

2026 MicroTCA/ATCA Workshop for Large Scientific Facility Control

Development and Application of MicroTCA in HEPS Timing System

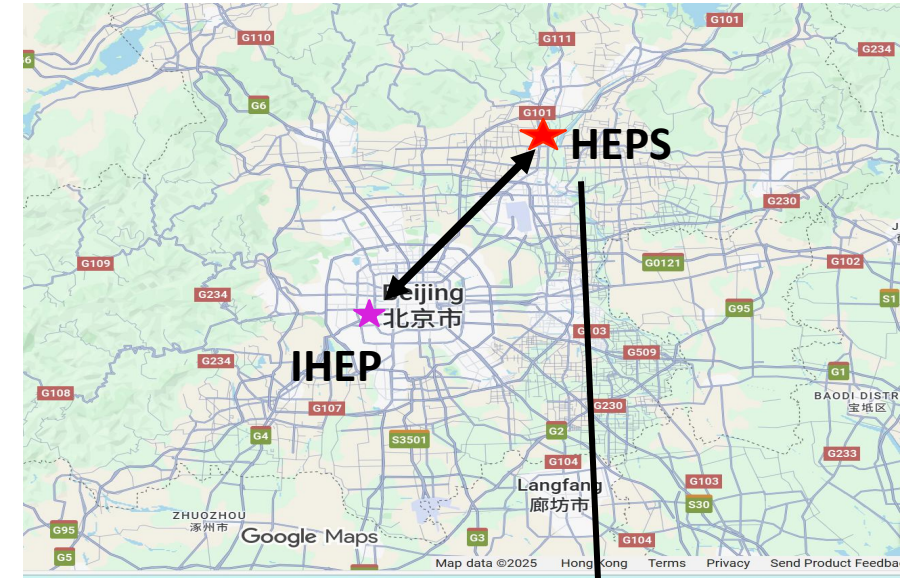
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Overview of HEPS Project

- The first 4th generation synchrotron radiation light source in China
 - 6GeV, 7BA-lattice , 14+1 beamlines for phase I
- Huairou District, Beijing, ~80 km far from IHEP
- Construction period – Jun. 2019 – Dec. 2025
 - Accelerator Acceptance Inspection: October, 2025
 - >100mA, <100pm·rad

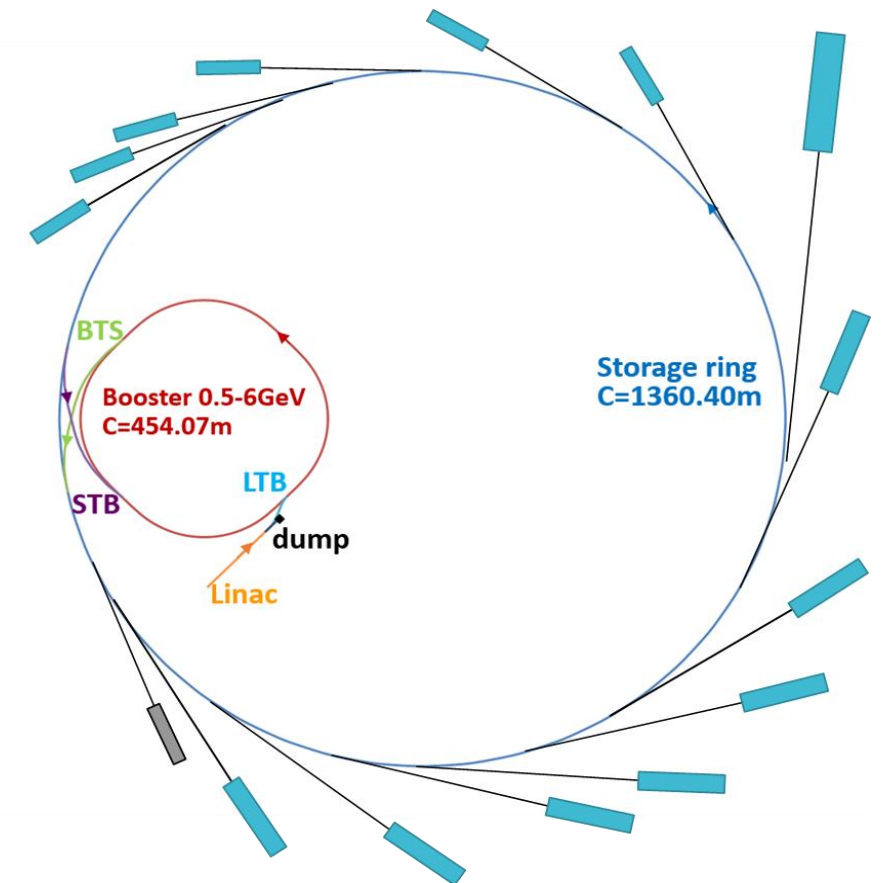
Main parameters	Value	Unit
Beam energy	6	GeV
Circumference	1360.4	m
Emittance	< 60	pm·rad
Brightness	$>10^{22}$	ph/s/mm ² /mrad ² /0.1%BW
Beam current	200	mA



Timing Related Parameters

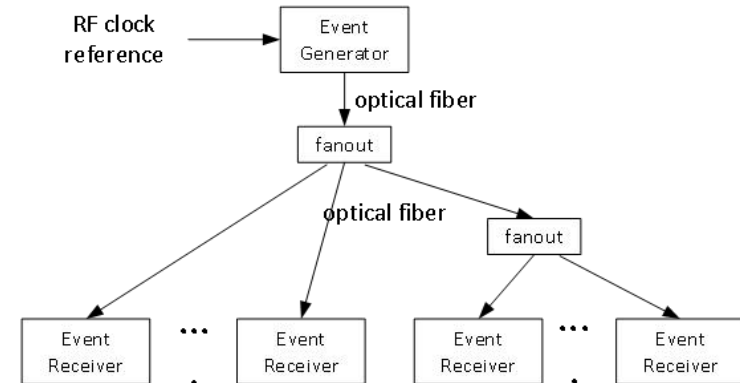
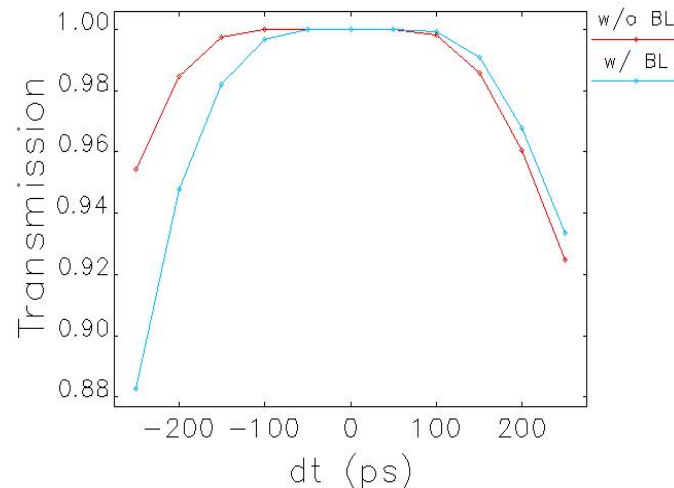
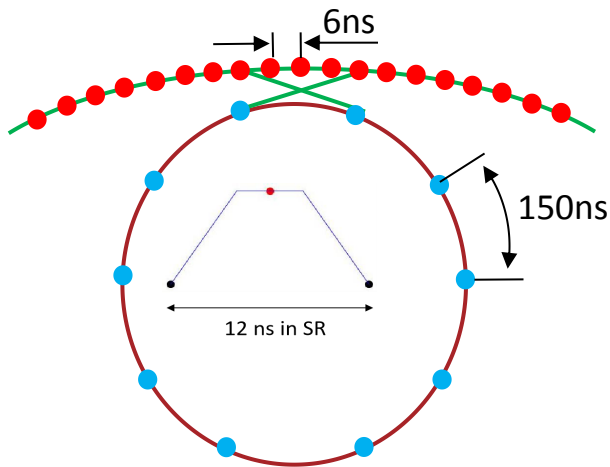
- 500MeV Linac , 0.5-6GeV Booster , 6GeV Storage Ring
- Three transport line : Linac to Booster , BS to SR , SR to BS

Parameter	Storage Ring		Booster	Linac
	High-brightness	High-charge		
Circumference	1360.40 m		454.06 m	48.85 m
RF Frequency	166.6/498.8 MHz		499.8 MHz	166.6/499.8/2998.8 MHz
Revolution /Repetition	220.370 kHz		660.239 kHz	<50Hz
Harmonic Number	756		757	
Bucket Numbers	680	63	10 (max)	
Bucket Interval	6 ns	72 ns		
Bunch Length (RMS)	106 ps		160 ps	
Booster Repetition Rate	1Hz			



Challenges of HEPS timing: Wide Range and High Precision

- Over 2km Range, More than 3000 output channels
- Multiple interface types and voltage levels
 - 5V/3.3V TTL, Optical Interface, 24V/12V output
- Less than 10ps adjusted step-size, More than 10s delay range
- 10ps jitter required by e-Gun and SR kicker, 30ps requirement for other systems , including accelerator and beam lines



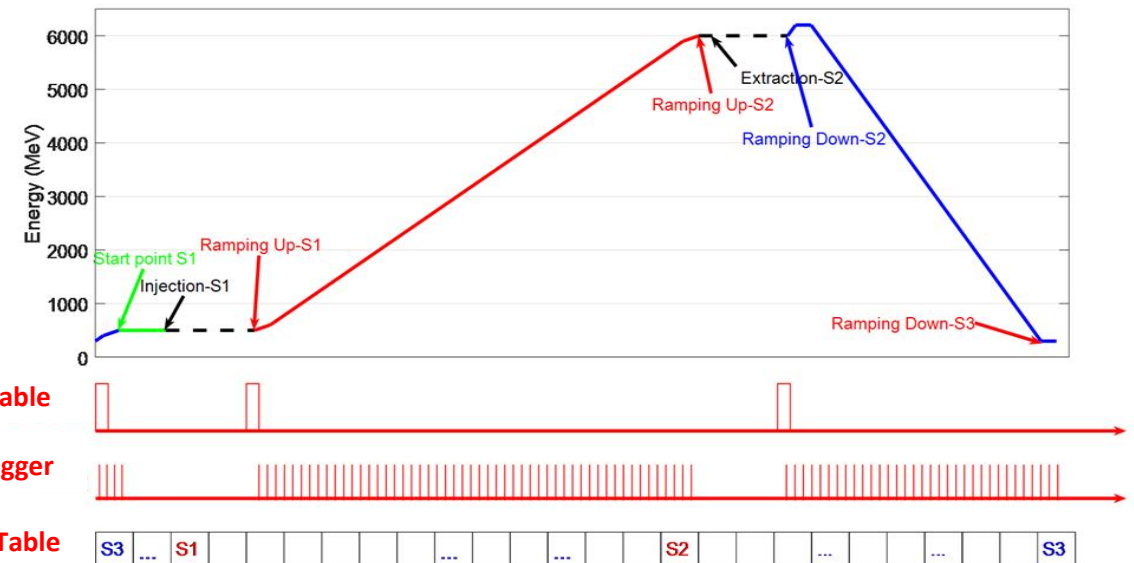
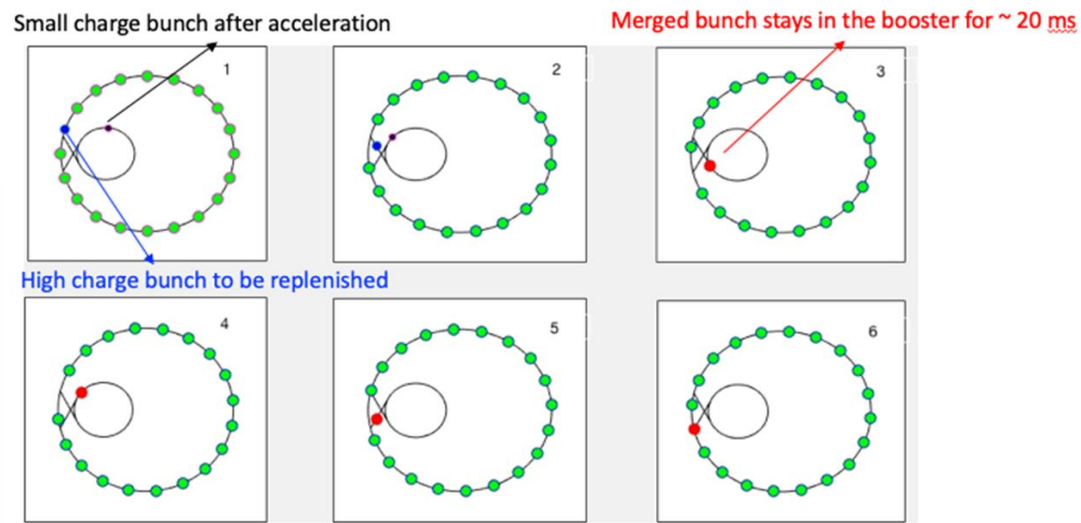
Challenge of HEPS timing: Sophisticated Logic

■ Novel on-Axis Swap-out Injection

- Booster acts as both the full-energy injector and accumulator
- Processes: Linac to BST , BST ramping BST to SR , SR to BST

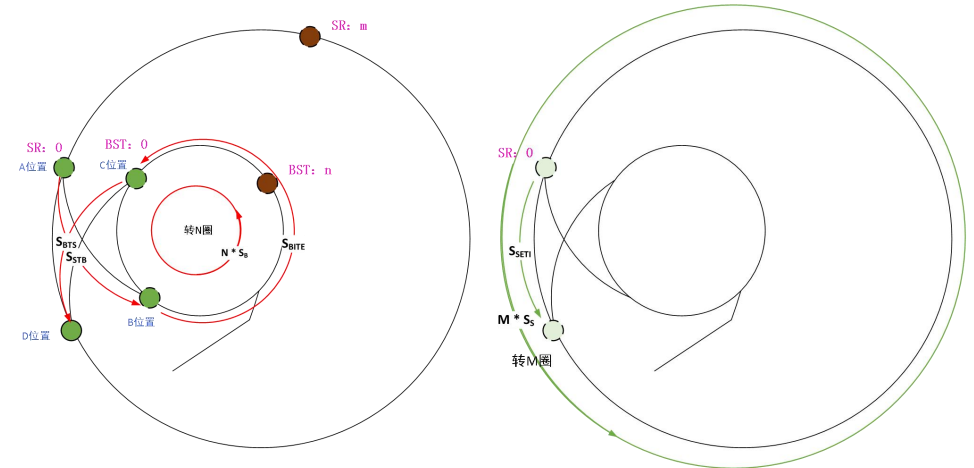
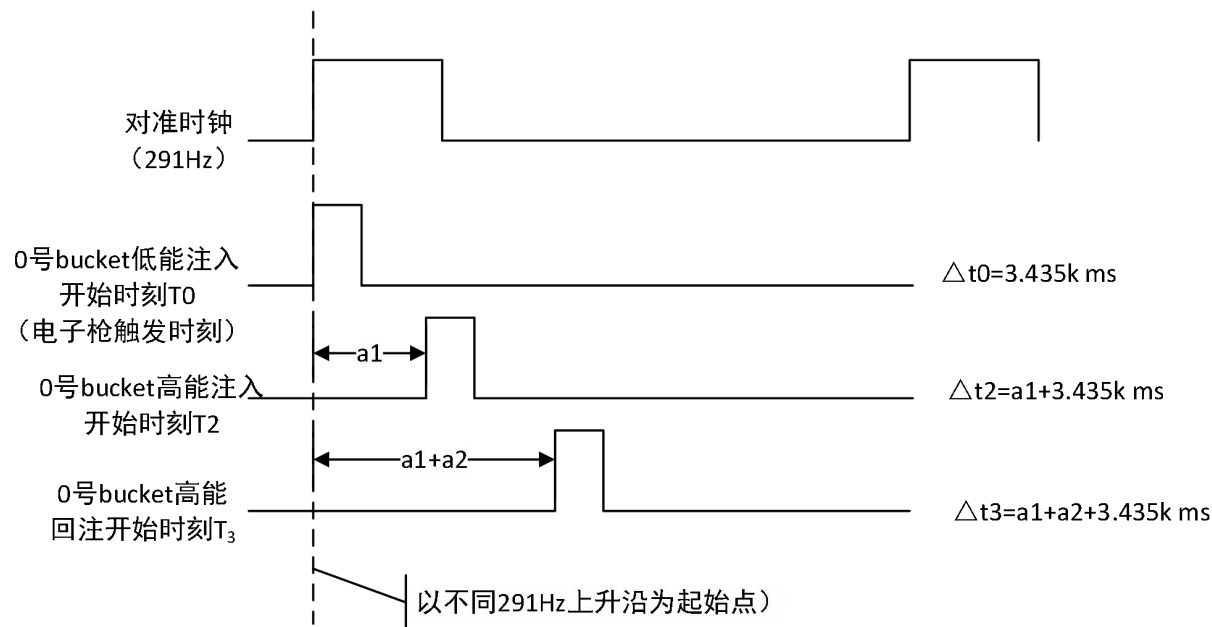
■ Synchronized Booster Ramping

- Step-by-step ramping, including power supplies and RF
- Synchronized start/stopped at any energy



Alignment for the Injection&Extraction processes

- Coincidence clock: ~291Hz; 166.6MHz/756/757
- 0th bucket alignment when Coincidence clock come



$$\Delta t * c = S_{STB} + N \times S_B + S_{BITE} + S_{BTS} = M \times S_S + S_{SETI}$$

$$\Delta t_0 = 6 \text{ ns} \times (m + 756M1) = 2 \text{ ns} \times (n + 757N1)$$

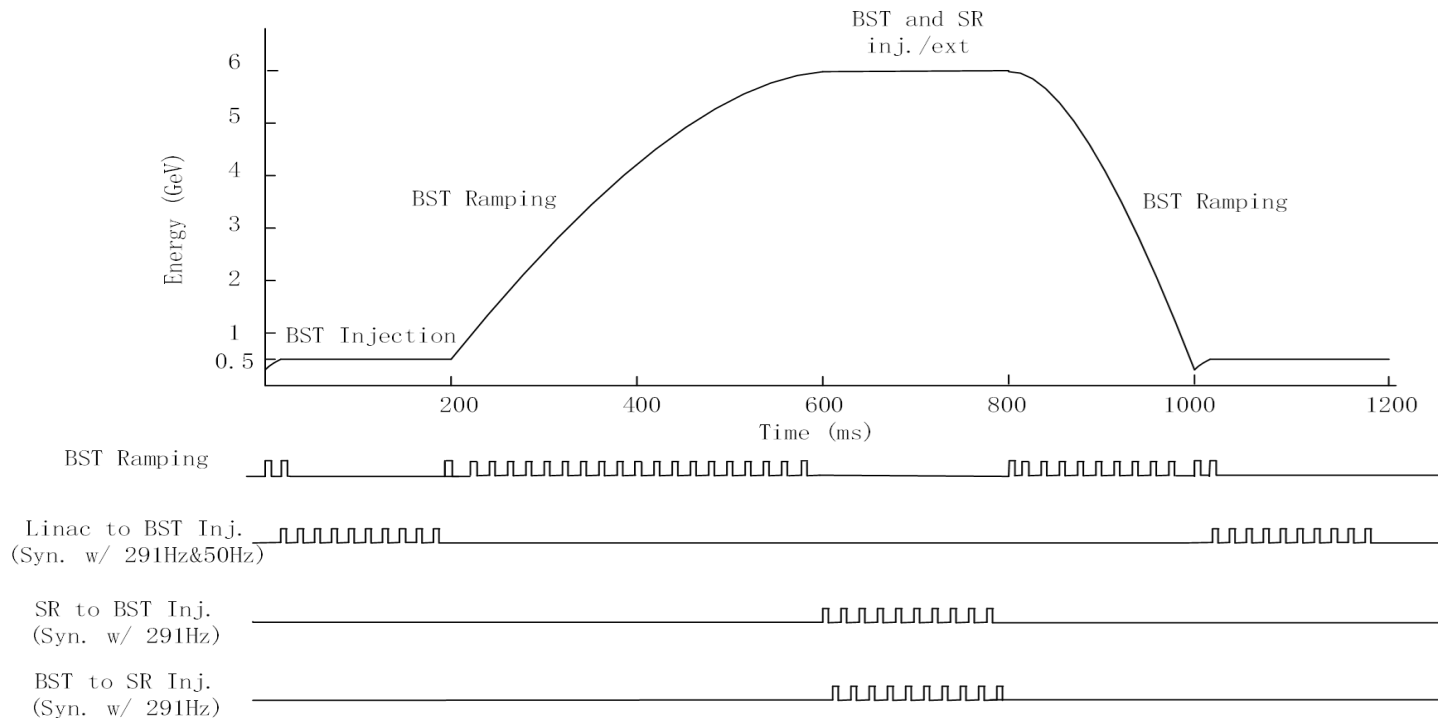
$$\Delta t_0 = 6 \text{ ns} \times \text{mod}(190512n + 757m, 572292)$$

- Using different event codes control each independent process, and each process can be controlled independently or combined to meet the various needs of operation

- After finding the start time of bucket 0 in each injection process, buckets in other locations can be injected into the specified bucket with an integer multiple delay of 6ns, calculated by the formula

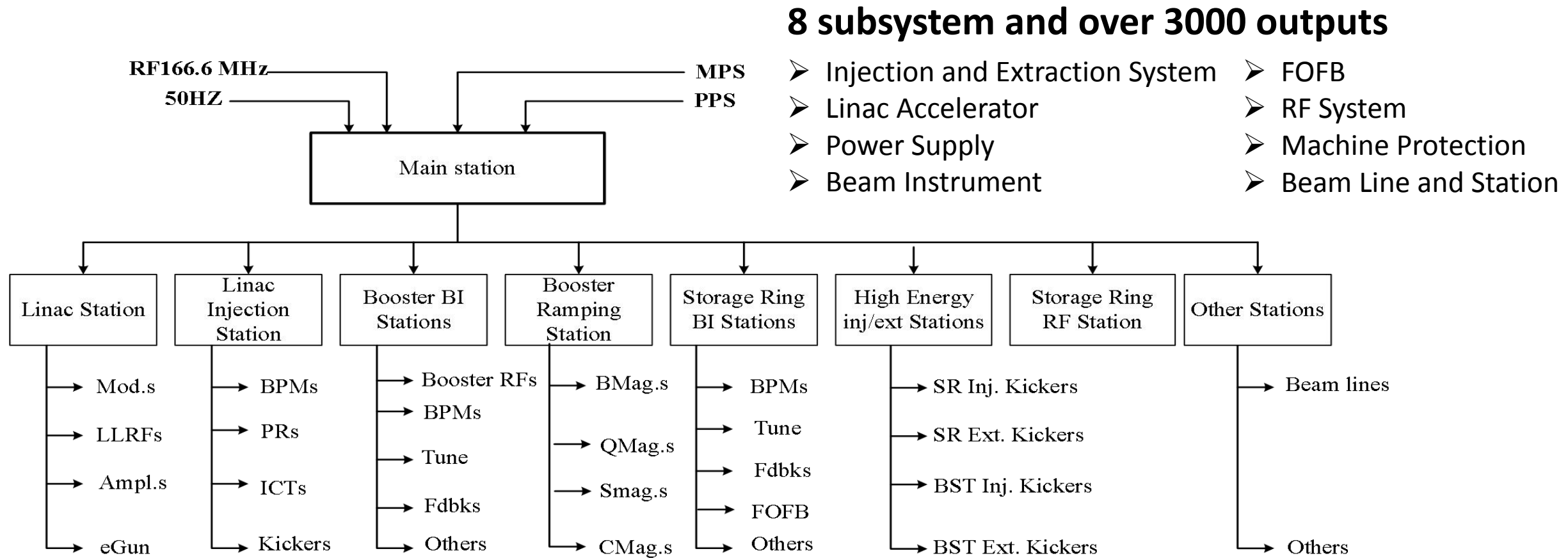
Control Cycle

- Modalized design: each process can **operate standalone or be flexibly combined**
- Any Selected Bunch Position :
 - Among 756 SR and 10 BST buckets;
 - Any bucket from SR to BS and vice versa;



- Rapidly tracks the phase changes of the MO
- All stations have feedback
 - correct drift
 - adjust delay between MS to SS
 - No cable length matching requirement

System Architecture



- No phase shift after power reboot Both Master and Slave : 166.6MHz RF in and 166.6MHz event clock
- Interface for MPS and FMPS : Post Mortem , Synchronized data acquisition
- PPS : Combine UTC code , high precision timestamp

Layout

36 timing stations : 1 Master, 28 Accelerator Slave, 7 beamline slave

OM4, Multimode Fiber, <400m

■ **Linac station : 2**

- ✓ 01 station : E-Gun、 Linac Klystron and LLRF
- ✓ 02 station : Low energy injection kicker、 Linac, low energy transport line and part booster BI

■ **High energy injection and extraction station : 4**

- ✓ 03: Booster extr. kicker and bumper
- ✓ 04: Storage ring injection kicker
- ✓ 05: Storage ring pre-kicker、 kicker
- ✓ 06: Booster injection kicker

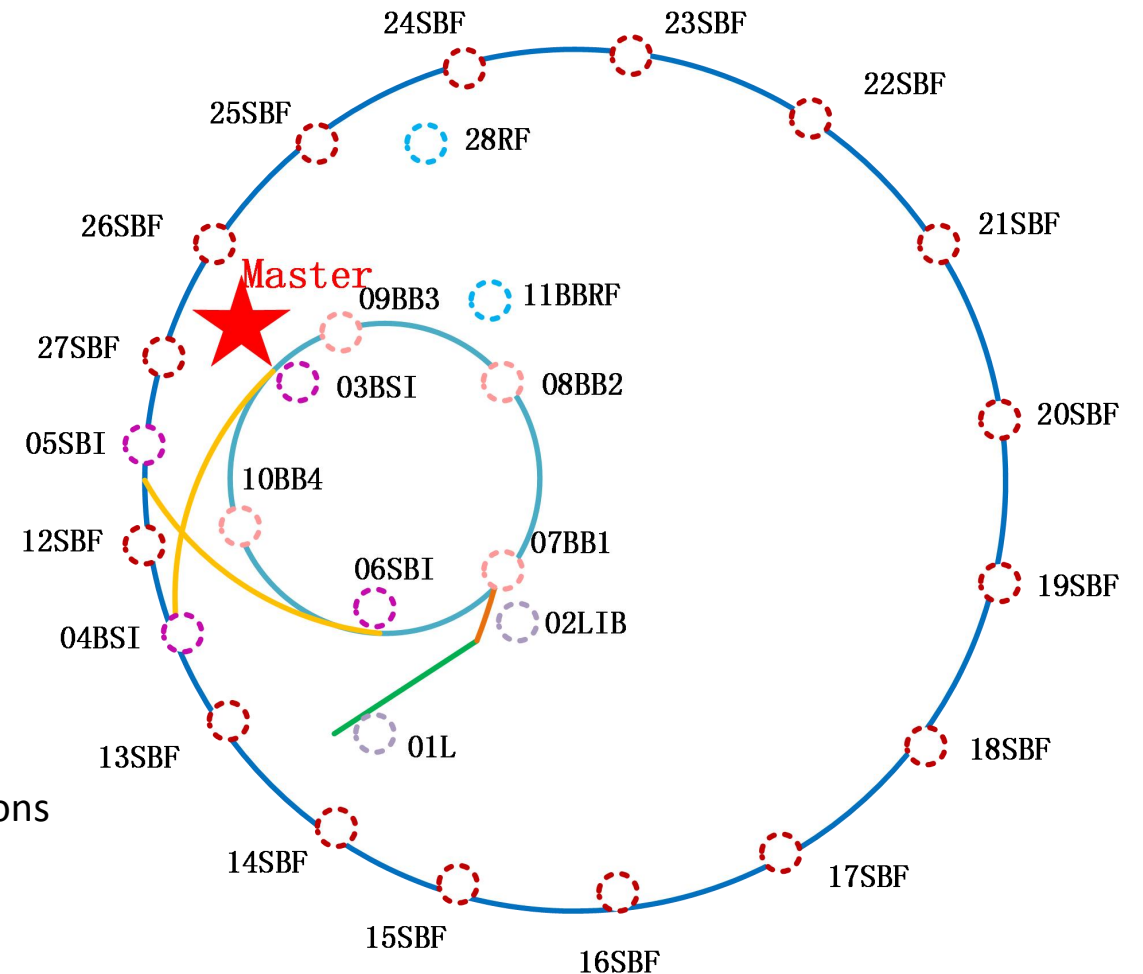
■ **Booster Stations : 5**

- ✓ 07-10 stations : Booster BI (BPM and others)
- ✓ 11 station : Booster BI and Booster RF

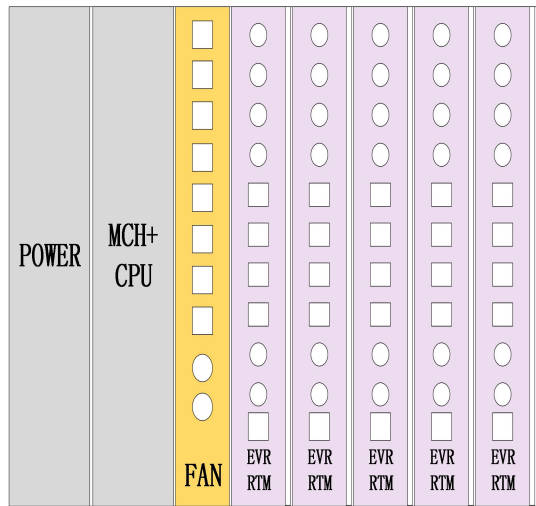
■ **Storage ring BI and FOFB stations: 16**

- ✓ 12-27 stations : 3 straight section's BI and FOFB in one stations
- ✓ Storage ring RF station : 1
- ✓ 28 stations : SR RF

■ **Beamline stations : 7**



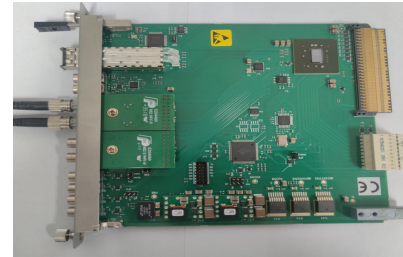
Slave Station



9U chassis



2U chassis



mTCA-EVR



EVRTM



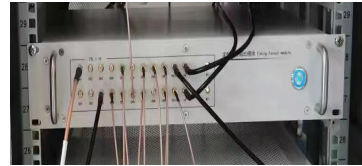
TTL-FineDelay



HFBR-1414



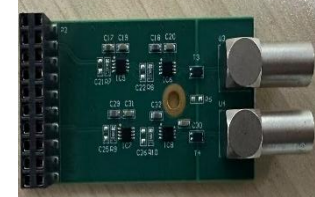
3U chassis



1-10 TTL FANOUT



1-10 HFBR-1414



TTL5V



TTL3.3V

■ Crate

- ❑ 9U : 12 slots
- ❑ 2U : 6 slots
 - MCH+CPU :
 - 4 Core Core E3 (E3-1505LV5 25W 4c/8t HDP530 2.0GHz 8MB incl. ECC 16 GB DDR3-1066)
- ❑ 3U : beamline

■ Timing Board

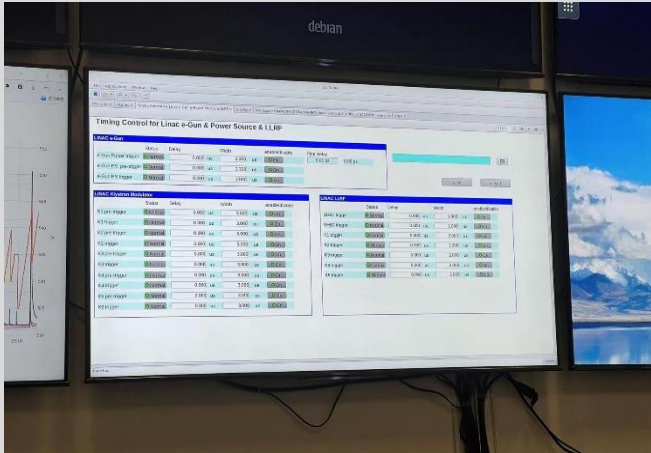
- ❑ FANOUT : mTCA-EVM-300
- ❑ EVR : mTCA-EVR-300
 - TTL:4
 - UNIV : 4
 - Pulser 16
- ❑ RTM : UNIV : 10

■ Output

- ❑ UNIV-TTL5V : LEMO
- ❑ UNIV-HFBR-1414 : ST
- ❑ UNIV-TTL-DLY : 10p delay step size
- ❑ 1-10 TTL FANOUT
- ❑ 1-10 HFBR-1414 FANOUT

Linac Timing

■ Timing system in the Linac commissioning stage



Temporary Linac Control Room



1. Temporary Main Timing Station
2. Microwave and Power Source
Timing Station



Linac BI Timing Station

Booster Timing

■ BI Timing

- 4 stations are located in Booster tunnel
- Both the cabinet power supply and the crates can be managed remotely



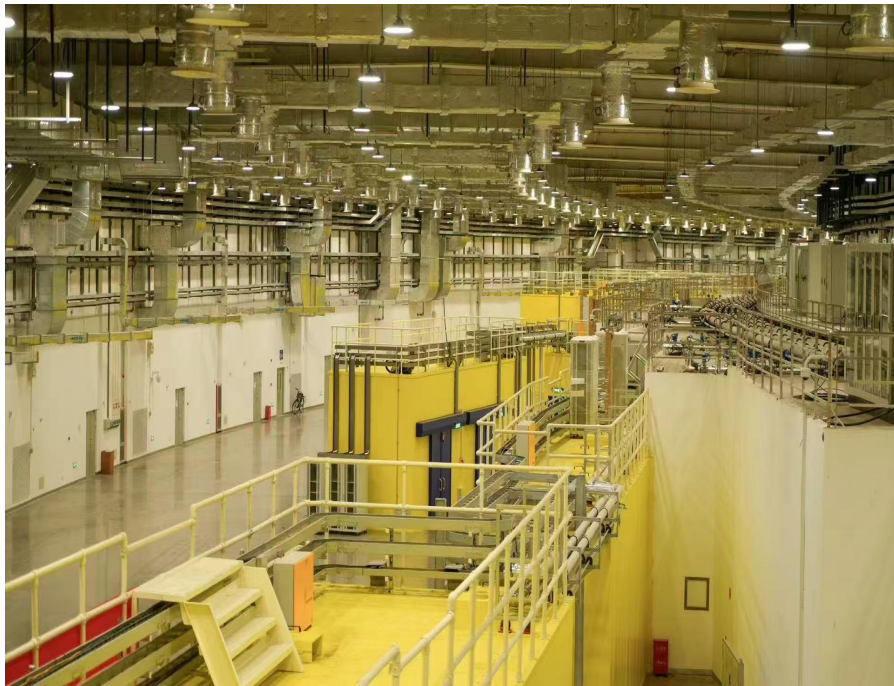
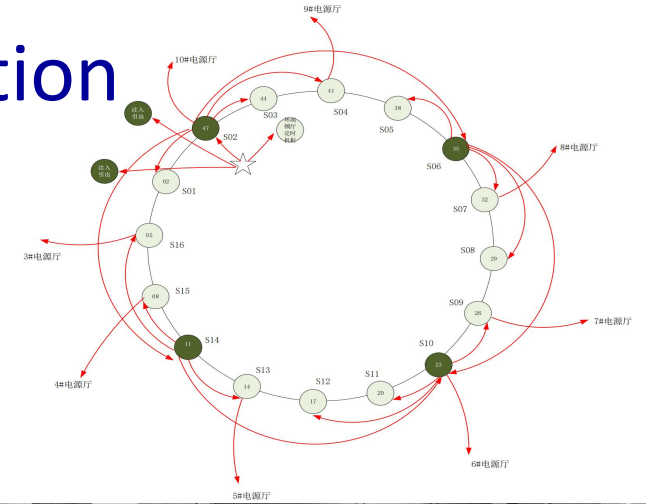
●Timing for Booster RF and Power Supply

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Storage Ring Timing

- Situate over the SR tunnel , 1 for 3 Straight Section

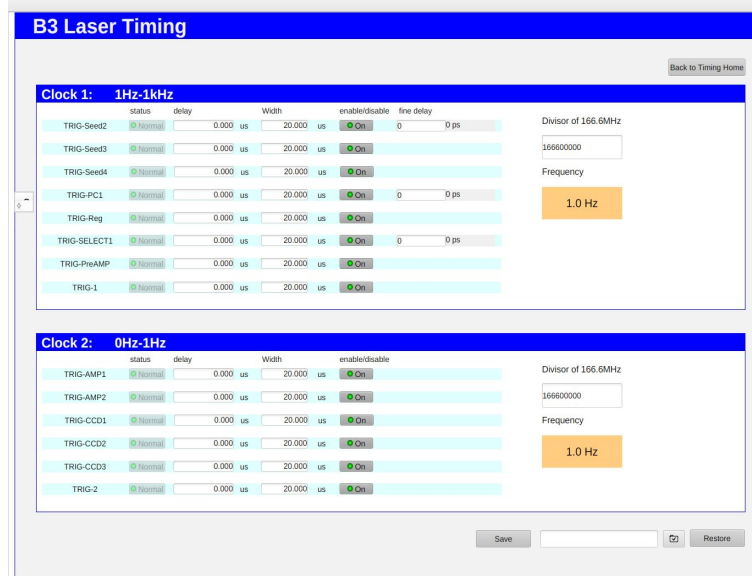
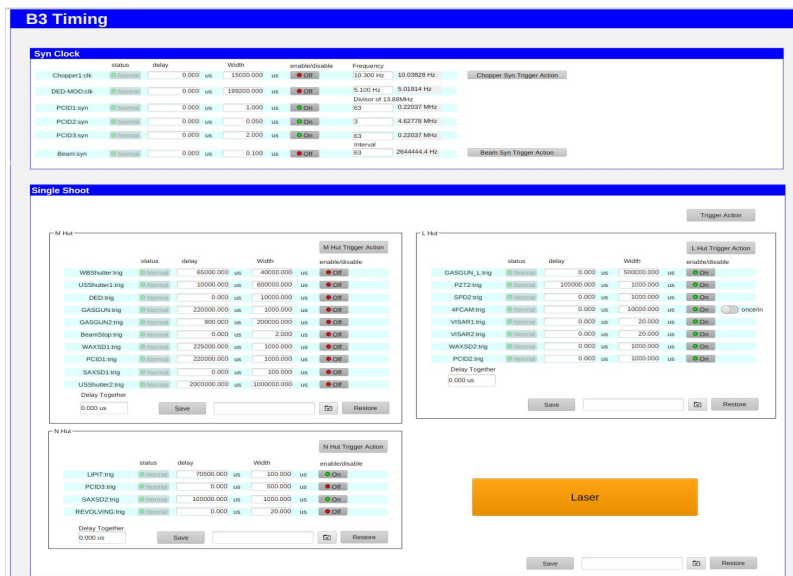
- BI : 576 BPM , ~200 BLM , BCM , Tune.....
- PS : ~2700 power supplies , Postmortem
- IE、FOFB、 RF



Beamline Timing

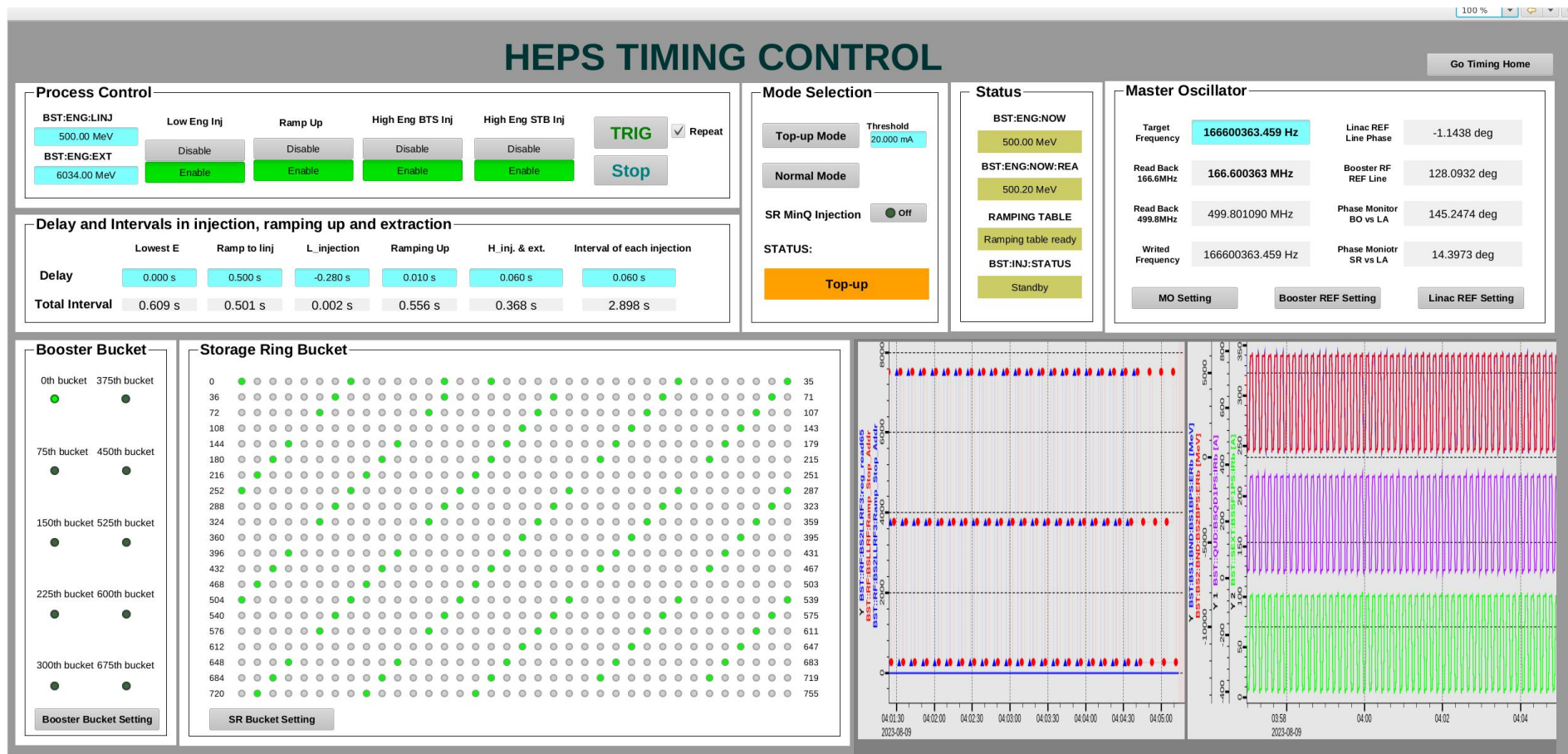
●B3: Structure Dynamics Beamline-ID30

- ❑ Two time slave stations---Inside :M Hut ; Outside: L and N Hut;
- ❑ EVG Cascaded from Acc. Master;
- ❑ Support beam synchronous triggers, one time triggers in three Huts or independtly
- ❑ Less than 1ps jitter clock for Laser experiments, minimum 10ps stepsize delay.
- ❑ Supports sending certain triggers, then waiting for an external trigger to send more



Operator Interfaces

- **Software** : Epics(base 7.6.01), Phoebus
- **Setting Store and Recover** : EPICS autosave , Archiver , Manual Button



- Top-up Mode
- Min-Q Injection
- Booster Energy Setting
- Any process
- ✓ Enable/Disable
- ✓ Delay setting
- Single/Repeat

RF ramping curves

Magnet Power Supply ramping curves

Device Control Interfaces

- **Easy to find:** Categorized by system and location
- **Independent control:** enable/disable, delay, width, direction
- **Trigger Switcher:** output can be assigned different functions and delays
- Delays grouped by category can be modified simultaneously

Beam Instrument Timing Control

BI Control

SR R48BPM02-07 trigger Switch

BS to SR 952.187 us

SR to BS 0.152 us

BPM SYN

BPM:SYN:ALL

BPM Setting

Linac BI

LTB BI

BS BI

BTS STB BI

SR BI

Go Timing Home

Timing Control for Linac e-Gun & Power Source & LLRF

LNAC e-Gun

	Status	Delay	Width	enable/disable	Fine Delay
e-Gun Pulser trigger	Normal	152.570 us	1.000 us	On	0.00 ps
e-Gun PS pre-trigger	Normal	0.000 us	2.000 us	Off	0.00 ps
e-Gun PS trigger	Normal	149.000 us	2.000 us	On	0.00 ps

Save

Reload

LNAC Klystron Modulator

	Status	Delay	Width	enable/disable
K1 pre-trigger	Invert	0.000 us	4.000 us	Off
K1 trigger	Normal	147.310 us	4.000 us	On
K2 pre-trigger	Invert	0.000 us	4.000 us	Off
K2 trigger	Normal	145.630 us	5.000 us	On
K3 pre-trigger	Invert	0.000 us	4.000 us	Off
K3 trigger	Normal	145.480 us	5.000 us	On
K4 pre-trigger	Invert	0.000 us	4.000 us	Off
K4 trigger	Normal	145.500 us	5.000 us	On
K5 pre-trigger	Invert	0.000 us	4.000 us	Off
K5 trigger	Normal	145.290 us	5.000 us	On

LNAC LLRF

	Status	Delay	Width	enable/disable
SHB1 trigger	Normal	108.000 us	1.000 us	On
SHB2 trigger	Normal	115.000 us	1.000 us	On
K1 trigger	Normal	150.310 us	2.000 us	On
K2 trigger	Normal	148.025 us	2.000 us	On
K3 trigger	Normal	148.160 us	2.000 us	On
K4 trigger	Normal	148.180 us	2.000 us	On
K5 trigger	Normal	147.970 us	2.000 us	On

Timing Control

Timing Control

Injection Control

Injection Setting

SR Bucket Display

Device Control

Linac

Injection&Extraction

RF

Power Supply

Beam Instrumentation

FOFB

Linac Beam Instrumentation Timing Control

Linac BI Timing

LNAC ICT

	status	delay	Width	enable/disable
ICT01	Normal	157.150 us	2.000 us	On
ICT02	Normal	157.150 us	2.000 us	On
ICT03	Normal	157.118 us	2.000 us	On
ICT04	Normal	157.100 us	2.000 us	On
ICT05	Normal	157.088 us	2.000 us	On
ICT06	Normal	157.098 us	2.000 us	On

LNAC PR

	status	delay	Width	enable/disable
PR01	Normal	50.000 us	35.000 us	On
PR02	Normal	50.000 us	35.000 us	On
PR03	Normal	50.000 us	35.000 us	On
PR04	Normal	50.000 us	35.000 us	On
PR05	Normal	50.000 us	35.000 us	On
PR06	Normal	50.000 us	35.000 us	On

LNAC BPM

	status	delay	Width	enable/disable
BPM01	Normal	155.120 us	2.000 us	On
BPM02	Normal	155.100 us	2.000 us	On
BPM03	Normal	155.127 us	2.000 us	On
BPM04	Normal	155.250 us	2.000 us	On
BPM05	Normal	155.240 us	2.000 us	On
BPM06	Normal	155.290 us	2.000 us	On
BPM07	Normal	155.260 us	2.000 us	On
BPM08	Normal	155.230 us	2.000 us	On

BPM SYN

	status	delay	Width	enable/disable
BPM SYN	Normal	0.000 us	2.000 us	On

BPM TEST

	status	delay	Width	enable/disable
BPM TEST	Normal	0.000 us	2.000 us	On

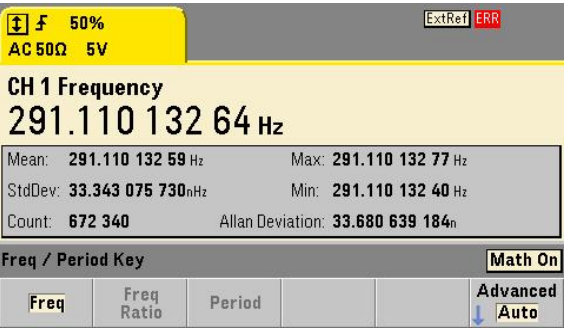
Save

Reload

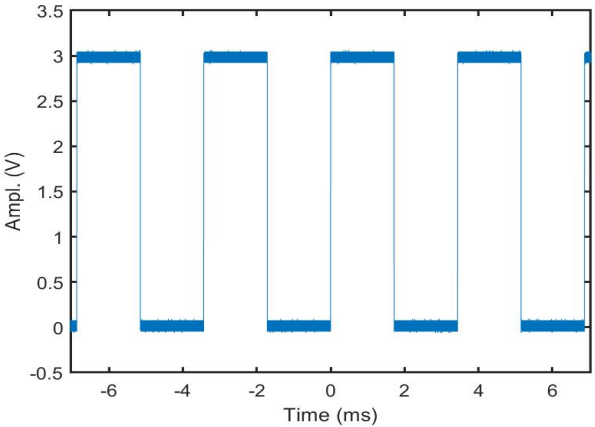
Testing: Distributed Clock

Name	Frequency	Divider
F _{CO}	291.11Hz	572292 (756×757)
F _{Srev}	220.370Hz	756
F _{Brev}	660.239Hz	757/3

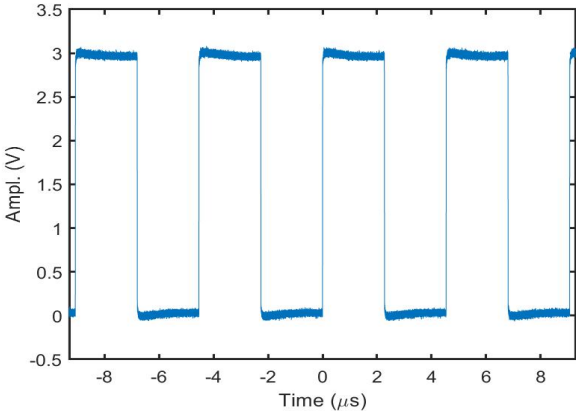
- Teledyne LeCroy SDA 820Zi-B oscilloscope measures the time-domain waveform of the output signal. The LeCroy oscilloscope has a bandwidth of 20GHz and a sampling rate of 80GS/s
- KEYSIGHT 53220A frequency meter measures the frequency and frequency stability.



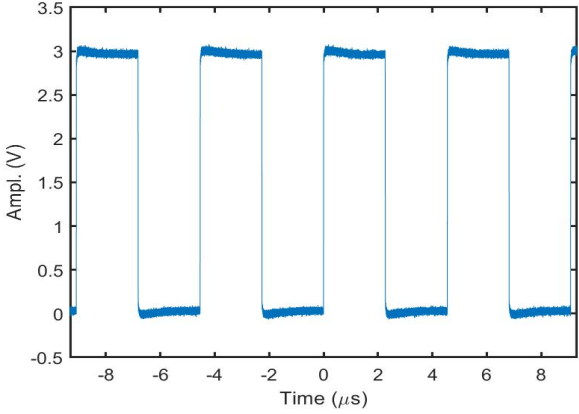
- Coincidence Clock:
291.11013264Hz
resolution 34nHz
- SR revolution clock:
220.37037037 kHz
resolution 7μHz
- BST revolution clock/3:
220.07926024 kHz
resolution 7μHz



DBUS0: Alignment clock



DUBS2: SR revolution clock

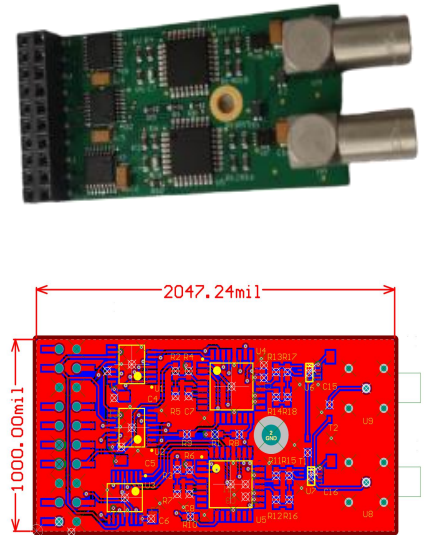
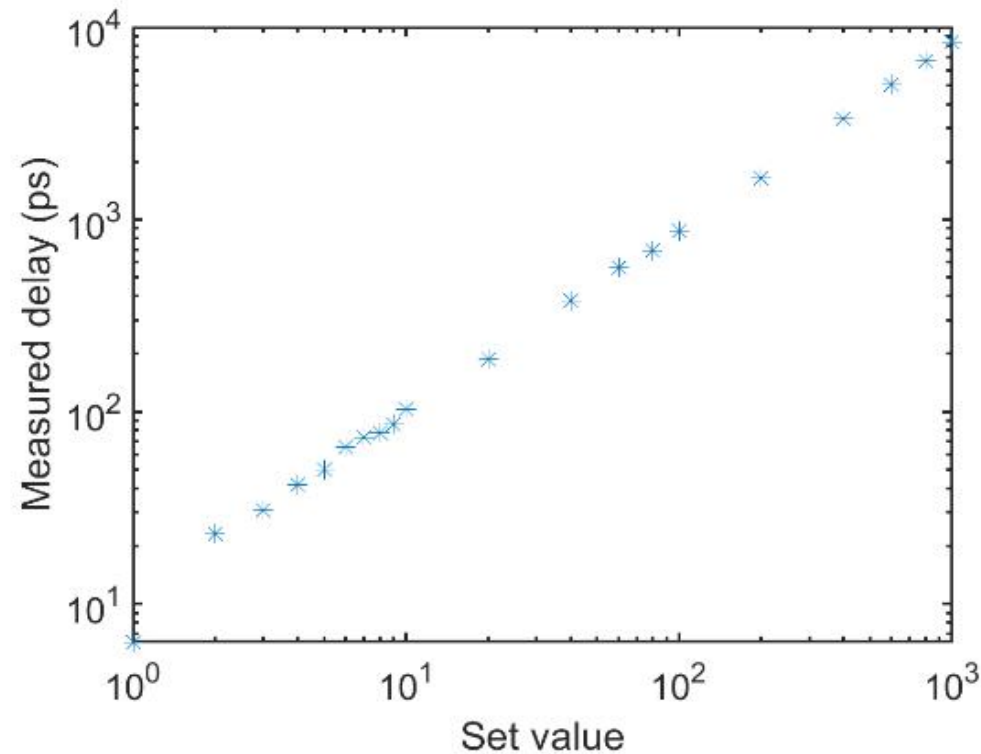
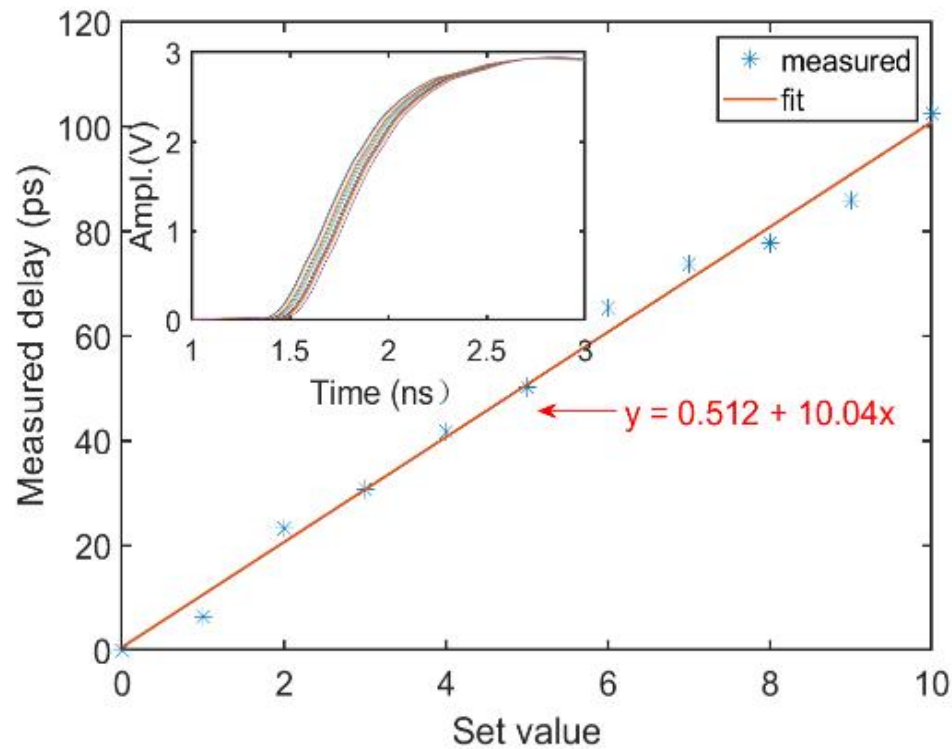


DUBS1: BST revolution clock/3



Delay Adjustment Test

- Since 6ns is a digital counting implementation, only 10ps adjustment accuracy is tested here.
- The delay adjustment is performed by adjusting the delay step size of the delay module in the EVR. For each delay value, 1000 waveforms are measured with an oscilloscope and averaged over the 1000 sets of data.

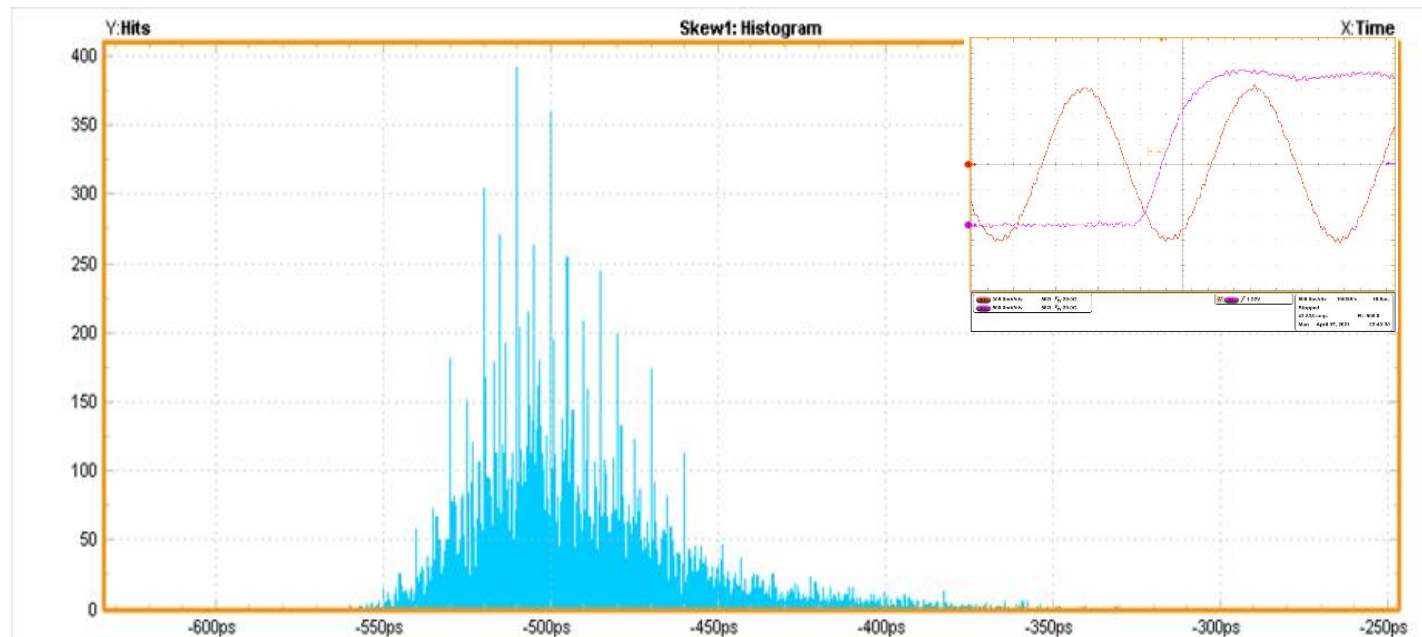


10ps step size adjustment 10 times, adjust 100ps

10ps delay step size, adjustment close to 10ns

Delay Compensation Test

- Optical fiber networks are susceptible to temperature and humidity, and are prone to slow drift due to diurnal temperature and seasonal changes
- All our timing modules equipt with delay compensation function
- The system does not require the use of contour wires, has an automatic measurement function

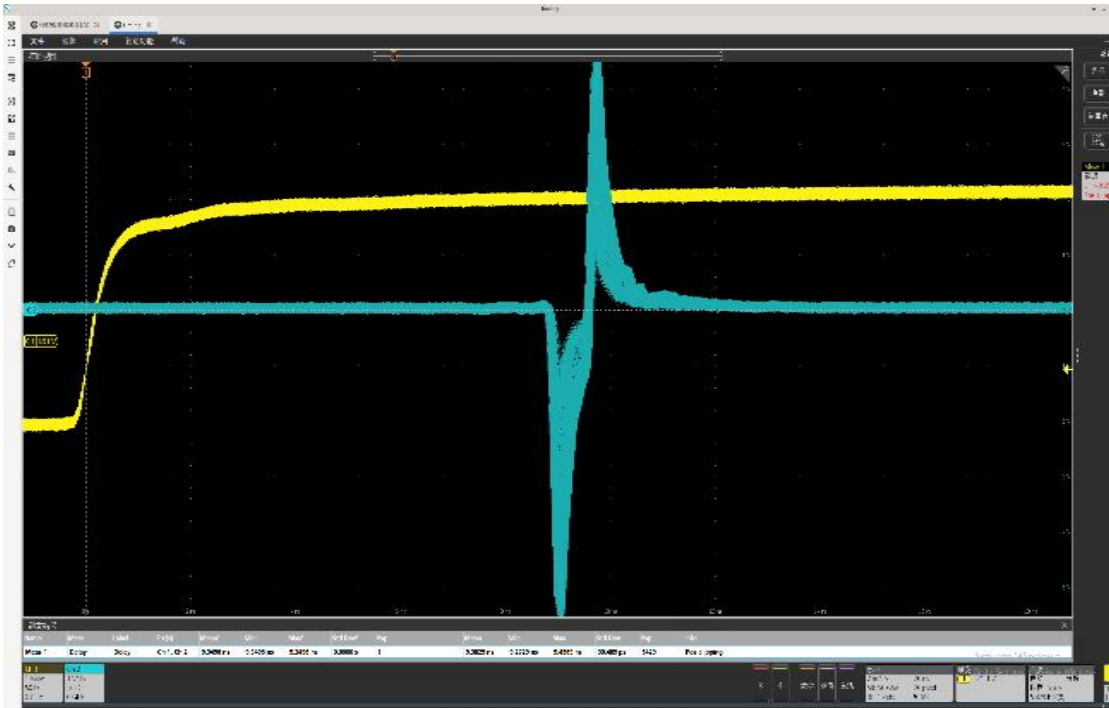


Description	Mean	Std Dev	Max	Min	Peak-peak	Points
Skew, ch1,ch3	-491.93ps	27.353ps	-357.93ps	-560.00ps	202.08ps	43827

- Due to the influence of experimental conditions, only qualitative experiments were conducted
- In the experiment, a heater was used to heat the 400m fiber from 27 degrees to 46 degrees (fiber surface temperature) for two hours, while the output jitter was measured.
- Test result: The output RMS jitter is 27.353ps

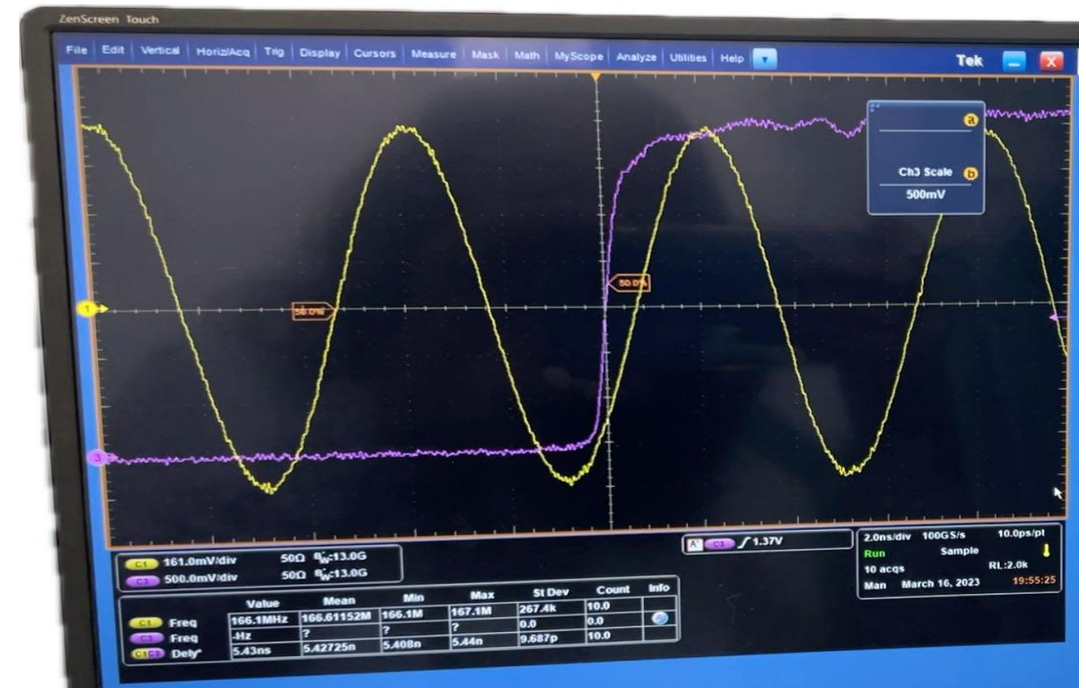
Jitter Test

- BRBPM08 trigger jitter



➤ RMS jitter is 22.35ps, long term is 30.4ps (5 days)

- e-Gun trigger jitter



➤ RMS jitter 9.68ps

Summary

- The HEPS timing adopts a MicroTCA-based event timing architecture..
- HEPS timing system is fully operational and has successfully demonstrated key functionalities, including swap-out injection, ramping scheme and top-up, min-Q operation, etc.
- Currently, the HEPS timing system is undergoing Phase II design and development, and there may be more MicroTCA devices in the future.

Thank you for your attention !



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