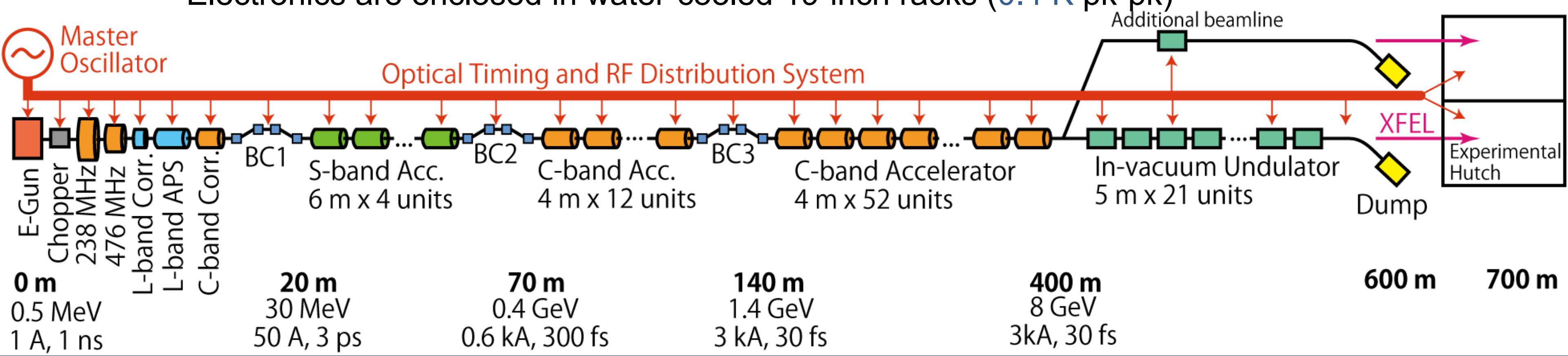
Design and Performance of the Optical Fiber Length Stabilization System for SACLA

H. Maesaka[1], T. Ohshima[1], S. Matsubara[2], Y. Otake[1]
1: RIKEN SPring-8 Center, XFEL R&D Division
2: JASRI XFEL Utilization Division

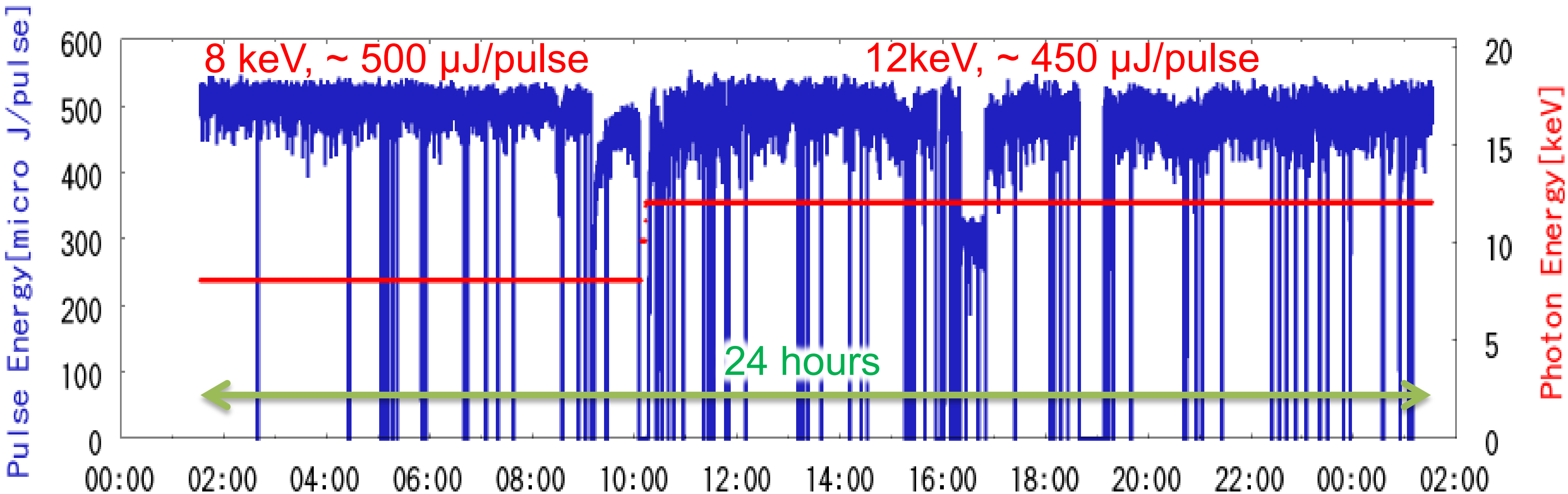
June 18th, 2014
IPAC2014, Dresden, Germany

Introduction

- X-ray Free Electron Laser Facility “SACLA”
  - Low-emittance thermionic electron gun (ε_n ~ 1 μm rad)
  - 238 MHz, 476 MHz, L-band (1428 MHz) and S-band (2856 MHz) accelerators for acceleration and bunch compression
  - High-gradient C-band Main Linac (5712 MHz, > 35 MV/m)
  - Short-period in-vacuum undulator (λ_u = 18 mm)
- Accelerator components must be precisely synchronized
  - Bunch length is compressed to be 30 fs.
- Pump-and-probe experiment also needs precise synchronization with accelerator
- Required timing stability: 50 fs
  - throughout the 700m-long facility
- Optical timing and RF distribution system
  - Wavelength region of 1550 nm
  - Phase-stabilized optical fiber (5 ps/km/K) is used
  - Temperature of optical fiber cables is regulated within 0.4 K.
  - Electronics are enclosed in water-cooled 19-inch racks (0.4 K pk-pk)

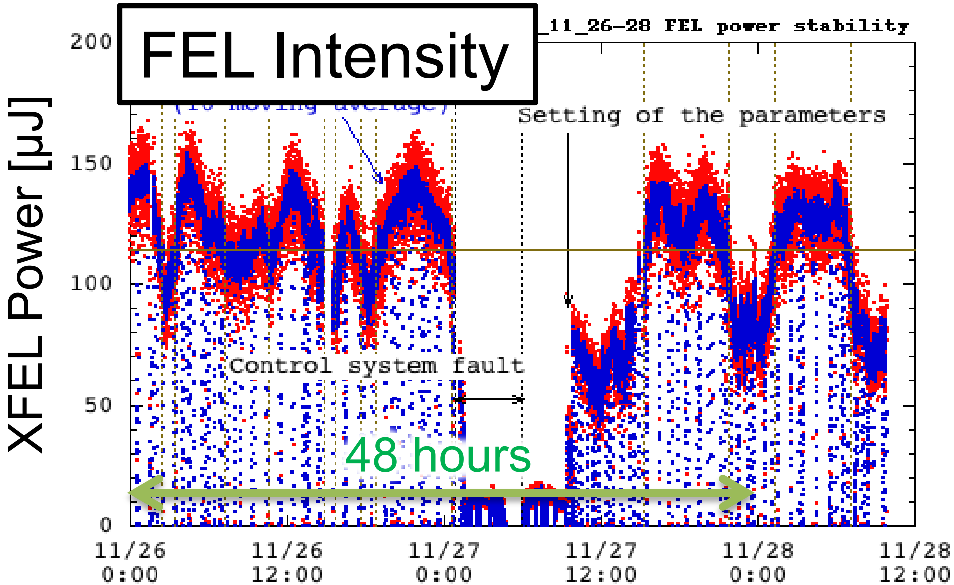


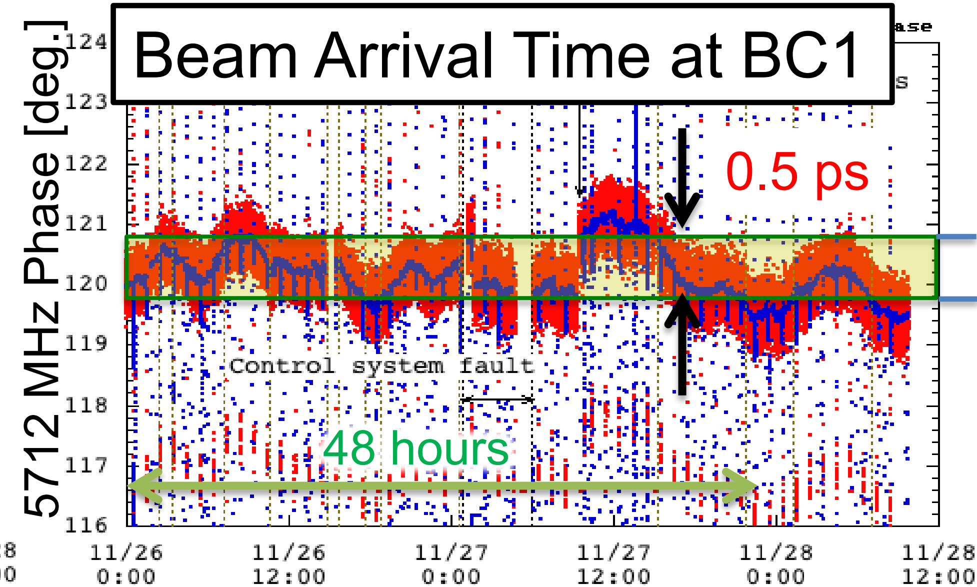
XFEL Stability



- Present performance of SACLA
  - 24-hour trend graph during a user operation
  - With various feedbacks and manual tuning
- XFEL Intensity: ~500 μJ/pulse
- Intensity fluctuation: ~10% (std. dev.)
- Pointing Stability: ~10 μm (std. dev.)

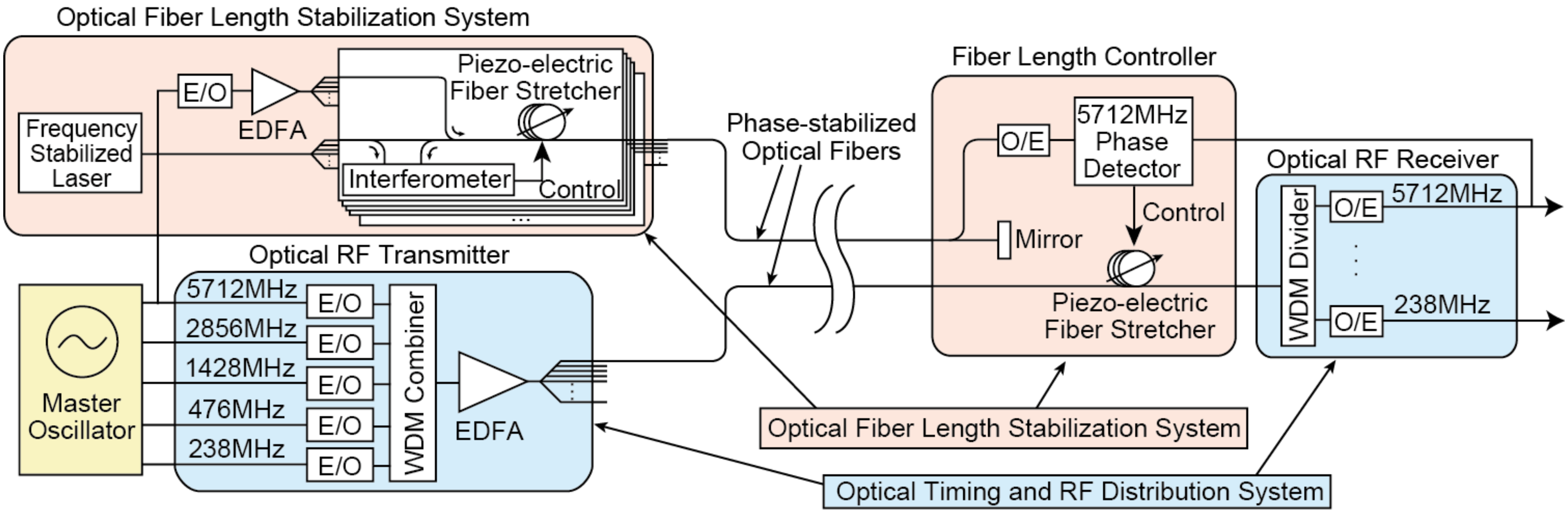
XFEL Stability without Feedback





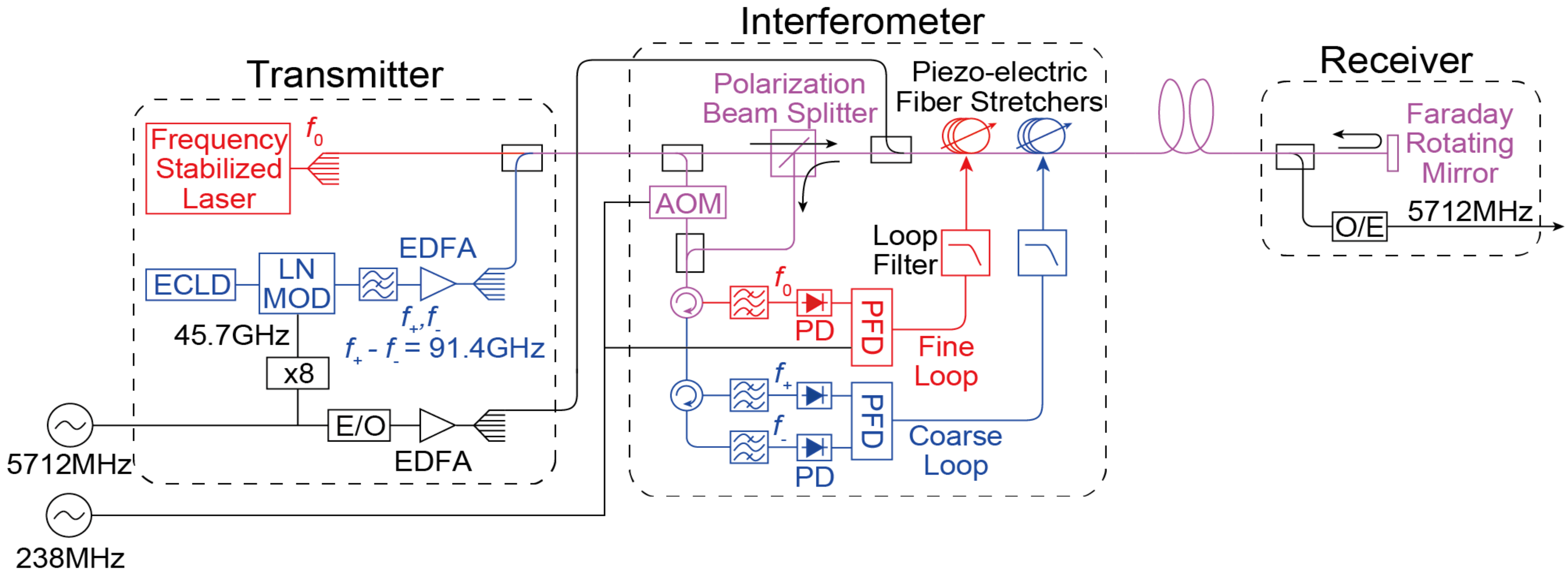
- Stability data was taken without any beam feedbacks or manual tuning in order to investigate perturbation sources
  - In the early stage of the XFEL operation
- XFEL intensity was not stable
- Timing drift more than 500 fs was observed.
  - One of the reasons could be timing drift due to optical fiber length variation.
- Regulation of the optical fiber length is demanded.

System Overview



- Optical Timing and RF Distribution System
  - Master Oscillator generates low-noise RF signals
  - E/O and O/E Converters for each RF frequency
  - Wavelength-division multiplexing (WDM) technology for multiple signal transmission
- Optical Fiber Length Stabilization System
  - Frequency-stabilized laser for a length standard
  - Interferometer detects the optical length variation and fed back to piezo-electic fiber stretcher
  - 5712 MHz RF signal is also transmitted for the phase reference.
- Optical fibers for these systems are separated
  - Flexible design for the optical fiber length stabilization system
  - Failure resistant
  - Length variation of optical components (EDFA etc.) can be regulated.

Optical Fiber Length Stabilization

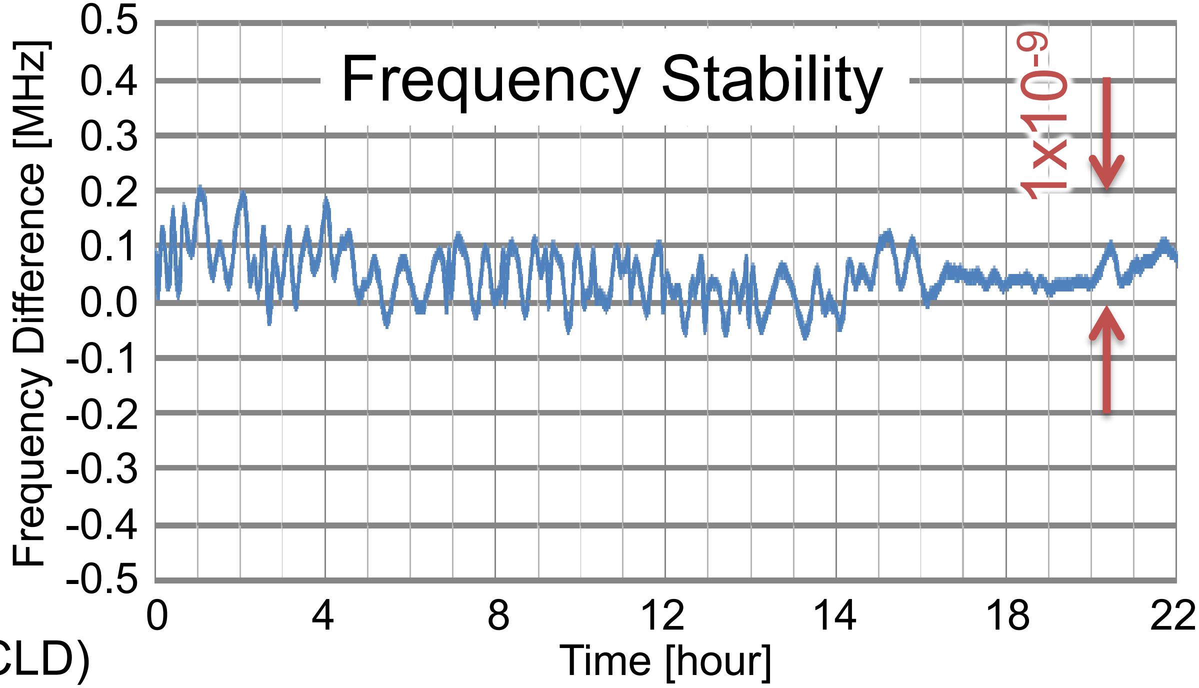


- Two length standards and two feedback control loops
  - Fine Loop: Frequency-stabilized laser (1549 nm, ~193 THz, 5 fs)
    - For precise control
  - Coarse Loop: Optical millimeter-wave signal (91.4 GHz, 11 ps)
    - This loop can restore the absolute length after the power off of the system.
  - For redundancy and for cross-check of the accuracy
- Interferometer
  - Polarization beam splitter (PBS) and Faraday rotating mirror (FRM) to eliminate scattered light.
  - Reference light is frequency-shifted by a 238 MHz signal with an acousto-optic modulator (AOM).
  - Each optical signal is separated by a band-pass filter and detected with a photo-diode (PD).
  - 238 MHz beat signal is obtained from the PD as an interferometry signal.
  - 238 MHz phase is detected by a phase-frequency discriminator (PFD).

Frequency-Stabilized Laser

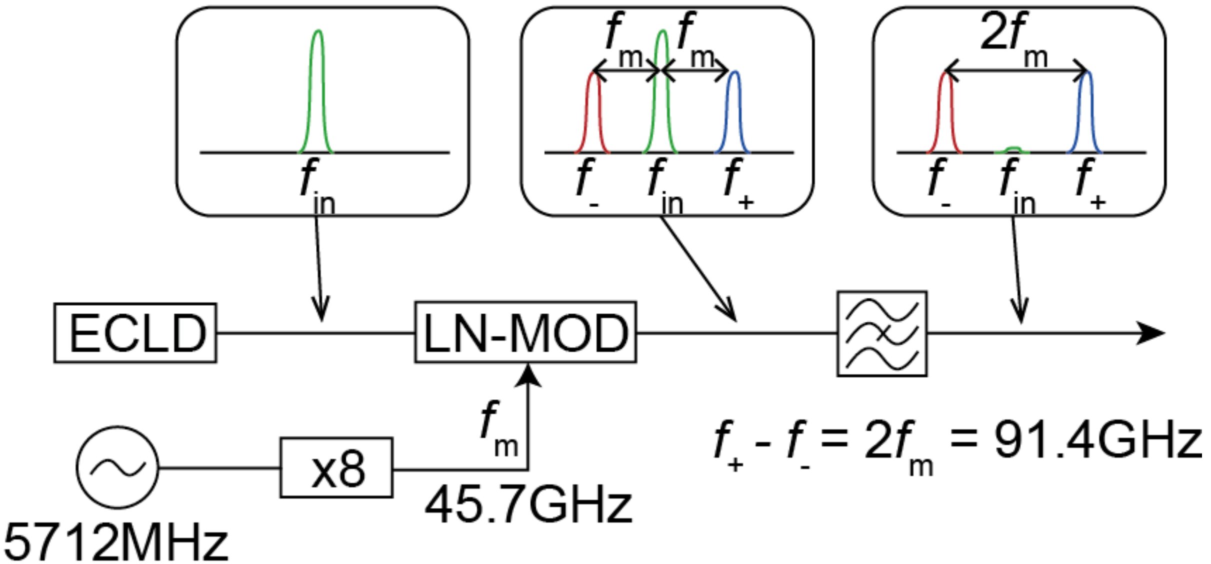
- Length standard for the fine loop
- Optical frequency is locked to an absorption line of hydrogen cyanide.
  - Wavelength: 1548.955 nm (193.545 THz)
  - P9 absorption line of $H^{13}C^{14}N$
- Frequency stability: 1×10^{-9}
  - Corresponding to 1 μm accuracy for 1km-long distance measurement.

External cavity laser diode (ECLD)

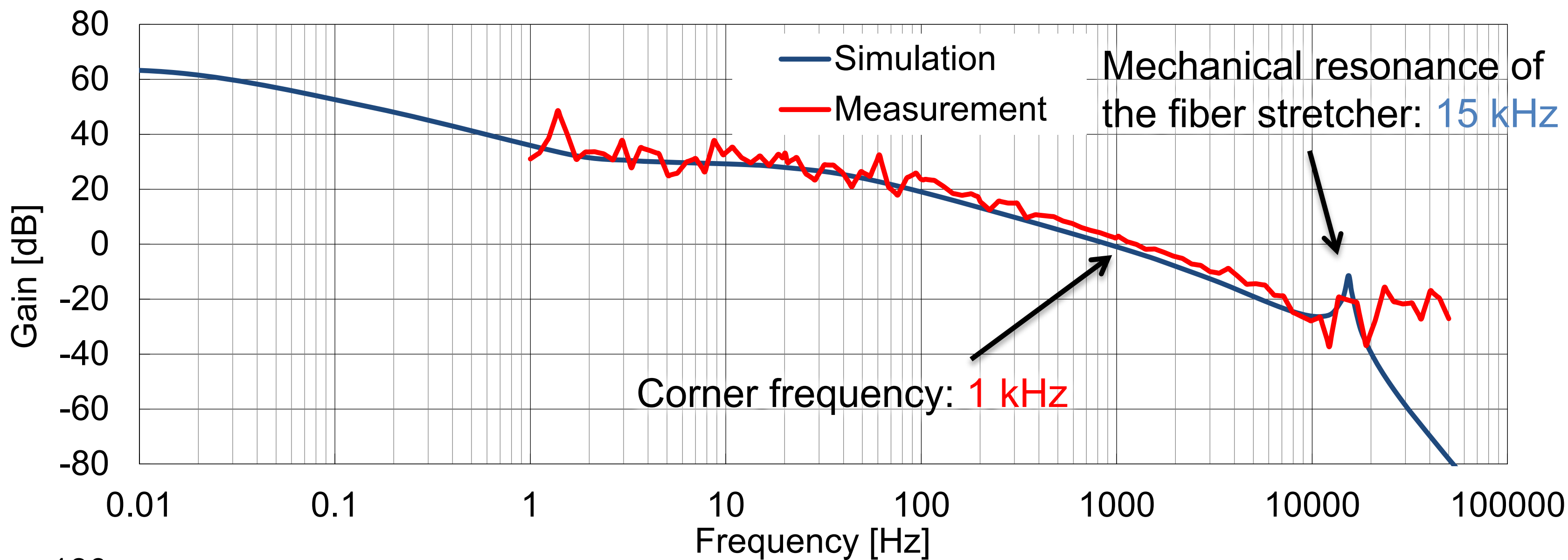


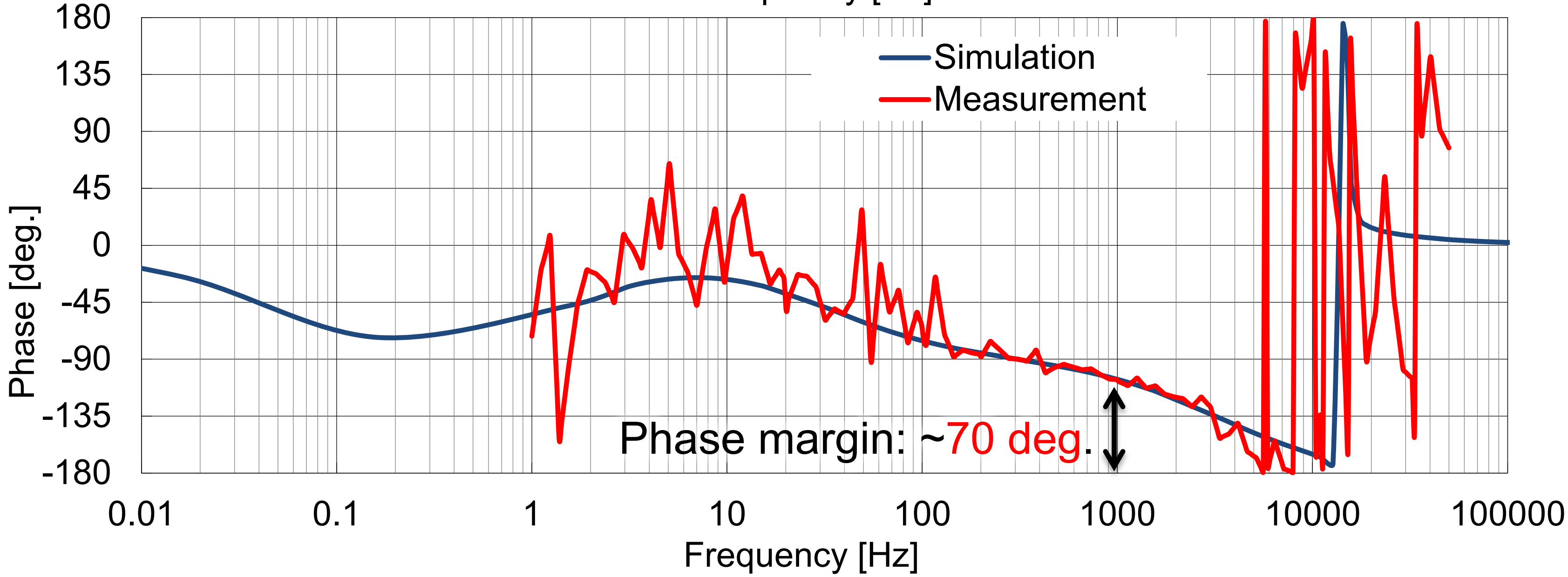
Light Source for Coarse Loop

- External cavity laser diode (ECLD)
- $LiNbO_3$ modulator (LN-MOD)
  - Driven by a 45.7 GHz signal (f_m = 5712 MHz x 8)
  - LN-MOD produces two sidebands (f_+ and f_-)
- Band-reject Filter
  - Eliminates the input light (f_{in})
- Two sidebands, f_+ and f_- , are utilized for the length measurement.
  - $f_+ - f_- = 2 f_m$ = 91.4 GHz
- Stability
  - Frequency stability of 5712 MHz: < 1×10^{-9}
  - This light source is carefully designed to obtain almost same frequency stability as 5712 MHz.
  - Same level as the frequency-stabilized laser for the fine loop

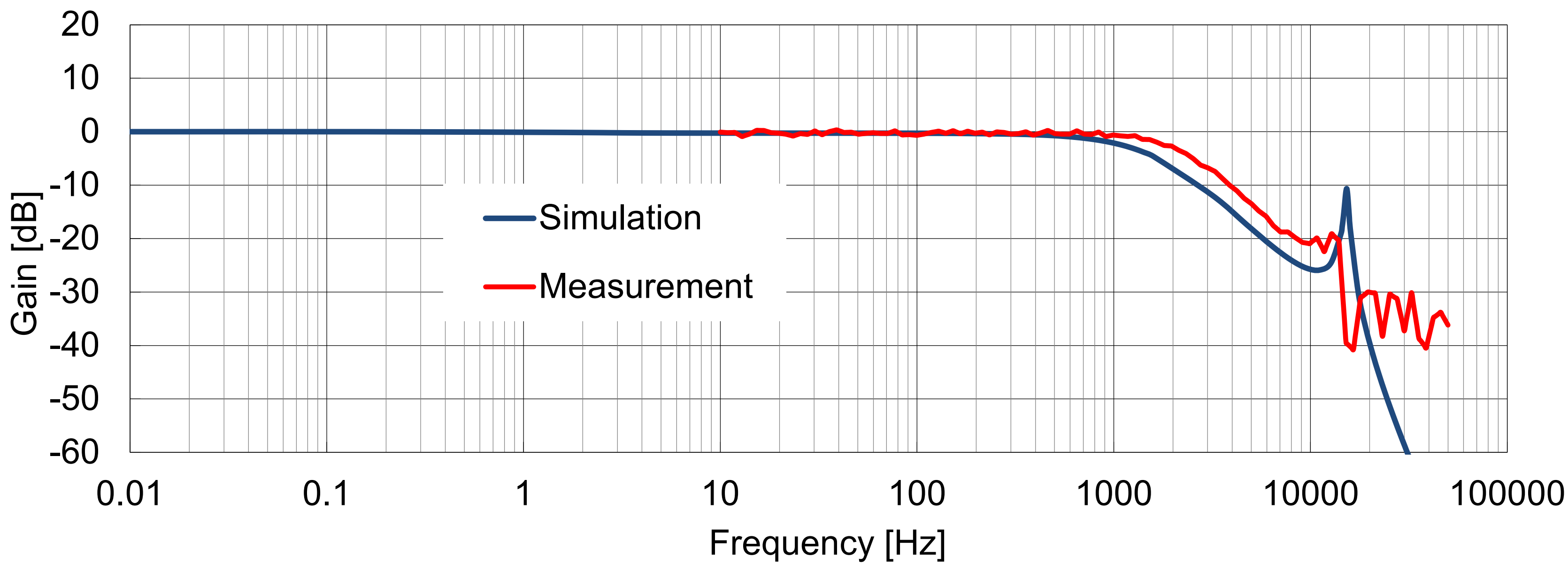


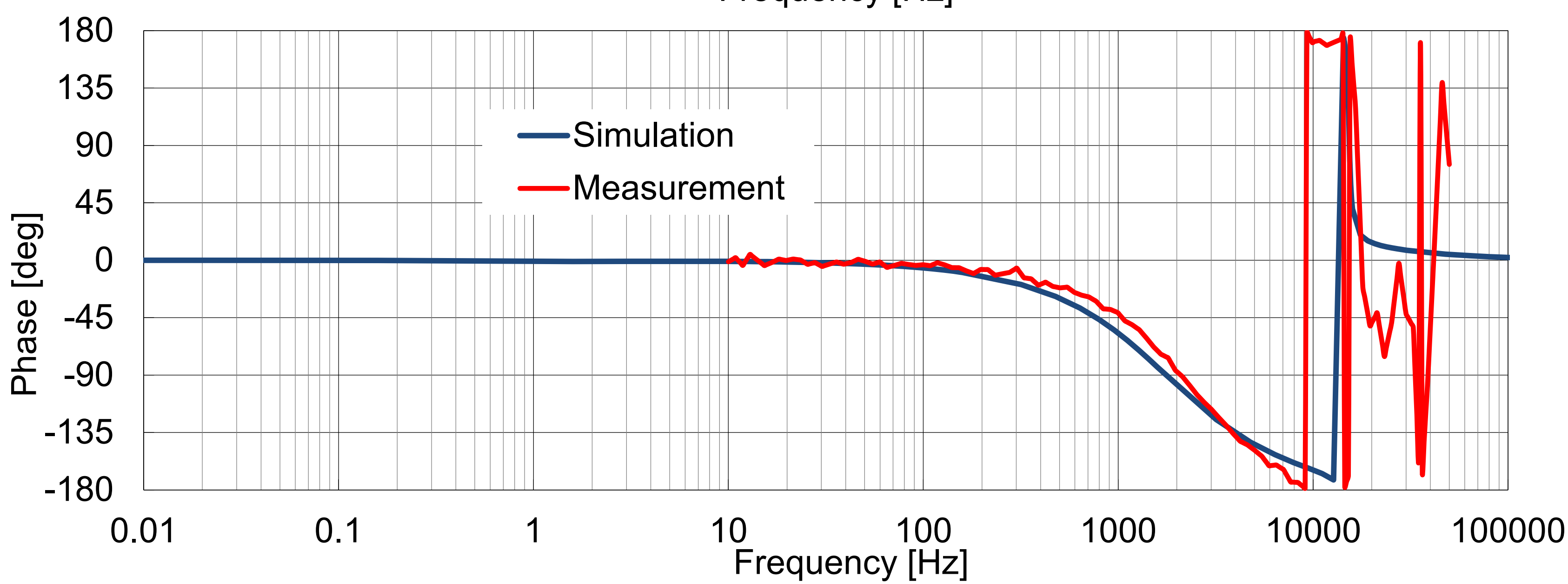
Open Loop Response (Fine)





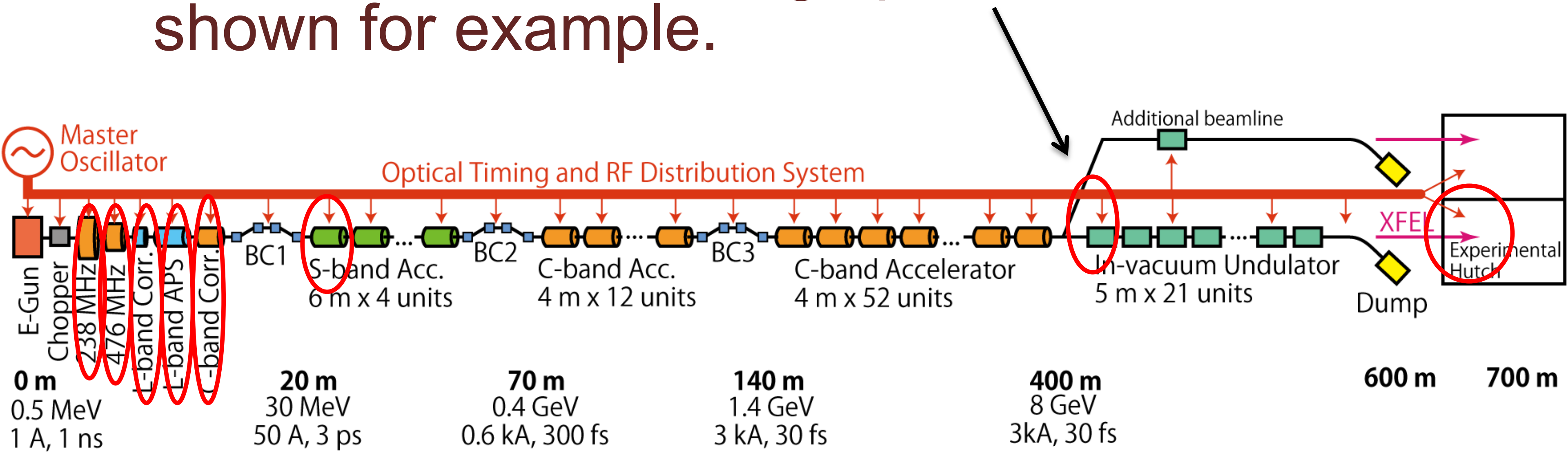
Closed Loop Response (Fine)





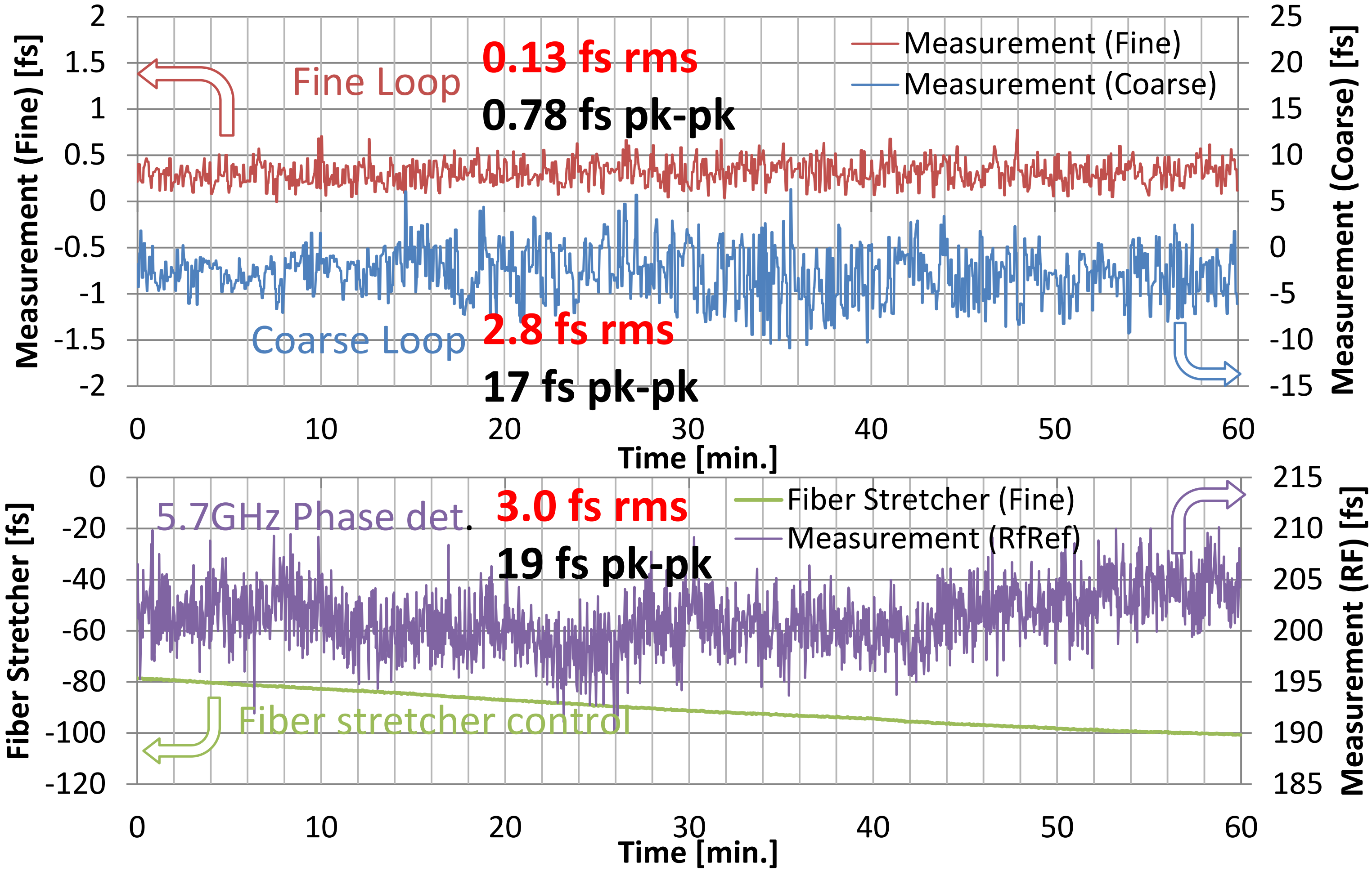
Present Status

- 8 channels of the optical fiber length stabilization system are installed into SACLA.
  - Under engineering run
  - 12 channels in total will be utilized for user-time operation from October.
- Data from a 400m-long optical fiber are shown for example.

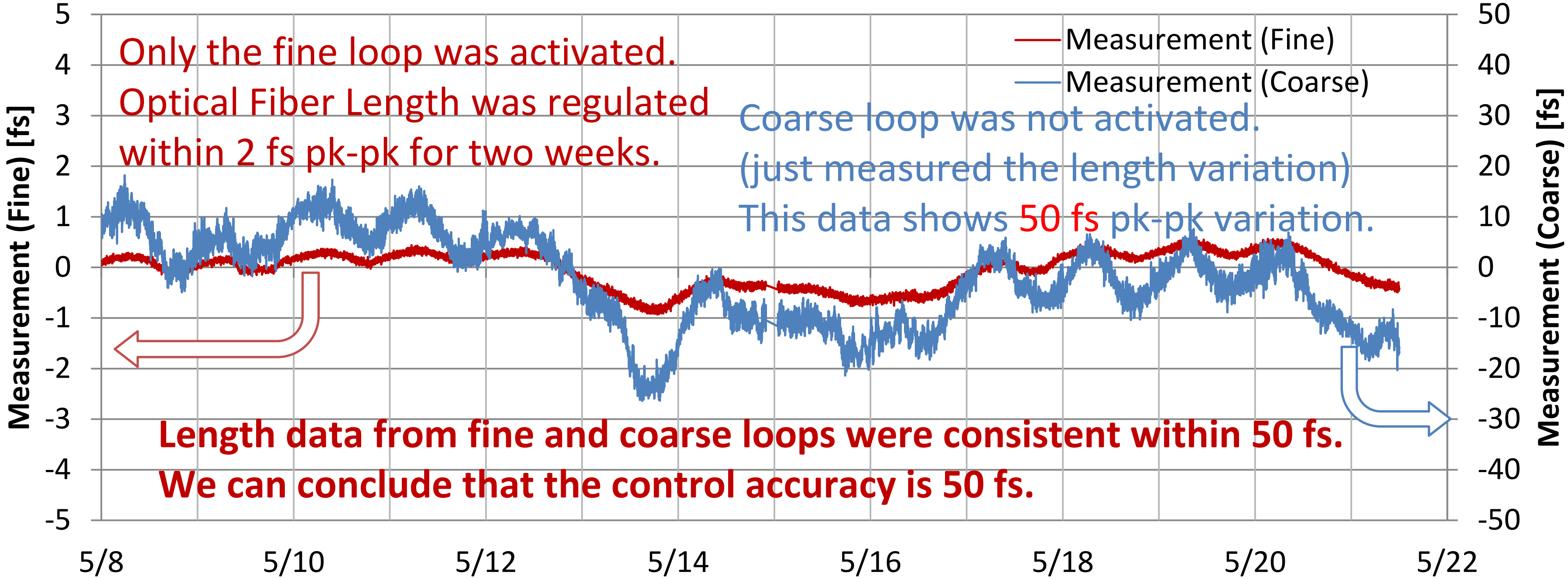


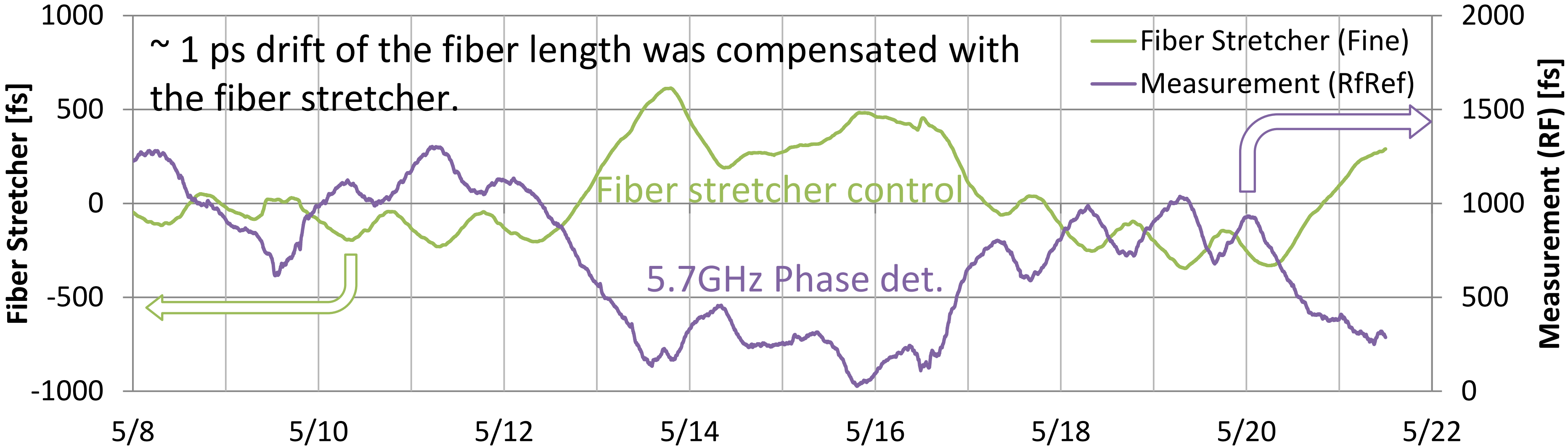
Short-term Data

- To estimate length measurement resolution
- Data for 1 hour stable period are plotted
  - Fiber length (~400 m) was regulated by the fine loop



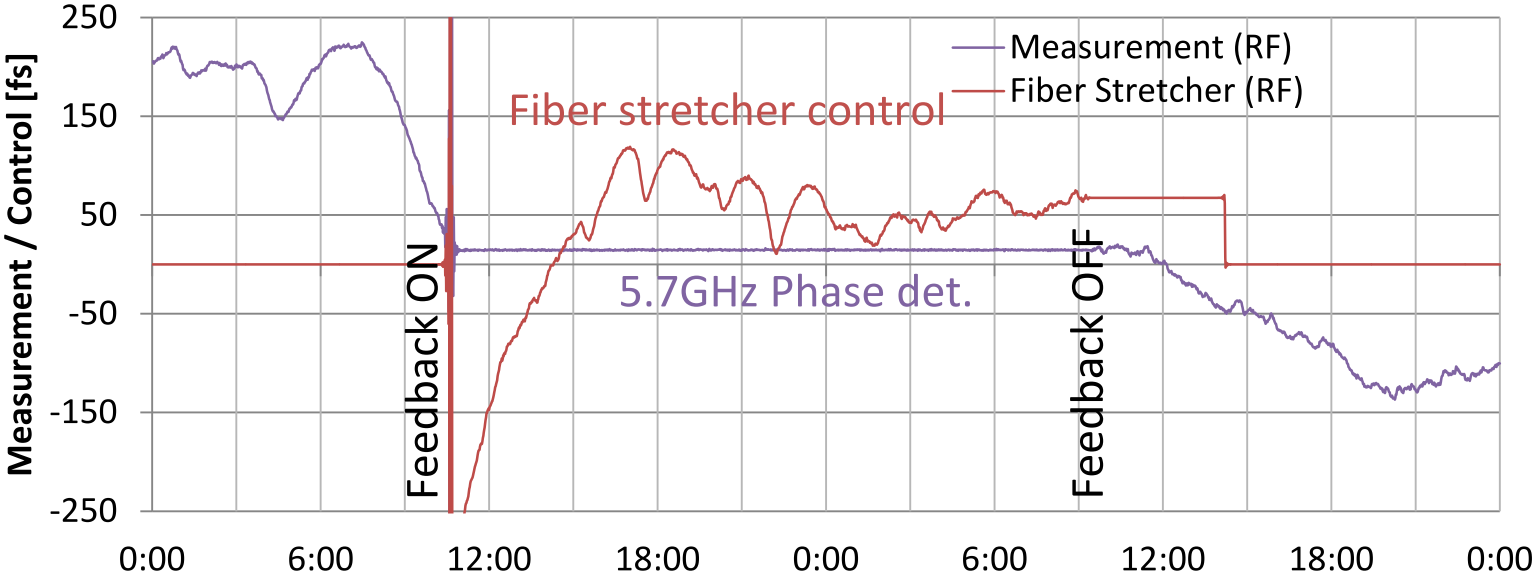
Long-term Stability

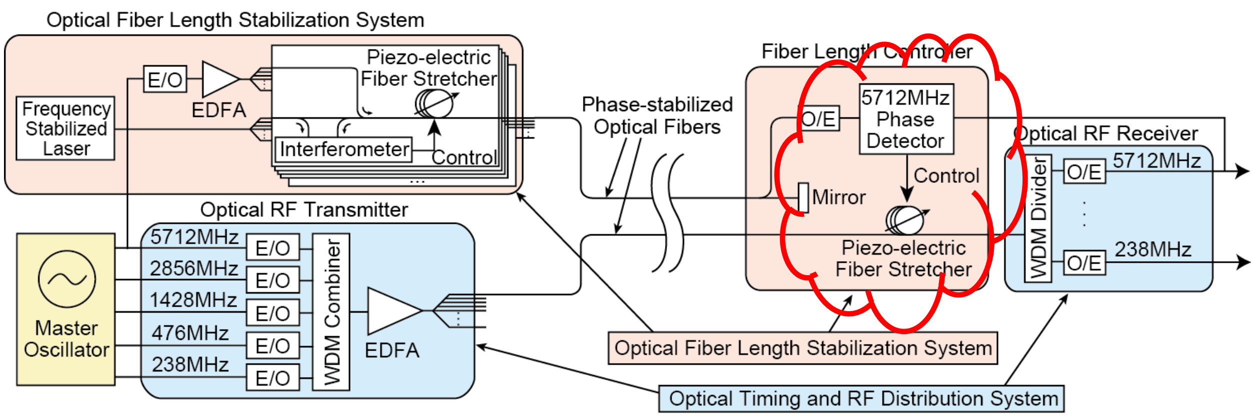




Length Regulation of RF Distribution Fiber

- Optical fiber length of the optical RF distribution system is regulated by a fiber stretcher at the receiver.
  - According to the detected phase of 5712 MHz





Summary

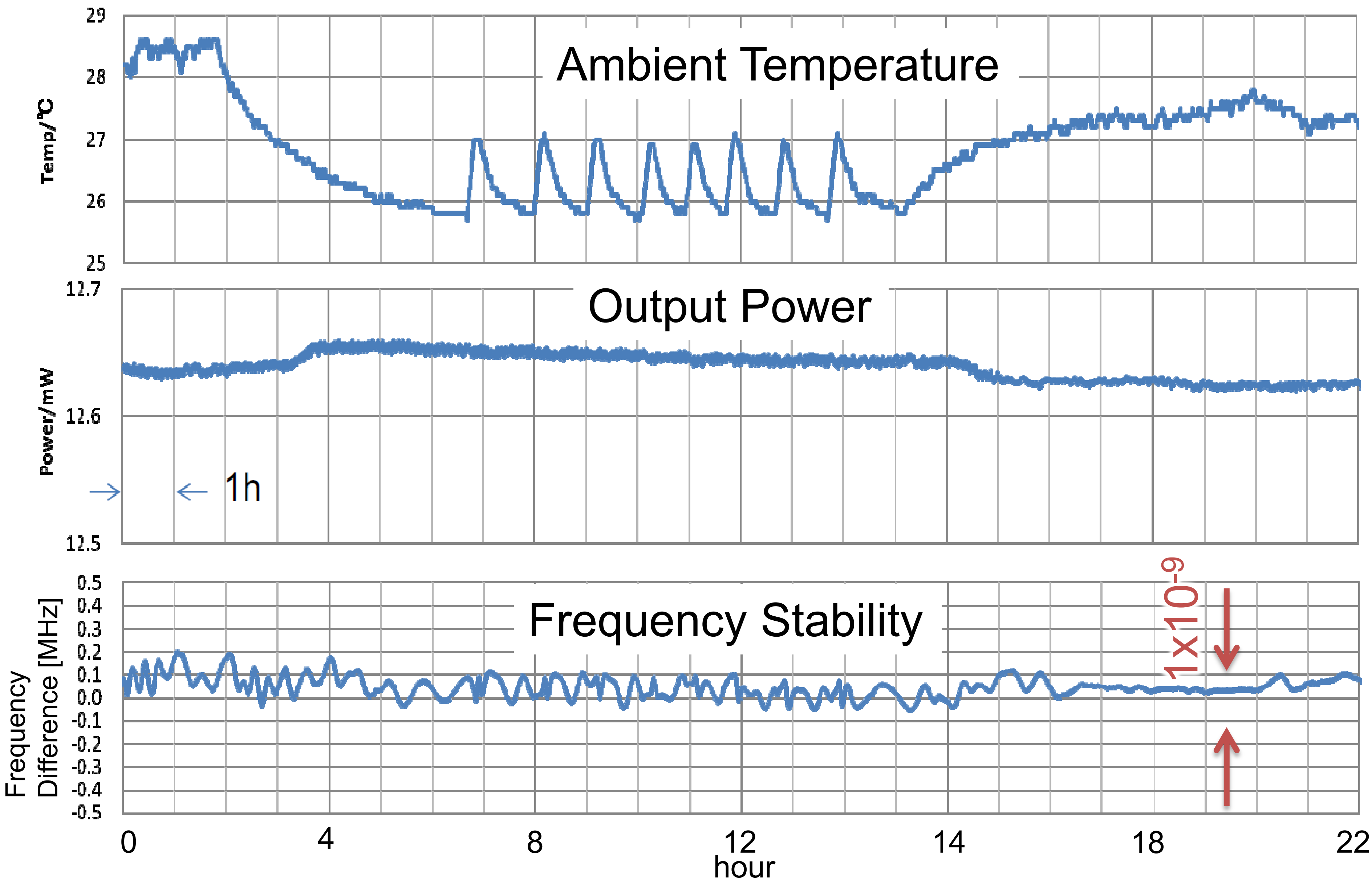
- An **optical fiber length stabilization system** for the timing and RF signal distribution system was developed.
  - For the x-ray free-electron laser facility, SACLA
  - To synchronize accelerator components with a master clock within 50 fs
- Setup
  - Additional optical fiber is prepared for the optical fiber length stabilization system.
  - Frequency-stabilized laser (1549 nm, fine loop) and 91.4 GHz optical signal (coarse loop) for length standards
  - Optical interferometer to measure the optical length variation
  - Optical fiber length drift is compensated by a piezo-electric fiber stretcher.
  - Optical 5712 MHz is also transmitted for the phase reference of the timing and RF signal distribution system.
- Performance
  - Measurement resolution: 0.13 fs rms (fine loop) and 2.8 fs rms (coarse loop)
  - Control accuracy: 50 fs pk-pk
    - Estimated from the length difference between the fine and coarse loops.
  - Optical fiber length for the timing and RF distribution system was also regulated properly.
- ***Required performance for the optical fiber length stabilization system was obtained.***

Acknowledgments

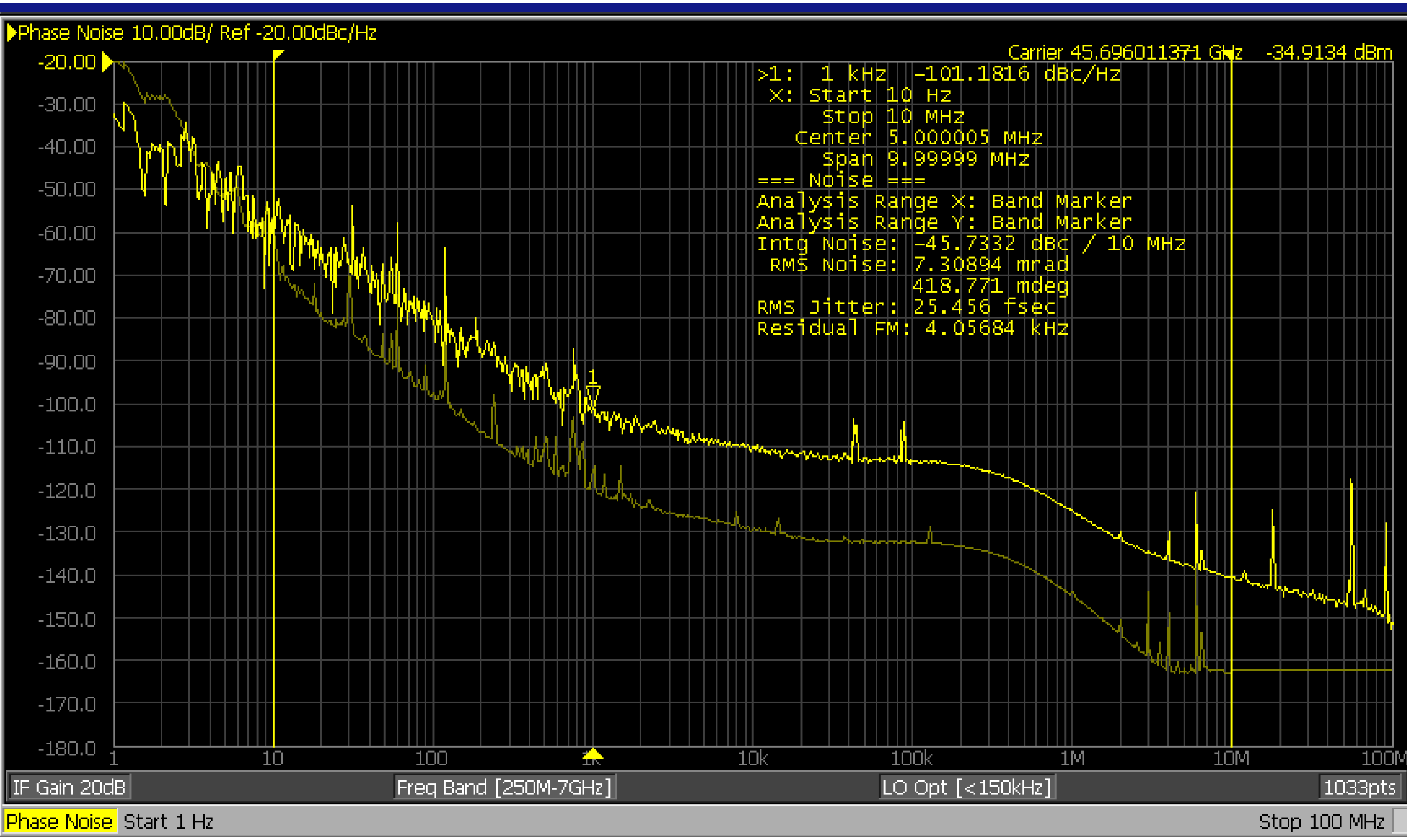
- Mr. Mukade, Mr. Ikeda, Mr. Miyamura, and their colleagues
  - Mitsubishi Electric Tokki Systems Corporation
  - For great efforts to construct the system
- Prof. Musha
  - The University of Electro-Communications
  - For helpful suggestions for the design
- Dr. Hirano, Dr. Ando, Mr. Akiyama and Mr. Kameyama
  - Mitsubishi Electric Corporation
  - For helpful suggestions for the design
- Dr. Kourogi and Dr. Imai
  - OptoComb, Inc.
  - For helpful suggestions for the design
- Dr. Morimoto
  - in SPring-8 Service Co., Ltd.
  - For effective cooperation of the software development of the feedback control process

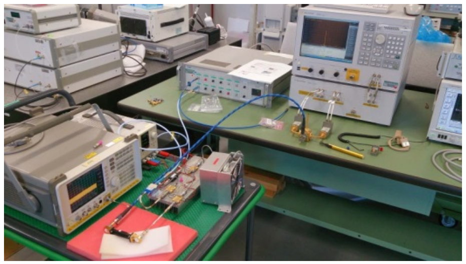
Backup

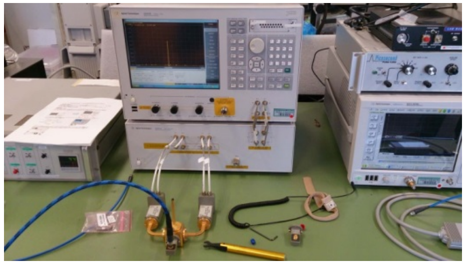
Frequency-Stabilized Laser Data

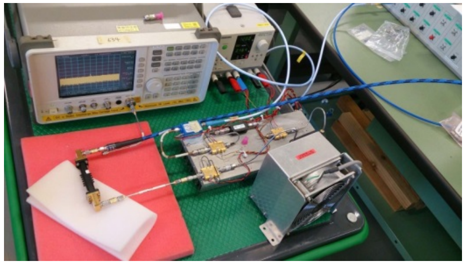


Phase Noise of 45.7 GHz Signal





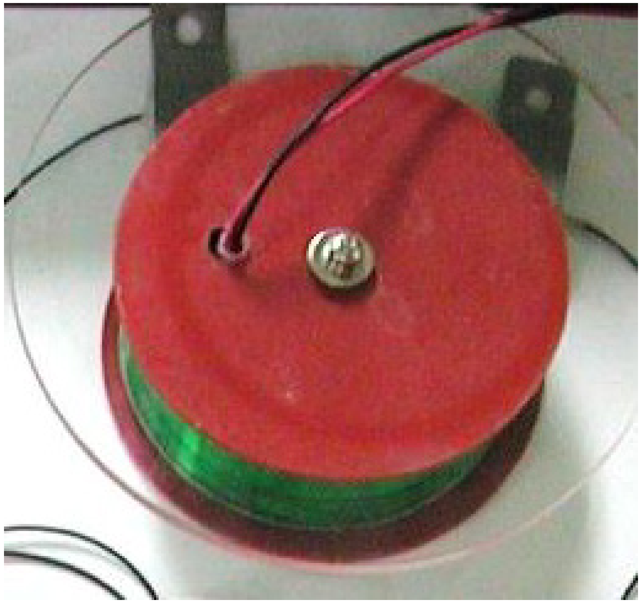


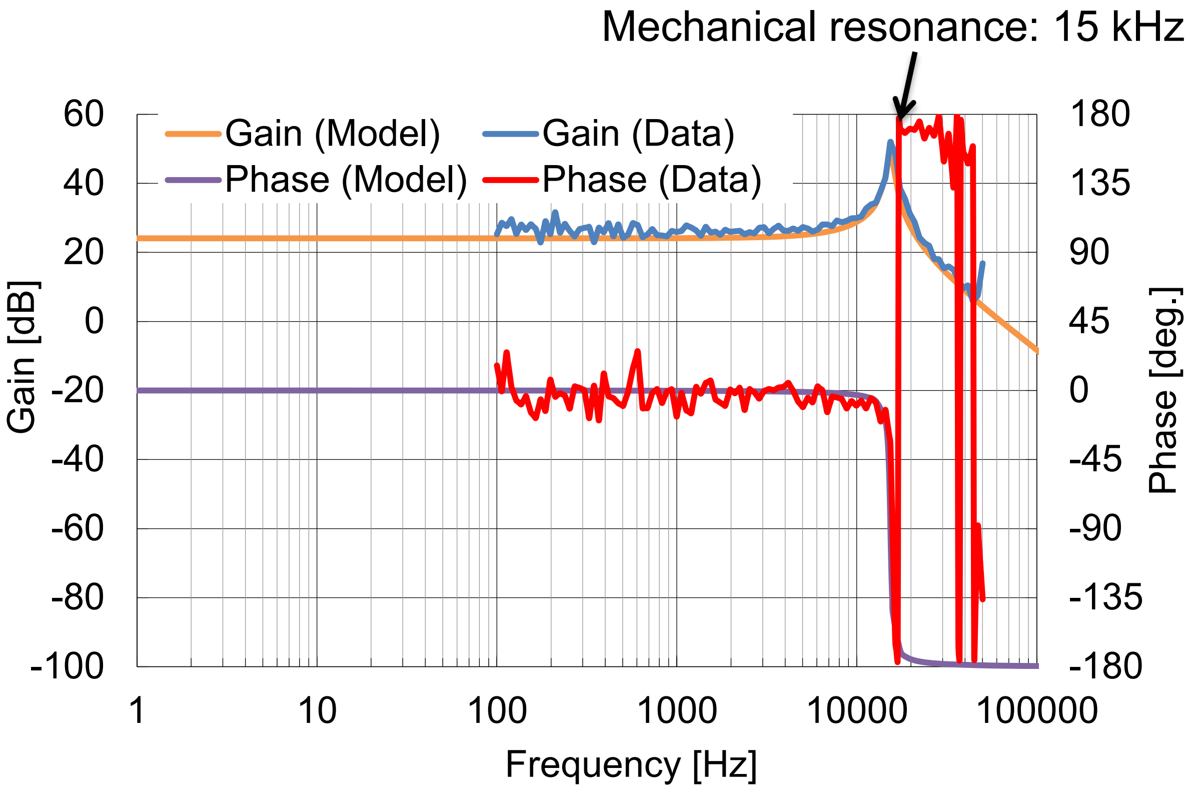


- Almost no additive noise from frequency multiplier
- Integral of the phase noise
  - RMS jitter: 25 fs (10 Hz – 10 MHz)

Fiber Stretcher

- Optical fiber is coiled around a cylindrical piezo-electric actuator
- Dynamic range 3 mm peak-to-peak
  - Bias voltage: 0 V – 300 V
- Frequency response
  - Sufficiently flat up to 3 kHz
  - Mechanical resonance at 15 kHz.





Other Loop Filters

- Coarse Loop
  - PI control
  - Corner frequency: ~0.01 Hz
- Fiber stretcher for the RF distribution system
  - PI control
  - Corner frequency: ~0.1 Hz
- Fine loop uses a wide band loop filter (1 kHz).
  - Fine loop is sensitive to small amplitude but high frequency vibration.
  - Phase detection range is only 1.5 μm
  - For a stable control under high-frequency perturbation

Polarization Mode Dispersion

- Polarization Mode Dispersion for a usual optical fiber
  - < 1 ps/√km
- If the length of a 1km-long optical fiber varies 1mm (1×10^{-6}), the optical length for different polarization varies only 1 as (=1 ps x 10^{-6}).