Lecture on Femto-Second Diagnostics

Part I: Motivation
Streak Camera
Deflecting Cavity
Coherent Radiation

Part II: Interferometric Techniques
Electro-Optical Techniques

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... to be able to present a state-of-the-art overview of femto-second diagnostics, I have been relying on the outstanding work of many colleagues from various accelerator institutes (mainly XFELs)

... this presentation is far from being complete! It tries to give an overview of fs diagnostics techniques with some – hopefully instructive – examples and (latest) measurements

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Motivation for fs Diagnostics – Requirements in XFEL Accelerators

Bunch Arrival Time Monitor
- $\tau_{\text{Gun}} < 1 \text{ ps}$
- $\tau_{\text{Injector}} \sim 100 \text{ fs}$
- beam pick-up & EO modulator
- cavity and RF-mixing

Electro-Optical BL-Monitor
- $\tau_{\text{Bunch}} \sim 10 \text{ ps} - 100 \text{ fs}$
- single-shot bunch length
- (spectral & temporal decoding)
- bunch arrival time

not covered in this talk…:
- Optical Replica
- Statistical Methods
- Photon Arrival Time Diagnostics
- Photon Bunch Length Diagnostics
  (Diamond detectors, non-thermal melting etc…)

Streak Camera
- $\tau_{\text{Bunch}} \sim 5 - 10 \text{ ps}$
- $\tau_{\text{RiseTime}} \sim 500 \text{ fs}$
- Laser diagnostics (IR, vis)
- vis. Cerenkov radiation
  (vis. transition radiation)

Coherent Radiation
- $\tau_{\text{Bunch}} \sim 10 \text{ ps} - 10 \text{ fs}$
- bunching diagnostics
- bunch length interferometers
- single-shot EO bunch length
- single-shot “poly-chromator”

Transverse RF Deflector
- $\tau_{\text{Bunch}} \sim 5 \text{ ps} - 10 \text{ fs}$
- single-shot bunch length
  “sliced” energy spread
  “sliced” emittance
Streak Camera – Operating Principle

- Visible light pulses (e.g.: Cerenkov radiation, optical transition radiation or synchrotron radiation) are converted on the photo-cathode into a number of electrons, which are proportional to the incident intensity distribution.

- The photo-electrons are accelerated along the streak tube, transversely (vertically) swept by deflecting plates to convert the incident time distribution in a spatial distribution on the MCP.

- The photo-electrons are amplified by the MCP and converted back to visible light on the phosphor screen.

- An initial spatial offset of the light pulses at the entrance slit is preserved at the phosphor screen.
Streak Camera – Limitations of Time Resolution (for Hamamatsu FESCA-200)

- streak camera time resolution is limited by transit spread and temporal spread of photo-electrons

- **transit spread** for FESCA-200 is given by:
  \[ \tau_S = 2.34 \cdot 10^{-6} \cdot (\Delta E)^{\frac{1}{2}} / E \]
  
  with accelerating electric field \( E = 9.4 \cdot 10^6 \text{ V/m} \)
  
  and photo electron energy distribution \( \Delta E \) (see graph for S-20 photocathode)

- **temporal spread** for FESCA-200 is given by:
  \[ \tau_F = \frac{w}{v} = 0.152 \cdot 10^{-12} \text{ s} \]
  
  with non-deflected line spread \( w = 60 \cdot 10^{-6} \text{ m} \)
  
  and sweep speed \( v = 3.96 \cdot 10^8 \text{ ms}^{-1} \)

**FESCA-200 time resolution...**

only measured / guaranteed time resolution

below 300 fs at 800 nm incident light wavelength
Example of fs Streak Camera Measurement at an Accelerator


- streak camera (FESCA-200) images were taken at 35 MeV beam energy behind University of Tokyo LINAC using visible Cerenkov radiation in air

- three set-ups with different optical band-pass filters were used to examine influence on time resolution:
  - ○ lens optics for light transport and SC imaging system
  - ● lens optics for light transport and mirror optics for SC imaging system
  - ◆ mirror optics for both, light transport and SC imaging system

FESCA-200 measurements of Cerenkov light for different optical set-ups

Schematic Layout for Lens Optics

Schematic Layout for Mirror Optics

FESCA-200 streak image of Cerenkov light

all images are courtesy of T. Watanabe et al. (Uni Tokyo)
Example of fs Streak Camera Measurement at an Accelerator

many thanks to D. Dowell, P. Emma and the LCLS commissioning team! See also: PR-STAB 11 30703 (2008) about LCLS injector commissioning
and D. Dowell et al., Proc. PAC’07, p. 1317 (TUPMS058)

Streak Camera and XCorr Images – LCLS Gun Laser Pulse

![Graph showing streak camera, single shot XCorr, and multi shot XCorr with FWHM = 6 ps.](image)

Optimization using XCorr in the UV

![Graph showing XCorr images with 7.2 ps and 6.9 ps.](image)

Streak Camera for fs Diagnostics – Summary

• streak cameras are useful and intuitive instrumentation to measure and optimize laser and electron beam bunch lengths and longitudinal bunch structures with ps and sub-ps time resolution

• the streak camera time resolution strongly depends on (is limited by)....:
  - the photon energy (wavelength) of the incoming light (preferably 600 – 800 nm for S20 photo-cathode) and the related energy spread of the photo electrons, produced at the photo-cathode of the streak tube
  - the bandwidth of the incoming light (10 nm – 20 nm band-pass filters should be used)
  - dispersion of the streak cameras in-coupling optics

• when using broad-band radiation sources like Cerenkov, transition or synchrotron radiation for electron beam diagnostics, fs time resolution can only be obtained with dispersion-free (mirror) optics for transferring light to the streak camera

• fs streak cameras are very useful instrumentation for... (personal opinion):
  - photo-gun laser diagnostics in order to verify longitudinal bunch shaping (rectangular bunch shapes)
  - low energy electron bunch length diagnostics (using Cerenkov radiation)
  - high repetition (MHz) rate bunch length measurements (using synchro-scan options)
  - on the experimental side as fast X-ray detectors (see: fs X-ray streak camera development programs)

• streak cameras are rarely used as online bunch length diagnostics, since they are usually not providing signals, which can be used in an automated feedback loop
Streak Camera Development as sub-ps Experimental X-Ray Detector

Sub-ps X-ray streak camera system as presently developed by Maik Kaiser at PSI (SLS) – present time resolution ~1 ps

streak image of UV laser pulses separated by 2 ps

above: hard X-ray pulse from SLS X05DA bending magnet

Gaussian fit to the line readout
**TW and SW Transverse RF Deflecting Structures**

- Iris-loaded RF waveguide structures have been designed to provide so called *hybrid* deflecting modes (HEM_{1,1}) which are a linear combination of TM_{1,1} and TE_{1,1} dipole modes to impart transverse forces to synchronously moving relativistic particle beams → beam separators, RF deflectors

**Traveling Wave “LOLA-type” RF deflector (SLAC-design)**

- "LOLA" deflectors have been named after their inventors: G.A. Loew, R.R. Larsen, O.A. Altenmueller (SLAC – 1960’s)

- “LOLA” (TW-structure) maximum deflecting voltage:

$$V_T \approx 1.6 \left[ \frac{MV}{m \cdot \sqrt{MW}} \right] \cdot L[m] \cdot \sqrt{P[MW]}$$

  Relation found analytically and confirmed experimentally

**Standing Wave RF deflector (SPARC – INFN design)**

- SPARC-type (SW-structure) max. deflecting voltage:

$$V_T [MV] \approx \sqrt{2 \cdot P[MW] \cdot R_s [M\Omega]}$$

  with shunt impedance $R_s \sim 0.5 \ M\Omega \cdot \text{number of cells}$

Transverse RF Deflecting Structures – LCLS, FLASH & SPARC

Low Energy TW LOLA-type RF Deflector @ LCLS

TW LOLA-type RF Deflector @ FLASH

High Energy TW LOLA-type RF Deflector @ LCLS

Standing Wave RF Deflector @ SPARC - INFN
Principle of Bunch Length Measurement with RF Deflector

Transversely Deflected Beam Size $\Delta y_B$ at Screen (for a drift space)

$$\Delta y_B = \frac{\omega_{RF} V_T}{2c E/e} \cos(\phi_{RF}) \cdot L_B \cdot \Delta L_{\text{def-screen}}$$

Assuming…:
- $\phi_{RF} = 0^\circ$ at the center of the bunch results in shearing of particle density distribution without changing mean particle position
- longitudinal stability (bunch arrival time vs. RF phase) must be high in case of averaging of measurements
- pencil-like beam (zero-emittance)
- no beam offset in the RF deflector

Example:

| Parameters for 250 MeV PSI FEL Injector Test Facility |
|----------------------------------------------|----------------|
| $\omega_{RF}$                                  | $2 \pi \cdot 3$ GHz |
| $V_T$                                         | 2.5 MV |
| $c$                                           | $3 \cdot 10^8$ ms$^{-1}$ |
| $E$                                           | 250 MeV |
| $L_B$ (FWHM)                                  | 600 fs |
| $\Delta L_{\text{def-screen}}$                | 12.25 m |

$$\Delta y_B = 770 \mu m$$
Principle of Bunch Length Measurement with RF Deflector

Beam Size $\Delta y_B$ at Screen (vertical deflection – including beam optics)

$$\Delta y_B \approx \frac{\omega_{RF} V_T}{\lambda_{RF} >> L_B} \frac{L_B}{2cE/e} \cos(\varphi_{RF}) \sqrt{\beta_{y-def} \beta_{y-screen}} \sin(\Delta \Phi)$$

- $\beta_{y-def}$ should be as large as possible for most effective kick
- $\beta_{y-screen}$ should be as small as possible to increase resolution
- $\Delta \Phi$ ideally 90° or 270°
- $\Delta L_{def-screen}$ depends mainly on optics (phase advance between RF deflector and screen)

Example (from PSI FEL Injector Test Facility)

- $\omega_{RF} = 2 \pi \cdot 3$ GHz
- $V_T = 2.5$ MV
- $c = 3 \cdot 10^8$ ms$^{-1}$
- $E = 250$ MeV
- $L_B = 600$ fs
- $L_{def-screen} = 200$ $\mu$m
- $\beta_{y-def} = 40$ m
- $\beta_{y-screen} = 5$ m
- $\Delta \Phi = 60$ °
- $\Delta L_{def-screen} = 3.5$ m

$$\Delta y_B = 770 \, \mu$m
Bunch Length Measurement with RF Deflector - Resolution

resolution considering finite emittance $\varepsilon$ and beam size $\sigma$

$$\sigma_{y \text{-screen},\varepsilon} = \sqrt{\sigma_{y \text{-def}}^2 + \sigma_{y \text{-screen}}^2}$$

$$= \sqrt{\frac{\varepsilon N \cdot \beta}{\gamma} + \left[ \frac{e V_T}{E} \sigma_z \left( \frac{\omega_{RF}}{c} \cos \varphi_{RF} \right) \cdot \sqrt{\beta_{def} \cdot \beta_{screen} \cdot \sin \Delta \Phi} \right]^2}$$

resolution limit: deflected spot size equals the un-deflected beam size $\sigma_{y \text{-screen}}$ taking finite $\varepsilon$ into account

$\rightarrow$ finite $\varepsilon$ beam size at the screen (for PSI FEL with anticipated $\varepsilon_N$ of 0.4 $\mu$mrad)

$$\sigma_{y \text{-screen},\varepsilon} = \sqrt{\frac{\varepsilon N \cdot \beta_{screen}}{\gamma}} = \sqrt{\frac{4 \cdot 10^{-7} mrad \cdot 5 m}{500}} = \sqrt{4 \cdot 10^{-9} m^2} \approx 65 \mu m$$

the optical resolution should be better than the “resolution limit” given by the spot size of the finite $\varepsilon$ beam

$\rightarrow$ “resolution length” for a drift space (12.5 m)

$$L_{res} = \frac{c E / e}{\omega_{RF} \cdot V_T \cdot L_{drift}} \cdot \sigma_{y \text{-screen}} \approx 8.5 \mu m \approx 28 f s$$

$\rightarrow$ “resolution length” for “PSI FEL beam optics”

$$L_{res} = \frac{c E / e}{\omega_{RF} \cdot V_T \cdot \sqrt{\beta_{y \text{-def}} \cdot \sin \Delta \Phi}} \approx 8.5 \mu m \approx 28 f s$$
Calibration Method of Transverse RF Deflector

- variation of the RF phase around the “zero-crossing” of the deflecting force results in a vertical beam offset on the screen
- a calibration of RF phase $\Delta \phi$ resp. time delay $\Delta t$ and beam excursion $\Delta y$
  can be derived in pixel / ° RF phase or mm / ps

LCLS RF deflector calibration curve (pixel vs. RF phase)
Calibration: 24.5 pixel / ° RF @ 2856 MHz ~ 45 fs / pixel

courtesy of M. Roehrs (DESY)

FLASH RF deflector calibration (mm vs. RF phase (time))
Calibration: ~ 42 mm / ps

courtesy of M. Roehrs (DESY)
Examples of Bunch Length Measurement with RF Deflector – LCLS

many thanks to Paul Emma and the LCLS commissioning team! See also: PR-STAB 11 30703 (2008) about LCLS injector commissioning

Low Energy RF Deflector off

OTR2 135 MeV

head
tail

Low Energy RF Deflector on

LCLS Bunchlength in front of BC1

97 A

10.3 ps FWHM

135 MeV

High Energy RF Deflector on

PR55 14 GeV

Maximum Compression @ 14 GeV

950 A

0.89 ps FWHM

14 GeV

Nominal Compression @ 14 GeV

520 A

1.7 ps FWHM

14 GeV
Volker Schlott

Examples of Bunch Length Measurement with RF Deflector – FLASH

many thanks to Michael Roehrs and the FLASH operations team!
see also: Michael Roehrs, DESY-thesis May 2008
measurements are courtesy of Michael Roehrs, DESY

FLASH Bunchlengths “on crest” Operation

FLASH Bunchlength SASE Operation Modes

677 MeV (13.7 nm)
494 MeV (27 nm)
964 MeV (6.8 nm)

Zoom in FLASH SASE Operation Modes

22 - 30 µm (FWHM)
75 - 100 fs (FWHM)
Beam Conditioning for Time Resolved Energy Spread Measurement

with both, RF Deflector and bending magnet off the un-deflected beam should be focused on a screen downstream of the bending magnet to obtain…:

- high temporal resolution (when vertically deflecting)
- good energy resolution (with dispersion dominated beam when switching bending magnet on)

for a finite $\varepsilon$ beam, the vertical beam size and thus the temporal resolution limitation is given by:

$$\sigma_{y \text{- screen}, \varepsilon} = \sqrt{\frac{\varepsilon_N \cdot \beta_{\text{screen}}}{\gamma}}$$
Principle of Time Resolved Energy Spread Measurement with RF Deflector

Time Resolved Energy Spread Measurement

- RF Deflector transforms vertical direction to the time axis
- time resolution is defined by vertical beam size and deflecting voltage
- bending magnet transforms horizontal direction to energy axis
- energy resolution for a finite e beam is defined by the dispersion at the screen location:

\[ \frac{\Delta E}{E} \bigg|_{\text{res}} = \sqrt{\frac{\epsilon_x \cdot \beta_x - \text{screen}}{D_{\text{screen}}}} \]

- time slices are usually defined by partition of the image and post processing using image processing SW
Example of Sliced Energy Spread Measurement with RF Deflector – LCLS

many thanks to Paul Emma and the LCLS commissioning team! See also: PR-STAB 11 30703 (2008) about LCLS injector commissioning

Sliced Energy Spread in LCLS Spectrometer @ 135 MeV

Special lattice configuration (low horizontal β resp. small beam size at screen) in spectrometer allows fine measurement of time-sliced energy spread

\[ \sigma_E \leq 6 \text{ keV rms (40 } \mu \text{m)} \]

at 150 pC bunch charge (limited to optics resolution of 30-40 \( \mu \text{m} \))

Time Energy Correlation in 1st LCLS Bunch Compressor @ 250 MeV

RF deflector OFF

RF deflector ON

energy chirp only

energy chirp & RF deflector

Bunch Compressor

B1
B2
B3
screen
B4
RF-deflector
Example of Sliced Energy Spread Measurement with RF Deflector – FLASH

many thanks to Michael Roehrs and the FLASH commissioning team! see also: M. Roehrs, DESY-thesis May 2008, measurements are courtesy of M. Roehrs, DESY

Sliced Energy Distribution @ FLASH
(650 MeV, 1 nC, uncompressed bunches)

Sliced Energy Distribution @ FLASH
(677 MeV, 0.5 nC, SASE conditions)

Mean Relative Energy Deviation (50 images)
Principle of Time Resolved Emittance Measurement with RF Deflector

- quadrupole scan in front of or behind RF deflector is used for “sliced emittance” measurement keeping the “shear parameter” of the measurement set-up constant
  → vertical (deflecting) axis provides time resolution
  → horizontal axis provides beam emittance
- time slicing of images is obtained by post measurement image processing
- emittance resolution is determined by resolution of optical system
  it should match the co-operation length of the FEL process after final bunch compression stage of an XFEL facility
Example of “Sliced Emittance” Measurement with RF Deflector - LCLS

many thanks to Paul Emma and the LCLS commissioning team! See also: PR-STAB 11 30703 (2008) about LCLS injector commissioning

- bunch has been binned into 12 slices with 1.7 ps slice length – data taken for 135 MeV beam
- horizontal emittance has been calculated for each slice individually – by analyzing quad scan
- “beta mismatch amplitude parameter” $\xi$ describes the difference between measured and design Twiss parameters

Deflected Beam for One Quad Setting

1 nC, 135 MeV

horizontal direction

time slices

vertical direction – time axis

HEAD

TAIL

1 nC, 135 MeV

100 A
Example of "Sliced Emittance" Measurement with RF Deflector - FLASH

many thanks to Michael Roehrs and the FLASH commissioning team! see also: M. Roehrs, DESY-thesis May 2008, measurements are courtesy of M. Roehrs, DESY

Sliced Emittance Tomography – uncompressed bunch

Sliced Emittance Tomography – SASE conditions
Transverse RF Deflector - Summary

- transverse RF deflectors are “fs streak cameras” for highly relativistic electron beams

- traveling wave (LOLA-type) and standing wave (SPARC-type) transverse RF deflectors are very powerful...
  - bunch length diagnostics
  - “sliced” energy spread diagnostics (complete time resolved longitudinal phase space)
  - “sliced” emittance diagnostics (complete time resolved transverse phase space)

- transverse RF deflectors can be used for low (SW structures) and high (TW structures) energy particle beams providing excellent (sub – 10 fs) time resolution in single-shot and averaging modes
  (in averaging mode good RF synchronization is critical !!!)

- **Unfortunately,...**

  RF deflectors are destructive diagnostics and cannot be used “online”
Introduction to Bunch Length Diagnostics using Coherent Radiation

- radiation emitted by relativistic particle beams (in the following: electron beams) contains information about the longitudinal and transverse bunch distribution

- typically Cerenkov radiation (CR), transition and diffraction radiation (TR and DR), synchrotron radiation (SR) edge radiation from bending magnets (ER) and Smith-Purcell radiation (SPR) are used for diagnostics purposes

- at wavelength (much) shorter than the bunch length the radiation is emitted incoherently because each electron emits its radiation independently from the others without a defined phase relation

- coherent enhancement occurs at wavelengths, which are equal to or longer than the bunch length, where fixed phase relations are existing, resulting in the temporal coherence of the radiation

- while the power of the incoherent radiation scales with the number N of particles in a bunch, the coherent radiation increases with the square of the number of particles N²
Coherent Radiation – The Longitudinal Bunch Form Factor I


using classical electrodynamics and the notation of Jackson, the radiation emitted by a single electron in the far field \((R \gg r)\), into a solid angle \(d\Omega\) in a frequency range \(d\omega\) is given by:

\[
\frac{d^2 I}{d\omega d\Omega} = \frac{e^2 \omega^2}{4\pi^2 c} \left| \int_{-\infty}^{\infty} \hat{n} \times (\hat{n} \times \beta) e^{i\omega[\tau - \hat{n} \cdot r(t)/c]} dt \right|^2
\]

→ for a bunch with \(N\) particles:

\[
\frac{d^2 I}{d\omega d\Omega} = \frac{e^2 \omega^2}{4\pi^2 c} \left| \int_{-\infty}^{\infty} \sum_{j=1}^{N} \hat{n} \times (\hat{n} \times \beta_j) e^{i\omega[\tau - \hat{n} \cdot r_j(t)/c]} dt \right|^2
\]

with \(\beta_j\) as the ratio of the \(j^{th}\) particle to the velocity of light \((v_j/c)\) and \(r_j\) the position of the \(j^{th}\) particle in the bunch

assuming \(\beta\) as the same velocity for all particles in the bunch and \(r(t)\) as their persistent position in relation to the center of mass of the bunch, the above relation can be rewritten to:

\[
\frac{d^2 I}{d\omega d\Omega} = \frac{e^2 \omega^2}{4\pi^2 c} \left| \sum_{j=1}^{N} e^{i\omega r_j/c} \left| \int_{-\infty}^{\infty} \hat{n} \times (\hat{n} \times \beta) e^{i\omega[\tau - \hat{n} \cdot r_j(t)/c]} dt \right|^2 \right|^{2}
\]

and with \(\beta = 1\):

\[
T(\omega) = \left| \sum_{j=1}^{N} e^{i\omega r_j/c} \right|^2
\]

the time dependent terms have been separated from the summation term and remain in the integral, which represents the intensity radiated by single (particle) electron
Coherent Radiation – The Longitudinal Bunch Form Factor II


\[
T(\omega) = \left| \sum_{j=1}^{N} e^{i\omega r_j / c} \right|^2 = \sum_{j=1}^{N} e^{i\omega r_j / c} \sum_{k=1}^{N} e^{-i\omega r_k / c} = \sum_{j=1 \atop j=k}^{N} e^{i\omega (r_j-r_k) / c} + \sum_{j,k=1 \atop j\neq k}^{N} e^{i\omega (r_j-r_k) / c}
\]

which in turn becomes unity for \( j = k \) and turns into…:

\[
N + \sum_{j,k=1 \atop j\neq k}^{N} e^{i\omega (r_j-r_k) / c}
\]

This equation can be rewritten as…:

\[
T(\omega) = N + N(N-1) F(\omega)
\]

with

\[
F(\omega) = \frac{1}{N(N-1)} \sum_{j,k=1 \atop j\neq k}^{N} e^{i\omega (r_j-r_k) / c}
\]

and the total radiated power by an electron bunch with \( N \) particles results in…:

\[
\frac{d^2 I}{d\omega d\Omega} = [N + N(N-1) F(\omega)] P(\omega)
\]

where \( P(\omega) \) is the power radiated by a single electron and \( F(\omega) \) describes the coherence of the emitted radiation:

- \( F(\omega) = 0 \) represents the incoherent limit with the total power \( \sim \) number of particles \( N \)
- \( F(\omega) = 1 \) represents the coherent limit with the total power \( \sim \) square of the number of particles \( N^2 \)
Coherent Radiation – The Longitudinal Bunch Form Factor III


In particle accelerators, it is usually justified to assume:

- a continuous particle distribution \( S(r) \)
- with a large number \( N \) of particles in a bunch (typically \( 10^7 - 10^{12} \))

This allows the expression of \( F(\omega) \) by the Fourier Integral of the charge distribution function

\[
F(\omega) = \lim_{N \to \infty} \frac{1}{N^2} \sum_{j,k=1(j \neq k)}^{N} e^{i\omega(r_j - r_k)/c}
\]

by assuming a circular transverse beam distribution in the far field \( (R >> r_{bunch}) \), the formfactor \( F(\omega) \) depends only on the longitudinal charge distribution:

\[
F(\omega) = \left| \int e^{i\omega z/c} S(z)dz \right|^2
\]
Coherent Radiation – Bunch Compression & Longitudinal Bunch Form Factor

Magnetic Bunch Compression (Schematic)

Longitudinal Phase Space at FLASH

courtesy of M. Dohlus (DESY)

LINAC...:
example taken from
Jan Menzel (PhD):
FLASH bunches

Longitudinal Charge Distributions

\[ \int e^{i \omega z/c} S(z) dz \]

bunch length meas. with coherent radiation typical units:

- 1 ps
- 100 fs

- 1 THz ~ 300 μm ~ 33 cm\(^{-1}\) ~ 4.1 meV ~ 47.6 K
- 10 THz ~ 30 μm ~ 333 cm\(^{-1}\) ~ 41 meV ~ 476 °K

Volker Schlott
Coherent Radiation – Bunch Slicing & Longitudinal Bunch Form Factor

FEMTO-
Bunch Slicing in SLS Storage Ring...:

\[ \int e^{i\omega z/c} S(z)dz^2 \]

(courtesy of G. Ingold - PSI)
Coherent Radiation – SLS FEMTO Bunch Slicing Experiment

SLS FEMTO Source: Hard X-Rays
(courtesy of G. Ingold – PSI)

Electron/Laser Interaction
Modulator (Wiggler)

Pulse Separation
Angular Dispersion (Chicane Magnets)

Sub-ps X-Rays
Radiator (Bend / Undulator)

(courtesy of G. Ingold – PSI)
Coherent Radiation – Emission Spectrum

for sub-ps (electron) bunches, the wavelength range of coherent emission is typically in the sub-mm & THz-regime
Coherent Radiation – Peculiarities of Sub-mm (THz) Wavelengths

- opening angles of coherent radiation (CSR, CER, CTR and CDR...) emitted from highly relativistic particle beams are much wider than the usual $1/\gamma$ approximation

Opening Angles of Coherent TR (vertical polarization) in the Sub-mm (THz) Regime (Theory & Measurement)

- Gauss Optics needs to be applied for design of THz beam transport systems
  - large apertures of so called quasi optical elements are required
  - first surface metal mirrors (typically gold coated) are used for beam transport (plane mirrors) and focusing (paraboloids, toroids etc...)
Coherent Radiation – Peculiarities of Sub-mm (THz) Wavelengths

Transmission of Typical (UH) Vacuum Window Materials

Optical set-ups and beam transport lines have to be well designed for sub-mm (THz) radiation

→ beam transport should be done with large aperture mirror optics
→ special materials for UHV windows (Diamond for fs bunches, Crystal Quartz well suitable for ps-pulses)
→ optical set-ups should be in vacuum (some mbar) or flooded with Nitrogen

Water Absorption as a Function of Air Pressure
Coherent Radiation – Example of SLS FEMTO THz Beam Transport Line

Electron beam
- 1 nC
- 2.4 GeV

FIR beam (λ = 1 mm) at location of slotted mirror absorber behind BE05 bending magnet

UHV-window

1st toroidal mirror

motorized mirror mount

2nd toroidal mirror

3D-view of transfer line

coherent FIR synchrotron radiation

3rd toroidal mirror

vacuum pump

Storage Ring Tunnel

Tunnel Wall (1m)

Experimental Area
Coherent Radiation – Detector Systems in the THz Regime

He- and N-cooled bolometers (InSb, Si, GeGa, Nb…)

Spectral response: ~ 5 mm to < 50 μm
Optical N.E.P: ~ 1.5 \times 10^{-12} \text{ W Hz}^{-1/2}
Dynamic Range: pW to μW
Opt. Responsivity: 15 kV / Watt
Detector BW: ~ 1 MHz
Operating Temp.: < 4.2 °K
Price: ~ 20 – 30 k£

Golay Cell Detectors

Spectral response: ~ 5 mm to visible
Optical N.E.P: ~ 1 \times 10^{-10} \text{ W Hz}^{-1/2}
Dynamic Range: pW to μW
Opt. Responsivity: 100 kV / Watt
Detector BW: ~ 15 Hz
Operating Temp.: 300 °K
Price: ~ 8 k£

Other useful FIR (THz) detectors are e.g.:

Pyro-Electric Detectors (LiTaO₃) and DTGS Detectors

Spectral response: ~ 5 mm to < 5 μm
Optical N.E.P: ~ 2 \times 10^{-9} \text{ W Hz}^{-1/2}
Dynamic Range: nW to mW
Opt. Responsitivity: 10 kV / Watt
Detector BW: ~ 15 Hz
Operating Temp.: 300 °K
Price: ~ 2 – 5 k€
Coherent Radiation – Transfer Function $G(\omega)$ of Measurement System

Transfer Function $G(\omega)$ accounts for wavelength dependent properties of all components in the THz measurement system (here: SLS FEMTO bunch slicing diagnostic)

Crystal Quartz and LDPE Windows

Diffraction through THz Transfer Line

Water Absorption through 0.5 m (MPI)

Liquid He-cooled InSb Bolometer

Transfer Function of FEMTO Slicing Diagnostics Line

\[ G(\omega) = \prod_i G_i(\omega) \]
Measurements with Coherent Radiation: LCLS Bunching Monitor

many thanks to J. Frisch & H. Loos and the LCLS commissioning team! See also: PR-STAB 11 30703 (2008) about LCLS injector commissioning

Coherent Edge Radiation from 4th Bend of BC-1

Signals from Pyro-Electric Detectors for Different RF Phases

RF Phase Scan behind BC-1 using CER from 4th Bending Magnet
**Measurements with Coherent Radiation – Martin-Puplett Interferometer**

**MPI Operating Principle…:**

- the MPI works like the well known *Michelson Interferometer* but takes advantage of the polarization of CTR, CSR...

- *radially* polarized CTR is transferred into *linearly* polarized light at the *wire grid polarizer* (in reflection or transmission)

- at the *wire grid beam splitter* (oriented at 45° in projection / 35.3° in the horiz. plane) half of the linearly polarized light is reflected and half is transmitted

- the *roof mirrors* in the interferometer arms flip the polarization state of the radiation so that the previously reflected beam is now transmitted at the *wire grid beam splitter* and vice versa

- recombination of the two linearly polarized light waves with perpendicular polarization states leads – in case of different path lengths in the interferometer arms – to elliptically polarized light

- the *analyzer* grid separates again the horizontal and vertical polarization states of the radiation

- the wavelength dependent phase differences in the MPI arms lead to different intensities of the two polarization states at the detectors

Interferometer scans are courtesy of Lars Fröhlich, DESY
Measurements with Coherent Radiation – Martin-Puplett Interferometer

Martin-Puplett Interferometer installed behind FLASH Synchrotron Radiation Beamline

PG - polarizing grid
BDG - beam splitter grid
FRM - fixed roof mirror
MRM - movable roof mirror
PM2 - parabolic mirror
AG - analyzing grid
VDET - pyro-detector for vertical polarization
HDET - pyro-detector for horiz. polarization

courtesy of Lars Fröhlich, DESY
Measurements with Coherent Radiation – Fourier Spectroscopy

- **incoming E-M wave** with horizontal polarization (behind polarizer)...
  \[ E_{\text{in}}(\omega, t) = E_{\text{in}}(\omega) \cdot \sin(\omega t) e_h \]

- **E-M wave behind wire grid beam splitter (45°)**...
  \[ E_{1,2}(\omega, t) = \frac{E_{\text{in}}(\omega)}{2} \cdot \sin(\omega t) (e_h \pm e_v) \]

- from roof mirrors back reflected E-M wave (90° pol. rotated)...
  \[ E_{1,2}(\omega, t) = \frac{E_{\text{in}}(\omega)}{2} \cdot \sin(\omega (t + \Delta t_{1,2})) (e_{h,\mp} e_{v}) \]

- interfering the E-M waves behind beam splitter...
  \[ E_{\text{out}}(\omega, t) = E_1(\omega, t) + E_2(\omega, t) \]

- the **mean intensity at the detectors** (slow compared to \(\omega\)) results to...
  \[ I_{1,2}(\omega) = \left( E_{\text{out}}(\omega, t) \cdot e_{h,v} \right)^2 \]

- using \(\tau = (\Delta t_1 - \Delta t_2)\) and \(I_{\text{in}}(\omega) = E_{\text{in}}(\omega)^2/2\), the **intensities at the detectors** can be expressed by...

\[
\begin{align*}
I_1(\omega) &= I_{\text{in}}(\omega) \cos^2\left(\frac{\omega \tau}{2}\right) \\
I_2(\omega) &= I_{\text{in}}(\omega) \sin^2\left(\frac{\omega \tau}{2}\right)
\end{align*}
\]

... integration over all frequencies \(\omega\) leads to interferograms at both detectors:

\[
I_{1,2}(\tau) = \int_0^\infty d\omega I_{\text{in}}(\omega) \left(1 \pm \cos(\omega \tau)\right)
\]
Measurements with Coherent Radiation – Fourier Spectroscopy II

- the MPI difference interferograms result in a **Cosine-Transformation** of the incoming radiation spectrum $I_{in}(\omega)$:

$$I_{1,2}(\tau) = \int_{0}^{\infty} d\omega \frac{I_{in}(\omega)}{2} \cdot (1 \pm \cos(\omega \tau))$$

- the intensity of coherent radiation (CTR, CDR, CSR...) in case of bunch length measurements (N >> 1) results in:

$$I_{in}(\omega) = N^2 I_{sp}(\omega) \left| F(\omega) \right|^2 \cdot \prod_{i} G_{i}(\omega)$$

...where $I_{sp}(\omega)$ is the **spectral intensity from a single particle in a bunch**

$F(\omega)$ is the **bunch form factor**

$G_{i}(\omega)$ is the **frequency dependent transfer function from the bunch to the detector**

- intensity fluctuations are eliminated by using interferograms from both detectors for data analyses

- acc. to **Nyquist Theorem**...: the frequency span and the spectral resolution is related to the roof mirror travel

$$f_{max} = \frac{\omega_{max}}{2\pi} = \frac{1}{2 \cdot \Delta t} = \frac{c}{\Delta s}$$

$$\Delta f = \frac{\Delta \omega}{2\pi} = \frac{1}{2 \cdot (t_{max} - t_{min})} = \frac{c}{\Delta s_{max} - s_{min}}$$

- keep in mind... MPI provides an auto-correlation measurement of radiation intensities $\rightarrow$ no phase information !!!
Reminder…: FEMTO Bunch Slicing – Longitudinal Bunch Distribution

FEMTO-
Bunch Slicing
in SLS
Storage
Ring…:

\[ \left( \int e^{i\omega z/c} S(z) dz \right)^2 \]

(courtesy of G. Ingold - PSI)
Coherent Radiation – Spectral Bunch Length Meas. from SLS FEMTO

Turn-by-Turn Long. Bunch Evolution after Bunch Slicing in SLS Storage Ring (Simulations by Davit Kalantarian (CANDLE))

Notice: the scaling of the bunch length axis is increasing from ± 200 μm (turn-0) to ± 8 mm (turn-4)
storage ring revolution rate ~ 1 MHz  →  turn-by-turn revolution time ~ 1 μs

Integrated THz-Signal on InSb-Bolometer

Spectral Intensities of Turns 0 – 4 (Simulations by D. Kalantarian (CANDLE))
Coherent Radiation – Spectral Bunch Length Meas. from SLS FEMTO

Interferograms from 5 consecutive turns after slicing

Spectral Intensities of Turns 1 to 4 after Slicing

Spectral Intensity of Turn 0 (Theory and Experimental Data)

Bunch Lengths Evolution after Slicing in SLS Storage Ring

Bunch Lengths Determination by Spectroscopic Measurements – Flow Chart

**Time Domain**

- long. bunch configuration \( S(z) \)
- auto-correlation
- MPI measurement \( a(\tau)/a(s) \)

**Frequency Domain**

- longitudinal Form Factor \( |F(\omega)| \)
- spectral intensity \( A(\omega) \)
- extrapolation (high and low frequencies)
- correction (transfer function)

---

Kramers-Kronig Relation (phase recovery → complex Form Factor)

Invers Fourier Transformation
determination of bunch in case of “slicing” is only possible due to deterministic slicing process by FEMTO-laser and well known “slice evolution” in storage ring
Bunch Lengths Determination by Spectroscopic Measurements

- intensity-based interferometry (MPI) reveals only the absolute value of the Form Factor → no phase information!

Symmetric Bunch Shapes

- for symmetric bunch configurations $S(z)$, the bunch Form Factor is retrieved from the coherent bunch spectrum by a cosine transform:

$$
F(\omega) = \left| \int e^{i\omega z/c} S(z) dz \right|^2 \quad \Rightarrow \quad S(z) = \frac{1}{\pi c} \int_0^\infty d\omega \sqrt{F(\omega)} \cdot \cos \left( \frac{\omega z}{c} \right)
$$

Asymmetric Bunch Shapes and phase recovery by Kramers-Kronig Analysis:


- the measured Form Factor $F(\omega)$ over the entire frequency spectrum provides directly the magnitude of the Form Factor amplitude $\rho(\omega)$:

$$
\rho(\omega)e^{i\psi(\omega)} = \int_0^\infty S(z)e^{i\omega z/c} dz \quad \text{and} \quad \rho^2(\omega) = F(\omega)
$$

- the Form Factor amplitude $\rho(\omega)$ is related to the long. bunch configuration by inverse Fourier Transformation:

$$
S(z) = \frac{1}{\pi c} \int_0^\infty d\omega \rho(\omega) \cdot \cos \left( \psi_m(\omega) - \frac{\omega z}{c} \right) \quad \text{with the minimal phase} \quad \psi_m(\omega) = -\frac{2}{\pi} \int_0^\infty \ln \left[ \frac{\rho(x)}{\rho(\omega)} \right] dx
$$

- this formalism allows the recovery of asymmetric bunch structures – as usually produced in LINACs – but leaves the ambiguity of not being able to distinguish between a given bunch shape from the one flipped front to back.
Bunch Lengths Determination by Spectroscopic Measurements

- intensity-based interferometry (MPI) reveals only the absolute value of the Form Factor → no phase information!

Symmetric Bunch Shapes
- for symmetric bunch configurations $S(z)$, the retrieval of the bunch Form Factor from the coherent bunch spectrum is achieved by a cosine transform...:

$$ F(\omega) = \left| \int e^{i\omega z/c} S(z)dz \right|^2 \quad \rightarrow \quad S(z) = \frac{1}{\pi c} \int_0^\infty d\omega \sqrt{F(\omega)} \cdot \cos\left(\frac{\omega z}{c}\right) $$

Asymmetric Bunch Shapes
- application of the Kramers-Kronig analysis provides the possibility to recover the missing phase information
- this formalism allows the recovery of asymmetric bunch structures – as usually produced in LINACs through bunch compression – but leaves the ambiguity of not being able to distinguish between a given bunch shape from the one flipped front to back
- in case of Fetmo bunch slicing, the bunch length and bunch shape is determined by the slicing laser pulse → both laser pulse shape and pulse duration are known by laser auto-correlation measurements → bunch evolution depends on storage ring optics, which is also well established and known

simulated bunch configurations can be fitted to measured bunch spectra
Bunch Lengths Determination by Spectroscopic Measurements – Overview

**Time Domain**

- long. bunch configuration \( S(z) \)
- MPI measurement \( a(\tau)/a(s) \)
- auto-correlation

**Kramers-Kronig Relation**

- (phase recovery \( \rightarrow \) complex Form Factor)

**Inverse Fourier Transformation**

**Frequency Domain**

- longitudinal Form Factor \( |F(\omega)| \)
- spectral intensity \( A(\omega) \)
- extrapolation (high and low frequencies)
- correction (transfer function)

- Fourier Transformation
**Single-Shot FIR Spectrometer – “Polychromator”** (DESY approach, courtesy of B. Schmidt)

- Single-shot spectrometer makes use of wavelength dependent reflection of gratings as dispersive elements.
- One reflective blazed grating covers ~ 1.8 x base wavelength → four stages needed to cover one decade in a single-shot.
- Custom-made 30 channel pyro-detector array and fast, high-sensitivity readout unit (250 ns gating, 70 pC / channel).
- Preliminary measurements show ultra short wavelength components → indicating very short bunch structures.

---

**Schematic Set-Up of Single-Shot Spectrometer**

- Focus on the grating elements and their arrangement.
- Diagram showing the grating, focusing, and pyro-array components.

---

**CTR Spectrum from FLASH bunches (raw data)**

- Graph showing the CTR spectrum from four grating stages.
- FLASH (DESY) – preliminary data, uncorrected.

---

**Readout Module 30 Channel Pyro-Array**

- Images of the readout module and 30 channel pyro-array.

---
Summary of Spectroscopic Bunch Lengths Measurements

- The integrated intensity of coherent radiation emitted by short relativistic electron bunches provides a sensitive diagnostics ($I \sim N^2$) for bunching control and RF phase adjustment of accelerator structures.

- Fourier spectroscopy using e.g.: Michelson or Martin-Puplett interferometers represents a robust and reliable method to determine the bunch Form Factor $F(\omega)$, which is proportional to the longitudinal bunch configuration $S(z)$.

- There are basically no limitations towards the short wavelength regime, allowing to examine shortest bunch lengths and short-range structures within a bunch.

- Good knowledge about the measurement system transfer function is mandatory to reconstruct long. bunch shapes.

- Intensity-based interferometry reveals only the absolute value of the bunch Form Factor $\rightarrow$ no phase information!

- If the complete spectrum is known, recovery of phase information is possible through Kramer-Kronig formalism.

- Typically interferometric techniques average over many shots and provide only the average long. bunch configuration.

- Single-shot spectrometers have been designed and delivered good (preliminary) results:...
  - see e.g.: Polychromator by Wanatabe et al., NIM-A 480 (2002) 315-327
  - see e.g.: FLASH Single-Shot Spectrometer by H. Delsim-Hashemi et al., Proc. FLS, Hamburg 2006, WG512
  - see e.g.: Spatial EO Auto-Correlation Interferometer by. D. Süttérlin et al., Proc. FEL’06, Stanford 2006, 648
EO Bunch Lengths Measurements – Introduction

- Electro-optical detection inside the electron beam pipe (UHV-system) allows the direct measurement of the Coulomb field from highly relativistic electron bunches in the time domain.

- The Coulomb field carried by short (sub-ps) electron bunches reaches – like coherent radiation – into the THz range.

- The electric field induces a refractive index change in a birefringent crystal (e.g.: ZnTe, GaP), which is probed by a short pulse (fs), high bandwidth (some tens of nm) laser (linearly polarized, 800 – 1100nm).

Schematic Set-Up of EO Bunch Length Measurements
EO Bunch Lengths Measurements – Pockels Effect & EO-Detection

- an external electrical field (here: THz Coulomb field from the electron bunches) changes the refractive index of an optically active crystal (e.g.: ZnTe, GaP)…:

→ Polarization change as a function of field strength: \[ P = \varepsilon_0 \left( \chi_e^{(0)} E + \chi_e^{(1)} E^2 + \chi_e^{(2)} E^3 + \ldots \right) \]

- the THz radiation \( E_{\text{THz}} \) passes the EO-crystal in the \((1,1,0)\)-plane

- the two components of a linearly polarized probe laser pulse \( E_{\text{laser}} \) will see different refractive indices \( n_j \) and \( n_\lambda \) in the crystal leading to a phase retardation and a subsequent polarization change (from linear to elliptical) of the laser pulse

- the phase retardation is proportional to the optical properties of the EO-crystal, the THz field strength and the crystal thickness…:

\[ \Gamma_{\text{max}} = \frac{\omega d}{c} (n_1 - n_2) = \frac{\omega d}{c} E_{\text{THz}} n_0^3 r_{41} \]

- a suitable arrangement of polarizers converts the ellipticity into an intensity modulation at the detector…:

→ cross polarizer arrangement: signal \( \sim \Gamma^2 \)  
→ balanced detection: signal \( \sim \Gamma \)
EO Detection – Velocity Matching of THz and Optical Fields

- group and phase velocities of THz-waves in EO-crystals are frequency dependent and differ from each other leading to gradual distortion and lengthening of the THz-pulse over the crystal thickness
- lattice resonances (ZnTe at ~ 5 THz and GaP at ~ 11 THz) limit the EO response of a material
- laser pulse broadening is also visible due to phase retardation but can be neglected for thin crystals (< 200 μm)

EO response function depends mainly on material and crystal thickness
EO Detection – Probe Laser Options

- typically commercially available Ti:Sa lasers are used as probe lasers for EO readout
  - providing short (few tens of fs) pulses with high bandwidth (some tens of nm)
  - velocity matching @ 800 nm is fairly good

- new more compact and more stable Yb-doped fiber lasers are presently under development (e.g.: DESY and PSI)
  - providing short (~ 50 fs) pulses with high bandwidth (some tens of nm) and superior amplitude stability
  - superior velocity matching @ 1030 nm, which allows the use of thicker EO-crystals
  - excellent synchronization to Er-doped fiber laser based optical master oscillators (~ 10 fs reference stability)

EO-response in GaP with Yb-doped fiber laser

simulations by B. Steffen (DESY / PSI)
Electro-Optic Sampling

Schematic Set-Up of Electro-Optic Sampling with Variable Delay

- EO sampling is technically “simple” and provides high resolution (in the order of the laser pulse length)
- averaging over many bunches and limited by synchronization between laser and electron bunches

Meas. taken at SLS LINAC. See also: A. Winter et al., THOAL01, EPAC’04

Meas. taken at FLASH. Courtesy of Bernd Steffen
Spatially Resolved Electro-Optic Detection

Schematic Set-Up of Spatial Decoding

- similar approach like EO sampling but single-shot measurement
- temporal to spatial mapping through oblique incident between laser and Coulomb field in the plane above the laser and the EO-crystal
- angle $\psi$ between laser and Coulomb field introduces a continuous time delay along the EO-crystal
- analyzer A turns spatial modulation of polarization into spatial intensity modulation, which is detected by a CCD camera
- requires spatially uniform laser beam and spatially uniform EO-crystal but stress induced birefringence prevents spatial uniformity in EO-crystals

Time Window

$$\Delta t = \frac{\Delta x}{c} \tan(\psi)$$

$\Delta x$ - laser beam width
$\psi$ - angle between laser and electron beam path

Example

$$\Delta t = \frac{3 \times 10^{-3} m}{3 \times 10^{-8} ms^{-1}} \tan(45^\circ) = 10 \text{ ps}$$

TEO measurement by A. Azima et al., DESY
Spectrally Resolved Electro-Optic Detection

Schematic Set-Up of Spectral Decoding

- EO spectral decoding is a single-shot measurement
- linear chirp is encoded on the laser pulse by passing a dispersive material or grating stretcher
- chirped laser pulse travels in parallel to the Coulomb field through EO-crystal encoding a frequency-time correlation onto the laser spectrum
- analyzer A turns modulation of polarization into an intensity modulation, which is sent through a spectrometer and measured by a CCD camera
- laser pulse energy spread over many pixel → higher laser pulse energy
- frequency mixing of THz wave and laser distorts frequency-time correlation

Time Resolution (Gaussian bunch shapes)

\[ \sigma_{\lim} \geq \sqrt{\sigma_0 \sigma_c} \]

\( \sigma_0 \) - laser beam duration
\( \sigma_c \) - chirped laser pulse duration

Example

\[ \sigma_{\lim} \geq \sqrt{7.5 \text{ fs} \cdot 1500 \text{ fs}} \geq 100 \text{ fs} \]

Spectral Decoding (GaP 175 μm, \( \sigma_0 = 7 \text{ fs}, \sigma_c = 1.5 \text{ ps} \))

Measurement by B. Steffen et al., DESY
**Temporally Resolved Electro-Optic Detection**

**Schematic Set-Up of Temporal Decoding**

- EO temporal decoding is a single-shot measurement, where the chirped laser pulse travels in parallel to the Coulomb field through the EO-crystal encoding a frequency-time correlation onto the probe laser spectrum.

- the analyzer A turns the modulation of polarization into an intensity modulation.

- SH light is generated by cross-correlating the modulated EO-pulse and the short laser pulse in a BBO-crystal.

- the SH-generation in the BBO-crystal works similar to the spatial decoding technique and is proportional to the square of the incoming intensities: $I_{SH} \sim I_{gate} \cdot I_{EO}$.

- using a 300 μm thick BBO-crystal and a 30 fs gate pulse, a time resolution of < 100 fs can be reached.

- due to the low efficiency of the SH-process, a pulse energy of 100 μJ from an amplified laser system is required.
Temporally Resolved Electro-Optic Detection

Measurement of FLASH Bunches with EOTD *

![EOTD signal graph]

\[ \sigma = 80 \text{ fs} \]

electron bunch lengths as short as 55 fs have been measured with temporally resolved EO detection!
(This is close to the resolution limit of GaP)

Comparison between EOTD and Transverse Deflector *

![Comparison graphs]

* EOTD measurements by B. Steffen et al., DESY, see also: B. Steffen, DESY-thesis-2007-020, July 2007
TDS measurements by M. Roehrs, DESY
Set-Ups of Temporal and Spectral Decoding in FLASH Accelerator Tunnel

**Electro-Optical Bunch Arrival Time Monitor – FLASH Design**

**Principle of EO Bunch Arrival Time Monitor (FLASH-design)**

- laser pulses from fiber link
- beam pick-up
- EOM
- ADC

**Commercial EO Modulator (10 – 40 GHz BW)**

- bias voltage
- Lithium Niobate
- RF signal

**Electro-Optical BAM Measurement Principle**

- electron bunch arrival time:
  - early
  - correct
  - late
- voltage modulating the laser pulse amplitude
- laser pulse (perfectly synchronized)

**EO BAM Resolution (~ 10 fs)**

- images and measurements taken from F. Löhl et al., DESY
**Femto-Second Diagnostics – Summary** (personal opinion…)

Various measurement techniques in the *Time Domain* and *Spectral Domain* have been developed and presented...

**Time Domain:**

- **fs streak cameras...**: → provide sub-ps (> 300 fs) time resolution for quasi monochromatic visible light  
  → very useful for optimization of gun laser profile and low energy electron beam  
  but quite limited time resolution and does not provide “feedback-usable” signals

- **transv. RF deflectors...**: → provide excellent (~ 10 fs) time resolution by deflecting directly the particle beam  
  → very versatile diagnostic for time resolved measurement of transverse and  
  longitudinal phase space (sliced emittances and energy distribution)  
  → unfortunately destructive measurement method

- **EO techniques...**: → provide excellent (> 50 fs) time resolution by measuring the beam’s Coulomb field  
  → spatial, spectral and temporal decoding are single-shot methods, which measure  
  the bunch length and provide high resolution (~ 10 fs) beam arrival time information  
  → unfortunately still very complex (optical) set-ups using (high power) fs lasers

**Spectral Domain**

- **Interferometers...**: → interferometric meas. are very robust and provide excellent spectral (temporal) resolution  
  → single-shot measurements have been accomplished  
  → transfer functions have to be known and phase information is usually not available