Upgrade of BEPC-II LLRF and synchronization system for the new PWFA research

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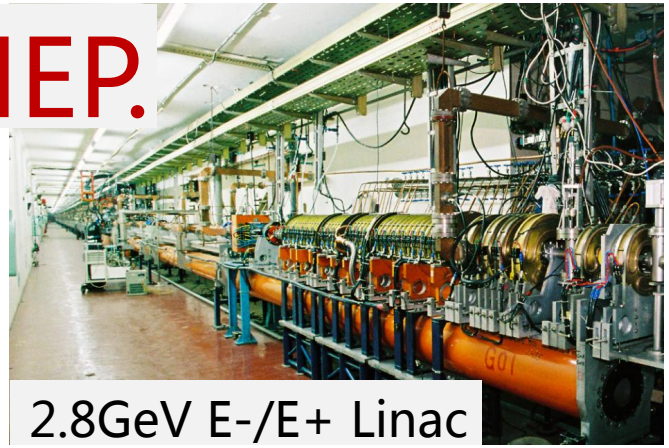
2025-10-15

Outline

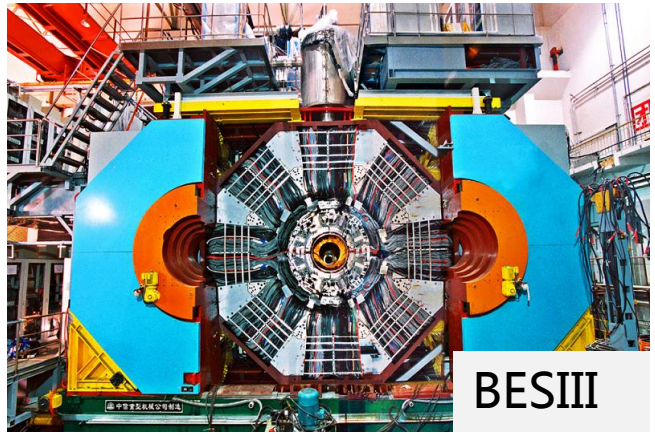
- IHEP and BEPCII-U (Beijing Electron Positron Collider)
- Plasma WakeField Acceleration(PWFA) at IHEP
  Upgrade LLRF and phase reference line

IHEP.

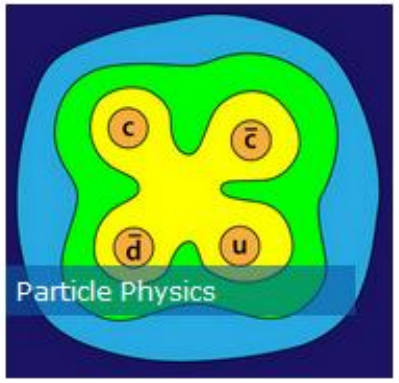


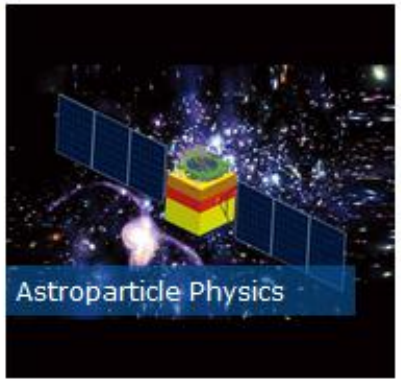
2.8GeV E-/E+ Linac

BEPCII-U: 2.8GeV E-/E+ Collider / SR

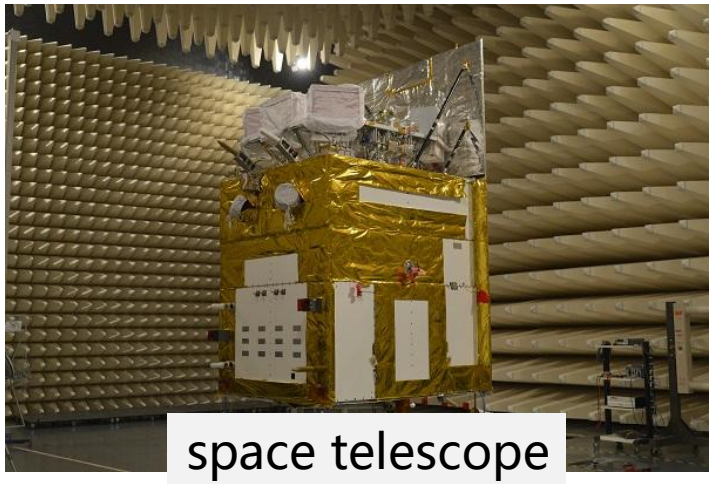


BESIII





Neutrino detector



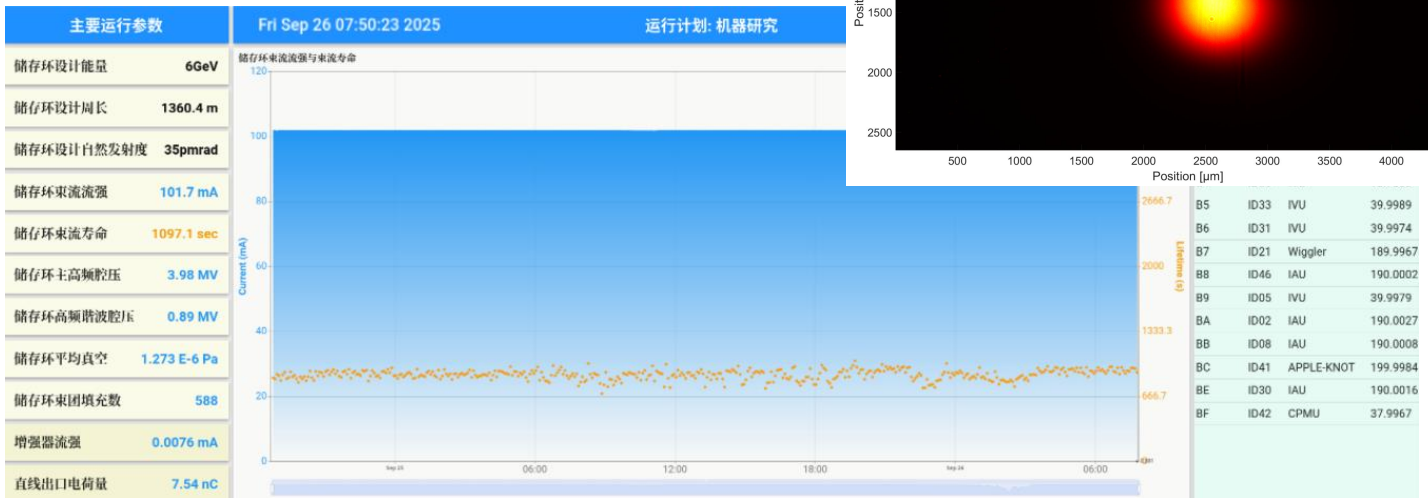
space telescope

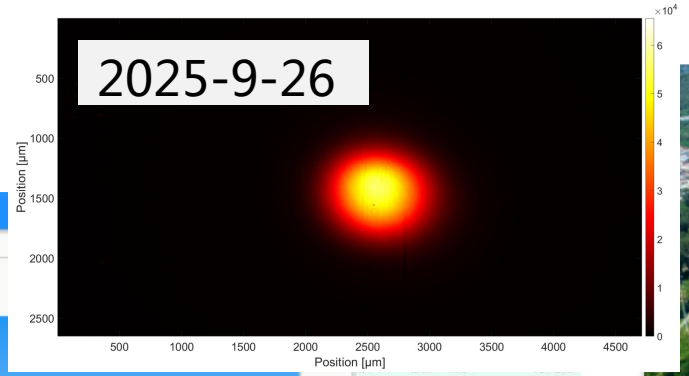
CSNS and CSNS-II (2024-2029)

News from **High Energy Photon Source** (HEPS, 2019-2025)

- 2019/06 Civil starts ✔
- 2022/02 Linac&Booster start to install ✔
- 2023/03 Linac first beam ✔
- 2023/11 Booster passed acceptance ✔
- 2024/07 Storage ring commissioning ✔
- 2024/12 First X-ray ✔
- 2025/09 Passed acceptance test, in (pre)-operation ✔

Parameters	Acceptance test results
Energy	6.01 GeV
Emittance	56.8 pm
Current	100.5 mA
Orbit stability	19.8% max
Brightness	4×10^{21} phs/s/mm²/mrad²/0.1%BW
Energy of X-ray	349.57 keV peak



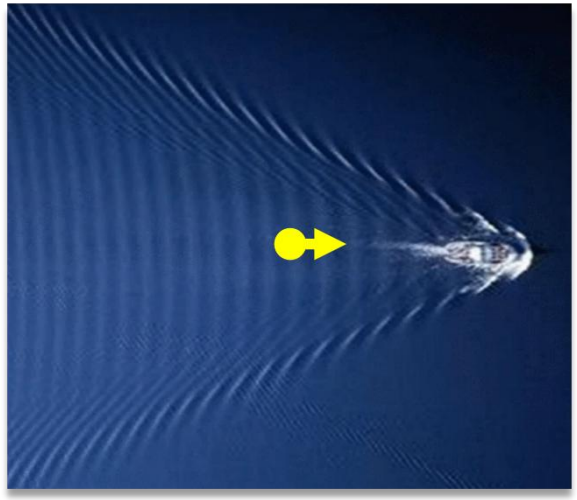


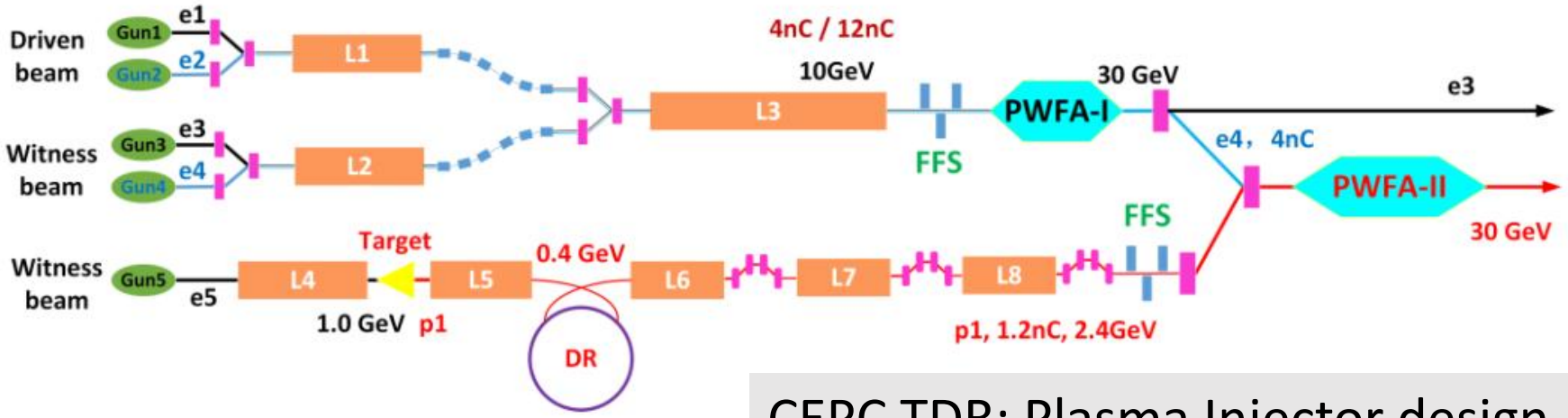
Outline

- IHEP and BEPCII-U
- Plasma WakeField Acceleration(PWFA) at IHEP
  Upgrade/new LLRF and phase reference line

PWFA

- PWFA (Plasma WakeField Acceleration) is a beam accelerated by another beam-stimulated wakefield when it pass through a plasma
- Pro: Very high acclerating gradient >10GeV/m!
- High energy physics future: Higgs factory needs e-/e+ collider, CEPC proposal is underway, but still too complex(100km) and expensive, PWFA is a candidate way for future collider and FEL



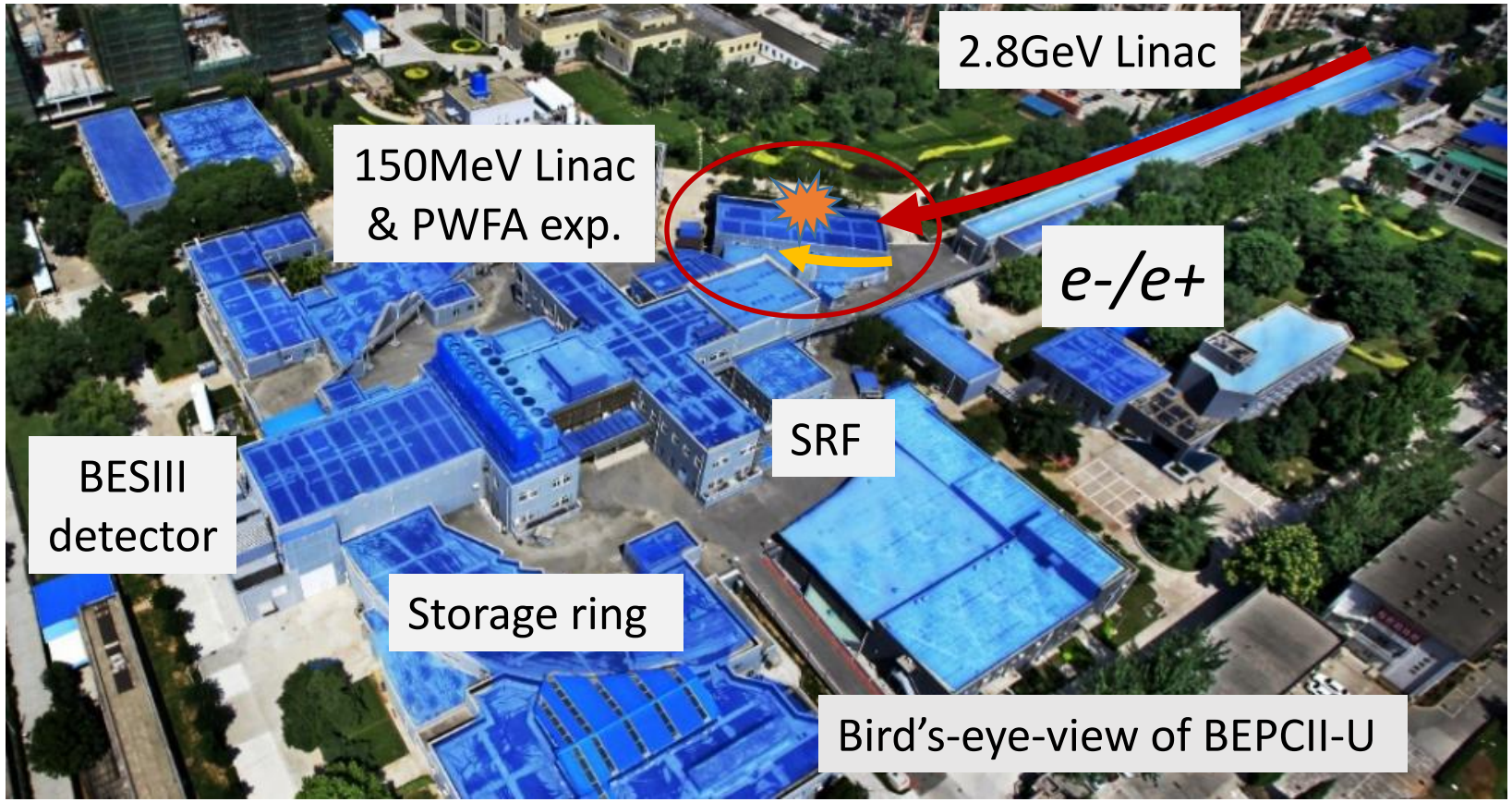


CEPC TDR: Plasma Injector design

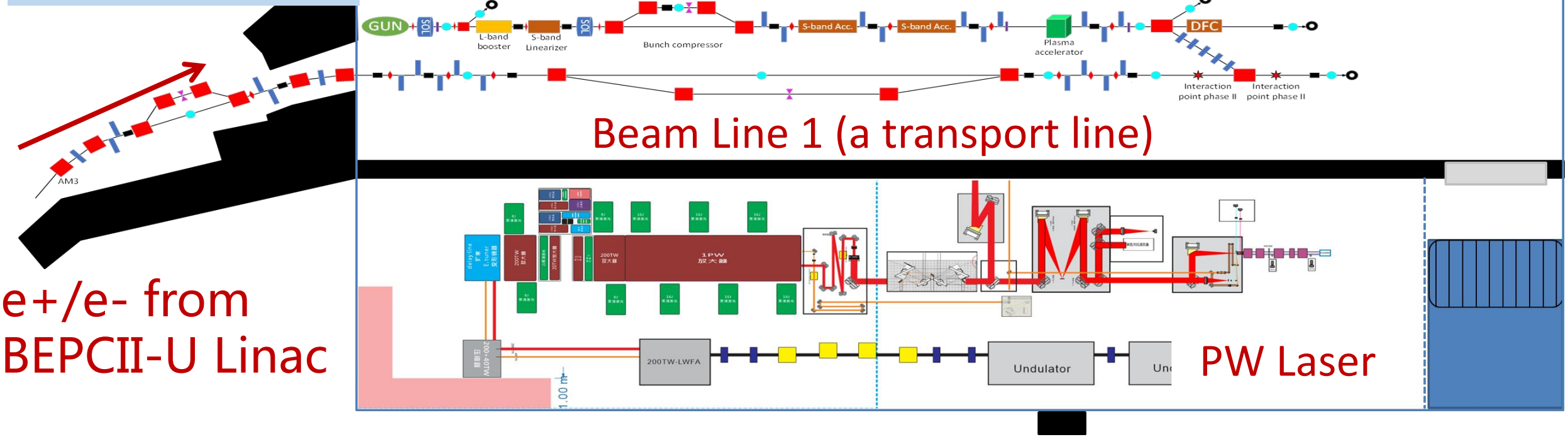
PWFA and BEPCII-U

- BEPCII is an e-/e+ collider from 2005, make it alive and thrive
- BEPCII-U project: upgraded during 2024.07-2025.02, to increase energy from 2.5GeV to 2.8GeV, 3 x higher collision luminosity broadening tau-charm energy region

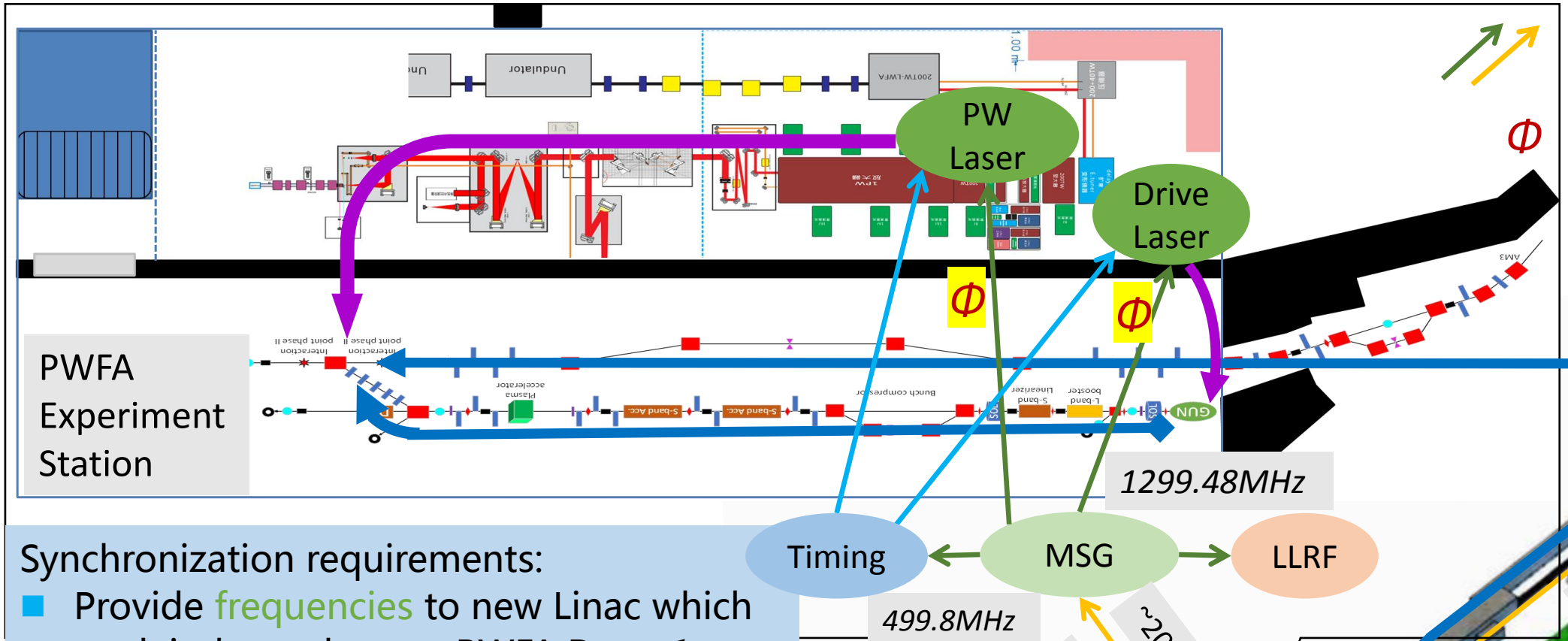
- BEPCII Upgrades:
  - upgraded Linac
  - 2 more SRF cavities
  - new IP magnets
  - upgrade in detectors ...
- **New PWFA test facility:** new science and new engineering, a new 150MeV Linac in PWFA exp. hall (2024 -)



PWFA station



- Goal 1. **Self PWFA** in new photon-cathode Linac by two bunches train. (BL2)
- Goal 2. First PWFA experiment of positron by one driven e-bunch from new Linac and **accelerated positron** from BEPCII-U Linac. (BL2+BL1)
- Goal 3. First **cascaded** PWFA of e+/e- by accelerated bunch together with bunch from BEPCII-U Linac based on Goal 1 + Goal 2. (BL2+BL1)
- Goal 4. Laser Plasma Acceleration(LPA): PetaWatts Laser.

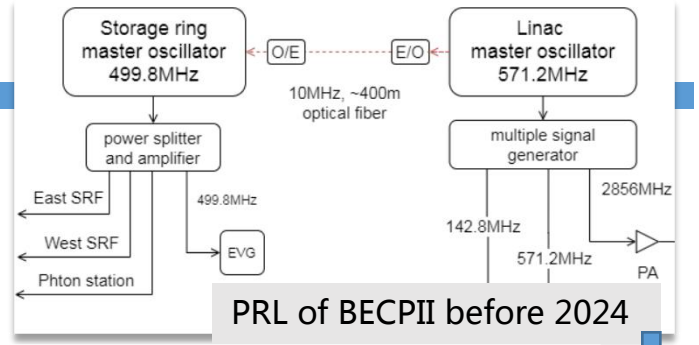


Synchronization requirements:

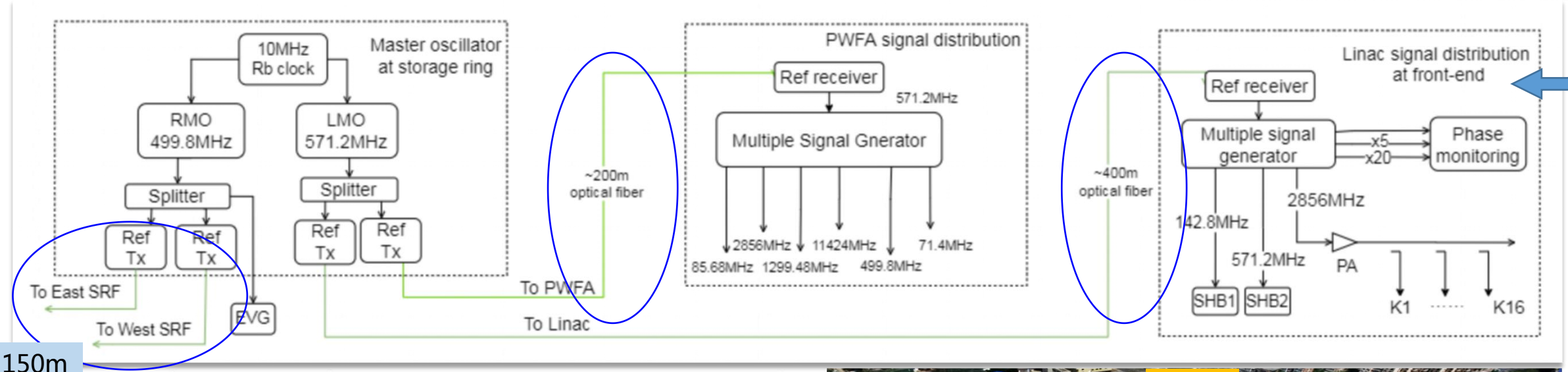
- Provide frequencies to new Linac which work independant on PWFA Demo1
- **Synchronize and merge** BL2(new Linac) beam with BL1 beam(from BECPCII Linac), bunch length <1ps, **arrival time jitter shall be <50fs(rms)**, for both Goal2 and Goal3
- Synchronize PW laser with beam on LPA

1. upgrade of main PRL

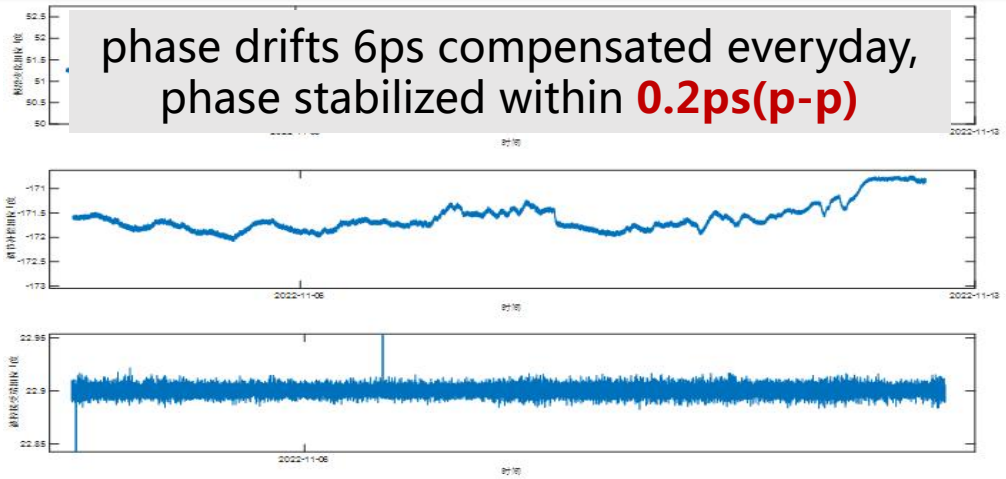
- **Upgrade/build BEPCII-U/PWFA phase reference lines** based on optical fibers, similar tech as HEPS: MO to the Linac(400m), to the PWFA(200m), to the East and West SRF(150m), replacing cables, active feedback of phase drift of fibers
- LMO and RMO are locked with single 10MHz Rb atom clock improving freq stability



PRL of BECPII before 2024



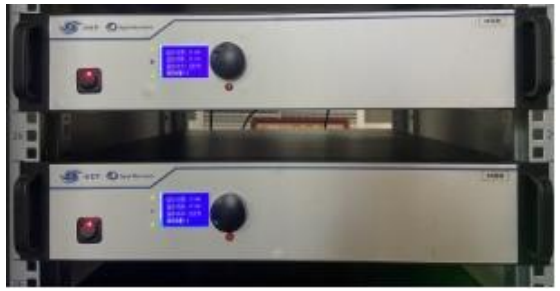
~150m optical fibers



phase drifts 6ps compensated everyday, phase stabilized within **0.2ps(p-p)**

1. upgrade of main PRL : Tx-Rx pair

- Revised from 499.8MHz on HEPS to **571.2MHz** on BEPCII-U
- 2x499.8 Tx-Rx pairs for SRF, 2x571.2MHz for Linac and PWFA

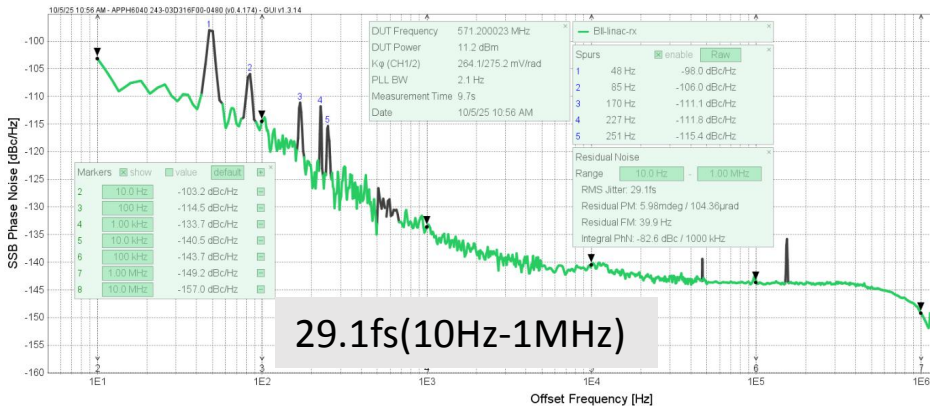


MO RF Tx

RF Rx

MO

Received RF from MO to Linac via 400m fiber



29.1fs(10Hz-1MHz)

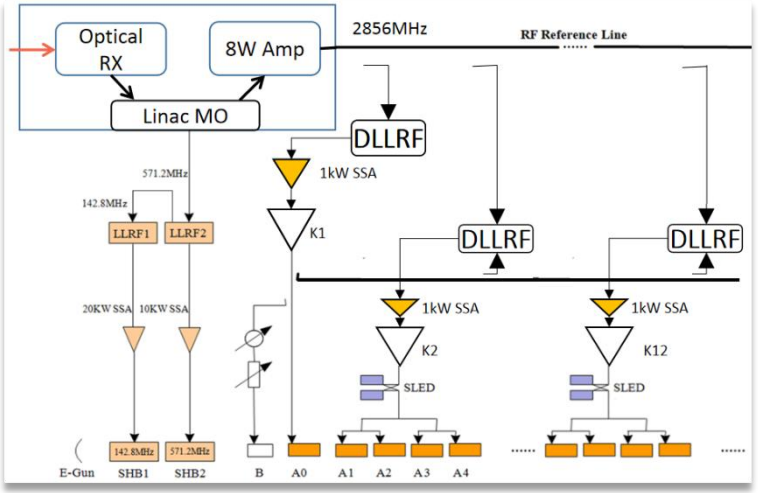
Specfication	
Center frequency	**499.8MHz / 571.2MHz**
Bandwidth	±3MHz@0.01dB ±10MHz@0.1dB
Input amplitude	>10dBm
Output amplitude	>12dBm x 2
Max phase delay range	120ps@0.01dB amp. sta. 540ps@0.1dB amp. sta.
Additive jitter	<18fs(10Hz-10MHz)
Long-term stability (out-of-loop)	200fs (p-p)- 3days
Long-term 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

Details in LLRF2024 ST WS: ”Phase distribution system of HEPS”

2. LLRF upgrade on BEPCII-U Linac

- BEPCII-U Linac: 200m, 2 more klystrons, 22 in total, full energy 2.8GeV for electrons and positrons
- Upgrade 22 + 2 new MTCA.4 LLRF 2856MHz system, 2x 142.8MHz and 571.2MHz bunchers system = 24
- Upgrade all signal module TEC-controlled ±0.01K

Fully MTCA based modenized LLRF



Frequency	2856 MHz
Pulse width	4 us
Klystron	50 MW
Repetation	1/12.5/25/50 Hz

PRL <- 8W PA

Phase monitor

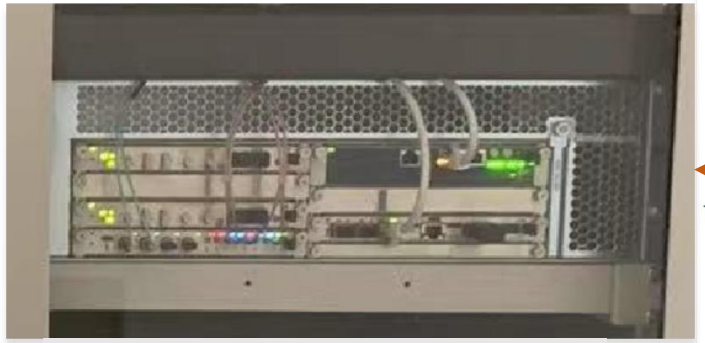
Freq Multiply

Linac MSG

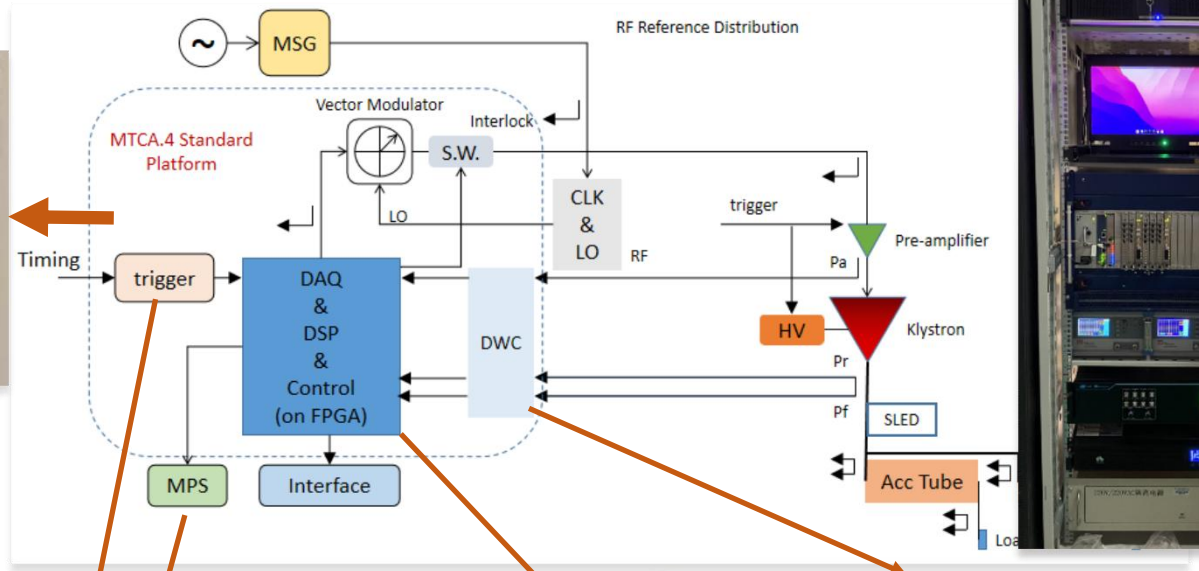
-> Optical Rx

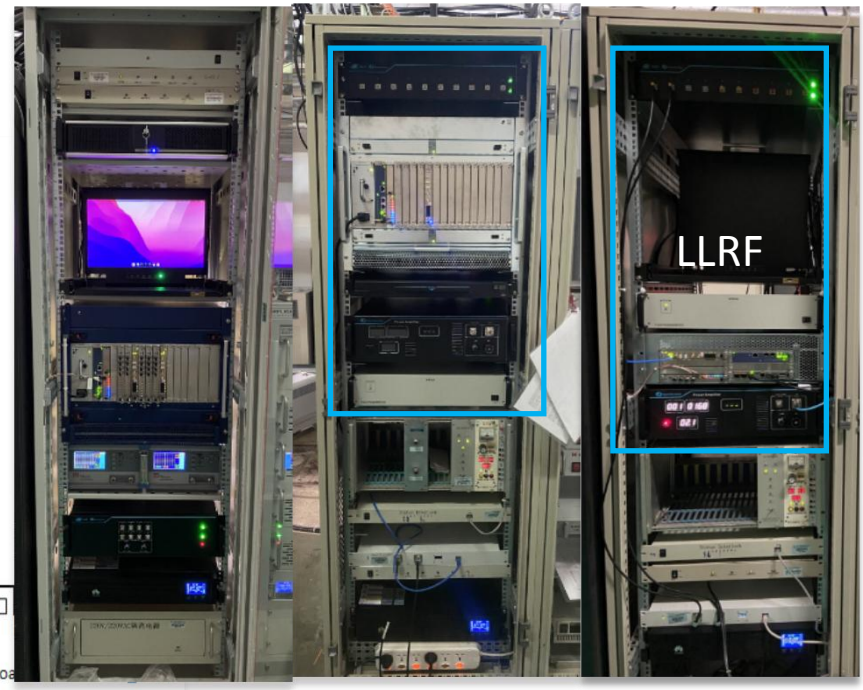
2. LLRF upgrade on BEPCII-U Linac

- 24 MTCA hardwares in last 4 years:



MTCA chassis (3U/9U) :
nVent/ELMA...





In-house made
CPU AMC board

In-house made Trig/DIO

DAQ controller

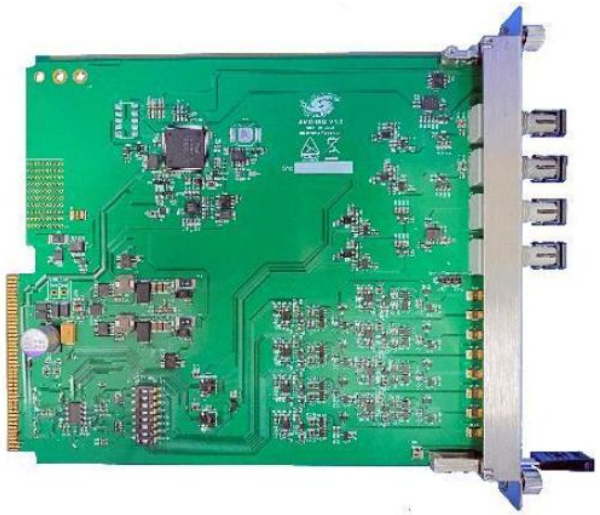
In-house made
DWC RTM 2856MHz

In-house made DS
RTM 142.8/571.2MHz

2. LLRF upgrade on BEPCII-U Linac

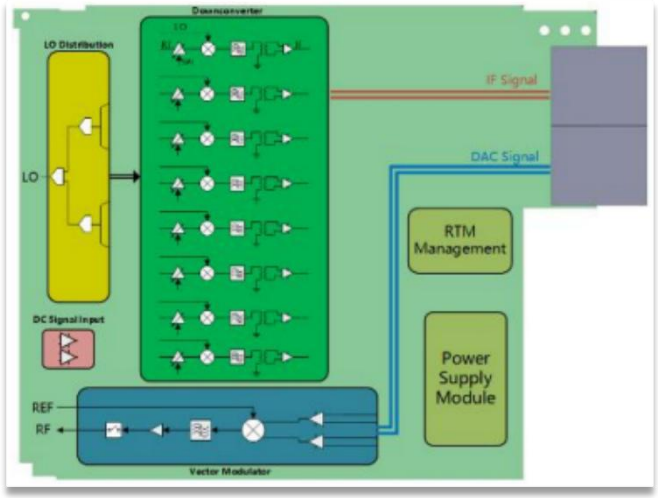
MTCA.4 AMC

- Double width
- local timing and protection
- 8 channels TTL/LVTTL
- in/out direction configurable
- Impedance 50 Ohm/Hi-Z
- Fanout through backplane
- optical 2 in/2 out
- MMC by I2C: voltage, current, temperature monitroring



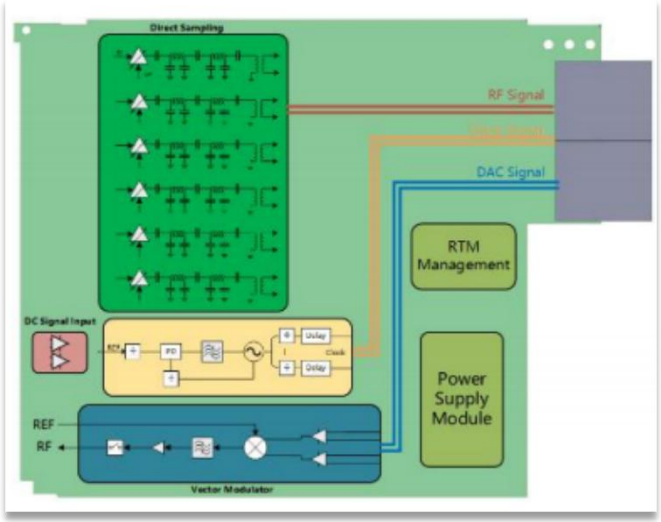
Downconverter RTM

- MicroTCA.4 RTM, Class A1.1
- 8 channels 600M-6GHz DWC
- 8 IF 5-100MHz
- 1 channel VM UPC 50M-6GHz
- 2 channels DC input (MMCX)
- LO/REF power monitor
- adjustable in/output attenuation
- 4 channels TTL digital I/O
- connector: SMP



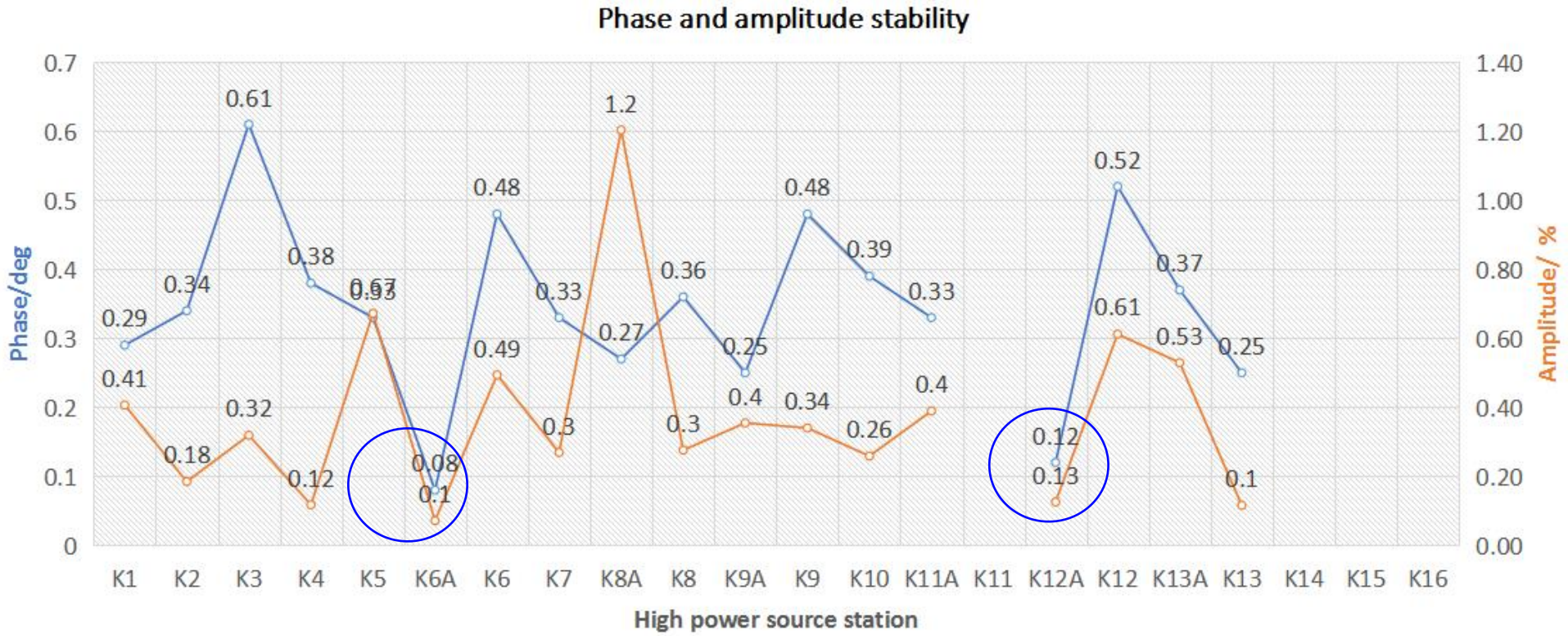
Direct-sampling RTM

- MicroTCA.4 RTM, Class A1.1
- 6 channels DC-600MHz DS
- 1 channel VM UPC 50M-6GHz
- dual-PLL, 100M-2GHz input
- LO/REF power monitor
- 4 channels TTL digital I/O
- connector: SMP
- I2C interface



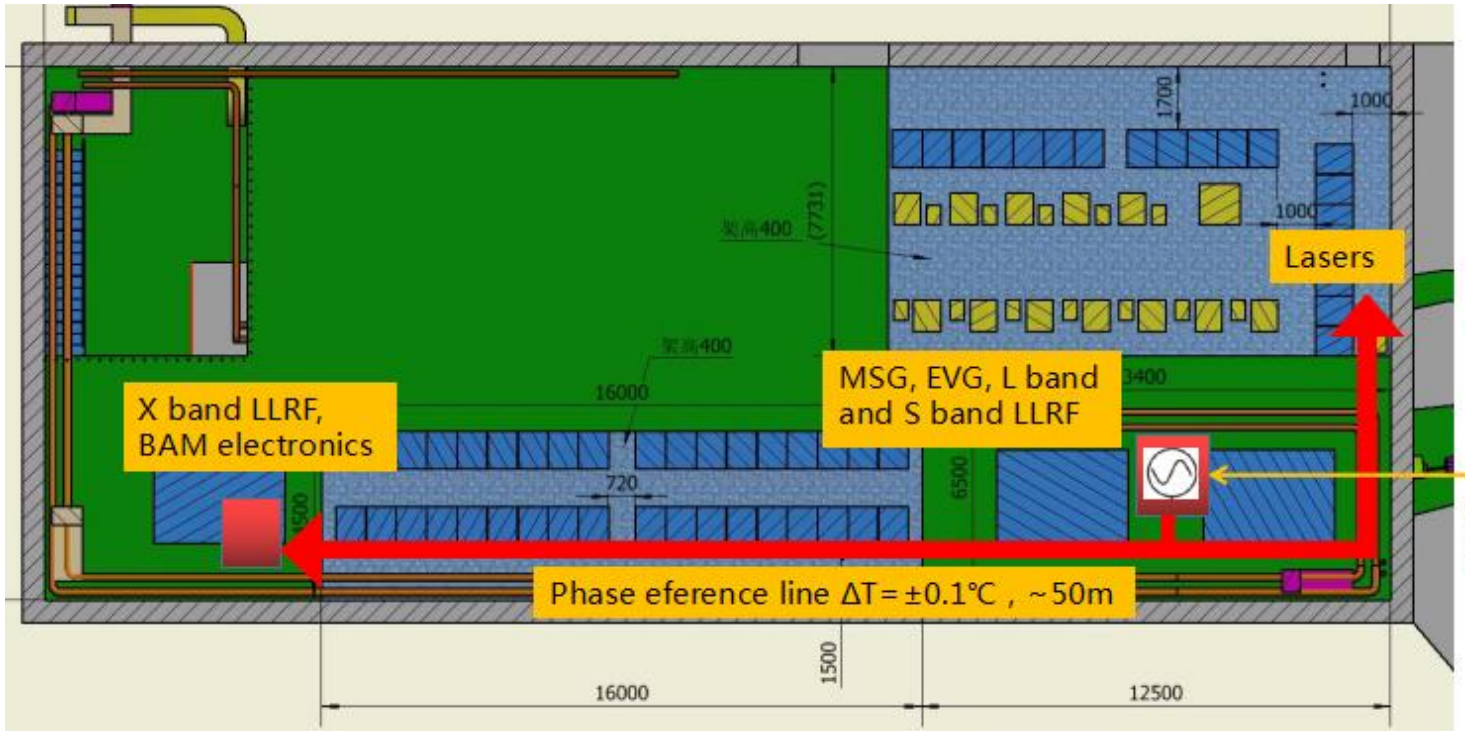
2. LLRF upgrade on BEPCII-U Linac

- **S-band LLRF Performance**: φ<0.6deg(p-p) and A<1%(p-p), short term error 4 times reduction, PFN type modulators used for klystrons.
- Two new K6A and K12A power sources are **solid state modulators**, stability are further improved
- Linac beam arrival time and energy stability much better



3. Distribute phase in the PWFA station

- To achieve engineering feasibility of PWFA with two accelerator beams, both short-term jitter and long-term stability shall be considered very carefully
- On the new Linac and PWFA station, all MSG, EVG, LLRF, BAM electronics are installed in the temperature stabilized cabinet (nVent) by ±0.1℃ cooling water
- The phase reference line cables are routed in the temperature controlled duct by ±0.1℃ cooling water, the cables with lowest temp-phase coefficient are chosen, Commscope LDF2-50A, <3fs/m/℃, estimated ~30fs(p-p) drift



PWFA experiment station - Control and power room (on top of beam line tunnel)

temperature stabilized cabinet

571.2MHz Ref from BEPCII-U

4. Frequencies of the new Linac

- Have to generate L band and 499.8MHz(for timing EVG) from BEPCII-U(existed 2856MHz)
- Those both L and S band machine, mostly from MO 1300MHz to 2856MHz
- Calculate from 2856MHz to near 1300MHz(because photon-gun been decided L band) , big enough common frequencies, near 1300MHz as gun can only be very few freq tuned
- Final solution is common frequency 14.28MHz=1/200*2856MHz, L band 1299.48MHz referenced for both L band gun and driven laser

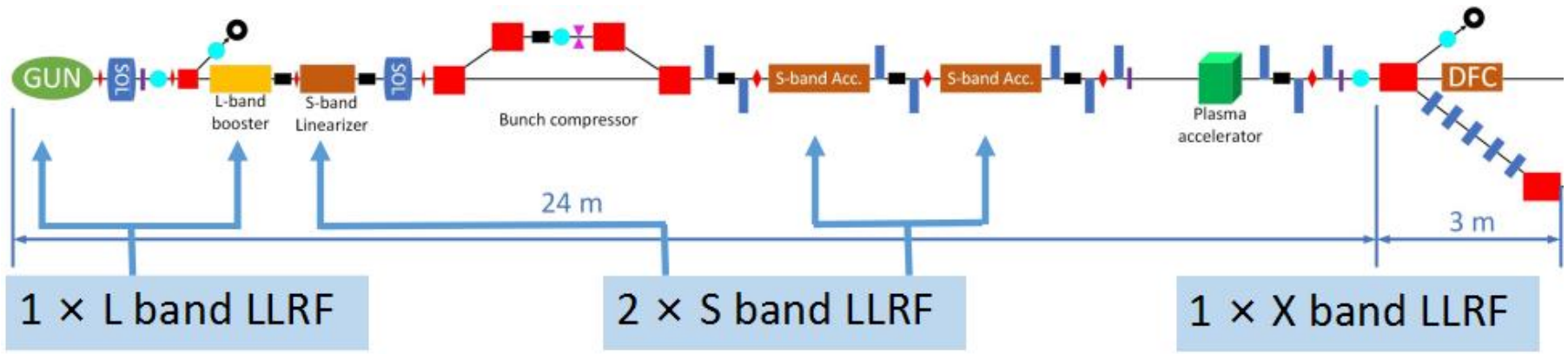
$$\frac{1300}{2856} = \frac{325}{714} = 0.45518207\ldots\ldots \qquad 0.455 = \frac{91}{200}$$

1/2 - 9/200: 1428-14.28*9 = 1299.48

$0.455 \times 2856 = 1299.48$

Common frequency: 14.28MHz

Beam line 2: new Linac, beam shall be sync-ed with beam from BEPCII-U Linac

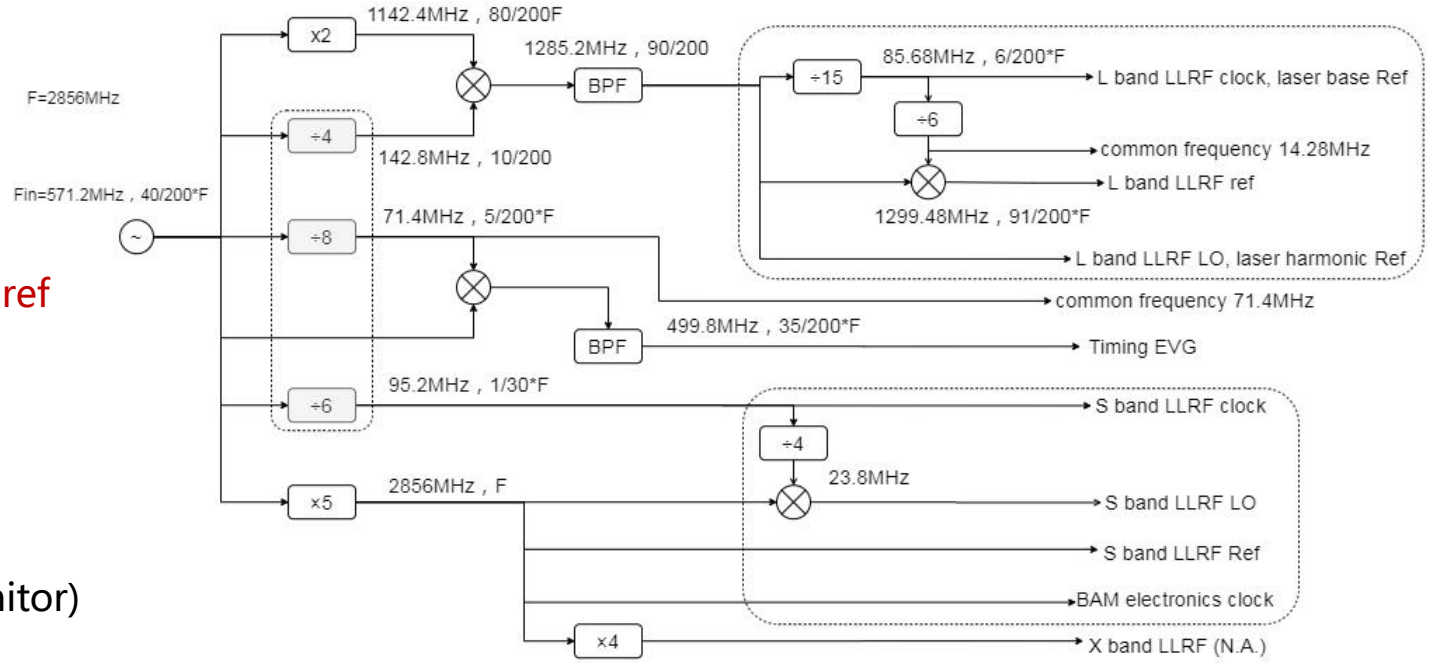


4. Multiple signal generator in the PWFA station

- Each power cycle, signal phases should be restored to easy beam commissioning , so tested and chosen dividers AD9514 (with special phase-reset-pin)
- Common frequencies 14.28MHz and 71.4MHz shall be used as the trigger to monitoring all other frequencies phases using oscilloscope

Common Freq: 14.28MHz =571.2/40

Out1 : 85.68MHz	14.28*6	laser locked rep(base) freq
Out2 : 1285.2MHz	14.28*90	laser locked harmonic freq
Out3 : 1299.48MHz	14.28*91	L band LLRF ref
Out4 : 2856MHz	571.2*5	S band LLRF ref/ BAM elect ref
Out5 : 499.8MHz	14.28*35	timing EVG ref
Out6 : 14.28MHz	571.2/40	common frequency
Out7 : 95.2MHz	571.2/6	S band LLRF clock
Out8 : 71.4MHz	571.2/8	common frequency(for monitor)
Out9 : 11424MHz	2856*4	X band LLRF



4. Multiple signal generator in the PWFA station

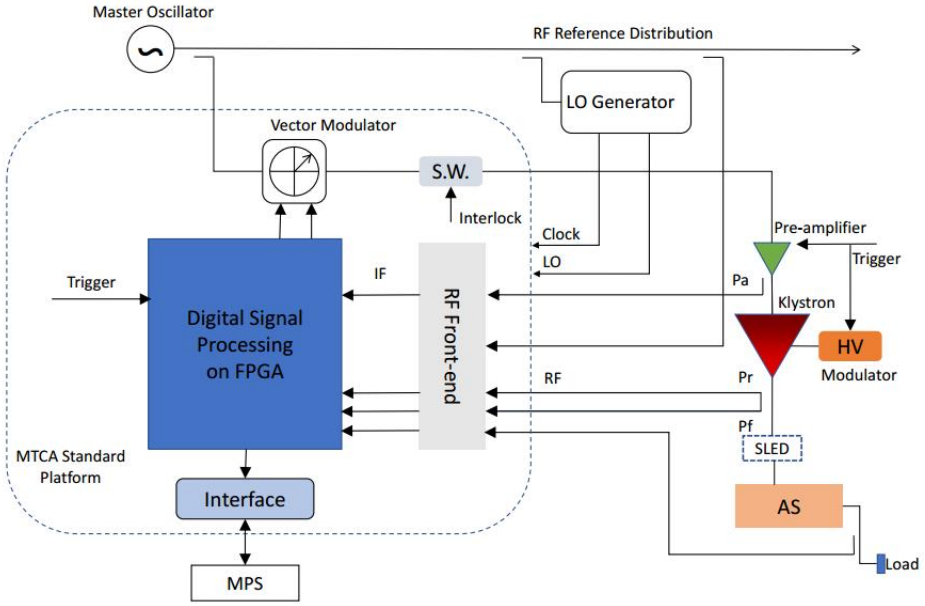
MSG（9 channels） pannel

- Received signals jitter was measured, L band 26.5fs(10Hz-10MHz)
- Phase recovery was also tested OK !

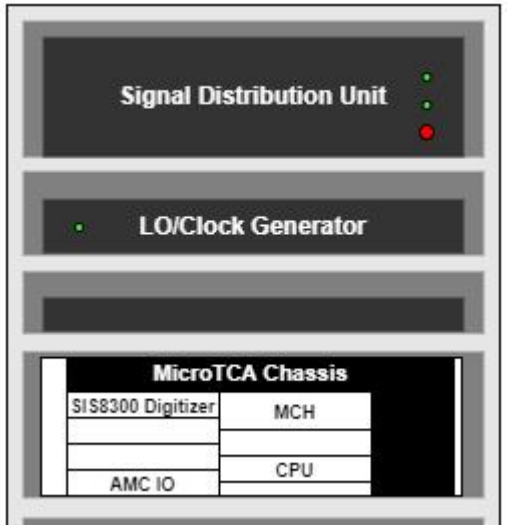
	In	Out1	Out2	Out3	Out4
Freq/MHz	571.2	85.68	1299.48	1285.2	14.28
jitter/fs（10Hz-10MHz）	16	111.6	26.5	34.2	709
Power/dBm		9.1	13.2	14.6	16.5
	Out5	Out6	Out7	Out8	Out9
Freq/MHz	2856	2832.2	95.2	499.8	71.4
jitter/fs（10Hz-10MHz）	32.3	34.5	136.2	59.5	149.7
Power/dBm	13.6	9.6	10.9	15.3	12.5

5. LLRF for PWFA new Linac

- 3 MicroTCA.4 LLRF system, L band(1299.48MHz), S band(2856MHz), X band(11.424GHz)
- Upgrade MicroTCA hardware includes one new 2U local made chassis, in-house made DAQ AMC/DWC RTMs/CPU boards for L&S band, 1 Trig AMC board, NAT MCH
- Firmware/software kept same with BEPCII-U and HEPS



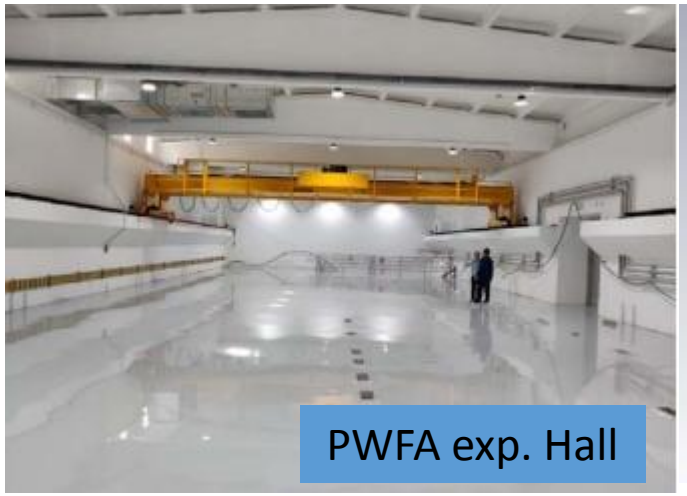
LLRF of L and S band

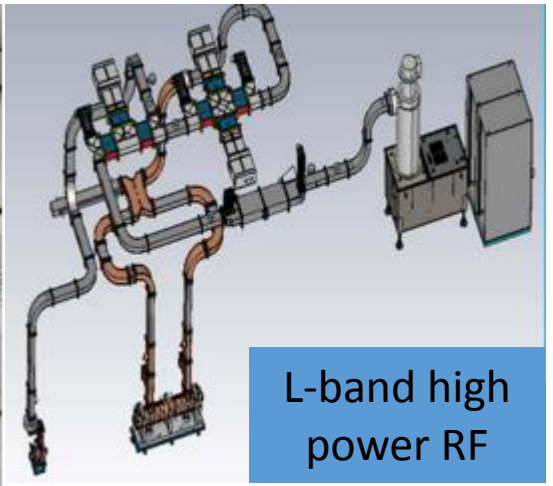


Summary

- IHEP is building a PWFA facility aiming to first positron and cascaded experiments, synchronizing two beams from two Linacs requires upgrade /new of LLRF and phase ref line of the BEPCII-U and PWFA complex

- Next step:
  Q4/2025 finished PWFA Linac installation
  Q1/2026 start PWFA beam
  … …


PWFA exp. Hall


L-band high power RF

Thank you for your attenention!

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