BERKELEY LAB
Bringing Science Solutions to the World

U.S. DEPARTMENT OF ENERGY
Office of Science

LLRF Activities in Berkeley Lab

Qiang Du

on behalf of LBNL LLRF team

2023/10/23
LLRF Workshop 2023

LLRF2023
LOW LEVEL RADIO FREQUENCY WORKSHOP 2023
OCTOBER 22-27, 2023
IN GYEONGJU, REPUBLIC OF KOREA

Innovations of LBNL instrumentation drives science

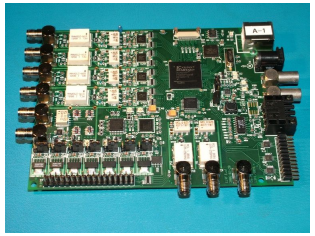
LLRF Gen 1-3

2001 - 2005

The first digital LLRF system built for SNS front end; Milestone of successful digital RF feedback to a large-scale accelerator.

2006

Non-IQ sampling developed. LLRF4 in production with Xilinx Spartan 3 FPGA, USB, 14-bit ADC x4 at 80 Msps



LLRF4

2008

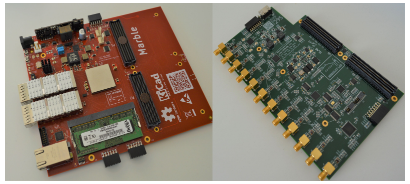
Integrated optical phase stabilization provides femtosecond synchronization at FERMI@Elettra, LCLS.

2014

Lead multi-lab collaboration for LCLS-II LLRF system, a large-scale SRF linac with 1E-4 stability requirements.

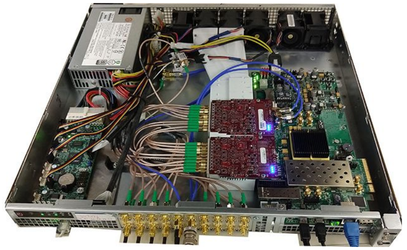
2020

Marble and Zest digitizer became a standard for U.S. LLRF systems.



2023

Coherent laser combining control, quantum bit control demonstrated combining LLRF and Machine Learning.



Our model

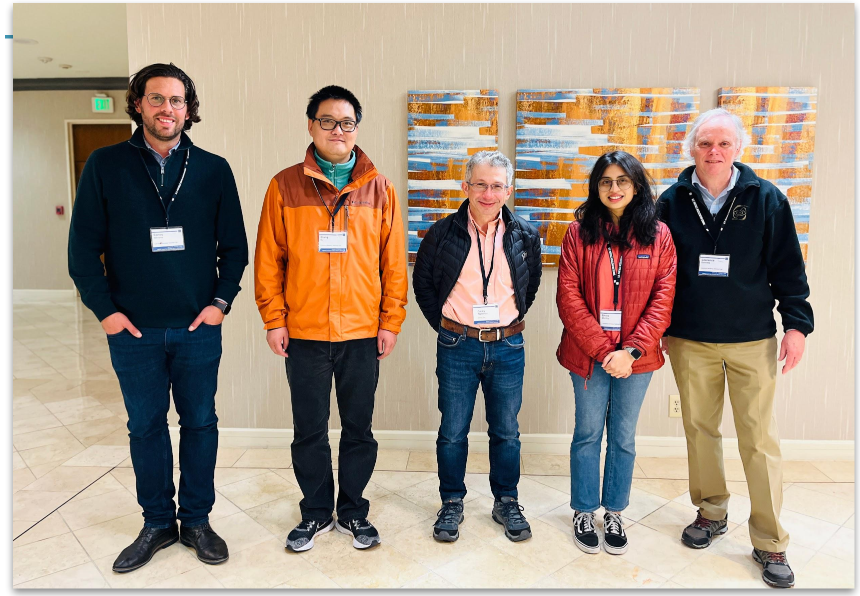
- One mission:
  - Build FPGA-based technology for “Big Science” projects (mainly accelerators)
- Two fronts:
  - Deliver (collaborate on) systems for projects:
    - ALS-U & HiRES (LBNL)
    - LCLS-II & LCLS-II HE (SLAC)
    - PPU (ORNL)
    - PIP-II (FNAL)
    - AWA (ANL)
  - Invest in the future: People + R&D
- One framework:
  - Collaboration under an Open Source environment

Taught Digital LLRF class in USPAS 2023

https://uspas.fnal.gov/programs/2023/houston/courses/low-level-rf.shtml

US Particle Accelerator School

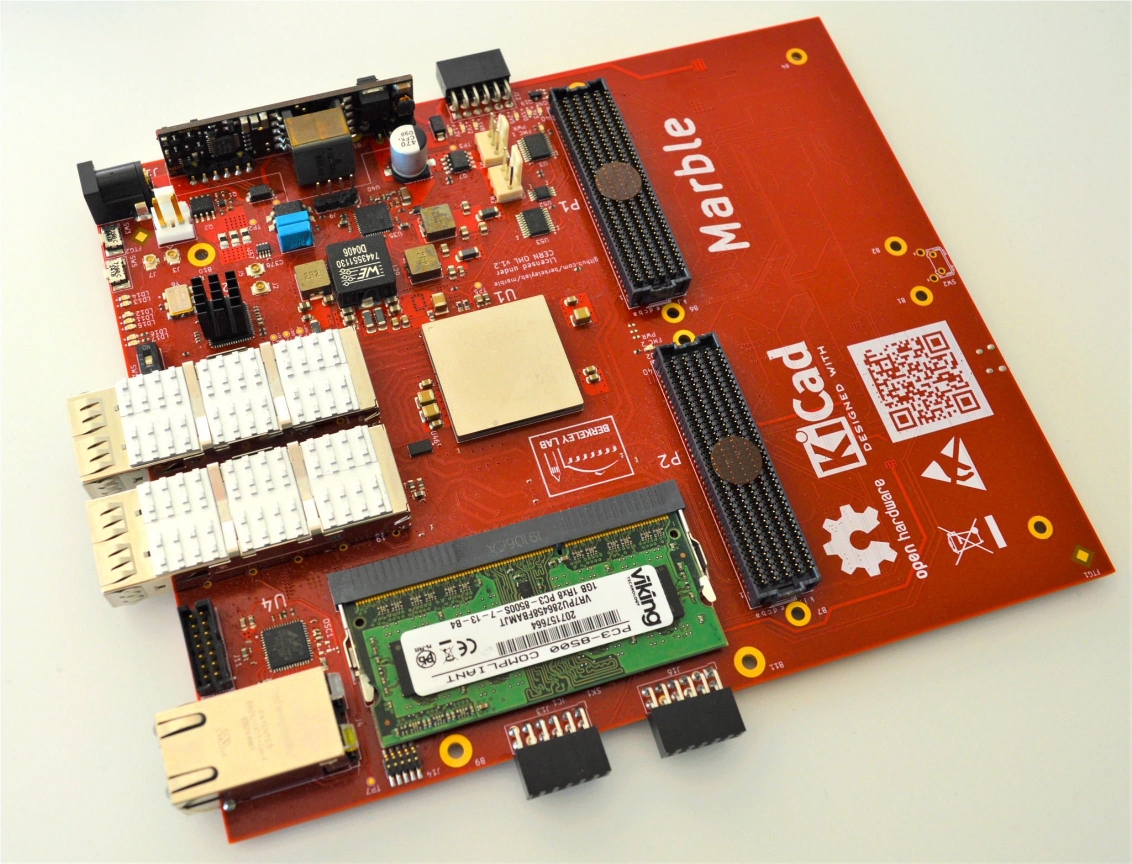
- Jan 2023, Huston, TX
- Instructors:
  - Larry Doolittle, Qiang Du, Carlos Serrano, Dmitry Teytelman, Michael Davidsaver, Jeremiah Holzbauer, Tim Berenc, Shree Murthy, Dan Wang



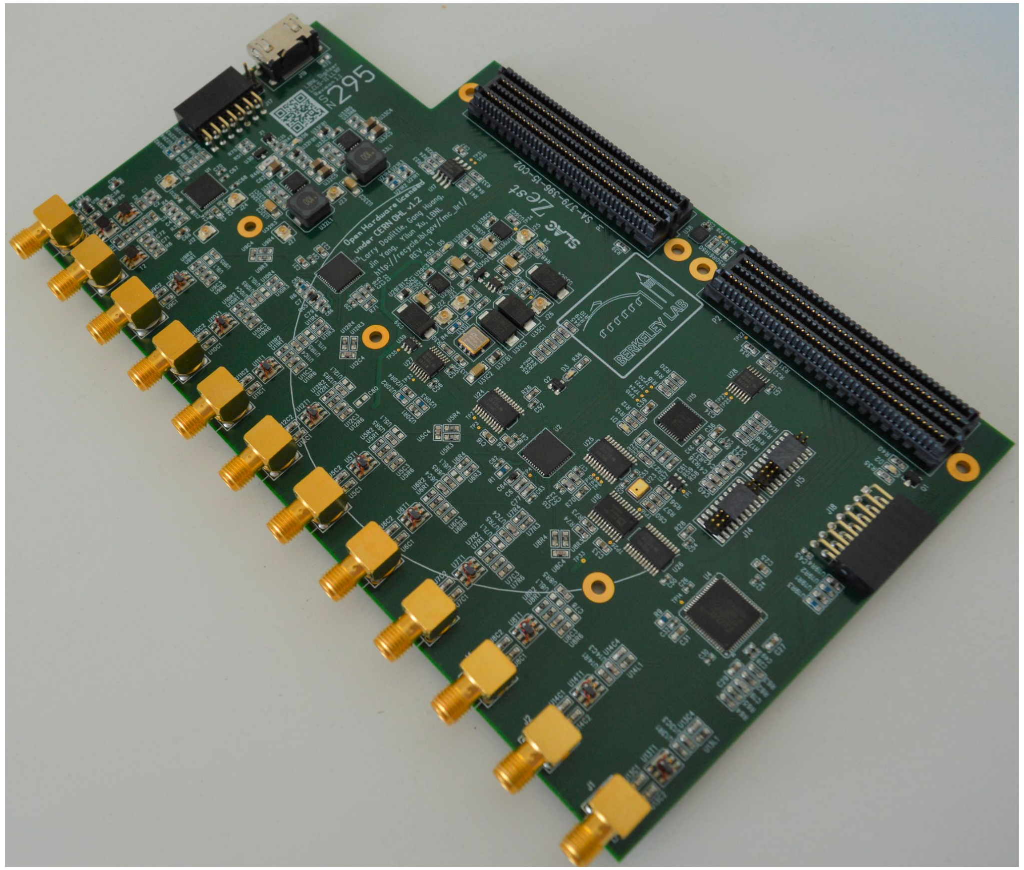
Marble FPGA carrier and Zest digitizer

Open source hardware licence: CERN OHL v1.2

https://github.com/BerkeleyLab/marble



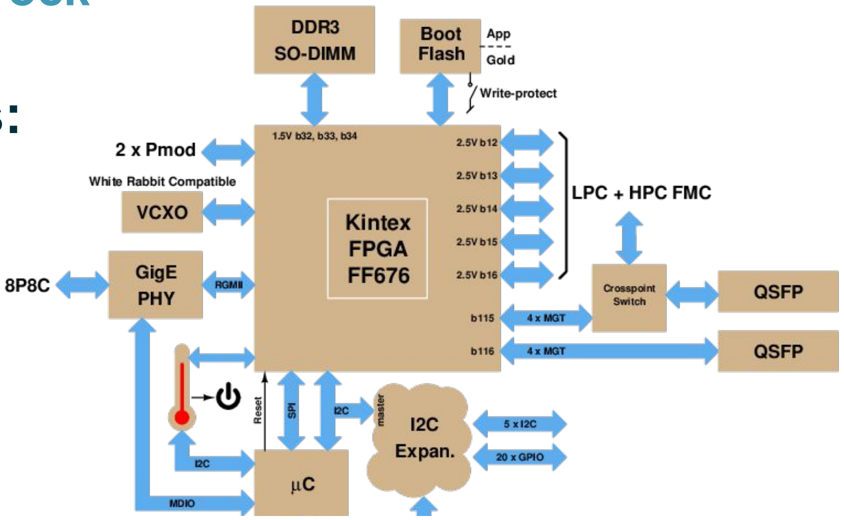
https://github.com/BerkeleyLab/zest

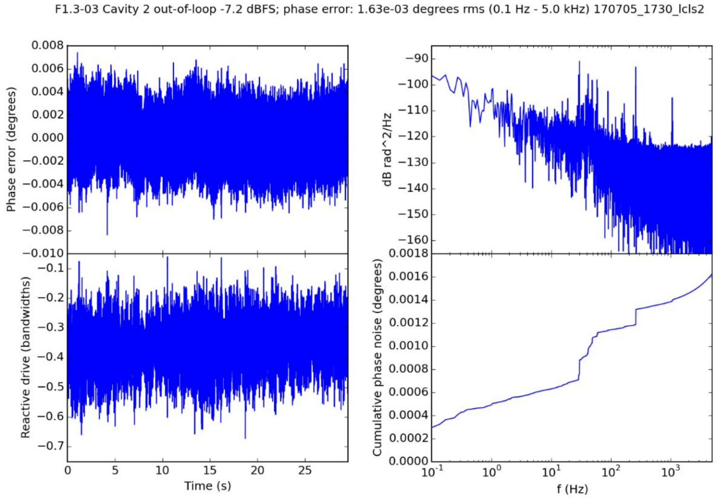


Marble FPGA carrier and Zest digitizer, on Bedrock

https://github.com/BerkeleyLab/Bedrock

- **Marble / Zest / Bedrock users:**
- LBNL: ALS / ALS-U
  - AR LLRF
  - Cell controllers
  - EVG / EVR
  - Gun LLRF
  - Buncher LLRF
- SLAC: LCLS-II / LCLS-II HE
  - LCLS-II Gun LLRF
  - LCLS-II HE
- FNAL: PIP-II LLRF
- ANL: AWA LLRF





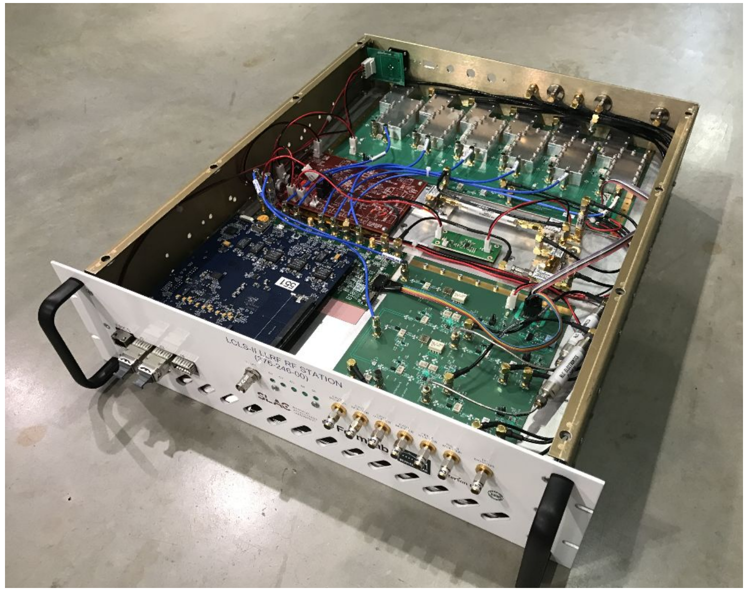
Out-of-loop LLRF chassis phase noise characteristics

- **Bedrock:**
- Open Source (BSD) license
- mostly vendor-neutral, synthesizable, regression-tested Verilog HDL published on github
- LLRF DSP library:
  - DDS
  - up / down conversion
  - various board support
  - feedback, waveform
  - SoC

LCLS-II and LCLS-II HE LLRF Collaboration

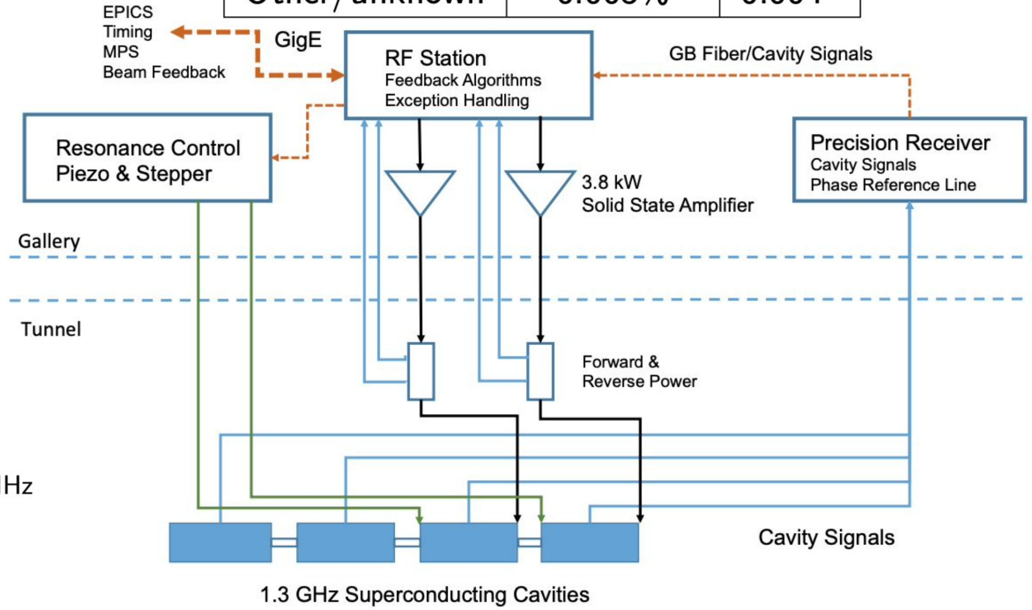
Congratulations to LCLS-II's first light and CD-4 Approval!

- LCLS-II Commissioning
- LCLS-II HE LLRF design
- LCLS-II Gun LLRF Control



- 1300 MHz carrier, variants at other frequencies including 3900 MHz
- -150 $dBrad^2/Hz$ white noise floor
- -110 $dBrad^2/Hz$ @ 1 Hz $1/f$ noise
- 80 to 120 dB isolation between channels
- about 30 MHz RF bandwidth

Noise Source	Amplitude	Phase
Measurement	0.005%	0.004°
PRL	N/A	0.004°
Plant pert.	0.005%	0.004°
Beam loading	0.005%	0.004°
Other/unknown	0.005%	0.004°

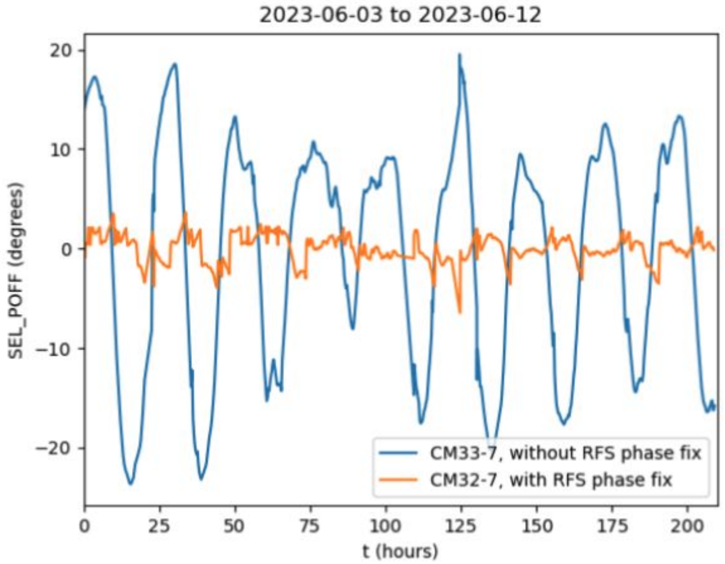


Talk: Drift Observations and Mitigation in LCLS-II RF

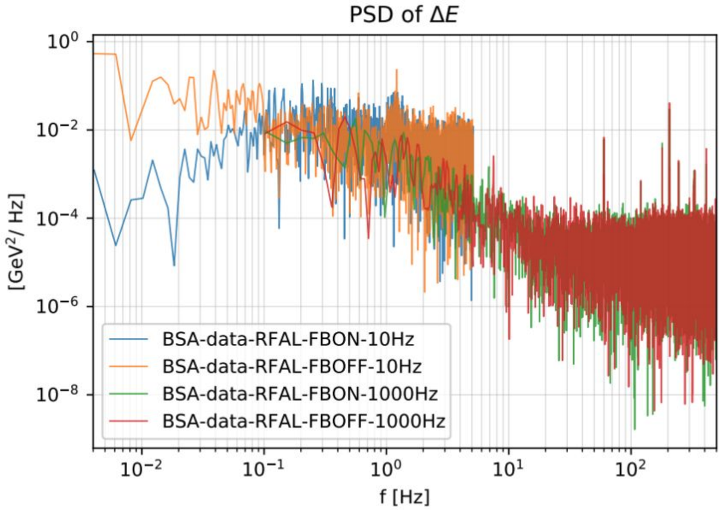
Shree Murthy on behalf of the LCLS-II LLRF collaboration, Monday 5PM

- A phase-averaging reference line is the primary system deployed in support of the phase stability goals. There are other, secondary subsystems (SEL phase offset, and determination of cavity detuning) that are also sensitive to RF phase drift.
- We present measurements of phase shifts observed in the overall RF system, and how diagnostics are able to sense and correct for them during beam operations.

SEL phase drift



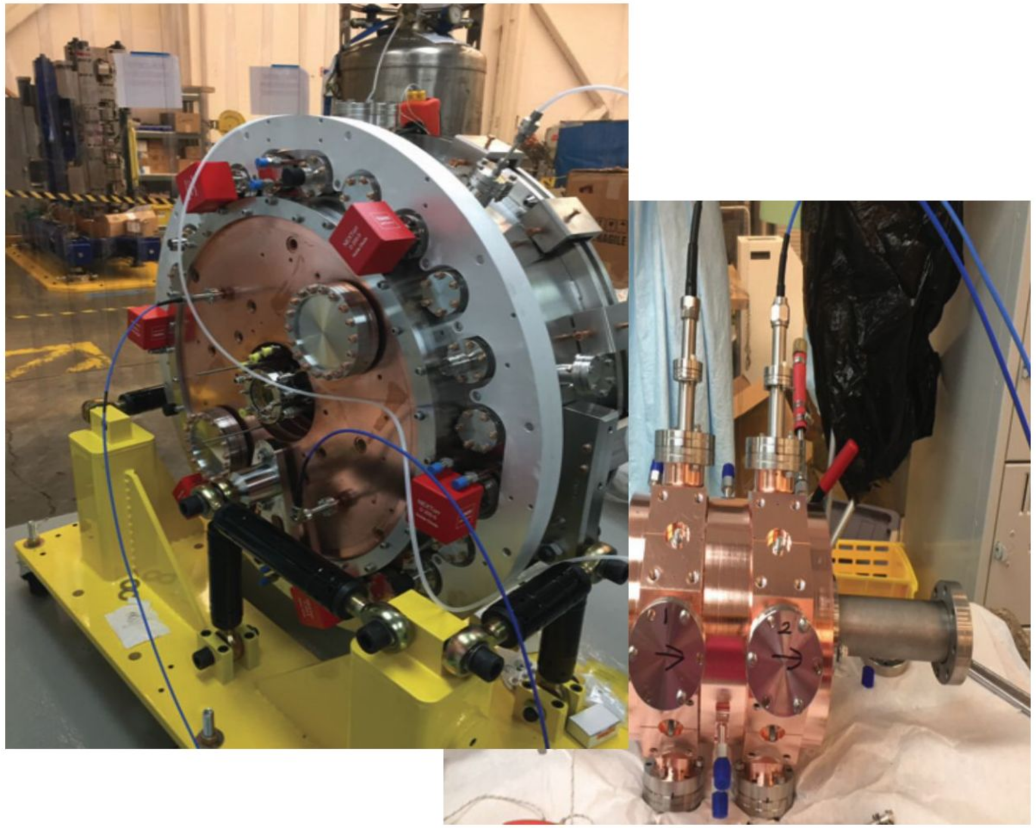
Beam energy noise spectra determined by BPM data, with and without feedback



Talk: Flat gateware architecture for low level RF control

Gang Huang, Monday 5:45PM

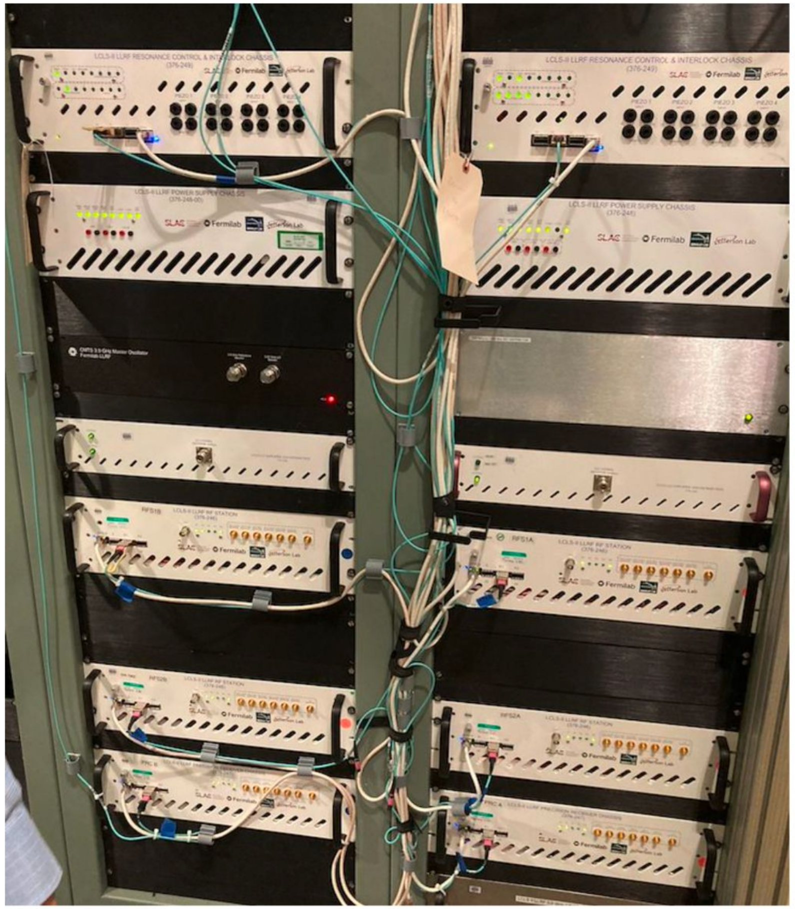
- A flatten architecture is introduced to improve the system modularity and so improve the code maintainability.
- This code architecture utilizes the new capability introduced in the systemverilog, such as interface and alias to realize the design goal.
- Preliminary bench testing with the LCLS-II LLRF system and the compatibility analyze in progress



LCLS-II Gun and Buncher

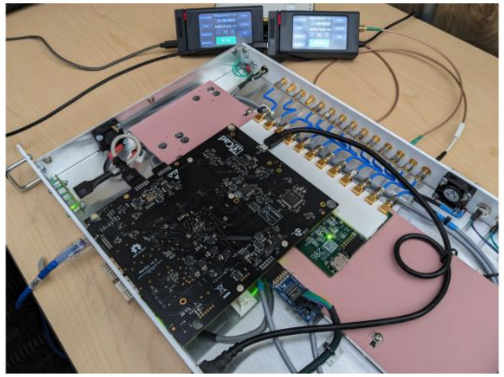
PIP-II LLRF Collaboration

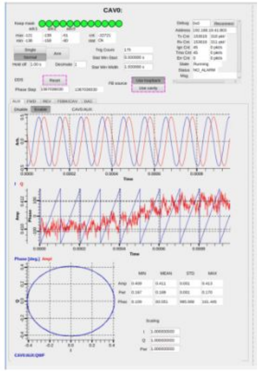
- Supported 650 / 325 MHz CM Test Stand LLRF control
  - CM / cavity characteristics
  - Deploy LLRF controller
- Provided LLRF hardware design:
  - Validation of thermal / mechanical design
  - Delivered 4 prototype Marble / Zest LLRF controllers
- PIP-II LLRF Final System Design
  - Supported the development of the RF Station test bench at FNAL.
- Supported the final design of the PIP-II LLRF firmware and software



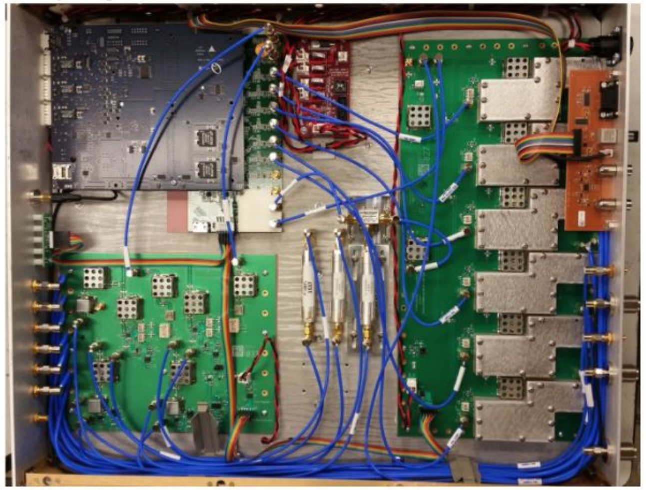
LBNL LLRF Upgrade for the AWA facility in ANL

- Built a complete LLRF system for 1300 MHz 5+ cavity control for AWA
- Address difficult-to-understand drift/jitter behavior



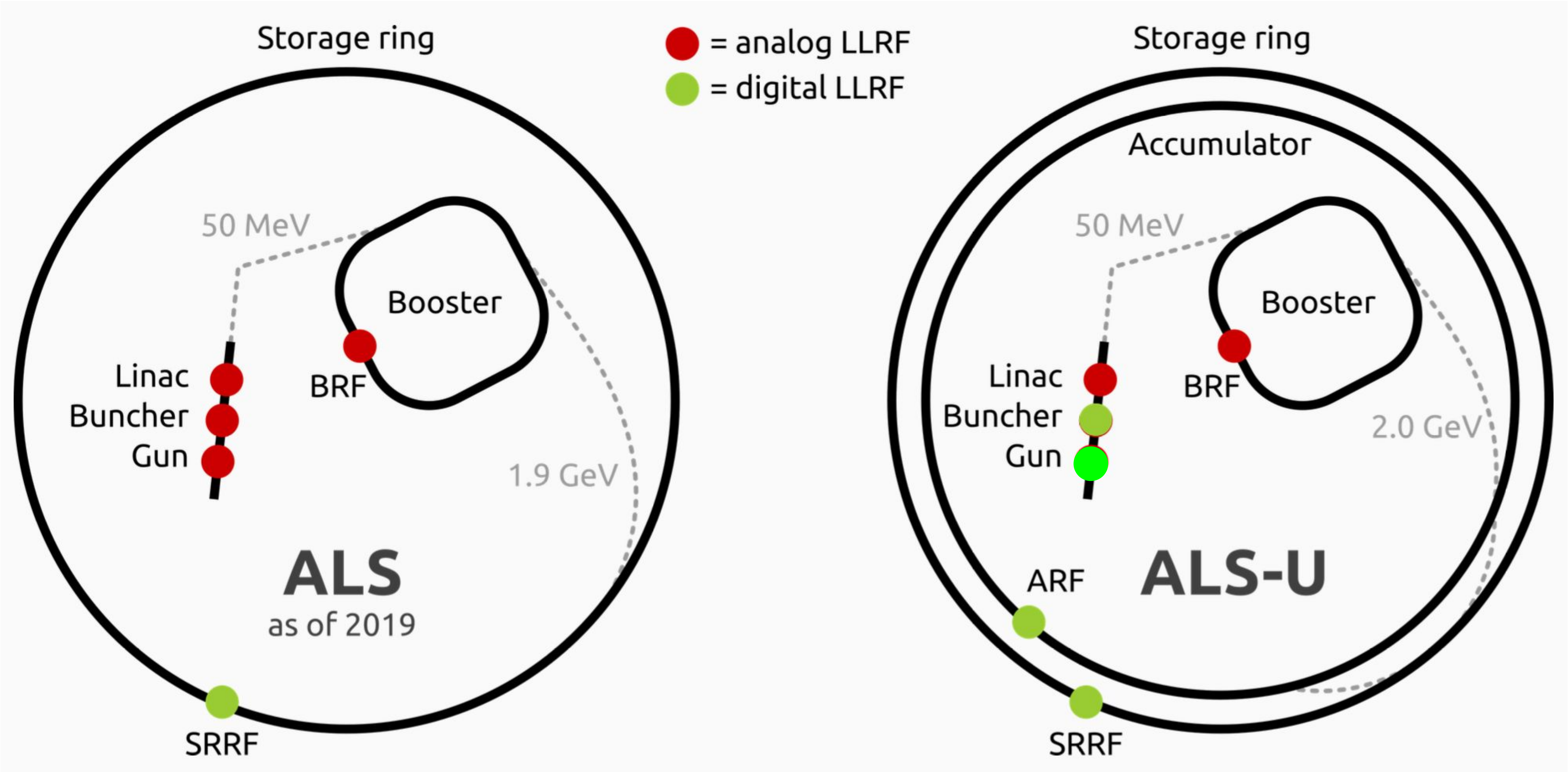


Deployed at AWA



Deployed at AWA

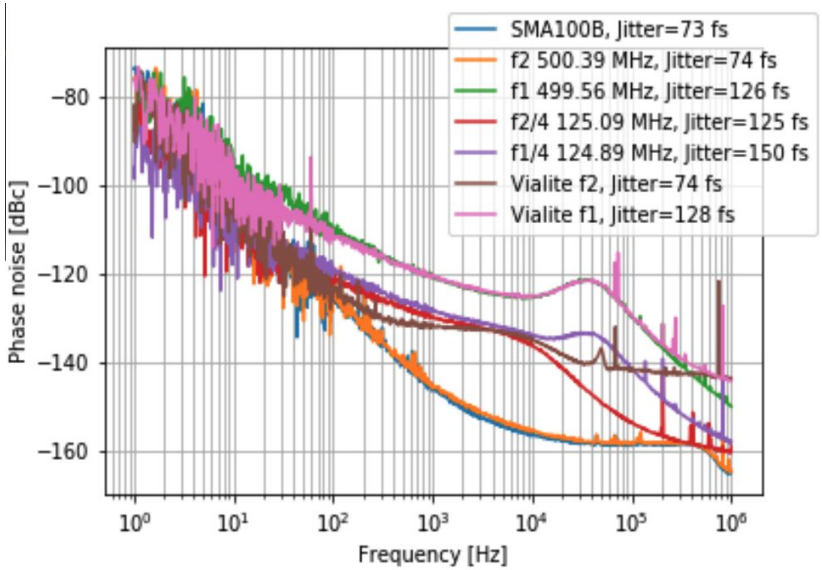
LLRF systems in ALS and ALS-U



Poster: Dual Freq MO Generation & Distribution for ALS(U)

Shree Murthy, et al

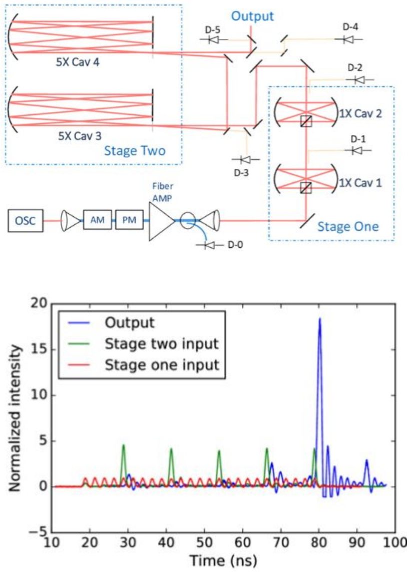
We demonstrate dual frequency generation at 608/609 fractional relationship, phase continuous, <200fs RMS jitter [1Hz, 1MHz] after optical frequency distribution system.



Digital Low-Level Optical Control for Coherent Laser Combining

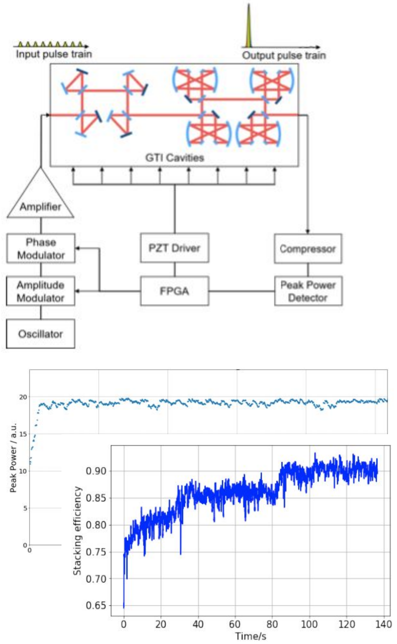
Talk: Qiang Du, LLRF control at 200THz carrier, Tuesday 9:05AM

25 pulses stacked at Berkeley



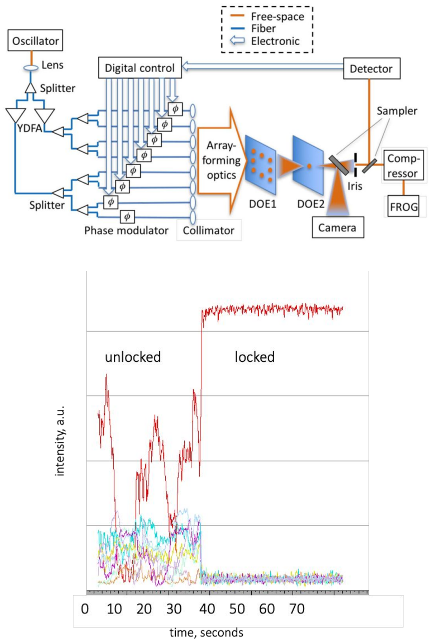
J. Opt. Soc. Am. B, 35(9), 2081, 2018
IEEE J.Quantum Electron. 54(1), 2018

81 high-power pulse stacked at University of Michigan



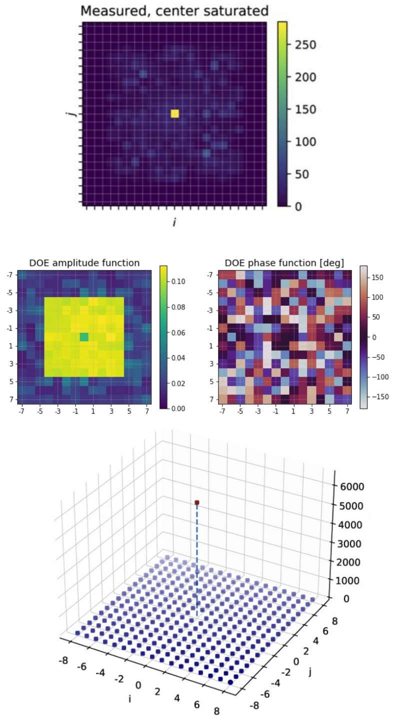
CLEO, STu2E.2, May 2021
AAC workshop, WG8, Nov 2022

8-beam combined using pattern recognition



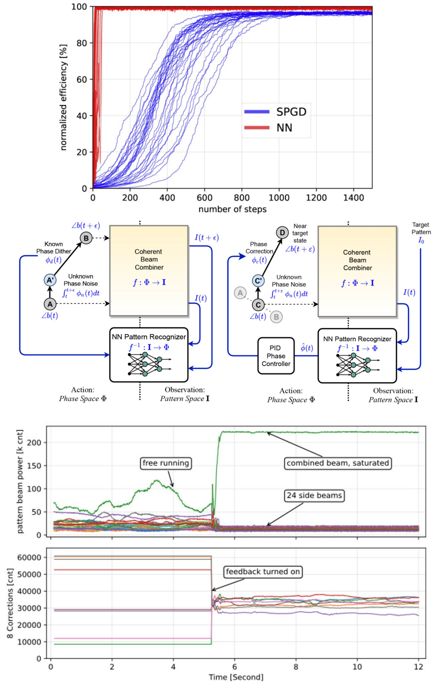
Opt. Lett. 44(18), 4554, 2019
Opt. Lett. 43(43), 3269, 2018
Opt. Lett. 42(21), 4422, 2017

81-beam combined in experiment



Optics Express 29(4), 5407, 2021

Machine Learning based feedback



Optics Express, 29(4) 5694, 2021
Optics Express, 30(8) 12639, 2022
IEEE J. Quantum Electron. 58(6), 2022
Plenary talk, AAC workshop, Nov 2022
Optics Express, 31(8) 12717, 2023

Thank you!