FLS2018

PAL-XFEL and Its Time-Resolved Experiment with sub-20-fs Timing Jitter

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and on behalf of PAL-XFEL team

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PAL-XFEL Status

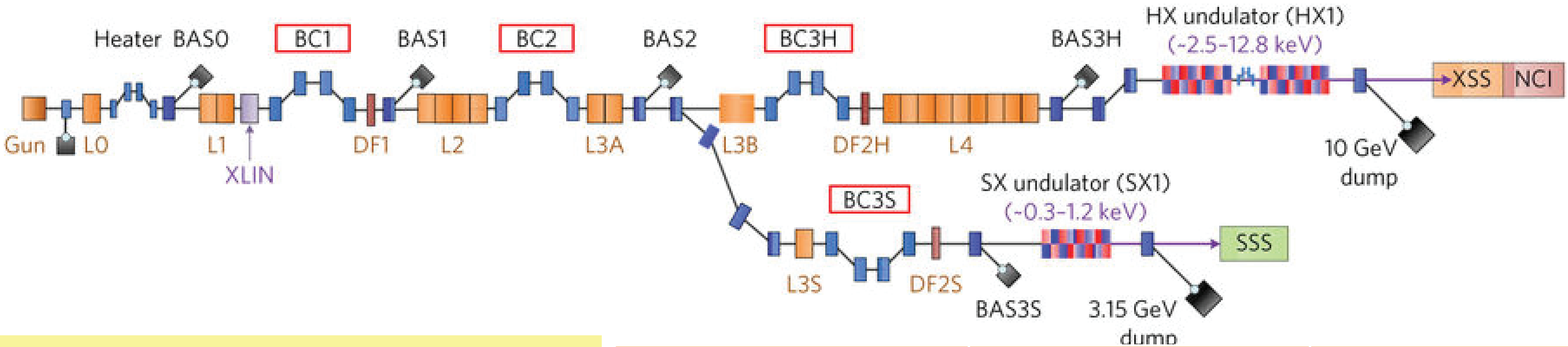
Apr. 2011: PAL-XFEL project started
Apr. 2016: Commissioning started
Jun. 2017: User-service start
(120 days for user, >95% of availability)

Plan in 2018
- 140 days for user
- HX self-seeding commissioning
  (user service starts in 2019)
- 30 Hz -> 60 Hz operation

◆ FEL position stability: 8~9% of beam size
◆ FEL power stability: ~ 4.0% RMS
◆ E-beam energy jitter: < 0.02 %
◆ E-beam arrival time jitter: < 20 fs
◆ FEL pulse energy: >1 mJ at 9.7 KeV

PAL-XFEL Parameters

30A 2 ps → 300A 200fs → 3kA 22fs

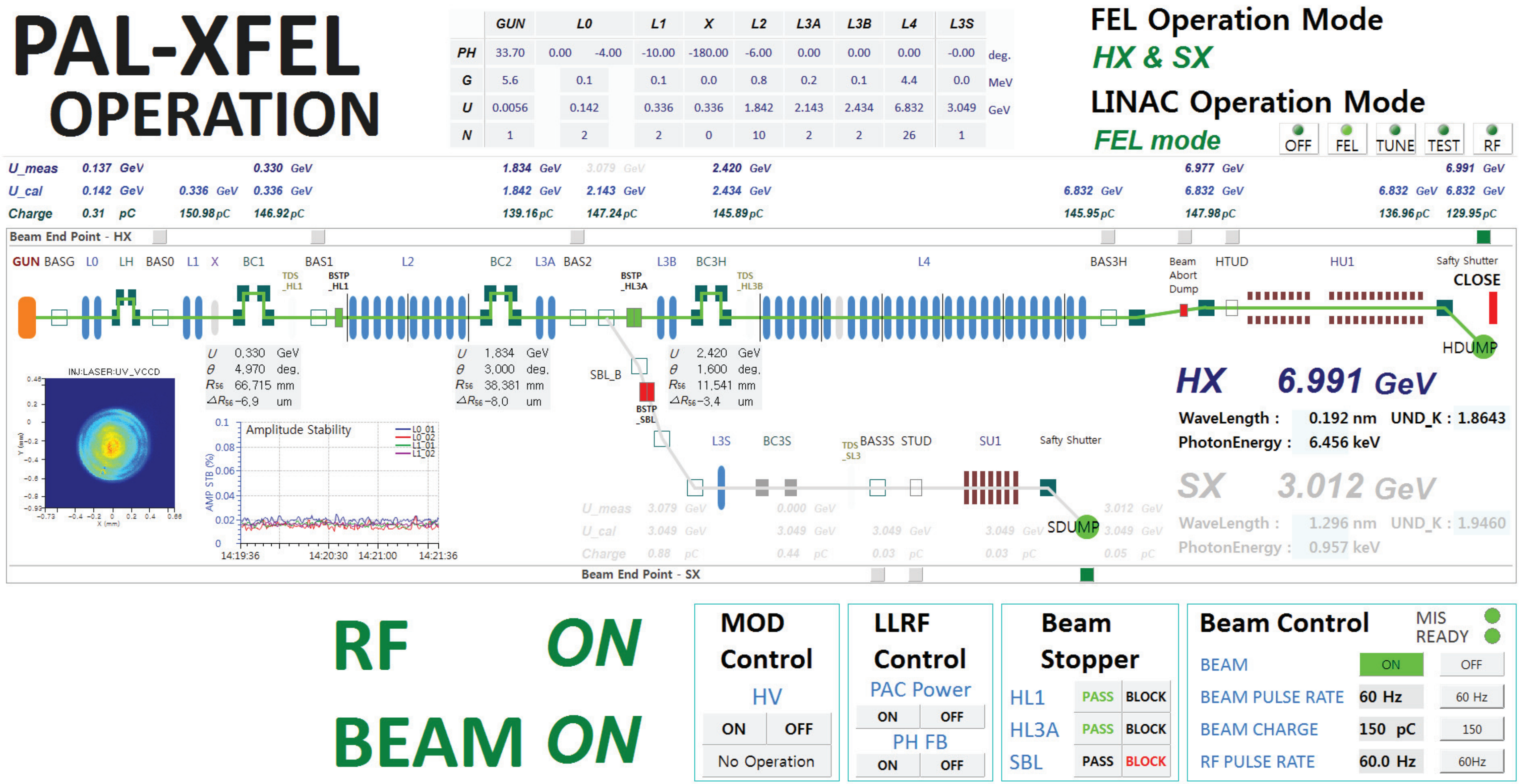


Main parameters

e^- Energy	10 GeV
e^- Bunch charge	20-200 pC
Slice emittance	0.5 mm mrad
Repetition rate	60 Hz
Pulse duration	5 fs – 100 fs
Peak current	3 kA
SX line switching	DC (Phase-1) Kicker (Phase-2)

Undulator Line	HX1	SX1
Wavelength [nm]	0.1 ~ 0.6	1 ~ 4.5
Beam Energy [GeV]	4 ~ 10	3.15
Wavelength Tuning [nm]	0.6 ~ 0.1 (energy or gap)	4.5 ~ 3 (energy) 3 ~ 1 (gap)
Undulator Type	Planar, out-vac.	Planar
Undulator Period / Gap [mm]	26 / 8.3	35 / 8.3

※ 3BC improves FEL power stability and phase tolerance by reducing CSR.



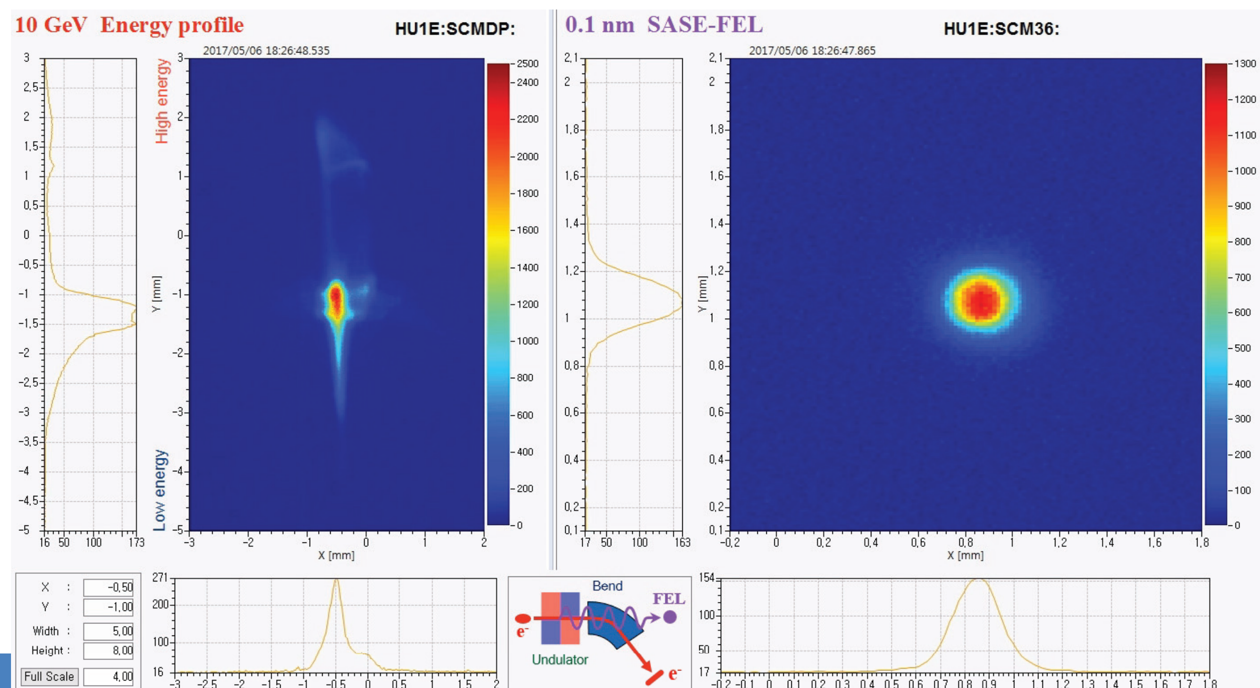
“FEL Optimization Through BBA with Undulator Spectrum Analysis and Undulator Optics Matching” by Haeryong Yang

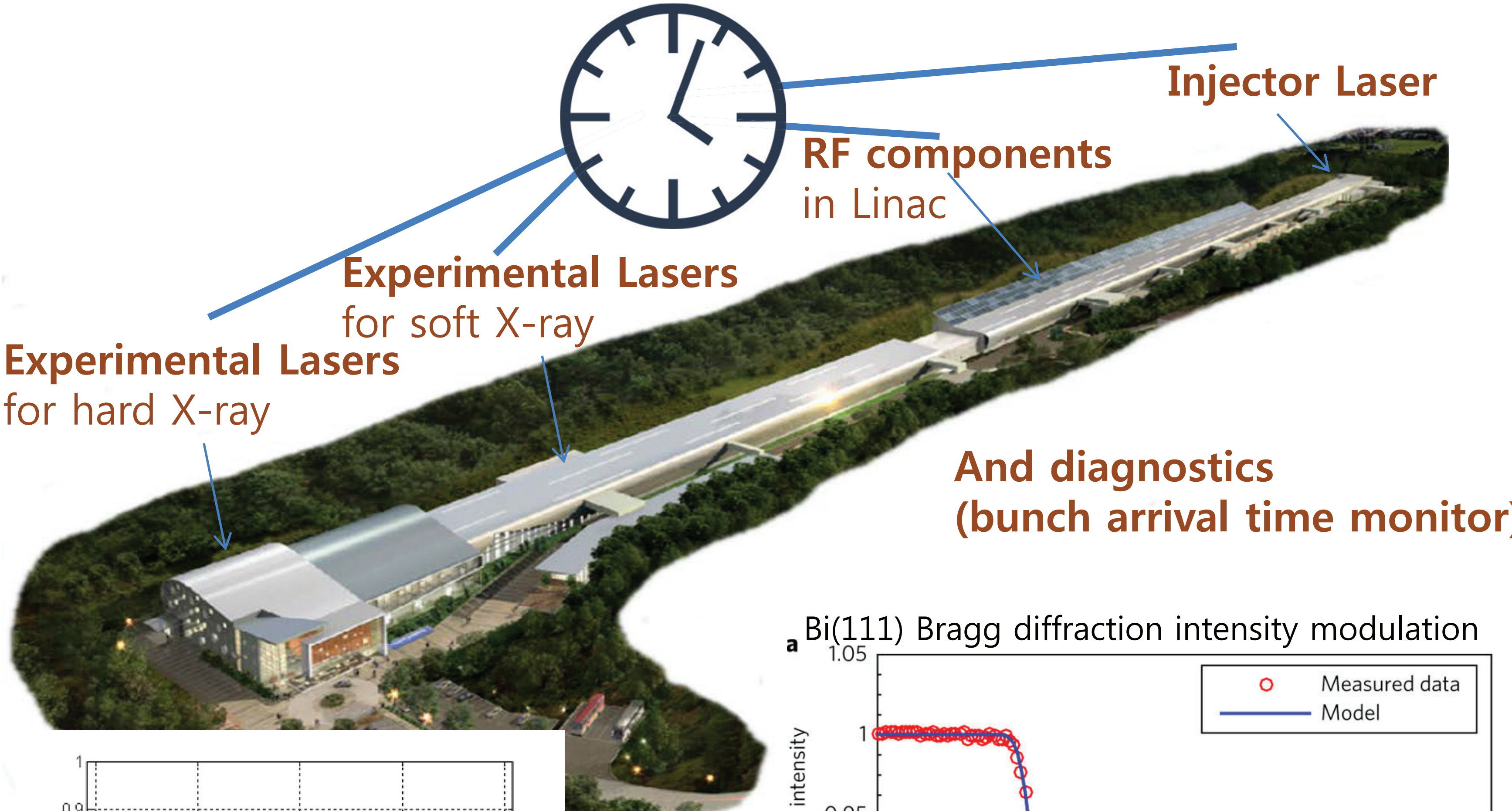
Time-resolved (Pump-probe) exp. using FEL

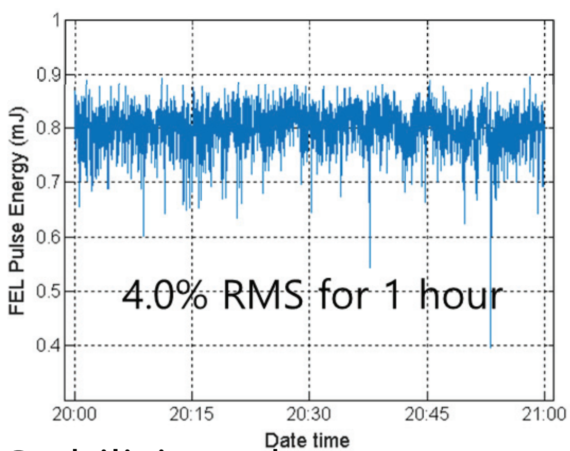
- Only way to see femtosecond dynamics directly

- Requirements will be

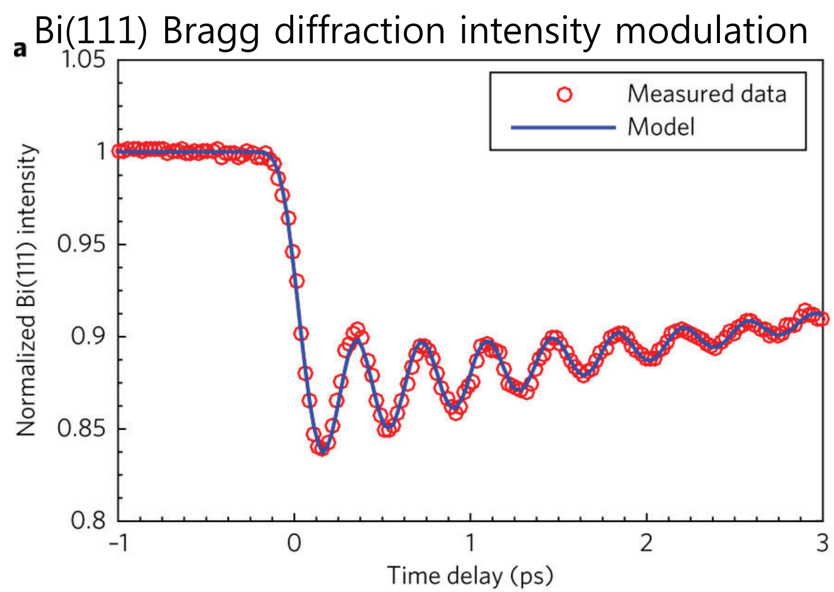
- Short pulse length of pump and probe pulses which determine the time resolution
  (PAL-XFEL, 20 fs FWHM at 1 mJ, 7~10 KeV, shorter pulse(~10 fs) with smaller charge optical pulse, 20~30 fs with moderate difficulty, <10 fs with self phase modulation attosecond pulses with high harmonic generation)
- Enough power to trigger events (reducing beamsize increase power density)
- Machine stability
  : Temporal jitter
  : Spatial jitter
  : Power fluctuation







Stabilizing phase space content
of e^- bunch



Time resolution
(timing jitter between FEL and optical laser)

Content

- Timing distribution based on low phase noise oscillator and coaxial cable with passive stabilization

- Optical laser synchronization to RF reference

- FEL timing jitter

  - Timing jitter performance of gun and linac in terms of e^- bunch arrival jitter

- Pump- probe timing jitter

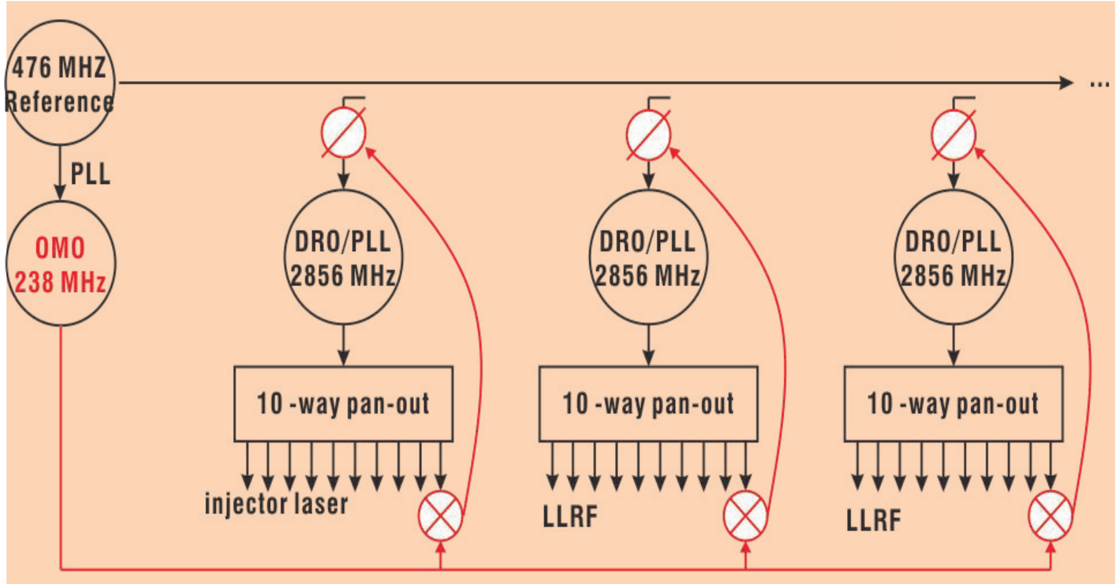
  - Jitter between FEL and optical laser using optical crosscorrelator

Timing distribution

- Hybrid system proposed

Low phase noise RF via coaxial cables + low drift optical via optical fiber (implemented in EU-XFEL)

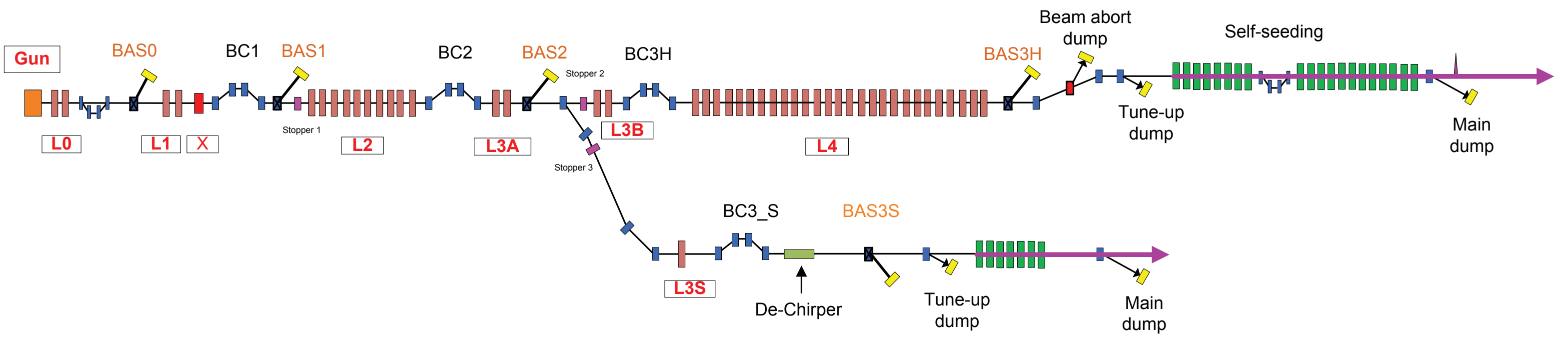
e.g.

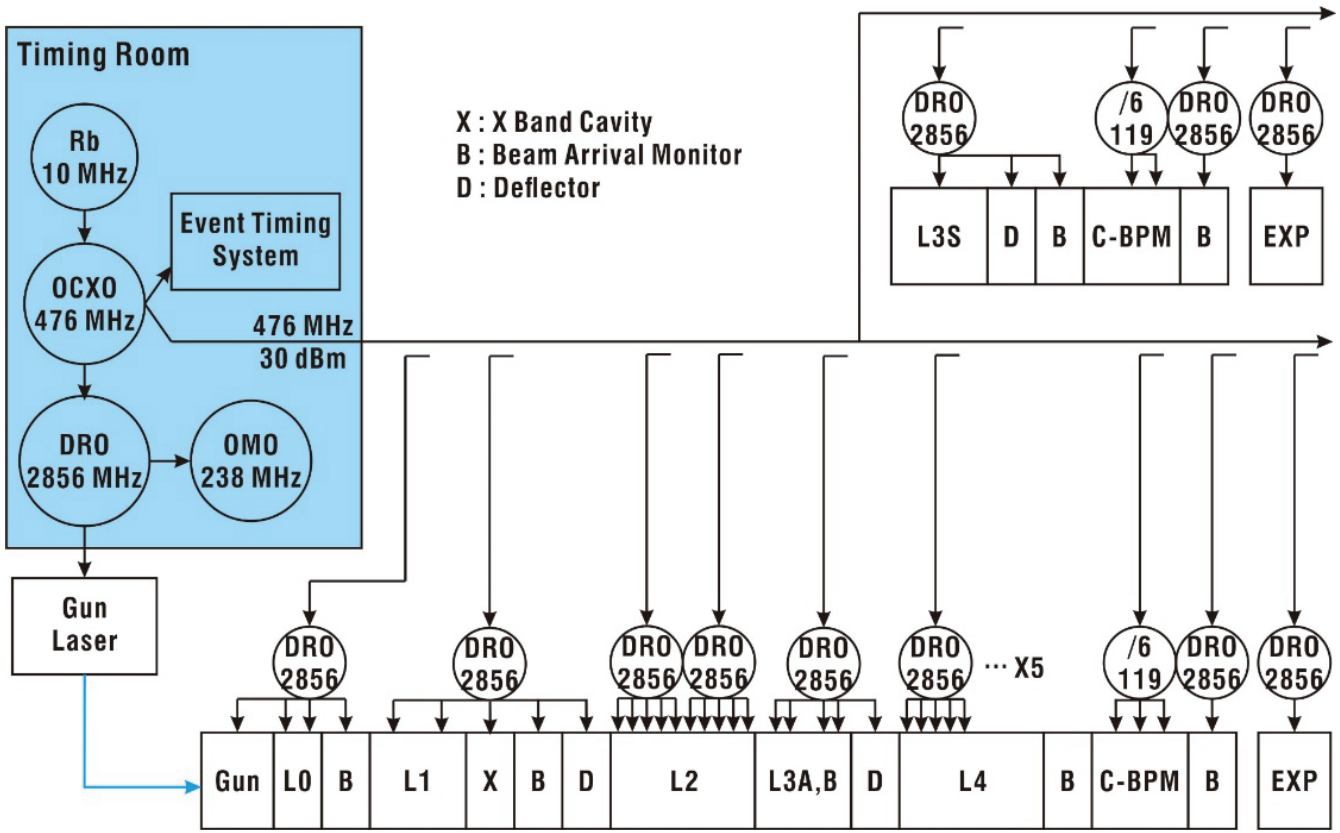


- Current implementation

RF only and Passive stabilization

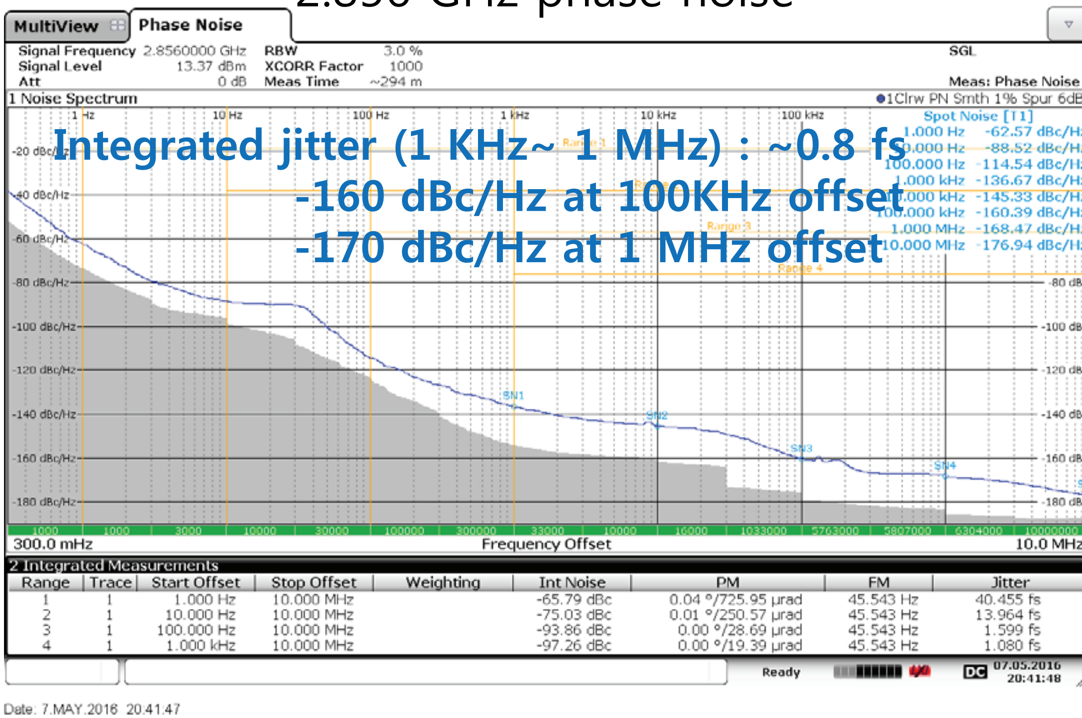
PAL-XFEL timing distribution (2.856GHz RF)





PAL-XFEL timing distribution (2.856GHz RF)

2.856 GHz phase noise



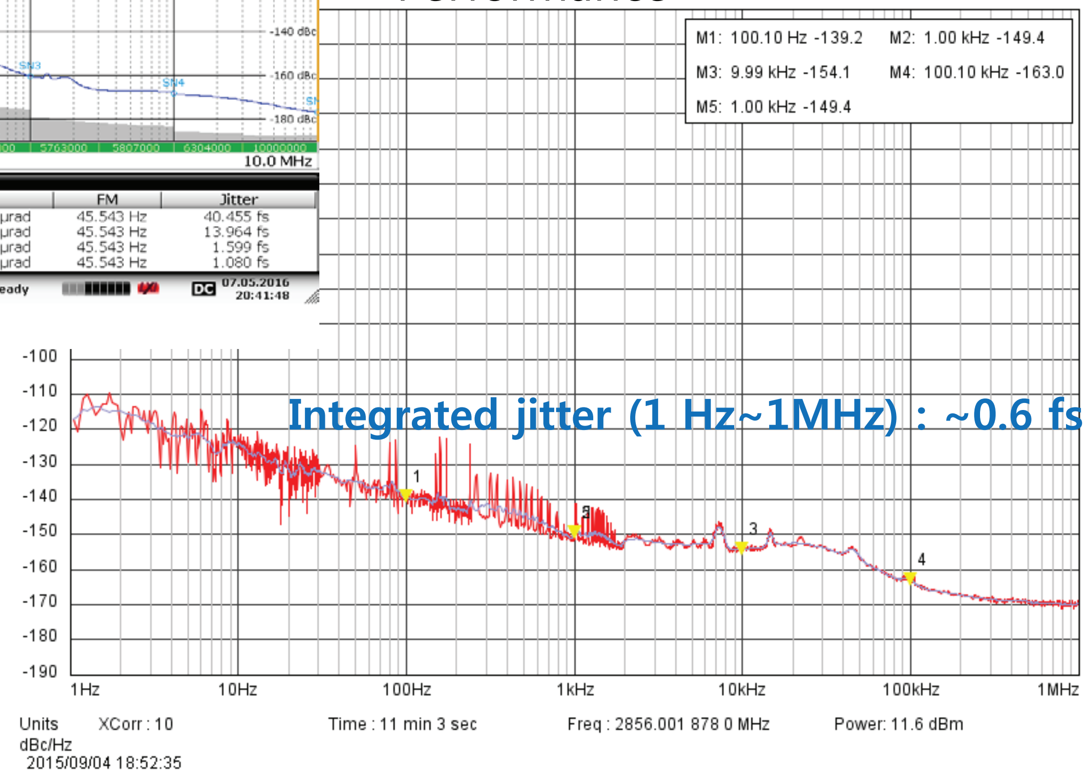
Range	Trace	Start Offset	Stop Offset	Weighting	Int Noise	PM	FM	Jitter
1	1	1.000 Hz	10.000 MHz		-65.79 dBc	0.04 °/725.95 µrad	45.543 Hz	40.455 fs
2	1	10.000 Hz	10.000 MHz		-75.03 dBc	0.01 °/250.57 µrad	45.543 Hz	13.964 fs
3	1	100.000 Hz	10.000 MHz		-93.86 dBc	0.00 °/28.69 µrad	45.543 Hz	1.599 fs
4	1	1.000 kHz	10.000 MHz		-97.26 dBc	0.00 °/19.39 µrad	45.543 Hz	1.080 fs

Integrated jitter (1 KHz~ 1 MHz) : ~0.8 fs

-160 dBc/Hz at 100KHz offset

-170 dBc/Hz at 1 MHz offset

476 MHz 2.856 GHz PLL Performance

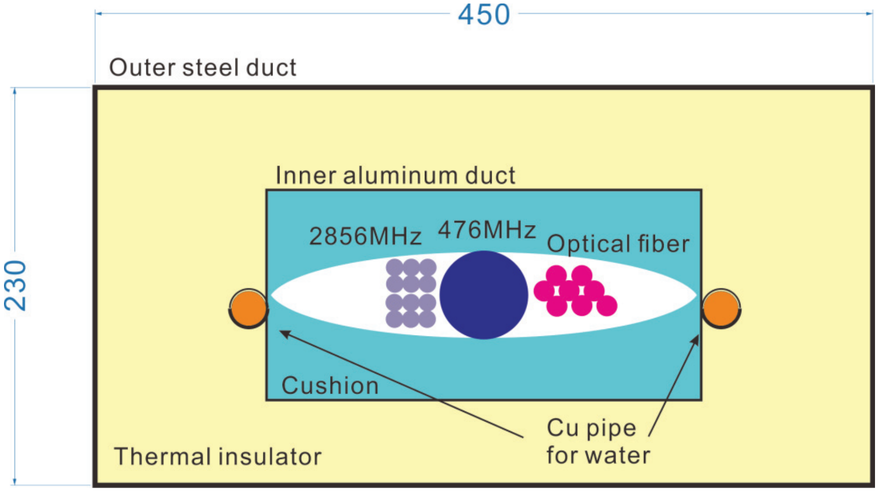


Integrated jitter (1 Hz~1MHz) : ~0.6 fs

Dr. Gronefeld

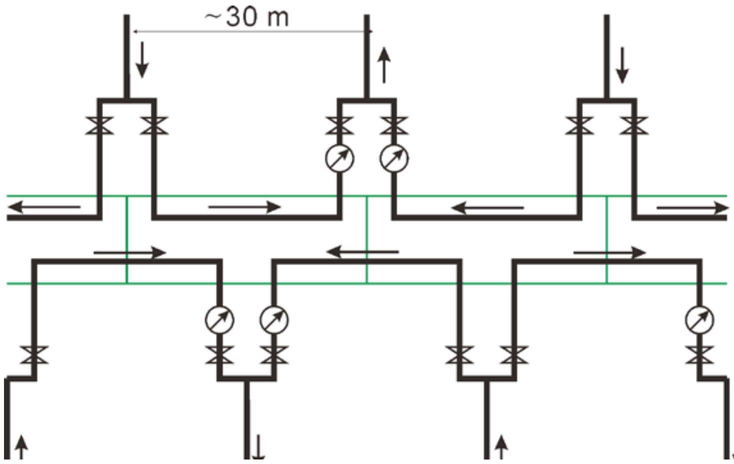
Temperature stabilization of RF Cables

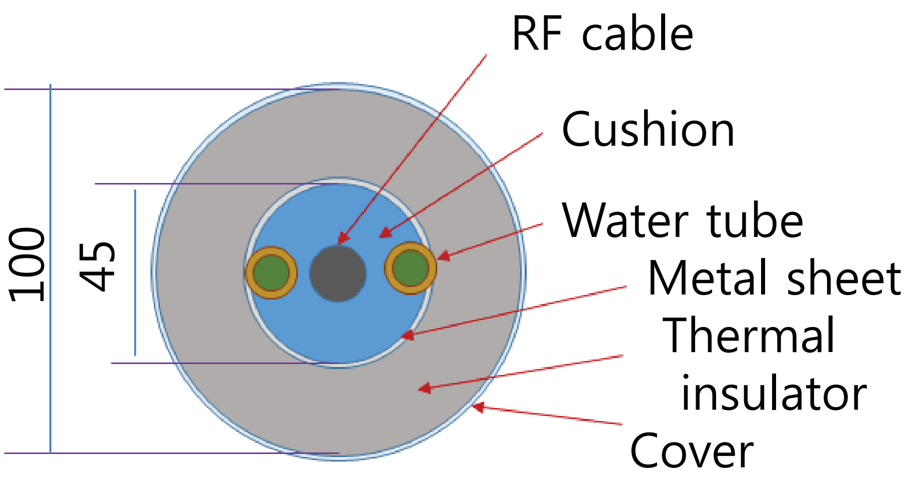
Duct cross-section



With cover open

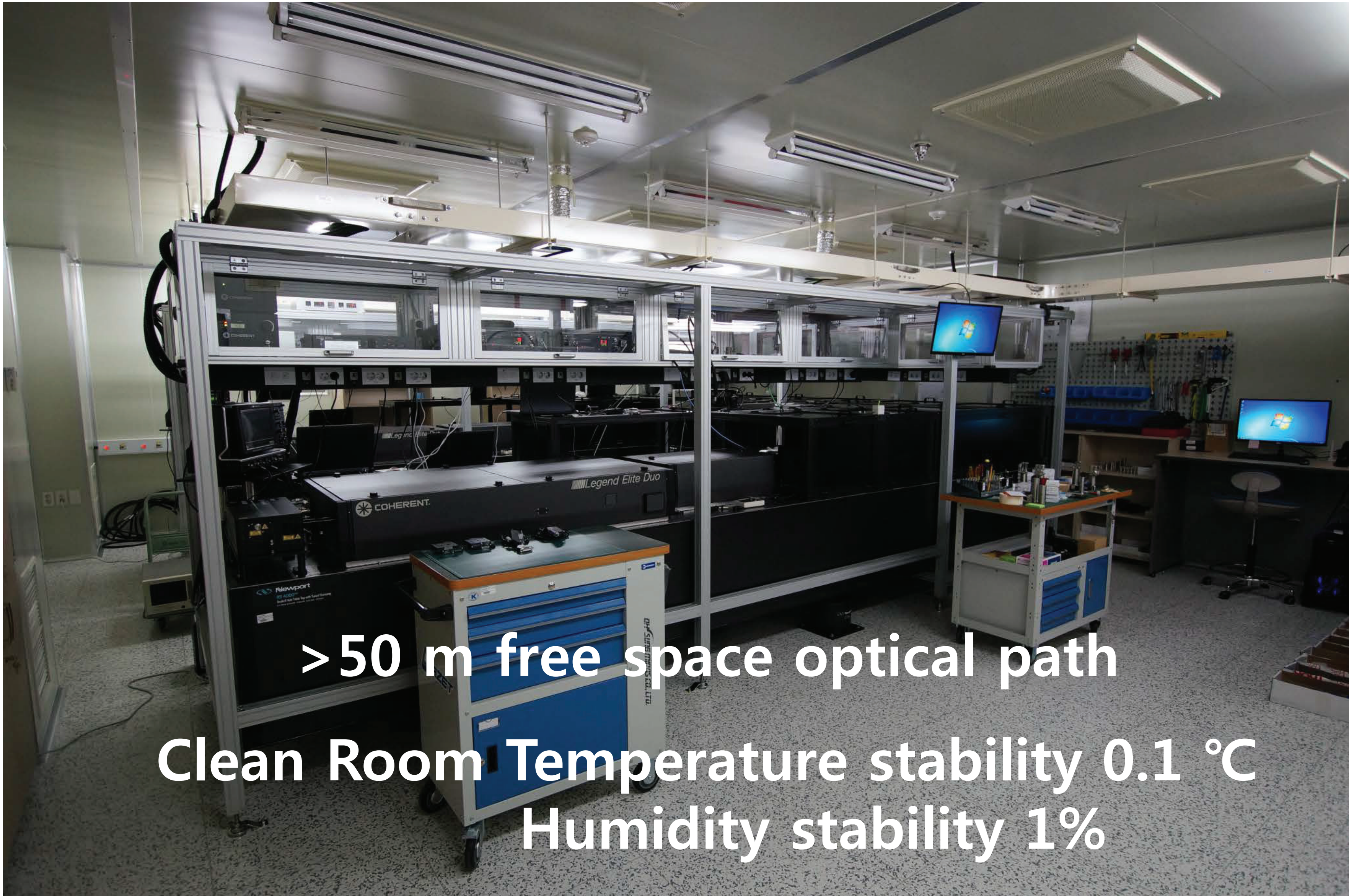
LCW flow diagram



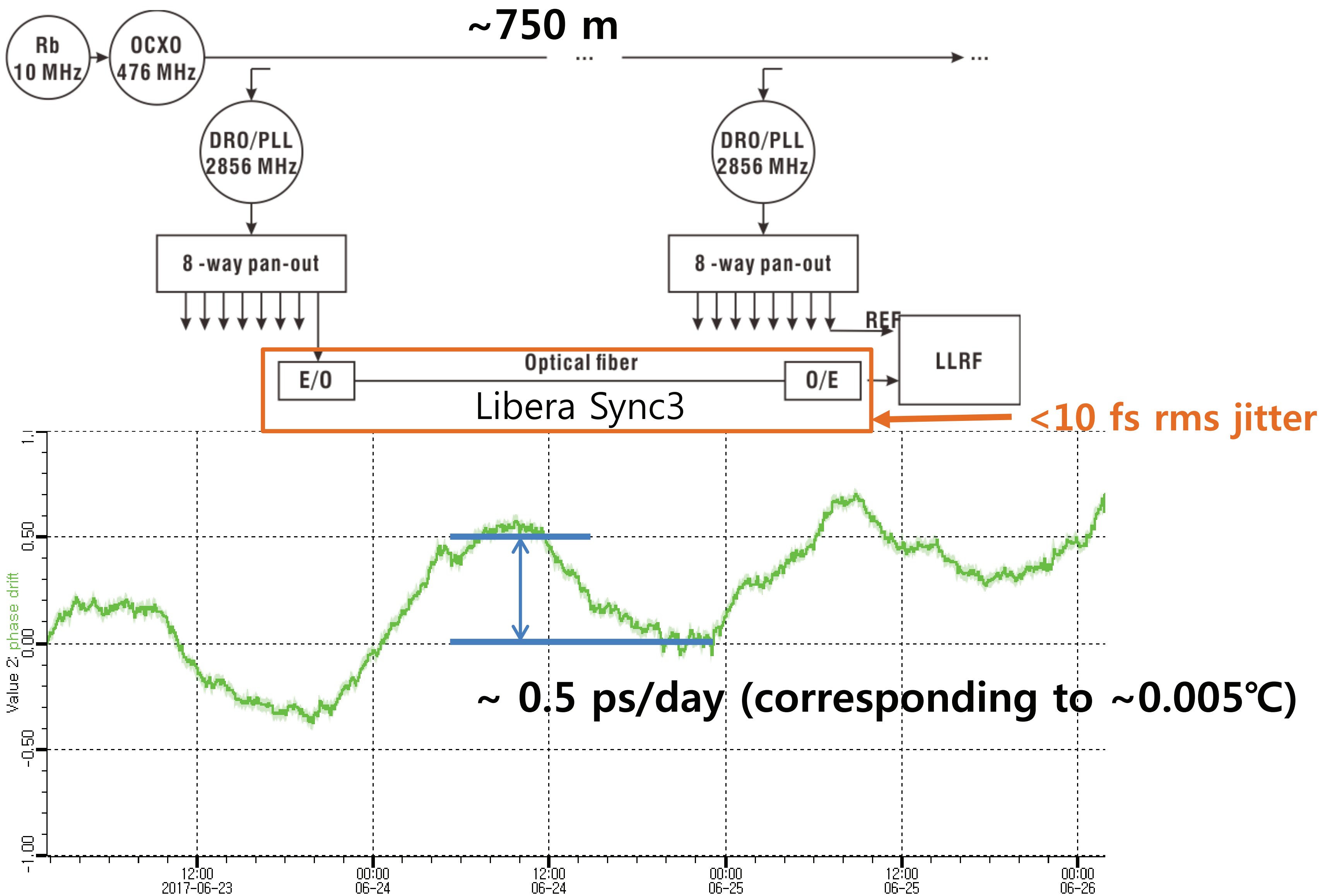


Temperature stability of Duct : **0.01℃/day**

Injector laser room

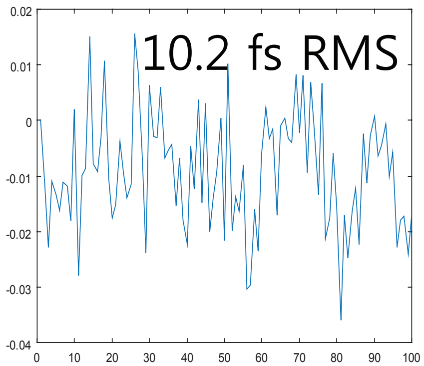


Phase Drift monitoring using drift-free optical link

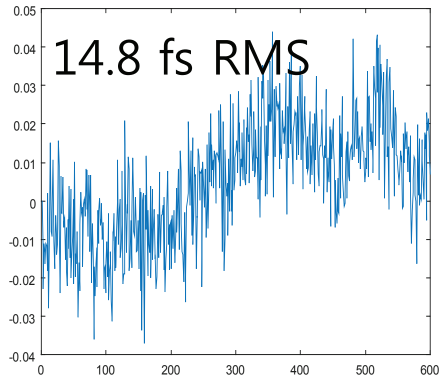


Time scale of timing error in reference timing distribution

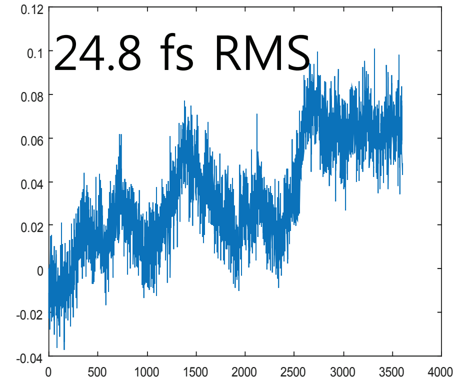
100 Seconds



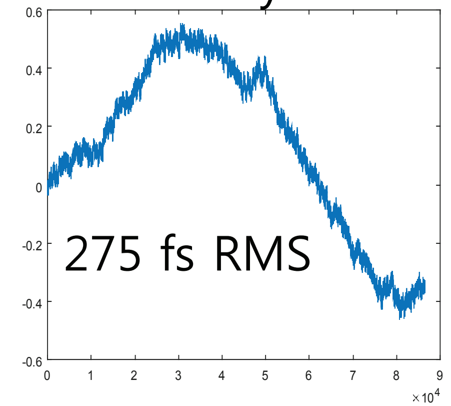
10 minutes

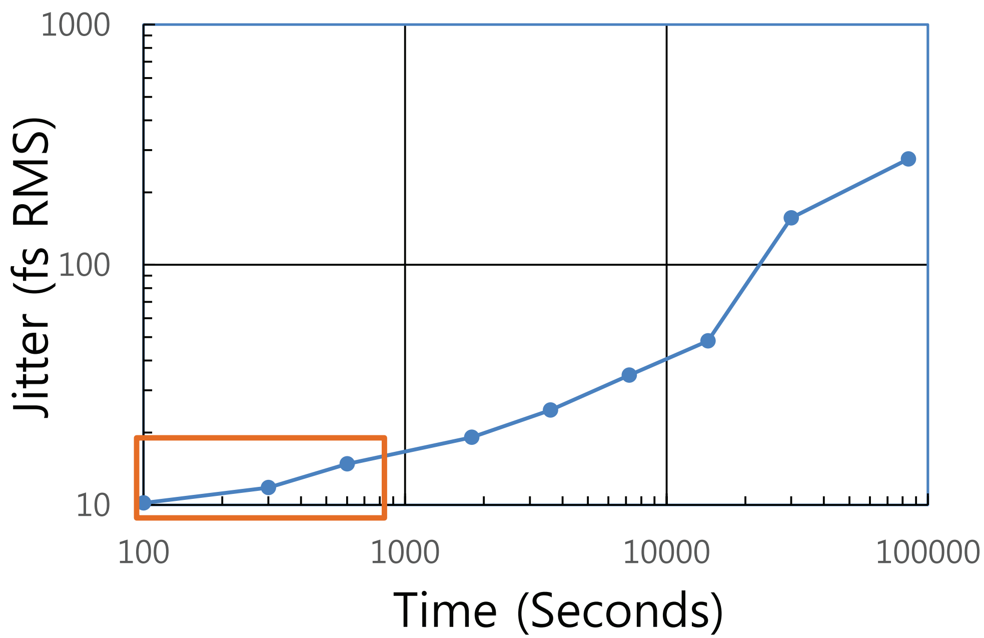


1 hour

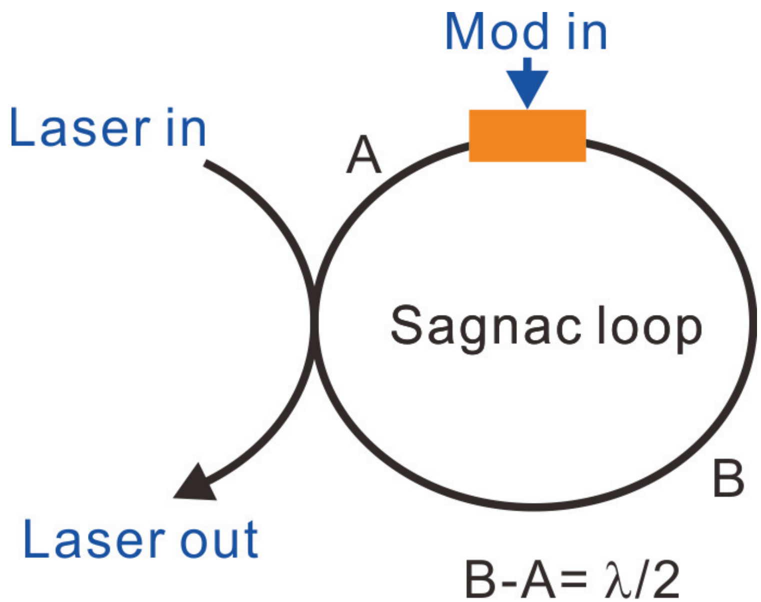


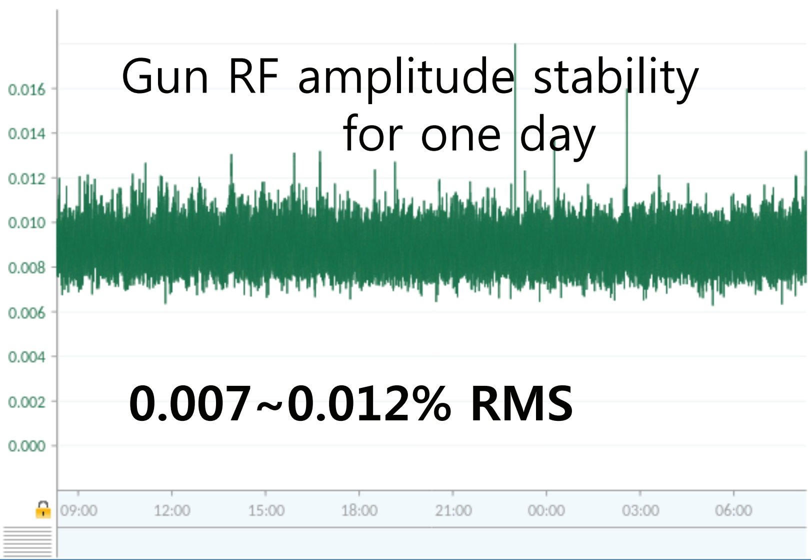
1day





Photocathode gun - e⁻ bunch arrival jitter





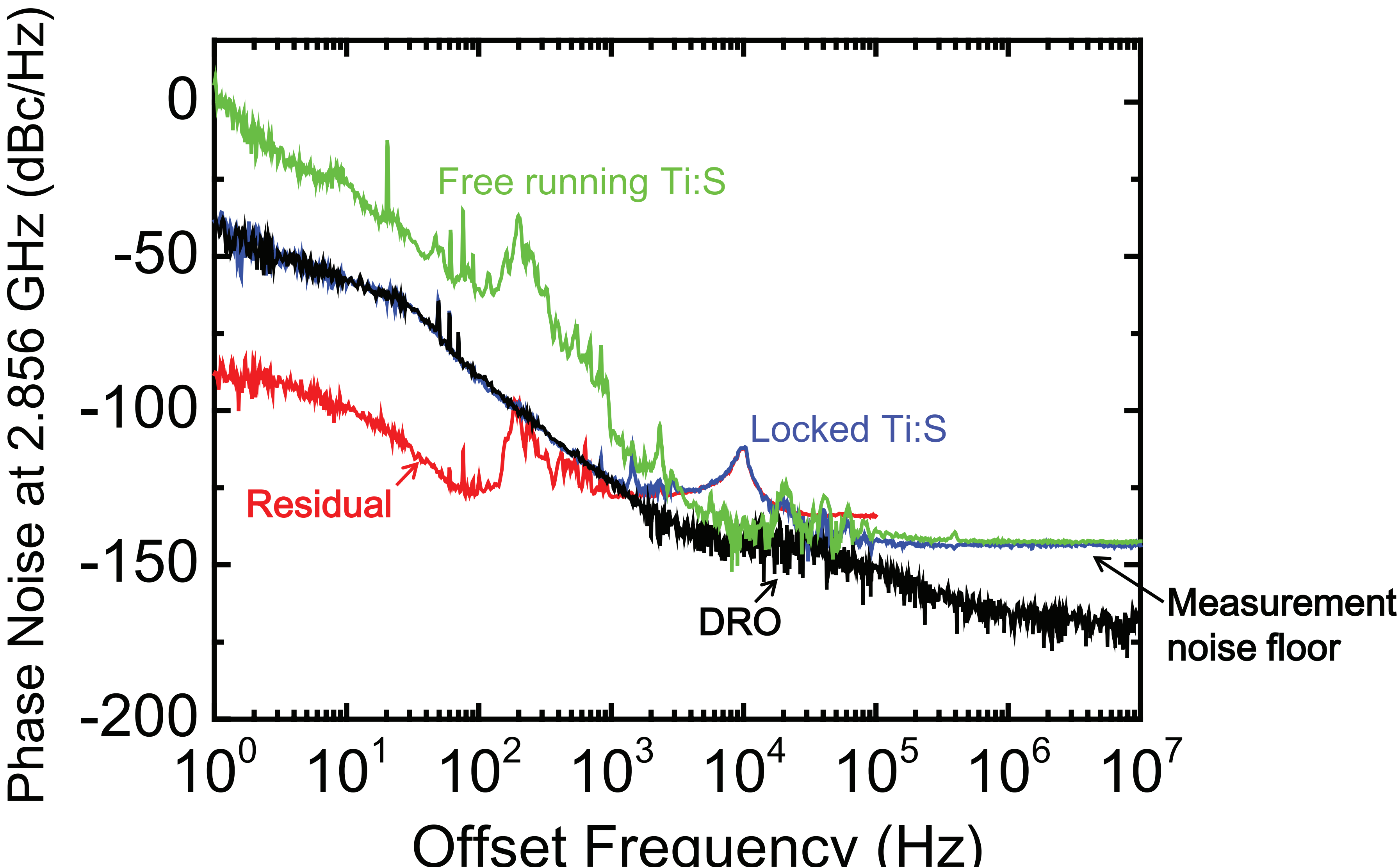
Home-built sensitive phase detector
Between RF and optical laser
(2.856 GHz) (79.33MHz Ti:S)

Provides **10 fs level jitter**

RF system adds ~10^{-4} amplitude jitter
~10 fs timing jitter

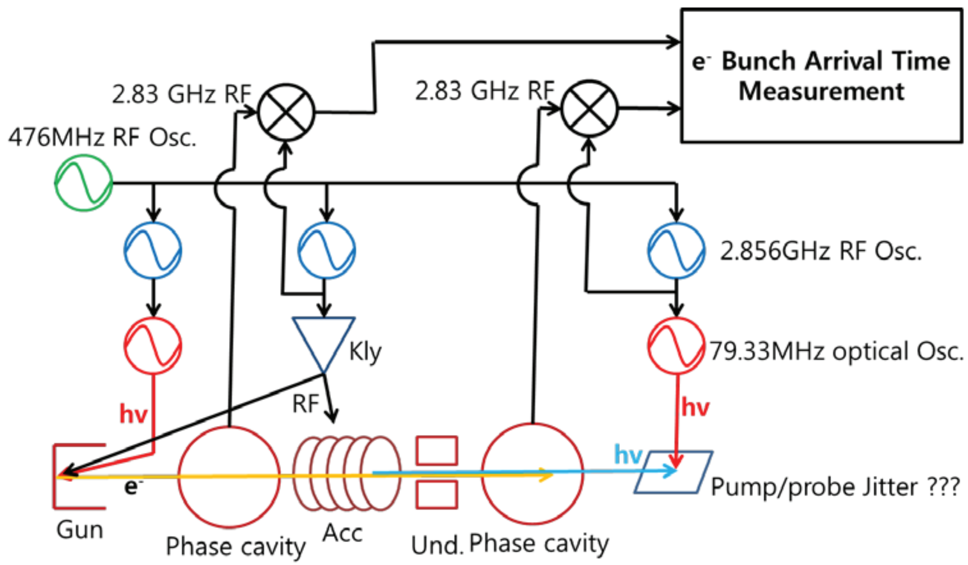
≈14 fs residual phase jitter from 1 Hz to 100 KHz

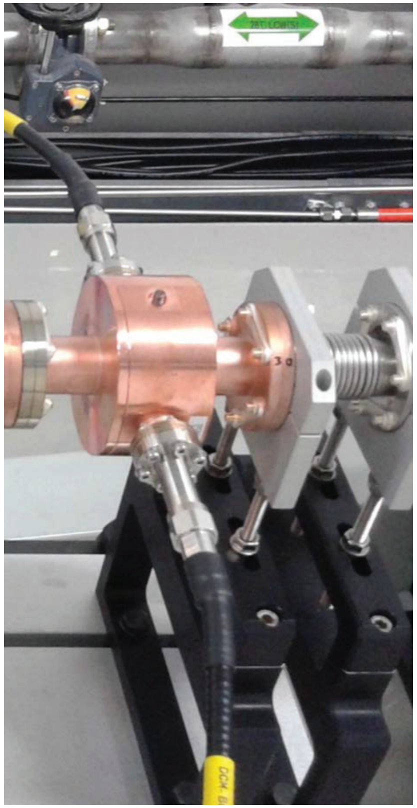
Out-of-loop measurement

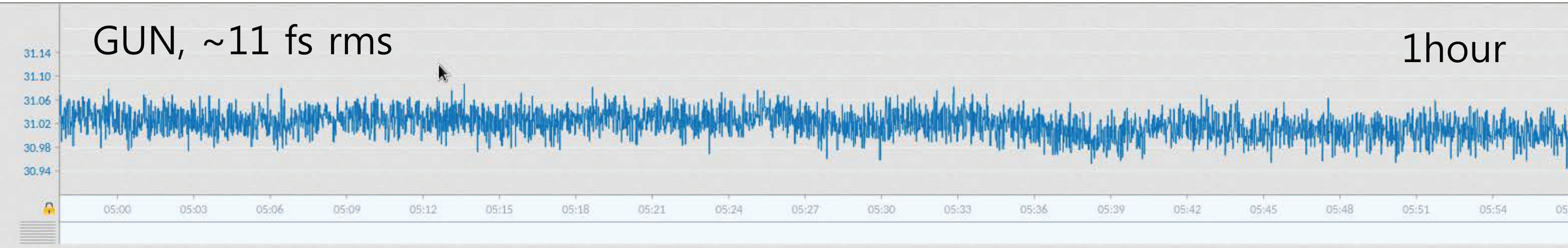


Beam arrival time jitter at gun

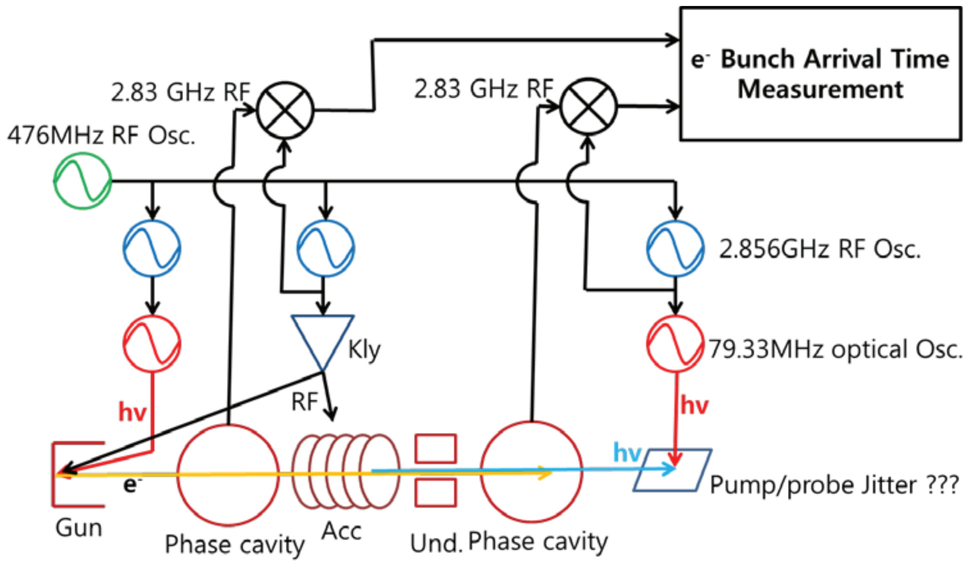
Monopole S-band cavity (phase cavity)

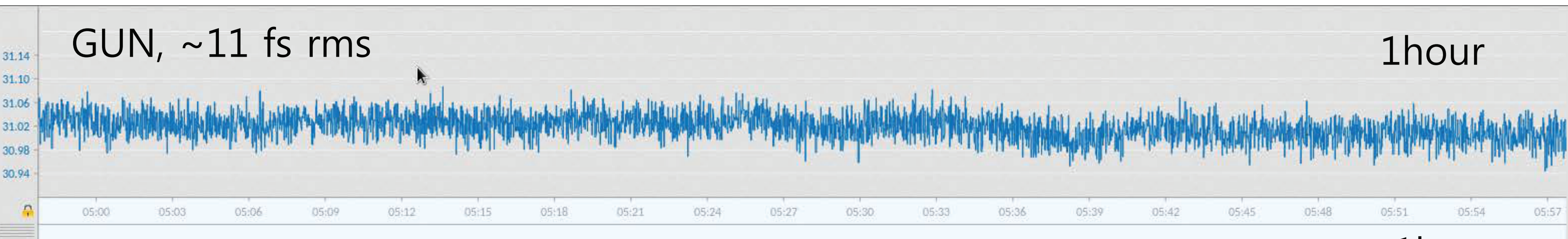


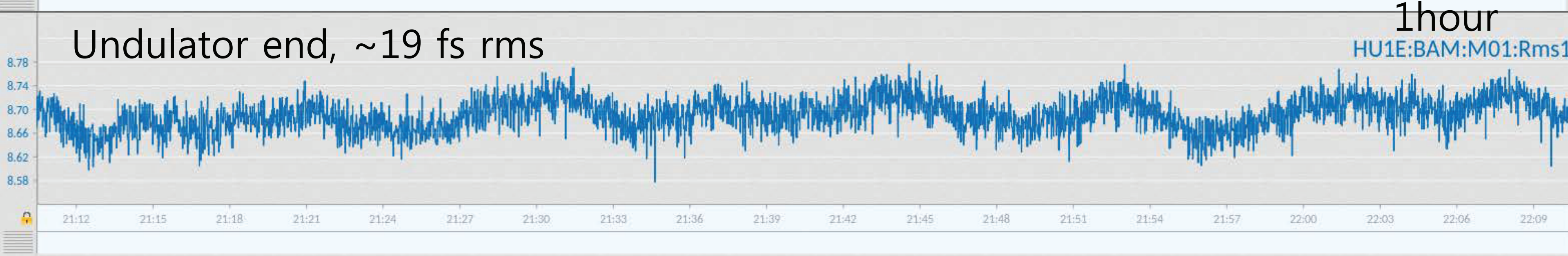




Beam arrival time jitter at gun and undulator end

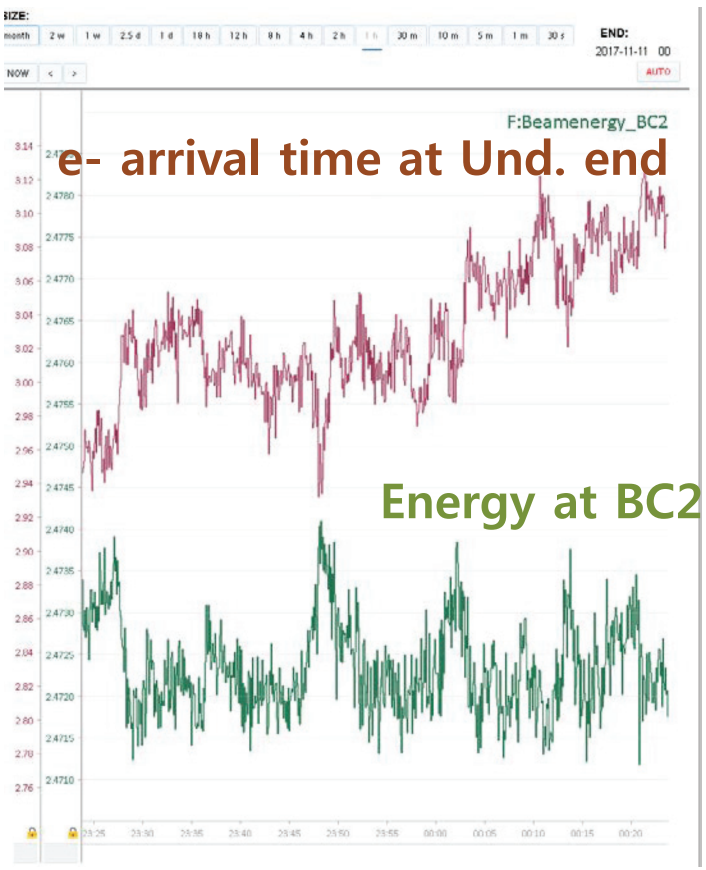


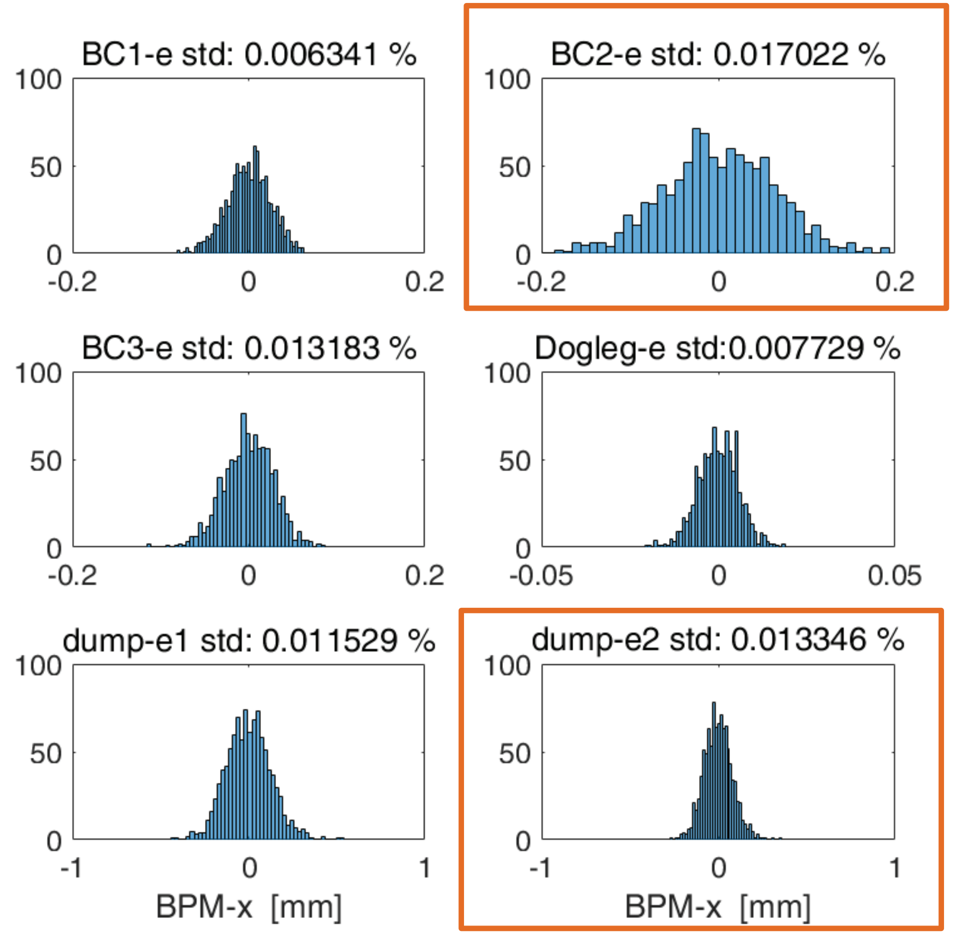




E-beam energy jitter

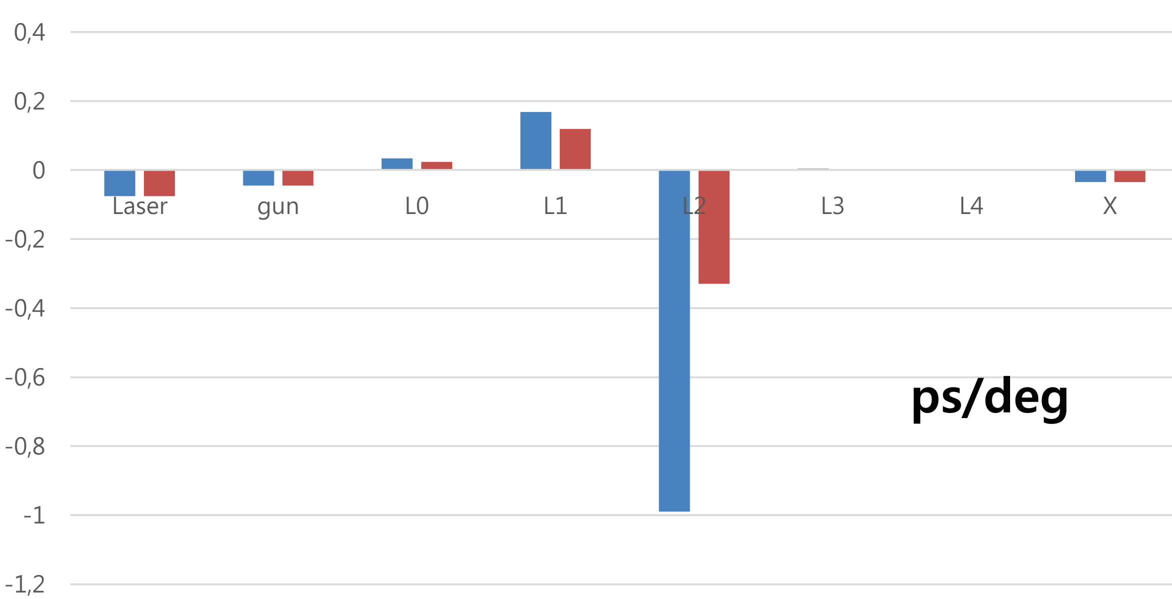
100 fs drift /10^{-3} energy change at BC2

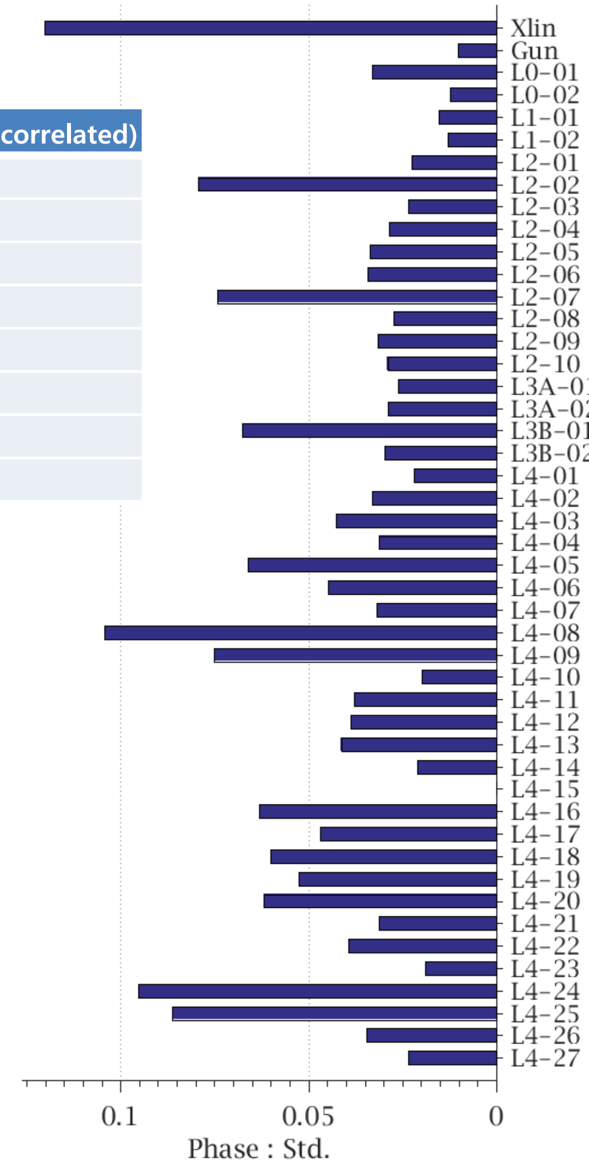




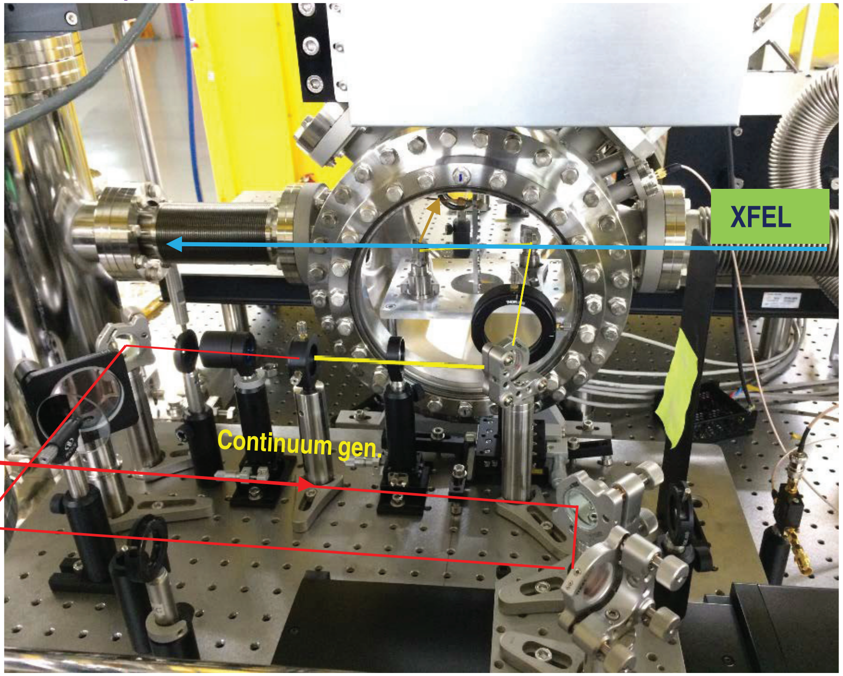
Measured longitudinal sensitivity of phase

	Sensitivity of single station	Number of station	Total sensitivy (correlated)	Total sensitivy (uncorrelated)
Laser	-0.076	1	-0.076	-0.076
gun	-0.045	1	-0.045	-0.045
L0	0.017	2	0.034	0.024
L1	0.084	2	0.168	0.12
L2	-0.11	9	-0.99	-0.33
L3	0.0011	4	0.0044	0.0022
L4	0.0001	25	0.0025	0.0005
X	-0.035	1	-0.035	-0.035





OXC (Optical laser & XFEL Cross-correlator) at EH1 (XSS)



SiN Membrane holder

Fast photodiode (30ps rise)

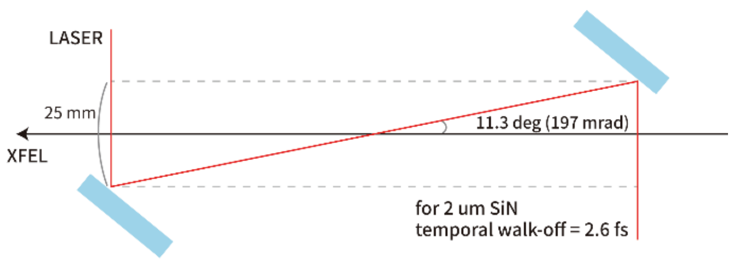
YAG:Ce

Pin-hole (100 μm)

SiN 500 nm

SiN (1 μm)

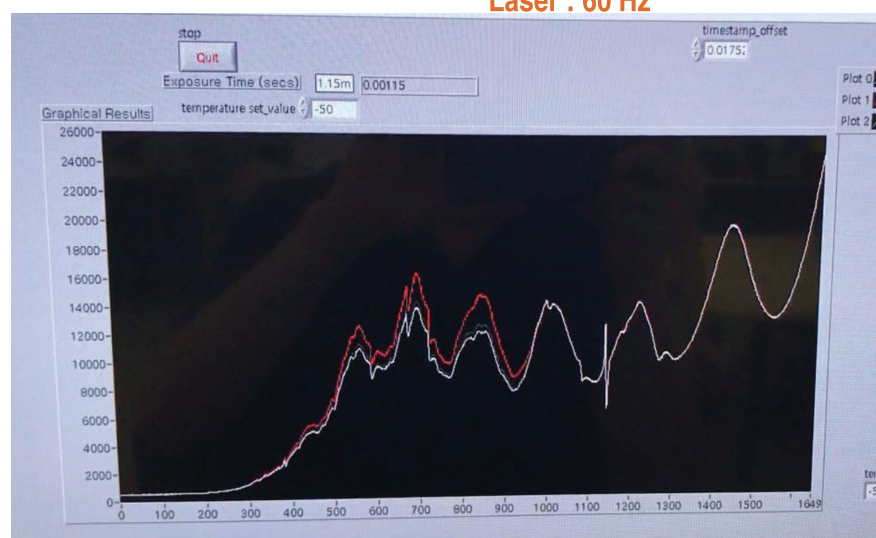
SiN (2 μm)



CCD spectra (single shot)

XFEL : 30 Hz at 7 keV

Laser : 60 Hz

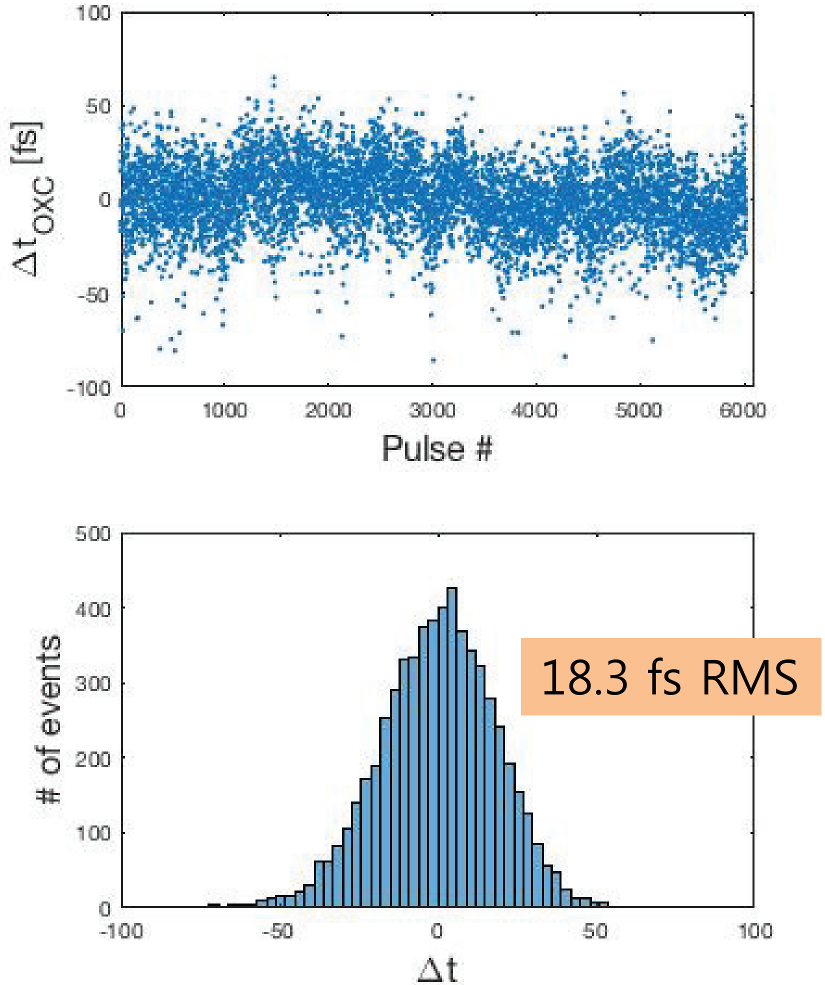


Optical Cross-correlator

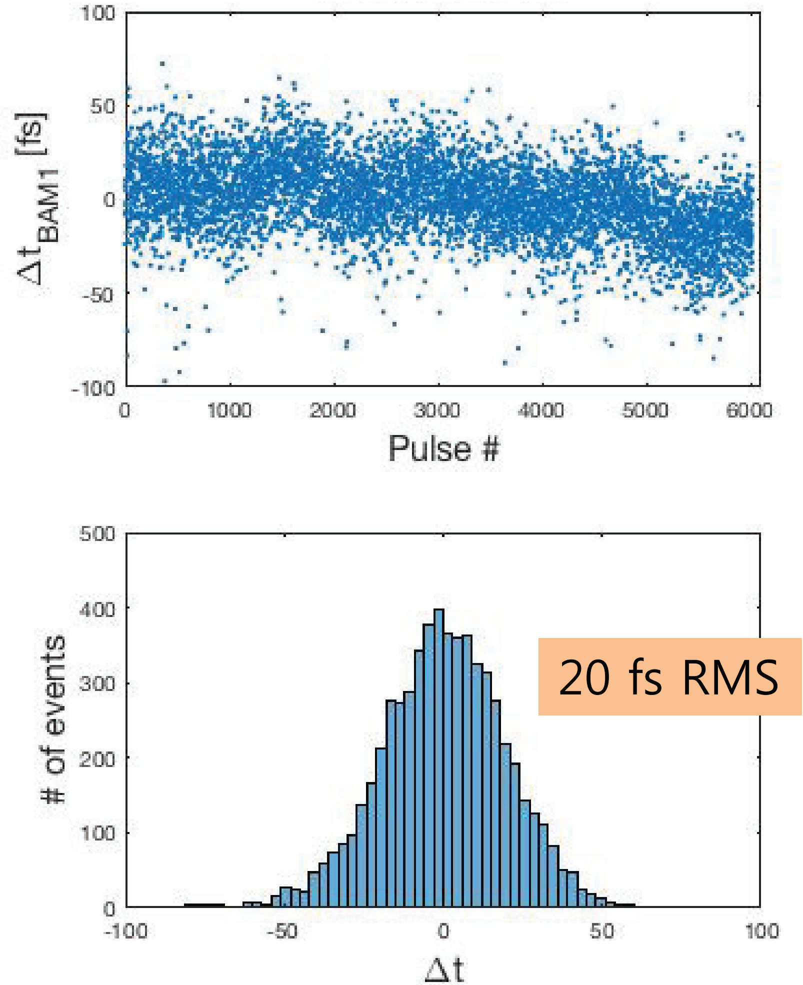
Dr. Eom

FEL timing jitter

FEL/optical laser cross-correlation

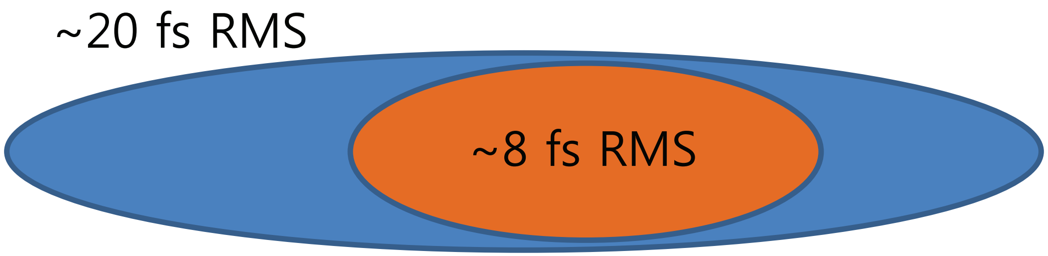


e^- bunch arrival time at undulator end

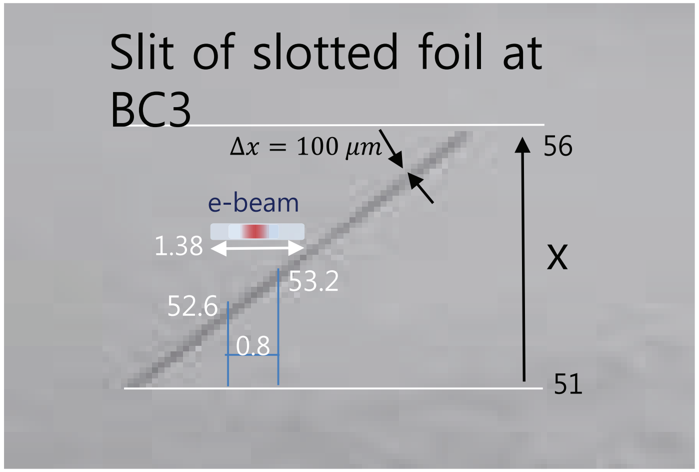


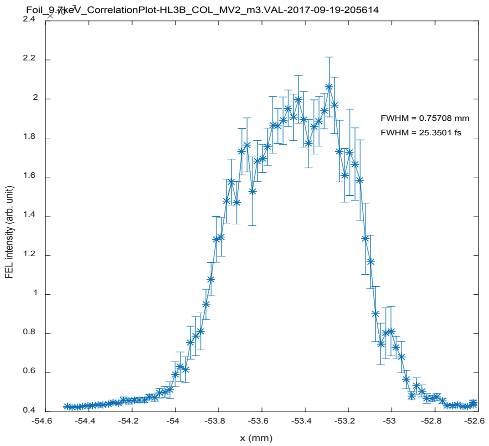
Stability of electron beam and FEL generation

In general,
e^- beam arrival time doesn't tell FEL pulse length fluctuation and position
(optical laser temporal profile will be stable)



In our case, e beam and FEL process seems to be stable in 10 fs scale (3 BC scheme, careful Undualtor BBA, Matching helps)





Summary

- PAL-XFEL and optical laser for exp. shows **sub 20 fs jitter** performance at the measurement time scale of pump-probe experiment(**~10 minutes**).
- Predominant timing jitter(or drift) is correlated to energy at BC2. It could be due to **L2 phase changes**
- In future, hybrid timing system may incorporate a **slow drift compensation** based on optical timing system(CW or pulse) with **~10 second bandwidth**, which could result in **a few femtosecond jitter**
- Laser synchronization may need improve to **a few fs** for **10 fs level pump-probe timing resolution**

Phase drift estimation due to RF Cables

- 476 Mhz **low loss cables**

  : Huber+Suhner, SUCOFEED_ 1_5/8_LA**,**

  Loss : <1.5 dB/100m

  Drift : ≈ 130 fs/mK

  → For 1 km and with 0.1℃ stability, 13 ps drift is expected

  (The huge drift will be compensated by LLRF and beam based feedback) **Should be compensated**

- 2856 Mhz **low drift cables**

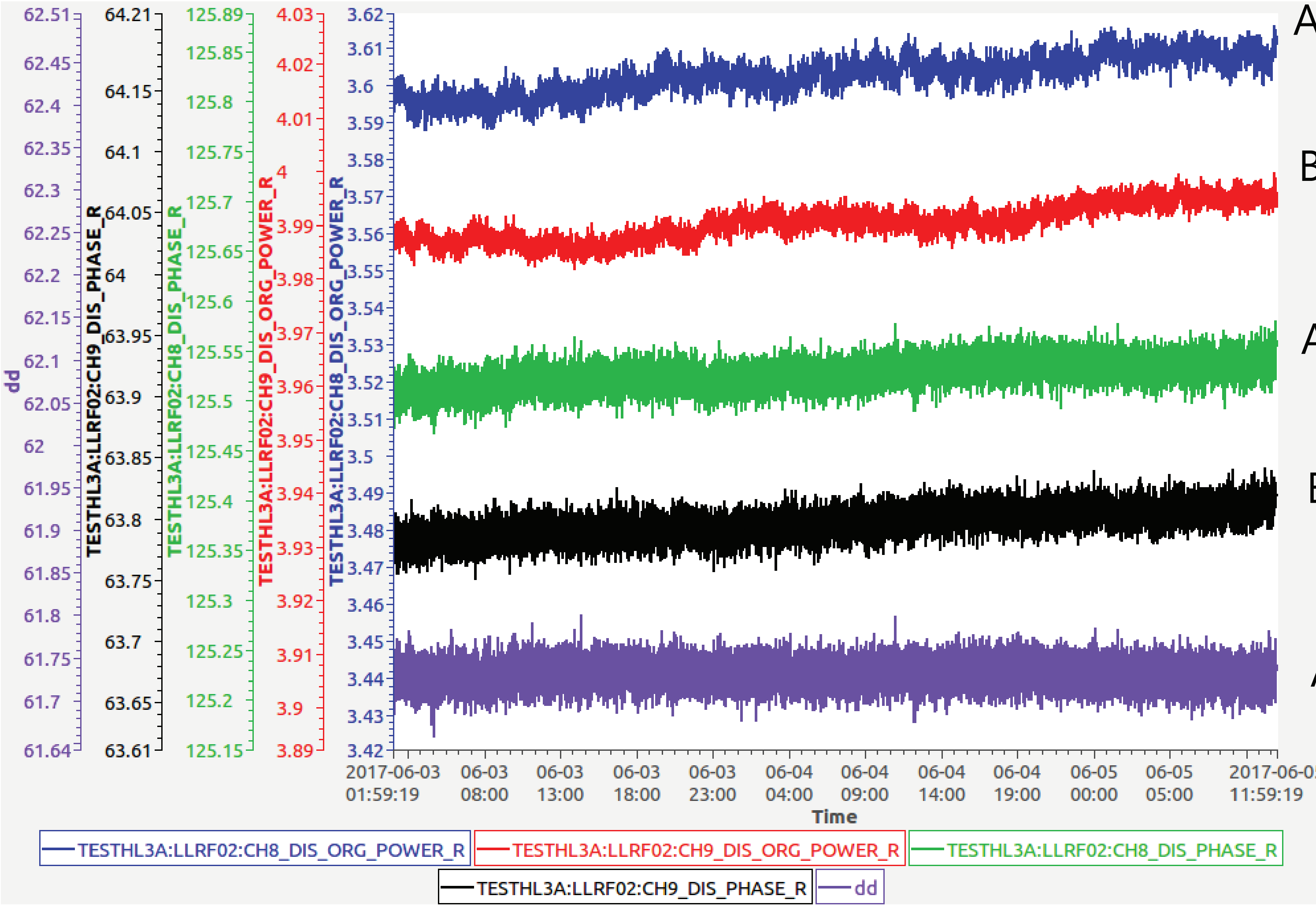
  : RFS, LCF38-50J 3/8" **,**

  Loss : 20.5 dB/100m at 3 GHz

  Drift : ≈ 7 fs/mK

  →For 50 m (max. distance for 2.856 GHz distribution and with 0.1℃ stability, 35 fs drift is expected. (15fs for L0, 20 fs for L1&L2) **considered as minimal**

Optical timing test (Libera Sync 3, 2.2 km, 3days)



A : Libera Sync amplitude

B : Reference amplitude

A : Libera Sync Phase

B : Reference Phase

A -B

Phase drift <10fs