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U.S. DEPARTMENT OF ENERGY
Office of Science

Machine Learning Optimization Upstream and Downstream of the Accelerator: The Cases of VENUS and GRETA

Heather Crawford, Ren Cooper, Larry Phair, Brian Quiter, Marco Salathe, and Damon Todd

NP AI/ML PI Exchange Meeting
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Research team

Heather Crawford (PI)
Staff Scientist
Nuclear Structure/GRETA Group

Marco Salathe
Research Scientist
Applied Nuclear Physics Program

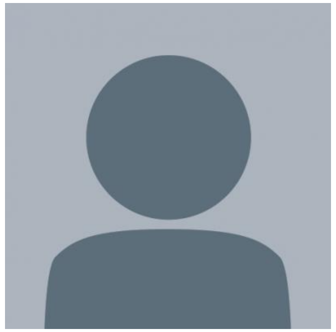
Yue Shi Lai
Research Scientist
Relativistic Nuclear Collisions

Chris Campbell
Senior Scientific Engineering Associate
Nuclear Structure/GRETA Group

Yubin (Harvey) Hu
UC Berkeley
Computer Sci./Physics
Class of 2023

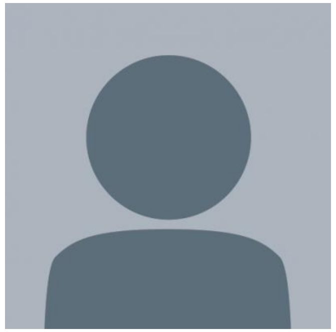
Victor Watson
Postdoctoral Researcher

Ezra Apple
UC Berkeley
Electrical Eng./Computer Sci.
Class of 2025



Julia Dreiling
Ohio State University
Electrical Eng./Computer Sci.
Class of 2024

Alex Kireeff
Carnegie Mellon University
Electrical Computer Eng.
Class of 2024



Wenhan Sun
UC Berkeley
Computer Sci./Physics
Class of 2023

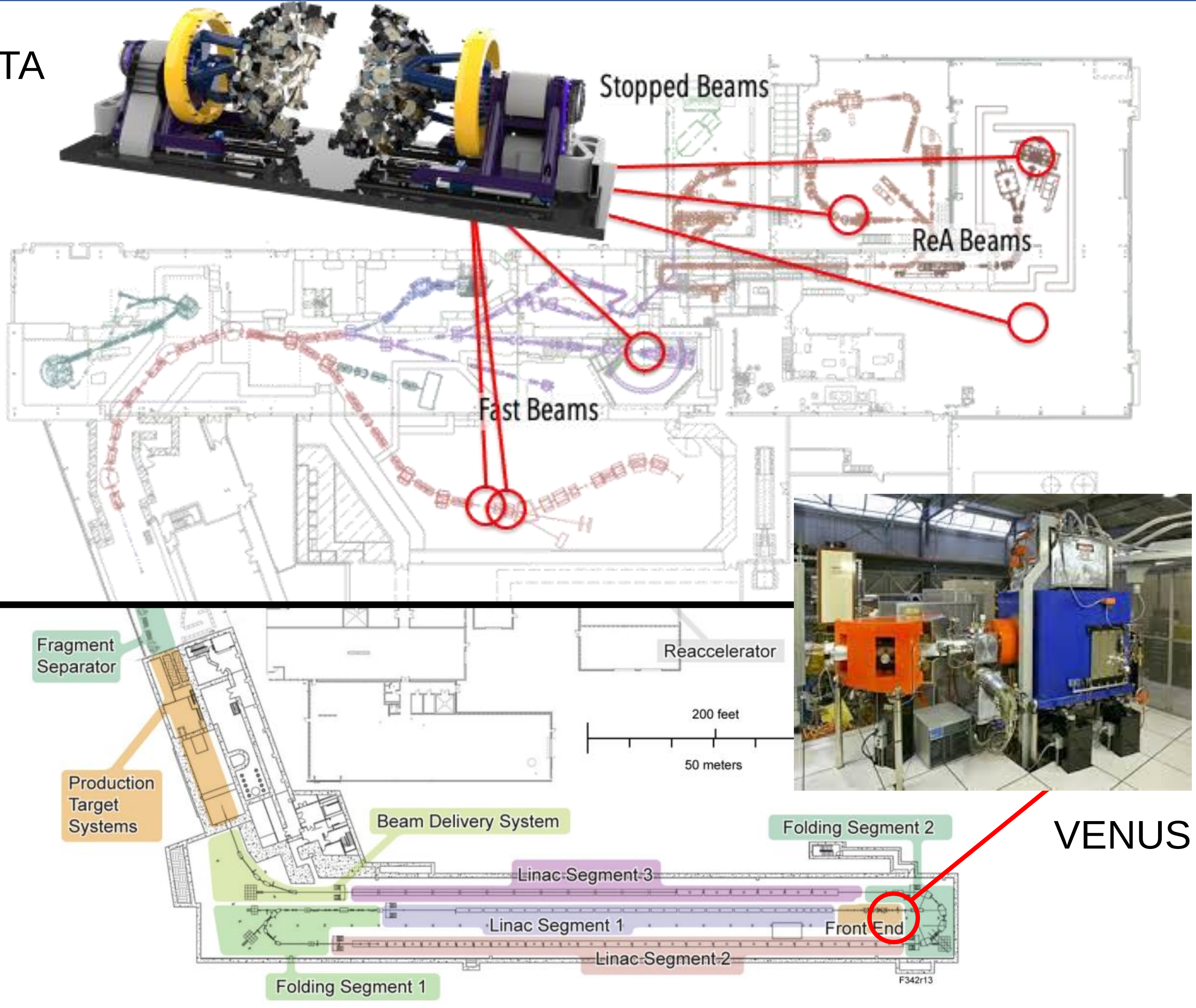
Applying Machine Learning to Berkeley hardware/software to aid FRIB

FRIB

GRETA

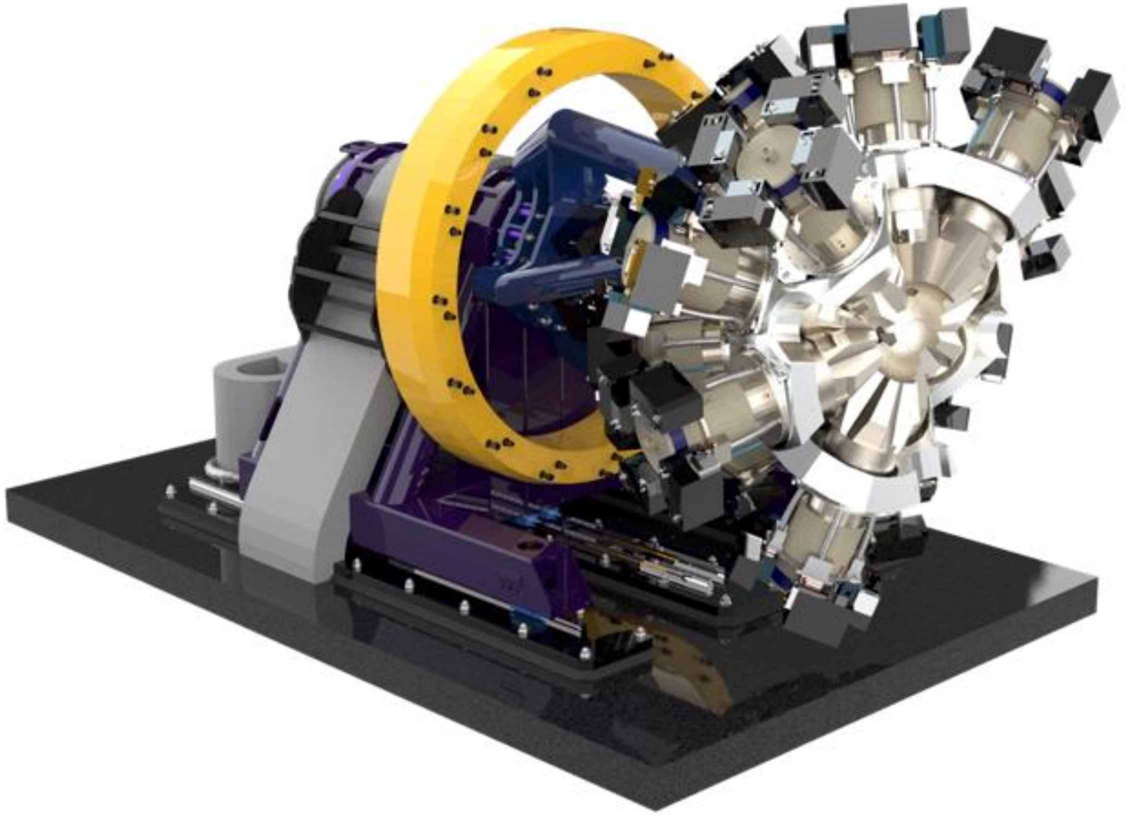
Experimental halls

Front end



VENUS

Gamma-Ray Energy Tracking Array, GRETA



- U.S. implementation of a gamma-ray tracking array
- Complete 4π solid angle coverage of active high-purity germanium (HPGe), consisting of 120 individual detector crystals, each with 37 electrical signals
- Gamma-ray tracking and Compton suppression is enabled by signal decomposition algorithm which localized gamma-ray scatter events to within ~mm^3 volumes

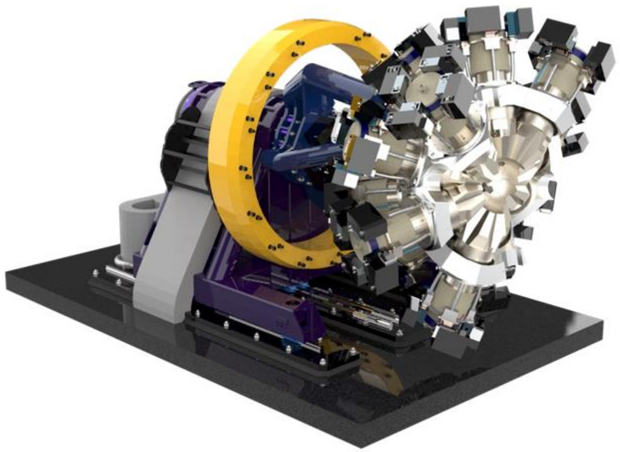
GRETA will be the world-leading gamma-ray spectrometer once delivered to FRIB in 2025, where it will be an experimental physics workhorse

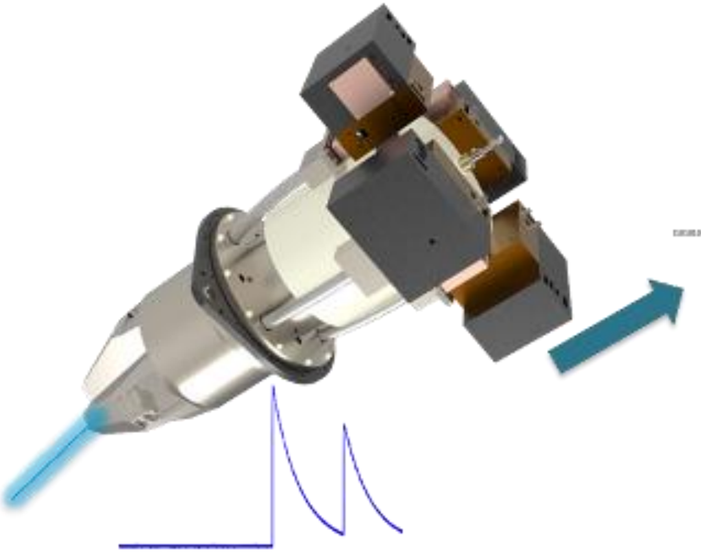
The GRETA optimization challenge

Simple control parameters include:

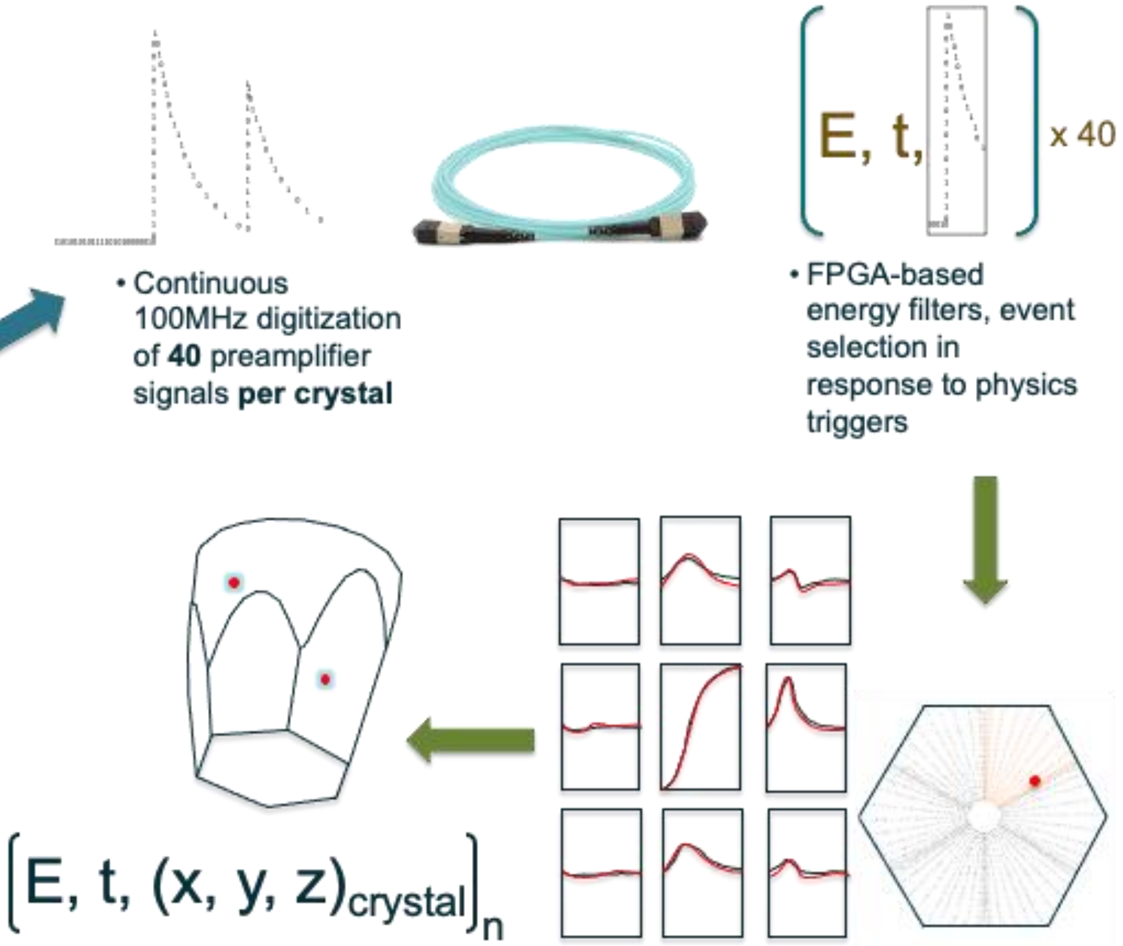
- 4-6+ energy filter parameters **per channel**
- 2+ calibration parameters **per channel**

~ 30k knobs just for energy spectra

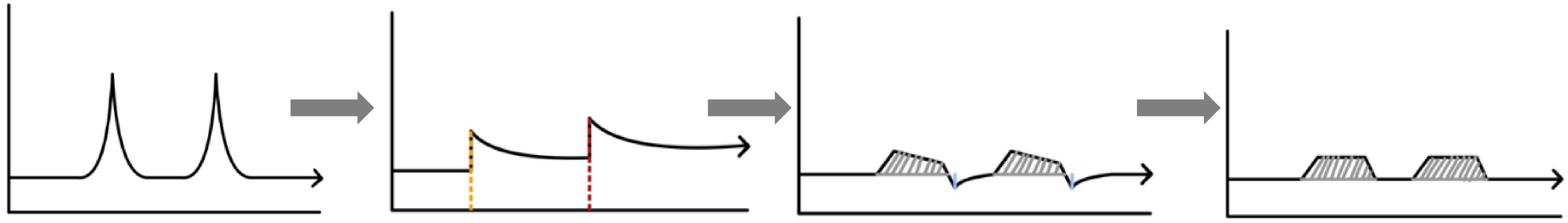


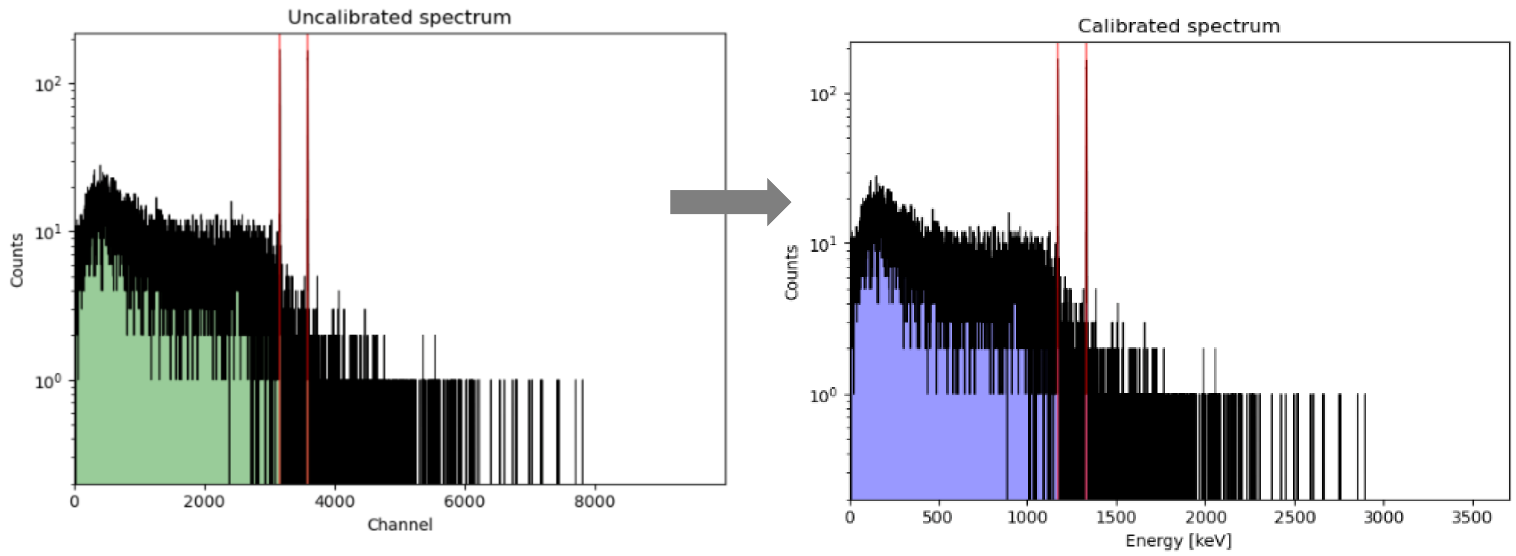


The GRETA challenge is optimizing consistently across the array to ensure every single channel is realizing its peak performance.



Optimization of offline data/calibration at each step (WBS 2.1)





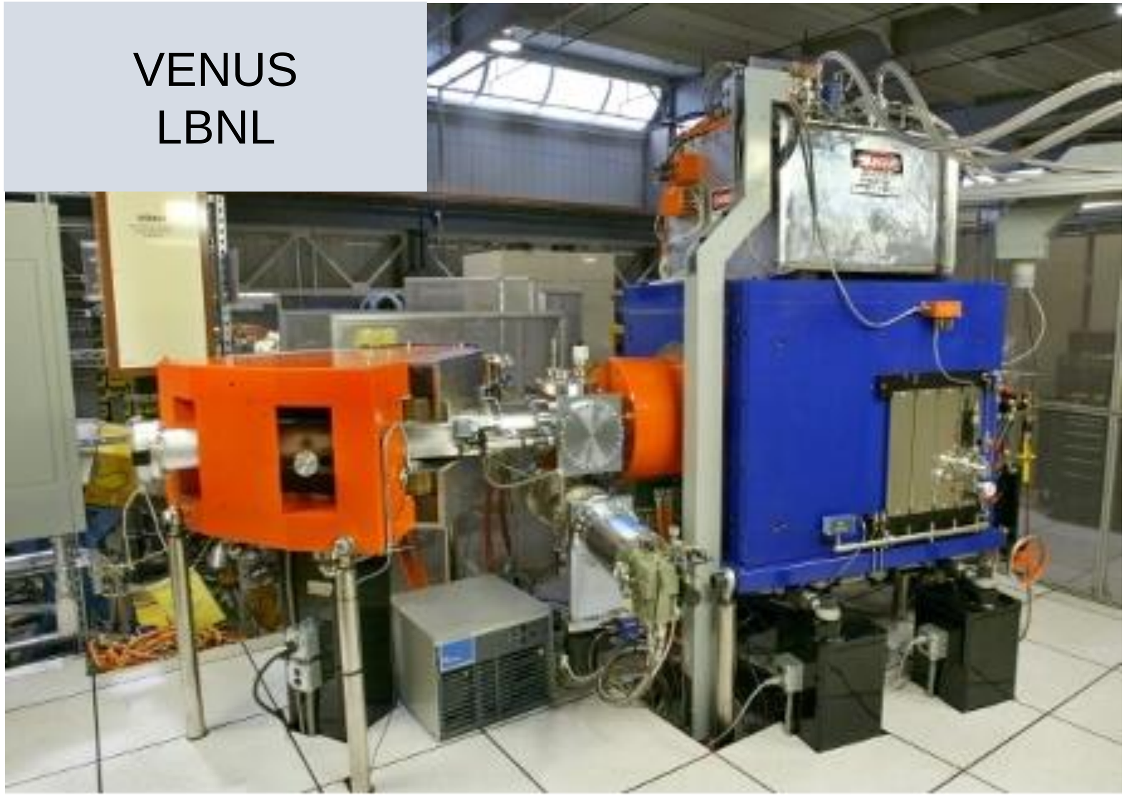
- Optimization of offline data completed
- LBNL-developed Becquerel package used to calibrate at each step

Interfaces with EPICS/GRETA components

- Communication with EPICS control interface demonstrated (WBS 2.1)
- Bayesian techniques to optimize signal chain for the core contact of a GRETA crystal (WBS 2.1)
- Interfaces with all available GRETA components demonstrated (WBS 2.2.2 as complete as possible). Will be completed when other GRETA systems are delivered.

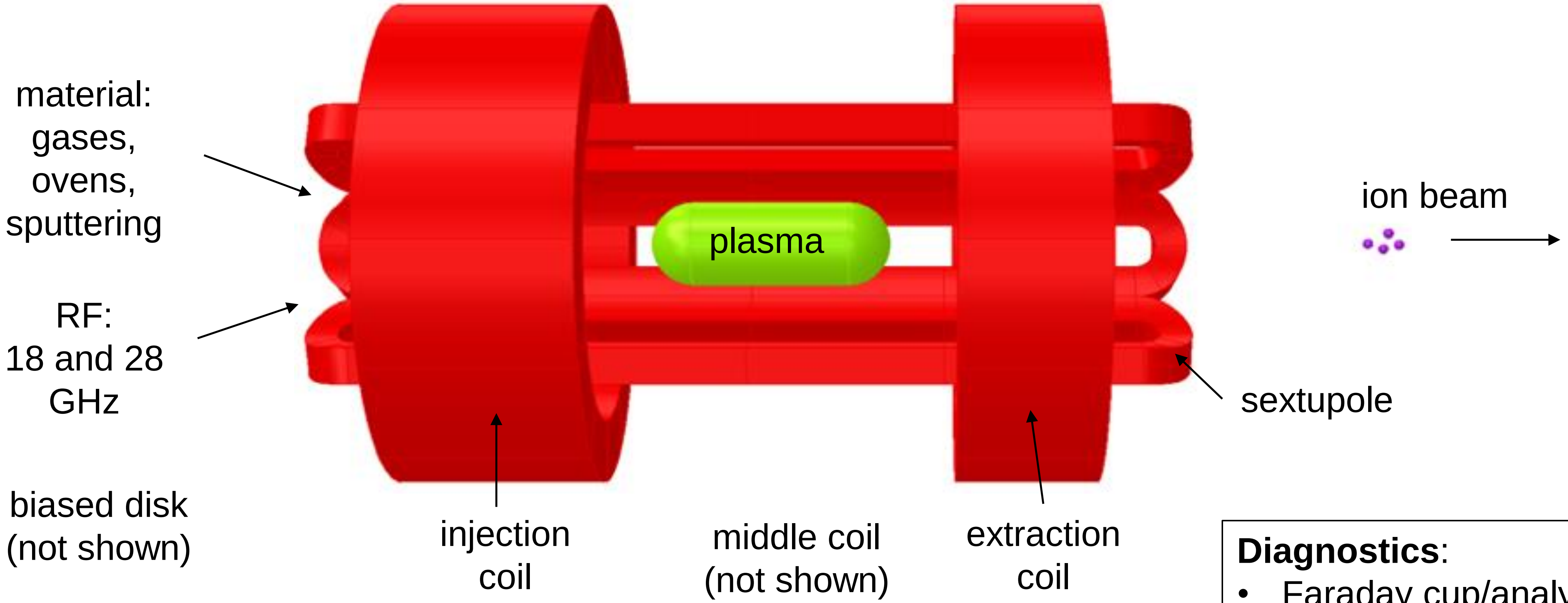
The electron cyclotron resonance (ECR) ion source, VENUS

VENUS:
- World's first fully-superconducting ECR ion source designed for 28 GHz operation
- One of the world's two highest-performing ECR ion sources
- Injector for LBNL's 88" Cyclotron
- Prototype ECR ion source for FRIB, where a near-identical copy has been installed



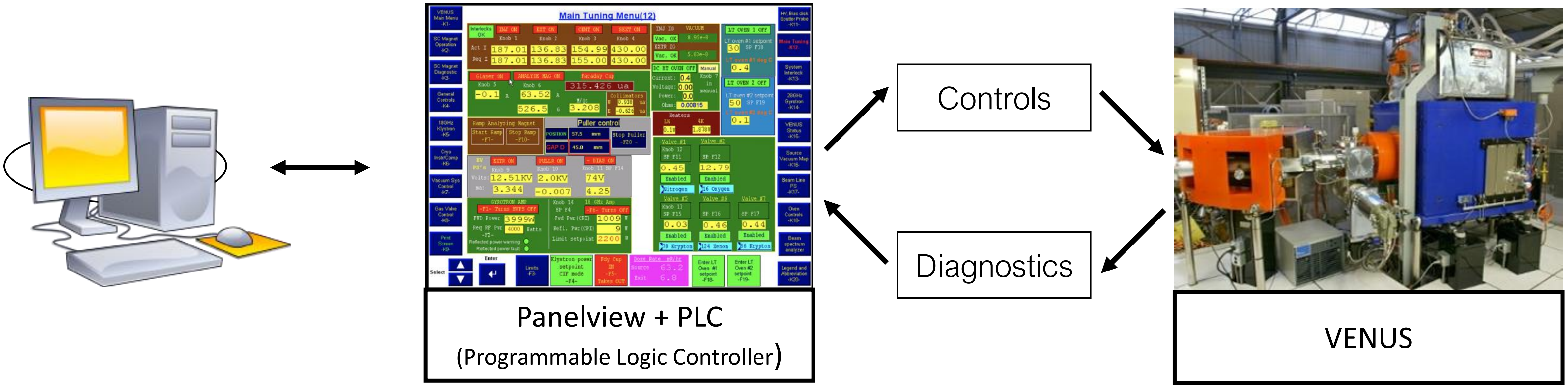
Example beams:
- > 4.7 mA O^{6+}, > 20 mA He^{+} from source
- > 2 pμA, 5 MeV/u $^{48}Ca^{11+}$ and > 1.4 pμA $^{48}Ti^{11+}$ from cyclotron for superheavy element research
- $^{197}Au^{61+}$ extracted from cyclotron (> 2.3 GeV!)

VENUS primary control and diagnostic parameters



Diagnostics:
- Faraday cup/analyzing magnet
- Emittance scanner
- Drain, bias currents
- Cryostat x-ray load
- Etc.

VENUS operation and data collection (WBS 1.1.1 and 1.1.2)



Computer control through PLC:

Advantage: Exploit 2 decades of safely logic in PLC

Disadvantage: Slow ~3 Hz communication

Data collection through PLC:

Over two years of all control and primary diagnostic data in database

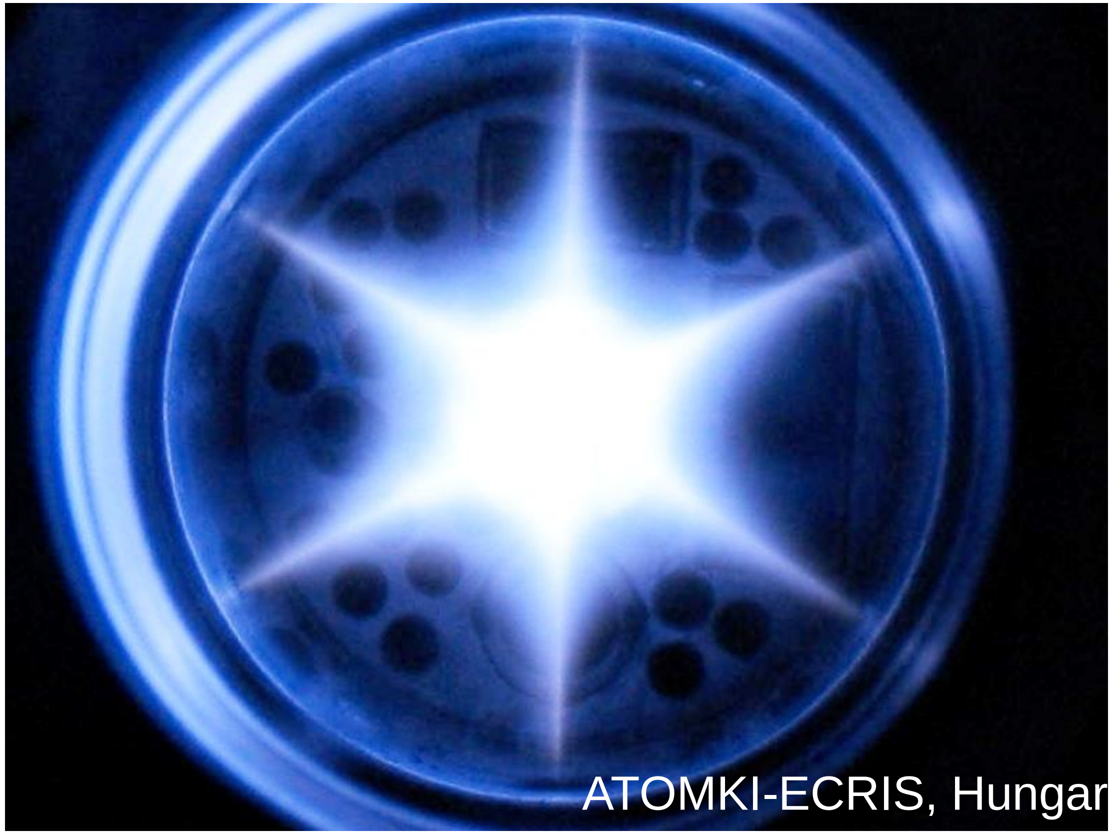
Computer-driven operation: baking

Blessing/curse of ECRIS: ion beams produced from any materials reaching plasma that don't destroy the plasma

Adsorbed particles later desorbed:

- Residues from previous work or handling of inner surfaces
- Water, salts, etc. on all surfaces after atmosphere exposure
- Prior beam materials (e.g., metals)

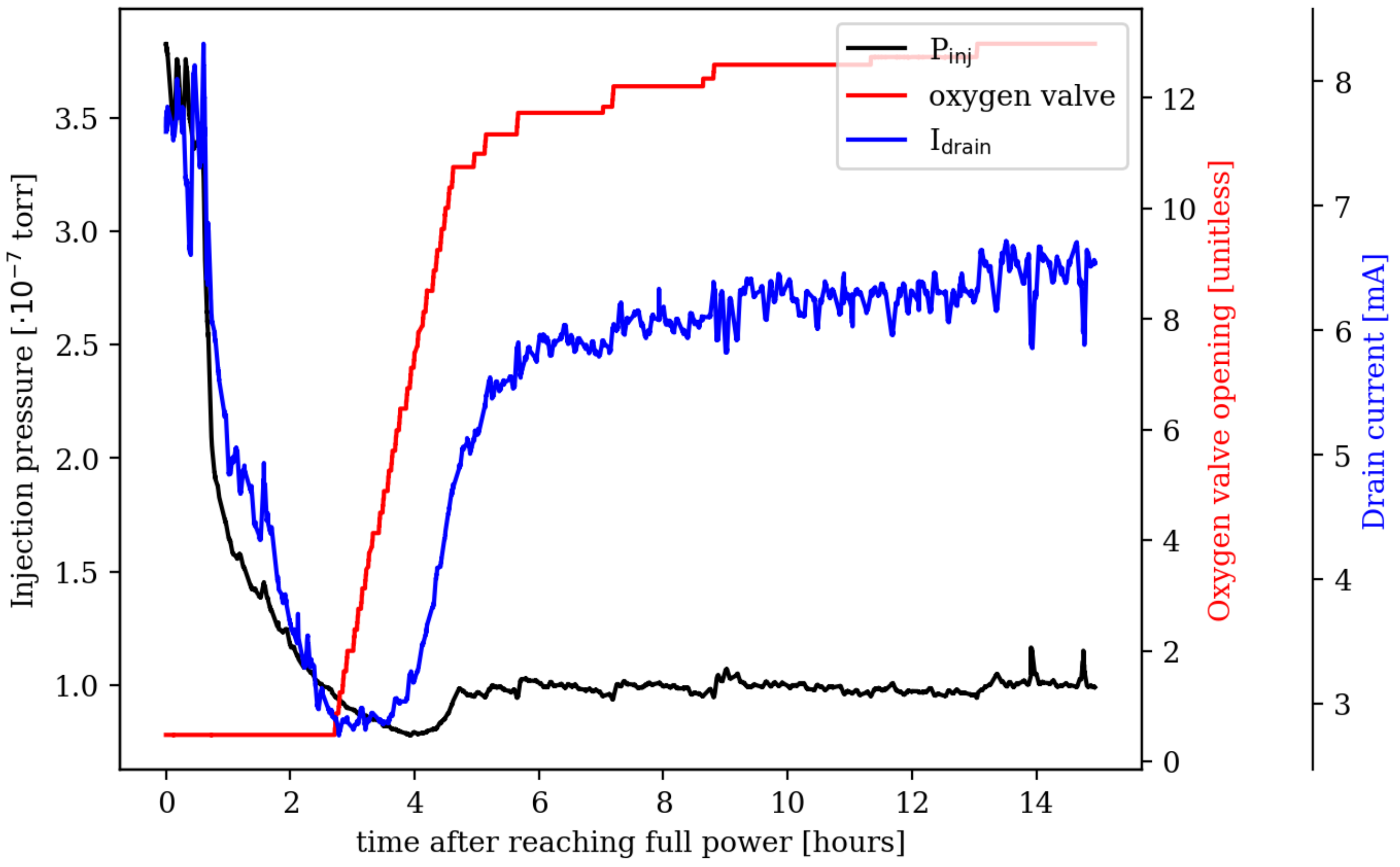
Plasma chamber desorption can be sped up using plasma as heating element



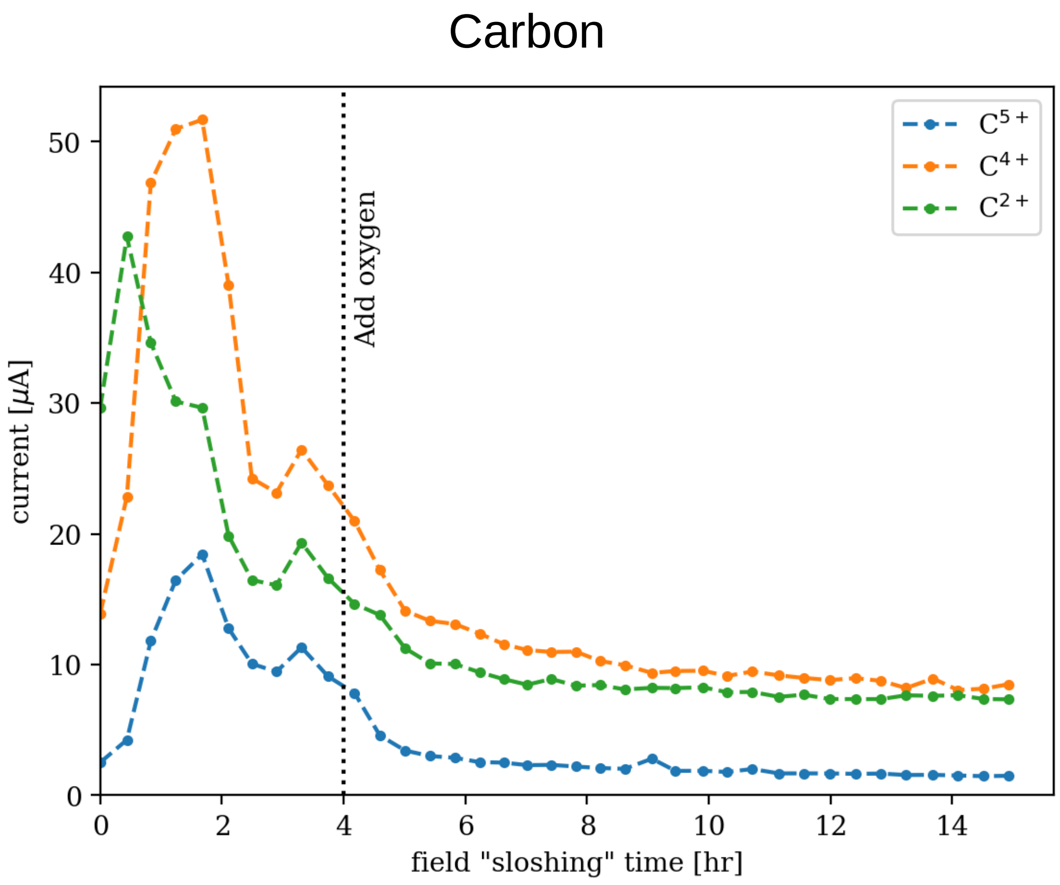
Computer-driven baking (WBS 1.3)

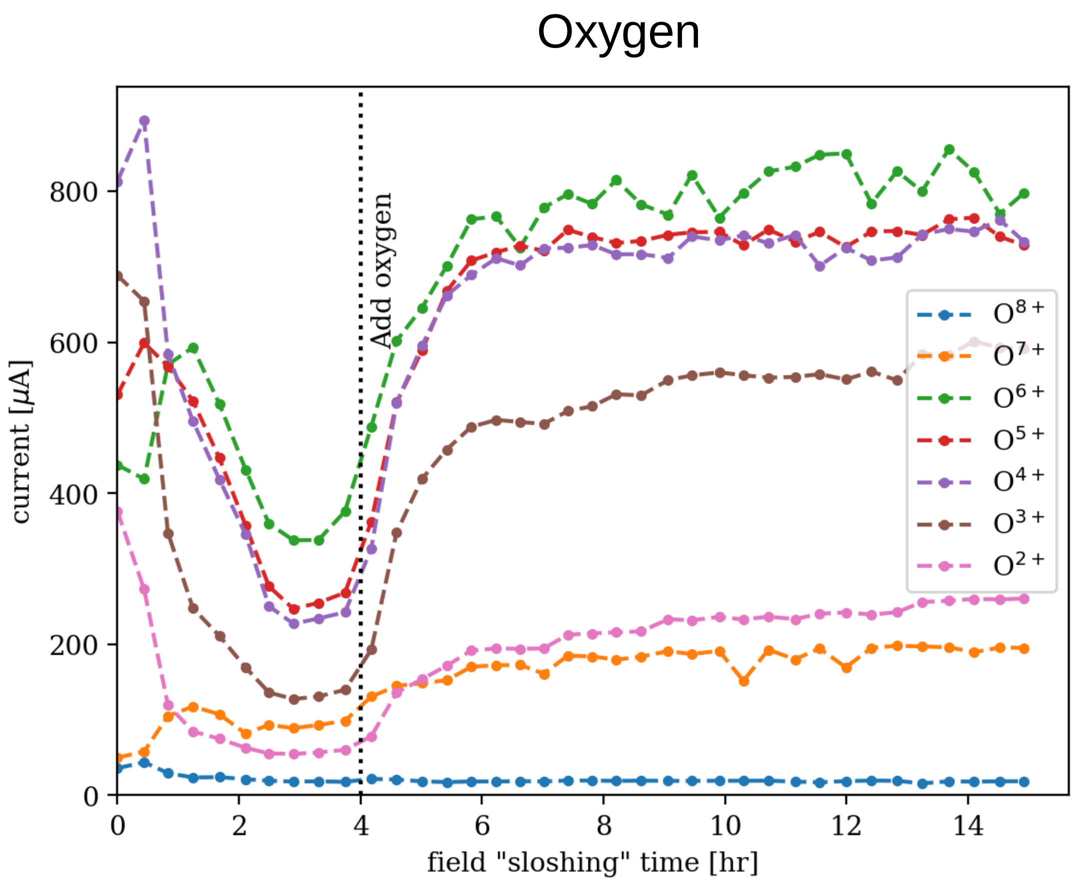
Two-step process:

- **Source to full RF power**
  - Monitor pressure, currents, etc. and raise safely
  - Time significantly reduced as the computer is persistent
- **“Slosh” plasma around to bake plasma chamber**
  - Change confining fields and add gas when desorption rate drops
  - Every 6th change return to “base” fields and perform charge state distribution to monitor evolution



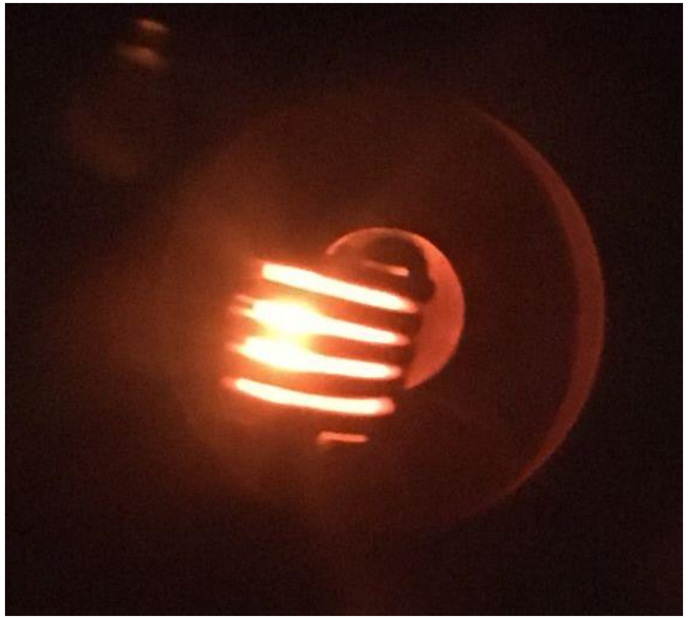
Charge state distributions (CSDs) give feedback on progress





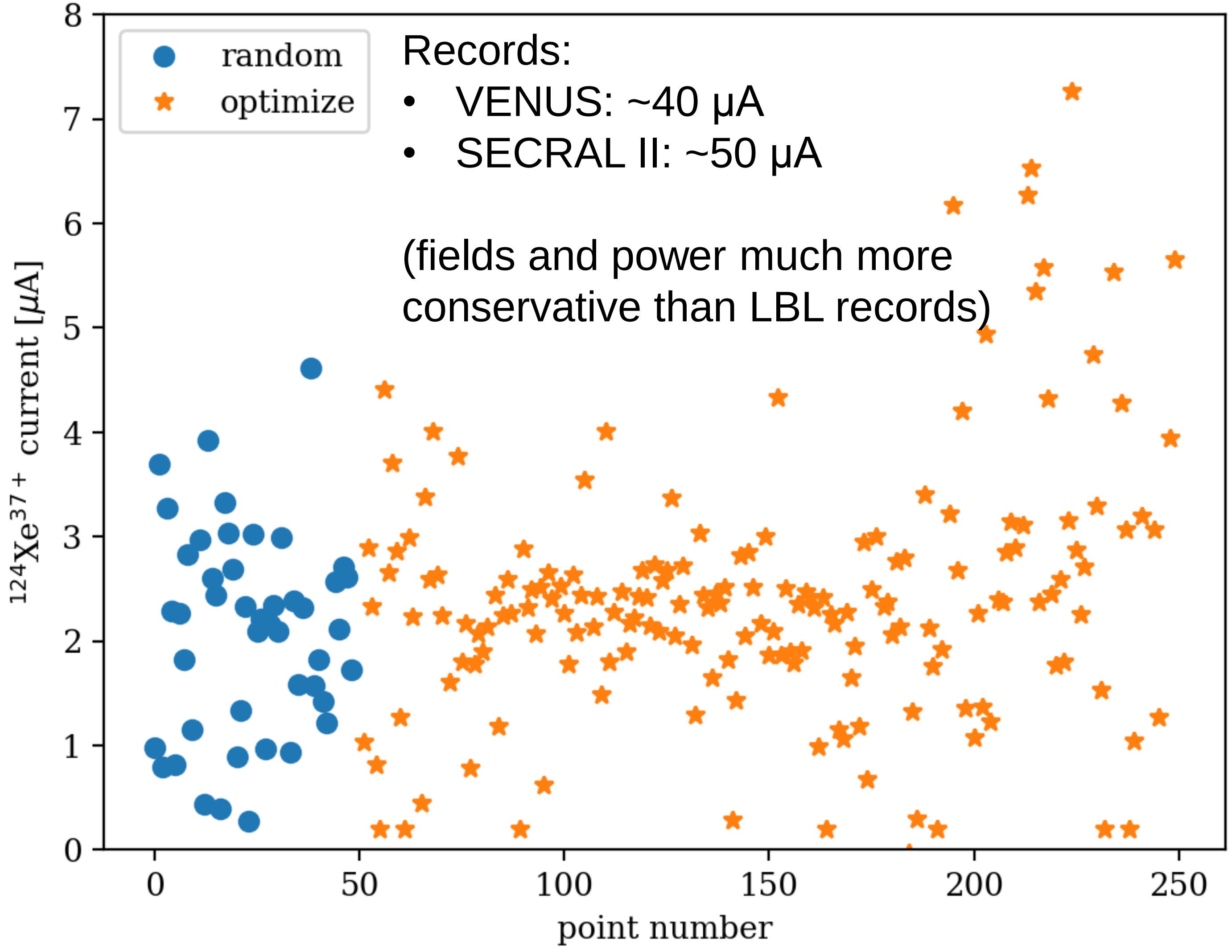
- Last ~10 bakes have been fully automatic with no human interaction
- Alone this is not machine learning, but collected data is being used to produce more efficient baking technique (ML!)

High-current titanium beam optimization for superheavy element production



- New inductive oven efficiently delivers titanium to plasma
- Titanium is a ”getter” metal
- Computer control has been used to constantly monitor and adjust mixing gases to maintain stability
- Not yet machine learning, but will be soon

Full Bayesian Optimization of $^{124}Xe^{37+}$ (WBS 1.2.1)

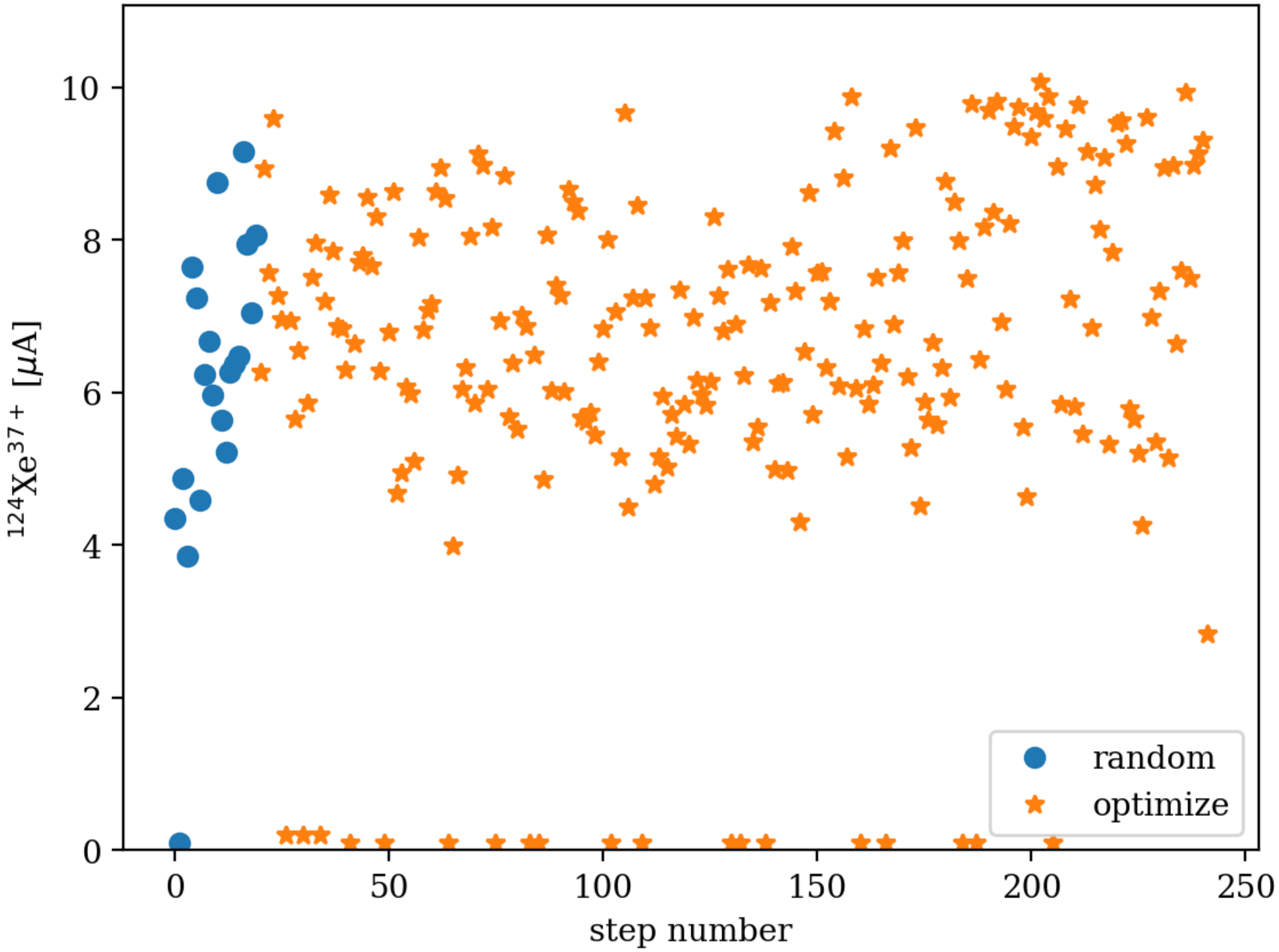


(~5 min/point)

Parameter	Min	Max
Bias voltage [V]	40	105
Oxygen valve	11.6	12.5
Xenon valve	8.0	13.0
Inj coil [A]	185.6	186.0
Ext coil [A]	136.6	136.8
Mid coil [A]	152.0	152.3
Sext coil [A]	430.3	430.5
18 GHz [kW]	1.4	1.8
28 GHz [kW]	5.2	6.0

- **This is machine learning!**

Optimizing a little more like a human



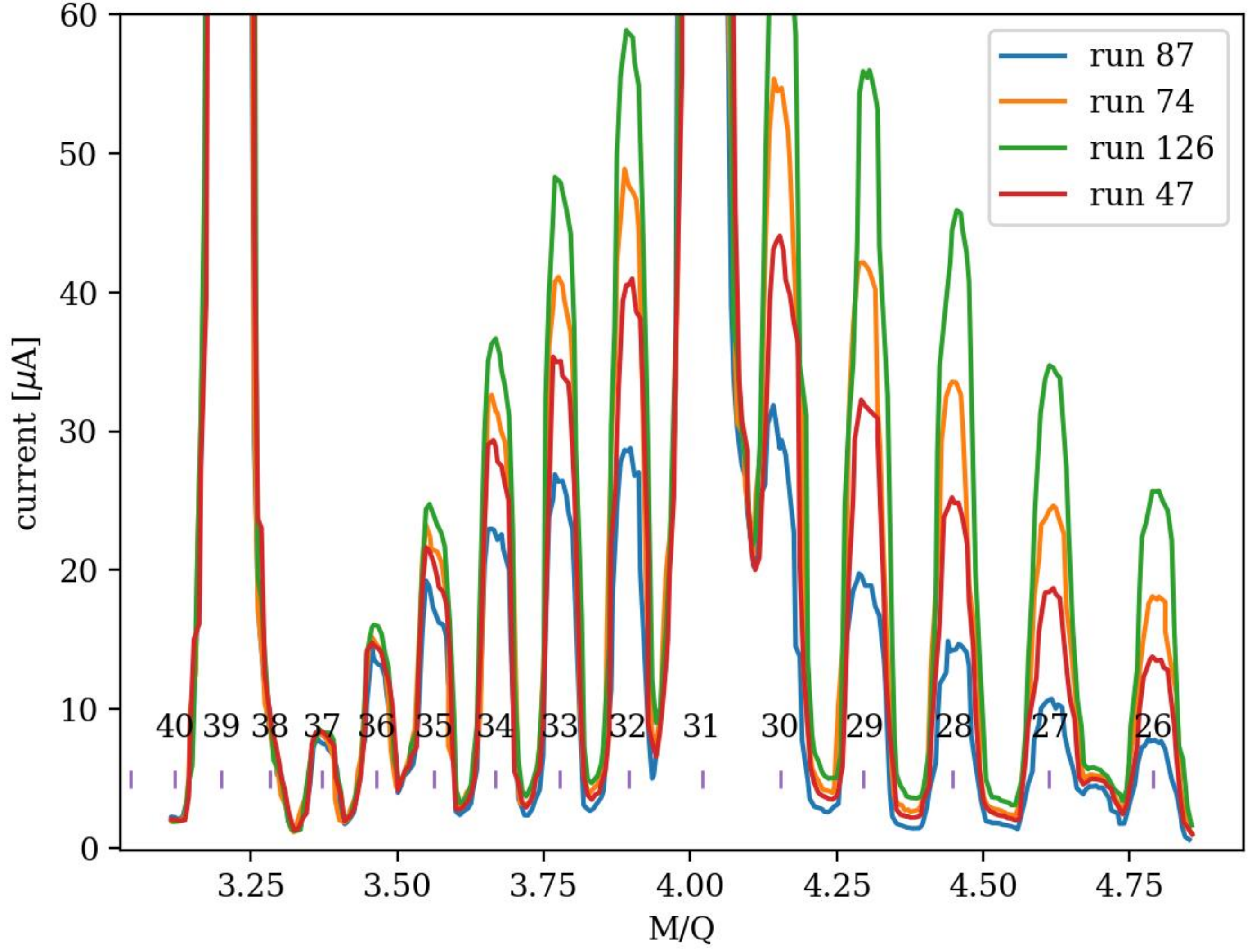
Parameter	Min	Max
Bias voltage [V]	25	65
Oxygen valve	11.5	12.0
Xenon valve	9.0	12.0
18 GHz [kW]	1.20	1.80

Many human records are achieved by using a cost-function-like approach:

- Coils are slow, so find a pretty good solution and work from there

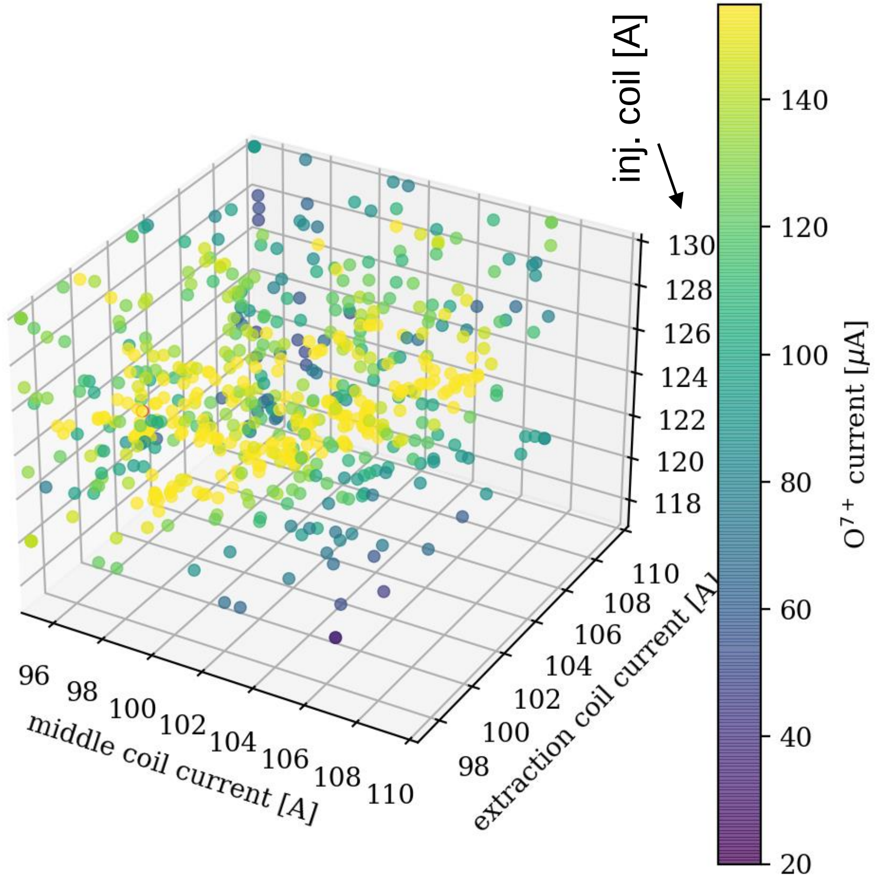
Note:
When instabilities or too low pressures encountered, low current is recorded

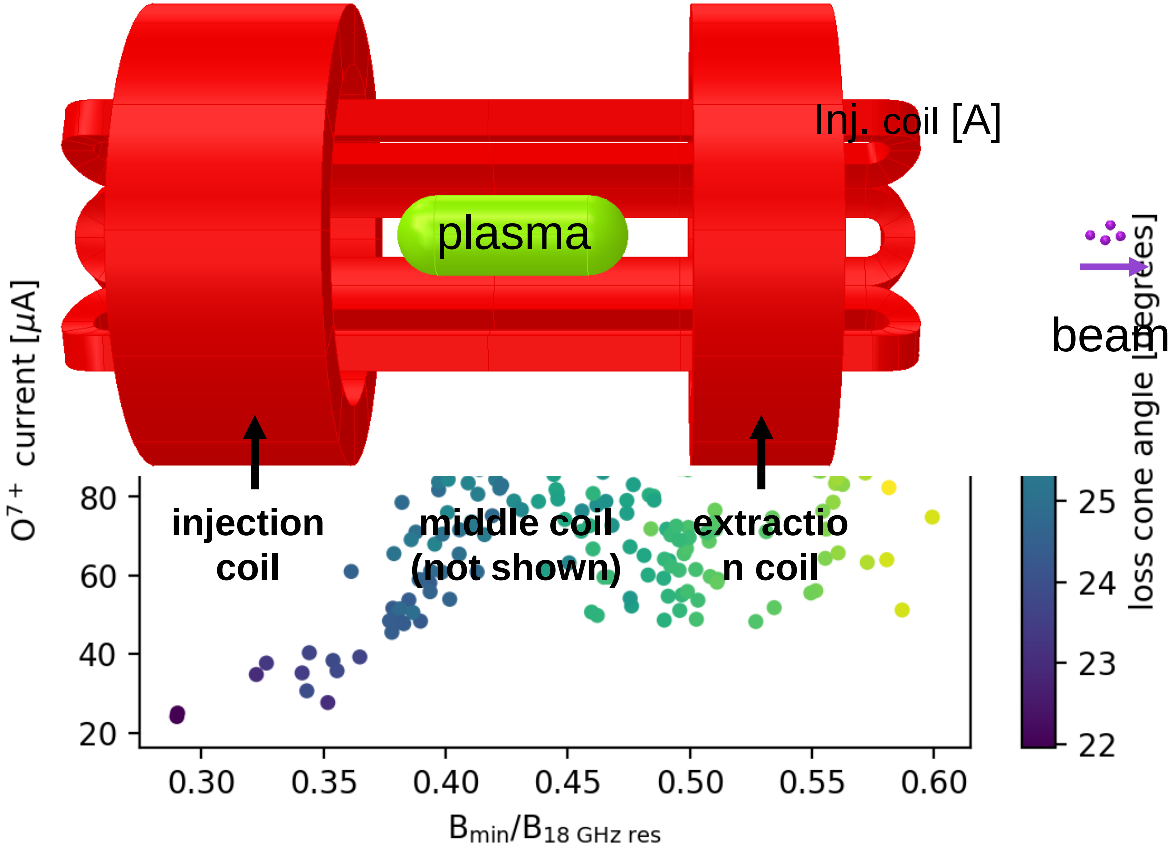
Exploiting patience of computer



- ~5 minutes between optimization as computer performed charge state distribution (CSD) measurement at each step (~1-2 minutes)
- Most human optimizations are missing CSD information
- These four runs had almost identical $^{124}Xe^{37+}$ currents but their CSDs were dramatically different
- This information will be fed into neural network efforts for general plasma understanding

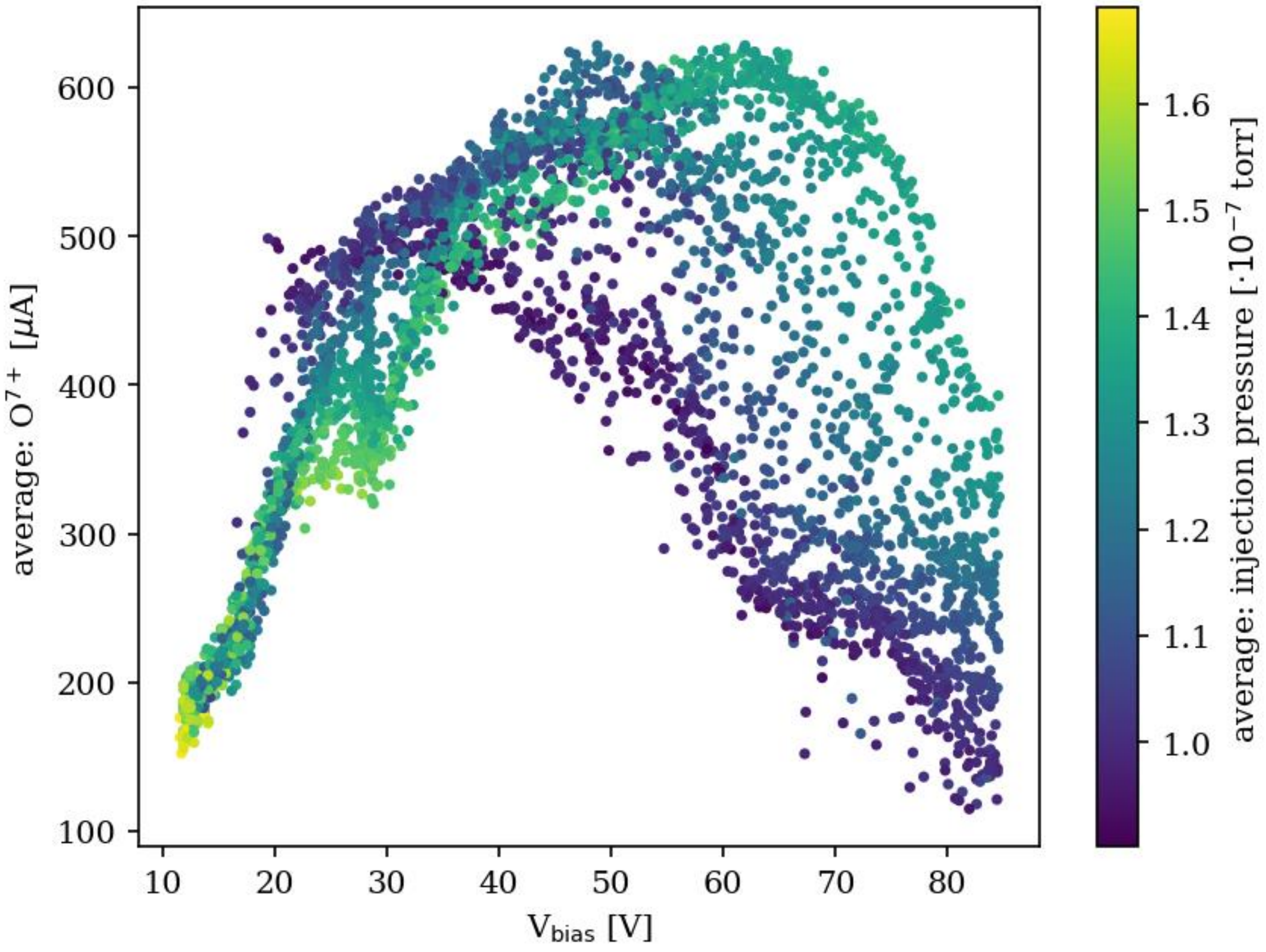
Computer-driven operation has allowed for the collection of lots of data





- Difficult to discern any pattern or trend

Lots and lots of data: explore bias voltage and pressure influence

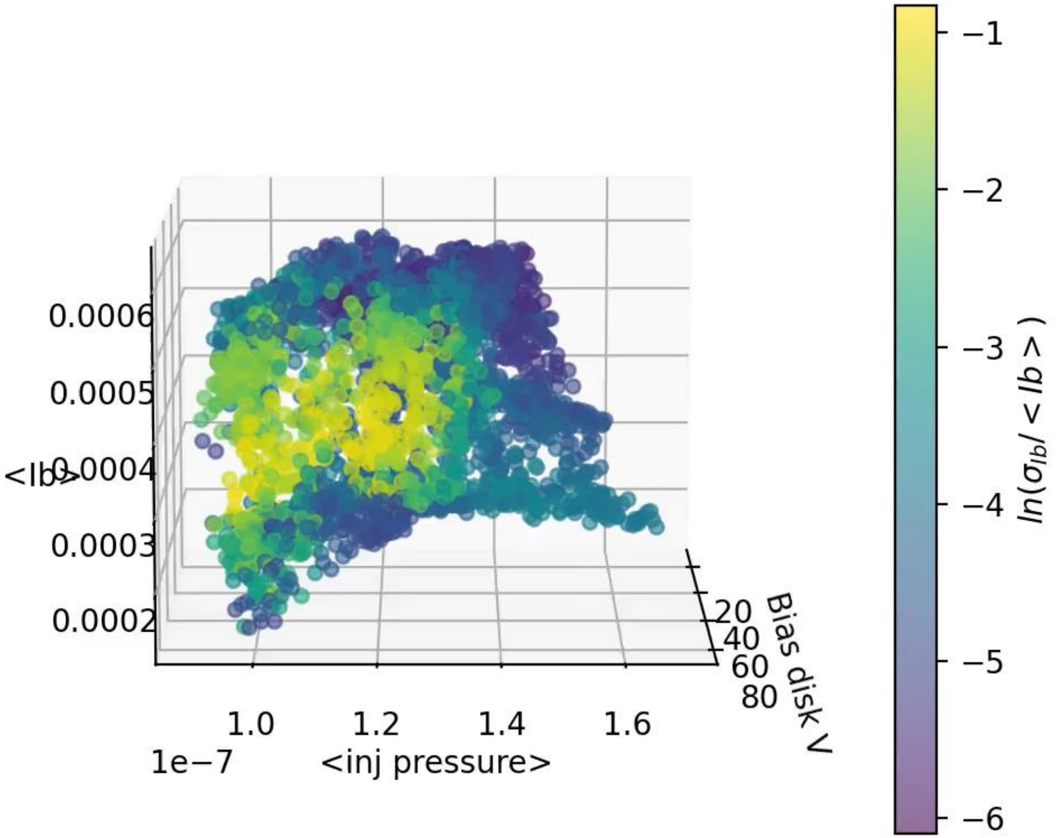


Two parameter space exploration:

- Biased disk voltage
- Oxygen gas flow

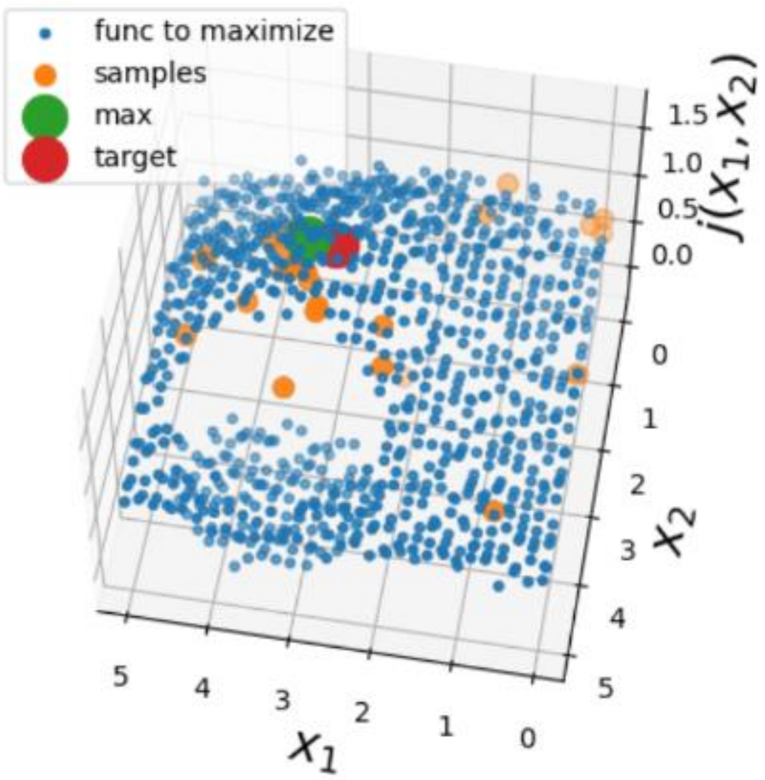
3695 configurations, averaged over 30 measurements each

Collection of data has allowed study of operation space structure

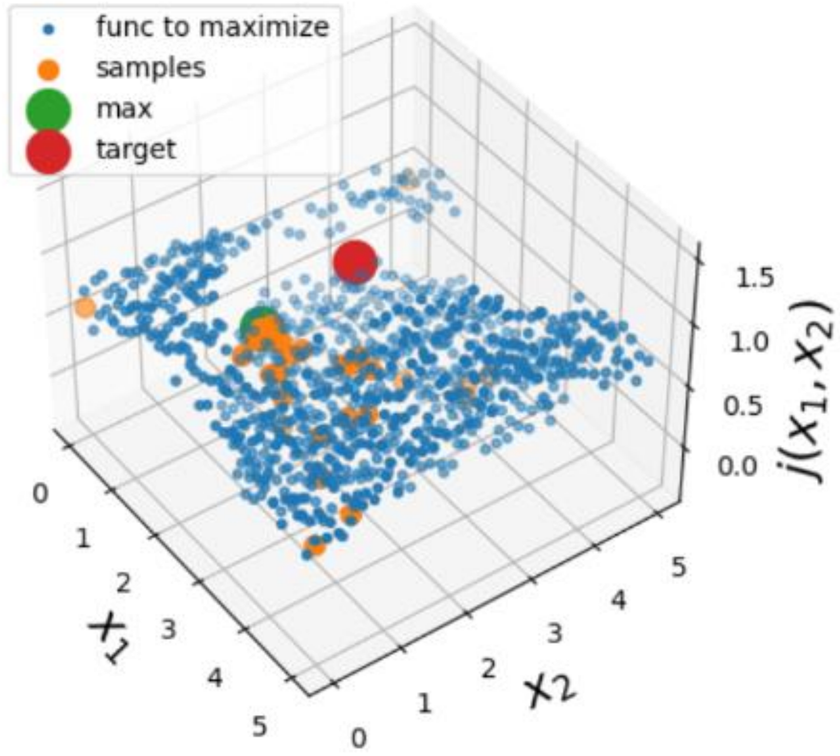


ML research by post-doc V. Watson from HAW23, 01 Dec 2023

Constrained optimization



Maximum out of the forbidden zone

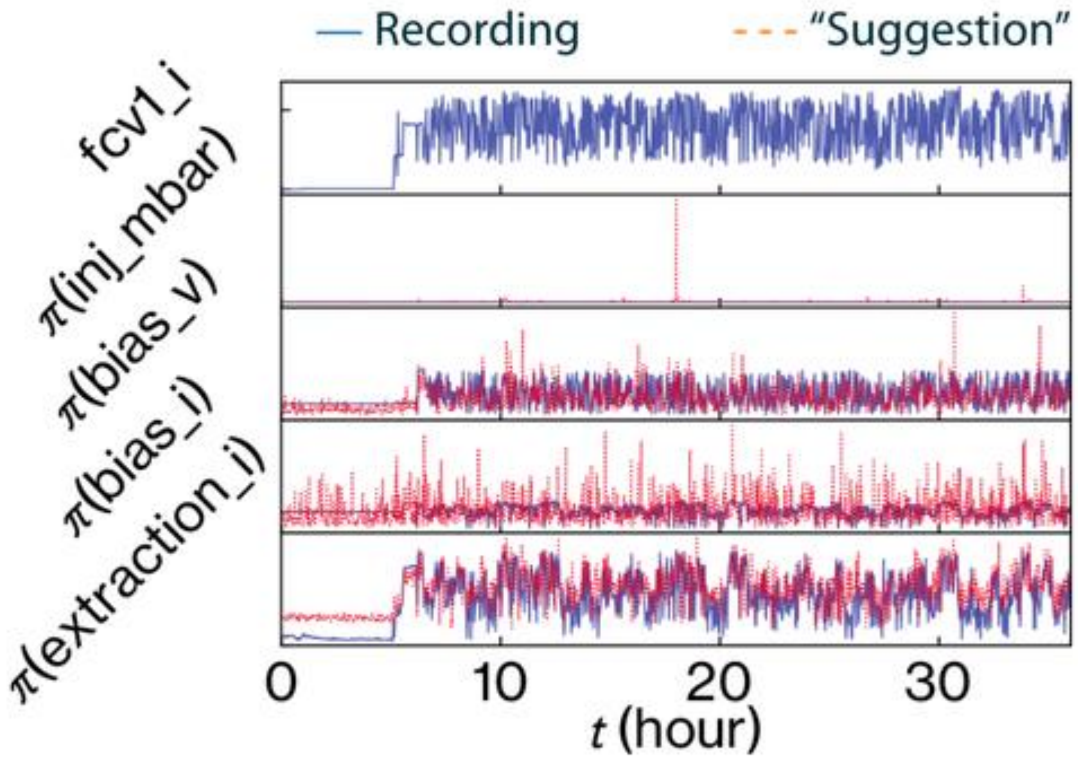


Maximum inside the forbidden zone

Neural network research with VENUS Y.S. Lai at HAW23, 01 Dec 2023

Result

- Running inference on historical data
  - ⇒ Algorithm "making suggestion" what the operator should do
- Non-reactive result: Neural network proactively activates the biased disc and extraction
- Simplified visualization due to the high dimensionality of value function



Offline RL for closed-loop control of the VENUS ion source | BERKELEY LAB

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Budget and expenditures

	FY22 ($k)	FY23 ($k)	Total ($k)
Funds Allocated	500	500	1000
Actual Costs to Date	187*	475	662

* our postdoc (V. Watson) did not start until 08/2022

Project Milestones

WBS	Milestone	Description	Projected Milestone Date	Status
1.1.1	**VENUS** PLC Interface Complete	Develop and test code to read/write from the VENUS PLC control system.	Dec-2021	✓
1.1.2	**VENUS** Database Implemented	Database for logging of VENUS parameters is defined, established and configured for use.	Mar-2022	✓
1.2.1	**VENUS** Current Optimization Started	Optimization of VENUS beam current through automated search of a limited parameter space has started.	May-2022	✓
2.1	**GRETA** Off-line Energy Resolution Optimization Implemented	Human-like process for optimization of energy filters in off-line data analysis for GRETA streamed data is complete.	Sept-2022	✓
1.3	**VENUS** Baking Control First Attempt Complete	Computer-driven codes to implement baking procedure for VENUS guided by human approach complete.	Dec-2022	✓
1.2.1	Full Parameter Space **VENUS** Optimization Implemented	Optimization of VENUS beam current implemented exploring the full parameter space of the controls system.	Feb-2023	✓
2.1	**GRETA** SFB Optimization Enabled	Optimization of the energy filter parameters is implemented for the signal filter board hardware via the EPICS interface in GRETA.	Jun-2023	✓
2.2.2	**GRETA** ML/AI Database Established	Database for logging of GRETA parameters is defined, established and configured for use.	Jun-2023	✓ (to degree possible)
3.1	Generalized Framework Communication Channels Complete	Complete generally configurable versions for all communication types used in VENUS and GRETA.	Aug-2023	✓

Thank you!