Common Specification F-CS-B-0005e:

Integration of the Beam Position Monitoring System into the Controls & Operation Environment

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Scope

• BPMs are bread-and-butter instruments after beam-trafos

• Primary goals:
  - improve use of beam-based optimisation techniques → better qualitative and quantitative beam/machine performance
    • better reproducibility of beam parameters
    • faster/more reliable setup of new BPCs
  - simplification and deployment of same optimisation, tools, OP paradigm for all FAIR (and existing) accelerators → no resources to support for “isolated island” solutions
    • abstraction of vendor specific HW & SW interfaces
OP Context: LSA enabling Beam-based cycle-to-cycle feedbacks

Generic Beam Control (focus on use-case):

1. **Transmission Monitoring System** (R. Steinhagen, FC\WG Meeting #6)
2. **Orbit Control** (work in progress)
3. **Trajectory Control** (threading, inj./extr., targets)
4. **Q/Q'() Diagnostics & Control**
5. **TL&Ring Optics Measurement + Control** (LOCO, AC-dipole techniques etc.)
6. RF Capture and (later) RF gymnastics
7. Longitudinal Emittance Measurement
8. Transverse emittance measurement
9. Transverse and longitudinal feedbacks

Machine-specific Beam-Based Systems:

- **SIS18**: multi-turn-Injection (N.B. highly non-trivial, complex subject), Slow-Extraction (K.O. exciter, spill-structure, …)
- **SIS100**: Slow-Extraction (K.O. exciter, spill-structure, …), RF Bunch Merging and Compression
- **ESR, HESR & CR**: Stochastic cooling, Schottky diagnostics, …, tbd.

**Generic:**

- Remote DAQ of Analog Signals (strong impact on HKR migration/operation!)
- Facility-wide fixed-displays, facility & Machine Status (“Page One”)
- context-based monitoring of controls and accelerator Infrastructure,
- … “the sky is the limit”
Scope of System and Specification

Primary Specification
- Focus on interfaces & HW abstraction
- "common" FAIR-wide specification
  → letter ‘B’

Detailed Specification
- Focus on HW & machine specifics
- ‘detailed specification’
  focus on HW & machine specifics

Conceptual design (provided by implementer)
# Tentative List of Known Users/Use-Cases

## A Cycle-to-Cycle Feedbacks
1. **Injection Steering**  
   `<orbit & trajectory>`
2. **Extraction Steering**  
   `<orbit & trajectory>`
3. **Cycle-to-Cycle Orbit-Feedback (& Radial-Loop)**  
   `<orbit interface only>`

## B Archiving System
1. **Regular/OP Archiving**  
   `<orbit & trajectory>`
2. **Post-Mortem System**  
   `<trajectory interface>`

## C Machine-Protection
1. **Software Interlock System / MASP**  
   `<orbit & trajectory>`

## D Optics Measurement
1. **LOCO-based**  
   `<orbit & trajectory>`
2. **Optics via phase-advance**  
   `<trajectory interface>`

## E Machine Specific Clients
1. **Multi-Turn Injection Optimisation (SIS18, CRYRING)**  
   `<orbit & trajectory>`
2. **Collimator/Cleaning set-up (SIS100)**  
   `<orbit interface>`
3. **MPS validation (SIS100)**  
   `<orbit & trajectory>`
4. **Luminosity Steering (HESR)**  
   `<orbit & trajectory>`

## F Machine-Development
1. **bunch-by-bunch expert diagnostics**  
   `<bunch-by-bunch>`
2. **machine development specific applications**  
   `<orbit & trajectory>`

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**Important constraint:**

Use-cases have to be served and data has to be provided *in parallel* for all beam production chains (BPCs) → multi-user || optimisation
Example Clients: Orbit (avg. Trajectory)

- **Global orbit**
  - minimise the aperture requirements; monitor/log closed orbit
  - improve machine reproducibility (e.g. w.r.t. dynamic aperture & slow-extraction)
- **Local orbit at critical points** – fine control of aperture limits (collimators, septa, etc.)
- **Machine Alignment** – beam-based alignment of quadrupoles, BPMs etc.
- **Linear optics model** → LOCO (N.B. rel. slow method)
  - Integer tunes – Fourier analyse of closed orbit
  - Dispersion D(s) – closed orbit versus momentum deviation
  - measure β(s) and μ(s), BPM & orbit corrector calibration, polarity checks
  - search for optics imperfections
- **Non-linear optics model**: $b_2/a_2$ to $b_5$, $b_3/a_3$ etc.
  - polarity checks of higher-order multipoles
  - optics linearisation
Example Clients: Trajectory and Oscillations

- **Trajectory** – beam threading, close trajectory on itself, visual inspection
- **Position and momentum error at injection**
  - Subtract orbit from first-turn trajectory and compute x,px,y,py at injection (injection matching)
    - N.B. this includes also HEBT BPMs
  - Deduce momentum from trajectory averaged over the azimuth → controls the SIS18/SIS100 energy matching
- **Linear optics model** ↔ beta-beating via. phase-advance measurement (N.B. rel. fast method)
  - measure $\beta(s)$ and $\mu(s)$ at injection, ramp, extraction, optics changes due to $\gamma$, shift
  - search for optics imperfections
- **Phase space measurement**
  - separatrix of slow-extraction → sextupole adjustment: amplitude & phase
  - dynamic aperture, driving terms
- **Local chromaticity**
  - Dependence of $\beta(s)$ and $\mu(s)$ on momentum for the measurement of $b_3$ versus azimuth
- **Local impedance** – dependence of $\mu(s)$ on beam intensity
- **Local coupling** – Identify the local 4D transport matrices
- **Optional/complementary (ie. covered by dedicated Q/Q' diagnostics):**
  - Transverse spectrum
    - Check on the presence and amplitude of harmonics of the betatron oscillation
  - Fast Tune → measurement of the tunes with all the BPM’s
  - Frequency maps → Variation of (fast) tunes with initial conditions for visual inspection of the non-linearity
**Data Acquisition, Client Interfaces & Synchronisation**

Circular Machine Cycle
- e.g. SIS100, CR, HESR, CRYRING, SIS18, ESR

Transfer line 1
- e.g. SIS18 → HEBT → SIS100
- or: SIS18 → HEBT → ESR
- or: ESR → HEBT → CRYRING

Transfer line 2
- e.g. SIS100 → HEBT → \( \bar{p} \)-target/CR
- or: SIS100 → HEBT → CBM

**FAIR Timing:**
- Orbit acquisition: @ 1 kHz (100 Hz, 10 Hz, 1 Hz, N.B. batch average)
- 1st, 2nd, 3rd, 4th batch
- Indiv. HEBT-in trajectories published per injection
- N.B. being discussed/proposed: bunched beam (≥100 MHz) during slow extraction
- Indiv. HEBT-out trajectories published per extraction
- Indiv. HEBT-out trajectories published per extraction
- Extracted beam (slow)

**Note:**
- Time (not to scale)
- Beam alignment: HEBT rigidity
- Beam righting
Low-Level Acquisition Modes
A.1) Streaming-mode acquisition I/II

acquisition schematic:

post-processed data
aggregated data
BPs
low-level BPM digitizer data
timing system/receiver

time

user-defined fast (70 MS/s) acquisition

FESA server tasks/secondary RT tasks
real-time task/BPM FPGA

N.B. ~250 MS/s

post-processing

E.g. instant orbit, closed orbit@ < 1 kHz,

post-processing

BP #1
BP #2
BP #3

BP #1
BP #2
BP #3

BP #1
BP #2
BP #3

BP #1
BP #2
BP #3

user-interface (JAPC)
Trajectory/Orbit Acquisitions I/II
Specified FESA Data Streams (Concentrator)

Following modes of acquisition would be expected to be served simultaneously (though some of them could be implemented as down-sampled copies of the higher bandwidth acquisition):

**A. Slow-acquisition** (FESA property: e.g. 'Orbit') – sub-choices (selected via CMW-filter):

1) 'Sequence' acquisition between 'beam injection' and 'beam extraction': the closed orbit position averaged and decimated to the rate needed for the given client (e.g. 1 kHz).
   → *property notifies complete trace as a function of time at the end of the sequence (up to 30-60 s)*

2) 'Continuous' real-time data publication during the cycle (↔ N.B long SIS100 cycles and/or storage rings):
   → *property notifies single measurement at typical update rate around 10-25 Hz*
   
   • use-case: user-level applications (inj./extr. steering), software-based real-time feedbacks, ...

3) 'Instant' orbit acquisition: → *property notifies single measurement at pre-defined time delays (ms-scale)*
   
   • software interlock on injection/extraction orbit deviations (via MASP)

**B. Fast turn-by-turn acquisition** (FESA property: e.g. 'Trajectory', or combined with above to 'Acquisition'):

1) average batch trajectories in HEBT/HEST (possibly different device)

2) First 1000 turns for 1\textsuperscript{st}, 2\textsuperscript{nd}, ... n\textsuperscript{th} injection
   
   • default & 1\textsuperscript{st} injection: average batch position
   
   • ≥ 2\textsuperscript{nd} inj.: gated turn signal on newly injected batch

3) Last 3 turns → injection/extraction steering (see bunch-to-bucket transfer scheme)

4) 3 study buffers covering 10k (optionally up to 100k) turns
   
   • data should be retained for one sequence and can be overwritten in subsequent sequences
   
   • event time window may overlap with above reduced acquisition (e.g. BCMS & last turn).

5) optionally: bunch-by-bunch data for predefined number of BPMs
   
   • N.B. large (10s of GB) data volumes
C. Post-Mortem (FESA property 'PostMortem'): not finalized yet but provisionally, it can be foreseen that:
   1) first circular buffer storing the orbit @ 1 kHz for the last second of beam or full cycle
   2) second circular buffer storing the last 1k (10k?) turns.

D. BI-Expert acquisitions
   1) “Raw ADC” acquisition. The raw ADC data within the time frame in a single cycle of a certain accelerator and a specific BPM defined via the FESA interface. The same acquisition data format should be used that is used internally by the low-level front-ends.
   2) Bunch-by-bunch acquisition. The Bunch-by-bunch data within the time frame, accelerator and BPM defined by client. For bunch-by-bunch the data structure may be similar as for orbit and trajectory data, but should be a different property because of the expected data amount.
   3) Tune measurements acquisition. Fourier transformations of the parts of Bunch-by-bunch data at times and within time frames provided by client.
BPM SW Requirements I/II

- All BPM data available from one single source/concentrator
- Two (possibly one) FESA properties for ‘orbit’ & ‘trajectory’ data
  - N.B. 'Orbit' and 'Trajectory' assumed to be based on turn averages
    (ie. no bunch-by-bunch → other property for optics control & MD purposes)

- Expected primary 'Orbit' & 'Trajectory' information:
  A) Average position: \( \mathbf{x}(t_i) = [x_0(t_i), x_1(t_i), \ldots, x_i(t_i)]^\top \)
    - Orbit: fixed 1 kHz rate or user-defined time stamps (adaptive rate)
    - trajectory: always first turn (injection), last turn (extraction), + user-defined timing events
  B) Measurement noise/error: \( \mathbf{\sigma}(t_i) = [\sigma_0(t_i), \sigma_1(t_i), \ldots, \sigma_i(t_i)]^\top \)
    - Error propagation of actual averaging variance and known HW noise (e.g. ADC, amplifier)
  C) Relative (qualitative) sum signal \( \Sigma = [-1, +1] \) w.r.t. ADC range
    - allows: cross-checks of ADC range w.r.t. amplifier gain & relative loss localisation
  D) BPM statuses (32/64 bit mask)
    - de-selection masks (BI expert, OP), ADC status, timing errors, bunch detection errors, temperature control, range checks, transient errors, etc.
Specified FESA Property Layout I/II

<table>
<thead>
<tr>
<th>Property</th>
<th>Variable</th>
<th>Description</th>
<th>Data Type</th>
<th>unit</th>
<th>dim1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acquisition</td>
<td>selectedFilter</td>
<td>CMW subscription filter</td>
<td>String</td>
<td>[]</td>
<td>[]</td>
</tr>
<tr>
<td>Acquisition</td>
<td>acquiredOk</td>
<td>measurement OK?</td>
<td>1D-array of booleans</td>
<td>[]</td>
<td>N_{bpm}</td>
</tr>
<tr>
<td>Acquisition</td>
<td>acquiredOk_dimensions</td>
<td>(N_{nuc}, N_{bpm}, N_{meas})</td>
<td>1D-array of integers</td>
<td>---</td>
<td>1</td>
</tr>
<tr>
<td>Acquisition</td>
<td>acquiredOk_labels</td>
<td>(&quot;device&quot;)</td>
<td>1D-array of Strings</td>
<td>---</td>
<td>1</td>
</tr>
<tr>
<td>Acquisition</td>
<td>acquiredOk_dim1_labels</td>
<td>device names of the BPMs</td>
<td>1D-array of Strings</td>
<td>---</td>
<td>N_{bpm}</td>
</tr>
<tr>
<td>Acquisition</td>
<td>beamPosition</td>
<td>average beam position</td>
<td>1D-array of floats</td>
<td>[m]</td>
<td>N_{nuc} x 2 x N_{bpm} x N_{meas}</td>
</tr>
<tr>
<td>Acquisition</td>
<td>beamPosition_names</td>
<td>(N_{nuc}, N_{bpm}, N_{meas})</td>
<td>1D-array of integers</td>
<td>---</td>
<td>4</td>
</tr>
<tr>
<td>Acquisition</td>
<td>beamPosition_labels</td>
<td>(&quot;device&quot;, &quot;plane&quot;, &quot;time&quot;, &quot;bunch&quot;)</td>
<td>1D-array of Strings</td>
<td>---</td>
<td>4</td>
</tr>
<tr>
<td>Acquisition</td>
<td>beamPosition_dim1_labels</td>
<td>device names of the BPMs</td>
<td>1D-array of Strings</td>
<td>---</td>
<td>N_{bpm}</td>
</tr>
<tr>
<td>Acquisition</td>
<td>beamPosition_dim2_labels</td>
<td>(&quot;horizontal&quot;, &quot;vertical&quot;)</td>
<td>1D-array of Strings</td>
<td>---</td>
<td>2</td>
</tr>
<tr>
<td>Acquisition</td>
<td>beamPosition_dim3_labels</td>
<td>timestamps of the samples</td>
<td>1D-array of long</td>
<td>---</td>
<td>N_{bpm}</td>
</tr>
<tr>
<td>Acquisition</td>
<td>beamPosition_dim4_labels</td>
<td>bunch identifier [0,9]</td>
<td>1D-array of byte</td>
<td>---</td>
<td>N_{bpm}</td>
</tr>
<tr>
<td>Acquisition</td>
<td>referencePosition</td>
<td>reference beam position</td>
<td>1D-array of floats</td>
<td>[m]</td>
<td>N_{nuc} x 2 x N_{bpm} x N_{meas}</td>
</tr>
<tr>
<td>Acquisition</td>
<td>referencePosition_names</td>
<td>(N_{nuc}, N_{bpm})</td>
<td>1D-array of integers</td>
<td>---</td>
<td>3</td>
</tr>
<tr>
<td>Acquisition</td>
<td>referencePosition_labels</td>
<td>(&quot;device&quot;, &quot;plane&quot;, &quot;time&quot;)</td>
<td>1D-array of Strings</td>
<td>---</td>
<td>3</td>
</tr>
<tr>
<td>Acquisition</td>
<td>referencePosition_dim1_labels</td>
<td>device names of the BPMs</td>
<td>1D-array of Strings</td>
<td>---</td>
<td>N_{bpm}</td>
</tr>
<tr>
<td>Acquisition</td>
<td>referencePosition_dim2_labels</td>
<td>(&quot;horizontal&quot;, &quot;vertical&quot;)</td>
<td>1D-array of Strings</td>
<td>---</td>
<td>2</td>
</tr>
<tr>
<td>Acquisition</td>
<td>referencePosition_dim3_labels</td>
<td>timestamps of the samples</td>
<td>1D-array of long</td>
<td>---</td>
<td>N_{bpm}</td>
</tr>
<tr>
<td>Acquisition</td>
<td>beamPositionError</td>
<td>std of orbit measurement</td>
<td>1D-array of floats</td>
<td>[m-m]</td>
<td>N_{nuc} x 2 x N_{bpm} x N_{meas}</td>
</tr>
<tr>
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<td>beamPositionError_names</td>
<td>(N_{nuc}, N_{bpm}, N_{meas})</td>
<td>1D-array of integers</td>
<td>---</td>
<td>4</td>
</tr>
<tr>
<td>Acquisition</td>
<td>beamPositionError_labels</td>
<td>(&quot;device&quot;, &quot;plane&quot;, &quot;time&quot;, &quot;bunch&quot;)</td>
<td>1D-array of Strings</td>
<td>---</td>
<td>4</td>
</tr>
<tr>
<td>Acquisition</td>
<td>beamPositionError_dim1_labels</td>
<td>device names of the BPMs</td>
<td>1D-array of Strings</td>
<td>---</td>
<td>N_{bpm}</td>
</tr>
<tr>
<td>Acquisition</td>
<td>beamPositionError_dim2_labels</td>
<td>(&quot;horizontal&quot;, &quot;vertical&quot;)</td>
<td>1D-array of Strings</td>
<td>---</td>
<td>2</td>
</tr>
<tr>
<td>Acquisition</td>
<td>beamPositionError_dim3_labels</td>
<td>timestamps of the samples</td>
<td>1D-array of long</td>
<td>---</td>
<td>N_{bpm}</td>
</tr>
<tr>
<td>Acquisition</td>
<td>beamPositionError_dim4_labels</td>
<td>bunch identifier [0,9]</td>
<td>1D-array of byte</td>
<td>---</td>
<td>N_{bpm}</td>
</tr>
</tbody>
</table>

Standardised layout for n-dim. arrays

- permits decoding of `beamPosition (1 dim) → beamPosition[bpmID, plane, measID, bunchID]`
- facilitates generic tools for filtering and indexing, e.g.
  - selection of orbit of all BPMs-vs-Cordinate-‘s’ @ given time
  - orbit selection of given BPM-vs-Time
  - ...


### Assumption:
- **Single Concentrator handling (/republishing)** 84 BPMs @ 100 Hz → 3.3 MB/s
- N.B. Raw BPM Concentrator Data Rate ~ 32 MB/s (Orbit @ 1 kHz, 10 x 1.5k turn Acq/s)
Additional FESA Properties

• ‘Settings’ – Supply and Settings Interfaces
  
  - standard BI-data supply from LSA: ionMassNumber, ionAtomicNumber, ionChargeState, kineticEnergy, maxIntensity, harmonicNumber, maxNumberOfBunches, bunchLength, spillLength, numberOfInjections, injectionBatchOffset, injectionBatchLength, revolutionFrequency, timeOfFlight, flightPath, BeamSpotSizeX, BeamSpotSizeY
  
  - triggers also automatic gain settings

• System status acquisition: HW/SW statuses, calibrations state, etc.

• Masks manually set by client (low-key OP status management):
  
  - ‘OP permanent’: device shall not be used for orbit steering or other similar purposes (for a variety of operational reasons)
  
  - ‘OP temporary’: device shall temporarily not be used for orbit steering or other similar purposes (for a variety of operational reasons)
  
  - ‘BI permanent’: device shall not be used for orbit steering or other similar purposes
  
  - ‘BI temporary’: the specific BPM/s is used for tests or concerns on functionality (e.g. used during BI expert diagnostics operation or setup procedures)

• Pre-amplifier Settings and Acquisition Interface (allows manual gain settings override)

• Properties required for gain calibration procedures
Top-Level Calibration Procedure

- Two types of calibration foreseen:
  - Pre-amplifier gain calibration (~ once per day, outlined in detailed specification)
  - Zero-line calibration (between each BPC when there is no beam in the machine)

- Mandatory calibration quality checks prior to applying new coefficients:
  - Quantitative comparison of the measured amplifier channel amplitude (including the lab-based calibration factor measurements) with the reference (which is calculated as signal generator waveform amplitude multiplied by the preamplifier gain value).
  - If the deviation exceeds the specified threshold, the calibration should not be applied for the given BPM, and the status notified via the calibration property which amplifier has failed and at which amplification.
  - **Important**: even if all calibrations passed successfully, the operator has to manually approve that the new calibration coefficients can be applied. Until then, the last parameters shall be used by the system.
    - N.B. operator may choose to override and provide a custom (constant) gain for given number of BPMs
Summary

• Joint Specification
  – Combines different aspects
  – Realization-independent and valid on longer time scales

• Technical solutions for common problems
  – n-dim. arrays and others

• Definition of standard acquisition schemes that are used for other systems as well
Appendix
2016-06-12: Orbit-FB Proof-of-Concept MD
B. Schlei, H. Liebermann, R. Steinhagen

- some workarounds needed, but overall success and results look promising
  - need to follow-up: reliability, performance issues related to CO & BI + detailed integration before being put into regular operation (→ routine operation for 2018 looks feasible)
  - N.B. remaining horizontal oscillation due to uncorrected $\Delta p/p$ mismatch → radial-loop/Energy-FB
LSA Parameter Hierarchy

**OPTICSIP**

- **SISMODI**
  - **QH_START_END**
  - **QH_THEO**
  - **QV_THEO**
  - **QV_START_END**

- **QH**
- **QV**
- **DQH**
- **DQV**

- **DKL**

- **Bp**

- **B_0 L(t)**

- **I(t)**

**KL_THEO**

- **KL(t)**

**Q_H(t)**

**KL(t)**

**I(t)**
Terminology: Accuracy & Precision (also ISO 5725)

Good summary: http://en.wikipedia.org/wiki/Accuracy_and_precision

- **Accuracy**: “[..] closeness of measurements [..] to its actual (true) value”

- **Precision** (also: reproducibility or repeatability): “[..] degree to which repeated measurements under unchanged conditions show the same results.”

- **Example**: “Target analogy” and the two extreme cases

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- **Resolution**: smallest change that produces a response in the measurement

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High **accuracy**, but low **precision**

obtained through beam-based alignment

High **precision**, but low **accuracy**

we need this from the BPMs