The code BADGER is developed and maintained by Zhe Zhang and Ryan Roussel, SLAC

Many thanks to the ESRF beam dynamics, diagnostics, operation and accelerator control groups

ESRF | The European Synchrotron

# Online tuning and optics monitoring at ESRF

- **Badger optimizations**
- **Online digital twin**
- **Future projects**

S.M.Liuzzo, J.-L.Pons, N.Leclercq, N.Carmignani, L.Carver, L.Hoummi,
T.Perron, S.White, ESRF, France
L.Malina, I.Agapov, J.Keil, E.Musa, B.Veglia, DESY, Germany
T.Hellert, LBNL, California
R.Roussel, Z.Zhang, A.L.Edelen , SLAC, California

# BADGER + XOPT FOR LIFETIME AND INJECTION EFFICIENCY OPTIMIZATION

Code used in the framework of **EURIZON EU** project by **DESY** and **ESRF**


**EASY** INTERFACE
**EASY** SETUP
**EASY** INSTALLATION
**MANY** DIFFERENT OPTIMIZERS

BADGER ➔ 2 PAPERS: ICALEPCS2023 TALK PROCEEDING + BO REVIEW (R.ROUSSEL SLAC)

https://github.com/ChristopherMayes/Xopt https://github.com/slaclab/Badger https://github.com/SLAC-ML/Badger-Plugins

https://arxiv.org/pdf/1910.01739.pdf

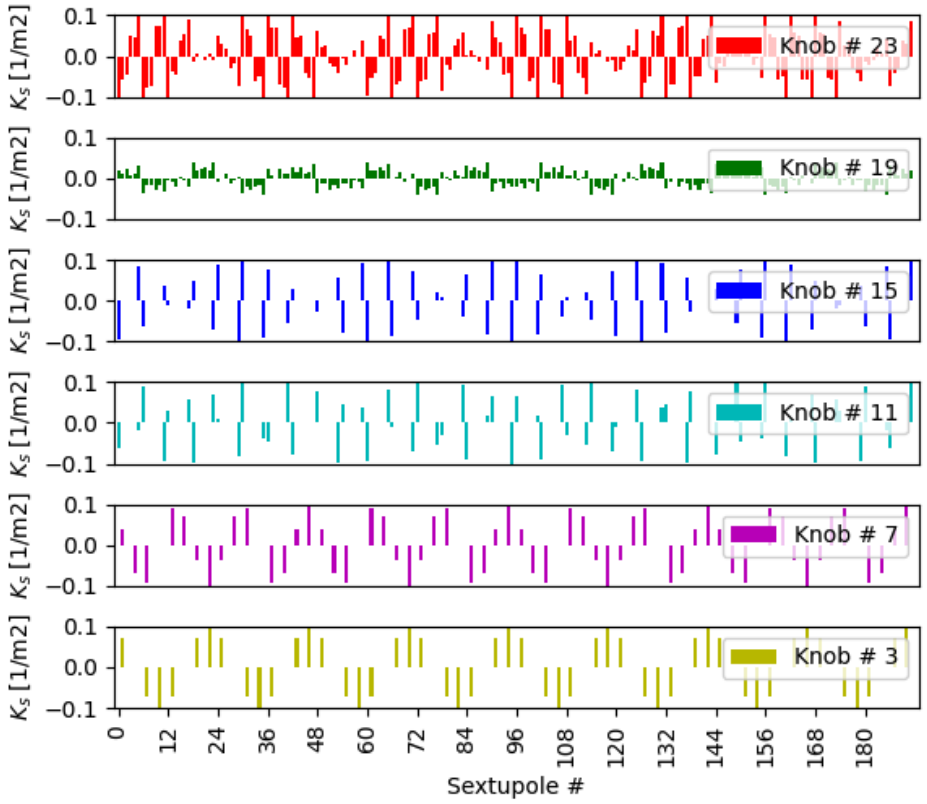
# FIND SEXTUPOLES/OCTUPOLES SETTINGS FOR OPTIMAL LIFETIME

## VARIABLES

192 sextupoles
64 octupoles

simulations
simulations
simulations
simulations
simulations

24 “knobs”
Large effect on lifetime
Small effect on dynamic aperture



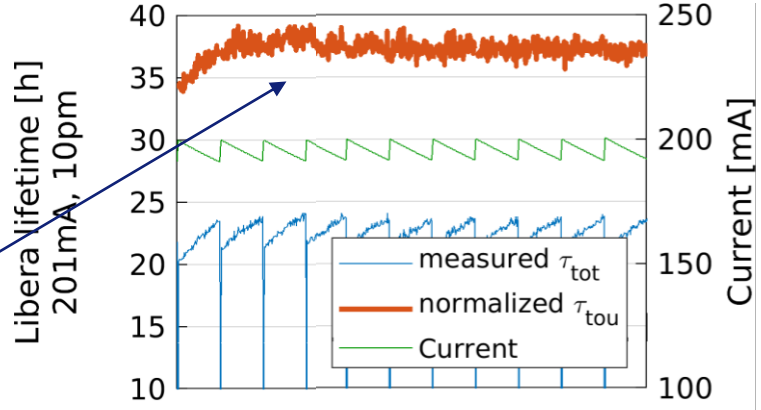

**Maximize**
normalized **lifetime**

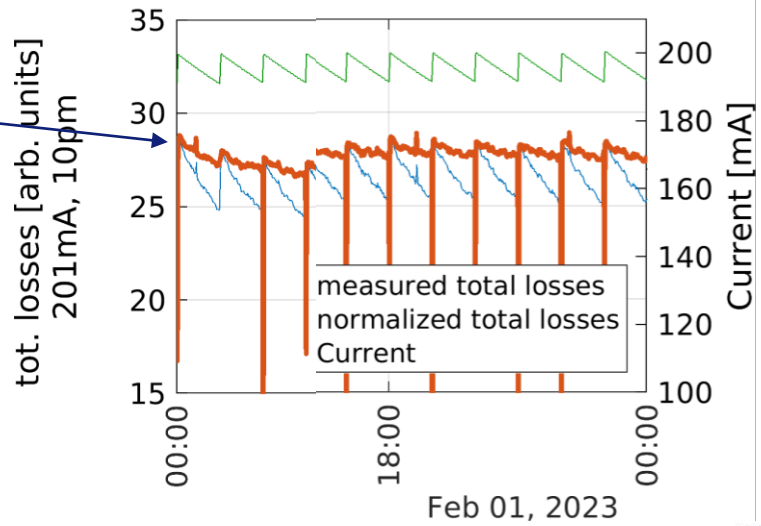
OR

**Minimize**
normalized **losses**

We use **total losses**:
128 Detectors
Reproducible
Reactive to changes
Sensible to small variations

## OBSERVABLES

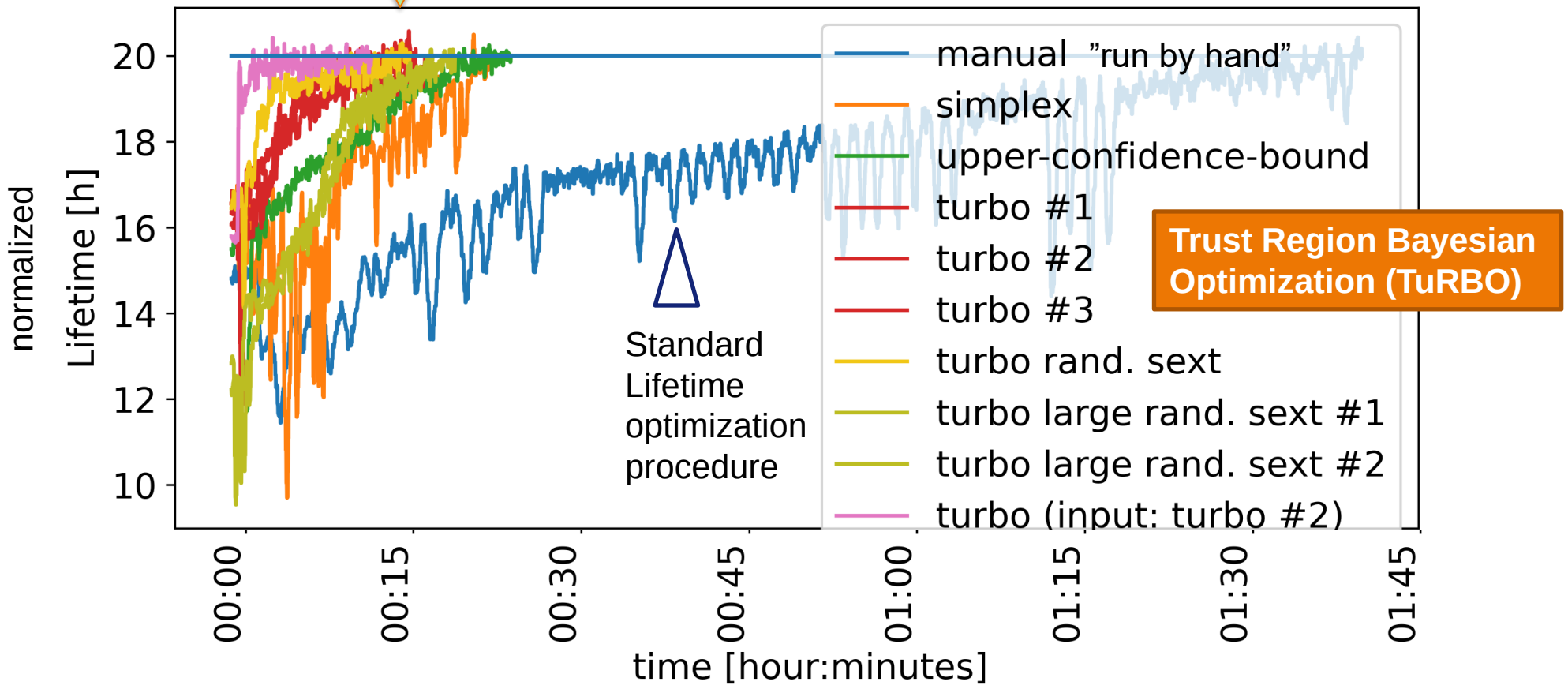


# 10-15 MINUTES INSTEAD OF 100 MINUTES FOR EQUIVALENT OPTIMIZATION

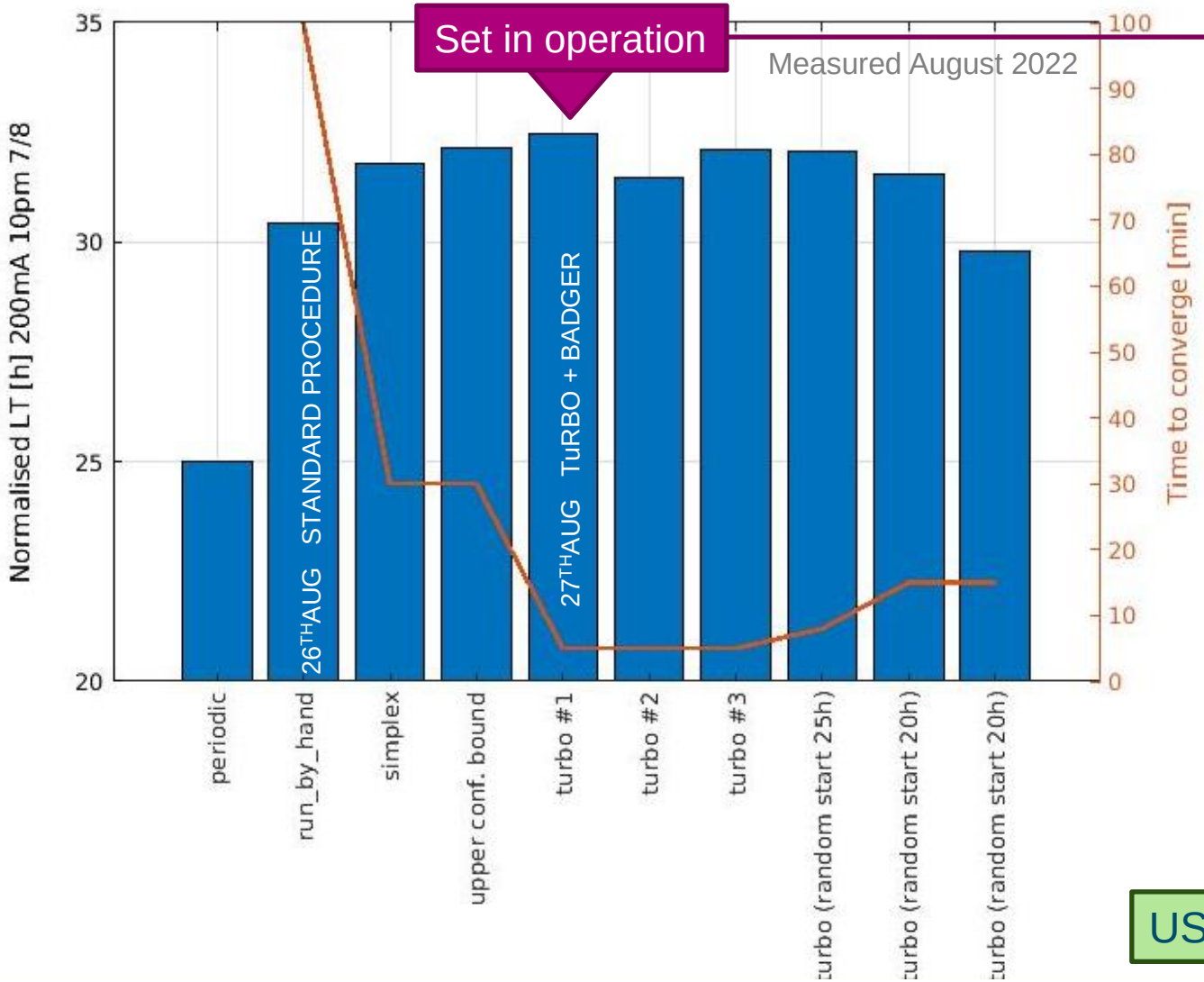
**Badger + XOpt**

https://arxiv.org/pdf/1910.01739.pdf



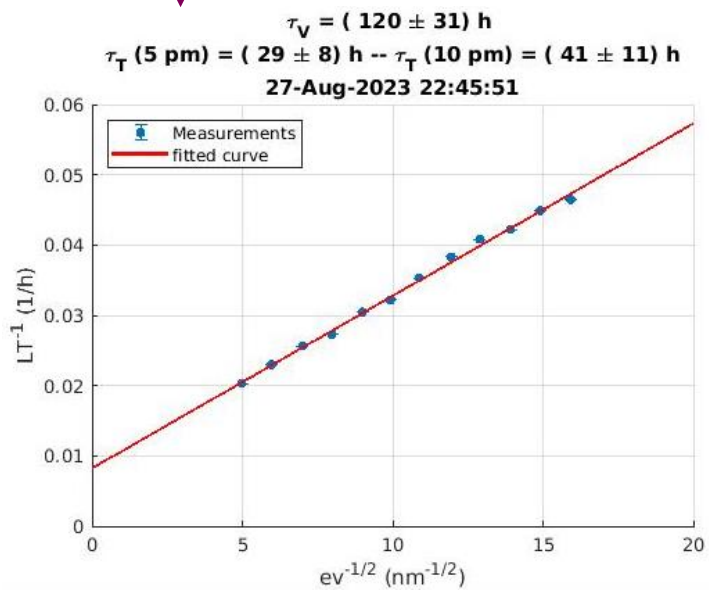

**Trust Region Bayesian Optimization (TuRBO)**

# LIFETIME COMPARISON FOR ALL THE OBSERVED CASES




Vacuum 120 ± 30h

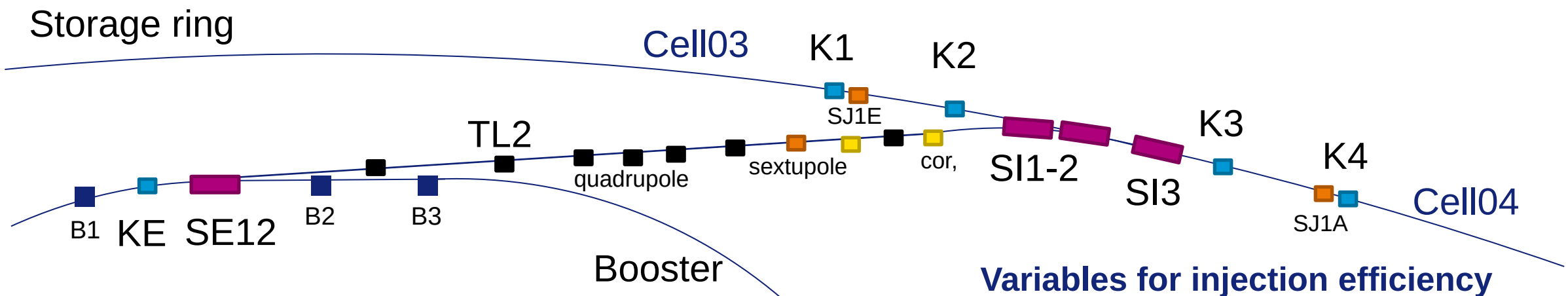
Touschek **41 ± 11h**

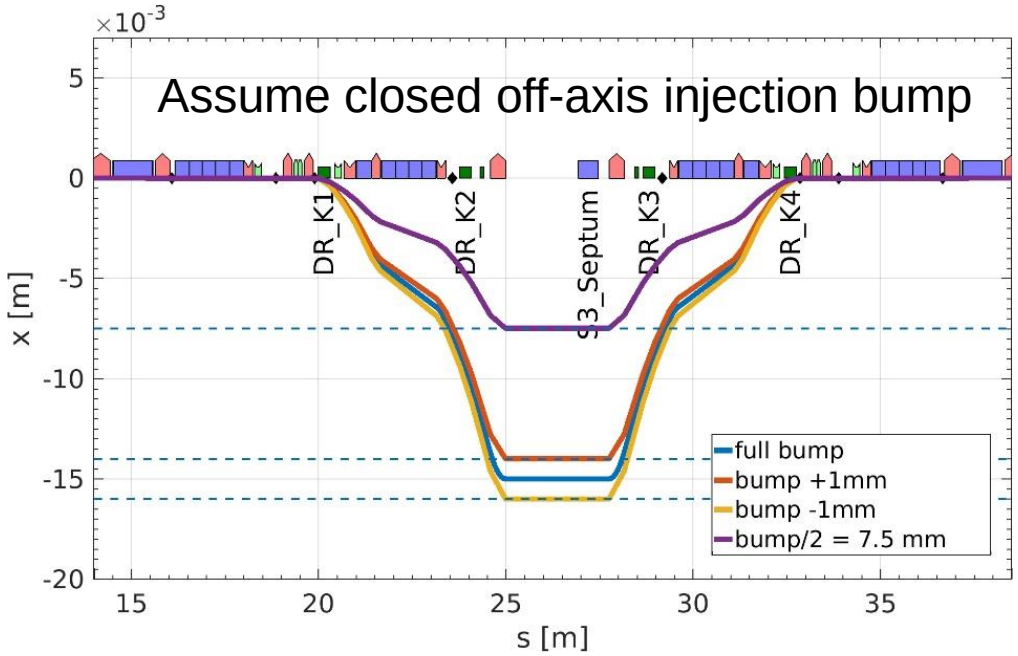



**BEST observed since MAY 2021**

USED in operation, during User Service Mode

# BOOSTER – TRANSFER LINE 2 – STORAGE RING KEY ELEMENTS TO TUNE FOR INJECTION EFFICIENCY

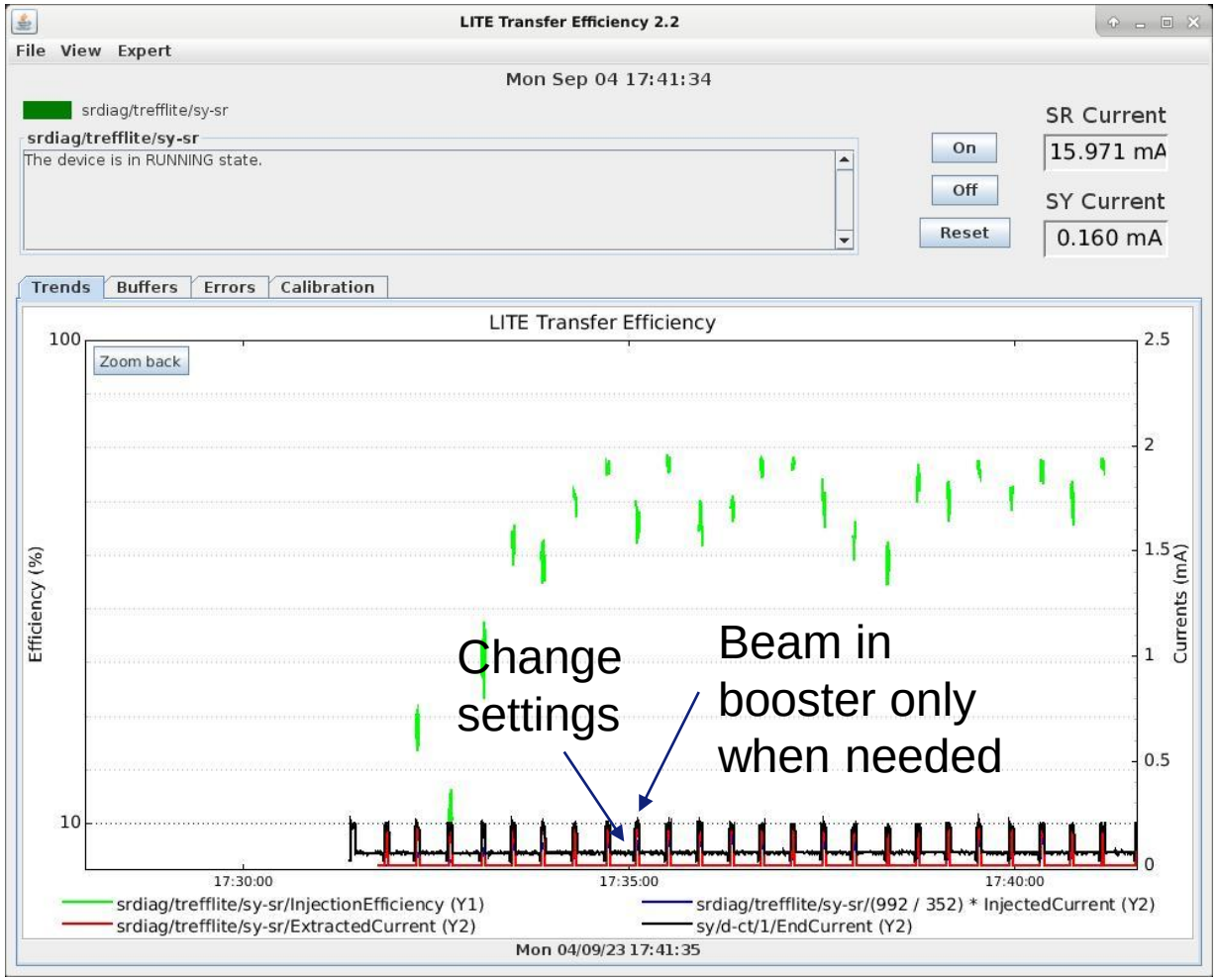


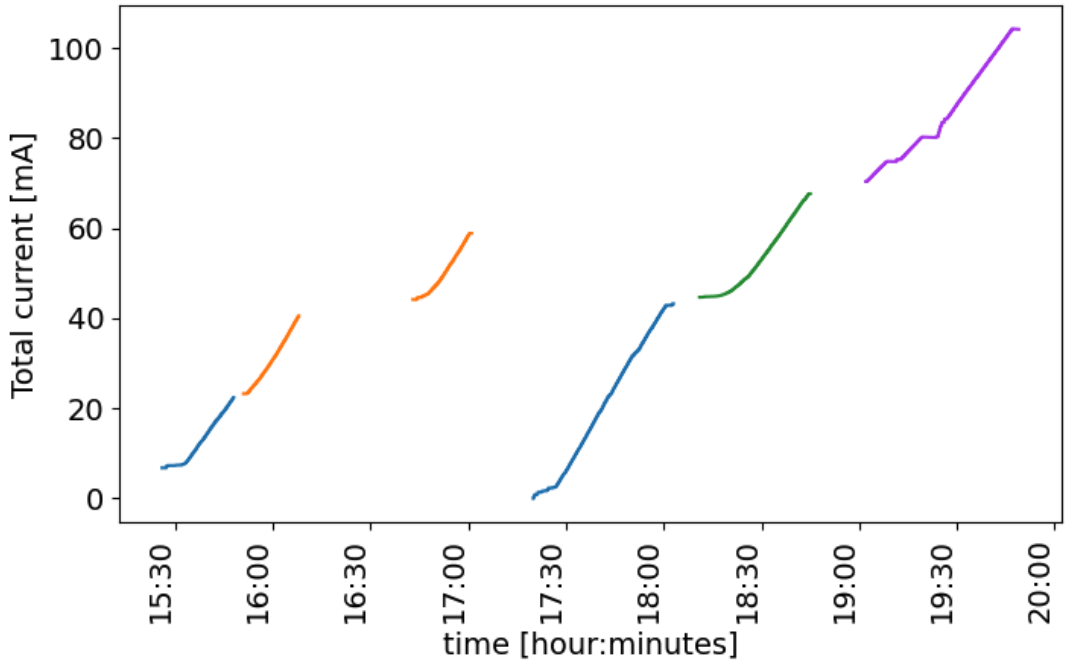

## Variables for injection efficiency tuning

- Pulsed elements
- TL2 steering
- Quadrupoles in TL2
- SE12, SI2, SI3 septa
- KE strengths for injection
- Extraction time
- phase difference between RF in BOOSTER and SR
- Sextupole in TL2

# INJECTION ONLY “ON-DEMAND”: MINIMAL INJECTED CHARGE, MINIMAL USE OF BOOSTER POWER SUPPLY

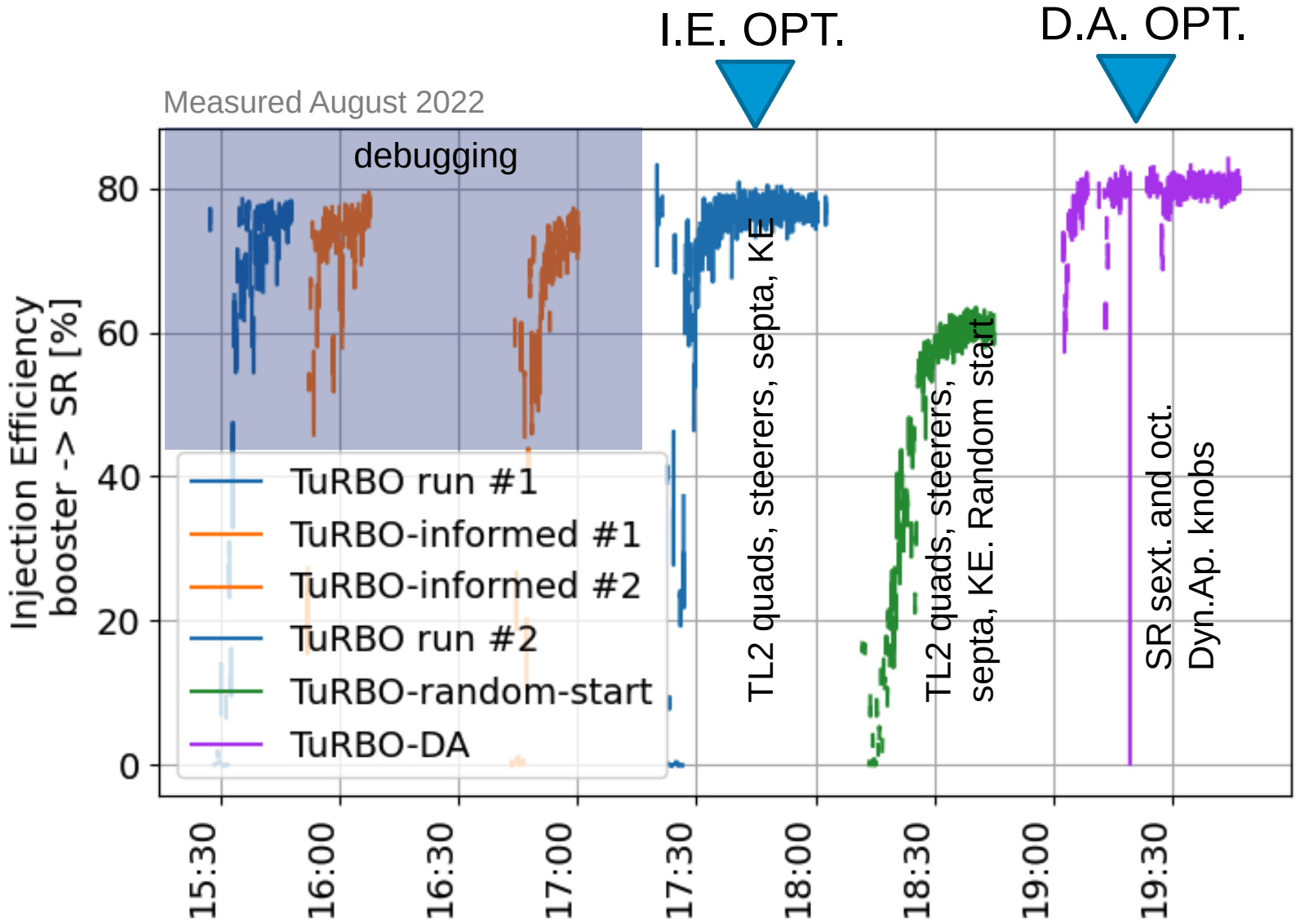



**40mA injected charge for the longest optimization (30min)**



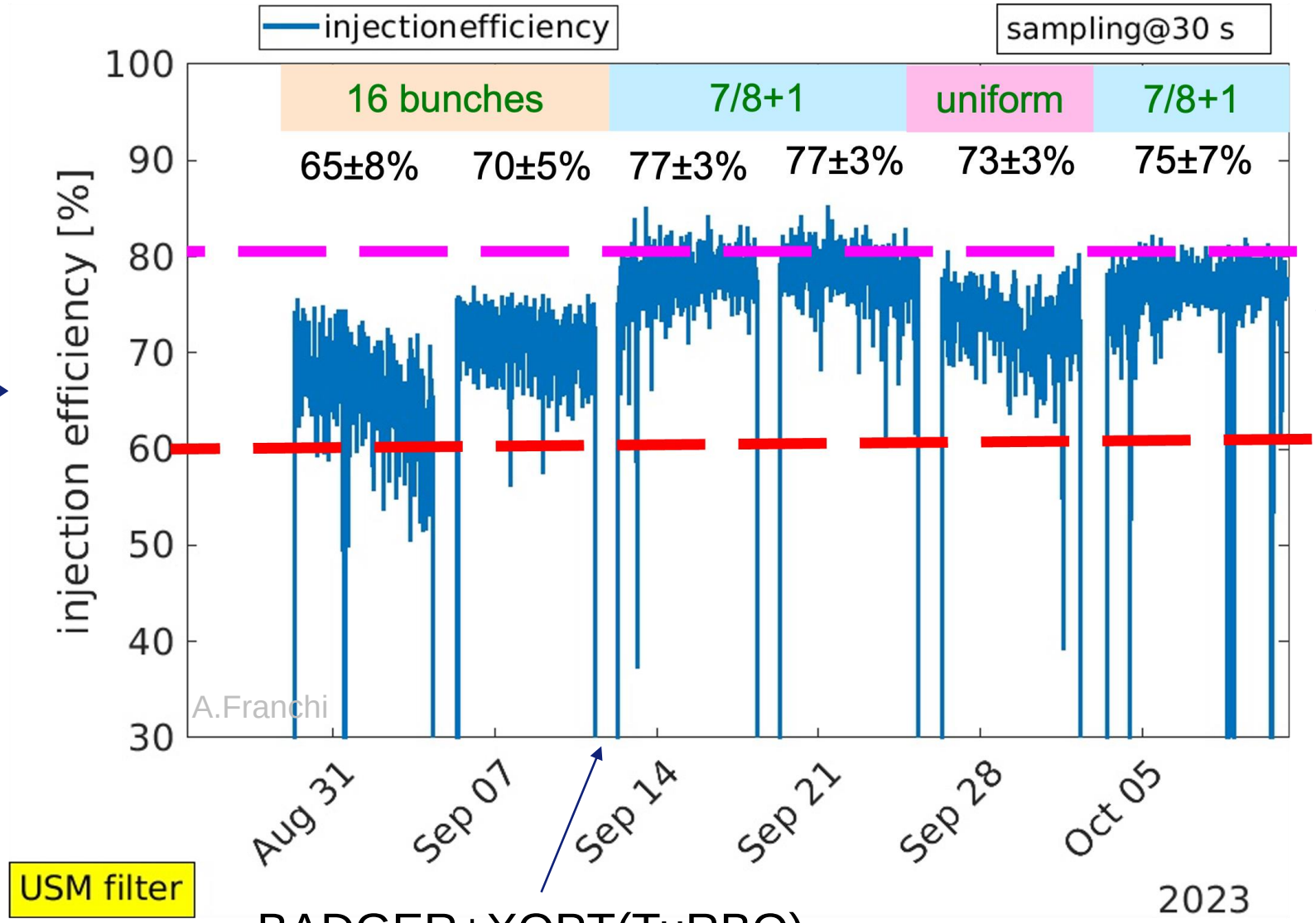

8h MDT < 200mA injected for 6 optimization runs

# OPTIMIZATIONS RUNS



# INJECTION EFFICIENCY OPTIMIZATIONS

**Previous**
run **~65%**
(60-73%)

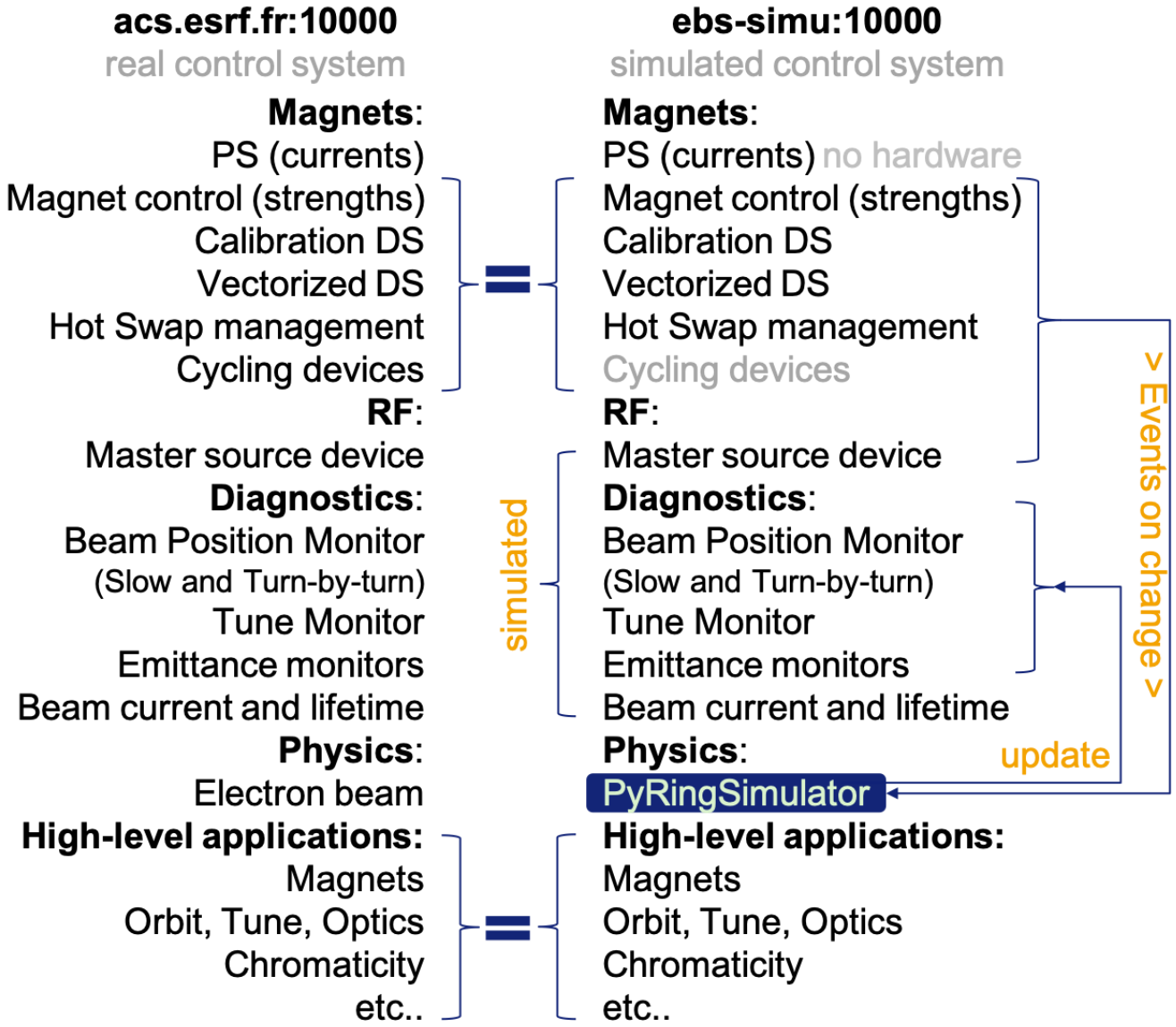



**TuRBO**
optimization
**~75%** (72-77%)

# DIGITAL TWIN / VIRTUAL ACCELERATOR / CONTROL SYSTEM SIMULATOR

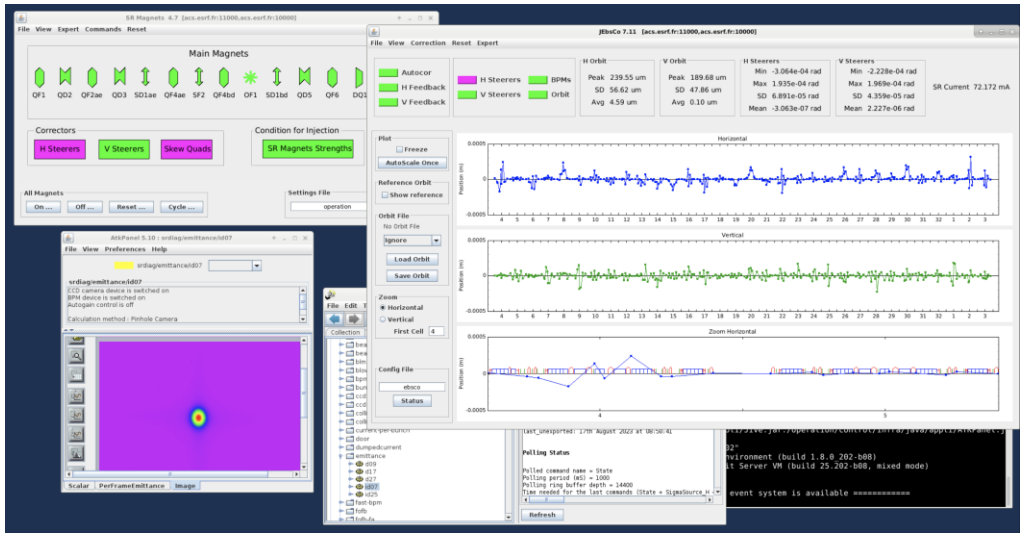
A copy of the accelerator that can be used without hardware and without beam to test new tuningdo developments.

Other existing examples:
- Matlab middle layer
- pyTAC atip (DIAMOND)
- SLS-PSI Epics virtual accelerator
- py4sin Brazilian light source
- etc…



# ESRF IN-HOUSE DIGITAL-TWIN

## **REAL** CONTROL



## **SIMULATED** CONTROL

ESRF based solution.
Cons: NOT easy TO SHARE, strongly linked to control system infrastructure.

Pros: Has online monitoring, SEE NEXT SLIDE.

PRESENT ESRF-EBS
Digital twin

PYTHON + TANGO

# ON-LINE VIRTUAL ACCELERATOR / DIGITAL SHADOW

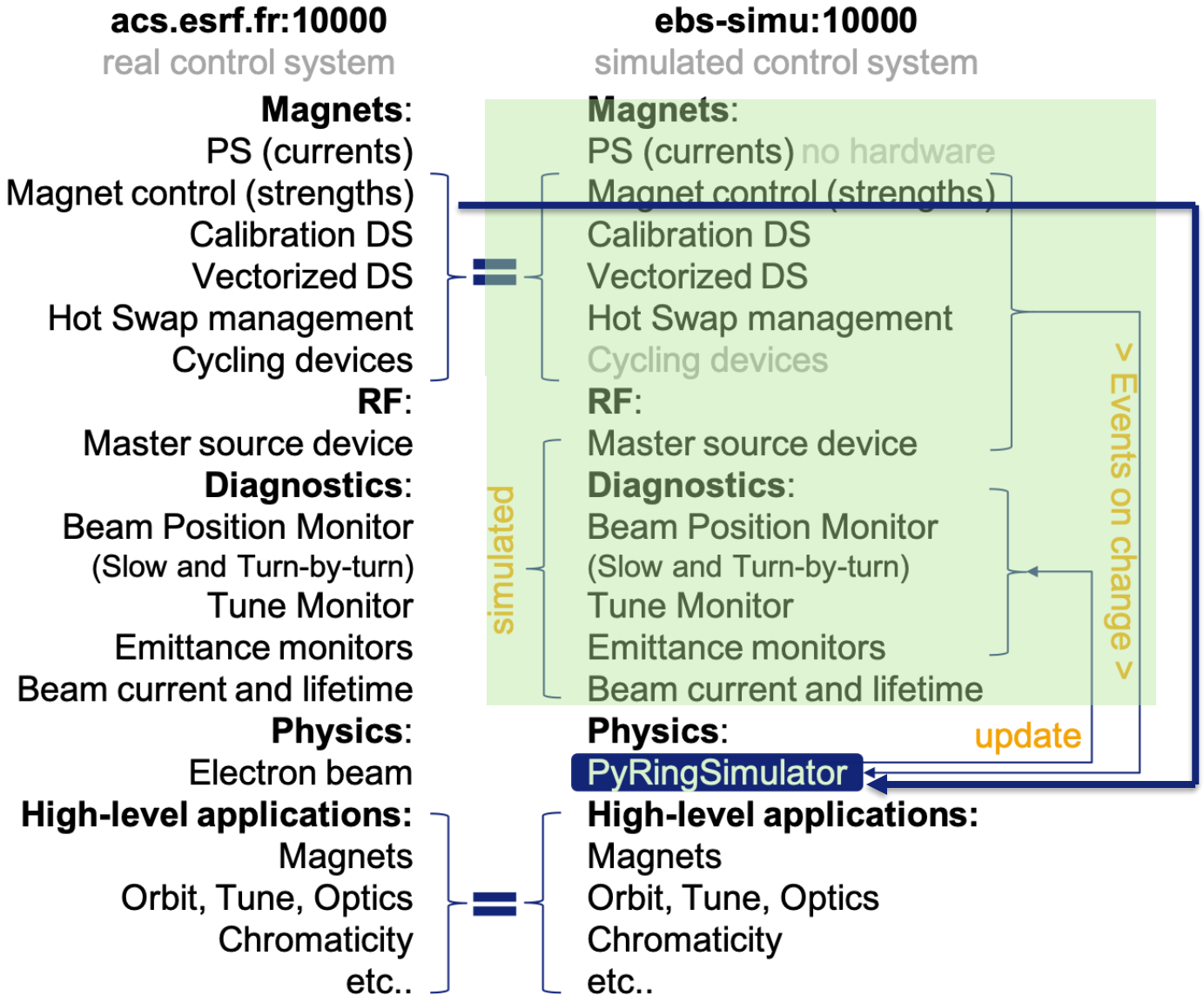
**A virtual accelerator instance constantly updated based on magnets strengths.**

Requires “strengths” from control system.

Works only in relative mode, with delta strengths not with absolute values.

Simulated data based on a lattice model including errors and all known lattice details.

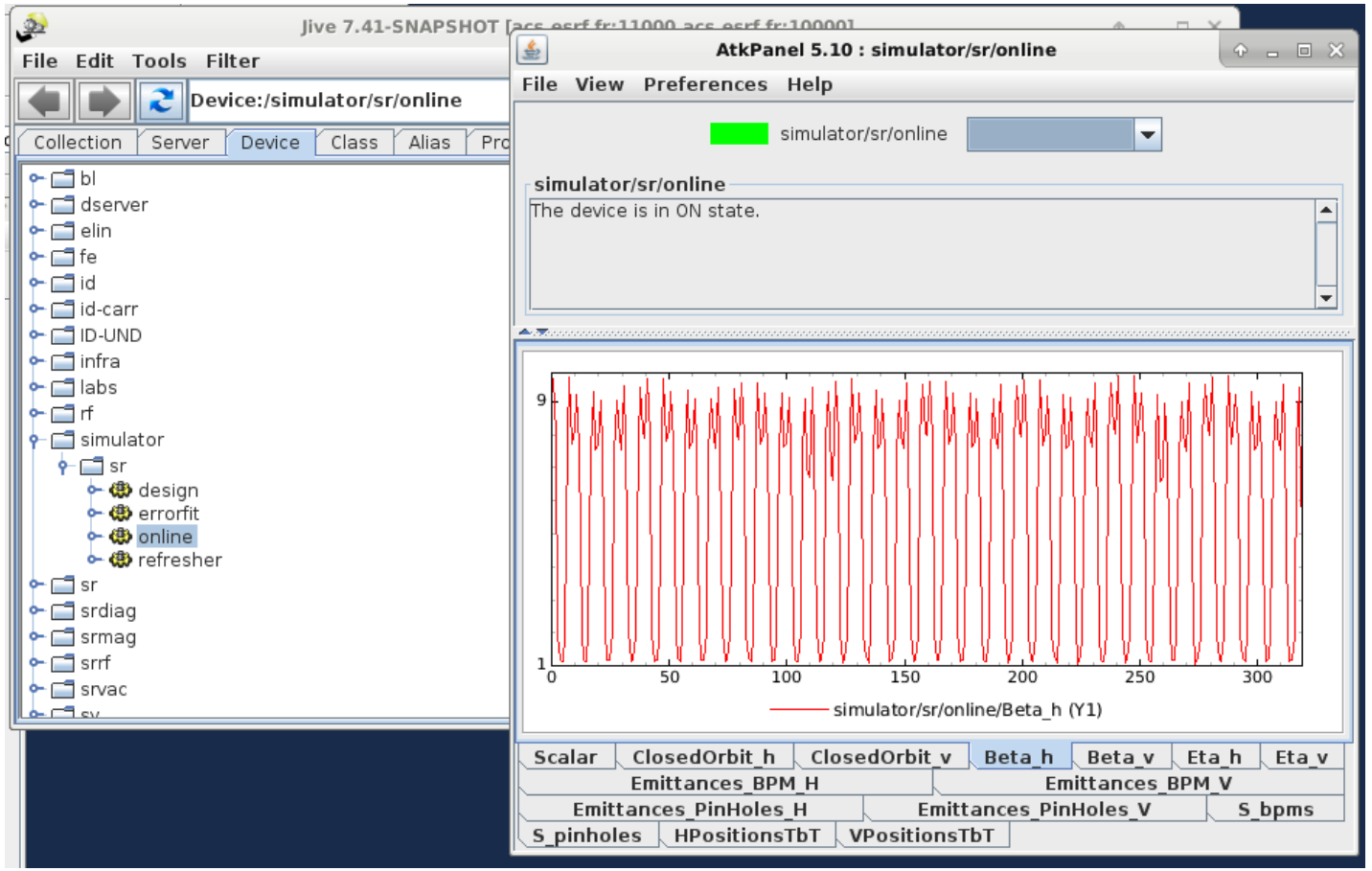
Possibility to update the online digital twin based on any subsets of magnets (ex. exclude steerers).



# SIMULATOR/SR/ONLINE

**Live (~2Hz) qualitative monitoring of relative variation of:**

1. **beta,**
2. **dispersion,**
3. **tune,**
4. **chromaticity,**
5. **orbits,**
6. **emittances,**
7. **etc..**



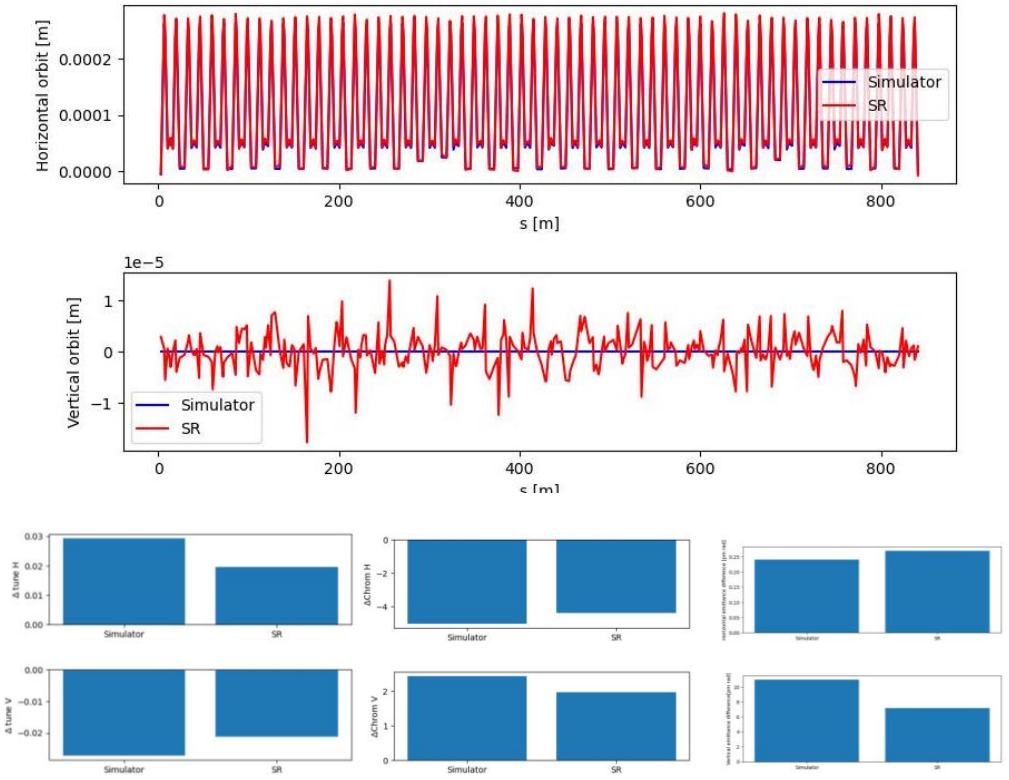

J.-L. Pons

J.L. Pons (ESRF) presently working to implement GPU tracking in AT. This will allow to add online simulated Touschek Lifetime and Injection Efficiency.

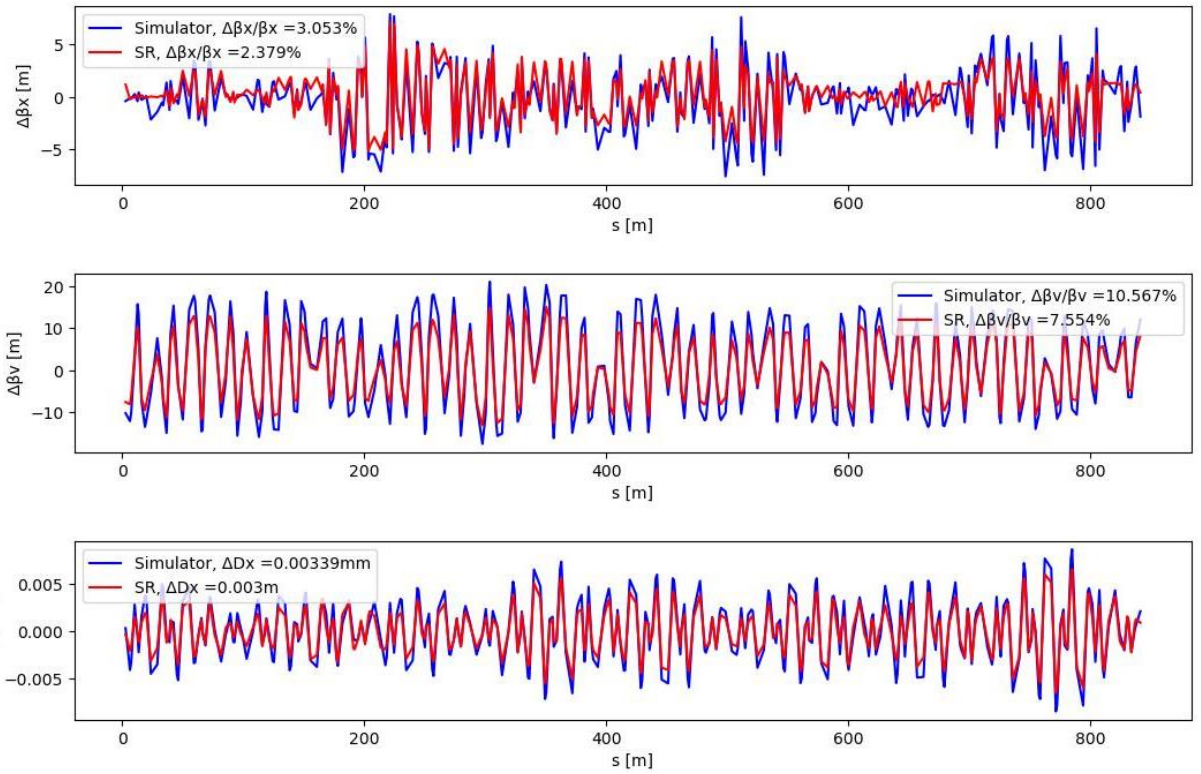
# TEST OF PRIMORDIAL DIGITAL-TWIN DS IN CTRM

**The simulators device-server is adapted to work as online "digital twin" or digital shadow of the EBS beam dynamics properties. Provides relative optics change compared to an initial set of magnets strengths.**

Frequency, tune, chroma change: measured vs digital shadow

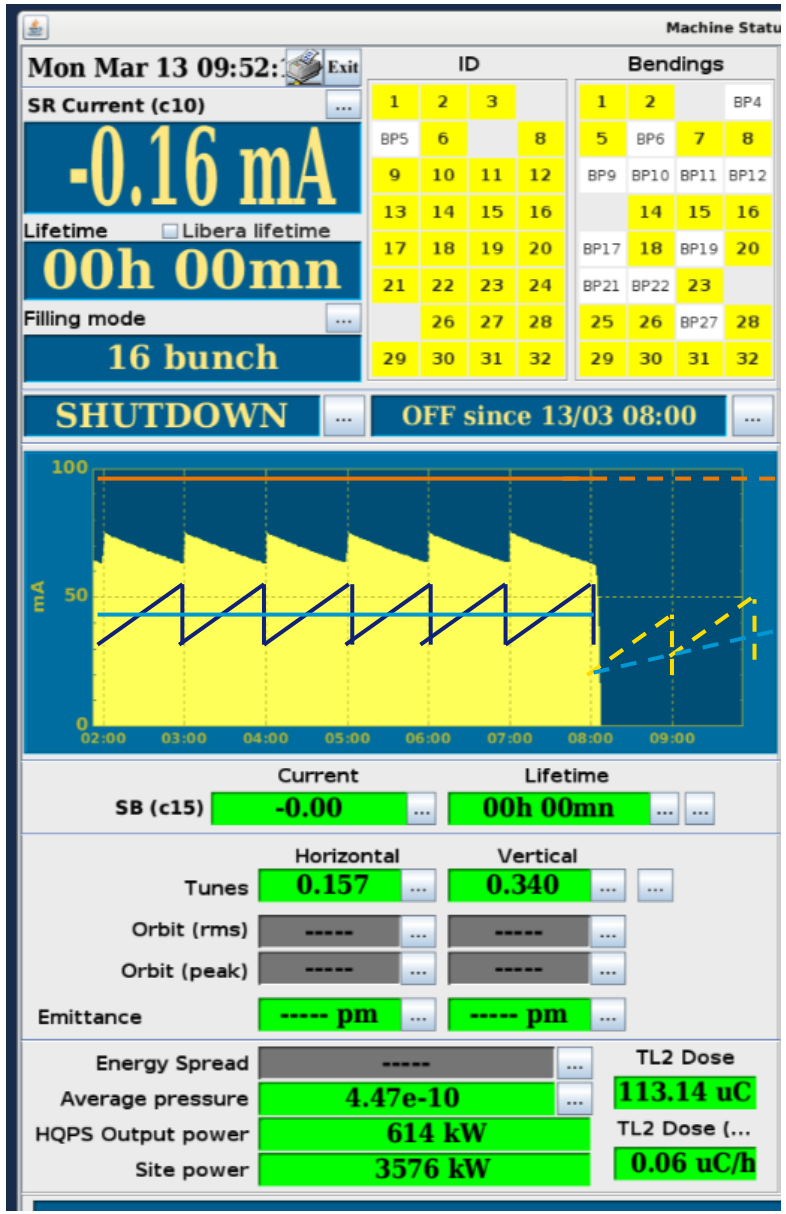



Random quad. errors in the SR: measured vs digital shadow




**All artificially introduced variations in the SR are observed in the simulator.**

# MONITORING AND PREDICTION OF TOUSCHEK AND VACUUM LIFETIMES AND INJECTION EFFICIENCY




$T_{vac}(I_{tot}$, filling patter, emittances, gaps, magnets, collimators, …)

$T_{Touschek}(I_{tot}$, filling patter, polarization, emittances, gaps, magnets, collima

Norm. Vacuum lifetime

Expexted Total lifetime

Norm. Touschek lifetime

TRAIN an AI (ML, neural network, Bayesian… informed regression, …)

Based on HDB data to provide continuous **normalized** values for Vacuum lifetime and Touschek Lifetime and the expected values of Vacuum, Touschek and total Lifetime for the few hours to come.

The DS model would continuously update based on fresh HDB data.

Measured vs Expected lifetime/injection efficiency could be used to trigger anomaly detection.

This case study has been proposed for ARTIFACT EU project

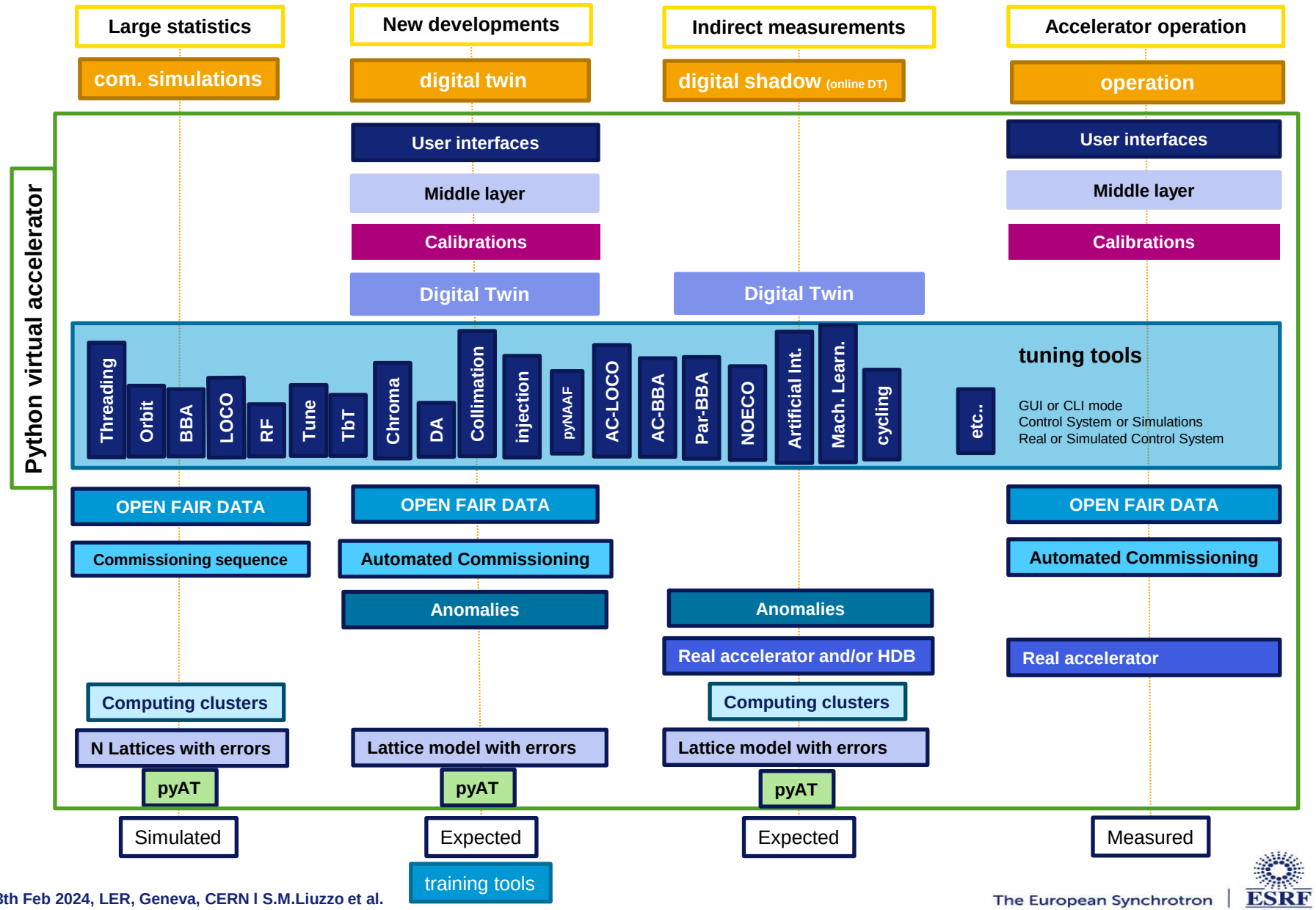
# PYTHON MIDDLE LAYER

Thanks to all the contributors to the “python middle layer” project.

Please contact me if you would like to join the project.

Next meeting 12th February at 16.00 Paris time.

**Python middle layer WORKSHOP JUNE 19-20, DESY**



# CONCLUSIONS

**Badger optimizations work very well. A new version has been released and will be tested at ESRF DESY and SOLEIL**

**An online digital twin / digital shadow is set up at ESRF.**

**Future plans:  integration of lifetime and injection efficiency in the “twinned” quantities. Very future work could include IDs gaps in the digital twin.**

**Artificial intelligence to forecast beam conditions over the next hours: ex after a beam loss. Allows to visually detect issues/anomalies.**

**Collaboration setting up for a new python middle layer software.**