

Autonomous Tuning at FACET II

AI Test Facility Workshop
July 2026

Speakers: Juan Pablo Gonzalez-Aguilera¹ and Yiheng Ye^{1,2}

Authors: Dylan Kennedy¹, Zhe Zhang¹, Sheldon Rego³, Zach Buschmann¹, Ryan Loney¹, Doug Storey¹, Brendan O'Shea¹, Auralee Edelen¹, and Ryan Roussel¹

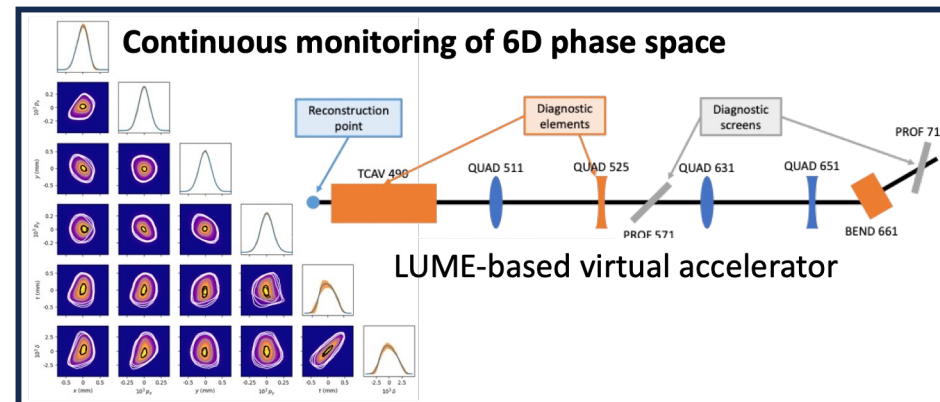
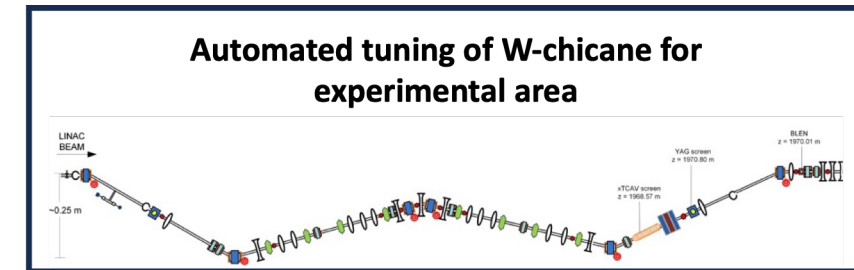
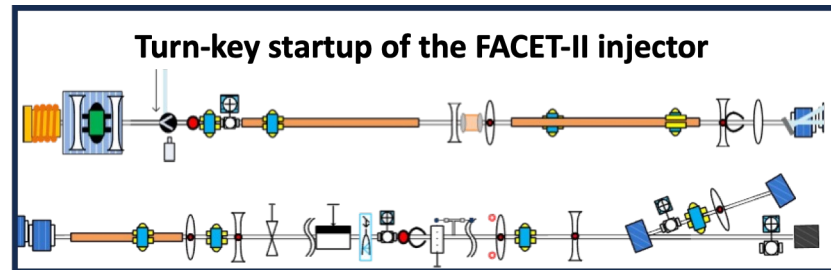
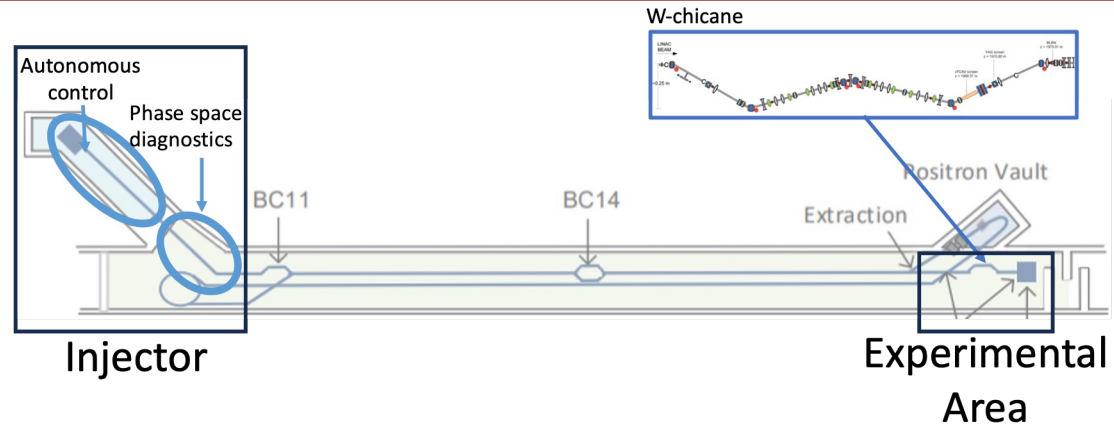
¹SLAC National Accelerator Laboratory, Menlo Park, CA, USA

²Physics Department, Stanford University, Stanford, CA, USA

³Laboratoire d'Optique Appliquée, Institut Polytechnique de Paris, Paris, France

Autonomous Tuning at FACET-II

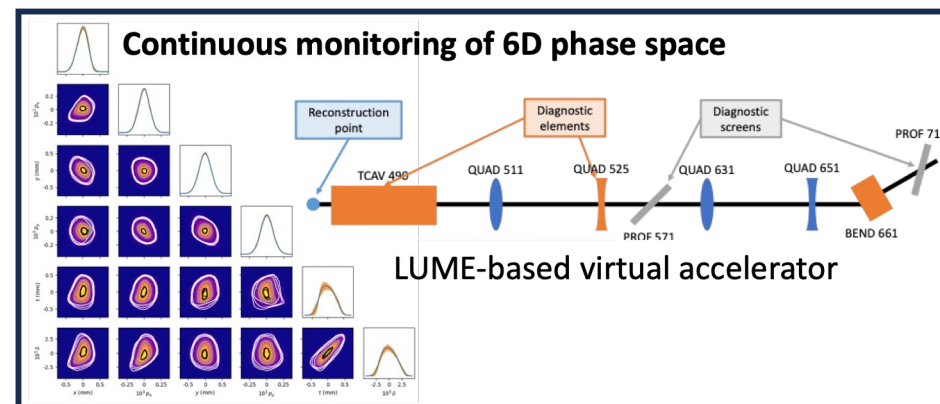
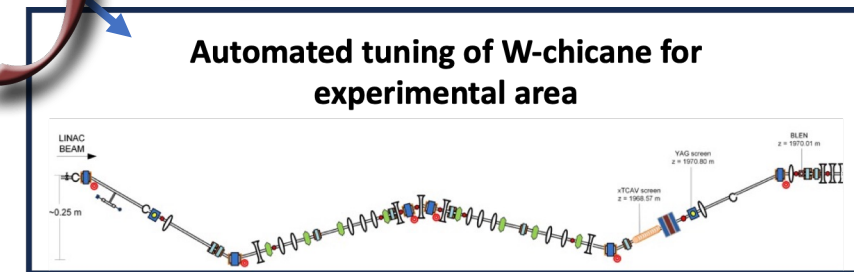
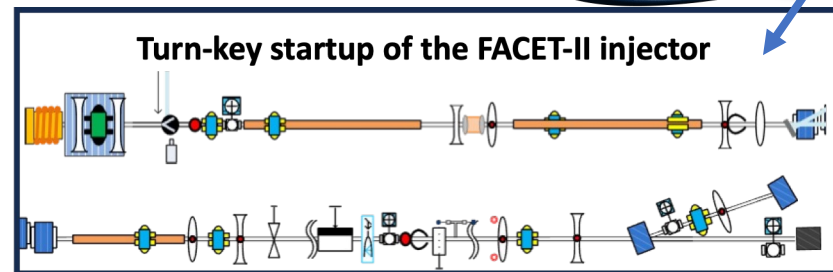
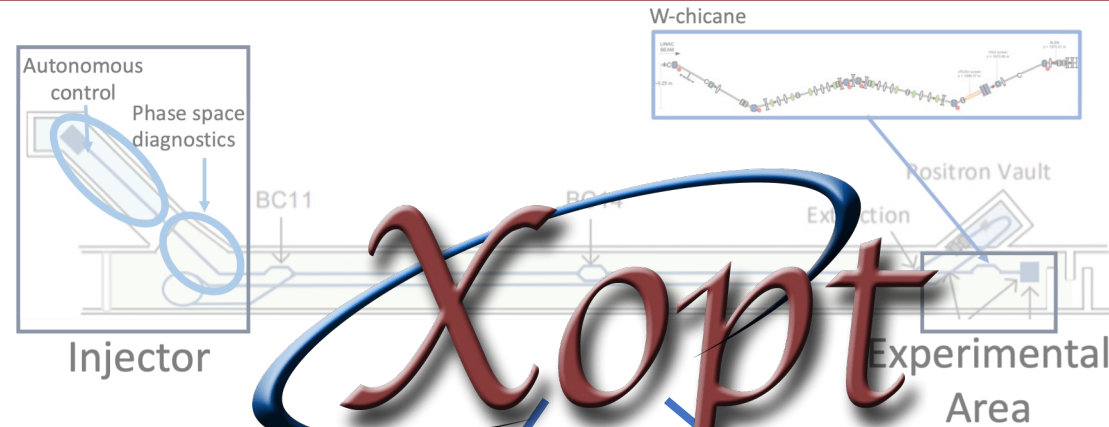
Utilize control techniques to autonomously configure / operate FACET-II to reduce the burden on operators + enable new capabilities



Autonomous Tuning at FACET-II

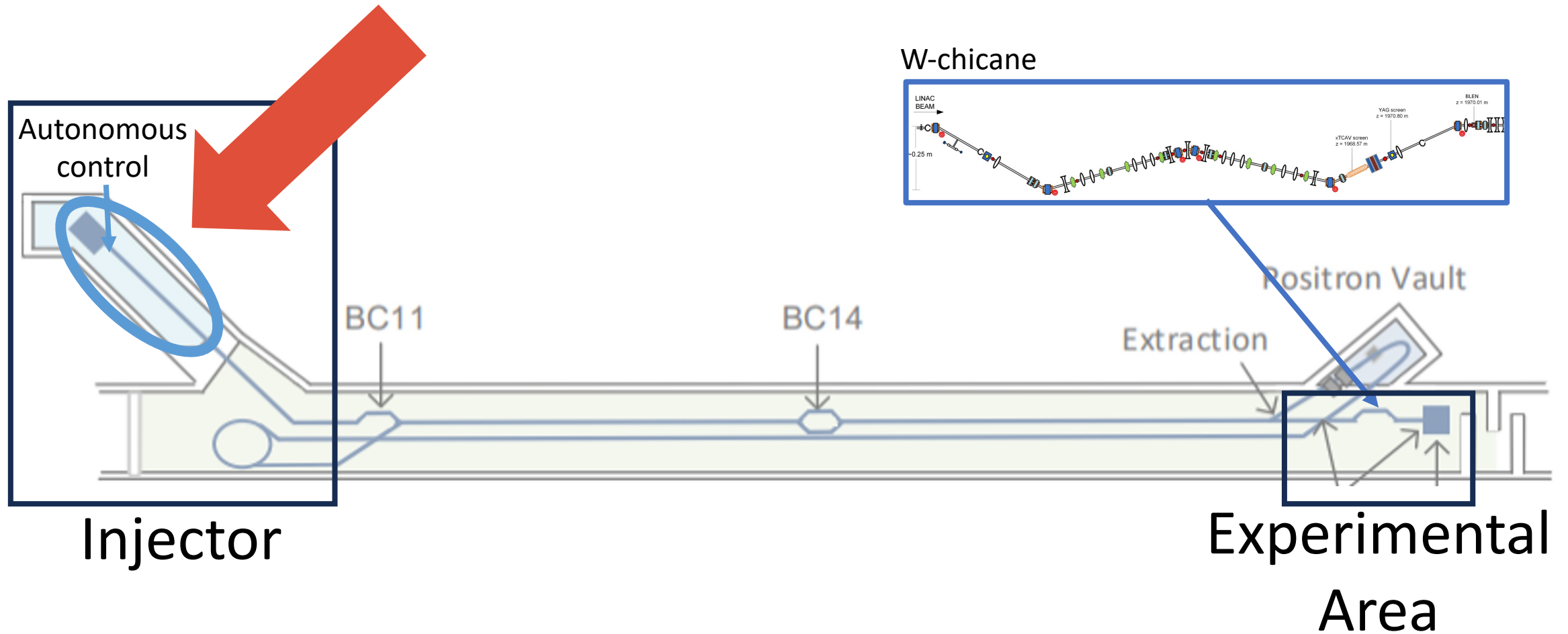
Utilize control techniques to autonomously configure / operate FACET-II to reduce the burden on operators + enable new capabilities

Osprey



LUME

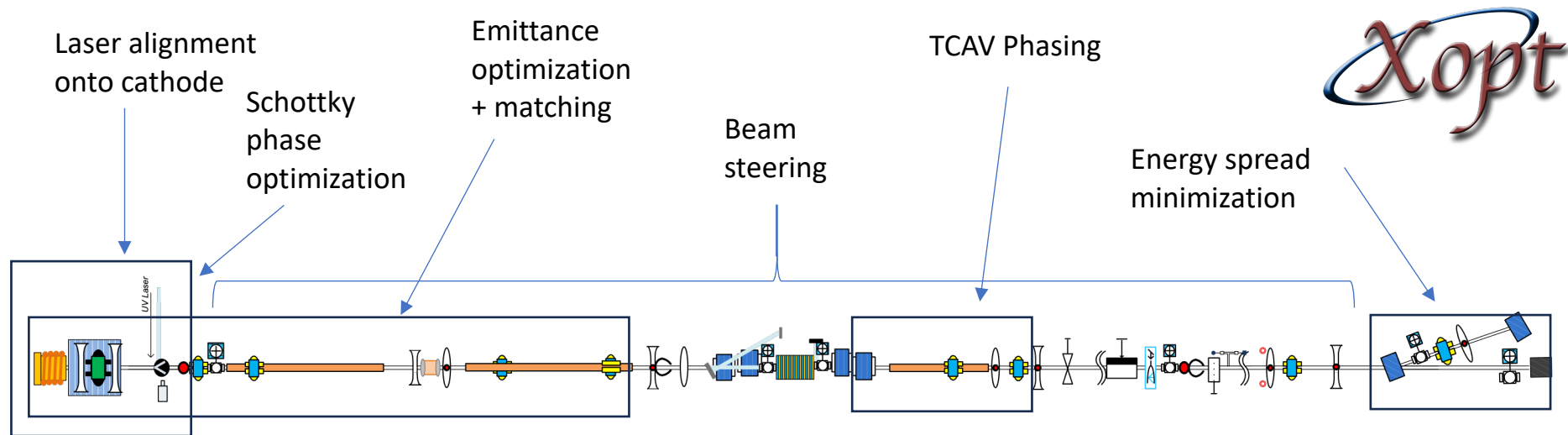
Injector Automation



Injector Startup Tasks

FACET-II injector startup requires operators to conduct multiple tasks to transport the beam to TD11, a subset of which are shown below.

Goal: Identify and deploy a set of algorithmic tools to address each of these challenges – then execute them sequentially to configure the beamline



Startup Automation Challenges

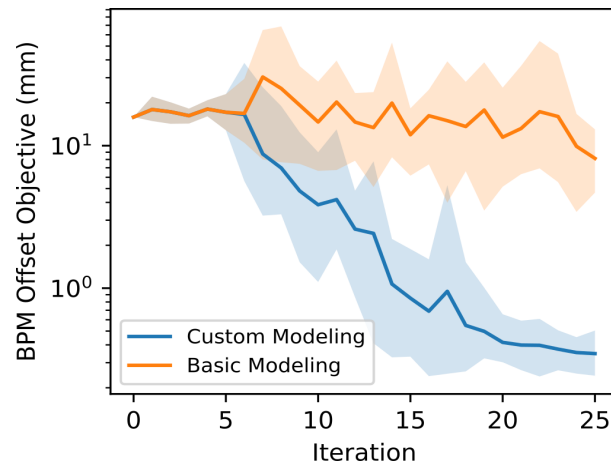
BO algorithm customization enables / improves autonomous control

Model free beam steering challenge:

- High dimensional optimization problem (14 steering magnets)

Solution:

- Independently model each BPM signal with separate Gaussian Processes and combine model samples into a single objective $\rightarrow$ substantial increase in convergence speed

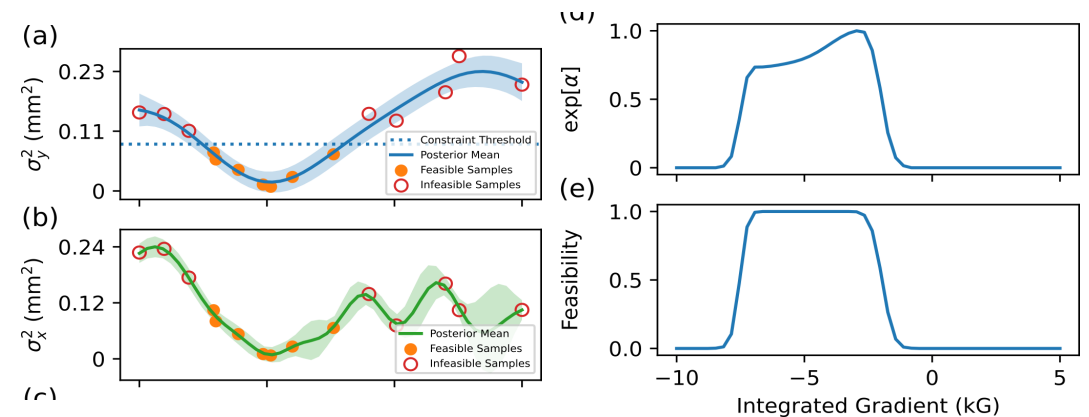


Emittance measurement challenge:

- Need to scan quadrupole to rotate beam in transverse phase space
 - Wide enough to capture enough tomographic info in both planes (x/y) (subject to beam transmission / beam size constraints)

Solution:

- Exploration-biased UCB ($\beta \sim 10^3$) with observable constraints on beam size, transmission



Startup Automation Challenges

BO algorithm customization enables / improves autonomous control

Laser-solenoid alignment:

- Want to align e-beam with solenoid magnetic center

Solution:

- Minimize deflection of beam when scanning solenoid strength → use virtual objectives via Bayesian Algorithm Execution (BAX)

Schottky scan optimization:

- Need to determine laser timing delay to match RF phase in injector

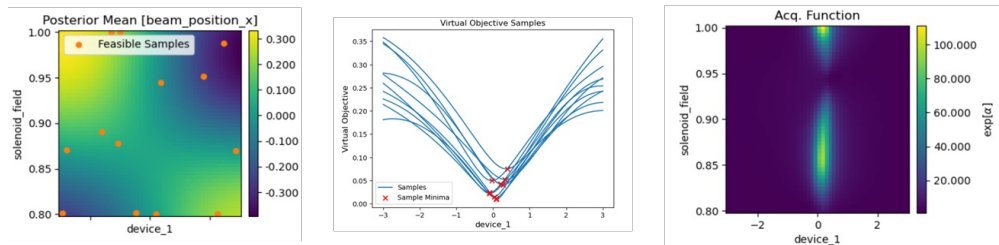
Solution:

- Use Amortized Bayesian Optimal Experimental Design (ABOED) → use a Bayesian probabilistic model to fit data + determine next observation that gives the most info about t_0

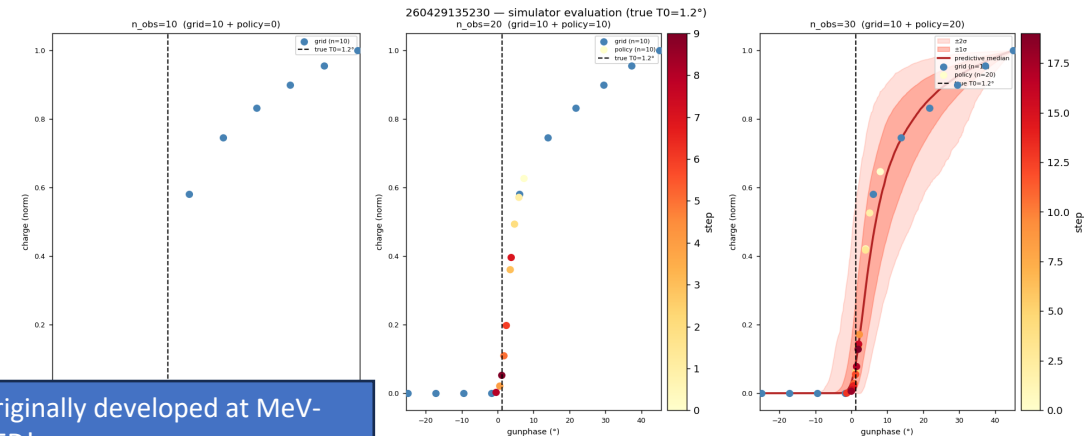
Model the
Observables
(centroid position)

Optimize **Virtual Objective**
samples with respect to
tuning devices

Use sample optima to
compute **Expected**
Information Gain (EIG)
acquisition function



*Plots from D. Kennedy



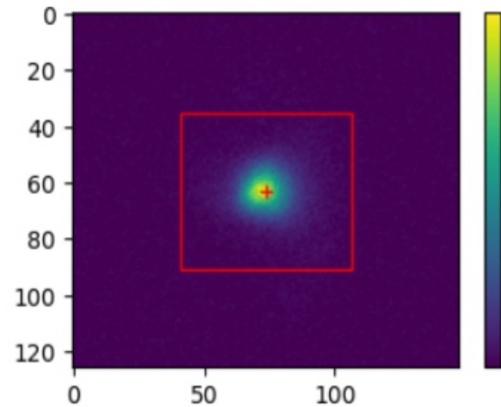
Originally developed at MeV-
UED!

Samuel Klein and Sean Gasiorowski

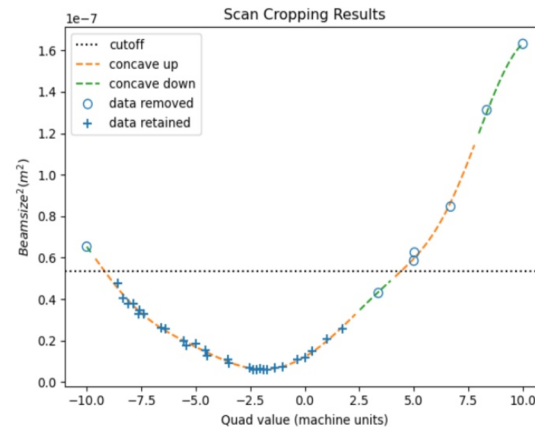
Startup Automation Robustness

Significant infrastructure is needed to enable robust autonomous operation

Robust data fitting / filtering
(e.g. removing failed measurements)

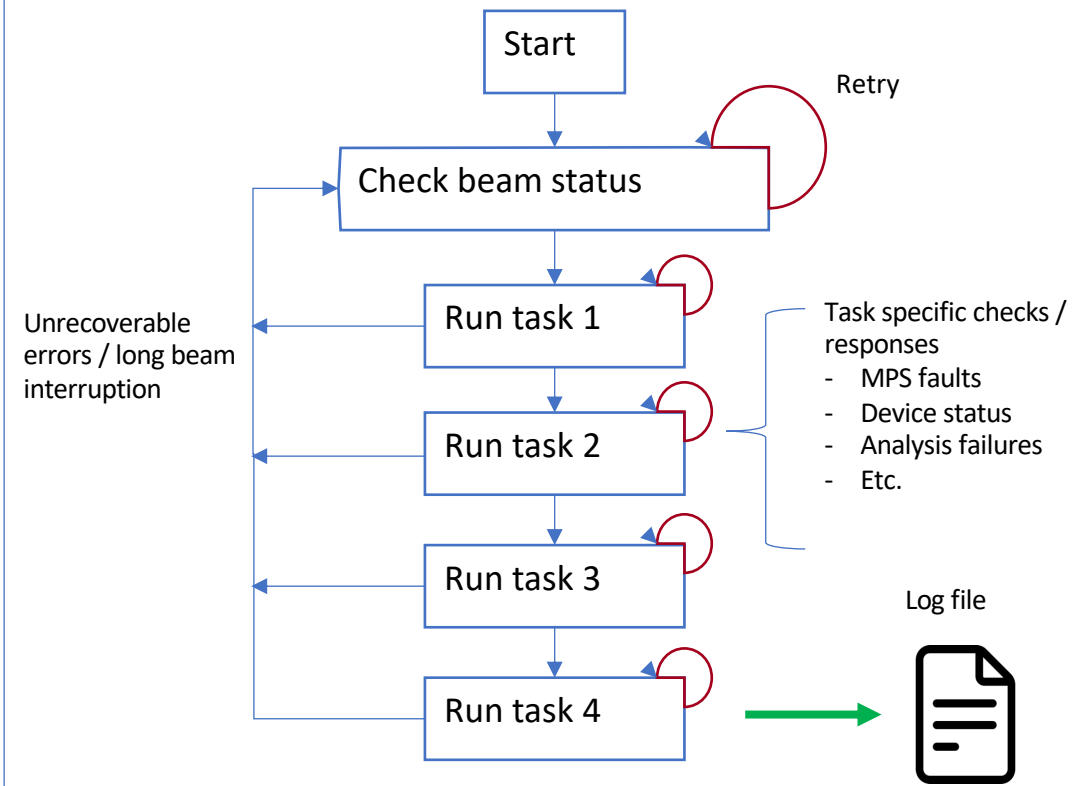


Verify beam is not clipping / present
on diagnostic



Concavity validation, image
selection

Identify / respond to beam interruptions,
measurement failures



Startup Automation Results

Start-to-end autonomous configuration of the FACET-II injector beamline w/o human intervention (~21 min)

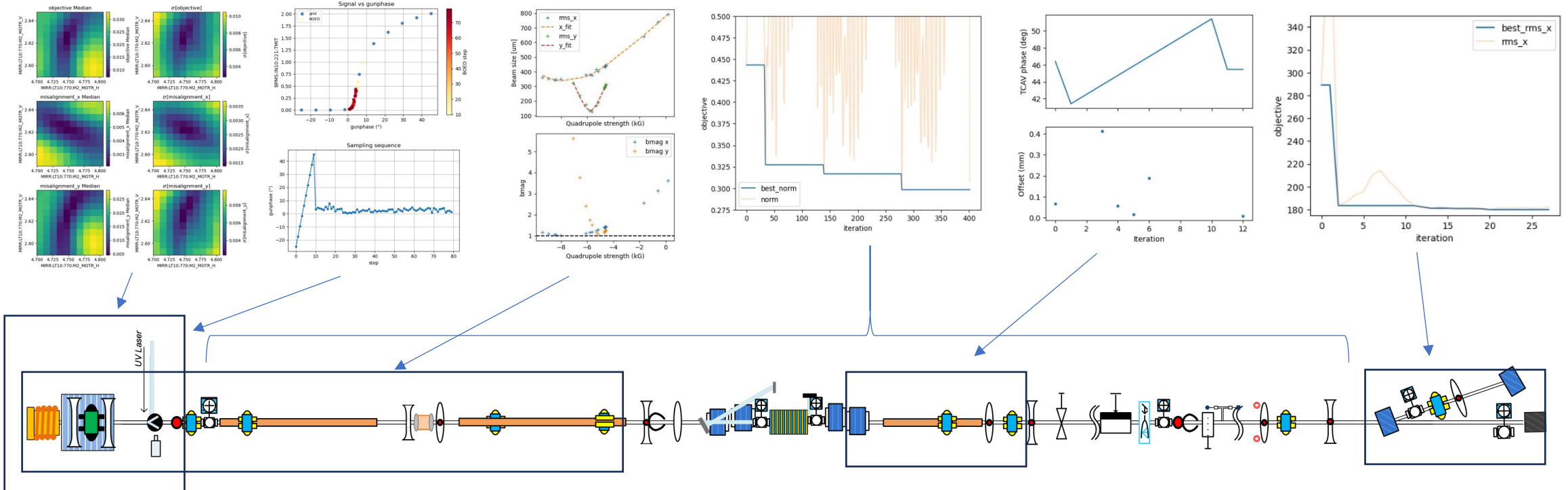
Laser alignment onto cathode (1 min) Schottky phase optimization (4 min)

Emittance optimization + matching (13 min)

Beam steering (3 min)

TCAV Phasing (7 sec)

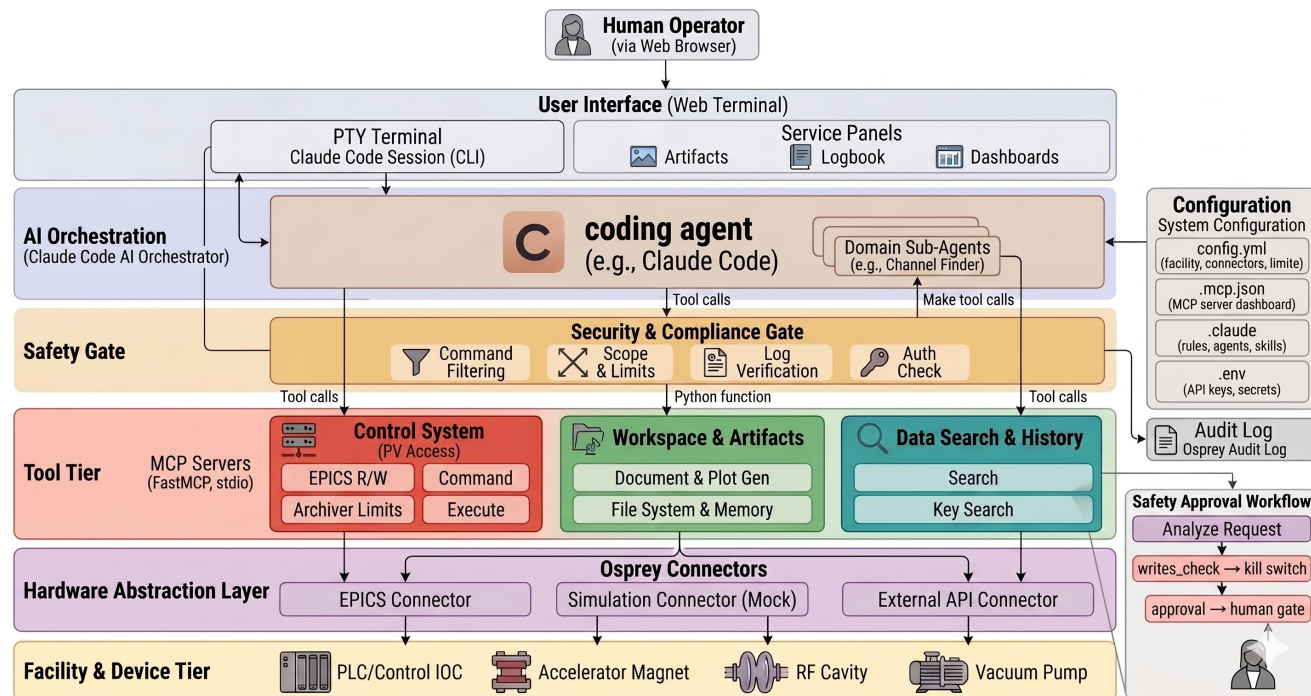
Energy spread minimization (2 min)



Startup Automation with AI Agent: Osprey

Osprey: Production-ready agentic AI for safety-critical control systems

AI agent for autonomous FACET-II injector startup



- The Xopt tools we build now (e.g. algorithms built to address specific tasks) are integrated to AI agent
- Human readable text is used to assign agents a task *“setup the FACET-II injector for bunch with charge of 1.6 nC”*
- This will free up human operators to address more complex (and fun!) tasks

*Hellert, Thorsten, et. Al. APL Machine Learning 4.1 (2026). <https://github.com/als-apg/osprey>

Startup Automation with AI Agent: Osprey

Demonstrated at FACET-II 2 weeks ago!

```
---
Now launching Task 4/6: minimize_energy_spread.

Called python (ctrl+o to expand)

• The fd error persists but based on prior behavior, the process likely
  launched. Let me monitor for file #13:

  Searched for 1 pattern (ctrl+o to expand)
• File #13 appeared! Let me check it:

  Searched for 1 pattern, read 1 file (ctrl+o to expand)
• [ ] Task 4/6: minimize_energy_spread – Done
```

Metric	Value
Evaluations	9
Errors	0
Best rms_x	256.2 μm (step 7, phase -9.34°)
Worst rms_x	375.5 μm (step 3, phase -4.31°)
Optimal phase	$\sim -9.3^\circ$ (consistent with round 1)

```
---
Now launching Task 5/6: minimize_injector_emittance (~10 min expected).

Called python (ctrl+o to expand)

• Launched. This one takes ~8-10 minutes. I'll monitor for file #14. Setting up
  a check:

• CronCreate(* / 3 * * * *: Check /home/fphysics/zhezhang/MD_260701/osprey_data/
  for fi...)
  [ ] _Scheduled b7e23dbd (Every 3 minutes)

• Task 5 (minimize_injector_emittance) is running – ~8-10 min for the full
  quad-scan emittance measurements. Monitoring every 3 minutes, will report when
  done and immediately launch the final task.

* Sautéed for 6m 20s
```

AI agent for autonomous FACET-II injector startup

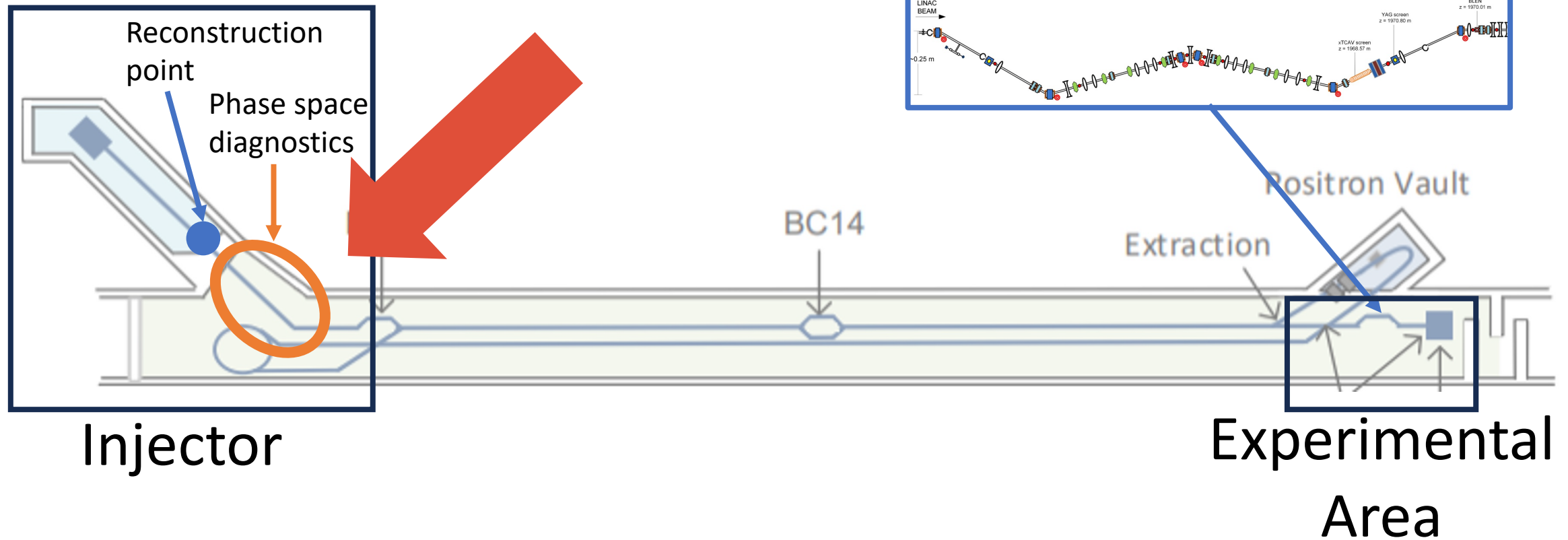
- The Xopt tools we build now (e.g. algorithms built to address specific tasks) are integrated to AI agent
- Human readable text is used to assign agents a task “*setup the FACET-II injector for bunch charge of 1.6 nC*”
- This will free up human operators to address more complex (and fun!) tasks

Startup Automation with AI Agent: Results

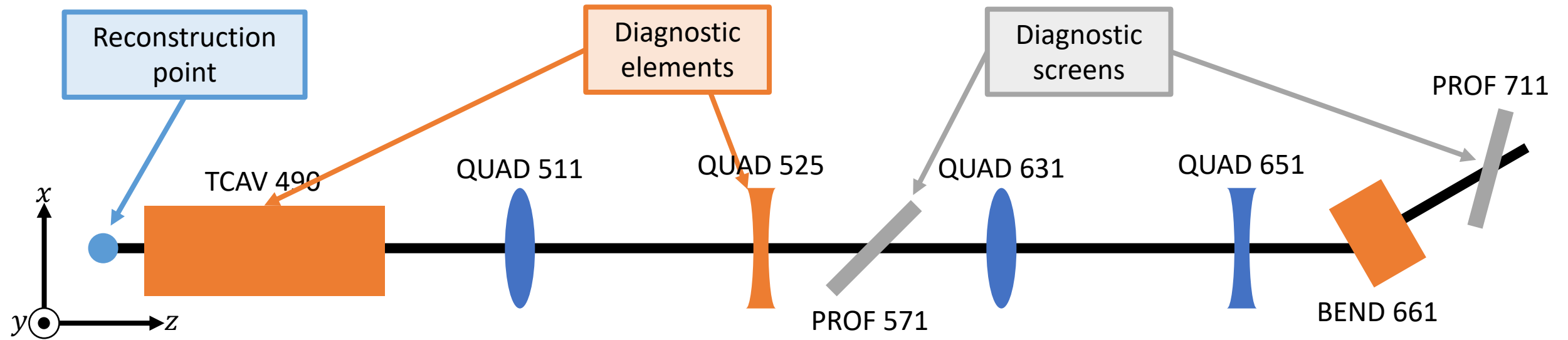
Osprey → used Xopt tools from each step given high-level task / instructions for injector startup

- Ran several charge changes and tuning: 1.6 nC, 2 nC, 2.2 nC
- ~20 minutes for entire task chain
- Recovered roughly equivalent or better emittance in each case (although back to 1.6 nC had poorer match)

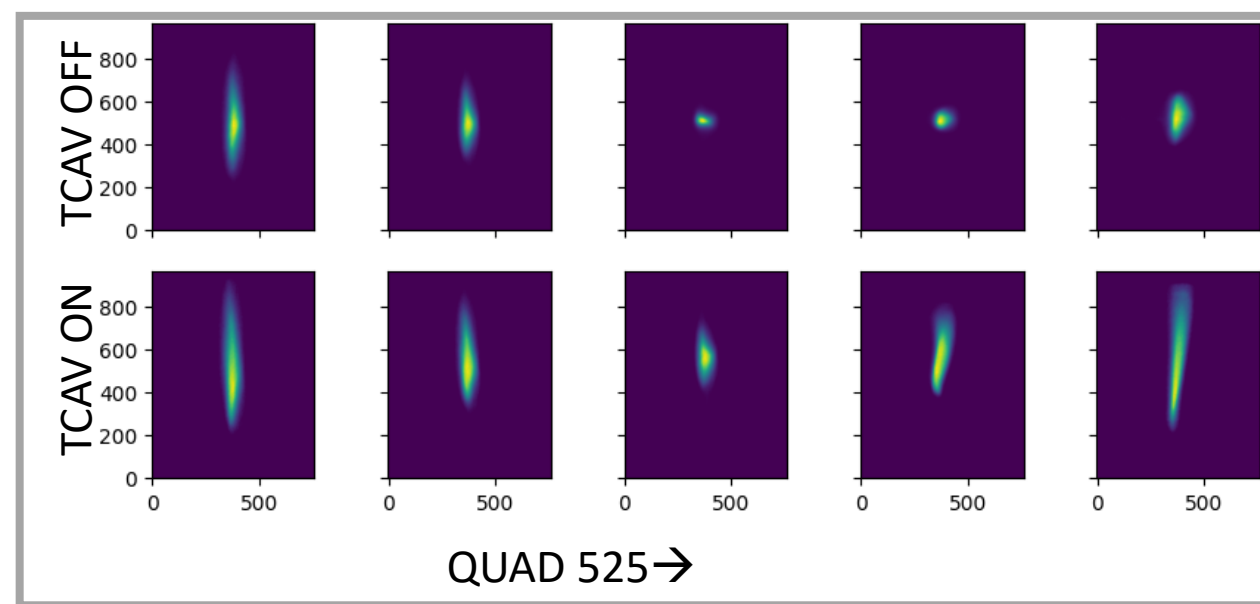
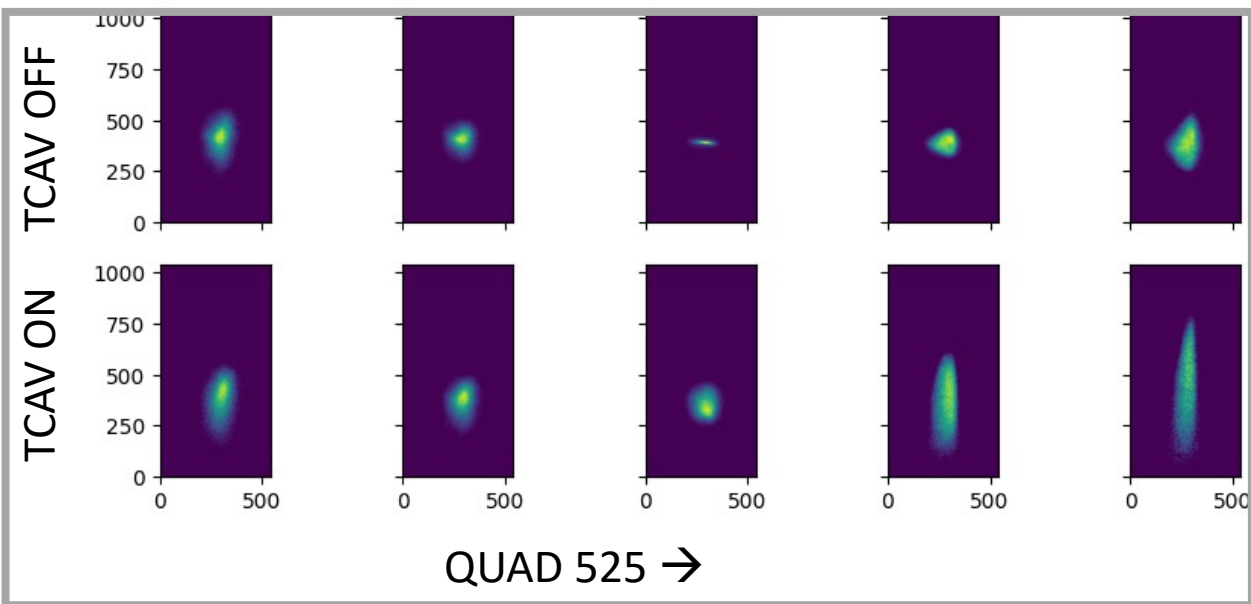
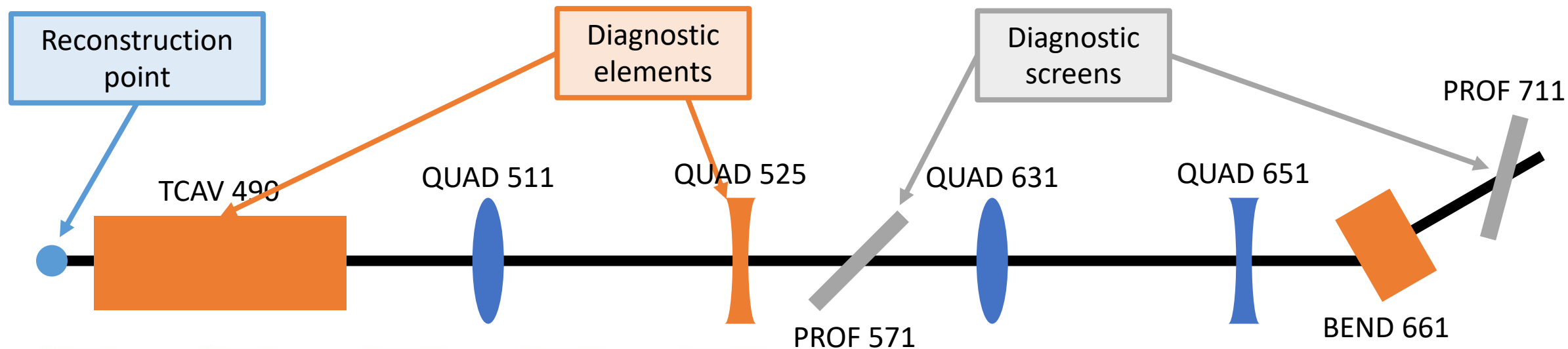
6D Phase Space Monitoring



Diagnostics Lattice

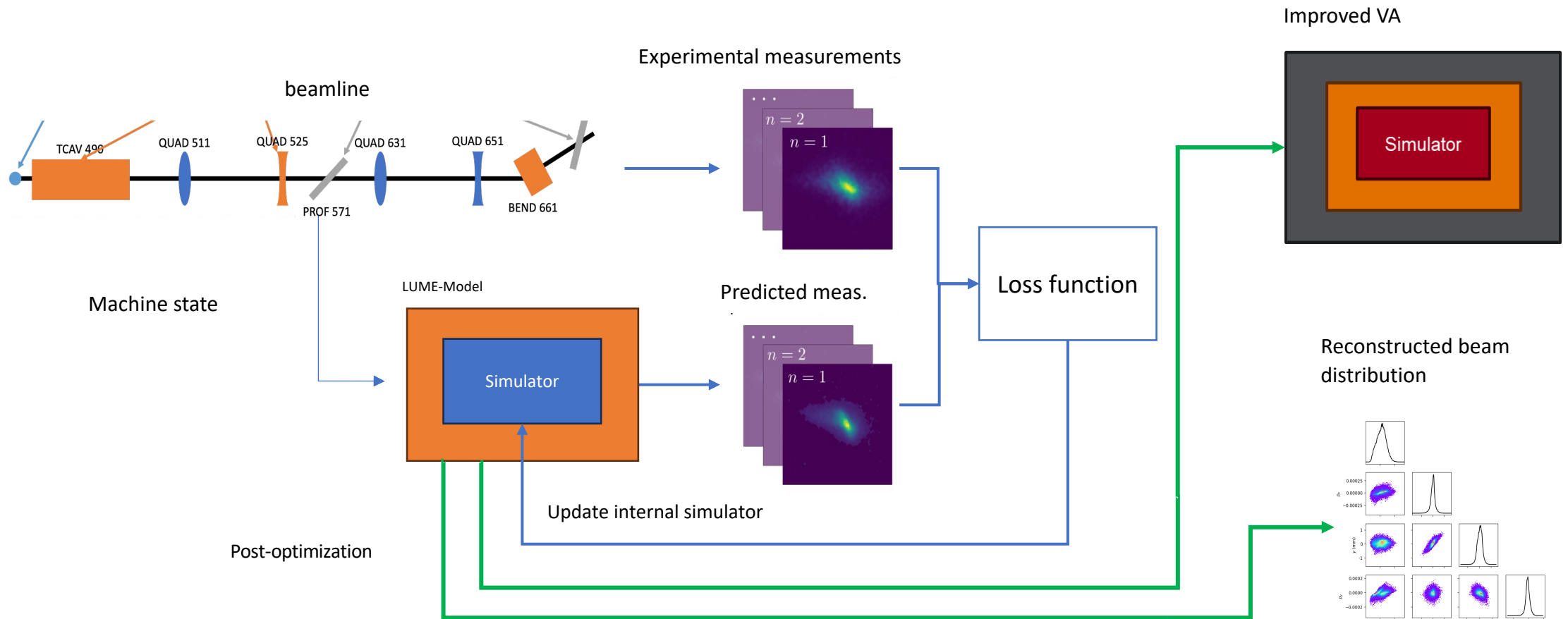


Diagnostics Lattice



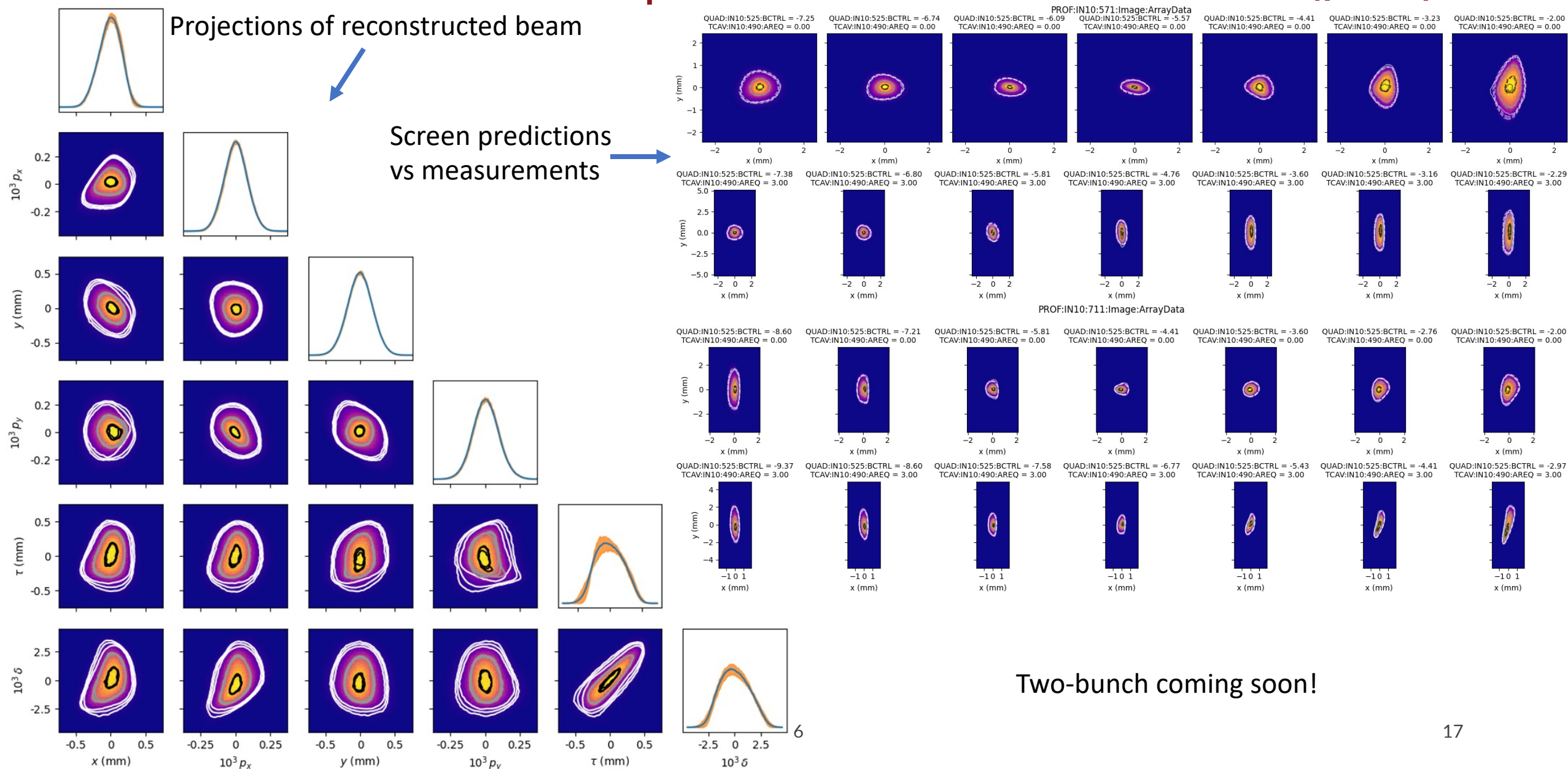
Virtual Accelerators and Phase Space Reconstruction

Virtual accelerator framework to perform phase space reconstruction and model calibration



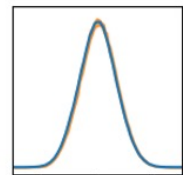
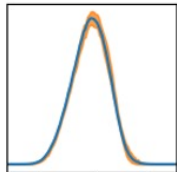
*modified from S. Miskovich talk

Generative Phase Space Reconstruction Results (prel.)



Generative Phase Space Reconstruction Results (prel.)

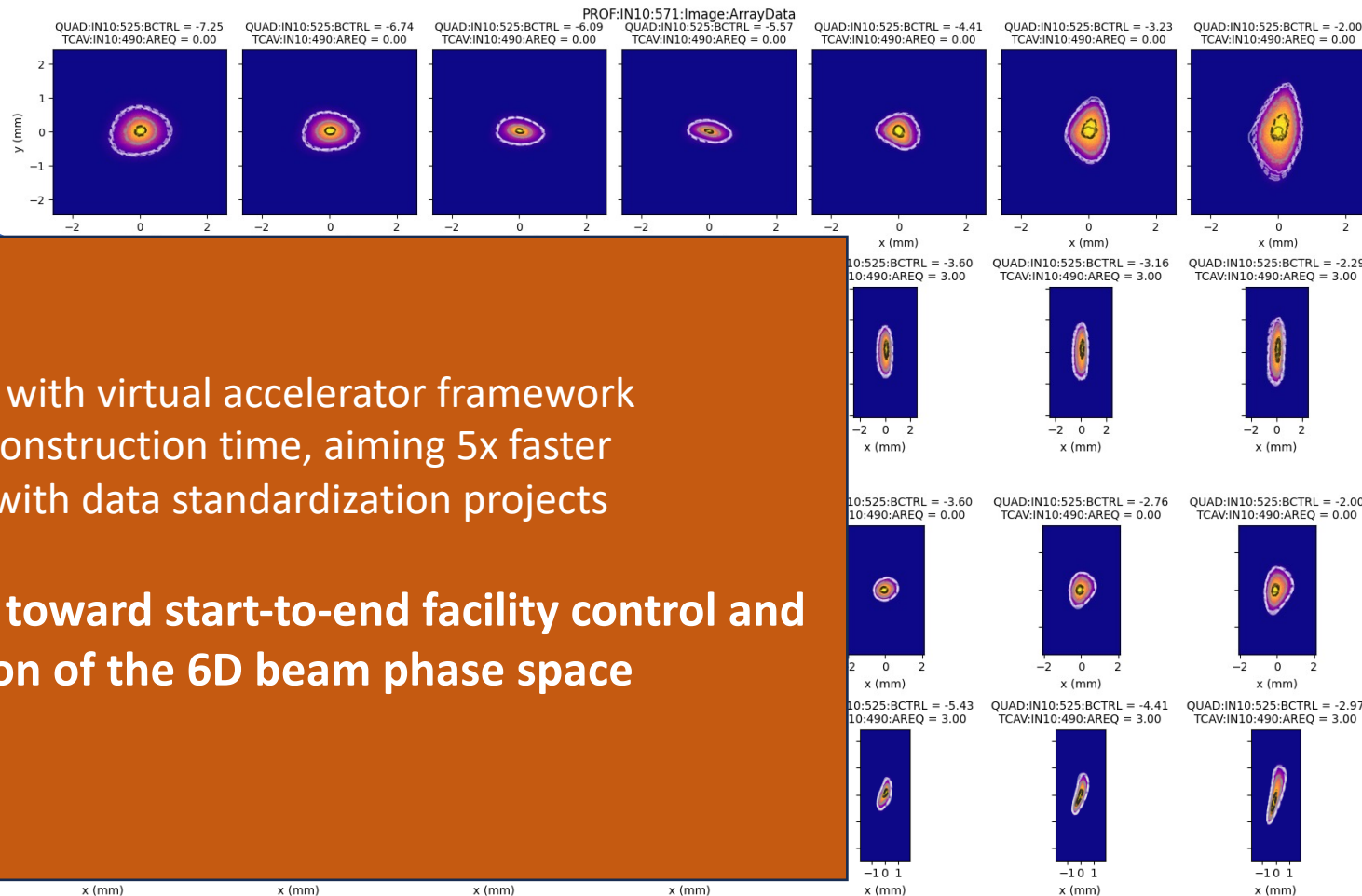
Projections of reconstructed beam



Screen predictions

- Integrated with virtual accelerator framework
- 5 min reconstruction time, aiming 5x faster
- Aligning with data standardization projects

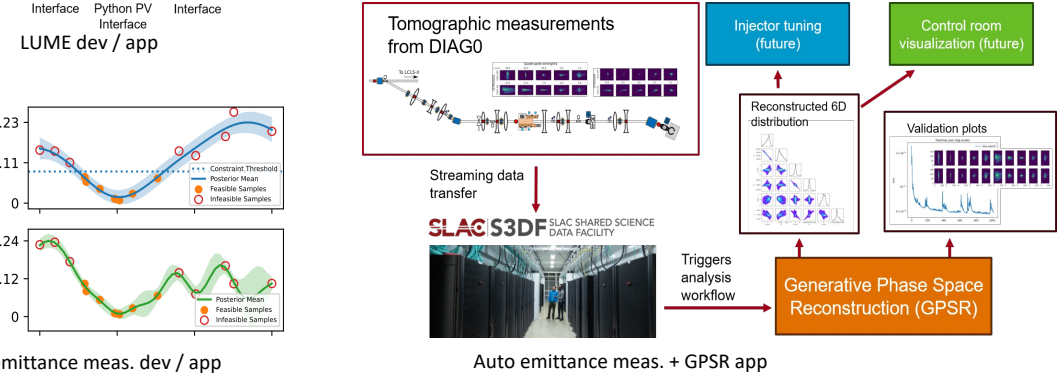
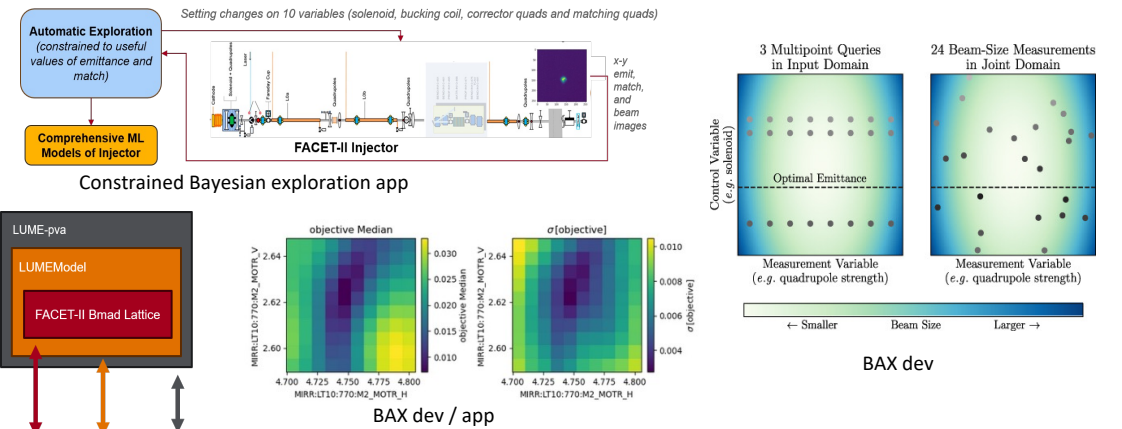
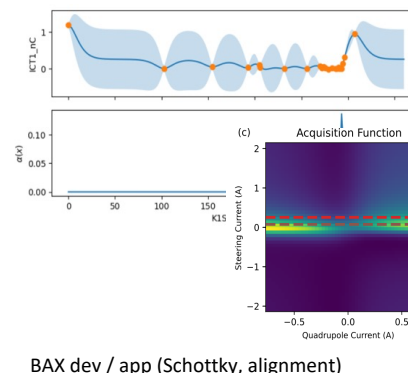
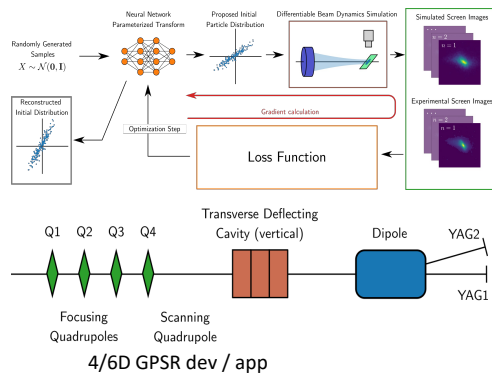
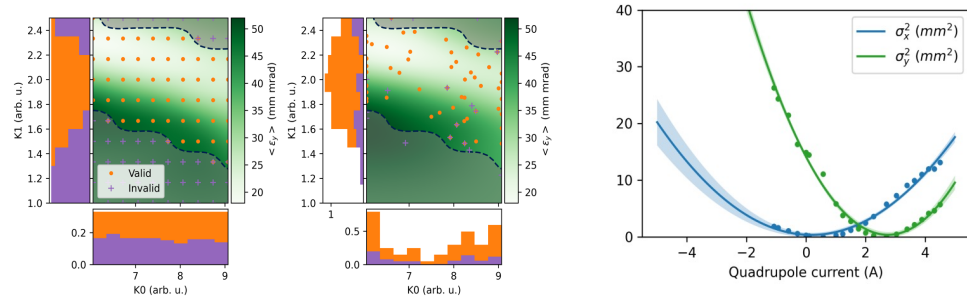
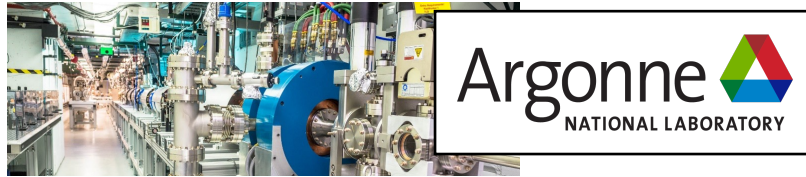
Steadily progressing toward start-to-end facility control and customization of the 6D beam phase space



Two-bunch coming soon!

Tech transfer among facilities: AWA, FACET, LCLS

AWA and LCLS/LCLS-II/FACET-II have served as reciprocal test facilities for one another – greatly enhancing AI/ML R&D progress at both

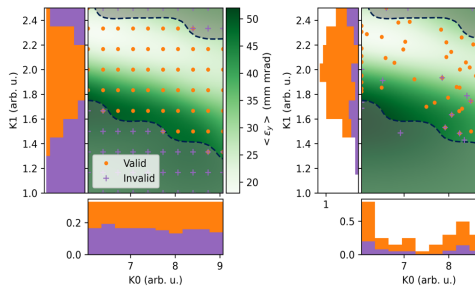
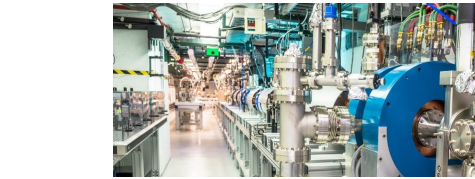


Tech transfer among facilities: AWA, FACET, LCLS

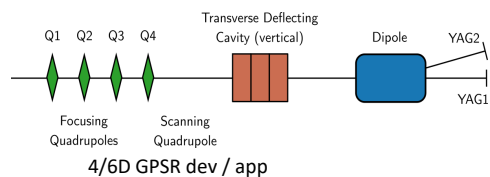
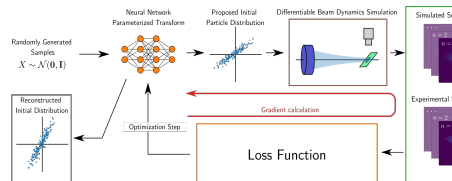
AWA and LCLS/LCLS-II/FACET-II have served as reciprocal test facilities for one another – greatly enhancing AI/ML R&D progress at both



SLAC NATIONAL ACCELERATOR LABORATORY

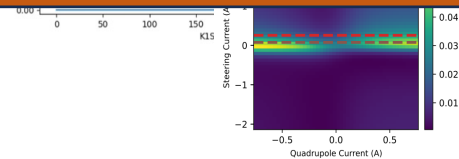


Constrained Bayesian exploration dev

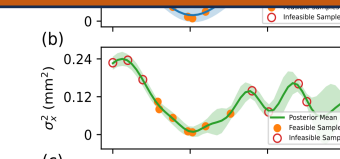


4/6D GPSR dev / app

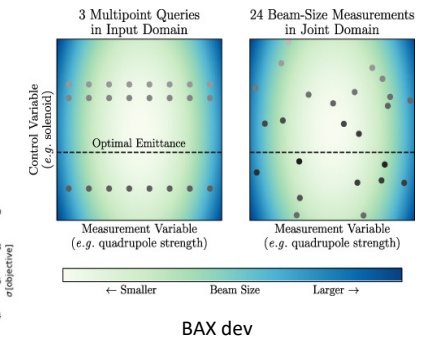
Long track record now of bi-directional transfer of algorithms and software between AWA, FACET-II, LCLS



BAX dev / app (Schottky, alignment)



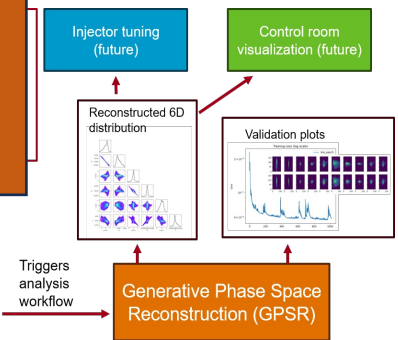
Auto emittance meas. dev / app



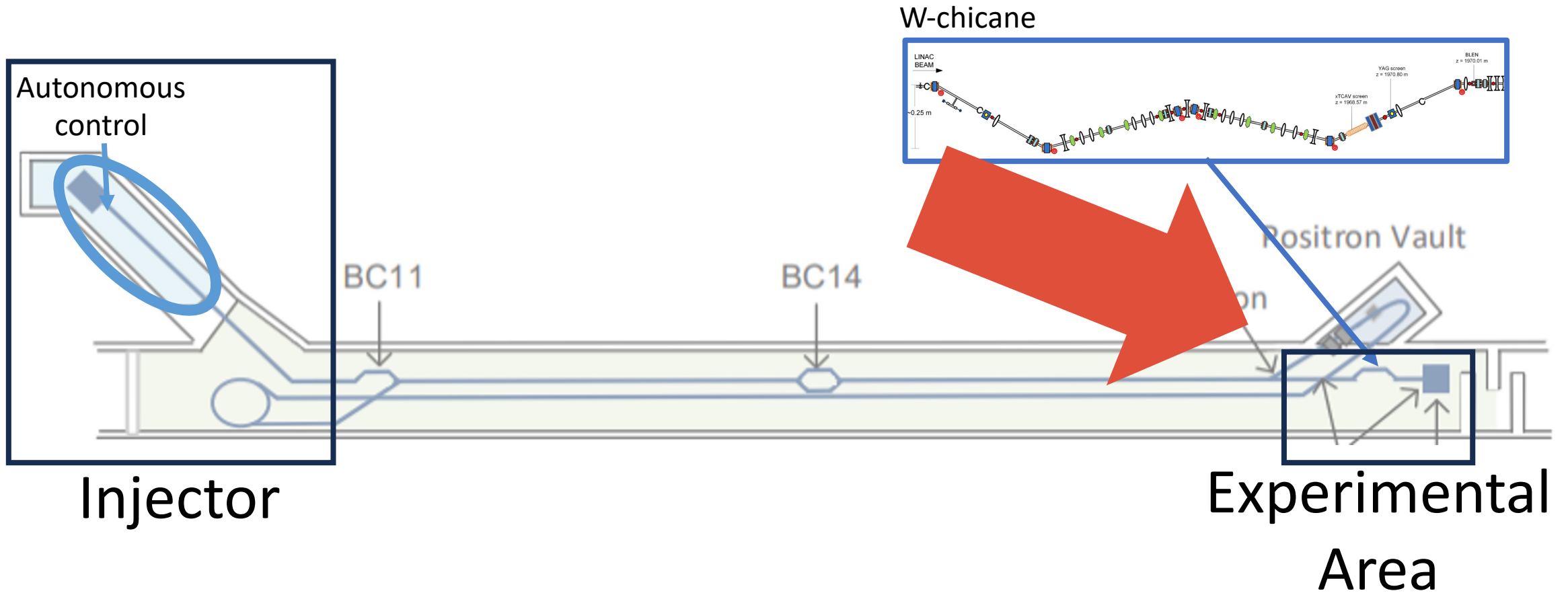
BAX dev



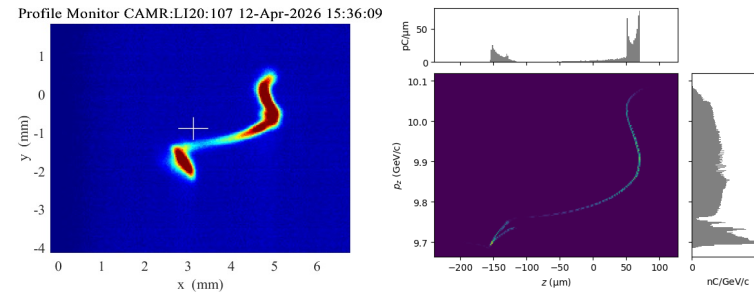
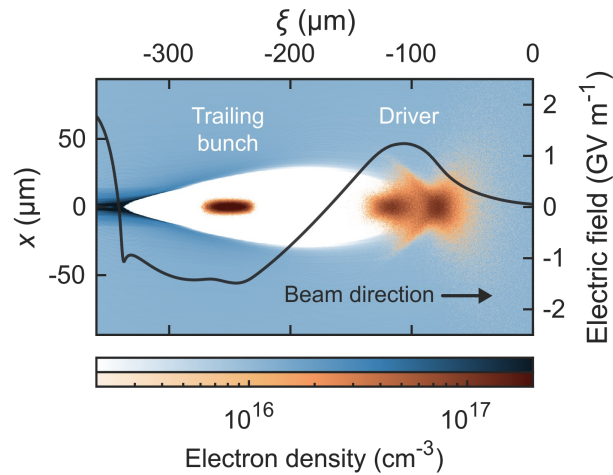
Auto emittance meas. + GPSR app



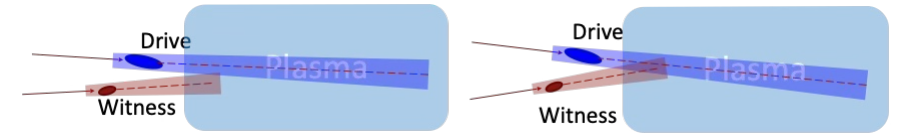
Tuning at W-Chicane and Experimental Area



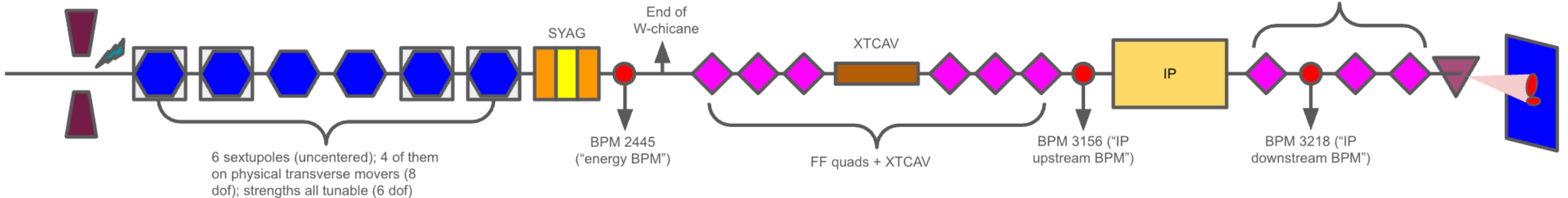
Transverse Control of Plasma Accelerator



Longitudinal phase space of drive-witness pair

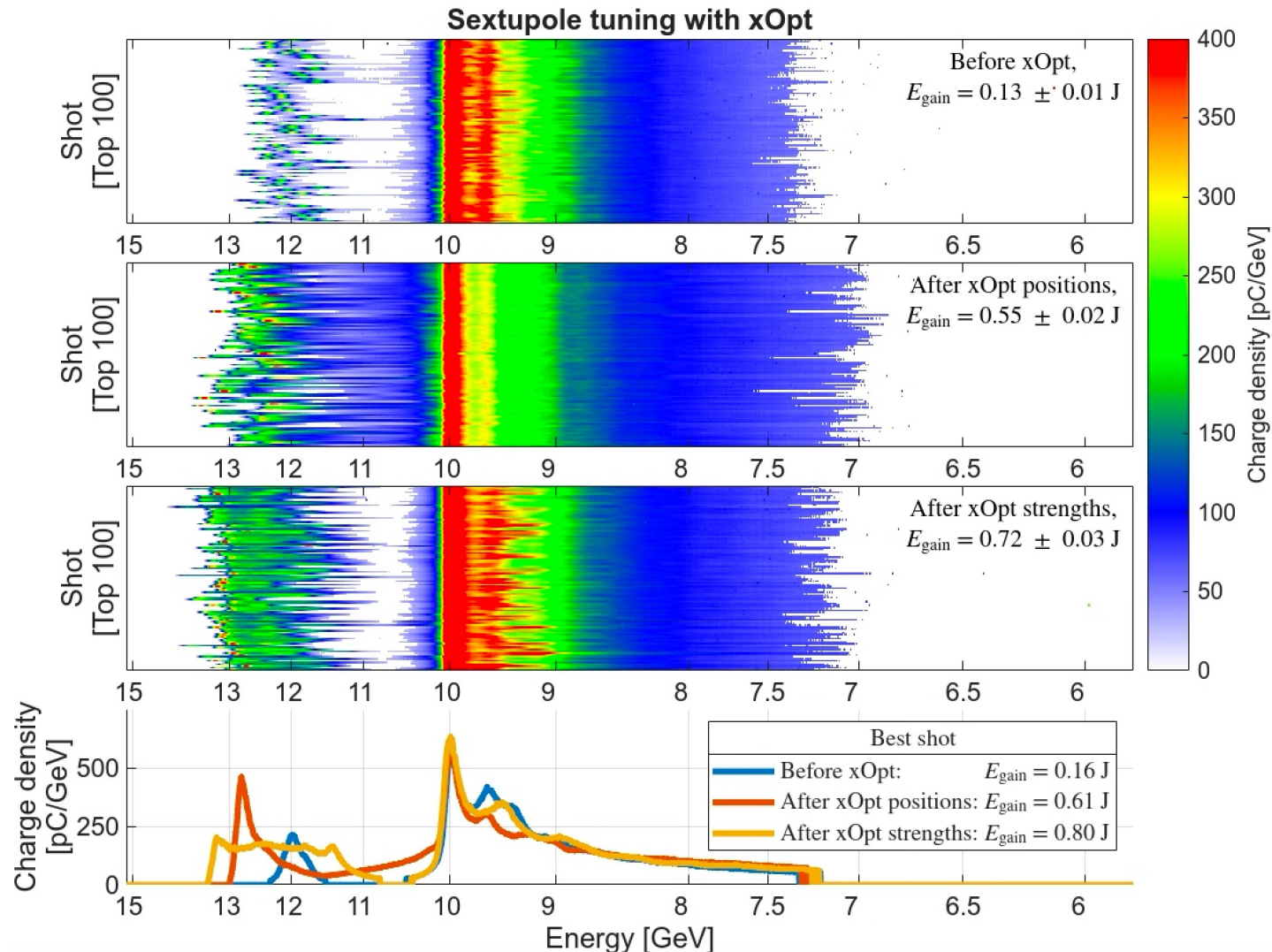


2*jaw + notch
collimators for
selecting energy slices



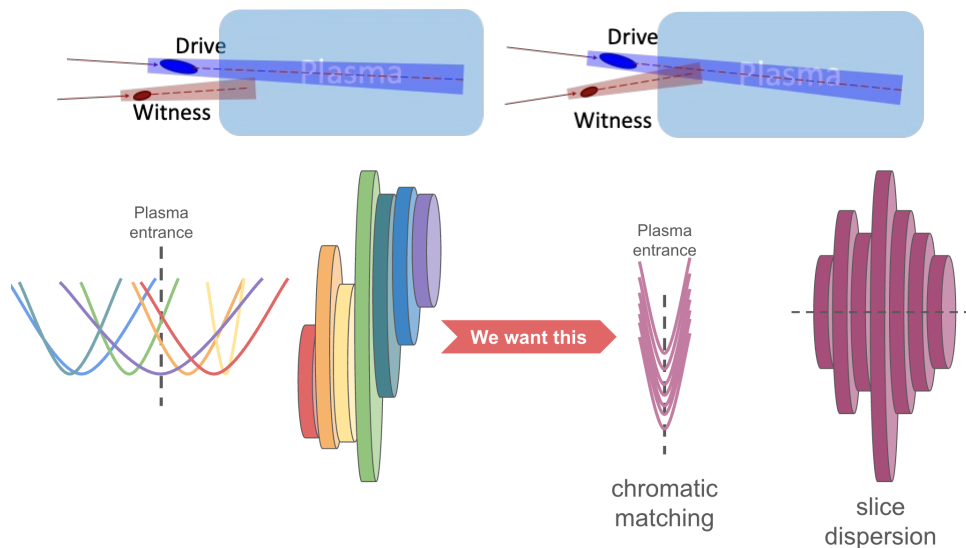
Schematics of the final bunch compressor ("W-chicane") at FACET-II

Plasma-Based Optimization



5x overall improvement in energy gain for plasma-based acceleration with ML-driven sextupole tuning (S. Rego)

ML Offset/Tilt Tuning



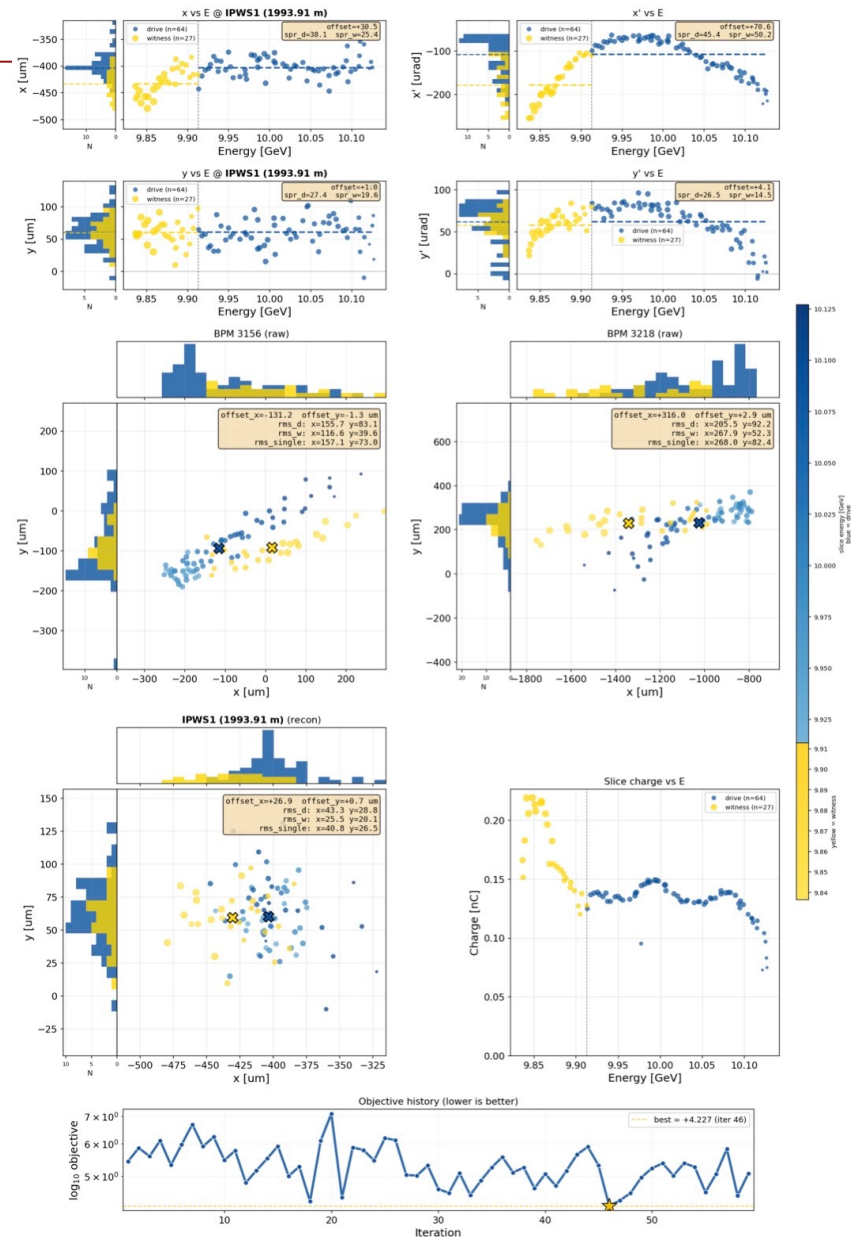
Novel diagnostics developed at FACET-II to efficiently measure slice offset/tilt of the beam; ML to minimize offset/tilt (Y. Ye)

Beam Physics
X
Machine Learning



Better accelerator
performance

Slice BPM sextupole optimization -- Iter 59 -- **IPWS1 (1993.91 m)**
split=frac E_cut=9.9130 GeV | drive n=64, witness n=27 -- log10 obj = +5.069

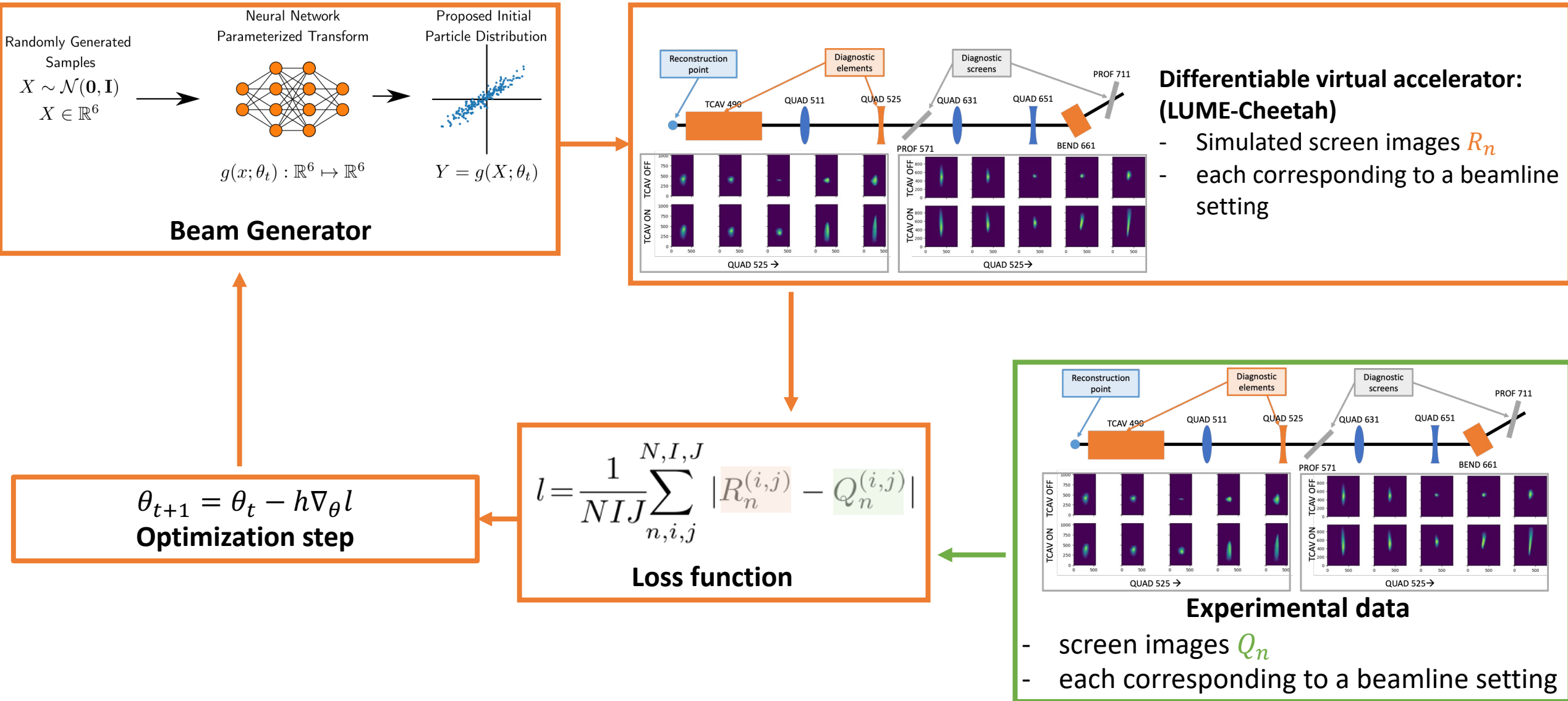


Conclusions

- Demonstrated autonomous injector startup:
 - ~ 20 mins for Schottky scan, laser steering, beam steering, E spread minimization, TCAV phasing, emittance optimization
 - Integrated tasks with AI Agent: change beam charge seamlessly
- 6D phase space monitoring
 - Now uses virtual-accelerator workflow
 - Steadily progressing toward start-to-end facility control and customization of the 6D beam phase space
- Long track record now of bi-directional transfer of algorithms and software between AWA and FACET-II
- ML optimization routinely used at FACET-II to improve accelerator performance:
 - 5x improvement on energy performance for PWFA
 - High-quality beam delivery to experiments

BACKUP SLIDES

Generative phase space reconstruction (GPSR)



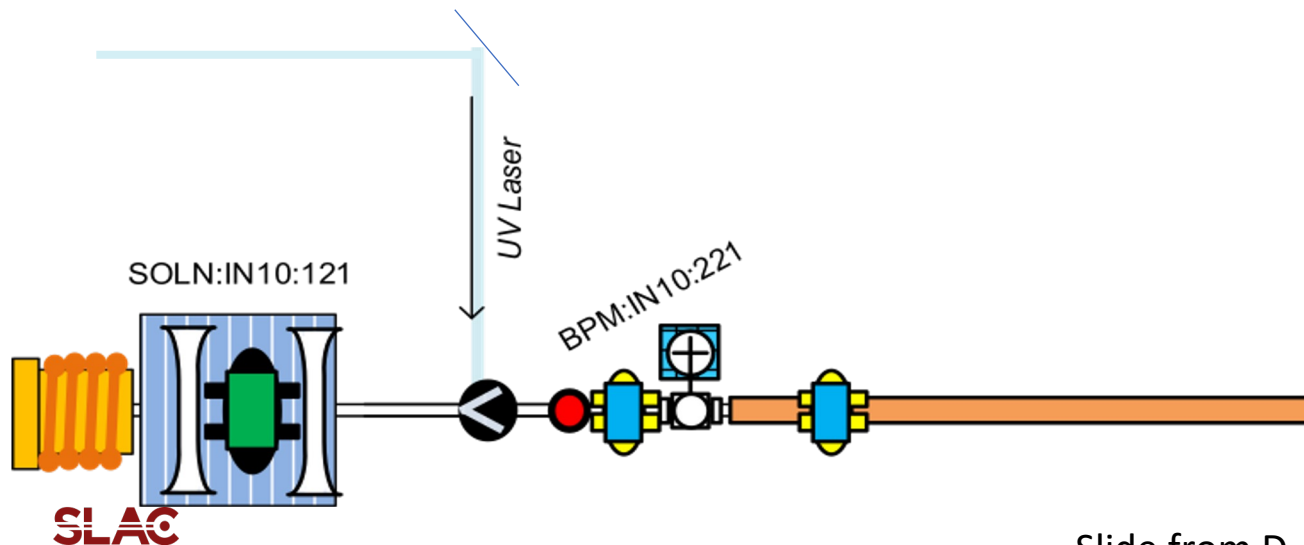
AGENT.md

<https://github.com/HAAI-mc/autonomous-control/blob/main/AGENT.md>

FACET-II Startup Automation: Laser Alignment

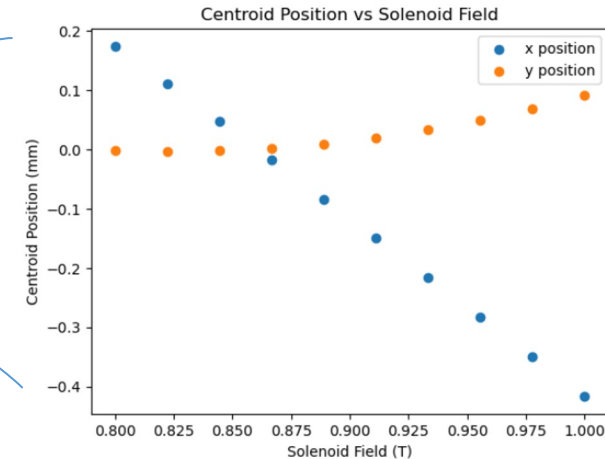
Goal: Move laser spot on cathode such that it is aligned w.r.t. the solenoid field center

- Misaligned beam gets kicked when scanning solenoid field $\rightarrow$ tune mirror to minimize kick amplitude



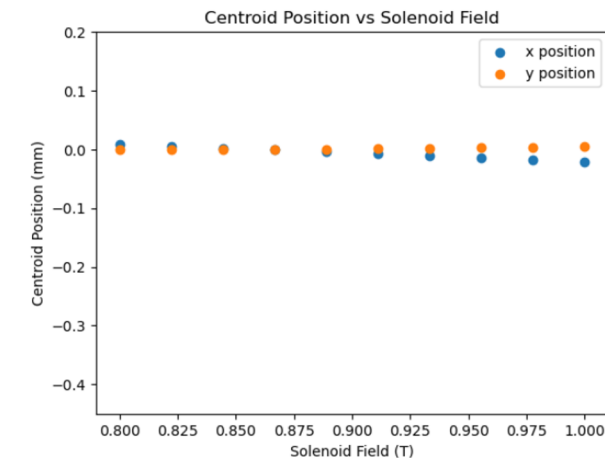
x misalignment

Poor Alignment



y misalignment

Better Alignment



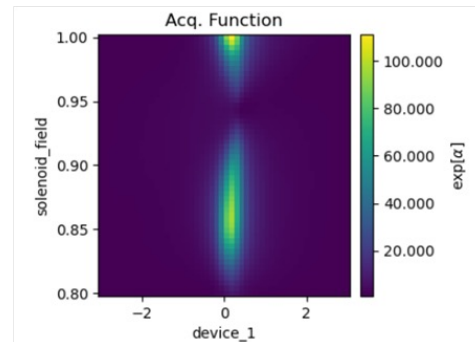
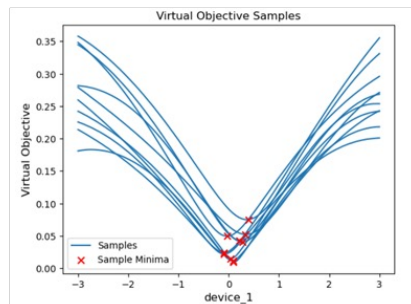
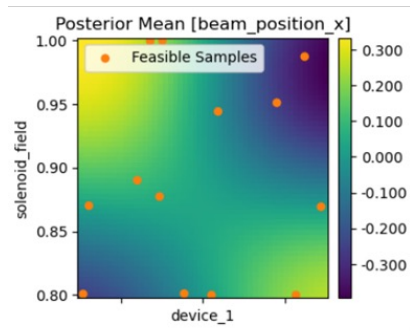
FACET-II Startup Automation: Laser Alignment

Solution: Use Bayesian Algorithm Execution (BAX) to tune laser mirrors such that scanning the solenoid does not kick the beam → good alignment with magnetic center

Model the **Observables** (centroid position)

Optimize **Virtual Objective** *samples* with respect to tuning devices

Use sample optima to compute **Expected Information Gain (EIG)** acquisition function



Model of the virtual objective (misalignment)

