# Phase distribution system of HEPS

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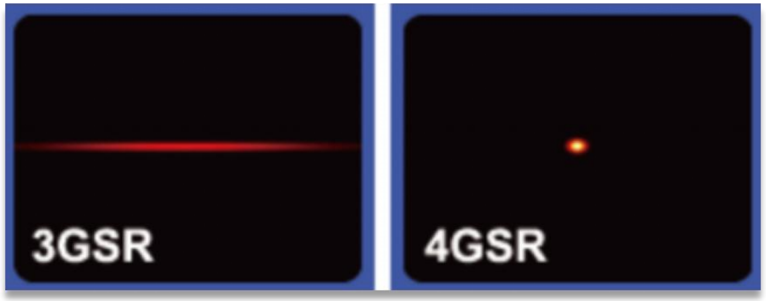
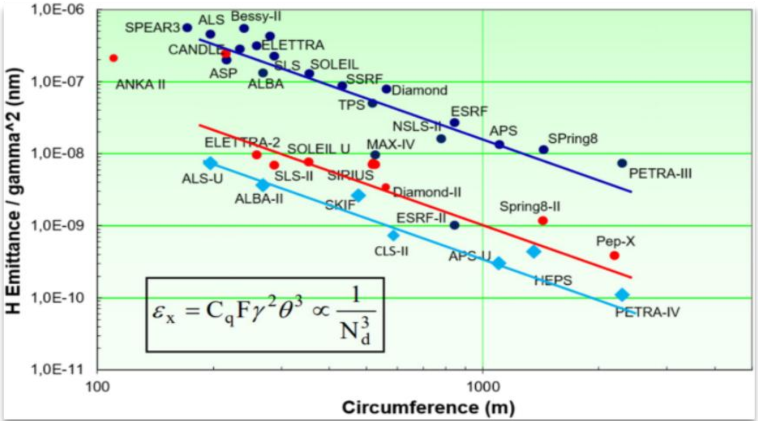
# Outline

- HEPS Project
- Master Oscillator system
- Phase distribution system
- Summary

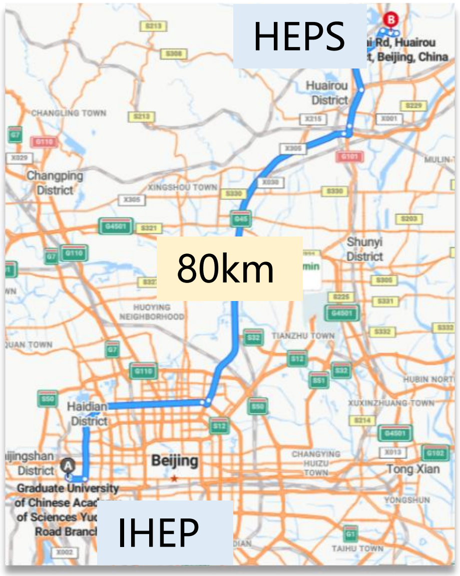
# HEPS High Energy Photon Source

- New constructed, first 4th gen high-energy SR in China
- Modified hybrid 7BA lattice




Shin, S. New era of synchrotron radiation: fourth-generation storage ring. AAPPS Bull. 31, 21 (2021)




| Parameter | |
|---|---|
| SR circumference | 1360.4 m |
| BS circumference | 454.5 m |
| Lattice structure | 48×7BA |
| Energy | 6 GeV |
| Current | 200 mA |
| Emittance | 60 pm·rad |
| Brightness | $>1\times10^{22}$ phs/s/mm$^2$/mrad$^2$/0.1%BW |

# HEPS High Energy Photon Source

- ☐ 2019/06 Civil starts ✔
- ☐ 2022/02 Linac&Booster start to install ✔
- ☐ 2023/03 Linac first beam ✔
- ☐ 2023/11 Booster passes acceptance ✔
- ☐ <u>2024/07 Storage ring commissioning</u> ✔
- ☐ 2024/12 First X-ray
- ☐ 2025/12 Project completed and operation

2024, August

2021, May

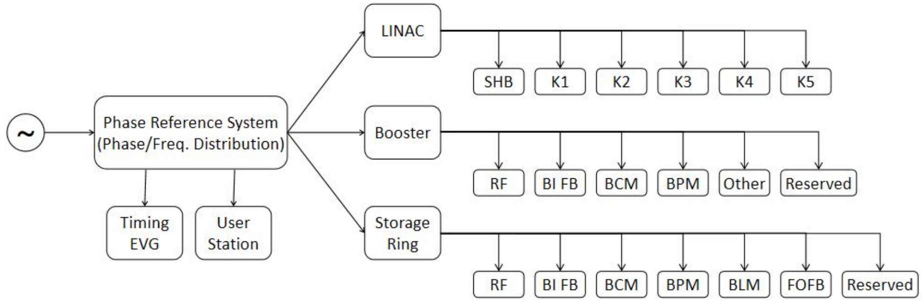
2022, May

# HEPS High Energy Photon Source

## Timing system:

+ Phase reference line *(or synchronization, MO + phase distribution)*

+ Global event timing *(timing triggers fanout)*

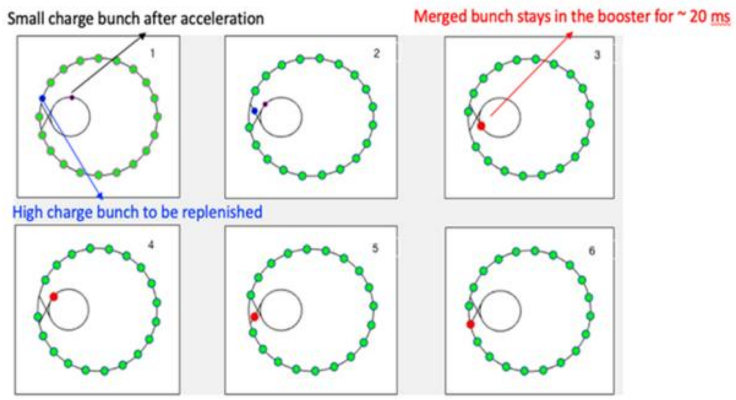



RF reference requires 700+ signals:

| Sub-system | Frequency/MHz | Number | Location |
|---|---|---|---|
| Linac | 166.6/499.8/2998.8 | 1/1/6 | Linac |
| Booster LLRF | 499.8 | 6 | RF Hall |
| Booster BI | 499.8 | 88 | Tunnel/Linac/HETL |
| SR LLRF | 166.6/499.8 | 5/3 | RF Hall |
| SR BI | 166.6/119/499.8/83.3 | 11/601/2/1 | ~50 stations in SR |
| EVG | 166.6/499.8 | 1/1 | Timing station |
| Beam Line | 499.8 | 1 | M10 |

Event timing

- Adopted MRF MicroTCA.4 hardware
- Dedicated swap-out injection




Liu, F., Lei, G., Duan, Z. et al. The design of HEPS global timing system. Radiat Detect Technol Methods 5, 379–388 (2021)

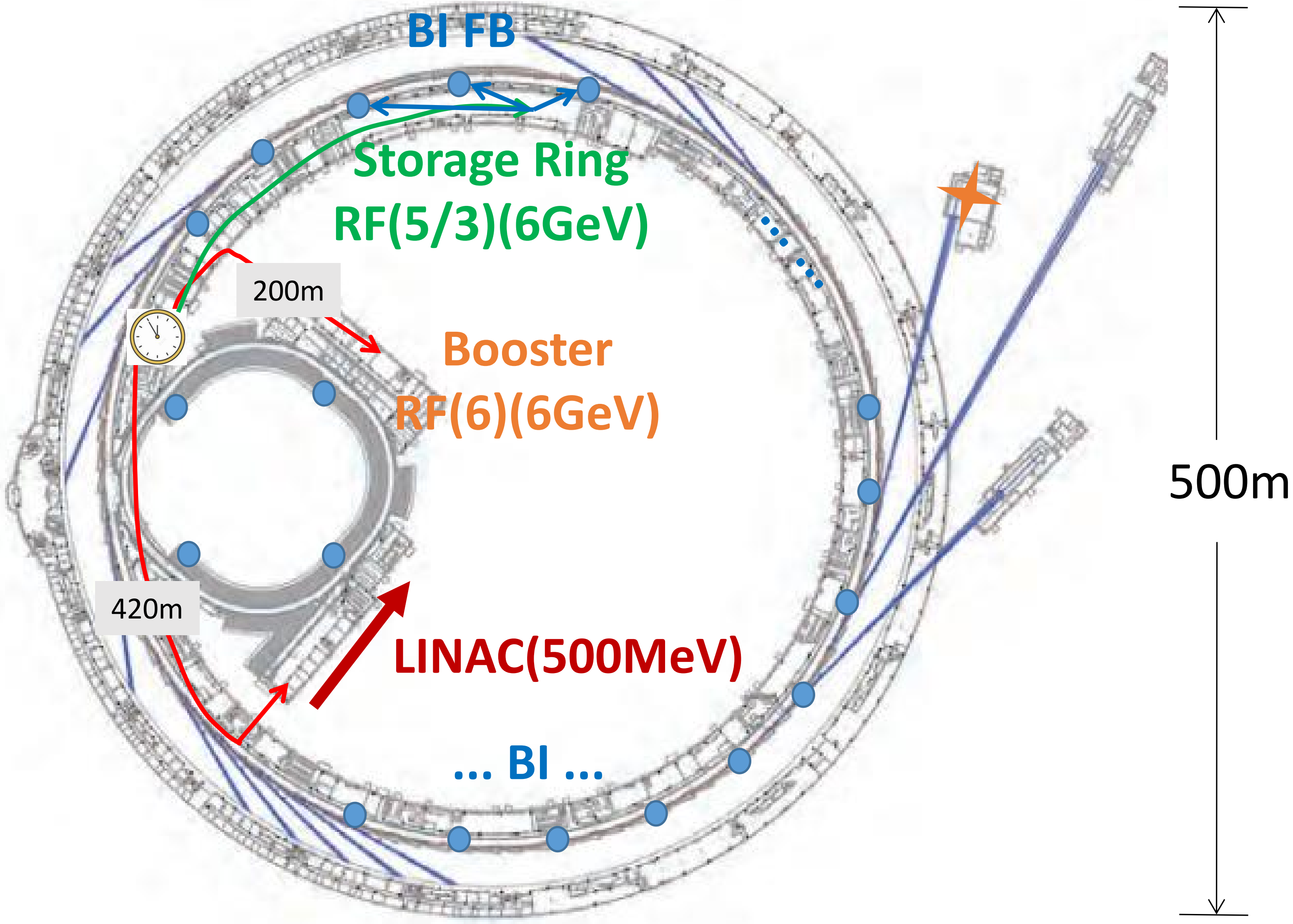
# HEPS High Energy Photon Source

- Timing system:
  - + Phase reference line
  - + Event timing

Master Oscillator system

RF transfer by optical fiber

RF transfer by coaxial cable



# Outline

- Master Oscillator system

# Master Oscillator system

□ MO requirements:

- 4 channels: ch1 - 166.6MHz and ×3=499.8MHz for SR active 3HC RF (more ×, less ÷)
  ch2 - 499.8MHz for Booster RF, ch3 - 499.8MHz for Linac, ch4 - time-reso exp./backup
- freq. tuning requires all the signals tuning simutaneously, resolution < 0.01Hz, and ch1 & ch2 ±100kHz for chromaticity/dispersion measure separately
- phase continuous when freq. tuning
- jitter should be low enough: better < 40fs(10Hz-10MHz)
- spurs no >-110dBc/Hz at 100Hz-1MHz especiall near sync. freq.
- phases monitored between 4 channels, and kept synchronized after freq. tuning & power cycle

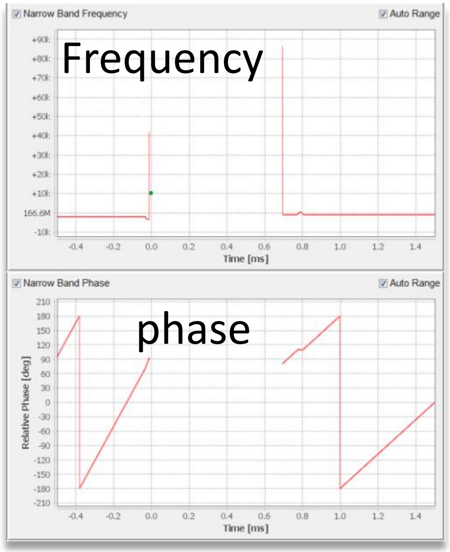
So MO SHOULD be low jitter, 4 independent signals, frequency tuning, phase continuous, phase recovery after Freq.tuning

# Master Oscillator system

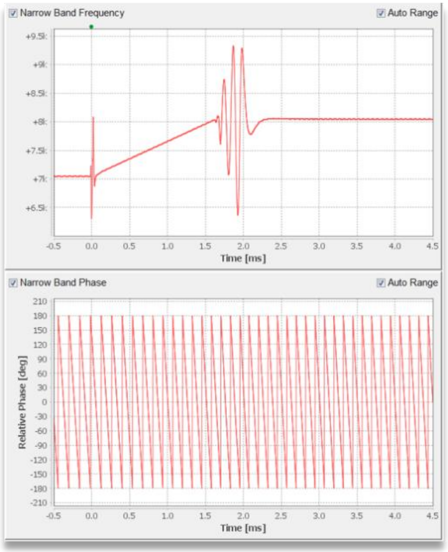
- ☐ Commercial oscillator freq. tuning test:
- R&S SMA100B flash-down
- Keysight 8257D flicker
- Anapico 4-ch APMS40G flash-down
- Keysight 2-ch N5191A(DDS based) freq&phase continuous
- AD9912/9914 based SG jitter >70fs(10Hz-10MHz) and noisy

- ☐ Keysight and R&S oscillators used by many labs - OK phase continuous, jitter good;
- ☐ 4 oscillators cost >1 million CNY ...
- ☐ Maybe enough, but not perfect, could be better?

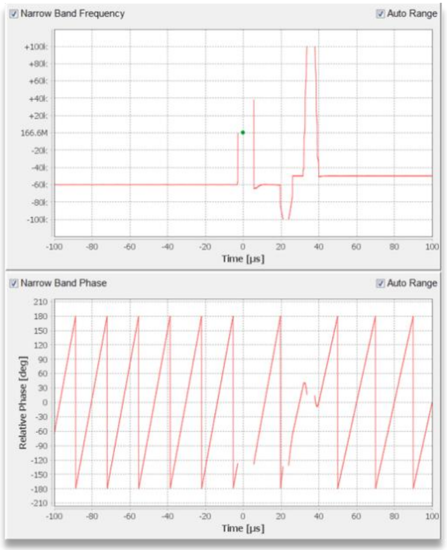
R&S SMA100B



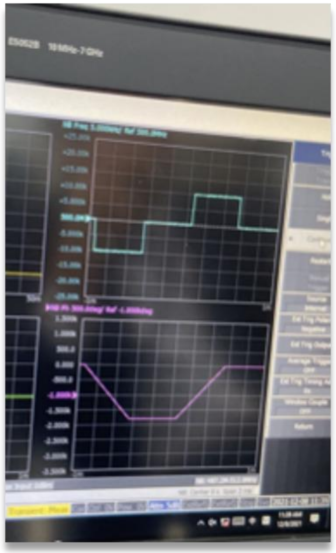

Keysight 8257D




Anapico APMS40G




Keysight N5191A



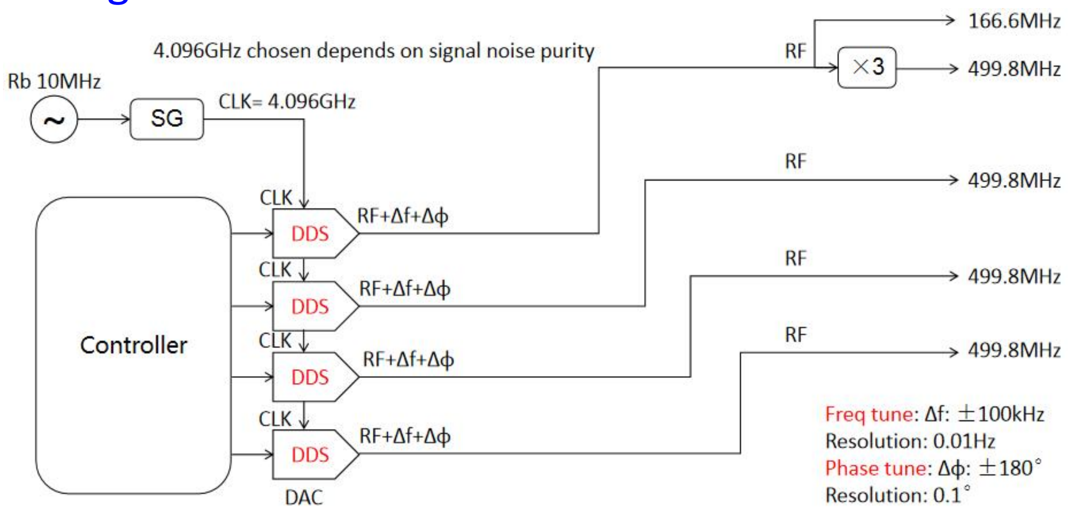
| Oscillator | jitter (10-10M) | Phase/freq. continue Freq. tune | Ch. No. |
|---|---|---|---|
| Keysight E8257D | 72fs | ✖ | 1 |
| Keysight N5181B | 35fs | ✖ | 1 |
| R&S SMA100B | 22fs | ✖ | 1 |
| Anapico APMS40G | 80fs | ✖ | 4 |
| Keysight N5191A | 85fs | ✔ | 2 |
| AD9914 based SG | 76fs | ✔ | 4 |
| AD9912 board | 50fs | ✔ | 1 |

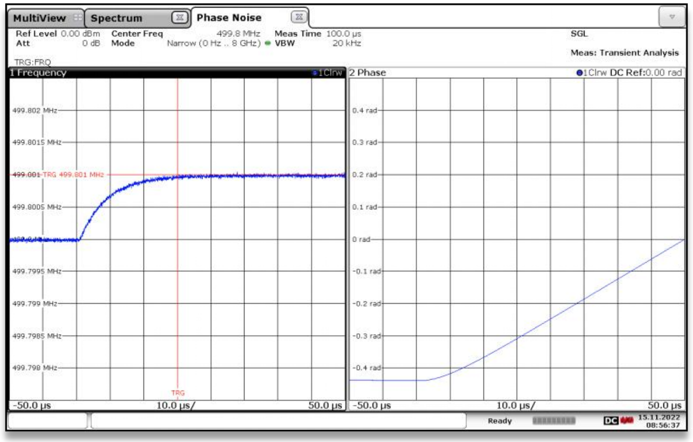
# Master Oscillator system

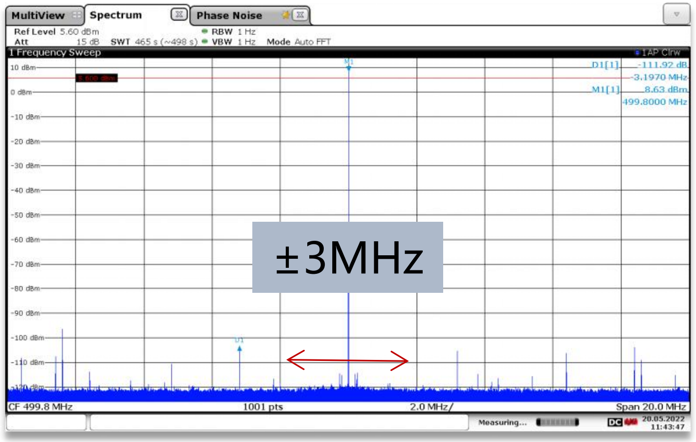
- ☐ New multiple signal generator(MSG)
- ☐ Signal Generator(SG) is SMA100B, as DAC/FPGA clock, global freq. tuning
- ☐ Clock jitter 27.3fs, chosen for signal noise purity, DAC works as DDS by FPGA, 48 bit freq. control register
- ☐ Measurement results

- CH1 166.6/CH2-CH4 499.8MHz jitter <35/34fs(10Hz-10MHz)
- no spurs within ±3MHz bandwidth
- both freq. and phase continuous when freq. change
- output power is within ±0.01dB at all freq.&phase
- frequency resolution <0.01Hz, phase < 0.1°
- phase between 4 channels restored after power cycles

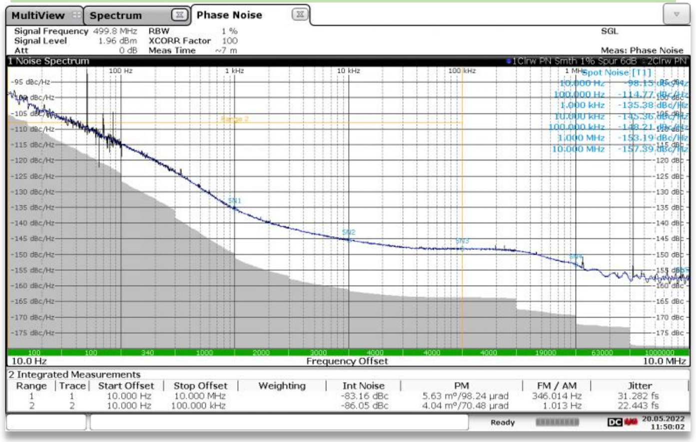
Master Oscillator System



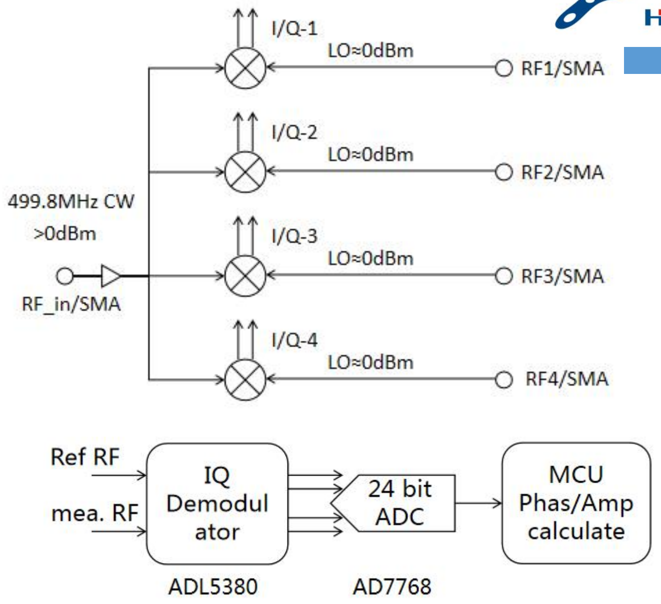




31fs/23fs(10Hz-10MHz/10Hz-1MHz)

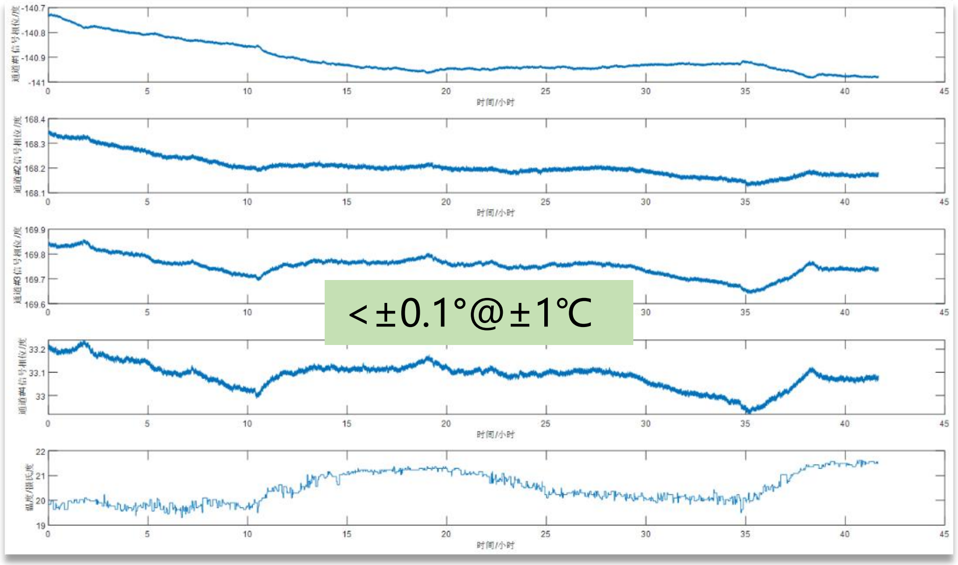


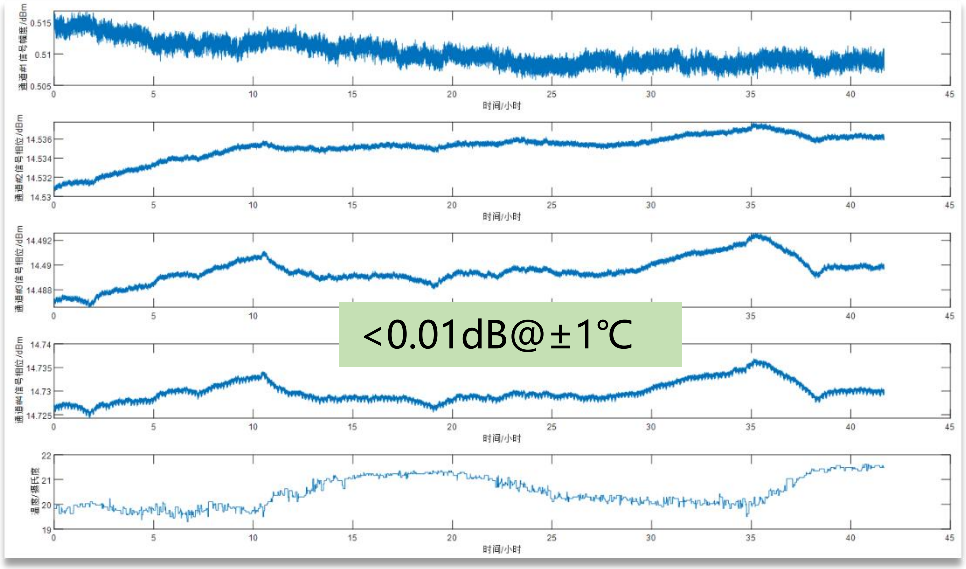
# Master Oscillator system




- 0.01°/0.01dB/0.01℃ Phase detector: to monitor phase drift of various signals, mostly MSG/MO system itself
  - I/Q demodulator (ADL5380) and 24 bits ADC (AD7768), resolution: <0.01°@499.8MHz, BW: 400M-3GHz.
  - phase stability<±0.1°@±1℃ room temp.
  - amplitude stability<0.01dB, temperatute stability<0.01℃
  - Pros: phase restored after power cycle

MSG 4 channels Phase vs temp. ←46h→ MSG 4 chnnels Amp. vs temp.



# Outline

- Phase distribution system

# Phase distribution system

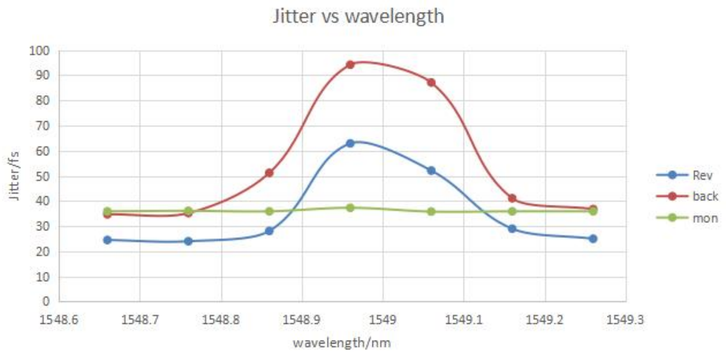
- Goal: Transfer RF signals from MO to Linac and booster by optical fiber in sub-ps scale
- To compensate the phase drift: detect → control → adjust (feedback) → stable

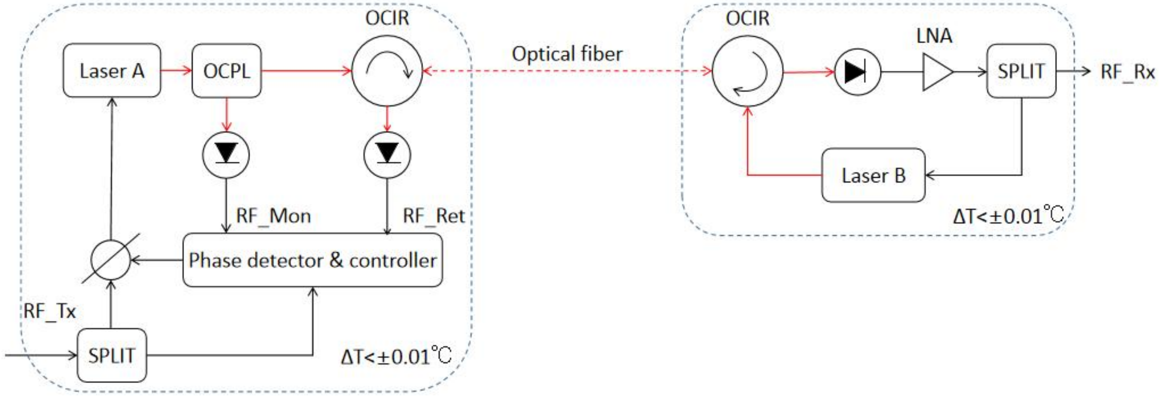
Very brief summary of phase reference line by optical fiber from control point

| Detect ways | | Adjust ways | Applications |
|---|---|---|---|
| ① phase detector/analog IC | | Ⓐphase shifter (analog) | KEK-②⑤Ⓔ/①⑤Ⓓ |
| ②digital LLRF | | Ⓑphase shifter (IQ) | I-T(Libra)-④Ⓐ/①Ⓕ |
| CW optical | ③heterodyne interferometer | Ⓒreceiver cali. | LBNL-③Ⓒ |
| | ④loopback+circulator | Ⓓoptical piezo | DESY-⑦ⒹⒺ |
| | ⑤two wavelength+circulator | Ⓔoptical motor | DLLRF-②Ⓑ |
| Pulsed optical | ⑥harmonic extract+BPF | Ⓕtemp.oven | HEPS-①⑤Ⓐ/Ⓑ |
| | ⑦OXC | | |

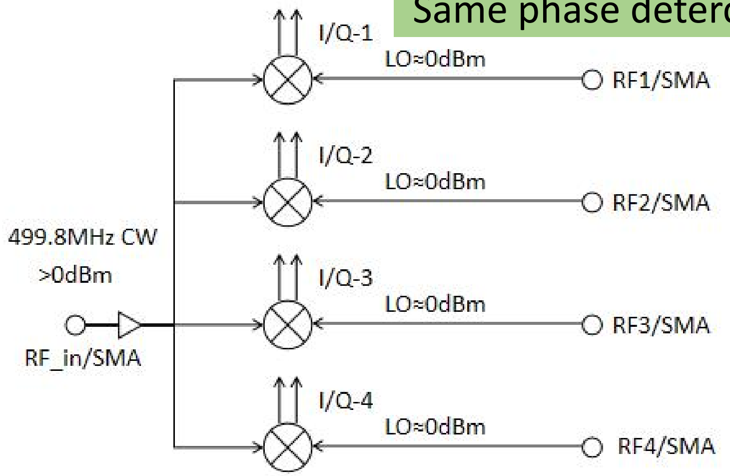
# Phase distribution system

- New optical reference transfer modules
- Based on Dense Wavelength Division Multiplex (DWDM)
- Two laser wavelength gap >0.3nm, avoid Rayleigh scattering, keep least phase error
- Detect phase error of return signal, phase shifter and Tx laser with reference RF input
- Feedback by RF analog phase shifter;




Same phase deterctor with MO




returned

laser_mon

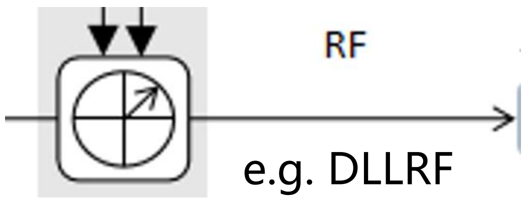
ϕ-shifter

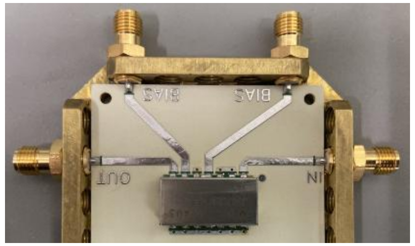
reserved: out-of-loop

# Phase distribution system

- IQ Φ-shifter *vs* passive Φ-shifter:

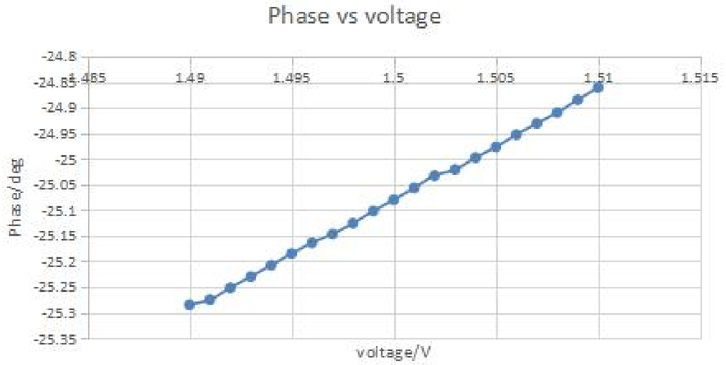
| IQ Φ-shifter | passive Φ-shifter |
|---|---|
| -Pros: 360° (big delay) | -no additive jitter |
| -Cons: additive ~10fs jitter | -not 360° |



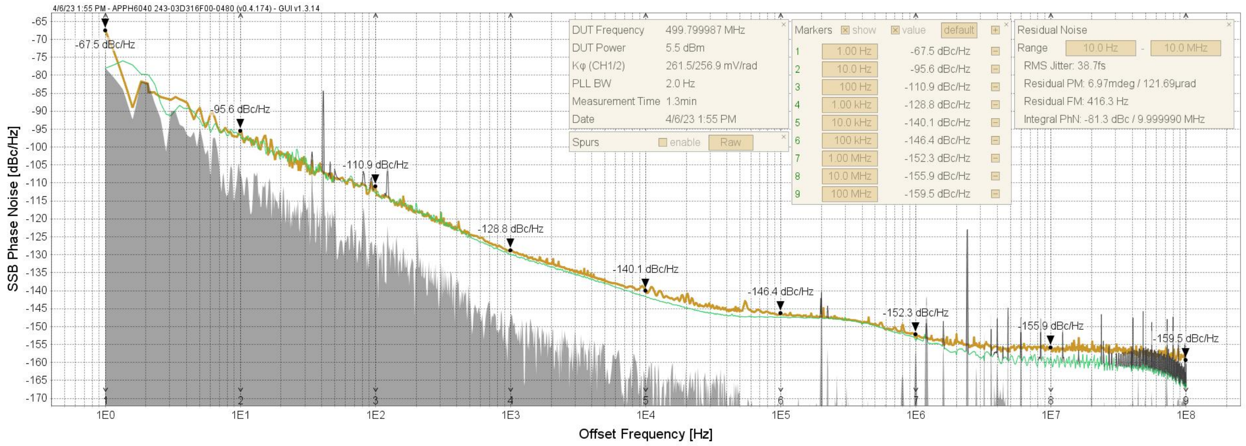

✔

- calibrate shifter phase vs voltage
- 220°@499.8MHz full range, 110fs/mV
- resolution could <0.01° if voltage allows

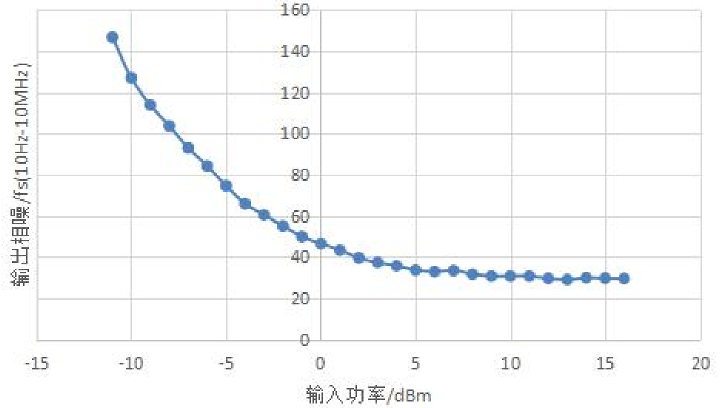



- Measure the phase noise

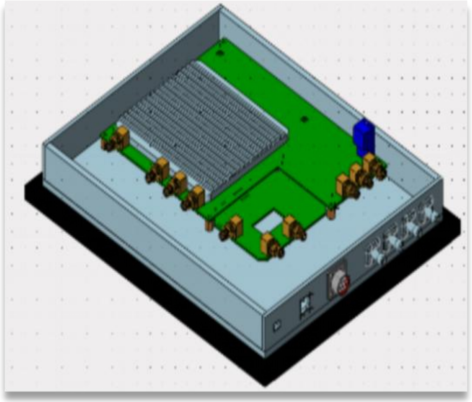
Input(Green), Output(Brown): 34.8/38.7fs (10Hz-10MHz)




- More input power, better jitter



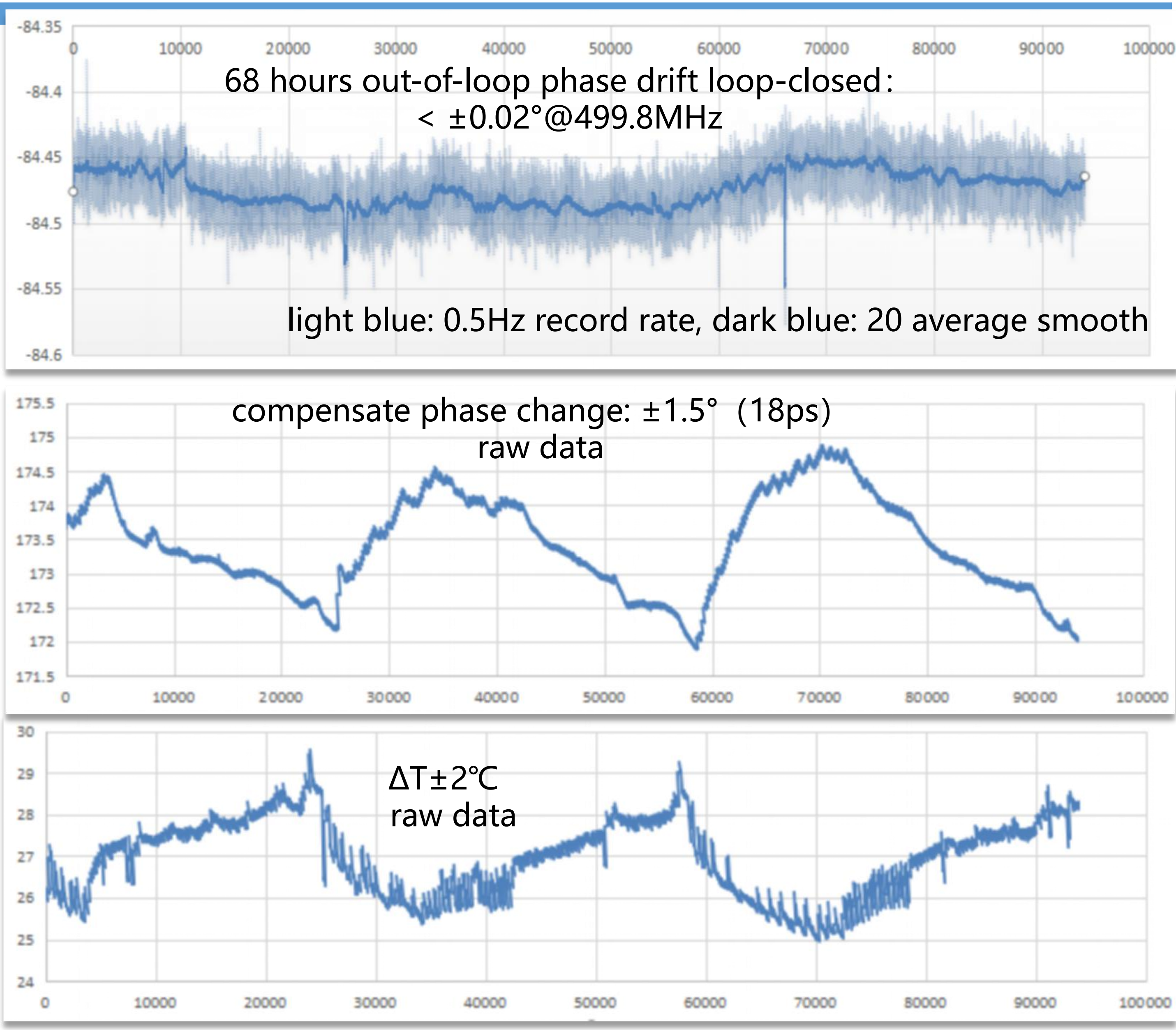
# Phase distribution system



| Specfication | |
|---|---|
| Center frequency | 499.8MHz |
| Bandwidth | ±3MHz@0.01dB<br>±10MHz@0.1dB |
| Input amplitude | >10dBm |
| Output amplitude | >12dBm x 2 |
| Max phase delay range | 120ps@0.01dB amp. sta.<br>540ps@0.1dB amp. sta. |
| Additive jitter | <18fs(10Hz-10MHz) |
| Long-term stability (out-of-loop) | 200fs (p-p )- 3days |
| Long-term stability (in-loop) | 100fs (p-p) - 7days |
| Temperature stability | ±0.01℃ |
| Remote communication | LAN/support EPICS |
| Cooling | Conduction cooled, no fans |
| Automation | work point recover after power cycle or close/open loop |

# Phase distribution system

- Results show: typical 3 days close loop
- Residual phase drift was measured by phase detector between Tx RF and Rx RF. ±0.02°(±110fs) out-of-loop in 3 days.
- Measurements agreed with calculation: 400m YOFC-PSOF was used, temp. coefficient is ~6fs/m/℃, the compensated phase change is twice the fiber length = 6*400m*4℃*2=19.2ps

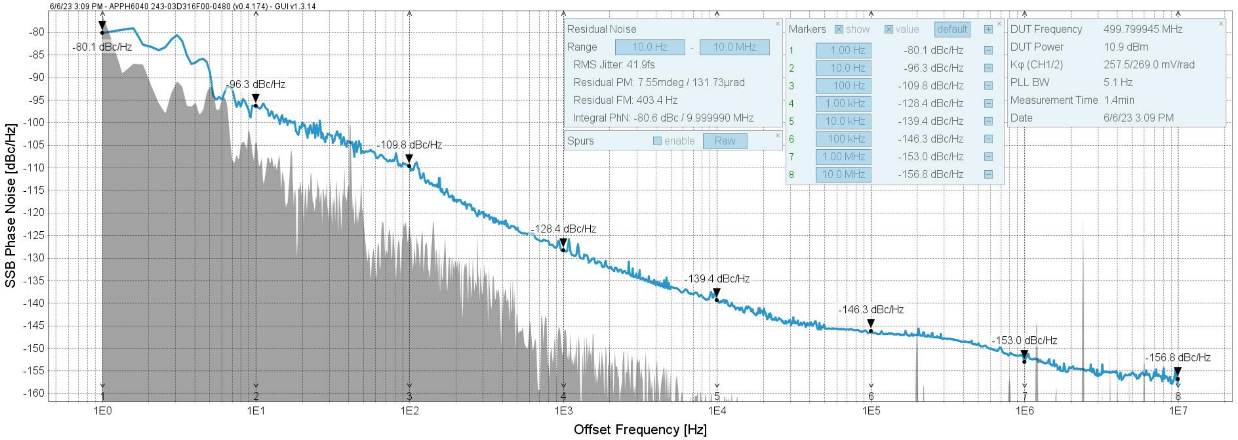


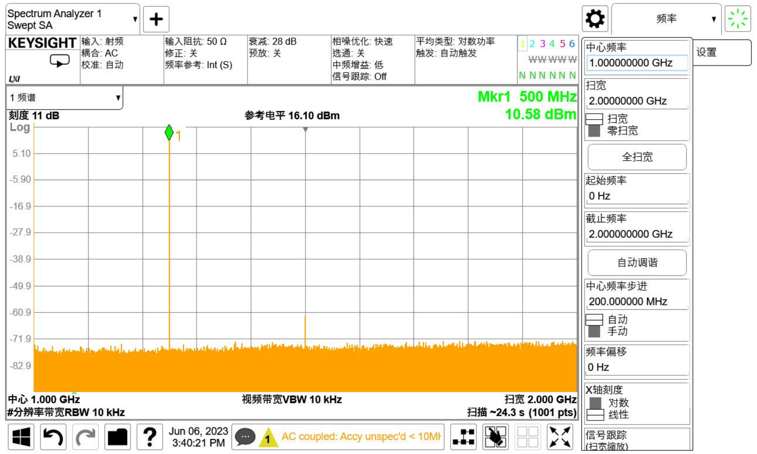
# Phase distribution system

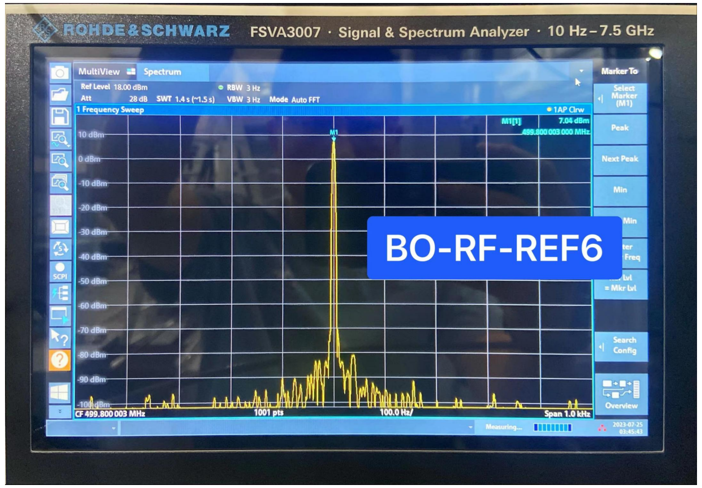
## Reference signals for Booster LLRF

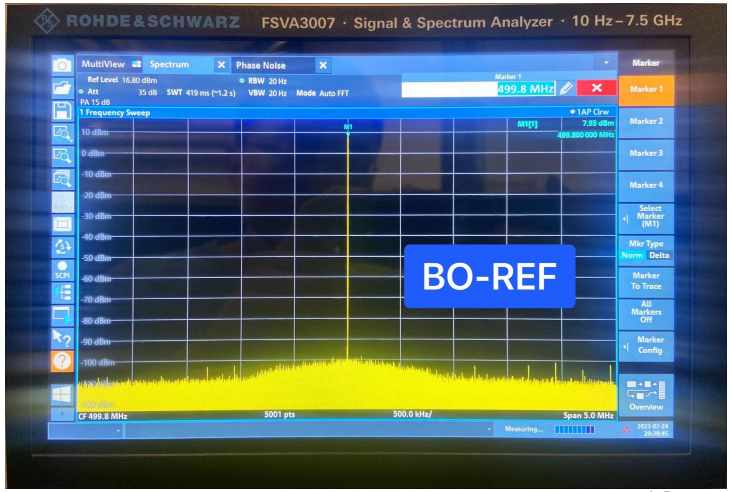
Received 499.8MHz of Booster LLRF jitter:

35.42fs / 41.9fs (10Hz-1MHz / 10Hz-10MHz)



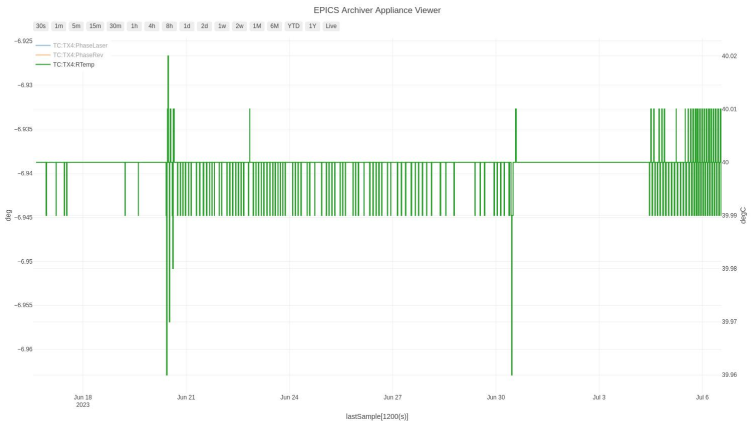



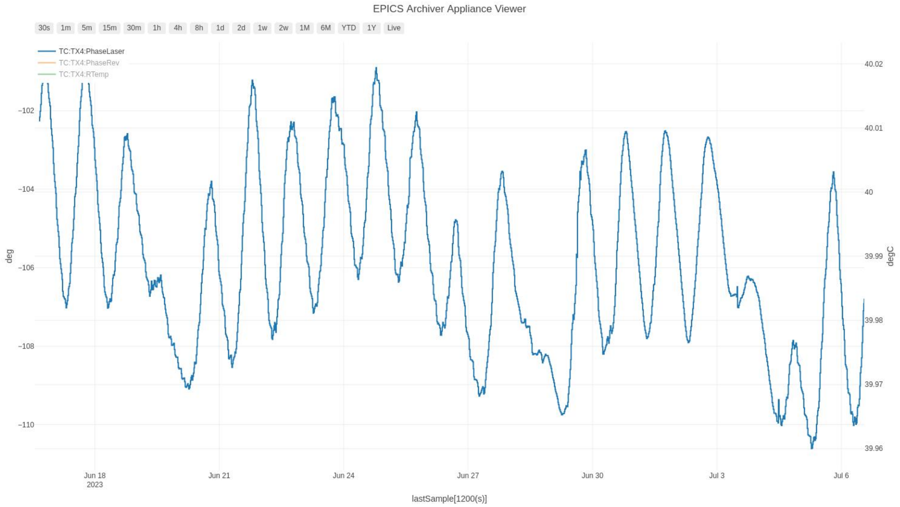
# Phase distribution system

- Phase reference signal to Linac stability:
  - June 17- July 7 (3 weeks)
  - 380m phase-stable optical, fiber TCD=6fs/m/℃
  - temperature variation ~15℃ per day
- Feedback ON, phase stability within <0.02° or 120fs
- Compensated phase by shifter drifts 6.5° or 38ps,

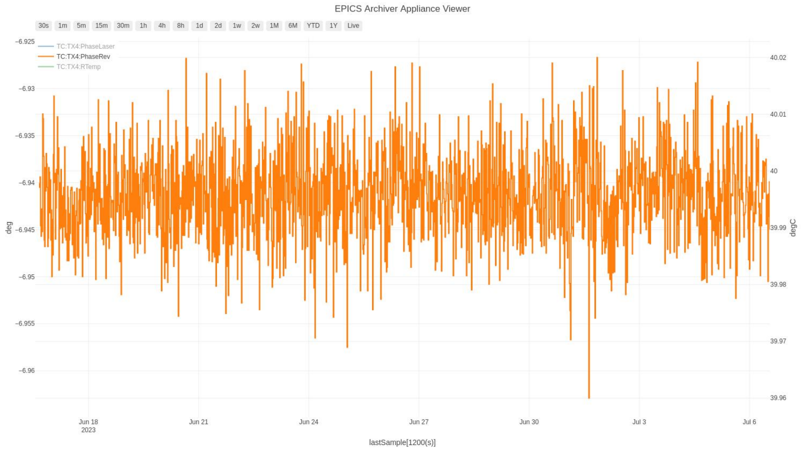
temperature stability < ±0.01℃




compensated phase drift ~38ps/day



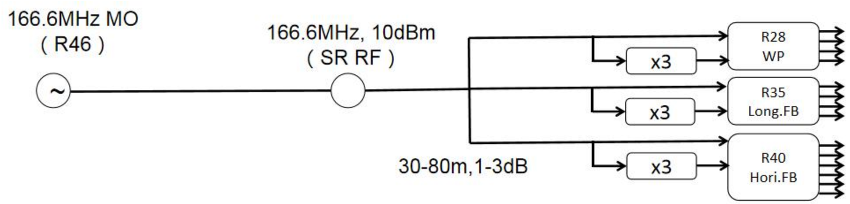

phase stability <±0.01°, feedback ON



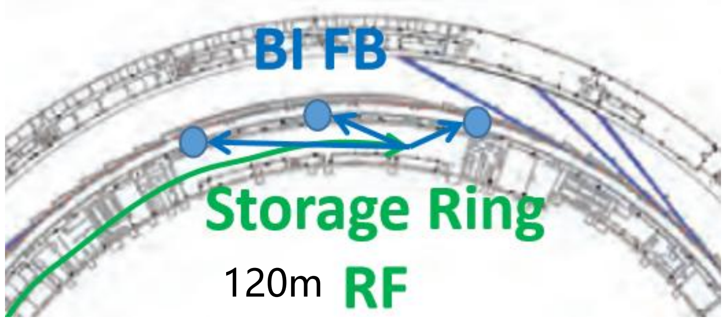
# Phase distribution system

- Reference clock to BI electronics: FB, BPM, BCM, Camera…
- Mostly by coaxial cables, so measured temp. coef. of delay (TCD), the best:

- From MO to SR RF: CommScope LDF2-50A: 3.5fs/m/℃
- Ref line of Linac: ZTT HCAAYZ-50-12: 10.2fs/m/℃
- Ref line of BI: Trigiant HCTAYZ-50-22: -8fs/m/℃

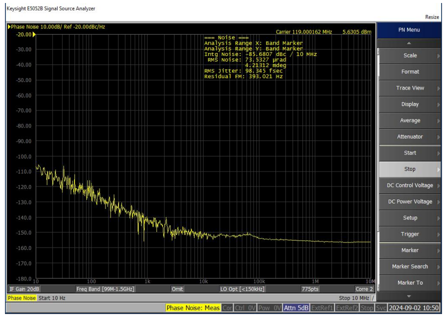


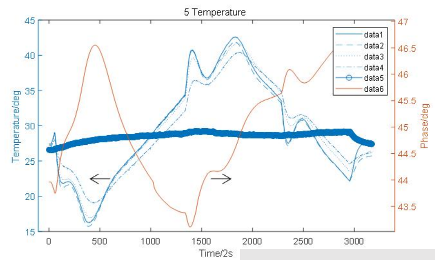

TUP46, IBIC2024

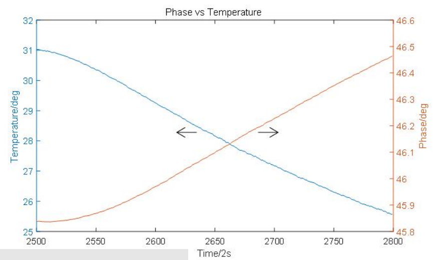



| Vendor/Brand | Type Name | Spec. /OD | Veloci-ty/ ρ (*c) | TCD@20~40 ℃（ppm） | TCD（fs/m/℃） |
|---|---|---|---|---|---|
| Commscope | LDF1-50 | 1/4" feeder | 0.86 | 2.4 | 9.3 |
| HU-BER+SUHNER | SUCOFLEX 104 | LD-PTFE,5.5mm | 0.77 | 5 | 21.6 |
| HU-BER+SUHNER | S-10162-B-11 | Flexible | 0.87 | 35 | 134.1 |
| WITC | WL60R | Flexible, 11.7mm | 0.87 | 5.9 | 23.1 |
| Commscope | LDF2-50 | 3/8" feeder | 0.85 | 1/-1.3/-0.5/0.9 | 3.5 |
| Trigiant | HCAAYZ-50-8 | 3/8" feeder | 0.86 | -2.5/-2.3 | -8.9 |
| Commscope | LDF4-50A | 1/2" feeder | 0.88 | -2 | -7.6 |
| Zhongtian(ZTT) | HCAAYZ-50-12 | 1/2" feeder | 0.88 | 2.5/1.2/2.7 | 10.2 |
| Kingsignal | HCAAYZ-50-12 | 1/2" feeder | 0.88 | -4 | -15.2 |
| Datang | HCAAYZ-50-12 | 1/2" feeder | 0.88 | -9.8 | -37.1 |
| Trigiant | HCAAYZ-50-12 | 1/2" feeder | 0.88 | 2.1/-4.8 | 8.0 |
| Commscope | FSJ4-50B | 1/2"SuperFlexible | 0.81 | -9.2/-7 | -37.9 |
| Hengxin | HRCAYZ-50-9 | 1/2"SuperFlexible | 0.82 | 7.5 | 30.5 |
| Kingsignal | HCAHY-50-9 | 1/2"SuperFlexible | 0.81 | 17.8/16.4 | 73.3 |
| Zhongtian(ZTT) | HRCAYZ-50-9 | 1/2"SuperFlexible | 0.82 | -5.5 | -22.4 |
| Trigiant | HCTAYZ-50-22 | 7/8" feeder | 0.88 | 2/3/-3/2/-2.1 | -8.0 |
| Wutong | HCTAYZ-50-22 | 7/8" feeder | 0.88 | -10/-9 | -37.9 |
| Hansheng | RF50Z-7/8" | 7/8" feeder | 0.88 | 4 | 15.2 |
| Commscope | AVA5-50 | 7/8" feeder | 0.91 | -8 | -29.3 |
| Boyang | HCTAYZ-50-22 | 7/8" feeder | 0.88 | -10.3 | -39.0 |

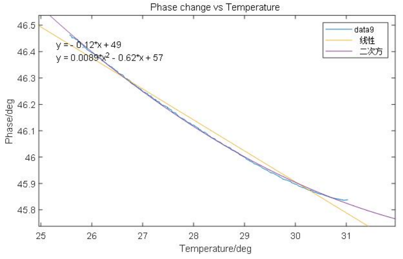
BPM clock jitter: 98fs

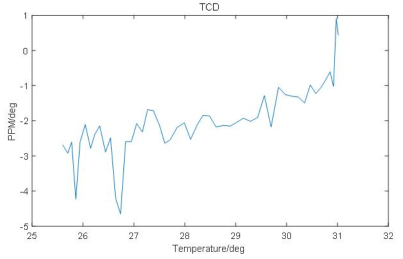





Trigiant HCTAYZ-50-22（14m)



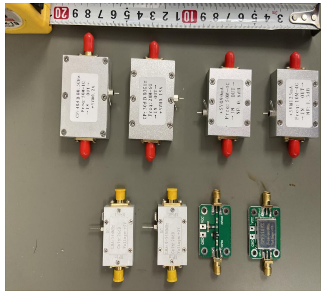
# Phase distribution system

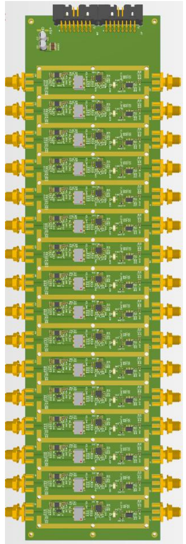
- Locally distribute RF signals in the rack/chassis
- Choose ultra-low noise amplifier: Mini-circuits PGA103, Qorva SPF5189 …
- Made 57 16-channels distribution chassis for BPM/LLRF/MO, with remote monitoring. Additive jitter of 499.8MHz is < 5fs(10Hz-10MHz)

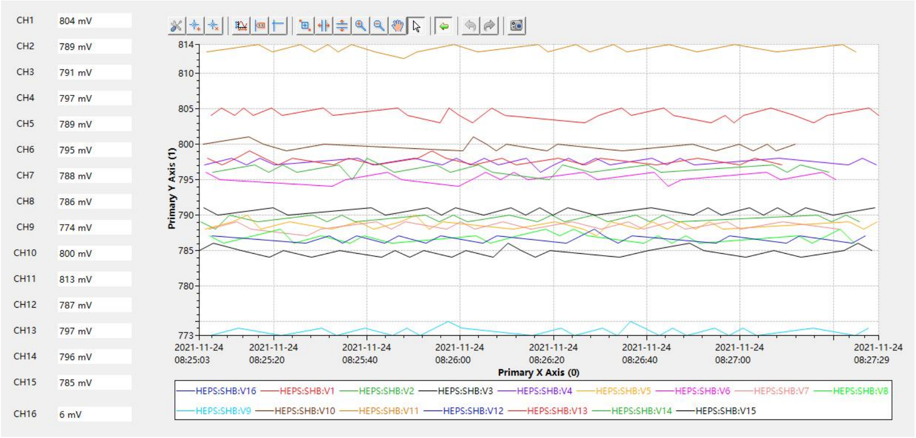
BPM station x 48

RF distribution

Trigger fanout







# Phase distribution system

MO rack

Rb clock-10MHz

Clock signal generator

Multiple signal generator

Ref signals distributor

4-channels phase detector

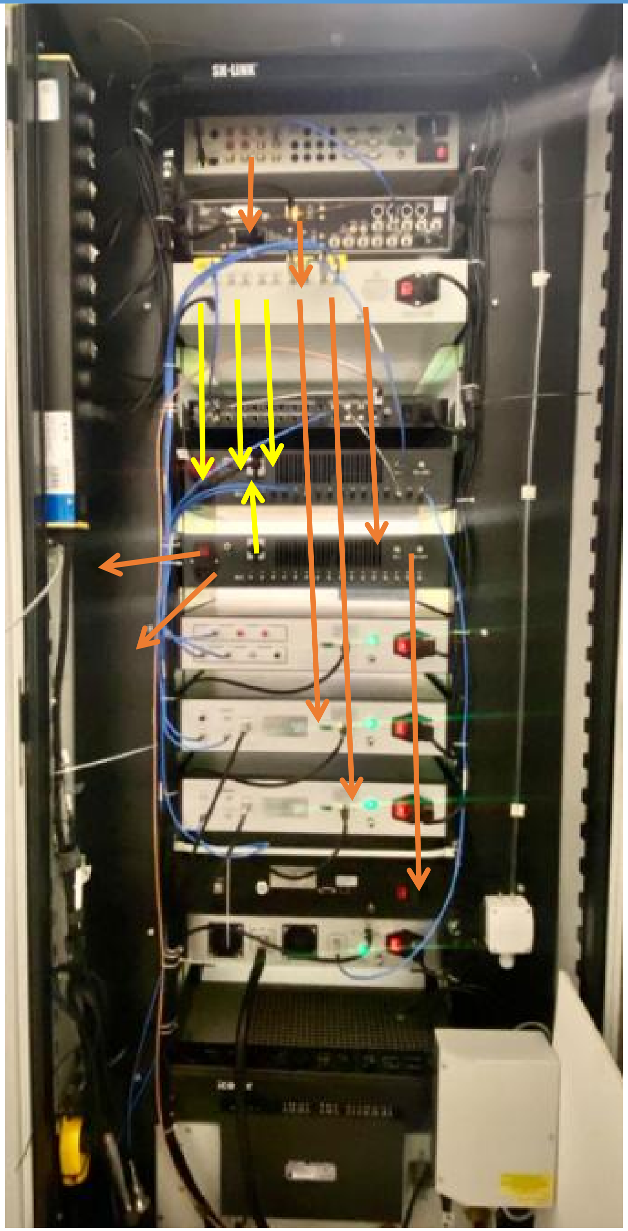
Transmitter for Booster LLRF

Transmitter for Linac

Ref signals PA for SR BI

Ref signals PA for Booster BI

Timing EVG rack



# Summary

- HEPS installation has completed and beam commission ongoing
- MO ‘system’ is DDS-based with freq. tuning and phase monitor
- Phase distribution system is optical based, stablized within 100fs
- The system is in stable operation 1.5 years
- Next more applications on BEPCII-U and PWFA project in IHEP

# Thank you very much!