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Brookhaven National Laboratory

U.S. DEPARTMENT OF ENERGY

Machine learning and model calibration at the RHIC injector compound

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CBB BDC Theme Meeting

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@BrookhavenLab

Summary

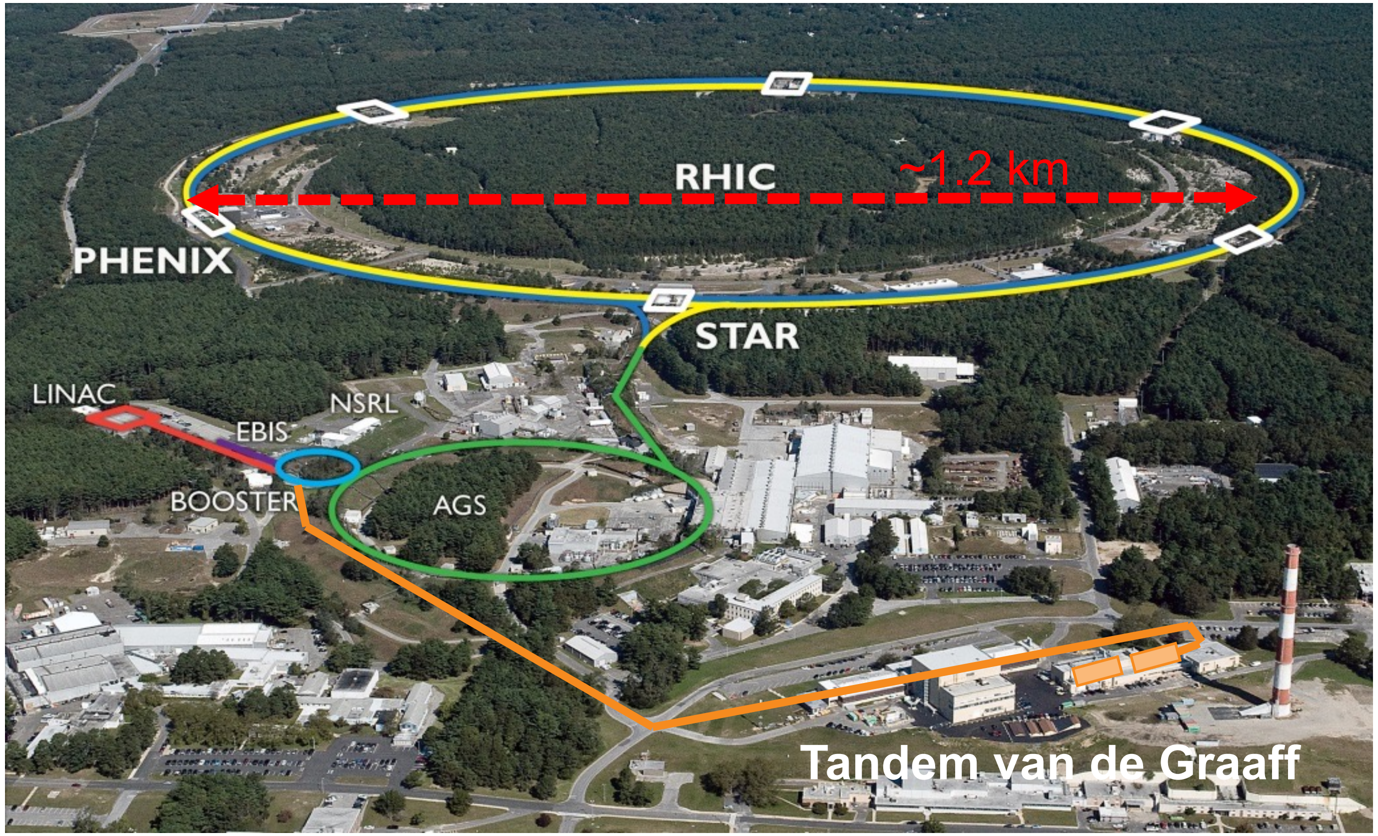
- Simulation studies with magnet misalignment at the AGS Booster
- Current to magnet strength calibration using orbit response at the AGS Booster
- AGS Booster injection optimization with Bayesian optimization

Motivation

<u>Relativistic Heavy Ion Collider (RHIC)</u>: world's only high-energy polarized proton beam and largest operating accelerator in the US

→ *unique opportunities to study from where nuclei obtain their spin*

<u>Electron Ion Collider (EIC)</u>: new successor to RHIC; will collide polarized proton and electron beams



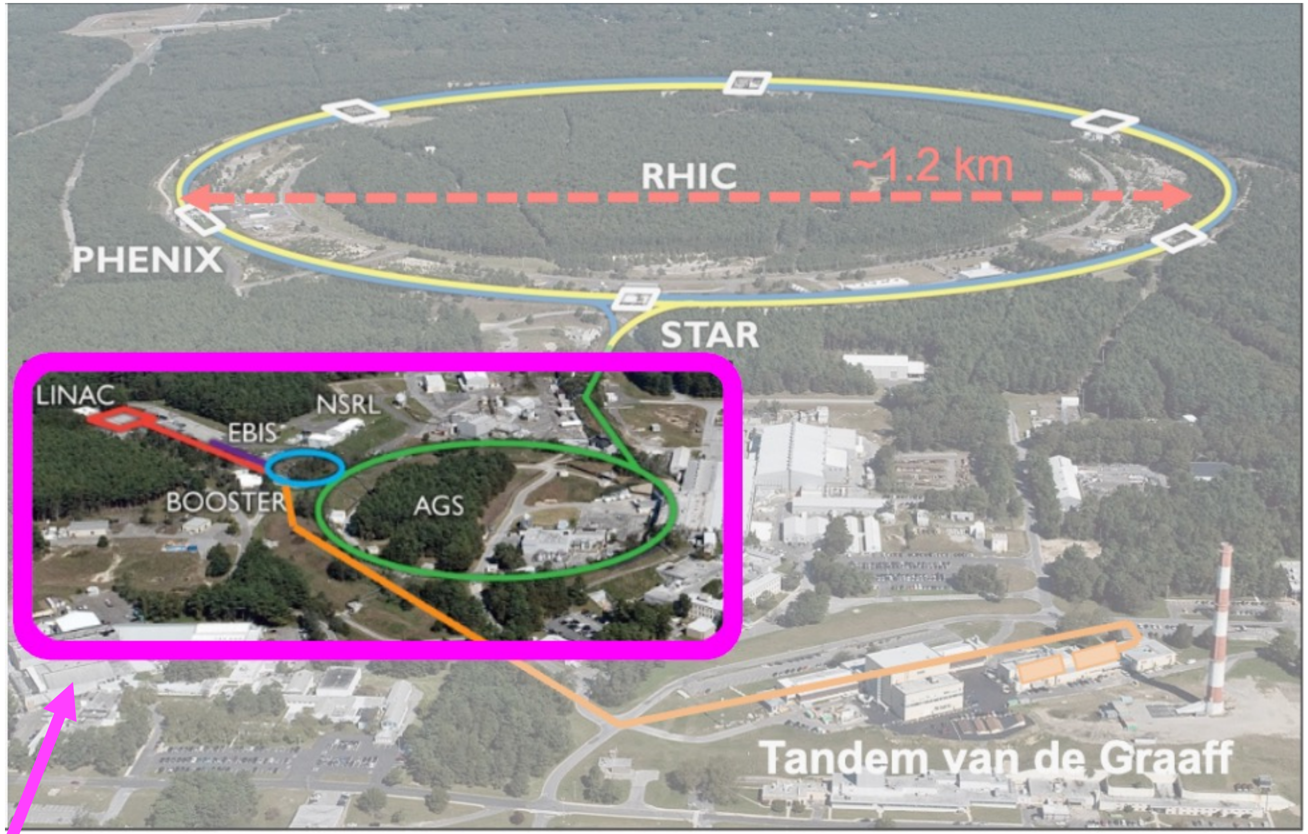
Increase in instrument complexity for EIC will require new tools to optimize accelerator performance and maximize the utility of polarized beam experiments

Motivation

Alternating Gradient Synchrotron (AGS) and its **Booster** serve as part of the **injector compound** for RHIC and future EIC

Typical Top Energies [Total, GeV/N]		
	Au	**Pol. Protons**
Linac (H^-)	--	1.1
Booster	1	2.3
AGS	10	23.8
RHIC	100	255

Bright ion beams in AGS / Booster are required for optimal luminosity and highest polarization in RHIC and EIC



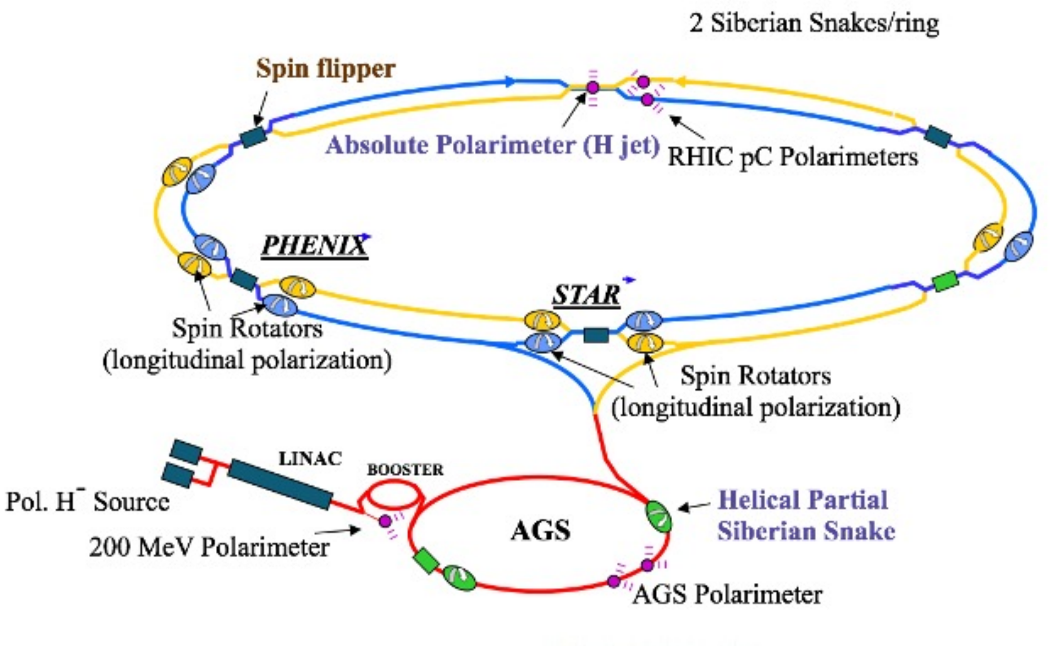
Heavy Ions	Protons
E-beam Ion Source (EBIS)	OPPIS (polarized)
Tandem Van de Graaf	High-intensity H^- (unpolarized)

Polarization at RHIC

	Max Energy [GeV]	Pol. At Max Energy [%]	Polarimeter
Source+Linac	1.1	82-84	
Booster	2.5	~80-84	
AGS	23.8	67-70	p-Carbon
RHIC	255	55-60	Jet, full store avg*

Loss in polarization along the chain

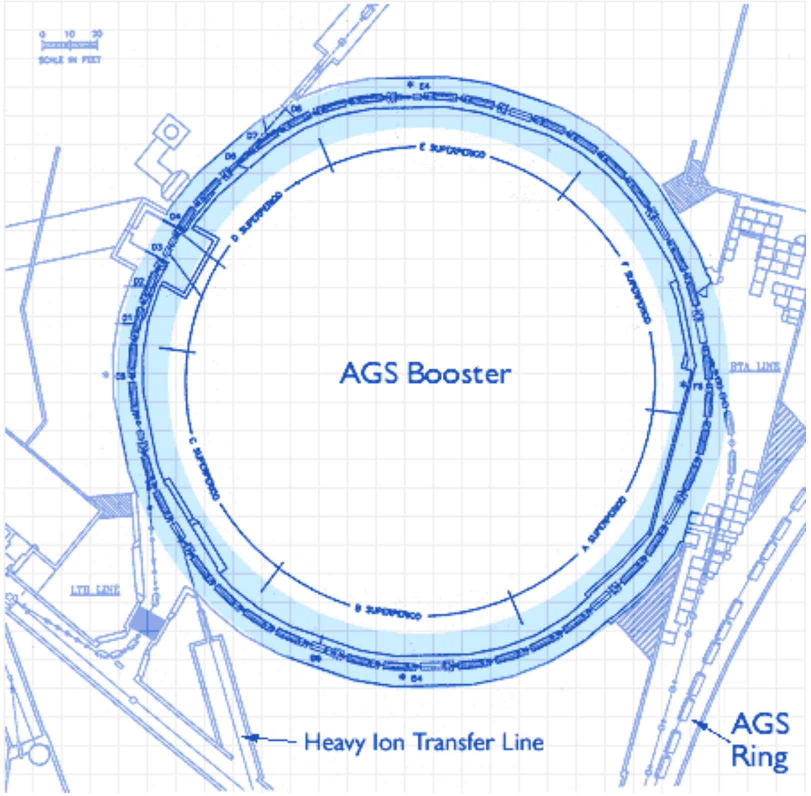
	Relative Ramp Polarization Loss (Run 17, full run avg)
AGS	17 %
RHIC	8 %



Polarimetry available at:
- Source
- End of Linac (200 MeV)
- AGS extraction
- RHIC injection energy
- RHIC flattop

No Booster polarimeter

Alternating Gradient Synchrotron (AGS) Booster

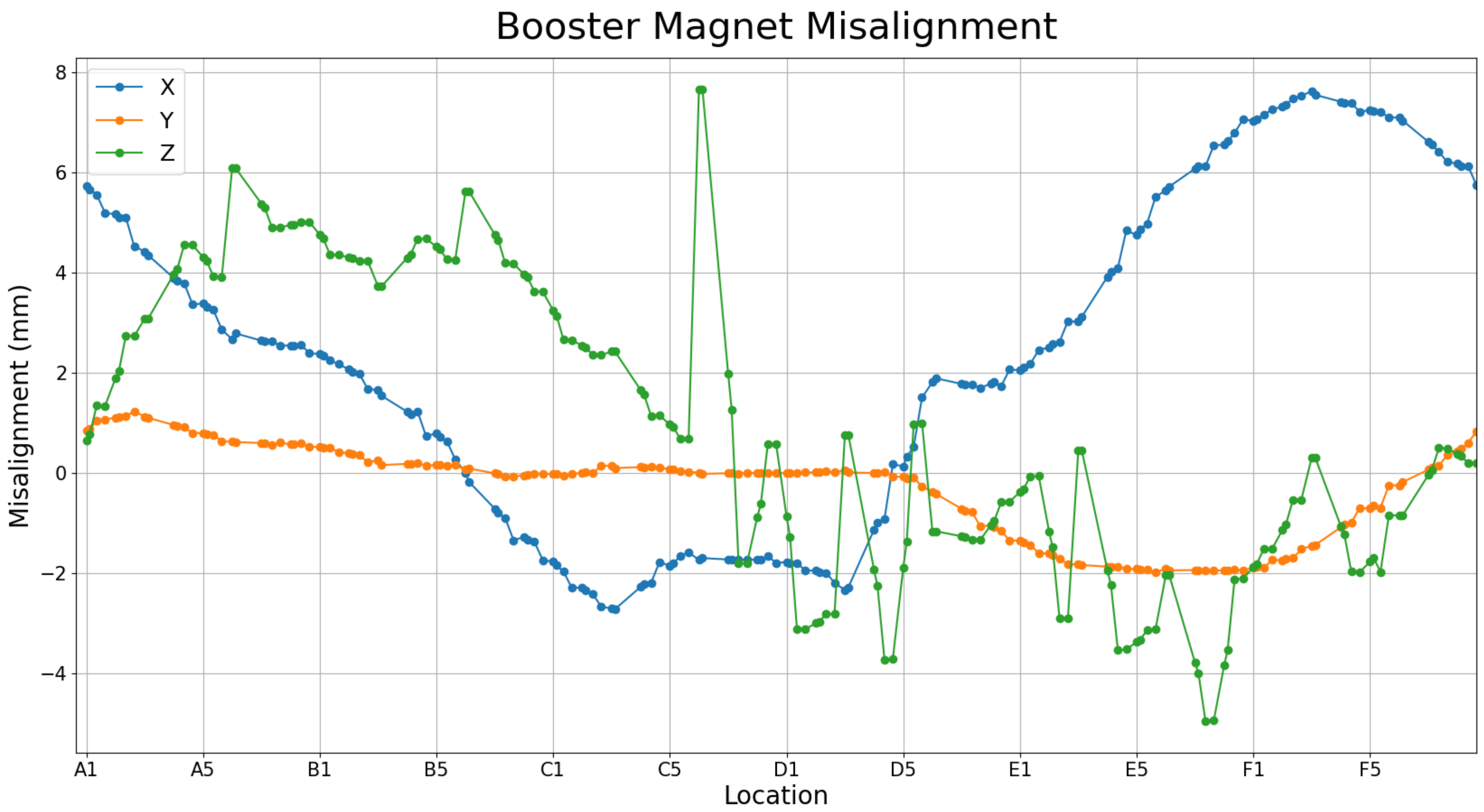


- Pre-accelerate particles entering the AGS ring
- Accepts heavy ions from EBIS or protons from 200 MeV Linac
- Serves as heavy ion source for NASA Space Radiation Laboratory (NSRL)
- 6 super-periods (A to F), 72 main magnets

Simulation studies with magnet misalignment at the ASG Booster

Booster magnet misalignment

- Magnet location in real machine from 2015 survey data
- Misalignment data for quadrupoles and dipoles
- There has been trouble with making physics simulation with misalignment agree with real orbit data

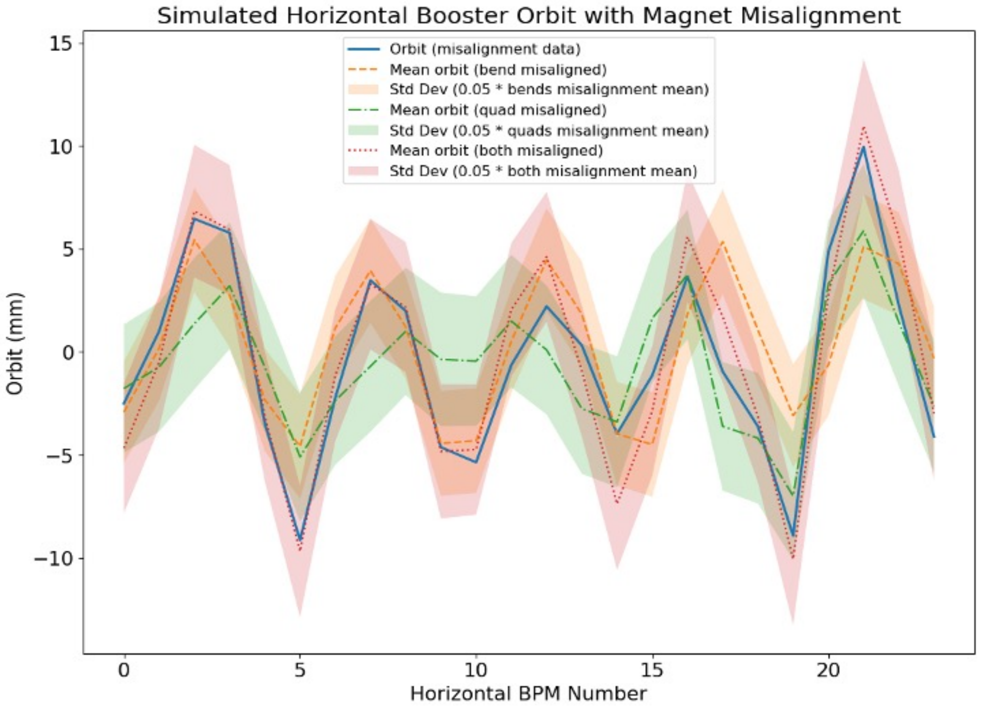


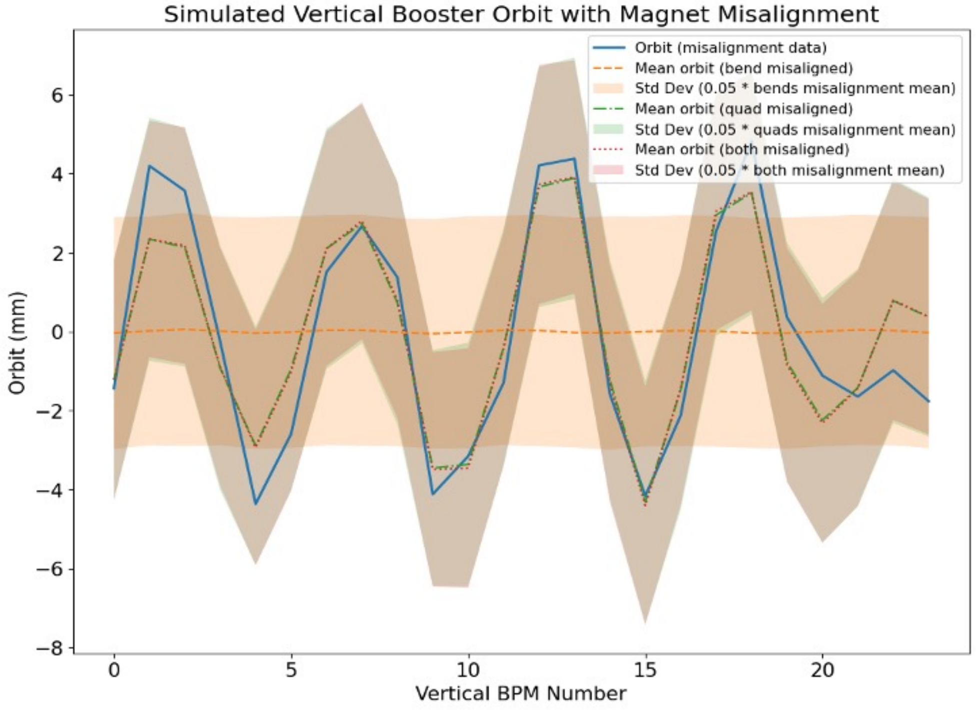
Misalignment simulation

- Simulation studies were done using Bmad Booster model to see how magnet misalignments affect the bare orbit (orbit with all correctors off).
- Survey misalignments from 2015 were used as the baseline values in the model.
- Three scenarios were studied: only misalign dipoles, only misalign quadrupoles, and misalign both.
- Using survey data as mean, normal distributions of misalignment values with 5% standard deviation were simulated.

Misalignment simulation results

- Quadrupole misalignment has much bigger impact on bare orbit than dipoles, especially in the vertical plane.
- 5% standard deviation can result in deviations as large as 2 mm.
- Further studies needed to compare simulation to real bare orbit.

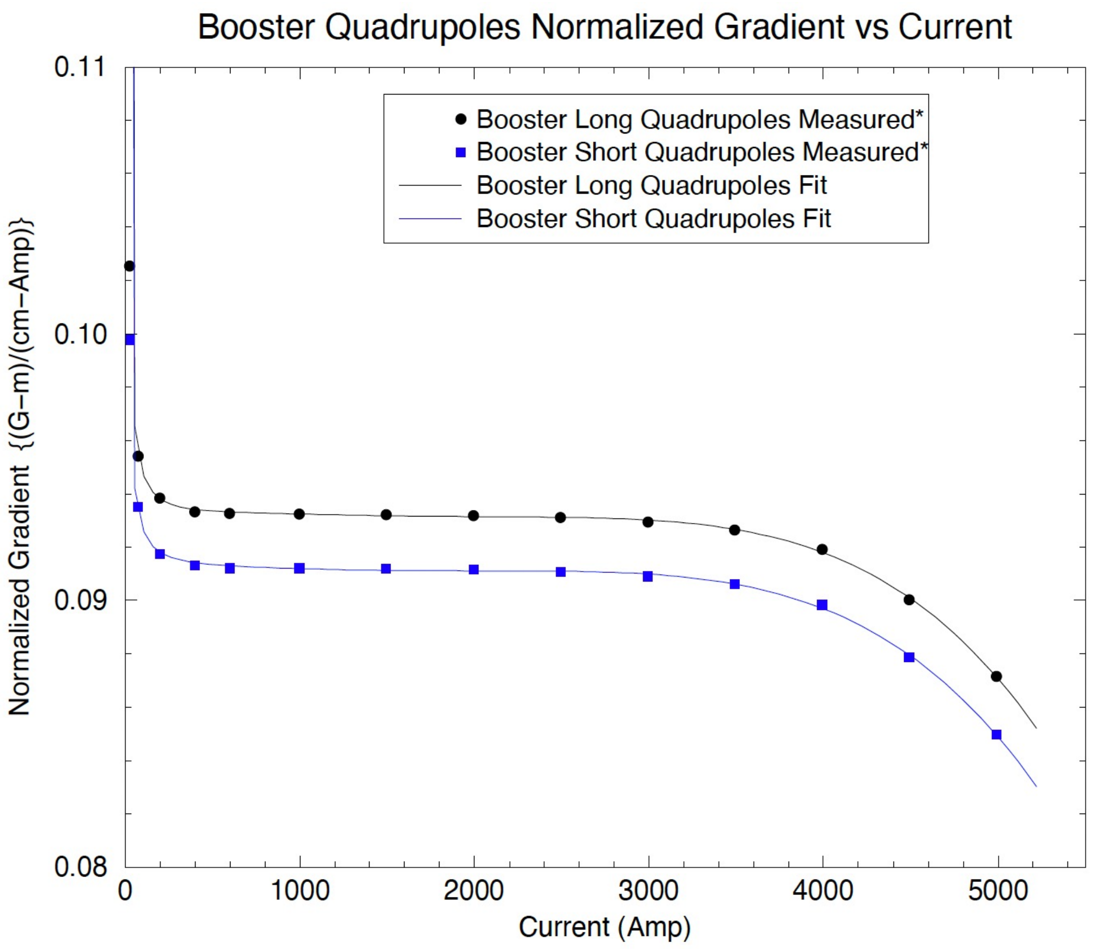




Current to magnet strength calibration using orbit response at the AGS Booster

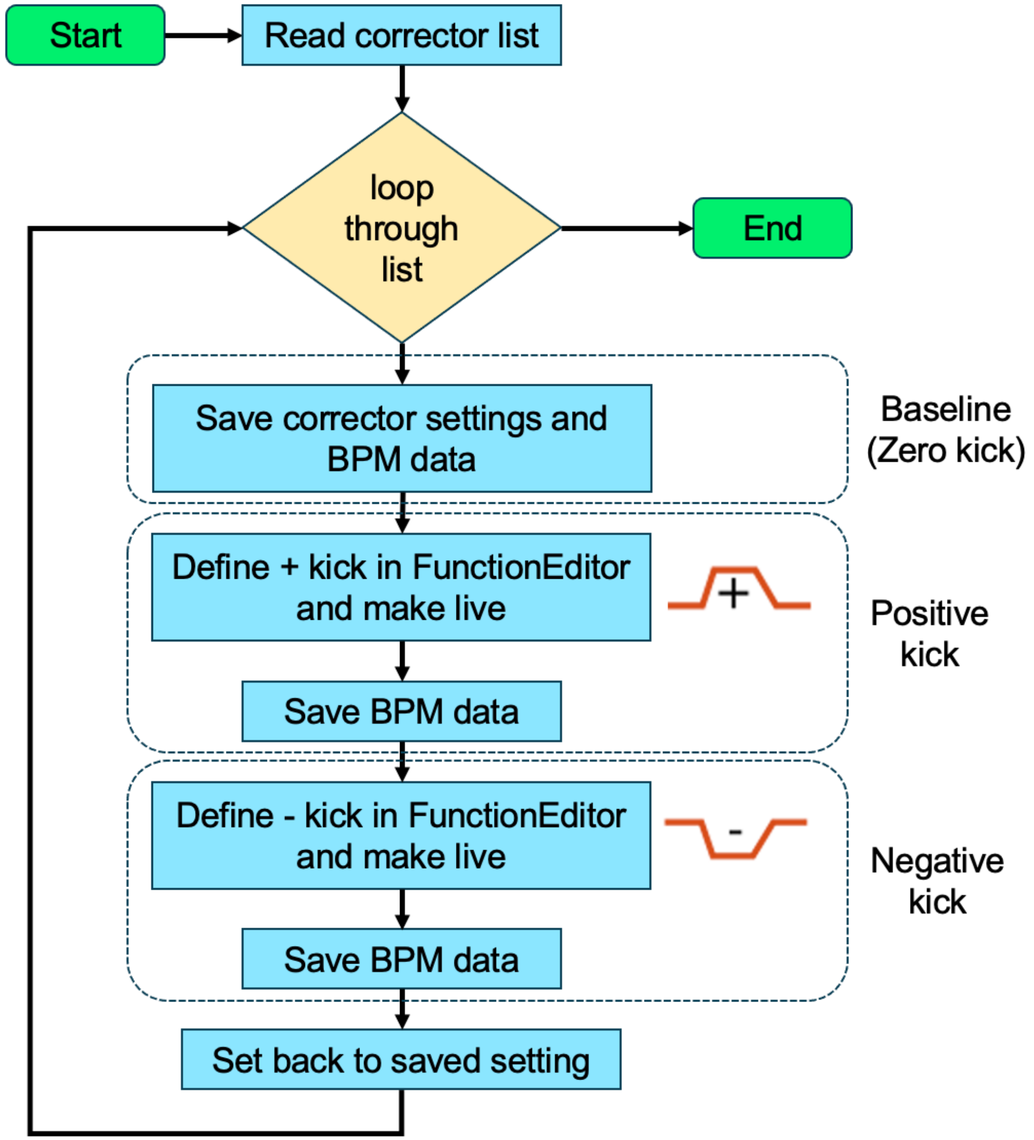
Magnet current to strength mapping

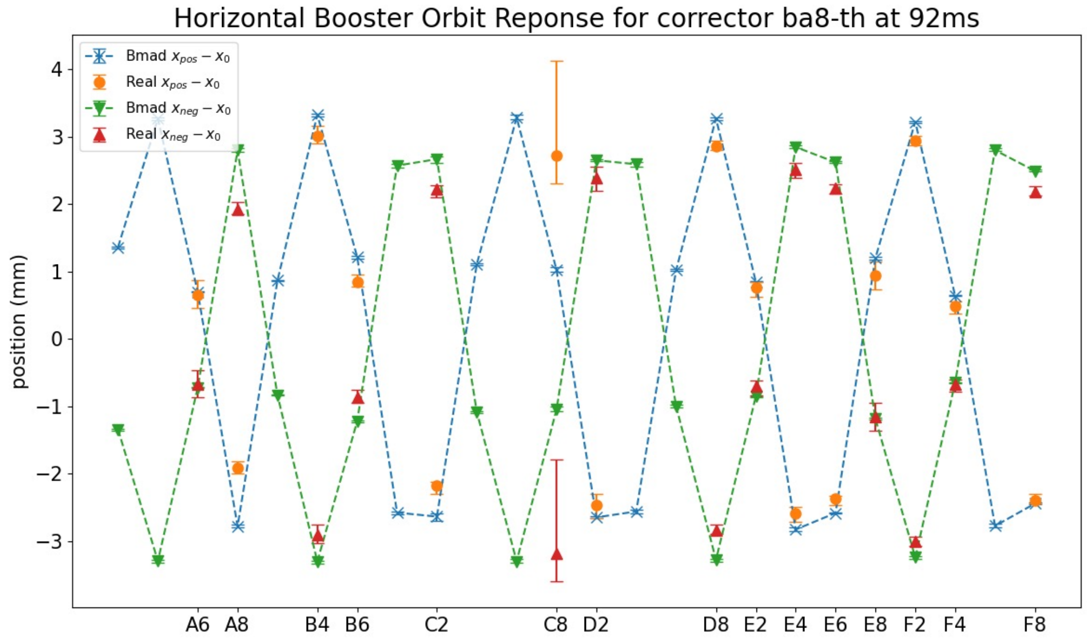
- **<u>Magnet transfer function</u>**: mapping between the power supply (PS) current and the resulting strength of a magnet
- Example: 5th order polynomial for Booster quadrupoles
- Transfer functions are measured before the magnets were installed in the ring, and there is no existing way to verify them after installation.

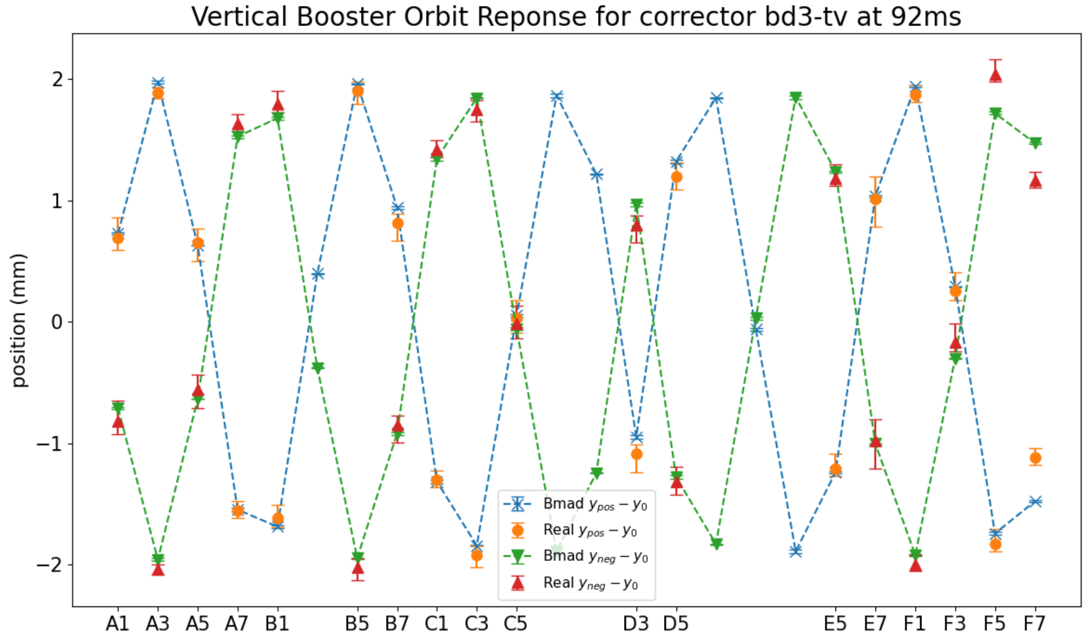


CAD script to get real orbit responses

- Script development with Collider Accelerator Department (CAD) Controls Group
- FunctionEditor: send trapezoid-like time-dependent function to corrector power supplies
- Script sets three corrector settings: positive, zero, negative; and save corresponding orbits
- All magnet settings (including dipoles and quadrupoles etc.) are saved for model comparison





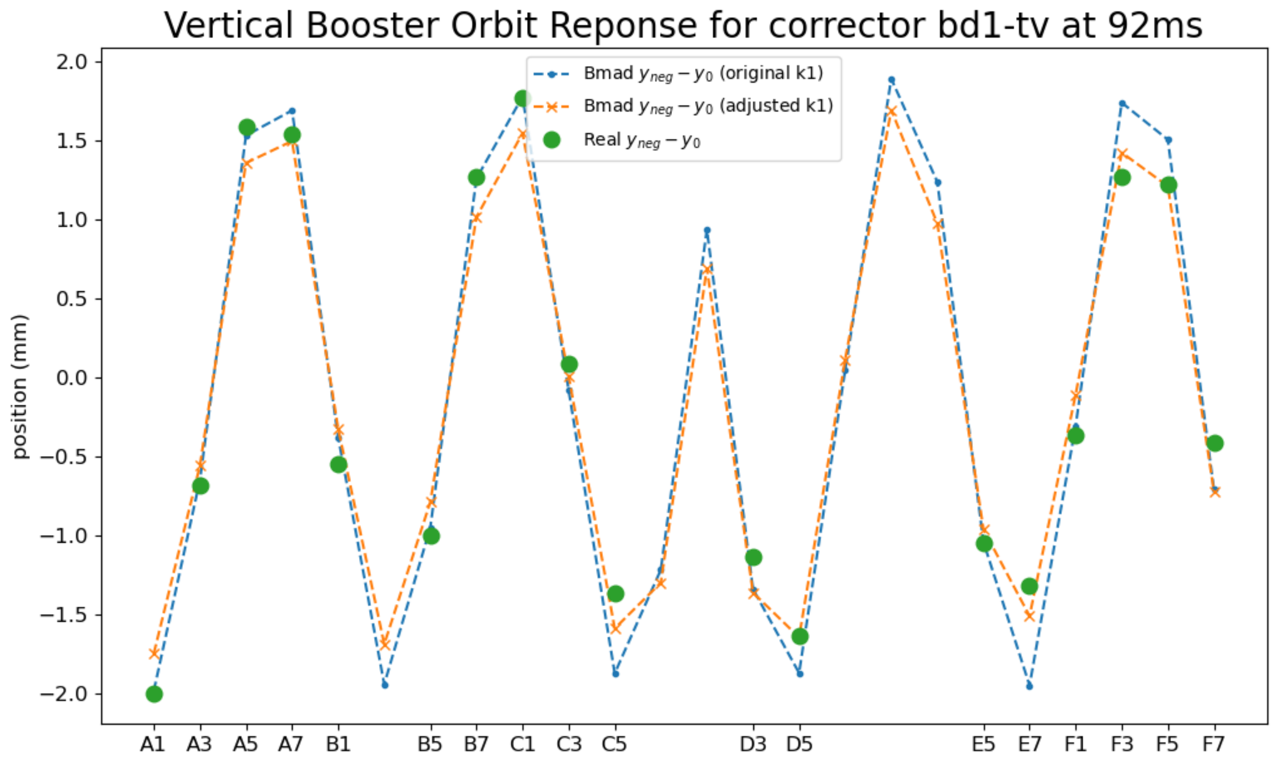


Orbit response data

- 2 difference orbits between 3 corrector settings: positive – zero, negative – zero
- Magnet settings saved during data collection are loaded into Bmad to generate simulated difference orbits
- Good agreements are reached, despite some faulty BPMs (i.e., PUEHC8)
- Small discrepancies (within 1 mm) beyond error bars could be results of inaccurate magnet transfer functions

Quadrupole transfer function calibration

- Discrepancies of difference orbits can be due to inaccurate quadrupole transfer function in the model (PS current → k1 value)
- Adjustments in k1 values of the quadrupoles are shown to affect difference orbit
- MSE between measurement and model decreases from 0.069 to 0.038



Summary of model calibration

- Simulation studies were done to show how magnet misalignments affect the bare orbit.
- Difficult to match model to reality , need new survey data.
- ORM script shows rough difference orbit agreement between measurements and Bmad simulation.
- Small deviations in difference orbit can come from inaccurate quadrupole transfer functions.
- Further investigation is underway to find best quadrupole adjustments to make model agree with measurements.

AGS Booster injection optimization with Bayesian Optimization

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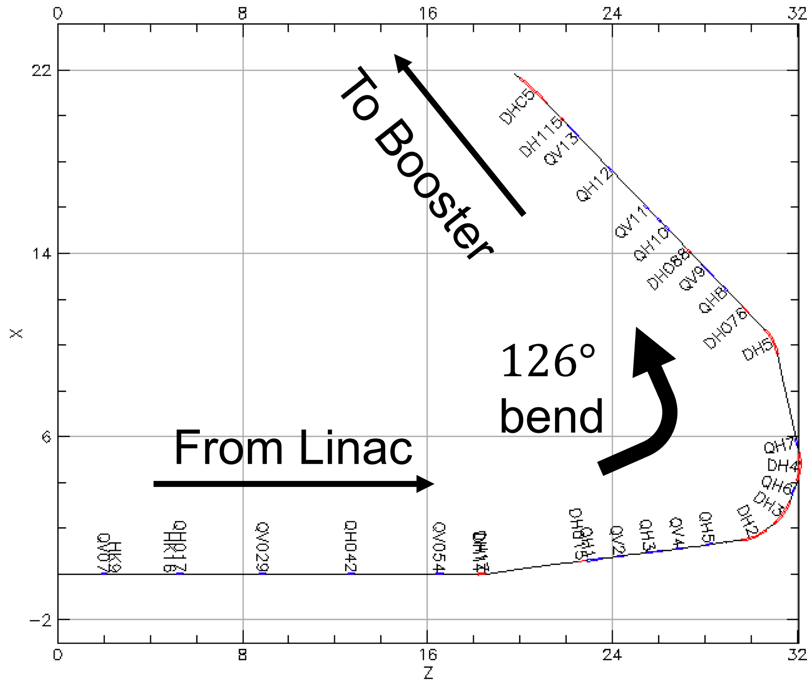
Booter injection

- Booster injection/early acceleration process sets maximum beam brightness for rest of acceleration through RHIC
- Linac pulse of 300 us, H^- beam ~6-9x10^{11} protons, strip through a carbon foil
- Intentional horizontal and vertical scraping reduce emittance (and intensity) to RHIC requirements
- Goal: minimize beam loss at scraper / maximize beam intensity after scraping
- Controls: Linac to Booster (LtB) transfer line optics
- Method: Bayesian Optimization

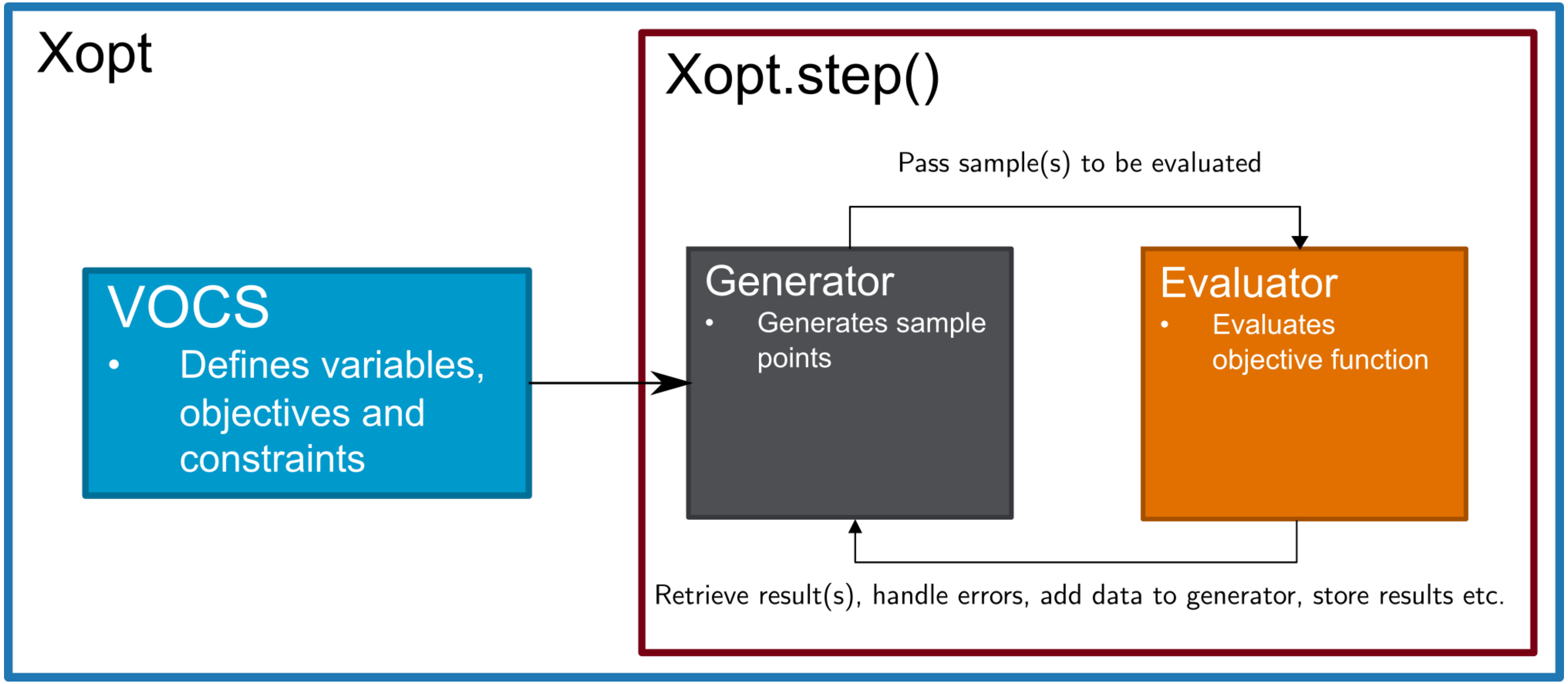


ML package: Xopt

- Flexible **framework** for optimization of arbitrary problems using python
- **Independent** of problem type (simulation or experiment)
- **Independent** of optimization algorithm & easy to incorporate custom algorithms
- Easy to use text interface

https://github.com/ChristopherMayes/Xopt

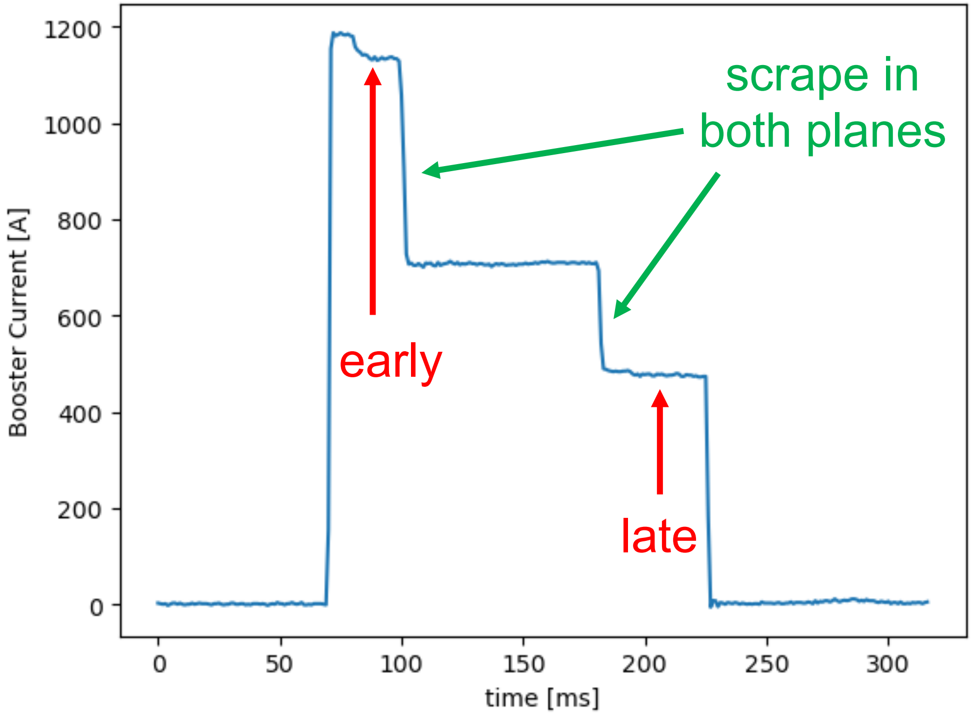
Xopt structure

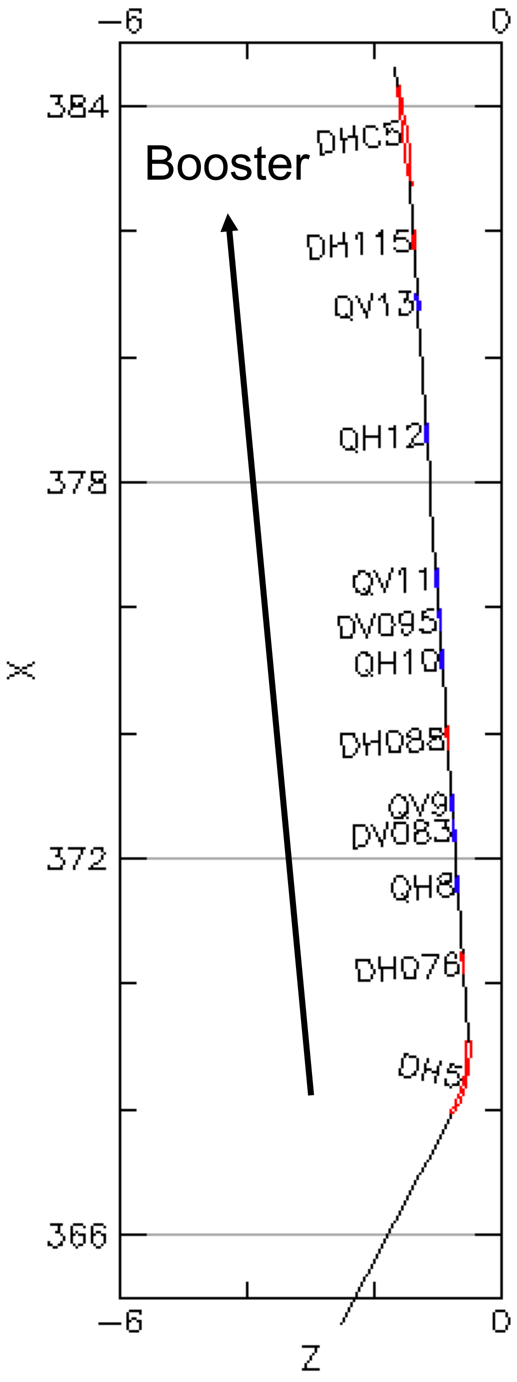


Note: this process can also be done asynchronously

LtB controls and measurement

- 13 quadrupoles and 16 correctors between Linac and Booster
- Common practice to improve Booster injection efficiency: tune last few correctors at the end of the LtB line
- Criteria to check injection efficiency: Booster early and late intensity

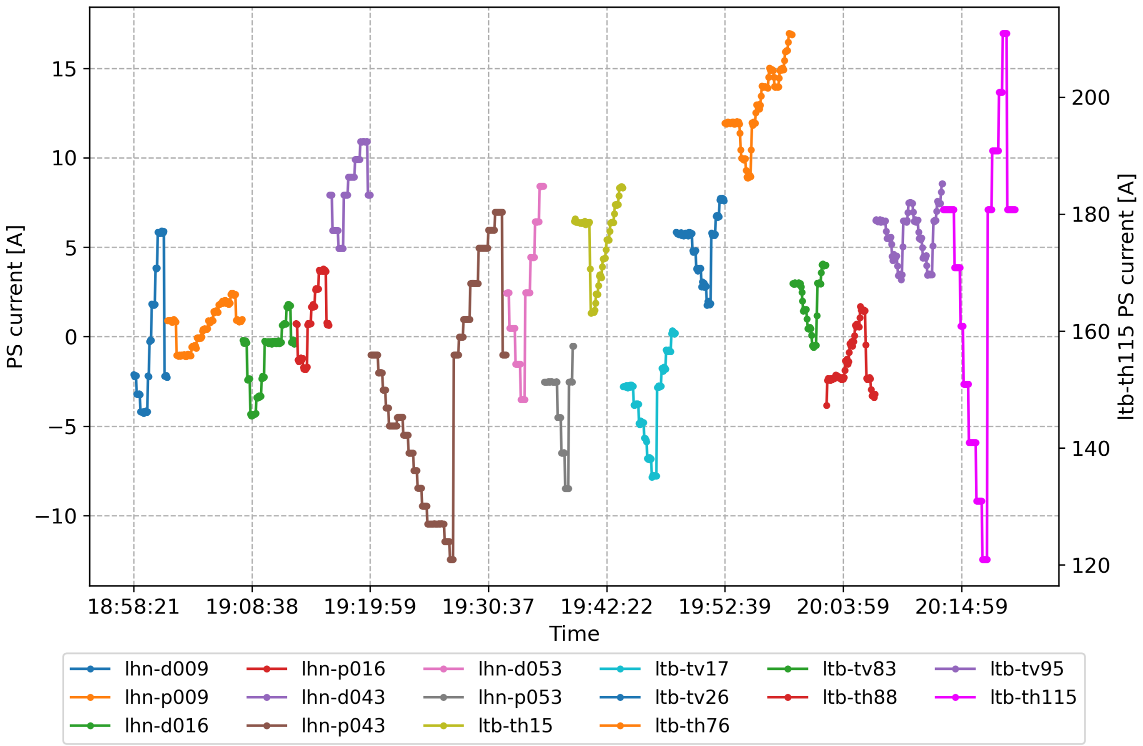


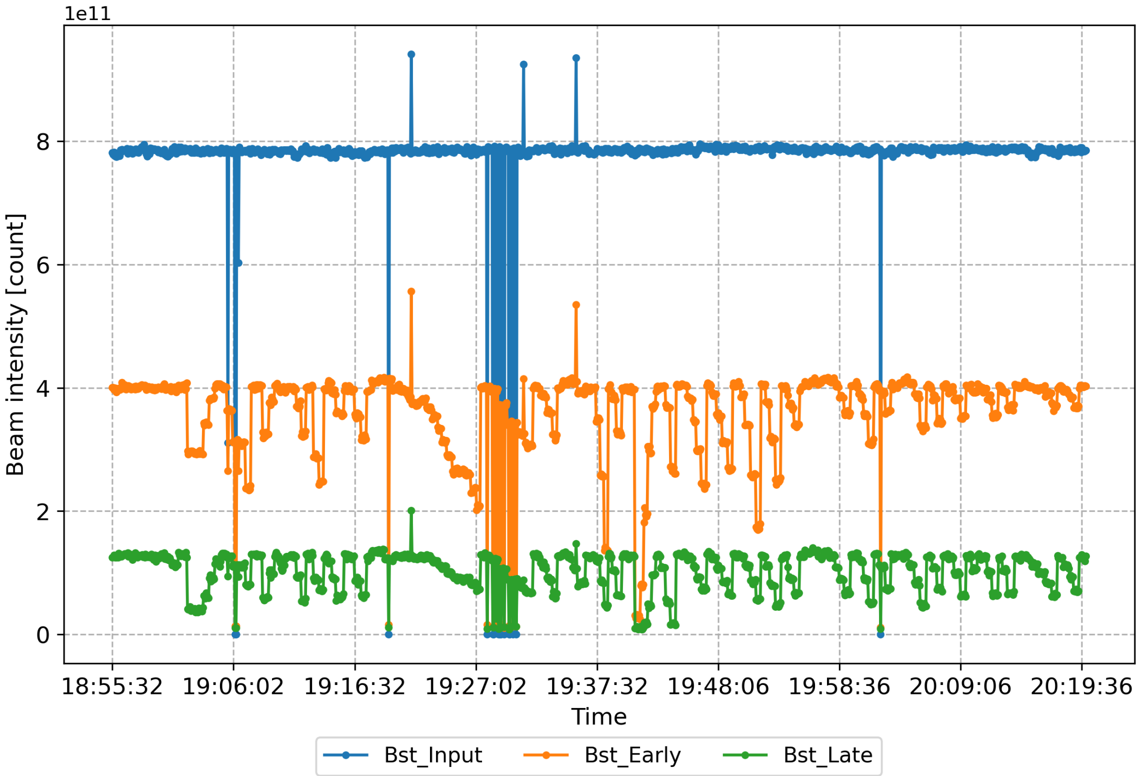


LtB corrector scan

Operator: Petra Adams

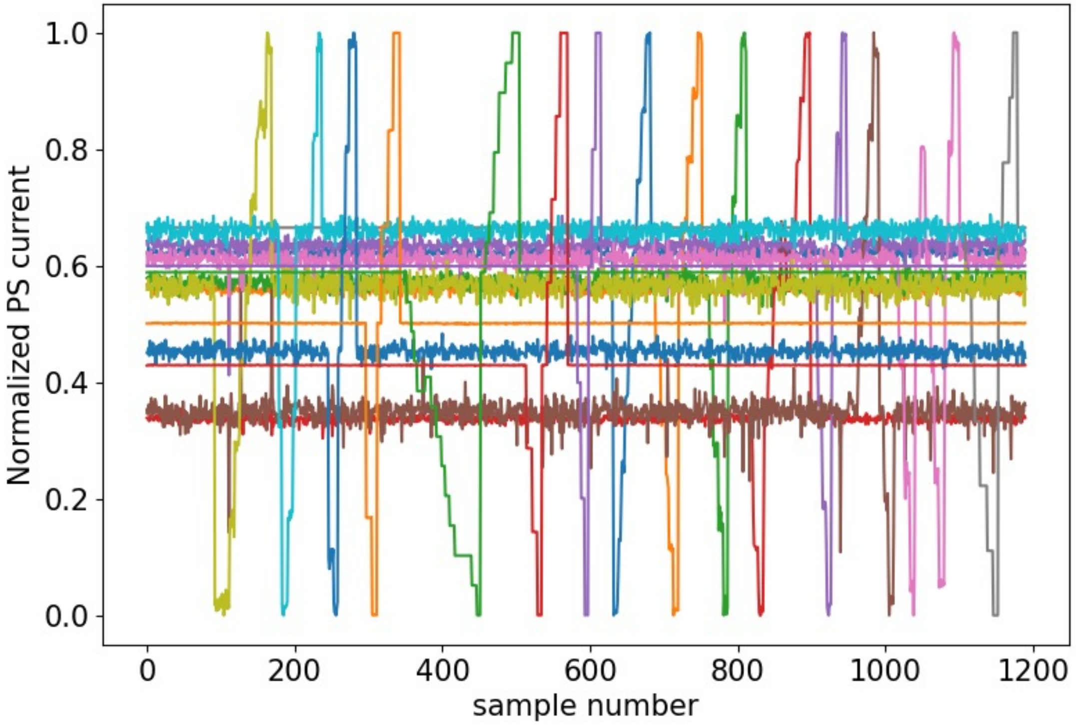
- All 16 correctors were scanned on Jan 25, 6:55pm – 8:20pm, on PPM user 4 until Booster late intensity dropped by 50%

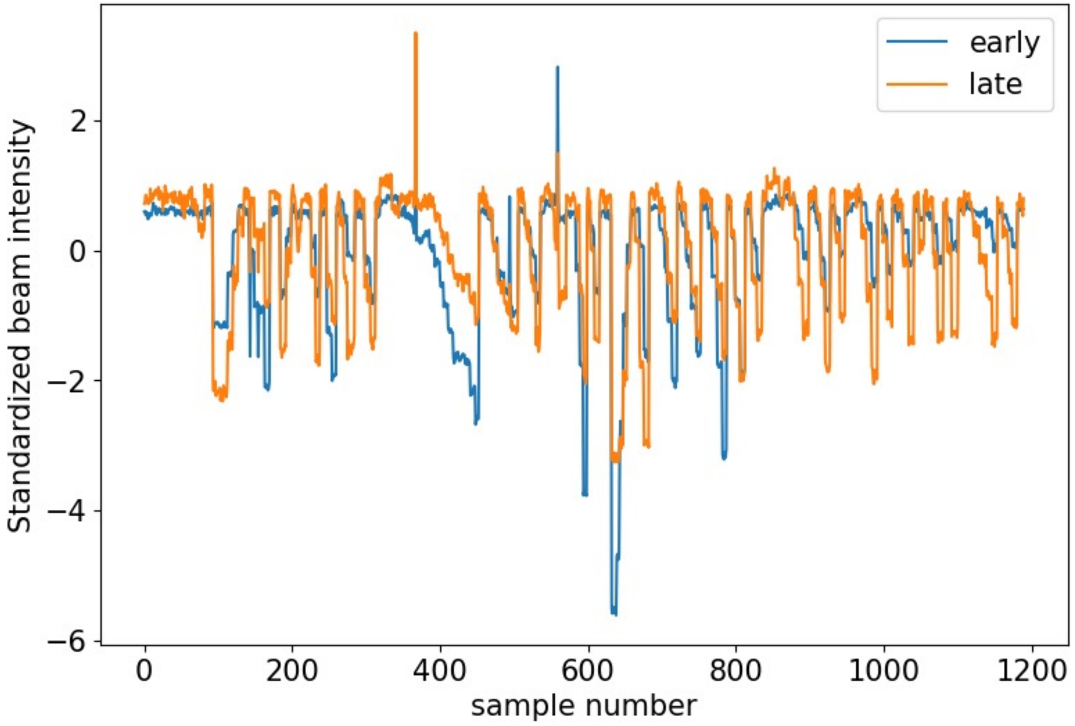




NN model for LtB scan

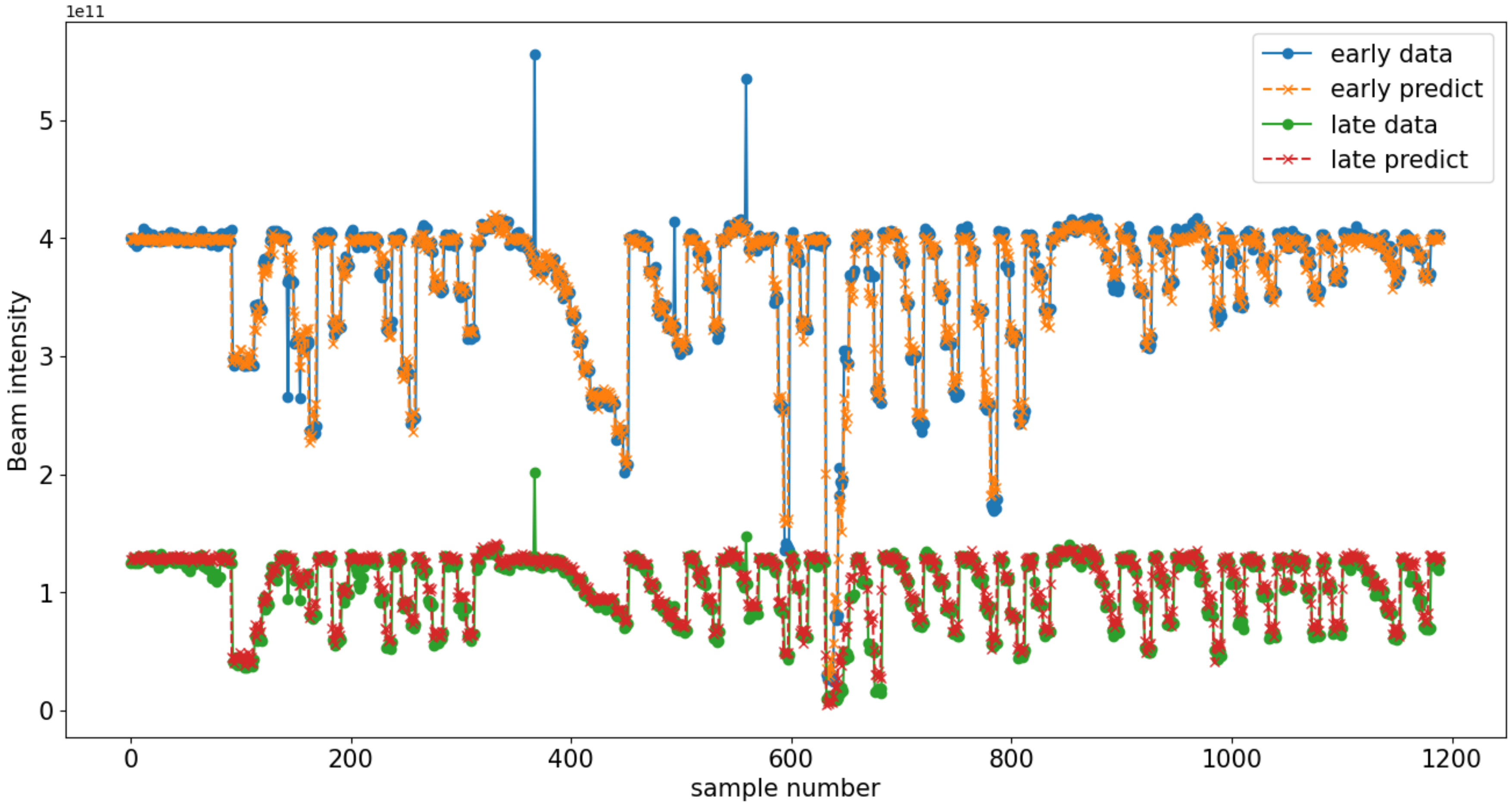
- Inputs: 15 correctors (lhn-d009 is excluded due to insensitivity)
- Outputs: 2 intensities (Bstr_Early, Bstr_Late)
- Got rid of points where input intensity dropped to zero
- Normalized inputs, standardized outputs





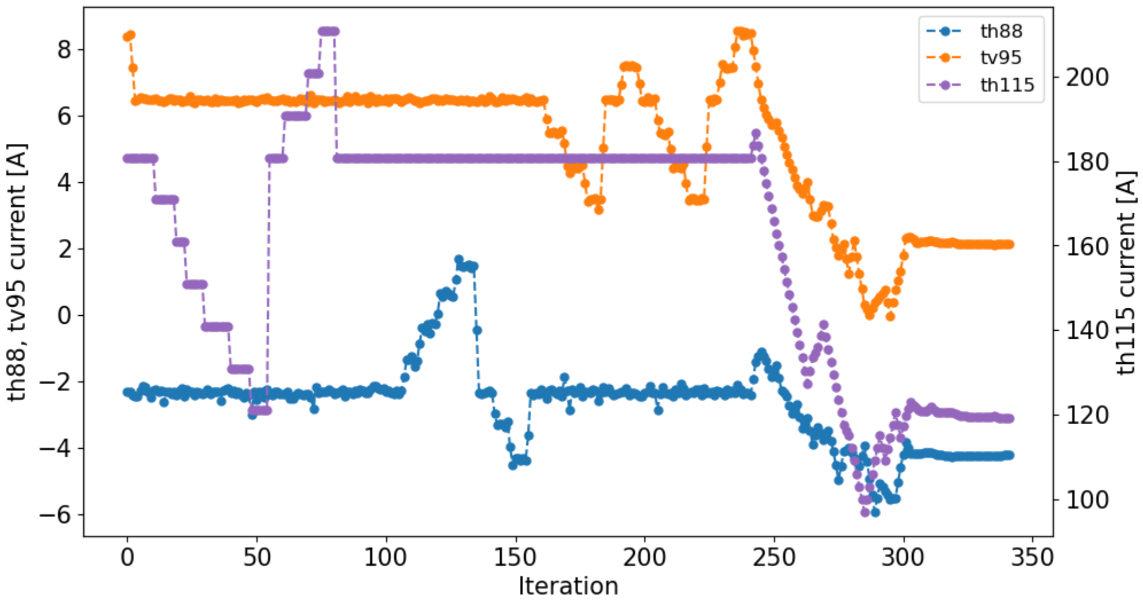
NN model for LtB scan

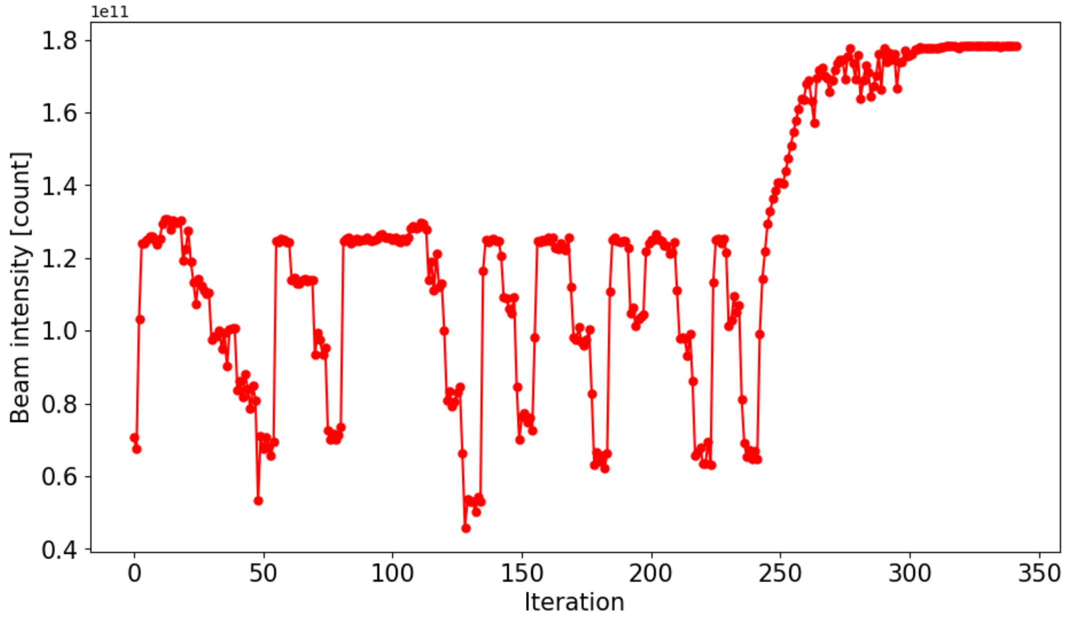
- 15 correctors → 2 intensities
- 2 hidden layers: ReLU + Tanh
- Training data 75% (893 points), testing data 25% (297 points), R^2 score = 0.85



Test Xopt on LtB scan NN model

- Controls: Power supply currents of three correctors (two horizontal, one vertical) at the end of the LtB line
- Booster late beam intensity (after scraping, before extraction to the AGS)
- BO algorithm developed using Xopt, using 242 LtB scan data points as training data
- Algorithm converged within 50 samples





Test Xopt on real machine

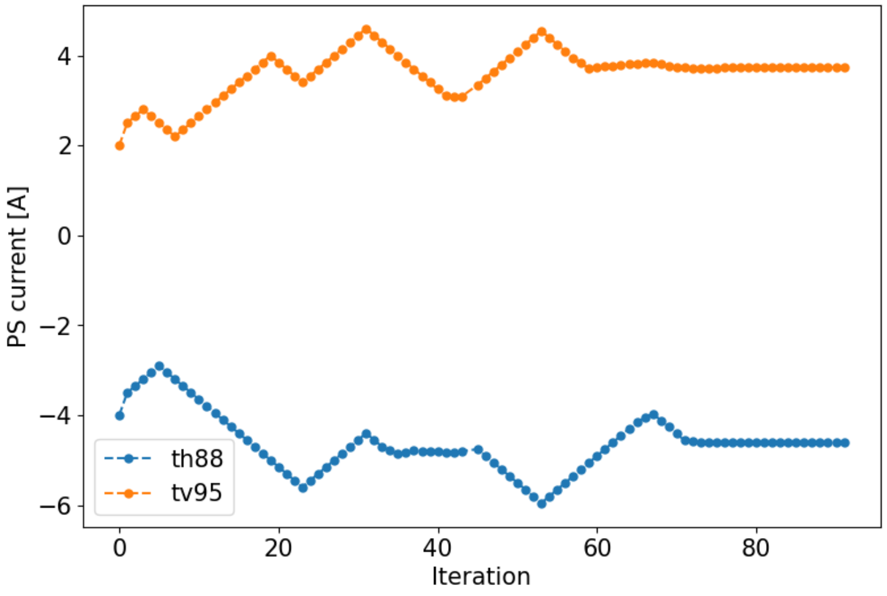
- Controls: Power supply currents of correctors and quadrupoles at the end of the LtB
- Goal: maximize Booster late beam intensity (after scraping, before extraction to the AGS)
- Objective function: send PS current to selected magnets, wait 5 seconds (each Booster cycle/injection pulse lasts ~ 4 seconds), read and return Booster intensity measurement
- BO algorithm developed using Xopt, with added features such as interpolated optimization and trust region BO (tuRBO)

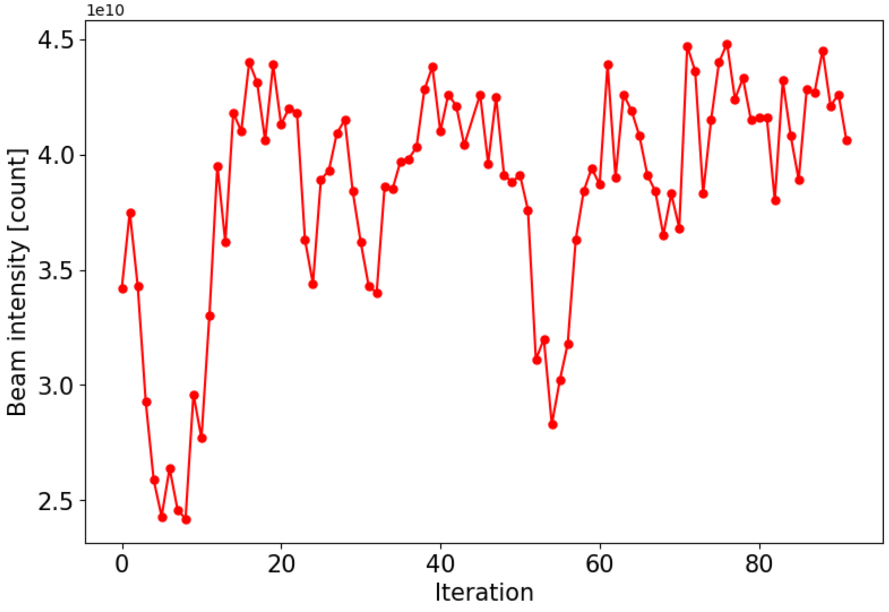
https://christophermayes.github.io/Xopt/examples/single_objective_bayes_opt/turbo_tutorial/

Case 1: 2 correctors

Operator: Petra Adams

- Feb 26, PPM user 4, 7pm – 9pm
- Controls: Power supply currents of two correctors (one horizontal, one vertical) at the end of the LtB line
- Algorithm converged within 100 samples (15-20 minutes)

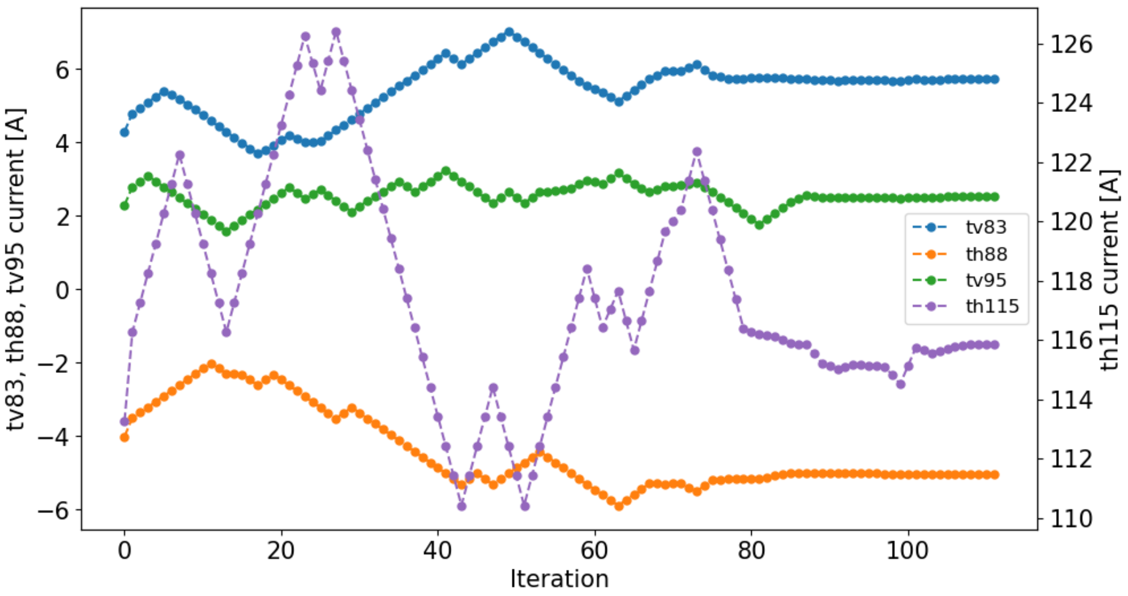


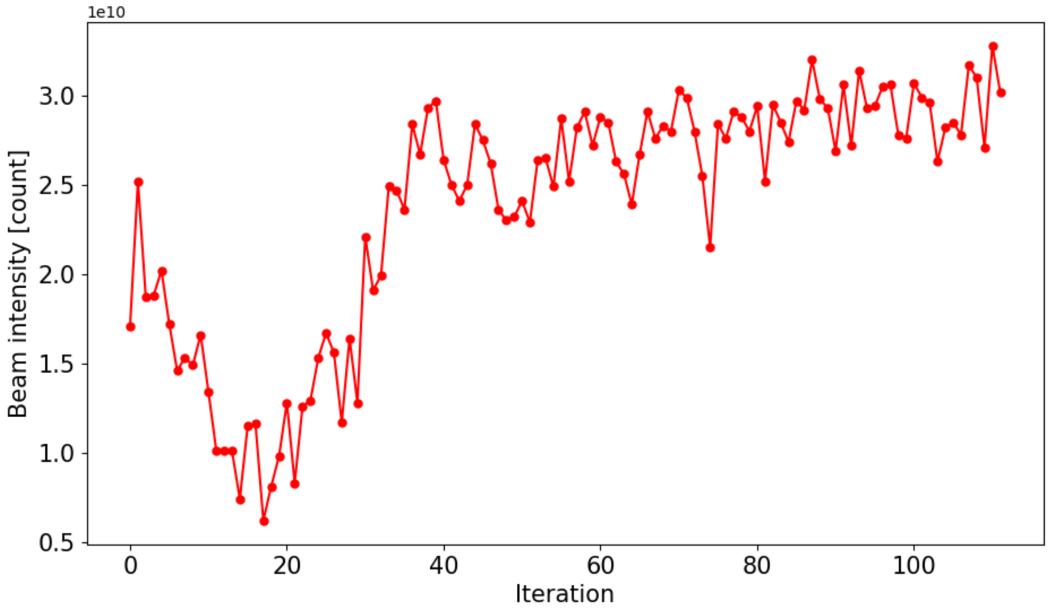


Case 2: 4 correctors

Operator: Petra Adams

- Feb 27, PPM user 4, 7pm – 9pm
- Controls: Power supply currents of four correctors (two horizontal, two vertical) at the end of the LtB line
- Algorithm converged within 120 samples (20-25 minutes)

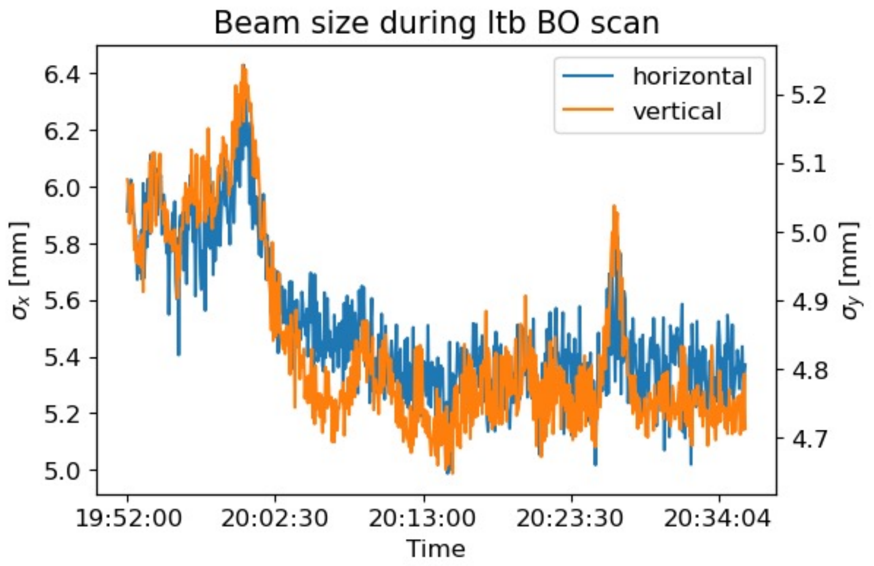


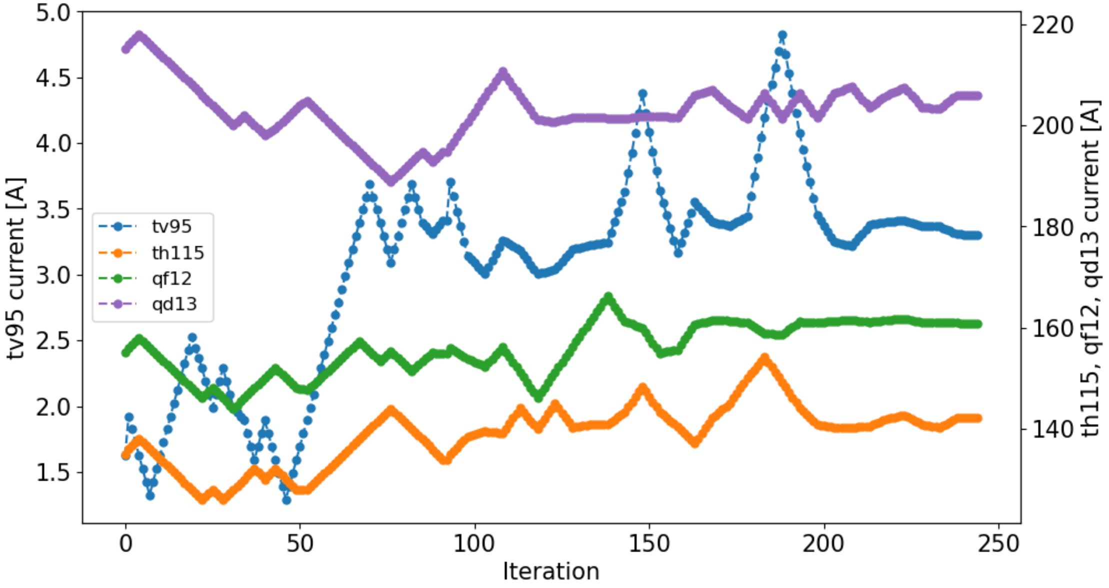


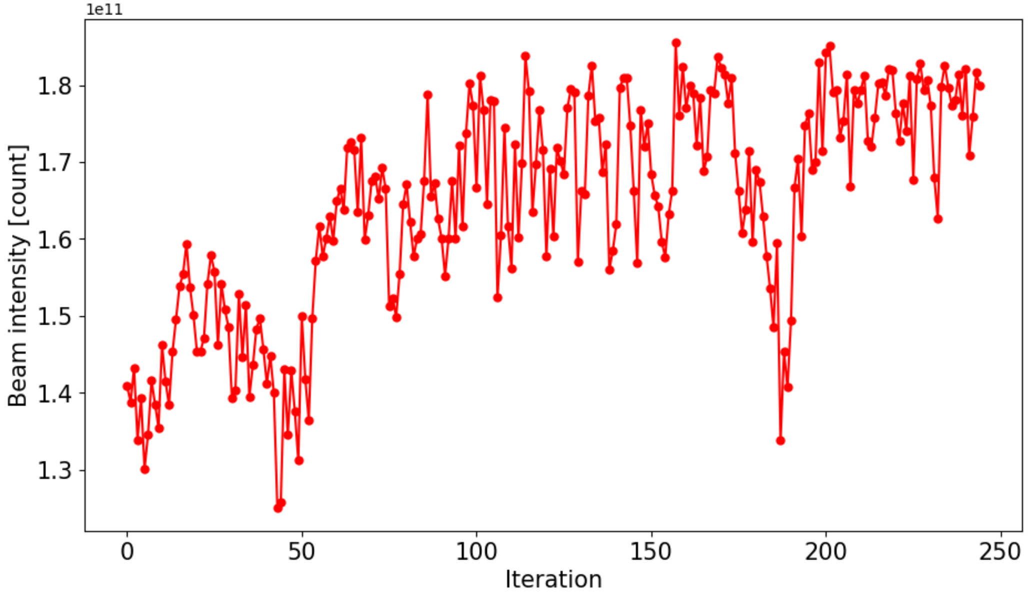
Case 3: 2 correctors + 2 quadrupoles

Operator: Petra Adams

- Mar 4, PPM user 3, 7pm – 9pm
- Controls: Power supply currents of two correctors and two quadrupoles at the end of the LtB line
- Beam size decrease in both planes in the BtA line in correspondence with intensity increase



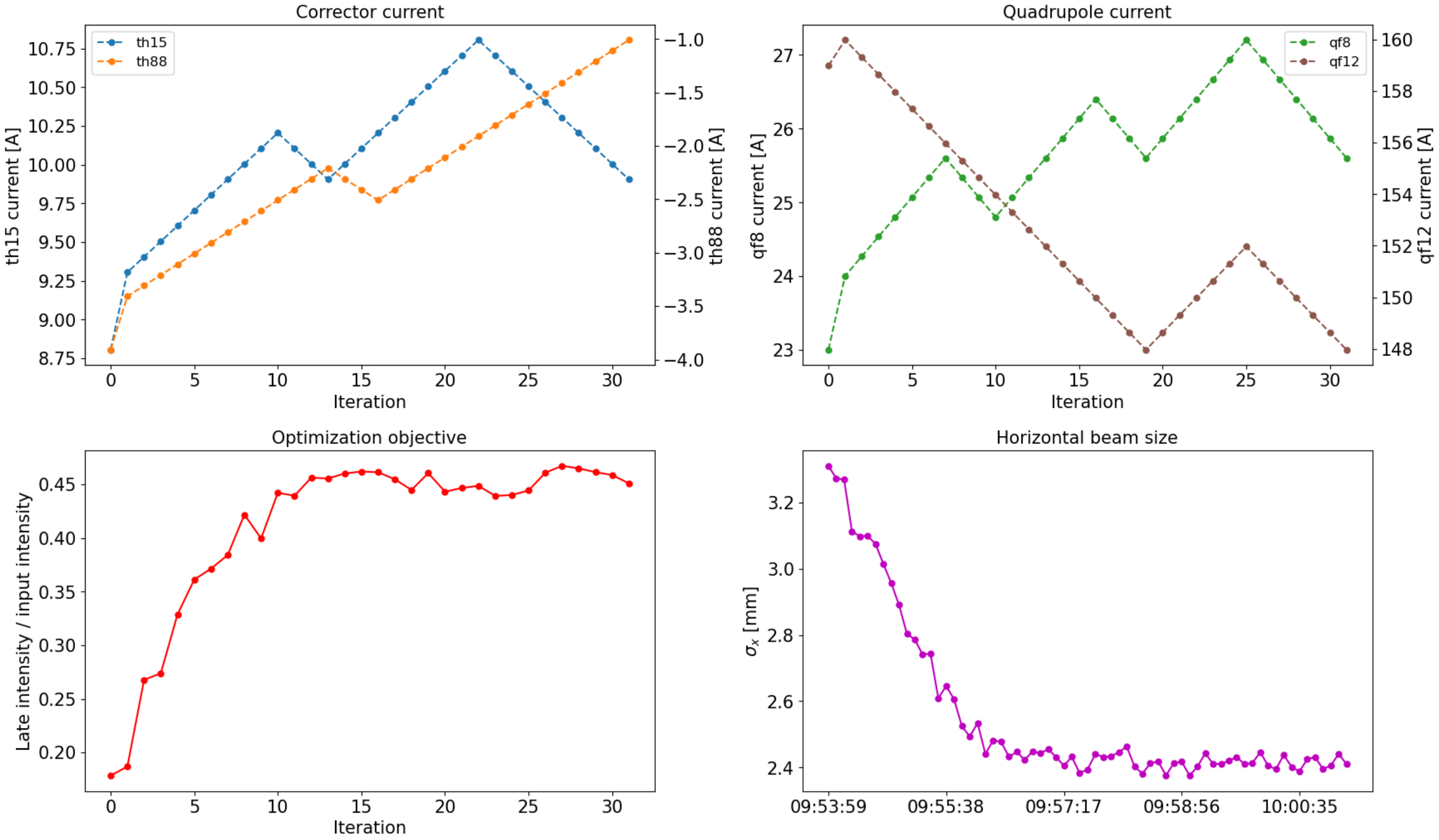




Case 4: horizontal only

Operator: Vincent Schoefer

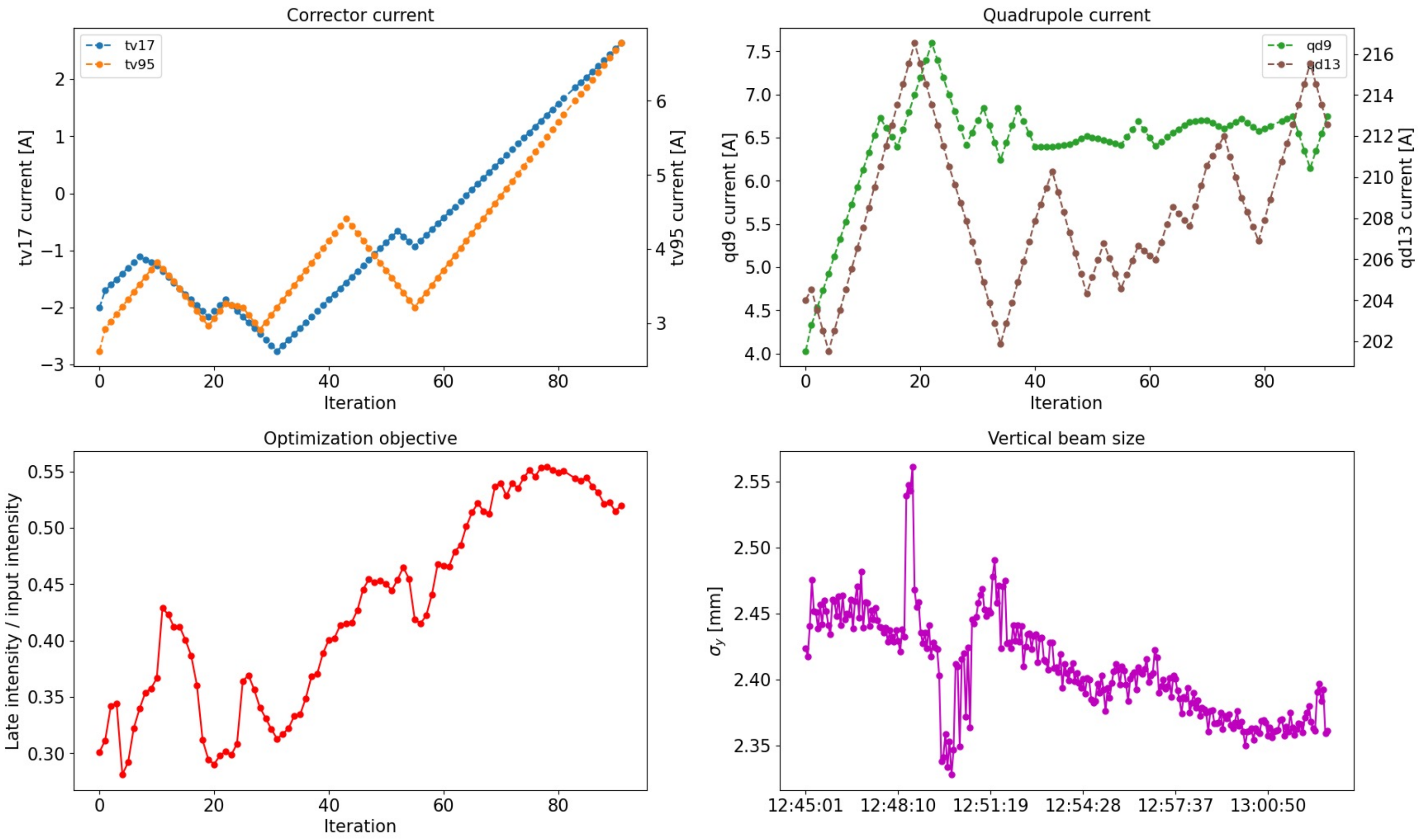
- Mar 13, PPM user 4, 9:30am – 10am
- Controls: Currents of two horizontal correctors and two horizontal quads
- Maximize Booster late intensity / input intensity (to reduce noise)
- Initial beam was sabotaged by changing magnets in the middle of LtB line
- Degeneracy problem: objective value converges but input values don't



Case 5: vertical only

Operator: Vincent Schoefer

- Mar 14, PPM user 4, 12:30pm – 1pm
- Controls: Power supply currents of two vertical correctors and two vertical quads
- Maximize Booster late intensity / input intensity (to reduce noise)
- Initial beam was sabotaged by changing magnets in the middle of LtB line
- Degeneracy problem persists



Summary of ML test

- Bayesian optimization algorithm has been demonstrated to work well to improve and maintain Booster injection efficiency in both planes under different system settings (PPM users).

- If controls include upstream and downstream LtB magnets, changes made in the middle can be compensated to bring Booster beam intensity back up.

- Decrease in beam size in the BtA is observed in both planes in correspondence with intensity increase, which signals decrease in emittance.

- Degeneracy problem encountered during experiment may need further investigation.

Thanks

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