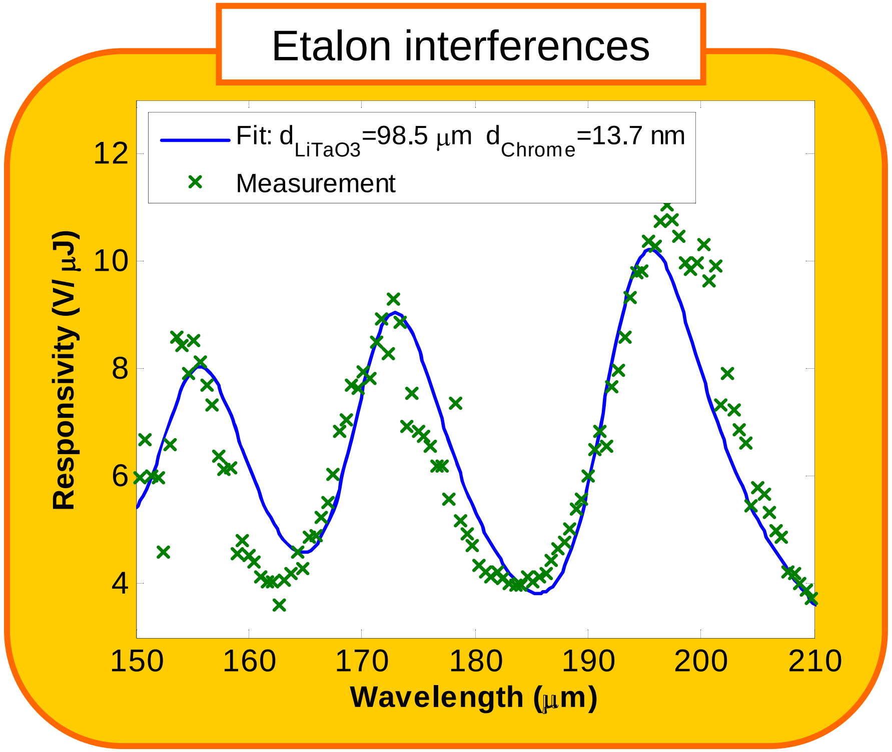
Courtesy J. Frisch, SLAC

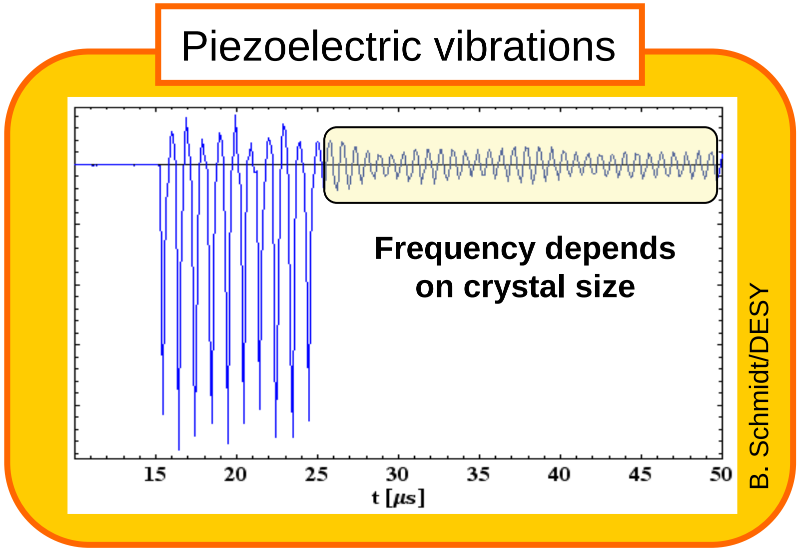
Pyroelectric detector

— room-temperature —

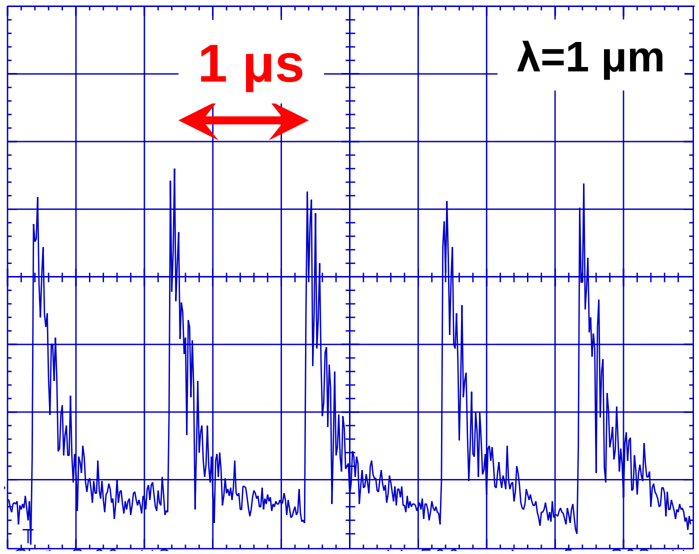


Absorption of radiation
→ Conversion into temperature variation
→ Conversion into polarization (pyroelectric effect)
→ Detection of charge/current/voltage

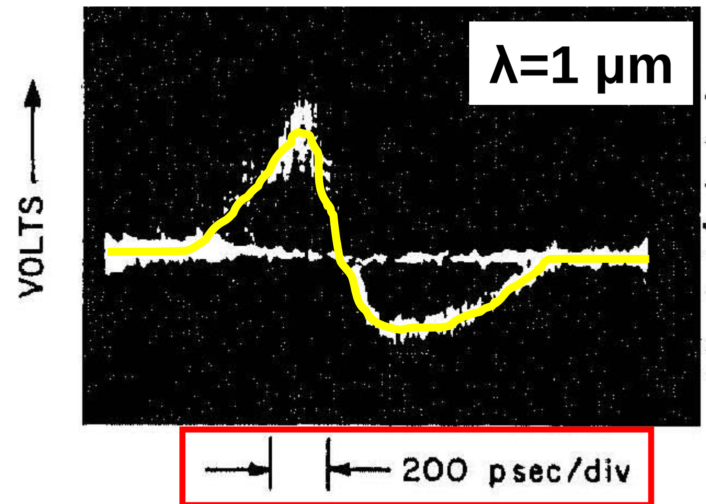




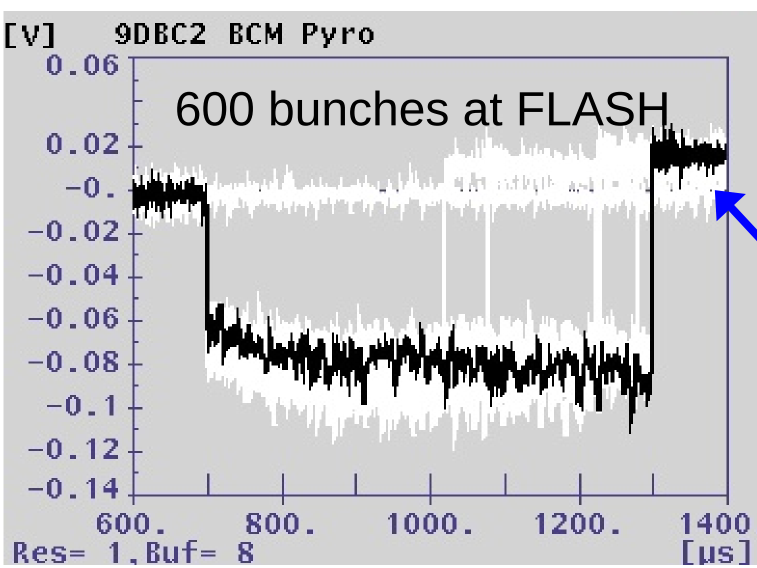
Pyros are intrinsically fast



…even very fast!



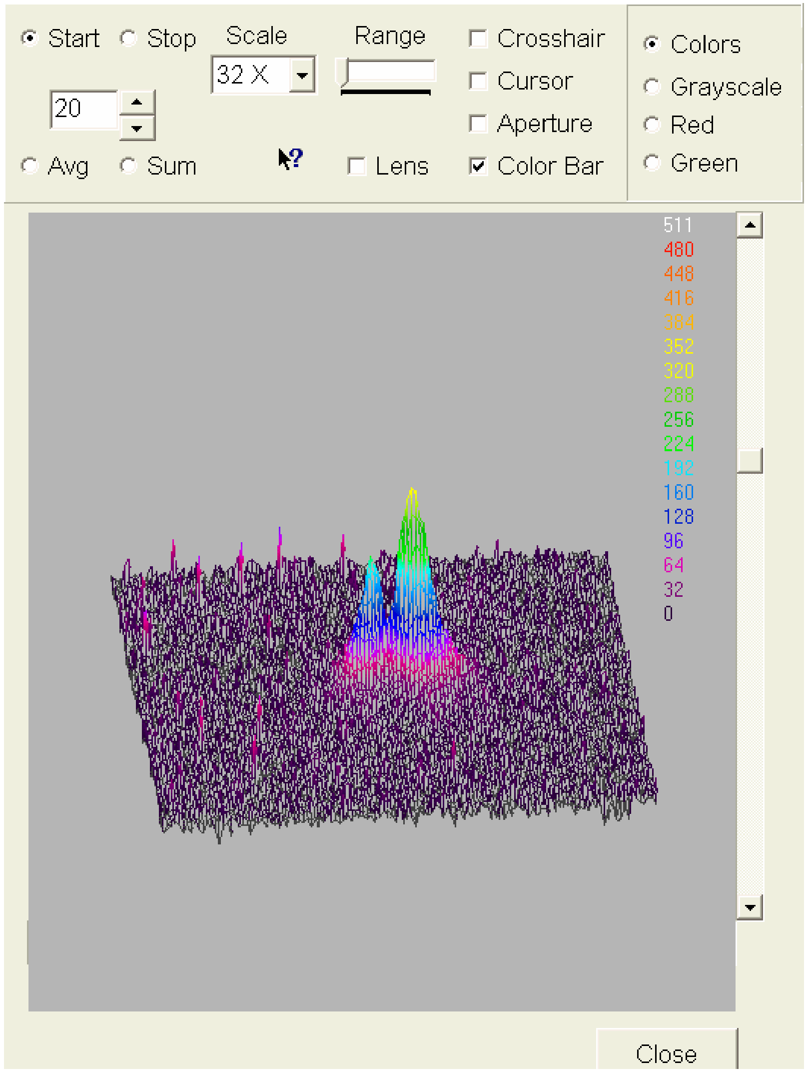
from: C.B. Roundy,
SPIE Vol. 62, 191 (1975) Infrared Technology



Heating of pyro
($\tau_{thermal}$ ≈100 ms)

Pyrocam

Transition radiation at FLASH



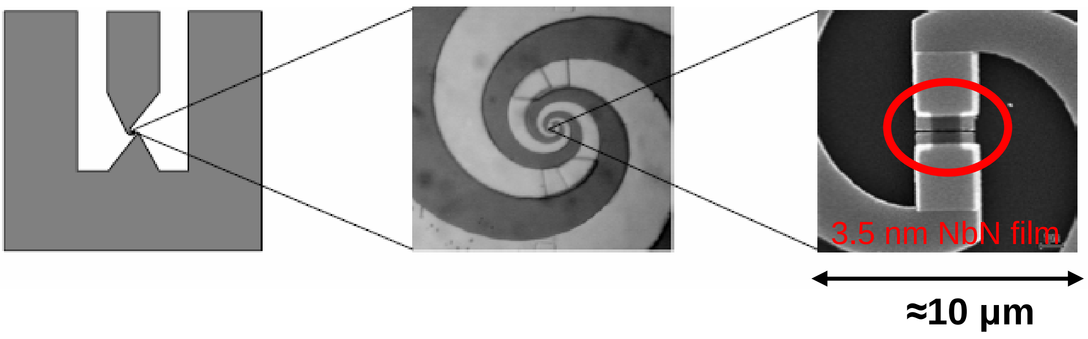
Spiricon pyroelectric camera ($LiTaO_3$)

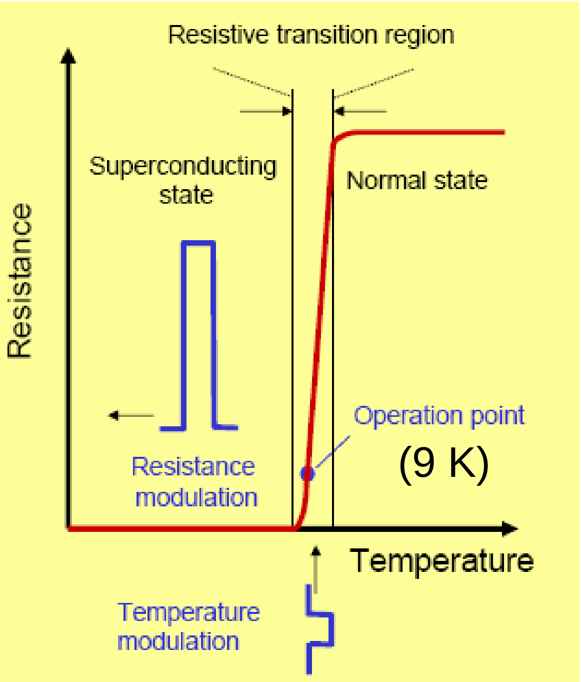
124x124 pixels, 100 µm pitch

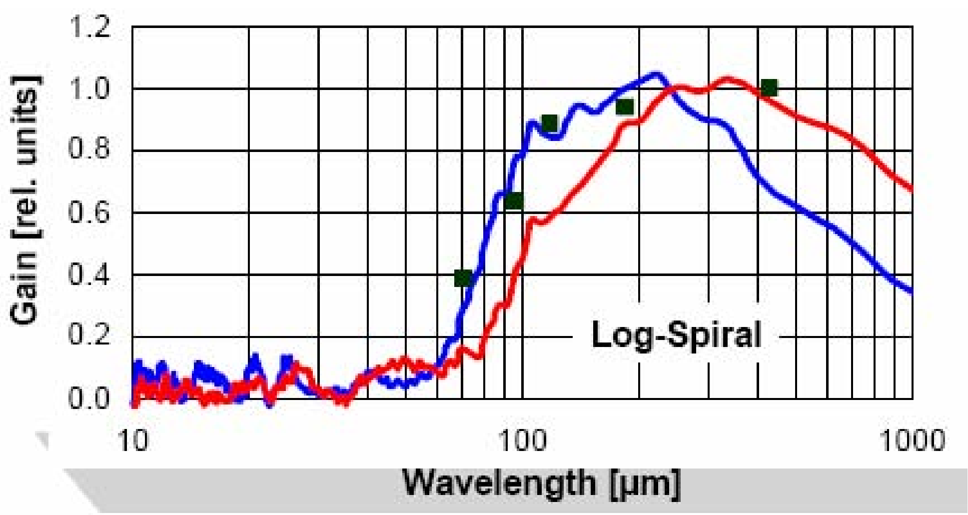
7 nJ per pixel noise limit

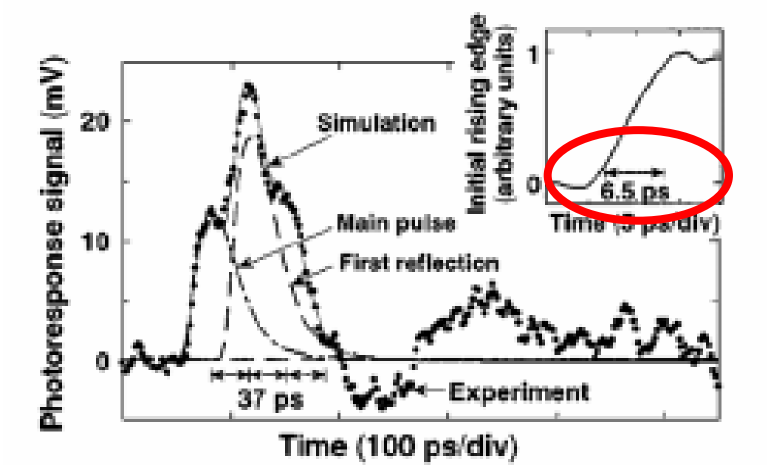
Fast superconducting hot-electron bolometer

Log-spiral antenna receiver





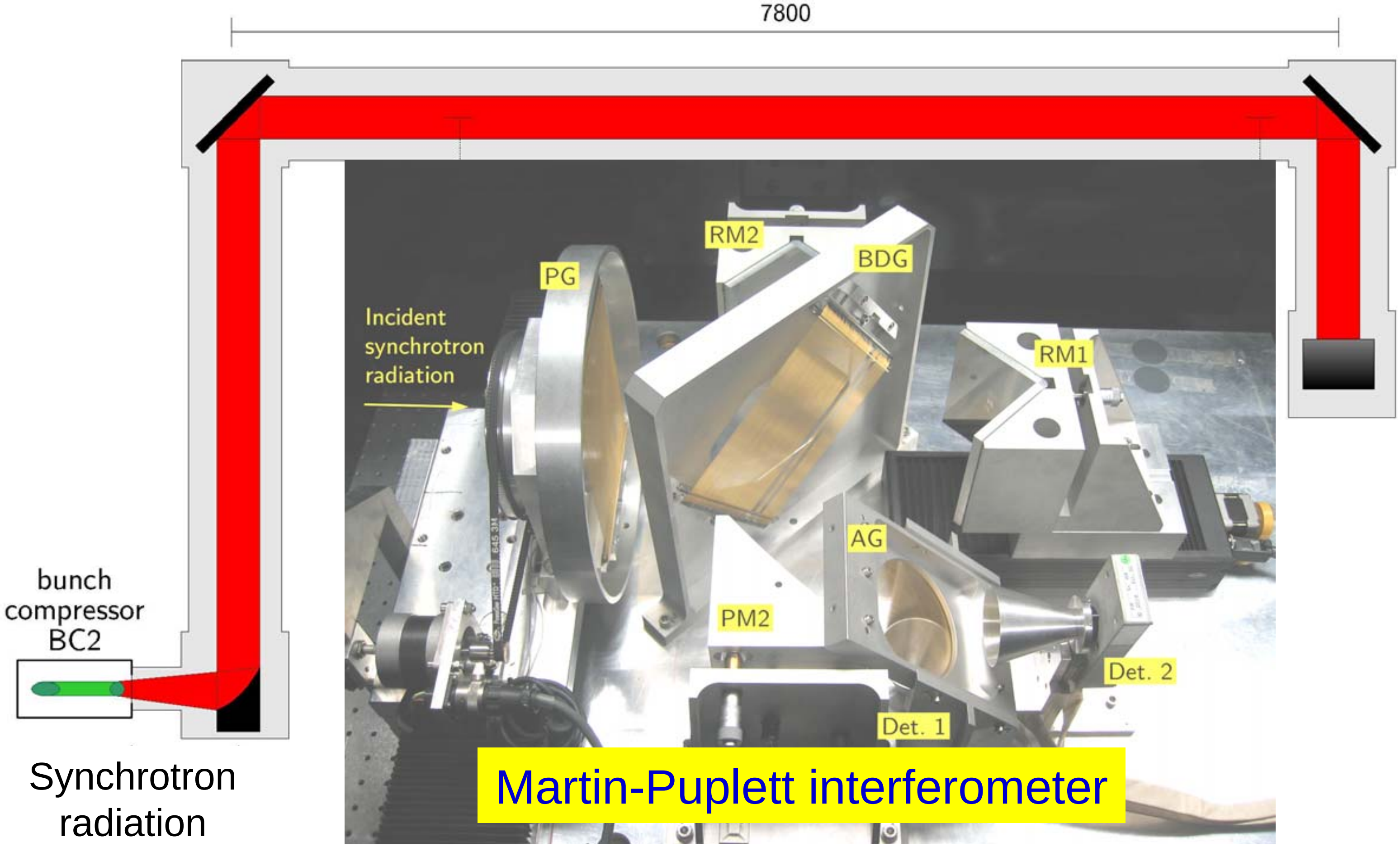




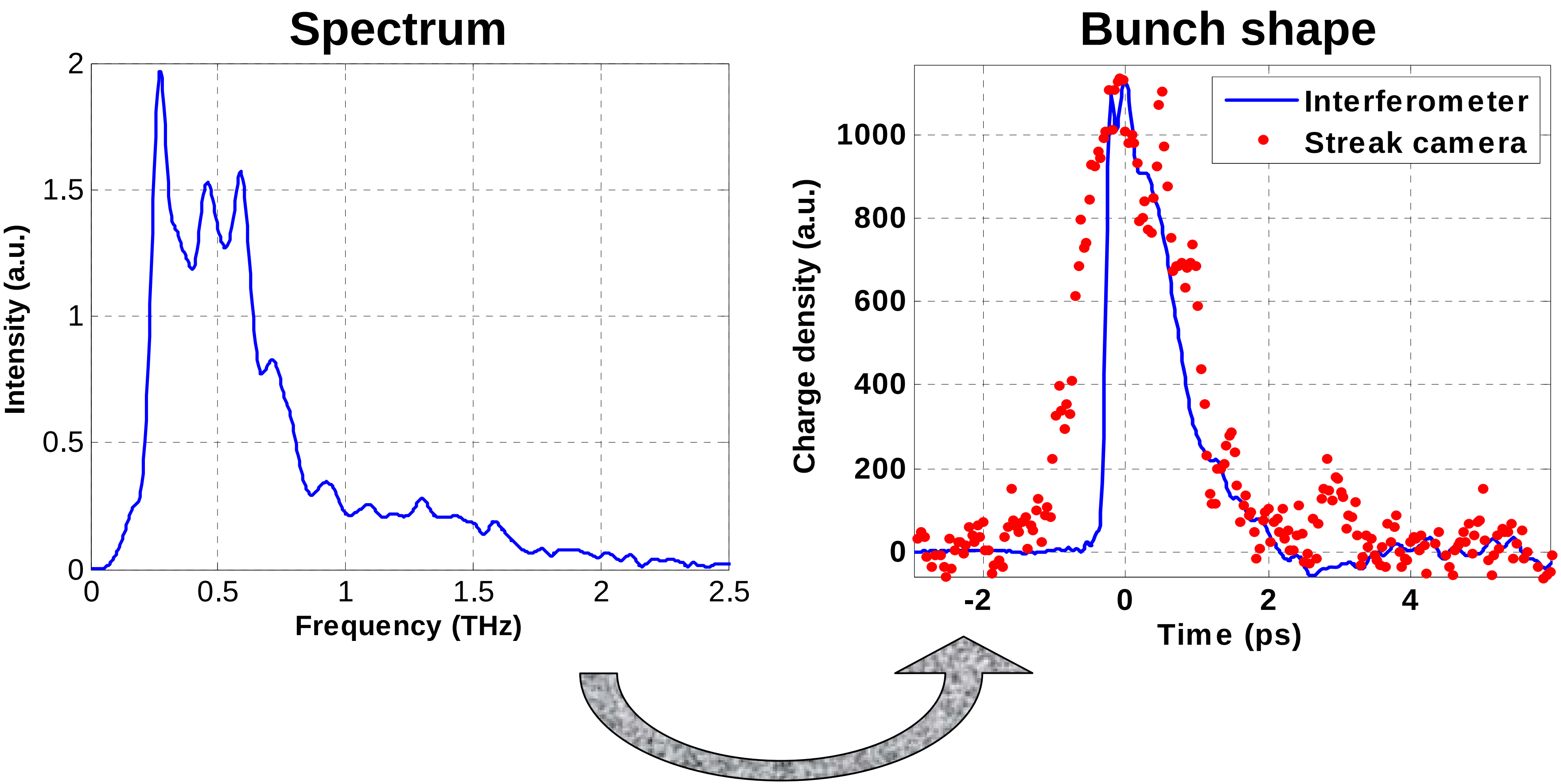
Courtesy H.-W. Hübers, DLR Berlin

FLASH synchrotron radiation beamline

For **experimental studies**, an **accessible laboratory** outside of the accelerator confinement is **mandatory**.



Bunch reconstruction



through inversion of

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

Courtesy L. Fröhlich, DESY

The reconstruction procedure

$$\left(\frac{\mathrm{d}U}{\mathrm{d}\upsilon}\right)_{\text{measured}} \Rightarrow \frac{\mathrm{d}U}{\mathrm{d}\upsilon} \Rightarrow \left|F(\upsilon)\right| \Rightarrow F(\upsilon) \Rightarrow S(z)$$

Beam line transmission, instrument response

Single-electron spectrum, bunch charge

Phase reconstruction

Inverse Fourier transform

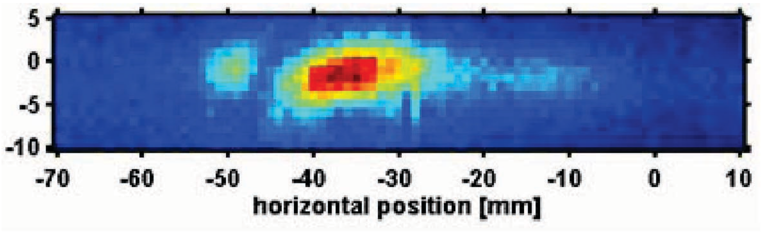
Complex form factor $F(\upsilon) = \left|F(\upsilon)\right| e^{i\Theta(\upsilon)}$

Kramers - Kronig relation $\Theta(\upsilon) \geq \frac{2\nu}{\pi}\int_0^\infty \frac{\ln\frac{\left|F(\upsilon')\right|}{\left|F(\upsilon)\right|}}{\upsilon^2 - \upsilon'^2}\,\mathrm{d}\upsilon'$

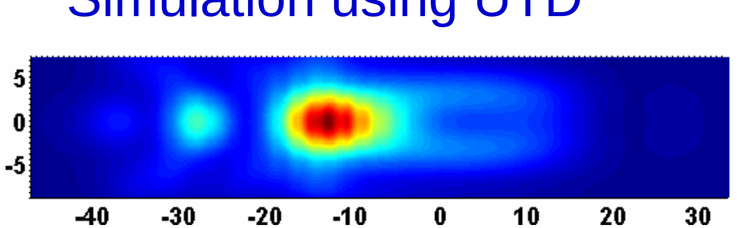
(phase retrieval)

Synchrotron radiation is a complex source…

Measurement (λ=155 μm)

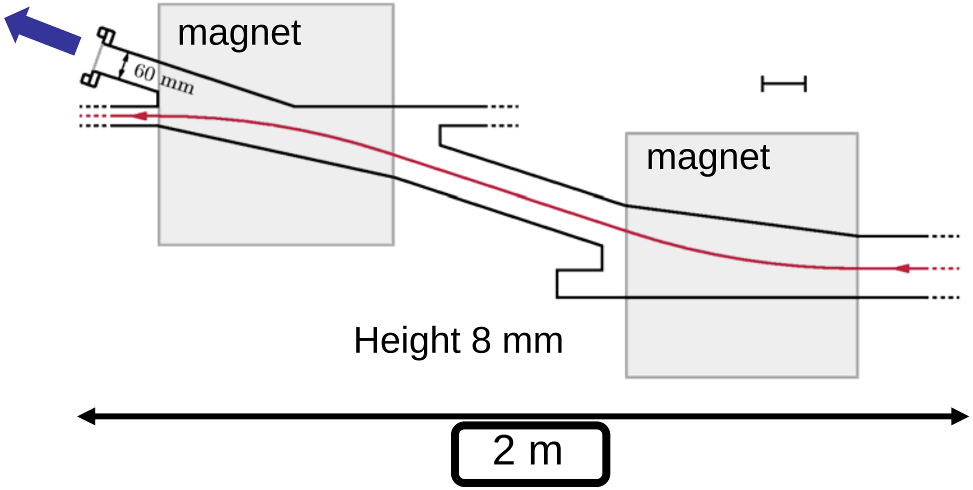


Simulation using UTD



Uniform **T**heory of **D**iffraction =
geometrical optics + diffraction

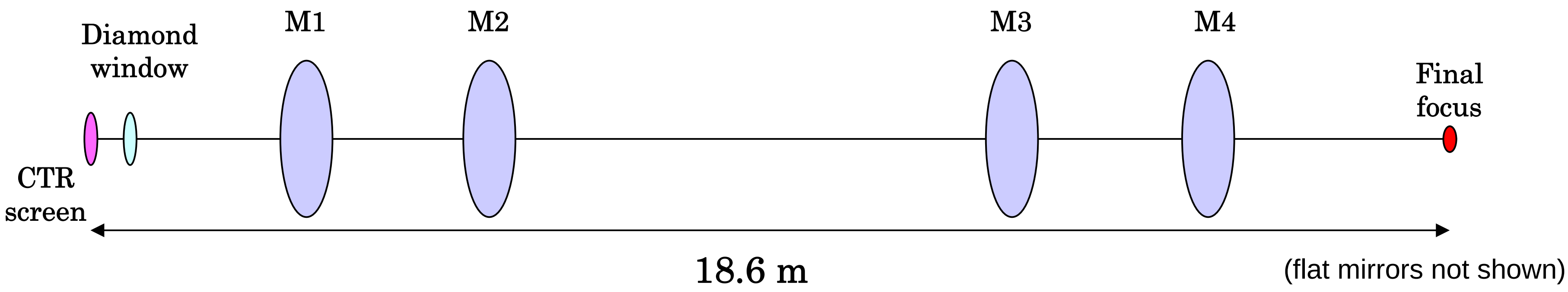
- Edge effects
- Shielding

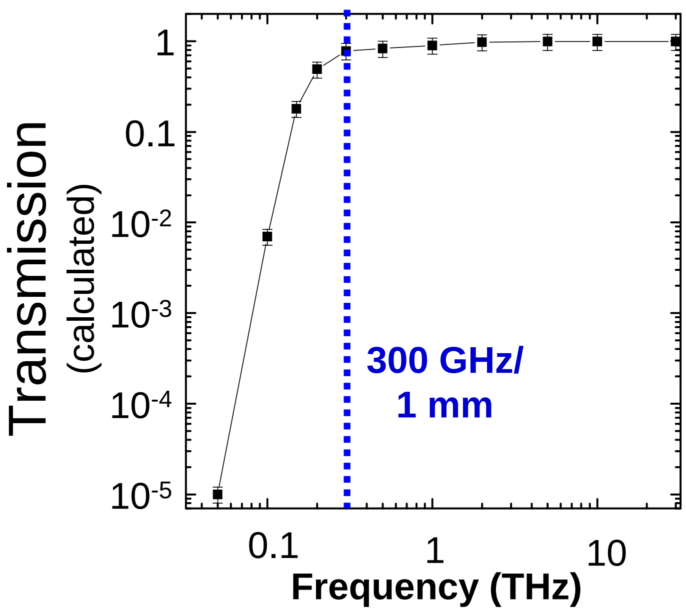


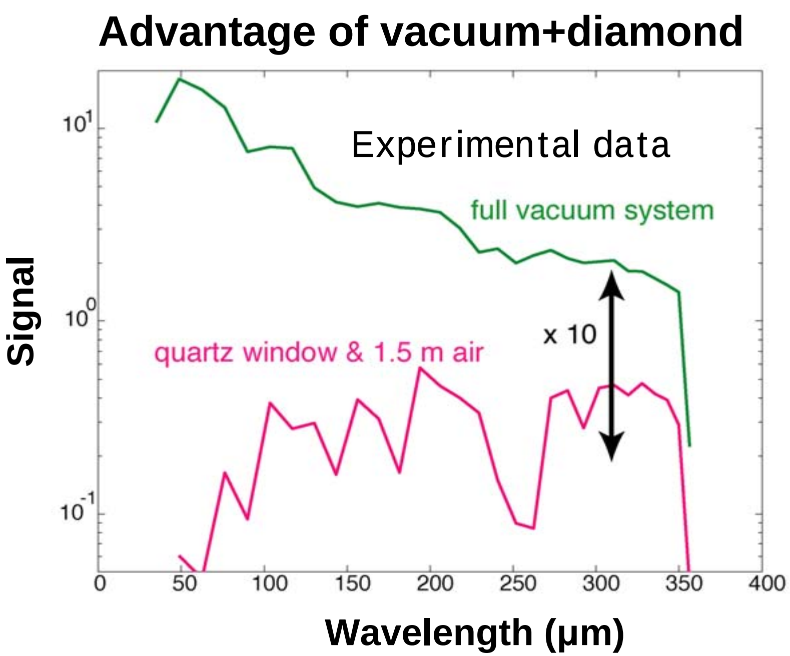
Poster Friday: FRPMN015

Courtesy A. Paech, TU Darmstadt

FLASH transition radiation beamline



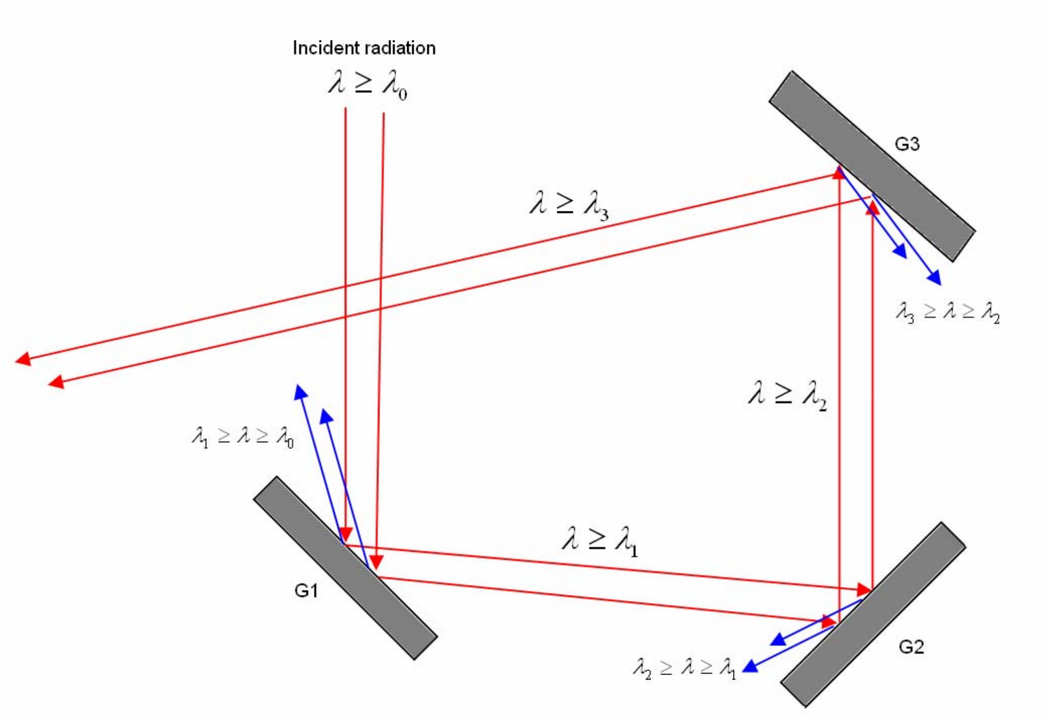


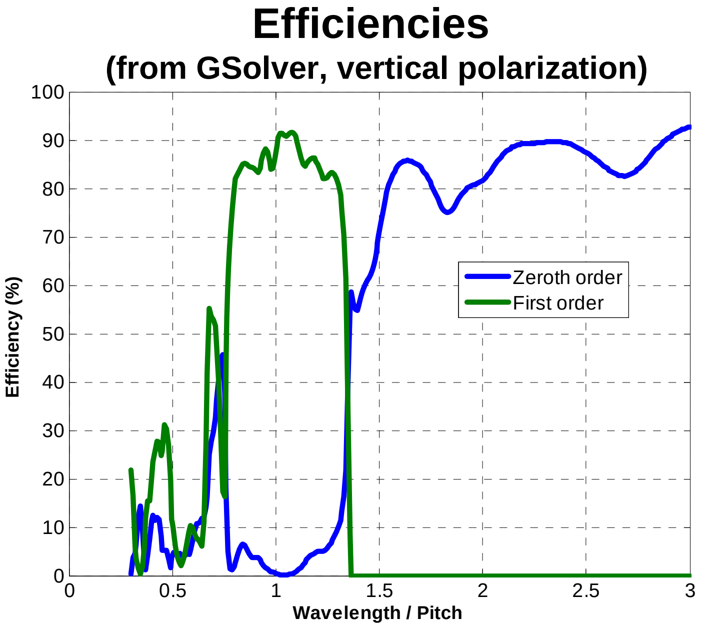


Courtesy B. Schmidt, DESY

Single shot grating spectrometer

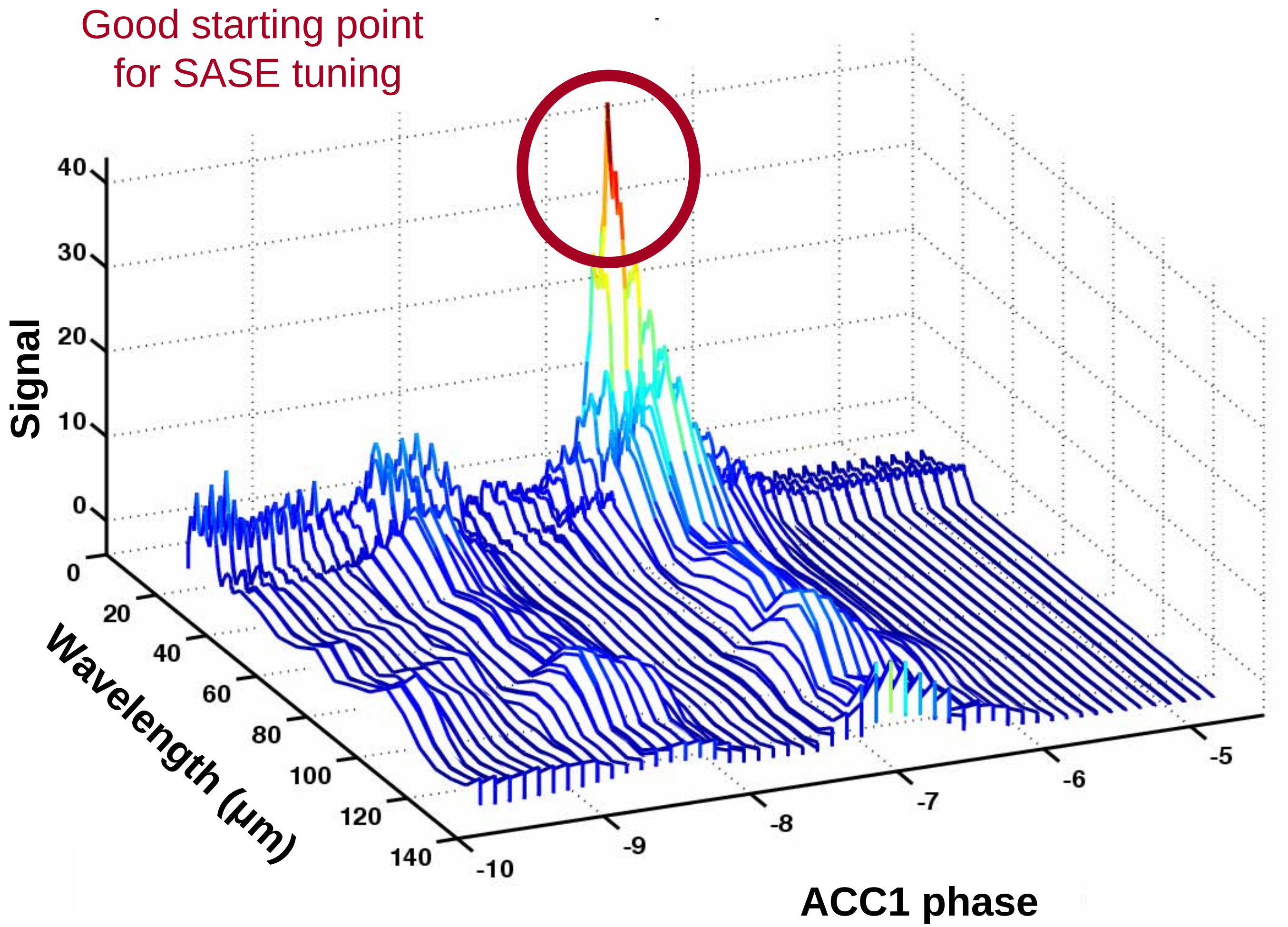
Based on staged blazed gratings





Courtesy H. Delsim-Hashemi, DESY

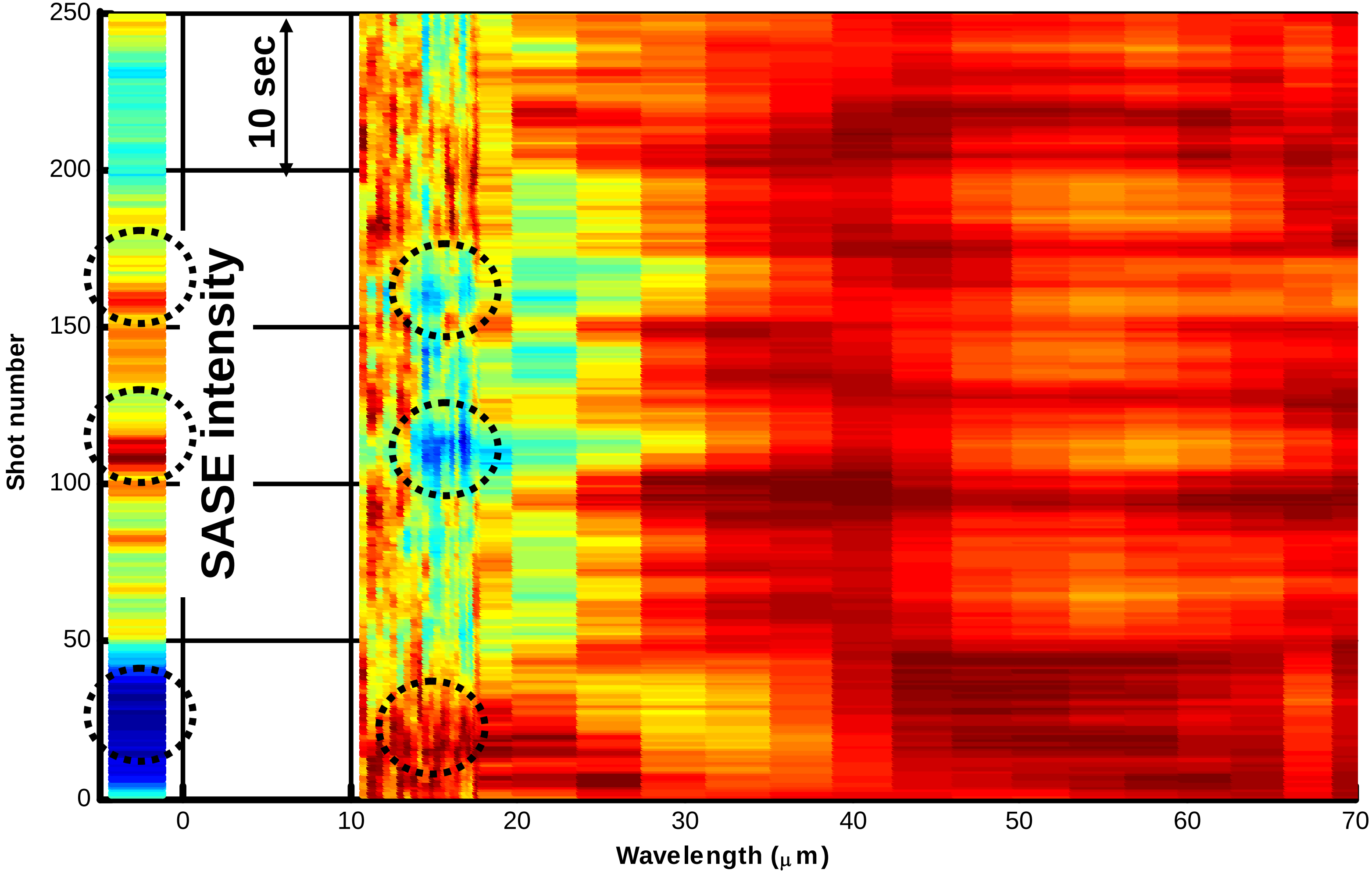
Phase scan



Courtesy
H. Delsim-Hashemi, DESY

Correlations

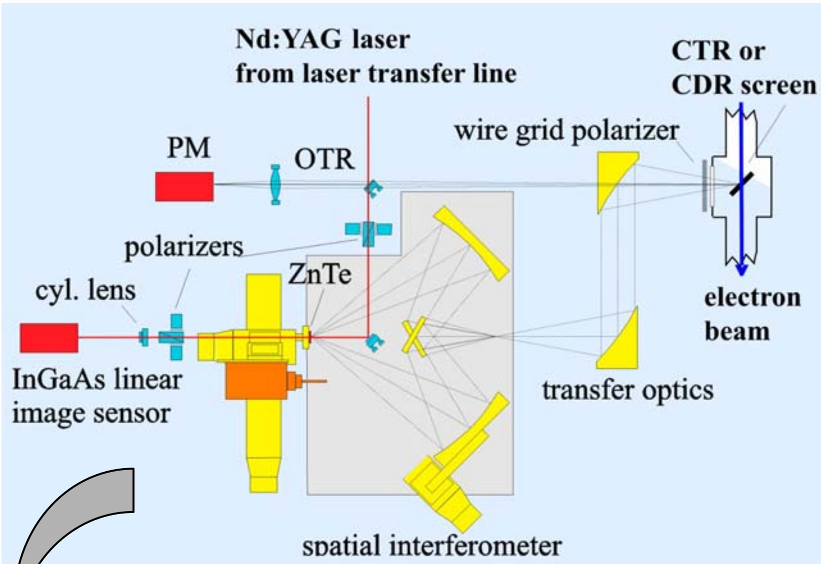
Fluctuations over 50 seconds of stable SASE run

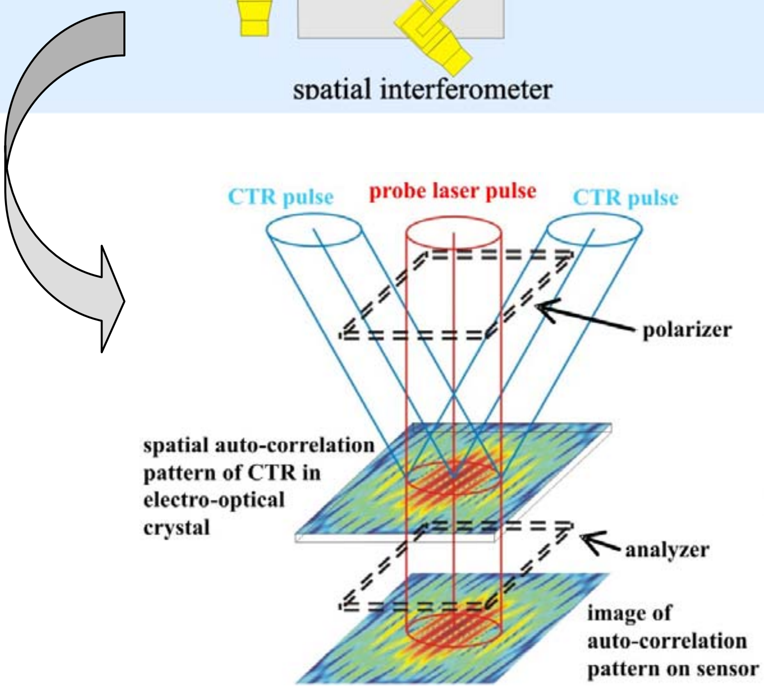


Anti-correlation!

Courtesy H. Delsim-Hashemi, DESY

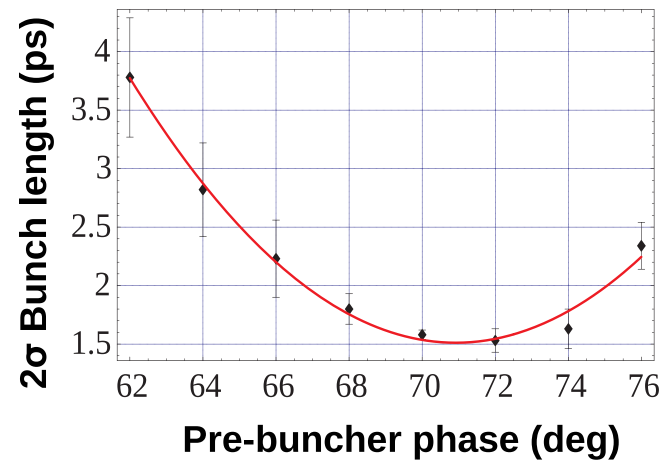
Spatial Electro-Optical Auto-Correlation Interferometer (PSI)





- Interferometer images coherent transition radiation onto electro-optic crystal
- Spatial auto-correlation pattern read out by Nd:YAG laser using cross polarizer scheme and linear image sensor
- Single shot bunch length monitor providing ~200 fs resolution

Measurement at SLS pre-injector LINAC



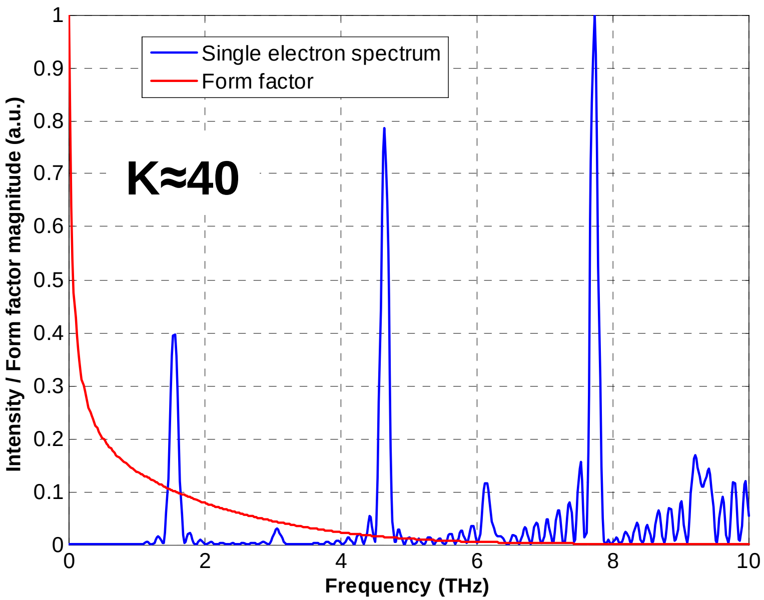
Courtesy V. Schlott, PSI

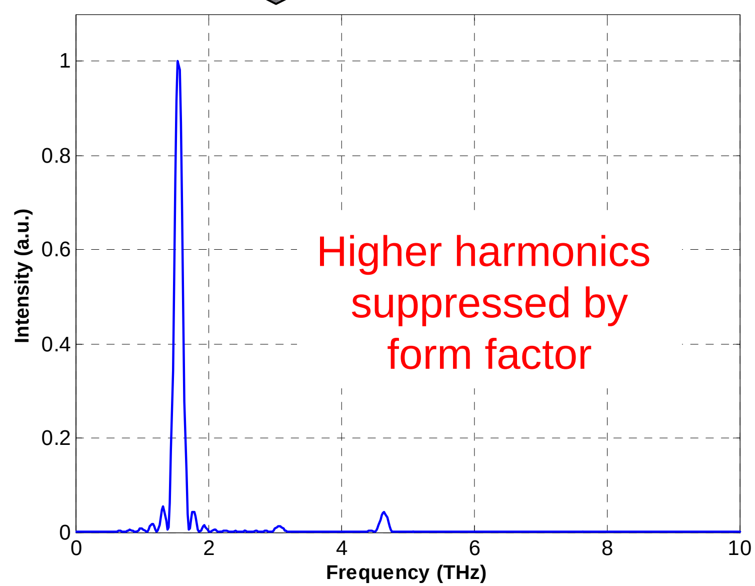
FLASH infrared undulator

Electromagnetic undulator, tuneable 1-200 µm (at 500 MeV)

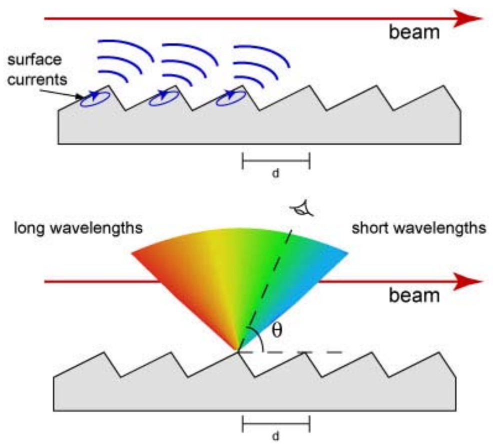
The same bunches generate SASE and infrared radiation (naturally synchronized)

Total emission spectrum

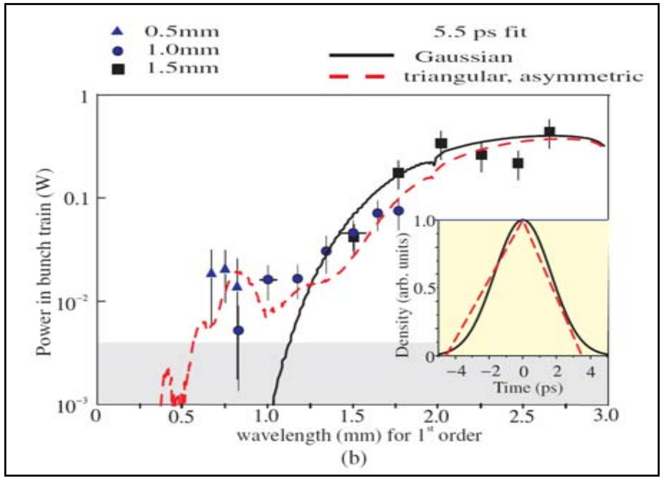




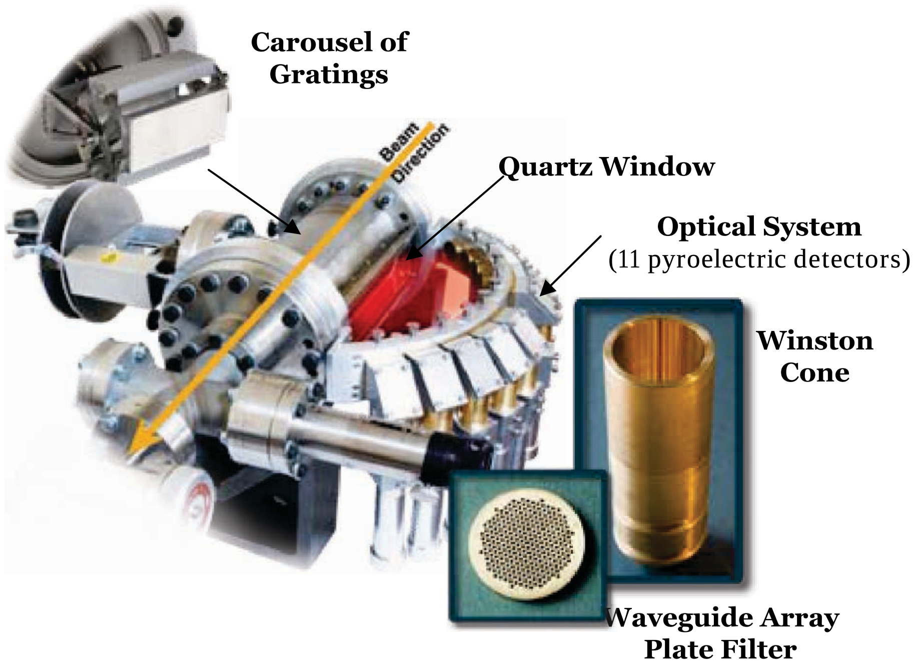
Smith-Purcell radiation measurements



Measurement at 45 MeV, FELIX



see PRST 9,092801 (2006)



Results of a run at 28.5 GeV from SLAC are currently being analyzed.

Courtesy G. Doucas, V. Blackmore, Oxford

Summary

- **Longitudinal bunch shape investigations** using coherent radiation are a **standard tool** for all machines operating with short bunches or bunch features (slicing).
- **Standard tools** employ **non-calibrated** devices.
- Full longitudinal charge profile reconstruction is a **specialist application** (thesis level…).
- Additional benefit from **wide wavelength coverage** in a **single-shot manner** — comes at the price of higher **hardware complexity** (vacuum, diamond window, optics)

Thanks very much for the kind help of many colleagues who provided material** (of which I could not cover everything, sorry!) **or advise!

Phase retrieval – Kramers-Kronig relations

Generally, Kramers-Kronig relations result from an expression

Response = Stimulus x Response function

and connect the real and imaginary part of the response function.*

— Formal relation —

$$\underbrace{\left\langle E(\upsilon)\right\rangle}_{\text{Response}} = E_1(\nu)\left\langle \sum e^{2\pi i \upsilon \Delta t}\right\rangle$$

$$= E_1(\nu)\int NS(z)\, e^{\frac{2\pi i \upsilon z}{c}}\, \mathrm{dz}$$

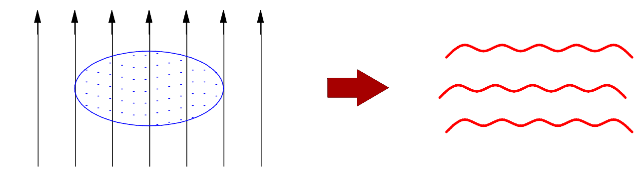
$$= \underbrace{NF(\nu)}_{\text{Response function}}\underbrace{E_1(\nu)}_{\text{Stimulus}}$$

Check concept with Lorentz-Transformation of static field etc.

— Conceptual picture —

(for synchrotron radiation)

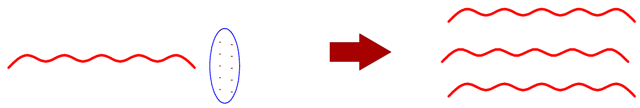
Laboratory system



Bunch moves through static magnetic field

Bunch emits coherent synchrotron radiation

Co-moving system



Bunch irradiated with electromagnetic wave

Bunch responds according to its response function

*John S. Toll, Phys. Rev. **104**, 1760(1956)

Where is the connection between phase and magnitude?

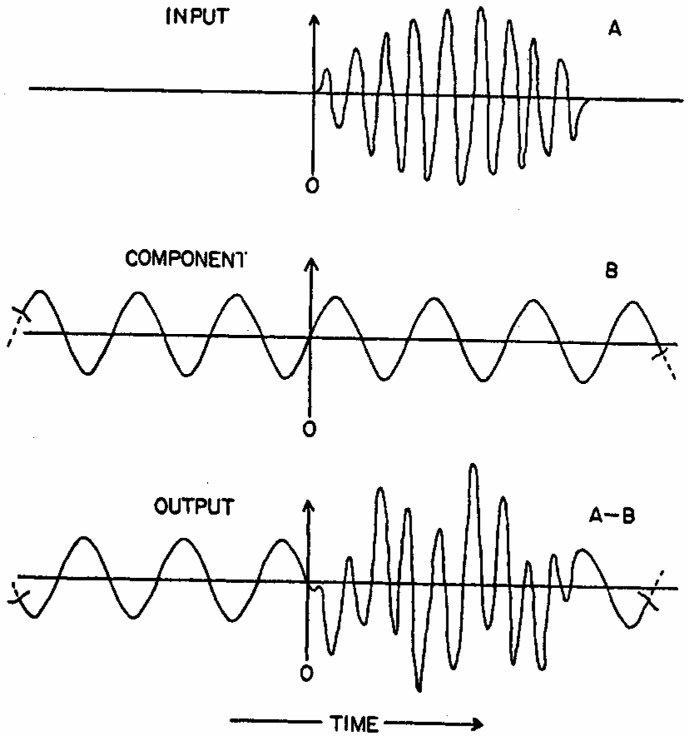


Fig. 1. This figure illustrates schematically the basic reason for the logical connection of causality and dispersion. An input A which is zero for times t less than zero is formed as a superposition of many Fourier components such as B, each of which extends from $t=-\infty$ to $t=\infty$. These components produce the zero-input signal by destructive interference for $t<0$. It is impossible to design a system which absorbs just the component B without affecting other components, for in this case the output would contain the complement of B during times before the onset of the input wave, in contradiction with causality. Thus causality implies that absorption of one frequency must be accompanied by a compensating shift of phase of other frequencies; the required phase shifts are prescribed by the dispersion relation.

Original time dependent signal
(=0 for t<0)

One Fourier component

Signal if this component is removed
(≠0 for t<0)

Conclusion: The phases must be automatically adjusted (e.g. by a filter) such that signal=0 for t<0.

From: John S. Toll,
Phys. Rev. **104**, 1760(1956)