CEPC instrumentation development status

On behalf of beam instrumentation group

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Content

- **The design of beam instrumentation in CEPC**
  - Booster and storage ring beam instrumentation
  - Linac and damping ring beam instrumentation
- **The related R&D of beam instrumentation in IHEP**
  - Beam position monitor
  - Beam loss monitor
  - Feedback system
  - Tune monitor
  - Profile monitor

Requirement List of the SR Beam Instrumentation

Item		Method	Parameter	Amounts
Beam position monitor	**Closed orbit**	**Button electrode**	**Measurement area： ±20mm ×±10mm** **Resolution: <1 μm Measurement time: < 4 s**	**4252**
	Bunch by bunch	**Button electrode**	**Measurement area： ±20mm×±10mm** **Resolution: <0.1 mm**	
Bunch current		BCM	Measurement range: 10mA / per bunch Relatively precision: 1/4095	2
Average current		DCCT	Dynamic measurement range: 0.0~1A Linearity: 0.1 % Zero drift: <0.05mA	2
Beam size		Double slit interferometer X-ray pin hole	Resolution: 0.2 μm	4
Bunch length		Streak camera Two photon intensity interferometer	Resolution:1ps@10ps	2
Tune measurement		Frequency sweeping method	Resolution:0.001	2
		Direct Diode Detection	Resolution:0.001	
Beam loss monitor		**PIN-diode/other type**	**Dynamic range:120 dB** **Maximum counting rates≥10 MHz**	**5800**
Feedback system		**TFB**	**Damping time <= 1 ms**	**4**
		LFB	**Damping time <= 65 ms**	**4**

Requirement List of the Booster Beam Instrumentation

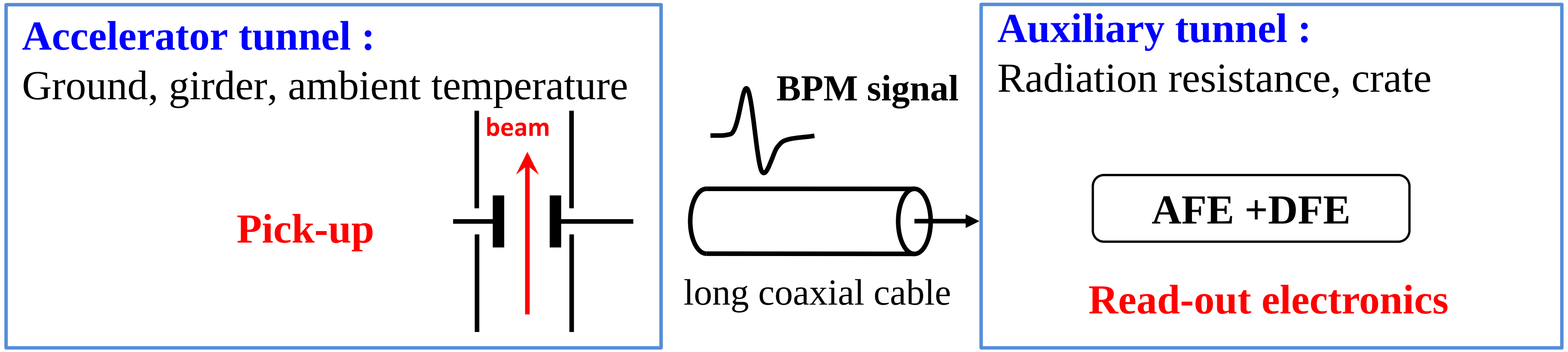
Item	Method	Parameter	Amounts
Beam position monitor	**Button electrode**	**Measurement area：±20 mm×±10 mm** **Resolution：<20 μm (Turn by turn)**	**2408**
Bunch current	BCM	Measurement range：10mA/per bunch Relatively precision：1/4095	2
Average current	DCCT	Dynamic range：0.0~1A Resolution:50μA@0.6-8mA Linearity：0.1 % Zero drift: <0.05mA	2
Beam size	Double slit interferometer x ray pin hole	Resolution:0.2 μm	2
Bunch length	Streak camera Two photon intensity interferometer	Resolution:1 ps	2
Tune measurement	Frequency sweeping method	Resolution:0.001	2
	DDD	Resolution:0.001	
Beam loss monitor	**Optical fiber**	**Space resolution:0.6m**	**670**
Feedback system	**TFB**	**Damping time<=10ms**	**2**
Feedback system	**LFB**	**Damping time<=200ms**	**4**

CEPC BS and SR beam instrumentation design

- Beam position monitor
- Beam loss monitor
- Feedback system (Yue’s report will give more details)
- Beam profile monitor
- Beam current monitor
- Synchrotron radiation based beam diagnostics
- Tune measurement
- ……

Beam position monitor

- With one Beam Position Monitor (BPM) near each quadruple, there will be **4252** BPMs in storage ring and **2408** in the booster.
- Generally, a design with higher transfer impedance (means more useful signal) $\propto r_b^2$ has also higher coupling impedance $\propto r_b^4$. Both the transfer and coupling impedances grow strongly with increase of the button radius. A compromise has to be found to satisfy **the two contradicting requirements.**
- The CEPC beam impedance budget is strict: **smaller buttons**
- Long transmission path → Severe attenuation of useful signals (-6dB/100m @500MHz): **bigger buttons**

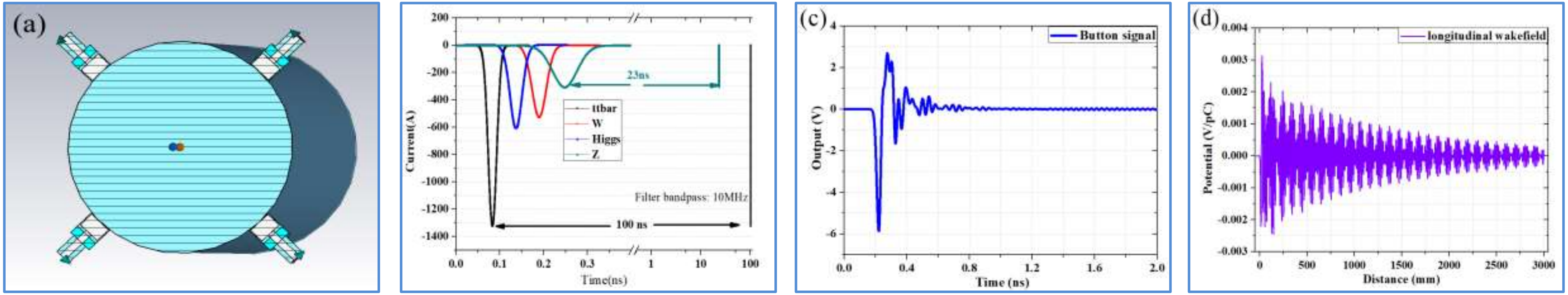


BPM system

- 1: The key components of BPM detector: Feedthrough with button
  - Design, mass manufacturing and testing
- 2: BPM Read-out electronics developed in house
  - Significantly reduce costs
  - Free development and addition of new functions

Beam position monitor design

- The basic design of the pick-up has been finalized based on CST calculation results



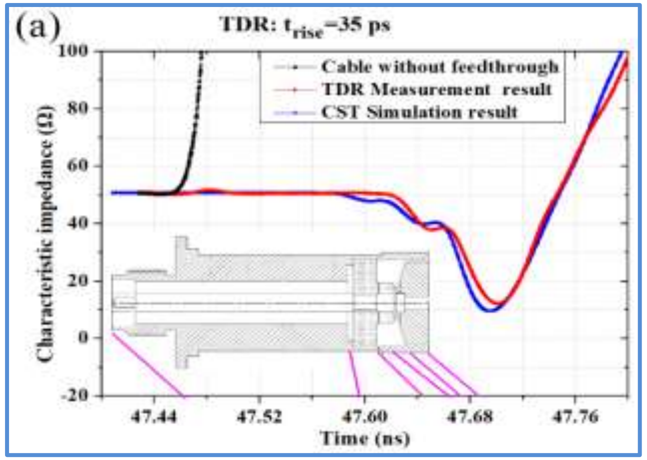
Parameters used for CST simulation and analytical calculations.

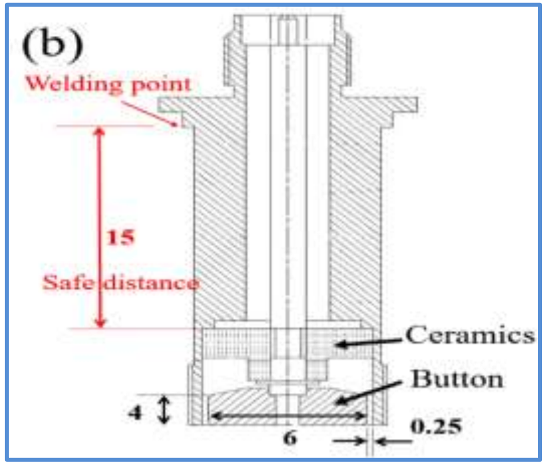
Parameters		
Bunch	Length	4.1 mm
	Charge	1 nC
Mechanical	r_b	3 mm
	t_b	4 mm
	g_b	0.25 mm
	b	28 mm

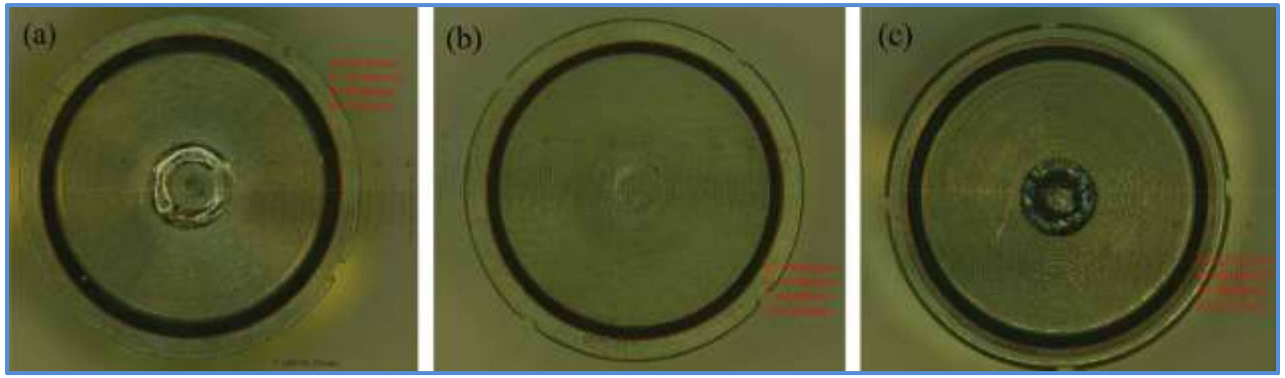
Signal strength before the cable attenuation

	Charge	Bunch length	Current peak	DC Current	650MHz
	nC	mm	A	A	dBm
Higgs	20.8	4.1	607	0.208	-24.4
Z	22.4	8.7	308	0.974	-10.9
W	21.6	4.9	527	0.216	-23.7
ttbar	32.0	2.9	1315	0.320	-20.2

BPM button Pick-up

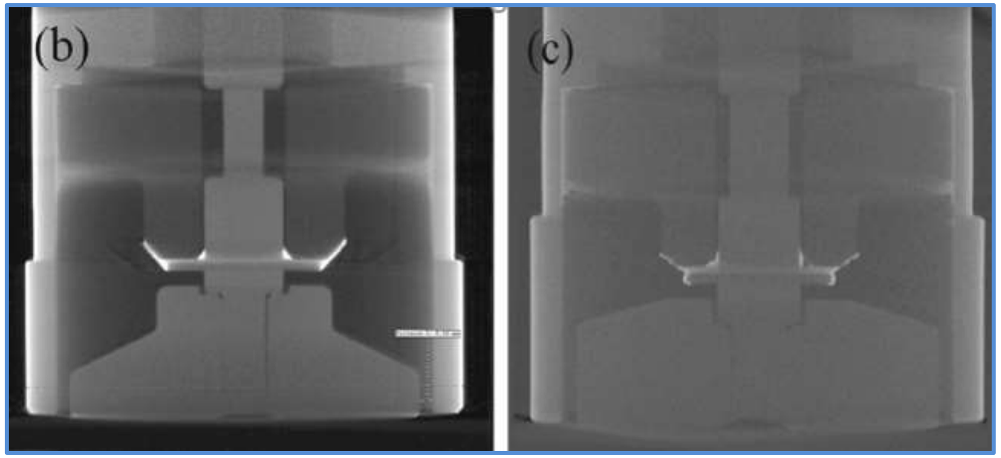




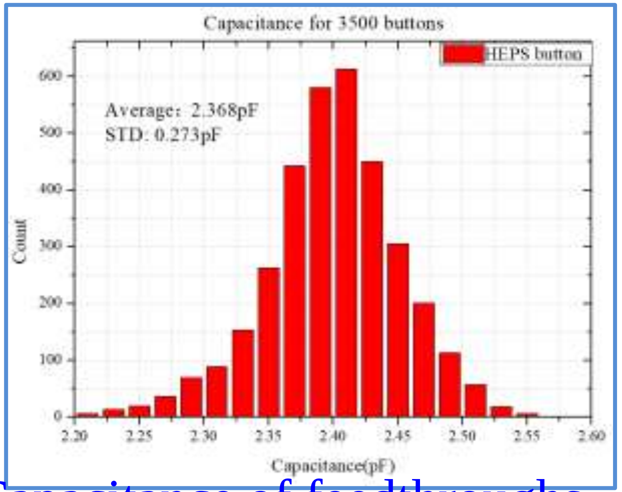


Optical microscopic imaging show the external structure

TDR results show the characteristic impedance



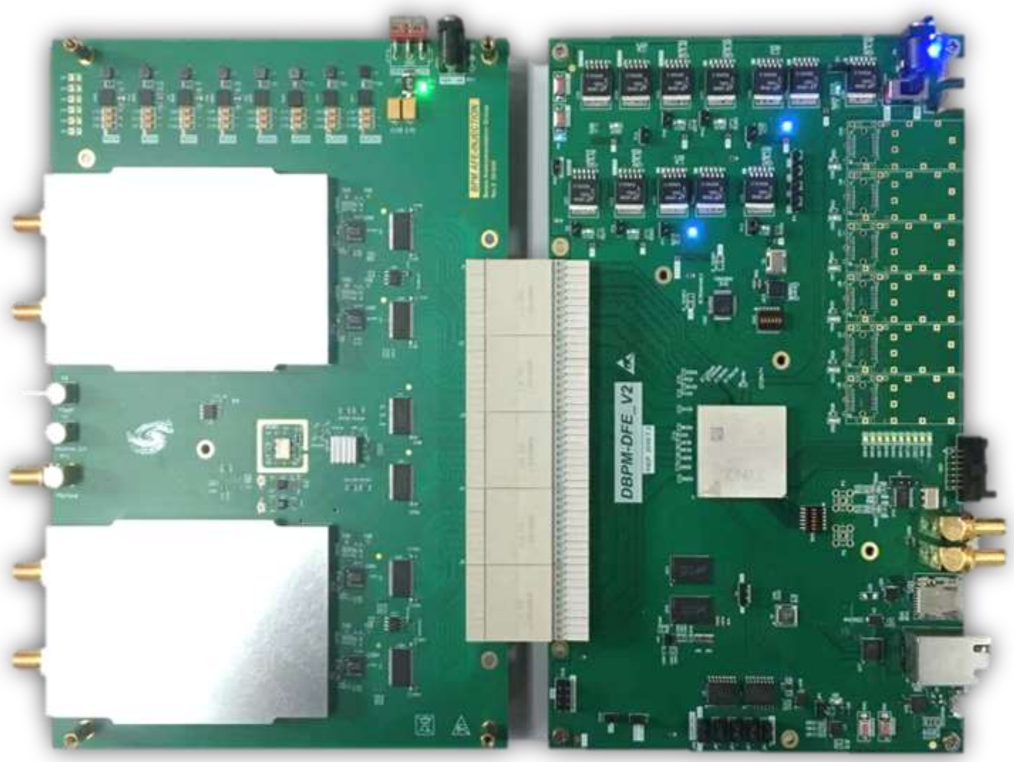
X-ray tomography results show the inner structure



Capacitance of feedthroughs

Batch consistency test

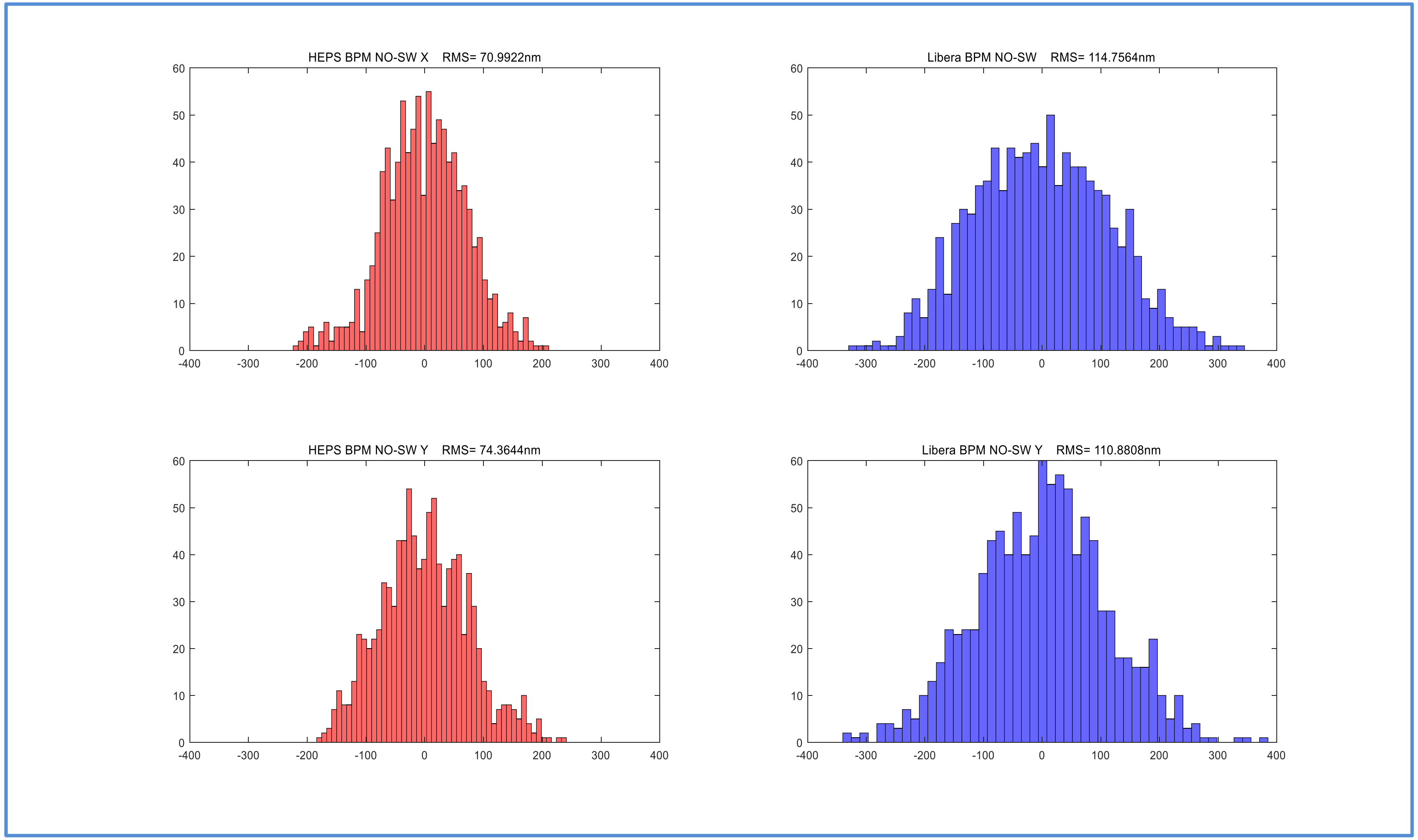
BPM readout electronics



AFE and DFE board

- AFE board： RF Processing+ ADCs + Clock + Pilot tone;
- DFE board： FPGA(ZYNQ) + DDR3 memory + SFPs + Ethernets;
- EPICS IOC： In ZYNQ FPGA, increasing the convenience of the system

BPM readout electronics



Commercial electronics

- SA x rms ≈ 114 nm
- SA y rms ≈ 110 nm

Electronics made in house

- SA x rms ≈ 71 nm
- SA y rms ≈ 74 nm

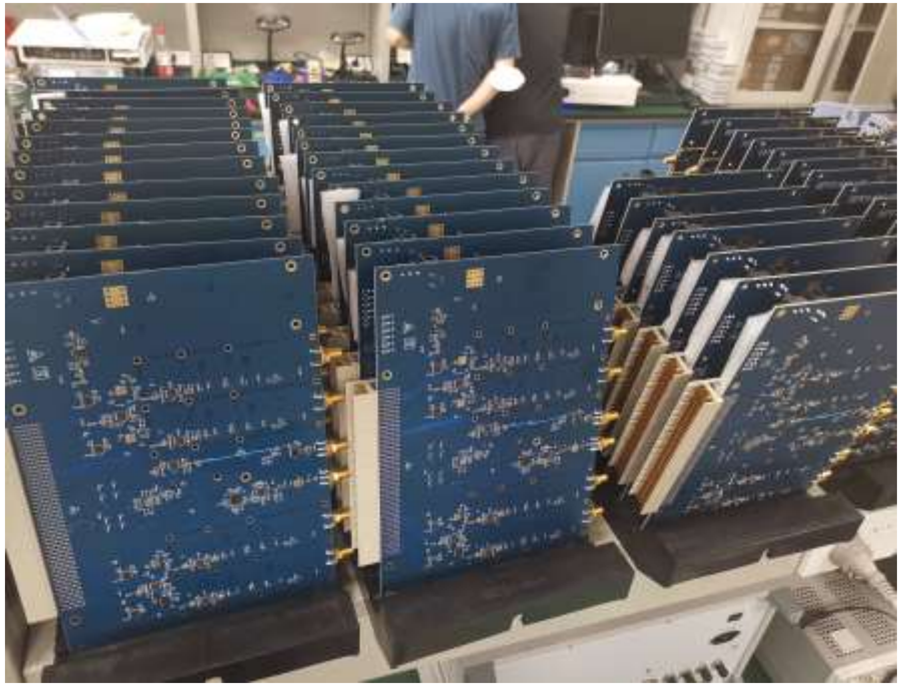
A sub-micron resolution and a performance close to commercial products (I-Tech Liberal)

BPM related R&D: readout electronics

110 sets of electronics have been utilized in BEPCII's linac and storage ring

100 sets have been installed in the linac and booster of the HEPS

600 sets will be installed in the HEPS storage ring.



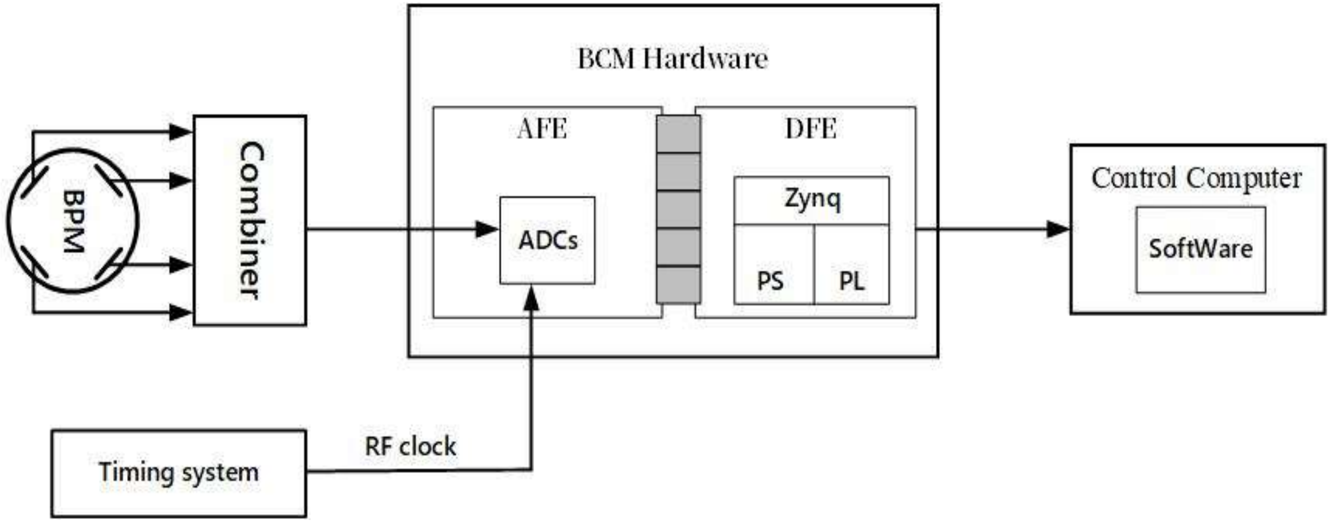
Beam current monitor

- Two types of beam current measurement systems are utilized: average beam current and bunch current measurement.
- The average current monitor employs Bergoz type DCCT (Direct-current current transformer) sensors, **two sets of systems are backup to each other**

	ttbar	**Higgs**	**W**	**Z**
Energy [GeV]	180	120	80	45.5
Beam current [mA]	3.3	16.7	84.1	803.5

Bergoz NPCT senor and front-end electronics

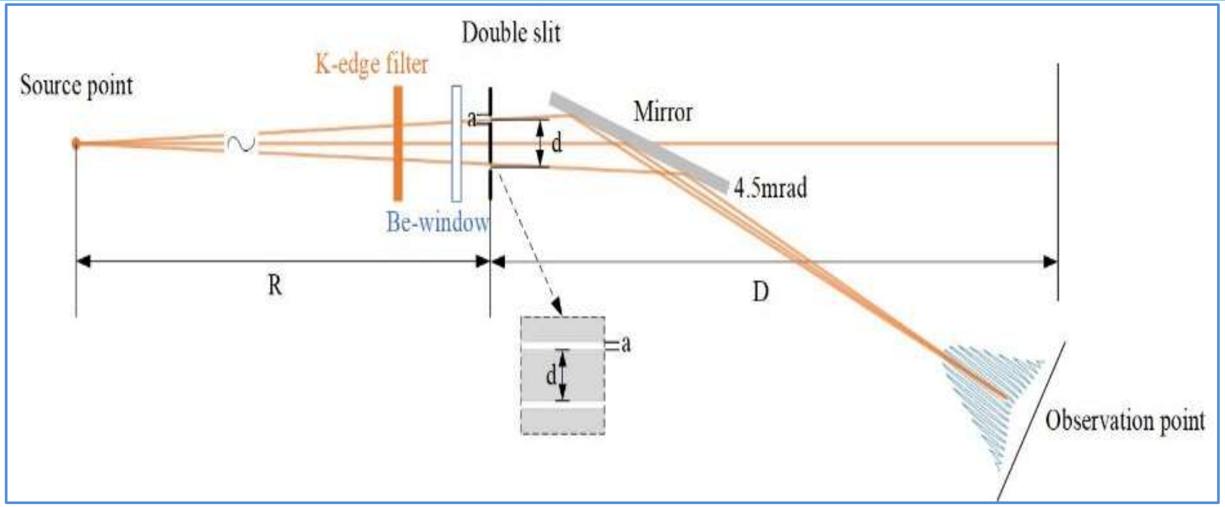
Bunch current monitor



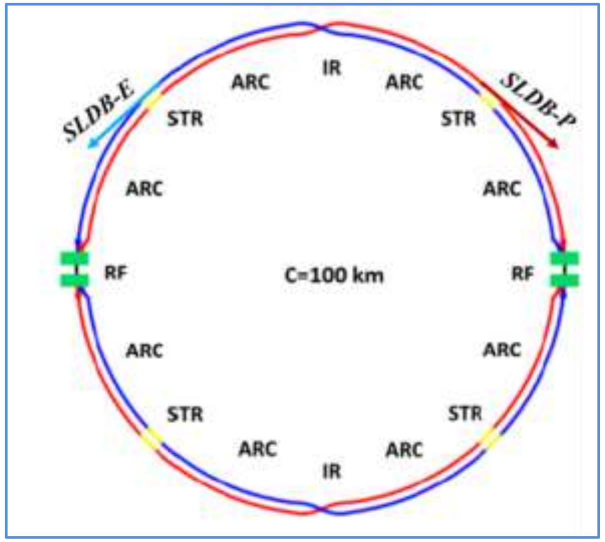
Bunch by bunch readout electronics (BPM sum signal) are used for measuring the bunch current.

- A fast ADC sampling BPM sum signal is utilized to measure the bunch current and share the data with the injection control system for bucket selection.
- The core part of the AFE is its high-speed ADC. **The signal is sampled at a frequency of 650MHz and normalized by the current measure by DCCT.**

Beam size measurement

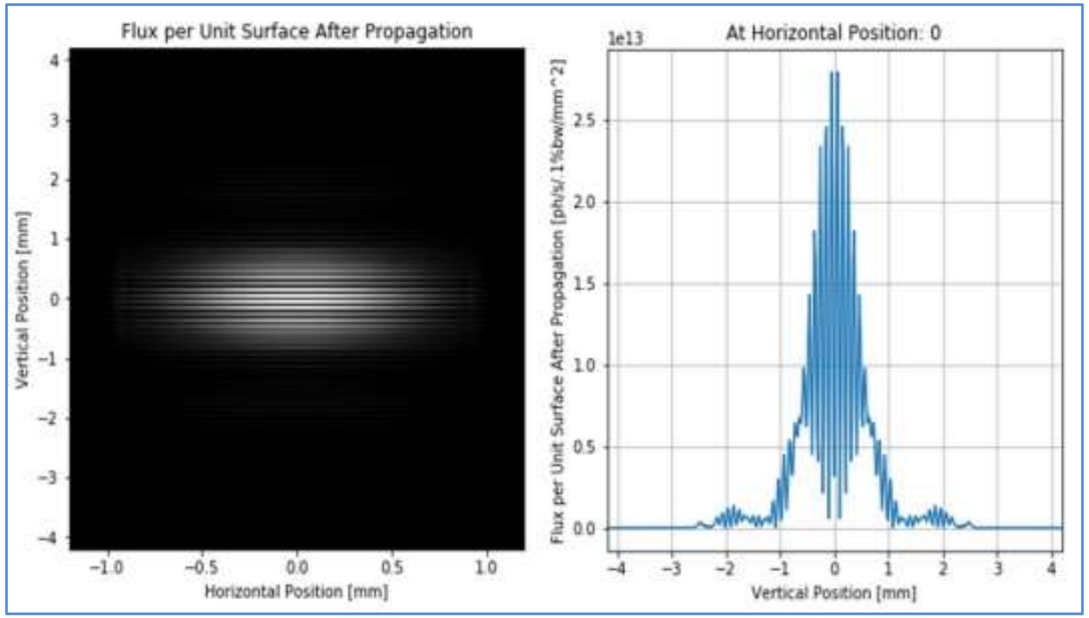


Configuration for **double slit X-ray interferometer**



The synchrotron light diagnostic beamlines

X ray energy： 12keV
Light spot size： x@ 40μm y@ 5μm
Slits： Distance@d=200 μm Width@ a=8μm
Distance from source to slit: R=100 m
Distance between observation point to slit 75 m



Typical interferogram and the intensity distribution curve in vertical direction.

Bunch length measurement

	ttbar	Higgs	W	Z
Energy [GeV]	180	120	80	45.5
Bunch length (SR/total) [mm]	2.2/2.9	2.3/3.9	2.5/4.9	2.5/8.7

- Bunch by bunch measurement system to monitor the bunch length and its lengthening. Visible SR beam line should be necessary.
- Resolution about 1ps (~10% of bunch length), **streak camera based on visible light will be used.**
- Heat deposit onto the SR extraction mirror is not so larger than existing SR machine, so we can use mirror design in SR facilities.(from T. Mitsuhashi)

Feedback system

Transverse resistive wall instability – N. Wang

Z mode: E = 45.5 GeV, I = 803.5mA

$$\tau^{-1} = \frac{I_0 c_0}{4\pi(E_k/e)\nu_\beta} \sum_{\mu=0}^{M-1} \sum_{p=-\infty}^{\infty} Z_1\left((\mu + PM)\omega_0 + \omega_\beta\right)$$

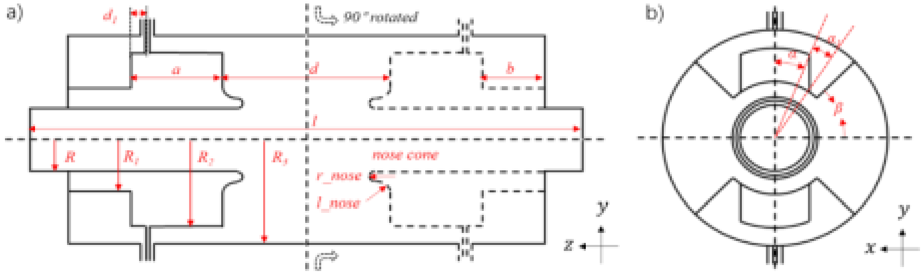
	30 MW
Instability growth time [ms]	1.9 (~6 turns)
Radiation damping [ms]	850
Bunch by bunch feedback [ms]	1.0 (~3 turns)

Growth of the most challenging mode vs damping factors

- Z mode is the most challenging

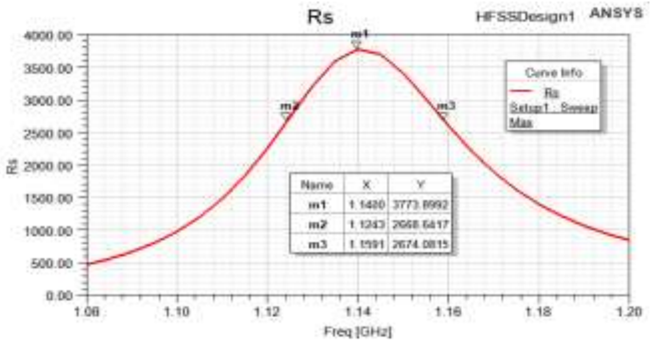
Parameter	Higgs	Z
Energy（GeV）	120	45.5
Beta functions at pickup (m)	250	250
Beta function at kicker（m）	250	250
Number of kickers	4	4
Kicker shunt impedance（kΩ）	140	140
Amplitude of oscillation（mm）	0.2	0.2
Damping time（ms）	-	1.0
Power(w)	-	2880

Longitudinal feedback system



The schematic of the longitudinal feedback kicker

Parameter	Value	Parameter	Value
Beampipe radius R	28 mm	Back cavity length	27.44 mm
Back cavity radius	56 mm	Cavity length	303 mm
Ridge radius	82 mm	Port angle	15.3 deg
Pillbox cavity radius	90 mm	Port base angle	6.7 deg
Cavity gap	91 mm	Barrier angle	61 deg
Distance of feedthrough	5 mm	Nose cone radius	6 mm
Ridge length	53.56 mm	Nose cone length	7 mm



The shunt impedance of the LFB kicker

The power of longitudinal feedback

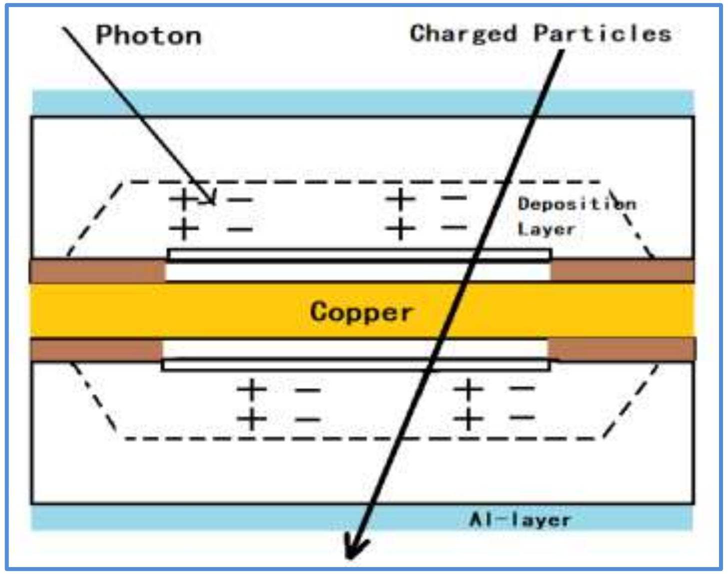
$$P = \frac{1}{2} \cdot \frac{\Delta V_{FB}^2}{R_K}$$

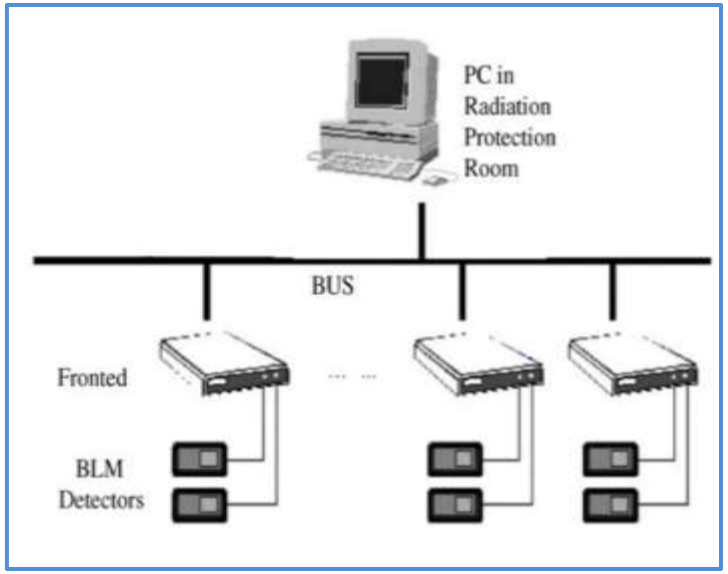
Parameter	Higgs	Z
Energy（GeV）	120	45.5
Momentum compaction （10^{-5}）	0.71	1.43
Longitudinal tune（m）	0.049	0.035
Phase acceptance（mrad)	1.7	1.7
RF frequency（MHz）	650	650
Kicker shunt impedance （kΩ）	2.6	2.6
Number of kicker	4	4
Damping time（ms）	-	65
Power(w)	-	4120

（More details in the Junhui Yue's report）

Beam loss monitor

- The following important factors are focused for selecting the type of BLM for a specific application in CEPC: intrinsic sensitivity, dynamic range, radiation hardness, response time and sensitivity to synchrotron radiation (SR).
- The improved PIN-photodiode in storage ring and the optical Fiber in booster for large range of beam energy

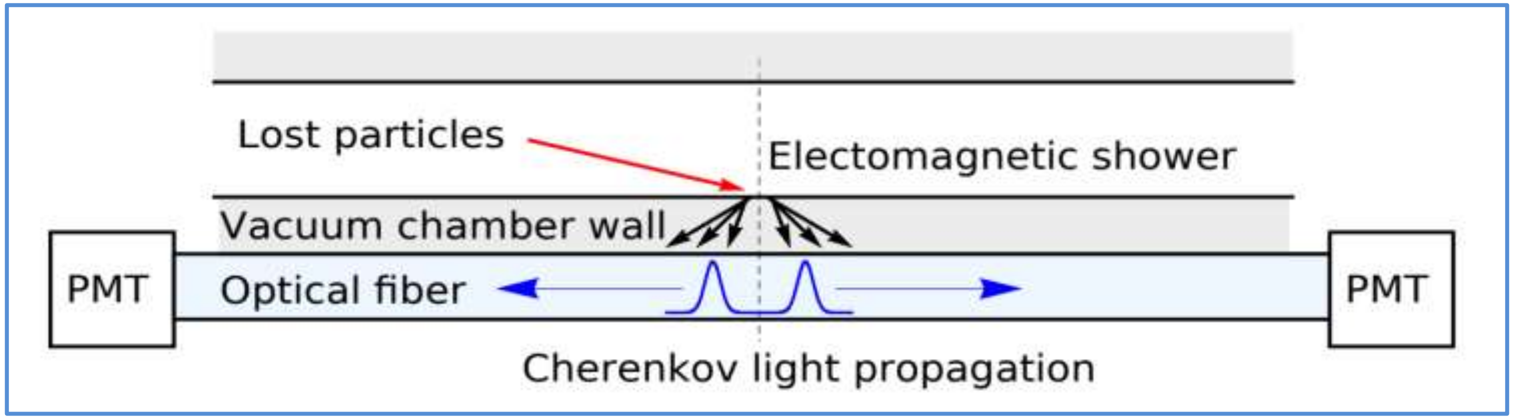




Schematic of PIN photodiode BLM

Fiber-based beam loss monitors (FBLM)

- A BLM based on the Cherenkov radiation (CR) in optical fiber is distributed and can cover an accelerator structure over long distances.
- The CR propagates upstream and downstream along the optical fiber and can be detected with a PMT ends. Timing of the PMT signal gives the location of the beam loss, the signal intensity being proportional to the number of lost particles.

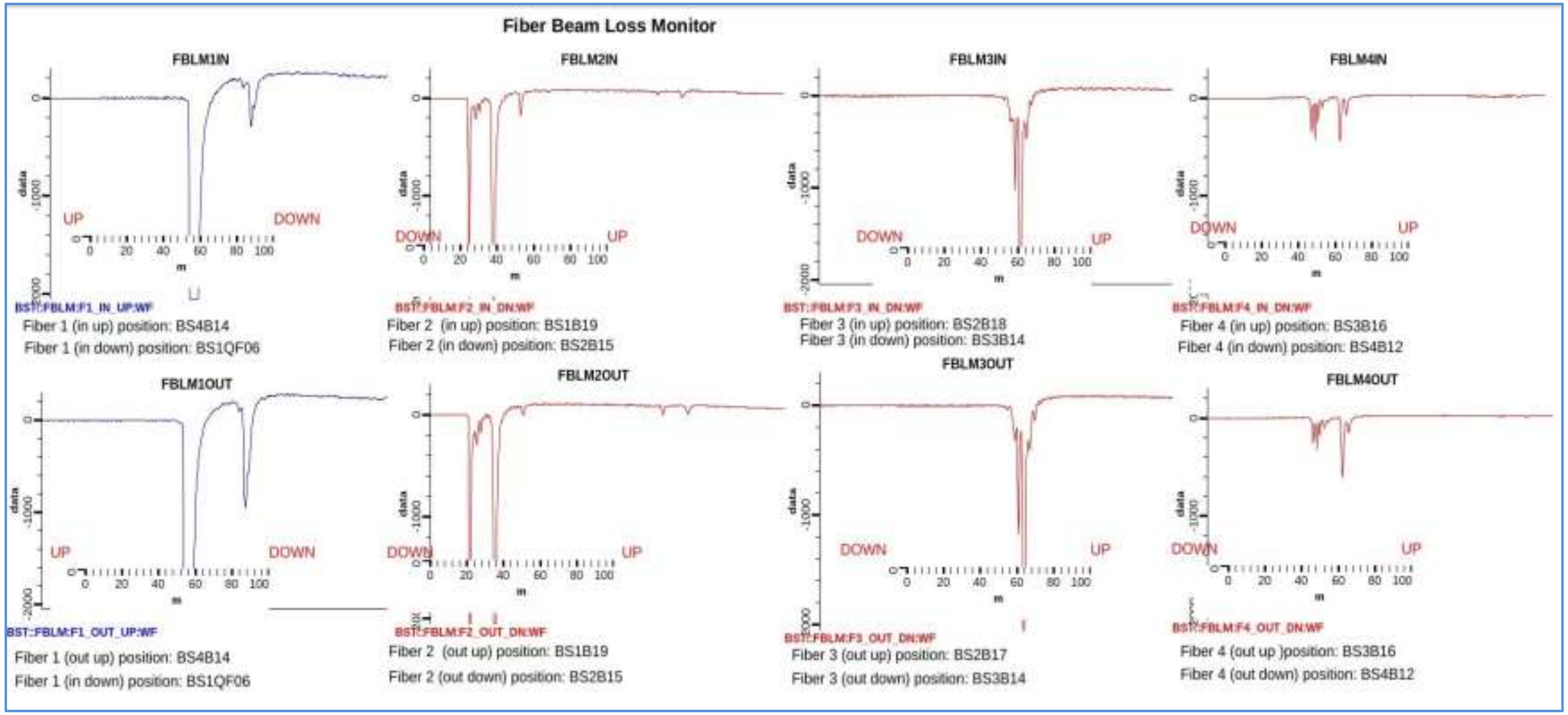


Schematic of FBLM

Fiber-based results

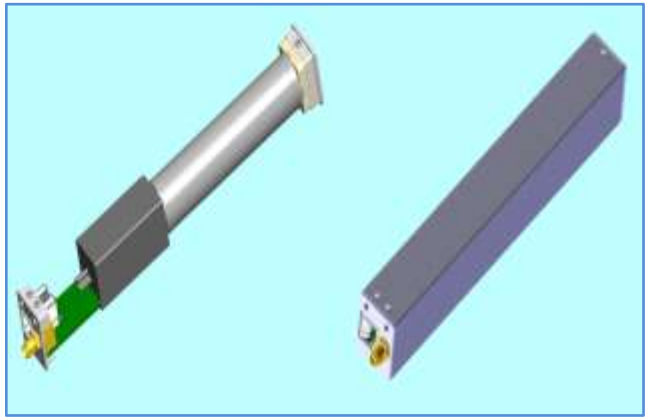
Fiber： OFS Company HCP-M0600T, **8×110 m,** Circumference 454m, in&out the pipe

Show the location of the beam loss, **peaks located BetaX$_{max}$ or Dx$_{max}$.**

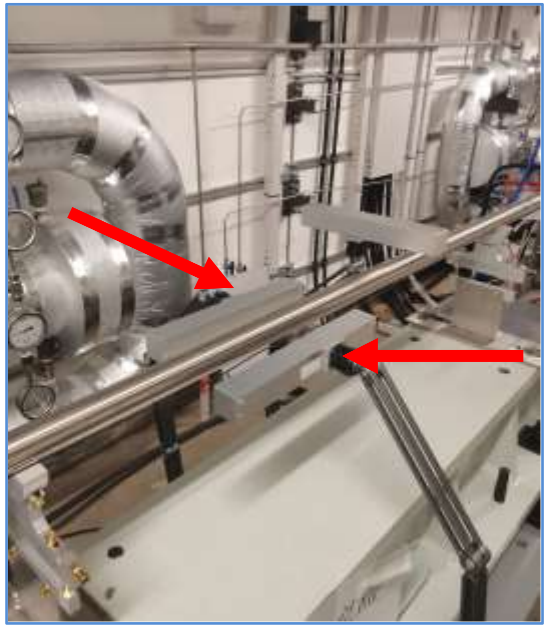


Scintillator-based beam loss monitors (SBLM)

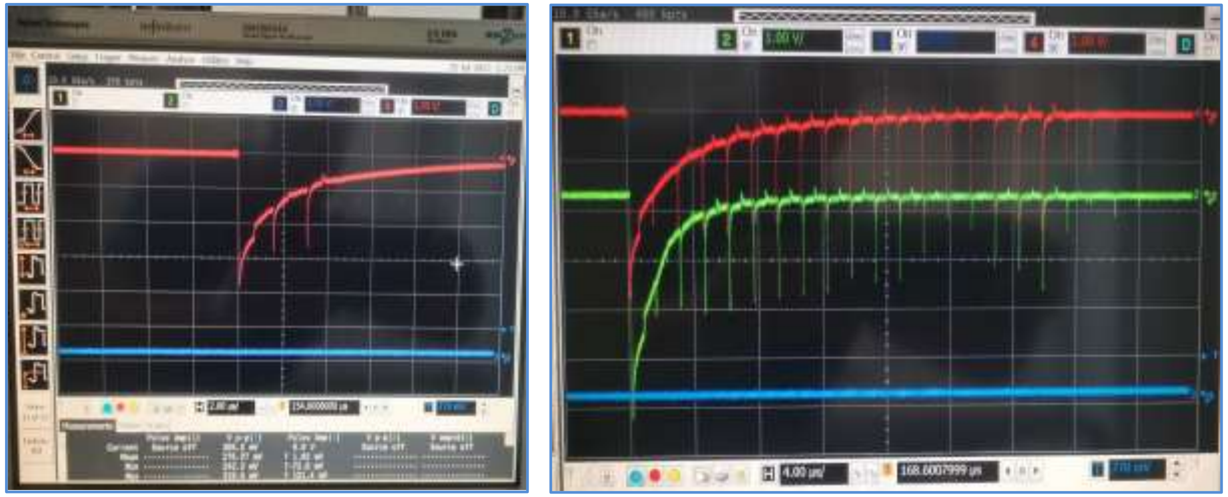
- SBLMs, with a **plastic scintillator and a photomultiplier** (PMT) as their main components. The scintillator chosen is a EJ-200 rod (100 mm length, 22 mm diameter), wrapped in reflective foil to minimize the light losses, which to **provide the turn-by-turn loss.**



Model of the PMT-scintillator system without and with the metallic casing



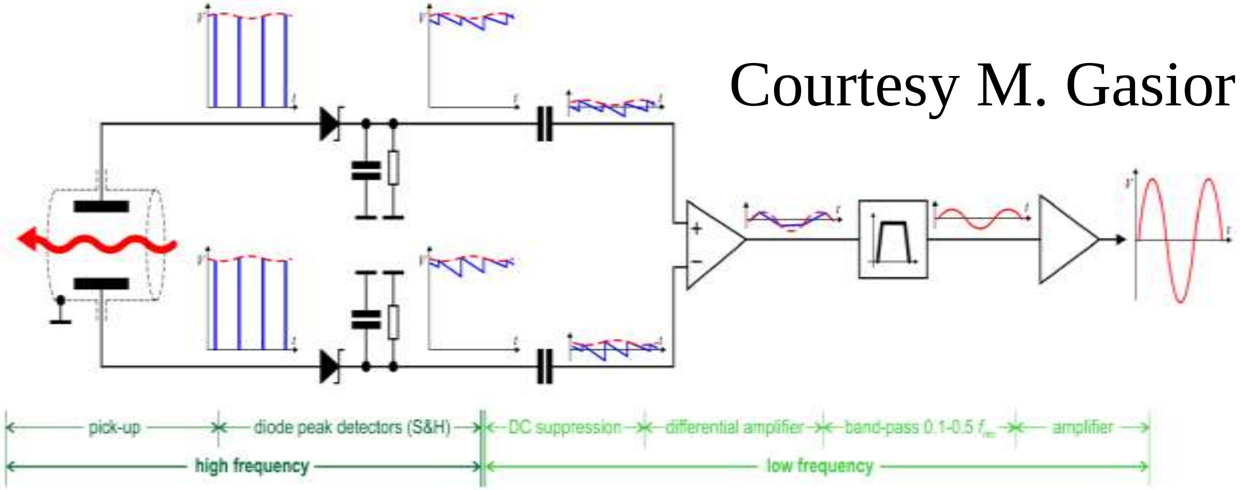
SBLMs installed in the HEPS booster



First turn commissioning results：
3 and 20 turns

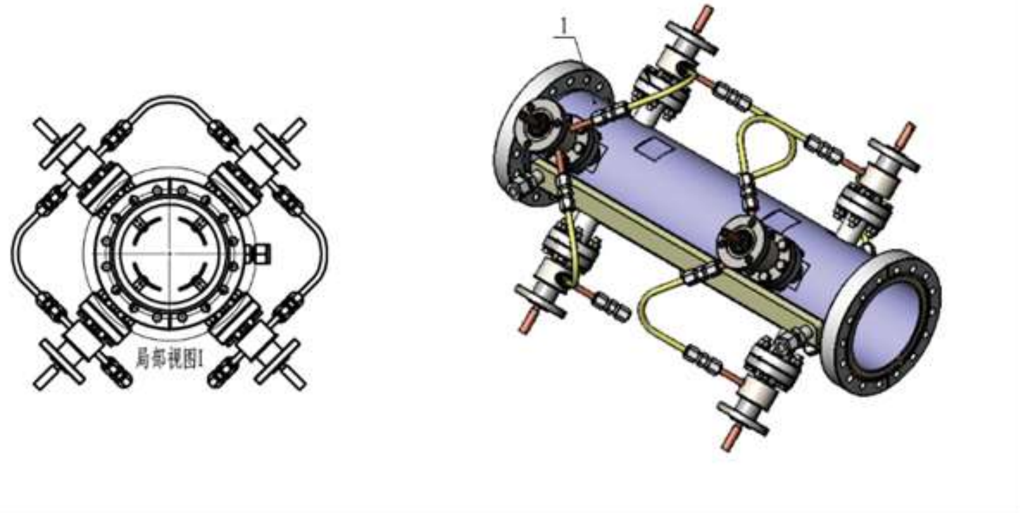
Tune monitor

Frequency sweeping method with gated pulse or FFT analyzing to the data from the digital BPM. **Direct Diode Detection (3D)** is another choice for the tune monitor



Courtesy M. Gasior

Direct Diode Detection method invented by Marek Gasior will be taken. Sub-micrometer oscillation can be detected.



4 Strip-line kicker

Pilot bunch exciting method will be used to measure the tune. Changing the phase in BbB feedback filter or kicking the appointed bunch to get the tune.

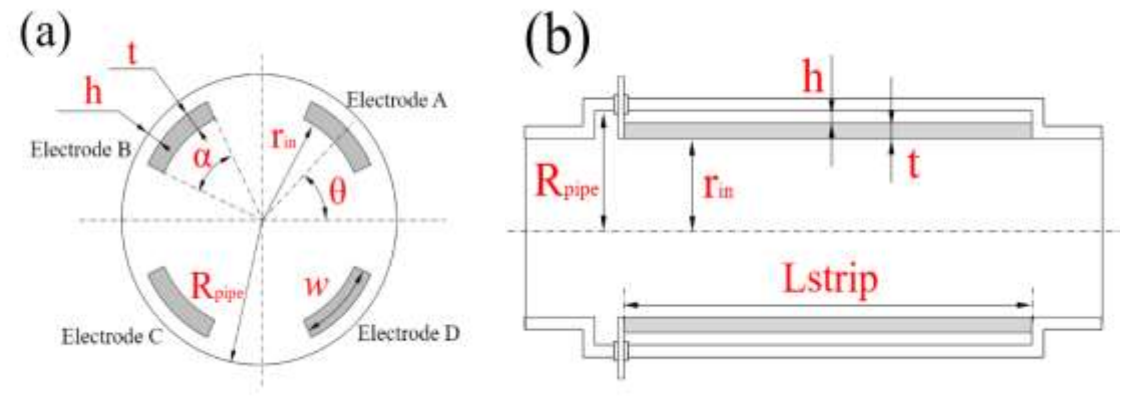
The beam instrumentation in CEPC Linac

	Item	Method	Parameter	Amounts
Linac	Beam position	Stripline BPM	Resolution： 30um	150
	Beam current	ICT	2.5%@1nC-10nC	63
	Beam profile	YAG/OTR	Resolution: 30um	30
	Beam emittance	Q+PR	10%	3
	Beam energy & spread	AM+PR	0.1%	3
Damping ring	Average current	DCCT	Resolution :50μA@0.1mA-30mA	1
	Beam position	Button BPM	Resolution : 20μm @ 5mA TBT	40
	Tune measurement	Frequency sweeping	Resolution:0.001	1

Linac BPM: Strip-line type

- There are 150 stripline BPMs in the Linac and transport lines, which are divided into two groups based on the size of the beam-stay-clear area, a diameter of 30 mm and 20 mm.
- To minimize signal reflection, the impedance of the strip electrode was also designed to be 50 Ω. Electromagnetic simulation software CST is utilized to compute the impedance of the stripline.

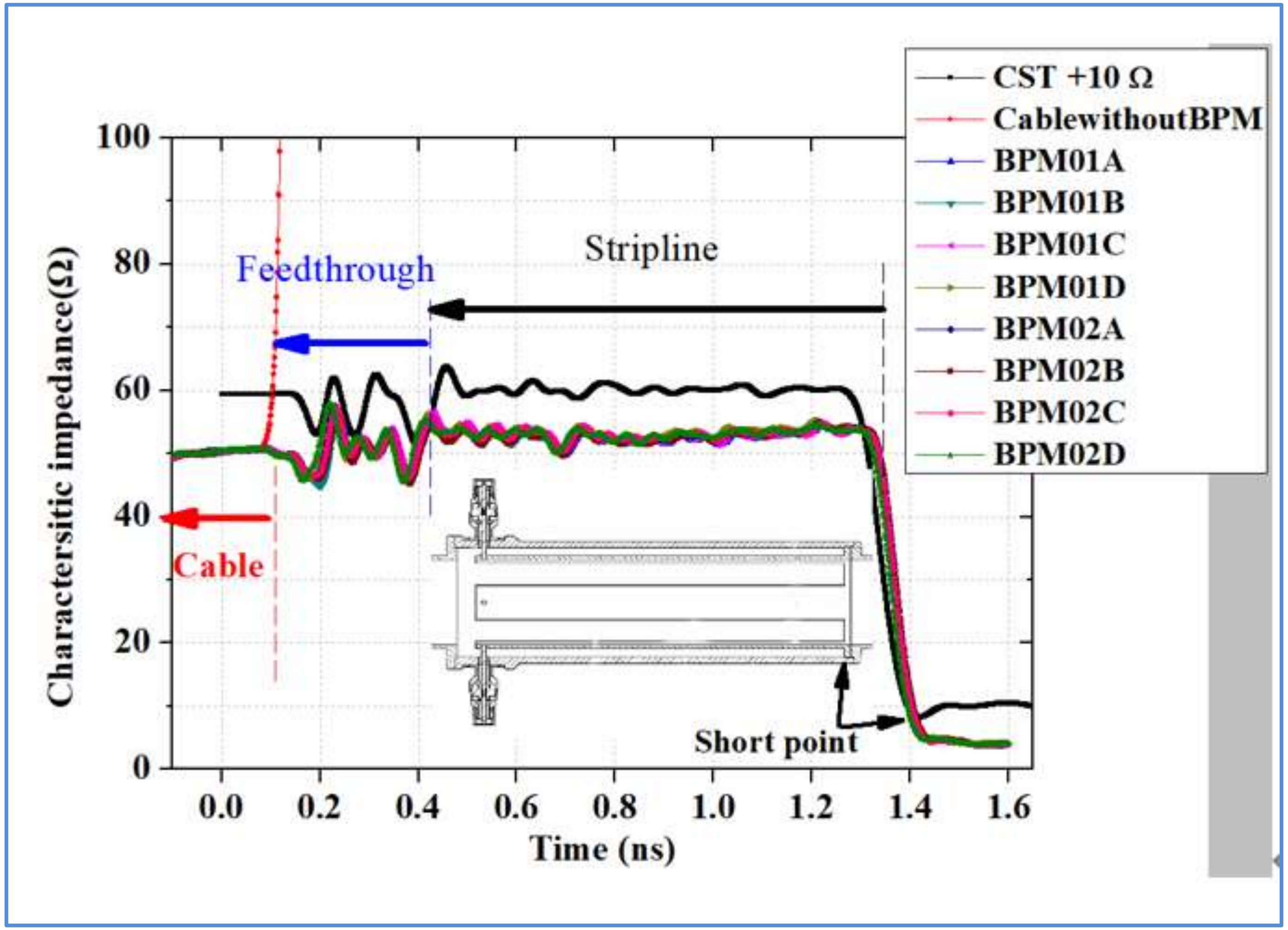
Mechanical parameters of CEPC stripline BPM

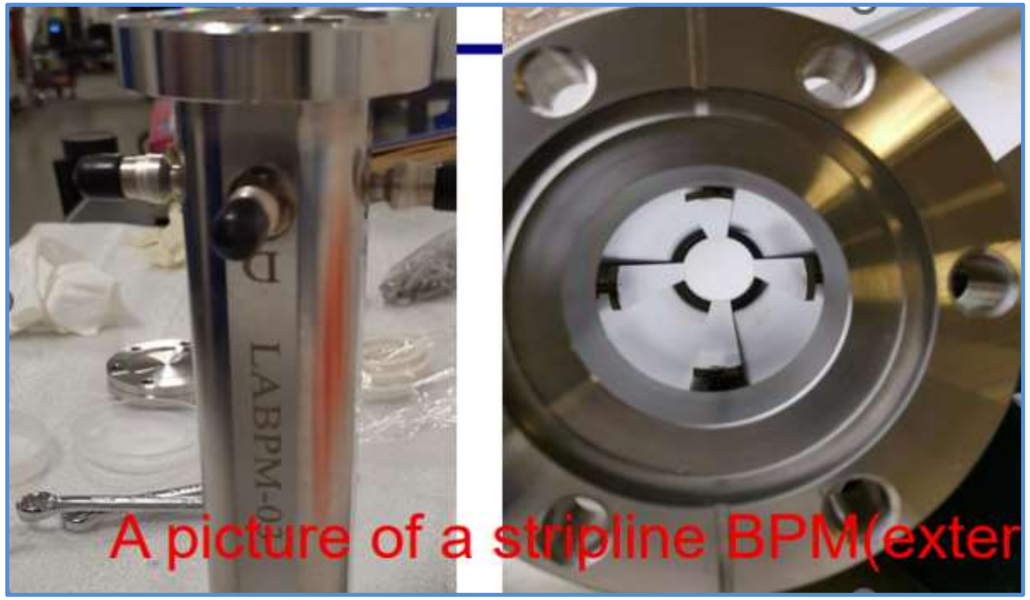


Location	r_{in}	t	h	α	θ*	Z_{single}	L_{strip}	Z_{CST}
	mm	mm	mm	degree	degree	Ω	mm	Ω
ESBS/EBTL/FA S/PSPAS/SAS	15	1.5	2.2	30	0	50.8	150	50.3±0.5
TAS	10	1.5	0.6	30	0	49.9	150	50.4±0.5

Schematic of strip BPM: (a) Front view (b) Side view

Strip-line type BPM





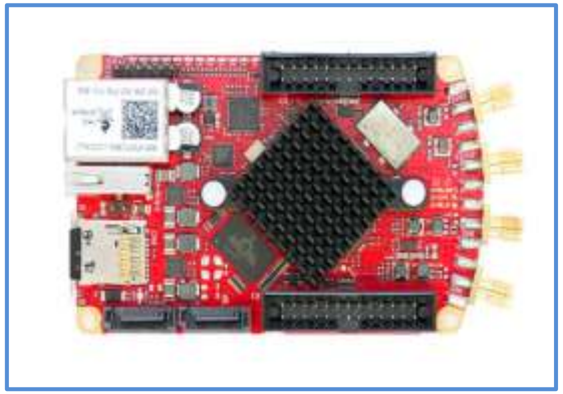
- The average impedances of the strip given by the experiment and CST simulation are **51.5 and 50.3 Ω.**

Characteristic impedance of stripline BPM measured by TDR.

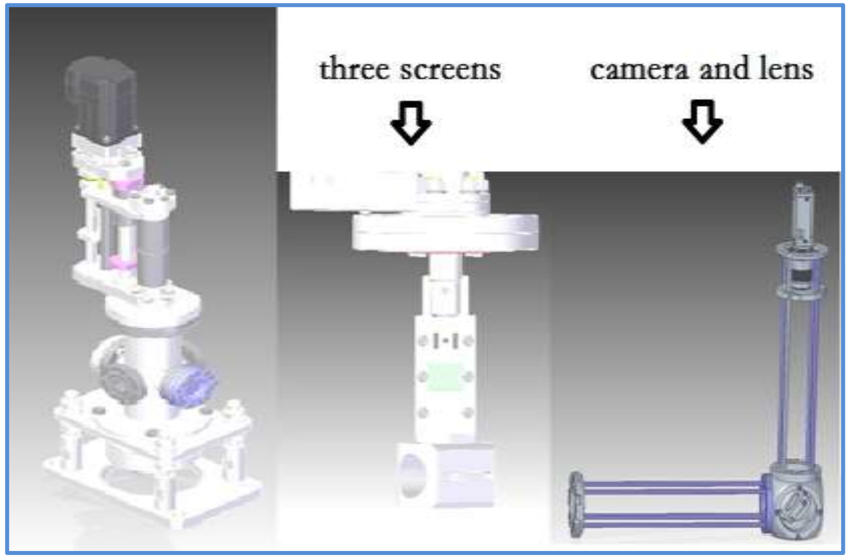
Beam current measurement

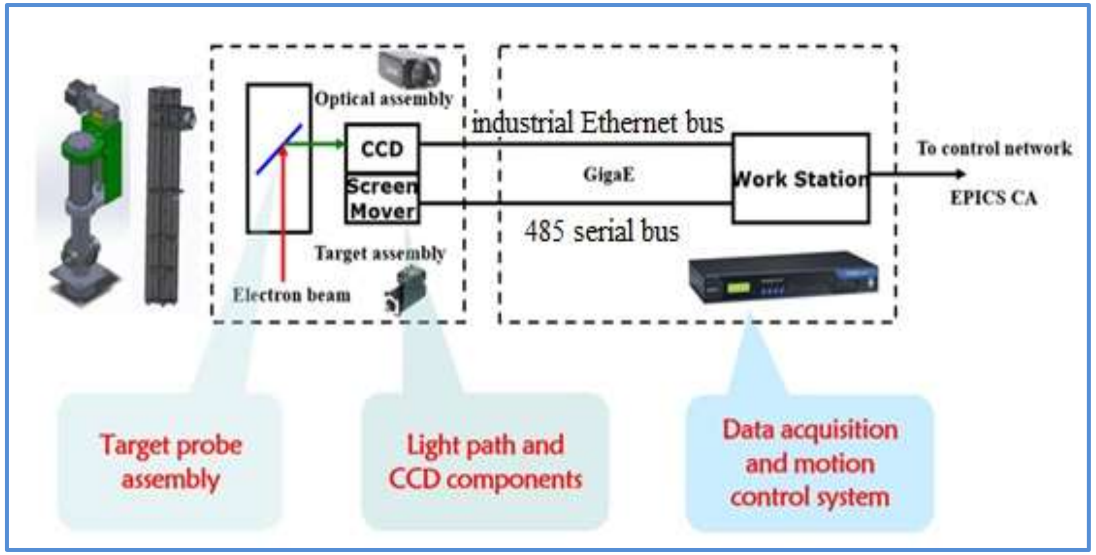
- The sensitivity of the ICT sensor must take into account the attenuation caused by the transmission cable to ensure accurate measurement results. For this reason, an on-line functional examination and re-calibration can be carried out using the Cali-winding within the sensor.

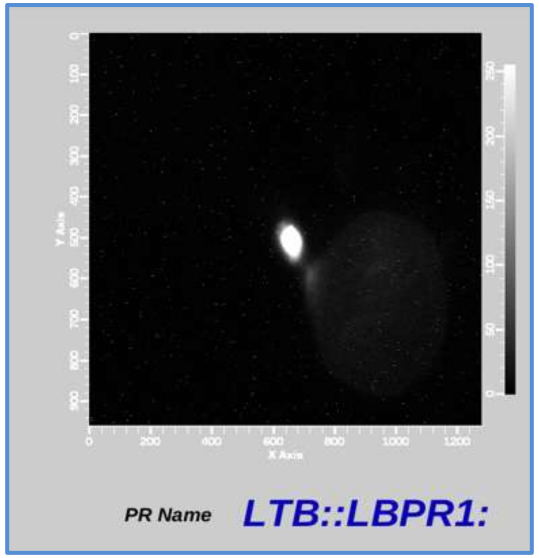
ICT (Tunnel) → BCM electronics A/D (Local station) → Data base



Beam Profile Measurement

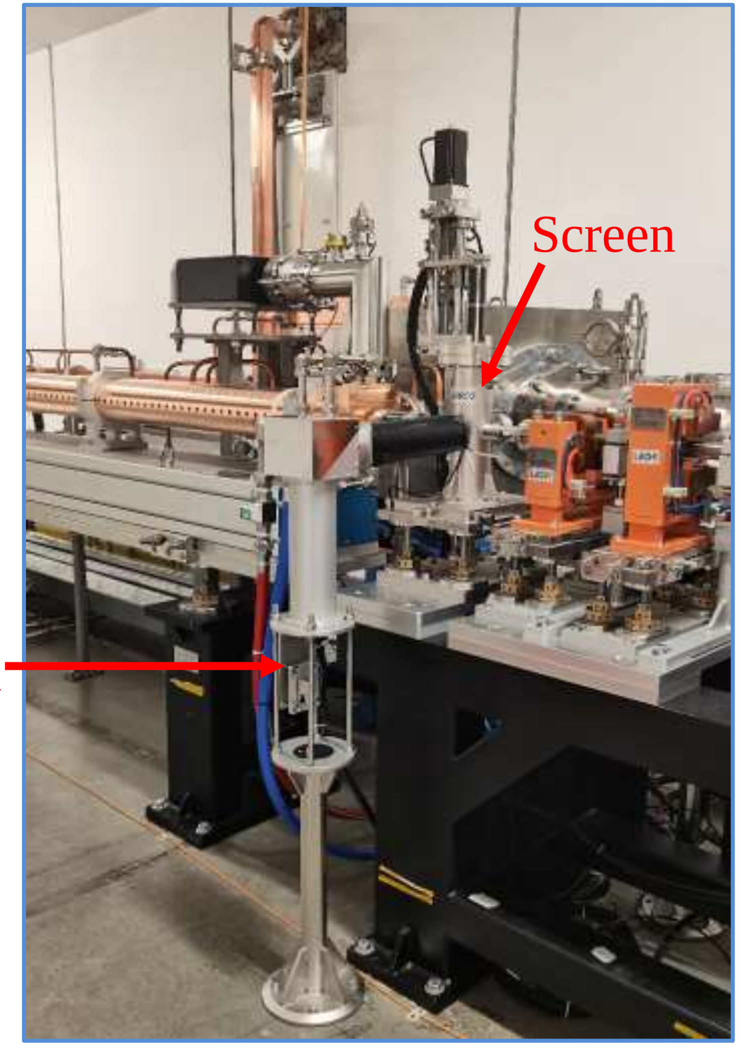






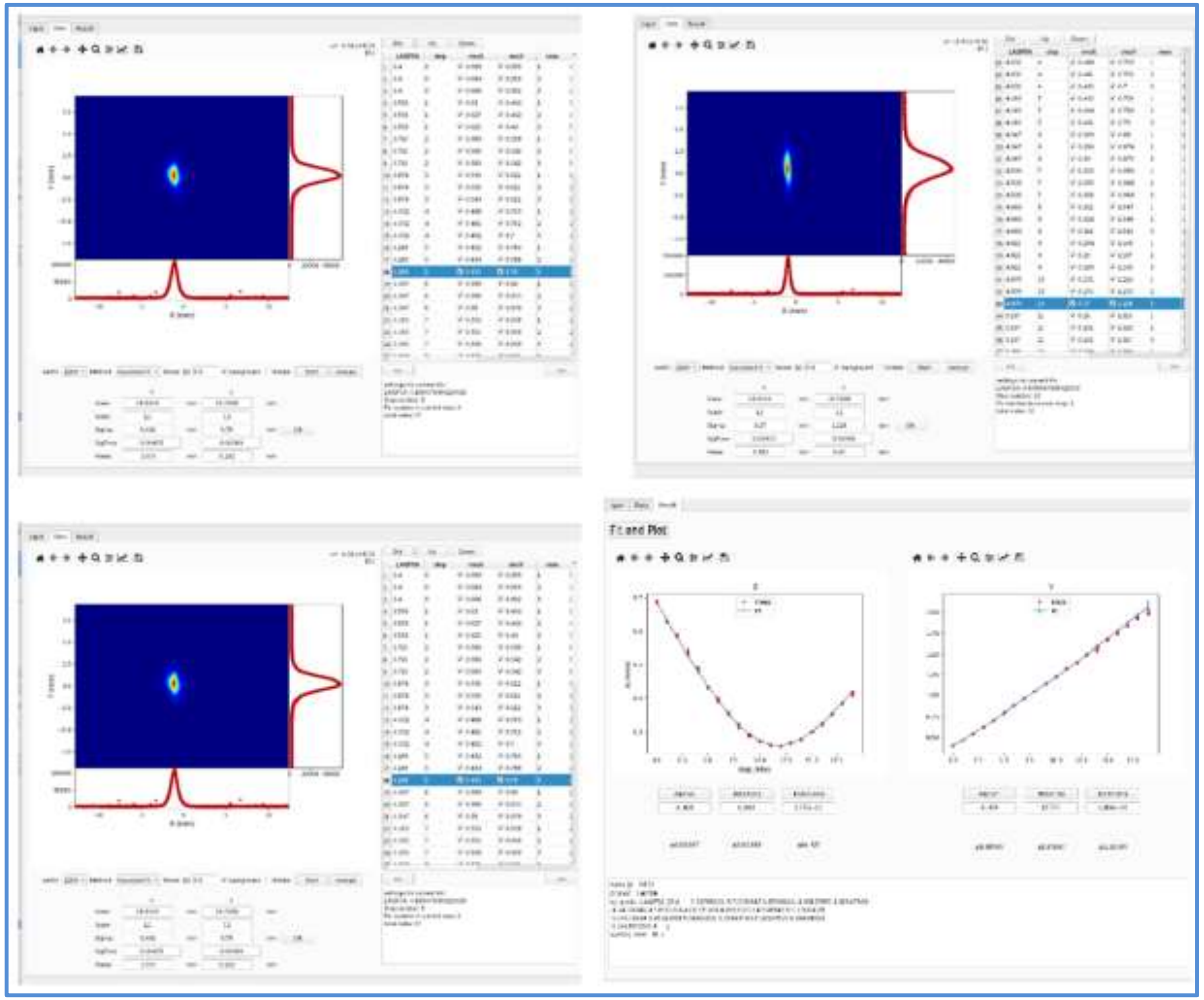
- The beam profile monitor is designed with **three screens. 1.** a YAG:Ce crystal screen for low current commissioning, **2. 100** nm aluminum (OTR) for high energy **3.** a calibration screen.
- The control system software for the beam profile is based on EPICS.
- Beam emittance and beam energy & spread measurement are both based beam profile measurement.

Beam Profile



A photo of beam profile monitor

Emittance measurement results

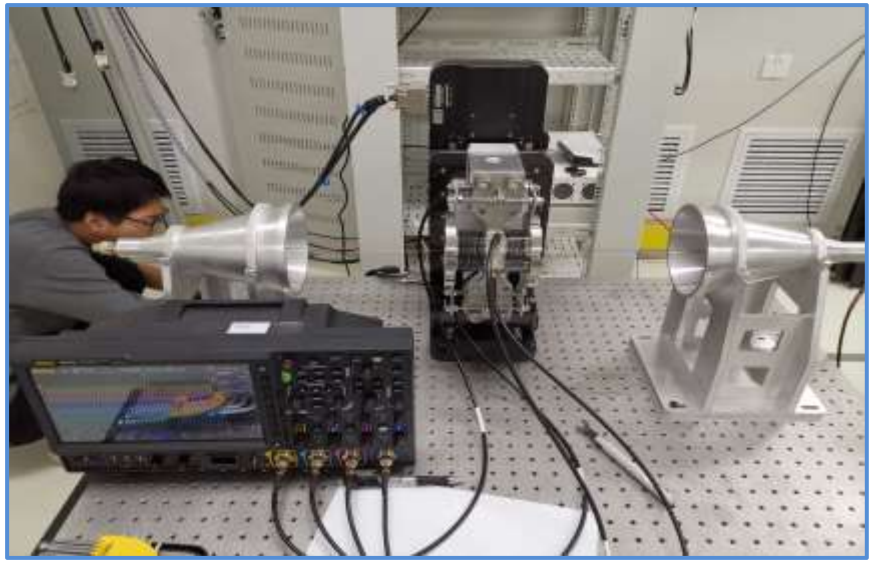


Beam instrumentation related R&D

- The R&D activities based on lepton accelerator beam measurement mainly include the following three aspects.
  - The design and fabrication of HEPS beam instrumentation
  - The maintenance and upgrade of BEPCII beam instrumentation
  - The R&D of CEPC beam instrumentation

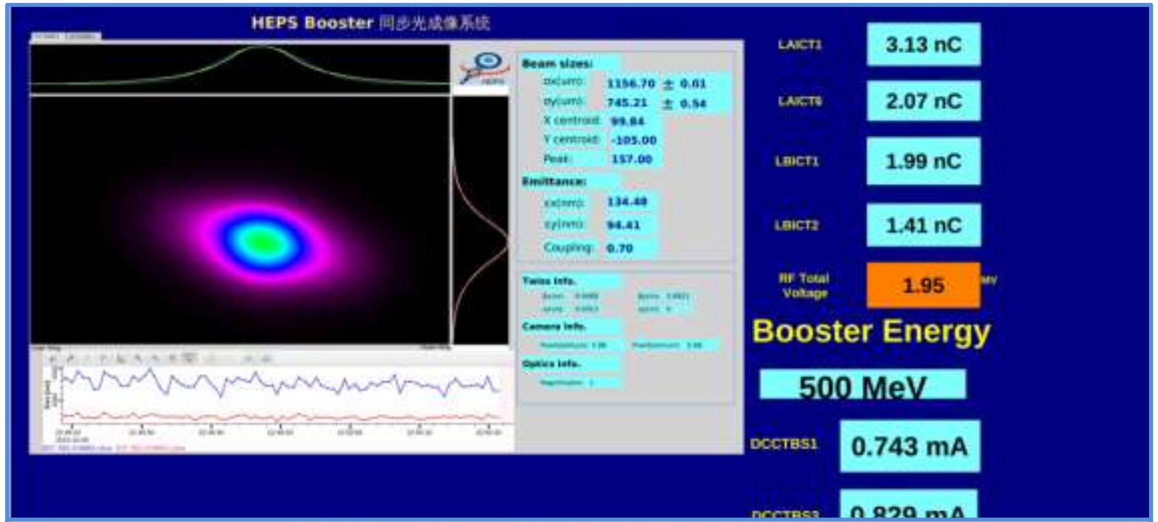
Beam instrumentation related R&D

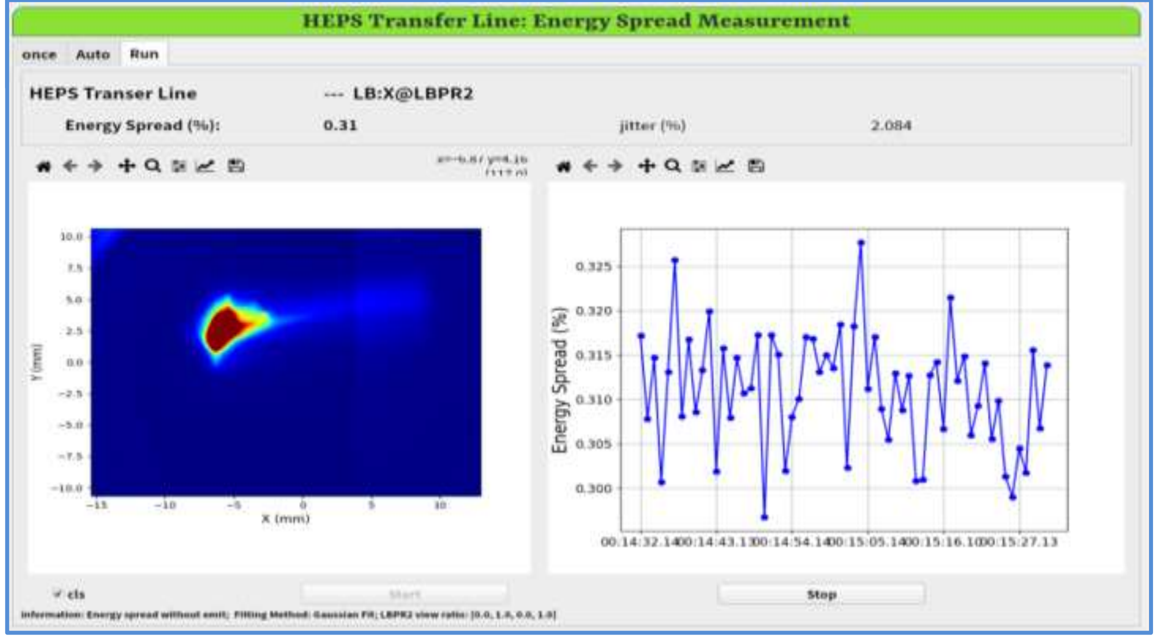


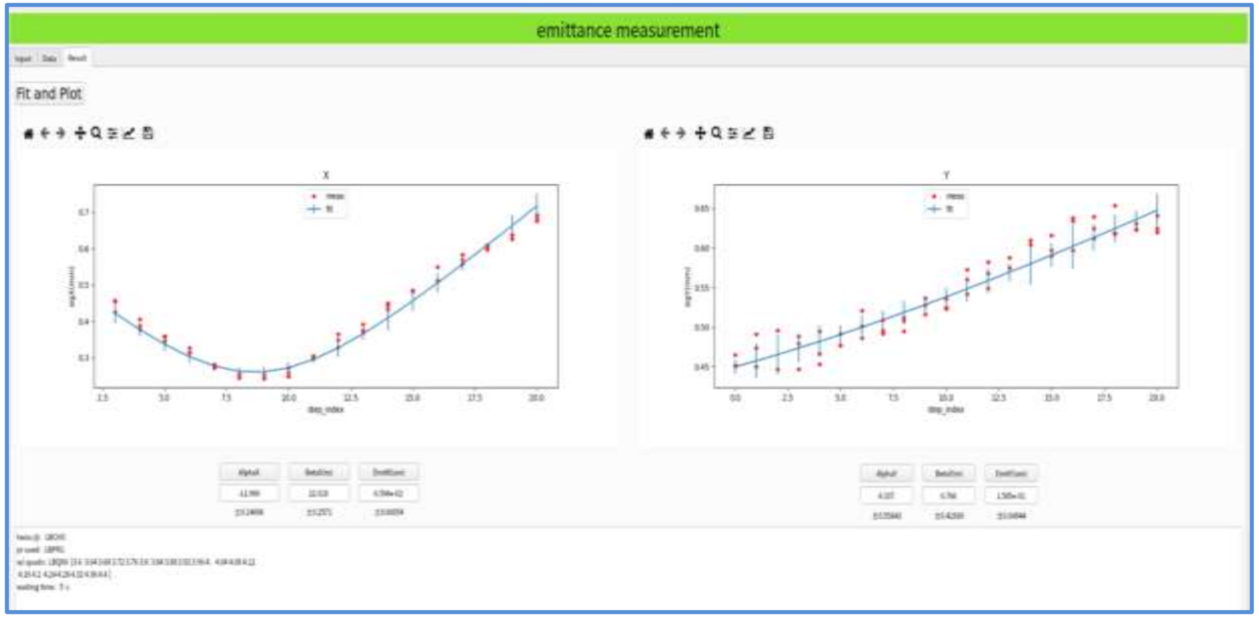


- We have developed button type and strip-line BPM for the HEPS
- Goubau line based wire calibration system were set to check BPM's sensitivity constants
- The home-made electronics were used in the HEPS and were proved to be good enough for beam commissioning

Emittance & energy spread measurement







Emittance measurement system are implemented by changing the focusing strength of the quadrupole.

Enery spread are inferred by the profile of where the dispersion’s contribution is relatively significant.

Beam instrumentation related R&D

- At BEPCII, the double feedback technique was successfully implemented, the results showed that the damping rate is almost equal to the sum of the two feedback systems. **This demonstrates the effectiveness of multi-feedback systems in improving the stability.**

NUCLEAR TECHNIQUES

March 2019

BEPCII 逐束团双反馈系统运行试验研究

Research of the double feedback system operating in BEPCII

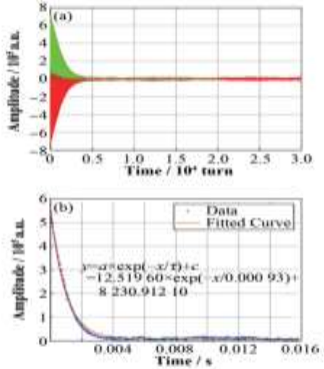


图7 商用反馈系统阻尼时间

(a) 振荡衰减逐圈信息，(b) 数据拟合曲线

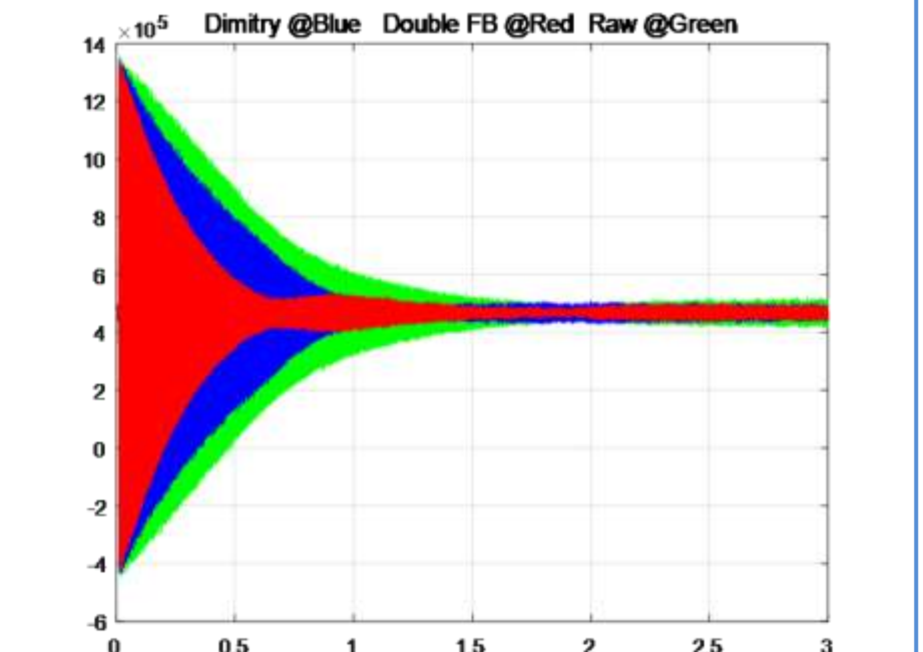
Fig.7 The damping time measurement of commercial feedback system

(a) Turn-by-turn information of beam oscillation, (b) Fitting curve of data

根据以上数据计算：

$$\boxed{\frac{1}{\tau_1}+\frac{1}{\tau_2}=1.26\ \mathrm{ms}^{-1}\approx\frac{1}{\tau_3}=1.33\ \mathrm{ms}^{-1}}$$

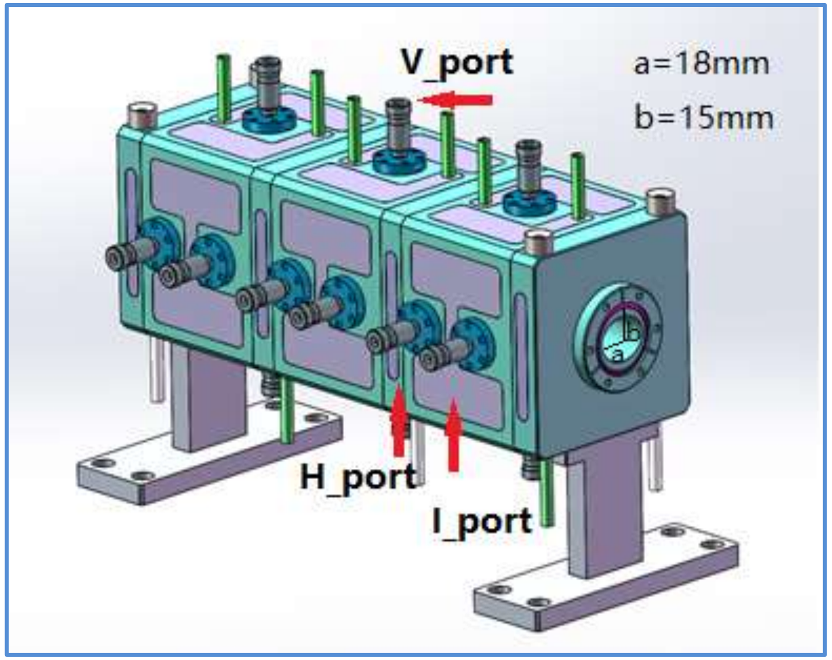
最后算得双反馈系统阻尼率 1.33 ms⁻¹基本是两套反馈系统（仅水平方向）同时运行的阻尼率的叠加 1.26 ms⁻¹。图9是根据本次实验获取的各系统作用



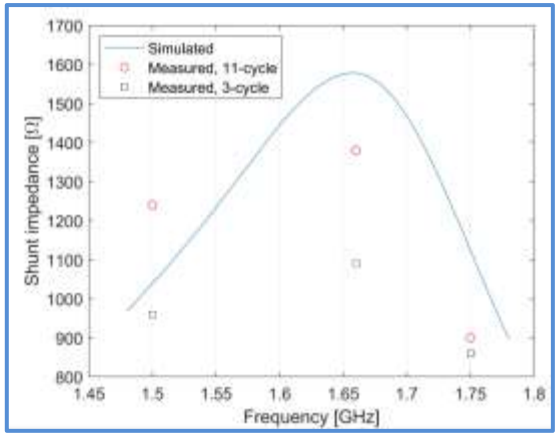
The damping time of two TFBs

Beam instrumentation related R&D

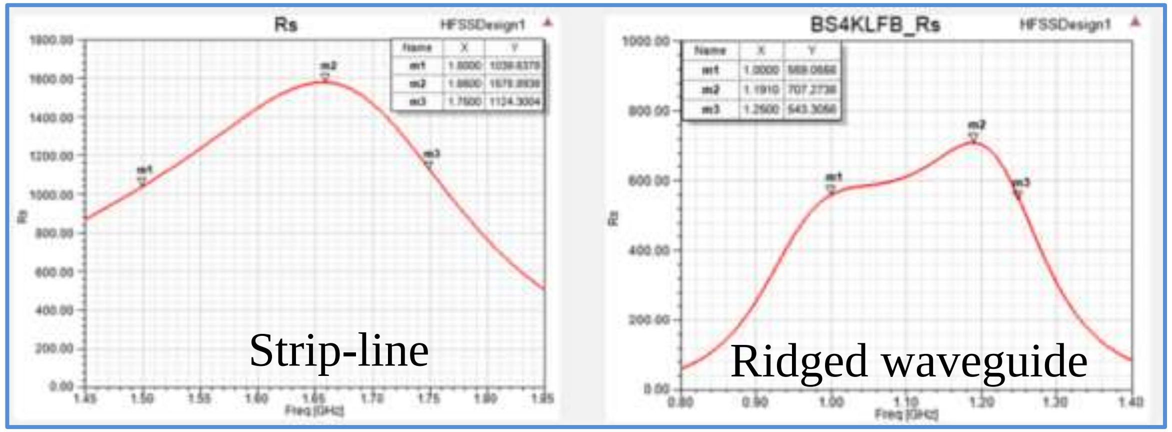
- Study on feedback system kicker



Resonant strip-line type longitudinal kicker: the shunt impedance is much bigger than ridged waveguide.



Shunt impedance Measurement system and results



Rs max =4734 Ω
Rs effective=3117Ω
f: 1.5 ~1.75 GHz

Rs max =707 Ω
Rs effective=559Ω
f: 1.0 ~1.25 GHz

Summary

- We have reviewed and improved the design report of the system based on the latest parameters
- We have understood the measurement requirements of CEPC and conducted extensive research on key technologies.
- Through our research and development activities, we have trained our personnel and mastered the necessary technology, which has prepared us for the construction of the project.

Thank you for attention！

Other systems

- Vacuum Chamber Displacement Measurement
  - Due to heat effects caused by synchrotron radiation and beam loss, the vacuum chamber will be displaced. In order to calibrate the BPMs, the displacement need to be measured.
  - The entire system includes Linear Variable Differential Transformer (LVDT), signal processing unit, computer and network.
  - Relevant research has been carried out on BEPCII. The displacement detector uses the DL6230 of Micro with dynamic range 500 μ m and accuracy 1 nm.