Absolute Characterization of sub-fs Electron Bunch-Length in SwissFEL using a Bunch-Compressor Monitor

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Absolute Characterization of sub-fs Electron Bunch-Length in SwissFEL using a Bunch-Compressor Monitor-THCC3

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Abstract

The shot-to-shot and non-invasive monitoring of the electron bunch length in a linac driven Free Electron Laser (FEL) relies on Bunch Compressor Monitors (BCMs). A BCM is designed to detect – and fully integrate in a given wavelength band - the radiation energy spectrum emitted at the threshold of the temporal coherence by the electron beam while crossing the last dipole of a magnetic chicane or a diffraction radiation screen placed just downstream of it. The BCM signal response is hence a direct - albeit non-absolute - function of the electron bunch length and of the beam charge as well. Due to its full non-invasiveness, a BCM is the ideal diagnostics to be integrated into the machine feedback to stabilize the bunch compression. Recently, we presented (*) a formal method for the absolute determination of the electron bunch length from the analysis of the signal readout of a BCM which is equipped with two independent detectors integrating the radiation energy pulse in two different wavelength bands. Theoretical highlights of the method as well as experimental results on the characterization in SwissFEL of electron beams with sub-fs bunch length will be presented in this contribution.

(*) 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

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Premise on the bunch-length measurement unit

For the sake of ease, bunch-length measurements are converted from μm to fs units

Contents

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- ✓ SwissFEL Bunch-Compressor-Monitors (BCMs)
- ✓ ECOL-BCM (Energy-Collimator-BCM): the experimental set-up
- ✓ 10 pC and sub-fs bunch-length SwissFEL set-up for “Cristallina” FEL end-station
- ✓ Absolute determination of bunch-length from a “two-detector” BCM: the method
- ✓ Absolute characterization of sub-fs electron bunch-length by mens of the “two-detector” method at ECOL-BCM: experimental results
- ✓ Conclusions and Outlook

SwissFEL Bunch Compressor Monitor (BCM)

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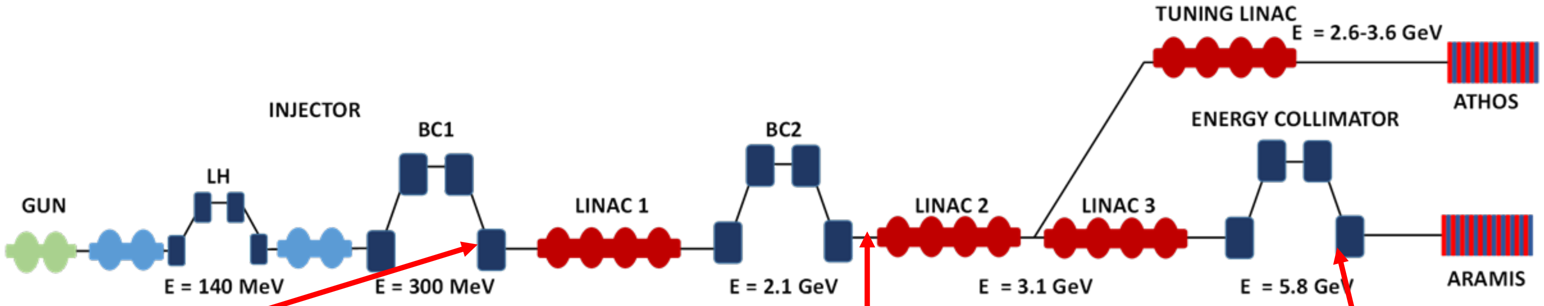


BC1-BCM: Edge CSR 4th dipole

BC2-BCM: CDR from a screen

ECOL-BCM: Edge CSR 4th dipole

First	
Electron beam	Aug 2016
Lasing	Dec 2016
Pilot experiment	Dec 2017
User experiment	Jan 2019

3 BCMs presently in operation at SwissFEL for a fully non-invasive and shot-to-shot monitoring of the electron bunch length and compression feedback

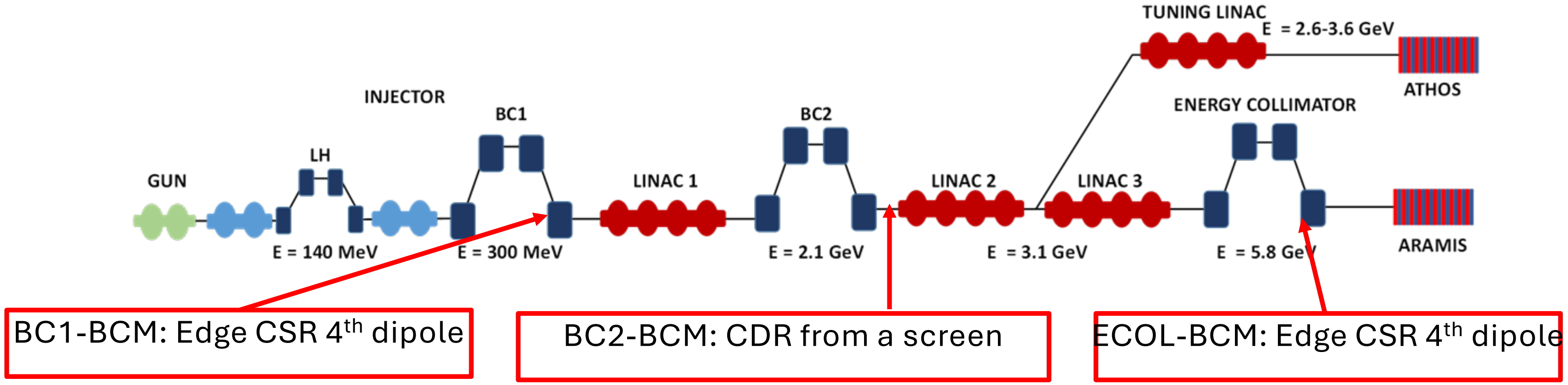
BC1-BCM (10&200 pC, 300-400 fs) and BC2 BCM (10&200pC, 3-25fs): monitors integrated in the machine compression feedback.

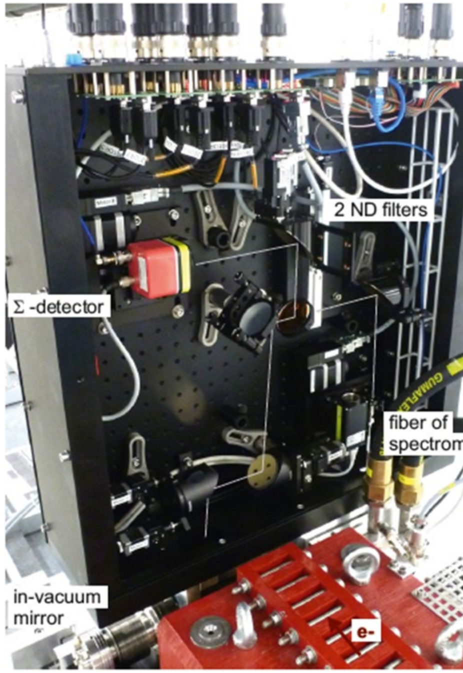
ECOL-BCM (0.7-3.0 fs): special compression setting (R56) of the energy collimator at 10 pC. Monitor integrated in the machine compression feedback for 10 pC and sub-fs machine operations

Main parameters	
wavelength	**0.1 - 5.0 nm**
photon energy	**0.2 - 12 keV**
pulse duration	**1< - 20 fs**
e^- energy	**6.2 GeV**
e^- bunch-charge	**10 – 200 pC**
repetition rate	**100 Hz**

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

ECOL-BCM: the experimental set-up





ECOL-BCM (5.8GeV, Edge SR):

- Diffractive cut-off (<4μm) of the radiation due to a narrow diameter of the light beam pipe
- 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 spectral energy 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 set-up for Cristallina (SwissFEL user end-station)

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- Cristallina FEL end-station set-up: 10 pC, 8.36 keV, 3-stage compression
- Bunch length measurements before ECOL-BCM with TDS-Cband in linac 3 : σ(rms)~(16.5+/-1) fs
- Bunch-length prediction downstream the ECOL: σ(rms)~(0.51+/-0.03) fs [30% systematic error (^)]

(^) systematic error due to uncertainties on estimated energy spread and bunch-length at the injector

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

where σ_δ is the uncorrelated energy spread before BC1, $E_{i,f}$ are the energies at BC1 and BC3, respectively, and $c = c_1c_2$ 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 ($c_{1,2}^{-1} \neq 0$).

“two-detector” BCM method for absolute bunch-length determination

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

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

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

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

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

Radiation energy spectrum of the Ne^- 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

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

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

“two-detector” BCM method for absolute bunch-length determination(*)

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

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

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

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

Calculate infinitesimal differential and convert into finite difference at the time unit of the machine repetition rate

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

Taylor series expansion of the FF at the first order in Δσ/σ

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.

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“two-detector” BCM method for absolute bunch-length determination

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

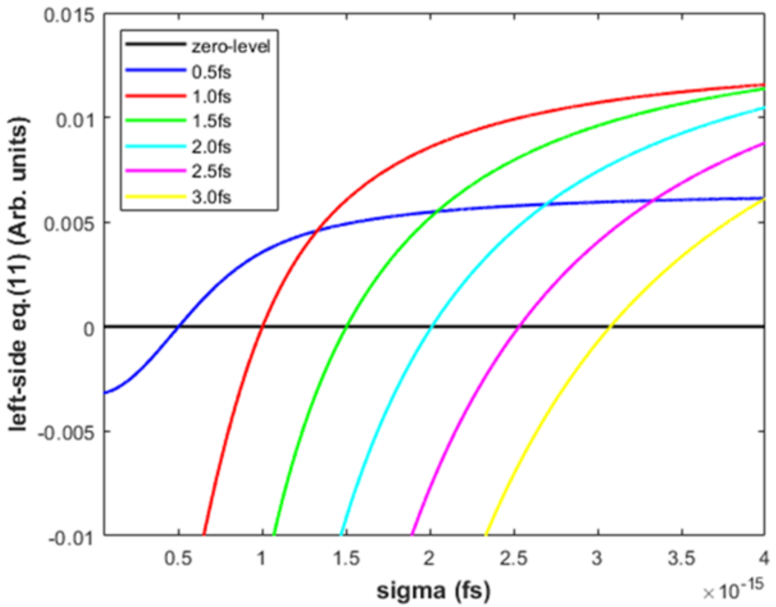
$$\left(\frac{\Delta I}{I}\right)_{j=1,2} = 2\frac{\Delta N}{N} + \frac{\Delta\sigma}{\sigma} G\left(\sigma, (\Delta\omega)_{j=1,2}\right)$$

BCM equipped with two detectors 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 [see plot above (*)]

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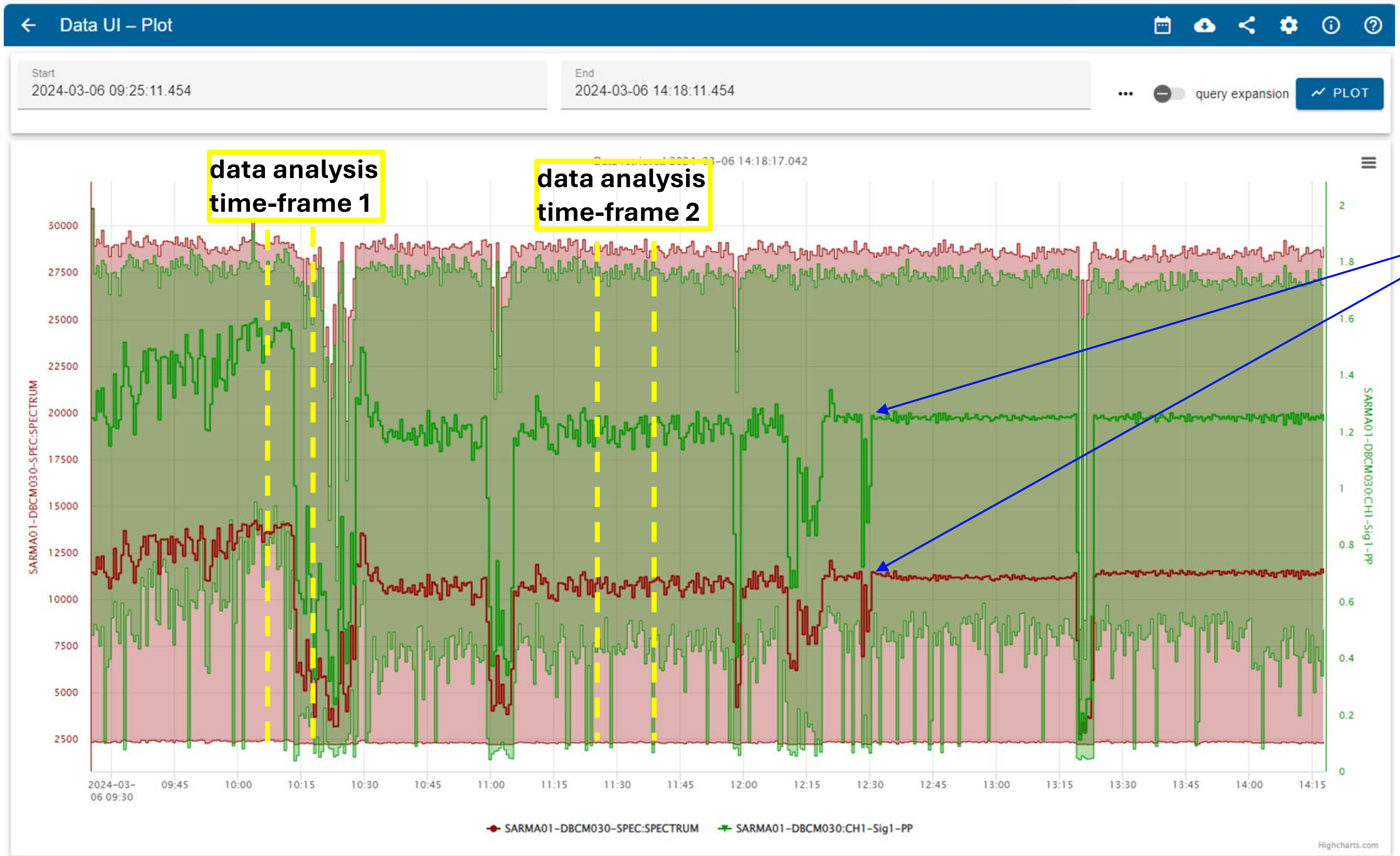
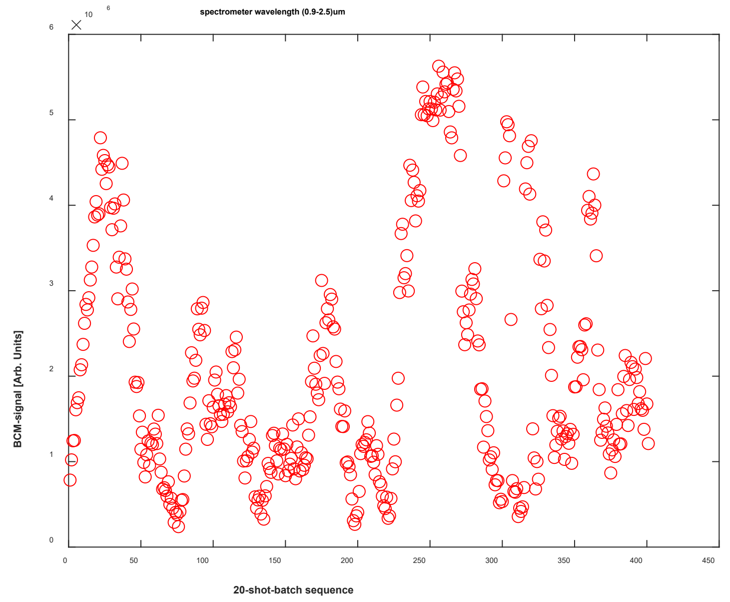
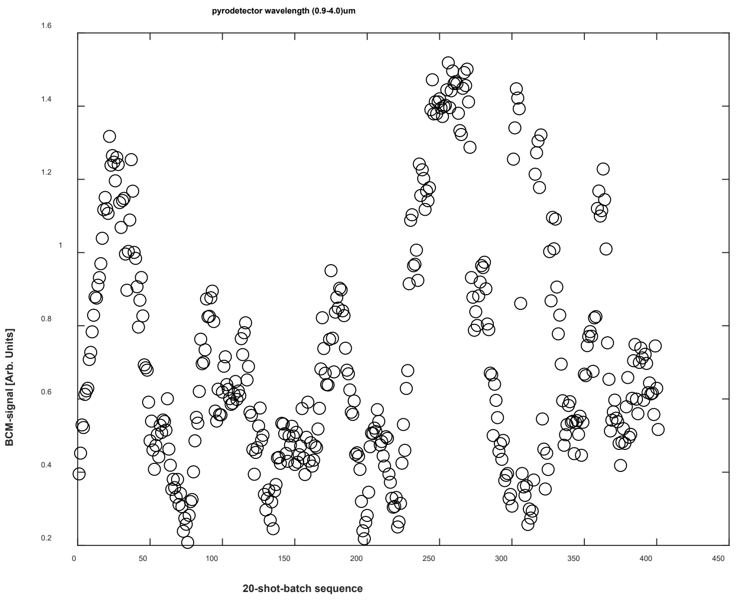
10pC SwissFEL operations: ECOL-BCM signals during machine set-up

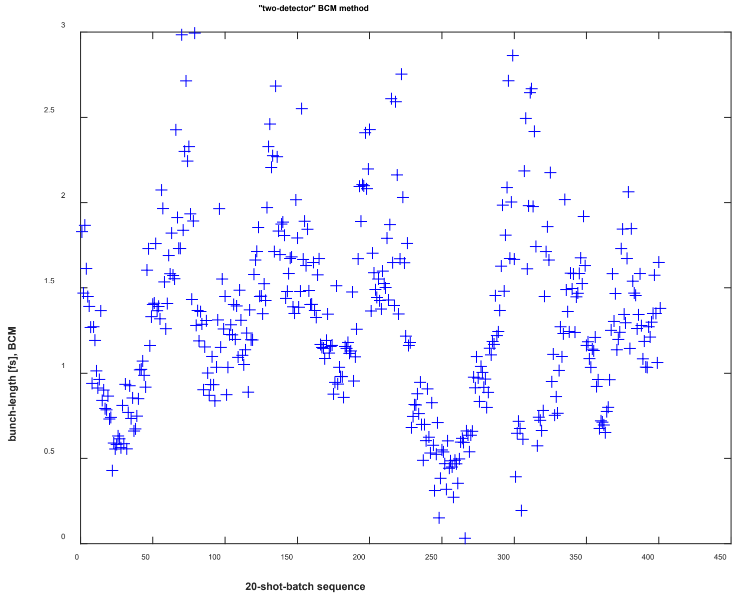


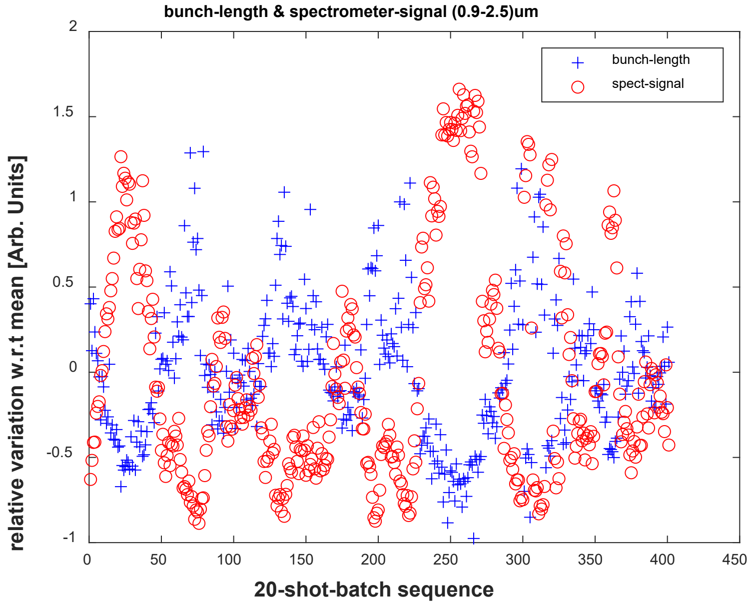
Optimal machine setting compression feedback locked onto BC1-BCM and ECOL-BCM signals

Data analysis time-frame 1









- **"two-detector" BCM method at ECOL for absolute bunch-length characterization**
- **Batches of 20 subsequent RF shots analyzed**
- **analysis of relative variations of pyrodetector, spectrometer (and charge) signals over each 20-shot batch.**

ECOL-BCM and monopole cavity-BPM signals (time-frame 2)

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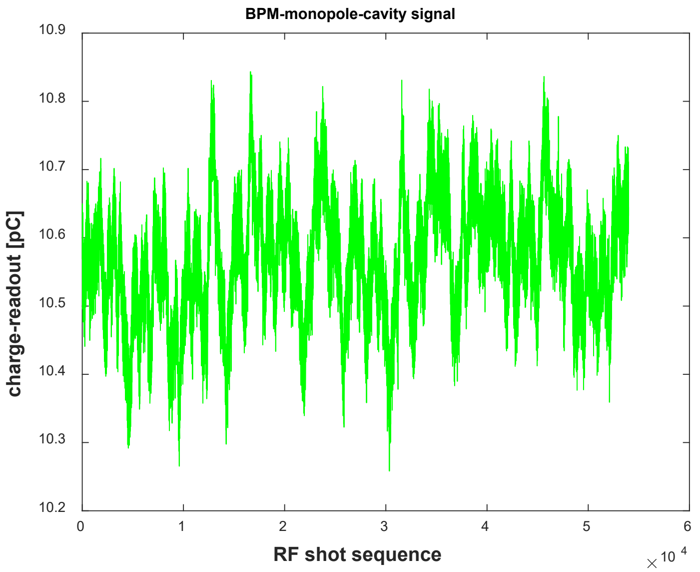
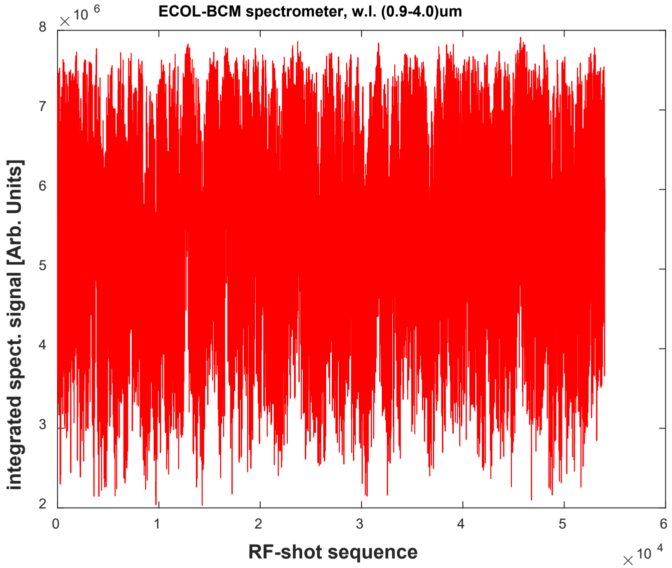
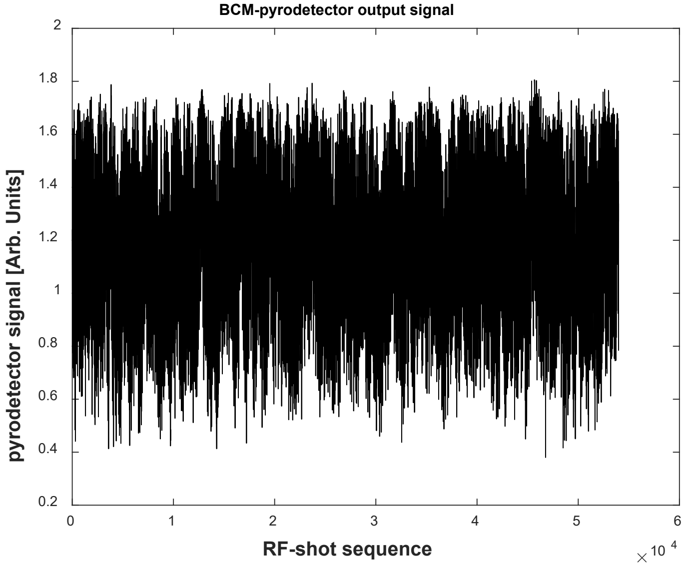
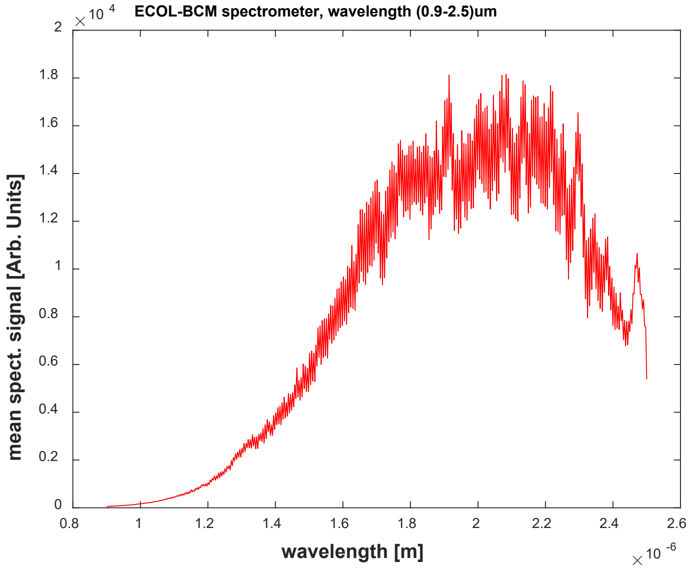




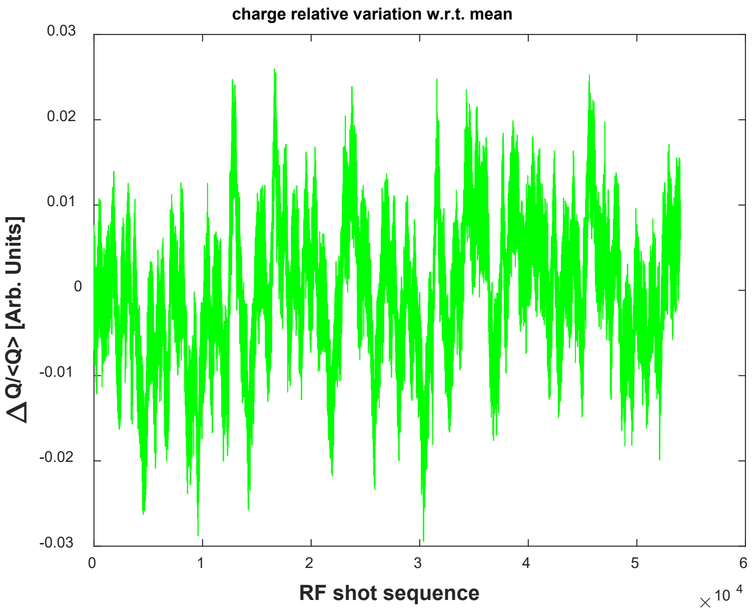


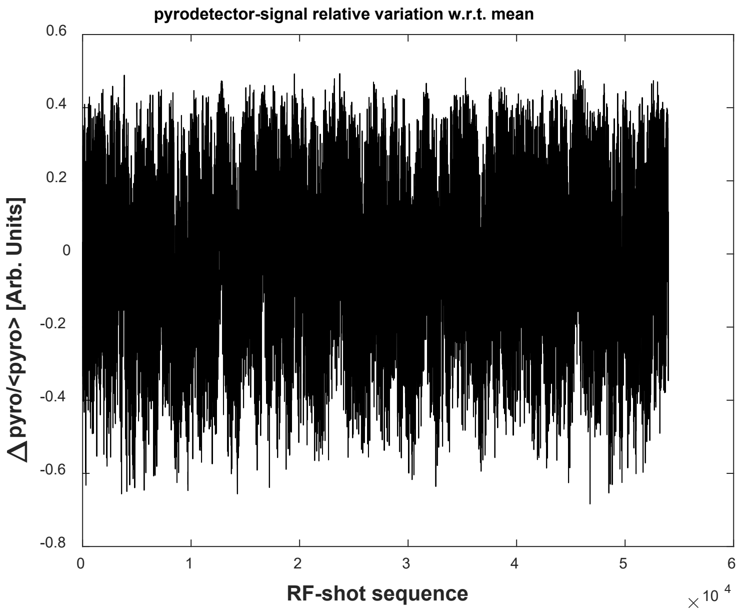


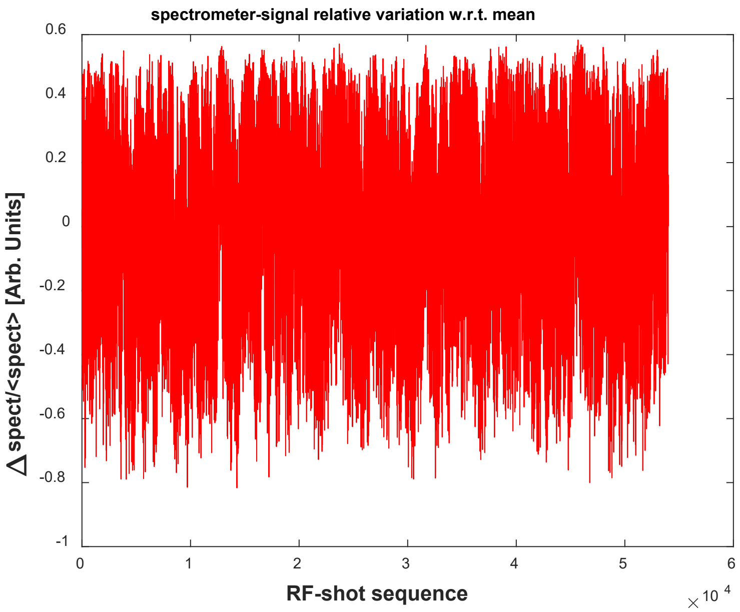
- Experimental data taking over ~54000 RF shots
- Raw ECOL-BCM output signal:
  - pyrodetector
  - spectrometer (integrated spectrogram)
  - Mean spectrogram
- Charge readout from the BPM-monopole-cavity

absolute bunch-length determination with «two-detector» BCM method (time-frame 2): input data of the model

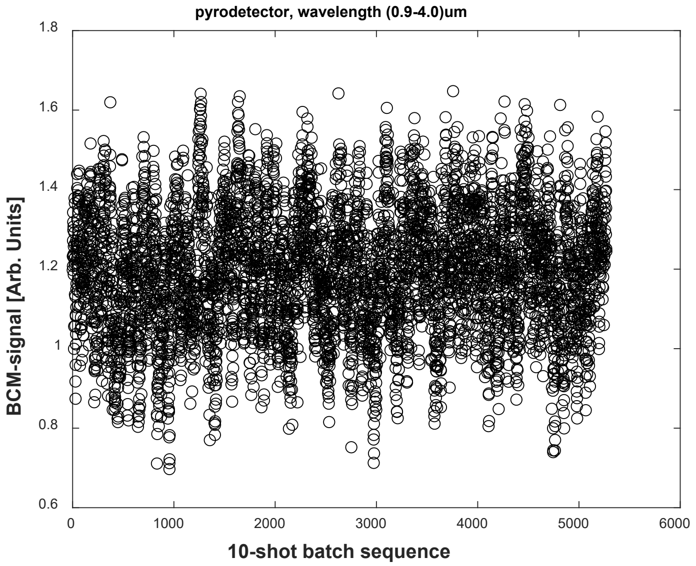
Relative variations w.r.t. average of charge and ECOL-BCM signals

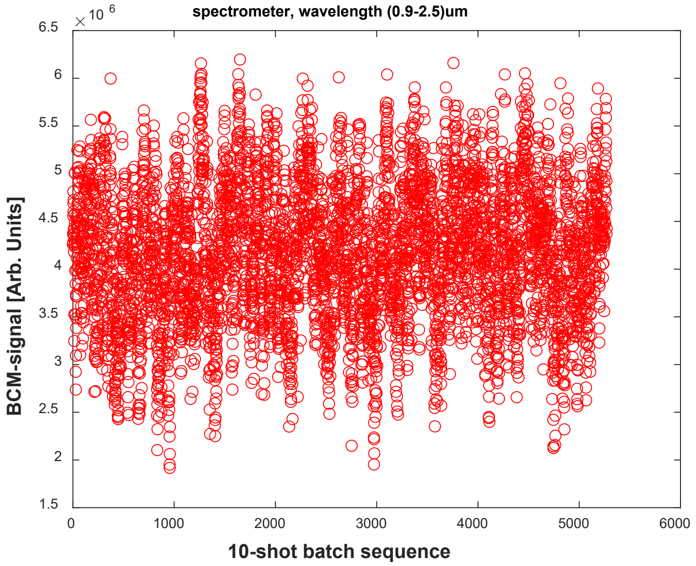


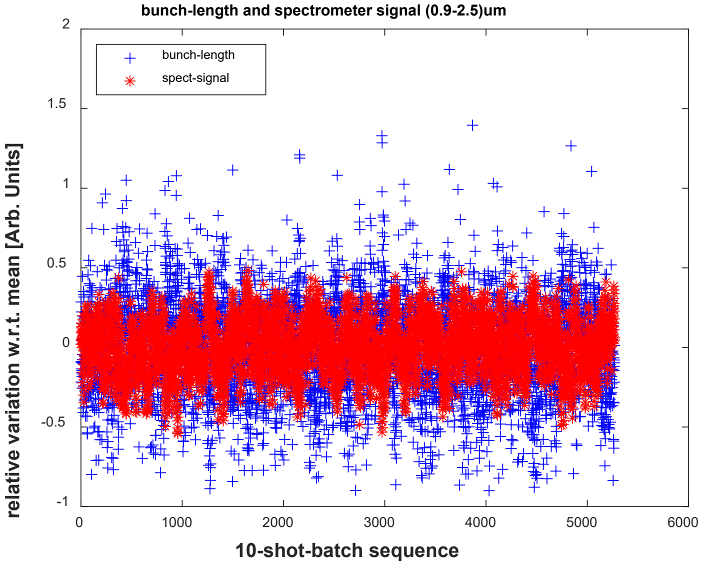


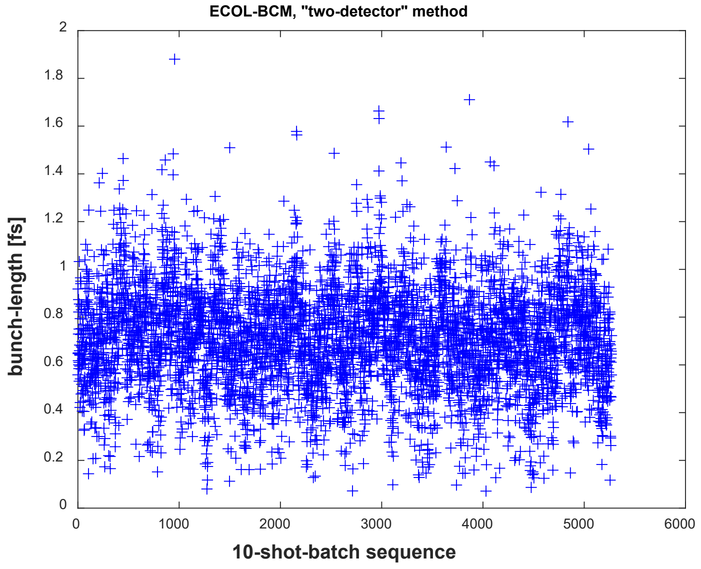


ECOL-BCM signals and «two-detector» method results (time-frame 2)







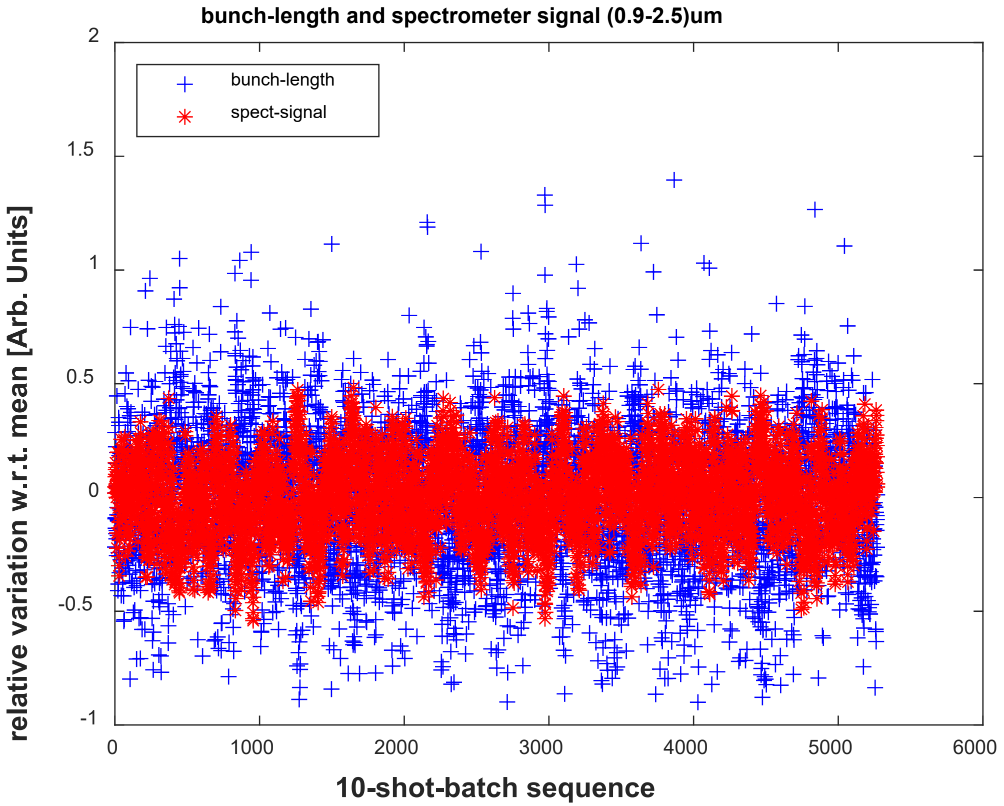


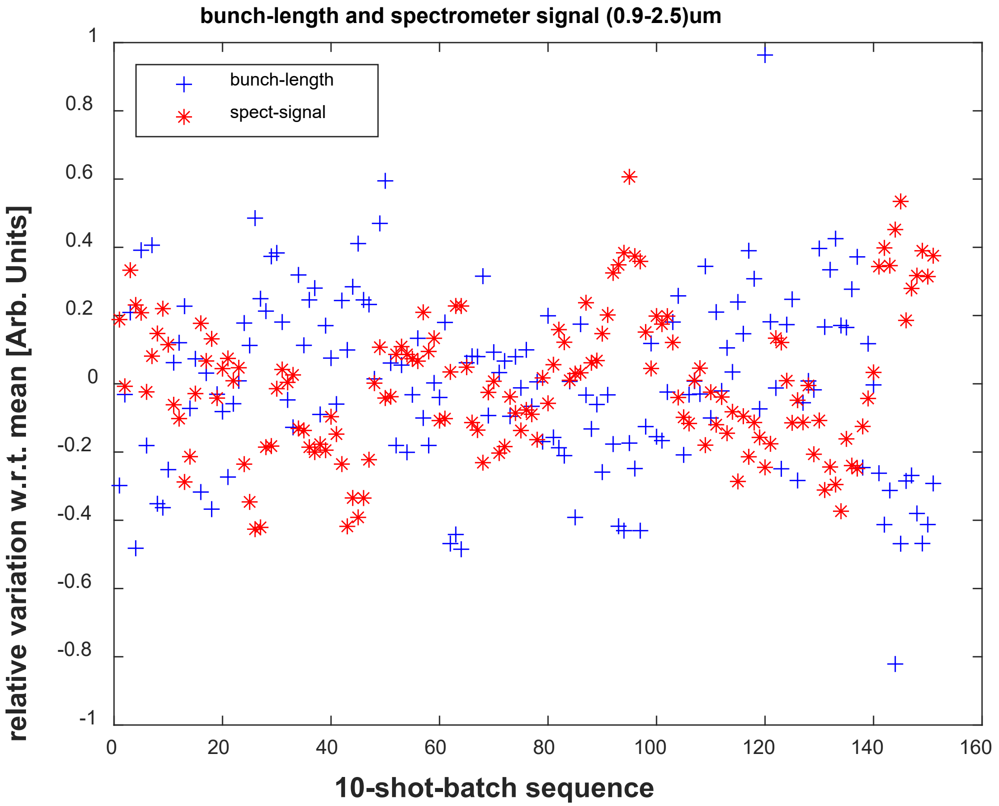
- average of ECOL-BCM signals (and charge signal) over 10 subsequent RF shots (~54000)
- bunch-length determination from "two-detector" BCM method applied to the 10-shot-sequence
- absolute bunch-length estimate (σ_{rms}), 10 pC "Cristallina" FEL user set-up:
  - (0.71+/-0.21) fs spect. w.l. band (0.9-2.5)µm (^)
  - (0.62+/-0.19) fs spect. w.l. band (0.9-2.3)µm
- beam-dynamics model prediction of the bunch-length (σ_{rms}):
  - (0.51+/-0.03) fs [30% systematic error]

(^) the effect on the bunch-length of the low frequency diffractive cut-off of the spectrogram is mitigated by restricting the effective spectrometer wavelength band from (0.9-2.5)µm to (0.9-2.3)µm

ECOL-BCM signals and «two-detector» method results (time-frame 2)

- left plot: full sequence of 10-shot-batch over ~54000 shots
- right plot: zoom on small fraction of the 10-shot-batch sequences





Conclusions and Outlook (1/2)

- Experimental test of the BCM “two-detector” method at the ECOL-BCM in SwissFEL, outcomes:
  - A method for the absolute and non-invasive characterization of the electron bunch-length at the sub-fs scale has been successfully tested and implemented in SwissFEL during 10 pC operations
  - Bunch-length measurements are in a good agreement with the beam-dynamics prediction at the ECOL-BCM
  - New perspectives and potentialities of a BCM in a FEL can be envisaged: a compression feedback of a FEL driven by the absolute measurement of the bunch-length instead of a bunch-length dependent signal of a BCM
- Test and possible implementation of the “two-detector” method to improve the potentialities of a BCM based bunch-compression feedback during FEL operations is in the list of future plans

Conclusions and Outlook (2/2)

- BCM “two-detector” method, relevant features:

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

  - the proposed method shows as an absolute determination of a physical quantity (bunch-length) can be obtained from the analysis of the bunch-length induced relative statistical fluctuations of a detector signal