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MicroTCA.4-Based Intelligent Control System for a Synchrotron Beamline

Physics and AI/ML
for beamline operation

MICROTCA.4 WORKSHOP

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APPLICATION CONTEXT

Synchrotron beamline control

Outline

The design follows one operating record from acquisition to a verified action

- | | | |
|-----------|--|-------|
| 01 | Beamline needs and intelligent operation
Experimental context · scale · correlated state | 03–04 |
| 02 | Architecture and four subsystems
Timing · motion · XBPM · detector acquisition | 05–09 |
| 03 | Platform selection
Design budgets · hardware routes · lifecycle value | 10–11 |
| 04 | Data, models and operation
Device interfaces · learned response · experiment execution · twin | 12–17 |
| 05 | Validation and implementation
Operating benefit · model and control evidence · staged delivery | 18–19 |

Beamline experiments and operating needs

Useful beamtime depends on coordinated execution and a reliable assessment of operating conditions

HEPS experimental station

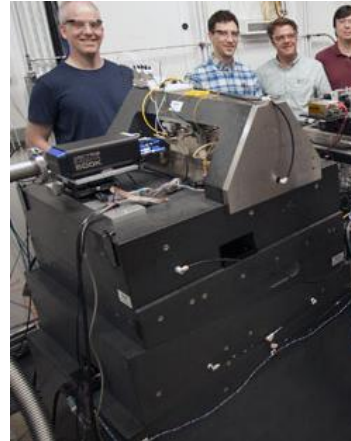


Precision optics and sample positioning

Position + actual readback
Beam condition + equipment state

Continue only with a valid state

APS Velociprobe

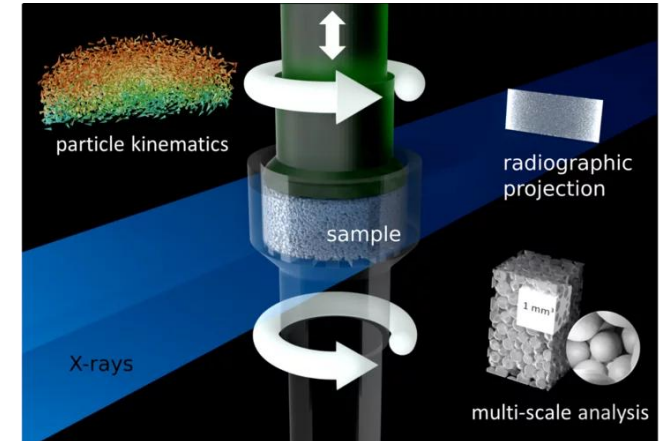


Position measurement during fast scans

Encoder position + accepted exposure
Beam and detector quality

Check the response to each operation

TOMCAT at SLS



Imaging during motion

Image sequence + motion phase
Sample and experimental context

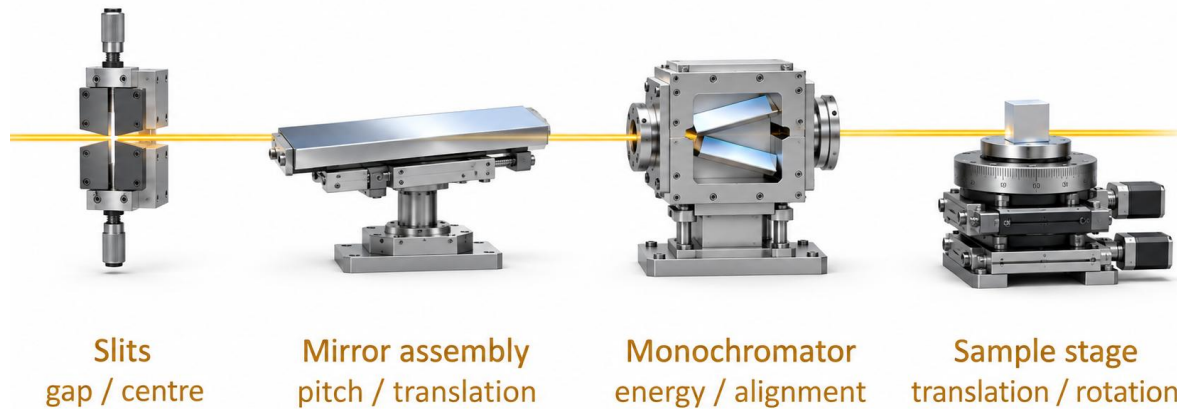
Assess quality before the next segment

Physics / AI models use the shared state to predict response, flag mismatches and support an operating decision.

Images: HEPS station; APS Velociprobe (2019); PSI TOMCAT tomo-rheoscopy schematic. Existing source images retained.

Beamline scope and system requirements

HEPS Phase I: 14 user beamlines + 1 test beamline. The proposed implementation covers one beamline.



DESIGN SCALE

≥48 motion axes overall
Selected devices for each task
6 XBPMs / 24 current inputs
Hundreds of process channels

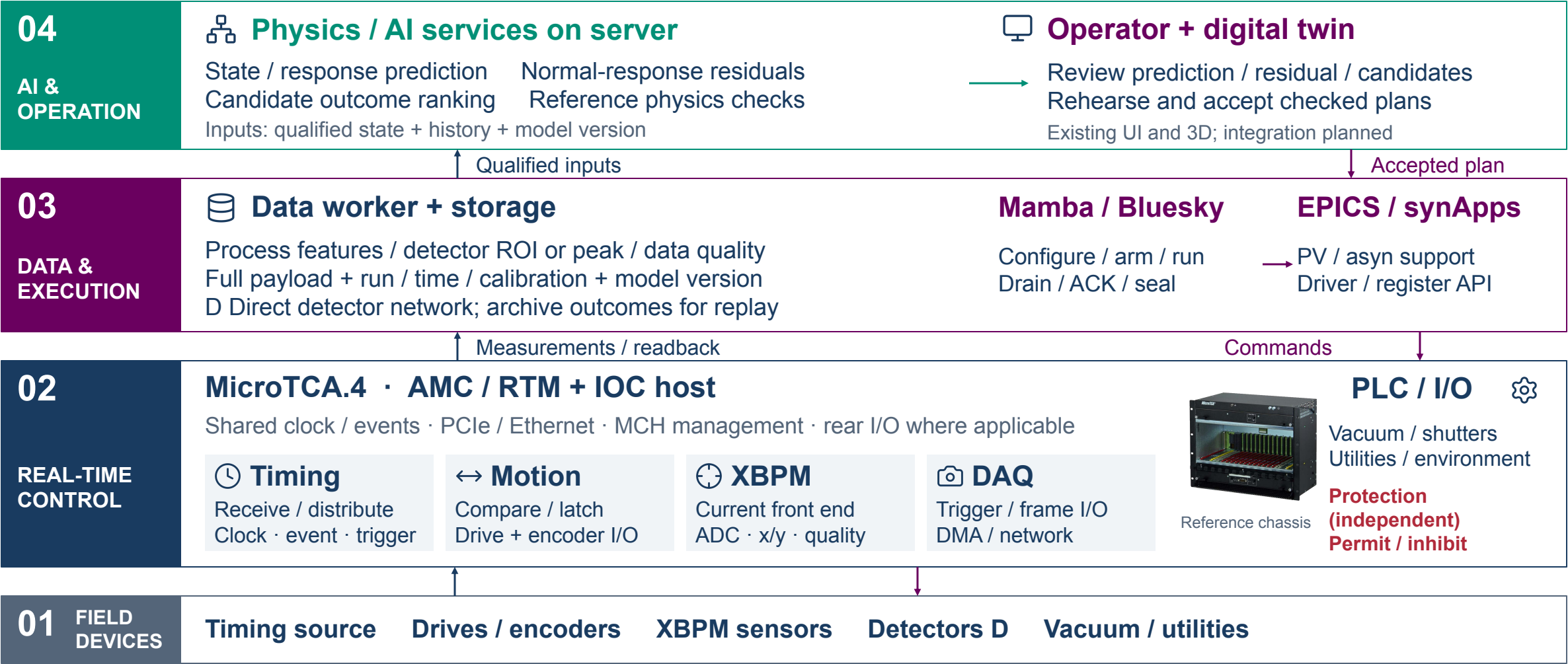
Detector load = frame bytes × frame rate
Instrument-specific parameters pending

Device / signal group	Required observation	Role in the intelligent system
Optics + sample motion	Command, encoder, achieved position, status	Execute settings; verify actual response
XBPM + process channels	Position / intensity, environment, quality	Describe the state; support prediction and diagnosis
Detector frames	Exposure identity, image / spectrum, validity	Assess experimental output; provide online features
Vacuum / shutters / utilities	Permits, alarms, state and slow readback	Constrain accepted operations; preserve protection

A common experimental state joins measurements to model assessment and reliable execution; scale is not a claim of simultaneous motion.

Intelligent control system architecture

One experimental state links the real-time front end, model services and accepted operating plans



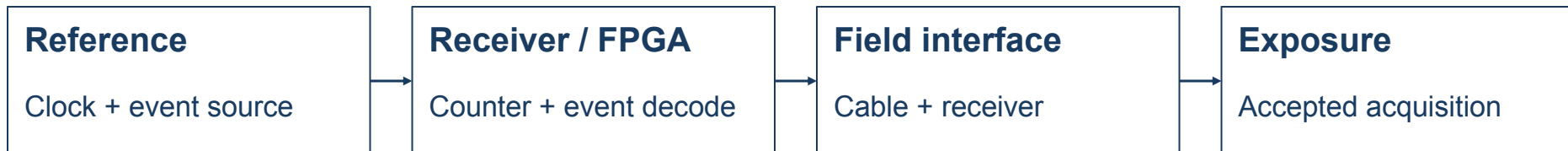
Detector images may stream directly to the worker over the data network. Hardware illustration: Chu, Digital Twin Workshop, slide 9.

Timing and correlated measurements

The timing contract covers the complete path from reference clock to accepted exposure



MRF receiver reference
mTCA.4-EVR-300RF



Fixed delay: calibrate each segment

Residual error: measure at the acquisition endpoint

Interface	Contract at the boundary	Failure / validity
Clock	Frequency, phase, discipline and receiver lock	Loss of lock: inhibit or flagged holdover
Event	Event code, sequence and scan-state meaning	Missing / duplicate events: mark invalid
Trigger	Level, polarity, impedance, pulse width, armed state	Reject unless armed; verify full path delay
Timestamp	Epoch, resolution, rollover and exposure association	Carry clock validity and input age

POSITION ERROR BUDGET

$$|\delta x| \approx |v_{\text{scan}}| |\delta t|$$

Local constant scan speed; δt is residual error after fixed-delay calibration.

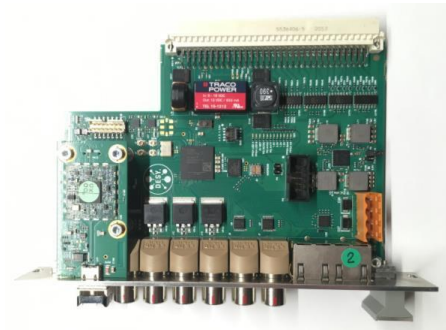
CALIBRATION OBSERVABLES

Reference edge → receiver output → detector exposure indication
Record delay, jitter, clock validity and the defined operating load.

WR alignment alone does not establish exposure accuracy.

Motion execution and position feedback

Trajectories, measured position and protection meet at the local execution interface



DESY DAMC-MOTCTRL
Reference implementation



Reference connection
board

EPICS / plan

Accepted settings
Selected axes

Local controller

Trajectory buffer
Execution state

Drive

Command interface
Mechanics / servo

Encoder

Actual position
Status

FPGA compare

Position condition
Acquisition event

Latch / record

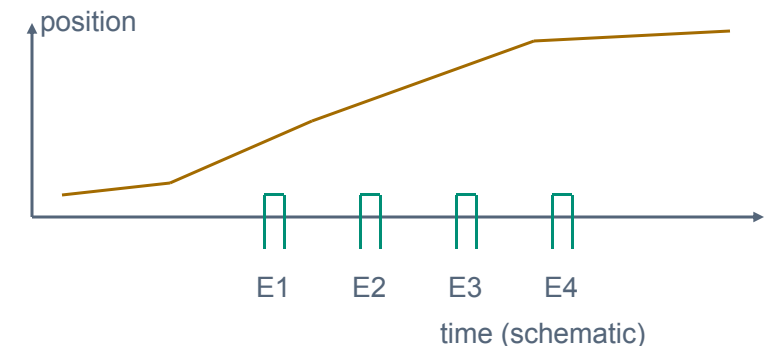
Position + time
Event ID

Limits / drive faults / independent permit → hardware enable or inhibit

LOCAL EXECUTION CONTRACT

ARMED → RUNNING → DONE / FAULT
Readback verifies achieved position and settling.
The drive / controller retains the servo loop.

POSITION-BASED ACQUISITION



Hardware images: MicroTCA-based Motion Controller, DESY Workshop, slide 4. Reference hardware; beamline interface compatibility remains to be checked.

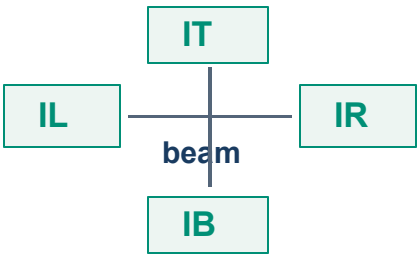
XBPM measurement and beam-state quality

The current measurement chain preserves calibration and validity with each beam-state estimate

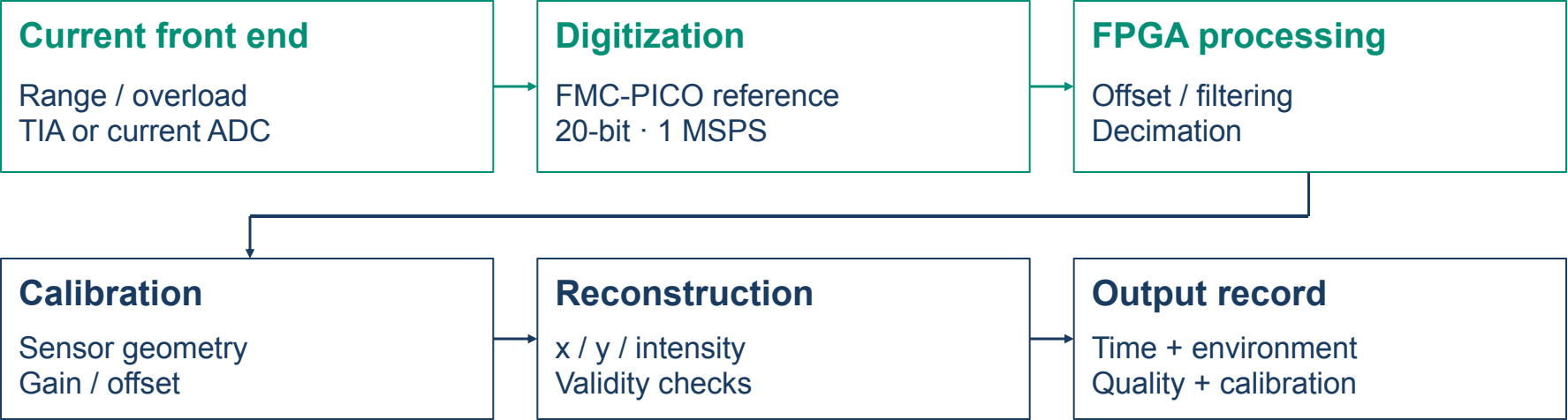


Beamline environment — existing reference image

FOUR CURRENT INPUTS



Four-channel schematic
Pairing follows sensor geometry
 $I_z = I_1 + I_2 + I_3 + I_4$



$$x \propto (I_R - I_L) / I_z \qquad y \propto (I_T - I_B) / I_z$$

Normalized-ratio example; calibration determines position scale and valid operating range.

Design item	Reference / output boundary
Input scale / channels	pA–μA process range; 6 XBPMs / 24 currents
Acquisition vs output	1 MSPS ADC reference; processed 10–100 kHz candidate
Invalid data flags	Low sum current · saturation · stale value · invalid clock
Model-ready state	Position / intensity + time + calibration + quality + context

FMC-PICO route: original beamline design report §4.4. ADC resolution is not a claim of system position accuracy.

Detector acquisition and online features

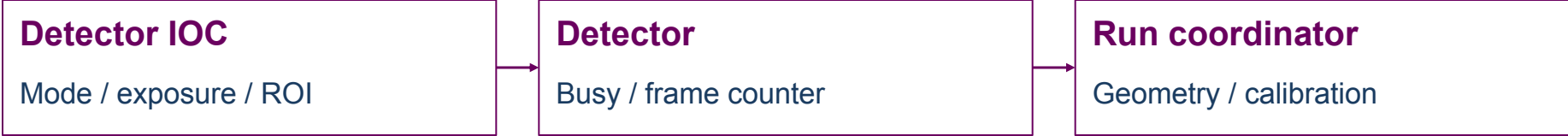
Separate command, trigger and image paths retain a common experimental identity



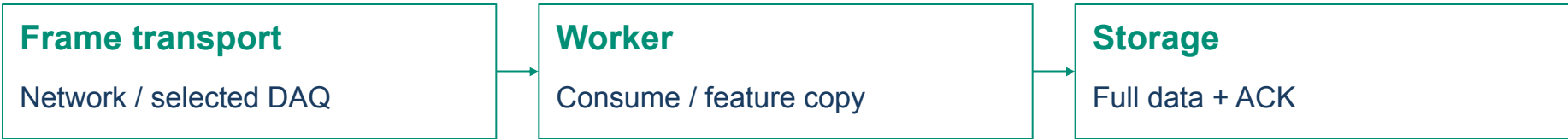
Detector / sample context



SIS8300-KU: DAQ reference
Not a selected detector interface



Trigger: timing / encoder compare → armed detector input



Owned online features: peak / ROI / quality

Frame context	Queue and record completion
run ID · frame ID · event / time	Observe queue growth and buffer ownership
Position · beam state · calibration	Count accepted frames; expose missing / dropped data
Quality · detector configuration	Drain buffers → storage ACK → metadata seal

Process example: $300 \times 10 \text{ kHz} \times 8 \text{ B} = 24 \text{ MB/s}$

Detector load = $\Sigma(\text{frame bytes} \times \text{frames/s})$

10/25 GbE candidates
Validate sustained load + backpressure

Process estimate excludes detector images and protocol / metadata overhead. Reference DAQ photograph supplied in the original material pack.

Design budgets and module selection

Each module choice follows a signal budget and a testable interface constraint

Design input	Budget / scope	Selection and acceptance check
Motion + timing	≥48 axes overall; selected task axes Residual timing budget from tolerance / scan speed	Encoder and trigger I/O; local execution Delay calibration to accepted exposure
XBPM chain	6 monitors / 24 current inputs 20-bit, 1 MSPS ADC reference	Current range, noise, overload, calibration Processed output: 10–100 kHz candidate
Process + detector data	24 MB/s process example Detector frame size / rate pending	Sustained link, DMA and storage load 10/25 GbE candidates; drops / queue growth
Model input path	Selected acquisition-to-input target: <10 ms Inference and motion budgets are separate	Time / calibration / quality / data age Model version and source record retained

ACQUISITION-TO-MODEL INPUT BUDGET



Integration gate: compatible AMC / RTM, backplane routes, firmware, drivers and server compute; references and targets require beamline tests.

Platform choice and lifecycle value

Hardware routes share the same signals, operating tasks and access to AI services

Comparison item	Dedicated / Panda-type route	PXle + FPGA / instruments	MicroTCA.4 + AMC / RTM
Timing / synchronization	External timing and coordinated I/O	Backplane clock / trigger resources	Shared clock / events; field timing I/O
Signal interfaces	Reuse installed drives and devices	Module range and application fit	Rear I/O and front-end / carrier matching
Software integration	Existing drivers + system stitching	Driver / OS / controller compatibility	IOC / driver / firmware development
Deployment / maintenance	Distributed boxes and cabling	Chassis / controller / module servicing	Shelf / MCH / power / cooling management
Project trade-off	Device reuse vs cross-device integration	Instrument fit vs lifecycle support	Shared services vs integration investment
AI connection	Server services through data interfaces	Server services through data interfaces	Server services through data interfaces

LIFECYCLE COST BASIS

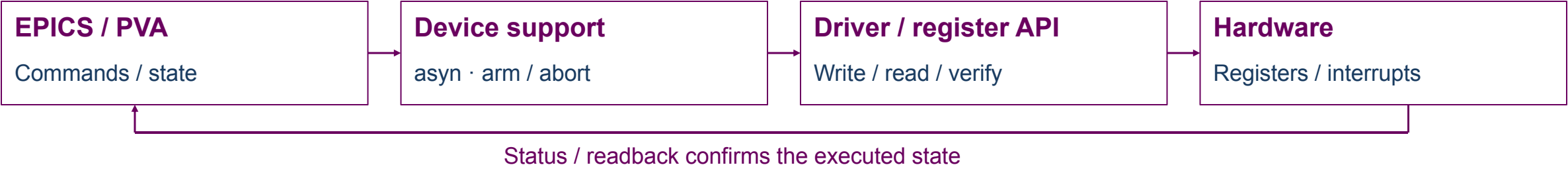
Hardware + drivers + model adaptation + calibration + commissioning + maintenance

The proposed allocation uses shared timing, transport and rear I/O. A beamline-specific quotation and effort estimate are still required.

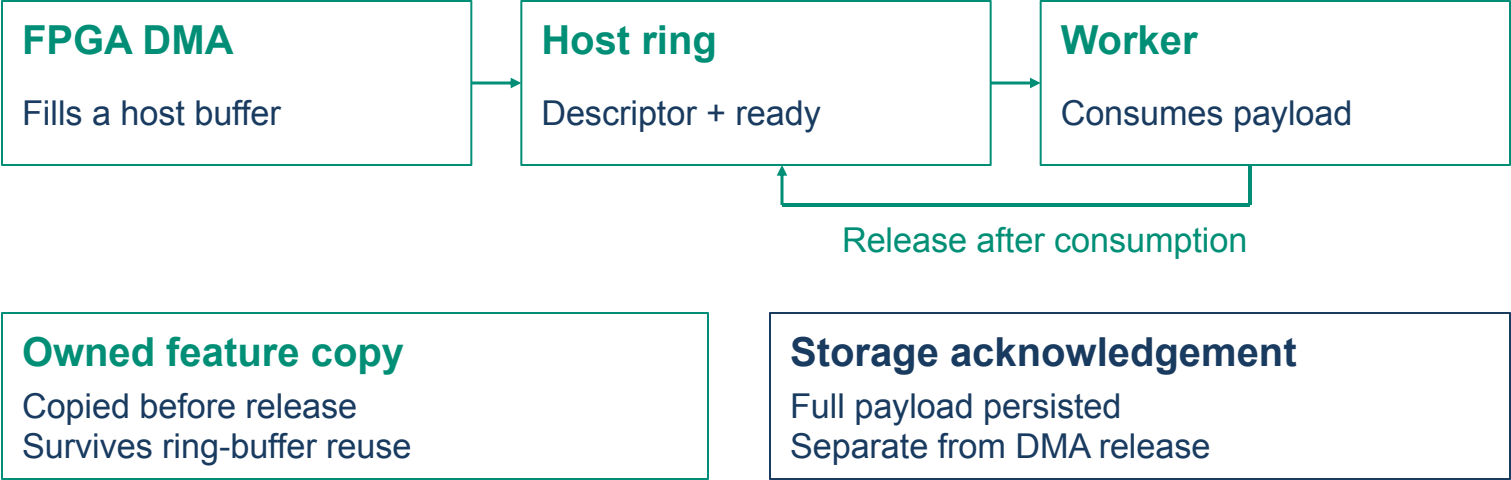
Reference comparisons use the original beamline report; route-specific capability depends on the selected modules and interfaces.

Device interfaces and model-ready data

Control access and bulk-data ownership expose different contracts to model services



BUFFER LIFECYCLE



Model record	Fields retained
Identity	run / point / event / device IDs
Observation	time · values · calibration · quality
Inference	model version · source observations
Output	prediction / recommendation / checks
Outcome	accepted action + observed response

Explicit ownership prevents stale buffer references.
Traceable records support replay and comparison.

Register API is a design boundary, not a claim that one generic driver supports all selected modules.

AI/ML services for beamline operation

Three service contracts share qualified measurements, with different targets and operating uses

STATE / RESPONSE PREDICTION

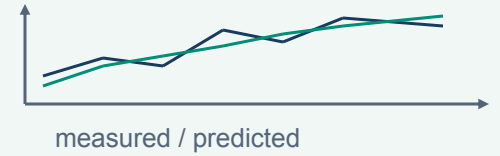
XBPM history · settings
Temperature · reference data

→ **Regression / response model**
Drift or reference property

→ Predicted state + source time
Virtual diagnostic estimate

Use: Monitoring and state assessment

State / prediction — schematic



ANOMALY DETECTION

Beam / equipment signals
Validated normal operation

→ **Normal-response model**
Measured – predicted residual

→ Residual / anomaly flag
Quality and operating context

Use: Evidence for investigation

Residual — schematic



OPERATING DECISIONS

State + candidate settings
Objective + constraints

→ **Surrogate response model**
Score candidate outcomes

→ Shortlist for physics checks
Recommendation or fallback

Use: Accepted plans through execution

Candidate evaluation

Ranked candidates
Model-predicted outcome

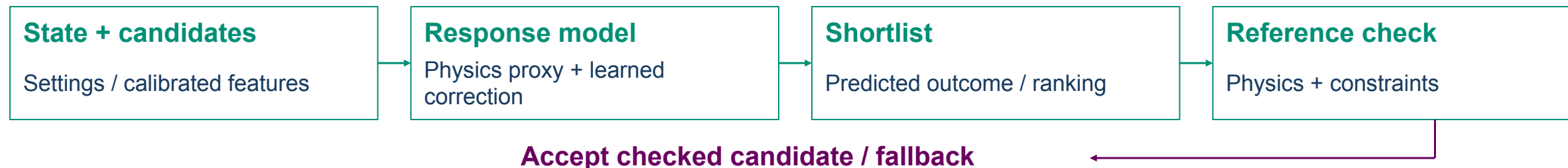
↓ **Top-K** → physics check

Input checks: time / calibration / validity / operating range. Reports can support operation without device commands.

Output plots are schematic. Targets, references and thresholds require beamline data; a residual alone does not establish a fault cause.

Physics-guided prediction and decisions

Fast learned response supports screening; reference physics checks the selected candidates



EXISTING BNCT IMPLEMENTATION

Bounded log residual for positive response rates

$$r = \text{clip}(\log((y_{\text{ref}} + \epsilon) / (y_{\text{proxy}} + \epsilon)), -c, c)$$

$$\hat{y} = \max(y_{\text{proxy}} \cdot \exp(\text{clip}(\hat{r}, -c, c)), \epsilon)$$

ϵ : positive floor; c : residual bound; y : response rate

Feature scaling $\rightarrow$ ridge residual fit $\rightarrow$ member predictions

Ensemble mean / spread + input-range distance

REUSABLE METHOD

Residual prediction · candidate ranking · physics re-score · fallback

Source: local S3 phase2 P2E v3 implementation, residual_target (307–309), ridge fit (484–488), recovery / ensemble (521–534).

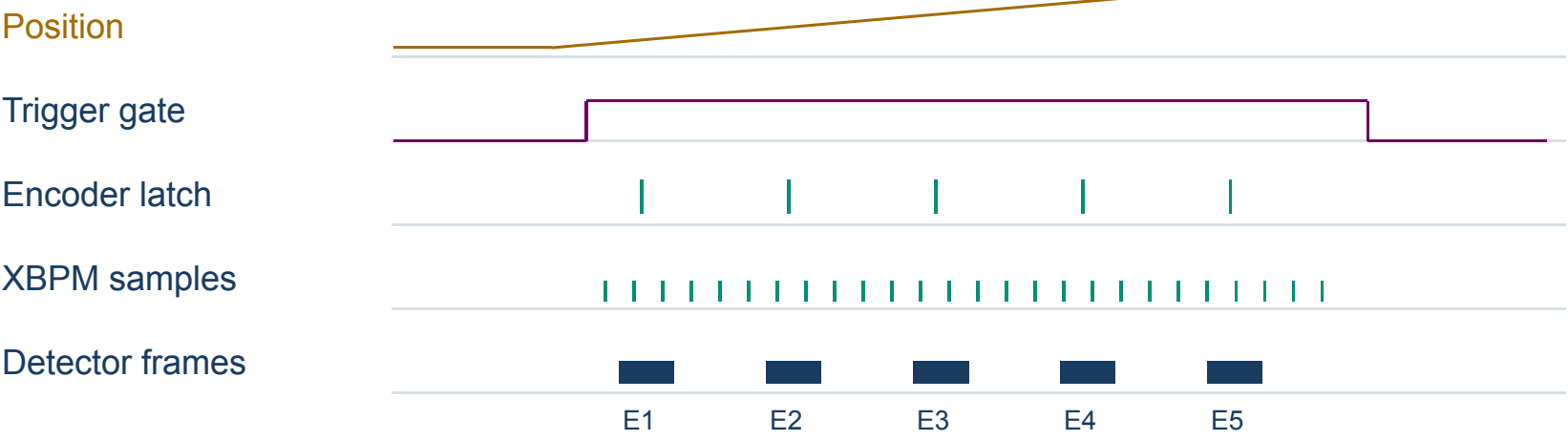
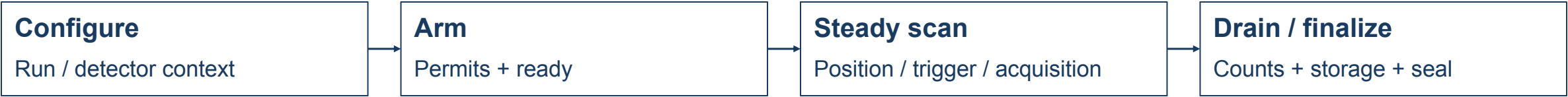
BEAMLINE ADAPTATION

Replace input variables and response targets.
Calibrate the physics proxy with beamline data.
Fit models using separated training runs.
Compare with reference physics on held-out runs.
Release a versioned model only after validation.

The original formula models BNCT response rates.
Beamline targets may need a different correction form.

Model-assisted experiment execution

A scan segment joins accepted exposures, measured state and the next checked operation



Exposure record	Association
scan_id / point_id	Run and intended point
event / trigger count	Accepted exposure identity
timestamp / position	Latched actual position
XBPM state / quality	Window or interpolation rule
frame ID / status	Payload and completion

Continuous XBPM: exposure window / defined interpolation.
Sample count need not equal frame count.



Schematic time, not measured. Completion: count / quality checks, DMA drain, storage ACK and metadata seal. Preserve partial data after failure.

Digital twin for review and rehearsal

The existing interface and 3D model will share device identity, observations and model results

PLANNED MODEL OUTPUTS

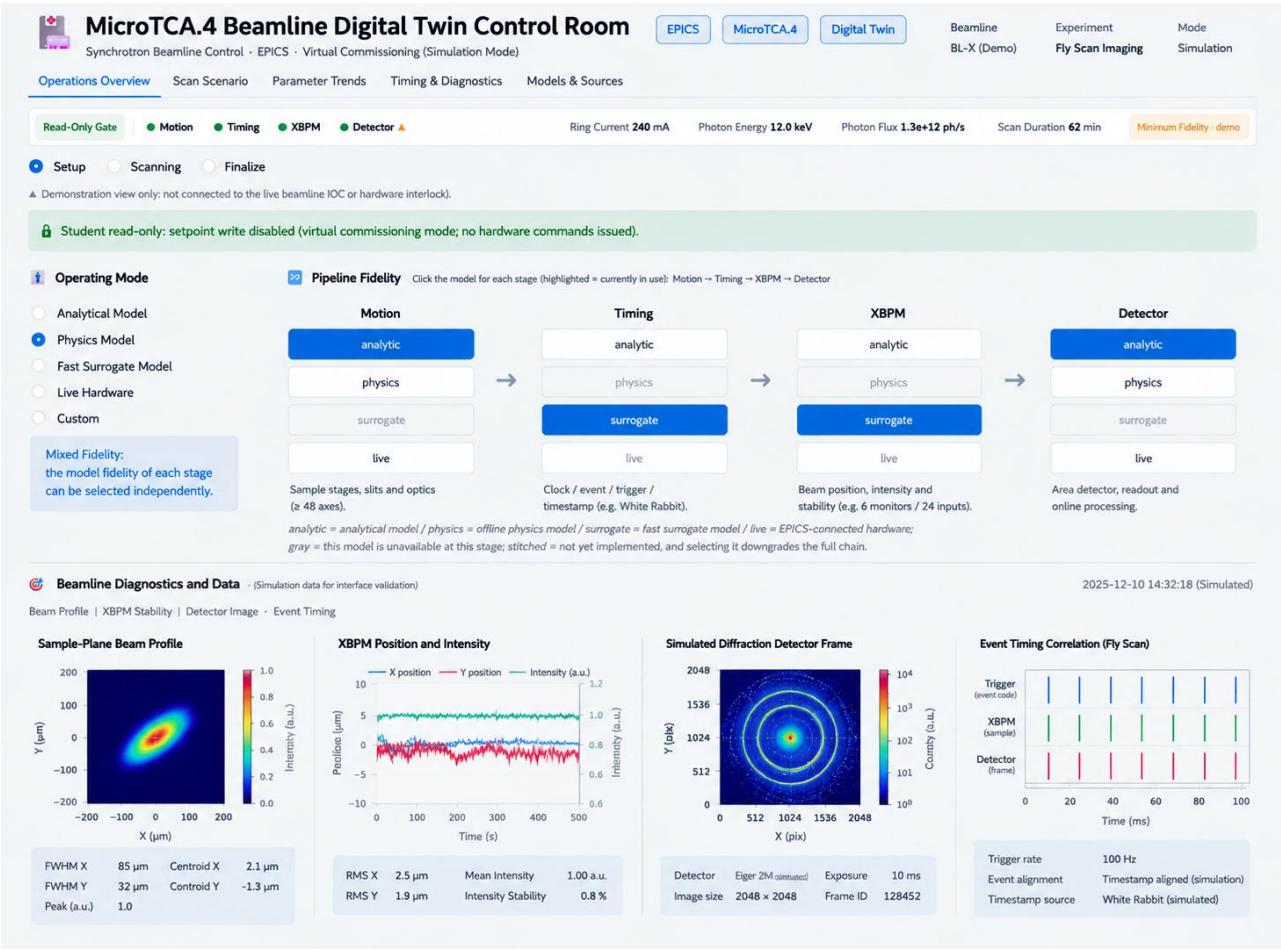
View	Data to display
Prediction	Measured + predicted state Response to candidate settings
Diagnosis	Residual / anomaly flag Input quality and model version
Decision	Candidate ranking Physics / constraint check result

INTEGRATION CONTRACT

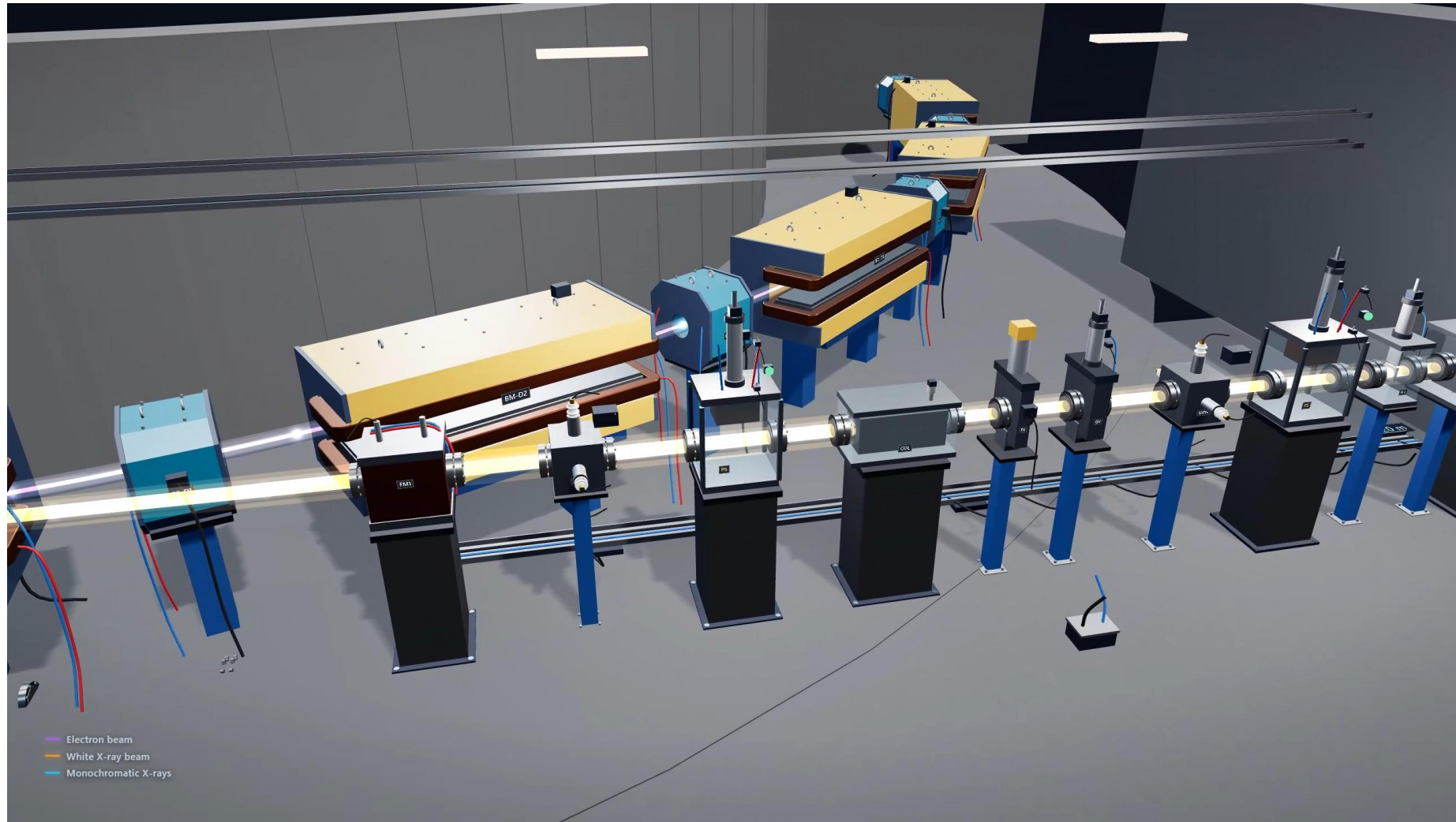
device_id + time + state
model_version + source record
UI selection ↔ matching 3D device

UI + separate 3D → shared state → real EPICS

AI result views are planned additions. The screenshot does not establish their implementation or connection to real devices.



3D beamline model and virtual commissioning



Next: interface and 3D state mapping, physical models, then real device connections.

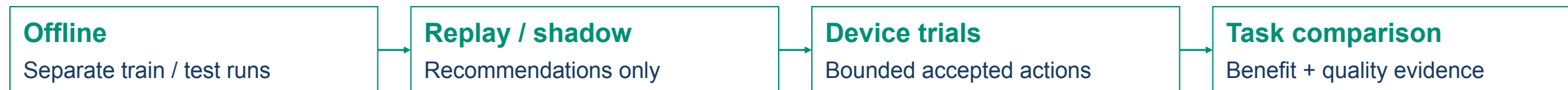
Validation against operating requirements

Operating benefit is tested against the current workflow; model and control tests explain the result

Test object	Test design / baseline	Metric and retained evidence
Operating task	Same task, defined conditions and current workflow	Task time + data quality; interventions and failed attempts
Prediction	Held-out runs; compare with physics baseline	MAE + tail error; valid range and per-run residuals
Diagnosis	Labelled events and periods of normal operation	Missed events, false alarms / hour, detection delay
Candidate ranking	Reference-ranked feasible candidates; physics re-check	Recall@K, feasibility after checks; fallback records
Timing + integrity	Exposure endpoint; count, queue and recovery tests	Delay / jitter, data age, missing records and recovery log

Planned timing test: source → receiver / field I/O → exposure indication → timestamp / scope record

STAGED VALIDATION



Initial targets: ≤5 min for one selected alignment task; <10 ms for selected process acquisition-to-model input. Neither is a measured result.

Implementation and expected operating value

Hardware integration and model development converge on a tested operating task

Workstream	Months 1–2	Months 3–4	Months 5–6	Months 7–9	Months 10–12
Control foundation	Interfaces / IDs Platform setup	Four subsystem I/O Local execution	Integrated bench Data + fault tests	Device access Trial workflows	Performance tests Handover
Intelligent services	Tasks / targets Reference data	Training data Method adaptation	Tested services Replay + twin	Calibration Shadow / trials	Validated services Benefit evidence
Integration evidence	Interface / signal list Task baseline	Module / driver fit Train / test split	Bench + model results Shared state mapping	Trial and recovery logs Observed outcomes	Task comparison Release / handover

M6 INTEGRATION GATE

Control records, model inputs and twin replay
use the same device / run identity.

Proposed 12 months assumes available modules and beamline access. First-release applications follow available data and successful tests.

EXPECTED OPERATING VALUE

Reliable measurements → informed decisions
→ verified execution and useful beamtime