ML+LLRF: From Demonstrated Laser Control to SRF Resonance Control

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Lawrence Berkeley National Laboratory

Dedicated AI/ML Accelerator Test Facility
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SLAC

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- **Teams & Collaborators**:

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Outline

- **ML enables simple, robust and effective controls in general**
- **LBNL-LLRF (Low Level RF) platforms enable science over decades**
- **ML+LLRF:**

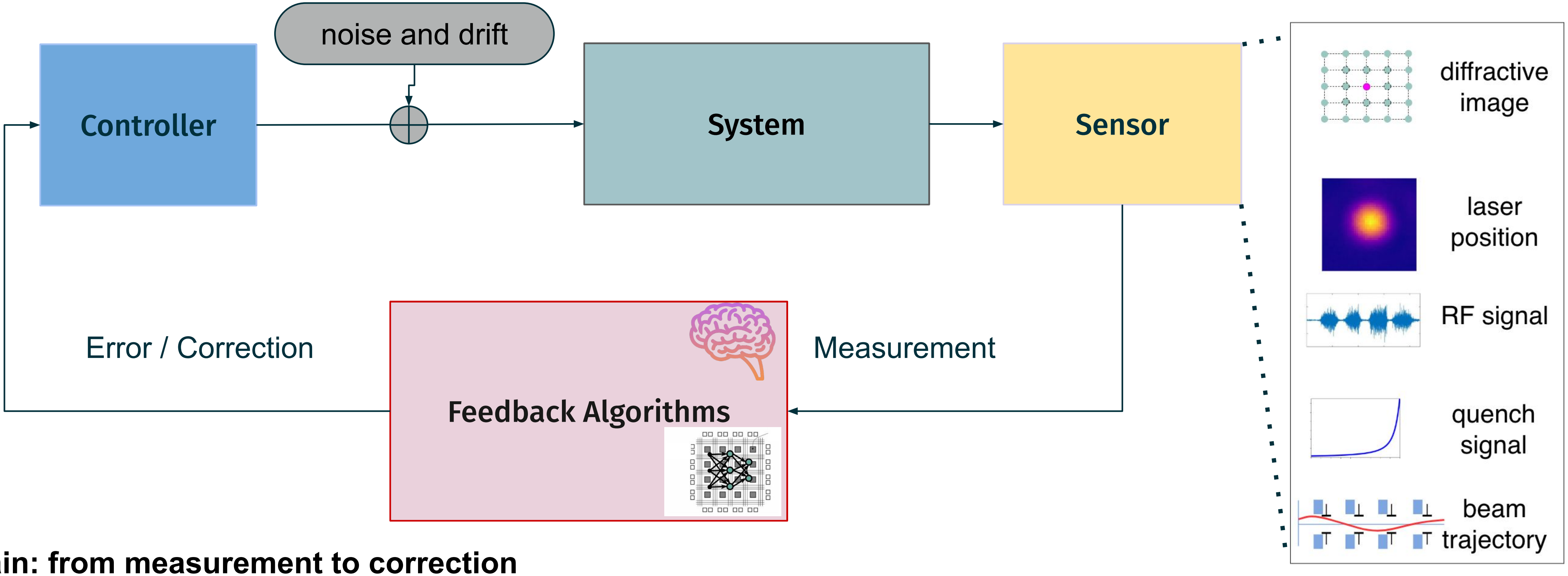
Data from LLRF is ML-ready (time-stamped, >kHz, synchronized), this open-source substrate can serve as a tool for general real-time control:

  - (1) demonstrated on lasers
  - (2) in progress on SRF
  - (3) open testbed & opportunities

- **Discussion and Outlook**

ML offers a simple, robust path to deterministic control (in general)

Feedback controls are widely used in Lasers & Accelerators:



The brain: from measurement to correction

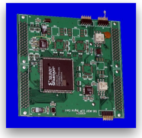
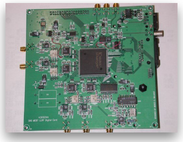
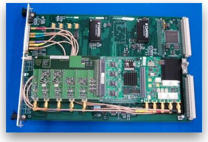
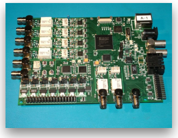
Hardware-aware AI — data-driven, deterministic (not stochastic exploration) + timing- and latency-aware

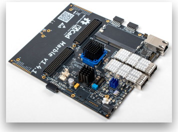
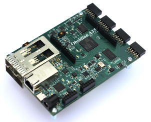
[1] A. Edelen & X. Huang, Annu. Rev. Nucl. Part. Sci. 74, 557 (2024)
[2] A. Scheinker, A. Edelen, et al., Phys. Rev. Lett. 121, 044801 (2018) — LCLS
[3] C. Emma, A. Edelen, et al., Phys. Rev. Accel. Beams 21, 112802 (2018)
[4] S. Leemann, et al., Phys. Rev. Lett. 123, 194801 (2019) — ALS
[5] A. Scheinker, F. Cropp, D. Filippetto, Sci. Rep. 11, 19187 (2021)

LBNL's control and timing technology serves DOE's accelerator projects opens a new opportunity for lasers, qubits and complex system controls

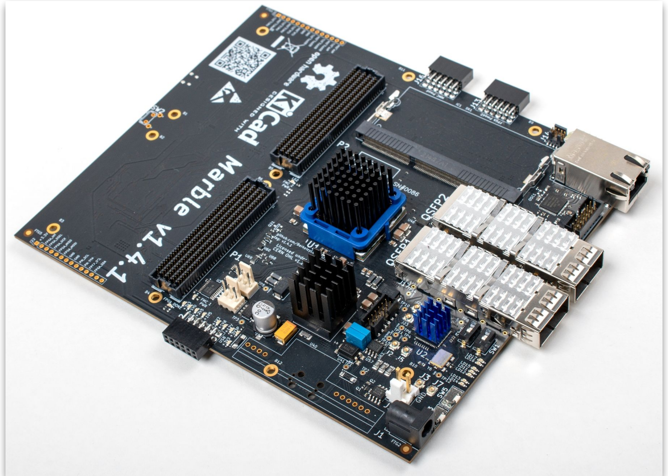
FPGA — Soft. defined radio — LCLS 10s fs fiber optics timing — 1E-4 SRF LLRF — Qubit / laser controls — RFSoC — AI-LLRF

2001 — 2006 — 2009 — 2014 — 2017 — 2022 — 2026

https://github.com/BerkeleyLab/marble



L. Doolittle et.al,. SLAC-PUB-17108

LLRF for LCLS-II and LCLS-II HE
PIP-II Accelerator complex controls
LLRF Upgrade for AWA, ANL
LLRF for ALS-U AR, LBNL
…

Scalable digital control in fiber laser combining
(Russell Wilcox, Qiang Du, Tong Zhou, et. al.,)

Digital controls for qubits
(Gang Huang et. al.)

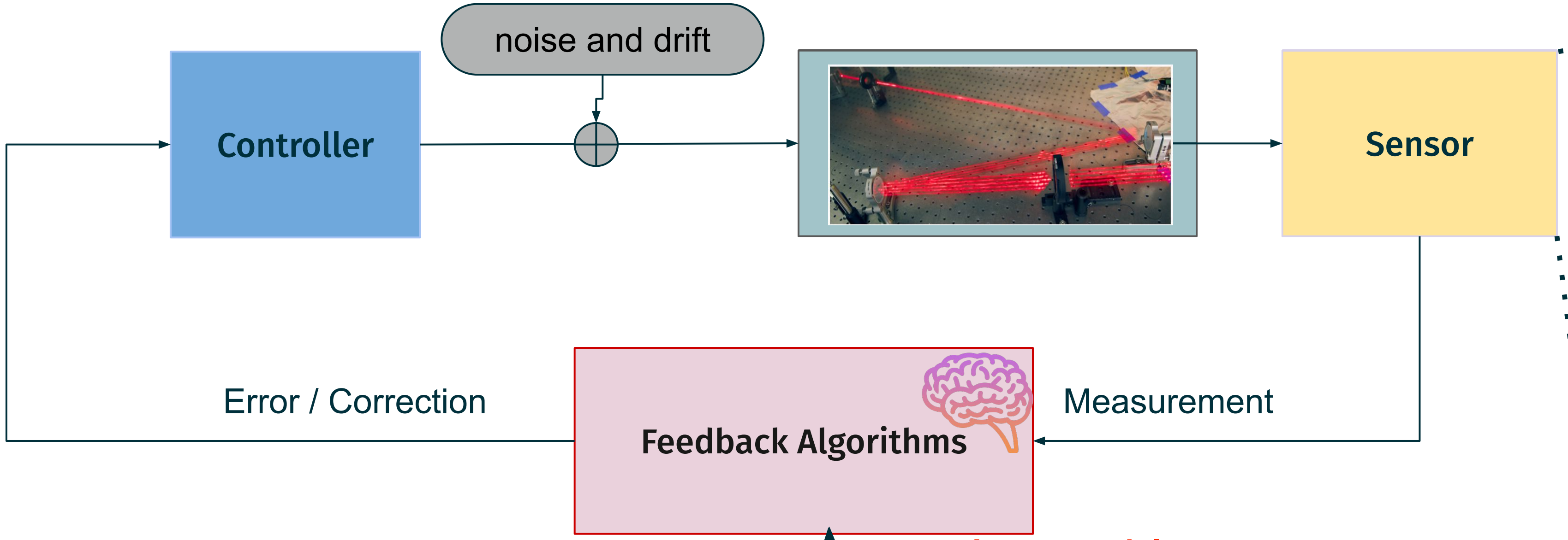
AI-enhanced LLRF (in progress)

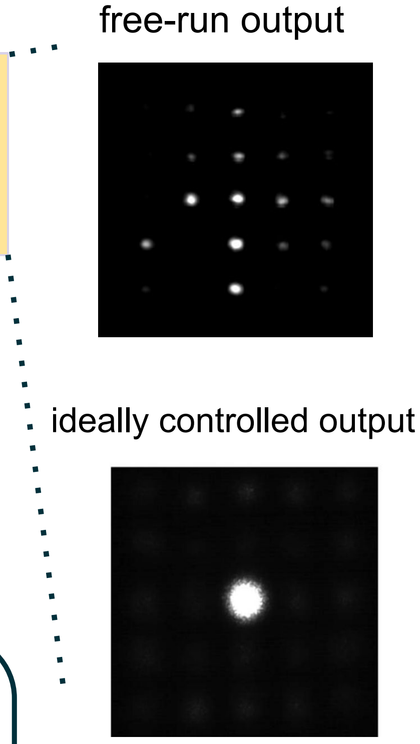
L. Doolittle, et al.; https://github.com/BerkeleyLab/Marble
Q. Du, et al., Digital Low-Level Optical Control for Coherent Laser Combining, 2023/10/23 LLRF Workshop 2023
G. Huang, et al., How a novel radio frequency control system enhances quantum computers, LBNL Lab News, 2021

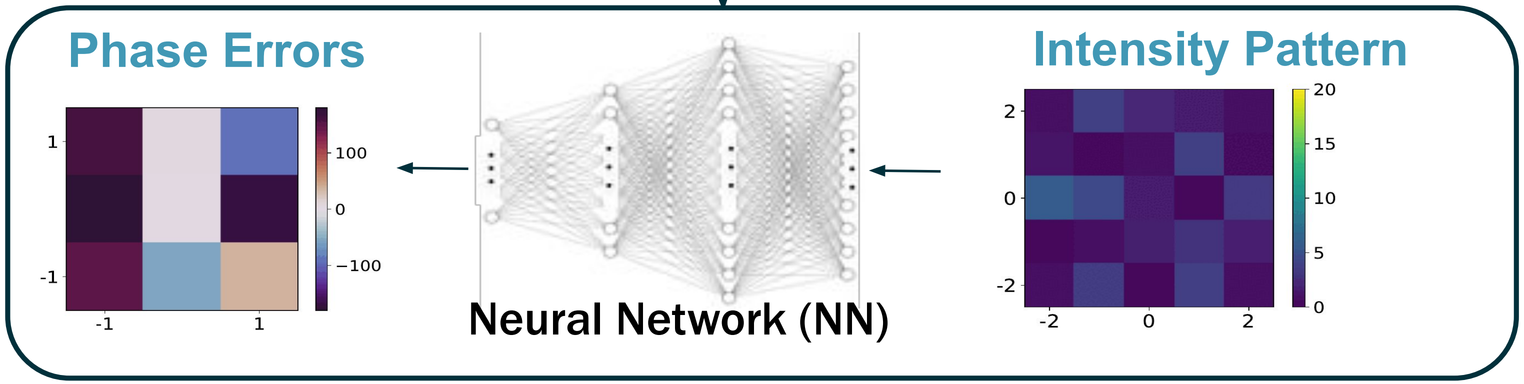
Over decades of innovation in precision control & timing technology and application under support of DOE SC.

Laser combining: ML offers solution with complex pattern recognition

Feedback controls in laser combining:







Example of one control chassis in the laser system

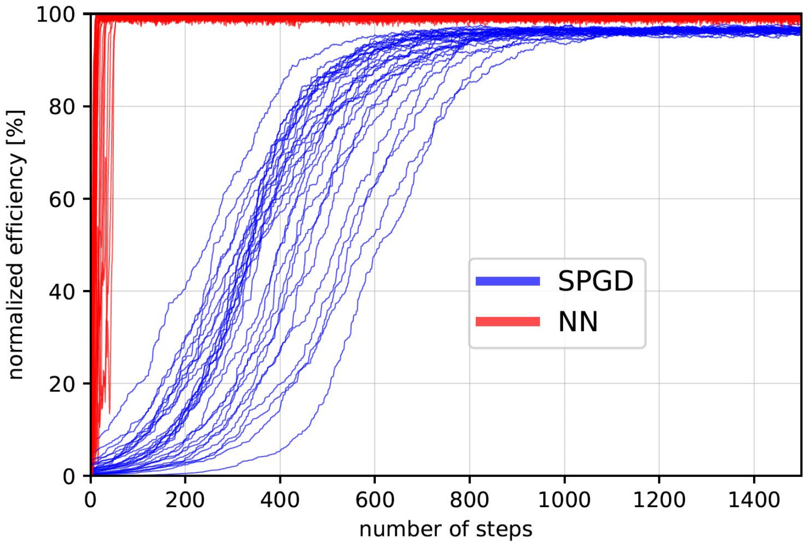
Qiang Du, et.al,

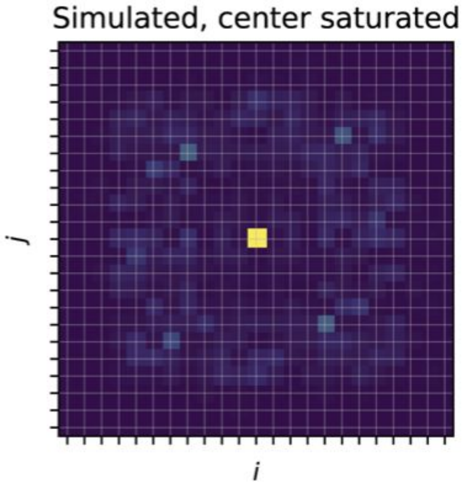
Synchronized kHz data + Physics-guided ML enables learning in the real world.

Recognition Neural Networks (NN): from pattern to error

Physics-guided ML delivers closed-loop simulation and real-world demonstration

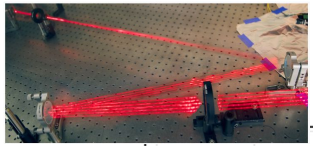
Simulation closed the loop:
- Fast convergence
- Better performance

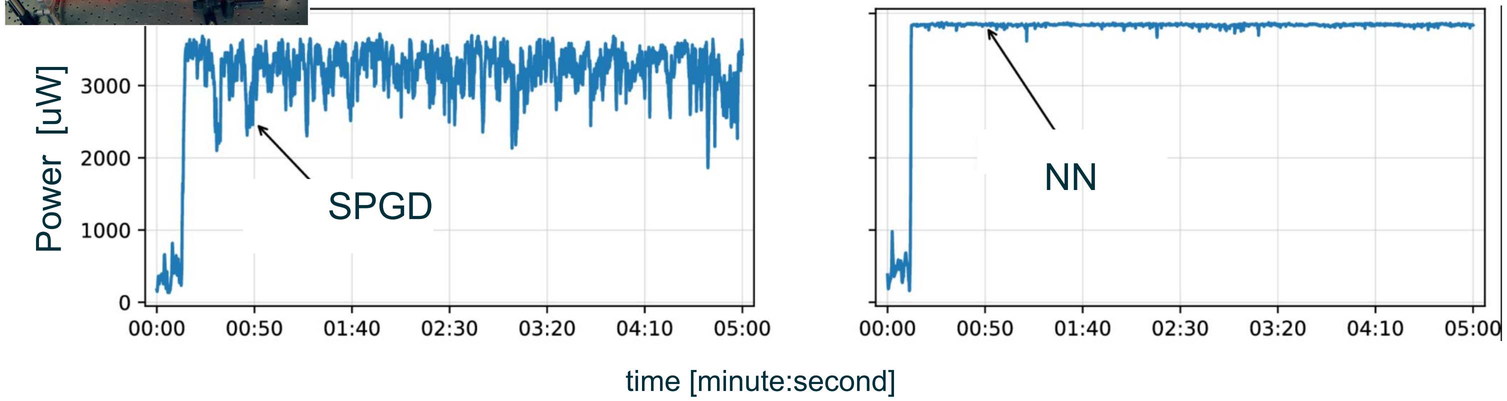




D Wang, Q Du et.al., (2021). Optics express, 29(4), 5694-5709

Q Du, D Wang et.al., (2021). Optics express, 29, 5407-5418

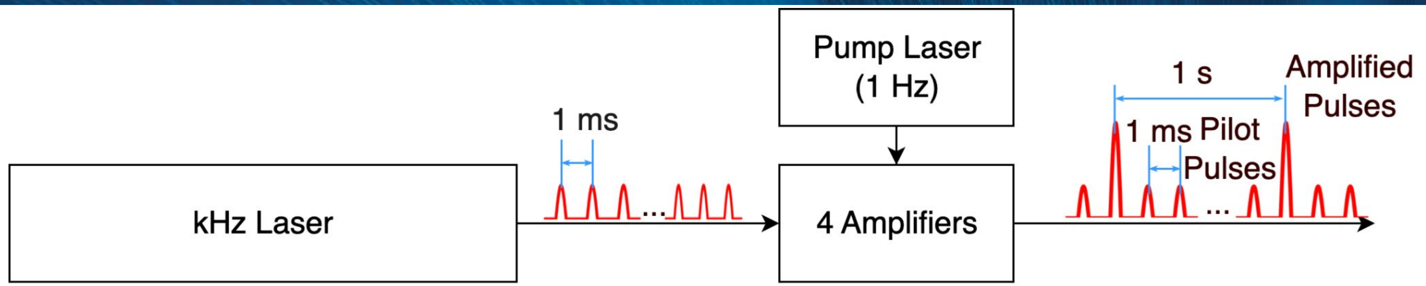


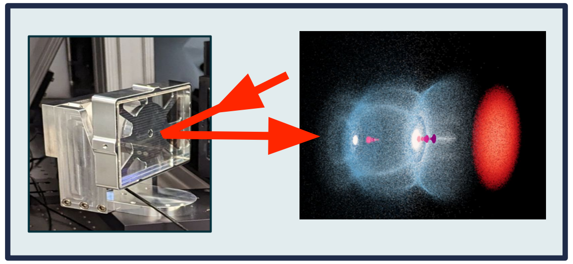


With NN control in **experiment**:
- Unprecedented stability

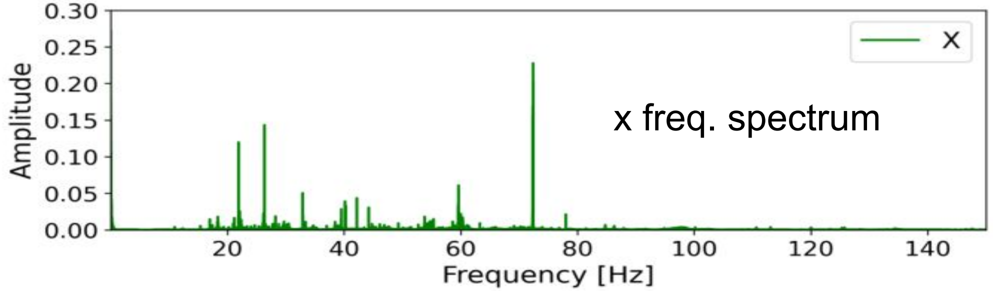
Q. Du, D. Wang, et al., Opt. Express 30(8): 12639 (2022)

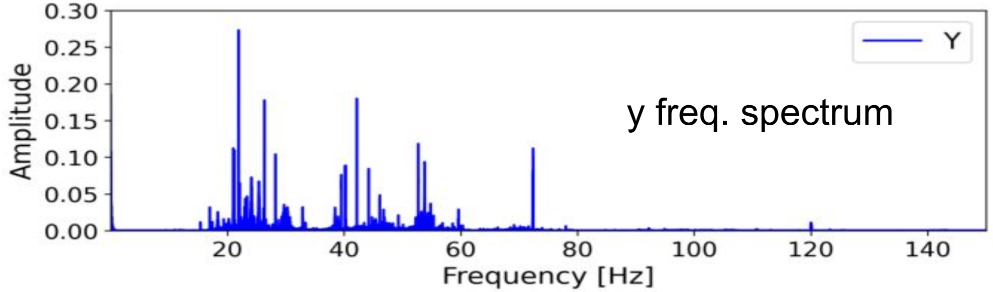
Laser pointing: traditional feedback is insufficient — low control bandwidth





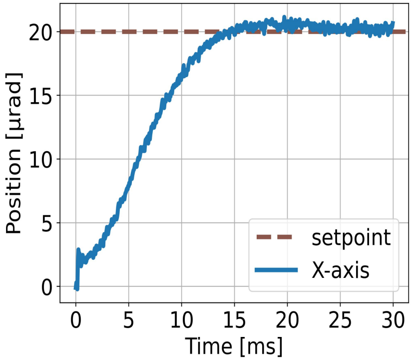
Noise Spectrum -> high frequency up to 100 Hz

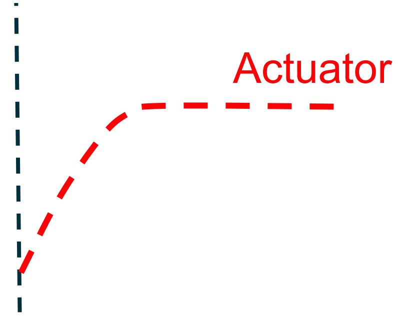




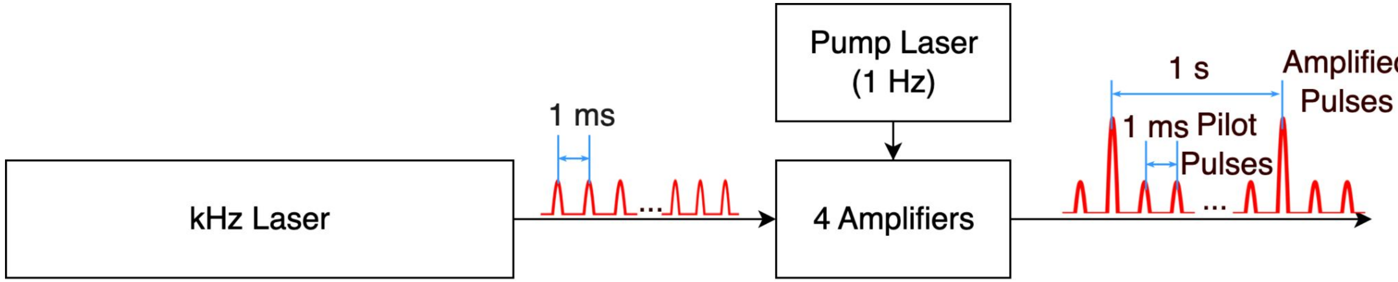
Challenges

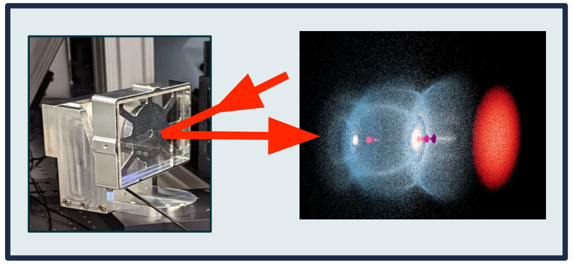
Slow mirror -> response time up to 20 ms





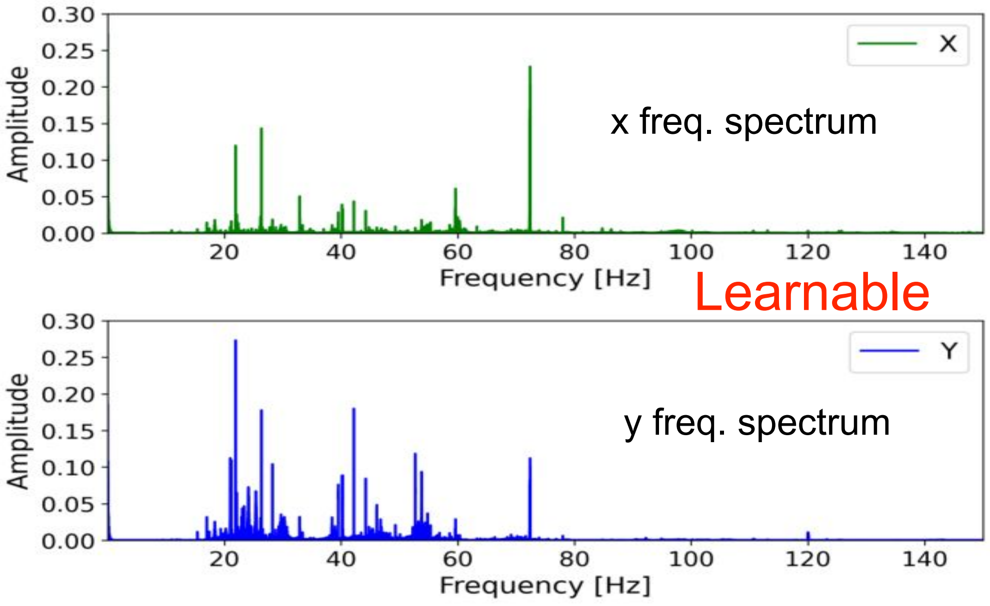
Feed-forward prediction from a kHz pilot beam enables predictive control

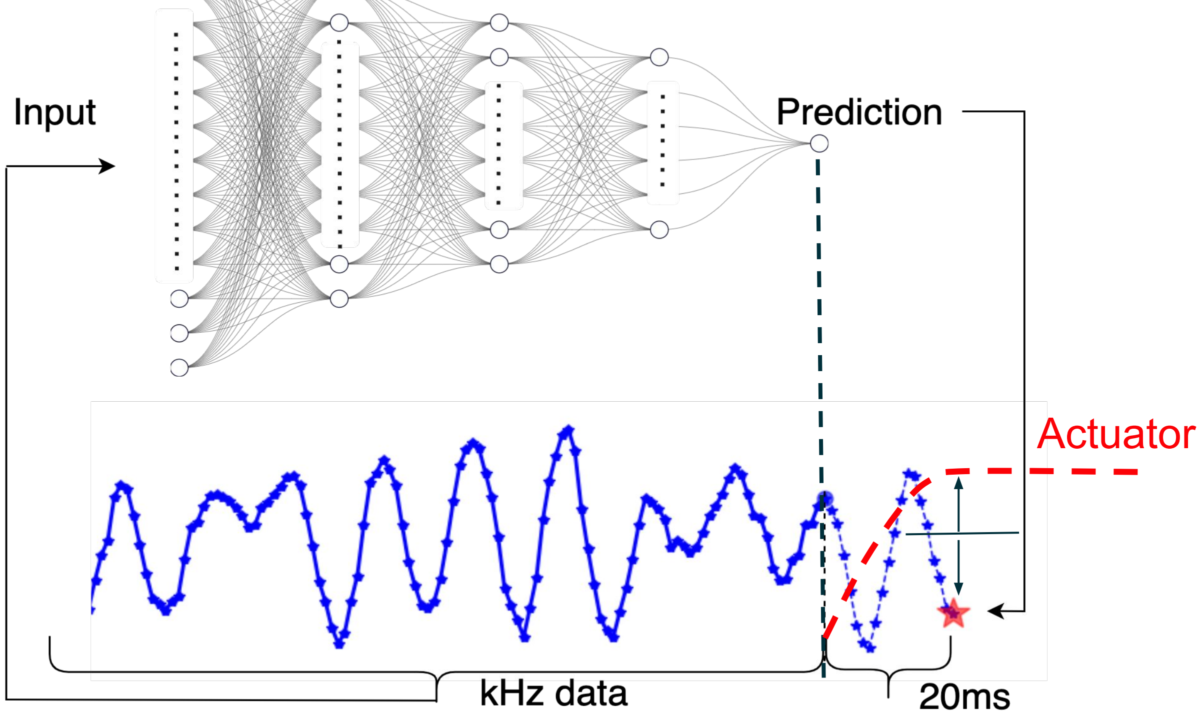




kHz pilot beam (complete noise information) used to train ML

Move mirror in advance

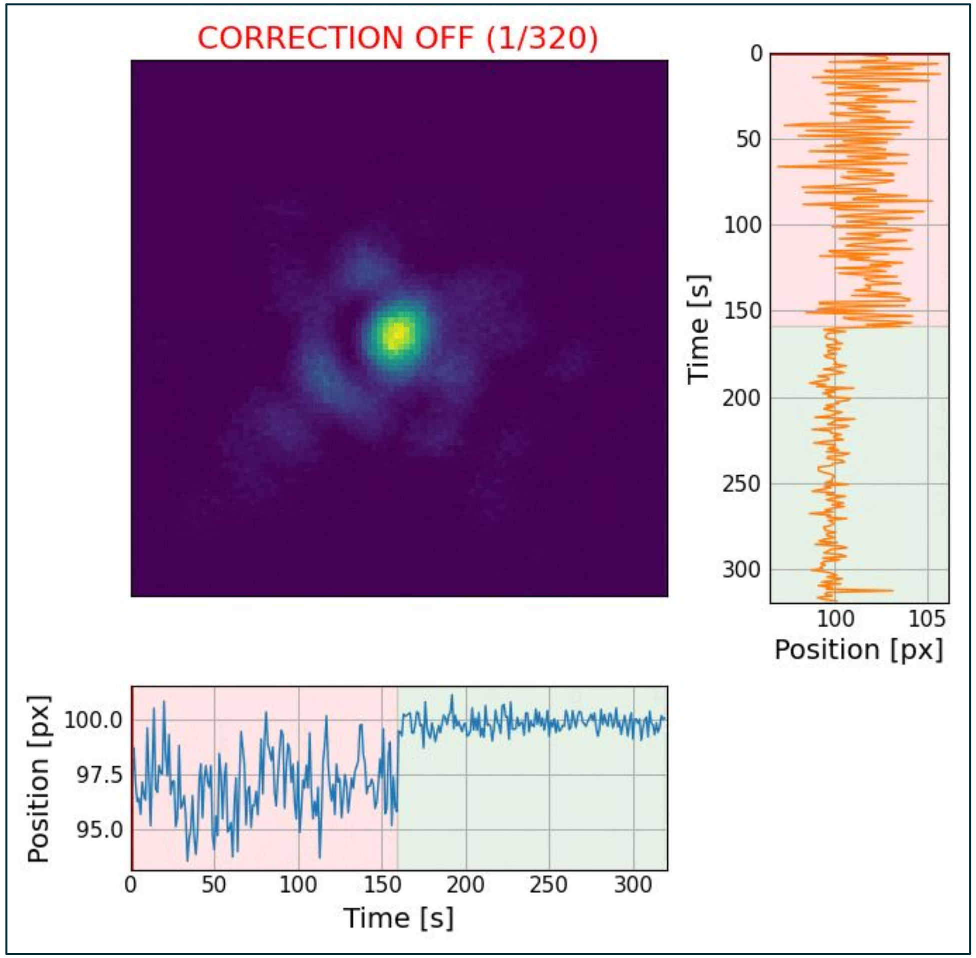




-F. Isono et al. High Power Laser Science & Engineering, 9, e10 (2021)
-C. Berger et al. NIMA 1078 (2025) 170561

Experimental Results for a 30 mJ (TW) Operation, Demonstrating Correction

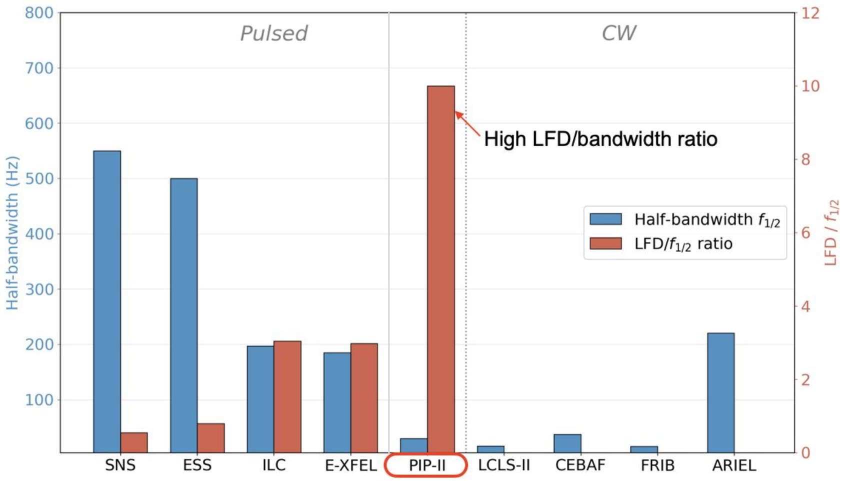
- Achieved jitter reduction of ~65% in X and ~47% in Y!

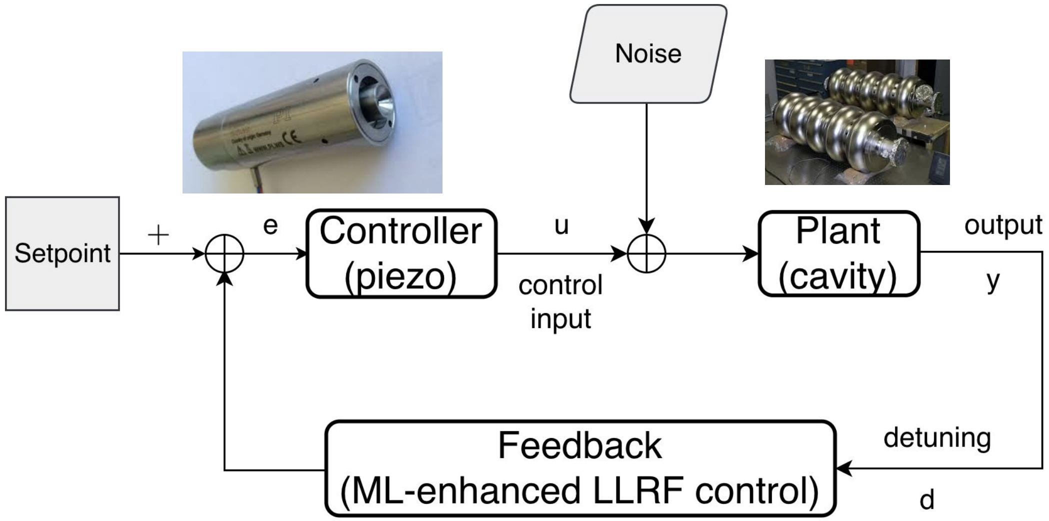


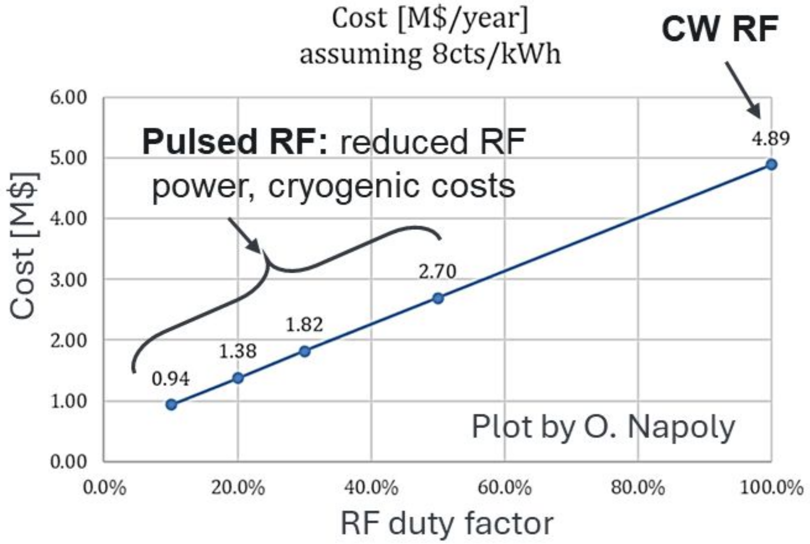
- A Amodio, D Wang, C Berger, et al. *High Power Laser Science and Engineering*. 2025;13:e35 (2025)
- https://newscenter.lbl.gov/2025/06/10/machine-learning-helps-ease-the-jitters-of-high-power-lasers/

AI+LLRF for SRF resonance control, enabling PIP-II pulsed operation

- SRF cavities: thin walls + narrow bandwidth → deformations from Lorentz-force detuning and microphonics detuning → off resonance (waste power + unstable operation) → active resonance control essential
- PIP-II LLRF baseline is CW operation — same as the LCLS-II LLRF system; the challenge comes from narrow-band cavities at high gradient, giving large + dynamic lorentz force detuning (LFD)
- Ongoing R&D on hardware-aware AI aims to enable PIP-II pulsed mode — building on today's LCLS-II LLRF systems —meeting the designed pulsed-beam specification at a potential $M/year lower operating cost.
- The complexity — and the opportunity for AI — comes from nonlinearity, disturbances spanning different amplitudes and time scales, and cavity-to-cavity and facility-to-facility variation.
- Again, years of LBNL-LLRF development provide a strong starting point.

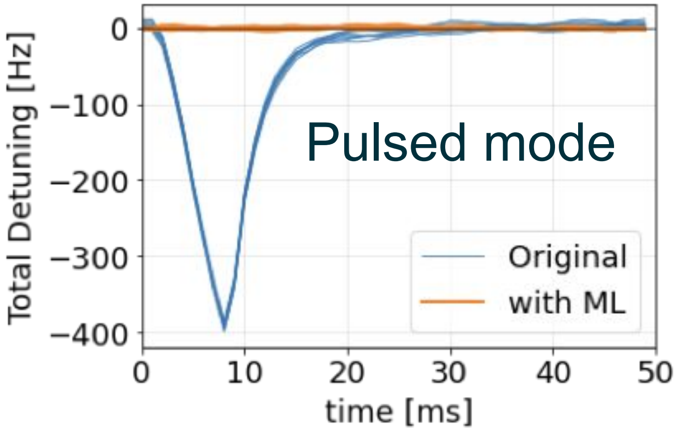


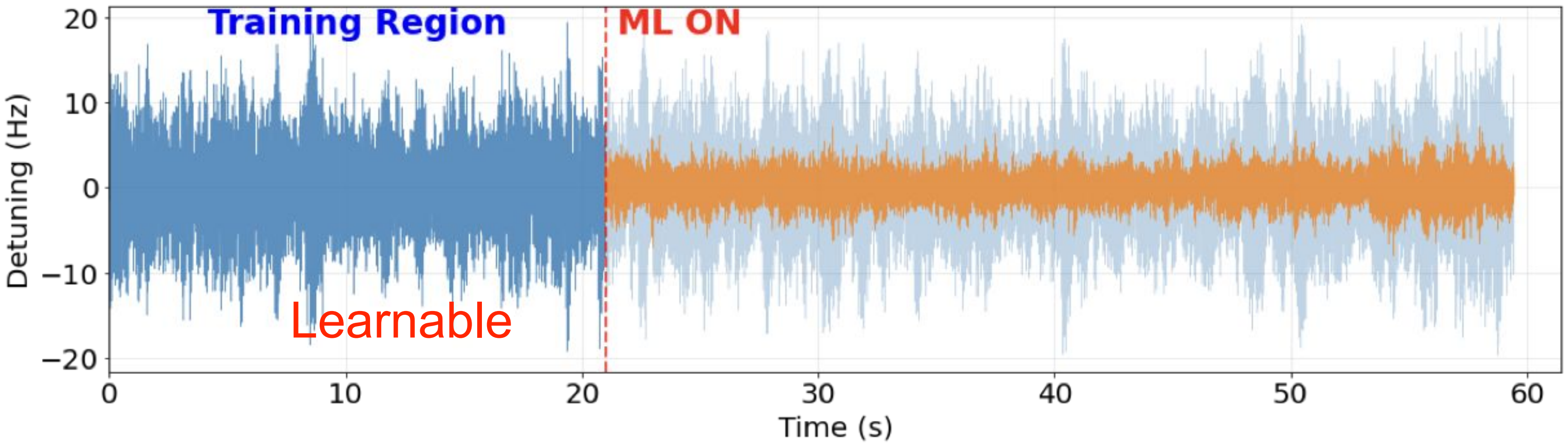


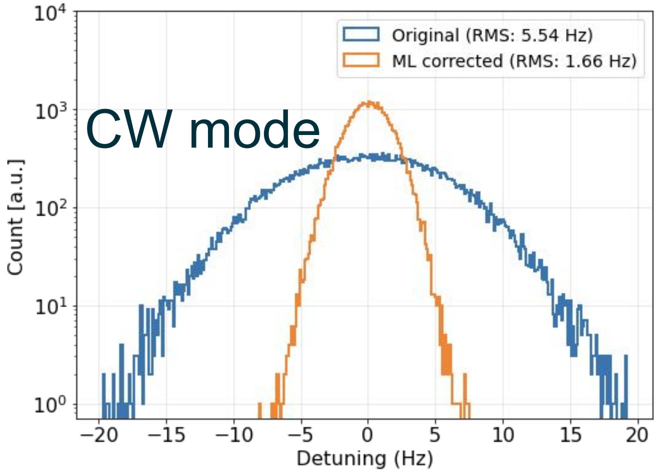


Recent updates: ML learns detuning patterns in a decoupled setup (pulsed & CW)

- Physics enables decoupling across gradient scales; Marble supports multiple functions. LFD can be cancelled out (feedforward / adaptive / ML), and the remaining microphonics — dominated by narrow-band frequency components — is therefore learnable [1-2].
- CW-mode results here are based on data from LCLS-II CM19-Cav2 [3–4].
- Data are available for all cavities (SLAC — Andy/Jorge's group), enabling broad studies and educational use.
- Preliminary but promising results — experimental demonstration is the goal for the coming years;







[1] Schappert, Warren. No. FERMILAB-CONF-16-742-TD. 2017.
[2] M. Liepe, et al., 2001 PAC, Chicago, IL, USA, 2001.
[3] A. Neumann et al., Phys. Rev. ST Accel. Beams 13, 082001 (2010).
[4] Bellandi, et al., arXiv preprint arXiv:2209.13896. (2022).

Summary: open source ML+LLRF substrate

- **The foundation**

  LLRF data is ML-ready (time-stamped, >kHz, synchronized); open Marble + DSP, portable across plant classes (lasers, SRF, qubits)

- **Demonstrated — lasers @ BELLA**

  Physics-guided ML: laser combining deterministically with fast convergence speed + pointing feed-forward → ~65% / 47% jitter reduction at TW

- **In progress — SRF resonance control (PIP-II)**

  Decouple Lorentz-force detuning from learnable microphonics; early VTS tests promising; cross-lab (FNAL, SLAC, ANL, MSU, JLab)

- **Next**

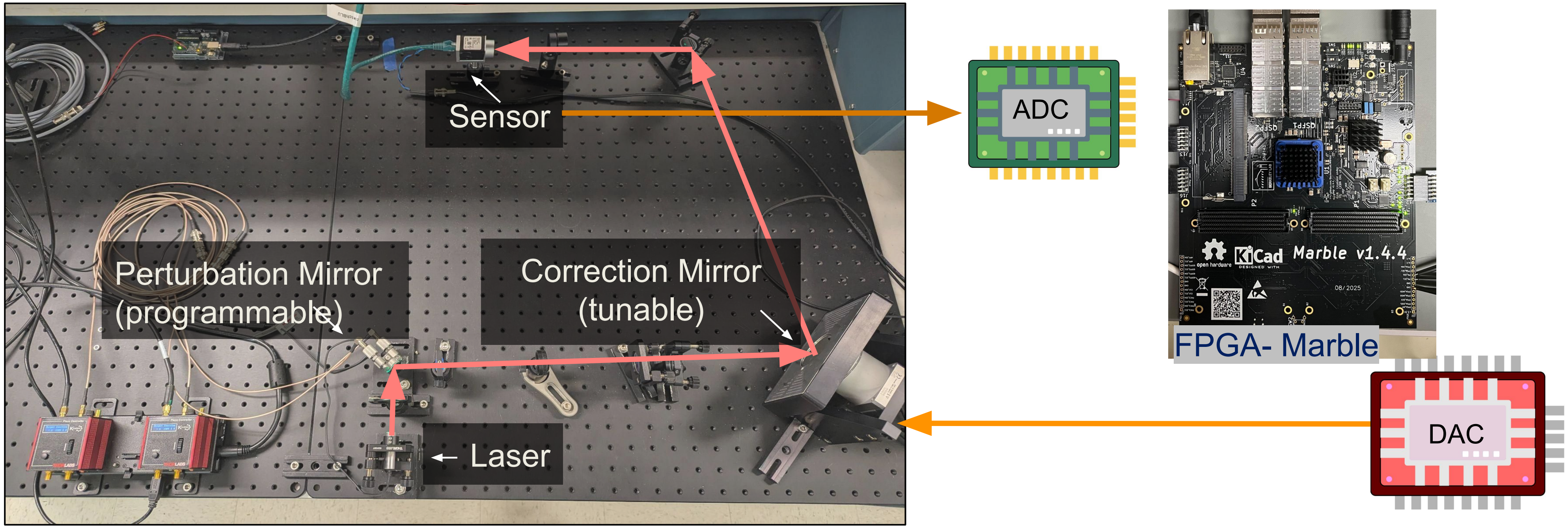
  One open ML + LLRF substrate, many control problems:

  Cross-lab collaboration can push it further into more useful, higher-impact tools for the community

Thanks!

hardware-AI: next step toward a more general scope

- Timing from FPGA is more accurate / stable → expect x2 further reduction for laser pointing
- Based on years of LBNL open-source Marble/common DSP development (used in LLRF, laser, quantum [1-3])
- A general-purpose testbed for control development, usable across many BES facilities: replay system noise, emulate different actuator dynamics, and validate algorithms before deployment.



[1] L. Doolittle, et al.; https://github.com/BerkeleyLab/Marble
[2] Q. Du, et al., Digital Low-Level Optical Control for Coherent Laser Combining, 2023/10/23 LLRF Workshop 2023
[3] G. Huang, et al., How a novel radio frequency control system enhances quantum computers, LBNL Lab News, 2021