Operational Integration of Machine Learning for Beam Size Control in the Advanced Light Source

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ALS Accelerator Physics Group

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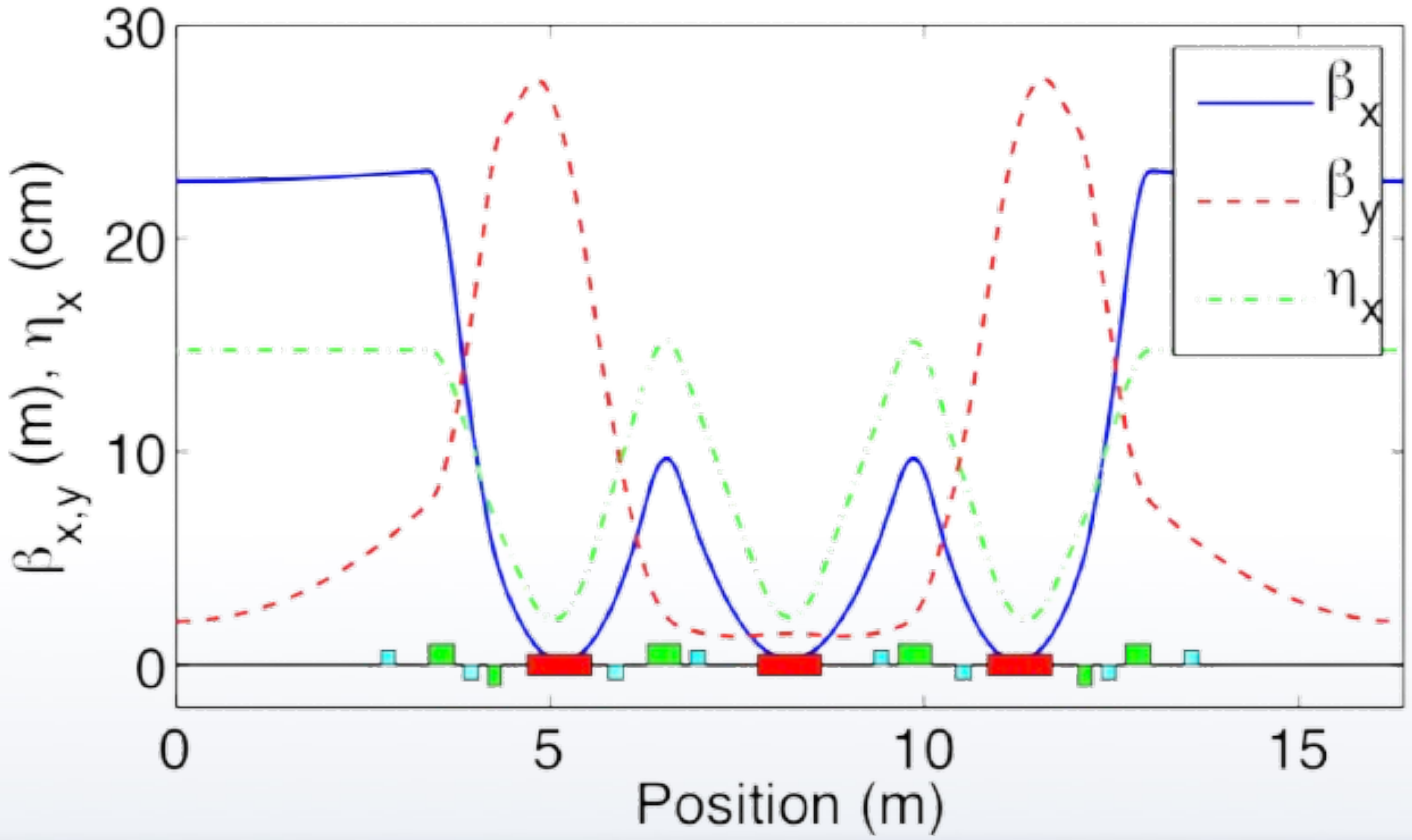
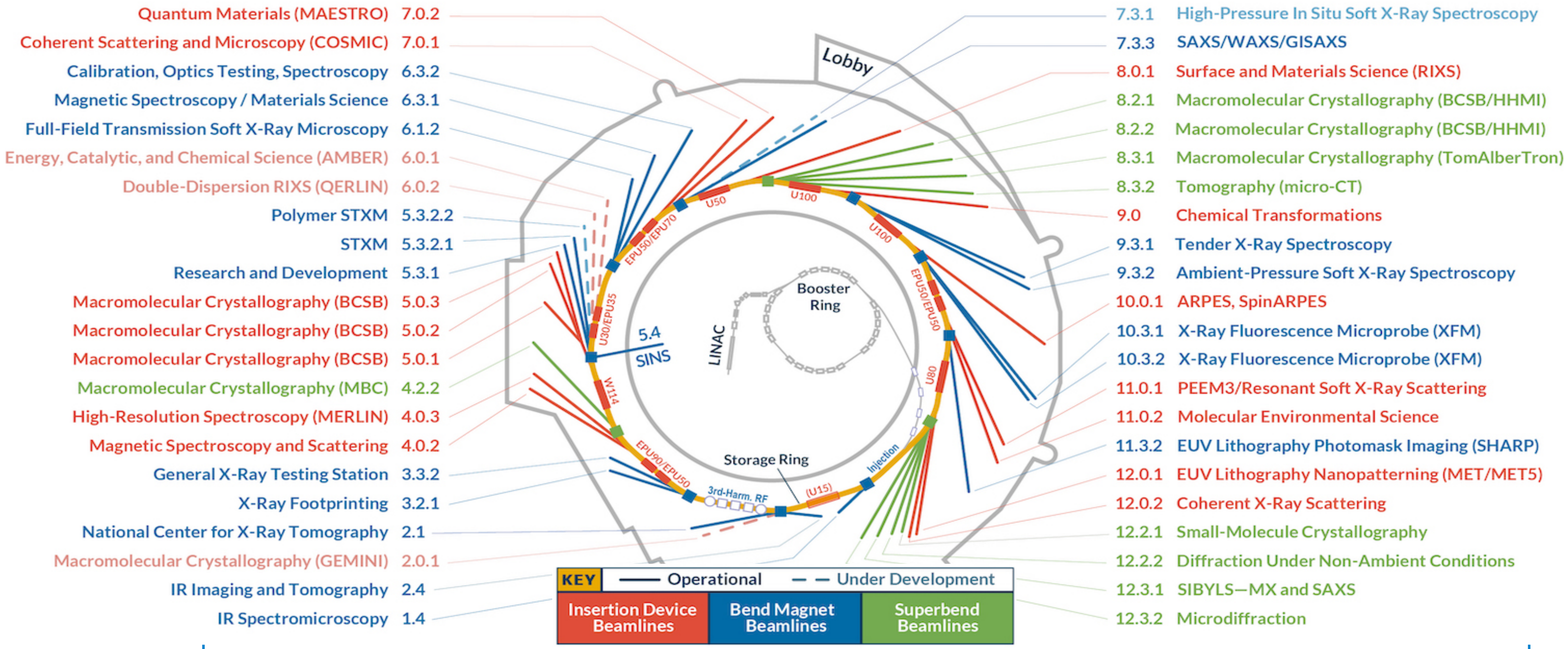
PARAMETER	VALUE
Beam energy	1,9 GeV
Circumference	196.8 m
Beam current	500 mA
Horizontal emittance	2 nm·rad
Vertical emittance	0.04 nm·rad

ALS Triple-Bend Achromat Lattice



Insertion Devices at the Advanced Light Source

14 vertical gaps (1 always fixed) + 7 EPUs with 2x horizontal offsets = 27 free parameters



Electron Beam Stability at the Advanced Light Source

- Beam Current:
  - Top-off operation keeps current variations below 1mA
- Beam Position:
  - Orbit feedback and ID feed-forwards stabilize source positions to sub-micron level
- Beam Size:
  - ID skew quadrupole feed-forwards stabilize source size
  - Requires lookup tables

Scanning Transmission X-ray Microscopy at the Advanced Light Source

- STXM Beamlines:
  - Widely used for nanoscale studies
  - Fast raster scanning
  - No averaging
  - ≈ 1 ms/pixel, 1 s/line, 6 min/scan

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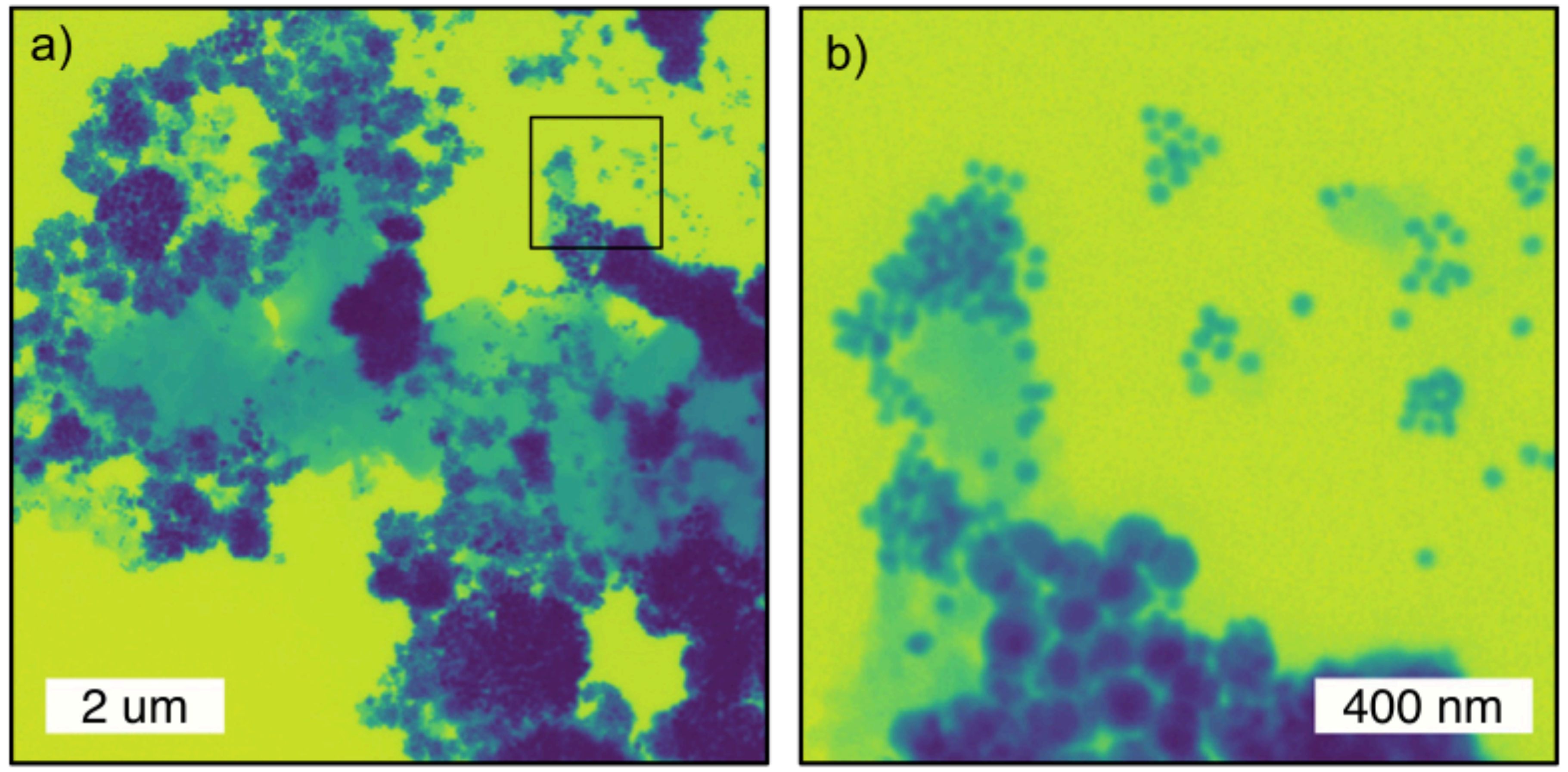
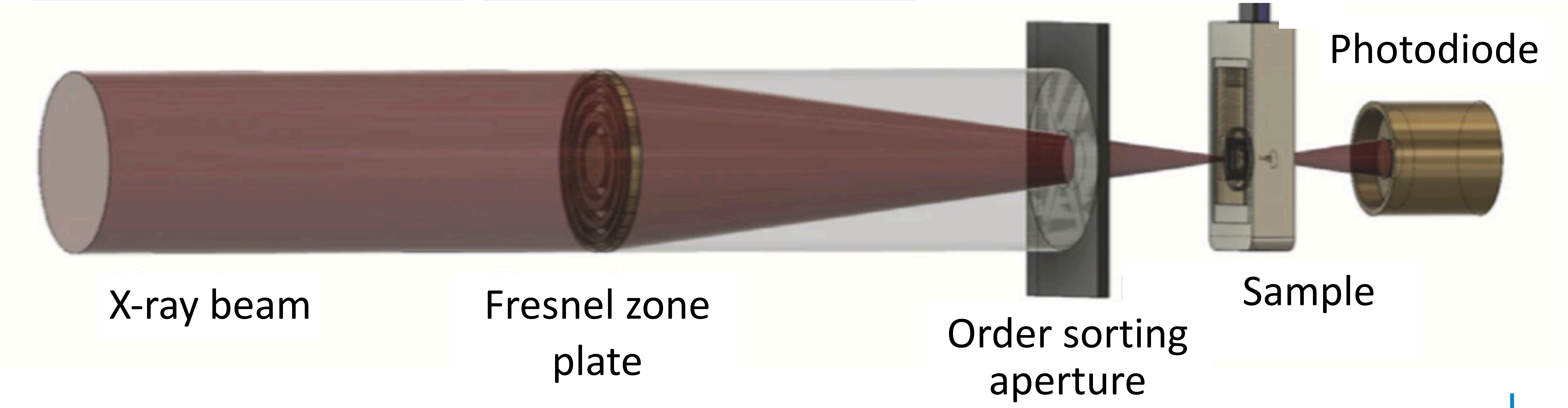
Scanning transmission X-ray microscopy at the Advanced Light Source

Thomas Feggeler [a,b,*], Abraham Levitan [c,b], Matthew A. Marcus [b], Hendrik Ohldag [b,d,e], David A. Shapiro [b]



“Section of a ptychography reconstruction of 40nm and 100nm gold nanoparticles on a silicon nitride membrane“



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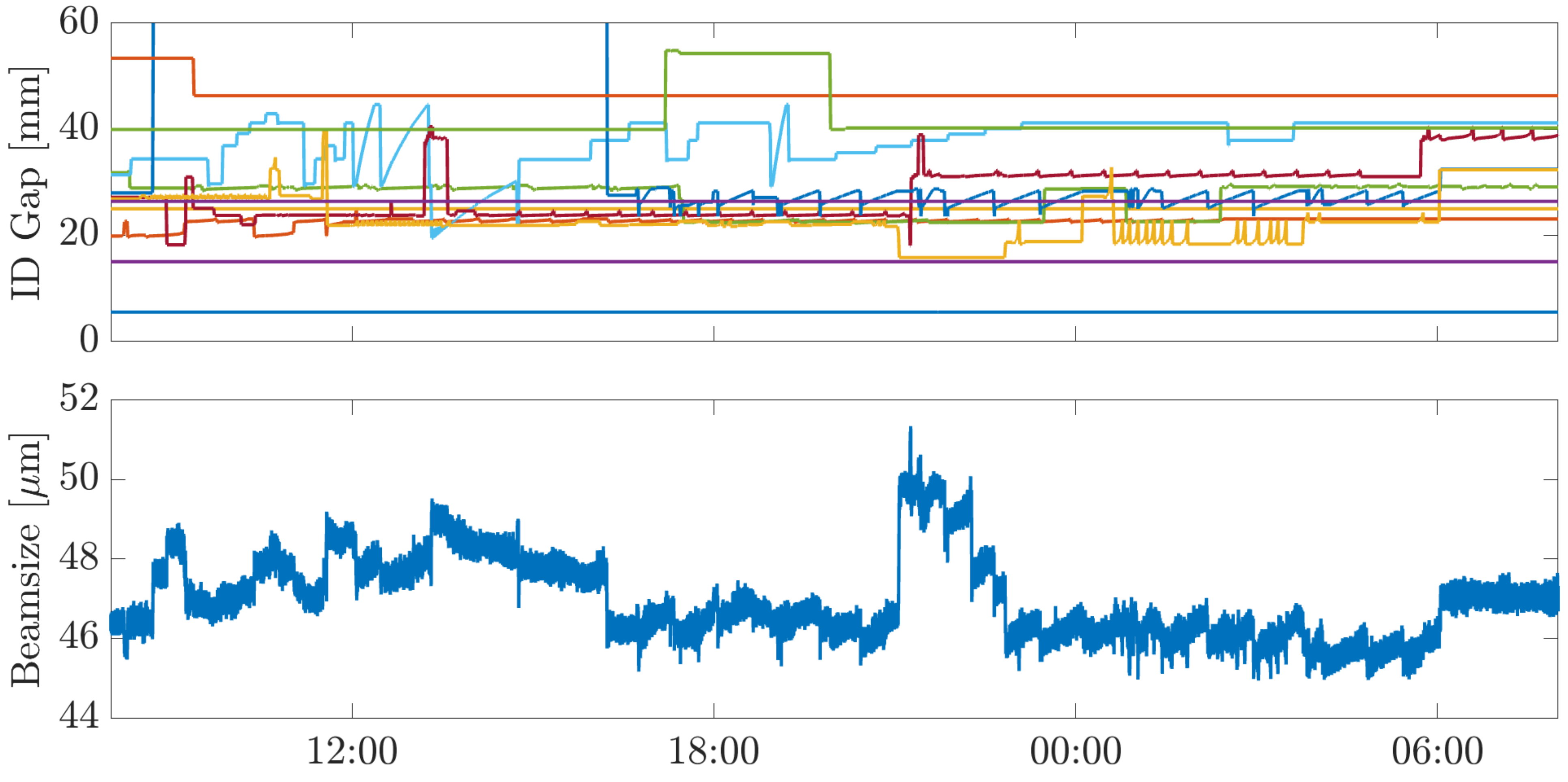
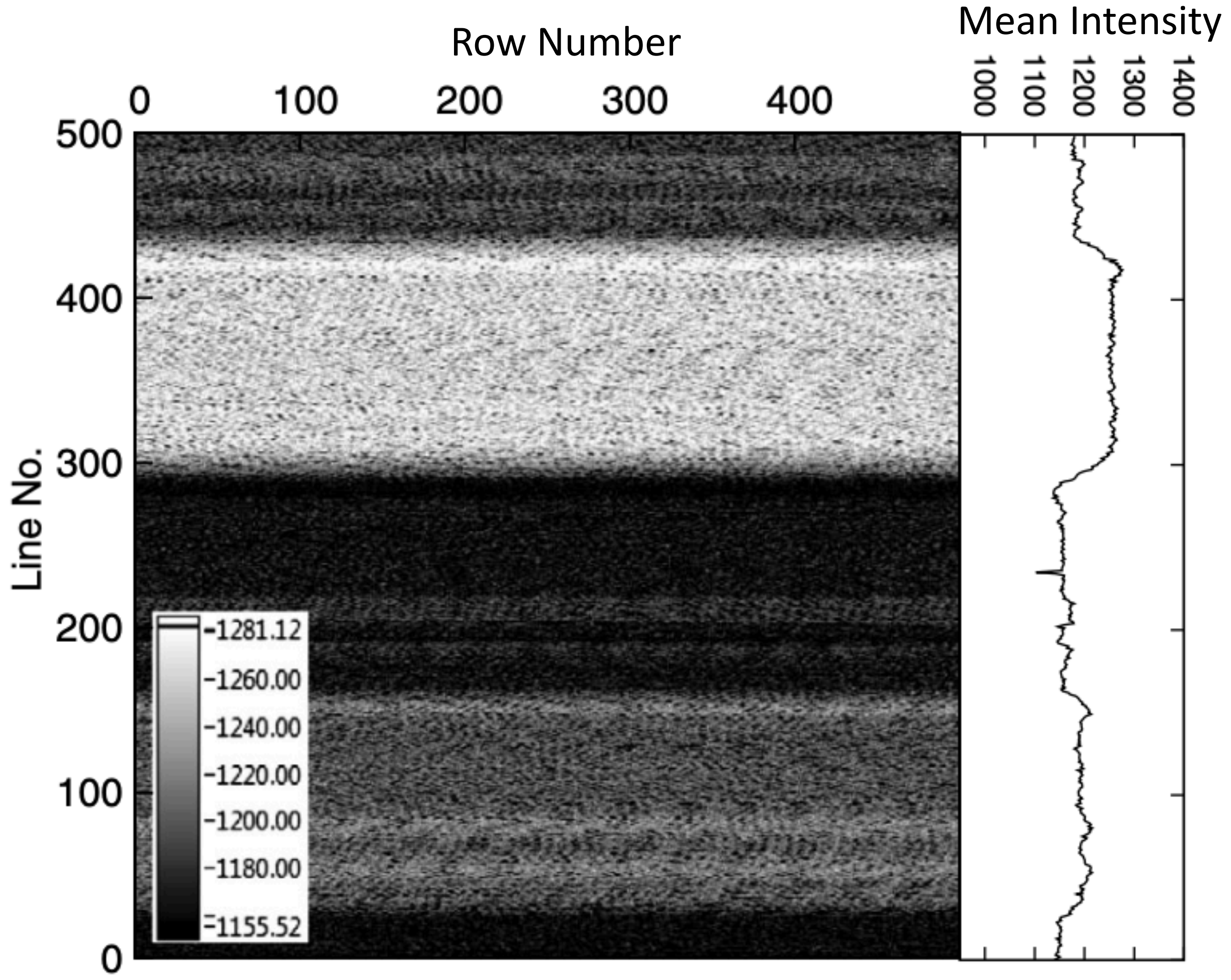
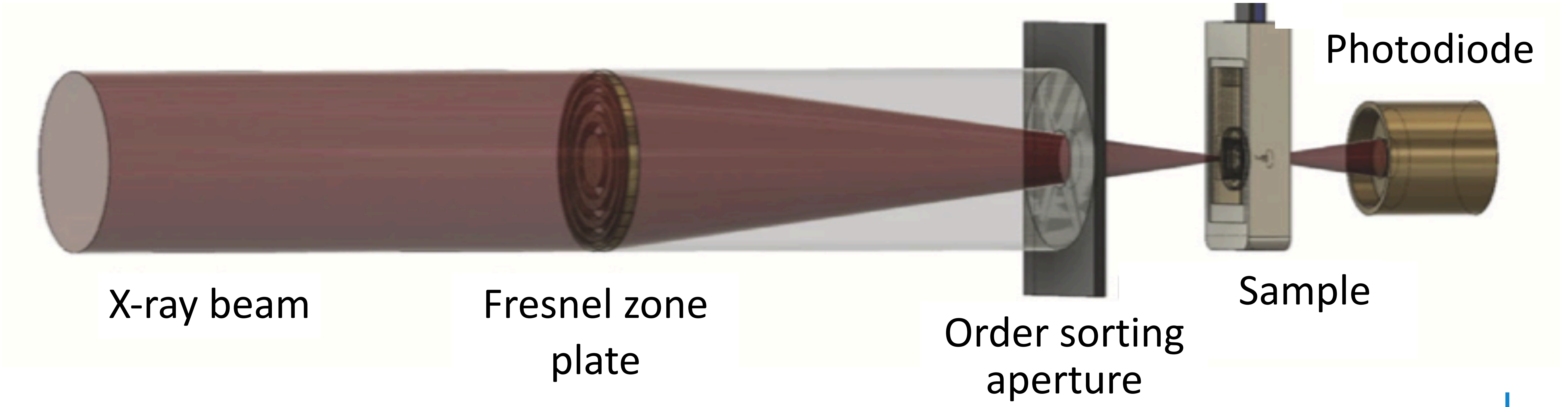
- Current ID Feed Forward:
  - LOCO at various gaps to obtain (local) skew quadrupole corrector settings
  - Interpolation table used in FF correction
  - Takes one night to measure
  - Aging of tables results in large variation of vertical beam size







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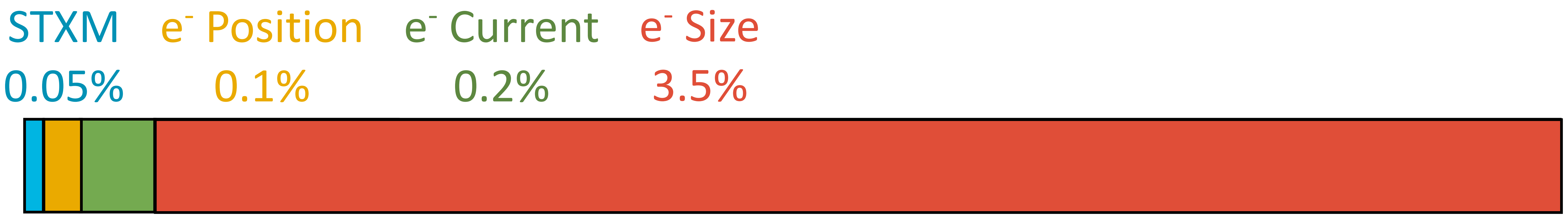
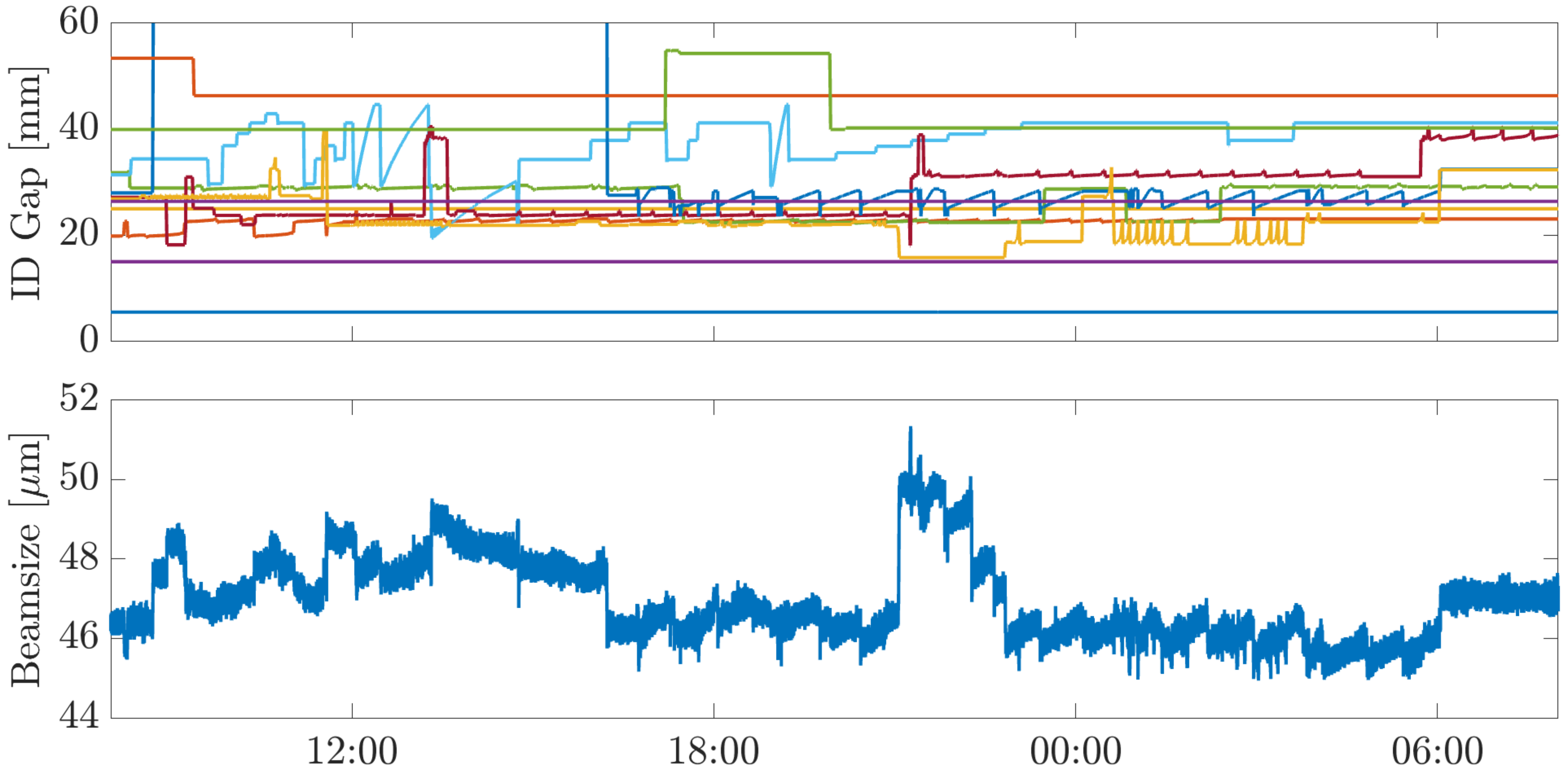
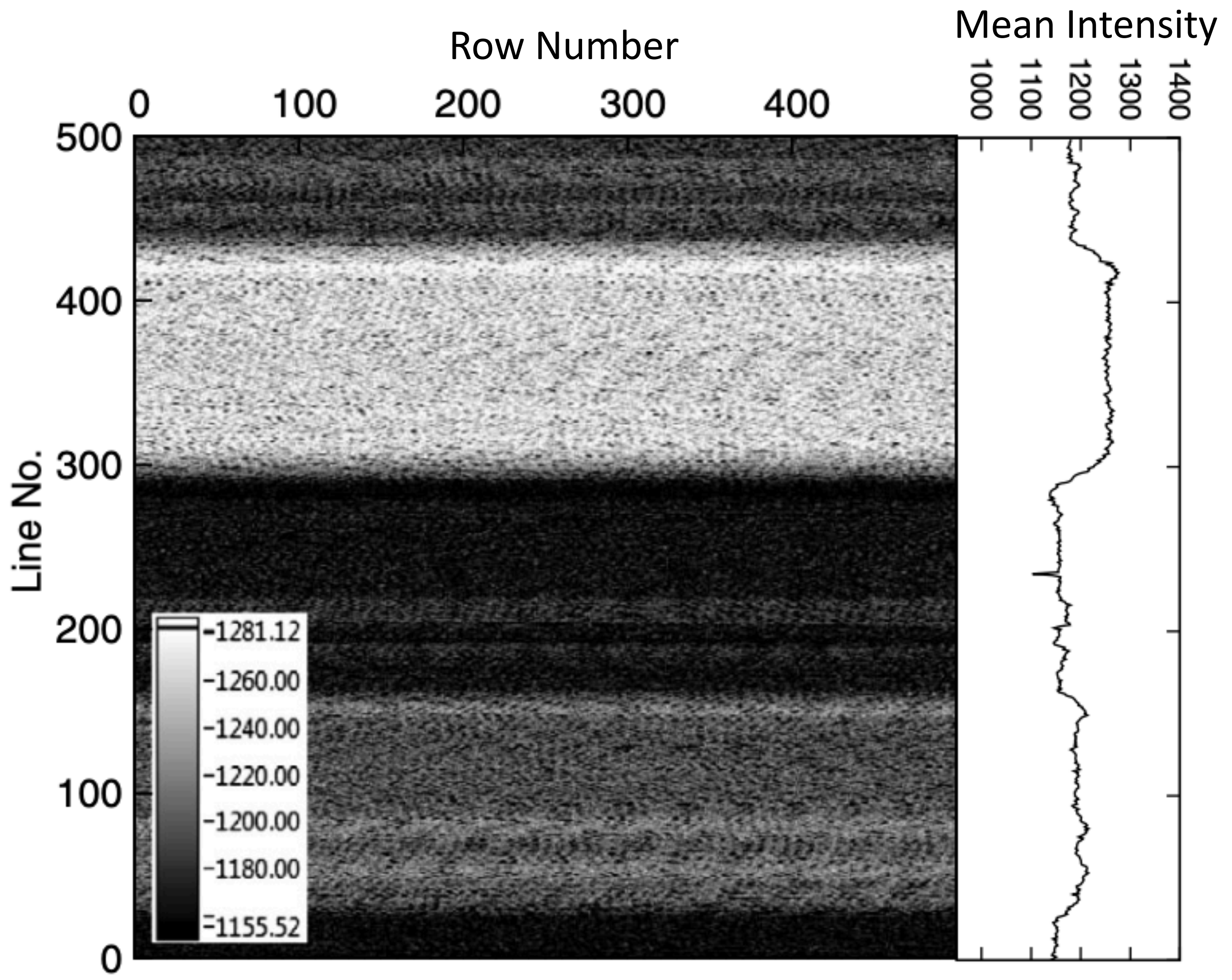
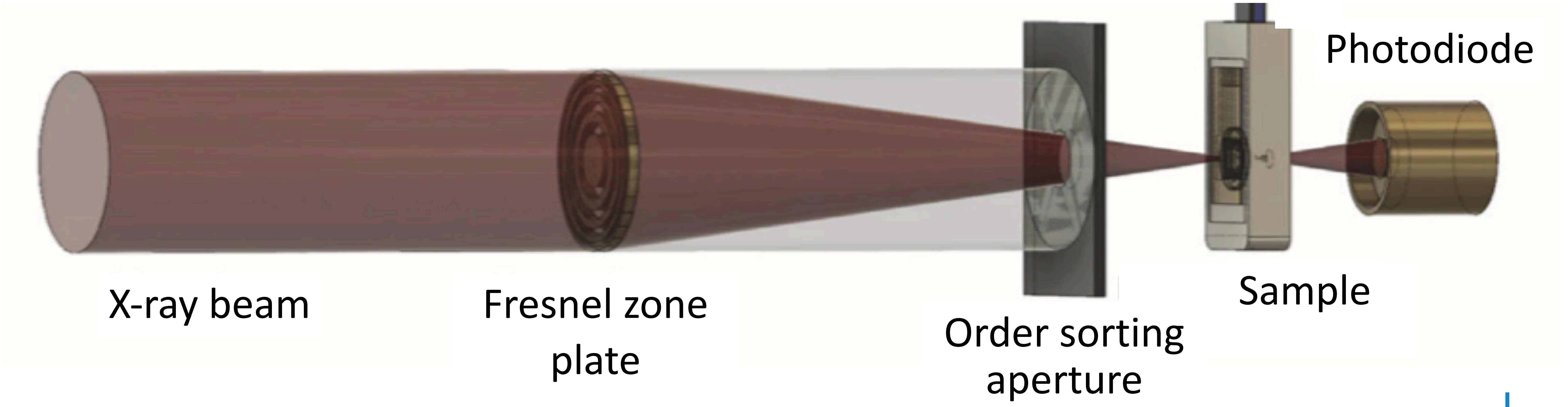
- STXM Intensity Fluctuations:
  - Residual ID induced vertical beamsize variations biggest contributor
  - POC: Leemann et al., PRL 123,194801









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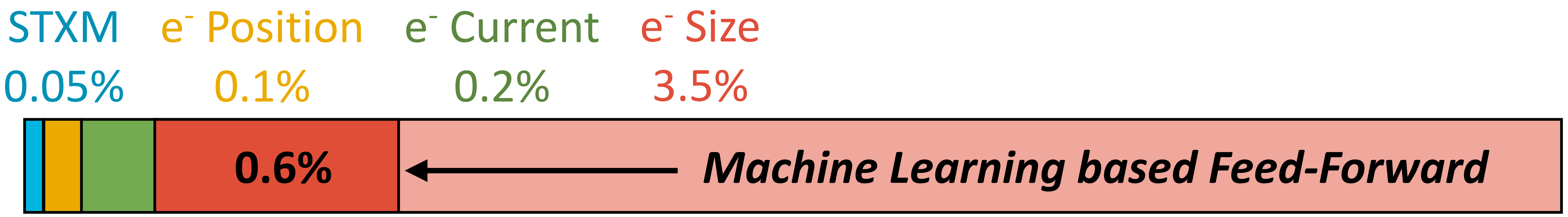
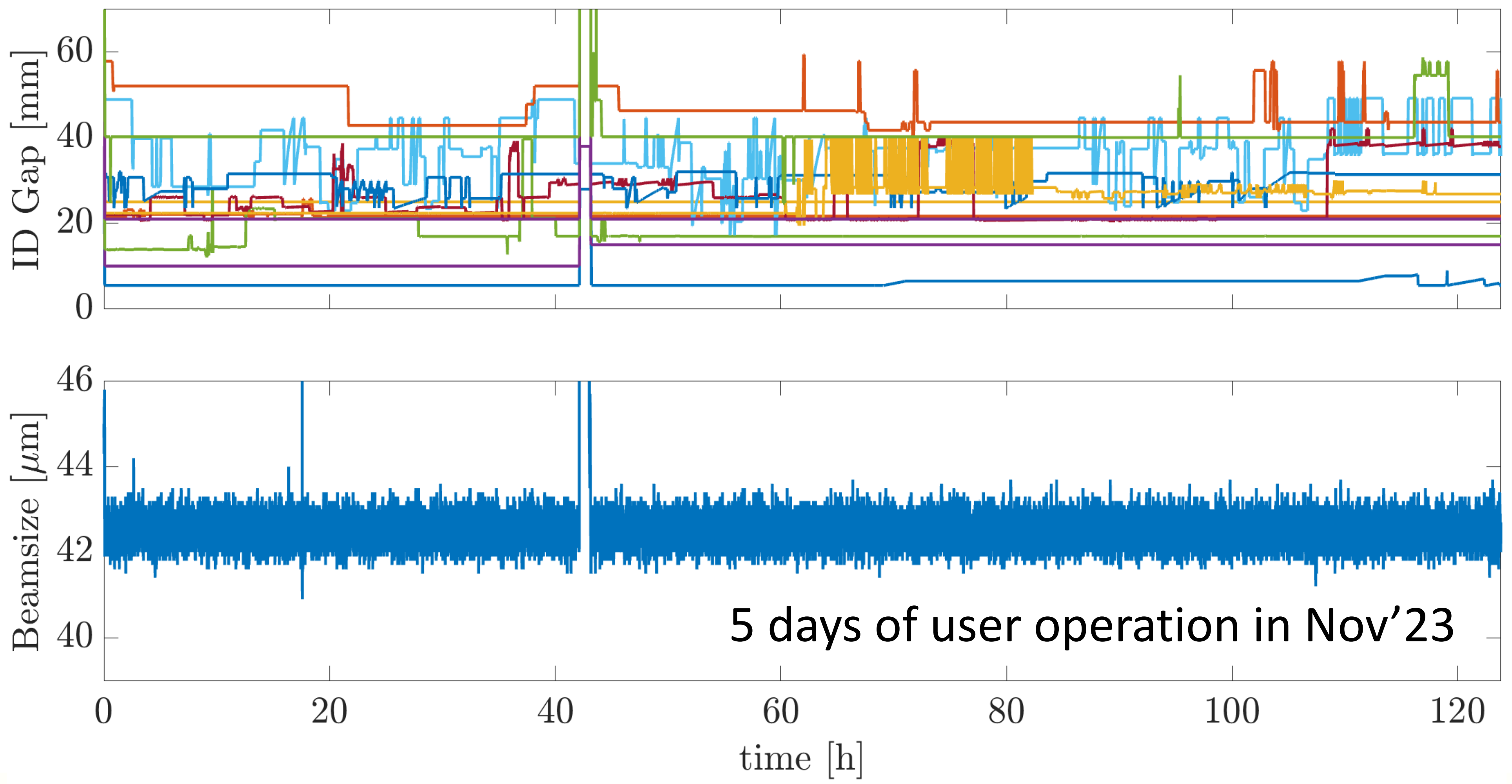
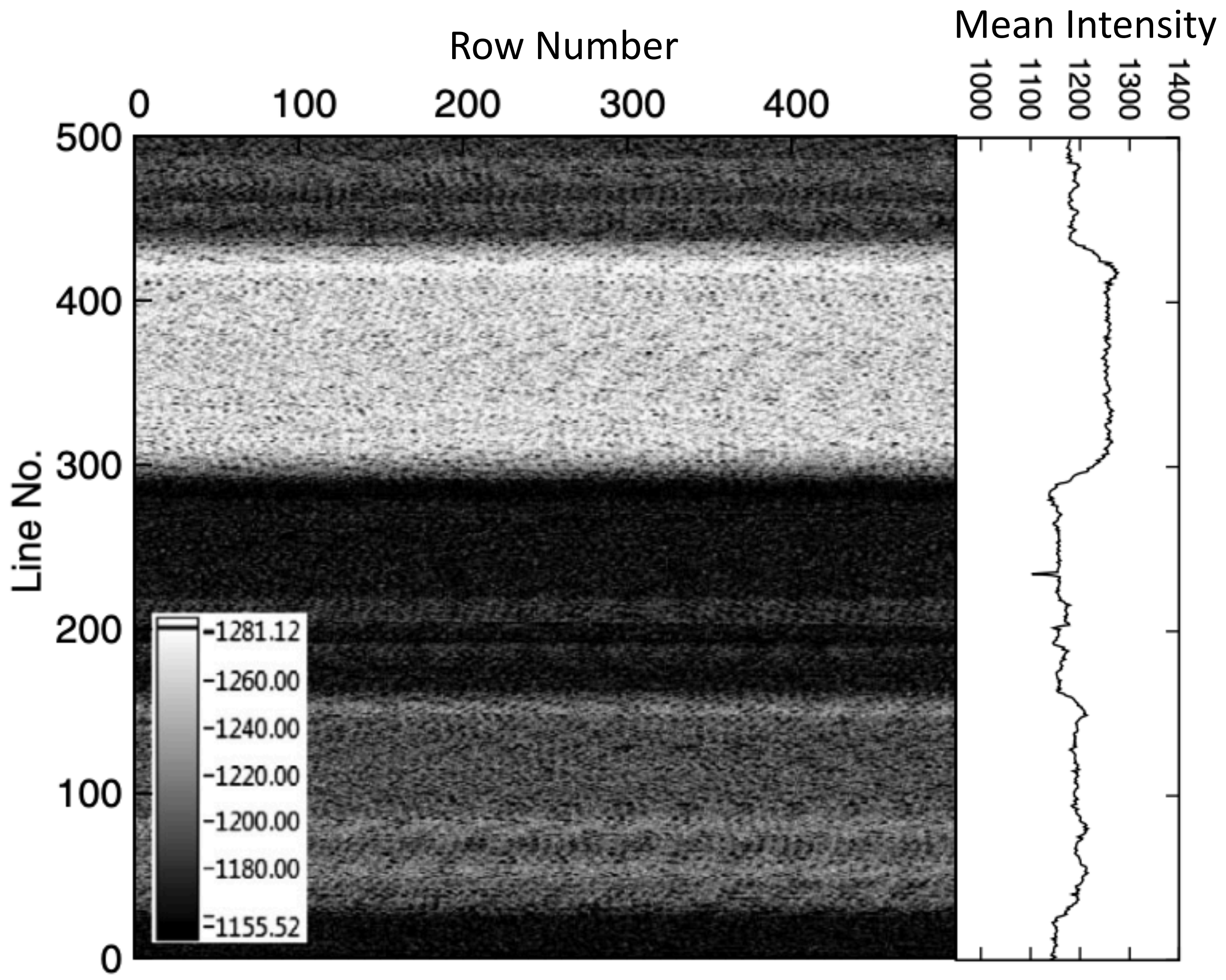
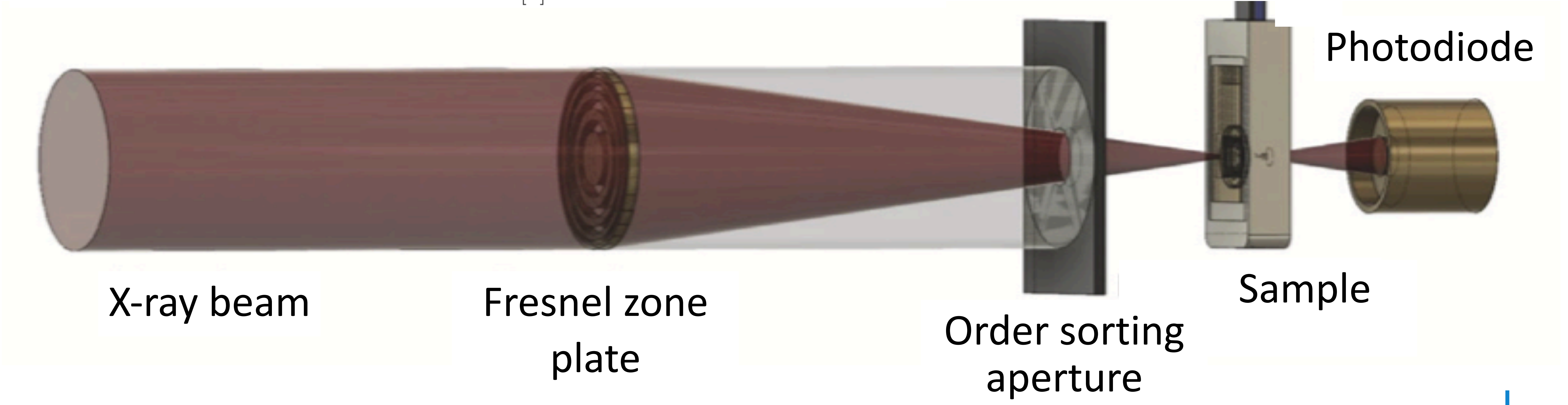




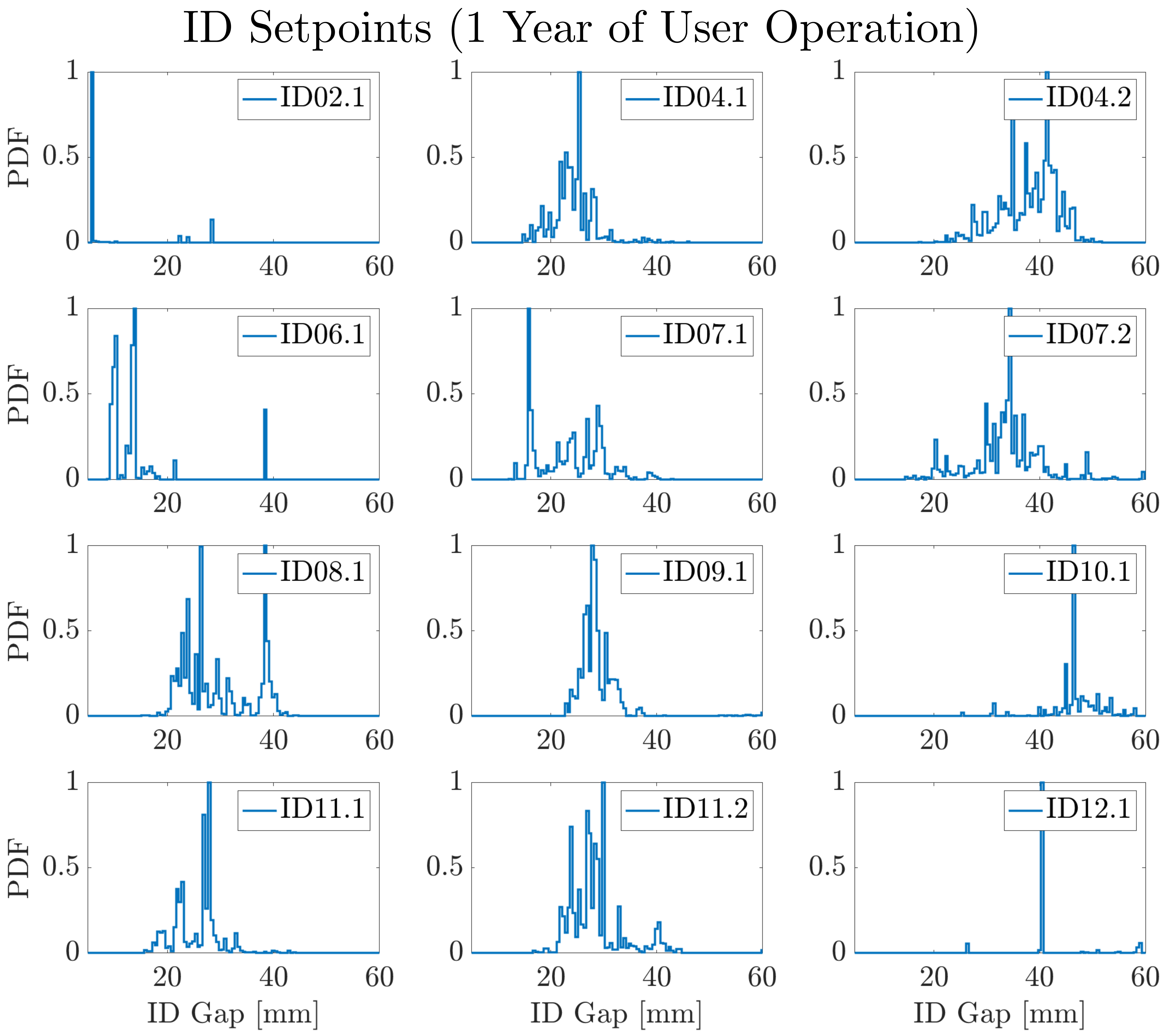




Model Development

Acquiring Training Data

- Data Sampling:
  - Derived from two years of user operation data
  - Ensures representative operational conditions



Acquiring Training Data

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- Data Acquisition and Recording:
  - Gathered during accelerator physics shifts
  - Independent exercise of each insertion device
  - All ID read-backs and beam size recorded at 10Hz
  - EPICS based archiver system
  - 12-hour, 27 ID parameters (466k x 27 samples)
- Operational Challenges:
  - High value of AP time leads to nighttime shifts
  - ID setup not optimized for fast ramping (ID amplifier trips, local ID FF trips)
  - Implementation of watchdog with for operational oversight very important

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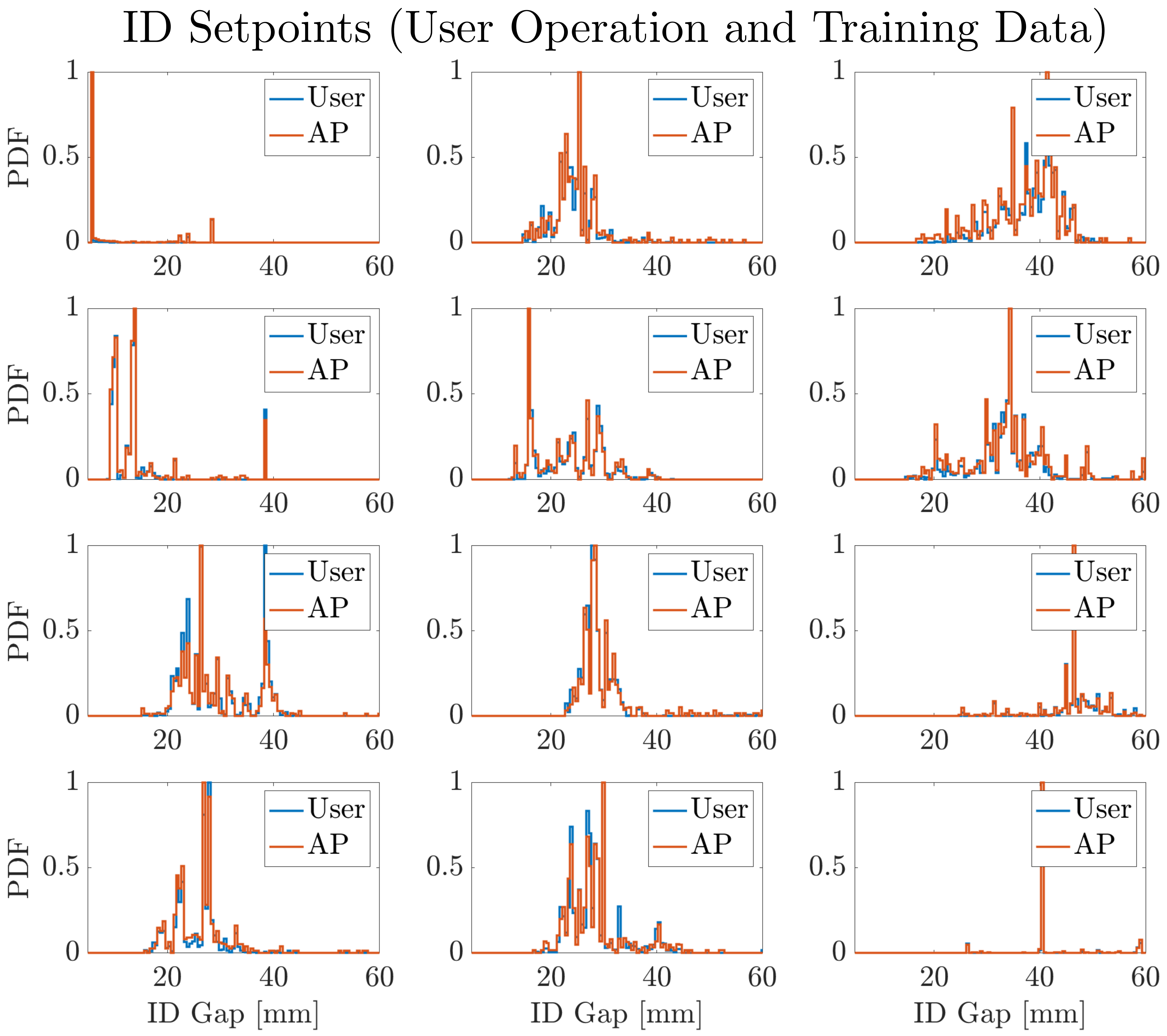
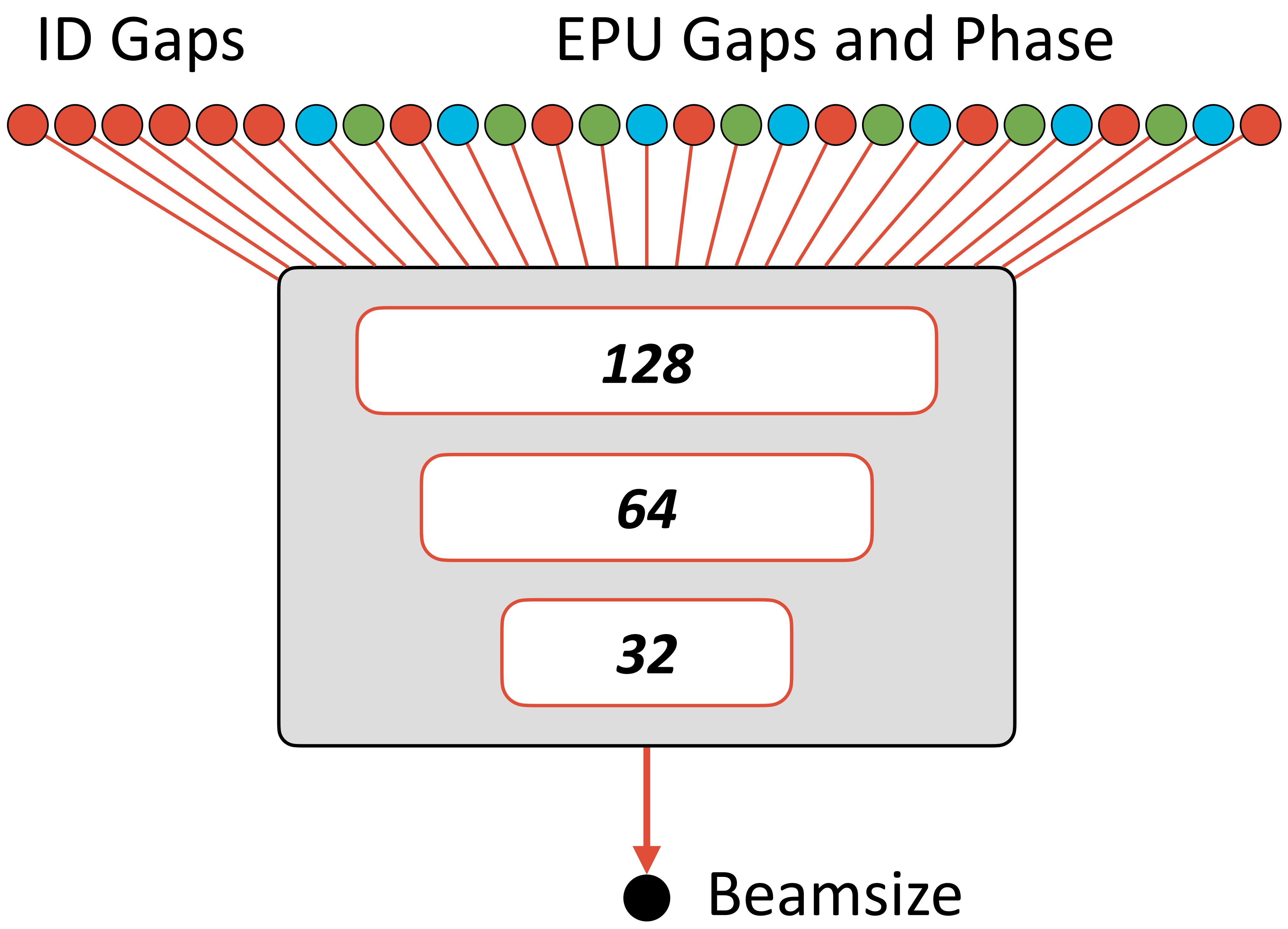


Neural Network Architecture

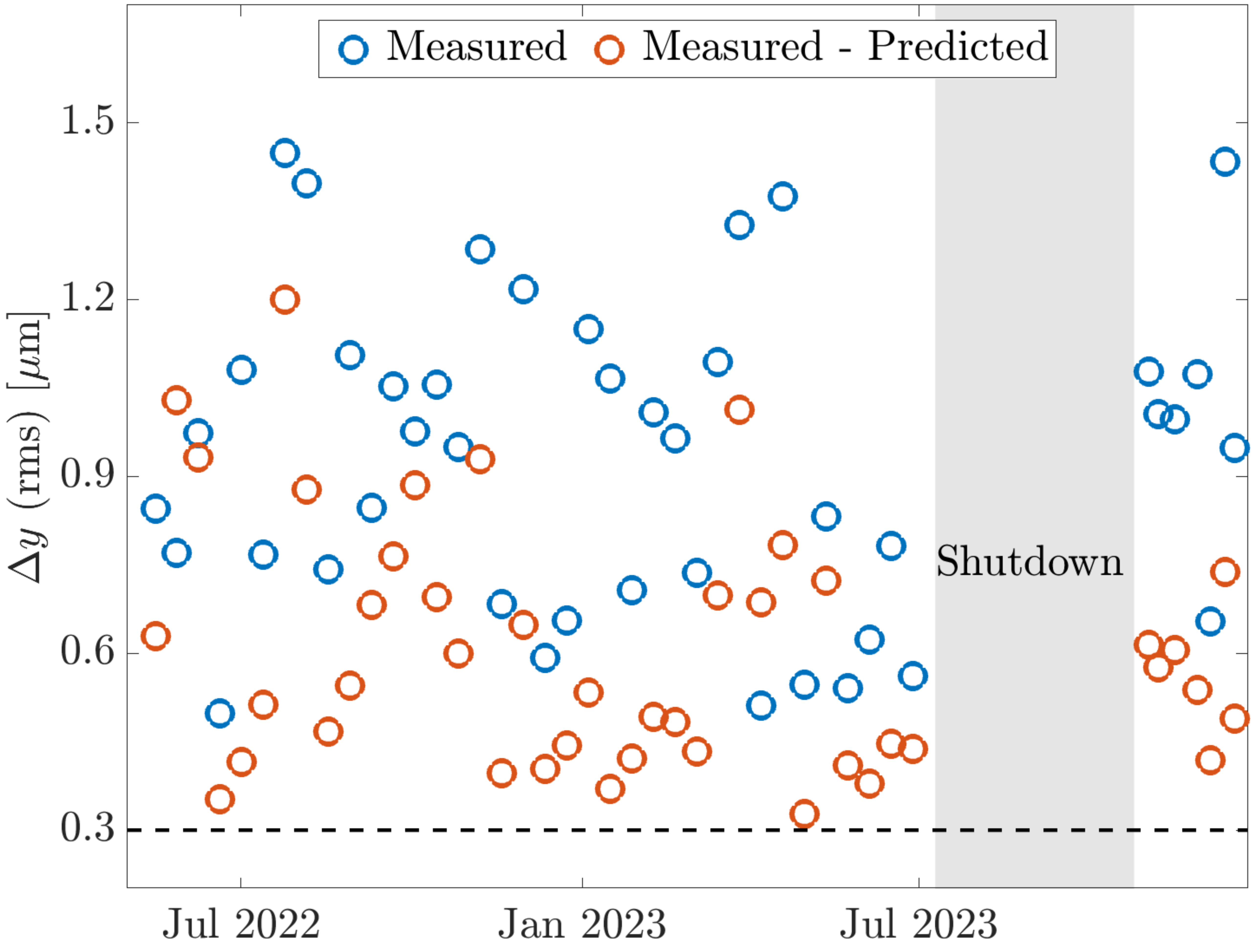
- Model Input/Output:
  - 27 ID input parameters
  - 1 beam size prediction output
  - Dispersion wave used to correct beamsize
- Studied Neural Network Types:
  - RNN, CNN, ***MLP***
- MLP Hyperparameter Search:
  - Number of hidden layers: 3
  - Neurons per Layer: 128/64/32
  - Activation Function: Tanh
- Final Hyperparameter Search:
  - Weight decay: 1E-3
  - Dropout rate: 0.2
- Takes about 15min on RTX2060 GPU



Hyperparameter	Search Space
Number of Hidden Layers	$\{1, 2, 3\}$
Number of Neurons per Layer	$\{2^n\}, 1 \leq n \leq 9$
Activation Function	{ReLU, Tanh, Sigmoid}
Weight decay	$\{10^{-n}\}, 1 \leq n \leq 5$
Dropout rate	$\{0.2, 0.4, 0.6, 0.8\}$

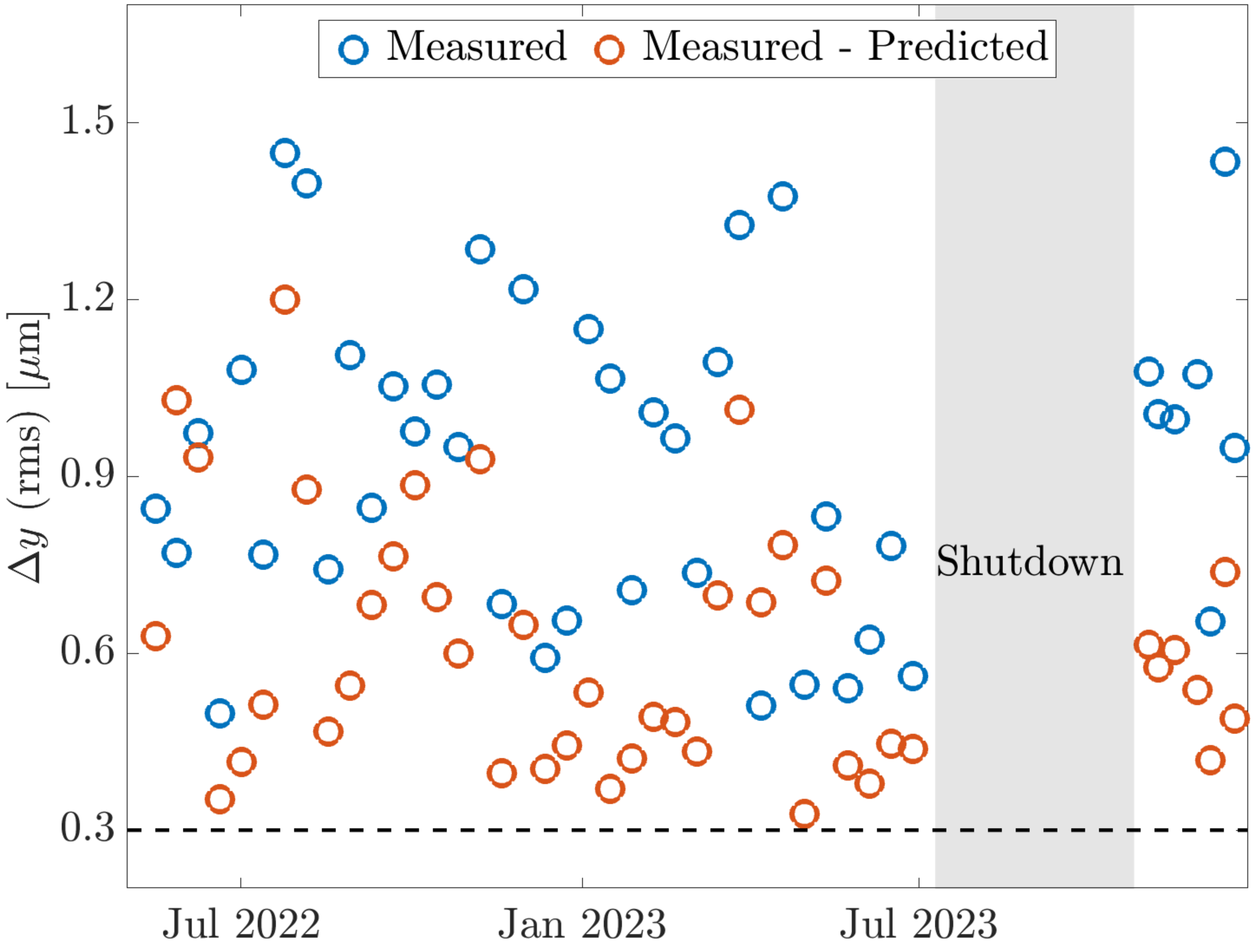
Evaluation on Historical User Operation Data

- Archive of Operational Data
  - 18 months of user ops data available
  - Subject to asynchronous downsampling before shutdown
  - Training on old data not possible
- Observations:
  - Prediction accuracy varies significantly between weeks
  - No significant long term drift apparent
  - Average performance of 0.6µm (noise floor: 0.3µm)



Impact of Training Data Size on Model Performance

- How much training time is required for *perfect* model?



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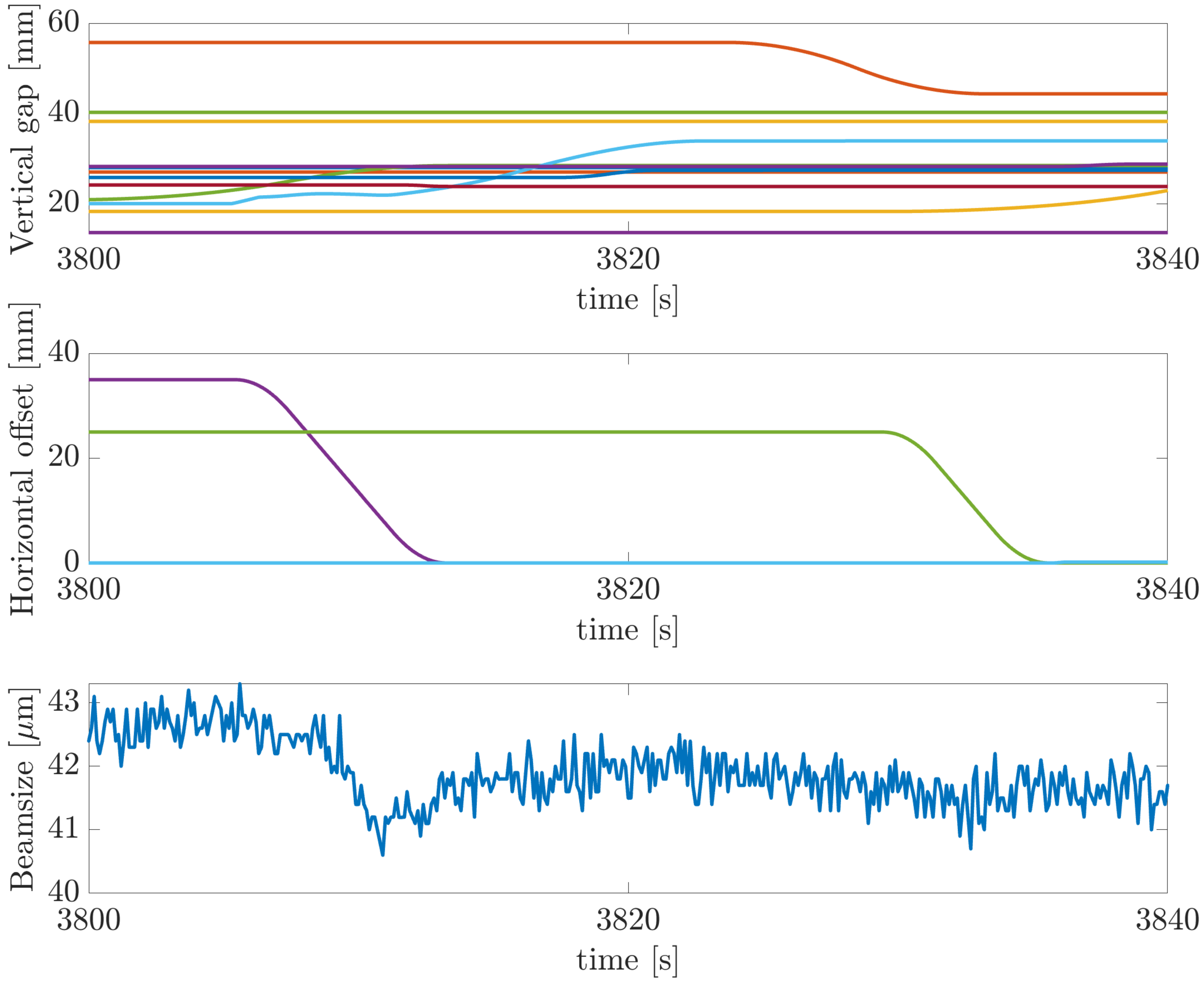

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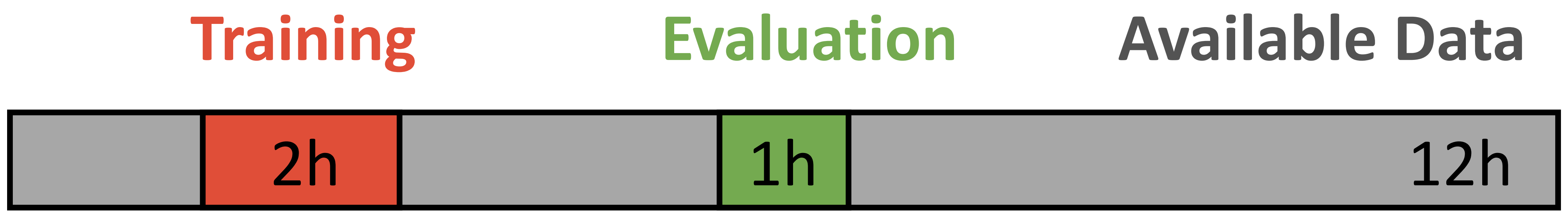
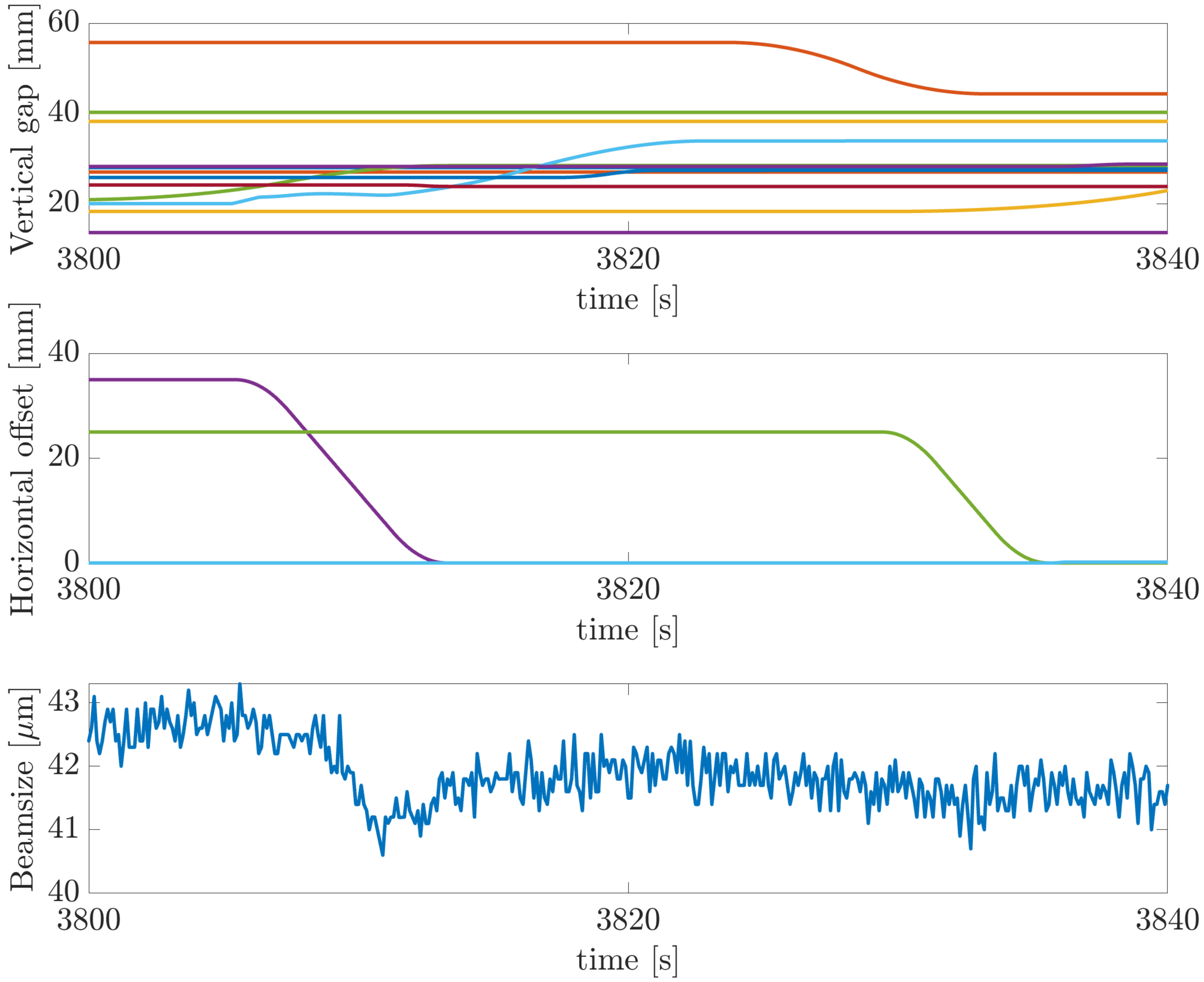
  - 10 seed for each configuration
  - Evaluate RMSE on evaluation data





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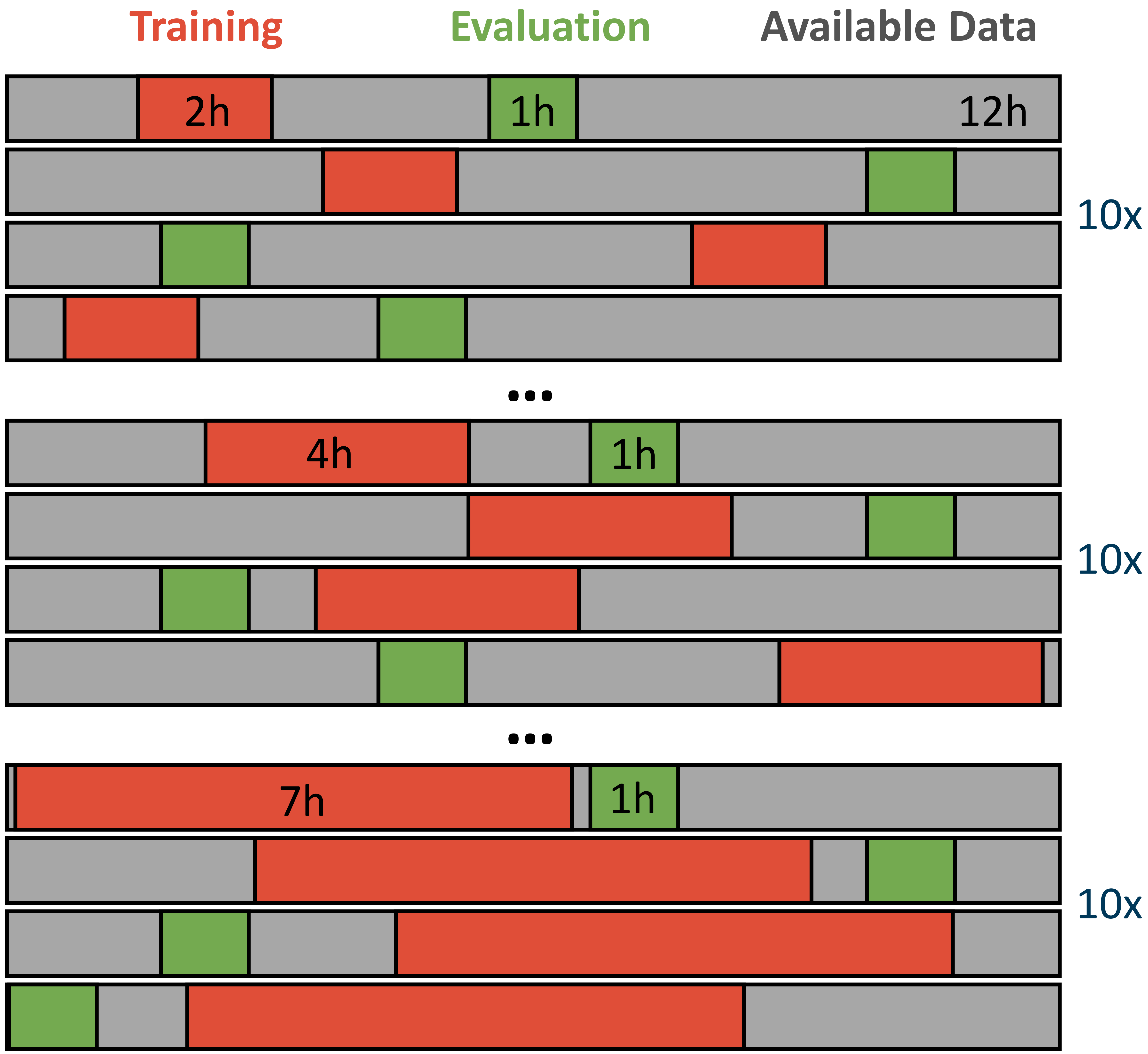

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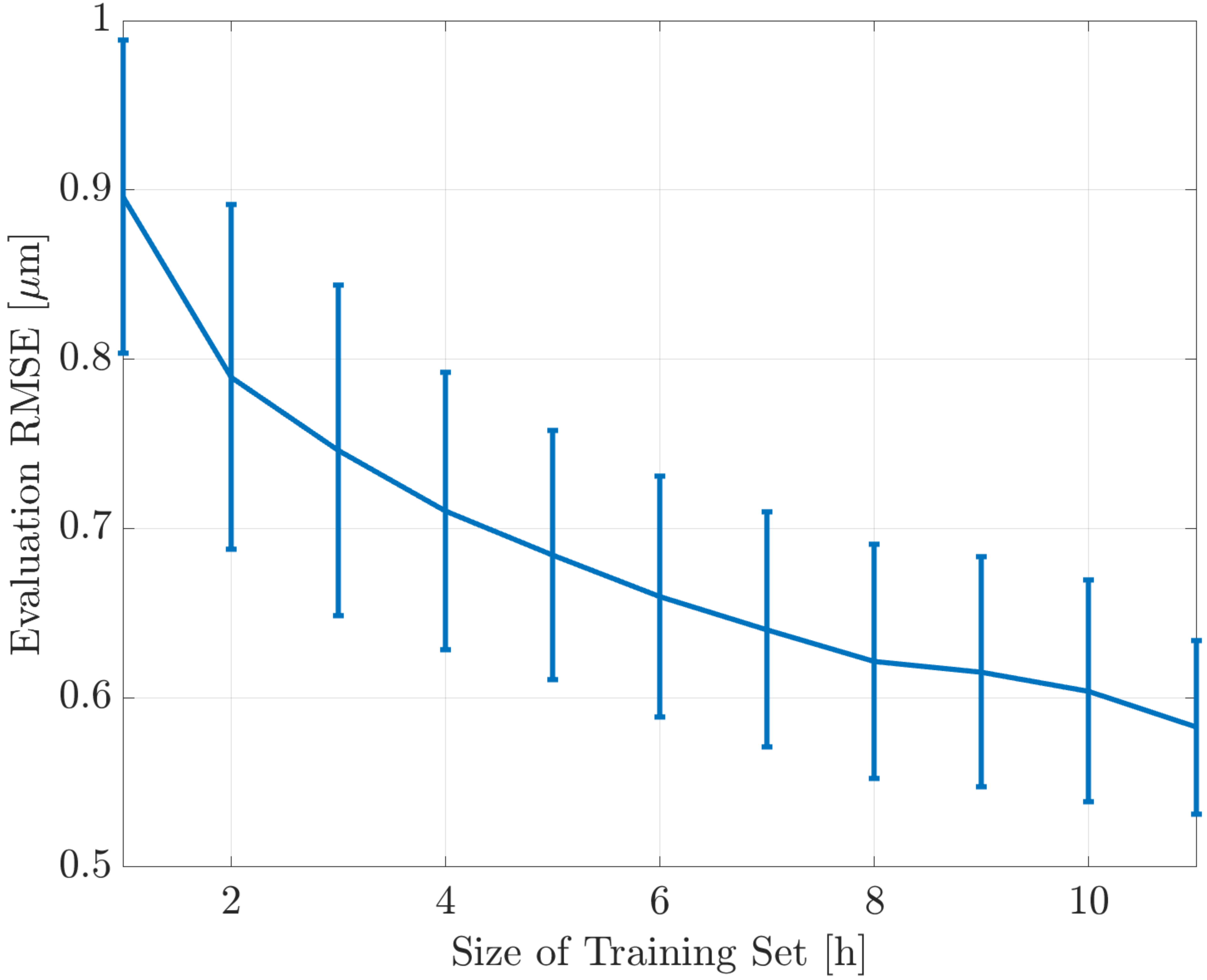

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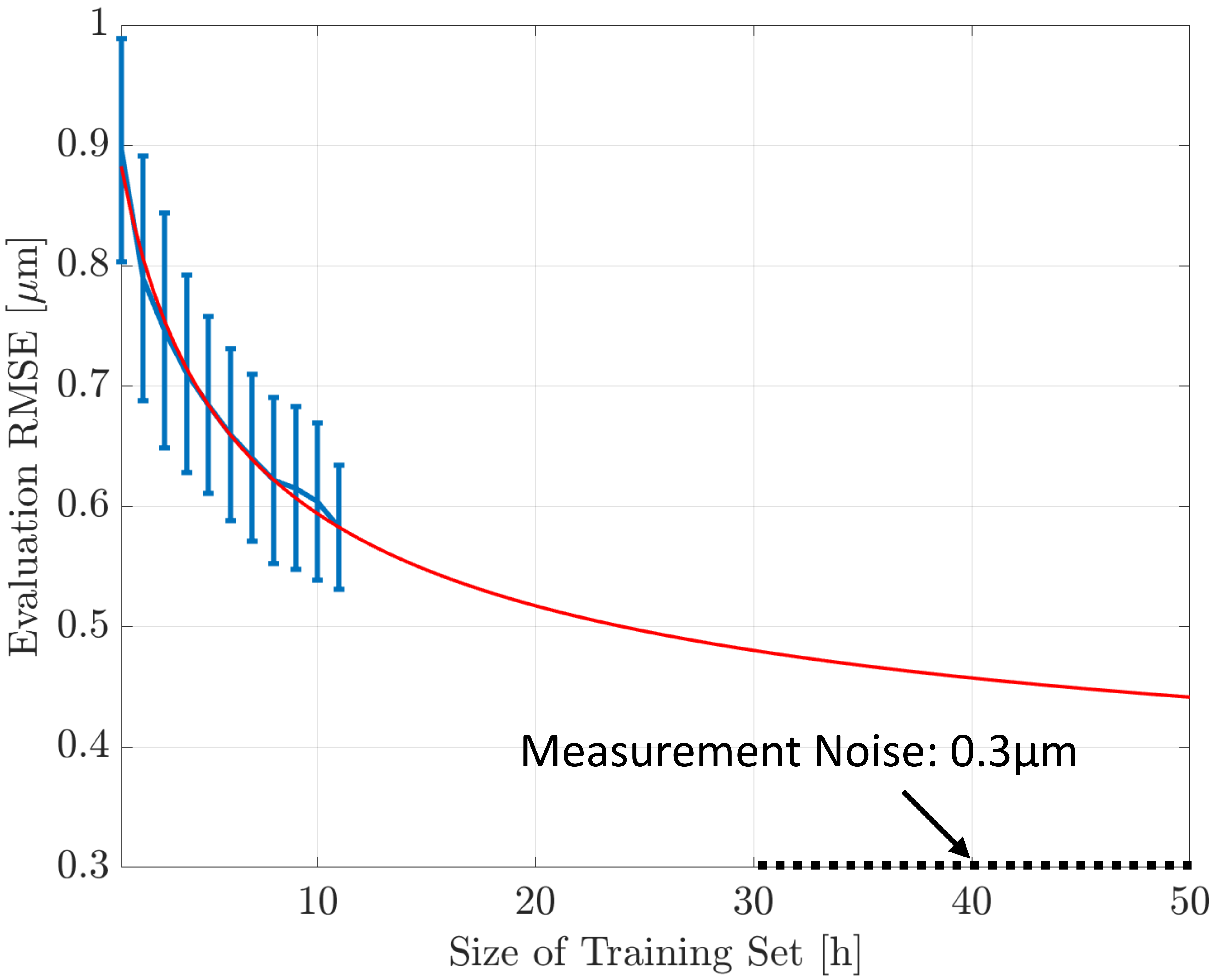
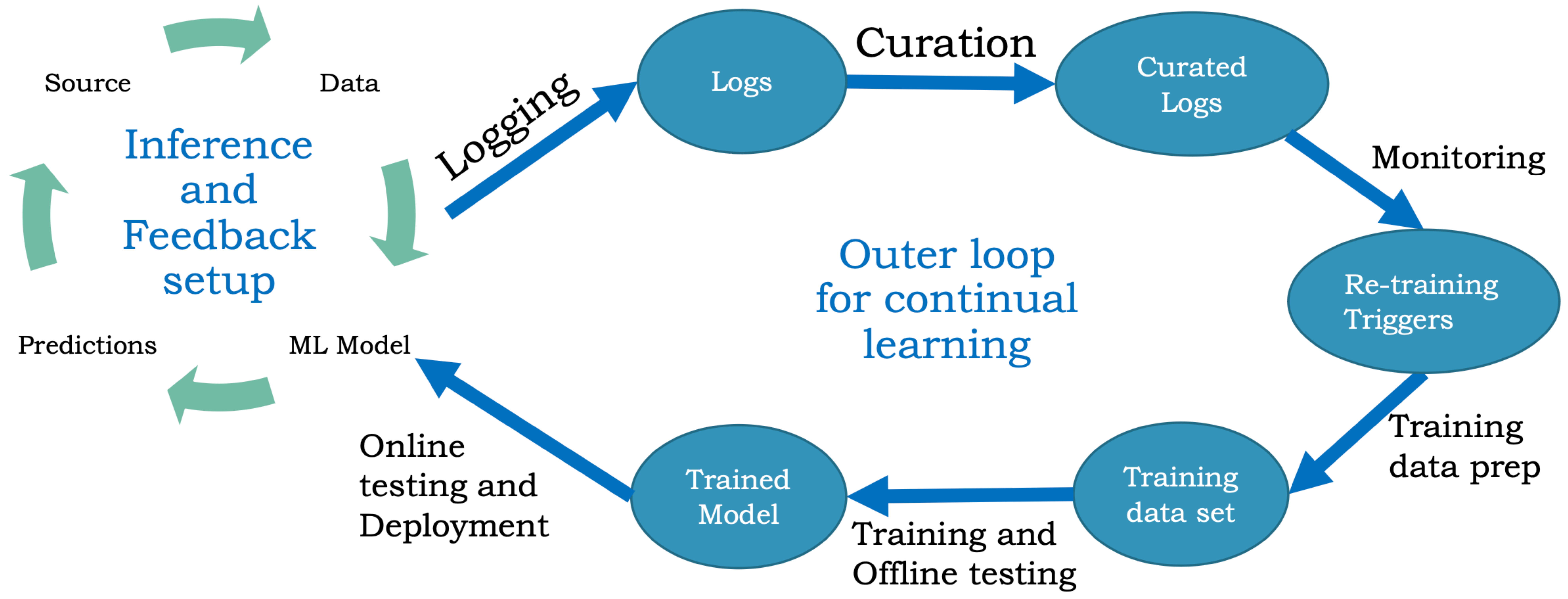


Continual Online Fine-Tuning



K. Rajput, "Model up-keep with continual learning", MaLAPA'24

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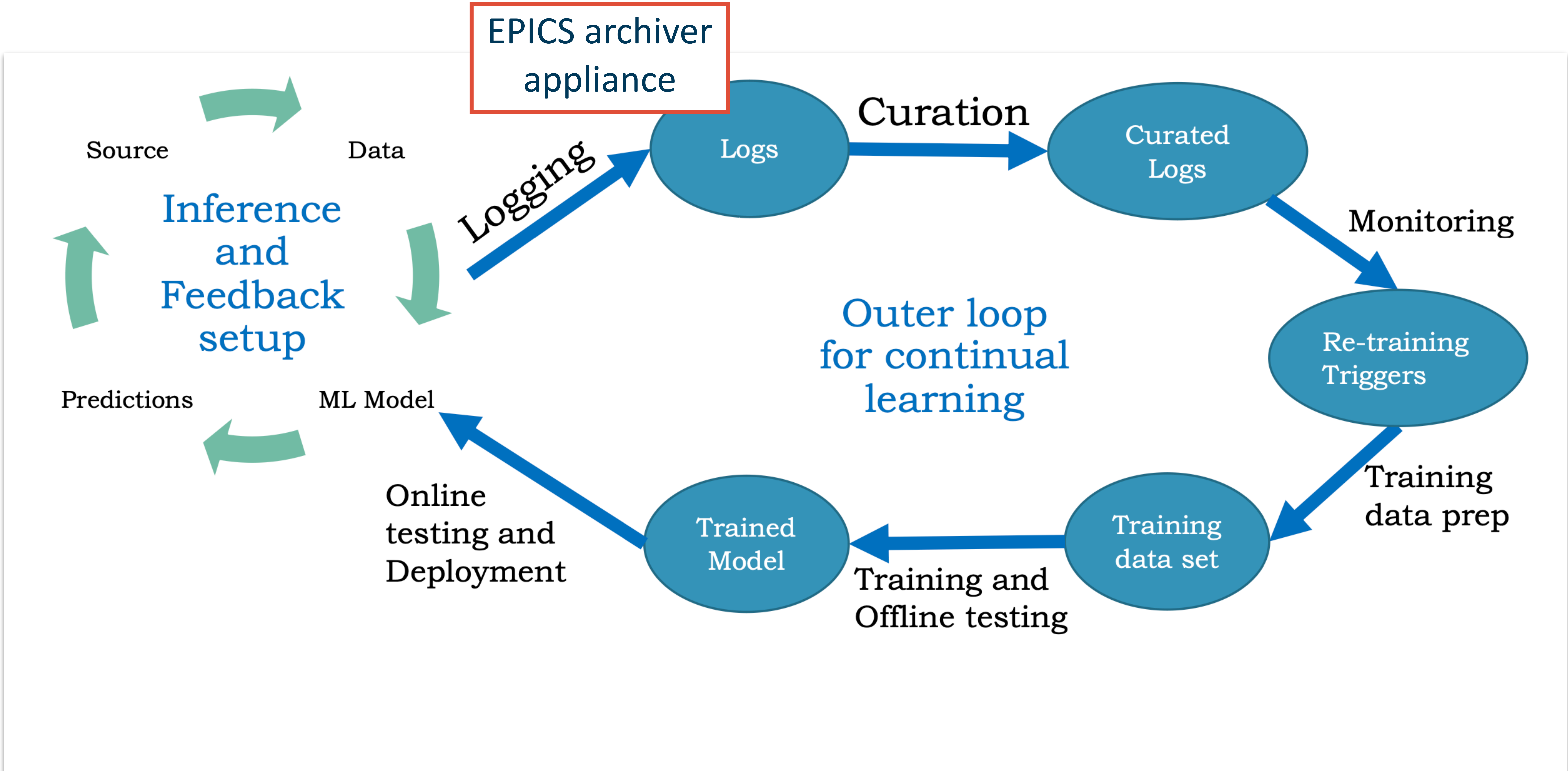

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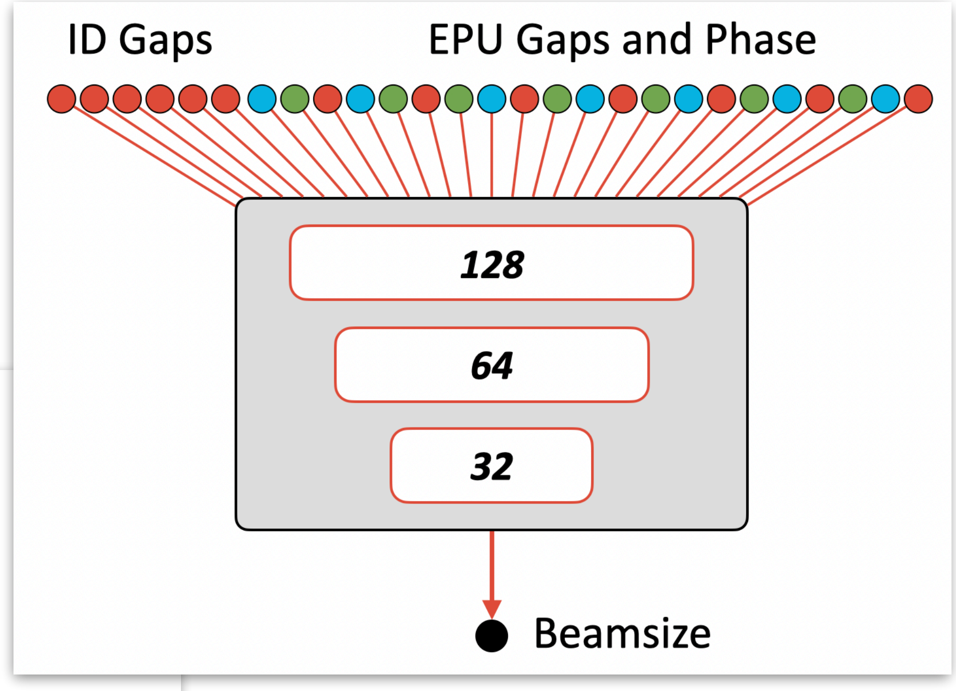

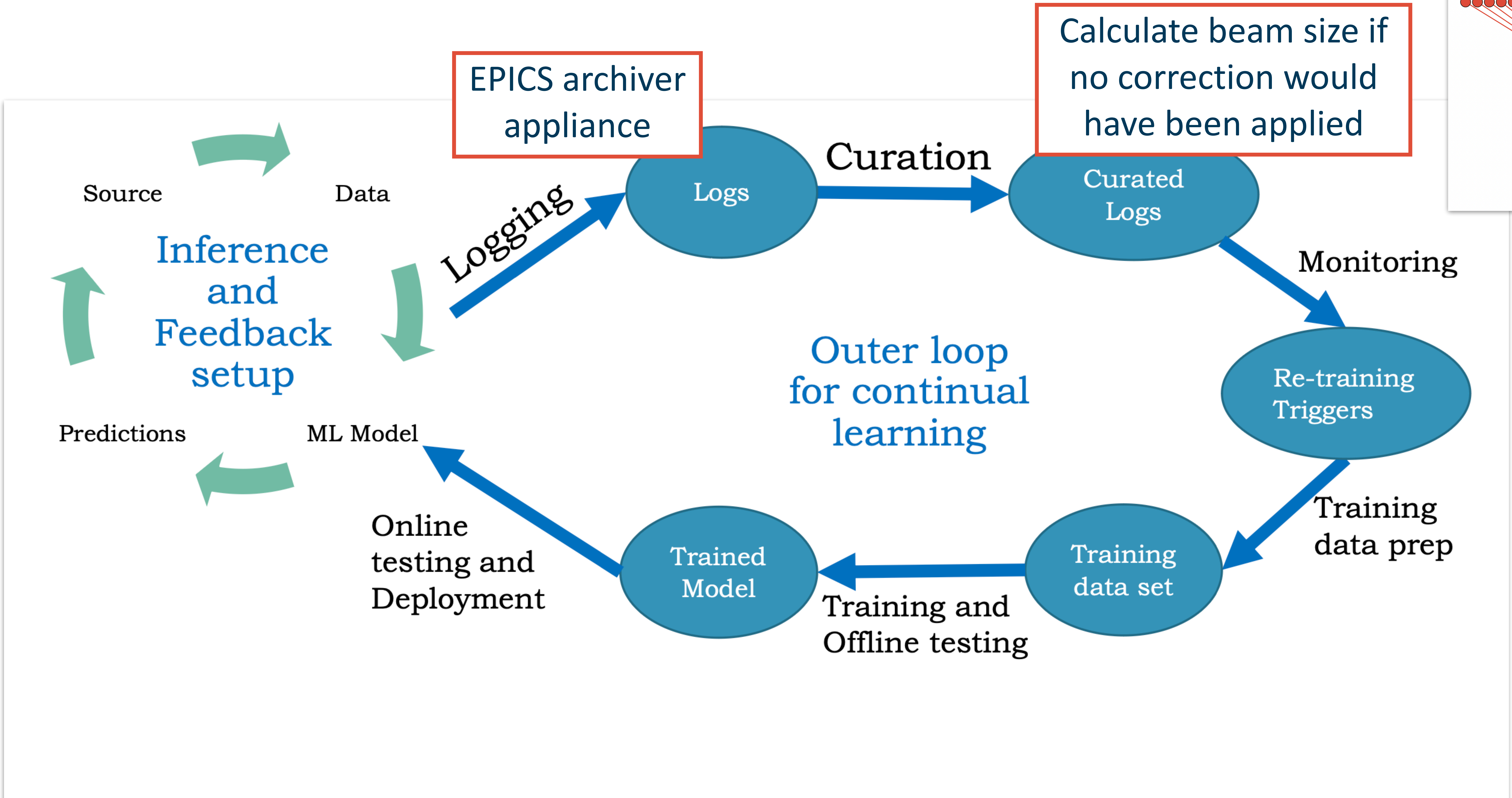

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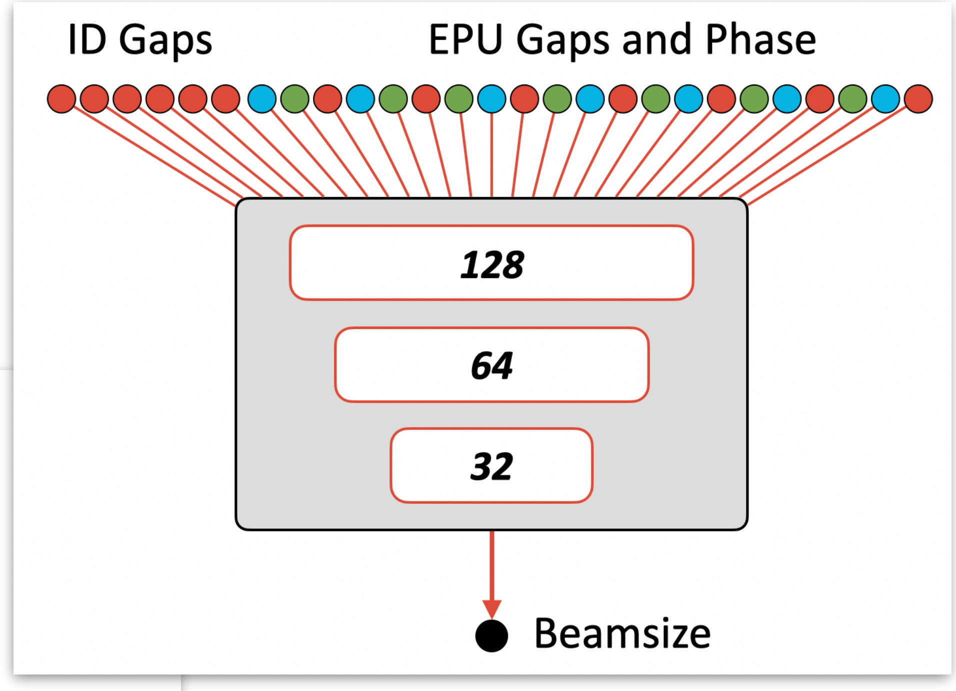
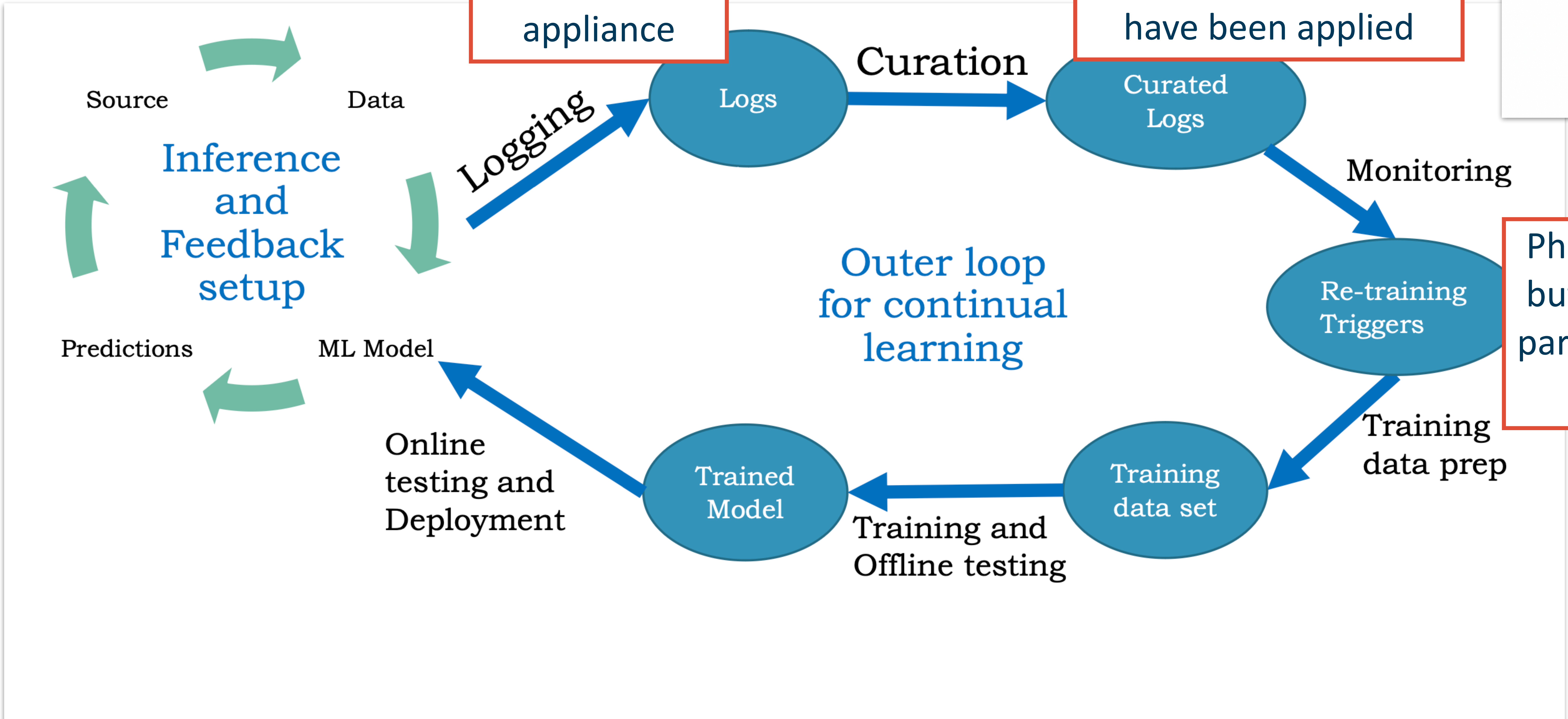
Continual Online Fine-Tuning

EPICS archiver appliance

Calculate beam size if no correction would have been applied





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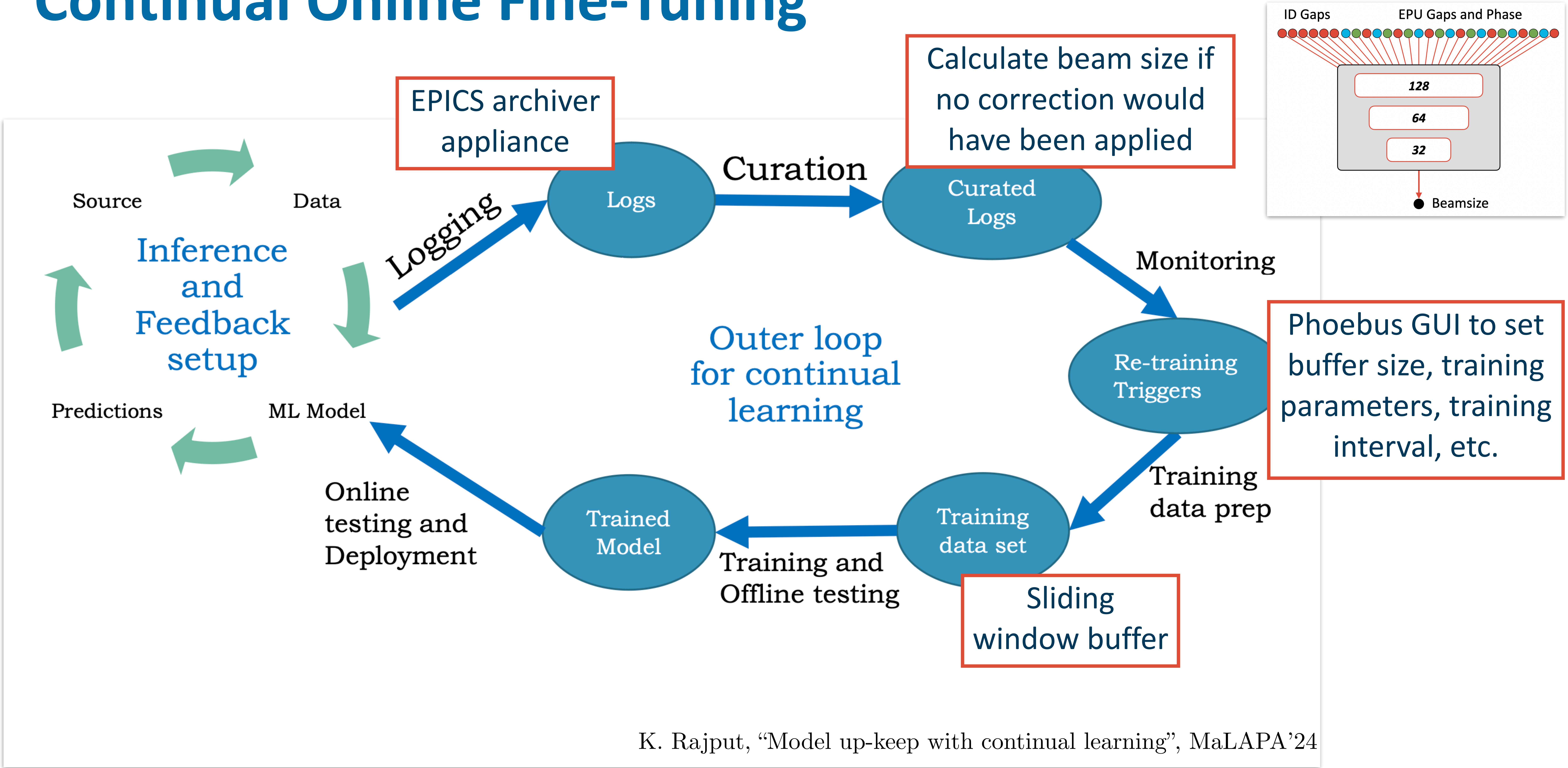
Phoebus GUI to set buffer size, training parameters, training interval, etc.

Continual Online Fine-Tuning



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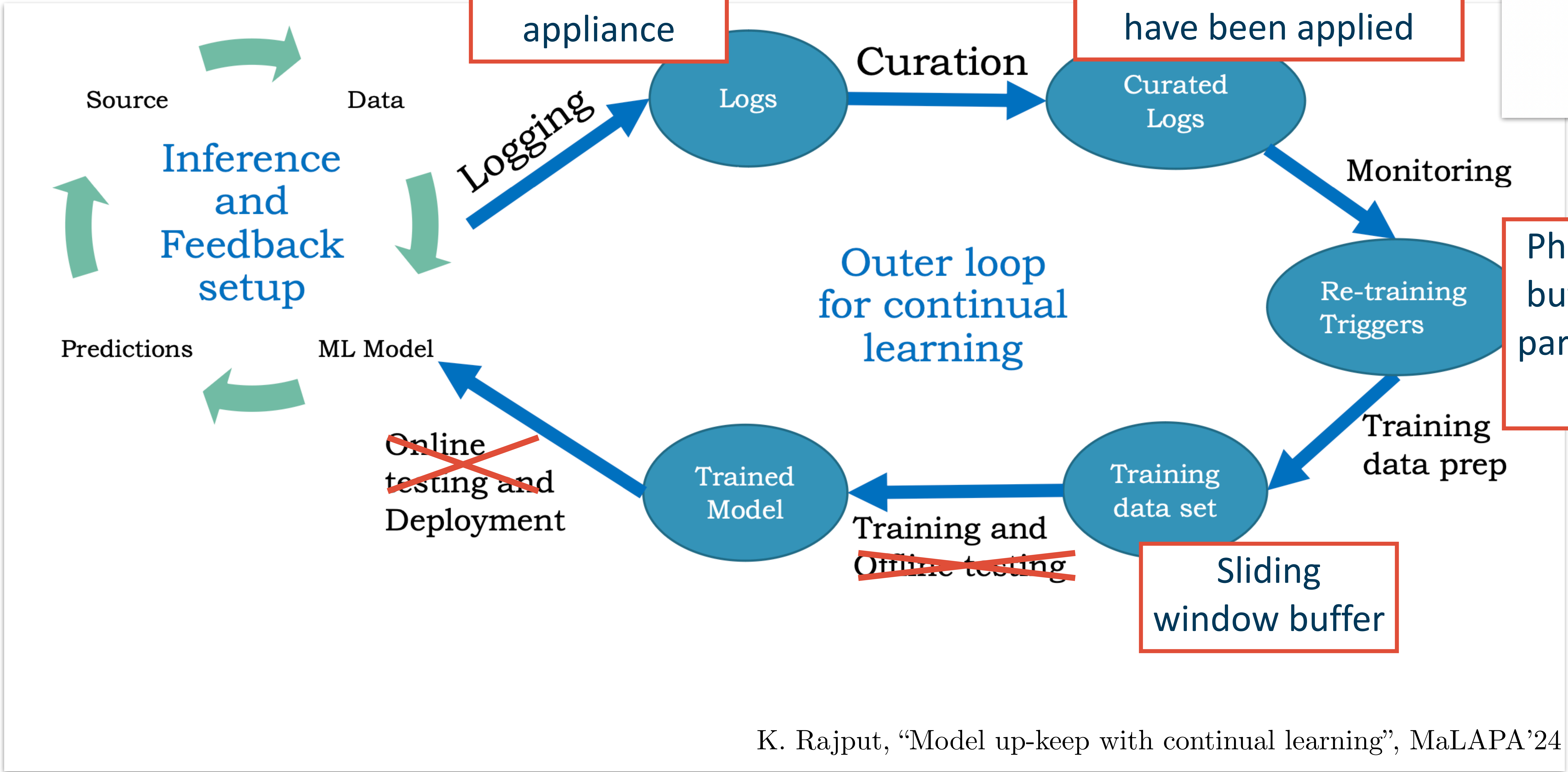

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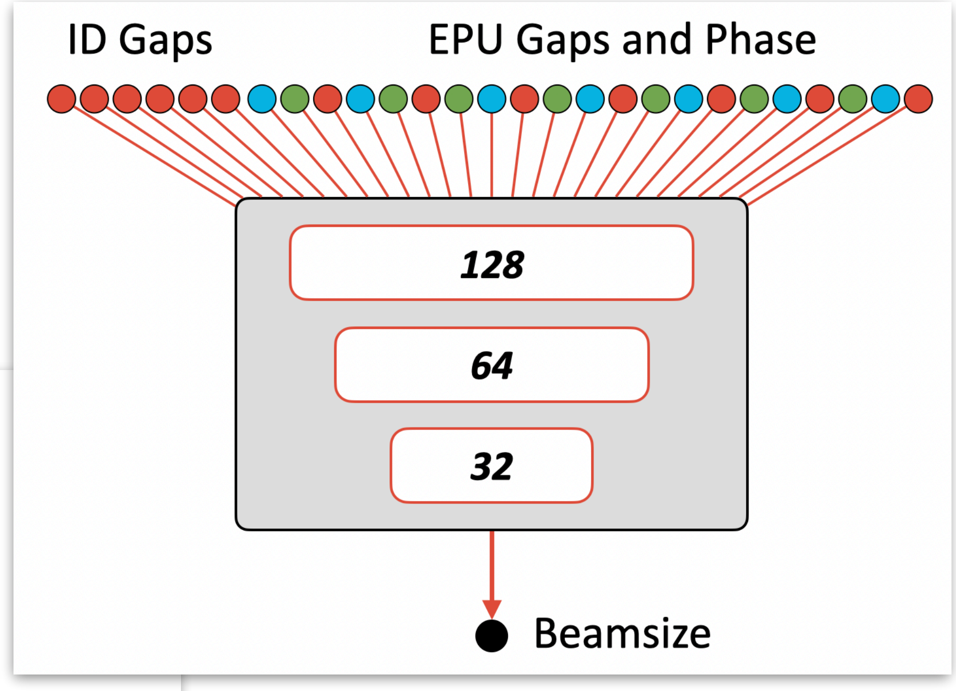

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Sliding window buffer

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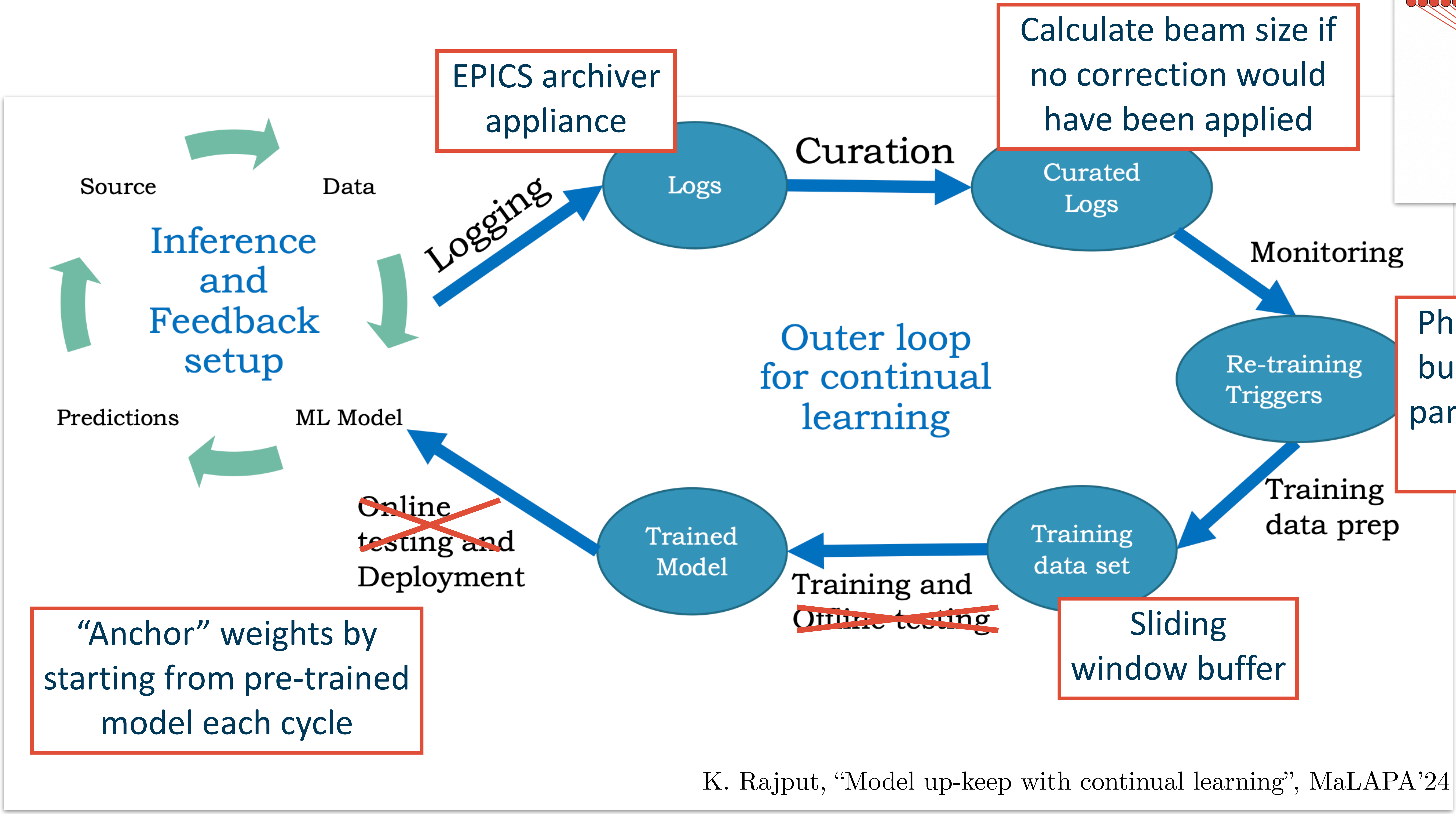

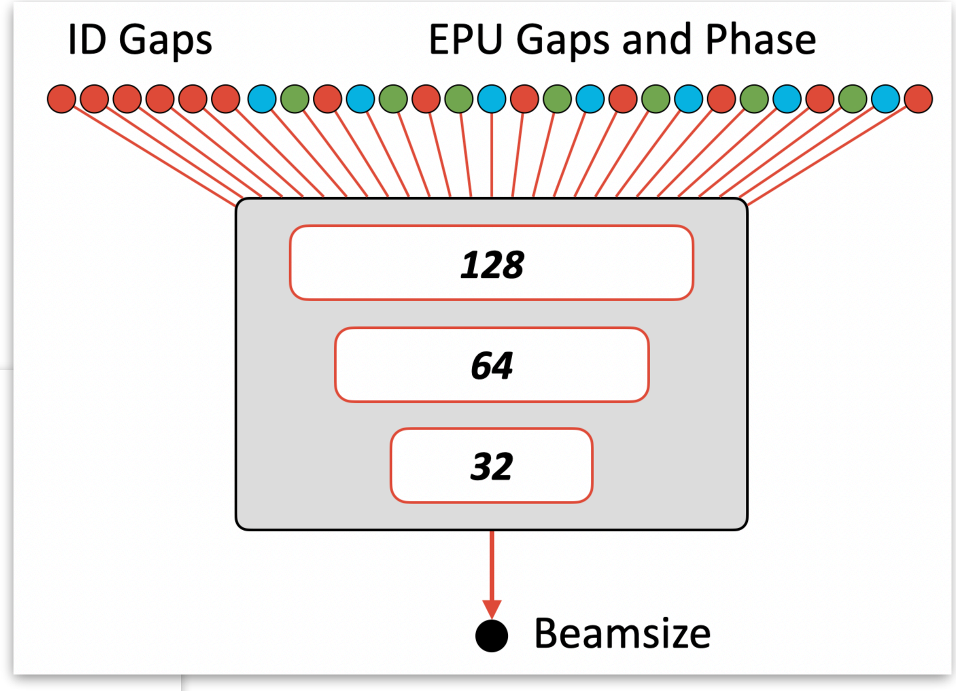

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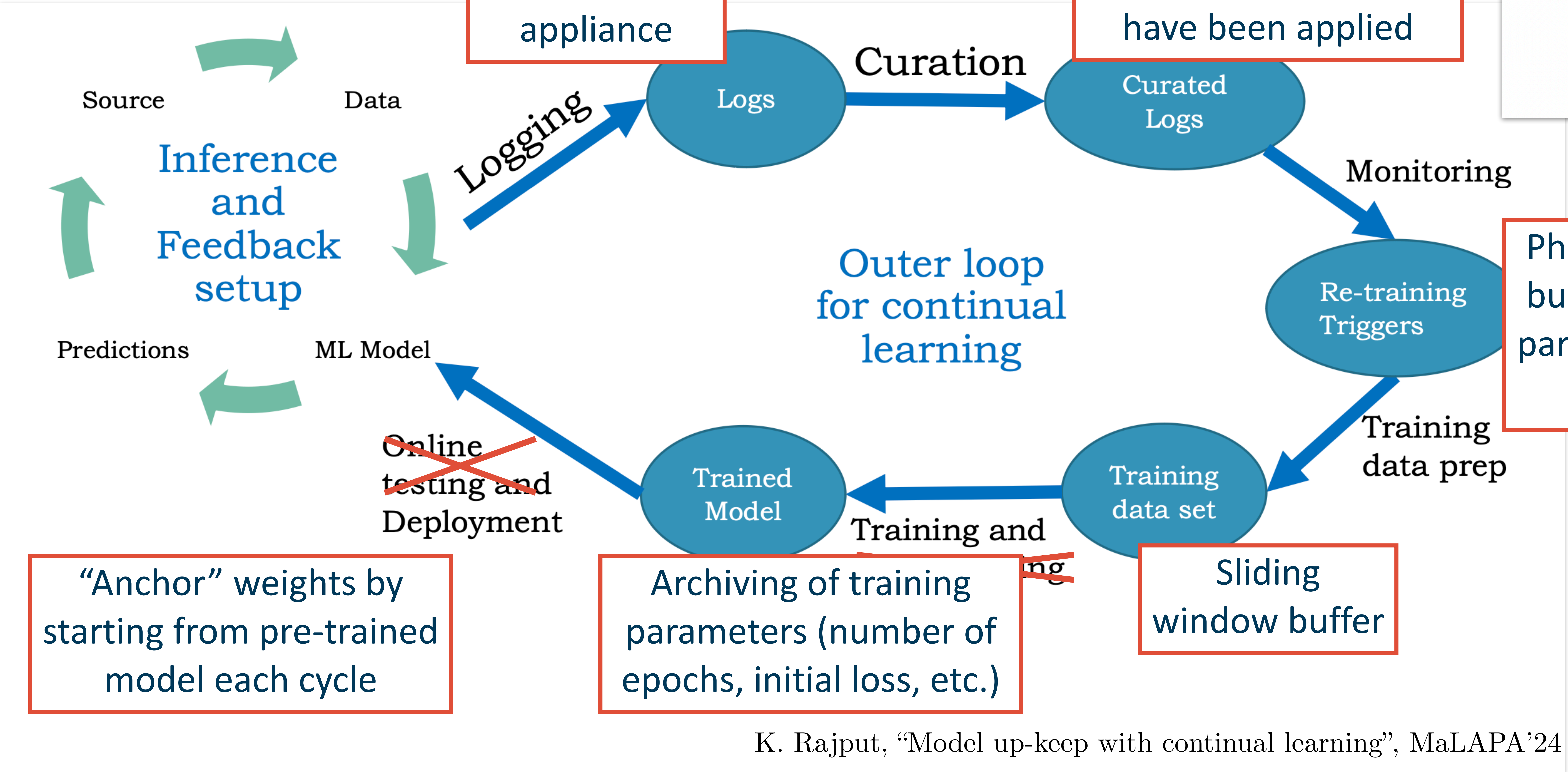

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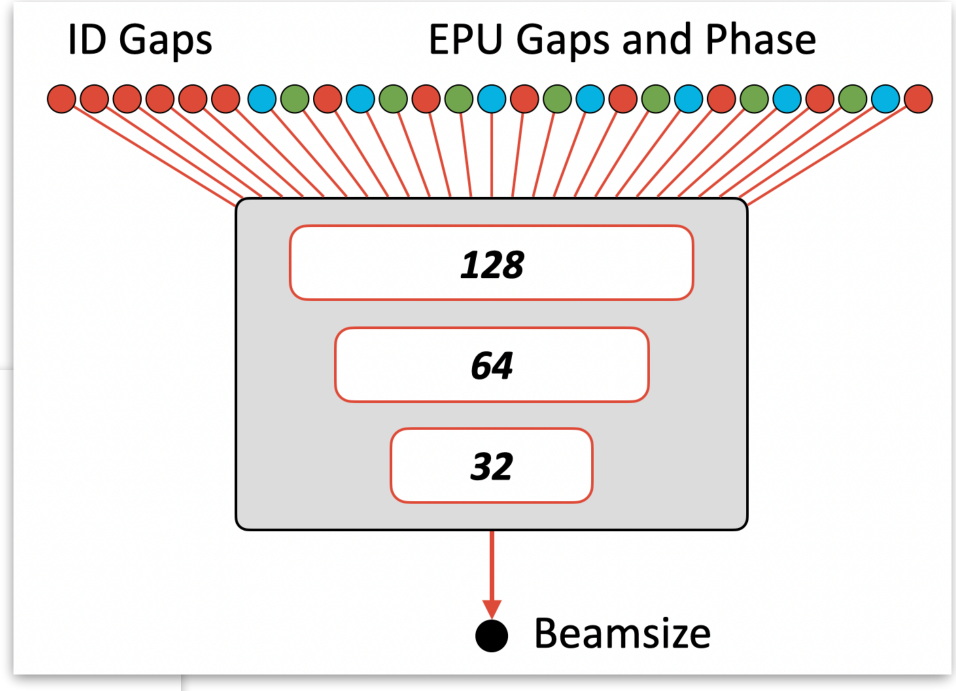
Phoebus GUI to set buffer size, training parameters, training interval, etc.

Sliding window buffer

Archiving of training parameters (number of epochs, initial loss, etc.)

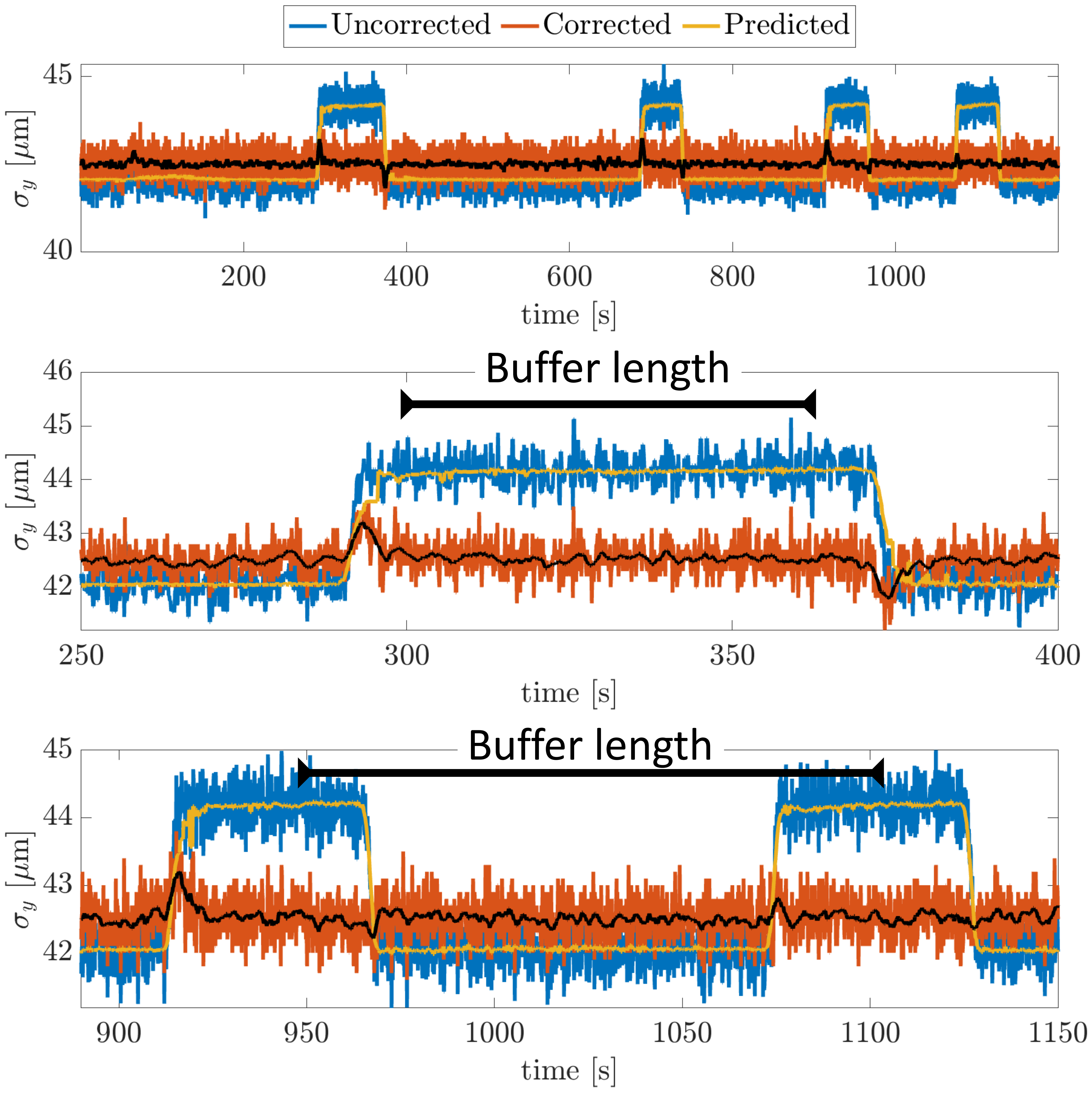
"Anchor" weights by starting from pre-trained model each cycle

K. Rajput, "Model up-keep with continual learning", MaLAPA'24



Continual Online Fine-Tuning

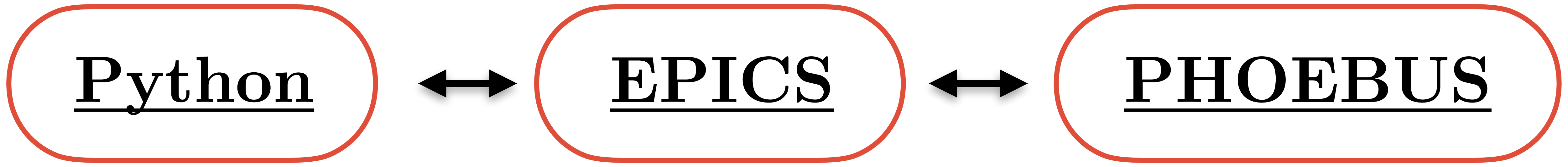
- Online Fine-Tuning:
  - Circular buffer to record model input
  - Train base model on data in buffer only
  - Start from base model each cycle to avoid runaway
  - Uncorrected beamsize calculated with DWP
- Parameters:
  - Typically 1k samples in buffer
  - Takes less then 100 epochs and about 1s
- Feedback vs Feedforward:
  - Online retraining acts as feedback
  - Buffer size controls impact of FB vs. FF

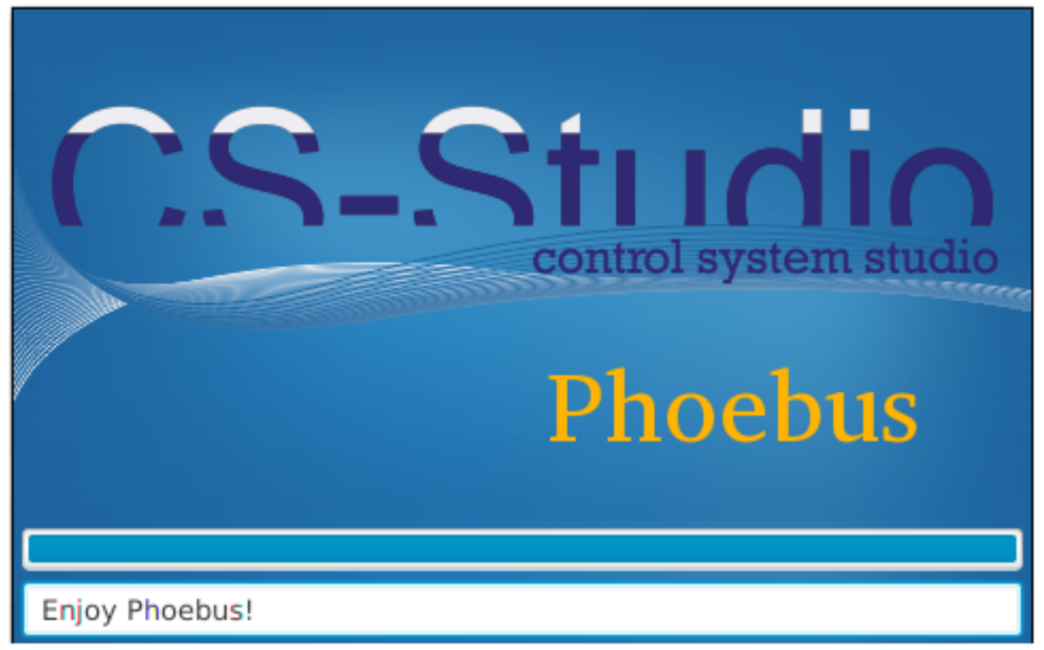


Model Deployment

Beam Size Control Backend Layout

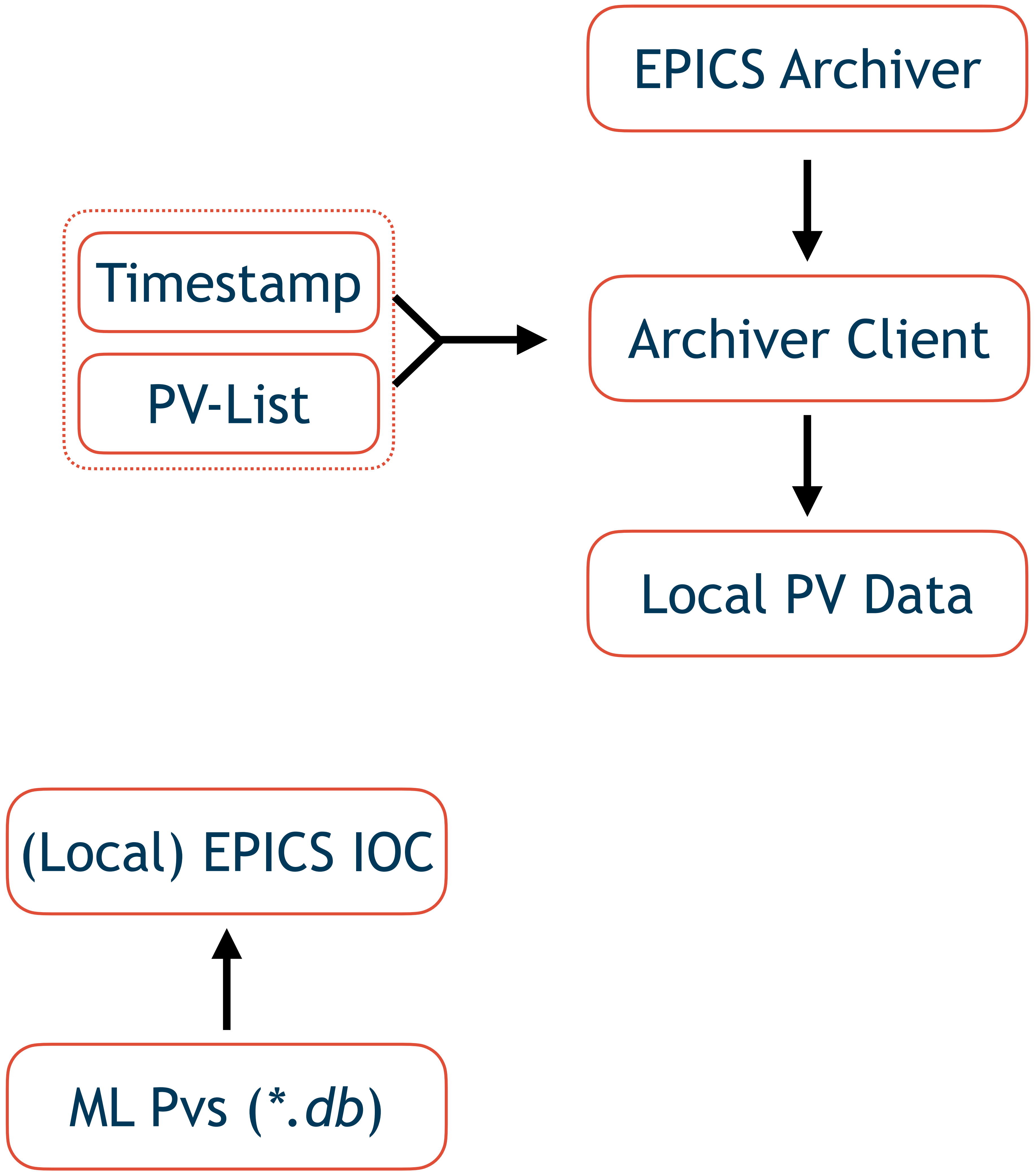
- Python Backend:
  - PyTorch
  - Currently on control room VM
  - Plan to implement on IOC this year
- Dedicated EPICS IOC:
  - 600 PVs required
  - Goal: concentrate all logic on EPICS
- PHOEBUS GUI:
  - State of the art control system GUI
  - Easy integration with EPICS
  - Expert/Operator Panel





Archiver Replayer: Invaluable R&D Tool

- Local IOC Sandbox:
  - Beam size control IOC acting as a development sandbox
- Archived Data Utilization:
  - Archiver client to download historical data



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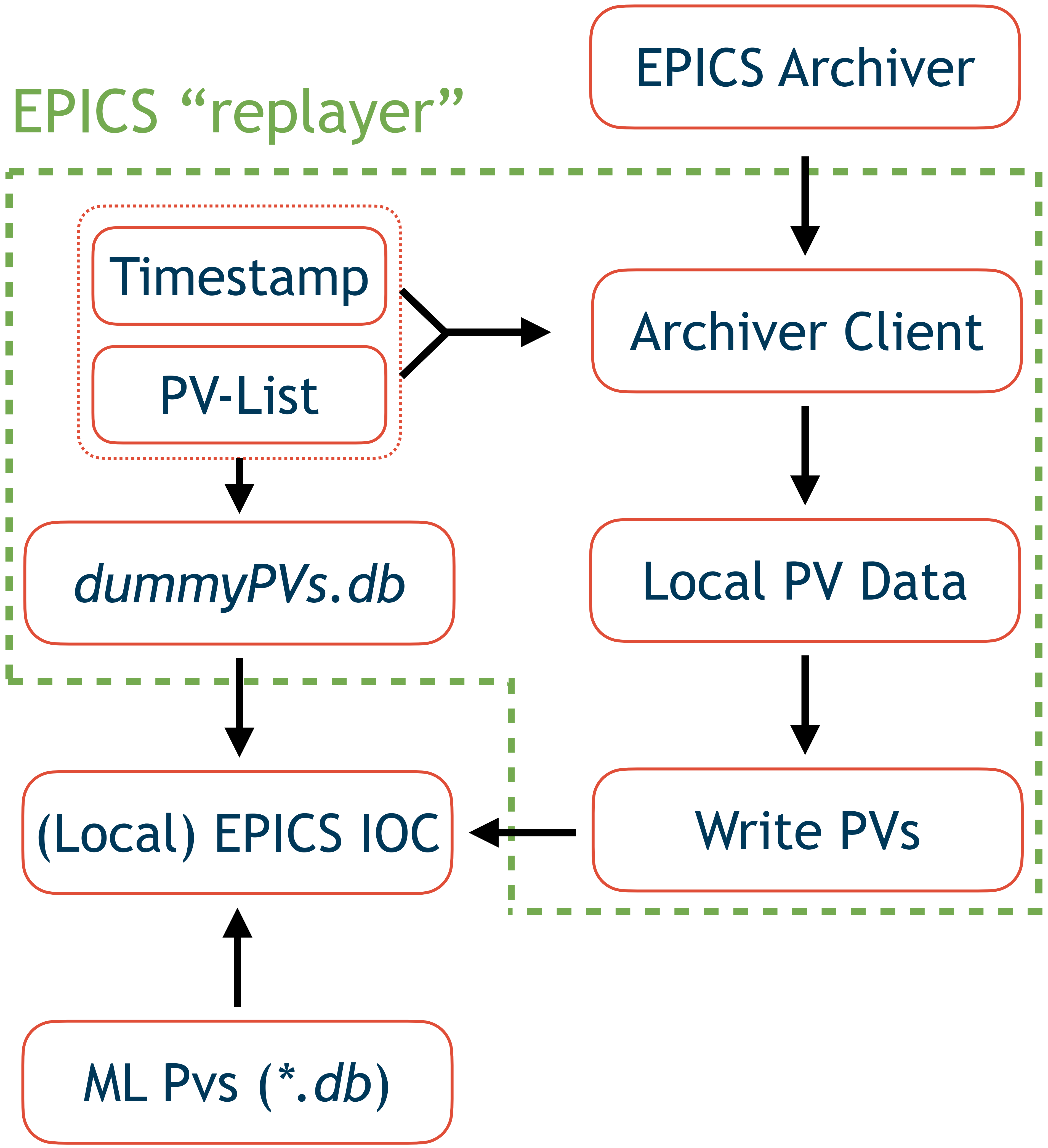

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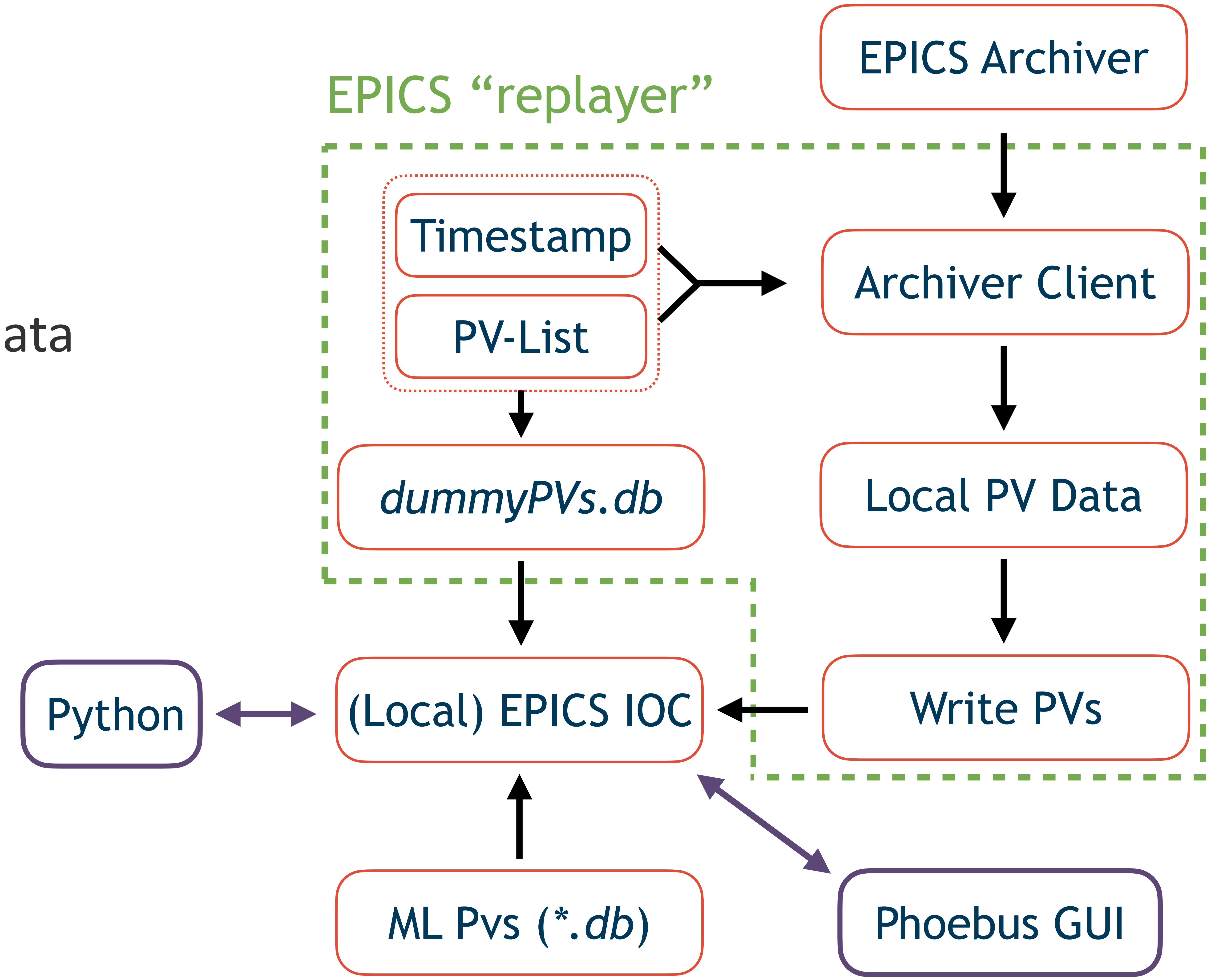

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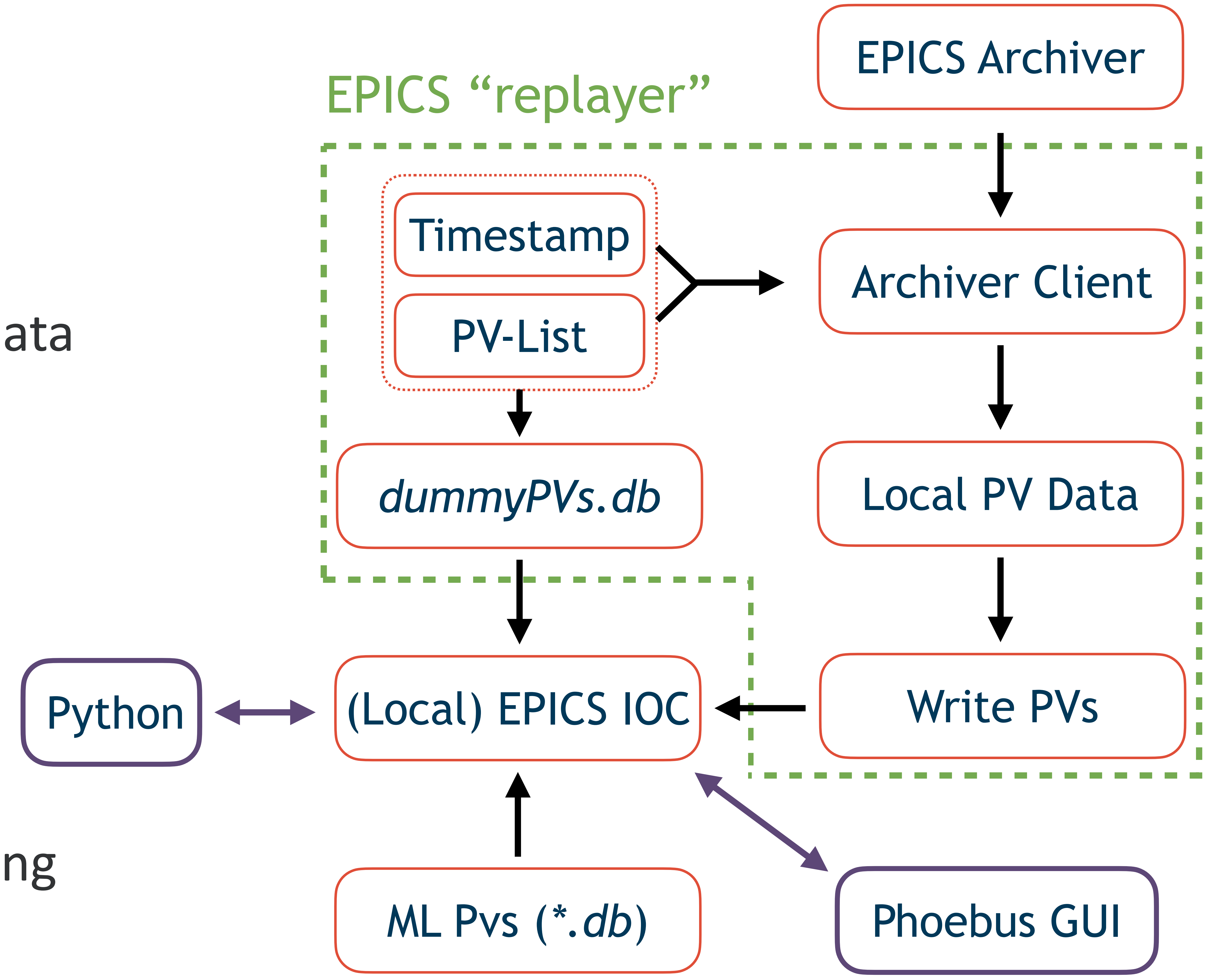
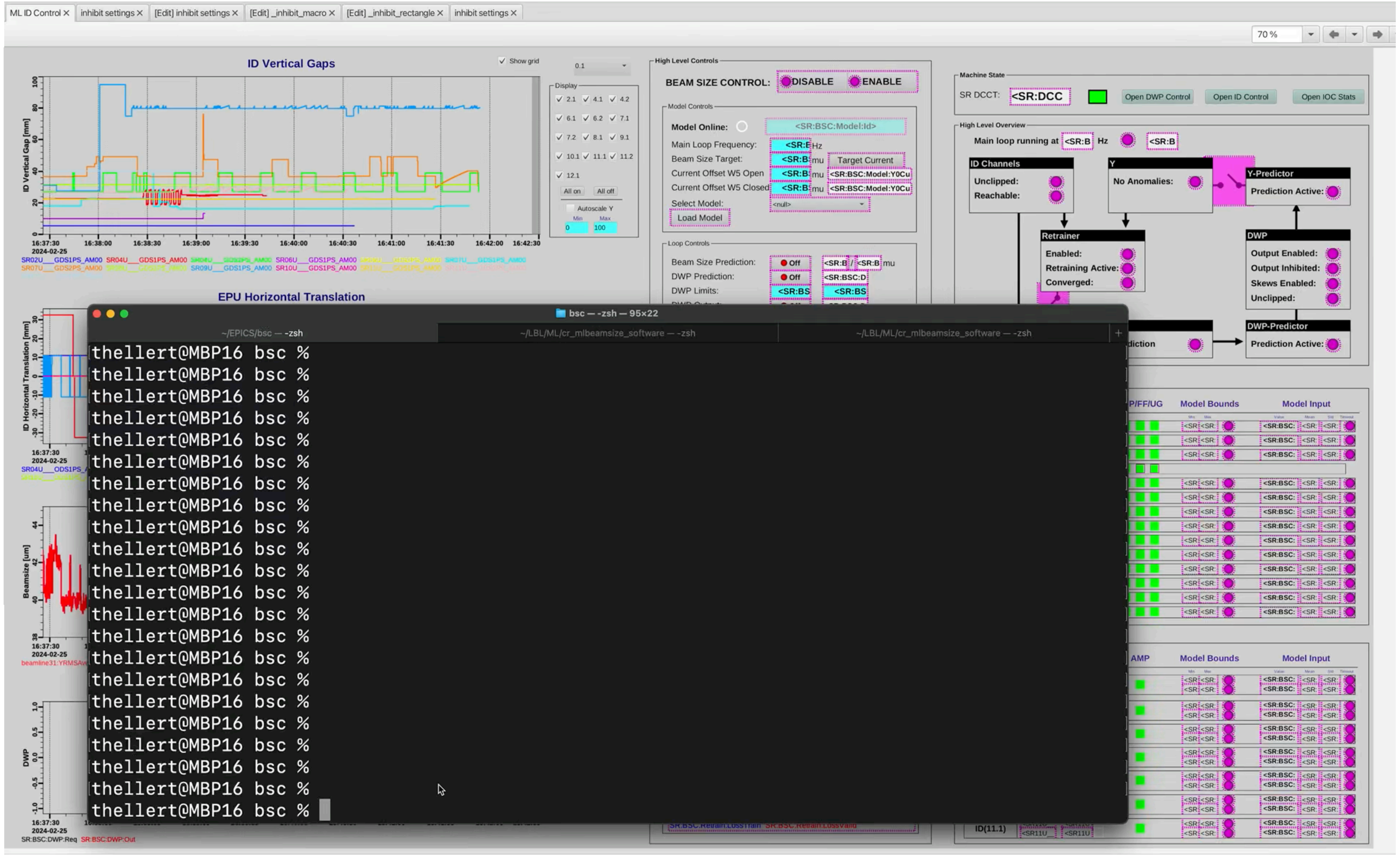
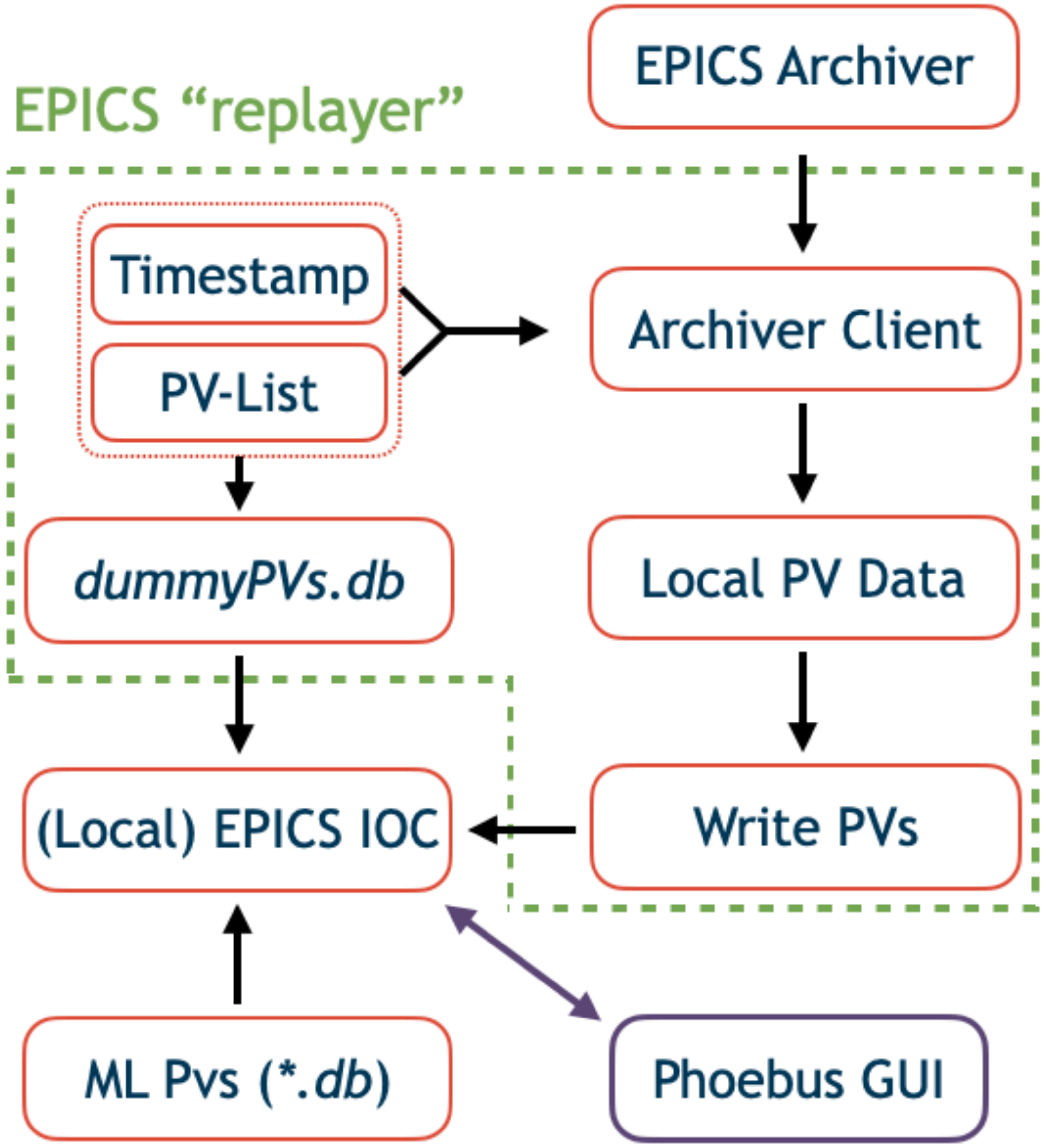
- Efficient R&D and Deployment:
  - Enabled rapid prototyping and debugging of the complete pipeline



Archiver Replayer: Invaluable R&D Tool





Inhibitor Chain

- Inhibitor Chain:
  - Can not activate beam size control
  - Can only pause operation
  - Includes manual override options
- Critical Conditions:
  - Beam current, FOFB, local ID FF
  - Skew quads ok, W5 closed
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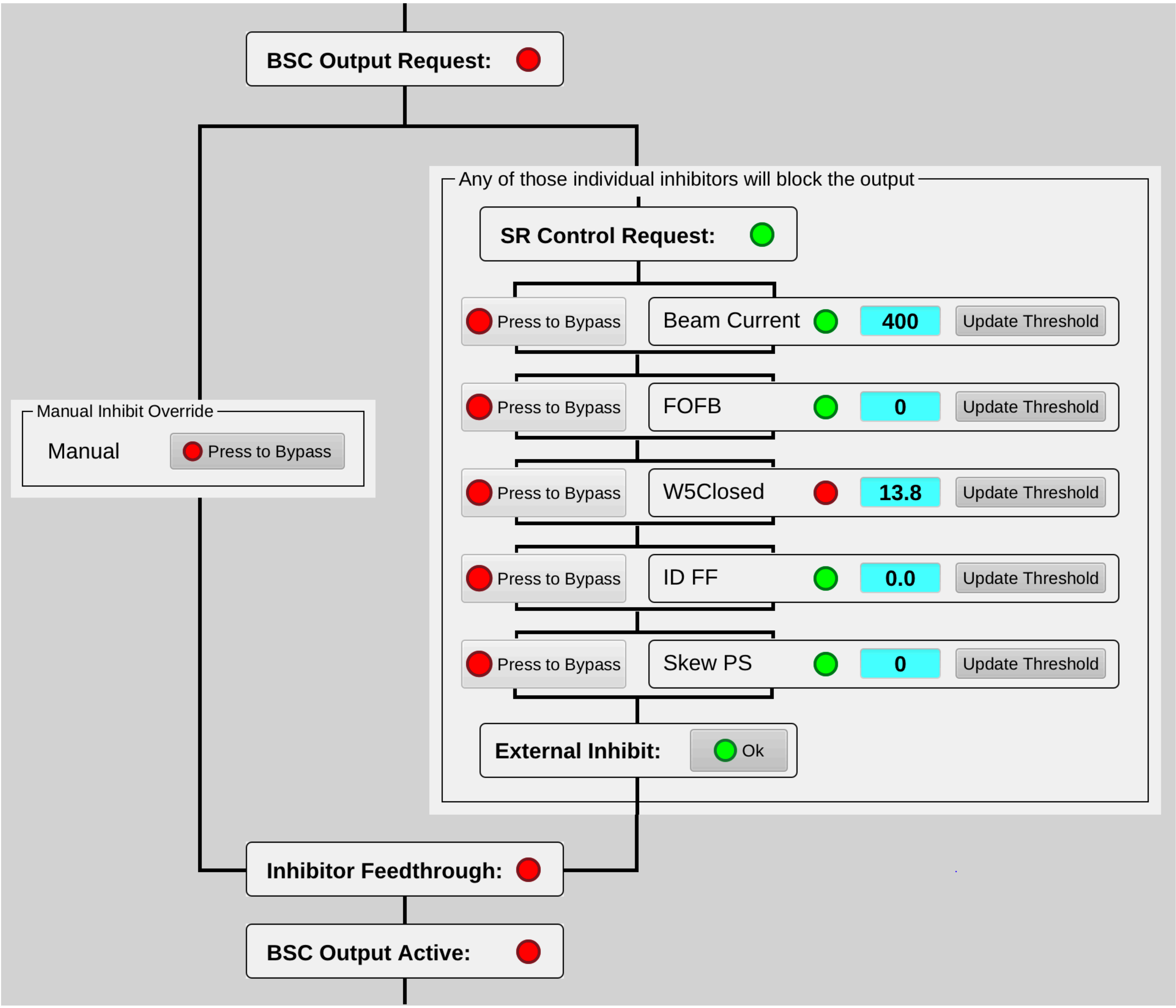
- Crucial for Reliable Operation



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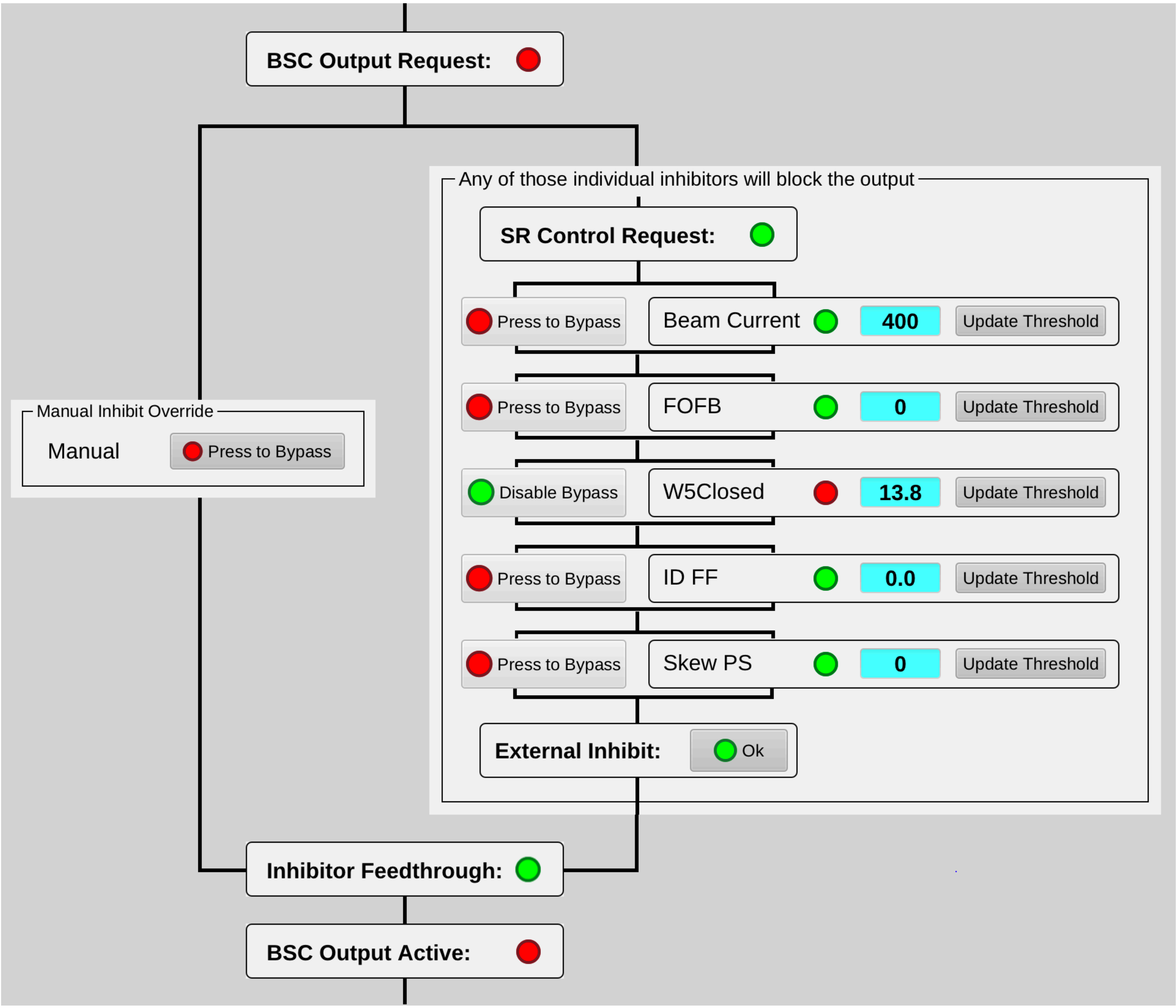

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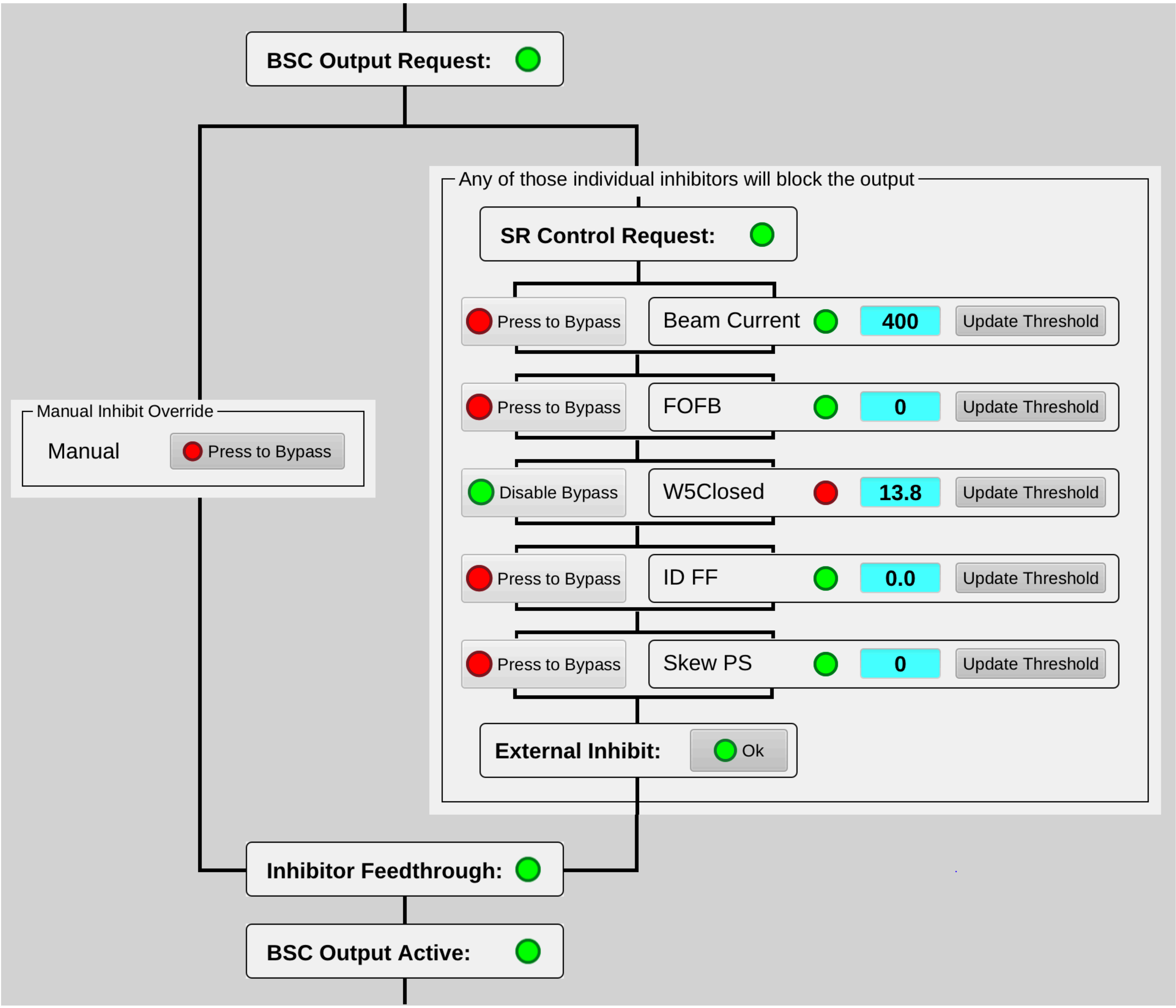

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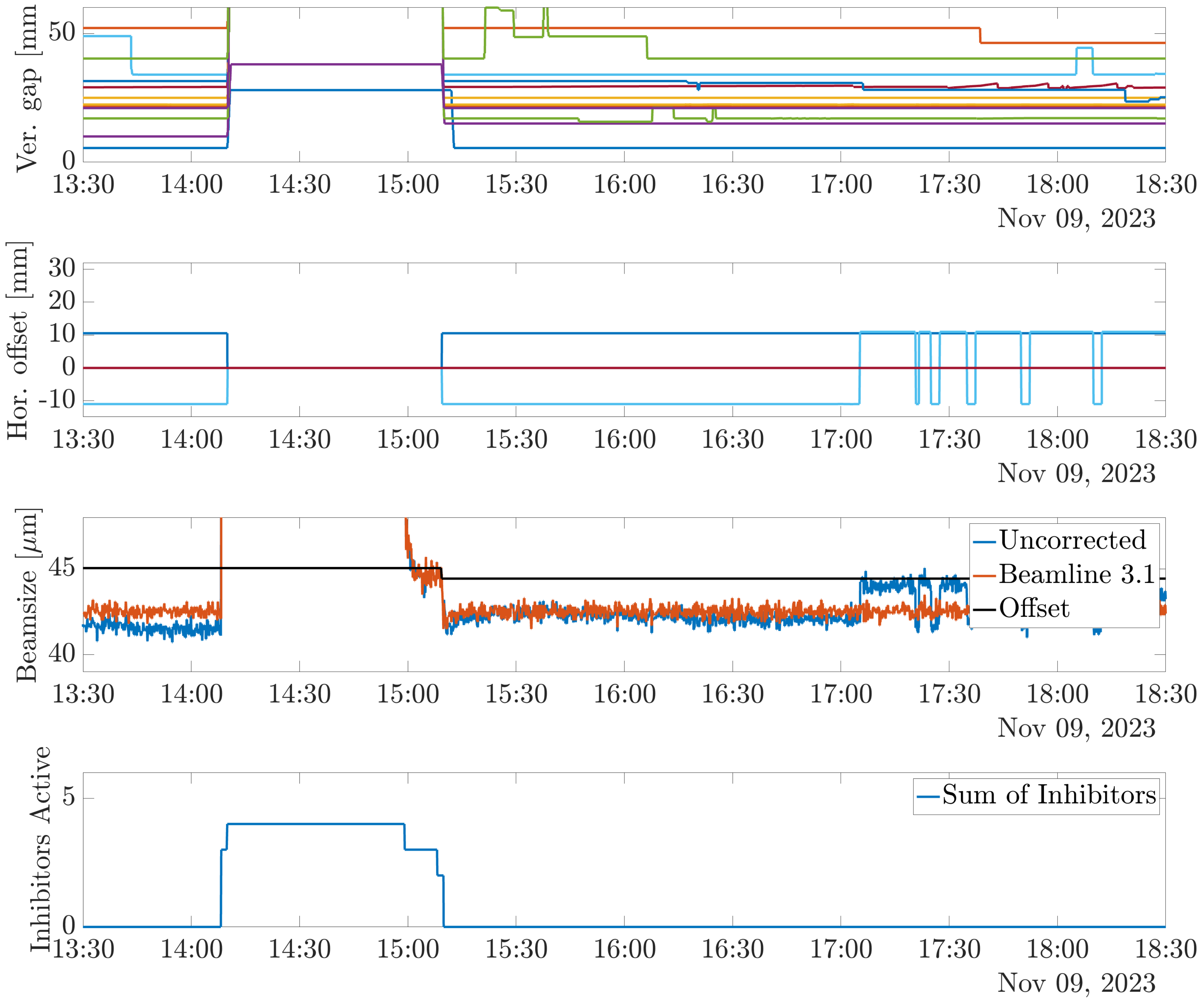

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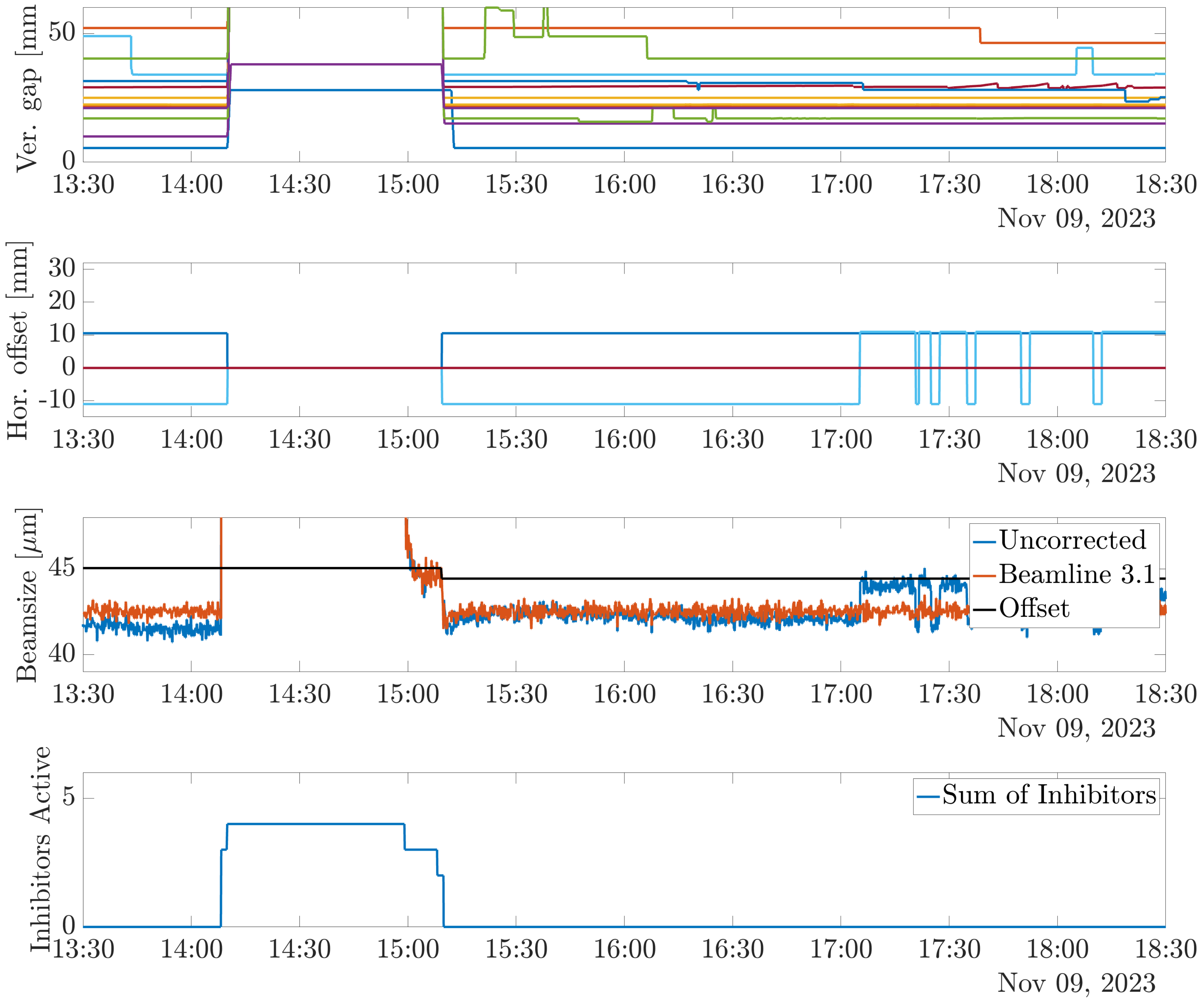
- Restoration Process:
  - Injection process from 14.55 am to 15.10
  - Conditions met for FF algorithm from 15.12
  - Vertical beam size back to target 42.5um



Summary

- Vertical Beam Size Variation at ALS
  - Dominating source of variation at STXM beamlines
  - Conventional correction techniques insufficient
- Model Development:
  - Comprehensive model- and hyper parameter search
  - Evaluation on historical user operation data
- Online Finetuning:
  - Continuous fine tuning of base model during operation
  - Outperforms conventional feedback correction
- Routine Deployment:
  - Utilization of EPICS backend and Phoebus Frontend
  - ML FF in routine operation since October’23