Machine Learning applications to Improving RHIC luminosity

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ICFA mini workshop: Beam-Beam Effects in Circular Colliders BB24

Outline:

1) Motivation and Methods

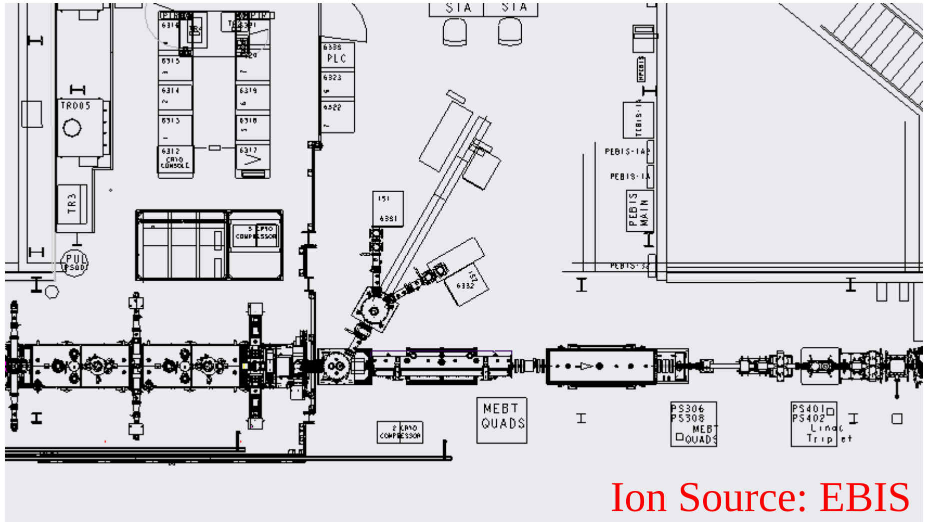
2) EBIS Beam Intensity Optimization

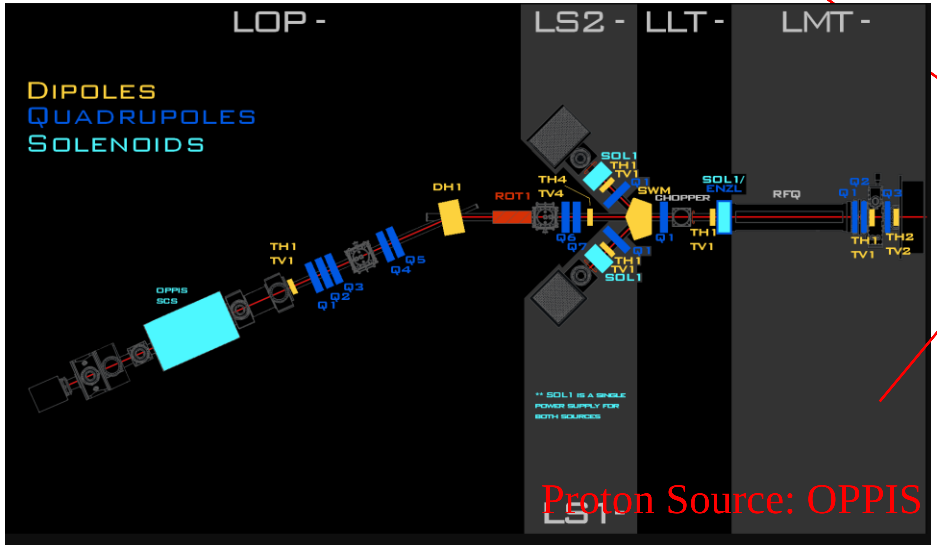
3) Luminosity Optimization

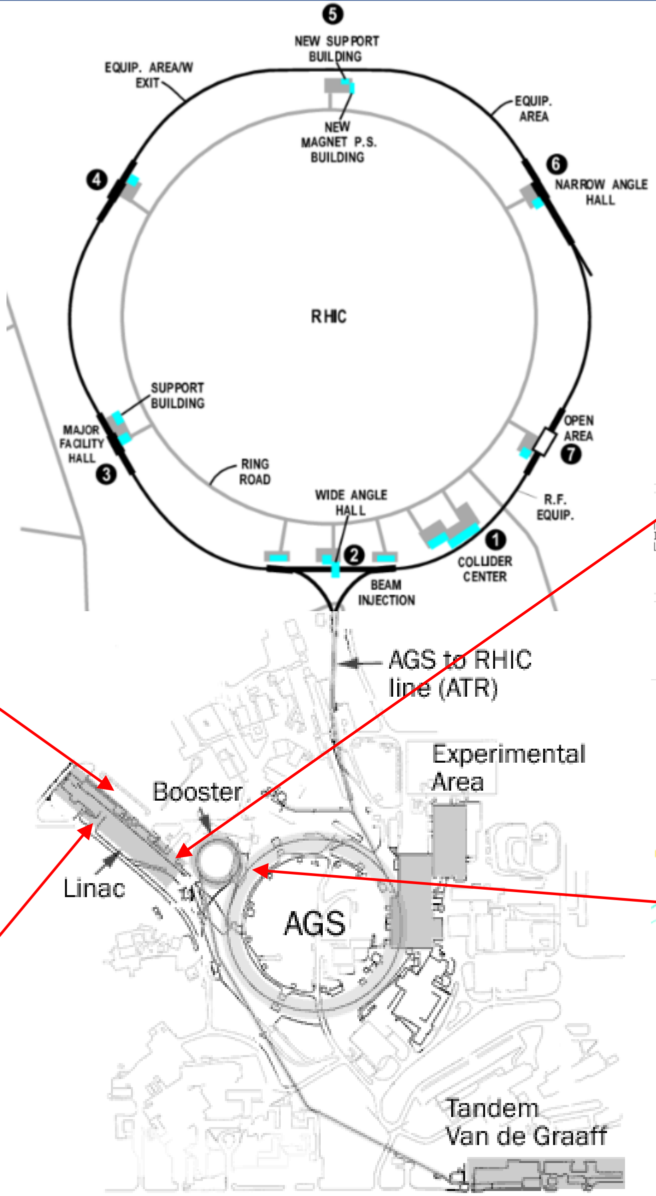
4) Plan & Summary

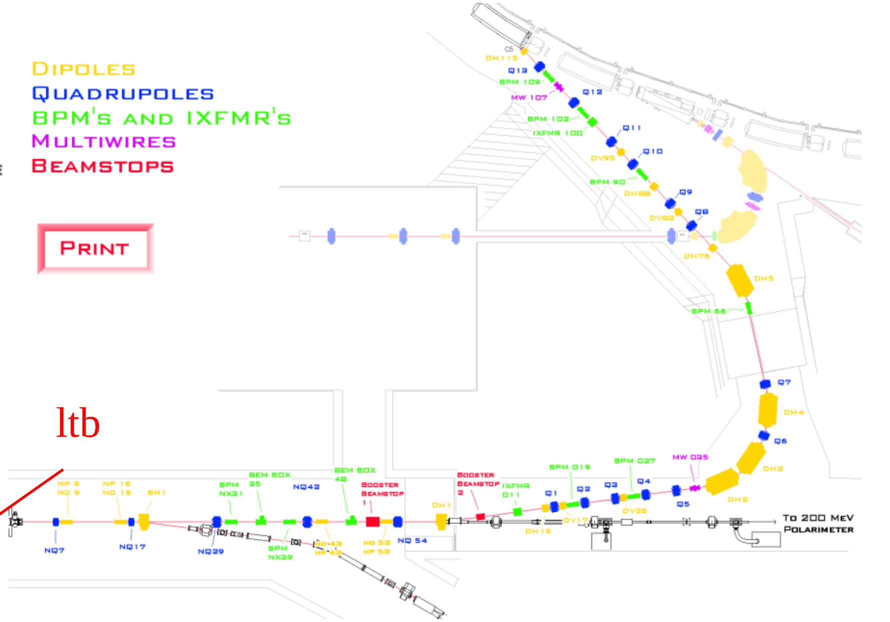
1) RHIC Complex Beam Optimization

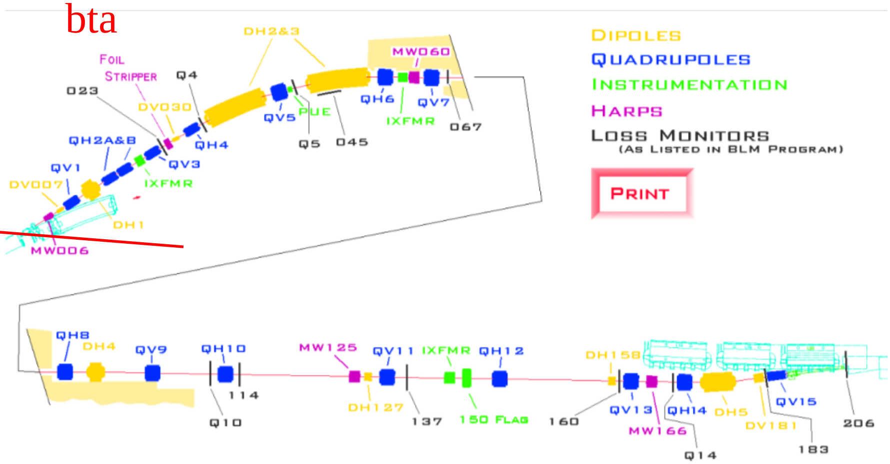
Intensity, emittance and polarization











1) sPHENIX luminosity Optimization (RHIC)

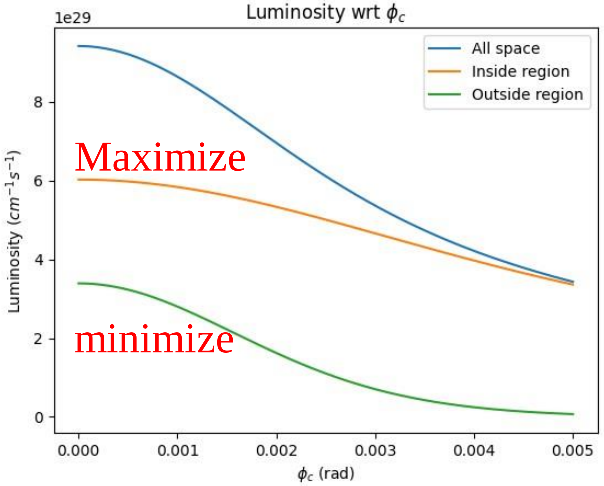
$$L = \frac{N_1 N_2 f H}{2\pi\sqrt{\sigma_{x1}^2+\sigma_{x2}^2}\sqrt{\sigma_{y2}^2+\sigma_{y2}^2}}$$

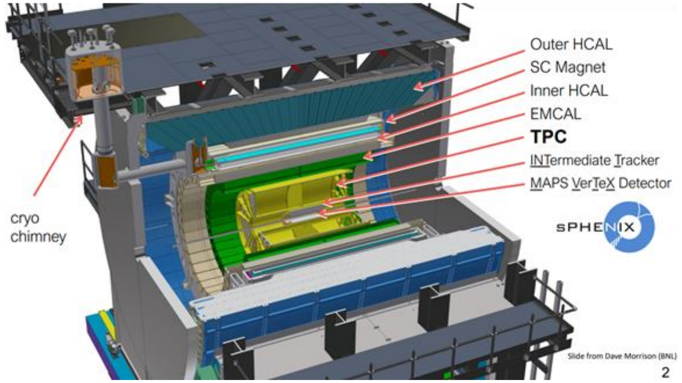
- Global Parameters:
1. Orbit (Dipole)
2. Tune (Quadrupole),
3. Chromaticity (Sextuple)
4. Octupole

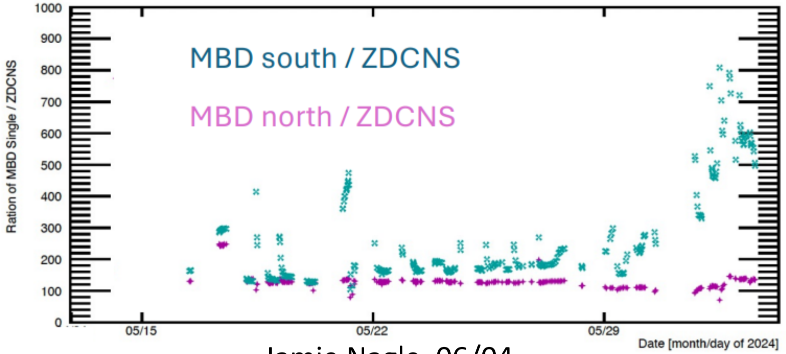
- Local (IR8) Parameters:
1. Beta* (beam size)
2. S* (longitudinal beam waist)
3. Transverse offset

- Other Parameters:
1. RF Voltage
2. Collimator Position

- sPHENIX:
1. max. MVTX (+/-10 cm)
2. min. unwanted signal
3. Crossing angle (2mrad)







Jamie Nagle, 06/04

1. Many variables;
2. Maximize the useful signal within VTX while minimize the unwanted signal outside of VTX
3. Machine learning could be a good tool for a fast, multi-objects tunning.
4. GPTune will be used for ONLINE optimization, XGBoost for offline analysis.

1) Bayesian optimization at LBNL GPTune

Several features of GPTune (BLNL) are very useful, including:

(1) relies on dynamic process management for running applications with varying core counts and GPUs

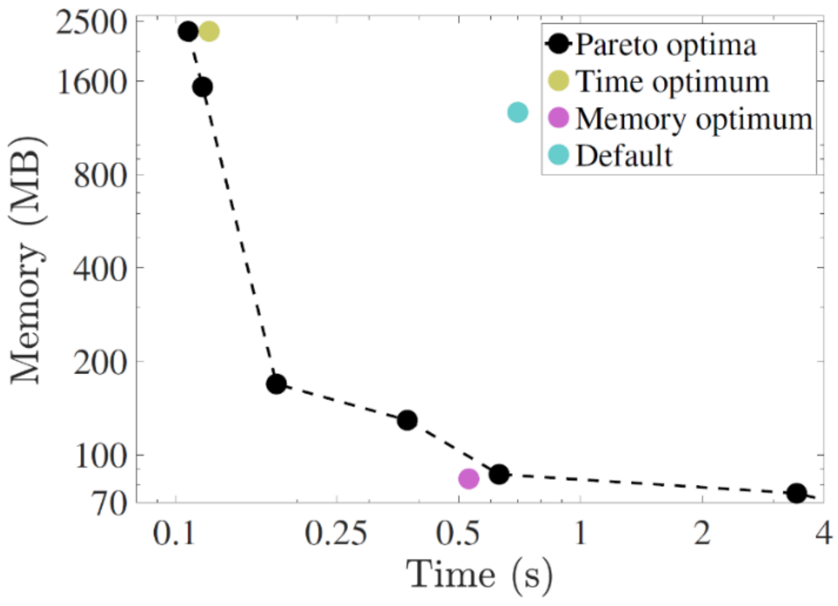
(2) can incorporate coarse performance models to improve the surrogate model

(3) allows multi-objective tuning such as tuning a hybrid of computation, memory and communication.

(4) allows multi-fidelity tuning to better utilize the limited resource budget

(5) supports checkpoints and reuse of historical performance database.

https://github.com/gptune/

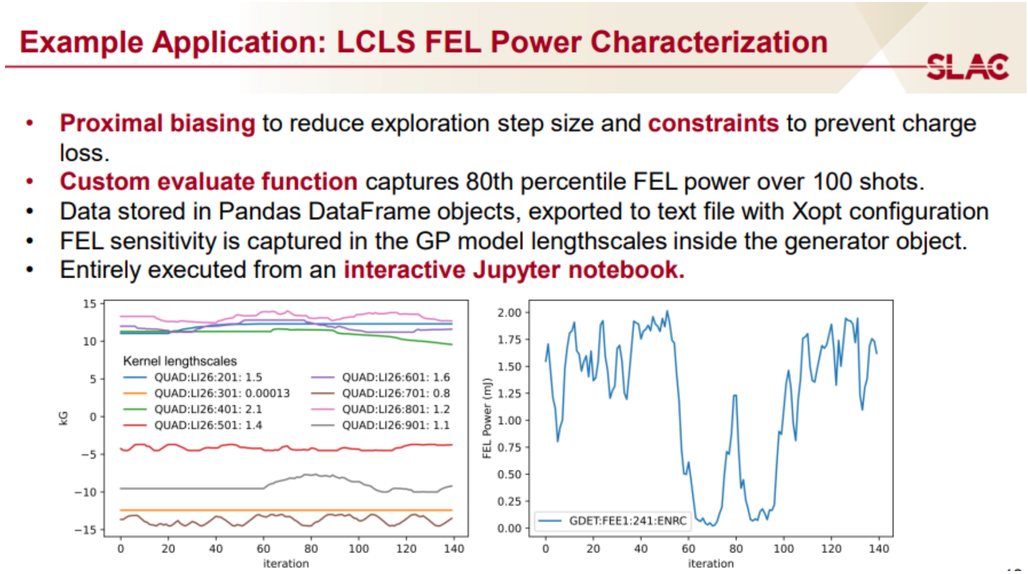


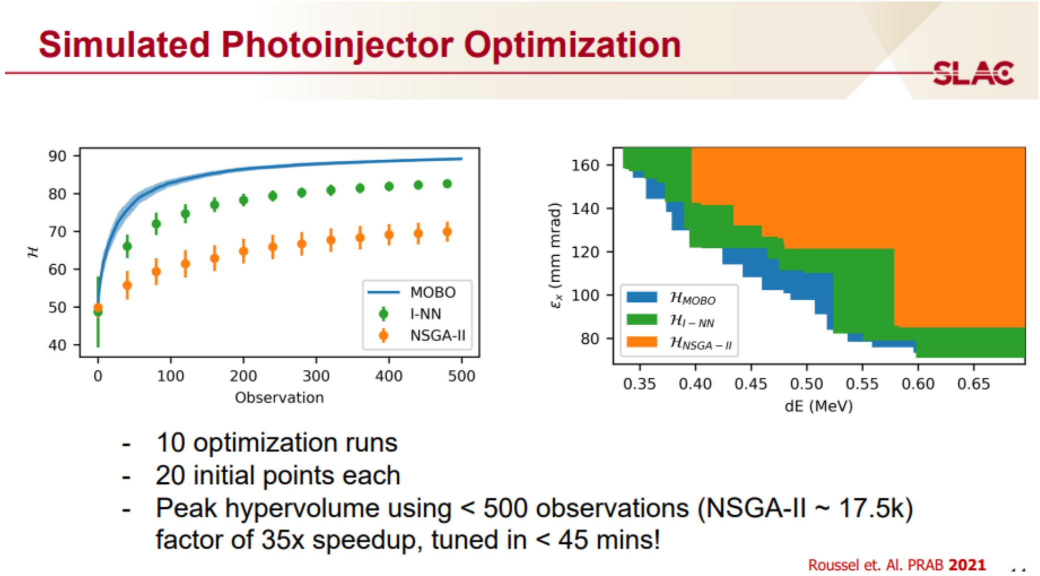
1. Many variables;

2. Maximize the useful signal within VTX while minimize the unwanted signal outside of VTX.

1) Bayesian optimization at SLAC

- optimization algorithms:
    - cnsga Continuous NSGA (nondominated sorting genetic algorithm)-II with constraints.
    - bayesian_optimization Single objective Bayesian optimization (w/ or w/o constraints, serial or parallel).
    - mobo Multi-objective Bayesian optimization (w/ or w/o constraints, serial or parallel).
    - bayesian_exploration Bayesian exploration.
- sampling algorithms:
    - random sampler
- Convenient YAML/JSON based input format.
- Driver programs:
    - xopt.mpi.run Parallel MPI execution using this input format.





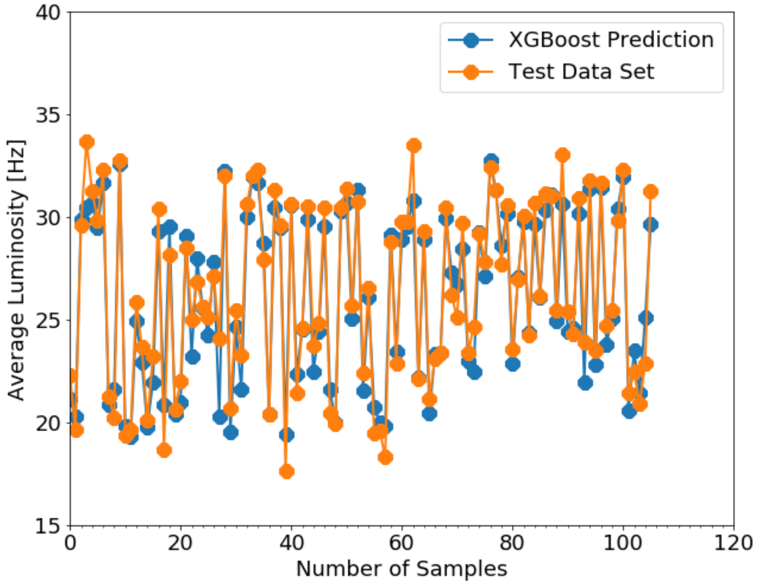
https://github.com/ChristopherMayes/Xopt
https://christophermayes.github.io/Xopt/assets/xopt_overview.pdf

https://arxiv.org/pdf/2312.05667

1) XGBoost for offline regression, SHAP for plotting

XGBoost python package:

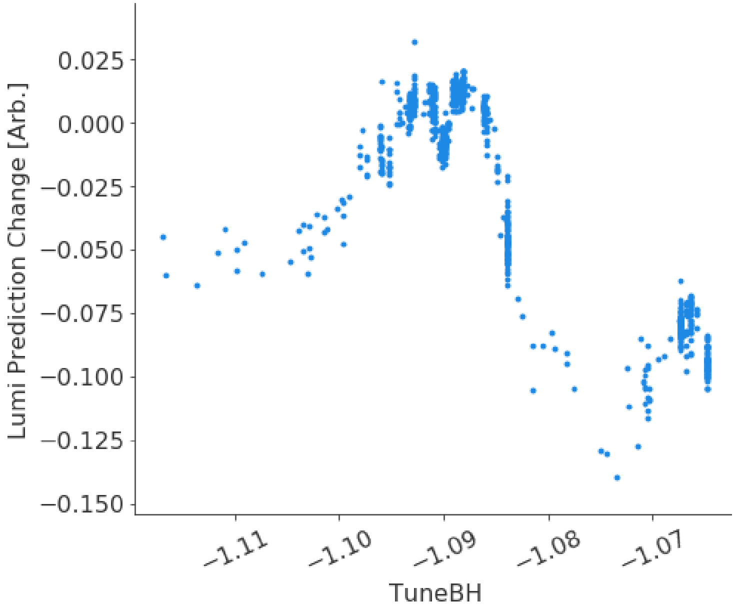
- **Multi-dimensions nonlinear regression algorithm: good for f(x1,x2,x3, … , xn) with n>3 or 4. (**Higgs Machine Learning Challenge**)**
- **The black-box model (LEReC data): 80% data for training, 20% data for test and comparison**
- **Model R_2 score: 0.90, predicts the luminosity very well.**
- **How to explanate the black-box model?**



SHAP python package:

- **an approach to explain the output of any machine learning black-box model via calculating their Shapley values (marginal effect), which are their contributions to the total performance.**
- **Taxi: A[$6] B[$16] C[$42]**
  Pay: $2 $5 $35

- **SHAP plot: Data visualization, and model explainability; Shapley values with offsets.**



Outline:

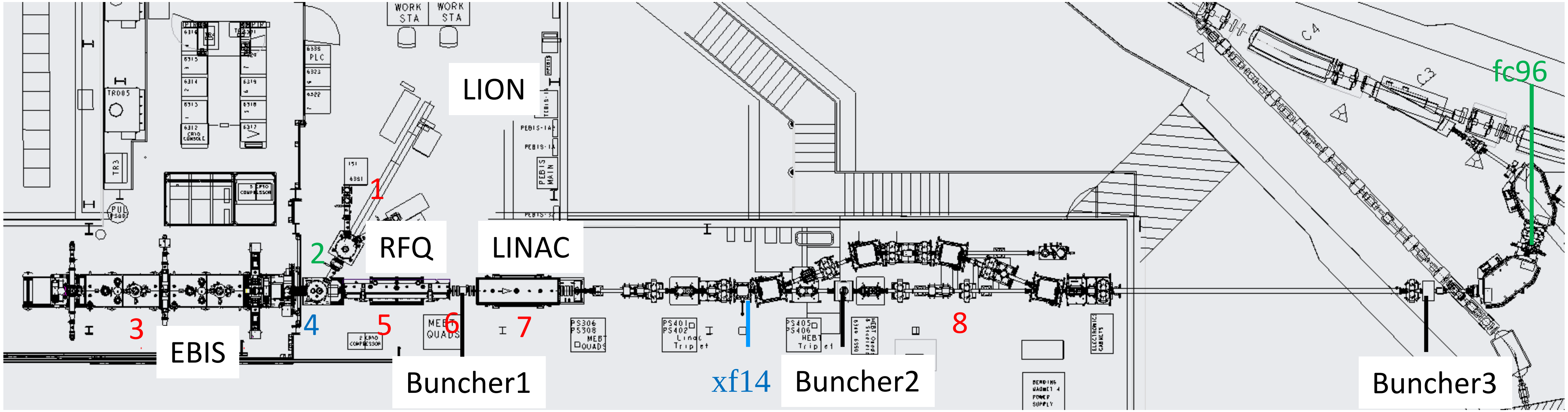
1) Motivation and Methods

2) RHIC Complex Beam Optimization

3) Luminosity Optimization

4) Plan & Summary

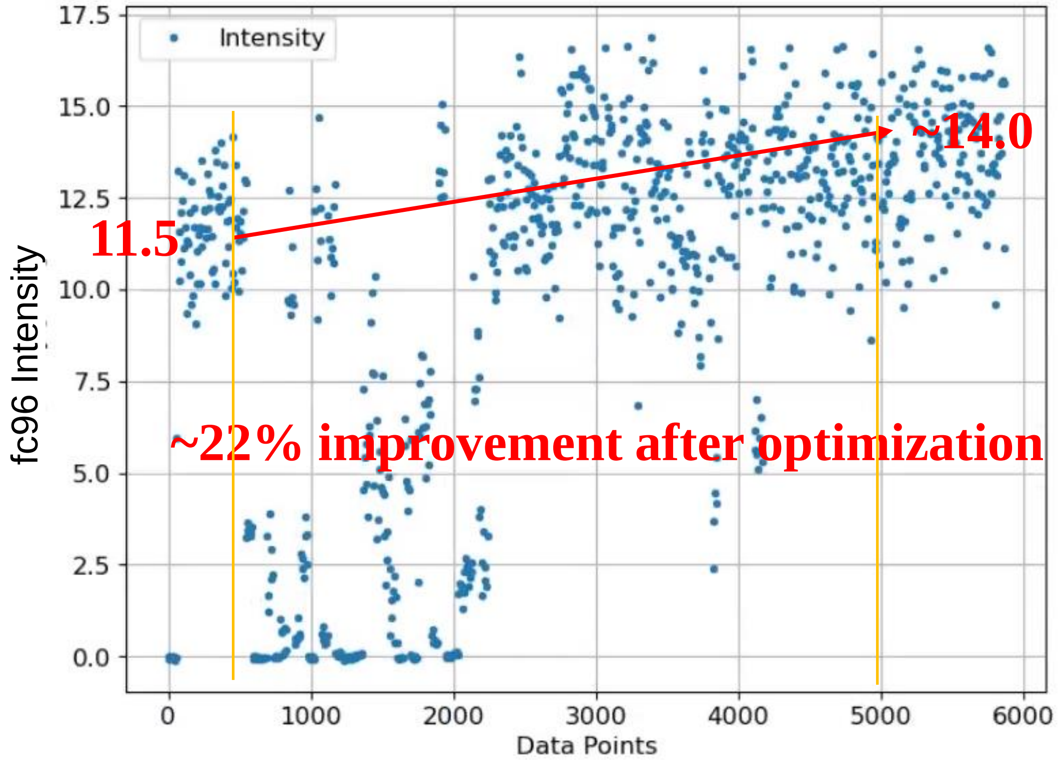
2) GPTune Test: EBIS Intensity Optimization

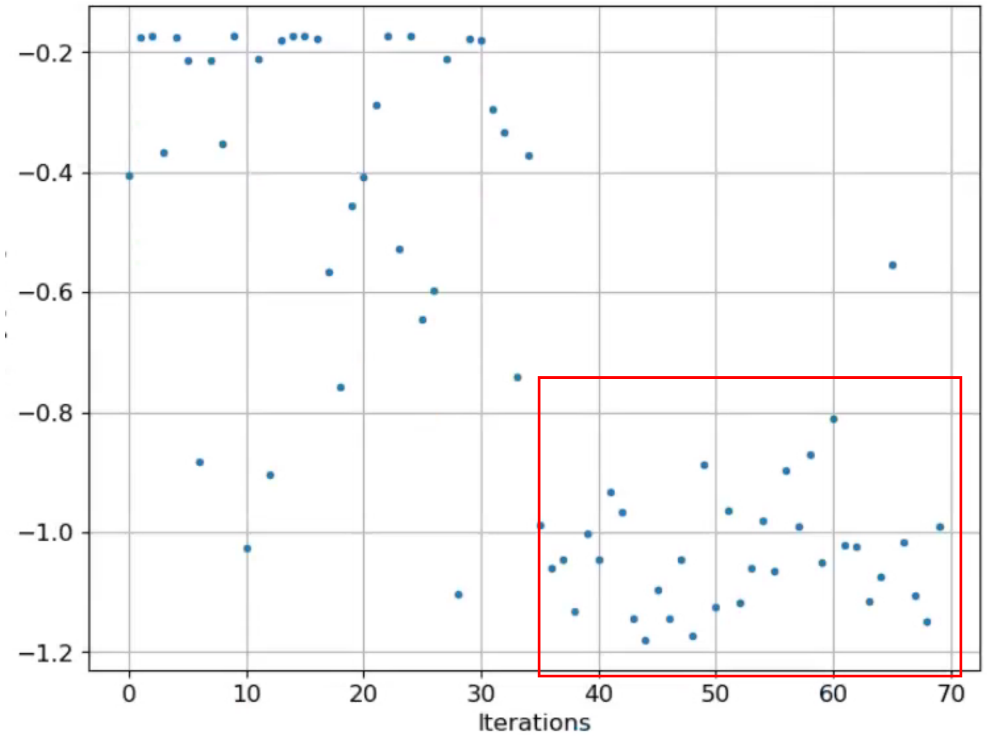


1. LION
2. EBIS Injection Line (fc96)
3. EBIS
4. EBIS Extraction line (xf14)
5. RFQ
6. MEBT
7. Linac
8. HEBT

		Injection [fc96]	Extraction [xf14]
1	IonLens20-40kV	✓	✓
2	DeflPlatBias	✓	✓
3	16PoleX	✓	✓
4	16PoleY	✓	✓
5	Gridded_Lens	✓	✓
6	Horiz_Bend_Defl	✓	✓
7	Inter_Vert_Defl	✓	✓
8	Inter_Vert_Defl_Lower	✓	✓
9	Horiz_Sphere_Bend	✓	×
10	RFQ_Horiz_Bend	×	✓
11	LEBT_Solenoid	×	✓
	Total Variables	9	10

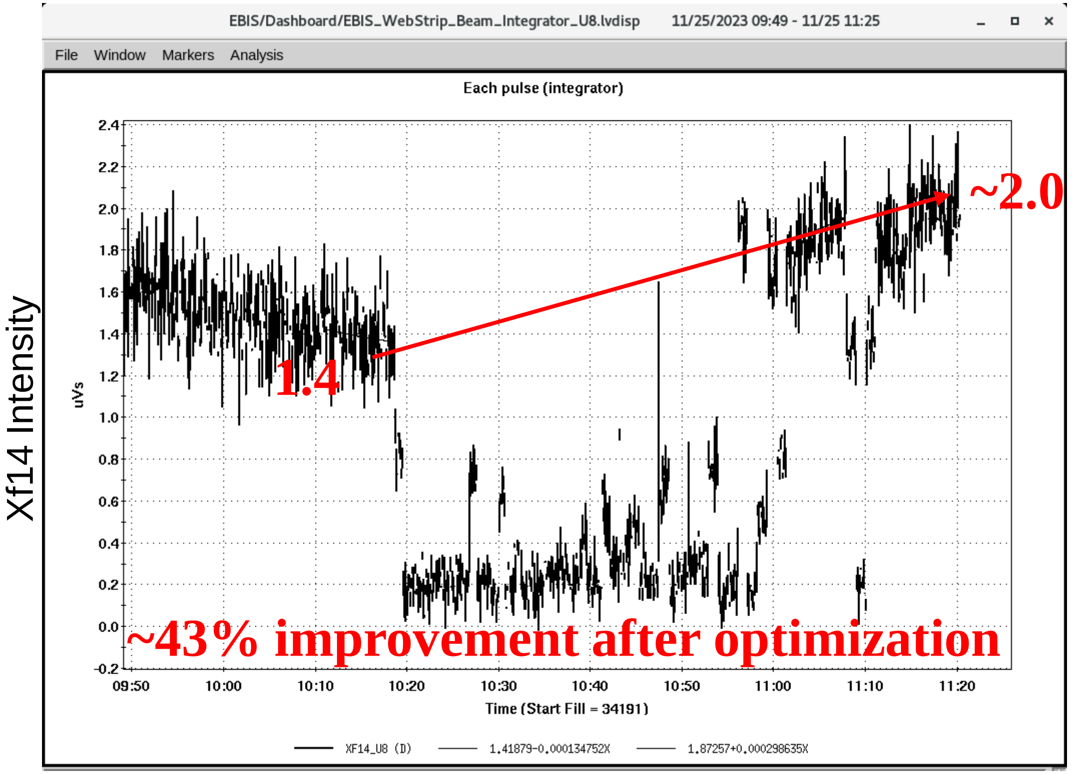
2) GPTune: EBIS Injection Line (9 parameters)

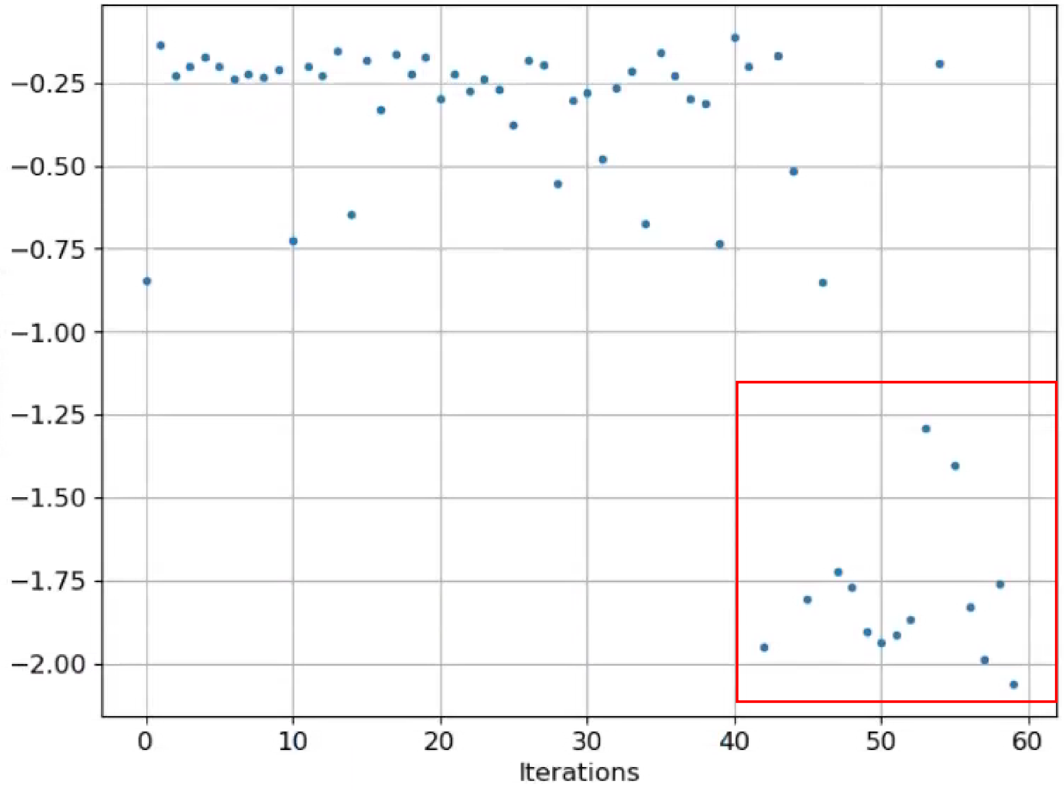




- script was running from 12:33 to 13:36 (~63 min)
- 1 beam / supercycle [6.6 s]; it takes 2 supercycles for the powers settle down;4 supercycles for measurement.
- fc96 measurement was used for injection optimization
- 9 control parameters after 70 iterations

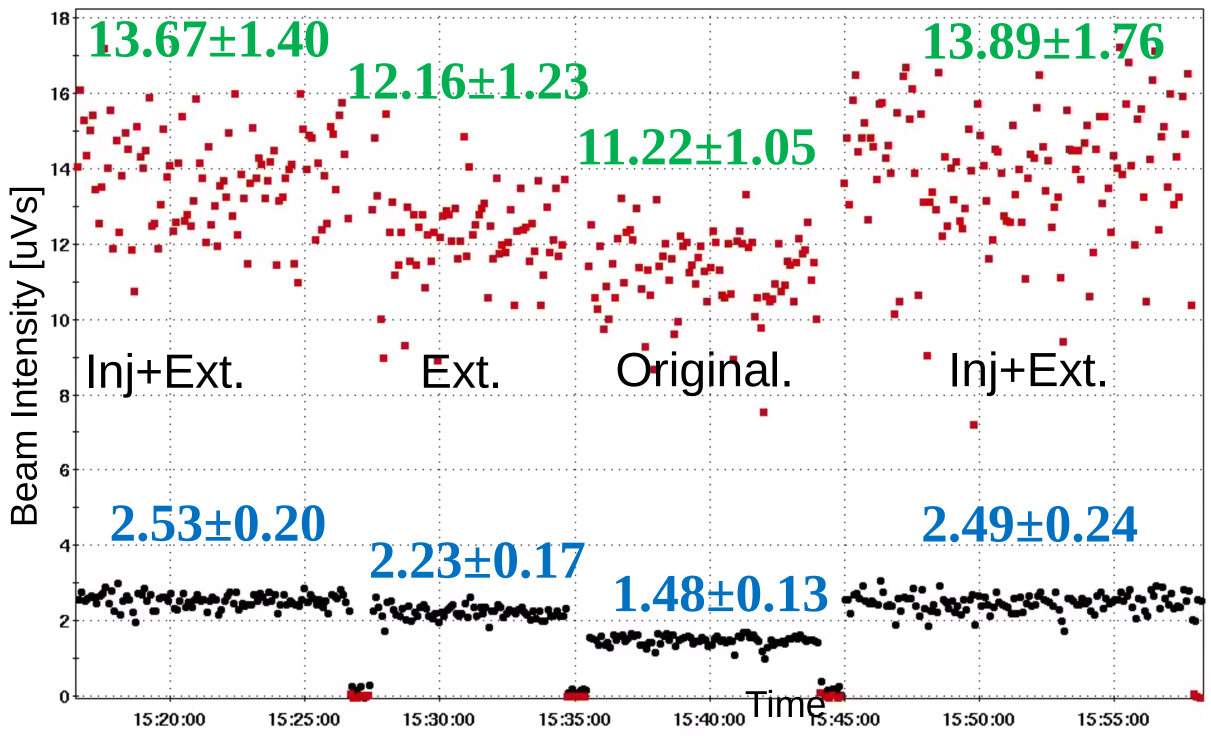
2) GPTune: EBIS Extraction Line (10 parameters)

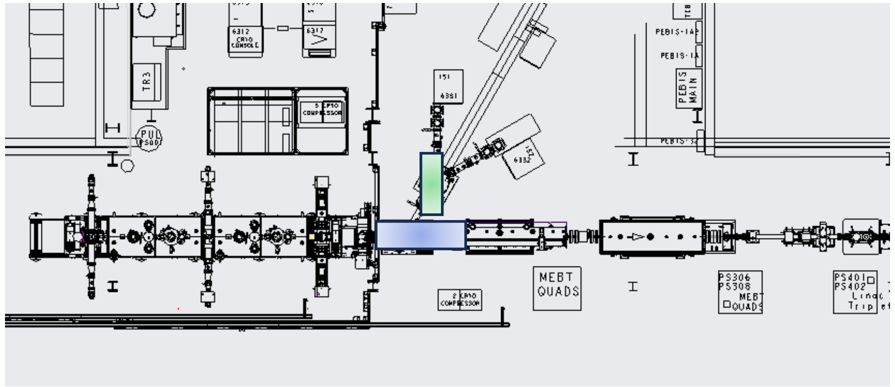




- script was running from 10:18 to 11:15 (~57 min)
- 2 beam / supercycle [6.6 s].
- xf14 measurement was used for extraction optimization.
- 10 control parameters after 60 iterations

2) GPTune: EBIS Intensity Gain (11/25/2023)





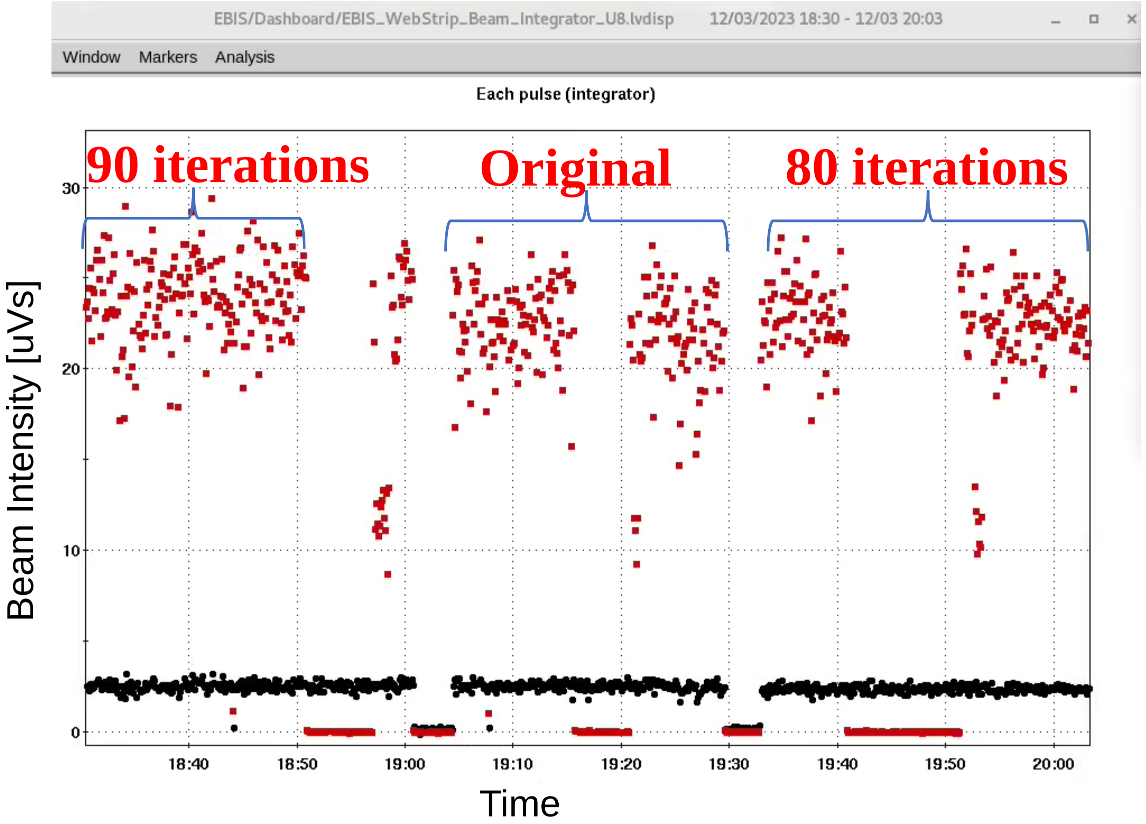
- **Original, Ext., Inj. + Ext.: use the saved parameters for these beam lines.**
- **GPTune works with std ±10% (pp ±15%) noisy signals!**
- **Possible more gain with fc96 instead of xf14 for the extraction line?**

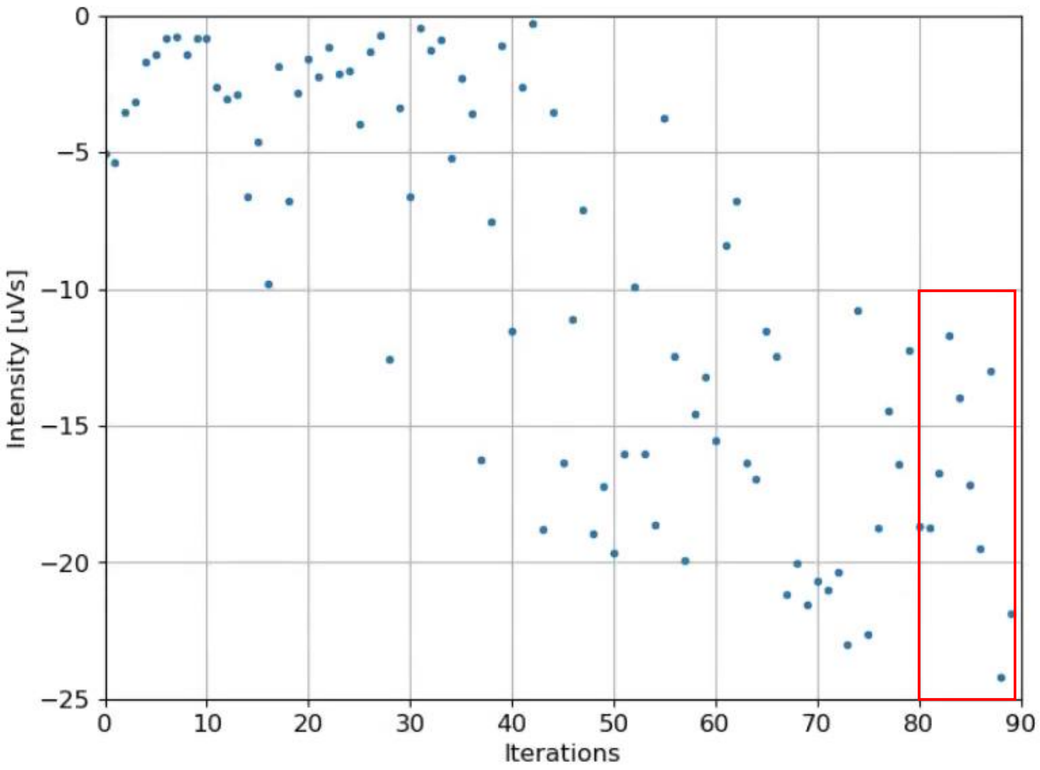
Table 3: Beam Intensity Optimization using different settings

Device	Orignal	Ext	Gain from Ext	Ext+Inj	Gain from Ext+Inj
xf14 [uVs]	1.48±0.13	2.23±0.17	42 %	2.53±0.20/2.49±0.24	68-71 %
fc96[uVs]	11.22±1.05	12.16±1.23	8.4 %	13.67±1.40/13.89±1.76	22-24 %

2) GPTune: EBIS Injection + Extraction (19 parameters)

- Continue to optimize the total 19 parameters simultaneously AFTER optimizing the injection and extraction separately.
- Fc96 was used. After optimization, the results were compared via reversing their corresponding settings.
- Original setting: 22 [uVs]
- 80-iterations setting: 23 [uVs]
- 90-iterations setting: 23.56 [uVs] (7%)
- 1.07×1.22 ~ 1.30 ?





2) Offline XGBoost Model and Important Features

Motivations (guide operation):

1. Find some most important parameters
2. Find their operation range.
3. Explore different operation region.

XGBoost python package:

- Multi-dimensions nonlinear regression algorithm: good for f(x1,x2,x3, … , xn) with n>3 or 4. (Higgs Machine Learning Challenge)
- The black-box model: 80% data for training, 20% data for test and comparison
- How to explanate the black-box model?

SHAP python package:

- an approach to explain the output of any machine learning black-box model via calculating their Shapley values (marginal effect), which are their contributions to the total luminosity.
- Separate the individual effect.

The models achieved scores of 79% and 80% for the injection and extraction beam lines.

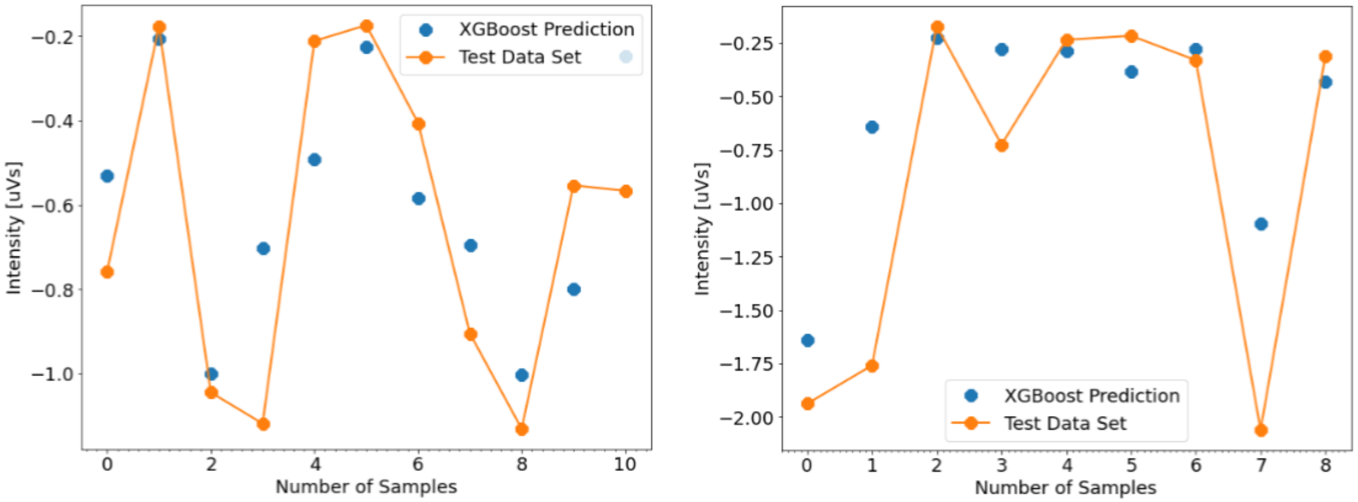
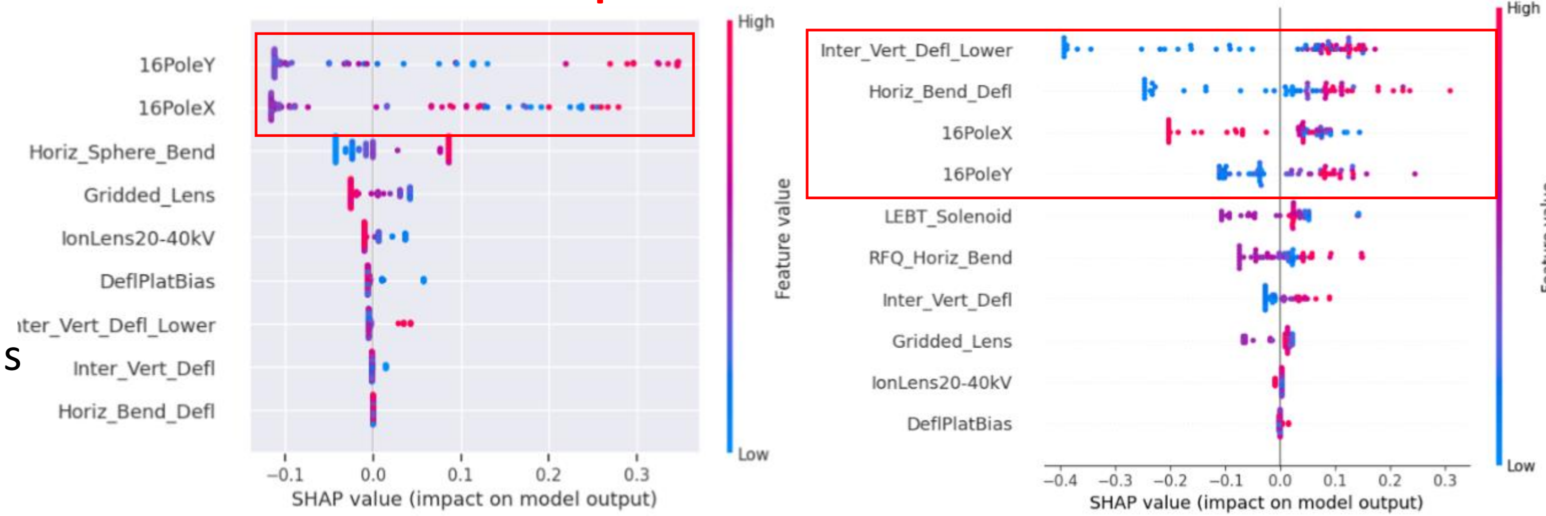


Fig. 10: XGBoost model predictions for the EBIS injection beam line (left plot) and extraction beam line (right plot)

Important Parameters



2) SHAP Plot: Prediction for Operation Range

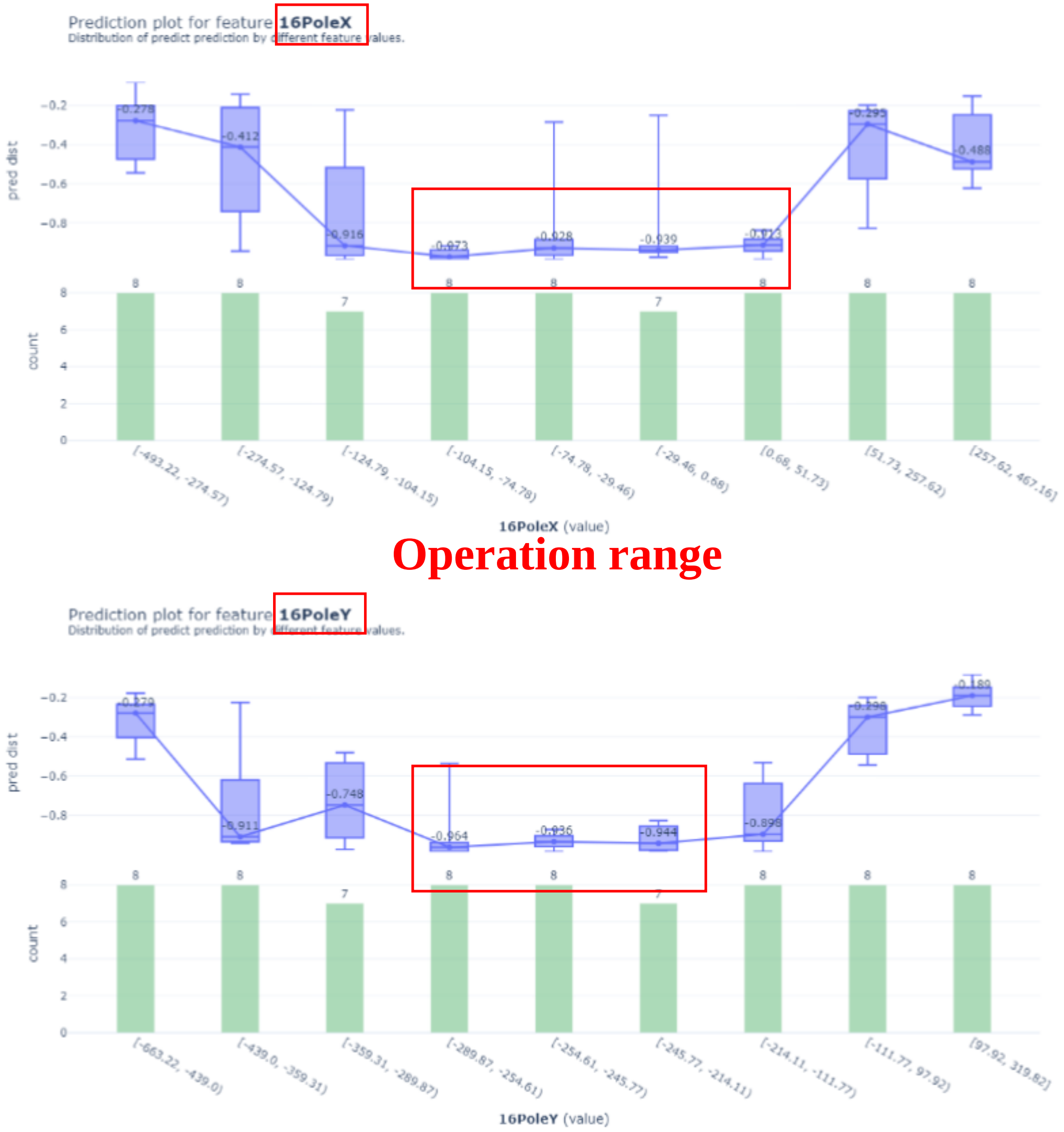


Fig. 13: The prediction plots for 16PoleX (top) and 16PoleY (bottom) in the injection line.

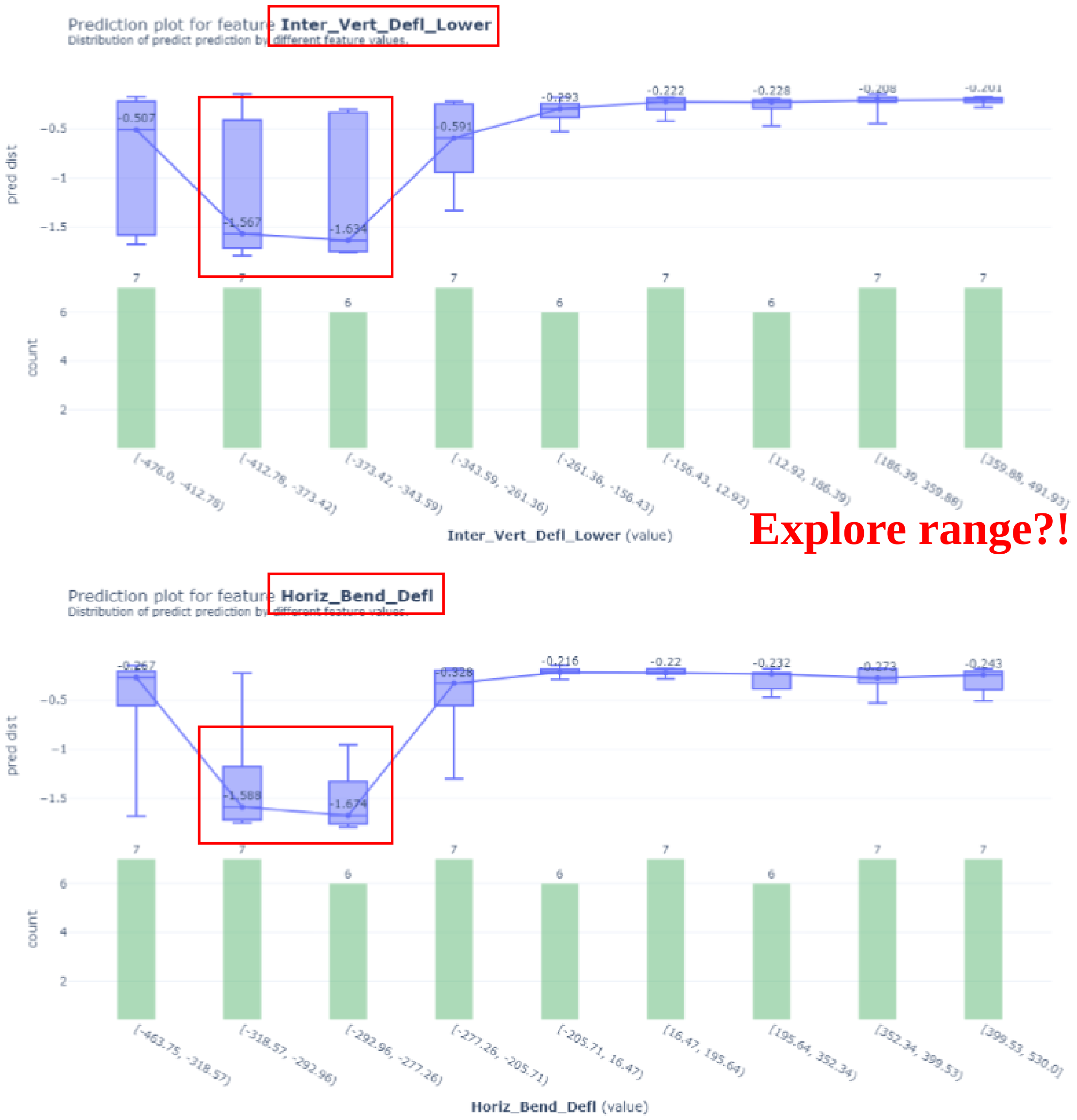
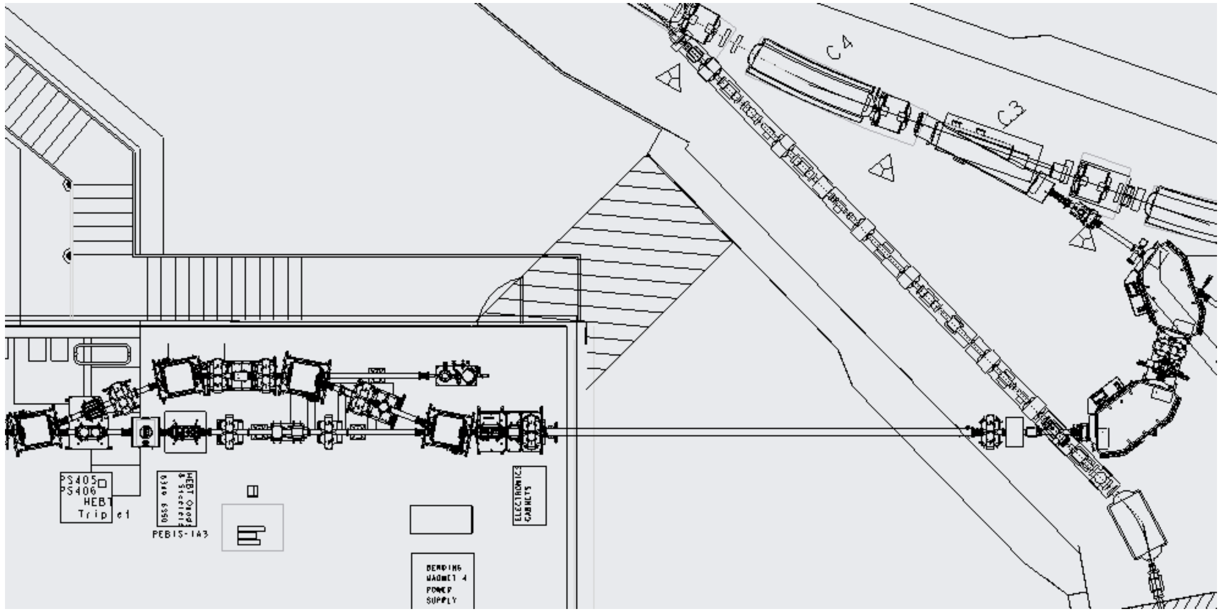
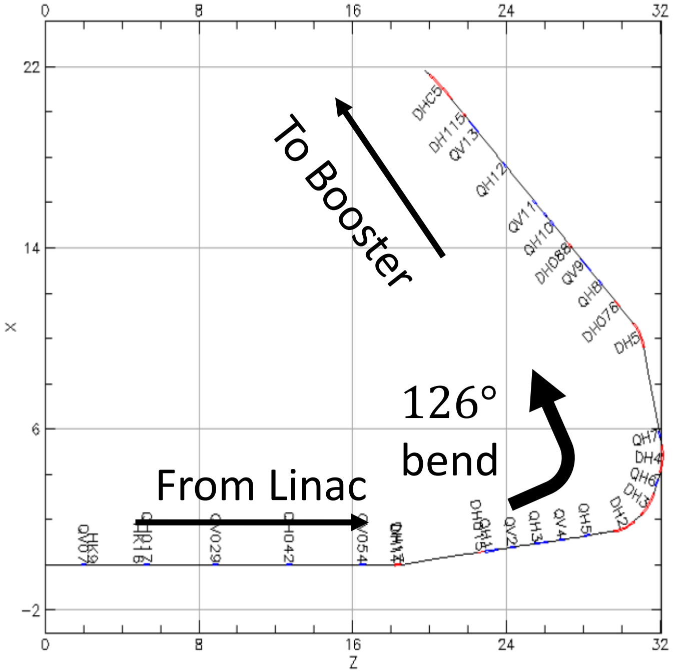


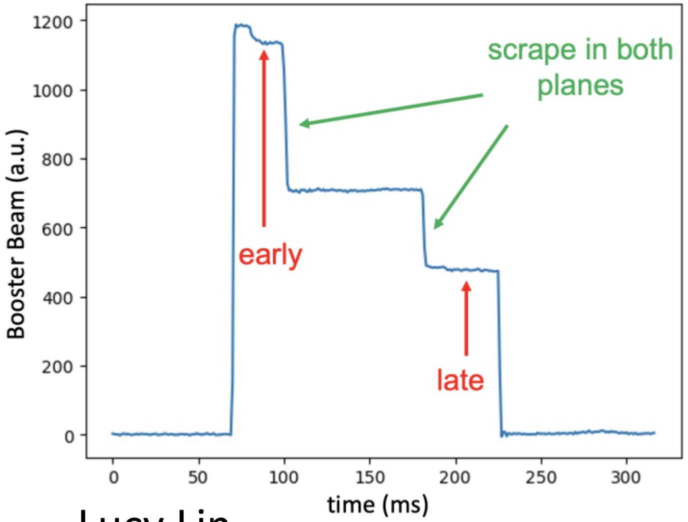
Fig. 14: The prediction plot for Inter-Vert-Defl-Lower (top) and Horiz-Bend-Defl (bottom) in the extraction line.

2) Xopt: Linac to Booster





- Booster injection process sets maximum beam brightness for rest of acceleration through RHIC
- Known emittance effect on polarization loss
- Intentional horizontal and vertical scraping reduce emittance to RHIC requirements
- Goal: minimize emittance / maximize beam intensity after scraping
- Controls: Linac to Booster (LtB) transfer line optics
- Method: Bayesian optimization (BO)

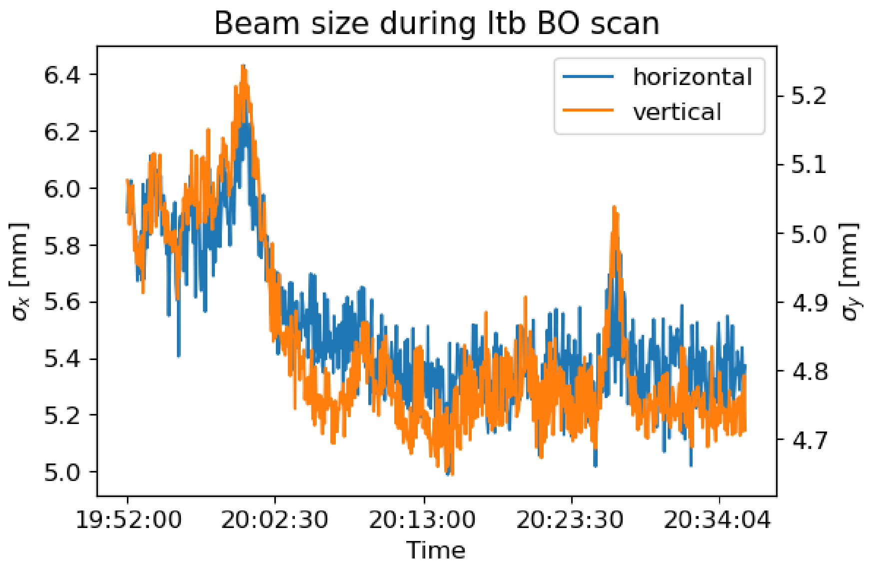


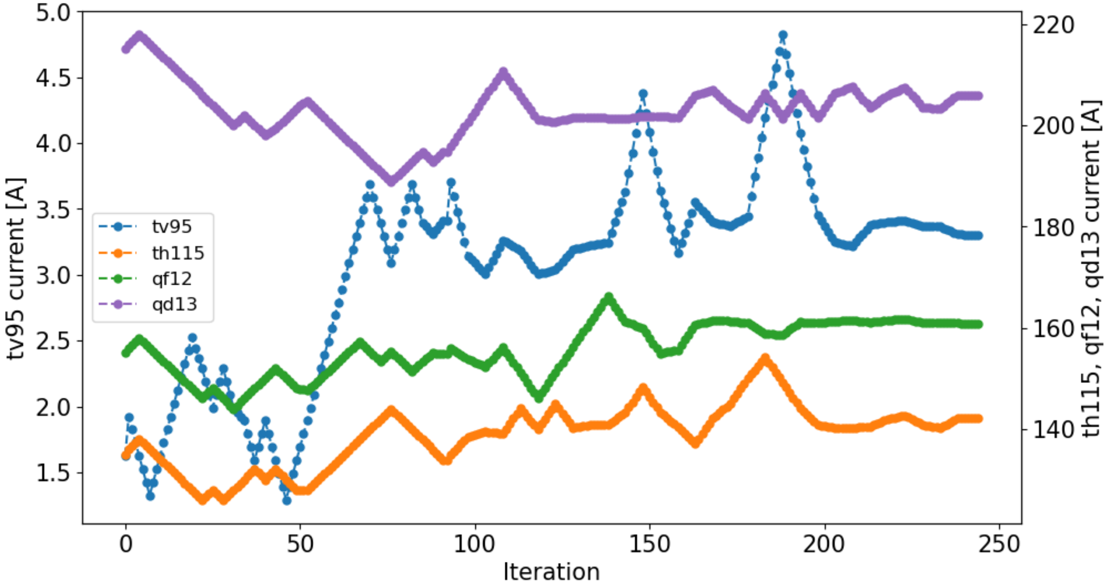
Lucy Lin

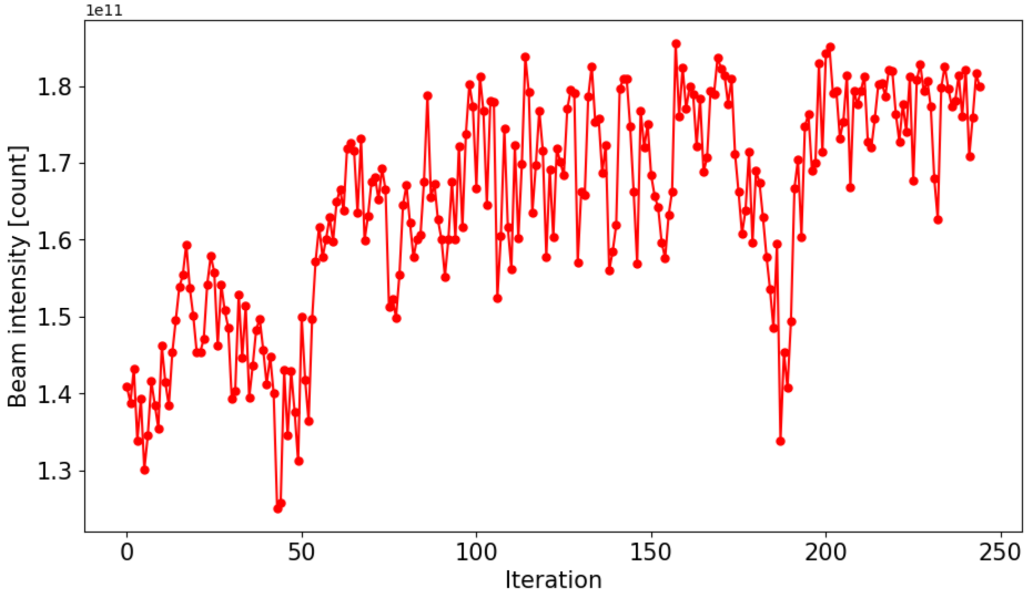
2) Xopt: Linac to Booster (03/04/2024)

- Controls: Power supply currents of 2 correctors and 2 quadrupoles at the end of the LtB line

- Beam size decrease in both planes in the BtA line in correspondence with intensity increase







Lucy Lin

Outline:

1) Motivation and Methods
   - Motivation
   - Methods
2) RHIC Complex Beam Optimization
   - EBIS (GPTune)
   - LTB (Xopt)
3) Luminosity Optimization
   - LEReC (XGBoost)
   - sPHINEX (GPTune)
4) Plan & Summary

3) RHIC Parameters and LEReC Parameters

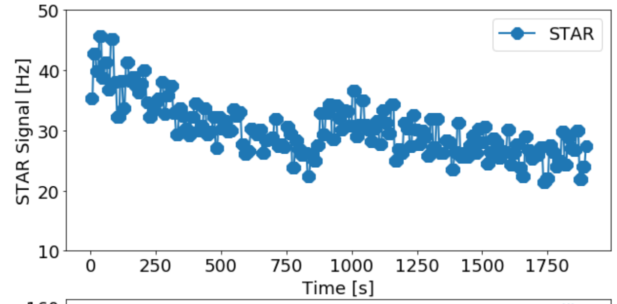
Table 1: Parameters and Their Abbreviations

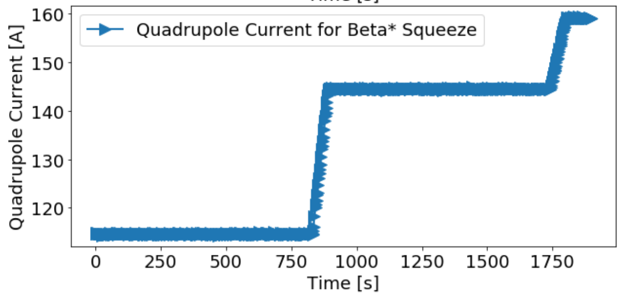
RHIC		LEReC	
Parameters	Abbreviations	Parameters	Abbreviations
Intensity B	IntenB	Electron BPM B Cooling	ebpmB
Intensity Y	IntenY	Electron BPM Y Cooling	ebpmY
Emittance B	SizeB	Ion BPM B	ibpmB
Emittance Y	SizeY	Ion BPM Y	ibpmY
Tune B H	TuneBH	Solenoid 1 B	Bsol1
Tune B V	TuneBV	Solenoid 1 B	Bsol1
Tune Y H	TuneYH	Electron Beam Current	Current
Tune Y V	TuneYV	Electron Beam Energy	Energy
Chrom B H	ChromBH	B Y Quadrupole Current	BYquad
Chrom B V	ChromBV		
Chrom Y H	ChromYH		
Chrom Y V	ChromYV		
Collimator BH	CollBH		
Collimator BV	CollBV		
Collimator YH	CollYH		
Collimator YV	CollYV		
Beta* Squeeze Ramp	Ramp		
Luminosity	Lumi		

26 input parameters

1 output parameter

Trigger rate [Hz]

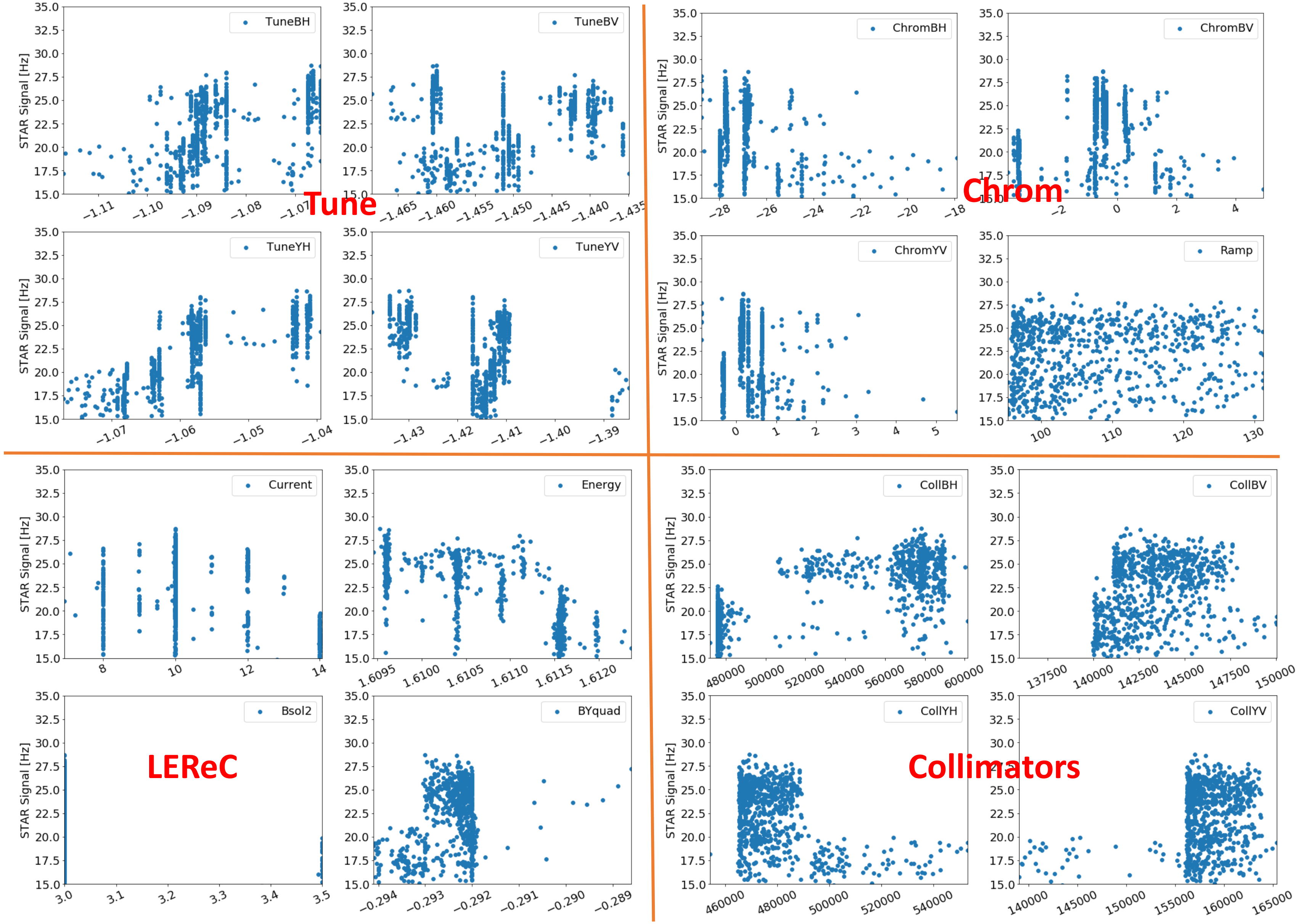




	Lumi	Current	Energy	TuneBH	TuneBV	TuneYH	TuneYV	ChromBH	ChromBV	ChromYV
0	22.826894	11.999802	1.611956	-1.087720	-1.46210	-1.058450	-1.422110	-26.5510	-0.752375	0.564760
1	22.391362	11.990360	1.611968	-1.087720	-1.46210	-1.058450	-1.423302	-26.5510	-0.752375	0.564765
2	21.924395	11.900414	1.611980	-1.091230	-1.46266	-1.058900	-1.425000	-26.5331	-0.756031	0.567406
3	23.389381	12.001050	1.611982	-1.091230	-1.46266	-1.058900	-1.425000	-26.5331	-0.756031	0.567406
4	22.602123	11.993456	1.611969	-1.088375	-1.46192	-1.058895	-1.424130	-26.5331	-0.756050	0.567405
...	...	...					...		...	...
698	30.531000	10.000625	1.611143	-1.067400	-1.46048	-1.043060	-1.429860	-27.7473	-0.707542	0.140645
699	29.794218	9.999789	1.611138	-1.067400	-1.46048	-1.043060	-1.429860	-27.7473	-0.707542	0.140645
700	29.117526	10.001532	1.611146	-1.067400	-1.46048	-1.043060	-1.429860	-27.7473	-0.707542	0.140645
701	29.903166	10.002073	1.611147	-1.067400	-1.46048	-1.043060	-1.429860	-27.7473	-0.707542	0.140645
702	29.372539	10.003549	1.611125	-1.067400	-1.46048	-1.043060	-1.429860	-27.7473	-0.707542	0.140645

703 useful stores **Data Table**

3) Luminosity as function of parameters



1. No clear message for most parameters. Their contributions the Lumi are mixed.
2. To decouple the correlation or separate the effects from each other.
3. Machine learning may help.

3) Validated XGBooster Model with 2020 Run data

Lumi (x1,x2,x3,….)

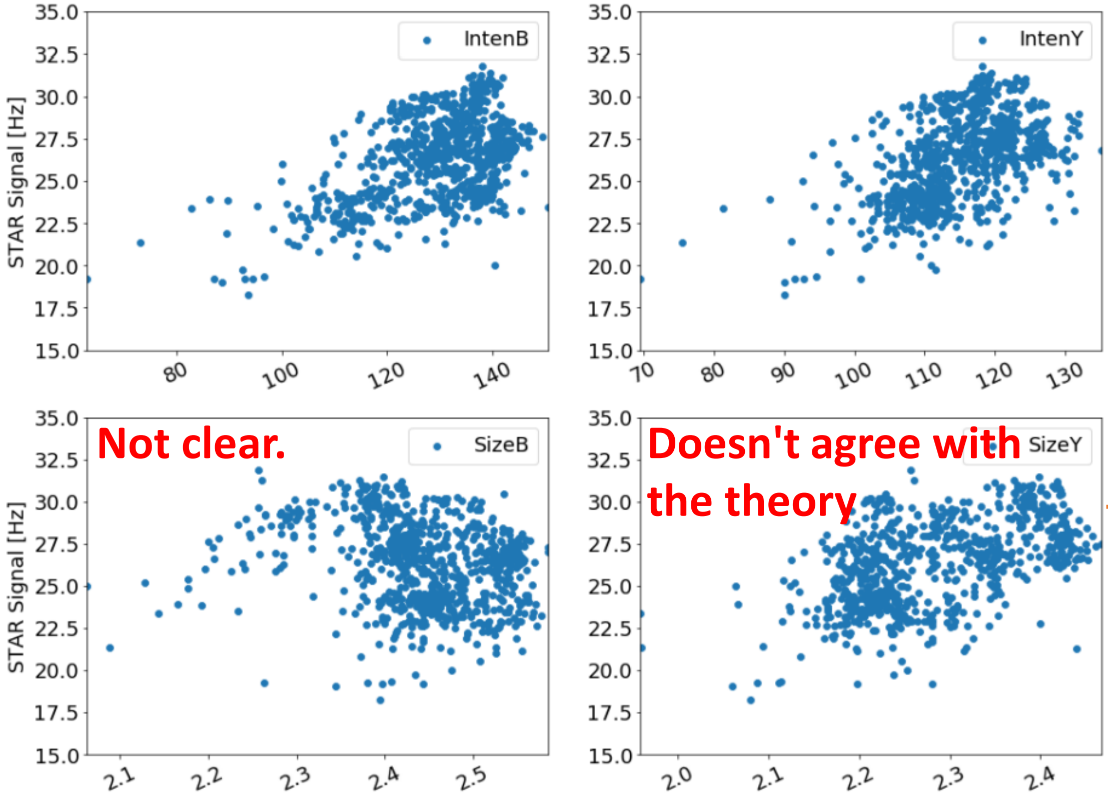


Fig. 3: The top plots are the luminosity scattering plot as a function of the blue and yellow ion beam intensity. The bottom figures are the luminosity scattering plots as a function of the blue and yellow ion beam size. The unit of the ion intensity is 1E9; the RMS beam size unit is um (emittance unit)

Lumi_SHAP (x1)

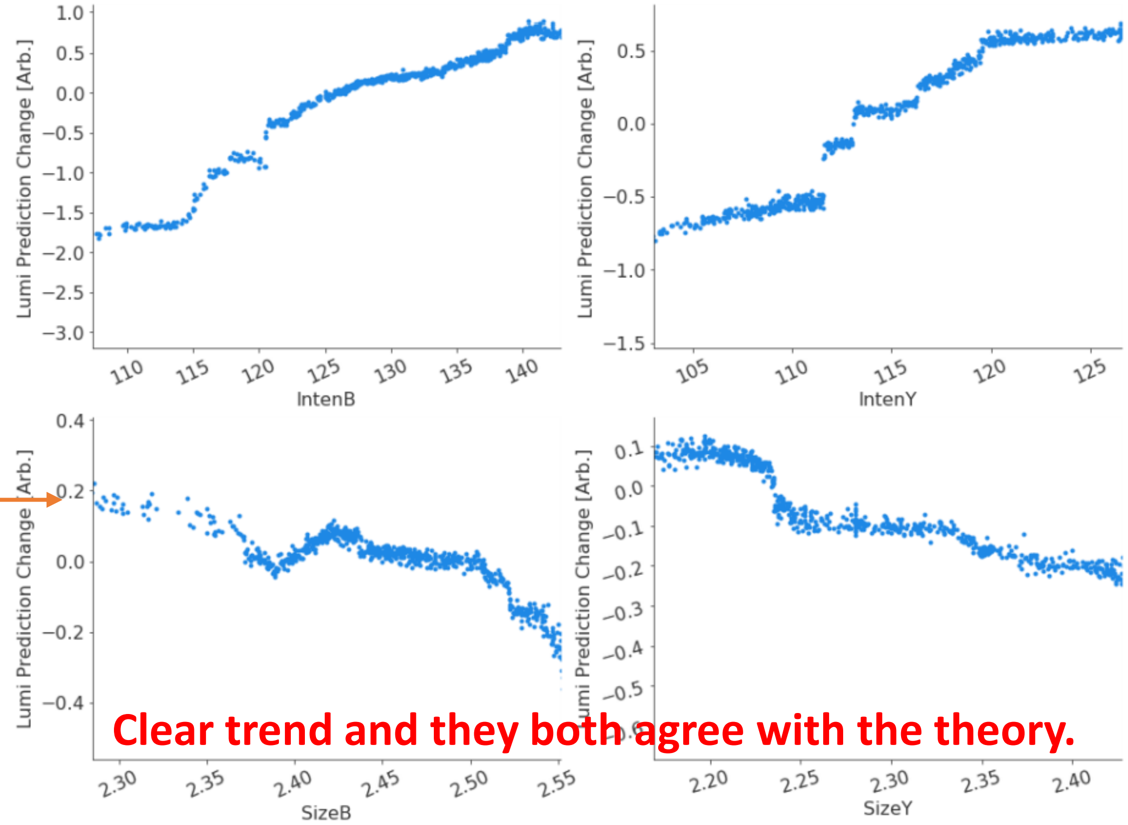


Fig. 13: The SHAP values plots for the ion beam intensity [1E9] and beam size [um] (emittance).

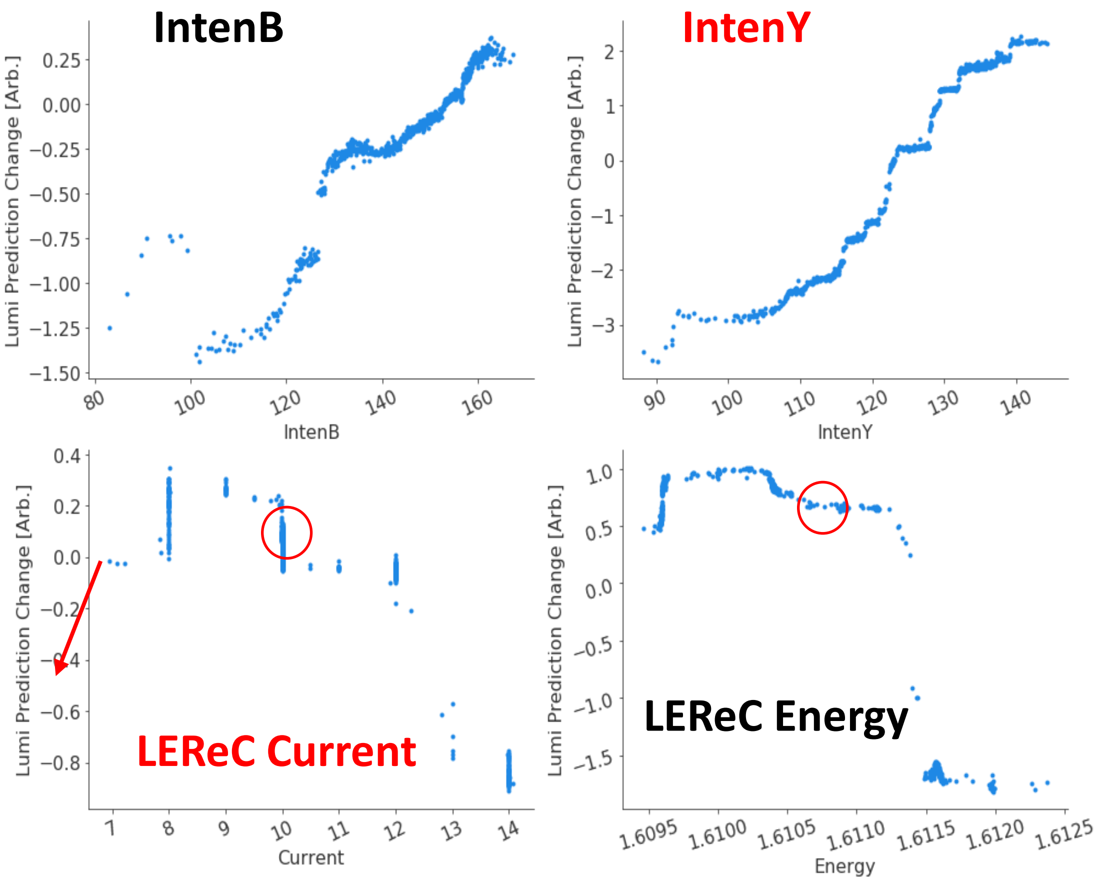
It makes sense now (within the existing data range).

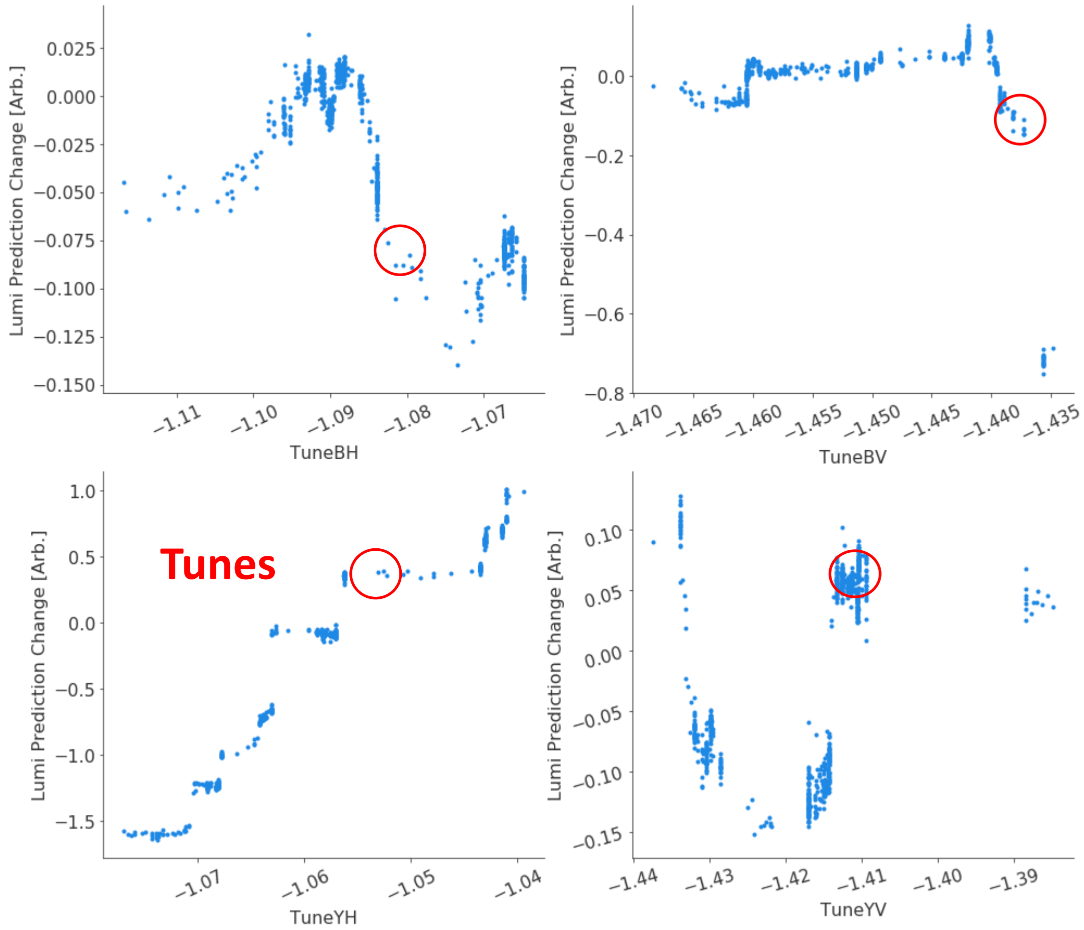
3) Offline Evaluate 2021 Operation data with XGBoost

1. Intensity: IntenY ~ 5 Hz, IntenB ~ 2 Hz; higher blue beam loss?

2. Current: 1 Hz, more data points (6A) to confirm the optimized value.

3. TuneYH and TuneBV

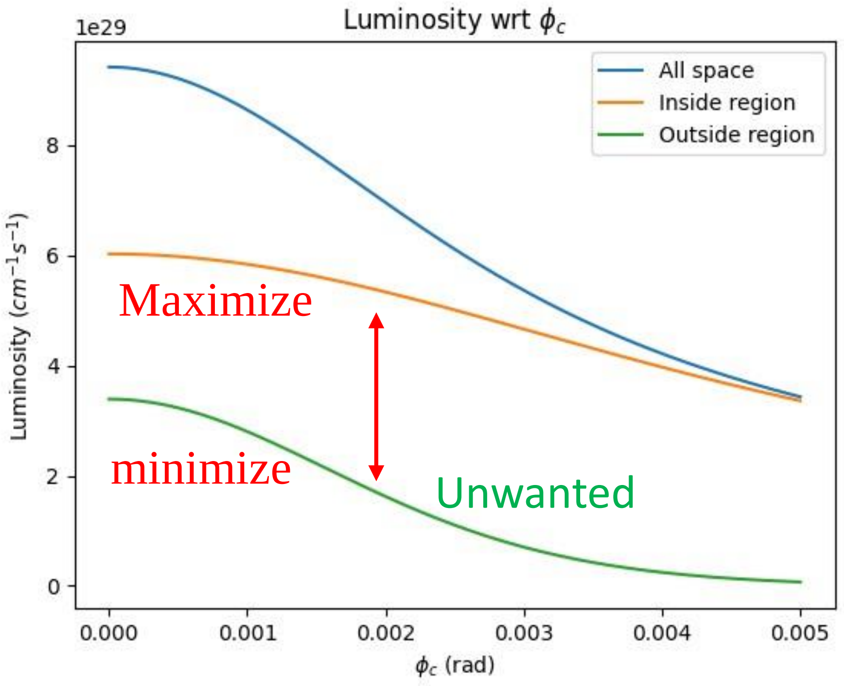


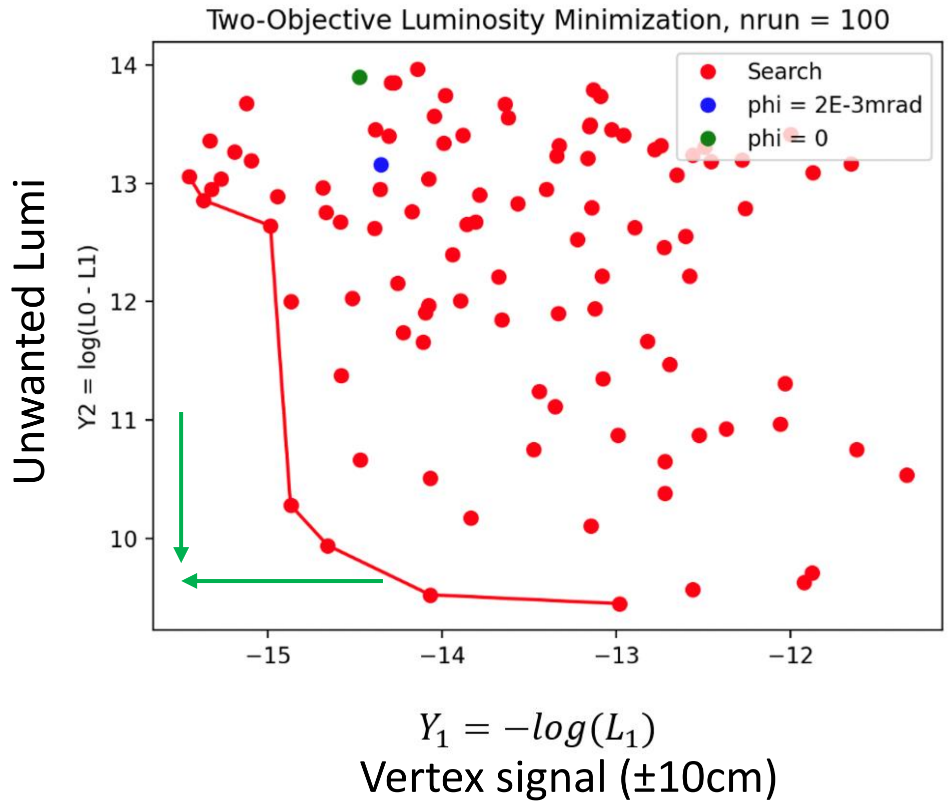


3) GPTune Luminosity Optimization-Analytical Model

$$L = \cos^2(\frac{\phi}{2}) f N_1 N_2 \int_{-D}^{D} \frac{ds}{4\pi^{3/2}\sigma_x^2\sigma_y\sigma_z\sqrt{\frac{\cos^2(\frac{\phi}{2})}{\sigma_x^2} + \frac{\sin^2(\frac{\phi}{2})}{\sigma_z^2}}} \exp(-s^2(\frac{\sin^2(\frac{\phi}{2})}{\sigma_x^2} + \frac{\cos^2(\frac{\phi}{2})}{\sigma_z^2}))$$

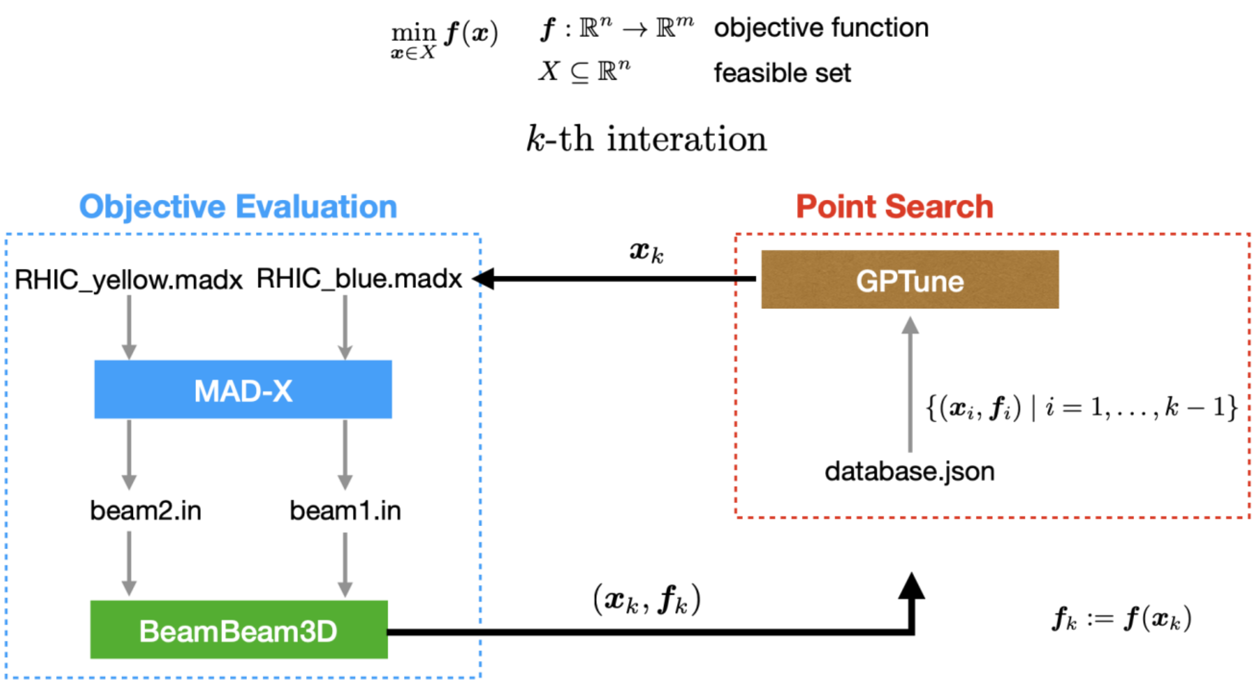
$\beta_{x,y}$ and σ_z	$[0.1, 1]$m
ϕ	[0,5] mrad

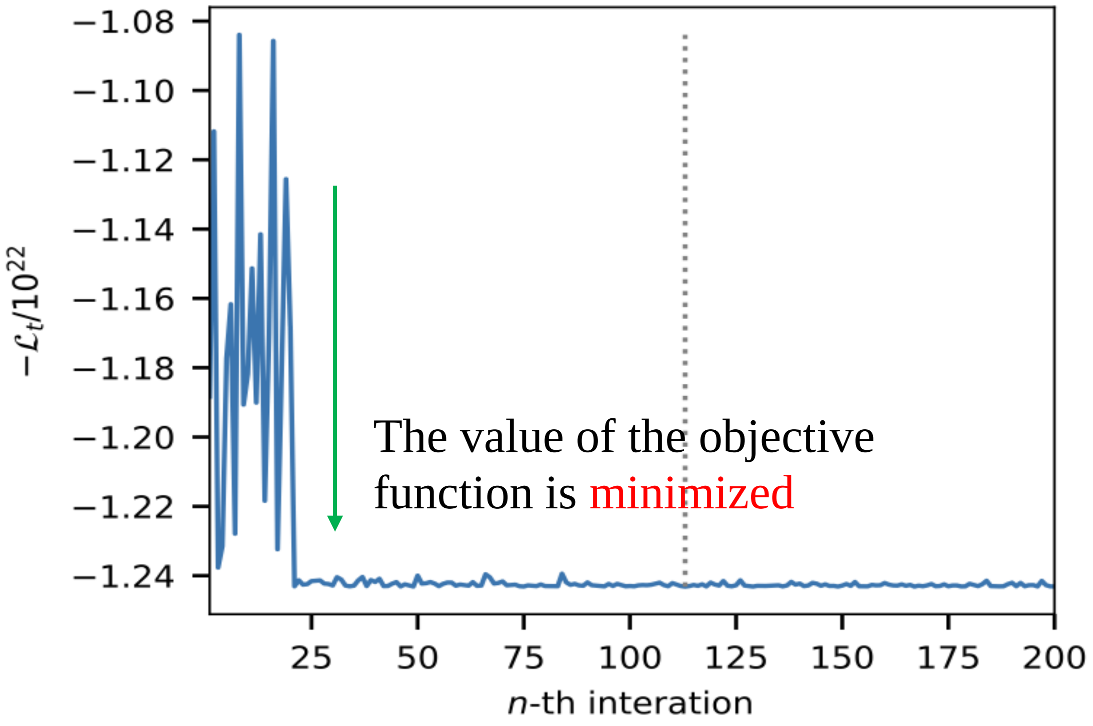




The value of the objective function is minimized.

3) GPTune Luminosity Optimization-Simulation





The optimization of the lattice setting with respect to the luminosity is performed for the head-on collision of two Au-Au beams in the Relativistic Heavy Ion Collider (RHIC). The parameters of the lattice setting with only two variables ΔS_x and ΔS_y.

The value of the objective function converges when more optimization steps are executed. This implies the value of the objective function is minimized and hence the total luminosity $L_t$is maximized.

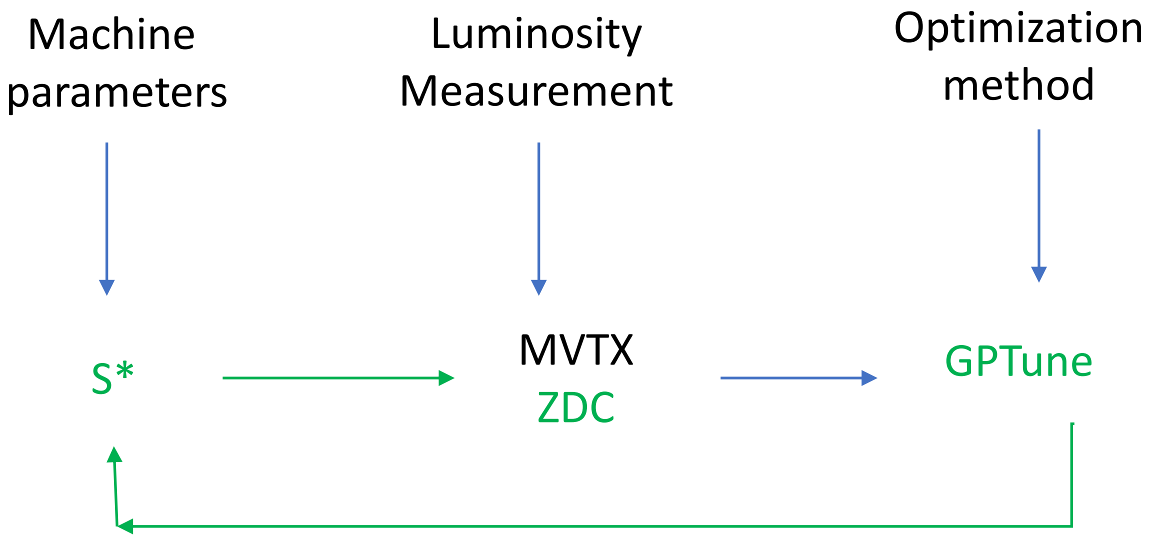
3) GPTune luminosity Optimization sPHENIX

- Global Parameters:
1. Orbit (Dipole)
2. Tune (Quadrupole),
3. Chromaticity (Sextuple)
4. Octupole

- Local (IR8) Parameters:
1. Beta* (beam size)
2. S* (longitudinal beam waist)
3. Transverse offset

- Other Parameters:
1. RF Voltage
2. Collimator Position

- sPHENIX (OFF):
1. max. MVTX (+/-10 cm)
2. min. unwanted signal
3. Crossing angle (2mrad)
4. ZDC rate

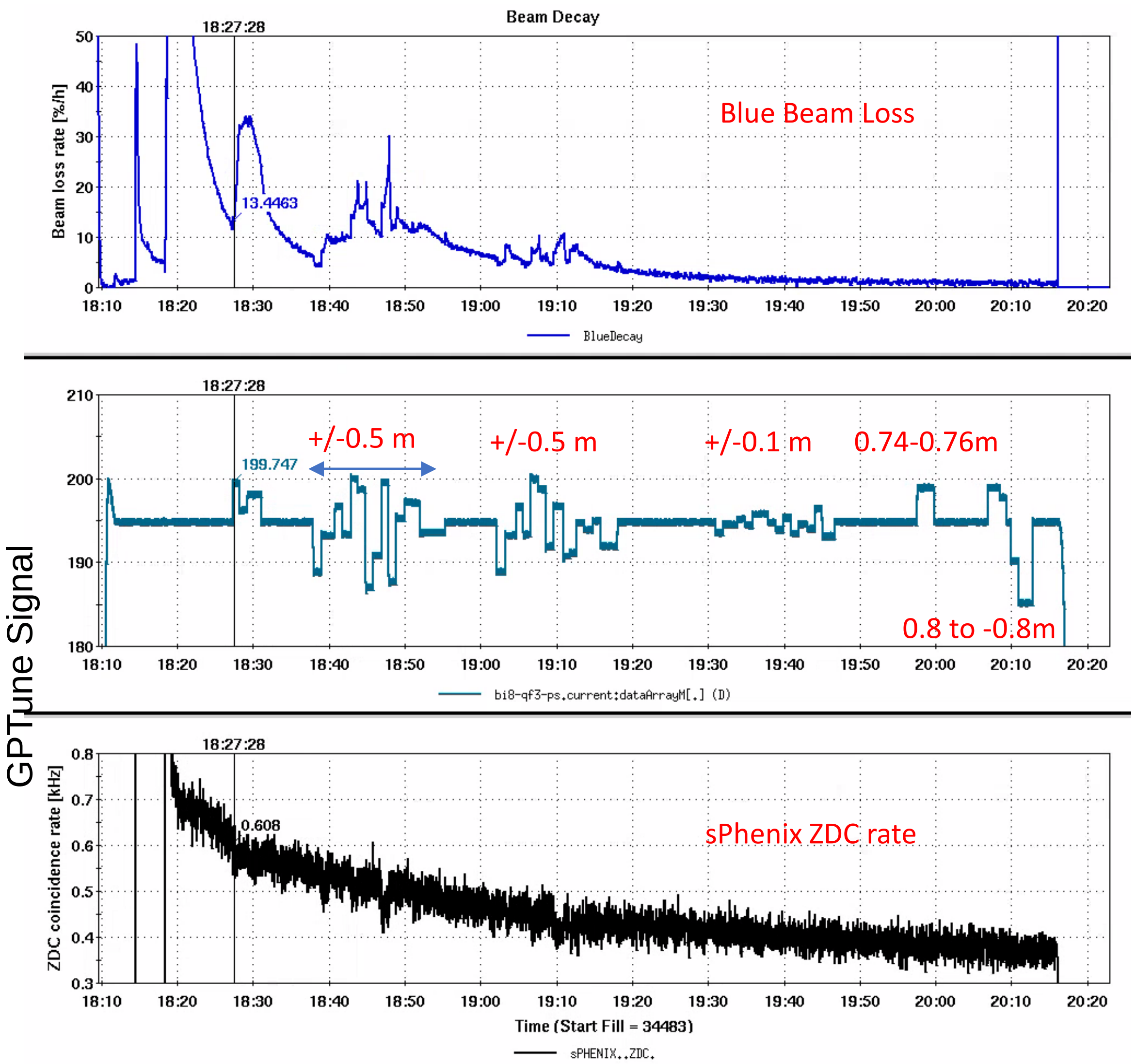


S* and beta* changing scripts: 2023
1. change the target s*, beta* within 'deltas.dat' file;
2. run 'madx job.madx' command, will get 'IP8knob.dat' file;
3. run 'CreateSend.IP8' command, will get 'SendTrim.IP8' file;
4. run 'SendTrim.IP8' command.

GPTune: 2023
1. Installed and tested
2. Did some optimizations EBIS and got some good results.

Optimization Loop: May, 2024

3) The First sPhenix ZDC GPTune Optimization 05/16/2024



- S*: +/-0.5 m without decay compensation
- S*: +/-0.5 m; +/-0.1 m.
- S*(x plane): 0.74-0.76m; 0.8m->0.4m->0m->-0.4m->-0.8m.
- S* > 0.8 m, MADX didn't find solutions.

- Beam loss is acceptable.
- ZDC rate was changed. Didn't see any visible improvement with ± 10% pp noise.
- With +/- 0.8m, it is expected 17% change for ZDC rate.
- GPTune works with std ±10% (pp) noisy signals ±15%!

3) Reasons and Plan for Luminosity Optimization

- **S* control:**

Base line: s*x = 1.19m, s*y = 0.67m
Move s*x -> -0.5 m: s*x = 1.14m, s*y = 0.01
Move s*x -> 0.5 m: s*x = 0.74m, s*y = 0.35

- **S* Measurement:** lattice and real machine
- **Magnet hysteresis:** Same current can have different field (up or down ramp)
- **Too large beam size:** the emittance was 3~4 higher than nominal.
- **Optimal S* already:** is very closed to its optimal and don't need to do anything!
- More than 20 times luminosity now.

1. **S* measurement to confirm**
2. **Using Power supplies instead of S***
3. **Control Power supplies only ramp to one direction**
4. **Improve Emittance: Done**
5. **Explore other control parameters?**
6. **Optimize Luminosity vs Reduce background?**
7. **sPHENIX detector or MVTX signal were OFF.**
8. **Orbit Tune feedback**

- Global Parameters:

1. Orbit (Dipole)
2. Tune (Quadrupole),
3. Chromaticity (Sextuple)
4. Octupole

- Local (IR8) Parameters:

1. Beta* (beam size)
2. S* (longitudinal beam waist)
3. Transverse offset

- Other Parameters:

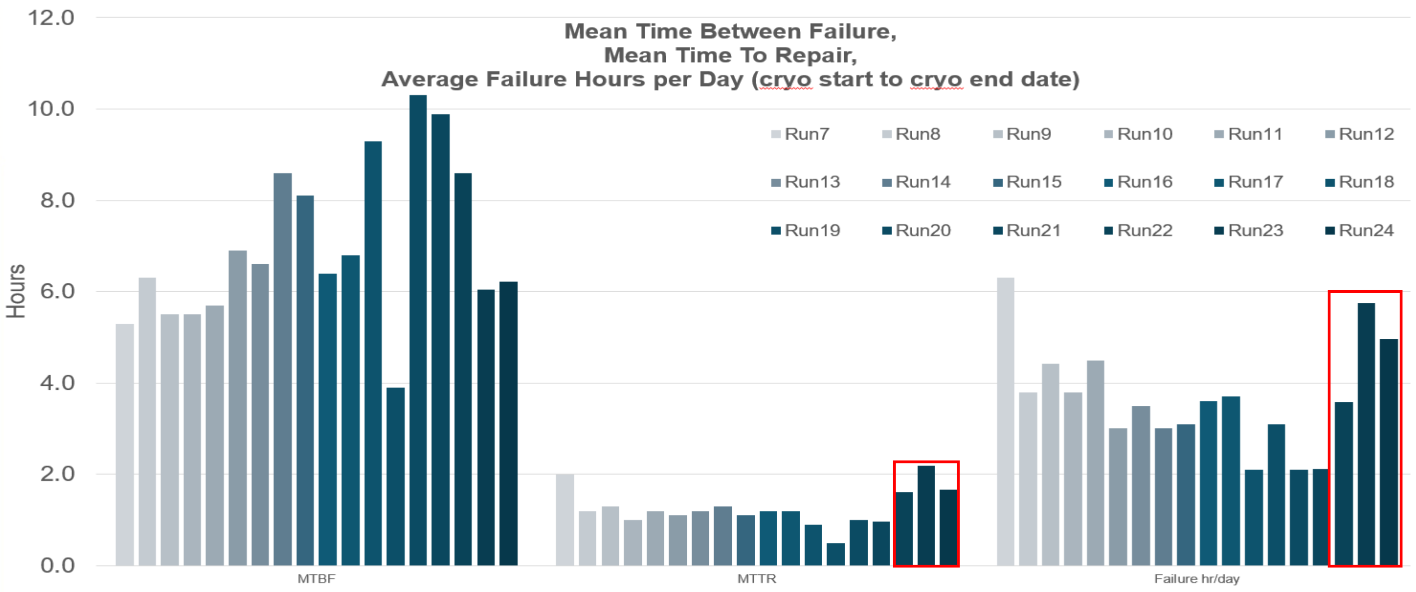
1. RF Voltage
2. Collimator Position

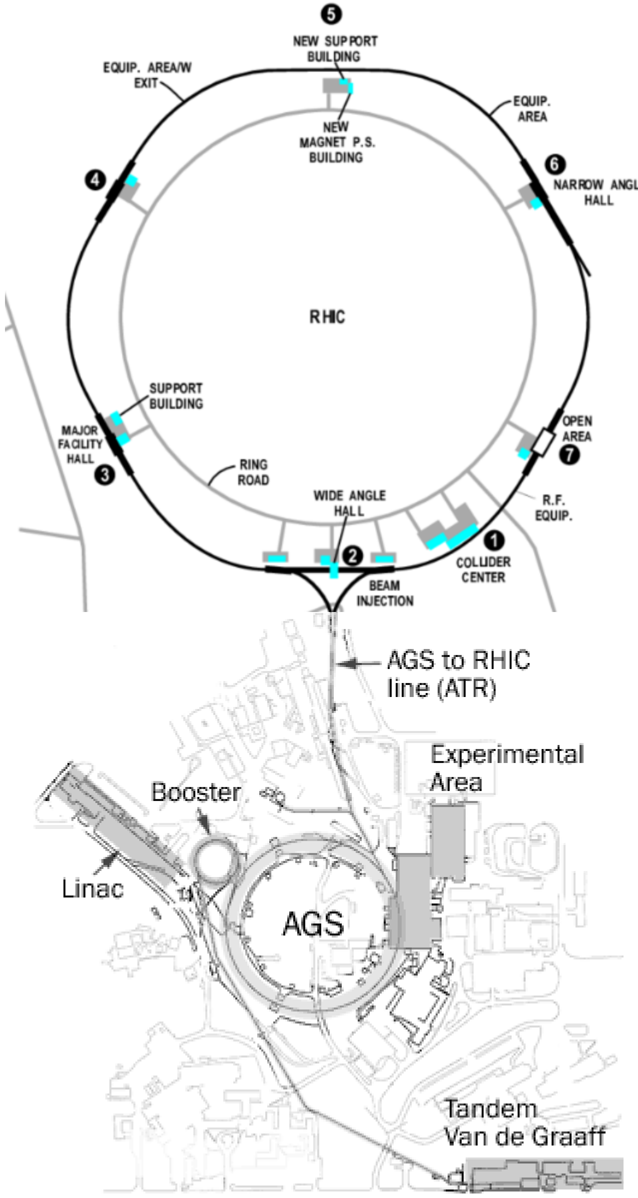
Outline:

1) Motivation
2) EBIS Intensity Optimization
3) Luminosity Optimization
4) Plan & Summary

4) Plan

1. AGS injection
2. NSRL: target beam line
3. Proton Beam Source: OPPIS
4. Tandem beam line
5. RHIC coupling
6. Machine anomaly detection





4) Summary

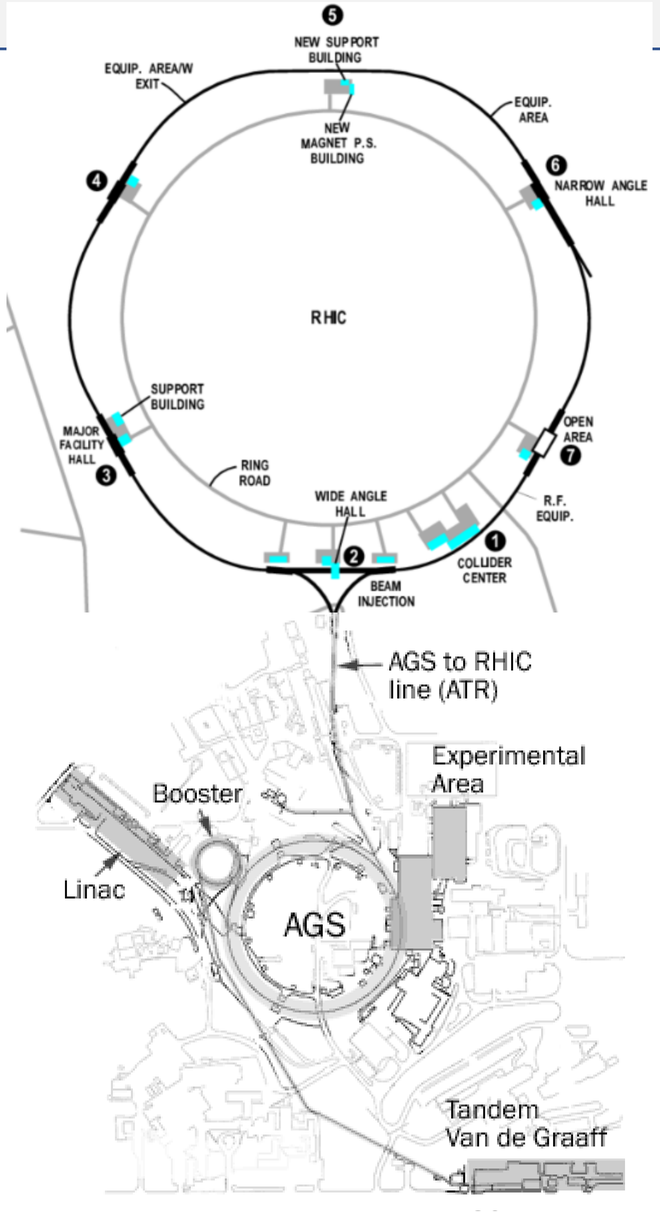
1. GPTune was used for EBIS intensity optimization and got 22~30% intensity improvement at xf14 CT (70% with fc96 CT) , with ±10% std noisy signals and 19 variables.

2. Xopt has been used for LTB and can optimize beam size and intensity at the same time

3. The luminosity optimization with sPHENIX ZDC has been carried out for the first time. More APEX time is required to confirm the results or optimize the integral luminosity with more/different parameters.

4. GPTune/Xopt has been demonstrated as a powerful tool for optimization. It is planned to be used for other beam lines (intensity, emittance and polarization) optimization in RHIC complex.

5. XGBoost is a good tool for offline machine optimization.



Acknowledgement

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