SPring-8 Joint Project for XFEL

Recent Progress of the RF and Timing System of XFEL/SPring-8

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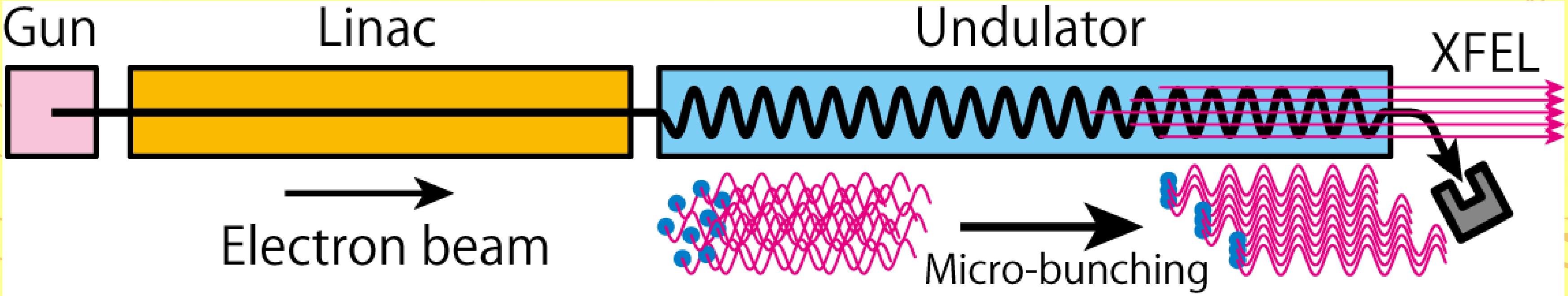
Outline

- X-ray Free Electron Laser (XFEL) project at SPring-8
- Design of the RF and timing system
  - Requirements
  - Design concept
  - Optical RF and timing distribution system
  - Precise low-level RF control system
- Water-cooled enclosure
  - Water-cooled 19-inch rack
  - Water-cooled optical cable duct
- Performance measurement
  - Optical system
  - Low-level RF system
- Summary

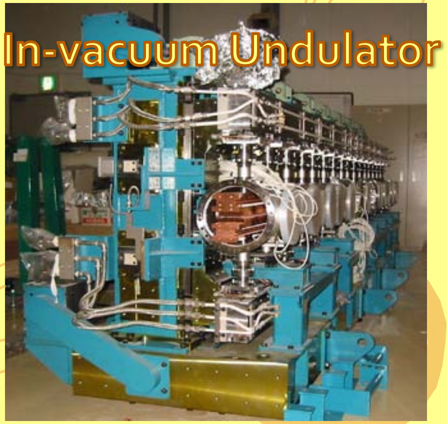
XFEL Project at SPring-8

X-ray Free Electron Laser (XFEL)

- To generate coherent and intense x-rays.
  - For life sciences and material sciences etc.
- SASE process
  - Self-Amplified Spontaneous Emission
  - No optical cavity
  - Long undulator beamline is needed
    - To give rise to the interaction between electrons and x-rays.
- Low-emittance and high-peak-current beam are required.

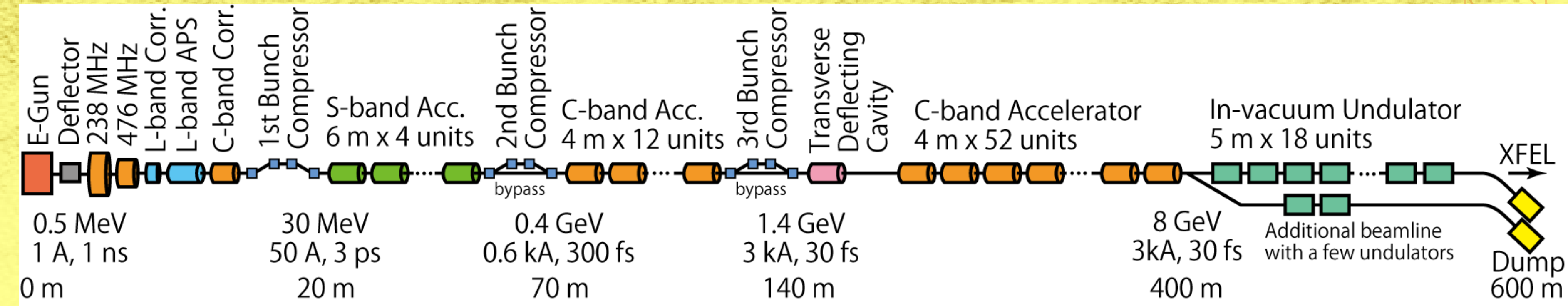


Project Overview

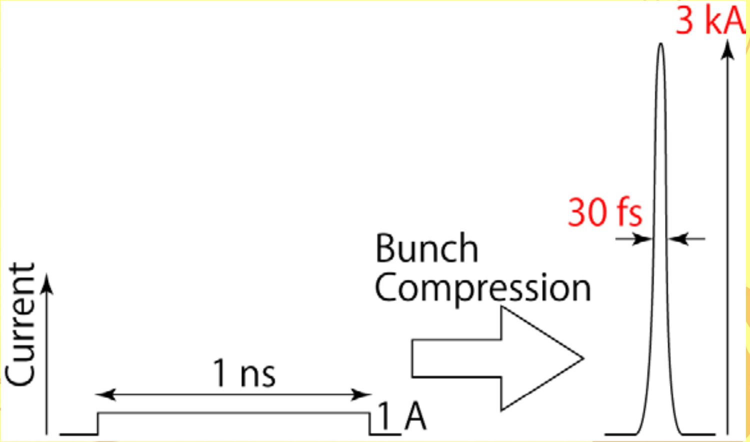


- X-ray wavelength: < 0.1 nm
- Beam energy: 8 GeV
- Key technologies
  - Low-emittance thermionic electron gun: 0.6 π mm mrad
  - High-gradient C-band accelerator: 35 MV/m
  - Short-period in-vacuum undulator: λ_u = 18 mm
- First FEL light will be delivered in 2011.

XFEL Machine Layout



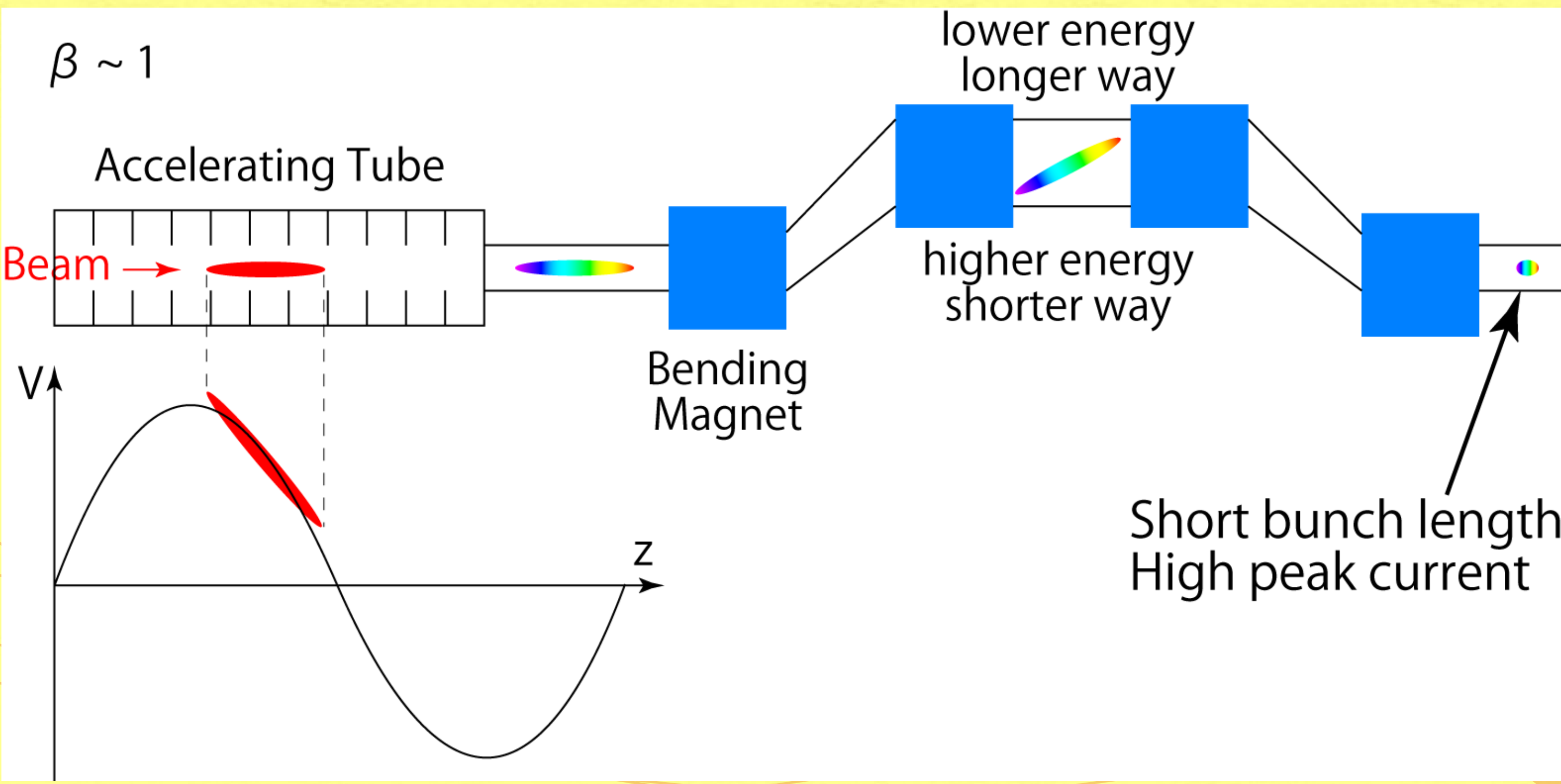
- 8GeV linear accelerator
  - 238 MHz, 476 MHz, L-band (1428 MHz), S-band (2856 MHz) and C-band (5712 MHz)
- Key parameters of SASE-FEL
  - Normalized slice emittance: 0.7 π mm mrad
  - Peak current: 3 kA
- Slice emittance
  - Accelerate without emittance growth
- Peak current
  - Compress the longitudinal bunch structure
- Bunch compression
  - Velocity bunching in the low energy region
  - Three bunch compressors (magnetic chicane)
  - Bunch length: 1 ns → 30 fs (FWHM)
  - Peak current: 1 A → 3 kA



Bunch Compressor

- In a magnetic chicane, low-energy electrons travels longer way than high-energy electrons.
- Accelerator gives an energy chirp to the beam.
  - Energy of head electrons is made lower than that of tail electrons.
  - Strength of the energy chirp is very sensitive to the compression ratio.

  → Precise RF phase and amplitude control system is demanded.



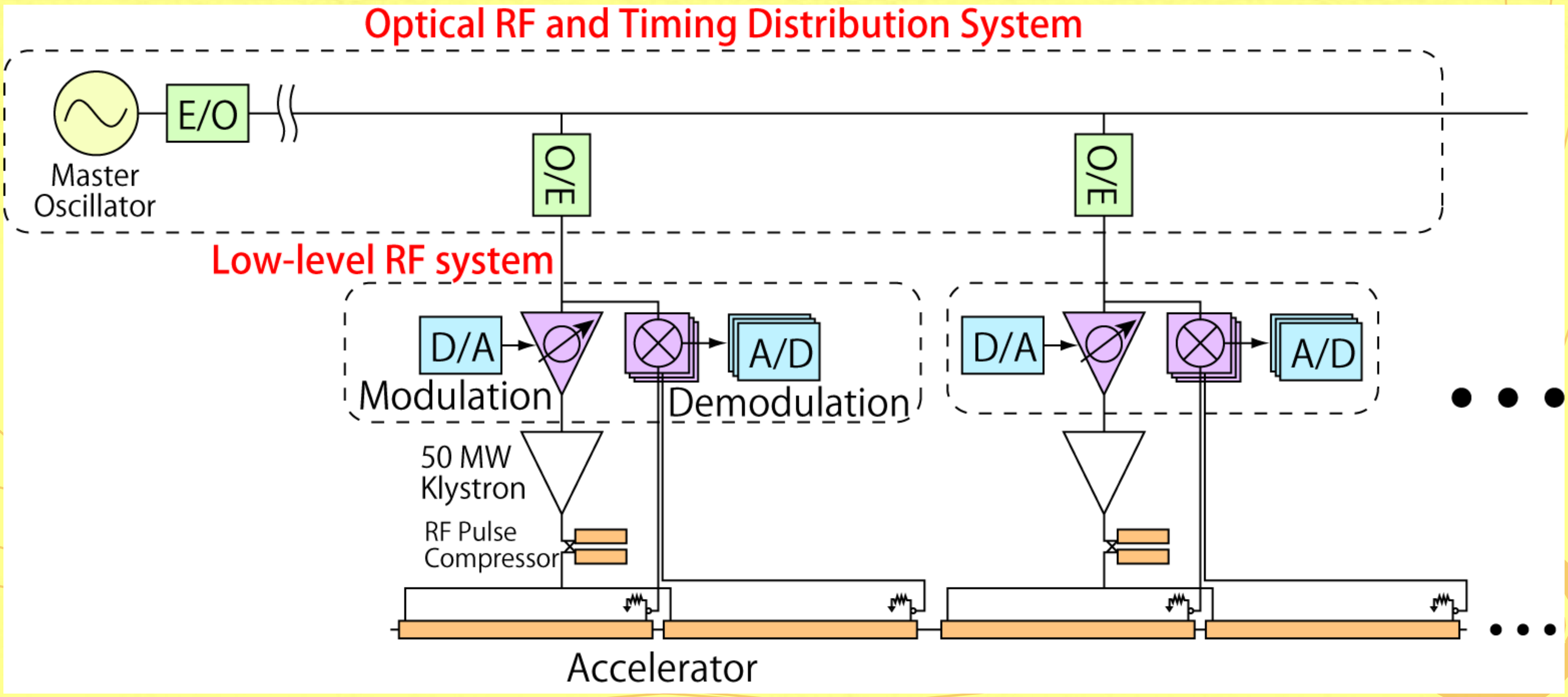
Design of the RF and Timing System

Requirements for the Timing System

- Should be as stable as possible!
  - This system provides the timing standard of the whole system.
- Timing stability of the acceleration field
  - Phase stability: 0.1 degree (rms) of 5712 MHz
  - Equivalent to 50 fs (rms)
- Amplitude stability of the acceleration field
  - 0.01% (rms)
- Many RF signals are needed
  - 5712MHz, 2856MHz, 1428MHz, 476MHz, 238MHz and Trigger pulse
- Long transmission length
  - Accelerator: 400 m
  - From the gun to the experimental hall: 700 m
    - Some experiments (pump-probe etc.) demand a precise time reference.

Design Overview

- Optical RF and timing distribution system
  - Attenuation of an optical fiber is much smaller than a metal cable
  - Need to stabilize the fiber length (1 μm = 5 fs)
- Low-level RF control system
  - IQ (In-phase and Quadrature) modulation and demodulation
  - High-speed D/A and A/D converters for baseband signals



Design Concept

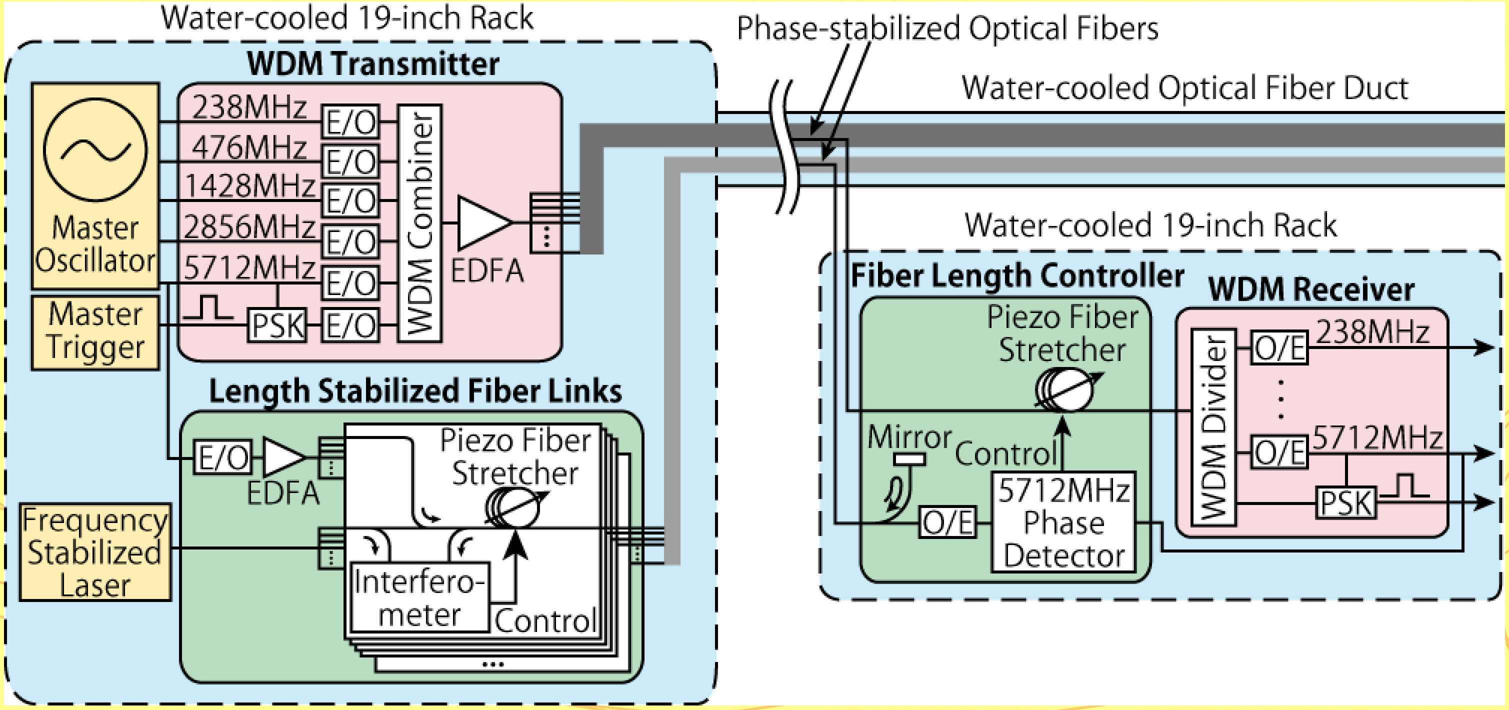
- Eliminate fluctuation sources as much as possible before applying active feedback loops.
  - Select stable components (ICs, cables, passive elements …)
    - Small temperature coefficient
    - Low-noise electric device
  - Stabilize the temperature of each component.
  - Provide low-noise electric power.
  - Reduce vibration of cables
- If there still remain any fluctuations, we use active feedback loops.

Optical RF and Timing Distribution System

- Wavelength Division Multiplexing (WDM) technique
  - To combine all signals to one fiber.
- Phase-stabilized optical fiber (~ 1 ps/km/K)
- Water-cooled 19-inch rack and water-cooled optical fiber duct
  - To reduce the thermal drift of the RF phase and amplitude
- Length-stabilized fiber link
  - Additionally prepared for the phase reference.
  - Michelson interferometer monitors the fiber length.
  - Fiber stretcher controls the fiber length.
  - Time drift of the WDM fiber is controlled at the receiver side.

Passive ~100fs stability

Active ~10fs stability

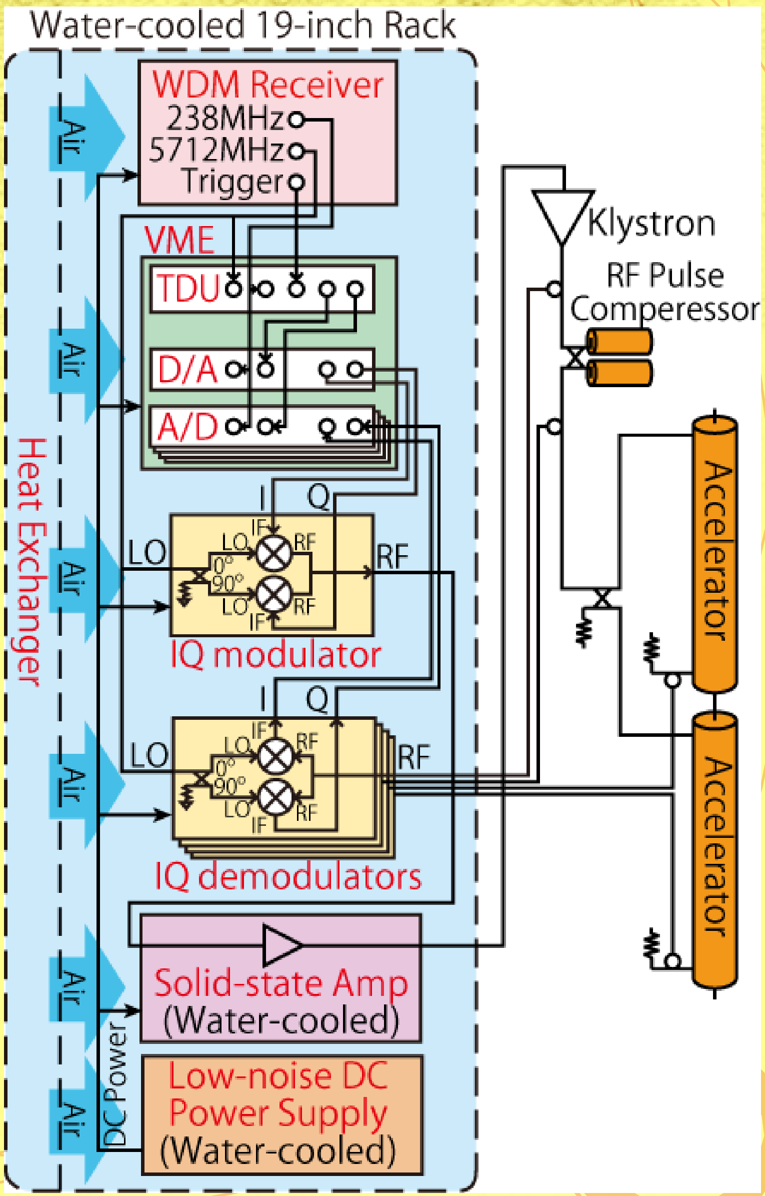


Low-level RF Control System

- IQ modulator produces the acceleration RF signal with appropriate phase and amplitude.

$$V(t) = I(t)\cos(\omega t) + Q(t)\sin(\omega t)$$

- IQ demodulator detects the phase and amplitude of the acceleration RF.
- Baseband waveforms are processed by VME high-speed D/A and A/D converter boards.
    - Sampling rate: 238 MSPS
    - Resolution: 14 bits (D/A) and 12 bits (A/D)
- All modules are enclosed in a water-cooled 19-inch rack.
    - To reduce the thermal drift.
- DC power is distributed from a low-noise power supply
    - Clean and stable power
    - Small heat load for the 19-inch rack



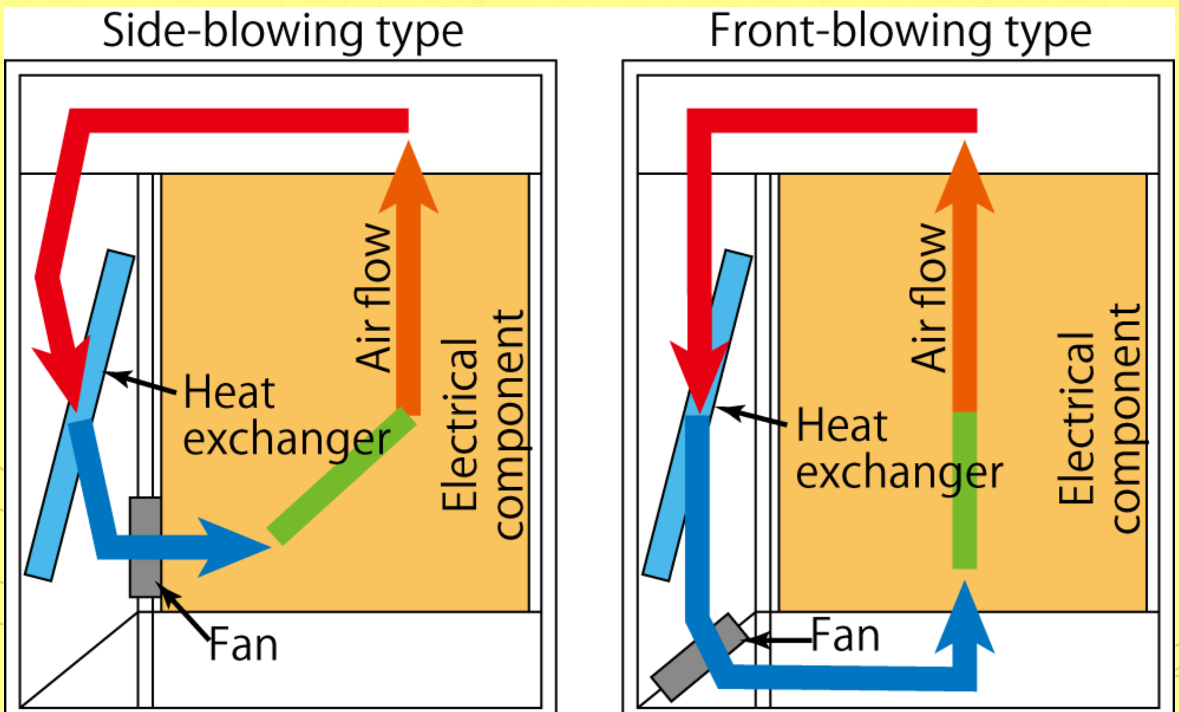
Water-cooled Enclosure

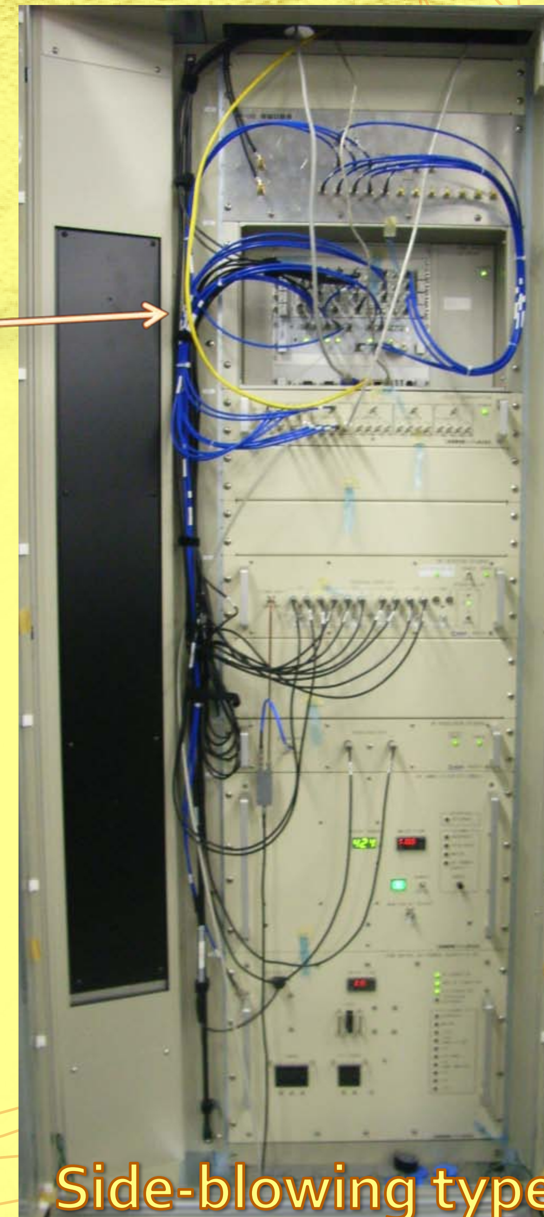
for the temperature stabilization

One of the features of our design

Water-cooled 19-inch Rack

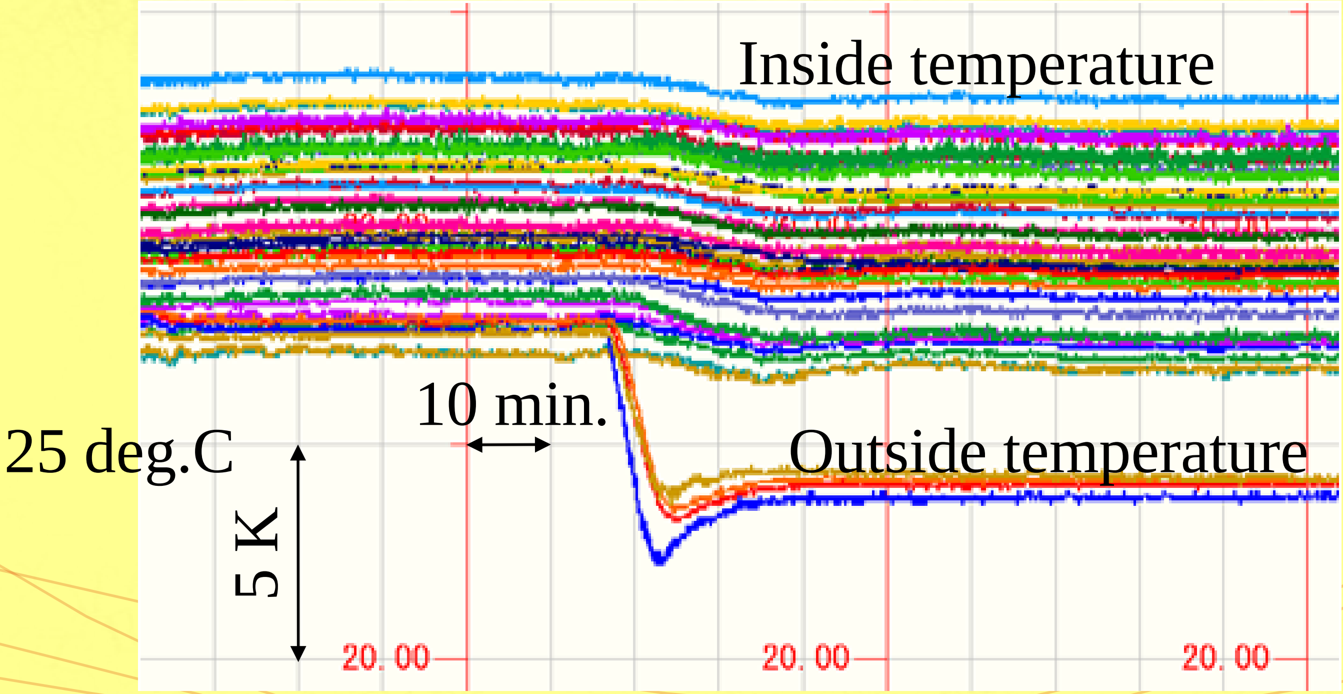
- Heat exchanger cools the circulating air.
- Temperature stability of the cooling water is 0.4 K (p-p).
  typically 0.2 K (p-p)
- Side-blowing type
  - Not to shake cables around the front panel.
  - Cable vibration is critical in the femto-second region!
  - VME boards are horizontally mounted.
- Front blowing-type
  - Other circuits (magnet power supply etc.)





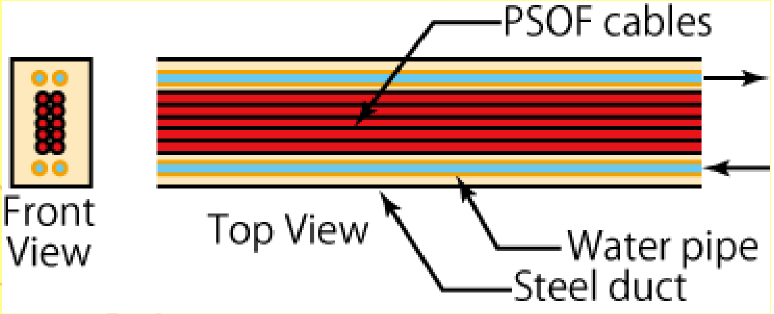
Temperature Stability of the Rack

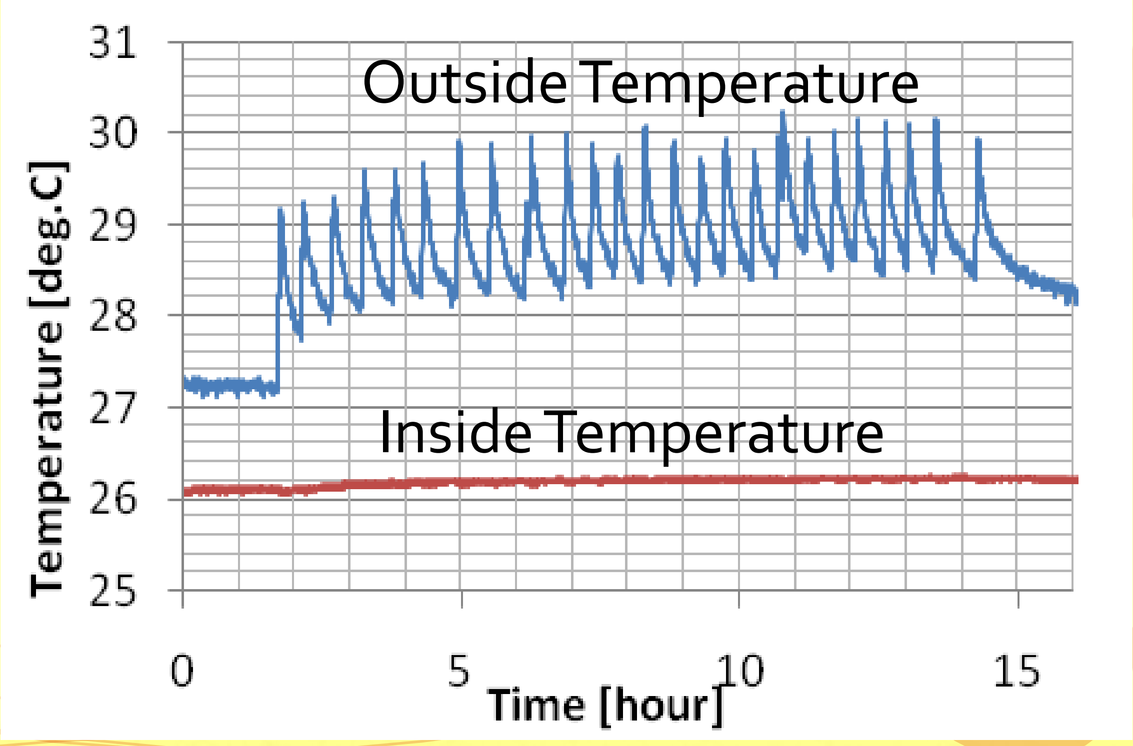
- We tested the temperature stability of the water-cooled rack.
- We intentionally decreased the water temperature by 0.4 K and outside temperature by 4 K at the middle of the measurement.
- Inside temperature drift was 0.42 K.
  - Appropriately follows the water temperature.
  - Almost no effect from outside.



Water-cooled Optical Fiber Duct

- Optical fiber temperature is stabilized by cooling water.
- Stability measurement
  - Water temperature fluctuation: 0.24 K (p-p)
  - Outside temperature fluctuation: 3.4 K (p-p)
- Inside temperature is regulated within 0.12 K (p-p)
  - < 200 fs (p-p) for 1km phase-stabilized optical fiber (PSOF)





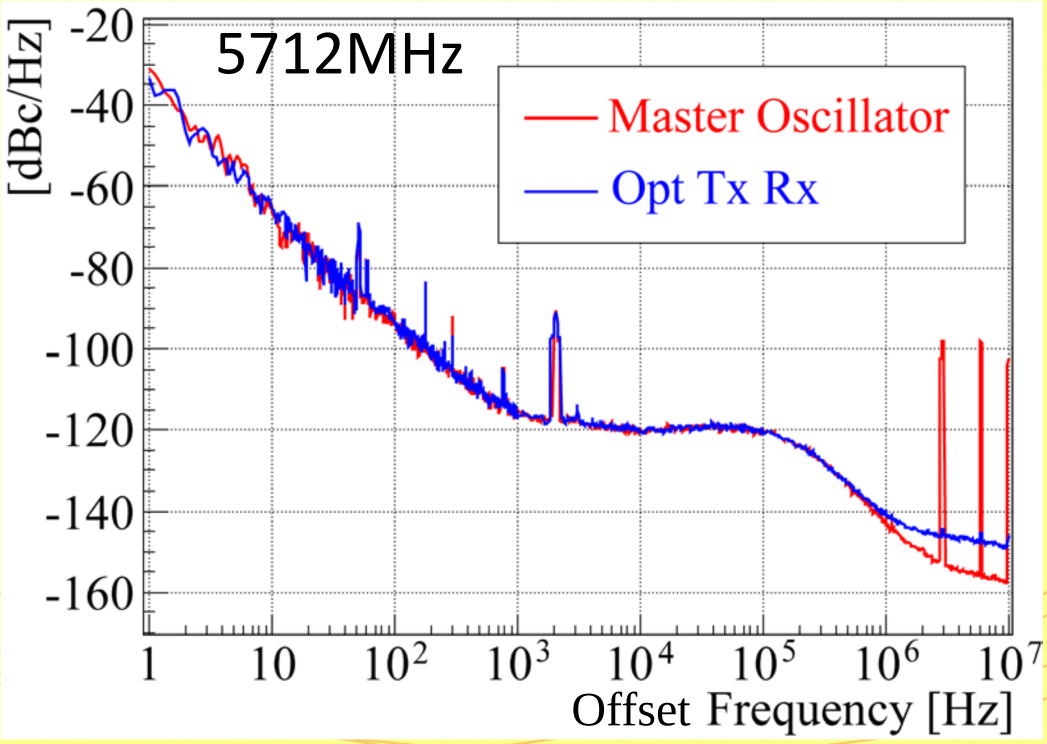
Photograph of the Klystron Gallery

- A part of the RF and timing system has been installed.

Performance Measurement of the RF and Timing System

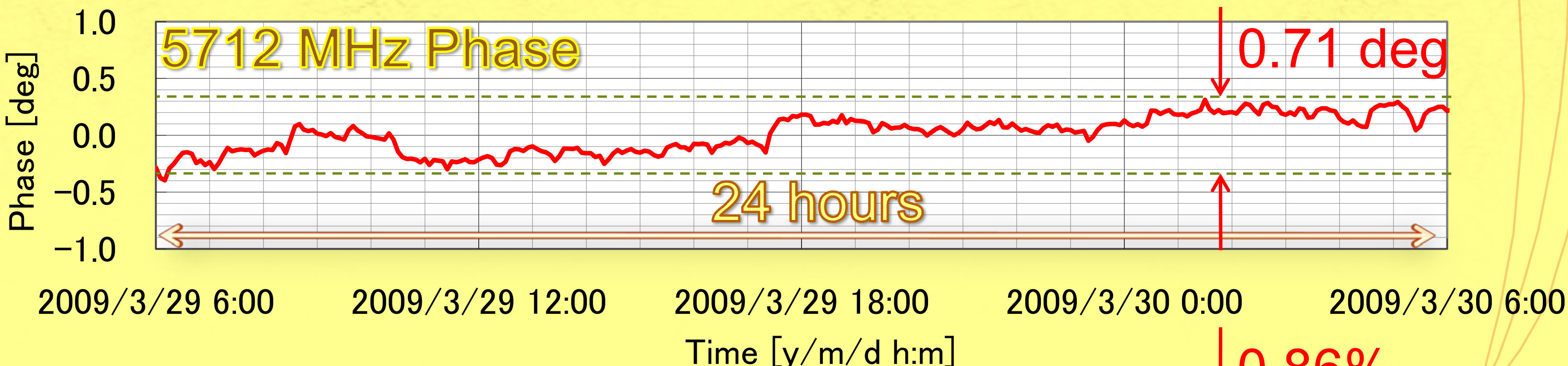
SSB Phase Noise

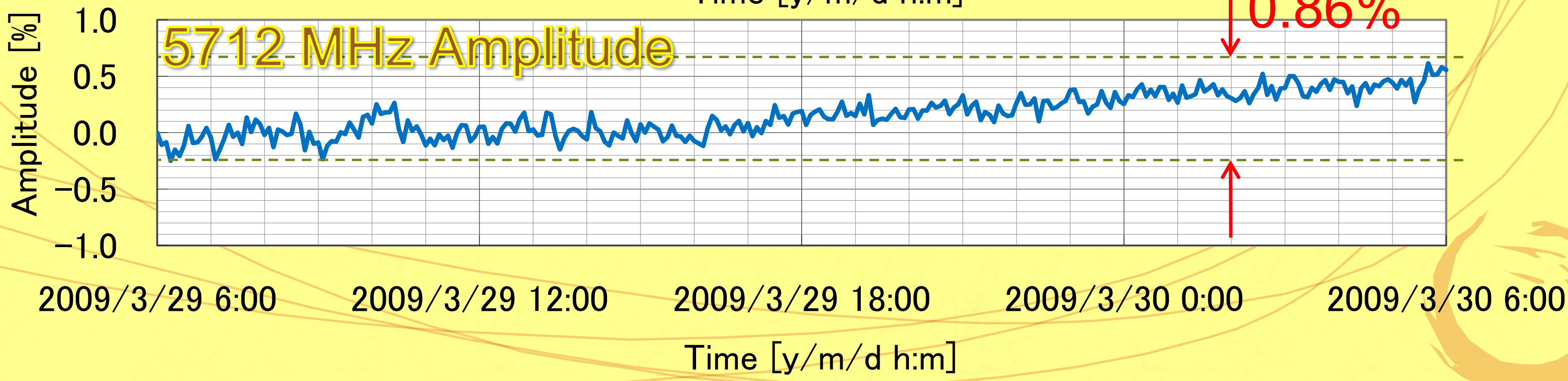
- We measured the SSB (Single Side Band) phase noise of the optical RF and timing distribution system.
  - Master oscillator itself
  - After transmission with the optical distribution system.
- No deterioration in < 1 MHz
- A little degradation above 1 MHz, but small enough (~7 fs)
- Time jitter is estimated to be 30 fs (rms)



Stability of the Optical System

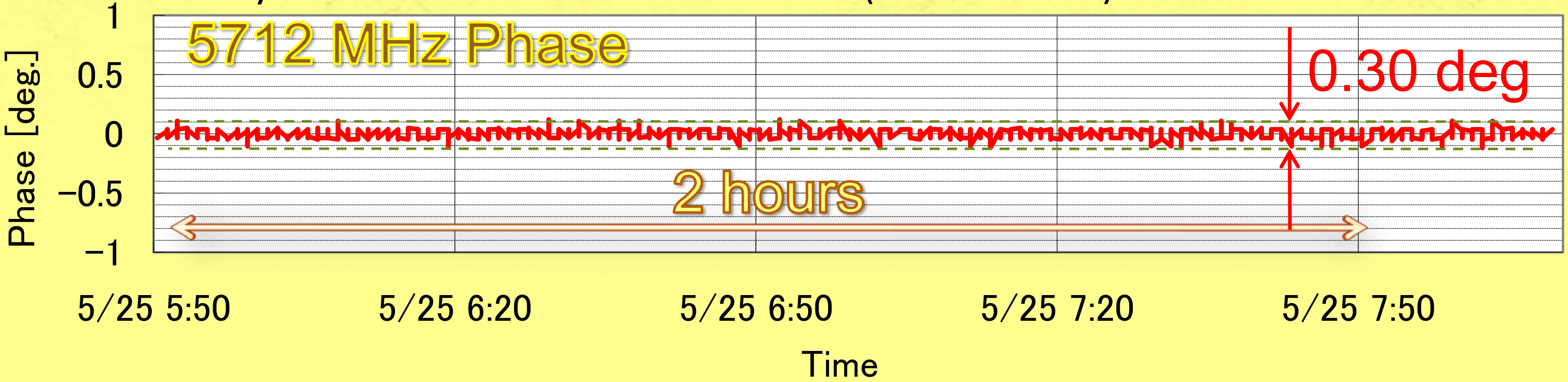
- Optical system was enclosed in a thermostatic chamber.
- Measurement period: 24 hours
- Temperature stability: 0.7 K (p-p)
- Phase stability: 0.71 degree (p-p)
- Amplitude stability: 0.86% (p-p)
- Drifts of detectors: 0.2 degree (p-p) and 0.06% (p-p)

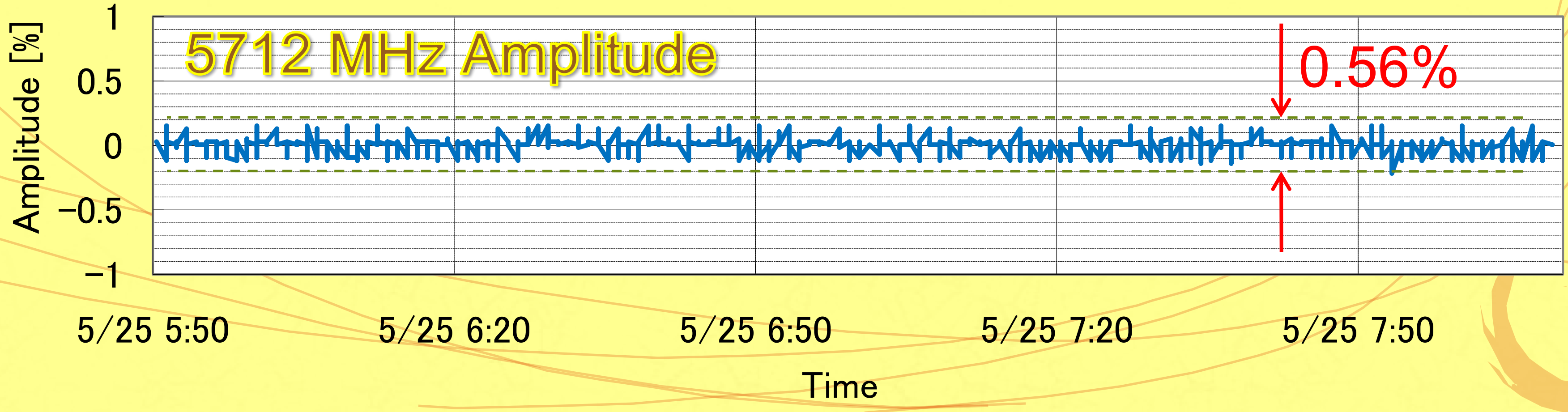




Stability of the Low-level RF System

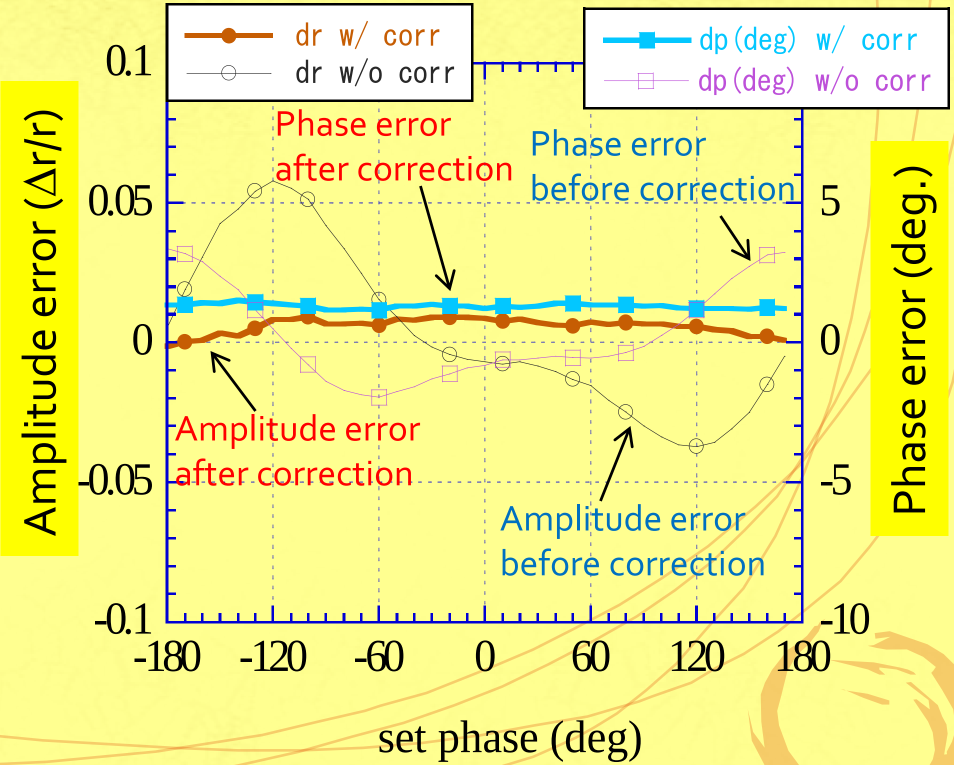
- VME-D/A → IQ modulator → Solid-state Amp. → IQ demodulator → VME-A/D
- Temperature stability: 0.3 K (p-p)
- Phase stability: 0.30 degree (p-p)
- Amplitude stability: 0.56% (p-p)
  - Resolution limit of 12-bit A/D converter.
  - Only random fluctuation can be seen. (No slow drift)





Error Correction of IQ modulator

- IQ modulator and demodulator have some errors.
  - Phase: ~ 5 degrees (p-p)
  - Amplitude: ~ 10 % (p-p)
  - These errors disturb the fine tuning of the accelerator.
  - Cause an interference between the feedback controls of RF phase and amplitude
- The error itself does not drift
  - Can be corrected by software.
- After correction
  - Phase error: 0.3 degree (p-p)
  - Amplitude error: 1% (p-p)
- Details are presented by T. Ohshima (WEP023).



Summary (1/2)

- XFEL/SPring-8
  - Generates coherent and intense x-rays with 0.1 nm wavelength region.
- Requirements for the acceleration RF field
  - Phase stability: 0.1 deg. (rms) of 5712 MHz (~ 50 fs)
  - Amplitude stability: 0.01% (rms)
- Precise RF and Timing system
  - Optical RF and timing distribution system
    - WDM technique and Length-stabilized fiber link
  - Low-level RF control system
    - IQ modulator and demodulator

Summary (2/2)

- Temperature regulation
  - Water-cooled 19-inch rack
  - Water-cooled optical fiber duct
  - Both enclosures can reduce the temperature fluctuation within 0.4 K (p-p).
- Phase stability
  - Optical system: 0.71 degree (p-p) of 5712 MHz
  - Low-level RF system: 0.30 degree (p-p) of 5712 MHz
  - Sufficient for XFEL/SPring-8
- Amplitude stability
  - Optical system: 0.86% (p-p)
  - Low-level RF system: 0.56% (p-p)
  - This drift is suppressed by a klystron that is operated at saturation point.

Acknowledgements

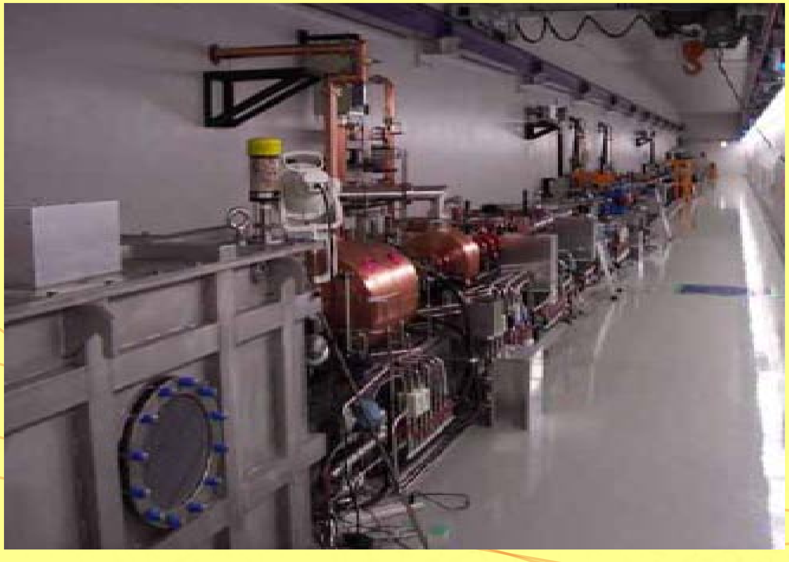
- We thank
  - **Mitsubishi Electric TOKKI System**
  - **Kinden**
  - **And many other companies**

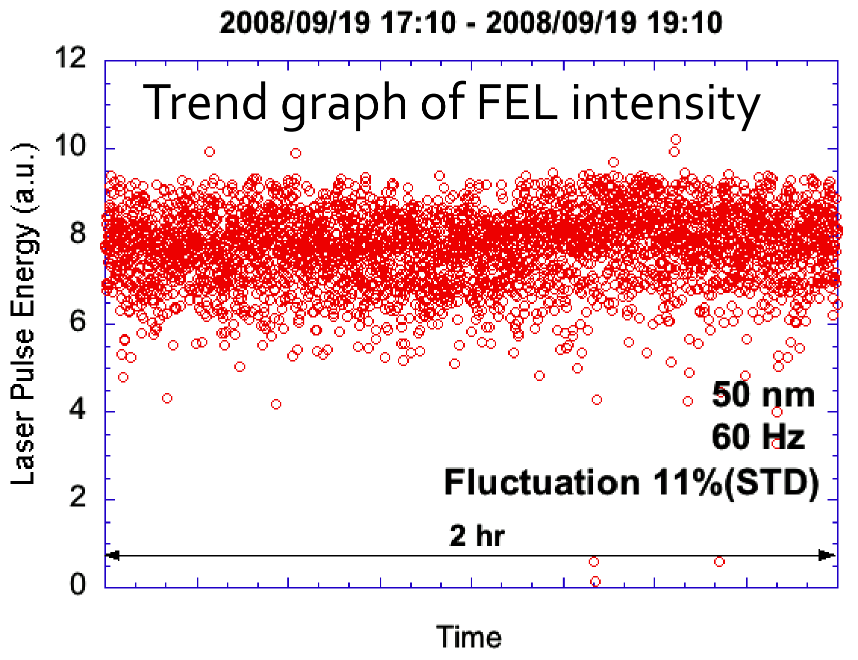
  for their grate efforts to develop the precise RF and timing system.
- Thank you for your attention!

Backup

SCSS Test Accelerator

- Extreme ultraviolet (EUV) FEL facility
  - Wavelength: 50 – 60 nm for saturated output
  - Beam energy: 250 MeV
- Saturated EUV laser light has been stably generated since 2006.



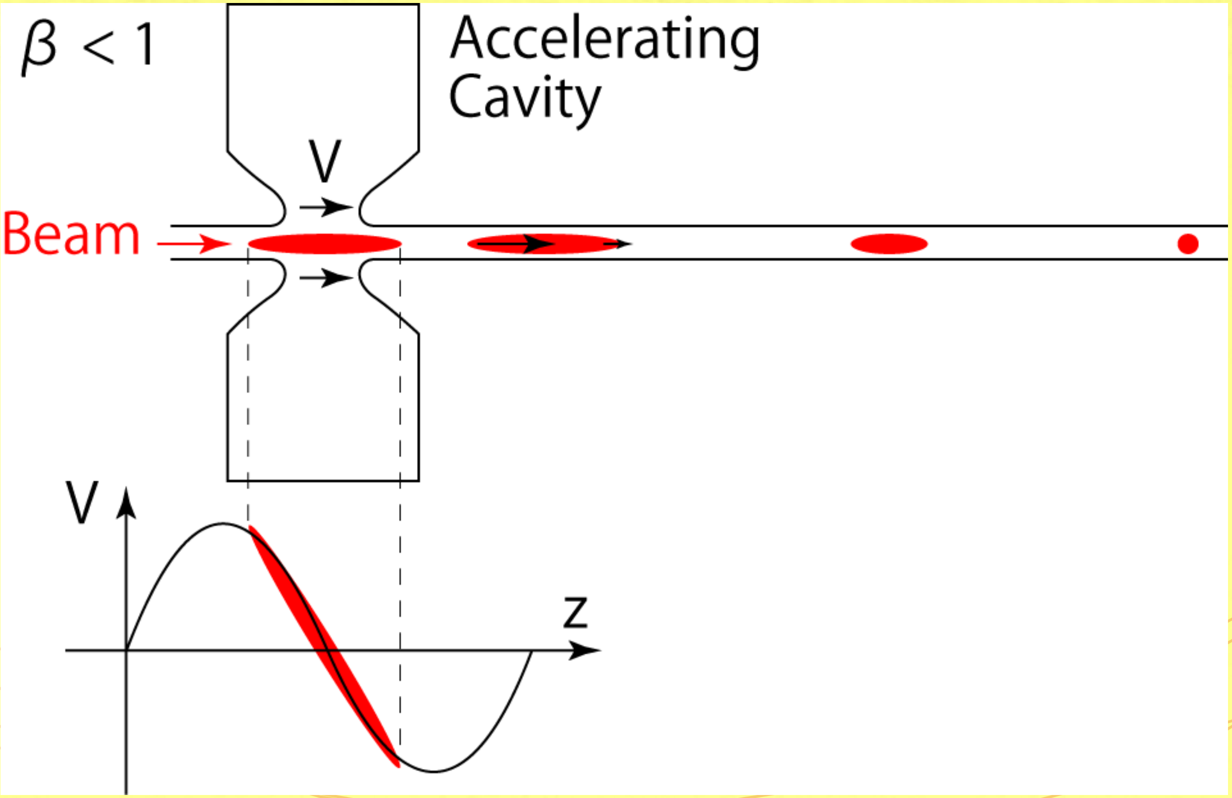


XFEL Machine Parameters

Beam Energy	8 GeV
Bunch Charge	0.3 nC
Normalized Slice Emittance	0.7 π mm mrad
Repetition Rate	60 pps maximum
Peak Current	3 kA
Bunch Length	30 fs (FWHM)
Beam Radius	40 mm (RMS)
Undulator Period	18 mm
Undulator K-value	2.2 maximum
Undulator Gap	3 mm minimum
Number of Periods	275 x 18 = 4950

Velocity Bunching

- For a low-energy beam (~1MeV)
- Head electrons are decelerated and tail electrons are accelerated by an accelerating cavity.
- Tail electrons approach head electrons.



Peak Current and FEL Gain

FEL parameter

Peak current

$$\rho = \left[\frac{I_e \gamma \lambda^2}{16\pi I_A \sigma_x \sigma_y} \left(\frac{K[JJ]}{1+K^2} \right)^2 \right]^{1/3}$$

FEL gain length

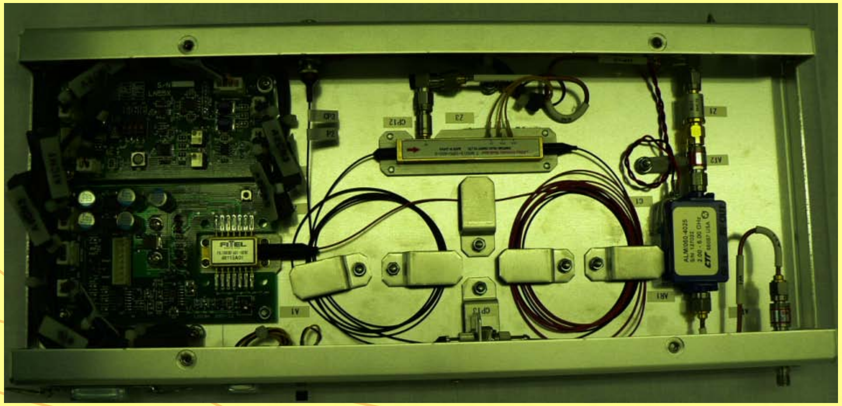
$$L_{G1D} = \frac{\lambda_u}{4\pi\sqrt{3}\rho}$$

FEL power growth

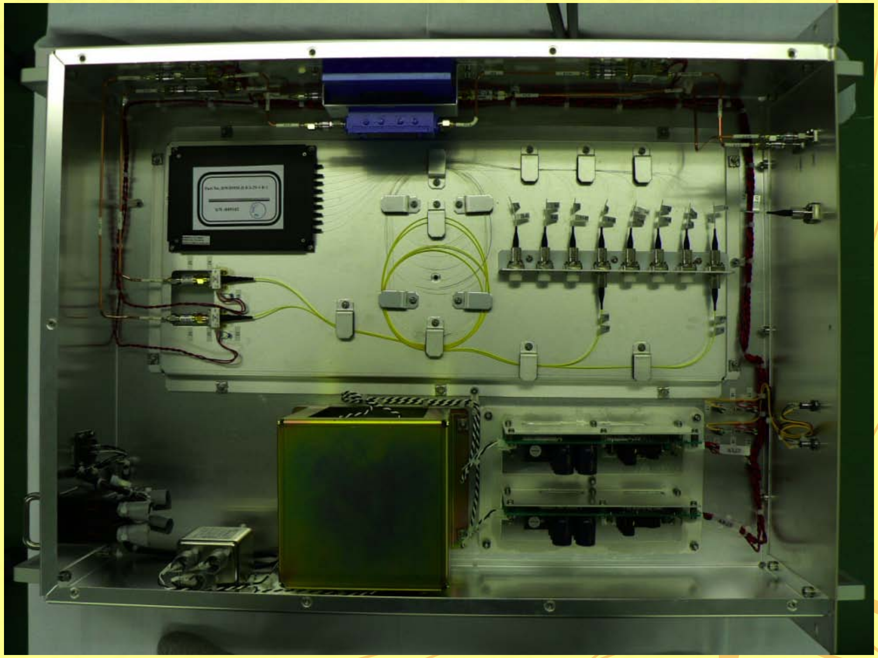
$$P_{FEL} \propto \exp(\alpha \cdot L_G)$$

E/O and O/E Converters

- E/O Converter
  - Light source: DFB-LD (Distributed FeedBack Laser Diode)
  - $LiNbO_3$ Mach-Zehnder modulator
- O/E Converter
  - Fast photo-diode

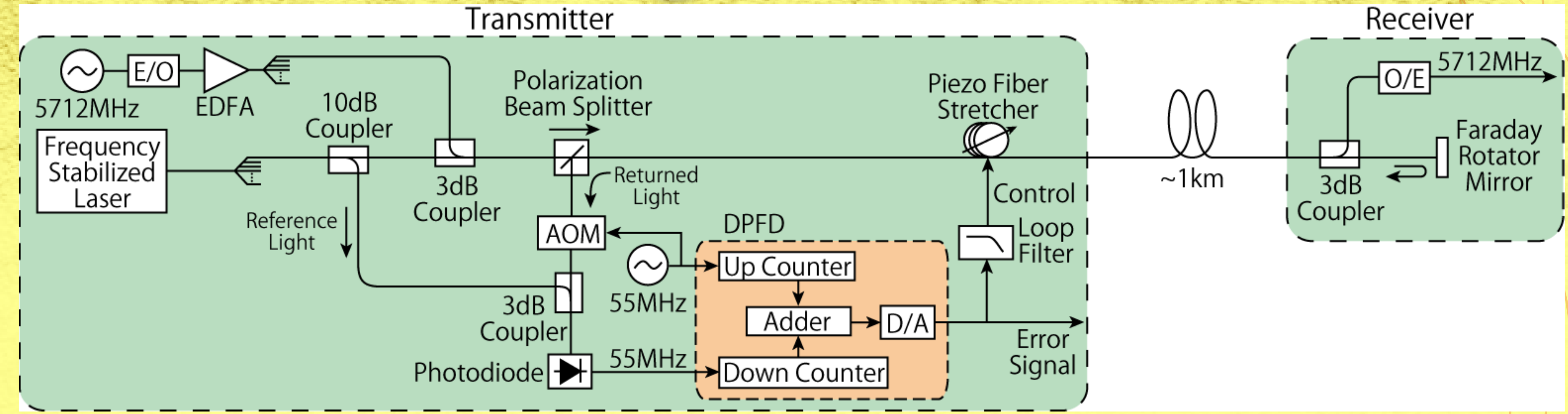


E/O Converter



O/E Converter

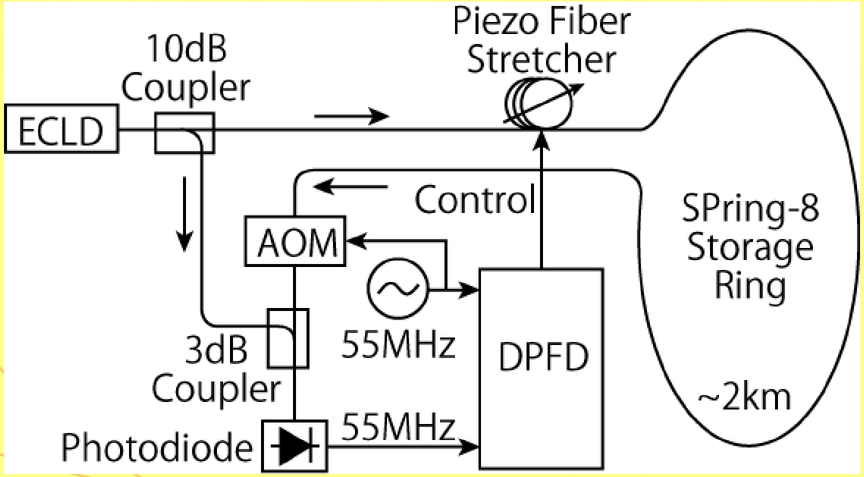
Fiber Length Stabilization

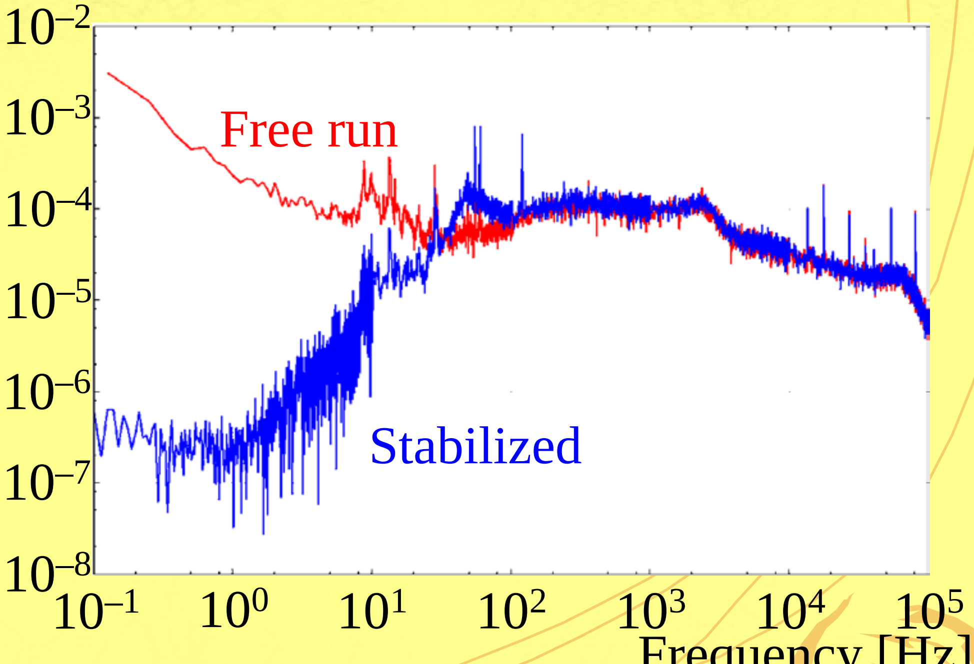


- Frequency-stabilized laser
  - Length standard
  - Frequency is locked to C_2H_2 absorption line.
- Transmitted light is returned by a Faraday rotator mirror.
- Polarization beam splitter discriminates the transmitted light and the returned light.
- Returned light is fed into an interferometer to monitor the fiber length.
  - 55MHz Acousto-optic modulator (AOM) enables a heterodyne detection of the optical phase.
  - Digital phase frequency discriminator (DPFD) for the phase detection.
- Piezo-electric fiber stretcher controls the fiber length.

Fiber Length Stabilization Experiment

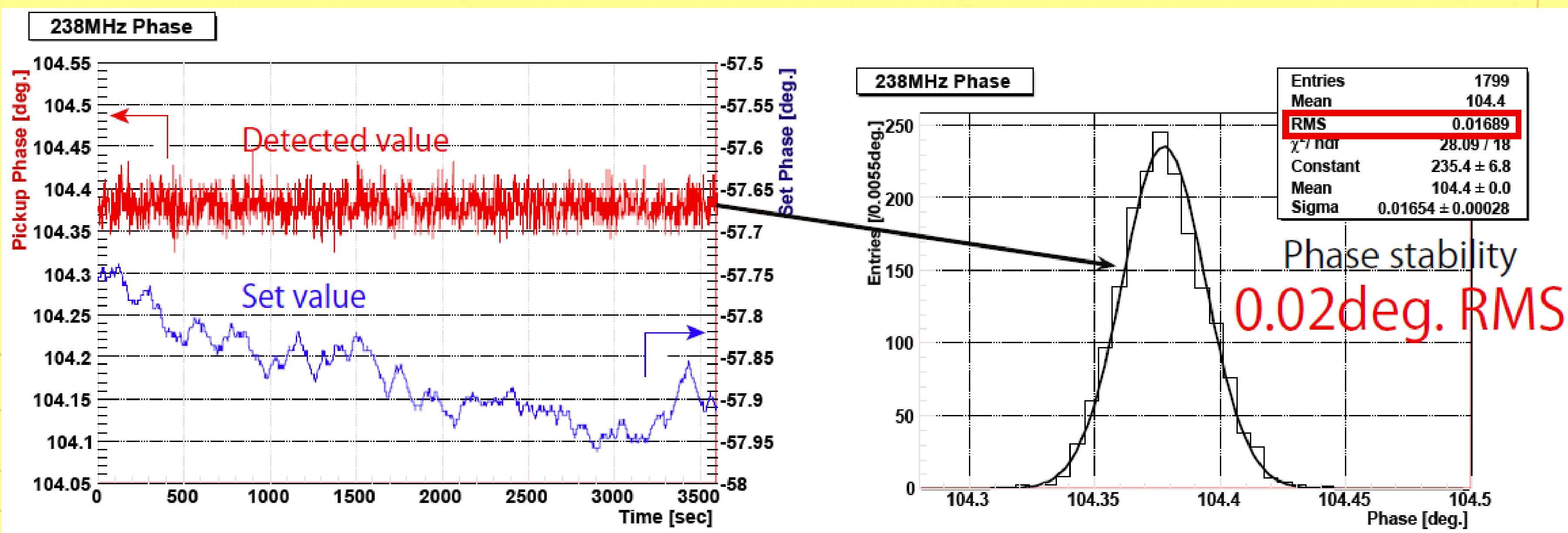
- We tested the fiber length stabilization system by using a optical fiber along the SPring-8 storage ring.
- Length fluctuation below 30 Hz was suppressed to 1 μm level.





PID Feedback Loop

- RF phase and amplitude detected by the IQ demodulator are fed back to the IQ modulator.
- PID (Proportional-Integral-Differential) algorithm
- Phase stability: 0.02 degree rms for 238 MHz
- Amplitude stability: 0.03% rms for 238 MHz



Stability of the Optical System