Fast Bunch Profile Monitoring with THz Spectroscopy of Coherent Radiation at FLASH.

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Thomas Jefferson National Accelerator Facility

Outline

- Longitudinal diagnostics @ FLASH
- Spectrometer design + setup
- Comparison with TDS
- Control system implementation

DESY

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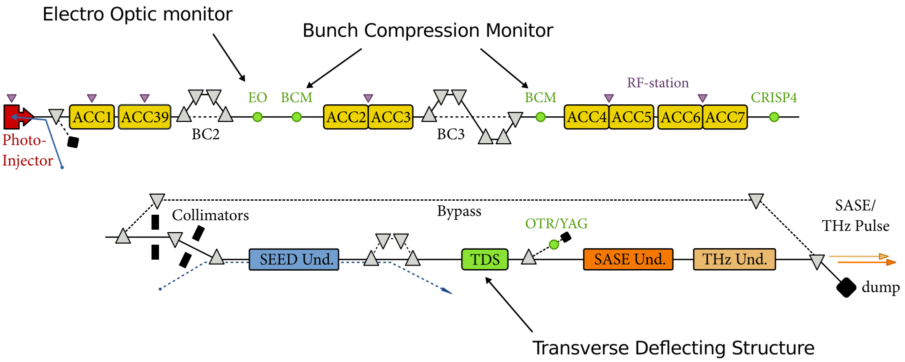
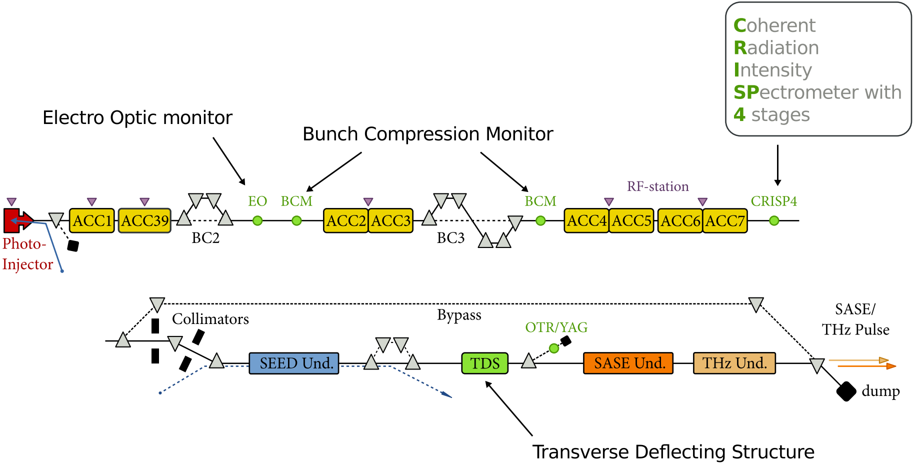
Longitudinal Diagnostic



Longitudinal Diagnostic



Spectrometer Requirements for FLASH

- Final bunch length from 10 to 100 µm (30 – 300 fs)

  → **Defines roughly covered wavelength range**

- Large shot to shot fluctuations (rollover compression 2009)

  → **Single shot measurement**

- High bunch repetition rate (up to 1 MHz)

  → **Fast readout electronics**

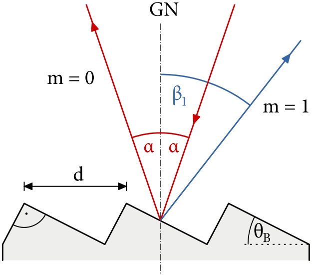
- Standard bunch length monitor

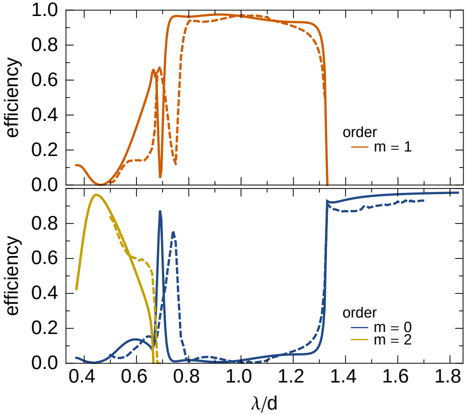
  → **Robust + easy to handle**

Design of CRISP4: Reflective Blazed Gratings

- Polarisation $\perp$ groove
- Blaze angle $\theta_B = 27°$
- Incident angle $\alpha = 19°$

$$m\,\frac{\lambda}{d} = \sin(\alpha) + \sin(\beta)$$

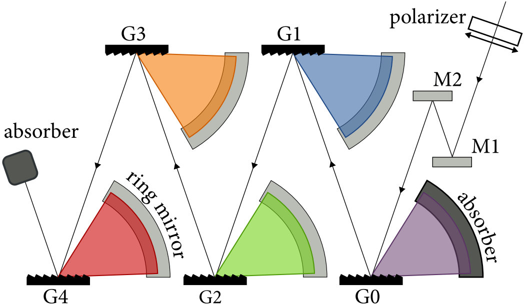


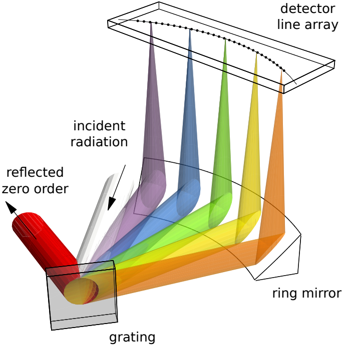


- **High efficiency** $> 90\%$
- **Band-pass character** $m = 1$
- **Low-pass character** $m = 0$

Design of CRISP4: Multi-staged Gratings

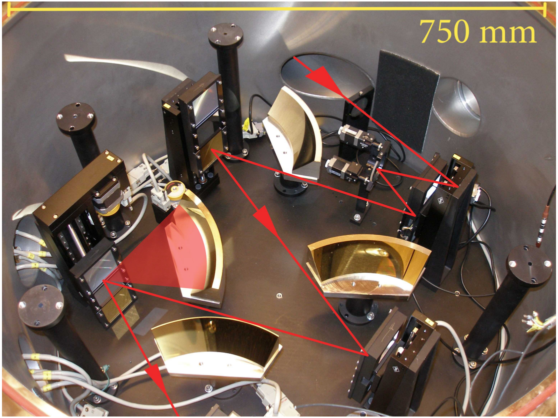
Each stage acts as dispersive element
+ filter for next stage





- Parallel readout
- 4 Stages cover one order of magnitude in λ

CRISP4: Setup

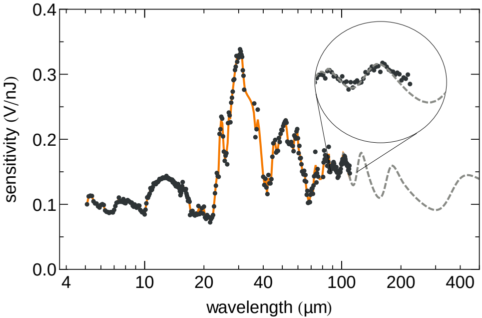


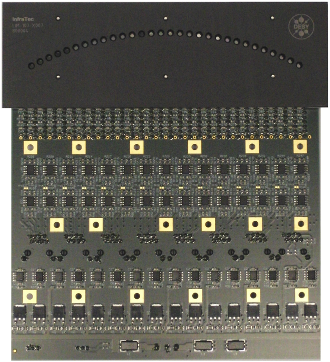
Specifications

- Engineered version
- 2 Grating sets
  $\rightarrow \lambda_{\text{Short}} = 5 - 44\,\mu\text{m}$
  $\rightarrow \lambda_{\text{Long}} = 45 - 435\,\mu\text{m}$
- Mirror set
  → set aligment
- Ring mirror
  → line focus
- Inside vacuum vessel
  → avoid IR absorption

CRISP4: Pyroelectric Detectors

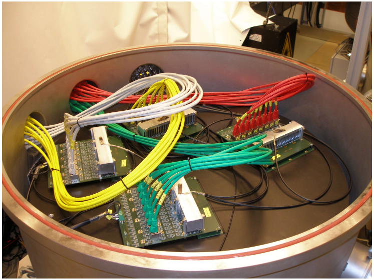
- Broadband
- Complex spectral sensitivity
- Calibrated @ FELIX

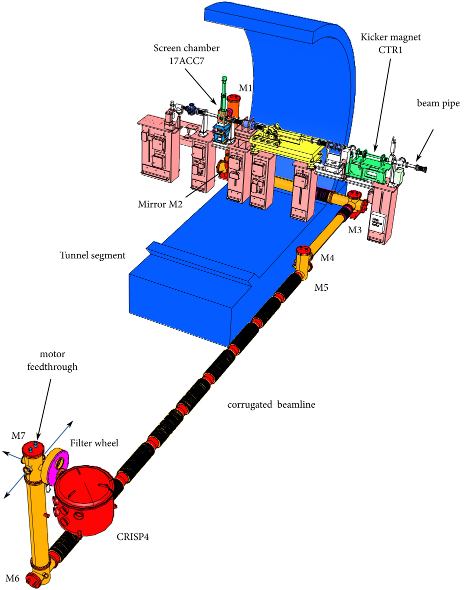




- Custom-made pyro line detector
- 120 channels in total
- Integrated amplifier board
- Fast readout with $9\,$MHz sampling

CRISP4: Attachment to CTR beamline





CTR beamline

- Length $20\,\mathrm{m}$
- Evacuated
- Separation from machine vacuum: diamond window
- High THz transmission

Coherent Radiation Diagnostic: Encoding of Bunch Structure

Coherent intensity density

$$\frac{d^2U_{\mathrm{coh}}}{d\lambda d\Omega} = \frac{d^2U_1}{d\lambda d\Omega} N^2 \, |F_{\mathrm{3D}}(\lambda,\Omega)|^2 \qquad \text{with} \qquad F_{\mathrm{3D}}(\vec{k}) = \int_{-\infty}^{\infty} \rho_{\mathrm{3D}}(\vec{x}) \, \mathrm{e}^{-i\,\vec{k}\cdot\vec{x}} \, d\vec{x}$$

Approximations

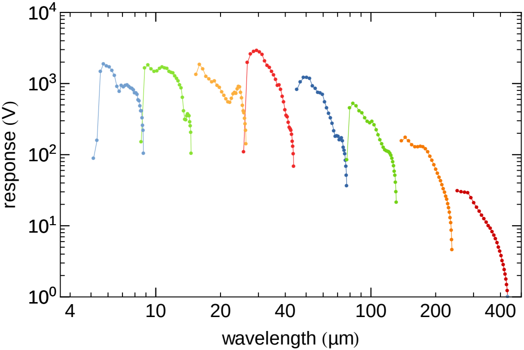
- No longitudinal-transverse coupling
  $\rightarrow F_{\mathrm{3D}} \approx F_t \, F_l$ or $\rho_{\mathrm{3D}} \approx \rho_t \, \rho_l$
- Observation in forward direction
  $\rightarrow F_l(\lambda \cos\theta) \approx F_l(\lambda)$

Coherent spectral intensity

$$\frac{dU_{\mathrm{coh}}}{d\lambda} \approx \left[\int_{\Omega_{\mathrm{Det}}} \frac{d^2U_1}{d\lambda d\Omega} \, F_t(\lambda,\Omega) \, d\Omega \right] N^2 \, |F_l(\lambda)|^2 \qquad \text{with} \qquad F_l(\lambda) = \int_{-\infty}^{\infty} \rho_l(z) \, \mathrm{e}^{-2\pi i \, z/\lambda} \, dz$$

- **Measure absolute spectral intensity $\rightarrow$ get longitudinal form factor**

CRISP4: Determination of the Longitudinal Form Factor



Calibration includes

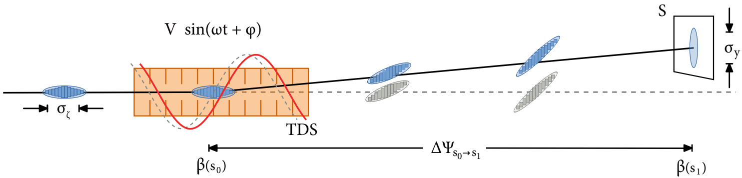
- CTR source
- Transport to detector
- Grating efficiency
- Detector sensitivity
- Electronics

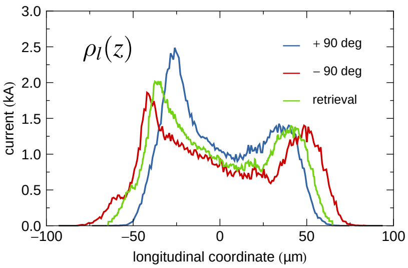
Electron Bunch Parameters

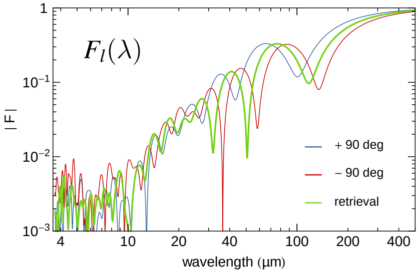
- $\sigma_l = 0$ $(F_l = 1)$
- $\sigma_t = 200\,\mu\mathrm{m}$
- $Q = 1\,\mathrm{nC}$

$$|F_l| = \left(\frac{adc\ signal[\mathrm{V}]}{charge[\mathrm{nC}]^2 \cdot response[\mathrm{V}]} \right)^{1/2}$$

Benchmark: Transverse Deflecting Structure (TDS)



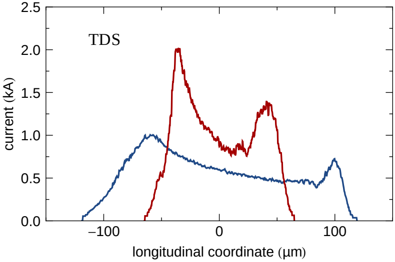




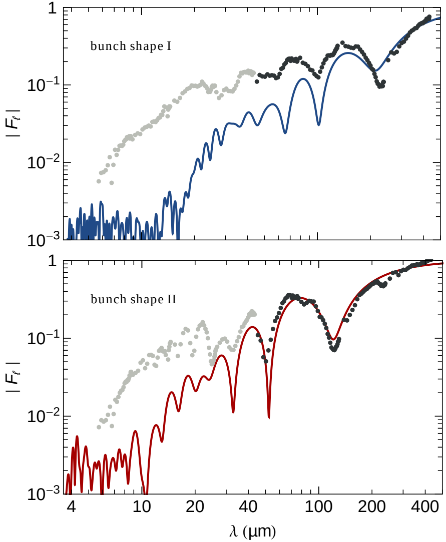
Hidden (y', z) correlation demands two-point “tomography” cf. Hendrik Loos, SLAC

Benchmark: TDS - CRISP4 Comparison

$$\rho_{l,\mathrm{TDS}}(z) \xrightarrow{FFT} |F_l(\lambda)|$$



- Agreement @ long wavelengths
- CRISP4: More short wavelengths content
  - Finite resolution
  - Smoothing due tomography
  - 60 m in between



Profile Determination by using Kramers-Kronig-Relation

R. Lai and A. J. Sievers, NIM A **397**, 221-231, 1997,
"On using the coherent far IR radiation radiation produced by a charged-particle bunch to determine its shape"

Complex form factor (ρ_l is real)

$$F_l(\lambda) = \int_{-\infty}^{\infty} \rho_l(z)\, \mathrm{e}^{-2\pi i\, z/\lambda}\, dz \qquad \text{with} \qquad F_l(\lambda) = |F_l(\lambda)|\; \mathrm{e}^{i\,\Phi(\lambda)}$$

Connection: real $\longleftrightarrow$ imaginary part (certain class of ρ_l)

$$\ln F_l(\lambda) = \ln|F_l(\lambda)| + i\,\Phi(\lambda)$$

Retrieval of minimal phase ($\Phi_{\mathrm{kk}} = \Phi_{\mathrm{min}}$)

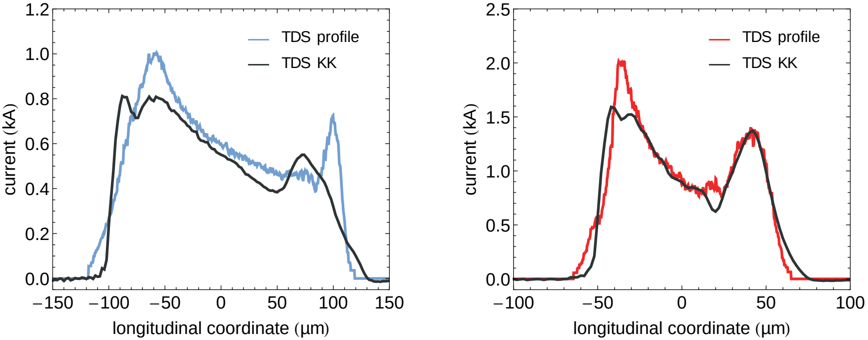
$$\Phi_{\mathrm{kk}}(\lambda) = -\frac{2\lambda}{\pi} \int_0^{\infty} \frac{\ln|F_l(\lambda')| - \ln|F_l(\lambda)|}{\lambda'^2 - \lambda^2}\, d\lambda'$$

Reconstruction of longitudinal profile

$$\rho_l(z) = -2 \int_0^{\infty} |F_l(\lambda)|\, \cos\left(\frac{2\pi z}{\lambda} - \Phi_{\mathrm{kk}}(\lambda)\right) \frac{1}{\lambda^2}\, d\lambda$$

Kramers-Kronig-Relation: Test with TDS Profiles

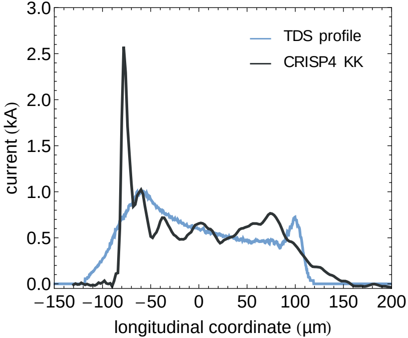
$$\rho_{l,\mathrm{TDS}}(z) \xrightarrow{FFT} |F_l(\lambda)| \xrightarrow{KK} \rho_{l,\mathrm{kk}}(z)$$

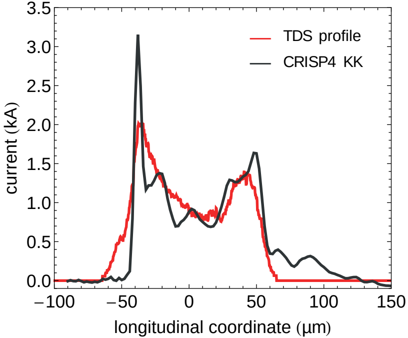


- Resonable reconstruction, but known deficits:
  - Steeper + smoother edges
  - Minimal phase $\Phi_{\mathrm{kk}} \rightarrow$ “most compact” bunch profile

Profile: TDS - CRISP4 Comparison

- Long wavelengths extrapolation Fit with $F_l(\lambda) = \exp\left[-A\,\lambda^{-2} - B\,\lambda^{-1}\right]$
- Short wavelengths cut at minimal CRISP4 range $F_l(\lambda < 5\,\mu m) = 0$



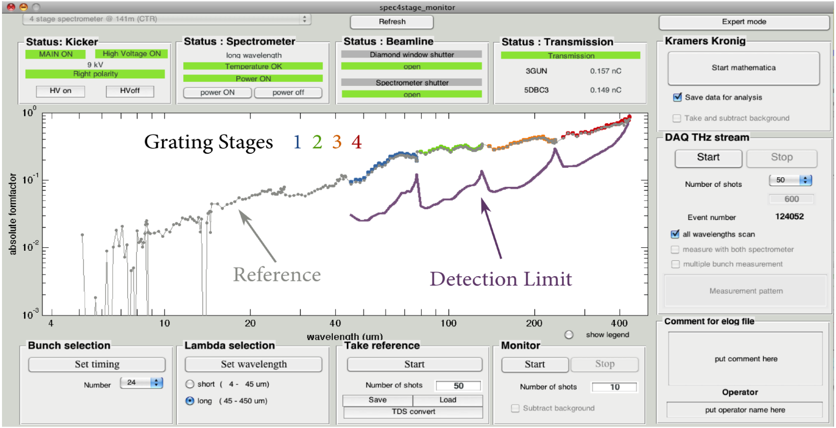


- Average currents agree
- Total bunch lengths agree

- More pronounced trailing spike
  - Short wavelengths!
  - Large local energy spread!

Control System Implementation: Online Spectrum Monitor

Kicker



Profile retrieval

DAQ

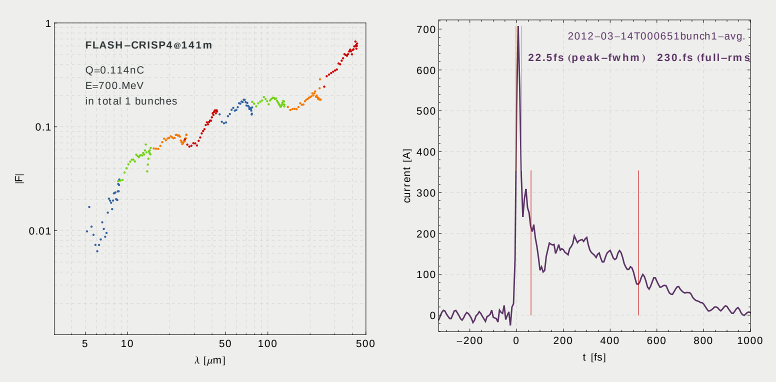
Bunch number

Wavelength

Examples: Short Pulses

Measured form factor

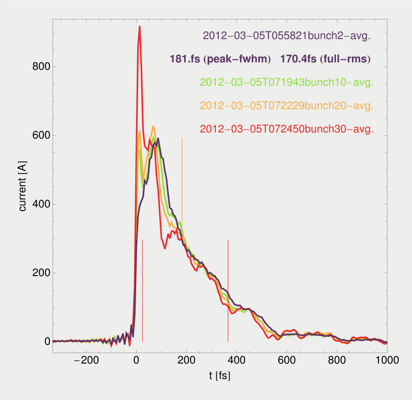
Reconstructed profile



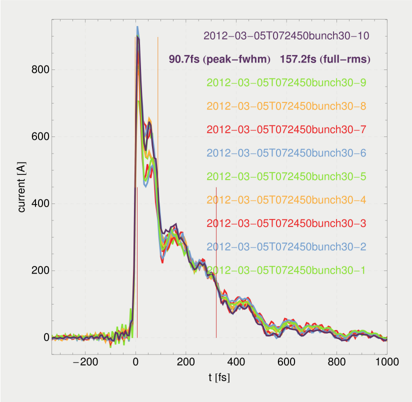
- $Q = 120\,\mathrm{pC}$
- $\sigma_z = 10\,\mathrm{fs}!$

Examples: Within Bunch Train / Double Shot

Along bunch train



Different shots same bunch number



- Possible variation can be detected
- Small shot to shot fluctuations

Summary

- Development of a broadband CTR THz spectrometer
- “Double” shot from $\lambda = 5 - 435\,\mu m$
- Capable down to charge of $100\,pC$
- Now routinely used by operators
- Complementary method to TDS measurements

Thanks to ...

- Lex van der Meer idea of staging gratings
- Hossein Delsim-Hashemi proof of principle + Prototype
- Technicians of FLA Group construction + infrastructure
- FLASH Team beam time + kicked bunch!

Backup: Wavelength Calibration