# AI/ML at FACET-II
# (E331 / E341)

## Broad goals for AIML program

- **Enable new capabilities in beam customization and delivery**
  - Advanced phase space manipulation for single and two bunch
  - High-dimensional tuning across multiple objectives
    - e.g. transverse and longitudinal phase space, minimize beam losses, improve beam stability
  - Automated injector startup, charge change, emittance growth minimization
  - Ability to tune complex components: e.g. sextupole tuning + w-chicane

- **Enable new capabilities in beam measurement / prediction**
  - 6D phase space reconstruction (GPSR)
  - ML-enhanced virtual accelerator → continual learning

- **Work with other experiments/ops to transition above to regular use**

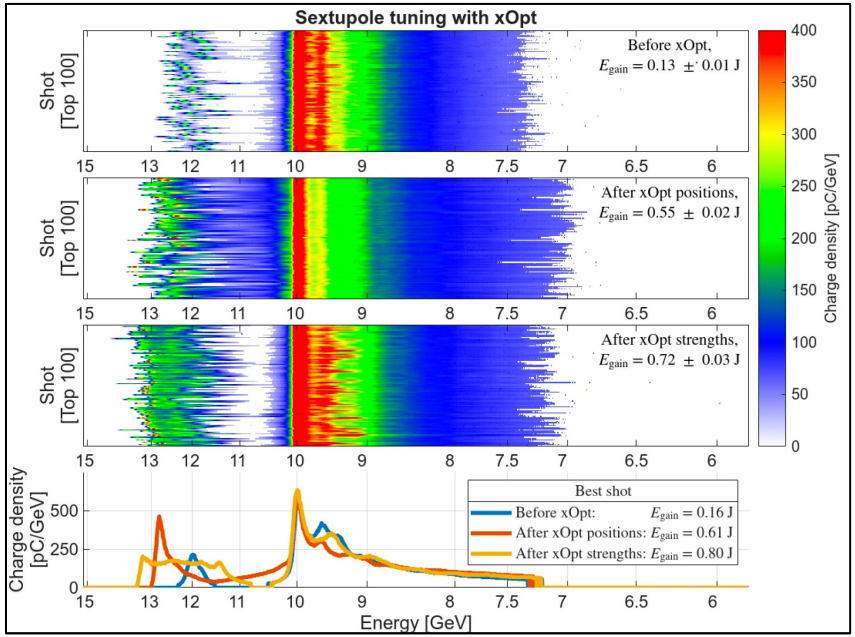
# Relation to broader AIML activities

- Have several AI/ML research grants:
  - Hardware-Aware AI (HAAI) focused on system modeling and two bunch tuning
    - Continual learning, novel representations for system modeling
    - Dynamic two-bunch tuning (time/energy separation)
  - Genesis MOAT (multi-office accelerator team) - agentic AI and digital twins for autonomous accelerators
- SLAC ISDCI well positions for Genesis AmS + HPC in the loop with experiments (including FACET-II)
- Effort to pitch FACET-II as a fully AIML integrated test bed
  - FACET-II experiment time has been heavily used to demonstrate AIML algorithms and software

# S20 Tuning on sextupoles (E331 → E300 success story)

Initial work on sextupole mover optimization with Xopt in E331

Now transferred over to E300 with excellent results and substantial further development by E300 folks



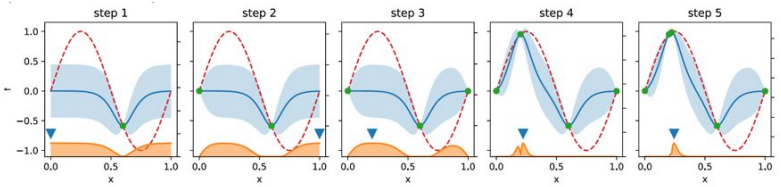

**5x overall improvement in energy gain for plasma-based acceleration** with ML-driven sextupole tuning

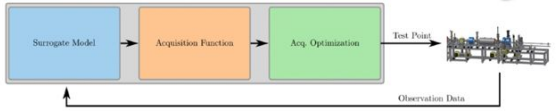
S. Rego

D. Storey and E300 team

# From 2024 initial tests ….

## Bayesian Optimization of Sextupole Mover Settings

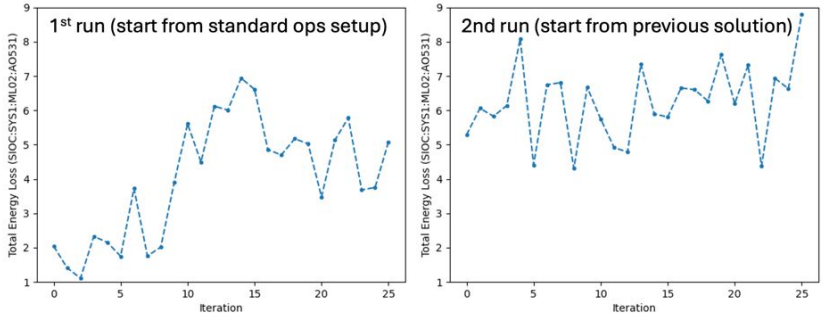



*Figs courtesy R. Roussel*

*Bayesian Optimization learns a Gaussian Process model on-the-fly during sampling. Model predictions and uncertainties guide the next point to sample.*
*→ no need for previous data*
*→ easy-to-adapt implementations of advanced BO techniques available in Xopt*

More BO info: https://arxiv.org/abs/2312.05667
Xopt: *https://github.com/ChristopherMayes/Xopt*




*Ran separate optimizations starting from initial operations setup*

8 variables – 4 sextupole magnet mover positions in x and y

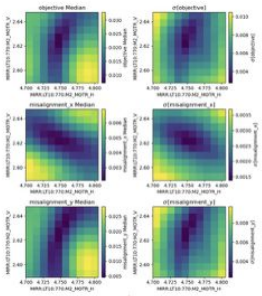
Objectives are beam size on screen or plasma parameters (measured on images)

Plan to put into Badger GUI for general use in operations

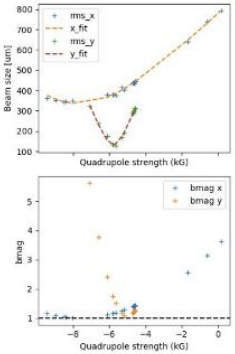
# Moving toward linking together chains of tasks autonomously

Autonomous configuration of the FACET-II injector beamline w/o human intervention in < 14 min (standard is ~1hr +)

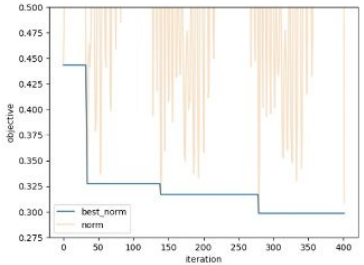
Laser alignment onto cathode (1 min)



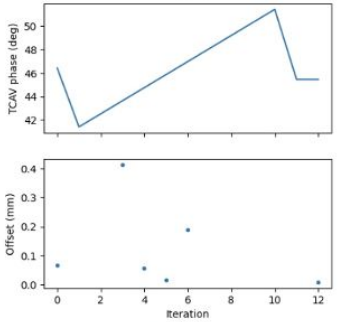
Emittance optimization + matching (7.5 min)



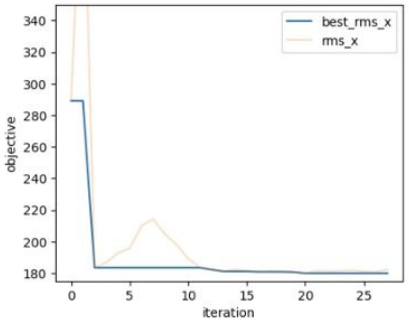

Beam steering (3 min)

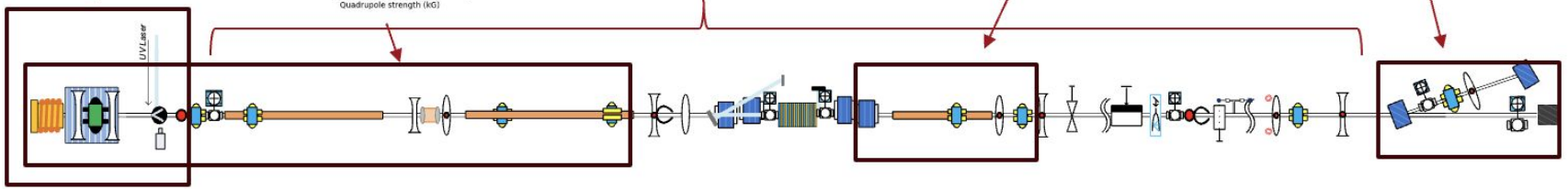



TCAV Phasing (7 sec)




Energy spread minimization (2 min)



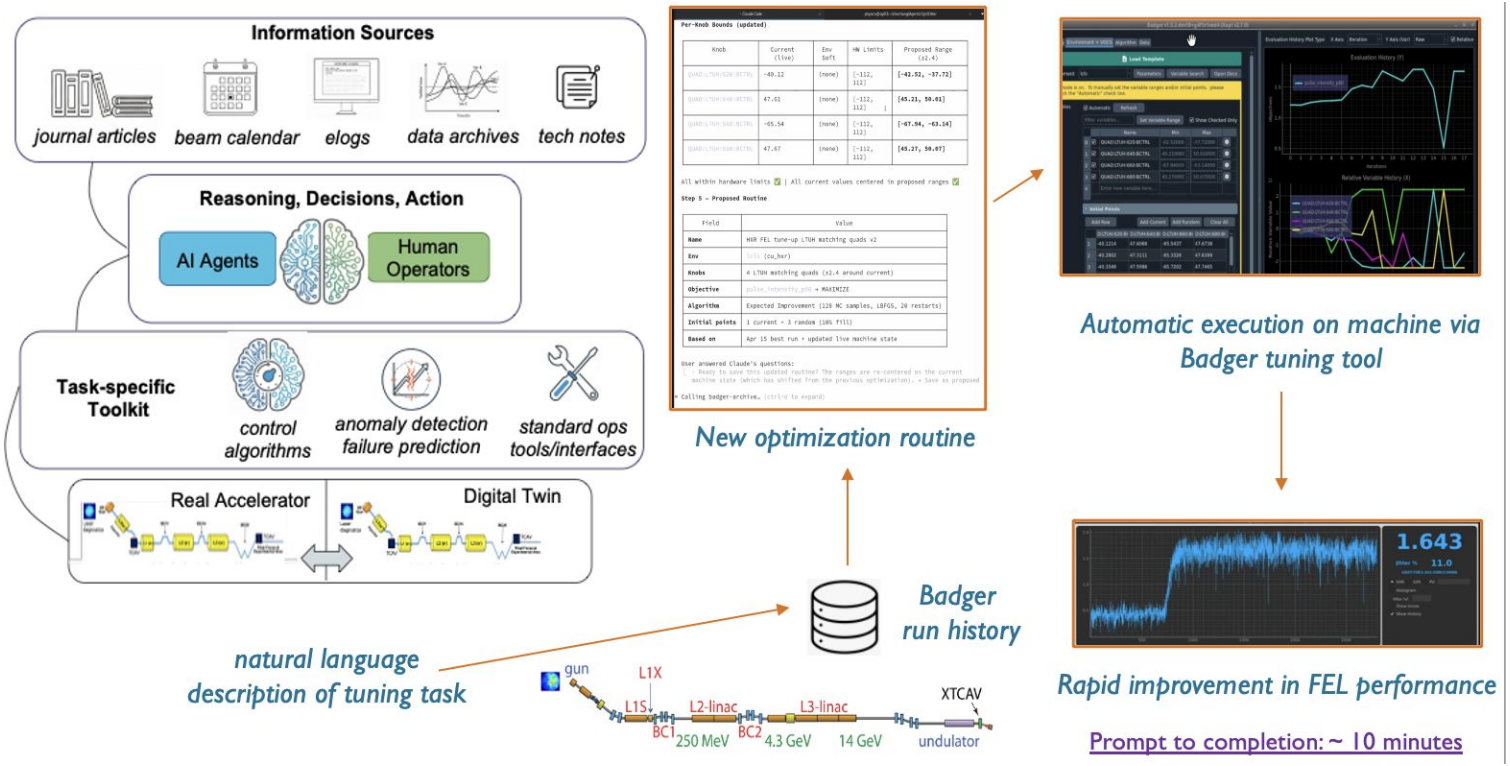




Ryan Roussel, Dylan Kennedy

# Agents Lower Barriers in Advanced Tool Use

Agentic AI (Osprey*) being developed for complex operations and design workflows for accelerators

Osprey orchestrates tool use and accesses disparate accelerator information sources




*Have demonstrated in live accelerator tuning at SLAC → agent uses complex AIML optimization tools, reducing burden on operators to configure them*

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

# Agent-driven startup for the injector

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

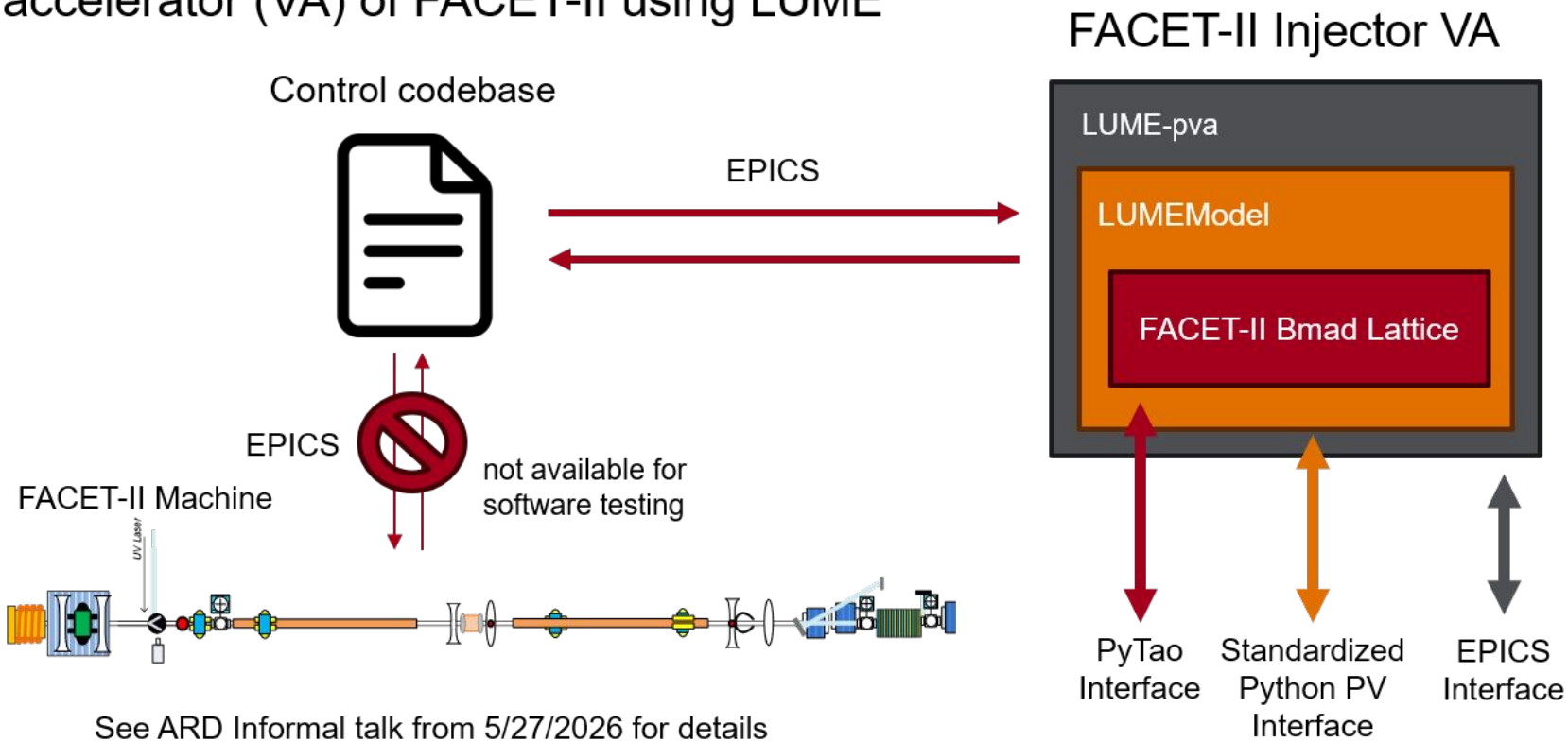
Ran several charge changes and tuning: 1.6 nC, 2 nC, 2.2 nC

- ~20 minutes for entire task chain
- Recovered roughly equivalent or better emittance in each case (although back to 1.6 nC had poorer match)

Ryan Roussel, Zhe Zhang

# Virtual Accelerator

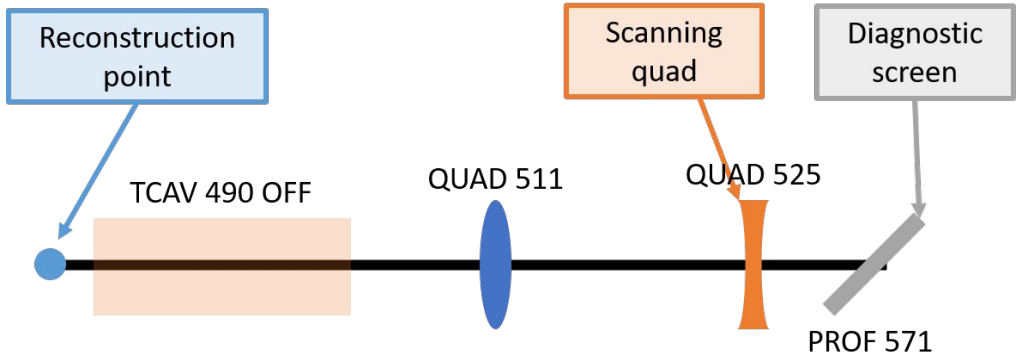
Prior to deployment on the machine, algorithms were tested on a virtual accelerator (VA) of FACET-II using LUME

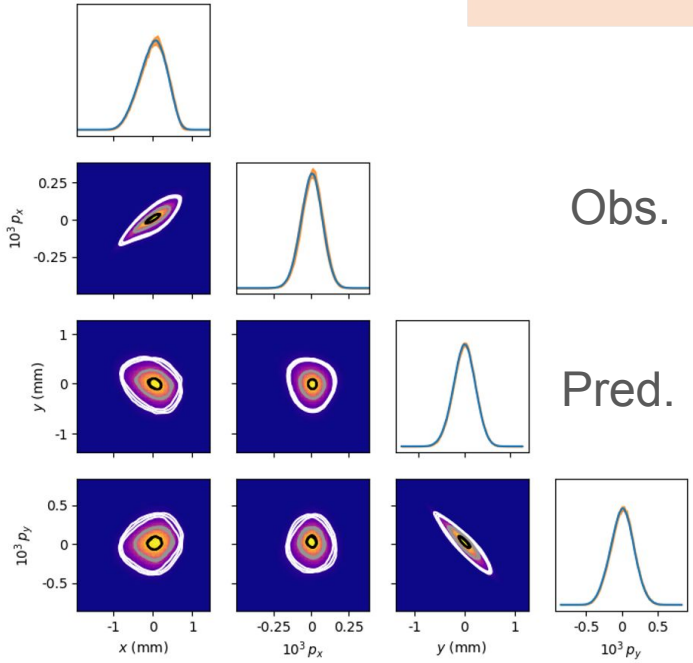


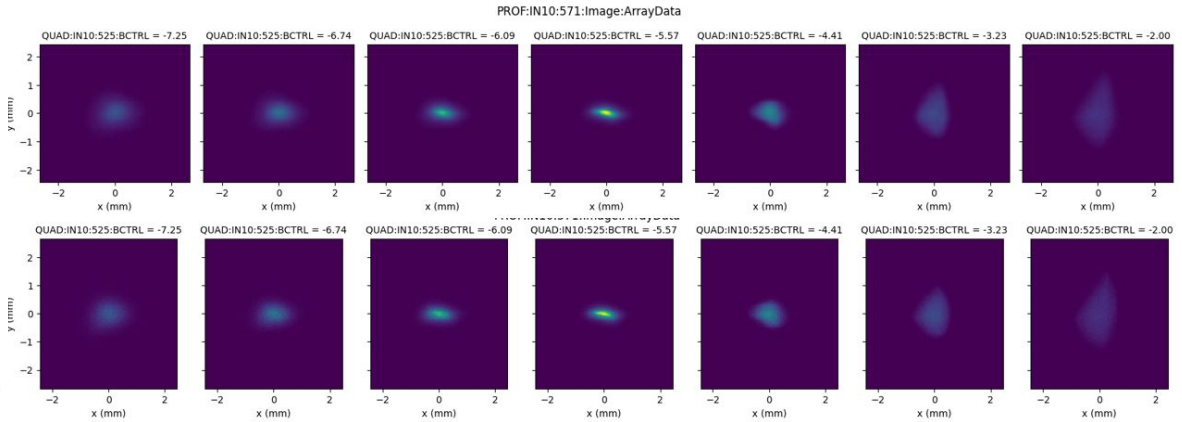

See ARD Informal talk from 5/27/2026 for details

Ryan Roussel, Zack Buschmann

# GPSR




Uses LUME-based FACET virtual accelerator to reconstruct distribution

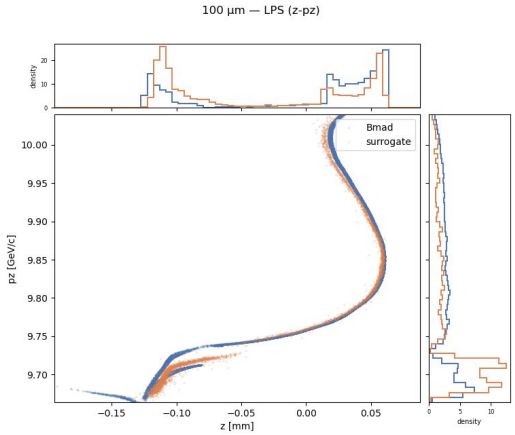
JP Gonzalez-Aguilera, Ryan Roussel

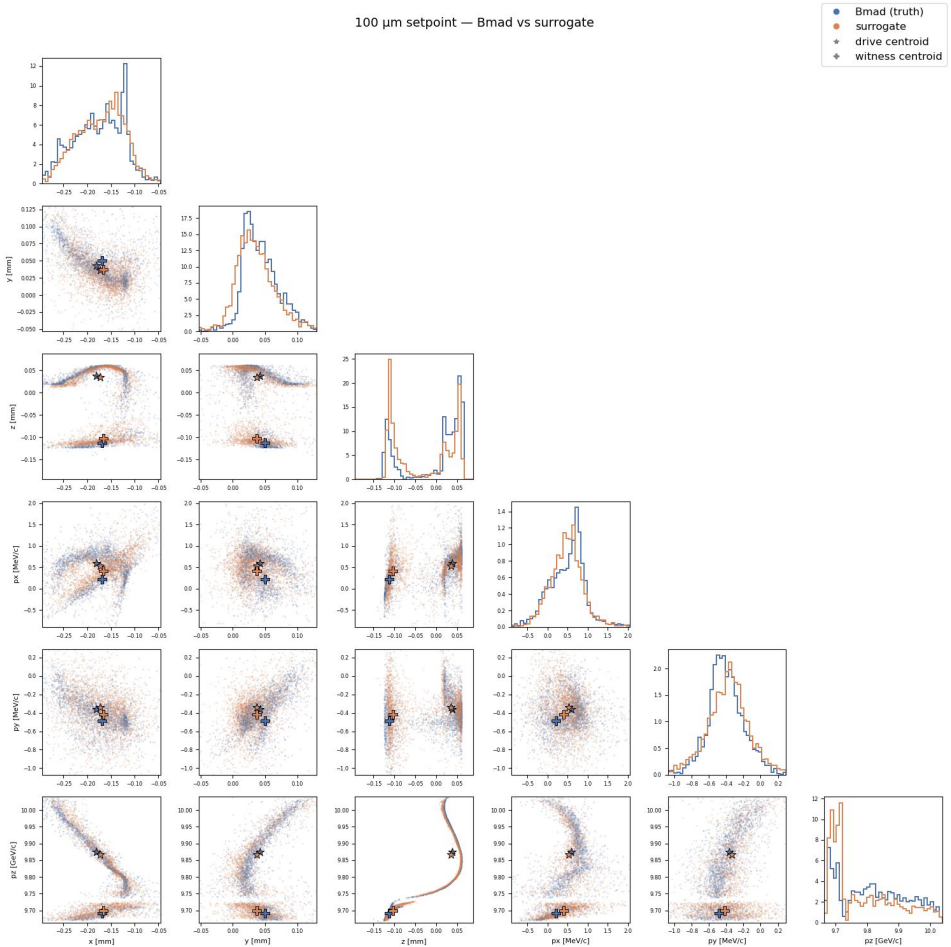
# Dynamic two-bunch tuning

Goal: specify timing and energy separation and be able to slew across these easily

Model-based reinforcement learning approach

Initial results from Bmad simulation




Ryan Wu

# Papers we are aiming for

1. Joint with E300 – ML based sextupole tuning and outcomes for plasma performance

2. Agent-driven tuning and/or autonomous injector startup → plan to start using again during machine startup

3. Dynamic two-bunch tuning with reinforcement learning (slew time/energy separation) → will request beam time when machine starts up

4. Model calibration / sim2real for FACET-II

Thanks to many contributors (not exhaustive)



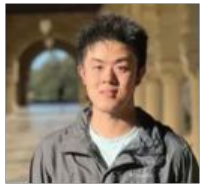













# Multi-office Accelerator Team (MOAT) - ModCon seed

- **Brings together DOE BES, HEP and NP (now HENP)**
  - 7 national labs: LBNL+ANL+BNL+FNAL+JLAB+ORNL+SLAC
- **MOAT vision: treat nation's accelerator ecosystem as a single, intelligent system**
  - using AI to connect expertise across labs and offices
  - views large accelerators as complex, dynamic socio-technical systems
    - *distributed teams of teams, thousands of physical components, vast stores of scientific knowledge, rigorous safety and management frameworks*
- **The MOAT-seed project builds initial foundations toward vision:**
  - deployment of shared accelerator agentic AI software across facilities (8 to date)
  - deployment of digital twin prototypes across facilities (3 to date)
  - AI-assisted accelerator designs
- **Genesis Mission's AmSC+ModCon provide the interconnecting tissue of computing + AI capabilities**
- **SLAC is a major leader/contributor within MOAT:** due to prior investment / infrastructure, experienced teams, and availability to test on accelerators
  - AI/ML methods development and shared software development
  - Demonstrations across different SLAC accelerator use-cases *(aided by S3DF/ISDCI and long-standing SLAC leadership/investment in AI/ML)*


BERKELEY LAB · Argonne NATIONAL LABORATORY · Jefferson Lab · OAK RIDGE National Laboratory · Fermilab · SLAC NATIONAL ACCELERATOR LABORATORY · Brookhaven National Laboratory