

# FPGA-Based Cavity Phase Stabilization for Coherent Pulse Stacking

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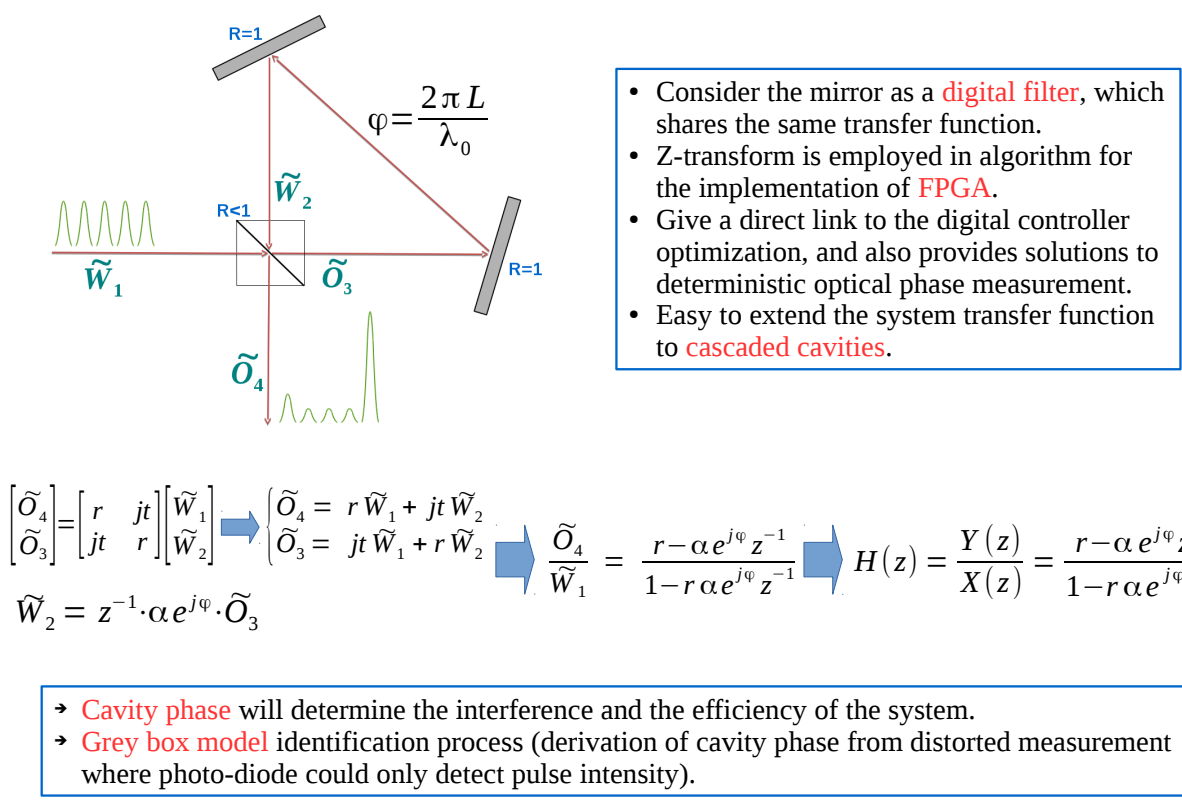


## Abstract

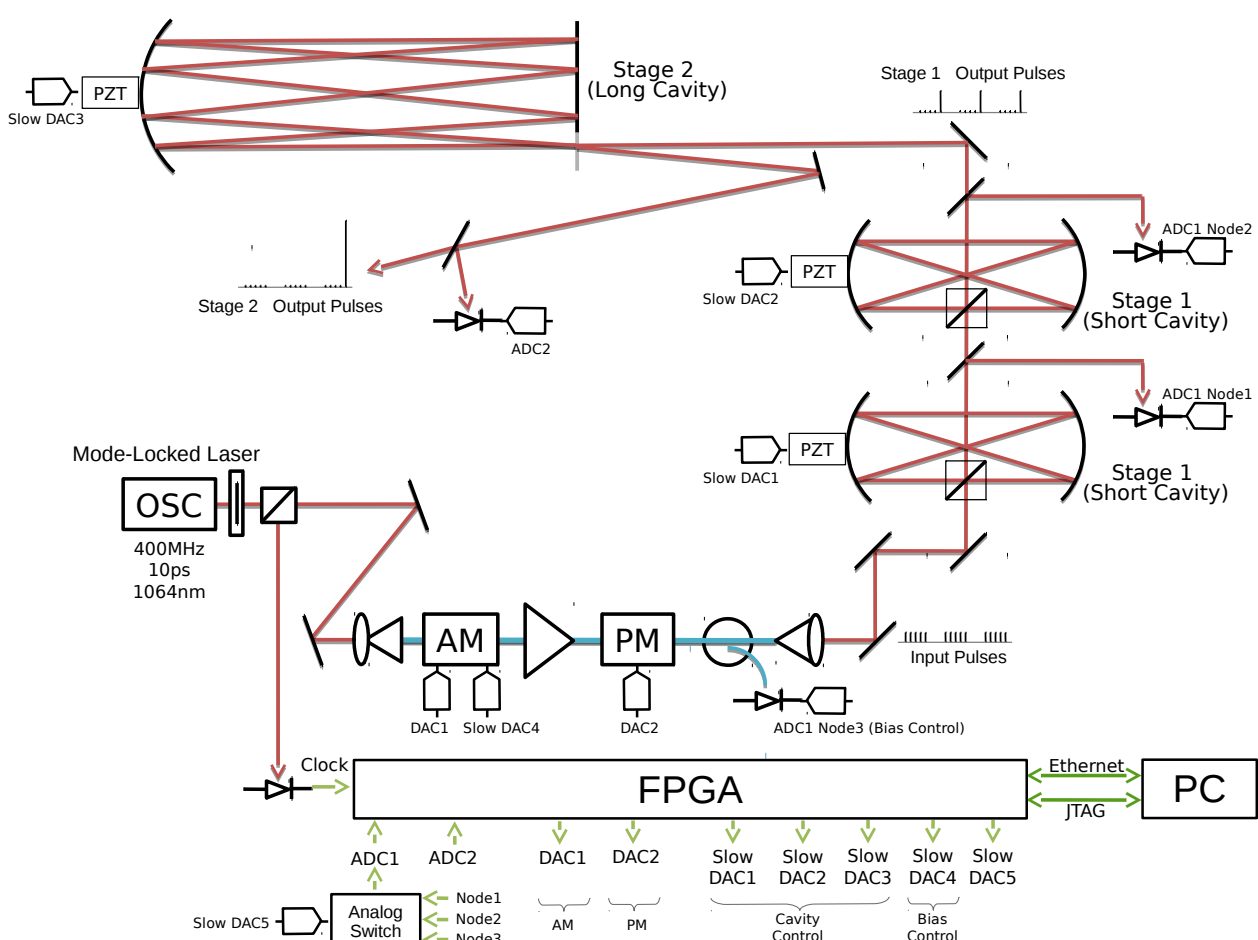
Coherent pulse stacking (CPS) is a new time-domain coherent addition technique that stacks several optical pulses into a single output pulse. This technique enables high average power, which will have a significant impact on laser-driven particle accelerators. We develop a robust and scalable digital control system with firmware and software integration for algorithms, to support the coherent pulse stacking application. We model coherent pulse stacking as a digital filter in the Z domain and implement a pulse-pattern-based cavity phase detection algorithm on an FPGA. A 2-stage (2+1 cavities) 15-pulse stacking system achieves a 11.0 peak-power enhancement factor. Each optical cavity is fed back at 1.5 kHz, and stabilized at an individually-prescribed round-trip phase with 0.7 deg and 2.1 deg RMS phase errors for Stage 1 and Stage 2 respectively. Optical cavity phase control with nm accuracy ensures 1.2% intensity stability of the stacked pulse over 12 hours.

## Z domain modeling

Model the coherent pulse stacking in Z domain.

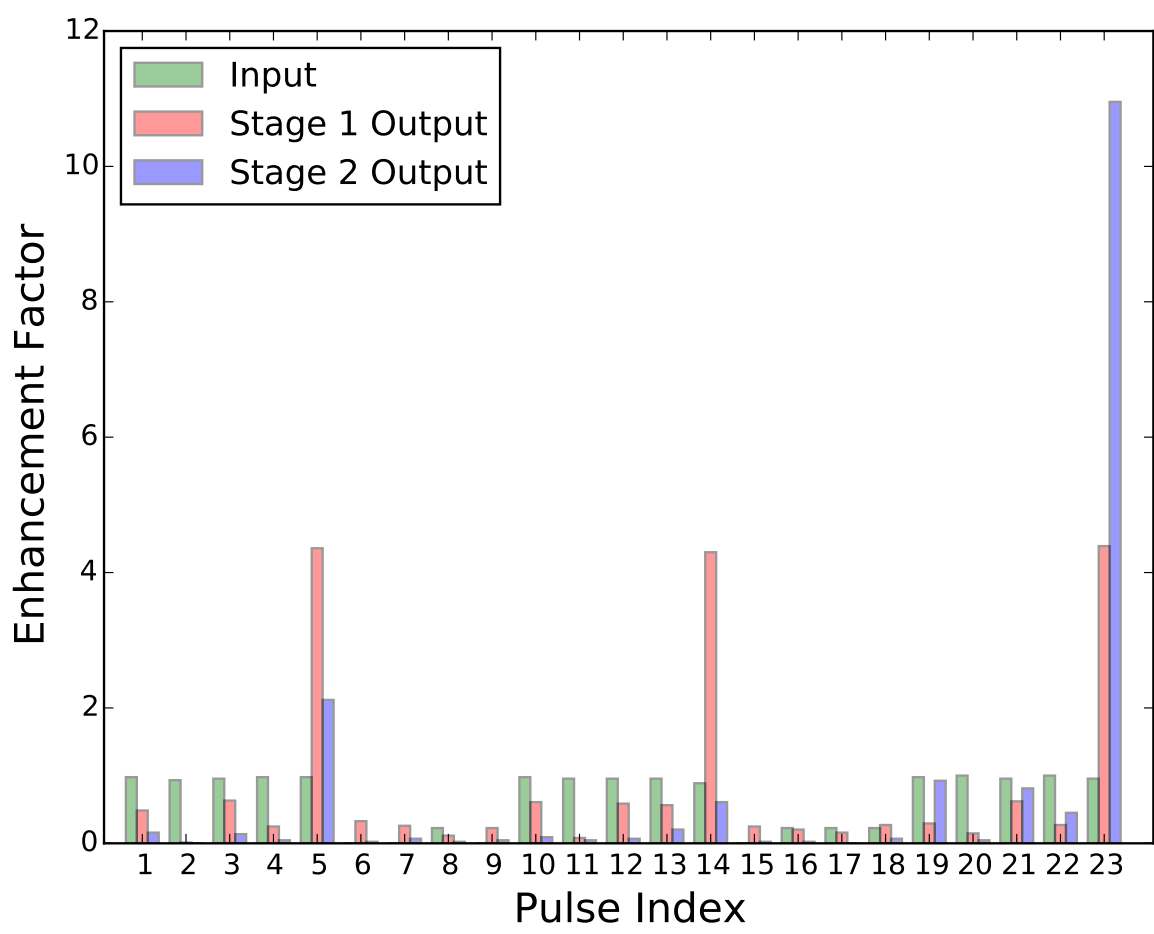


## System architecture



- Hardware:
- ML605 + FMC110 + XM105
  - 2-CH 12-bit A/D & 2-CH 16-bit D/A & 400MSPs
  - kHz Feedback Control Repetition Rate
- Firmware:
- Bottom Layer: Hardware-Dependent Drivers
  - Intermediate Layer: Data Communication (UDP)
  - Top Layer: Project Specific DSP and control modules

## Stacking result

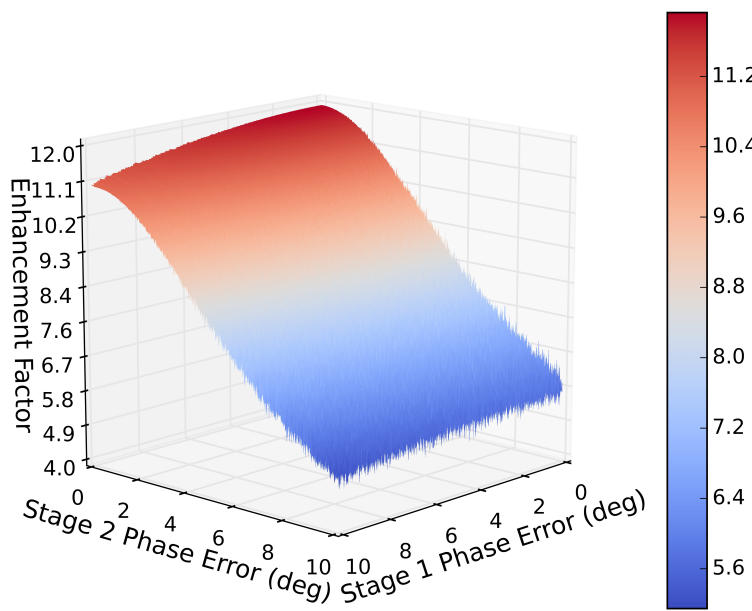


- A 2-stage (2+1 cavities) 15-pulse stacking system achieves a 11.0 peak-power enhancement factor, compared to the theoretical limit of 12.0.

## Algorithm of cavity phase stabilization

Failure to maintain the cavity phase matching translates into a decrease of the stacking efficiency and combined peak power.

Stabilizing the cavity phase in Stage 1 and Stage 2 with errors less than 1.0 deg and 2.5 deg respectively will keep the peak-power enhancement higher than 91% of its theoretical maximum.



Pulse-pattern-based cavity phase detection algorithm.

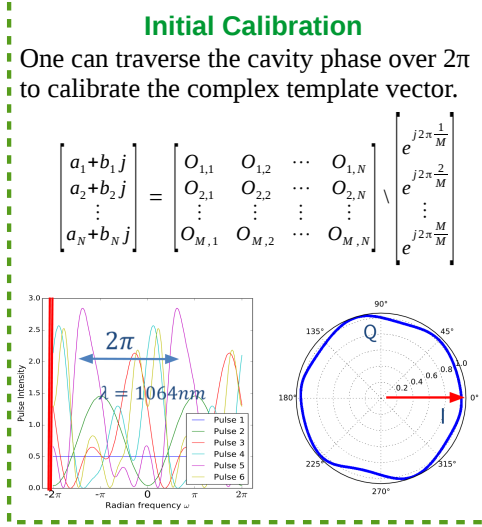
- Cavity phase is stabilized by proper feedback control of a **piezo driven mirror** for each cavity against **thermal drift**, **acoustic perturbation** and **mechanical vibration**.
- **Round-trip length** of each cavity is adjusted within a fraction of optical wavelength for prescribed phase.
- Failure of maintaining the cavity phase matching translates into a decrease of the **stacking efficiency** and **combined peak power**.
- Cavity phase is different from pulse phase which is modulated by the phase modulator.

An approximate **cavity phase** can be computed simply and quickly by a dot-product of the N-long **optical vector** measurement with a complex **template vector**.

$$\vec{o}(\varphi) \cdot \vec{v} = e^{j\varphi}$$
$$\vec{o}(\varphi) = [O_1, O_2, \dots, O_N]$$

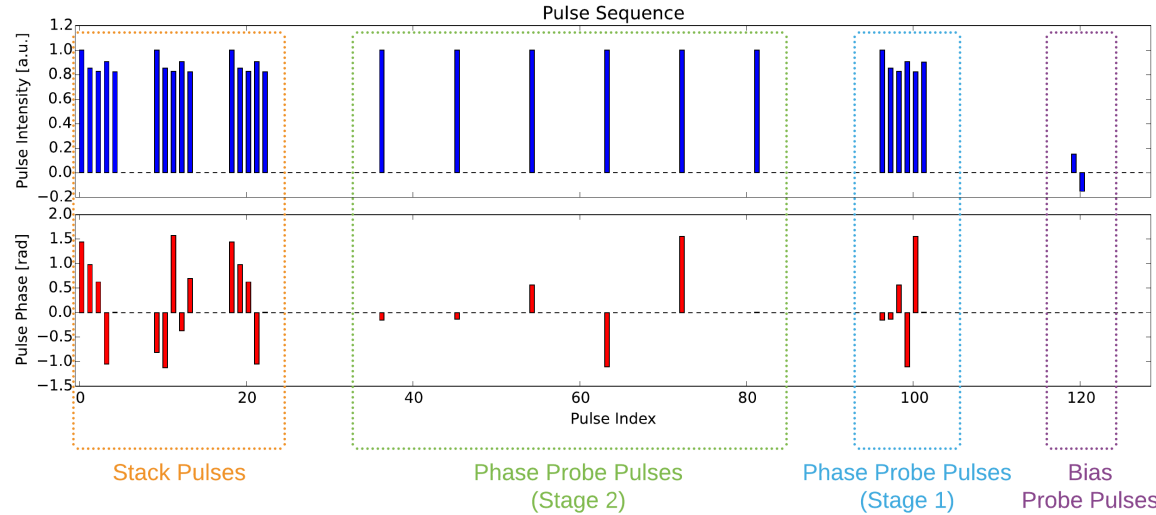
Template Vector

$$\vec{o}(\varphi) \cdot (\vec{a} + j\vec{b}) = \cos(\varphi) + j\sin(\varphi)$$

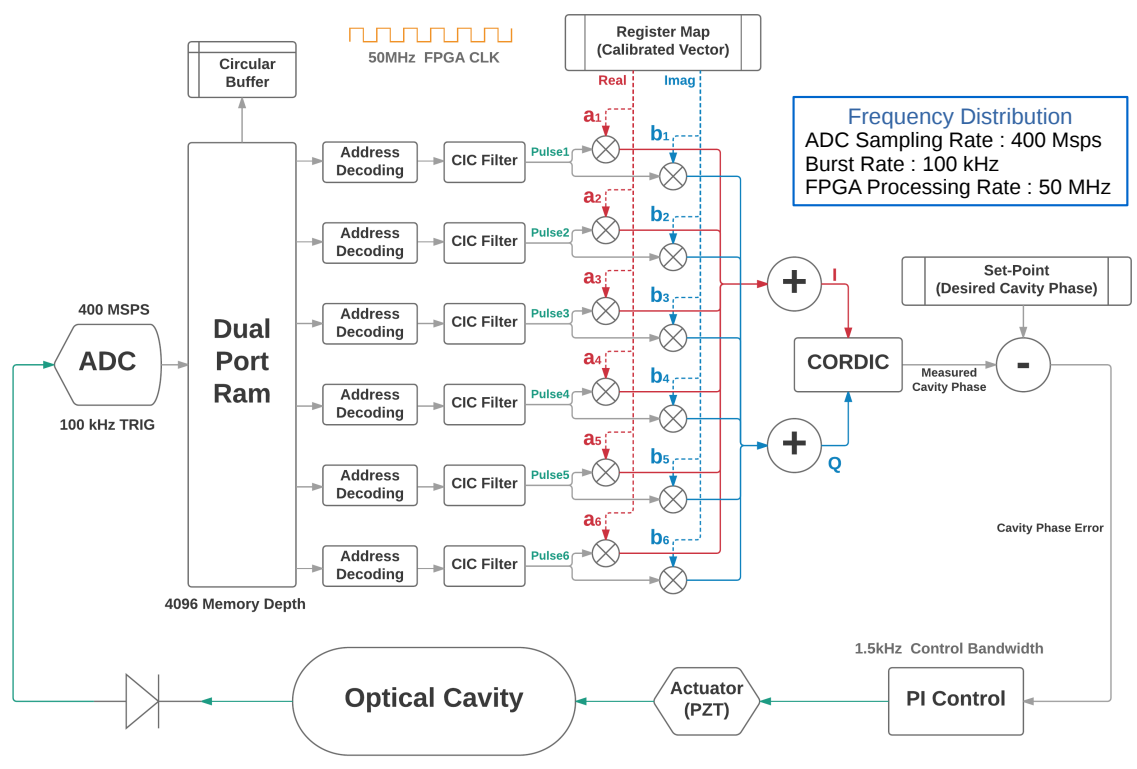


Phase probe pulses are introduced to detect cavity phase.

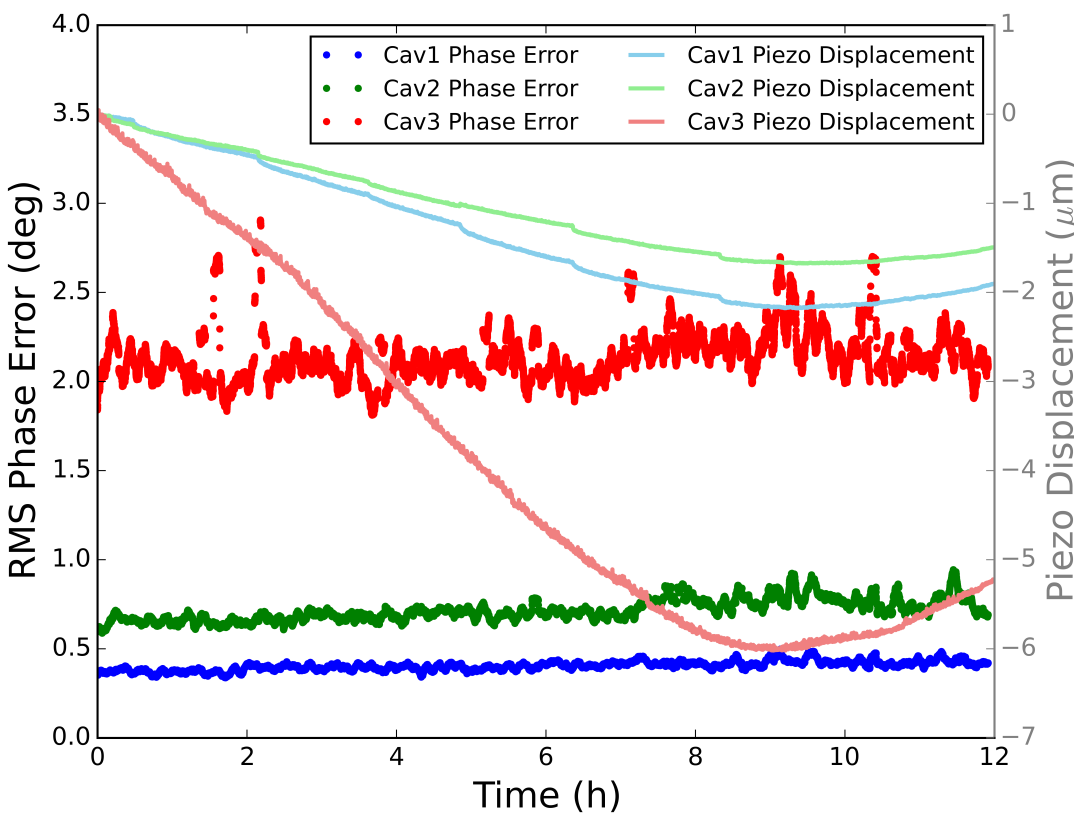
- A **pulse-pattern-based cavity phase detection algorithm** is employed in FPGA-based feedback control system.
- Instead of using the stack pulse train itself, a **phase probe pulse** burst can be optimized and injected behind the stack pulse train to diagnose the optical cavity fluctuation and lock the cavity phase according to the described cavity control model.



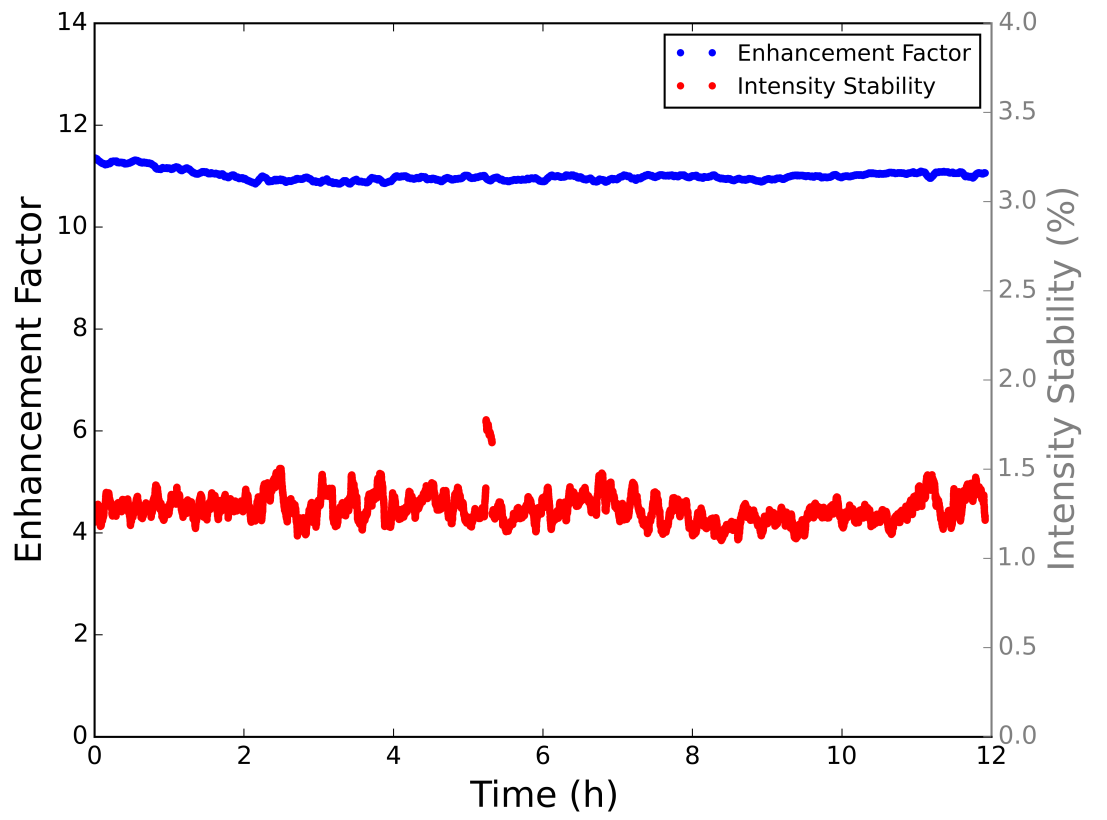
Digital processing chain of cavity control module.



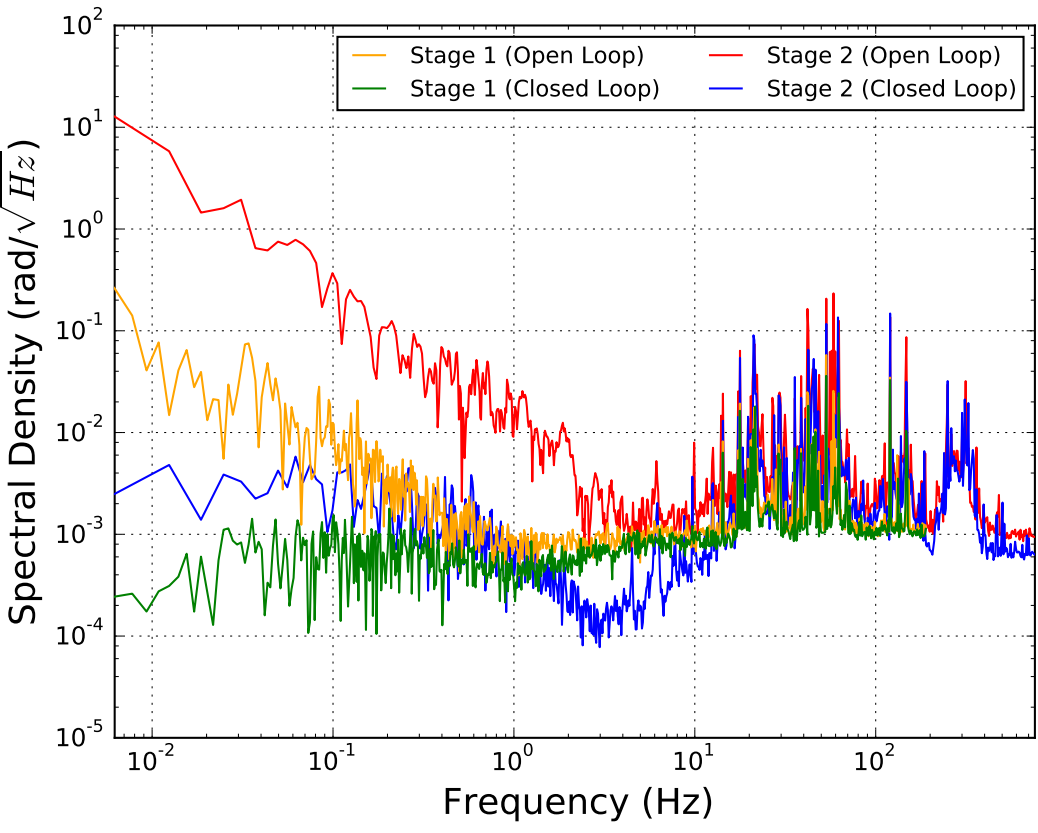
## Stabilization results of coherent pulse stacking



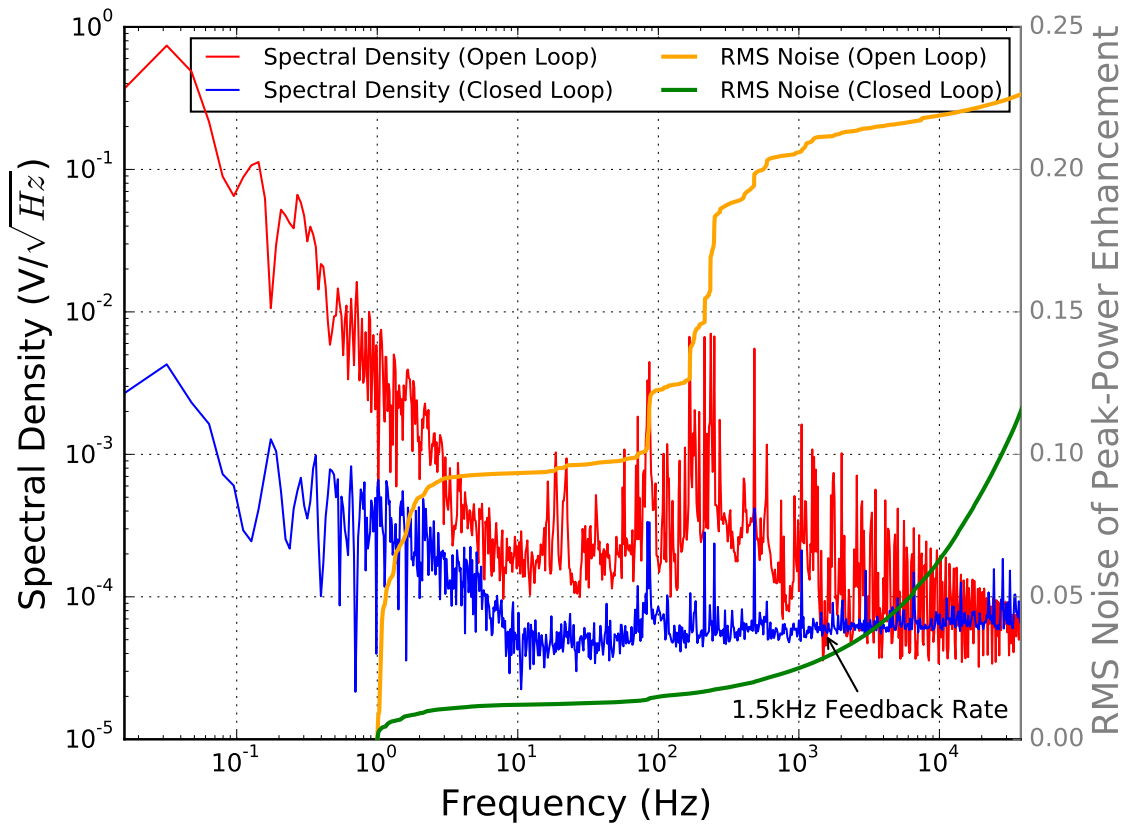
- Each cavity is stabilized with 0.7° and 2.1° (RMS) phase errors for Stage 1 and Stage 2.



- Intensity stability of the stacked pulse is kept within 1.2% (RMS) over 12 hours.



- Noise spectrum of the cavity phase.



- Noise spectrum of the stacked pulse.