Design and Performance of the Synchronization System for SACLA

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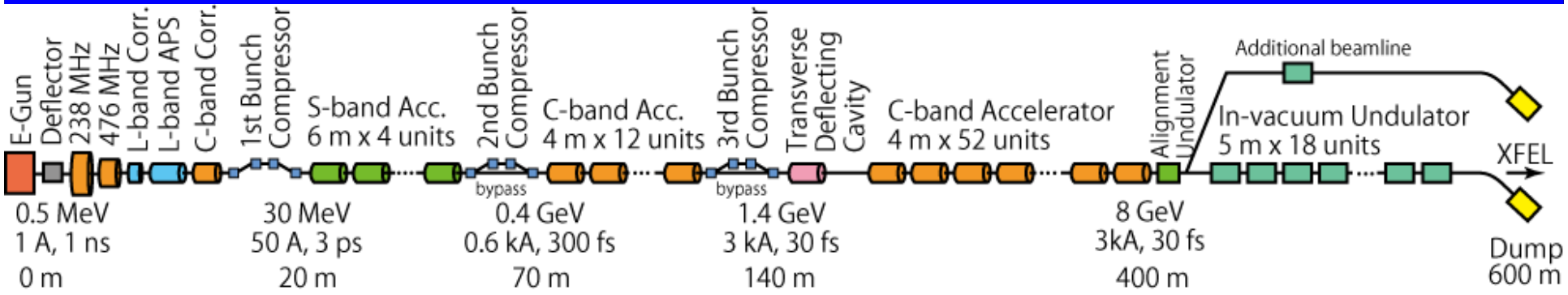
Outline

- Overview of SACLA
- Optical RF transmission system
  - Master oscillator
  - E/O and O/E converter
  - Fiber length stabilization
- Low-level RF control system
  - IQ modulator and demodulator
  - High-speed waveform generator (D/A) and detector (A/D)
- Suppression of temperature drift and power supply noise
  - Water-cooled 19-inch rack
  - Water-cooled optical fiber duct
  - Low-noise DC power supply
- Possible application to ERL
- Summary

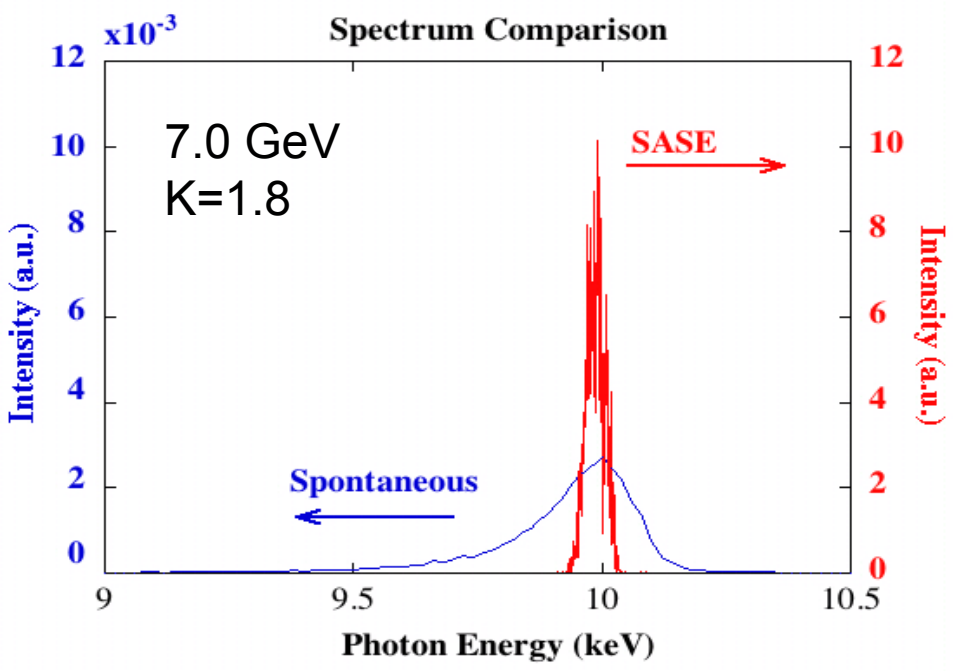
Overview of SACLA

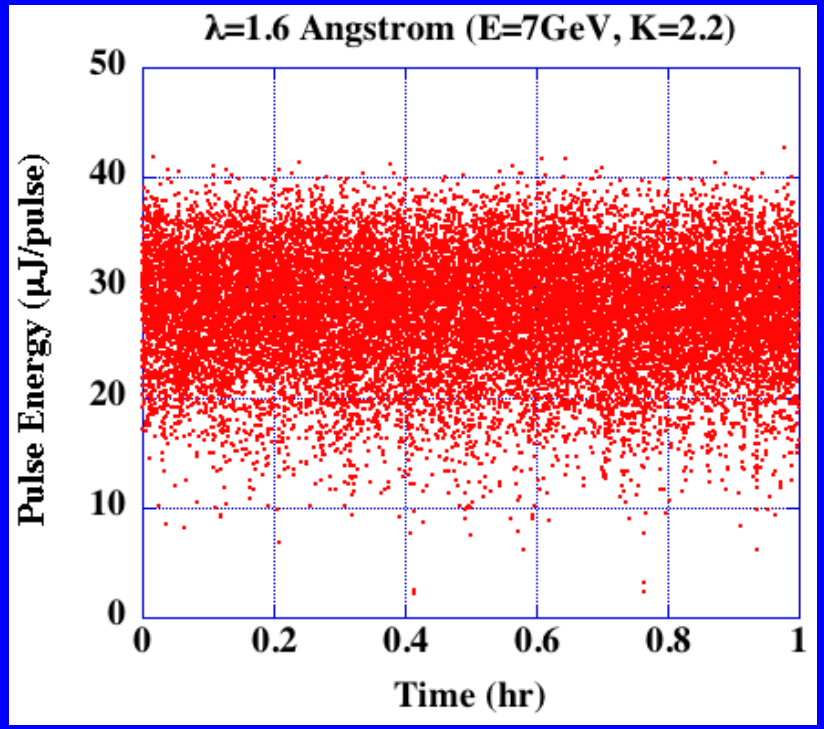
- 8GeV linear accelerator
  - 238 MHz, 476 MHz, L-band (1428 MHz), S-band (2856 MHz) and C-band (5712 MHz)
- Bunch compression
  - Velocity bunching in the low energy region
  - Three bunch compressors
  - Bunch length: 1 ns → 30 fs (FWHM)
  - Peak current: 1 A → 3 kA
- Coherent X-rays are generated by in-vacuum undulators.



XFEL Performance

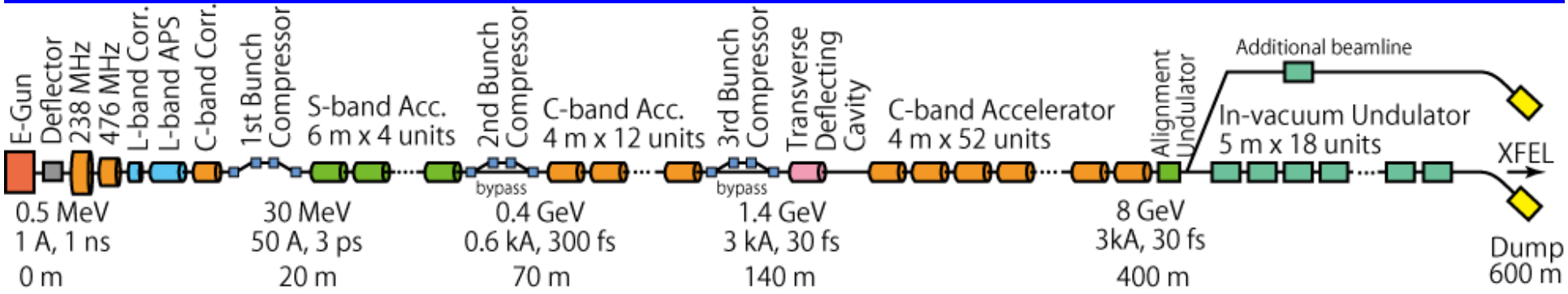
- Laser power amplification at wavelengths from 1.6 to 0.8 Angstroms
- Maximum laser power ~4 GW
- Intensity fluctuation ~18 %
- Laser being reproducible
  - without beam feedback keeping the peak current
  - at ~25% of peak intensity





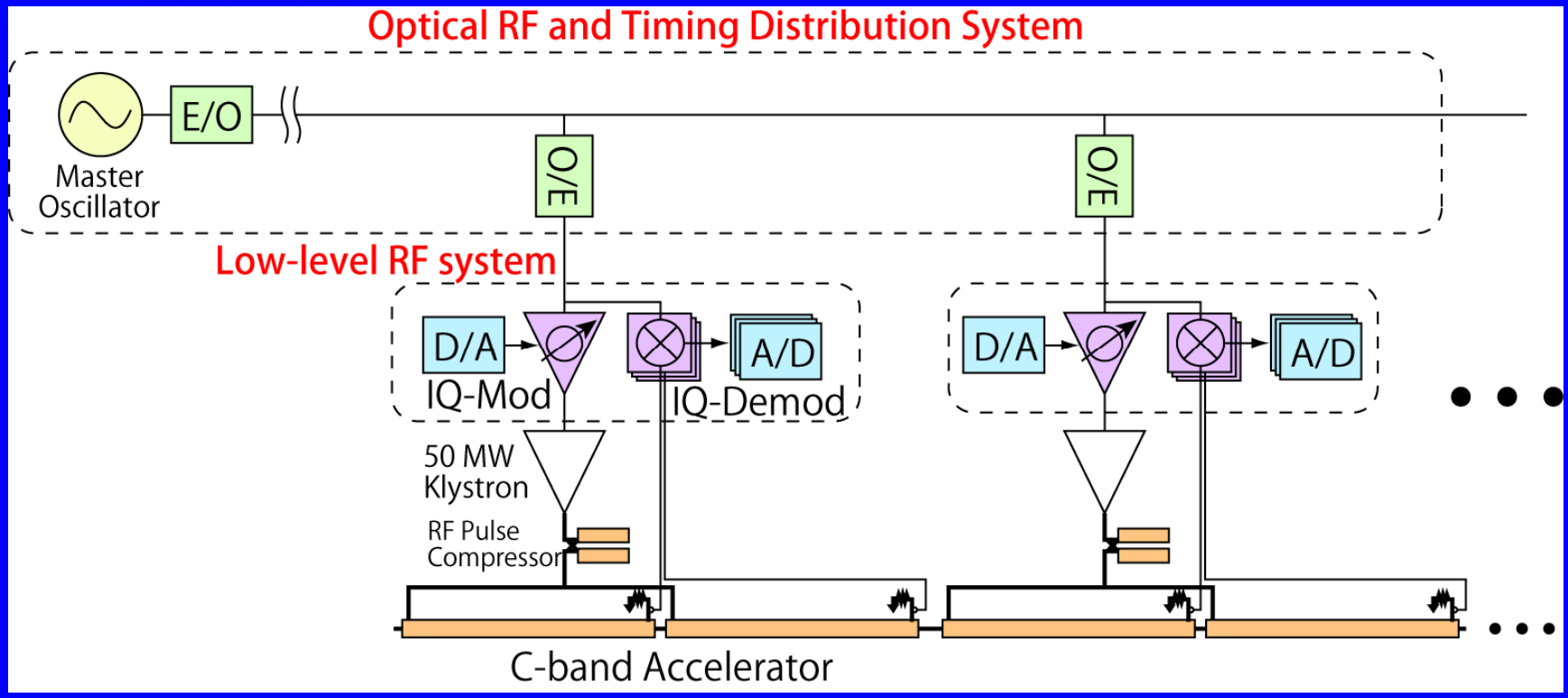
Requirements

- RF frequency: 5712, 2856, 1428, 476, 238 [MHz]
- Facility length: 700m
- Number of timing signal receivers: ~90
- Amplitude stability: 1×10^{-4} (rms)
- Phase stability: < 100fs (rms) (0.2deg. @ 5712MHz)
- For both accelerator and user

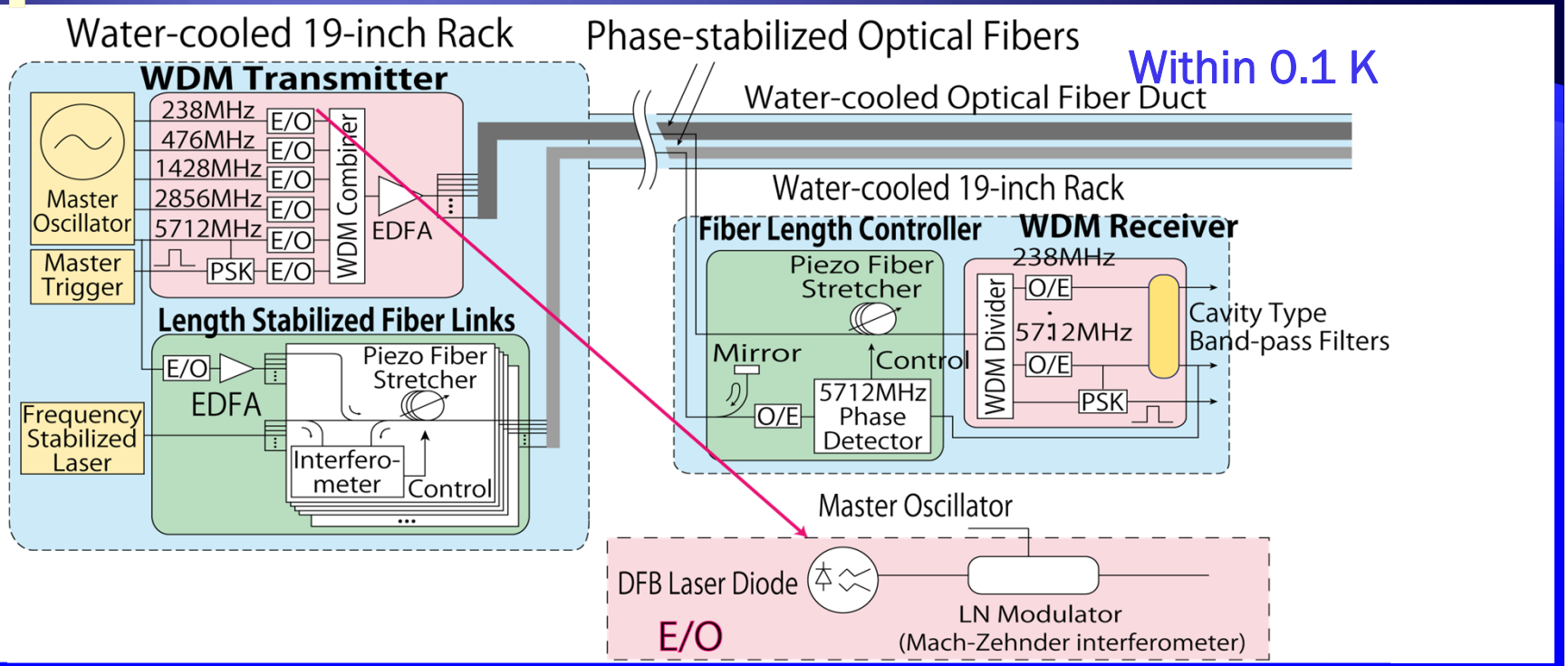


Synchronization System

- Optical RF and timing distribution system
  - Attenuation of an optical fiber is much smaller than a metal cable
- Low-level RF control system
  - IQ (In-phase and Quadrature) modulator and demodulator are employed to control the acceleration RF signal.



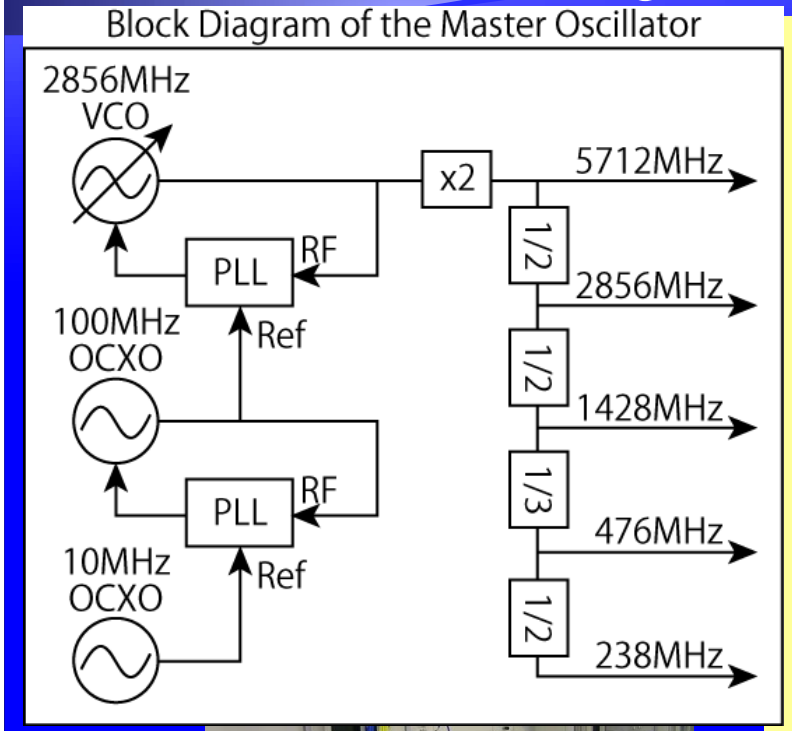
Optical RF Distribution

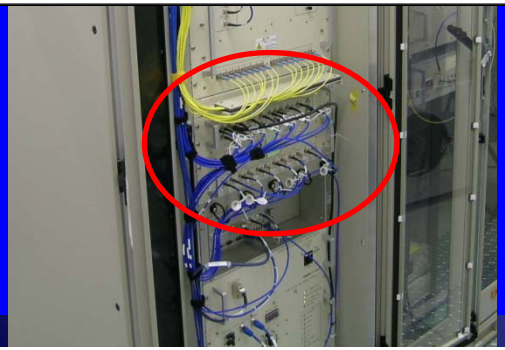


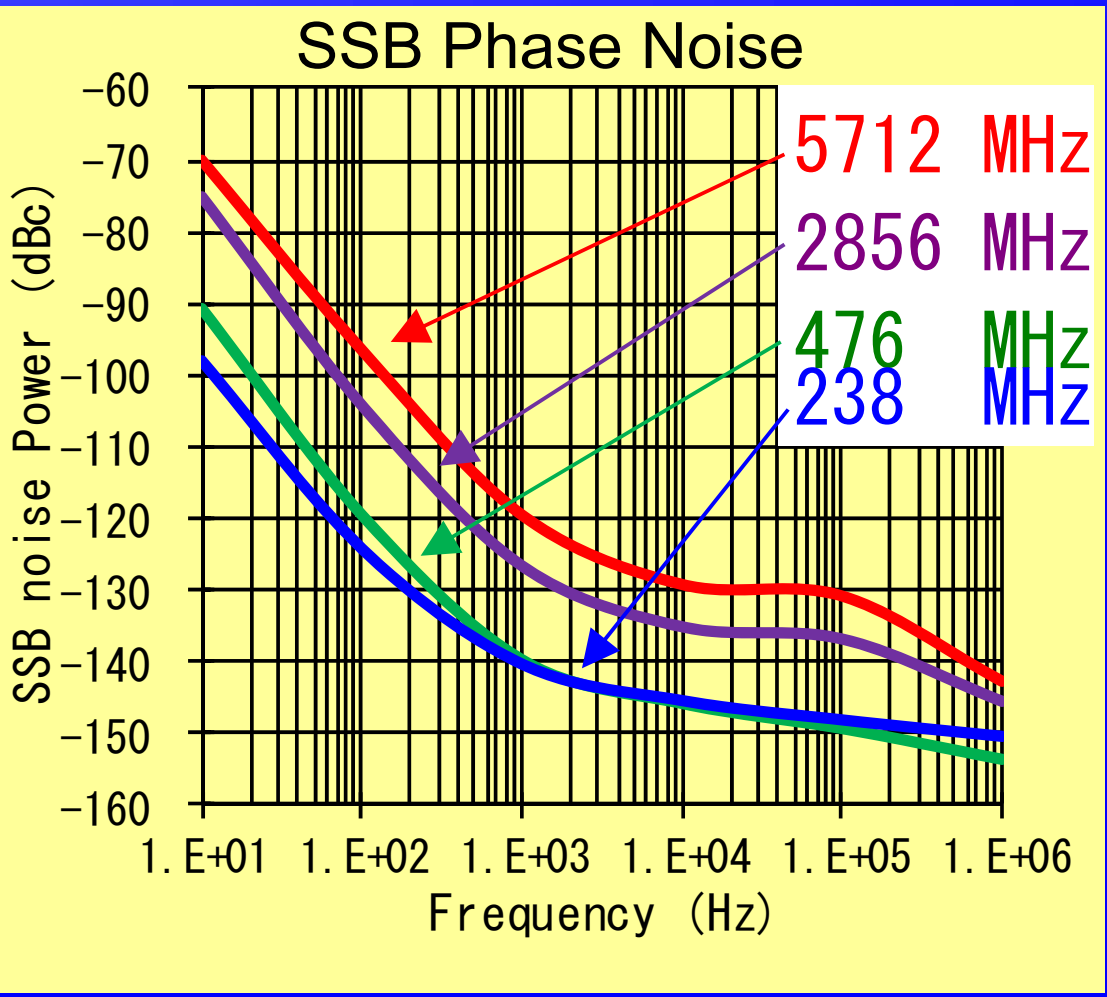
- E/O and O/E Converter
  - E/O: LN Modulator (Sinusoidal modulation)
  - O/E: Fast PIN Photodiode
- Wavelength Division Multiplexing (WDM)
  - To combine all signals to one fiber.
- Phase-stabilized optical fiber
  - Temperature coefficient: 2 ppm/K
- Water-cooled 19-inch rack and water-cooled optical 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.
  - Length stabilization system will be installed in the next year.

Master Oscillator

- 2856 MHz VCO is phase-locked to 100MHz OCXO and 10 MHz OCXO
- Sub-harmonic signals are generated by frequency dividers.

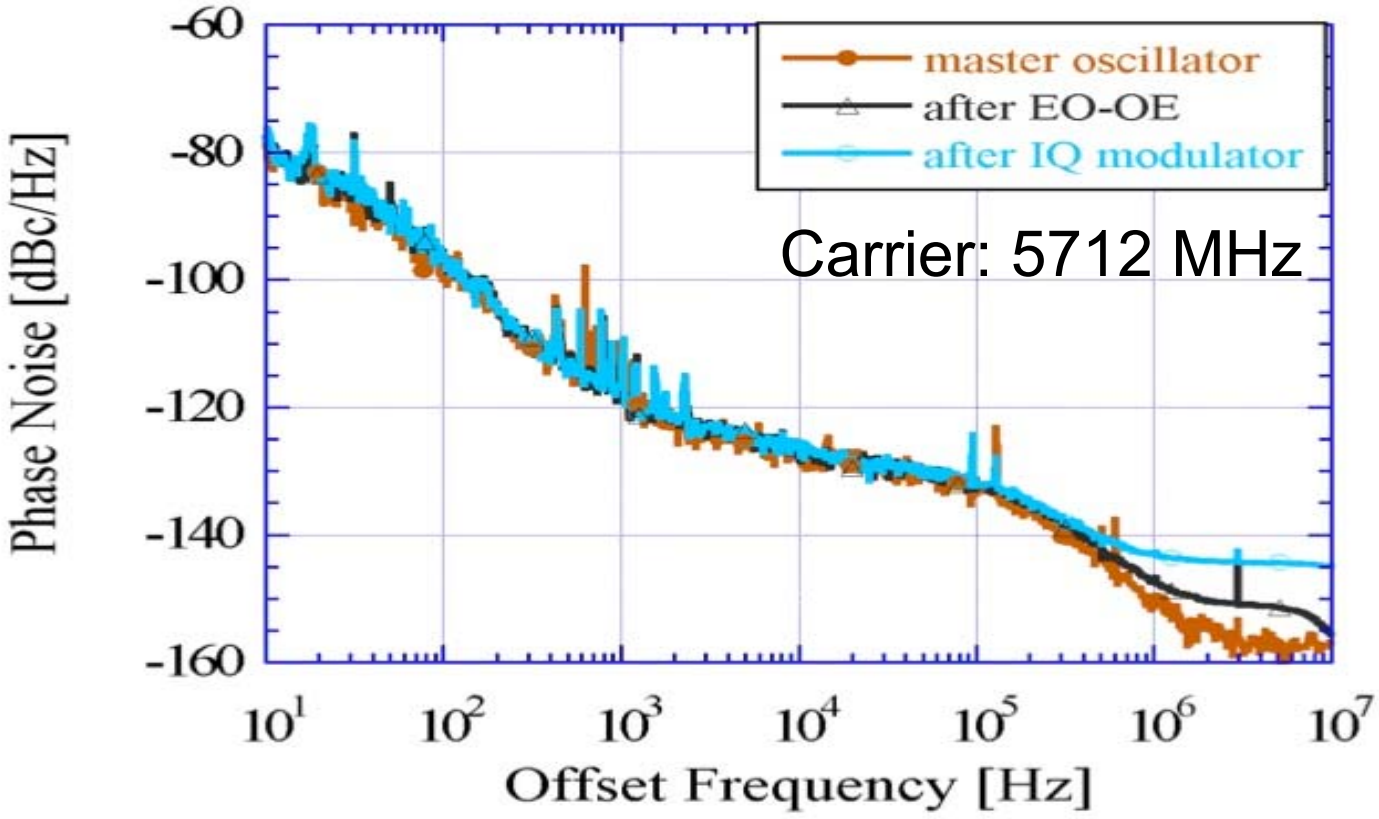




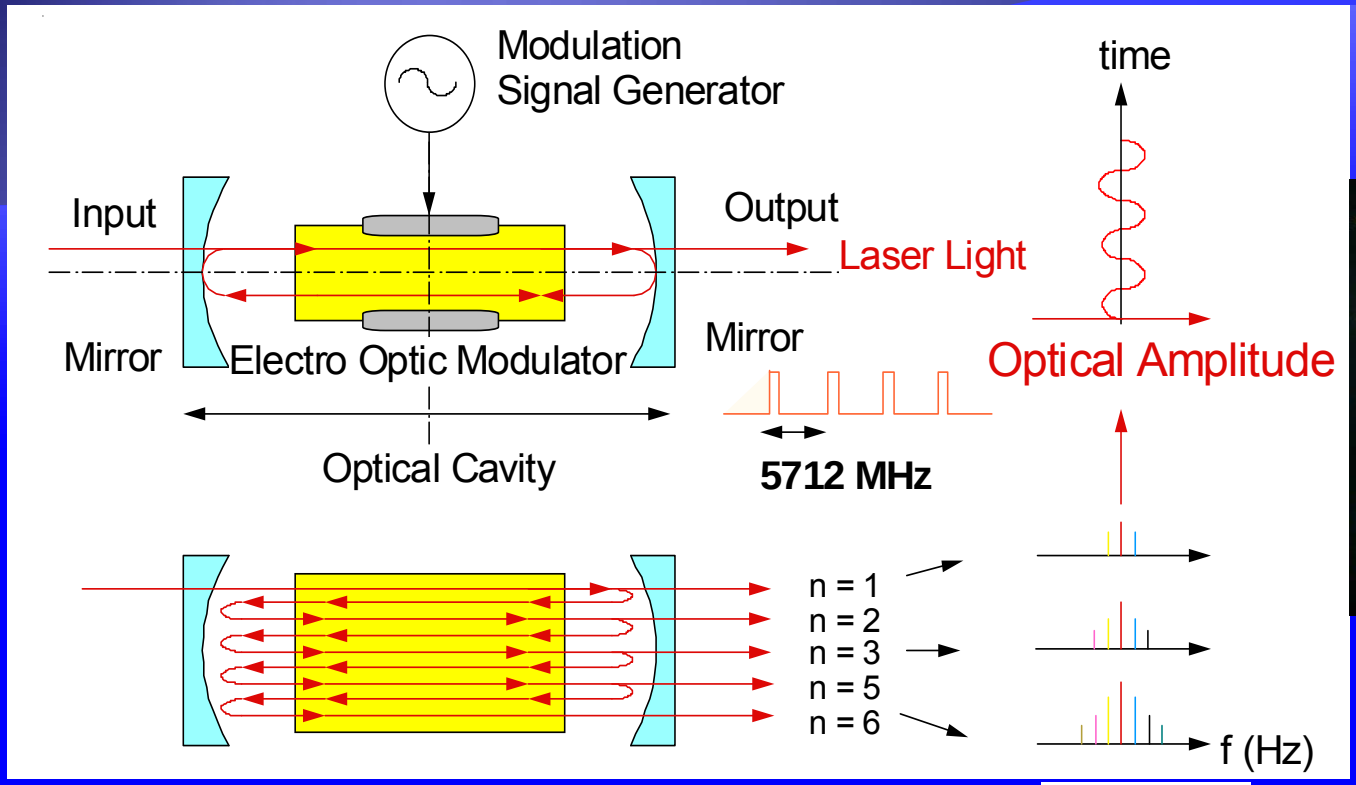


Phase Noise after 400 m Optical Signal Transmission

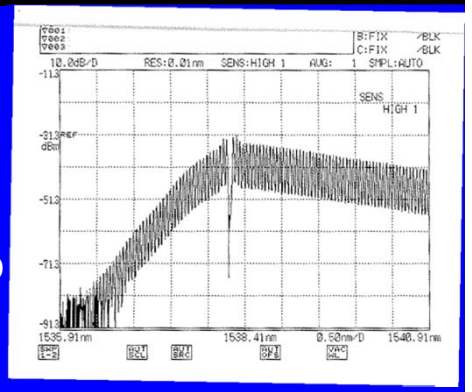
- Time jitter is 10 fs level.



Optical Comb Generator



5712 MHz Repetition,
1ps pulse width



In the optical comb generator, an electro-optic (E/O, LN) crystal is inserted into an optical Fabriot-Periot cavity.

The output rf signal of the master oscillator is added into the E/O crystal to generate the comb pulse having a period of the rf signal.

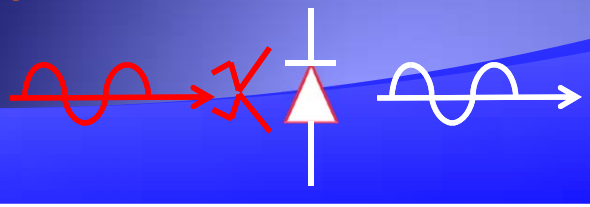
Optical comb pulse & its spectrum

Optical Comb Generator

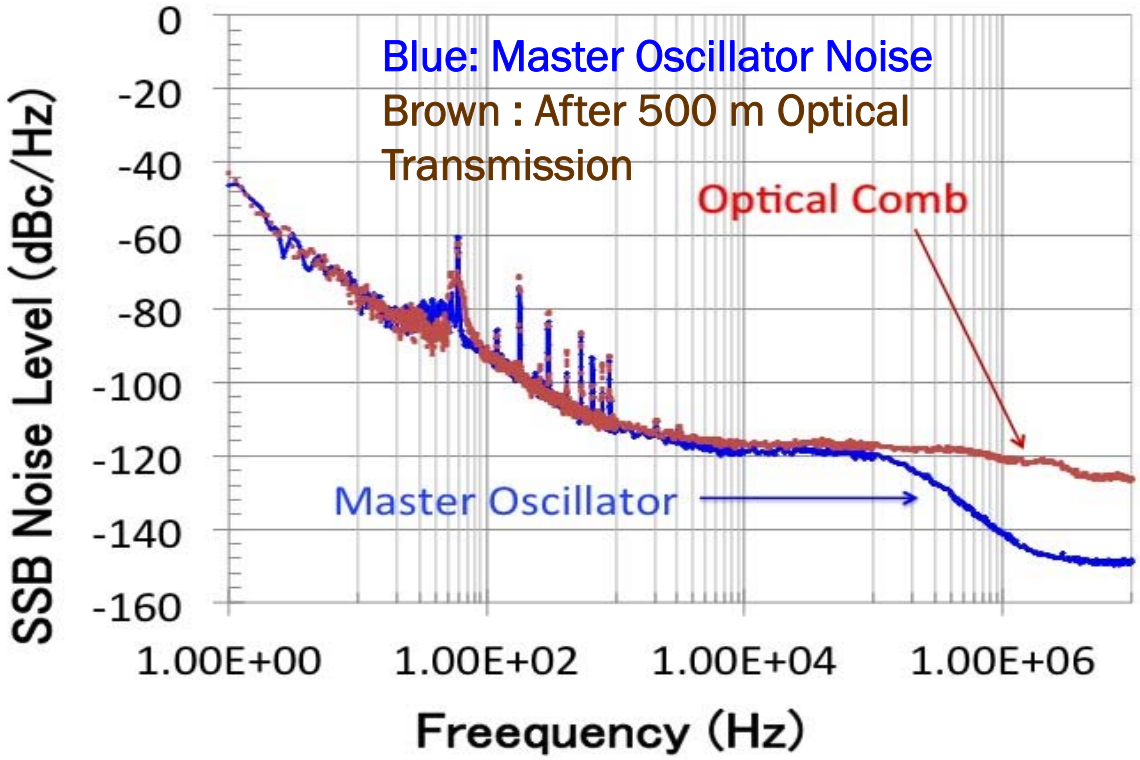
M.Kourogi, et al., Generation of Expanded Optical Frequency Combs, Edited by A.N Luiten, Frequency Measurements and Control, *Springer-Verlag Berlin Heidelberg*, 315-335 (2001).

SSB noises of sinusoidal & comb signals before/after 500 m optical fiber signal transmission

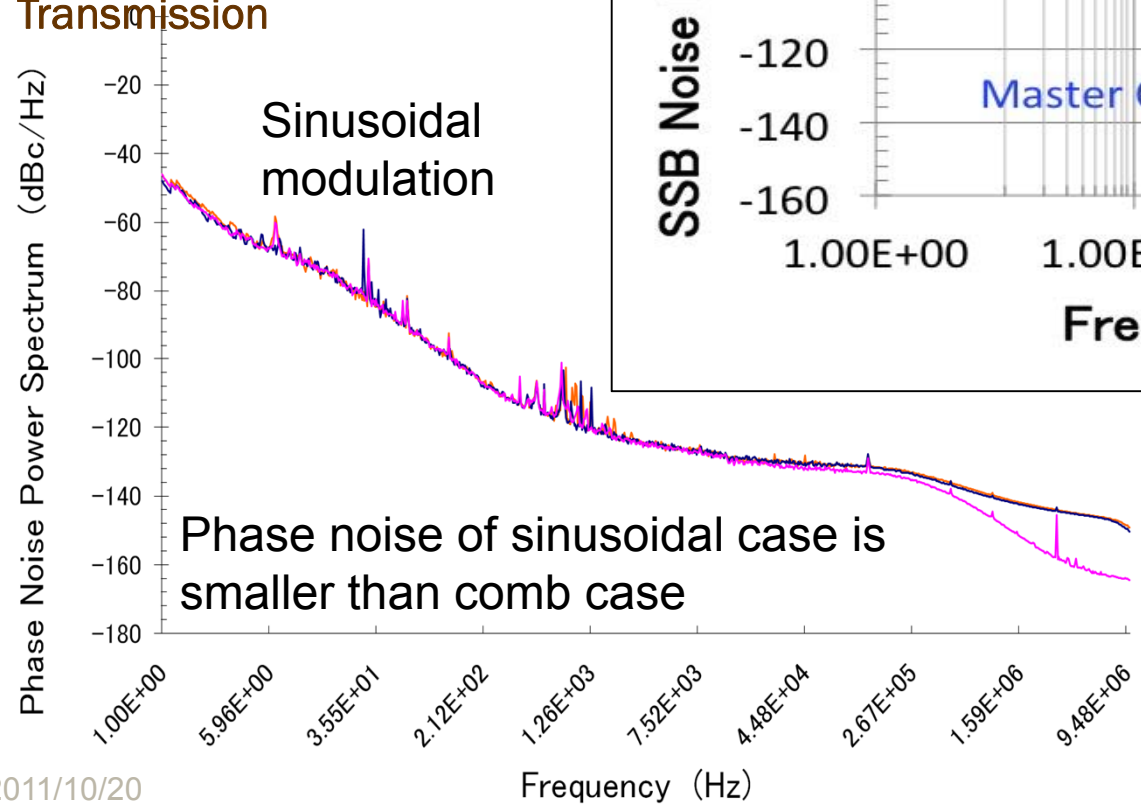
Optical PIN Photo Diode Electrical



Blue: Master Oscillator Noise
Brown : After 500 m Optical Transmission

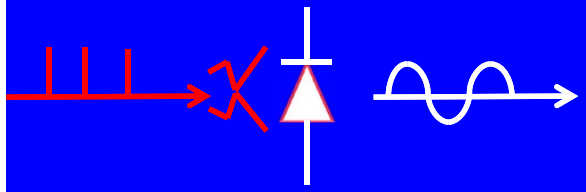


Pink: Master Oscillator Noise
Brown : After 400 m Optical Transmission



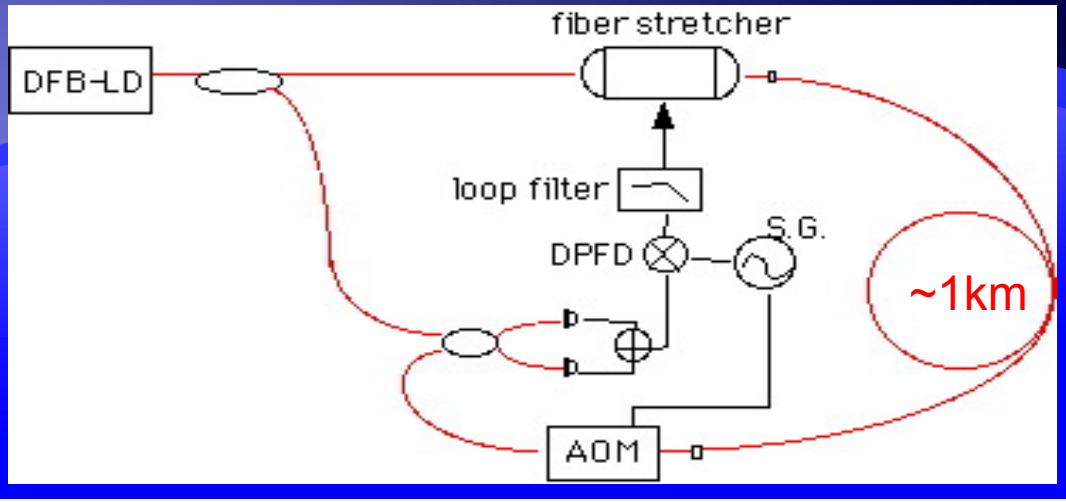
Comb pulse case

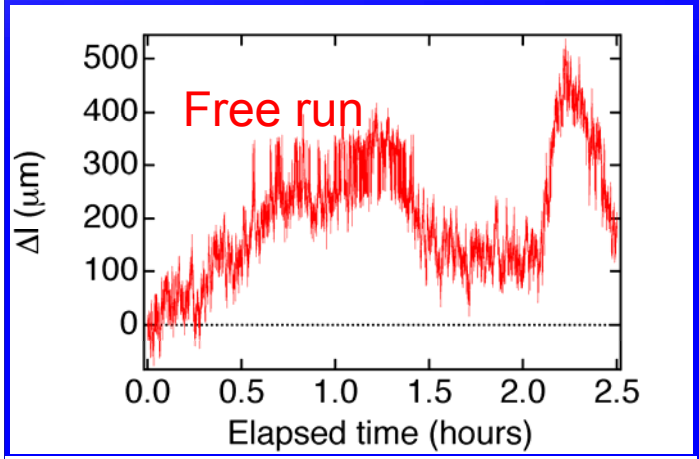
Optical Pin Photo Diode Electrical

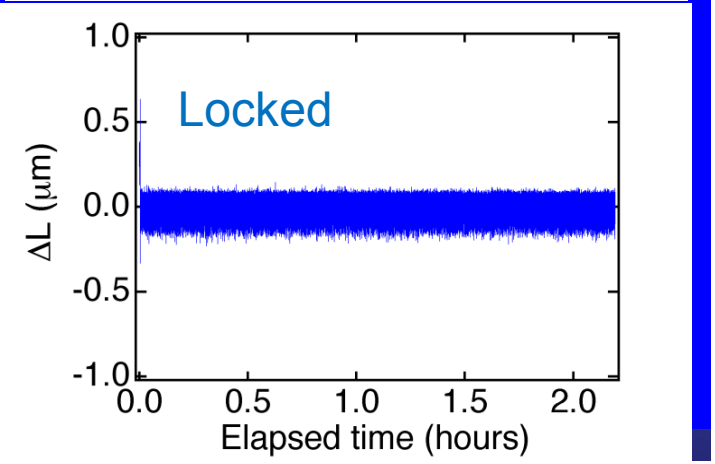


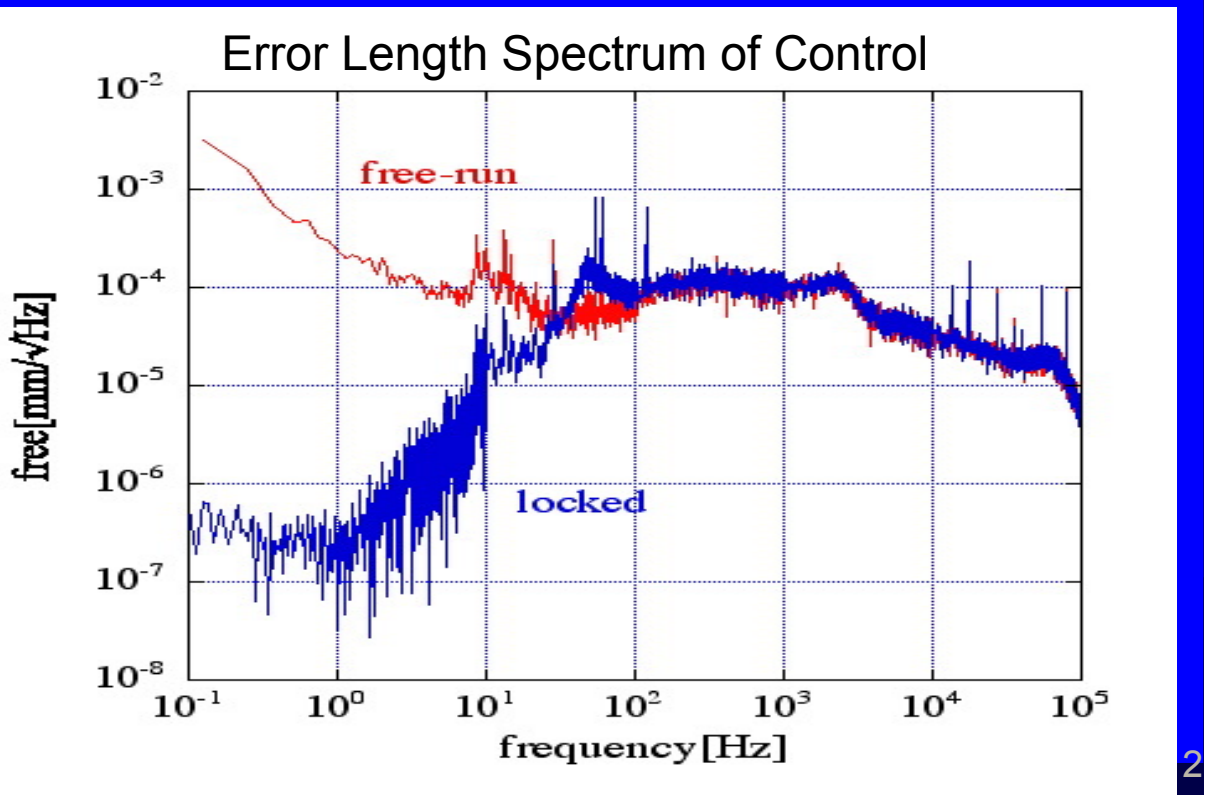
Experiment of Fiber Length Control

Use the 1 km phase stabilized optical fiber cable settled along the circumference of the SPring-8 ring



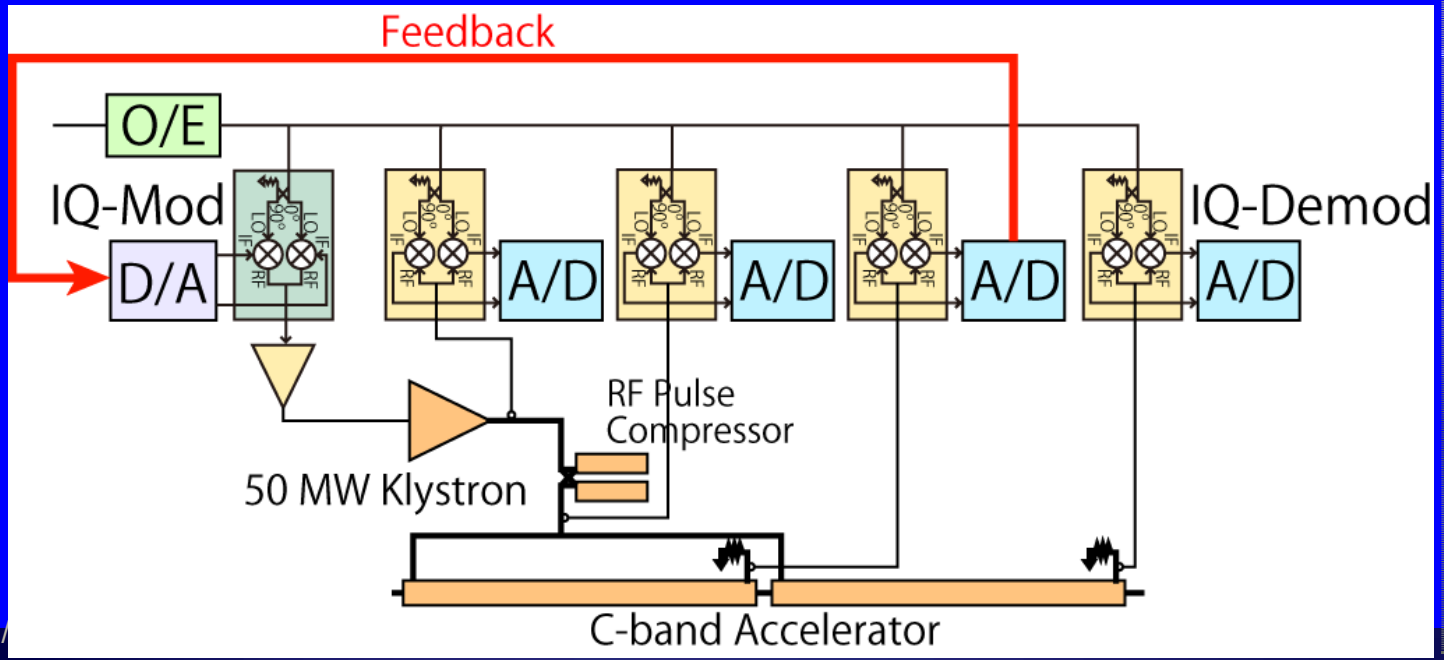


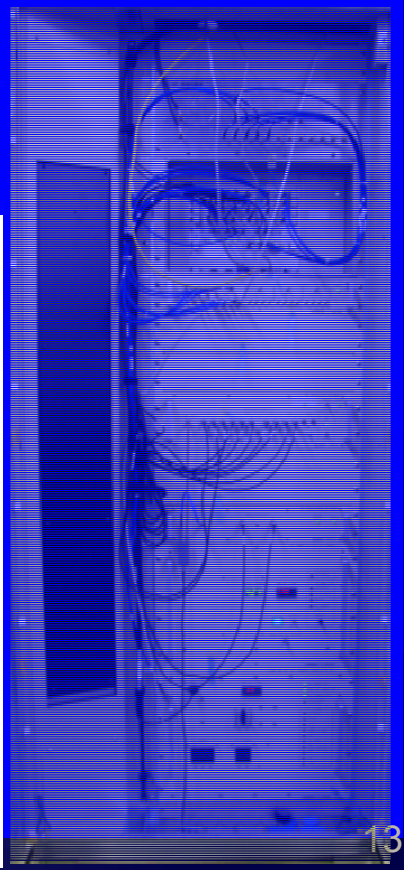




Low-level RF Control System

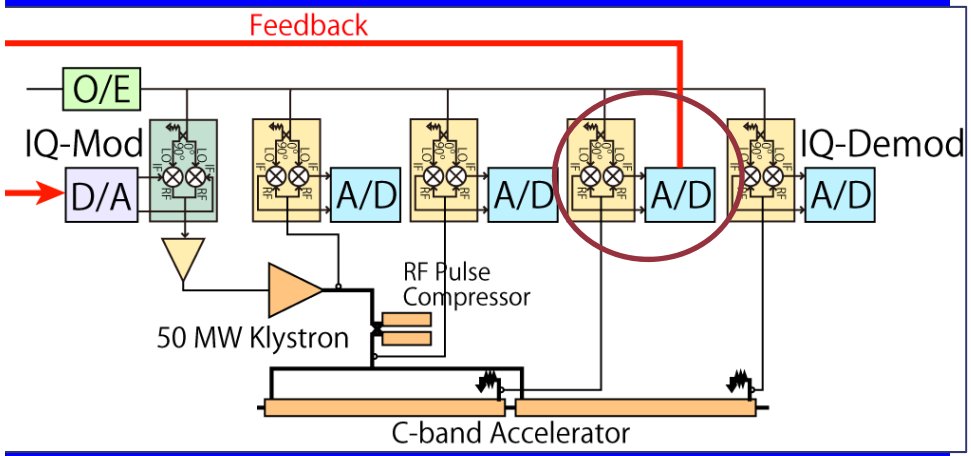
- IQ modulator produces the acceleration RF signal (pulsed RF) with appropriate phase and amplitude.
- IQ demodulator detects the phase and amplitude of the acceleration RF.
- Baseband waveforms are processed by VME high-speed D/A and A/D converters.
  - Sampling rate: 238 MSPS
  - Resolution: 14 bits (D/A), 12 bits or 16 bits (A/D)
- Phase is regulated by feedback control process (<10Hz).
  - Amplitude is also regulated for the injector part.
- All modules are enclosed in a water-cooled 19-inch rack.

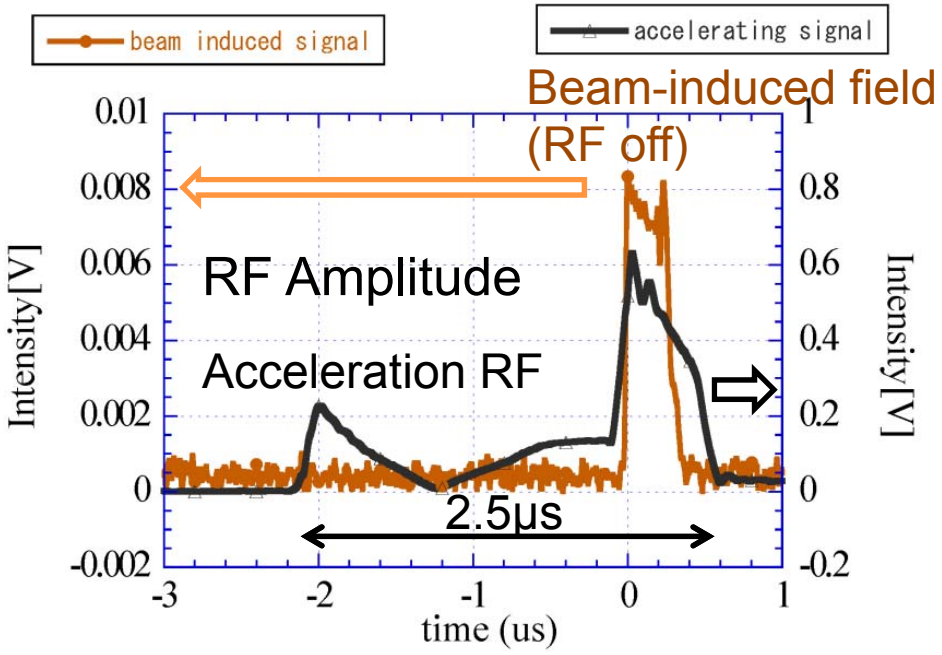


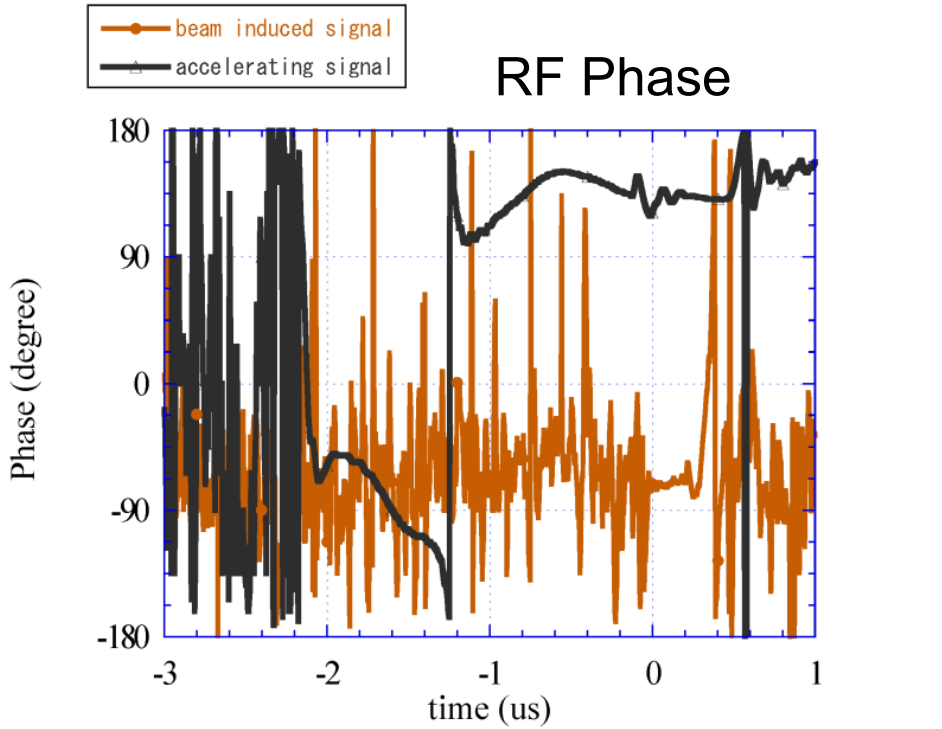


RF Waveform

- Waveforms of the RF amplitude and phase can be monitored in real time.





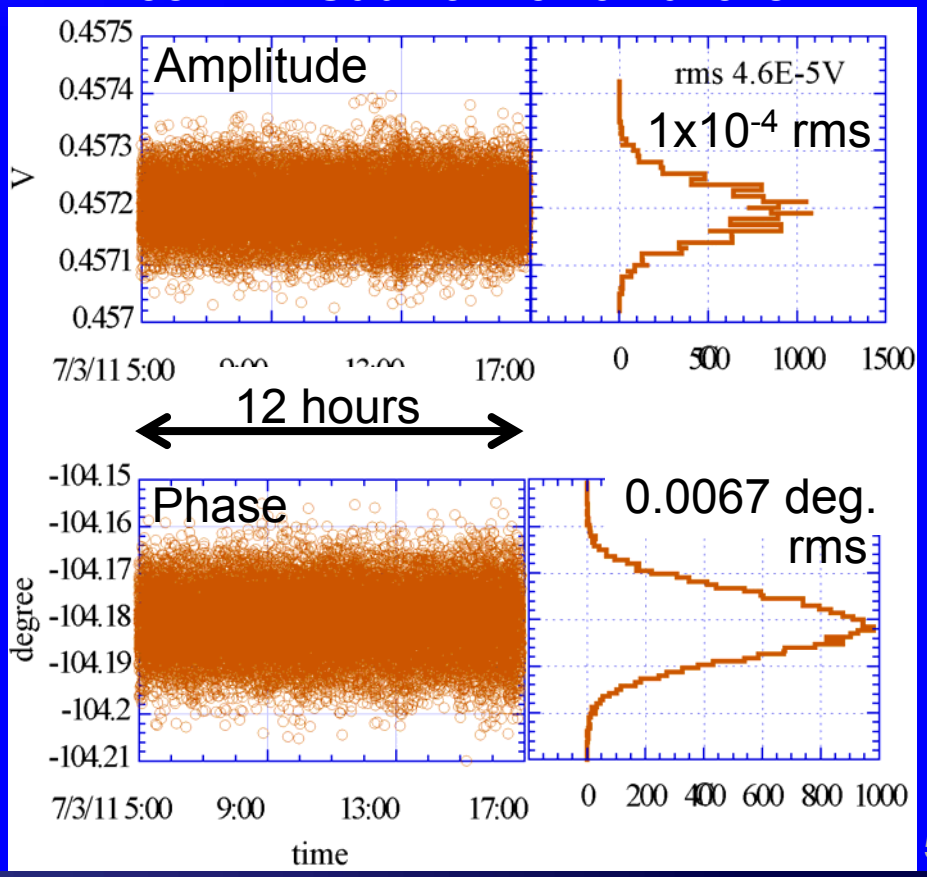


RF Phase and Amplitude Stability

- RF stability measured by IQ-demodulator
- 238MHz Cavity: Amplitude 1.0×10^{-4}, Phase 0.0067 deg. (79fs)
- 5712MHz Acc.: Amplitude 5.6×10^{-4}, Phase 0.032 deg. (16fs)
  - RMS values of 10-shot moving average are plotted.

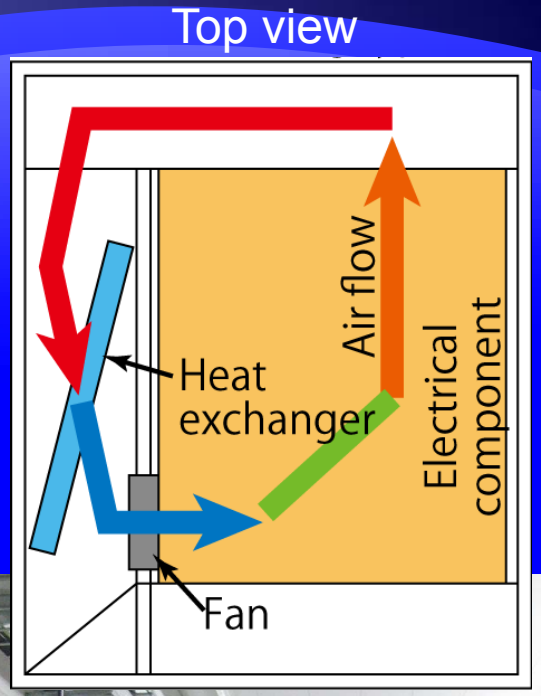
	Tolerance		Measurement	
	Voltage	Phase	Voltage	Phase
238 M SHB	0.01 %	0.01°	0.010 %	0.006°
476 M Booster	0.01 %	0.02°	0.004 %	0.009°
LB Correction	0.03 %	0.06°	0.02 %	0.02°
L-Band APS 1	0.01 %	0.06°	0.06 %	0.03°
L-Band APS 2	0.01 %	0.06°	0.03 %	0.05°
C-Band Corr.	0.2 %	0.06°	0.06 %	0.05°
S-Band acc. 1	0.01 %	0.1°	0.04 %	0.03°
C-Band acc.1	0.01 %	0.2°	0.05 %	0.03°

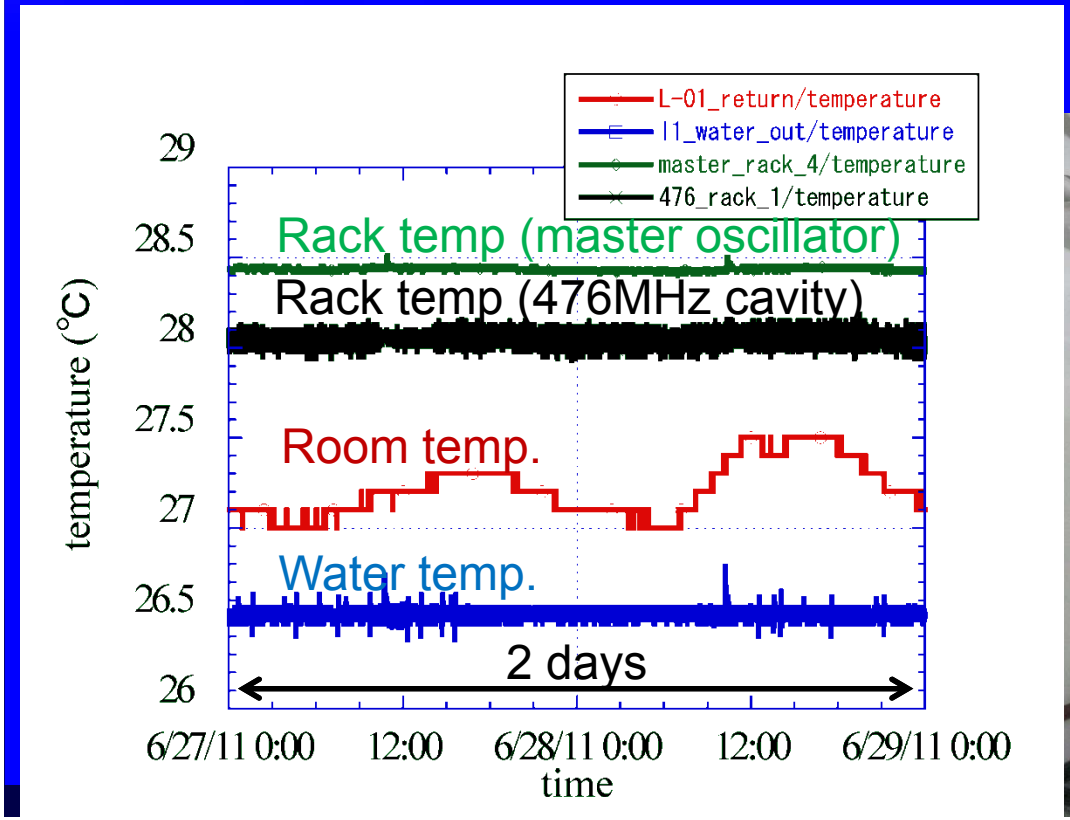
238 MHz Sub-harmonic Buncher

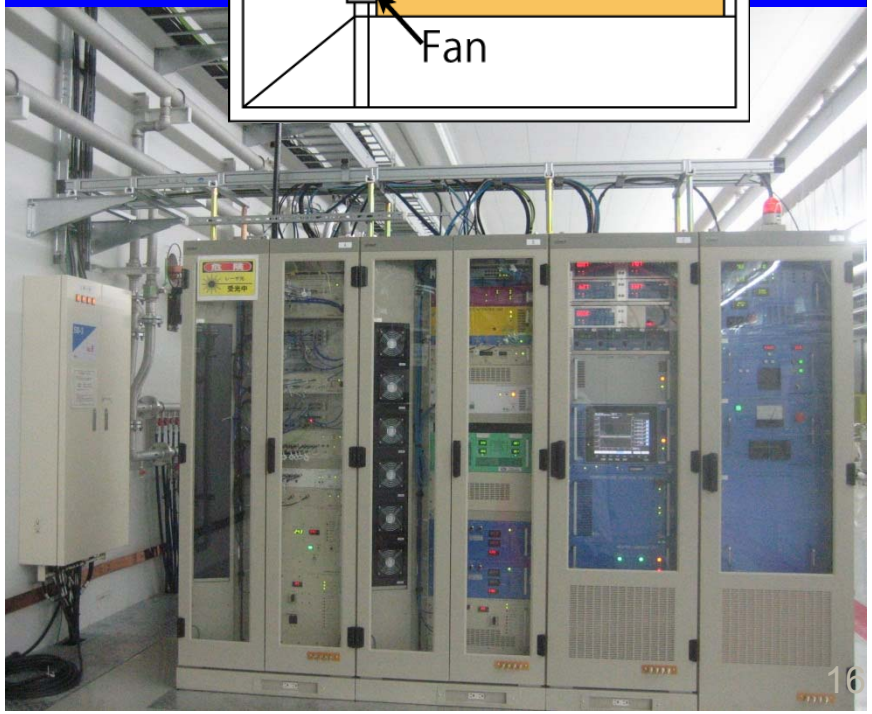


Water-cooled 19-inch Rack

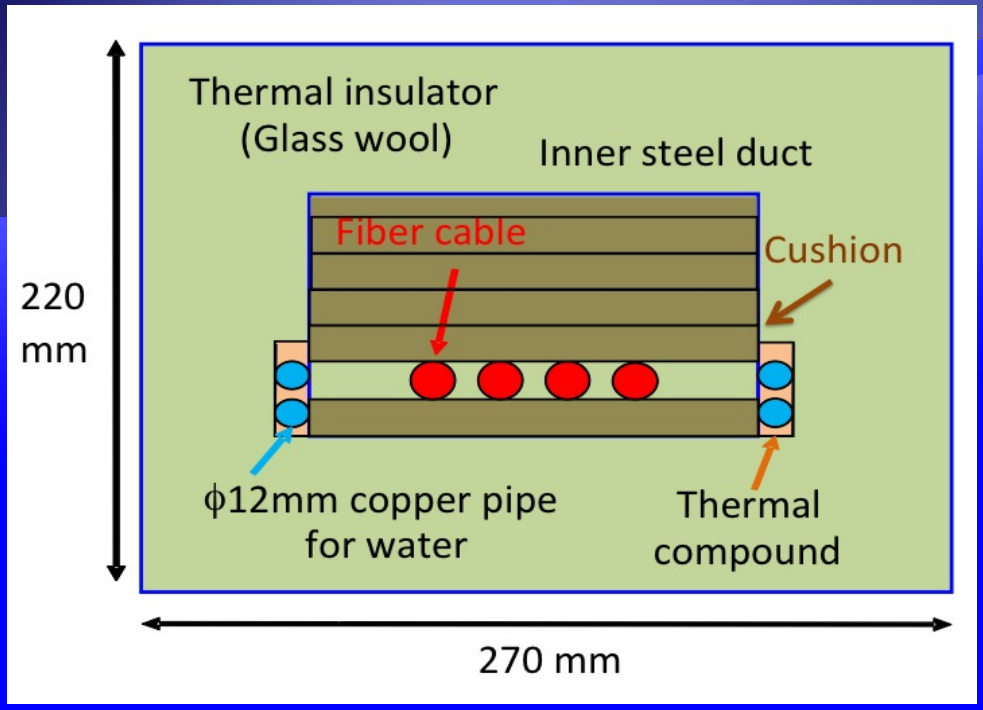
- LLRF electronics are enclosed in water-cooled 19-inch racks.
- Circulating air is cooled by a heat exchanger.
- Temperature stability: 0.2 K (pk-pk)

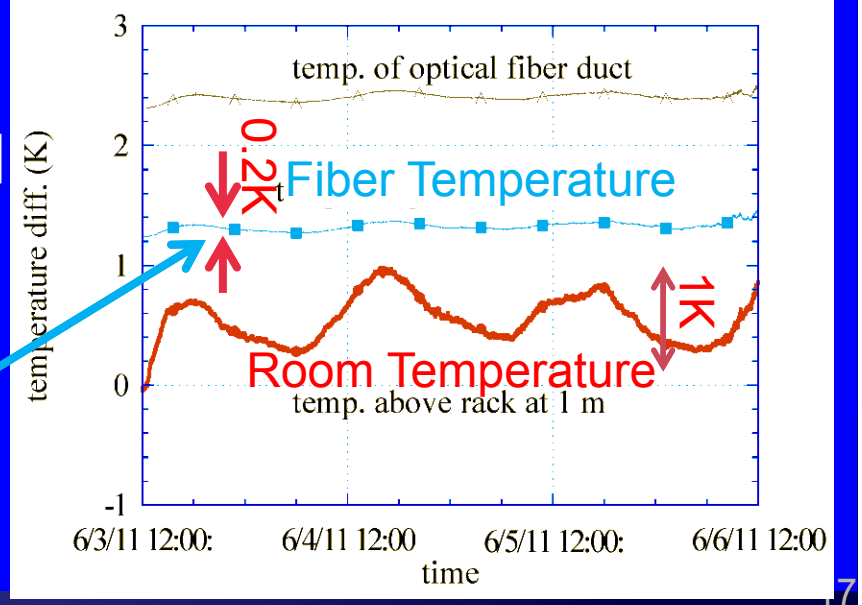






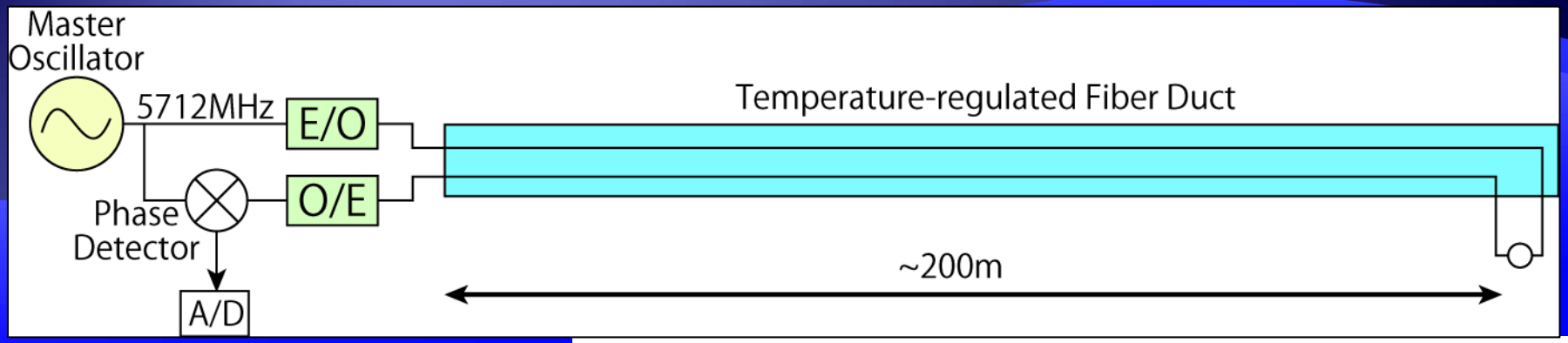
Temperature Regulated Fiber Duct



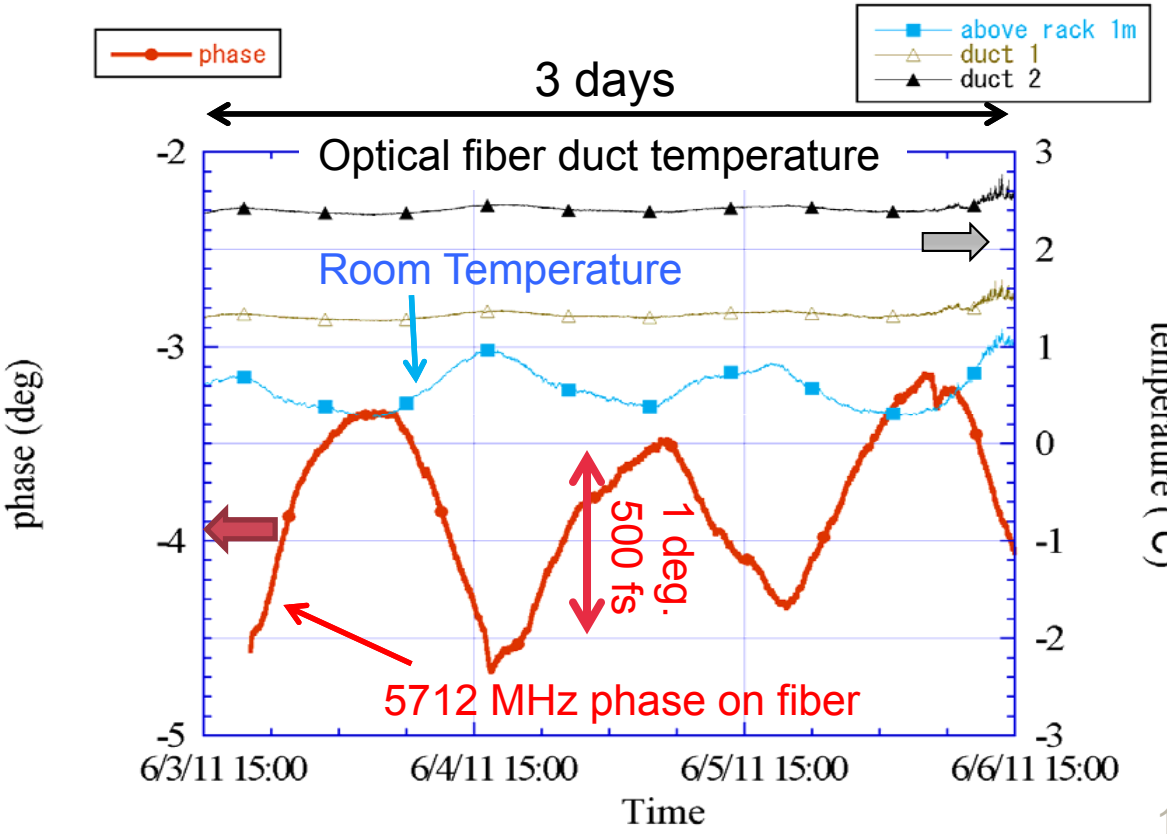


- Optical fiber cables are installed into a temperature-stabilized and water-cooled duct.
- Temperature stability of the cable is within 0.2 K (pk-pk).

Optical Fiber Length Stability

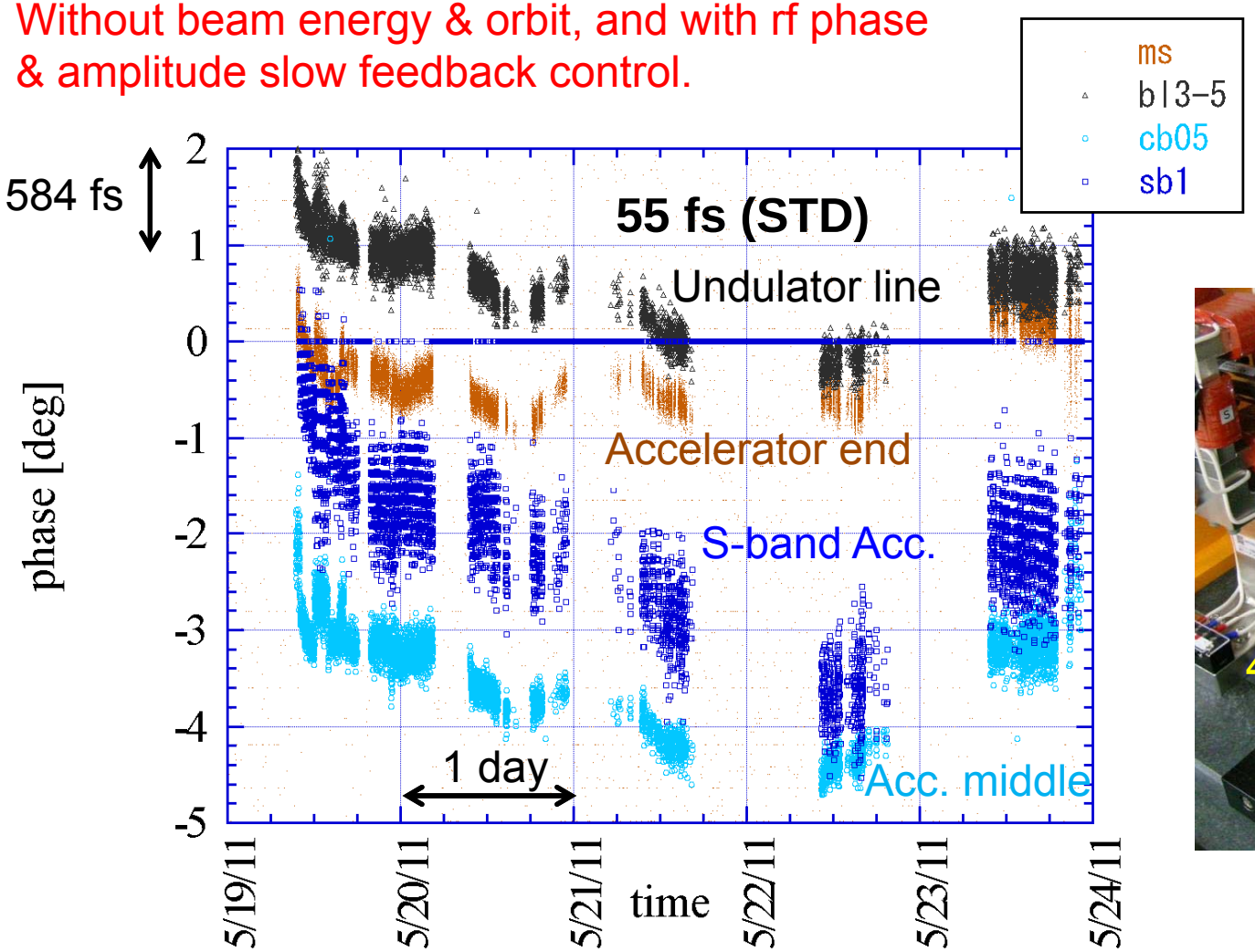


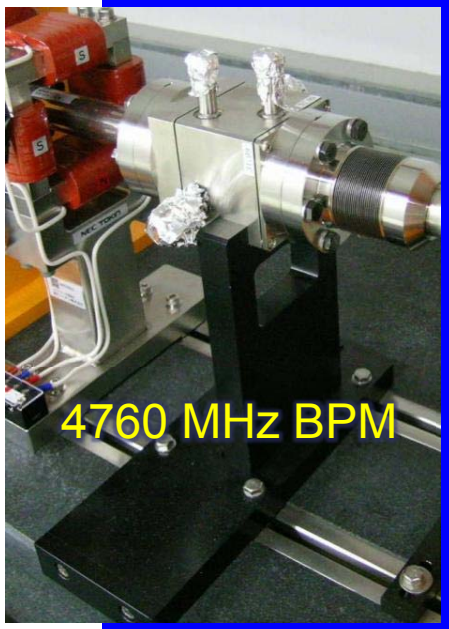
- RF fiber length is monitored by 5712 MHz RF phase on a round trip fiber (~ 400 m in total).
- Temperature stability of the optical fiber duct:
  0.2 K (pk-pk)
- RF phase stability:
  1.5 deg. (pk-pk) [5712 MHz]
  equivalent to 750 fs
- Consistent with the temperature coefficient of the fiber.
- Fiber length stabilization system is required.
  - Required stability: < 100 fs



Beam Arrival Time Monitor using BPM Reference Cavity

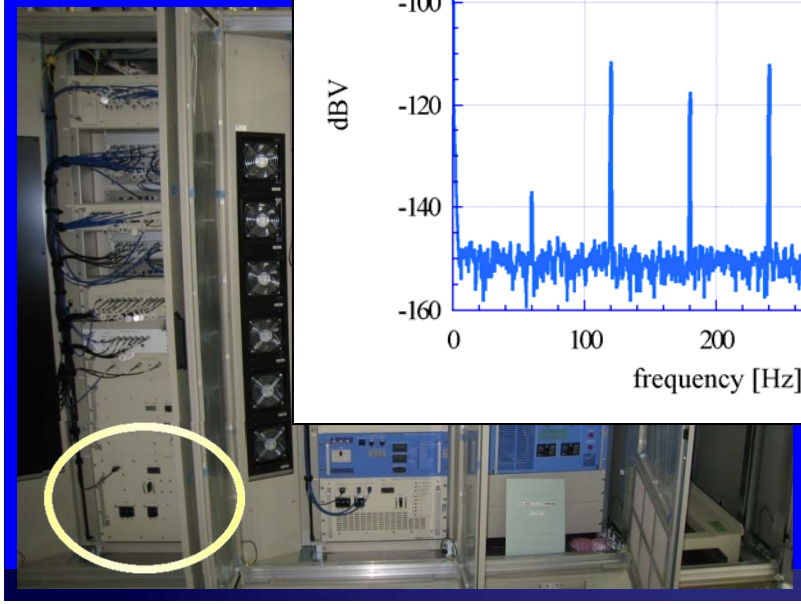
Without beam energy & orbit, and with rf phase & amplitude slow feedback control.

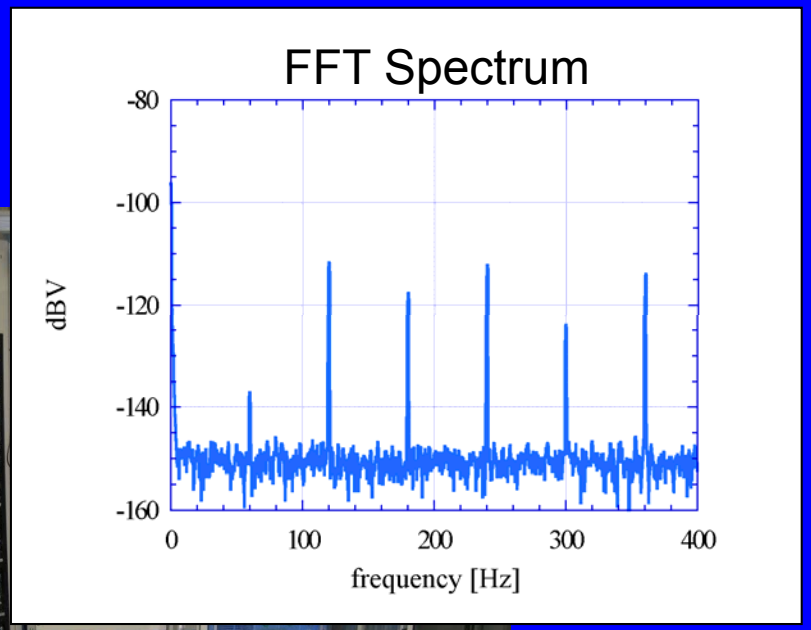


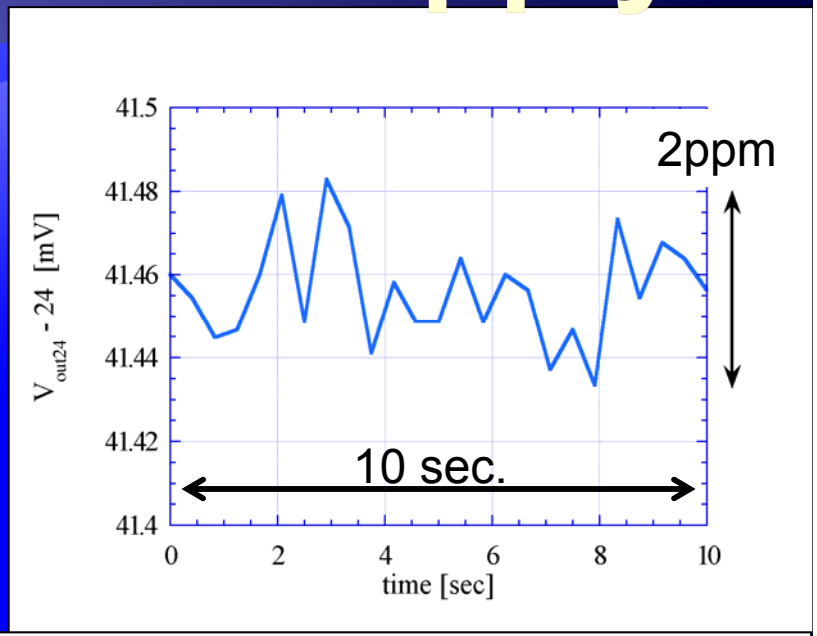


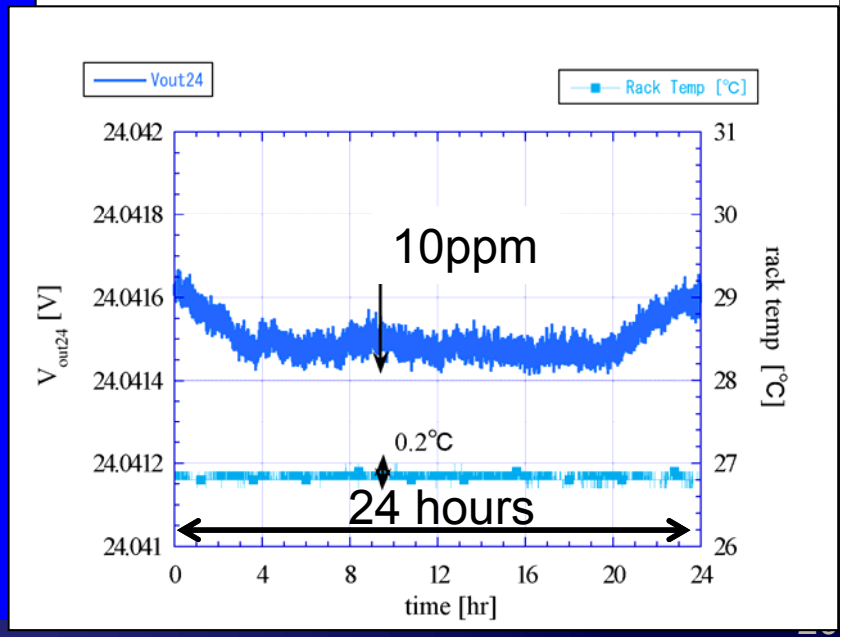
Low-noise DC Power Supply

- Linear regulator is employed
- Voltage stability of 24 V output.
  - Short term stability: 2 ppm pk-pk for 10 sec
  - Long term stability: 10 ppm pk-pk for 24 hr
  - FFT spectrum: noise floor ~ -140 dBV/√Hz
  - Harmonics of line frequency: < -110 dBV









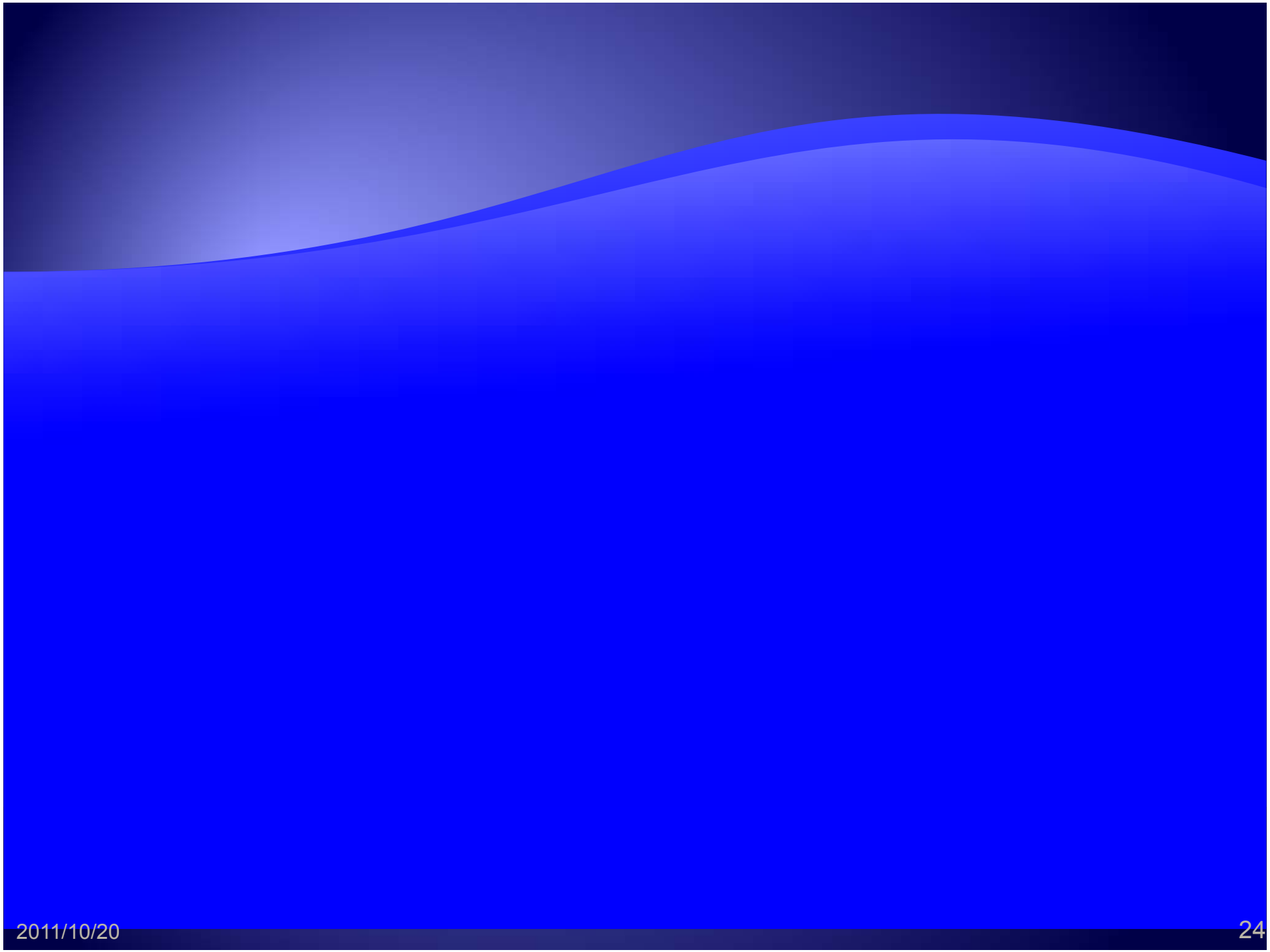
Possible Application to ERL

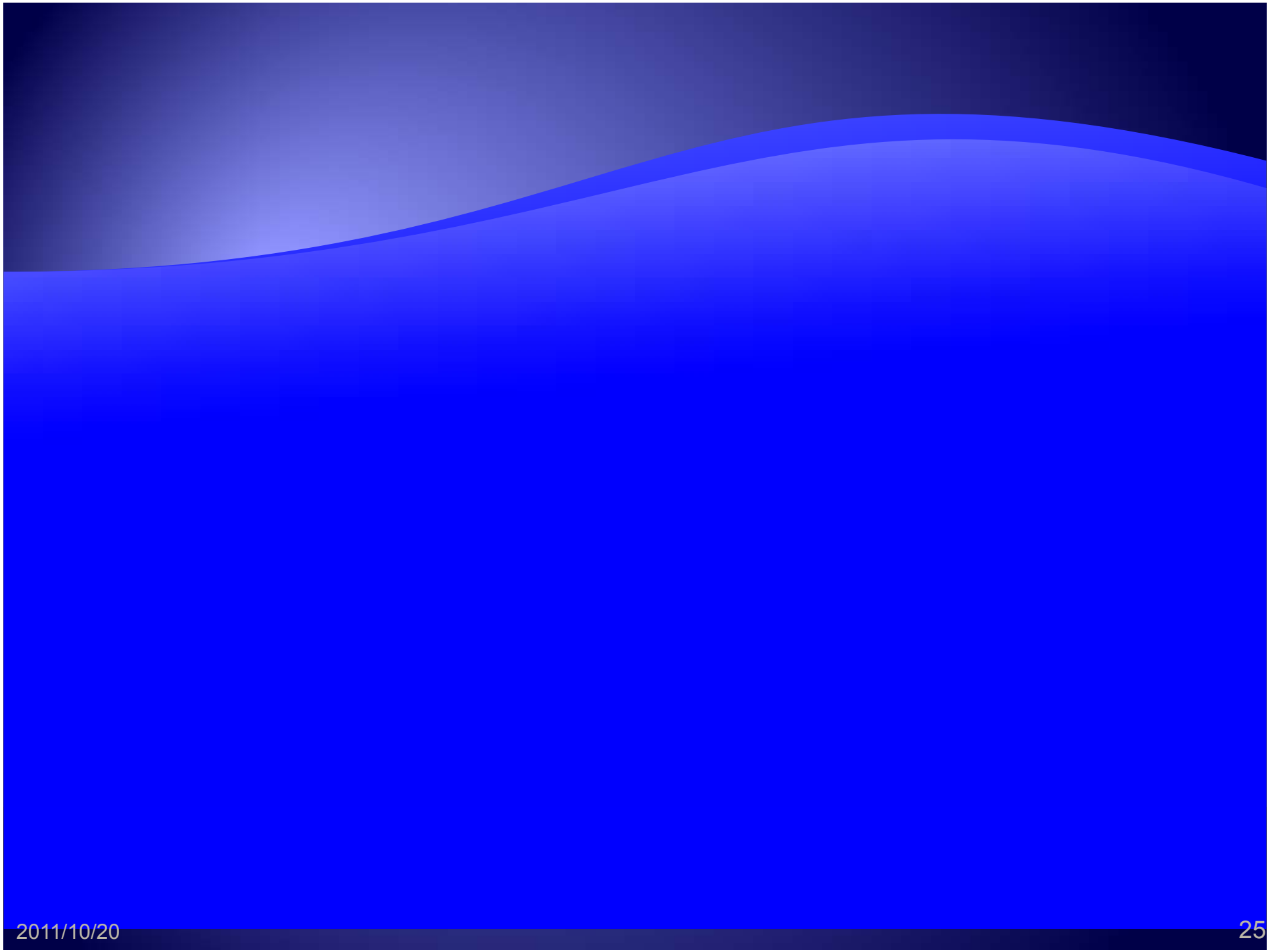
- Optical RF and Timing Distribution System
  - Some component can be applicable to ERL.
    - E/O and O/E converter
    - Fiber length control with Michelson interferometer
  - I think each ERL project has similar design.
  - Sinusoidal modulation is better than comb pulse modulation for the RF distribution
  - But, comb pulse is useful for cross-correlation
    - Synchronization with pump laser
    - Fiber length measurement
- Low-level RF Control System
  - Difficult.
  - Our IQ-mod/demod system is intended for pulsed RF signals and for normal conducting accelerators.
  - Need considerable modification for CW signal or super-conducting accelerator.
    - Vector sum
    - Intra-pulse feedback

Summary

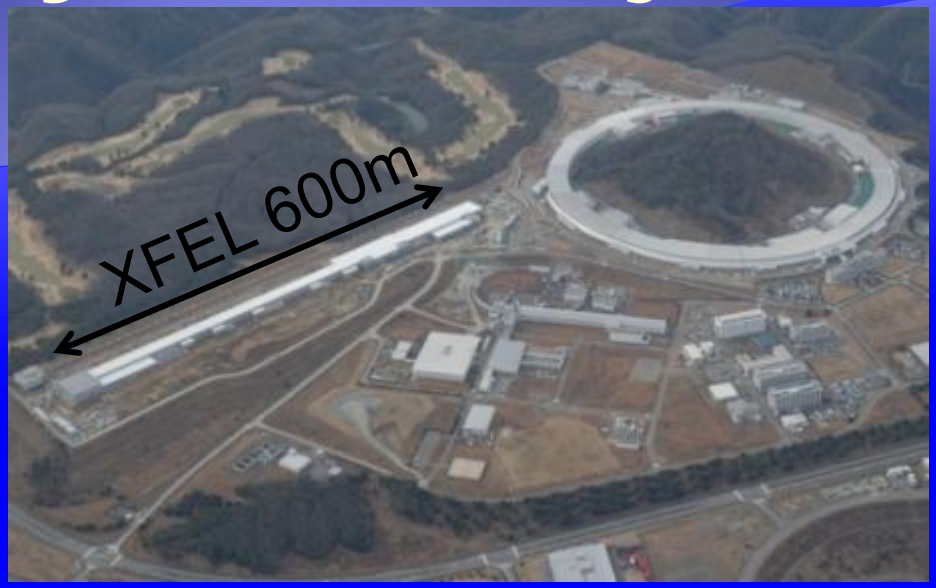
- Optical RF and Timing Distribution
  - Jitter: ~ 10 fs (from phase noise measurement)
  - Drift: 750 fs (pk-pk) for 400m cable → Fiber length controller will be installed.
- Low-level RF System
  - Acceleration RF signals are precisely generated and detected.
  - Phase stability of acceleration cavity: < 100 fs (rms)
- *By using this system, stable x-ray lasing was achieved at SACLA.*
- Some of our instruments can be applied to ERL.

Thank you for your attention.



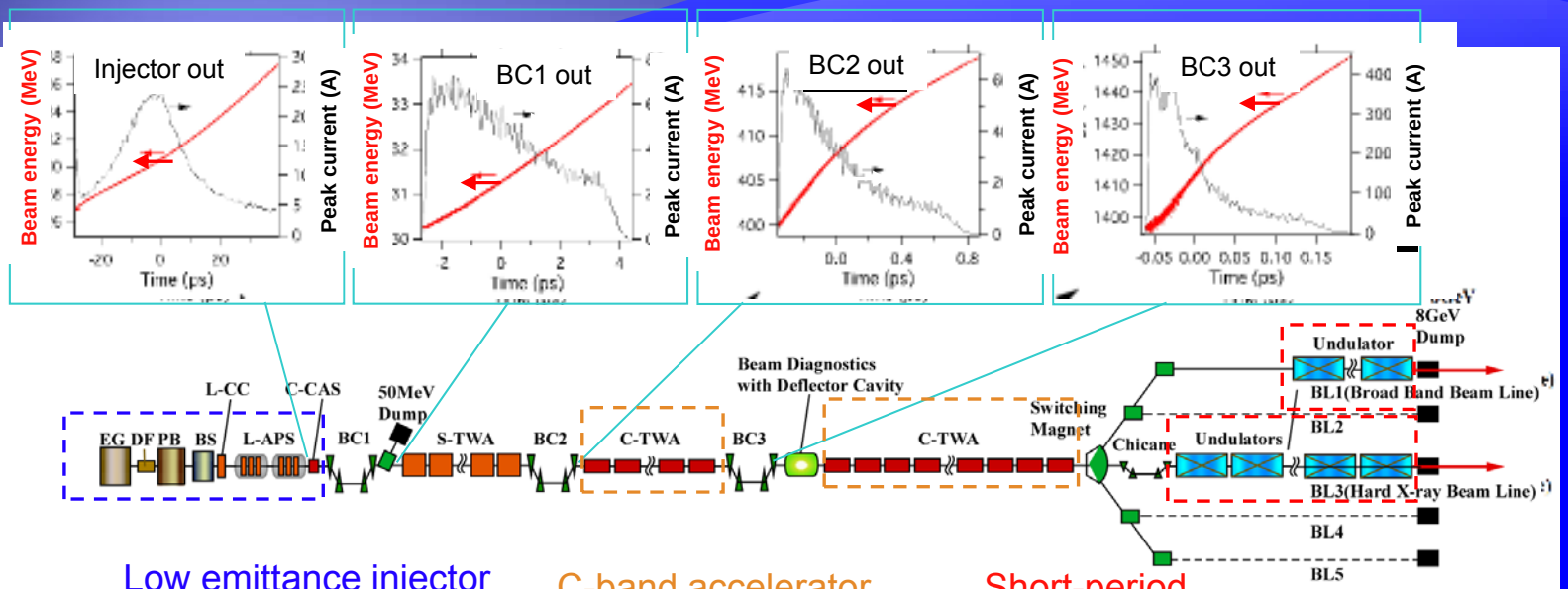


X-ray FEL Project at SPring-8



- X-ray wavelength: < 0.1 nm
- Self-amplified spontaneous emission (SASE) process
- Beam energy: 8 GeV
- Key technologies
  - Low-emittance thermionic electron gun: 0.6 mm mrad
  - High-gradient C-band accelerator: 35 MV/m
  - Short-period in-vacuum undulator: λ_u = 18 mm, K < 2.2

SACLA System Overview



Low emittance injector with CeB6 E-gun

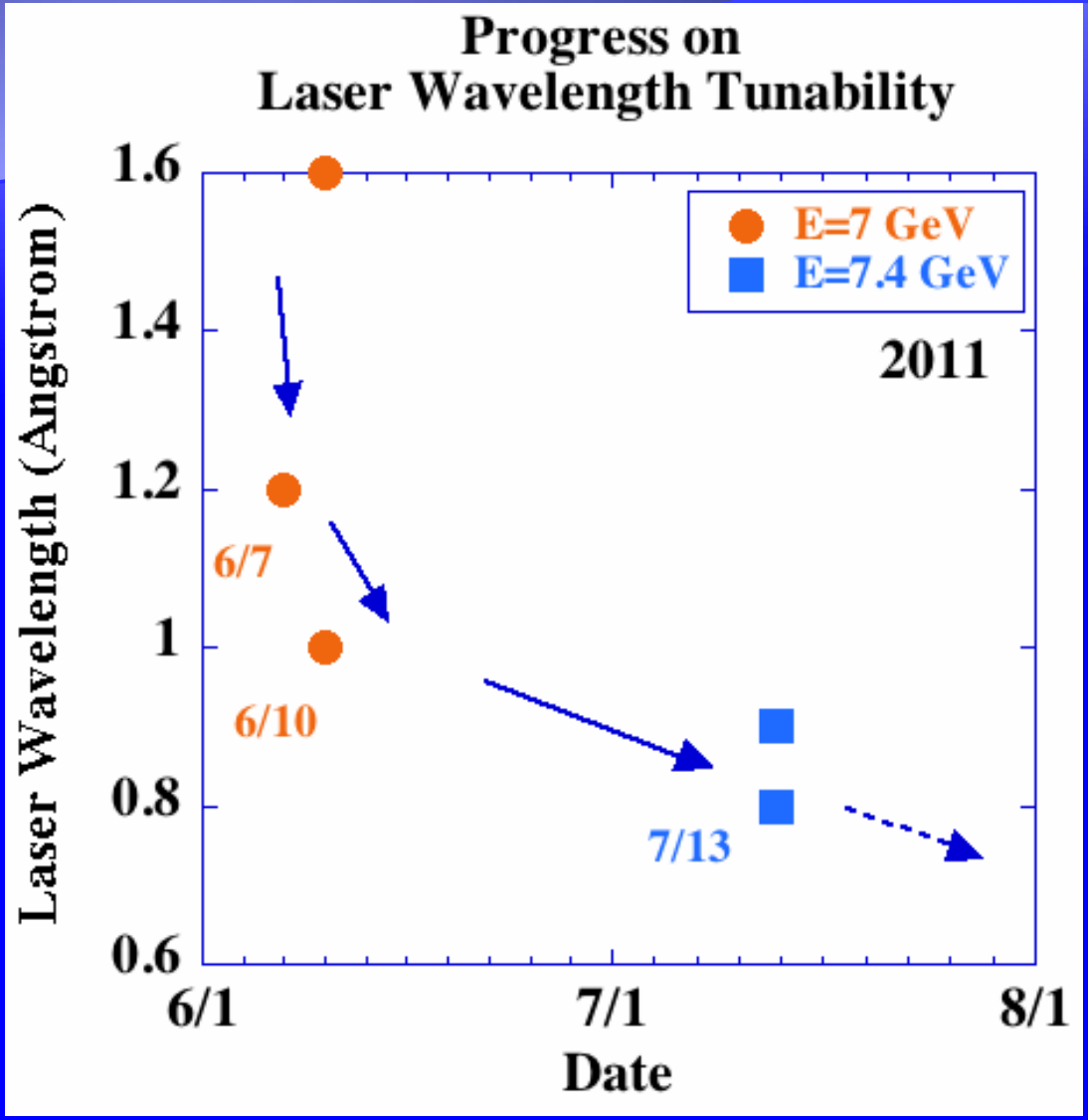
C-band accelerator system

Short-period In-vacuum undulators

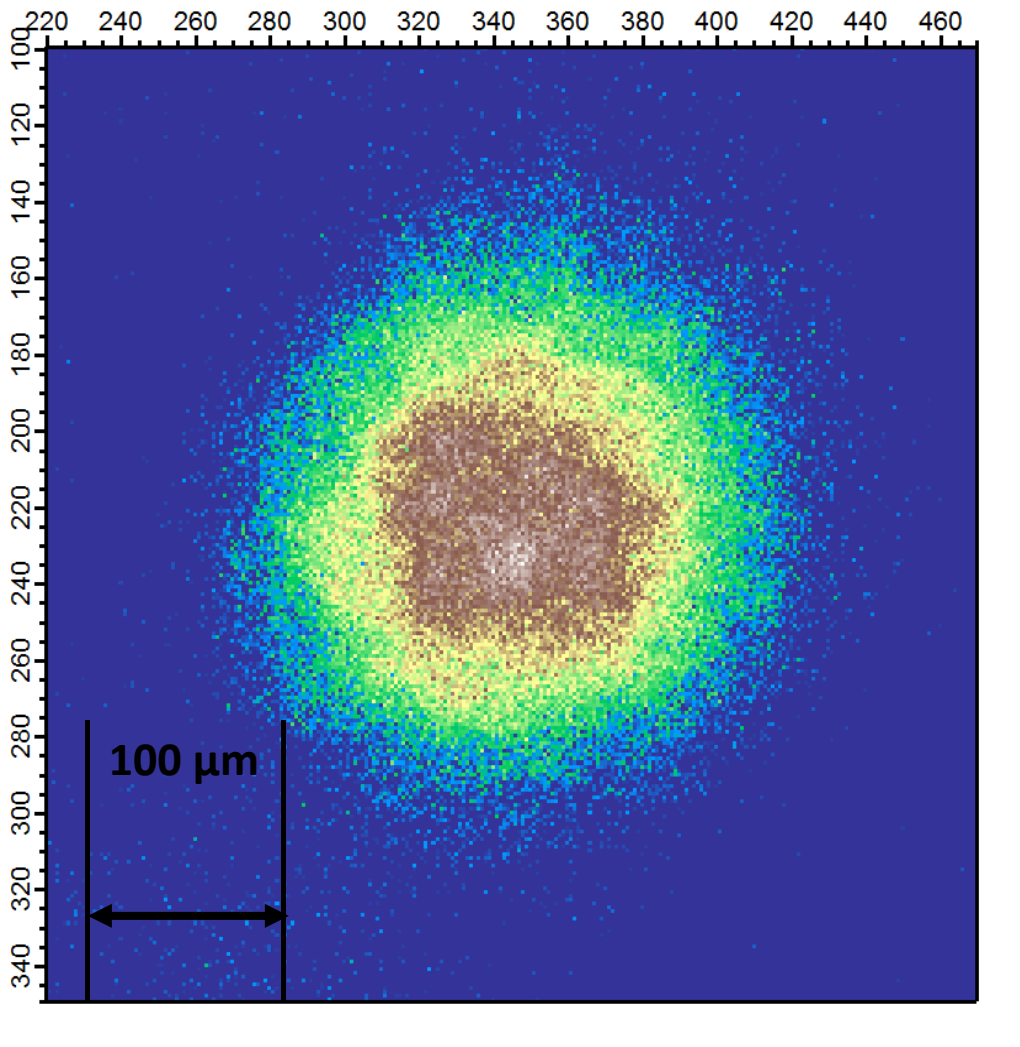
XFEL Machine Parameters

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 μm (RMS)
Undulator Period	18 mm
Undulator K-value	2.2 maximum
Undulator Gap	3 mm minimum
Number of Periods	275 x 18 = 4950

3. Shortening Laser Wavelength



6. Spatial Profile

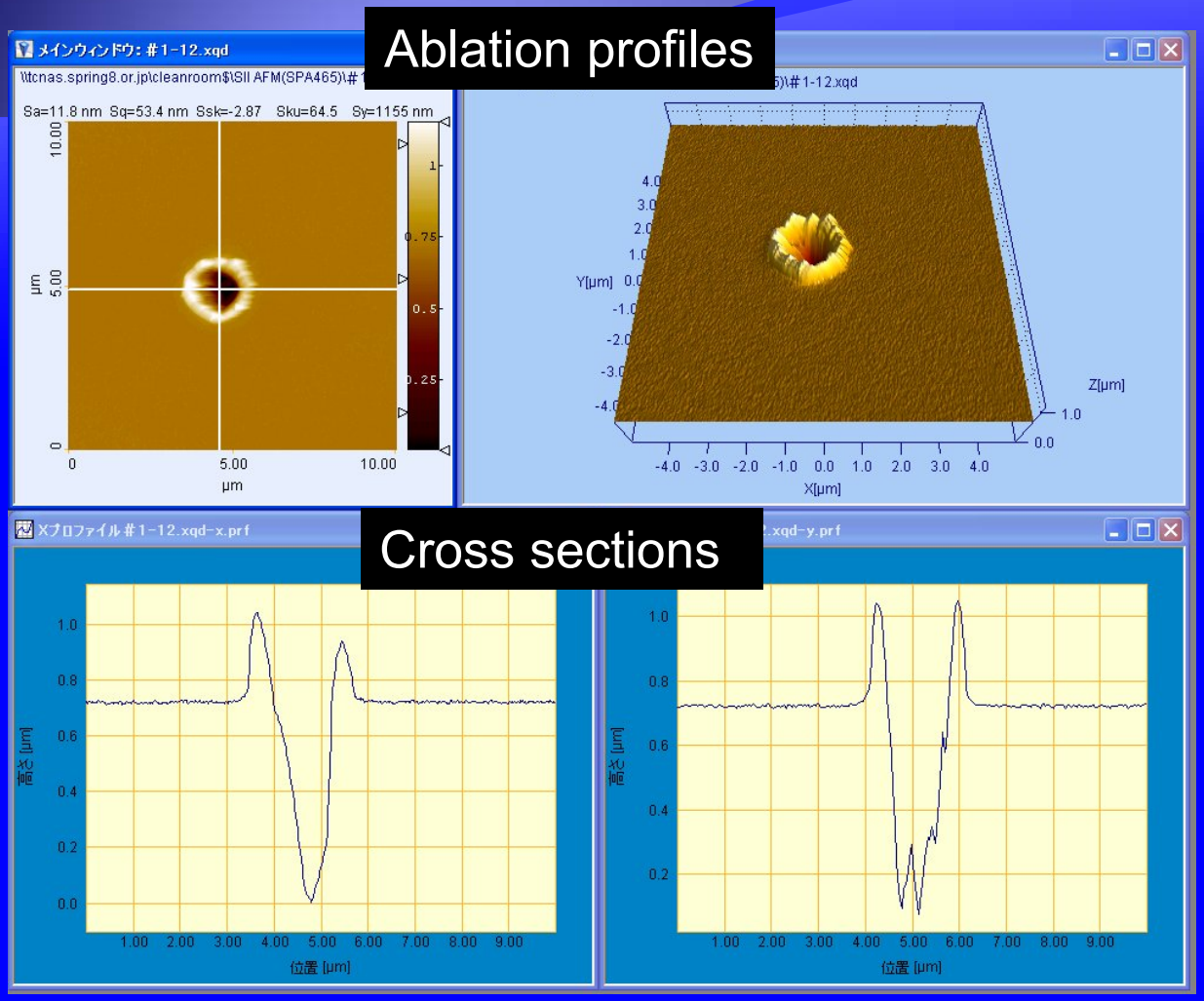


Photon energy: 10 keV

110 m from exit of ID18

7. Focused Laser Beam

Focused down to 1.1 μm x 0.9 μm (FWHM)

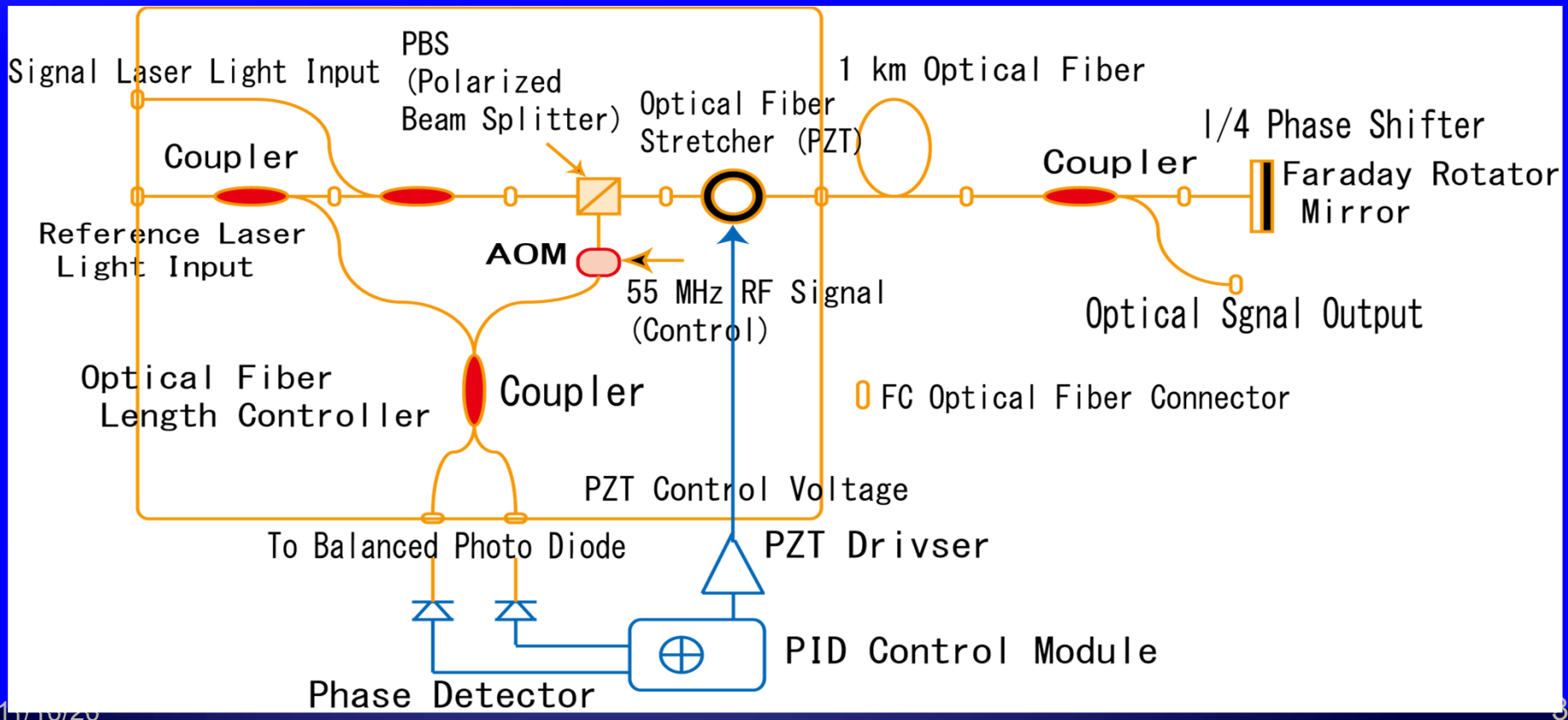


Ablation pattern by focused XFEL on gold-deposited film

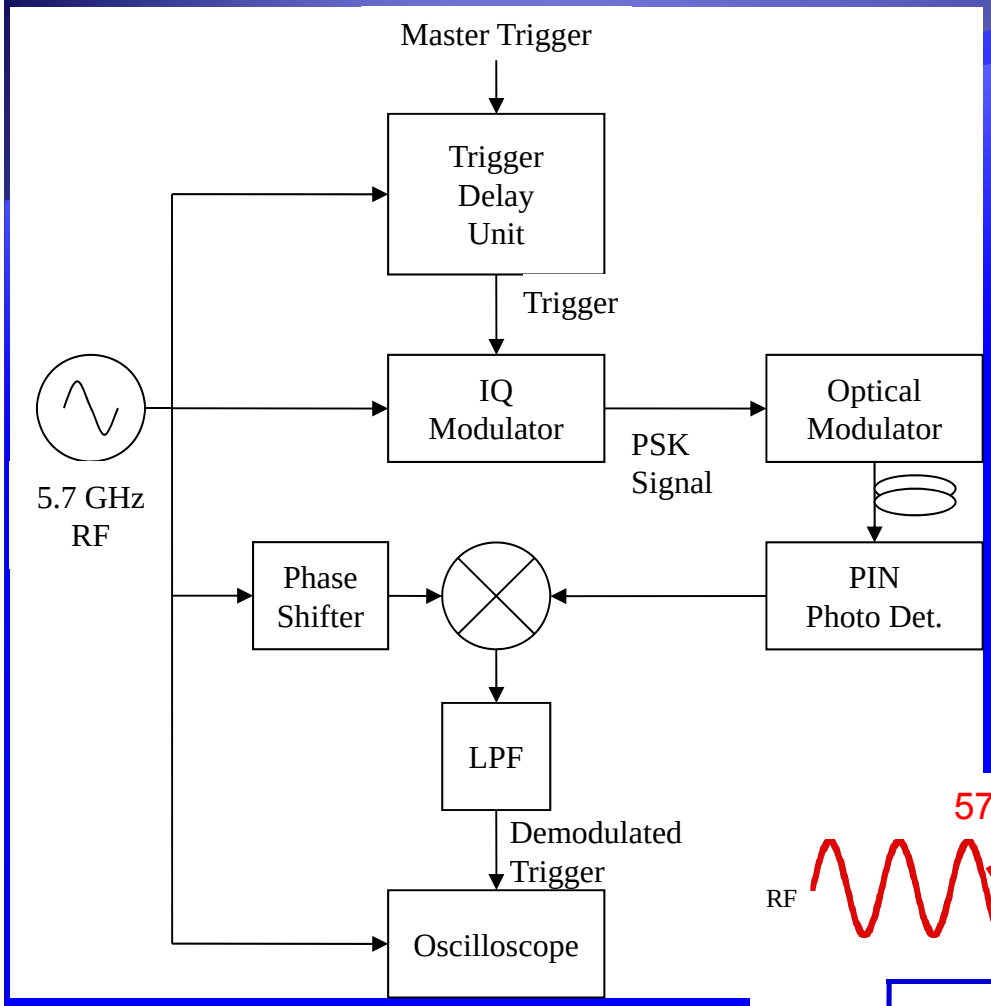
Collaboration with Osaka Univ. (Prof. Yamauchi) and Univ. Tokyo (Prof. Mimura)
(MEXT「X線自由電子レーザー利用推進研究課題」/ RIKEN「SACLA利用装置提案課題」)

Fiber Optical Length Control (Michelson Interferometer)

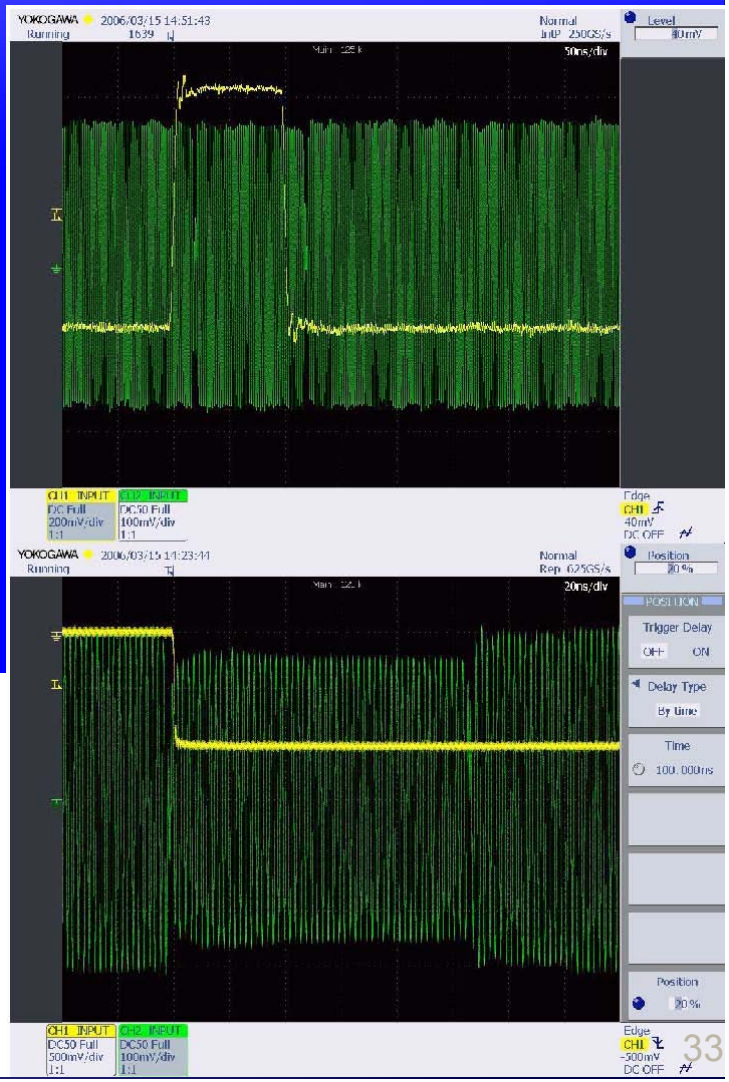
E.G. Phase-stabilized optical fiber has a thermal optical length coefficient of 2 ppm/K. The optical length of the fiber moves 1.6 μm/K for 800m. This values corresponds to a phase shift of 1 deg./K and 500 fs/K at 5712 MHz, and is not acceptable to employ this method for the X-FEL.

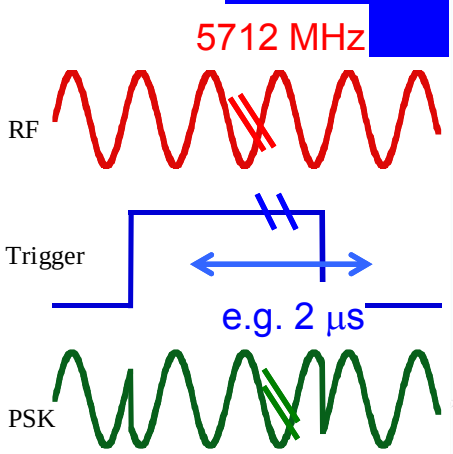


PSK trigger pulse transmission using optical fiber



A laser diode can not treat the DC component of a signal.



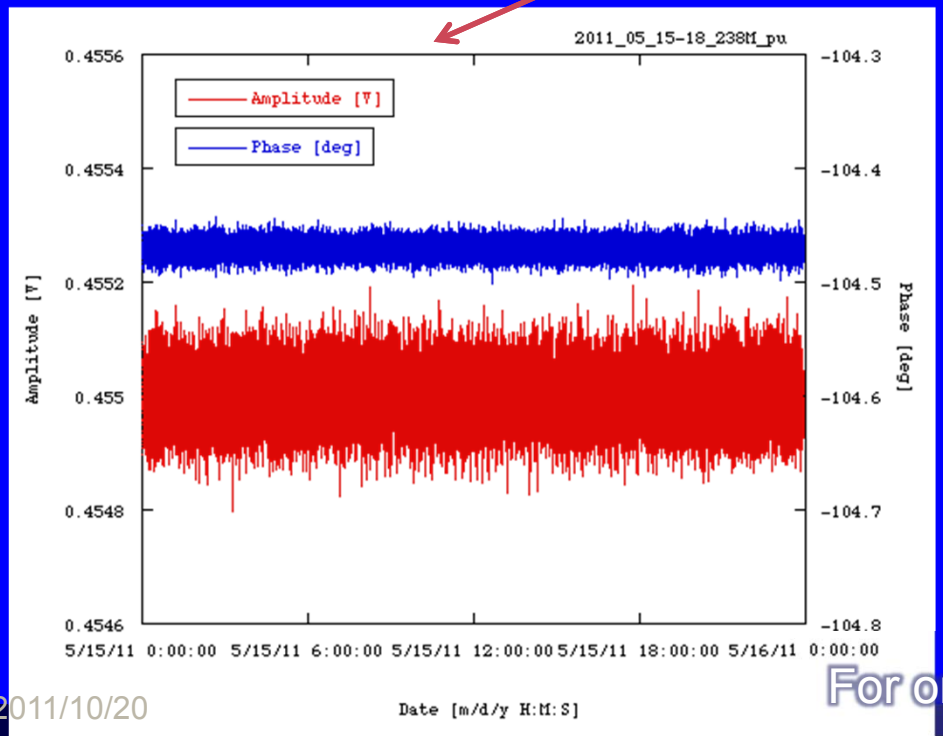


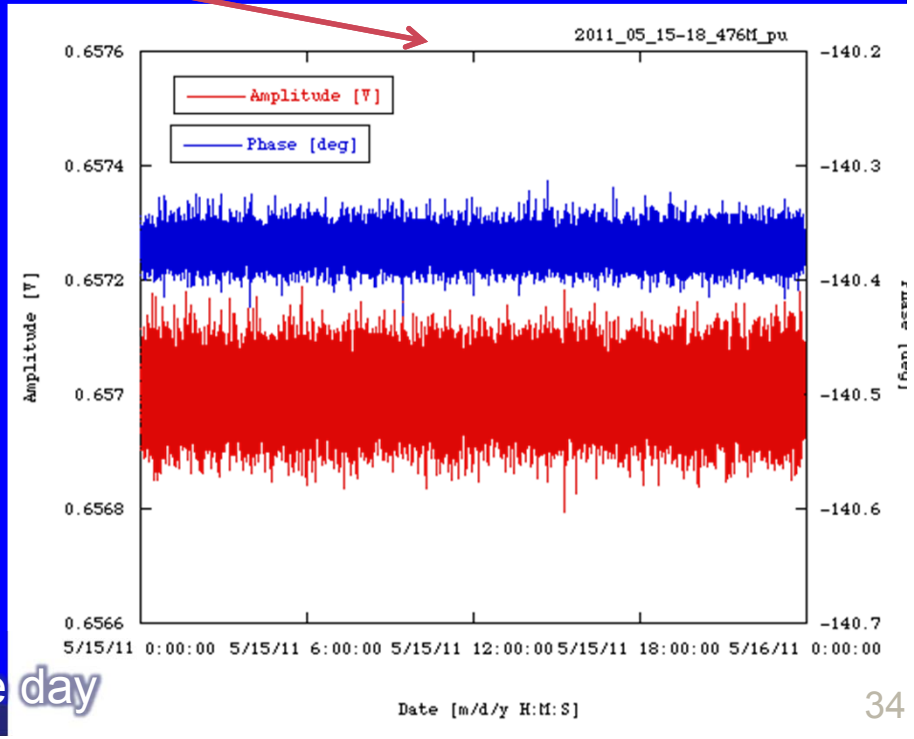
5712 MHz RF after PSK pulse modulation

Rf Phase and Amplitude Stability of Injector

10 shots average at the individual data points.

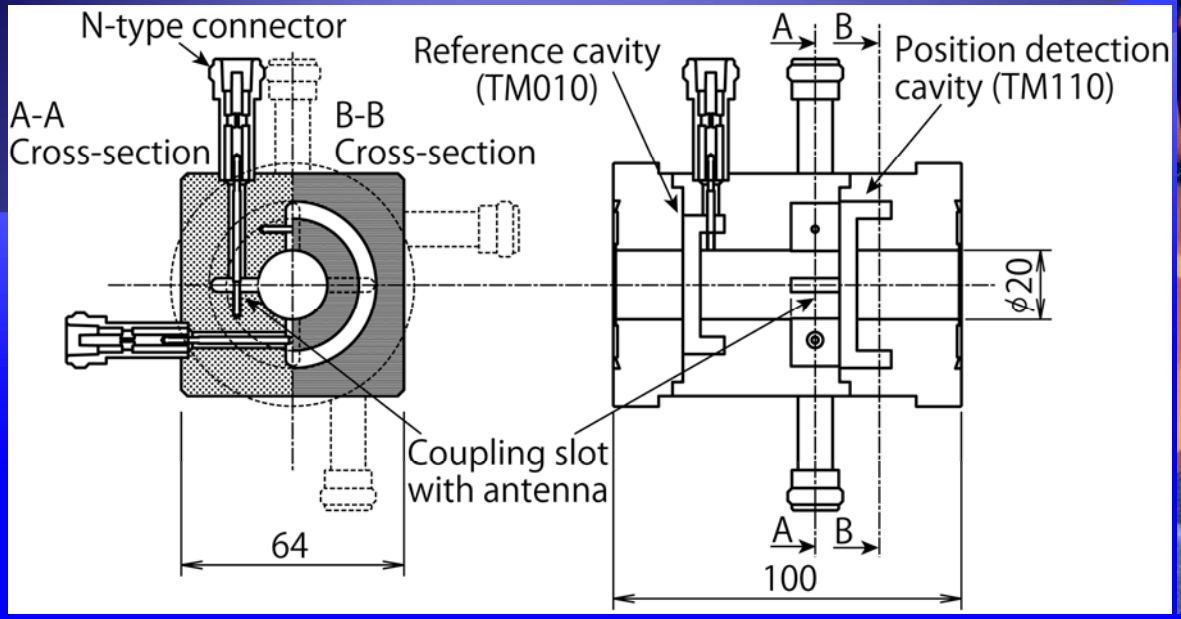
		SHB	Booster	L-corr	L-APS_1	L-APS_2	C-corr
Tolerance	Voltage	0.01%	0.01%	0.03%	0.01%	0.01%	0.1%
	Phase	0.01˚	0.02˚	0.06˚	0.06˚	0.06˚	0.06˚
Measurement	Voltage	0.006%	0.005%	0.019%	0.044%	0.052%	0.093%
	Phase	0.007˚	0.011˚	0.021˚	0.048˚	0.057˚	0.081˚

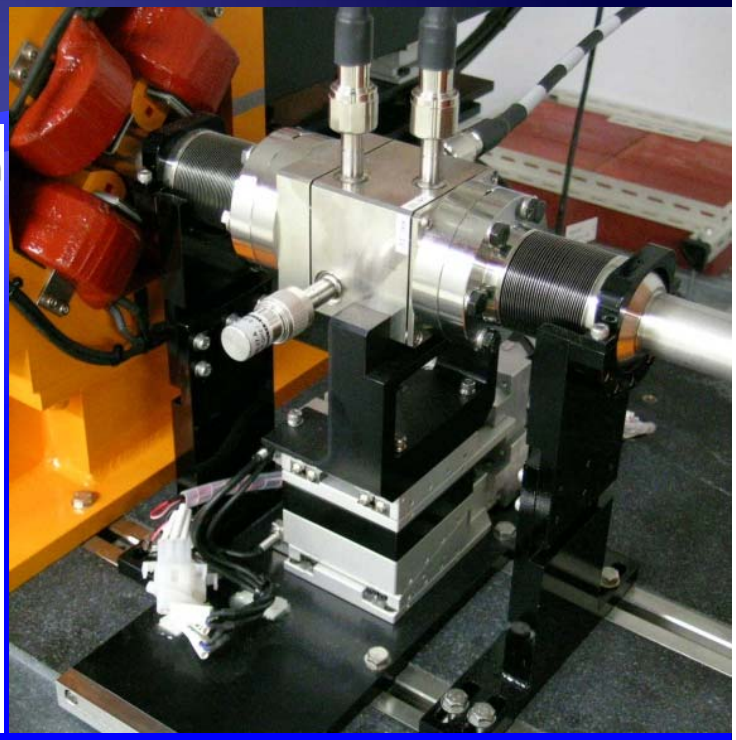




For one day

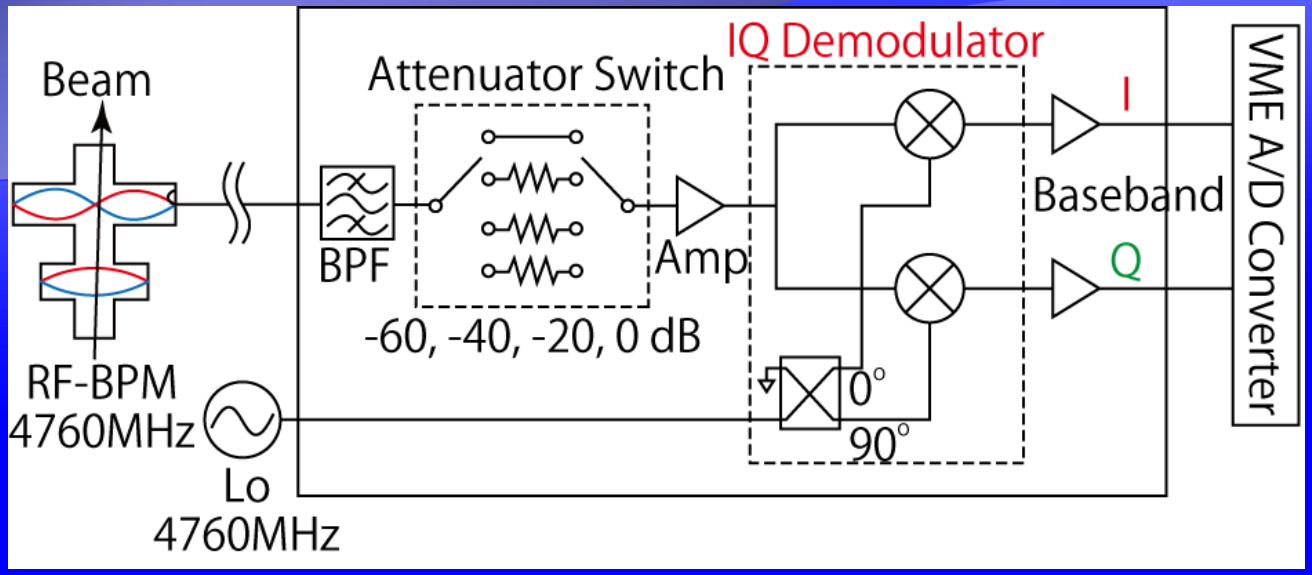
RF Cavity BPM





- Beam-induced RF field is used.
  - Beam position is obtained from TM110 dipole mode cavity.
  - TM010 cavity determines the phase reference and the beam charge.
- Resonant frequency : 4.760 GHz (C-band)

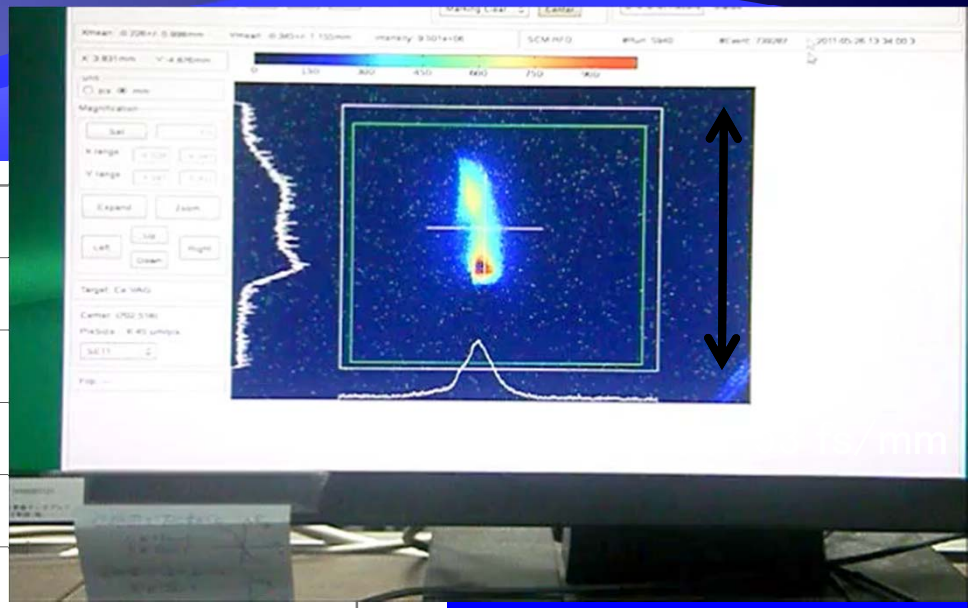
BPM Electronics

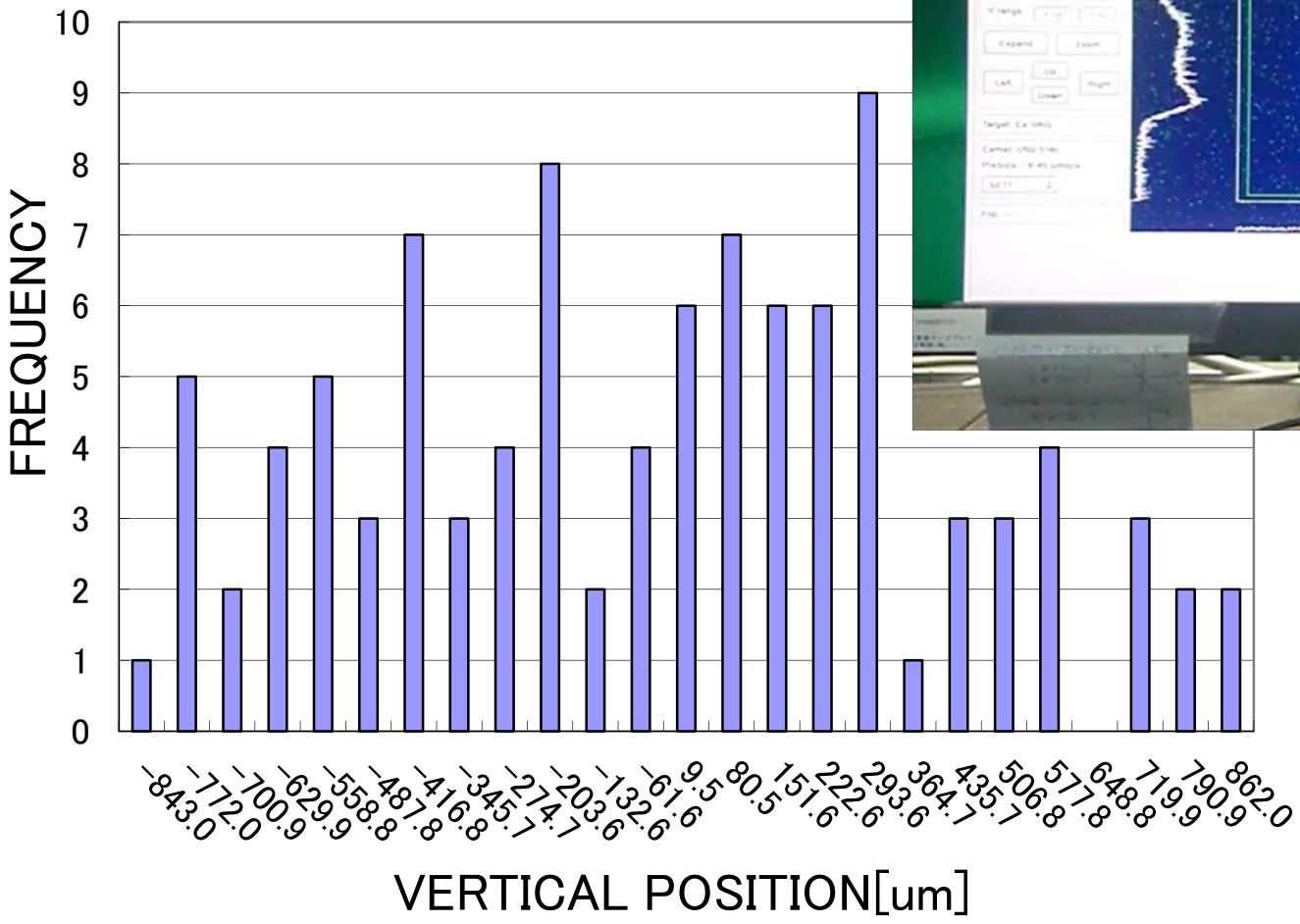


- IQ demodulator
- Attenuator switch extends the dynamic range to 100 dB
  - From sub-μm to a few mm
- Baseband signals are recorded by a 12-bit or 16-bit VME waveform digitizer.

Beam Arrival Time jitter observed by the rf deflector

5/26/2011”





HISTOGRAM OF VERTICAL POSITION, 100 shots

436.81[um, STD] = 22.7 fs, 53 fs/mm

1pps

1.45 GeV