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U.S. DEPARTMENT OF ENERGY
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LLRF system upgrade at AWA

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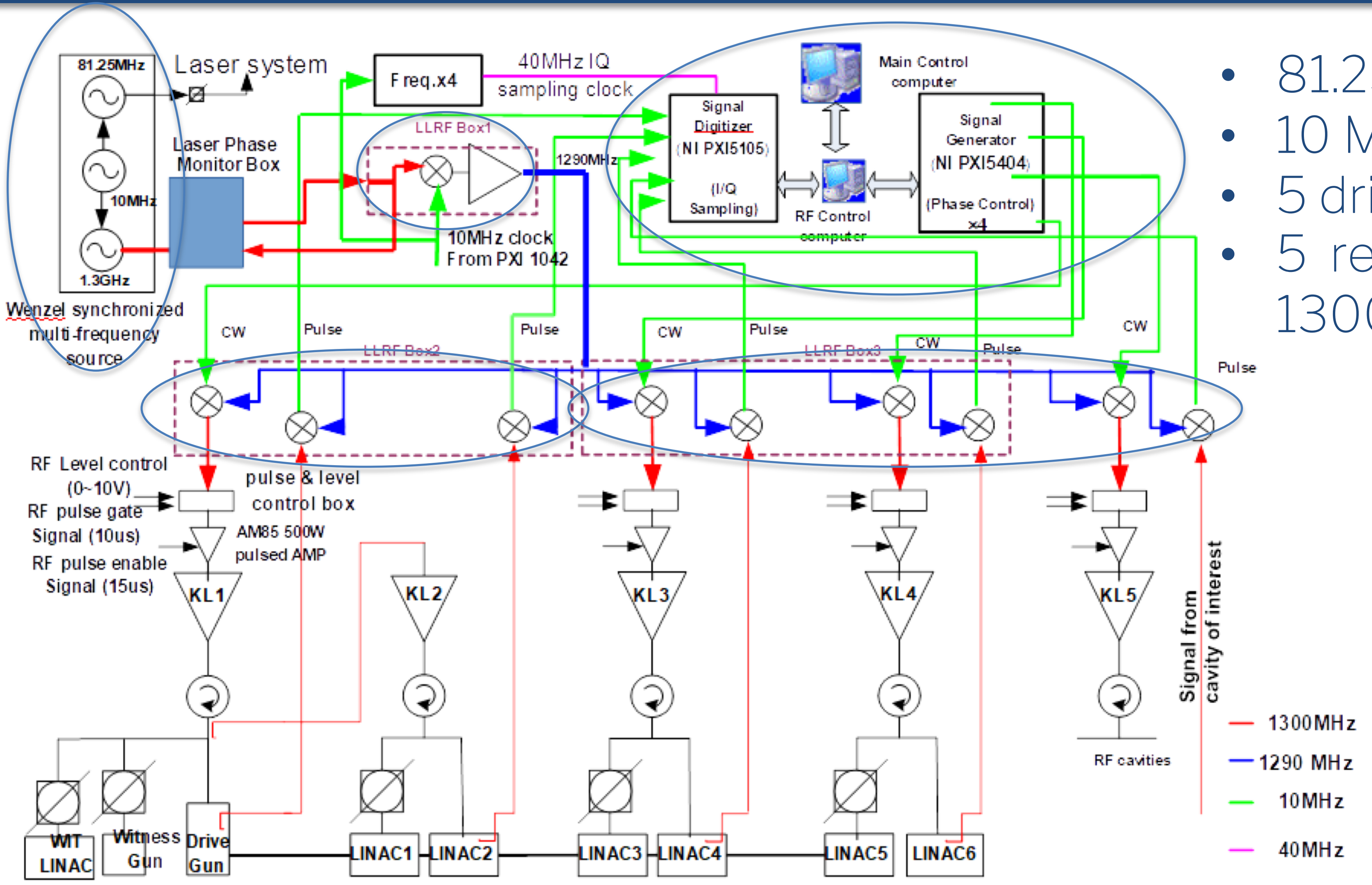
Outline

- Description and analysis of current system
- Proposal for AWA LLRF Upgrade
- Example of deployments: LCLS-II and HiRES
- Future upgrades and budget considerations

AWA current system configuration



- 81.25 MHz to laser
- 10 MHz for down-conversion
- 5 driving 1300 MHz channels
- 5 receiving channels at 1300MHz

General observations from LBNL

Potential areas of improvements to the benefit of AWA beam stability:

- Mechanical vibrations could induce noise in the long waveguides (up to 40m)
- Implementation of a phase reference line would minimize relative drifts.
- Improved clocking scheme to guarantee overall system coherence
- Improvements may be needed in laser-to-RF synchronization
- Consider adding a timing system, to make events RF synchronous
- LLRF system uses NI COTS components, and computer in the loop
- Consider moving to EPICS

Identified items for upgrade

- Re-define architecture based on available resources.
- Build and deploy 1.3 GHz, LCLS-II (and HiRES) style LLRF hardware.
- Define clocking scheme, design, build and deploy MO/LO system.
- Transition to RF-synchronous, event-based timing system.
- Add a temperature controlled phase reference line.
- Tightly integrate laser to RF synchronization.
- Review beam diagnostics and integration with instrumentation.
- Deploy EPICS control system.

Collaboration proposal: LBNL/ANL

- The collaboration will leverage off both engineering and physics experience at LBNL in designing controls and beam measurements for LCLS-II, HiRES, PIP-II, PPU and ALS-U LLRF systems. It will align the AWA LLRF system with other accelerators in the DOE complex.
- The LLRF upgrade will happen in the context of a larger effort, including a control system upgrade (EPICS) and a High power RF upgrade. Coordination is needed since all subsystems are tightly interconnected!

- LBNL will work with ANL to:
  - Provide a design solution for a new RF control architecture
  - Provide new LLRF chassis, identical to LCLS-II (and similar to HiRES) hardware
  - Assist in the characterization and deployment of RF controls in the field.
  - LCLS-II EPICS IOC and supporting tools, with initial custom software and firmware for AWA.
  - Path forward for future upgrades beyond the present SOW.

Description of work

Effort is separated in 3 phases:

- **Phase 1: SOW definition and RF chassis production**
  - Define effort and responsibilities (Completed)
  - Identify and order long-lead items for RF and MO/LO chassis (Completed)
  - Manufacture 3 LCLS-II 1.3 GHz LLRF chassis (In progress)
- **Phase 2: Characterize present AWA RF system stability**
  - Use LBNL-built hardware in "witness mode" during accelerator operations
    - Basic software functionalities provided, but any custom high-level screens will be developed by ANL personnel
  - Perform and analyze out-of-loop measurements of the characterize baseline performance
- **Phase 3: Deploy LBNL LLRF system as driver system for the accelerator.**
  - Deploy LBNL hardware, firmware and software at AWA
  - Characterize performance of newly deployed hardware
  - Establish plans for future upgrades: Laser-to-RF synchronization, phase reference line, produce more RF chassis for increased performance and simplified architecture.

Phase 1 in detail:

- **Summary of LBNL responsibilities:**
    - Initial firmware and software code base to support pulsed RF operation of AWA cavities using the 1.3 GHz LCLS-II LLRF platform.
    - Schematic diagram and BOM of the MO/LO generation chassis for AWA.
    - Schematic diagram and BOM of the 1.3 GHz hardware cavity emulator chassis.
    - Assistance with the installation and deployment of the LCLS-II LLRF hardware, firmware and EPICS IOC connected to a cavity emulator in the Lab.
    - Assistance with deployment of LLRF hardware, software and firmware in the field at AWA.
    - Assistance with tests and RF measurements of the installed deployment at AWA.
    - Provide a flexible electronics design for future upgrades (laser synch, reference line, etc.)
    - Provide a design path for the LLRF-side of laser-to-RF synchronization which bypasses the current hardware

- **Procurements in place:**
    - All components for 3 LCLS-II 1.3 GHz LLRF chassis, except for up/down converters and FPGA boards
    - All long-lead items for RF and MO/LO chassis ordered
    - Contract established with manufacturing house for RF chassis assembly

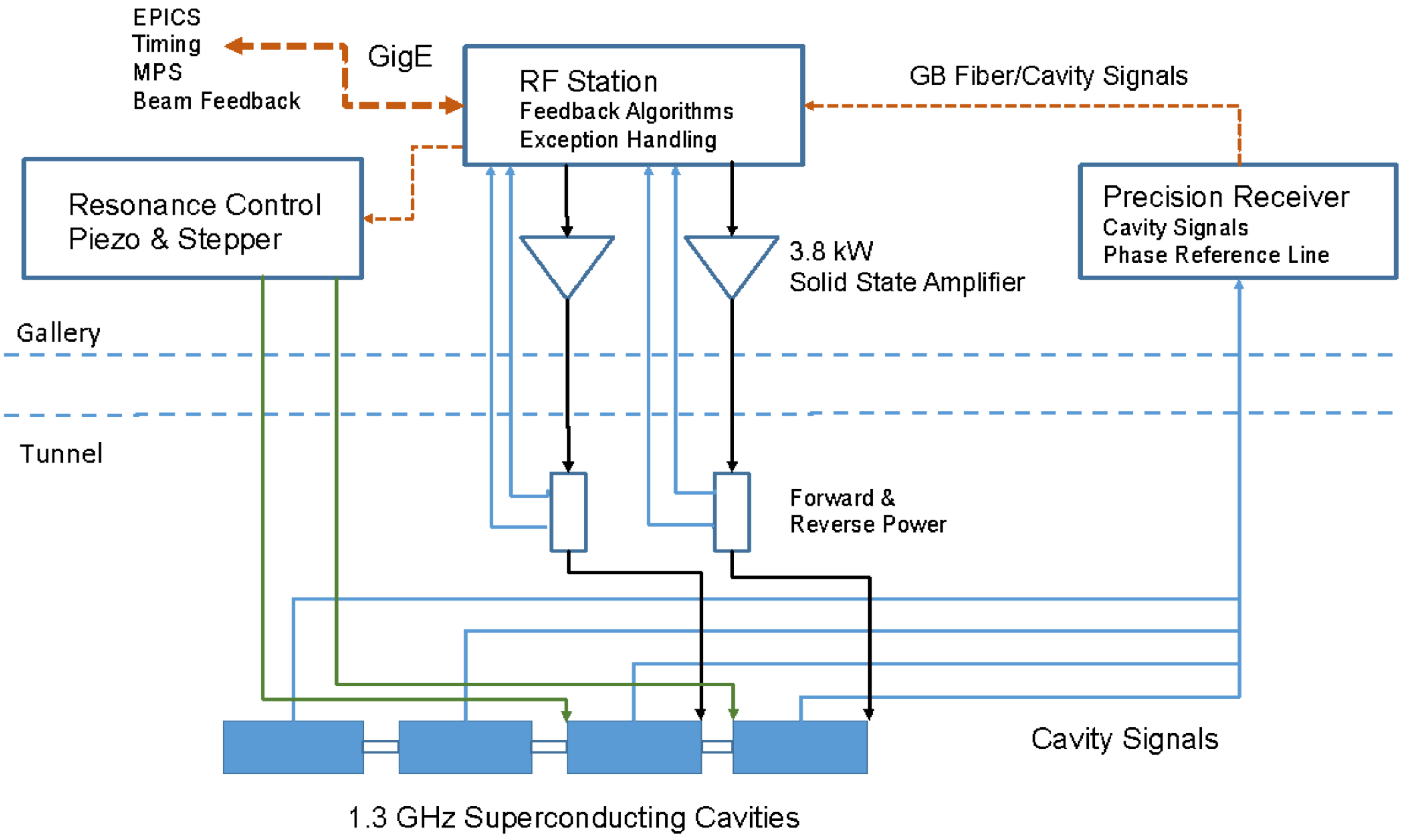
LBNL hardware

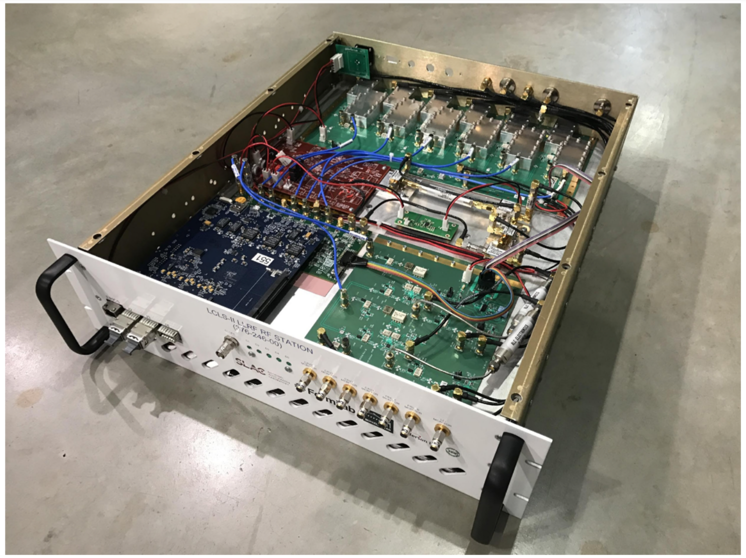
- LCLS-II 1.3 GHz RF controls chassis
  - 2 drive channels
  - 6 receive channels
  - State-of-the-art RF performance

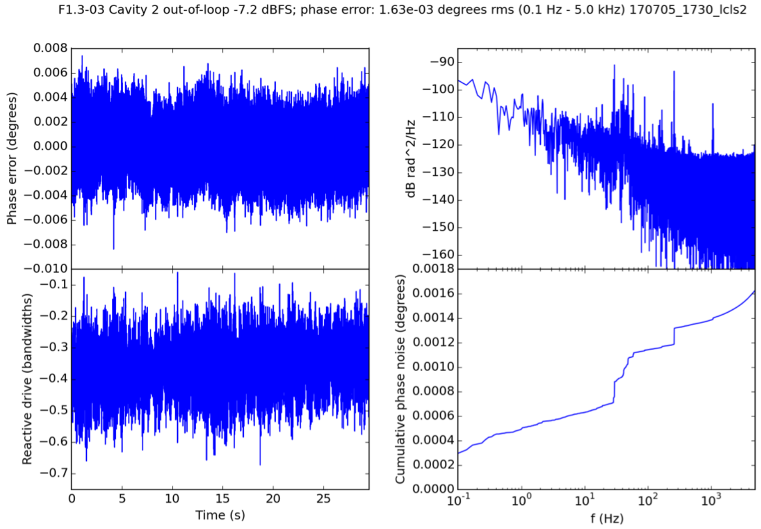
- AWA initial deployment: 3 RF controls chassis
  - 6 drive channels total
  - 18 receive channels total
  - Minimum set of hardware to control 5 cavities based on channel count and budget constraints: the architecture is intricate, but can be simplified adding more hardware

- MO/LO chassis
  - Provides necessary (synchronous) RF frequency references: 1300 MHz main reference, 1320 MHz LO signal, and 81.25 MHz reference for the laser system

Example of system deployment: LCLS-II Linac (280 cavities)



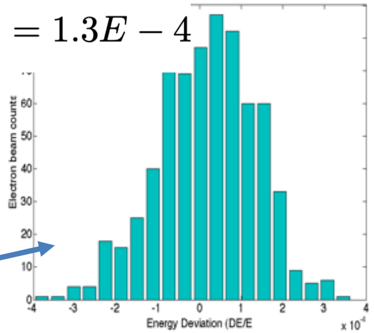


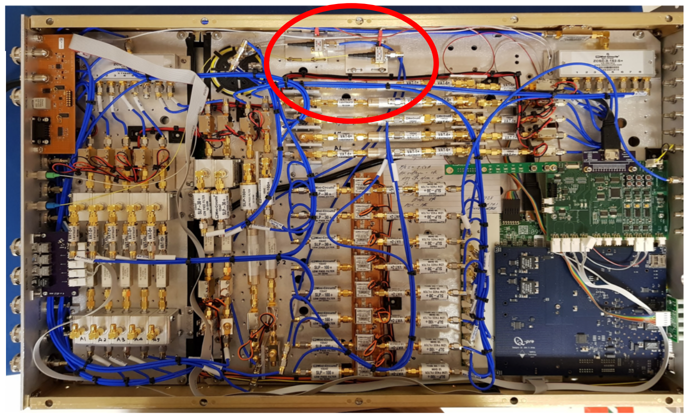


Example of deployment and performance: HiRES Gun

e-beam energy

$$\frac{\delta E_k}{E_k} = 1.3E - 4$$





Crosstalk characterization

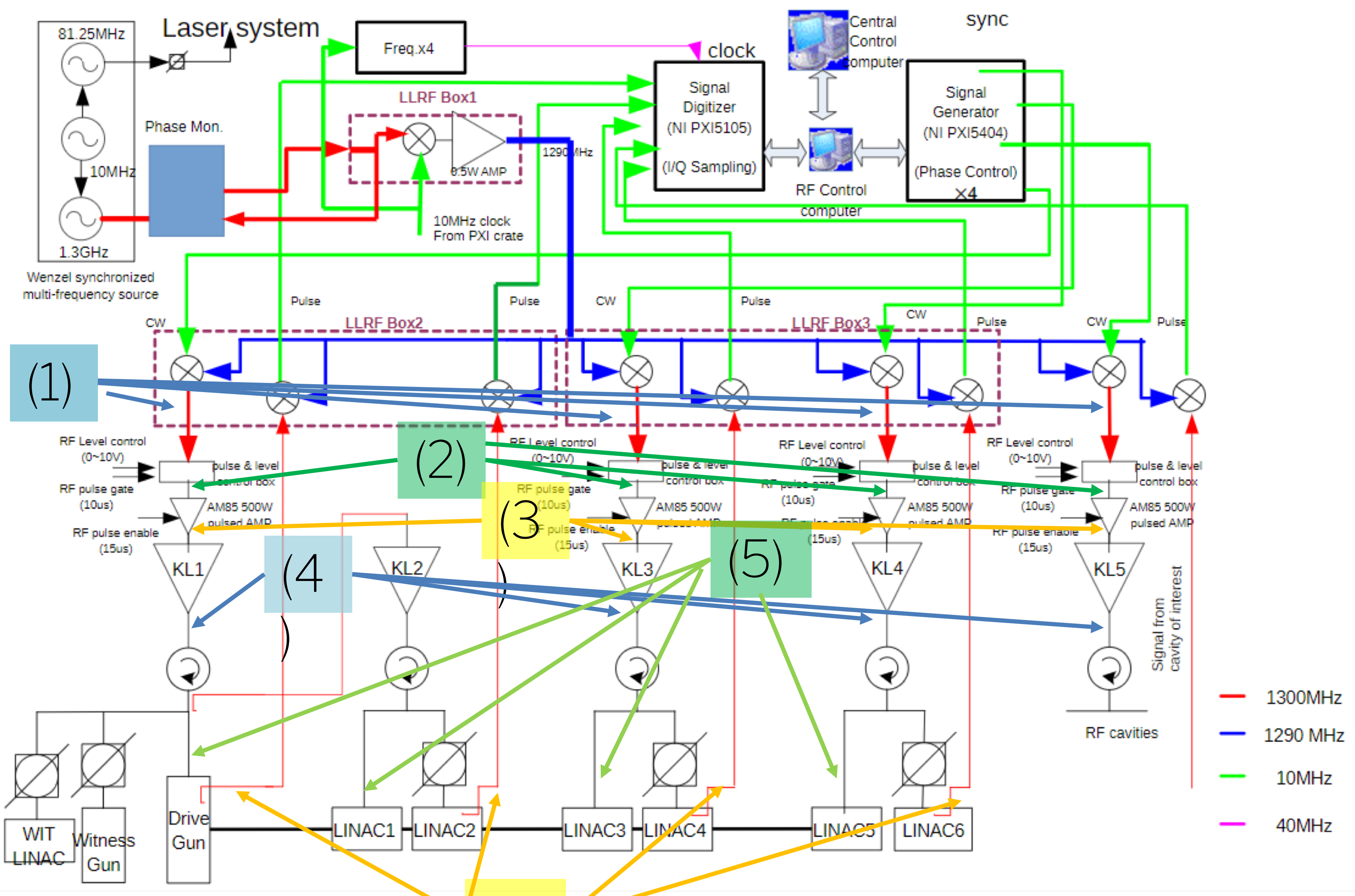
dB Fs	CAVIN_FWD (A1)	CAVIN_REV (A2)	CIRCLD_FWD (A3)	CIRCLD_REV (A4)	SPARE (A5)
A8	-116.74	-118.50	-111.53	-110.25	-105.27
A7	-117.67	-112.82	-106.57	-118.71	-115.83
A6	-112.90	-117.31	-112.50	-120.13	-115.98
A5	-103.97	-109.09	-107.95	-106.57	**-8.73**
A4	-102.10	-102.43	-94.16	**-9.26**	-104.21
A3	-102.64	-105.83	**-9.16**	-97.44	-119.13
A2	-90.07	**-9.23**	-104.09	-100.99	-105.52
A1	**-9.17**	-93.39	-103.51	-102.28	-104.80

AWA current system characterization with LBNL hardware

Potential test points:

(1) 1.3GHz LLRF driving RF gate & Level control boxes
(2) LLRF Gate & Level control output
(3) Pulsed Klystron drive signal (using directional couplers)
(4) Pulsed Klystron output (attenuated signal from waveguide bi-directional coupler)
(5) Pulsed RF forward and reflect signal before feed into RF cavities (attenuated signal from bi-directional couplers)
(6) Cavity pickup signals from field probe in cavity(attenuated signal).

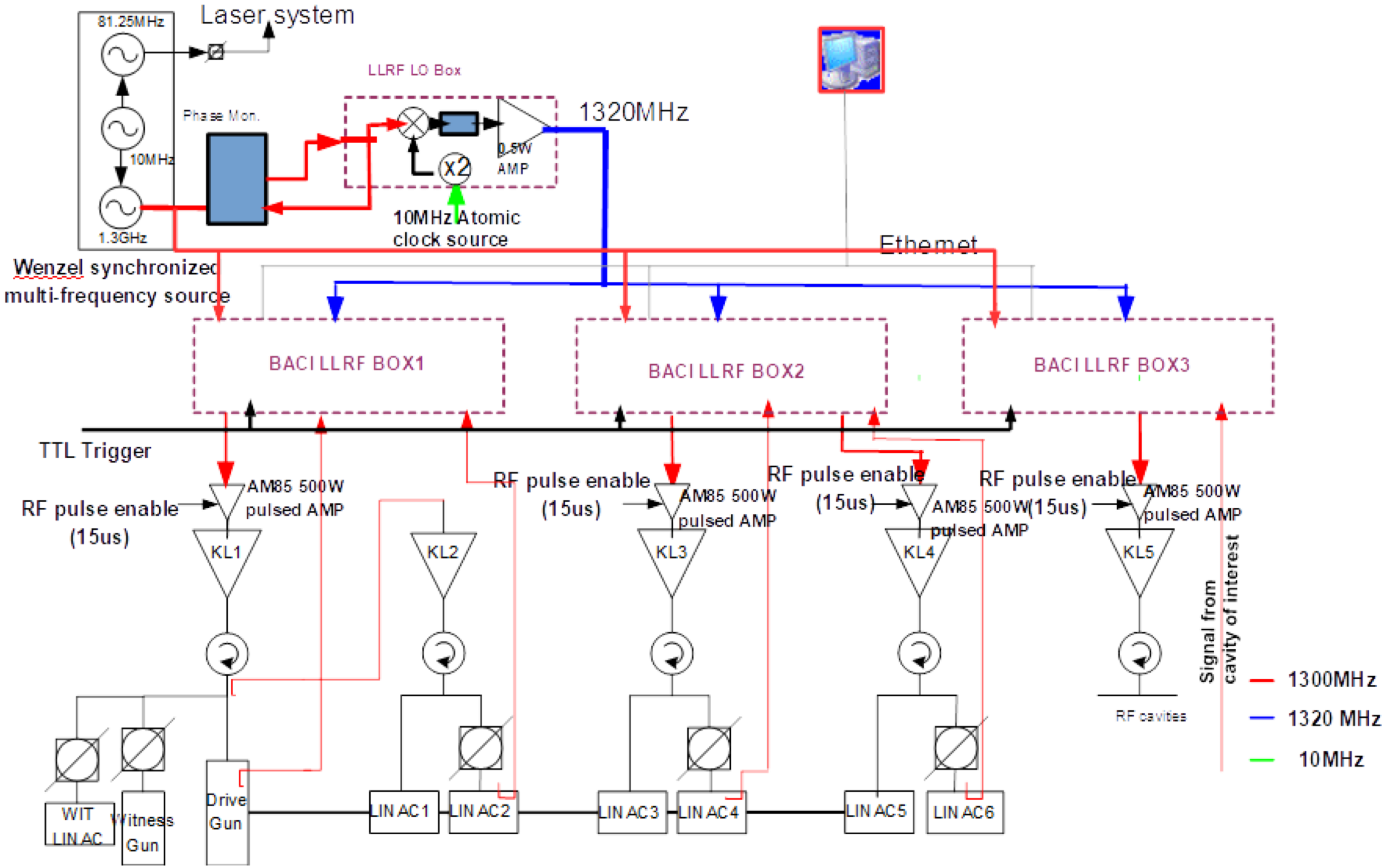
With 18 ADCs we would read FWD, REV and Probe from each cavity/klystron + laser signal



LBNL LLRF system implementation at AWA

The initial deployment will be replacing old AWA LLRF boxes with BACI LLRF box with minimum signals (the signals currently monitored with AWA old LLRF system, most of them were not drawn here for simplicity) monitored.

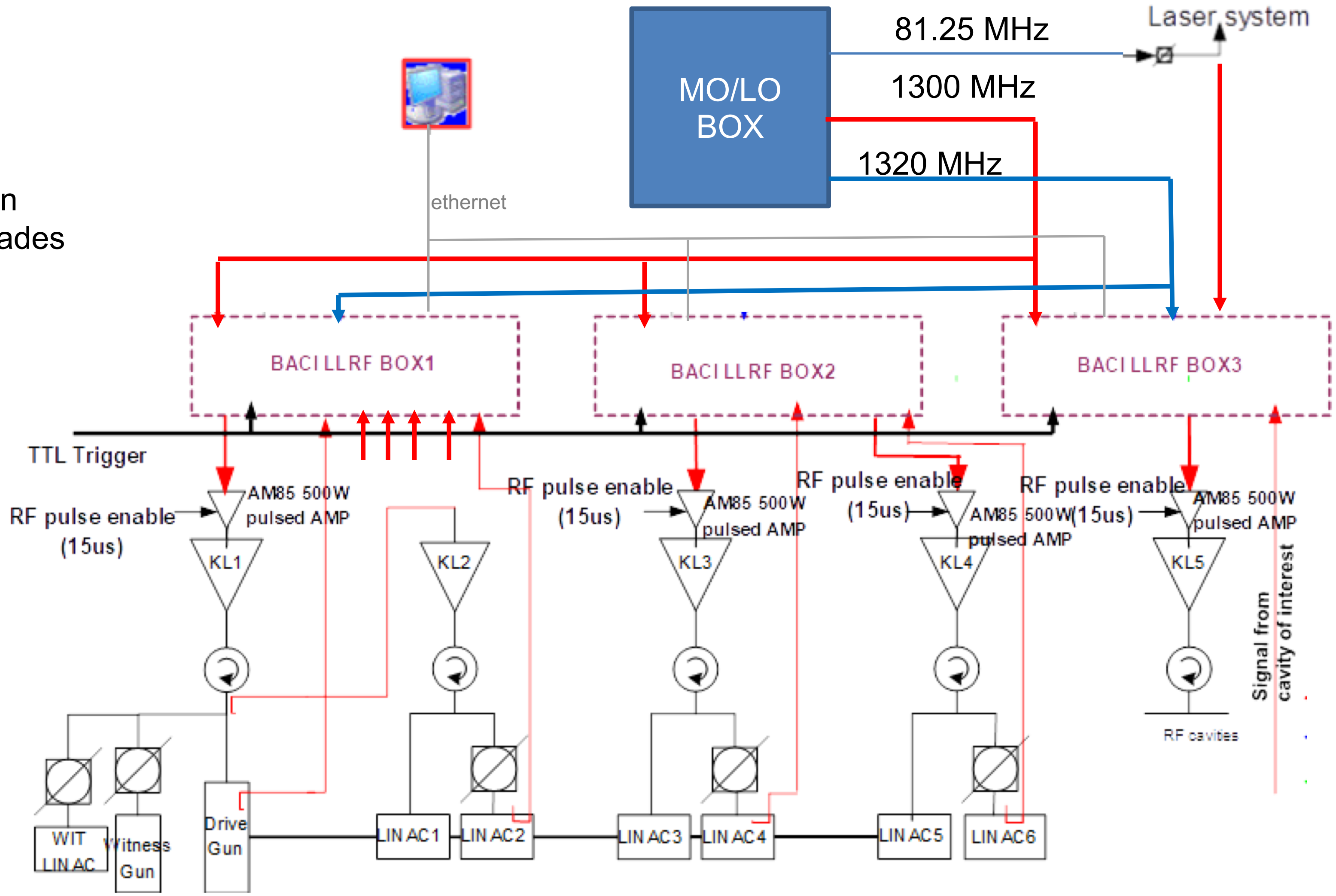
After the initial deployment, spare monitoring channels on the BACI boxes will be used to monitor signals from additional monitoring points from RF distribution waveguide system.



LBNL LLRF system implementation at AWA

Will drive 4-5 systems
Will read up to 18 RF signals
(5 Probes, 5 FWD, 5 Rev, 1 laser, …)

Actual architecture to be discussed, based on needs, high level operations and future upgrades



Future upgrades

- Laser-to-RF synchronization
  - Ideally a separate chassis including photodiode(s) and HV amplifier for piezo-actuator
- Phase reference line
  - Phase drift between LLRF systems is invisible to LLRF and is a direct contributor to RF phase instability.
- Event-based, RF-synchronous timing system
  - Provides ability to trigger instrumentation along the machine synchronously
  - Provides ability to time-stamp data in acquisition systems, needed to compute correlations, post-mortem fault analysis and future ML-based tuning
- Fabricate more RF hardware
  - Simplify architecture
  - Increase channel-to-channel isolation (cavity to drive) from 90 to 120 dB

Effort estimates: LBNL Team

Task/Category	Effort Estimate (h)	Schedule
Study of AWA clocking scheme & schematic and BOM for MO/LO generation chassis and 1.3 GHz	80	May 1 - June 30 2021
Development of RF-Laser synchronization firmware and software	200	July 1 - July 31 2021
Development of pulsed RF firmware and software	200	Aug. 1 - Aug. 31 2021
Deployment support at AWA	320	Sept. 1 - Oct. 30 2021
Measurement & characterization support at AWA	370	Nov. 1 - March. 31 2022
Total effort and period of performance	**1,170**	**May 1 2021 - Mar. 31 2022**