Sub-fs bunch length measurements with ECOL-BCM during 10 pC operations

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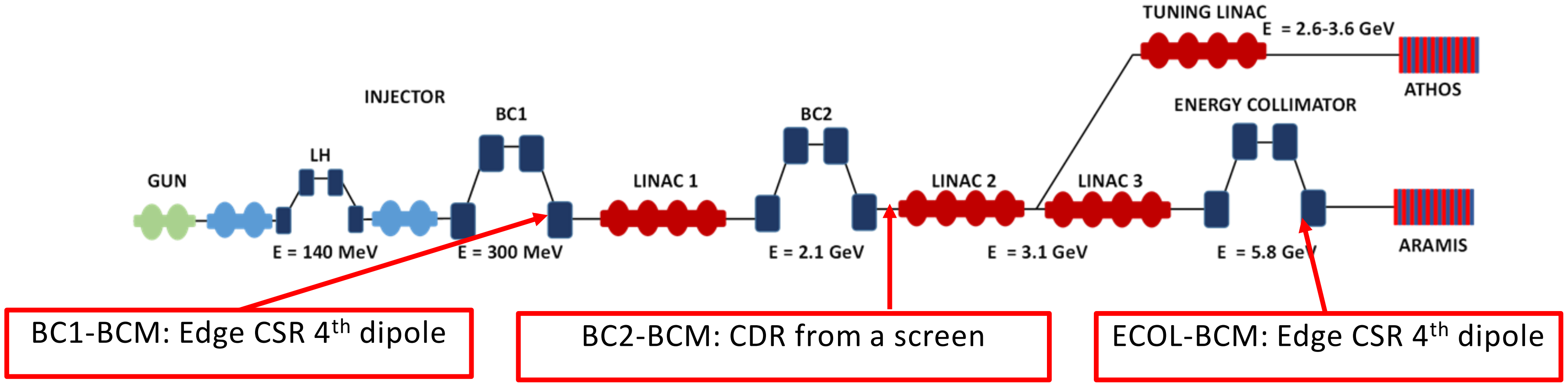
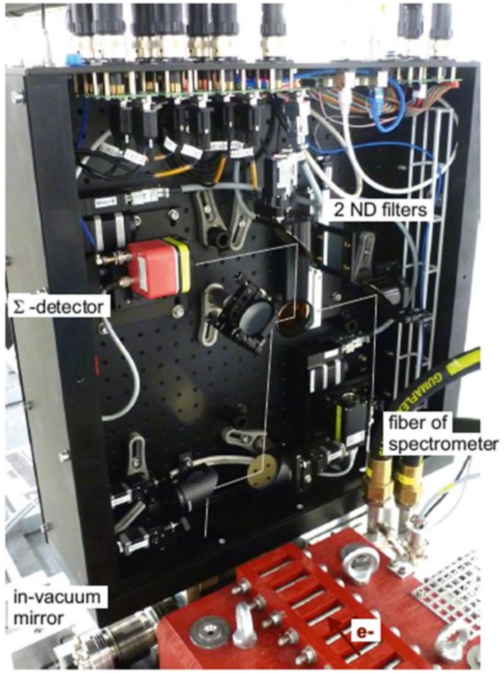
ECOL-BCM: the experimental set-up





ECOL-BCM (5.8GeV, Edge SR):

- Vacuum chamber cutoff of the radiation (<4μm)
- Design optimized for bunch length 0.7-3.0 fs (10 pC),
- Detectors:
  - Pyroelectric sensor (0.9-4.0)μm
  - Spectrometer (Ocean Optics, 0.9-2.5 μm)
- Output Signals:
  - Pyrodetector: voltage signal, radiation energy spectrum spectral fully integrated over the detector wavelength band
  - Spectrometer: 512-pixel array spectrogram

F. Frei, R. Ischebeck, Electron bunch compression monitors for short bunches - commissioning results from SwissFEL, Proc. IBIC2019, Malmoe, Sweden, Sep. 2019, pp. 578--581. doi:10.18429/JACoW-IBIC2019-WEPP026

10 pC and sub-fs bunch-length SwissFEL set-up for Cristallina

- Cristallina set-up 05.03.2024 (Prat, Reiche, Dijkstal et al.): 10 pC, 8.36 keV, 3-stage compression
- Bunch length measurements before ECOL with TDS-Cband in linac 3 : σ(rms)~15 fs
- Bunch-length prediction downstream the ECOL: σ(rms)~0.56 fs

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Rapid Communications

Single- and two-color attosecond hard x-ray free-electron laser pulses with nonlinear compression

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$$\sigma_{z,f} = c\frac{E_i}{E_f}R_{56(3)}\sigma_\delta, \qquad (1)$$

where σ_δ is the uncorrelated energy spread before BC1, $E_{i,f}$ are the energies at BC1 and BC3, respectively, and $c = c_1 c_2$ is the accumulated compression before BC3, where $c_n = (1 + R_{56(n)}h_n)^{-1}$ are compression factors in the first and second stages ($c_{1,2}^{-1} \neq 0$).

Method for absolute determination of bunch-length from “two-detector” BCM

$$\frac{dI^{Ne}(\omega)}{d\omega} \simeq N(N-1)F(\omega)\frac{dI^{e}(\omega)}{d\omega} \simeq N^2 F(\omega)\frac{dI^{e}(\omega)}{d\omega}$$

Radiation energy spectrum by a Ne^- bunch at the threshold of the temporal coherence enhancement upon integration over the solid angle of acceptance of the detector

$$F(\omega) = \left| \int_{-\infty}^{+\infty} e^{j\omega z/c} \rho_z(z) dz \right|^2 = e^{-(\frac{\omega\sigma}{c})^2}$$

Gaussian bunch form-factor (longitudinal), highly collimated beams as usual in a FEL

$$I = \int_{\omega_{min}}^{\omega_{max}} d\omega \left(\frac{dI^{Ne}(\omega)}{d\omega} / \frac{dI^{e}(\omega)}{d\omega} \right)$$

Radiation energy spectrum of the Ne- is normalized w.r.t. the single particle energy spectrum $dI^e/d\omega$ and integrated over the frequency band of acceptance $\Delta\omega$ of the detector. Assumption: $dI^e/d\omega$ either constant or weakly varying over the wavelength band of the detector

$$\ln(I) = 2\ln(N) + \ln(\int_{\omega_{min}}^{\omega_{max}} d\omega F(\omega))$$

Calculation of the natural logarithm upon single particle normalization and integration of the spectrum over $\Delta\omega$

Method for absolute determination of bunch-length from “two-detector” BCM (*)

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$$\frac{\Delta I}{I} = 2\frac{\Delta N}{N} + \frac{\int_{\omega_{min}}^{\omega_{max}} d\omega [F^*(\omega) - F(\omega)]}{\int_{\omega_{min}}^{\omega_{max}} d\omega F(\omega)}$$

$$F^*(\omega) - F(\omega) = e^{-\left(\frac{\omega\sigma}{c}\right)^2\left(1+\frac{\Delta\sigma}{\sigma}\right)^2} - e^{-\left(\frac{\omega\sigma}{c}\right)^2} \simeq$$
$$\simeq -2\frac{\Delta\sigma}{\sigma}\left(\frac{\omega\sigma}{c}\right)^2 e^{-\left(\frac{\omega\sigma}{c}\right)^2} = -2\frac{\Delta\sigma}{\sigma}\left(\frac{\omega\sigma}{c}\right)^2 F(\omega)$$

$$G(\sigma, \Delta\omega) = \left\{ \frac{2\sigma}{\sqrt{\pi} c} \frac{\left[e^{-\left(\frac{\omega\sigma}{c}\right)^2}\omega\right]_{\omega_{min}}^{\omega_{max}}}{[erf(\omega\sigma/c)]_{\omega_{min}}^{\omega_{max}}} - 1 \right\}$$

$$\frac{\Delta I}{I} = 2\frac{\Delta N}{N} + \frac{\Delta\sigma}{\sigma} G(\sigma, \Delta\omega)$$

$$\frac{\Delta I}{I} = \frac{I^* - I}{I}$$

$$\frac{\Delta N}{N} = \frac{N^* - N}{N}$$

ΔI/I and ΔN/N: shot-to-shot relative signal variations from the one shot to another or relative statistical fluctuations of the signals w.r.t. a reference value: for instance, the mean value over a sequence of signal readouts acquired under a machine steady state regime.

(*) Orlandi, G.L. Absolute and non-invasive determination of the electron bunch length in a free electron laser using a bunch compressor monitor. Sci Rep 14, 6319 (2024). https://doi.org/10.1038/s41598-024-56586-1

Method for absolute determination of bunch-length from “two-detector” BCM

Two-detector BCM: absolute determination of bunch length σ vs $(\Delta I/I)_{j=1,2}$ and $\Delta N/N$

$$\left(\frac{\Delta I}{I}\right)_{j=1,2} = 2\frac{\Delta N}{N} + \frac{\Delta\sigma}{\sigma} G\left(\sigma, (\Delta\omega)_{j=1,2}\right)$$

For a BCM equipped with two detectors simultaneously illuminated and with different wavelength band of acceptance $(\Delta\omega)_{j=1,2}$

$$\left[\left(\frac{\Delta I}{I}\right)_2 - 2\frac{\Delta N}{N}\right] = \frac{G(\sigma,(\Delta\omega)_2)}{[G(\sigma,(\Delta\omega)_2) - G(\sigma,(\Delta\omega)_1)]} \times \left[\left(\frac{\Delta I}{I}\right)_2 - \left(\frac{\Delta I}{I}\right)_1\right]$$

Formula for the shot-to-shot tracking of the absolute value σ of the bunch length

$$\backslash std\left(\left[\left(\frac{\Delta I}{I}\right)_2 - 2\frac{\Delta N}{N}\right]\right) - \backslash abs\left(\frac{G(\sigma,(\Delta\omega)_2)}{[G(\sigma,(\Delta\omega)_2) - G(\sigma,(\Delta\omega)_1)]}\right) \times \backslash std\left(\left[\left(\frac{\Delta I}{I}\right)_2 - \left(\frac{\Delta I}{I}\right)_1\right]\right) = 0$$

Formula for determining the absolute value the bunch length (σ) from the analysis of a sequence of data acquired under a steady state regime of the machine: I and N are the mean values of the BCM and charge readout of the sequence of acquired data.
The variable σ runs into a test interval until the value corresponding to the “zero” of the equation is found

Method for absolute determination of bunch-length from “two-detector” BCM

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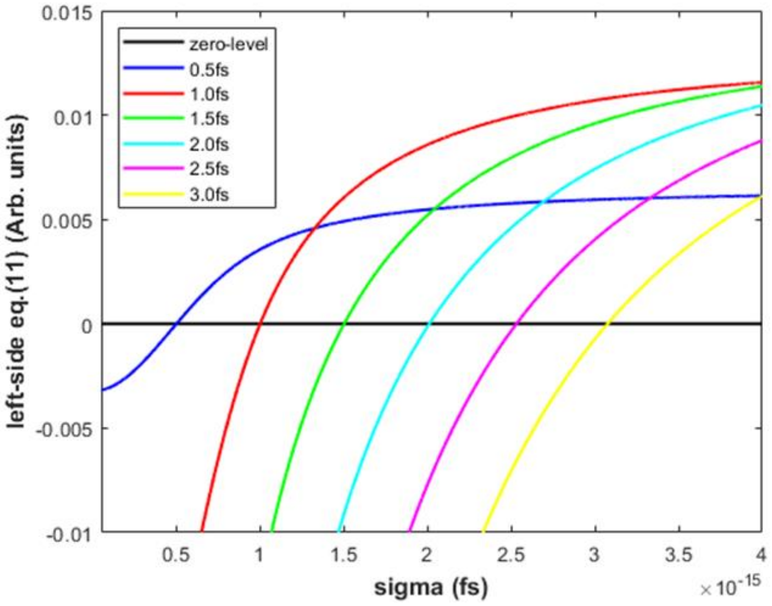
Results from a numerical simulation based on ECOL-BCM (5.8GeV**):**

- Design optimized for bunch length 0.7-3 fs (10 pC),
- Detectors: Pyroelectric sensor (0.9-4.0)µm
  Optical fiber spectrometer (Ocean Optics, 0.9-2.5 µm)

$$\backslash std\left(\left[\left(\frac{\Delta I}{I}\right)_2-2\frac{\Delta N}{N}\right]\right)-\backslash abs\left(\frac{G(\sigma,(\Delta\omega)_2)}{[G(\sigma,(\Delta\omega)_2)-G(\sigma,(\Delta\omega)_1)]}\right)\times\backslash std\left(\left[\left(\frac{\Delta I}{I}\right)_2-\left(\frac{\Delta I}{I}\right)_1\right]\right)=0$$



ECOL-BCM:

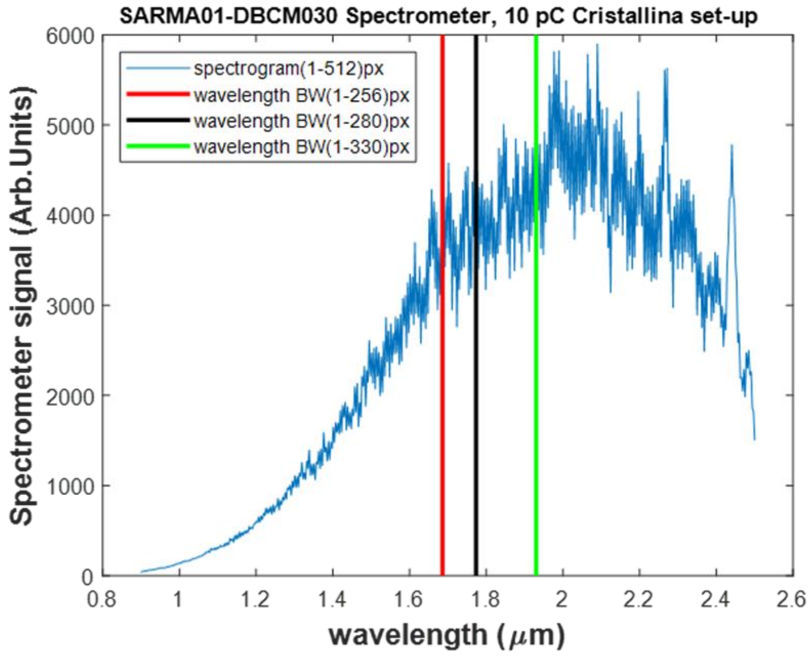
- numerical prediction of the absolute bunch length σ determination in case of Gaussian Form-Factor for different σ under a steady state machine regime.

- I and N are mean values over a sequence of acquired shots

the abscissae of the curve intercepts with the "zeros-level" line are the model-estimated absolute values of σ. Simulation settings: Gaussian Form Factor with =0.5-3.0 fs; BCM signals (pyro & spectrometer) simulated with rms deviation of 1 % for Δσ/σ and ΔN/N

ECOL-BCM spectrometer

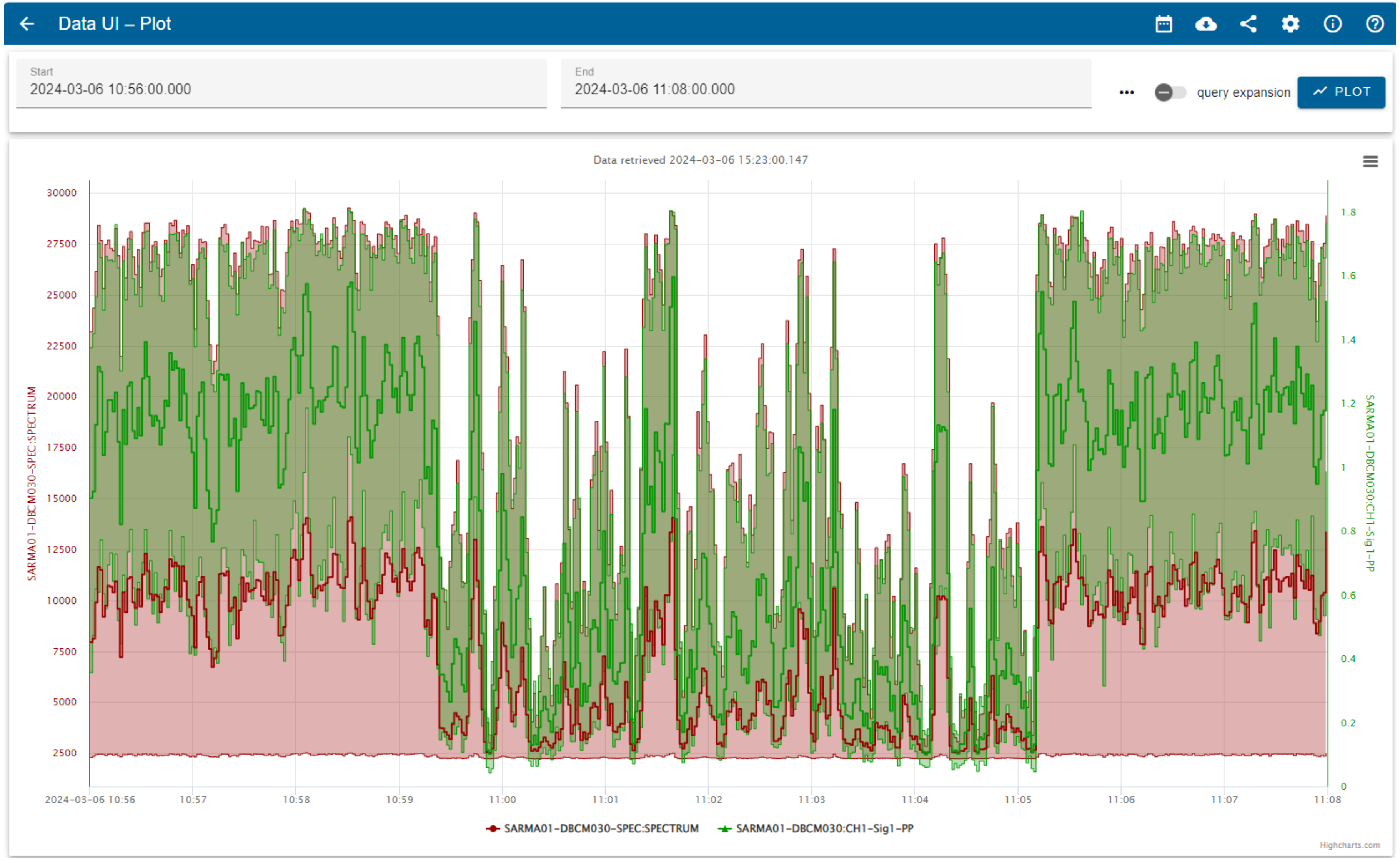
- Optical fiber spectrometer (Ocean Optics, 0.9-2.5 μm):
  - form-factor signature in the spectrogram
  - bunch length (σ) estimate by fitting the spectrogram with a Gaussian form-factor
  - main issue, the diffractive low frequency suppression of the spectrogram: non-univocal results of the Gaussian fit vs the frequency cut-off
  - Alternatively, "two-detector" BCM method



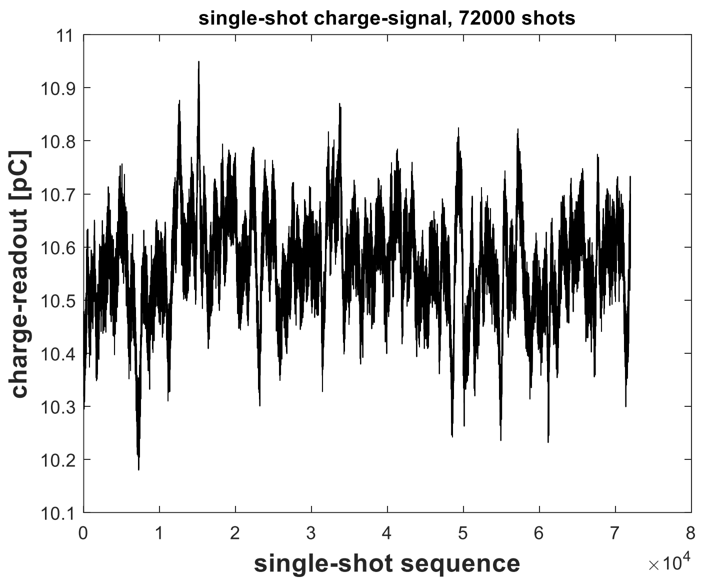
"Two-detector" BCM method, analysis of relative variations of:
- **pyro-detector signal $(\Delta I/I)_{j=1}$**
- **total spectrogram energy (spectrogram integral) $(\Delta I/I)_{j=2}$**
- **charge monitor signal $\Delta N/N$**

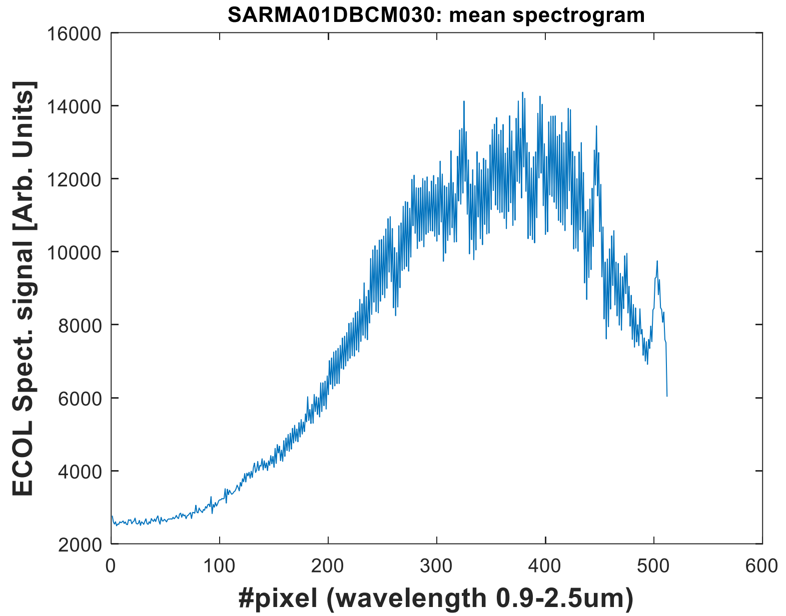
10pC Aramis operations: from the set-up to the compression feedback ON

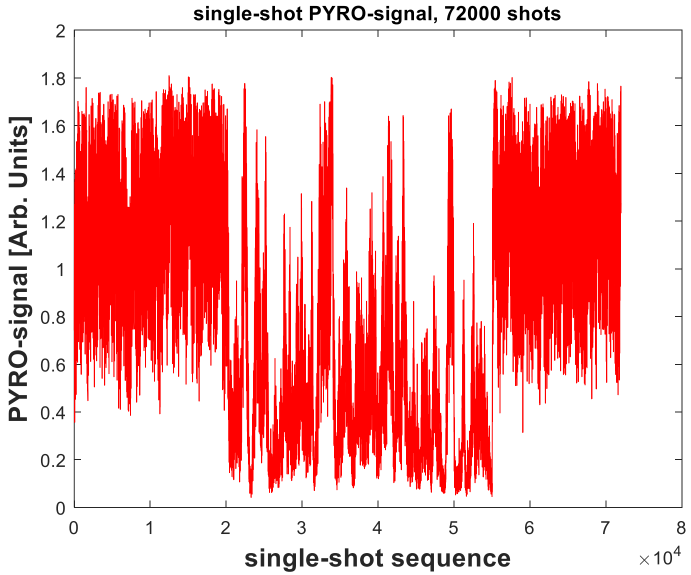
10pC Aramis operations: time-window of data analysis

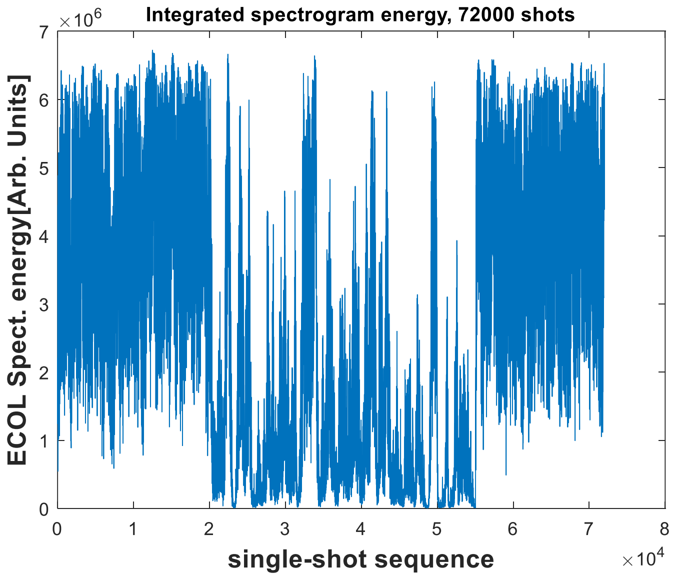


Charge, pyrodetector and integrated spectrogram signals: 72000 shots







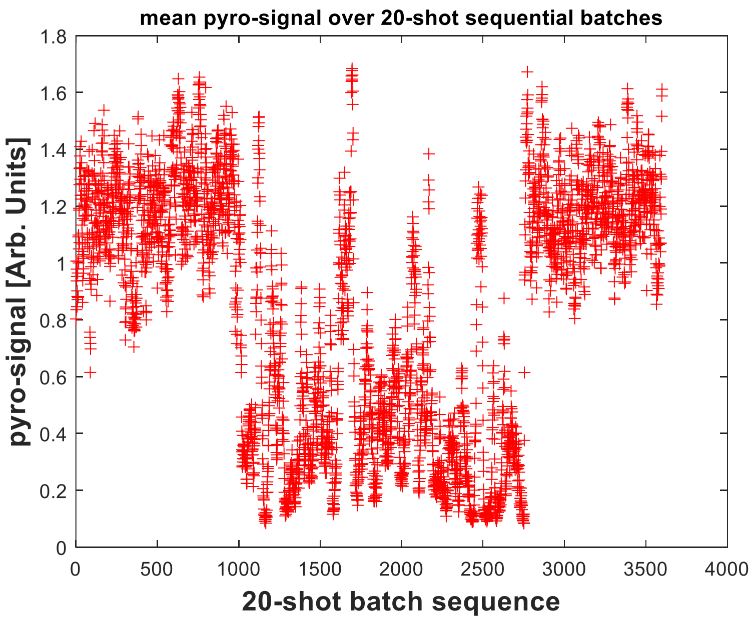


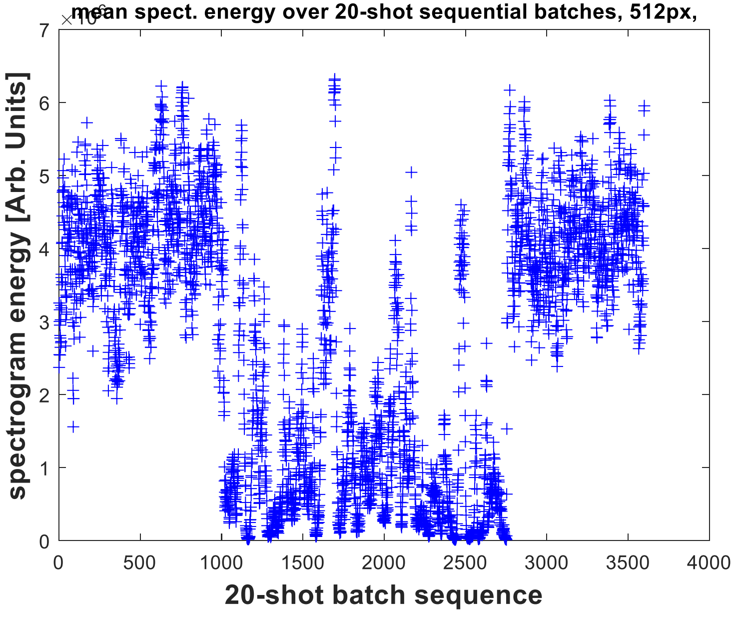
bunch-length characterization with “two-detector” BCM method

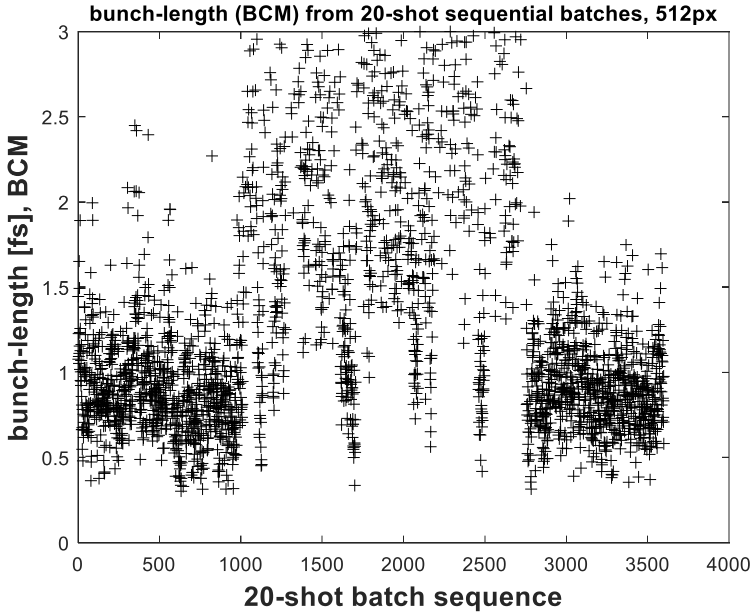
Data Analysis processing:

- divide the 72000 data array into 20-shot sequential batches;
- for each batch, calculate the mean values of the signals [charge, pyrodetector, spectrogram-energy-(512px)]
- for each batch, calculate $(\Delta I/I)_{j=1,2}$ and $\Delta N/N$ w.r.t. the resulting mean values
- for each batch, find the “zero” of the equation below as a function of a test σ ranging from 0.3 to 3.0 fs (small step)
- save and plot the test value of σ which equalizes to zero the right side of the equation

$$\backslash std\left(\left[\left(\frac{\Delta I}{I}\right)_2 - 2\frac{\Delta N}{N}\right]\right) - \backslash abs\left(\frac{G(\sigma,(\Delta\omega)_2)}{[G(\sigma,(\Delta\omega)_2) - G(\sigma,(\Delta\omega)_1)]}\right) \times \backslash std\left(\left[\left(\frac{\Delta I}{I}\right)_2 - \left(\frac{\Delta I}{I}\right)_1\right]\right) = 0$$



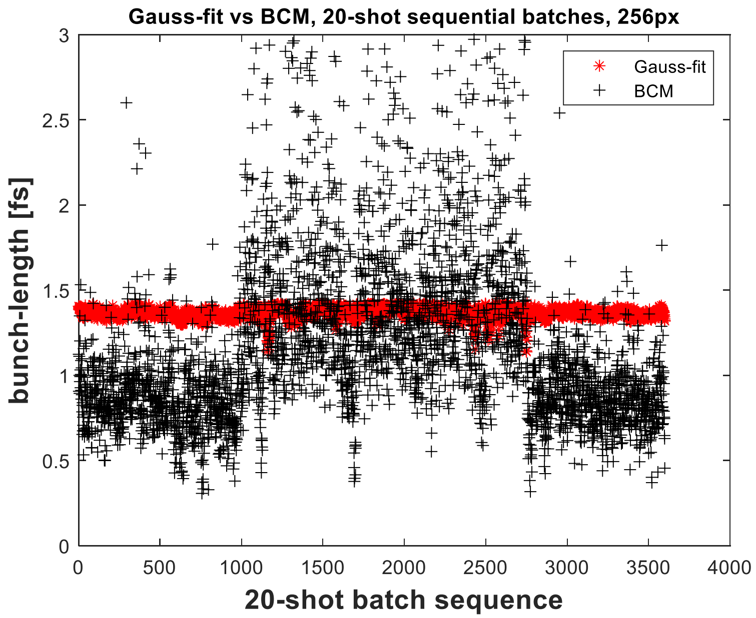


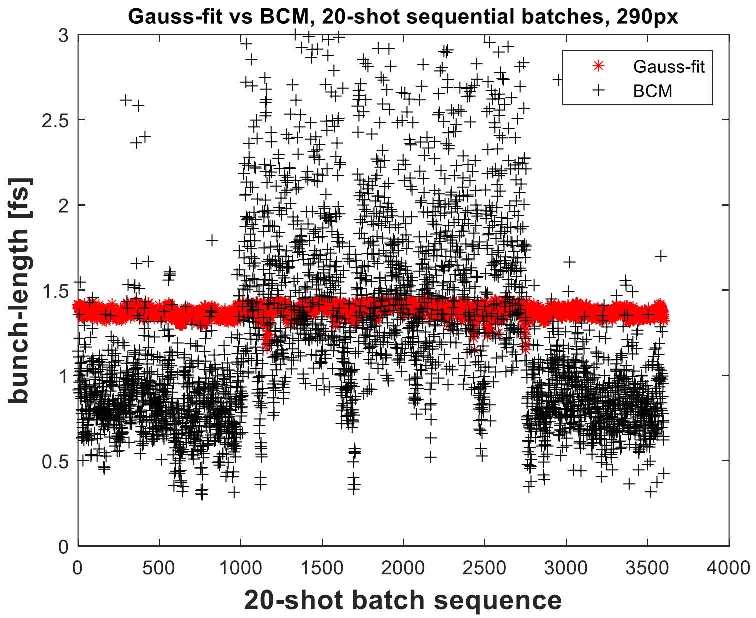


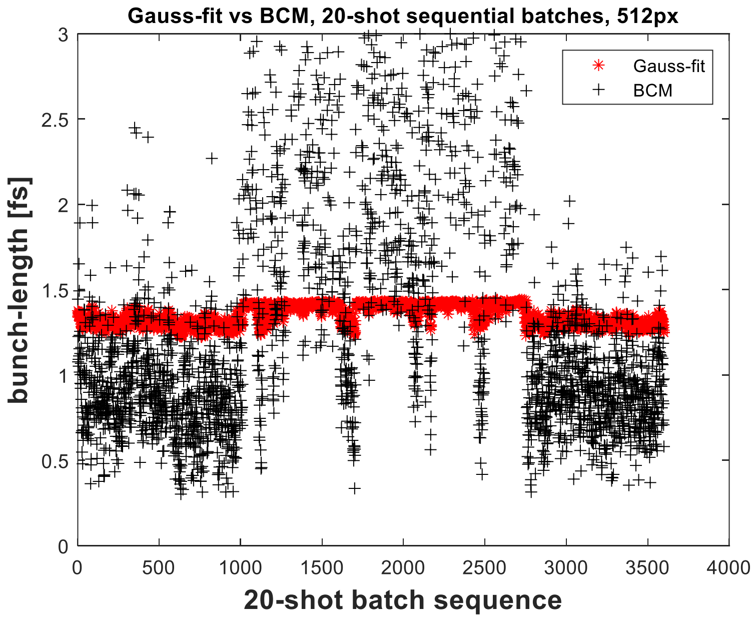
bunch-length characterization with "two-detector" BCM method

"two-detector" BCM method vs Gauss fit of the spectrogram:

- consider spectrogram in different wavelength band (low-frequency cut-off):
    - (1-256)px←→(0.9-1.7)μm; (1-290)px ←→(0.9-1.8)μm; (1-512)px ←→(0.9-2.5)μm
- divide the 72000 data array into 20-shots sequential batches and calculate (ΔI/I)j=1,2 and ΔN/N as usual
- apply the «two-detector» BCM method to the processed data
- apply a Gaussian fit to the mean spectrogram of each 20-shot batch for the 3-wavelength band







Conclusions and Outlook

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- the processing of the BCM – and charge signal- according to the “two-detector” method allows for an absolute characterization of the bunch-length

- In a FEL/SwissFEL, compression stabilized by feeding back the RF settings with the BCM signals (pyro-detector signal)

- “two-detector” BCM method allows for direct tuning of the compression feedback with the expected absolute value of the bunch-length instead of the bunch-length dependent signal of a BCM

- The method of processing the relative fluctuations of the BCM detector signals $(\Delta I/I)_{j=1,2}$ reduces the sensitivity of the analysis on systematic effect such as non-uniformity of the single particle spectrum or diffractive low-frequency cut-off of the radiation energy spectrum

- To be noticed: absolute value of a physical quantity (bunch-length) obtained from the analysis of the bunch-length induced relative statistical fluctuations of a detector signal