

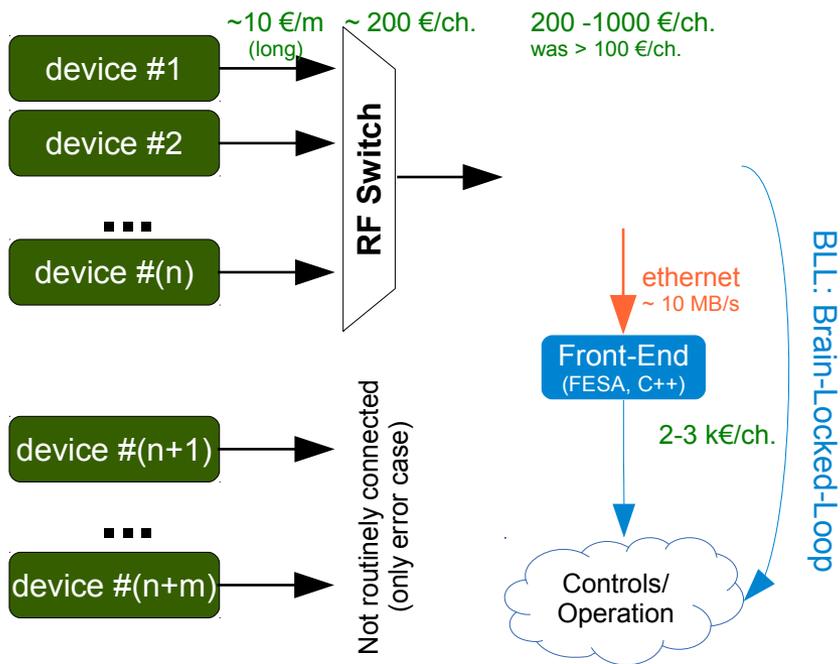
Integration Specification for the Digitization of Analog Signals

Ralph J. Steinhagen

with input from: R. Bär, J. Fitzek, D. Ondreka

- traditional/old concept

(underlying assumption: scopes/digitizers are expensive, RF switches are cheap)



on-demand measurement

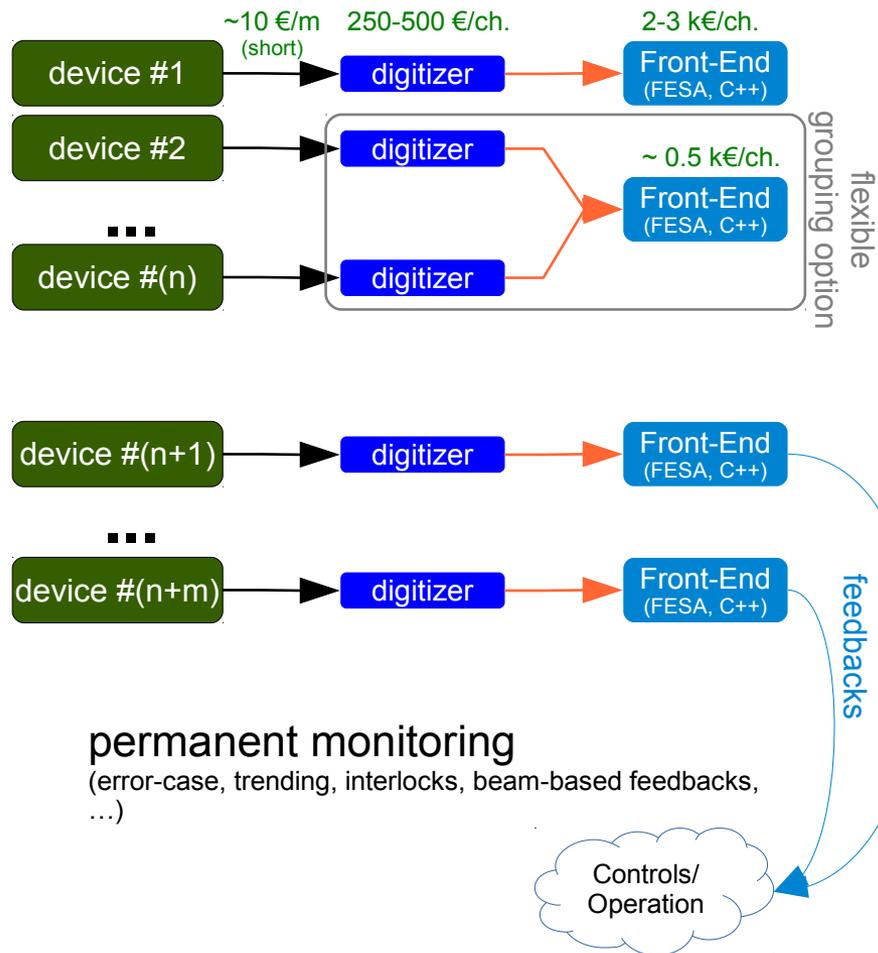
(selected signals, error-case, ...)

con:

- high-reconfiguration overhead (manual)
- limited test-coverage, trending

- targeted concept

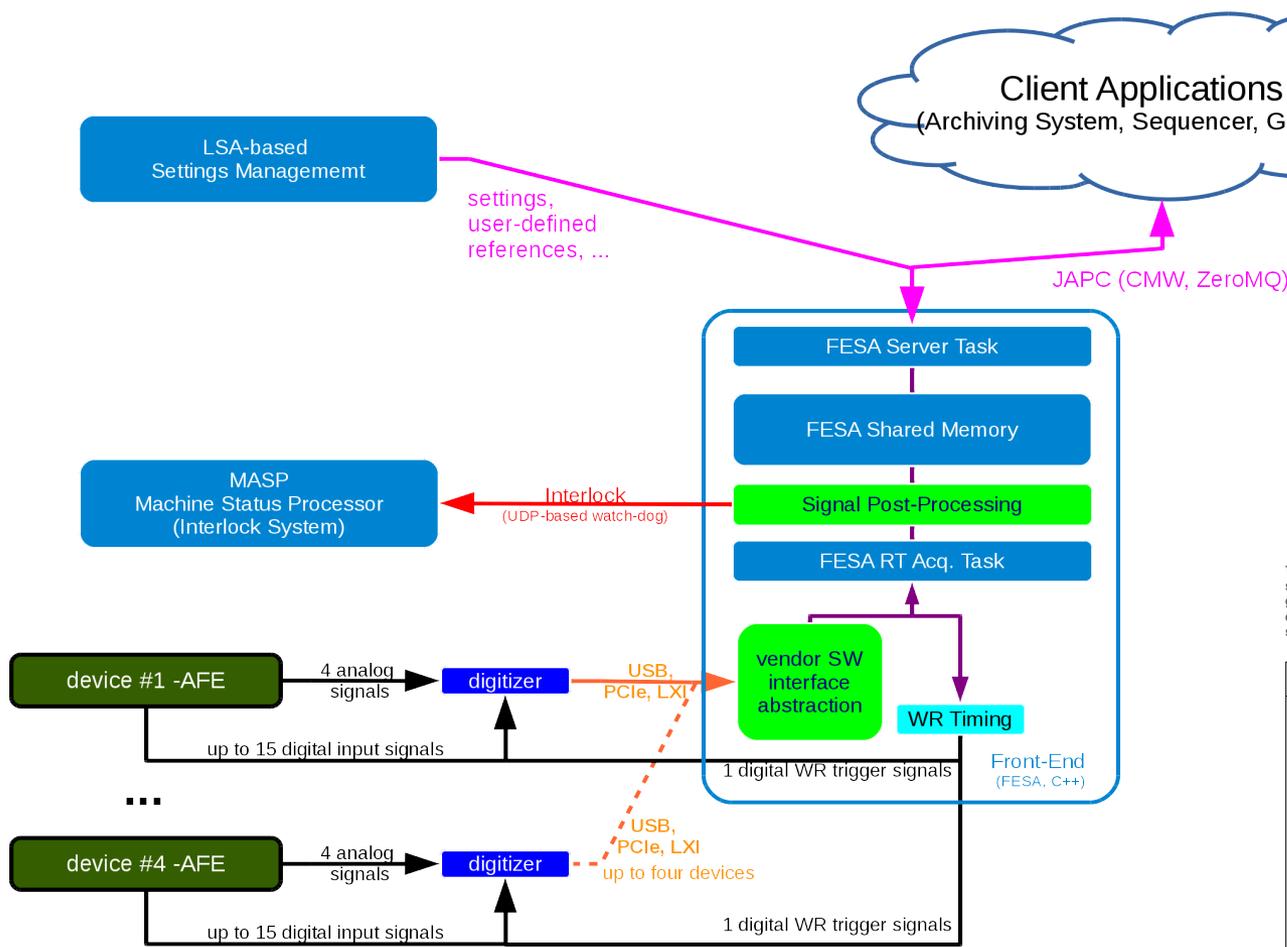
(underlying assumption: scopes/digitizers are cheap, RF switches are expensive)



permanent monitoring

(error-case, trending, interlocks, beam-based feedbacks, ...)

- Primary goals
 - generic abstraction of the vendor-specific digitizer software interfaces
 - limited range of generic data post-processing on the acquired data
 - control system integration by providing standardised FESA interface
- Secondary goals
 - simplify further extensions, compactness, readability, re-usability, testability, and maintainability of the FESA implementation
 - Use of open-source signal processing and data fitting libraries
 - GNU-Radio – frame-work: www.gnuradio.org
 - ROOT – frame-work: <https://root.cern.ch/>



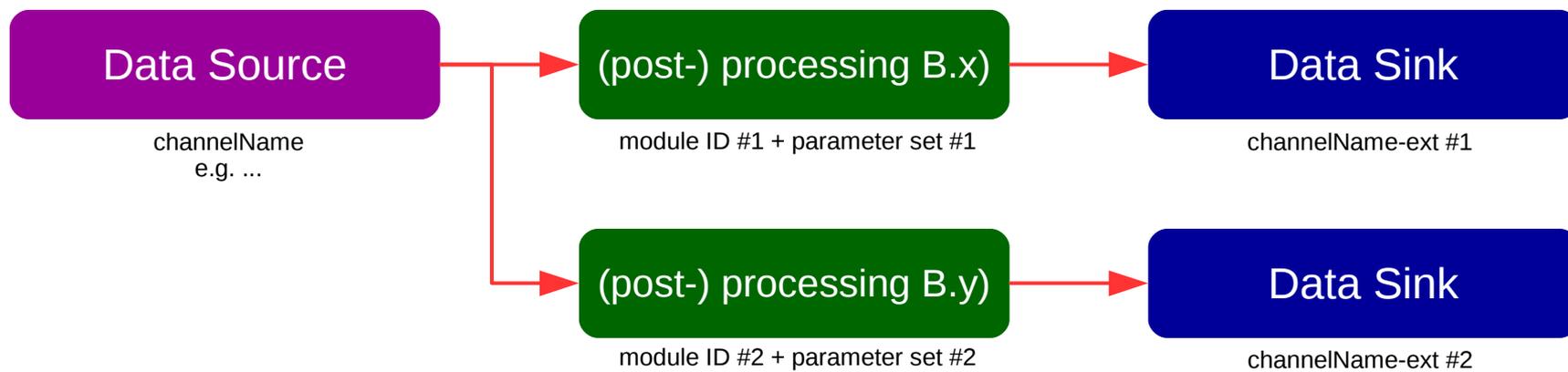
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	Detailed Specification	F-DS-C-XXe	
		Template Number:	Page 1 of 25
		Q-FO-QM-0005	

Document Title:	On the Digitization of Analog Signals in the FAIR Accelerator Complex
Description:	Detailed specification for the integration of time-domain digitizers with analog bandwidths and sampling frequencies ranging from a few MHz to hundreds of MHz into the accelerator control system
Division/Organization:	FAIR
Field of application:	FAIR Project, existing GSI accelerator facility
Version	V 0.2

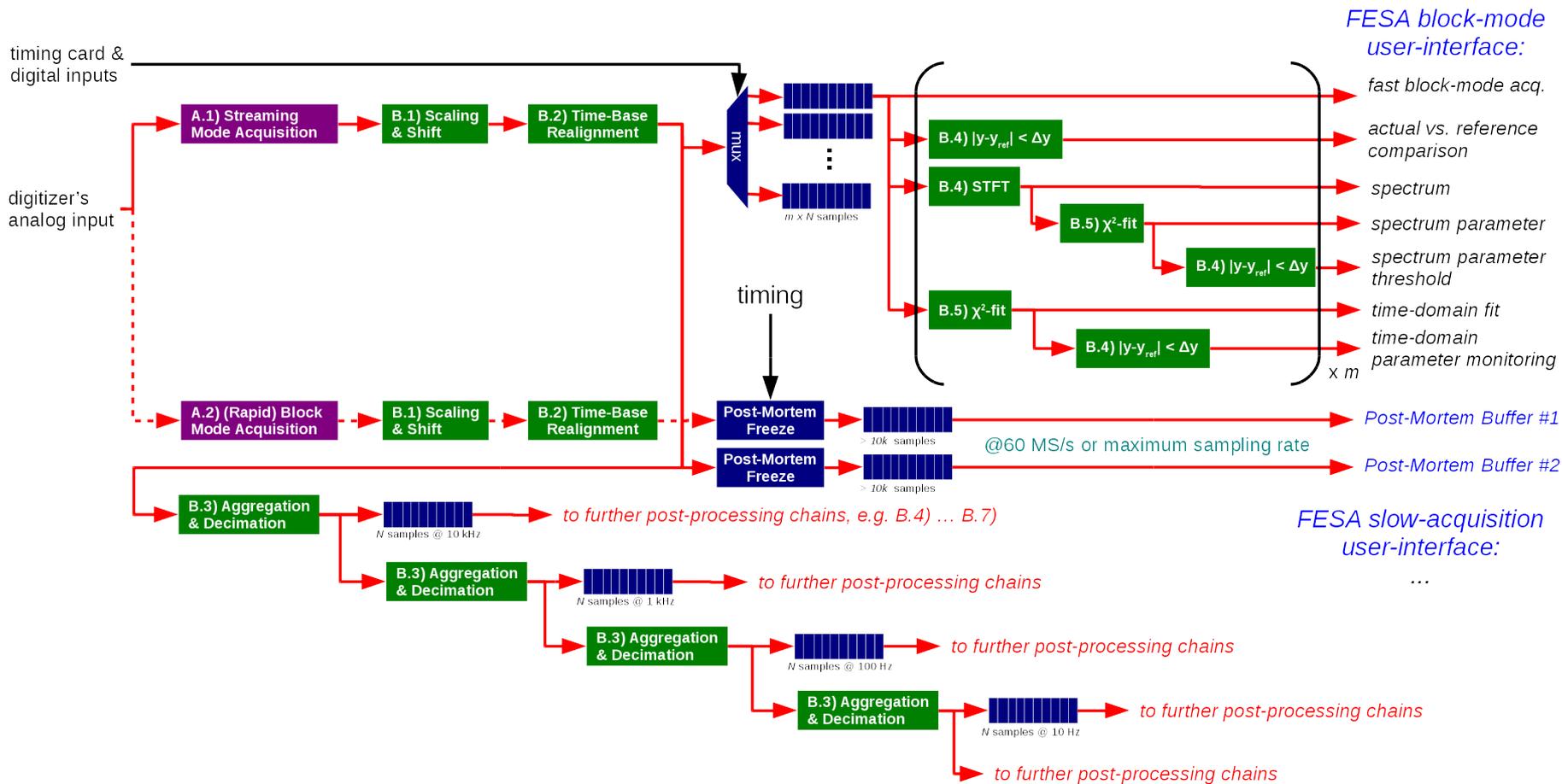
Abstract

This document describes the integration of time-domain digitizers with analog bandwidths and sampling frequencies ranging from a few MHz to hundreds of MHz. The primary aim is to provide a generic abstraction of the vendor-specific digitizer software interfaces, a limited range of generic data post-processing on the acquired data, and integration of these devices into the FAIR control systems by providing FESA standardised software interfaces.

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- Scheme can be further cascaded and combined with other modules
 - based on GNURadio's signal-flow concept <https://www.gnuradio.org/>
 - N.B. there are conceptually also other similar other projects: e.g. ADS, QUCS, Spice, LabVIEW ... but with a different non-real-time (RF) signal processing

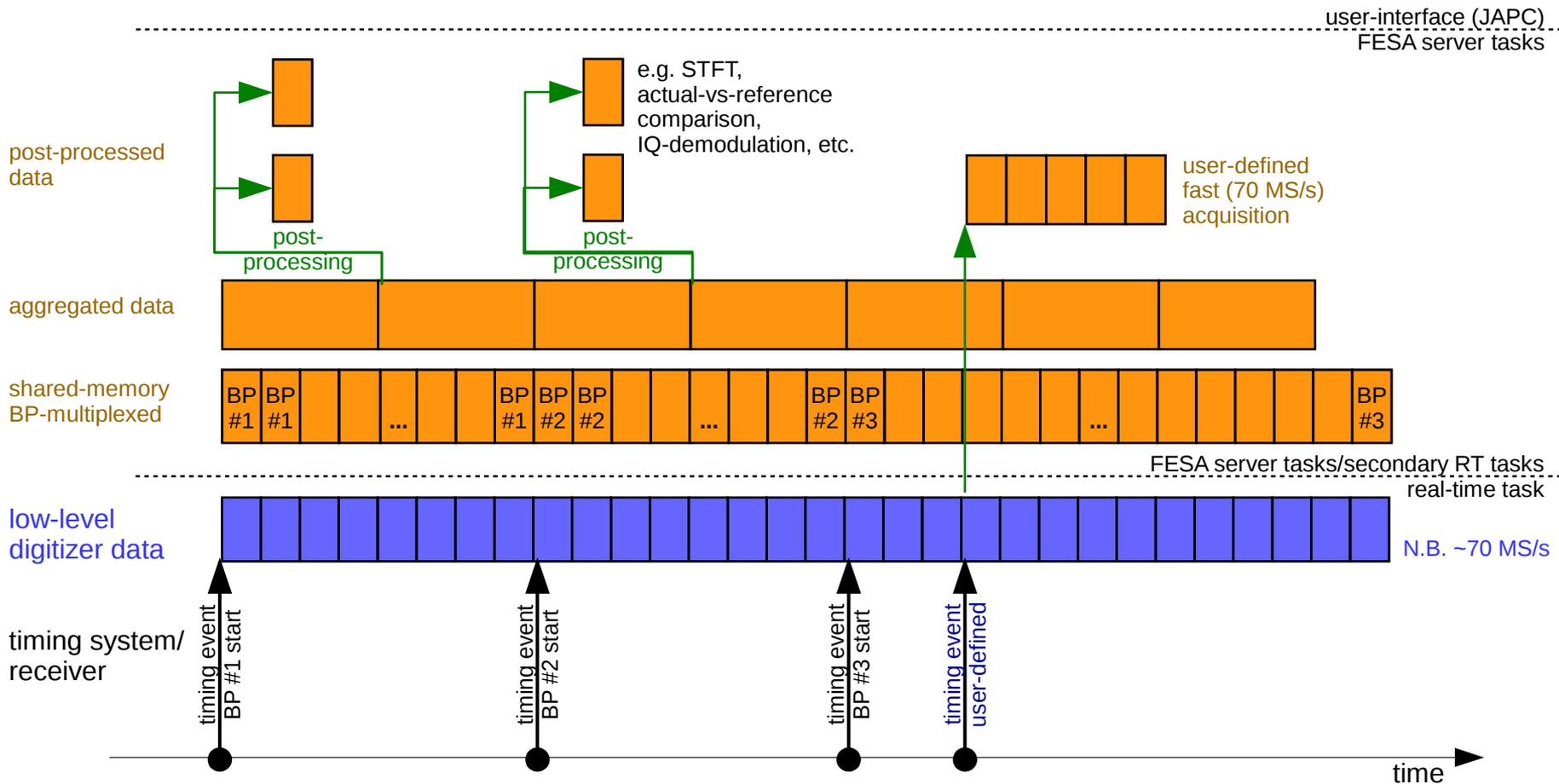


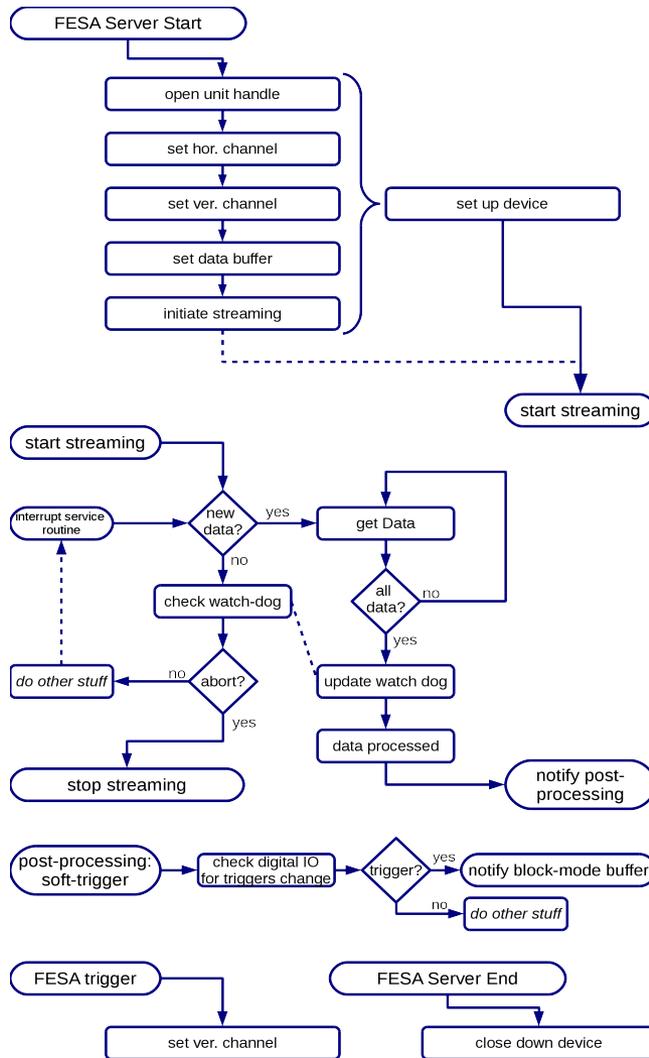
signal flow-chart defined during device instantiation/start-up (tbd.)

- Two data acquisition modes:
 - A.1) Streaming-mode acquisition
 - A.2) (Rapid) block-mode acquisition
- Limited set of post-processing modules:
 - B.1) raw-measurement scaling and offset shift
 - B.2) time-base re-alignment (lag & extr. event offset compensation)
 - B.3) data aggregation and decimation (typ. to kHz → Hz)
 - B.4) real-time Short-time Fourier Transform (STFT)
 - B.5) amplitude, phase and frequency detection (I-Q demodulation)
 - B.6) χ^2 -type fitting and basic peak detection
 - B.7) actual versus reference comparison → interlock

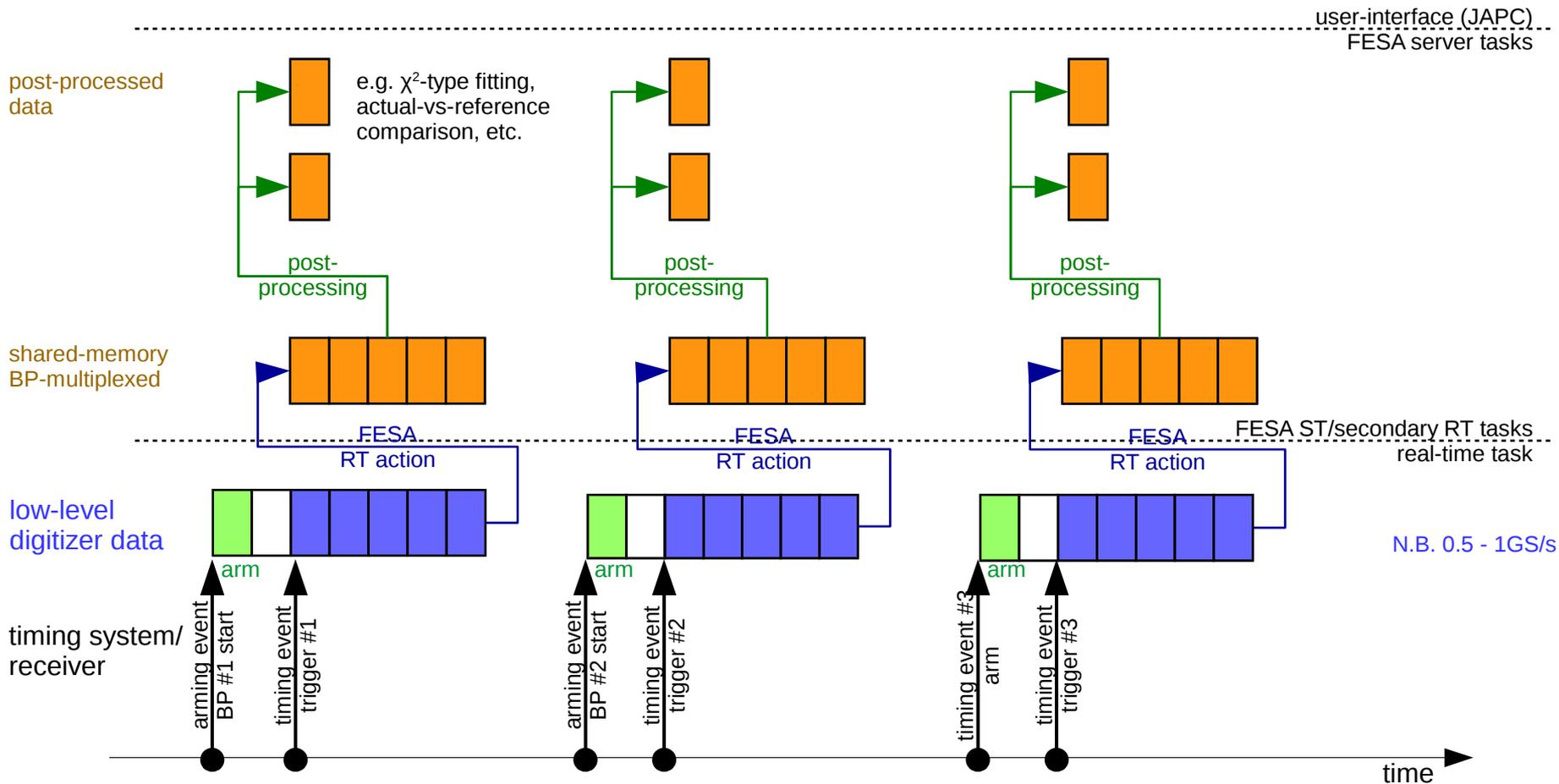
A.1) Streaming-mode acquisition I/II

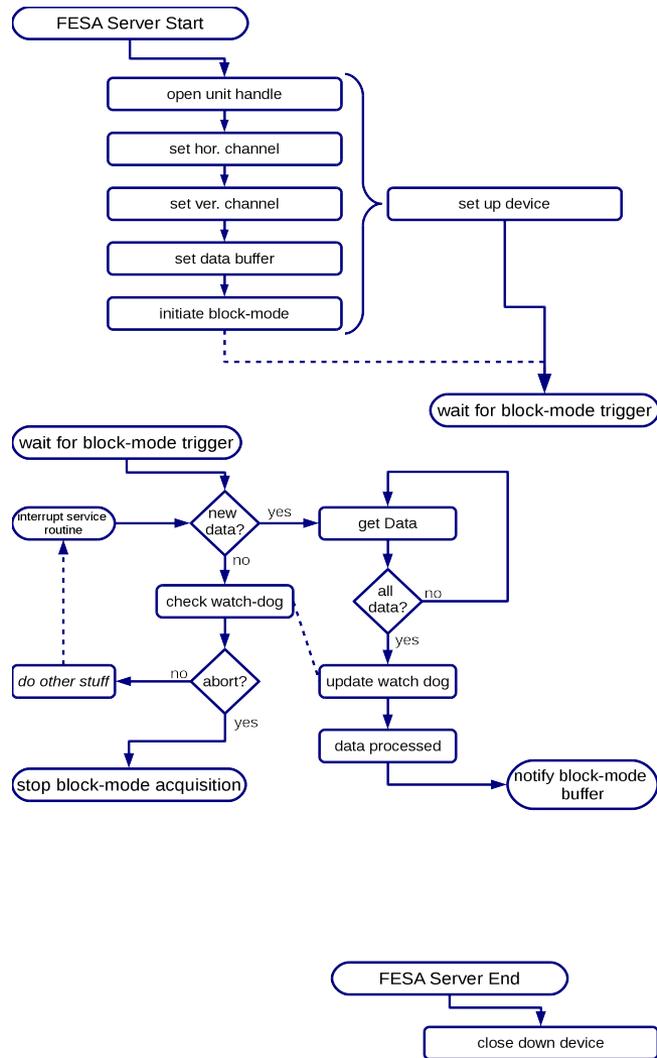
acquisition schematic:

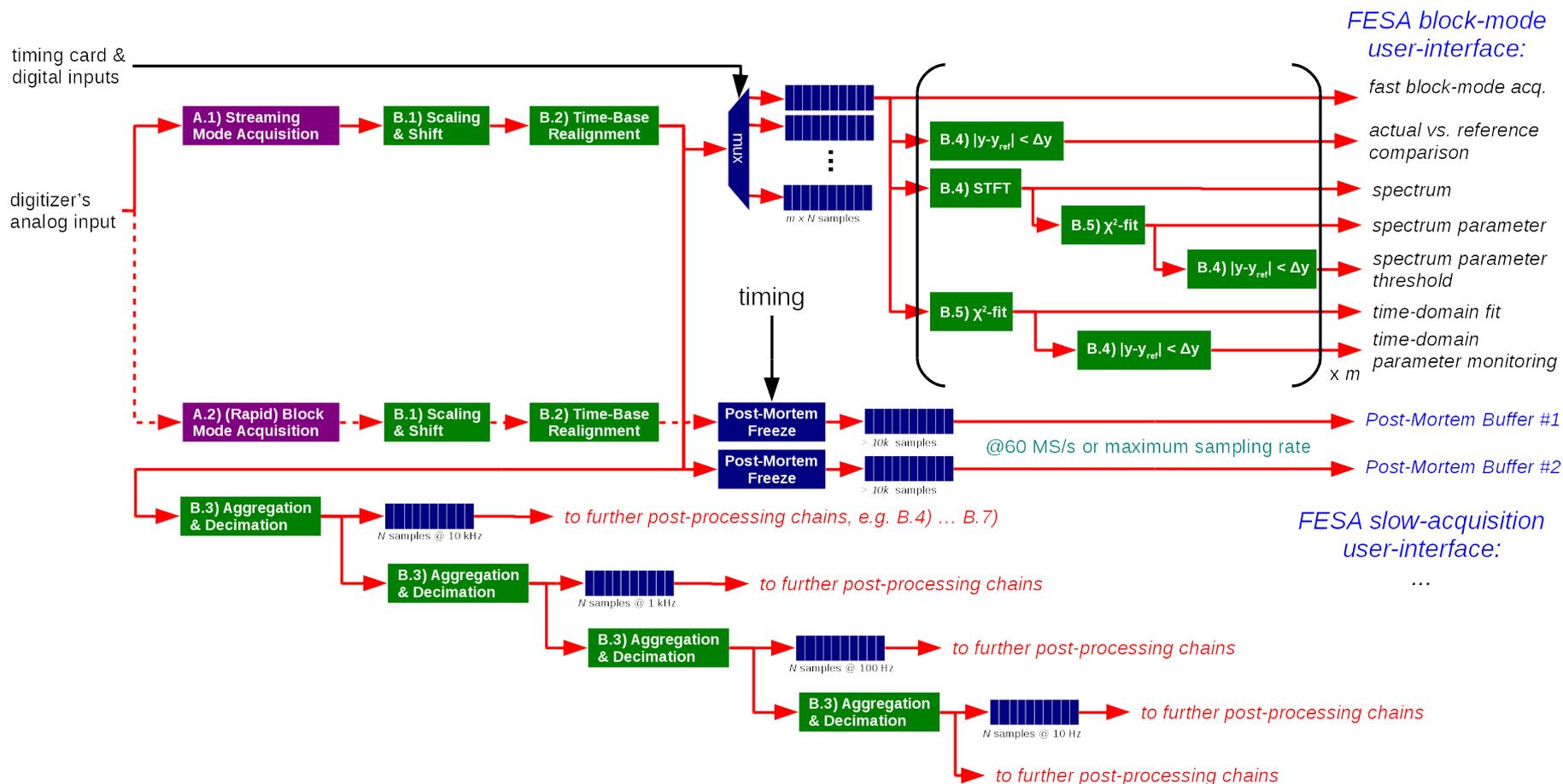




acquisition schematic:







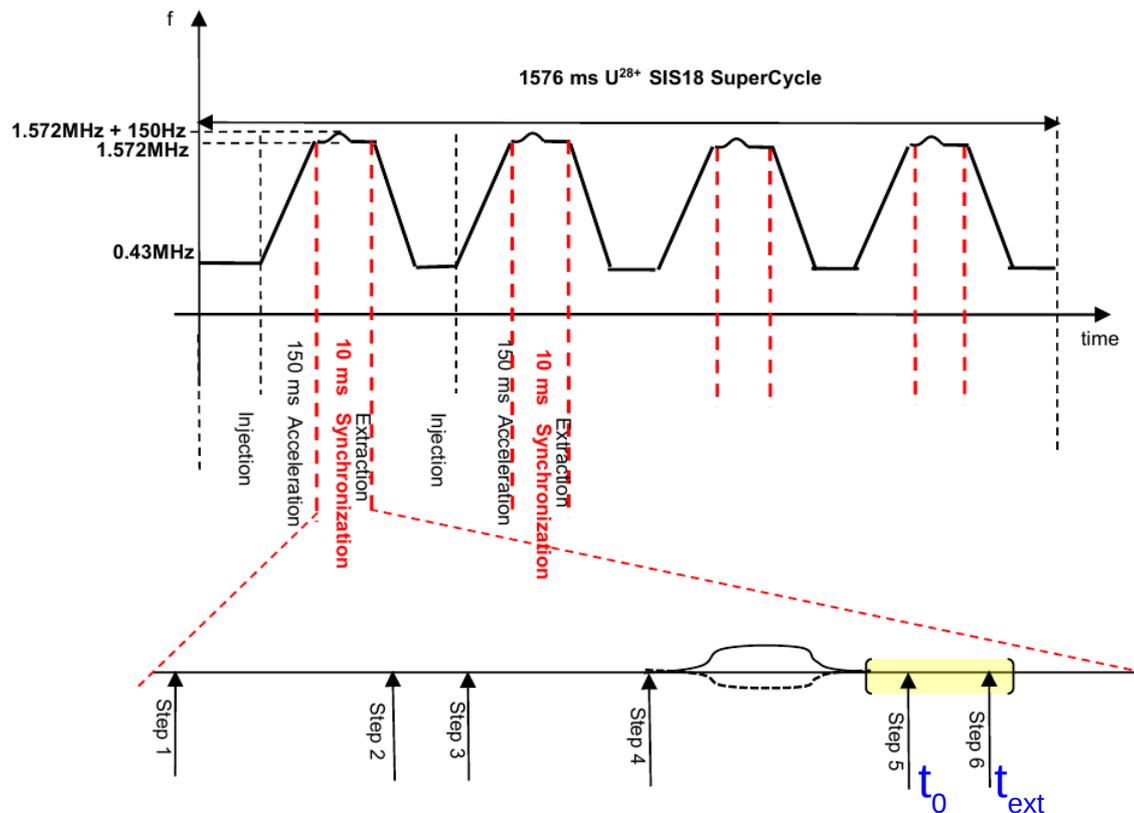
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- *nomen est omen:*

$$y_{\text{meas}} = a_{\text{cal}} \cdot y_{\text{ADC}} [\text{V}] + y_{\text{offset}}$$

- aim: a_{cal} relating low-level digitizer voltage measurement to physical device property (e.g. kV kicker voltage, RF gap-voltage, ...)
- calibration factor a_{cal} and offset option, either
 - multiplexed \leftrightarrow (possibly) different for each beam processes & beam-production chains
 - non-multiplexed \leftrightarrow constant for all beam processes & beam-production chains

- Correction for the actual extraction event (see Bunch To Bucket Transfer System¹⁾)
 - Digitizer-Step 1: acquire ' $t_{\text{meas}} > 10 \text{ ms} + 10\text{k samples}$ ' with extraction timing event t_0
 - Digitizer-Step 2: wait for timing meta-information informing about actual t_{ext} (low-level mechanism tbc.)
 - Digitizer-Step 3: shift and crop data by $t = t_{\text{ext}} - t_0$



¹Technical Concept of the FAIR Bunch To Bucket Transfer System (F-TC-C-05e), <https://edms.cern.ch/document/1514162/6>

- Digitizer Streaming to FECs
 - min/max value over the last N values
 - simple decimation or arithmetic mean μ of the last N values
- FEC-based Low-Pass Filter and Decimation
 - IR-based band- or low-pass filter (GNU Radio)
- Band-Pass Filtering and Down-Conversion
 - GNU Radio: *'Frequency Xlating FIR Filter'*:

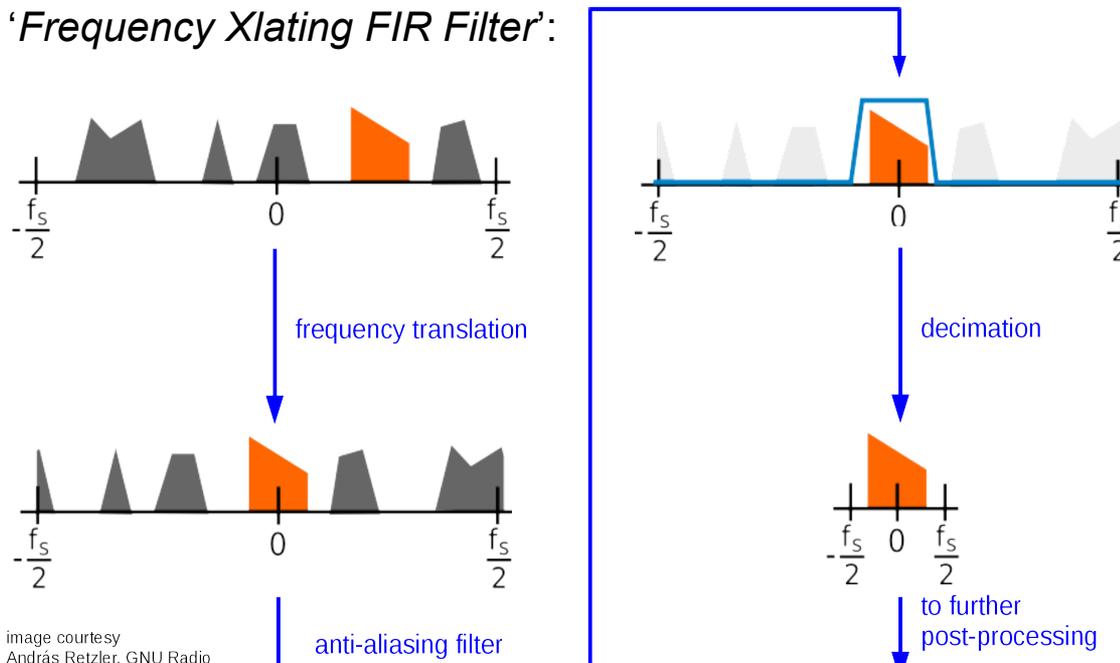
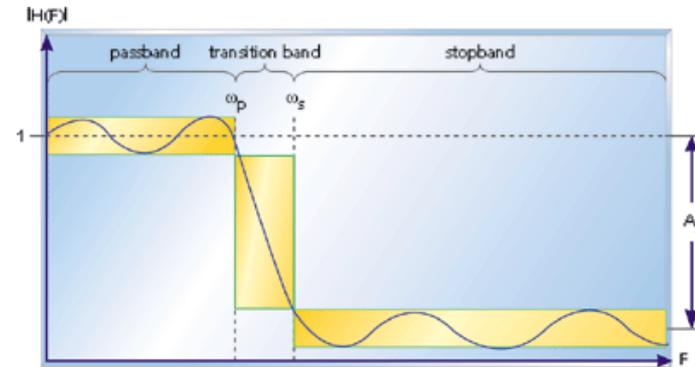


image courtesy
András Retzler, GNU Radio

$$STFT \{ [x] \} (m, f_k) := \sum_{n=-m/2}^{n=+m/2} x_n \cdot w_n \cdot e^{i2\pi f_k n} \quad \text{and} \quad f_k = f_{min} + k \cdot \Delta f = f_{min} + k \cdot \frac{f_{max} - f_{min}}{n_f}$$

- with x_n being the n -th sample of the input, w_n one of the user-selectable windowing function (e.g. Hamming, Hann, Blackman, Rectangular, Kaiser), m the acquisition length in terms of samples, f_i in $[f_{min}, f_{max}]$ for which the frequency component in the signal should be evaluated, and n_f the frequency binning (N.B. $k = 0 \dots n_f$).

Noteworthy choices, ...

A) whether $f_k \leftrightarrow$

- sampling clock $f_s \rightarrow$ standard spectrum analyser functionality \rightarrow further norm. needed
- revolution frequency $f_{rev} \rightarrow$ normalised spectrum \rightarrow e.g. direct $\Delta p/p$ or $\Delta E/E$ measurement

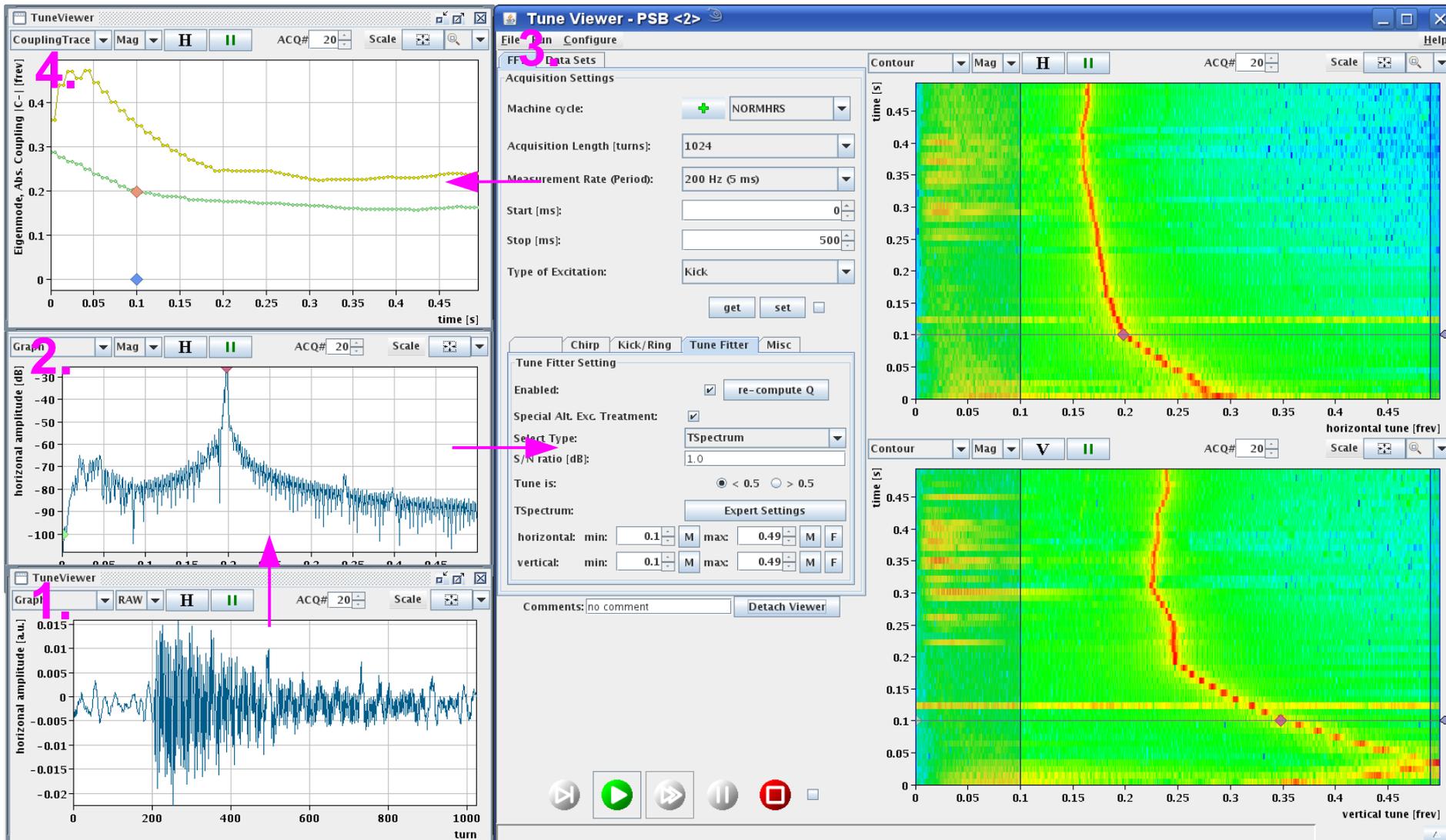
B) on f_{min} & f_{max} whether to compute spectrum¹

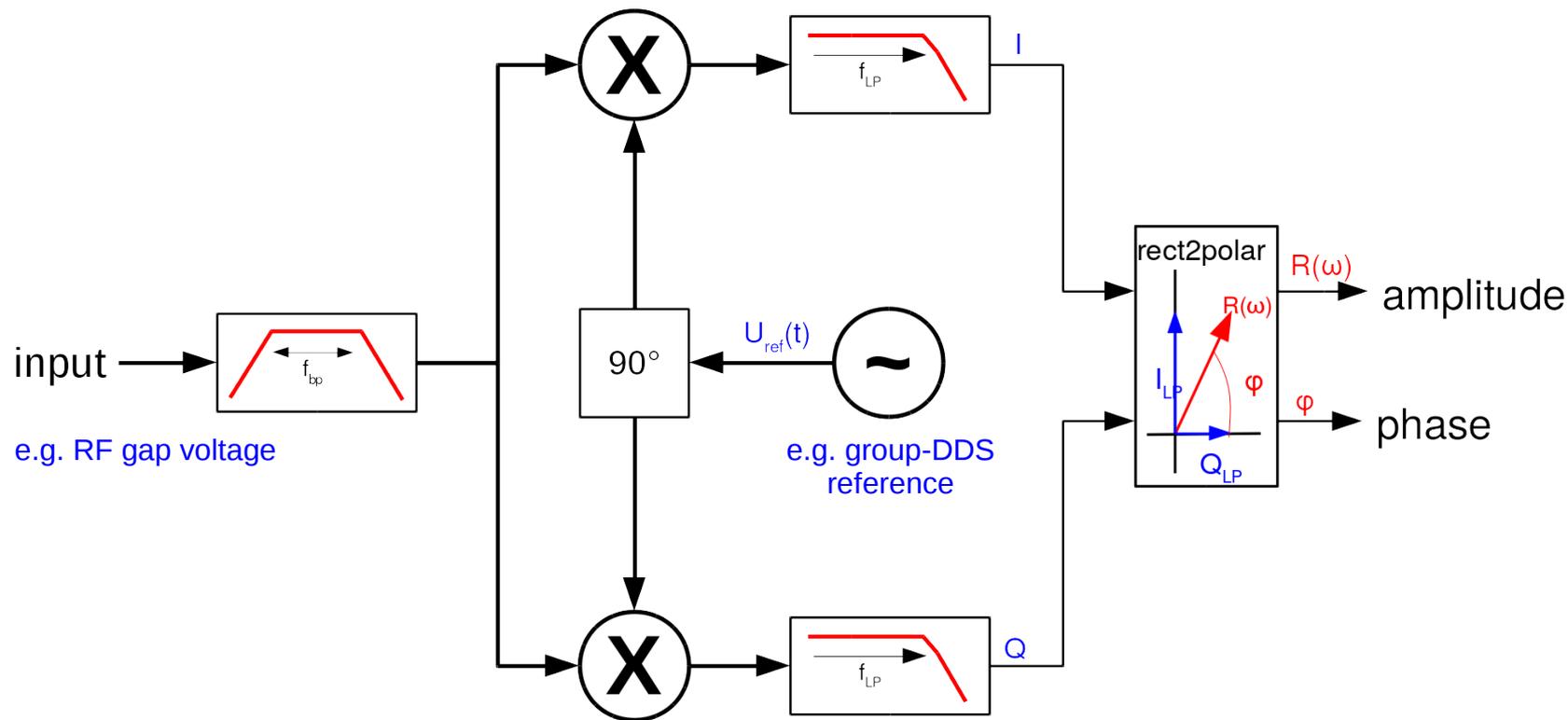
- full spectrum (DC $\rightarrow f_{max} = f_s/2$ or $f_{rev}/2$), or
- subset of spectrum (e.g. n -th harmonic of $f_{rev} \rightarrow f_k$ in $[(n-1)f_{rev}, (n+1)f_{rev}]$), or

C) on frequency binning Δf (normally $\Delta f \geq 1/T_{acq}$)

- Examples on next slide

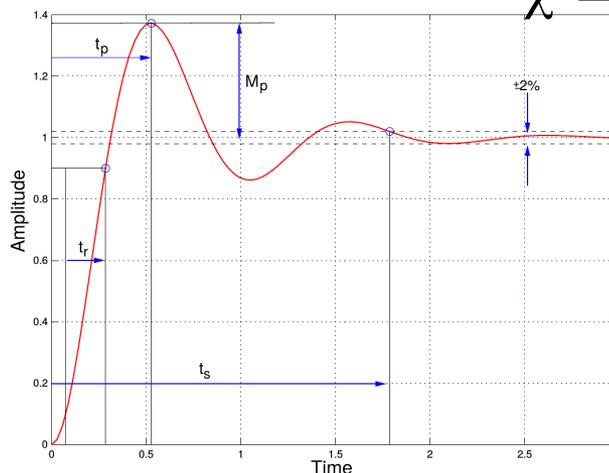
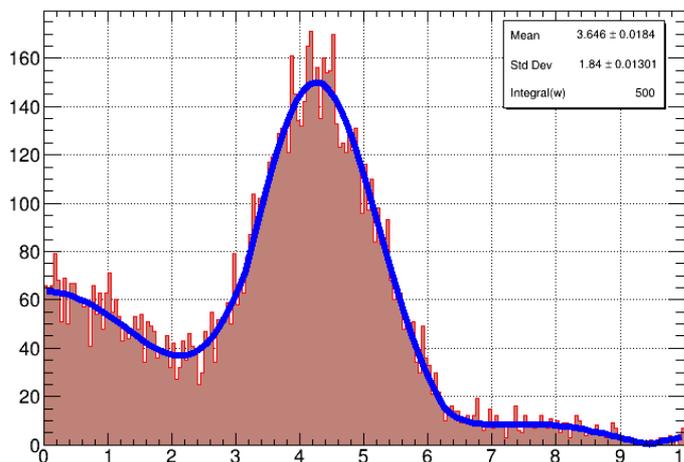
¹ N.B. $f_{min} = 0$, $f_{max} = f_s/2$ & $\Delta f = 1/m$ implies FFT implementation, DFT or Goertzel algorithm otherwise





- Main application:
 - Ring-RF Cavity monitoring, actual-to-reference comparison → interlock

a) Generic Chi-square based fitting (ROOT-based):



$$\chi^2 = \sum_{i=0}^N \left(\frac{y_i - f(x_i)}{\sigma_i} \right)^2$$

$$G := \frac{\chi^2}{n_p}$$

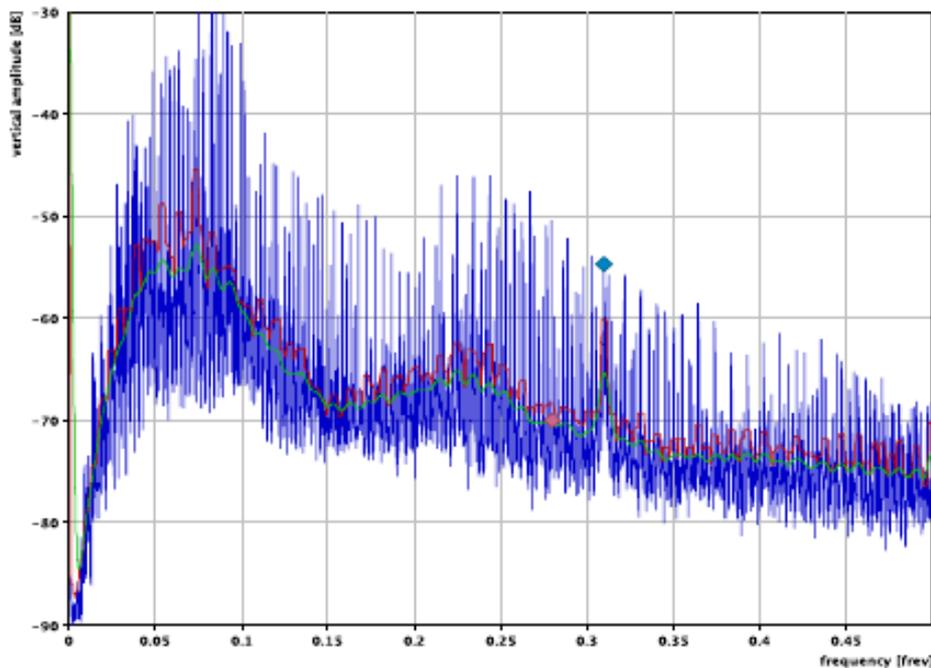
$$\Delta G = |G - 1|$$

- Function representation (type: string): ROOT allows a wide range of string-based function description (see class documentation for 'TFormula' for reference¹), some examples include, e.g.
 - 'gaus' for a simple fit of a Gaussian function,
 - 'sin(x)/x'
 - '[0]*sin(x) + [1]*exp(-[2]*x)'
 - 'x + y**2'
 - 'gaus + pol0(3) + expo(4)', 'gaus+(x>30 && x<90)*pol2(3)', or
 - '(x<[0]?0:1*[1])' for fitting the time offset and amplitude of a Heaviside step function.

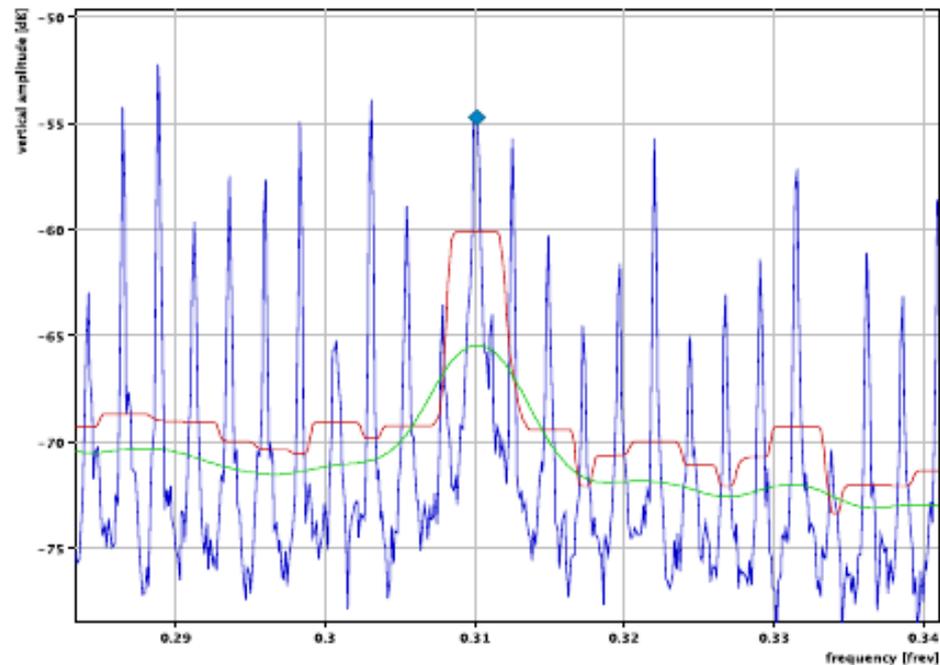
see¹: <https://root.cern.ch/doc/master/classTFormula.html>

a) Generic Chi-square based fitting (ROOT-based)

b) Fitting of spectral peaks:



(a) LHC BBQ spectra



(b) Zoom around betatron tune

[1] R.J. Steinhagen, M. Gasior, and S. Jackson, "Advancements in the Base-Band-Tune and Chromaticity [..]", Proceedings of DIPAC2011

[2] R.J. Steinhagen, "Tune and Chromaticity Diagnostics", CAS, Dourdan, France, 2008, pp.317

... based on operational experience at CERN and similar systems, the following post-processing algorithm shall be implemented^{1,2}:

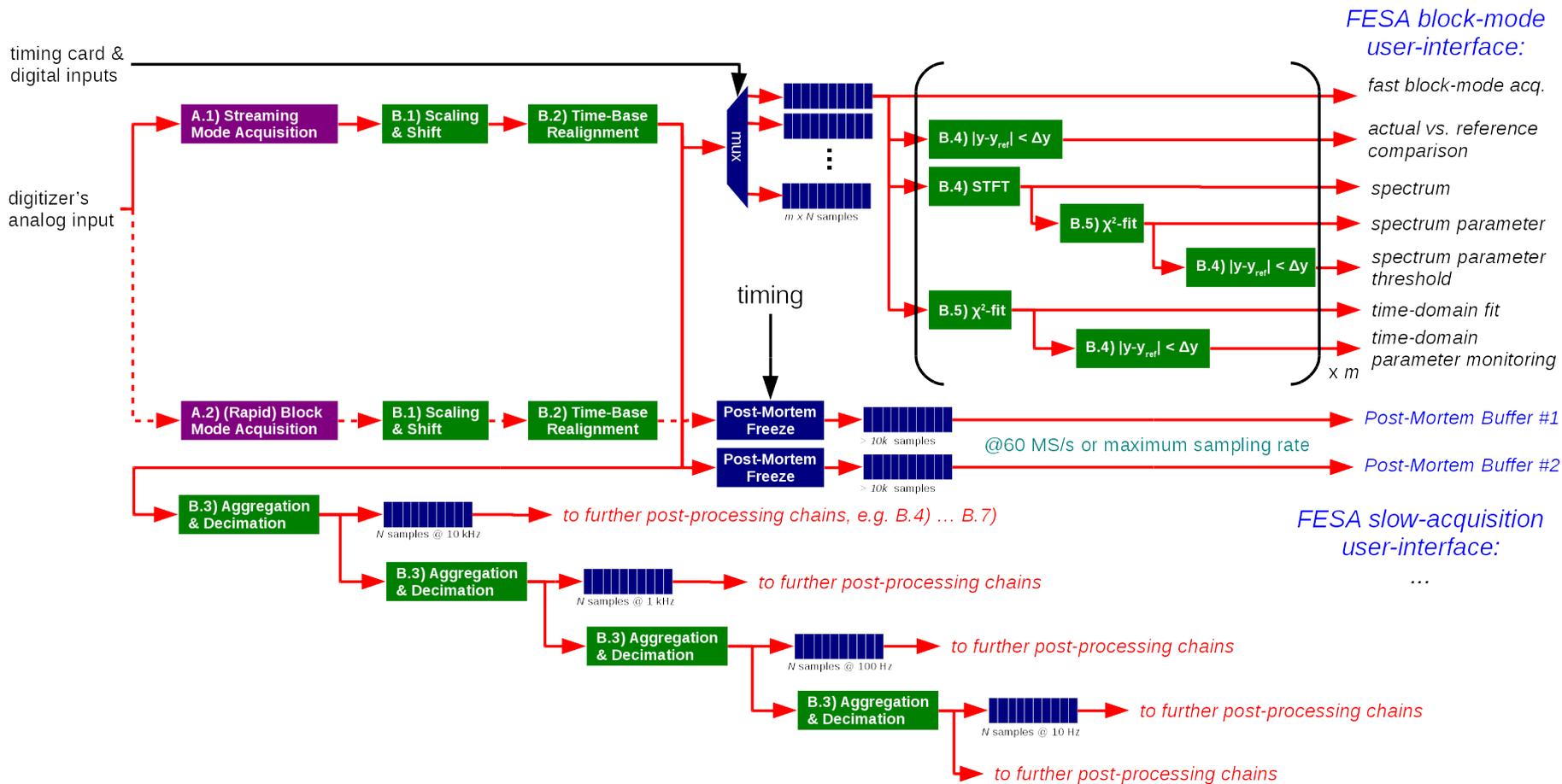
1. calculate the raw-spectra $S_{raw}(f)$ based on the n-sample oscillations data,
2. compute (averaged) magnitude spectra $|S_{raw}(f)|$,
3. apply a n_{med} -wide median-filter $\rightarrow |S_{med}(f)|$,
4. apply a $\pm n_{lp}$ -wide sliding average-filter $\rightarrow |S_{lp}(f)|$,
5. find highest peak $Q_{est.}$ in $|S_{lp}(f)|$ within the given
6. boundaries $Q_{est.} \in [f_{min}, f_{max}]$,
7. find highest peak Q_{raw} in $|S_{raw}(f)|$ around the previous ' $Q_{est.} \cdot n/2 \pm n_{med}/2$ ' estimate,
8. refine the binning-limited Q_{raw} estimate by fitting the tune resonance to a Gaussian distribution.
9. compute the full-width-half-maximum estimate at the peak, and compute the Gaussian-equivalent width as:

$$\sigma \approx \frac{\text{FWHM}}{2\sqrt{2\ln 2}}$$

[1] R.J. Steinhagen, M. Gasior, and S. Jackson, "Advancements in the Base-Band-Tune and Chromaticity [..]", Proceedings of DIPAC2011

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- Main focus: generic acquisition and common post-processing of analog signals in the range of a few MHz to hundreds of MHz (in theory: also > GHz)
 - vendor-specific HW abstraction (→ future upgrades of newer version or different models)
 - two basic low-level acquisition modes: continuous & rapid block-mode
 - set of 6 post-processing modules
 - maintainability & testability (unit testing, testing, testing, ...)
- Next steps:
 1. (informal) 'Engineering Check' via FC2WG (& in-kind partner), main aim:
 - identify important missing features
 - identify important conceptual errors or consistency errors
 2. formal 'Engineering Check' via EDMS (↔ collection of signatures of those who gave feedback)
 3. formal 'EDMS Approval' (↔ collection of signatures)
- Open Items (N.B. not just digitizer, but also BPMs, BBQ, ...):
 - handling of 3D-data structures in FESA: Japc, Archiving, ...
 - ???
 - generic handling of ($N > 3$)-dim data structures
 - staged not for 2018
 - transmission of extraction event meta-information (via timing message, data-supply, ... ?)
 - staged not for 2018
 - 'Form' over 'Performance', but should define a minimum standard and practical upper-boundary (engineering margin)
 - parallelisms, FEC platform, ...
 - ...