Instrumentation and Beam Diagnostics

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On behalf Beam Instrumentation Team,

Accelerator Center, IHEP

Outline

- Update of CEPC beam instrumentation system design
- Progress of beam instrumentation R&D
  - **BPM electronics**
- Summary

The beam instrumentation in CEPC Linac

	Item	Method	Parameter	Amounts
Linac	Beam position	Stripline BPM	Resolution : 30um	140
	Beam current	ICT	2.5%@1nC-10nC	42
	Beam profile	YAG/OTR	Resolution: 30um	80
	Beam emittance	Q+PR	10%	3
	Beam energy & spread	AM+PR	0.1%	3
Damping ring	Average current	DCCT	Resolution :50uA@0.1mA-30mA	1
	Beam position	Button BPM	Resolution : 20um @ 5mA TBT	40
	Tune measurement	Frequency sweeping	Resolution:0.001	1

The beam instrumentation in CEPC booster

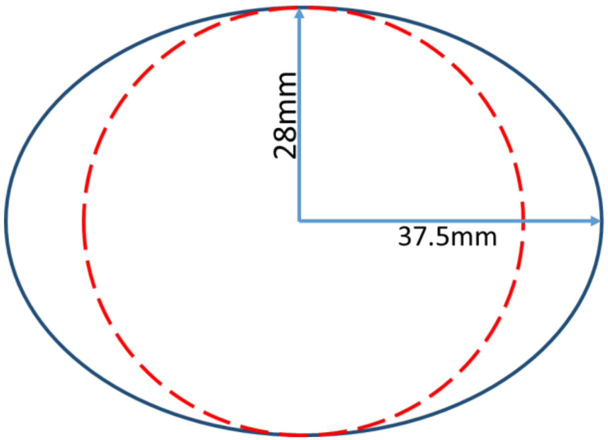
	Item		Method	Parameter	Amounts
Booster	Beam position monitor	Turn by turn	Button electrode BPM	Measurement area (x × y) ：±20mm×±10mm Resolution：<0.02mm Measurement time of COD：< 4 s	1808
		Bunch by bunch	Button electrode BPM	Measurement area (x × y) ：±40mm×±20mm Resolution：0.1mm	
	Bunch current		BCM	Measurement range：10mA / per bunch Relatively precision：1/4095	2
	Average current		DCCT	Dynamic measurement range：0.0~1.5A Resolution:50uA@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	400
	Feedback system		TFB	Damping time<=3ms	2
	Feedback system		LFB	Damping time<=35ms（50ms）	2

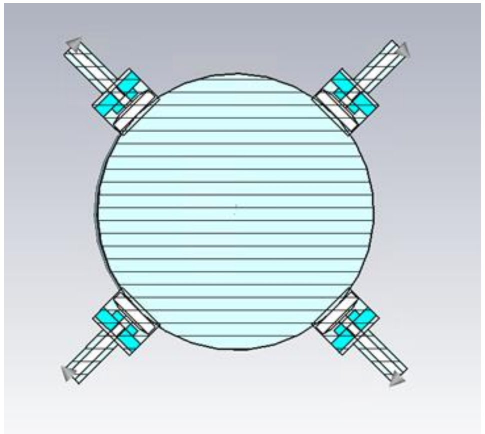
The beam instrumentation in CEPC ring

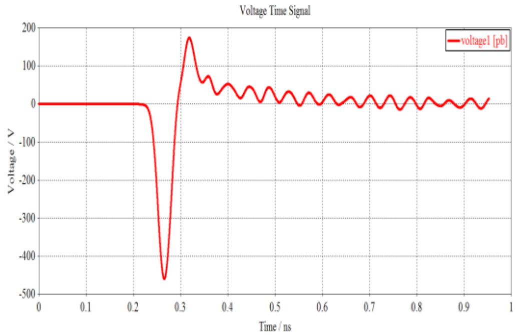
	Item		Method	Parameter	Amounts
Storage ring	Beam position monitor	Closed orbit	Button electrode BPM	Measurement area (x × y)：±20mm×±10mm Resolution：<0.6μm Measurement time of COD：< 4 s	2900
		Bunch by bunch	Button electrode BPM	Measurement area (x × y)：±40mm×±20mm Resolution：0.1mm	
	Bunch current		BCM	Measurement range：10mA / per bunch Relatively precision：1/4095	2
	Average current		DCCT	Dynamic measurement range：0.0~1.5A 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
			DDD	Resolution:0.001	
	Beam loss monitor		PIN-diode	Dynamic range:120 dB Maximum counting rates≥10 MHz	5800
	Feedback system		TFB	Damping time<=2.2ms	2
			LFB	Damping time<=12ms	2

Update of BPM pick-ups

- Due to modification of vacuum chamber in storage ring, the BPM pick-ups have been redesigned.
- Considering the suggestions of the IARC, the diameter of the button are reduced to 5mm.

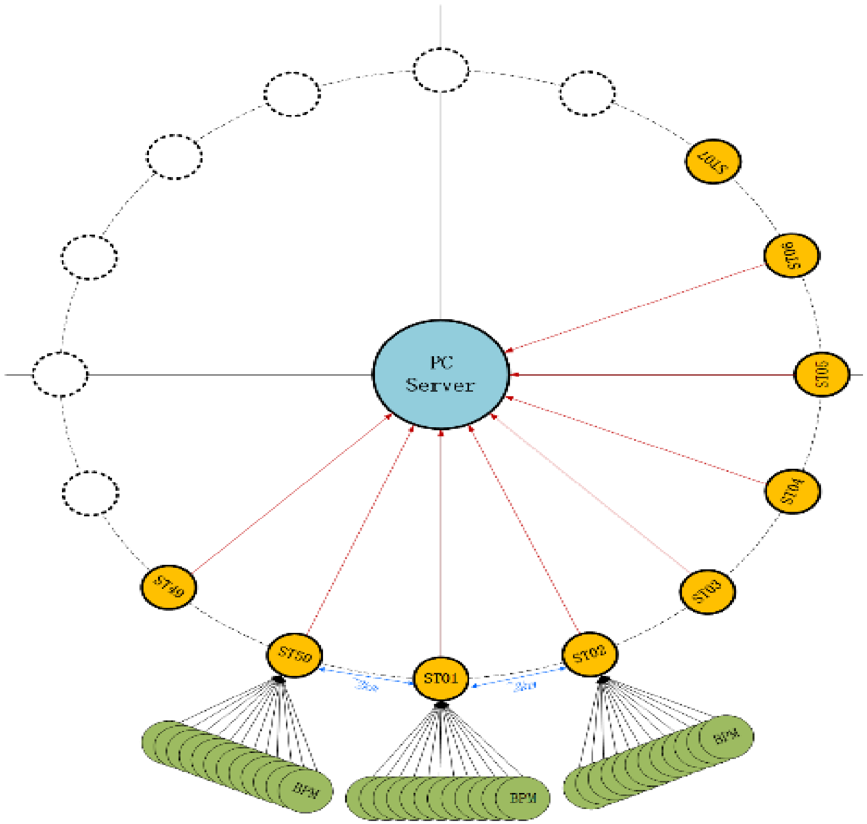


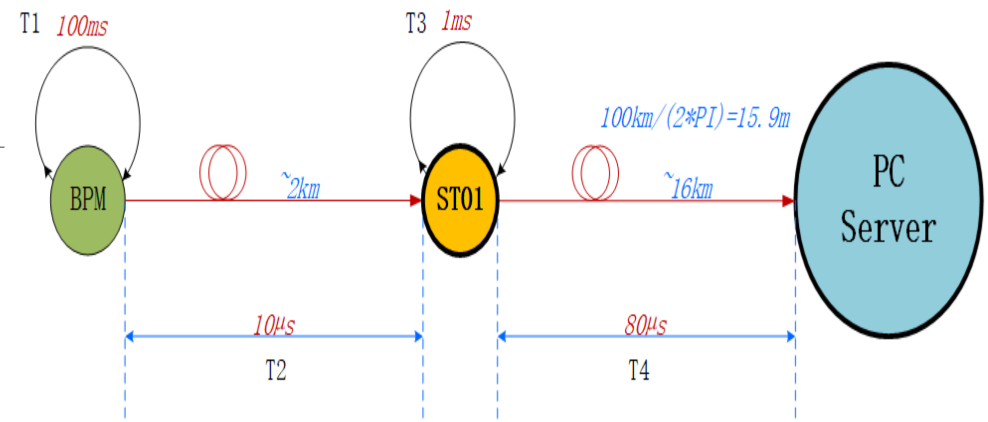




	ttbar		Higgs		W		Z	
	Real	CST	Real	CST	Real	CST	Real	CST
Charge	20e10	32 nC	14e10	22.4 nC	13.5e10	21.6 nC	14e10	22.4 nC
Bunch length	2.2/2.9	3 mm	2.3/3.9	4 mm	2.5/4.9	5 mm	2.5/8.7	8.7 mm
Vpp	635V		359V		295V		179V	
Z_500M	0.22Ω		0.22Ω		0.22Ω		0.22Ω	
P_500M	-7.3dBm/320mA		-12.8dBm/170mA		-10.6dBm/216mA		-10.4dBm/224mA	
Kx=Ky	19.9mm		19.9mm		19.9mm		19.9mm	

Time cost calculation of the COD measurement





- 50 stations along the storage ring and connecting with PC sever station with the star topology fiber optic network.
- Consider the delay of whole system, the BPM COD measurement takes about 1s .

Update of beam feedback system

Transverse resistive wall instability - wang na

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

- The worst case lowest energy and highest current, so Z mode is the most dangerous.

	30 MW
Instability growth time [ms]	2.2 (~7 turns)
Radiation damping [ms]	850

Growth of the most dangerous mode vs. damping factors

The power of transverse feedback

$$\frac{1}{\tau_{FB}} = \frac{f_{rf}\sqrt{\beta_m \beta_k}}{2 \cdot h \cdot E / e} \cdot G$$

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

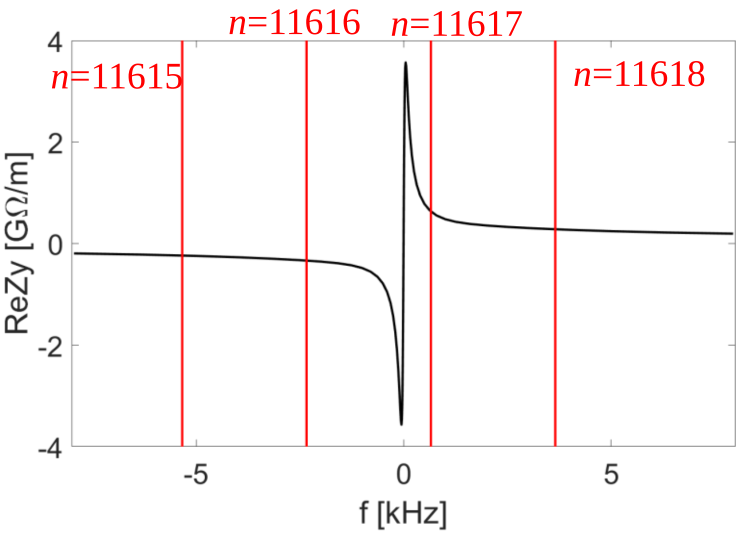
TFB CEPC ring（CDR）	
Parameter	Value
E	4.55E+10
R	1.55E+05
Beta-k	2.25E+02
Beta-m	2.25E+02
A	2.00E-04
T	3.30E-04
tao	1.60E-03
P（W）	8.98E+02

TFB CEPC Ring （30MW）	
Parameter	Value
E	4.55E+10
R	1.55E+05
Beta-k	2.25E+02
Beta-m	2.25E+02
A	2.00E-04
T	3.30E-04
tao	2.2E-03
P（W）	4.75E+02

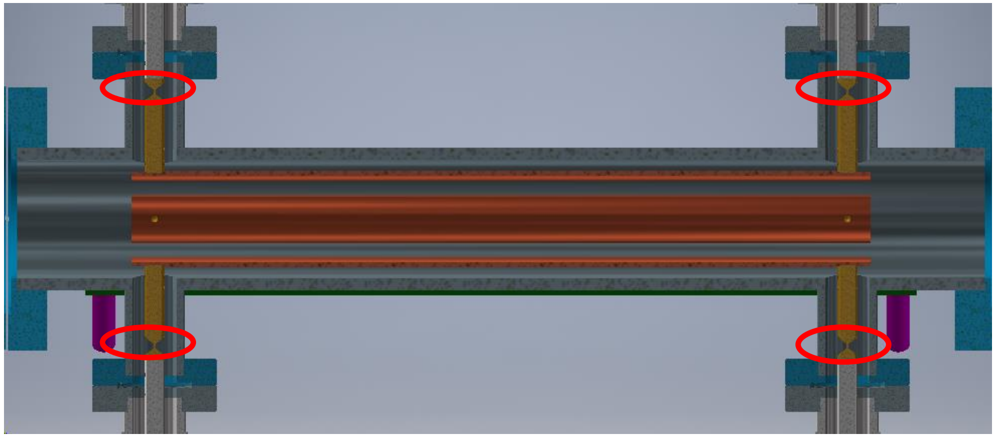
The update of TFB feedback system

- Narrow-band feedback + bunch by bunch feedback
- Consider narrow-band feedback, in addition to bunch-by-bunch ones, for specific instabilities such as resistive wall coupled bunch. Mode No. 11616 & 11615

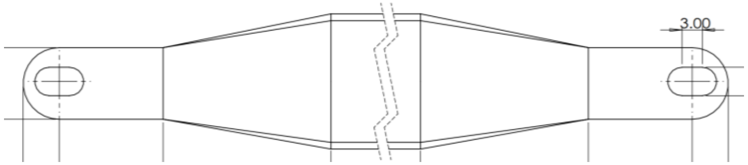
f [kHz]	Mode index	Growth *t* [ms]
-2.338	11616	2.2 (7 turns)
-5.335	11615	3.2 (10 turns)
-8.332	11614	4.0 (12 turns)
-11.330	11613	4.6 (14 turns)



The update of TFB kicker



Variable diameter of pins to overcome the thermal deformation in electrodes



The electrode with slotted holes connecting with feed through

- To reduce deformation, the electrodes will be made of copper plated aluminum to reduce own weight.
- For the thermal deformation of kicker, slotted holes on electrode are adopted to allow relative movement between the electrodes and the feed through along the beam direction; second, the pin of the feed through will use variable diameter to allow the deformation.

The power of longitudinal feedback

$$\frac{1}{\tau_{FB}} = \frac{f_{rf}\alpha}{2\nu_s E / e} \cdot G \qquad P = \frac{1}{2} \cdot \frac{\Delta V_{FB}^2}{R_K}$$

CEPC LFB（CDR）	
Parameters	Value
f	6.50E+08
alpha	1.11E-05
mus	2.80E-02
deltaphi	1.70E-03
Tao(s)	2.00E-01
E	4.55E+10
Rk(Ω)	2600
V(V)	3.00E+03
P(W)	1.73E+03

CEPC LFB（30MW-12ms）	
Parameters	Value
f	6.50E+08
alpha	1.48E-05
mus	3.50E-02
deltaphi	1.70E-03
Tao(s)	1.20E-02
E	4.55E+10
Rk(Ω)	2600
V(V)	4.69E+04
P(W)	4.23E+05

CEPC TDR Collider Ring Cavity HOM CBI –Zhai Jiyuan

30 MW SR per beam. Consider only SR damping for HOM Q_L requirement. Cavity HOM spread not included.	ttbar		Higgs	W	Z
	new 5-cell common cavity	old 2-cell common cavity	common cavity	separate cavity	by-pass separate cavity
Cell number / cavity	**5**	**2**	**2**	**2**	**1**
Beam energy [GeV]	180.0	180.0	120.0	80.0	45.5
Beam current per beam [mA]	3.4	3.4	16.7	84.0	802.6
Revolution time [μs]	333.6	333.6	333.6	333.6	333.6
Momentum compaction	7.1E-06	7.1E-06	7.1E-06	1.4E-05	1.4E-05
Synchrotron tune	0.08	0.08	0.05	0.06	0.04
S[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
L[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Cavity number on line per beam	240	240	240	120	30
Average beta-x/y in RF region [m]	30	30	30	30	30
Longitudinal impedance threshold per cavity [ohm*MHz]	3.58E+11	3.58E+11	9.62E+09	9.05E+08	2.27E+07
Transverse impedance threshold per cavity [ohm/m]	1.88E+08	1.88E+08	7.48E+06	1.18E+06	5.12E+04
Cavity higher order mode	**Required Q_L**				
TM011	7.2E+06	9.4E+06	2.5E+05	2.4E+04	**1.5E+03**
TM020	9.3E+06	4.0E+08	1.1E+07	1.0E+06	**4.2E+04**
TE111	4.5E+05	1.3E+06	5.3E+04	8.4E+03	**6.5E+02**
TM110	5.5E+05	9.0E+05	3.6E+04	5.6E+03	**3.5E+02**

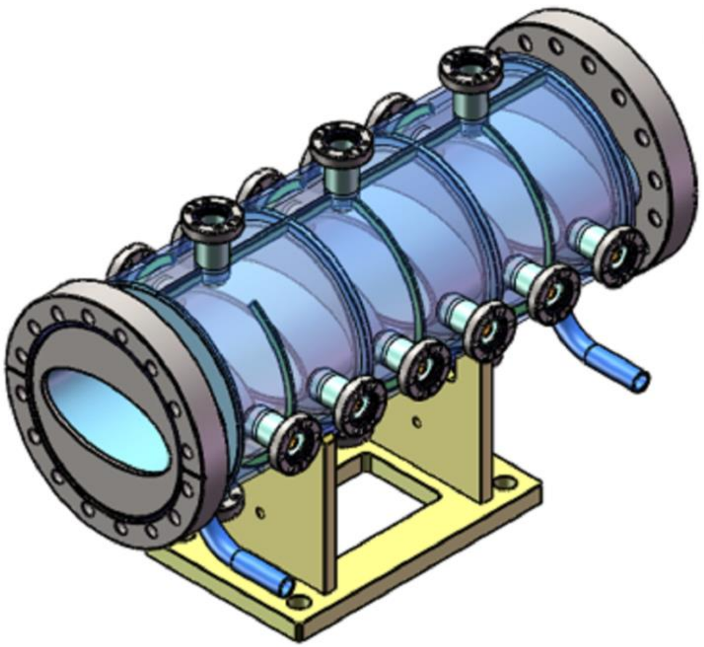
- No beam feedback is needed for 30 MW.

2-cell	**f (GHz)**	**R/Q (Ω)**
TM011	1.17	65.20
TM020	1.38	1.29
TE111	0.84	279.82
TM110	0.91	420.05
5-cell	**f (GHz)**	**R/Q (Ω)**
TM011	1.17	84.80
TM020	1.43	54.15
TE111	0.82	832.23
TM110	0.93	681.15
1-cell	**f (GHz)**	**R/Q (Ω)**
TM011	1.09	28.17
TM020	1.32	0.82
TE111	0.79	157.00
TM110	0.90	291.07

- …signed 650 MHz 2-cell cavity HOM coupler Q_L can meet Higgs and W damping requirement.
- 1-cell cavity similar to BEPCII can meet 30/50 MW Z HOM damping requirement. No beam feedback is needed even for 50 MW.
- Low lumi Z with 2-cell cavities may need beam feedback depending on the operation beam current.

Study of LFB kicker

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

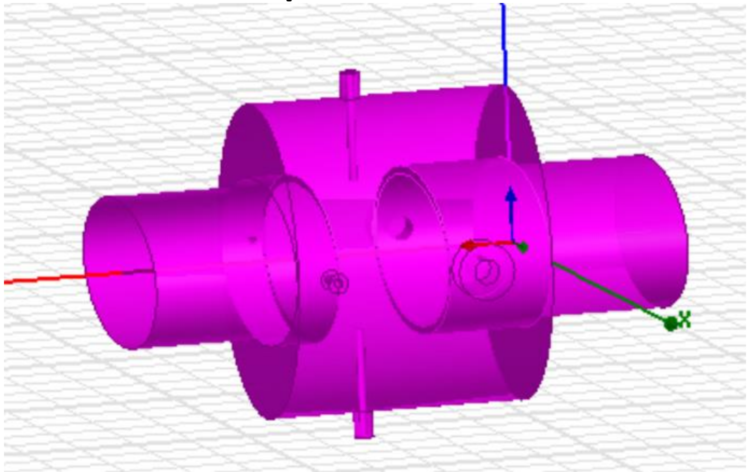


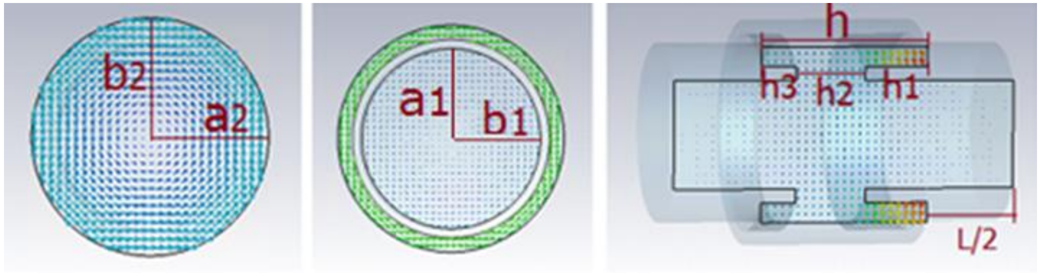
Resonant strip-line type longitudinal kicker

Pillbox cavity with ridged waveguides type kicker

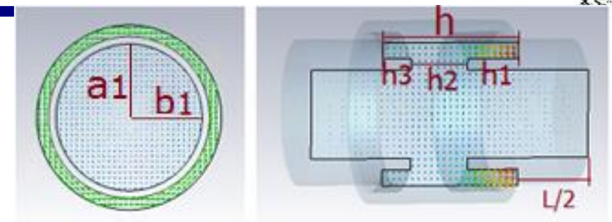
Study of longitudinal feedback kicker

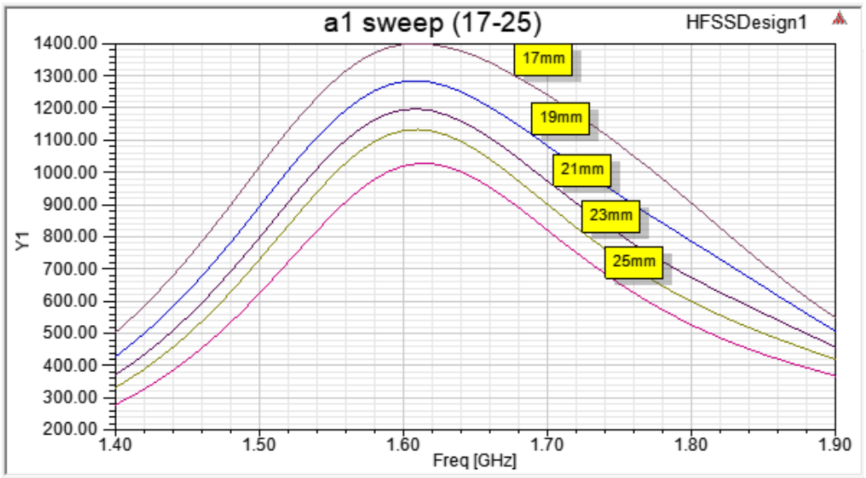
- The procedure for designing the was based on initially rescaling Spring-8 design to our vacuum chamber diameter and desired center frequency.
- The CST Microwave Studio and HFSS code has been used for the electromagnetic simulations.
- Multiple parameter sweeps were performed to set the longitudinal shunt impedance curve, with maximum amplitude (Rs).





Sweep the geometric parameters to maximum RS





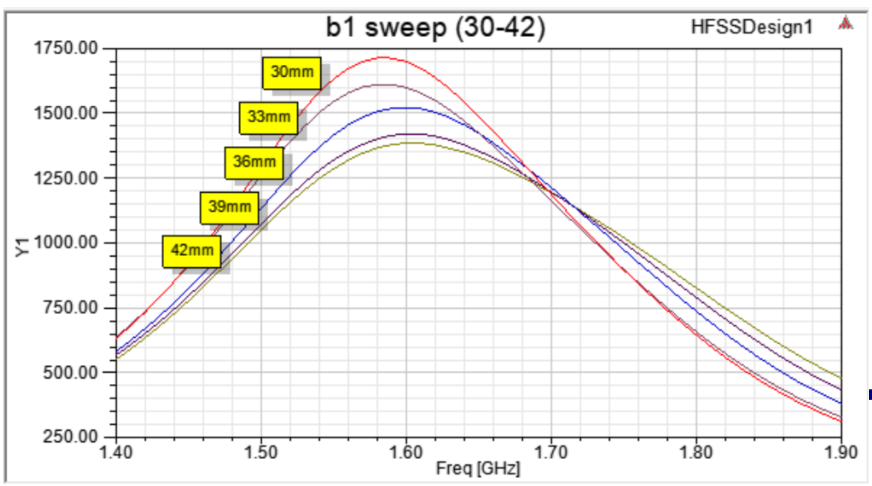
Rs VS a1

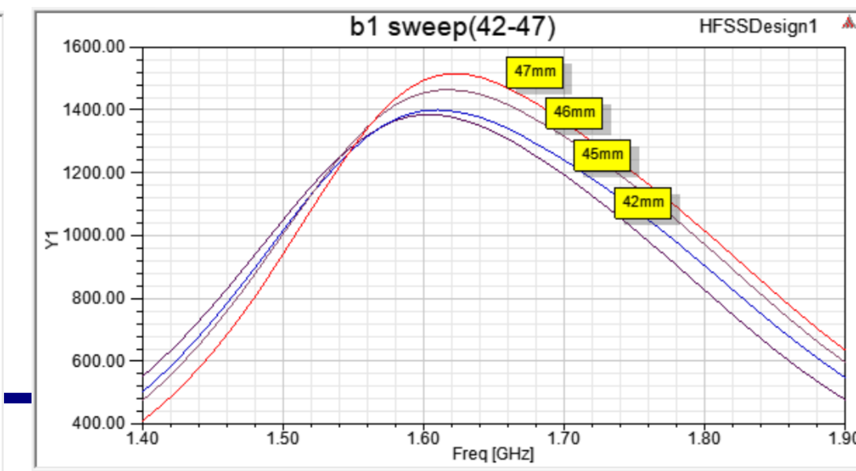
17mm->25mm

Rs VS b1

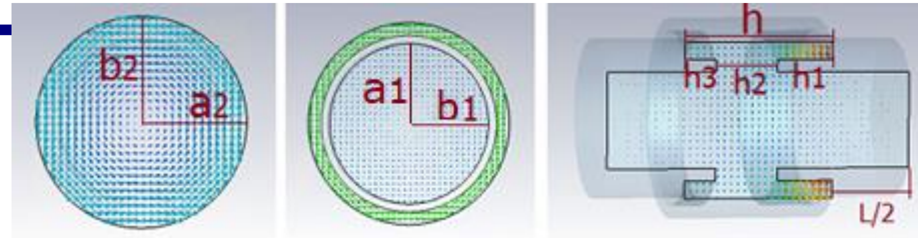
30mm->42mm

42mm->47mm

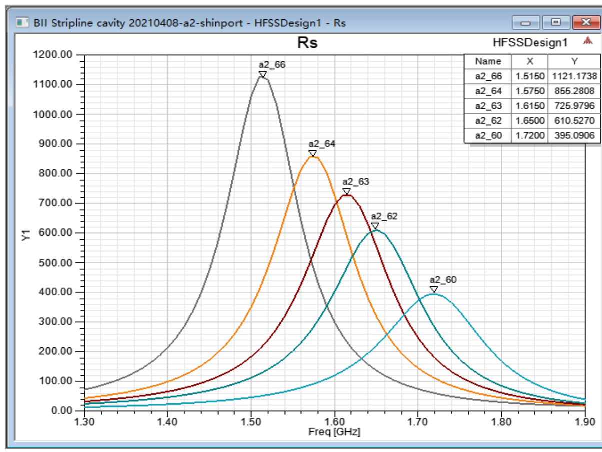


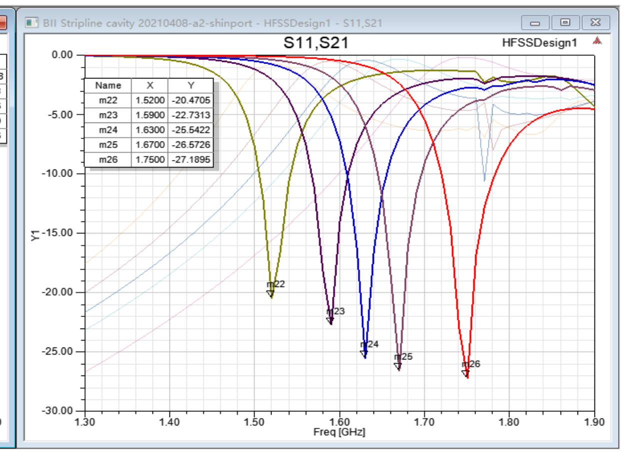


Sweep the geometric parameters to maximum RS

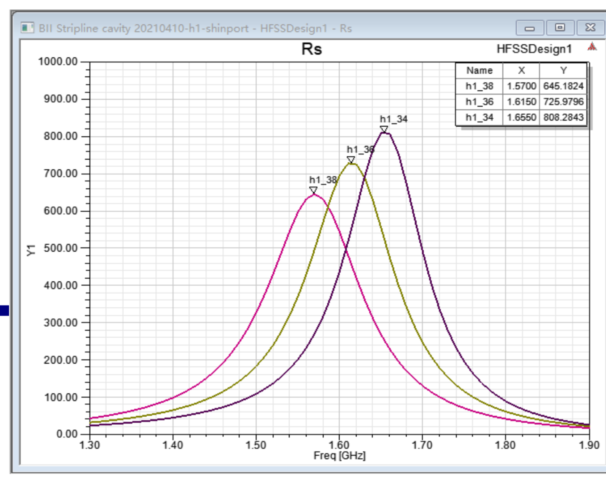


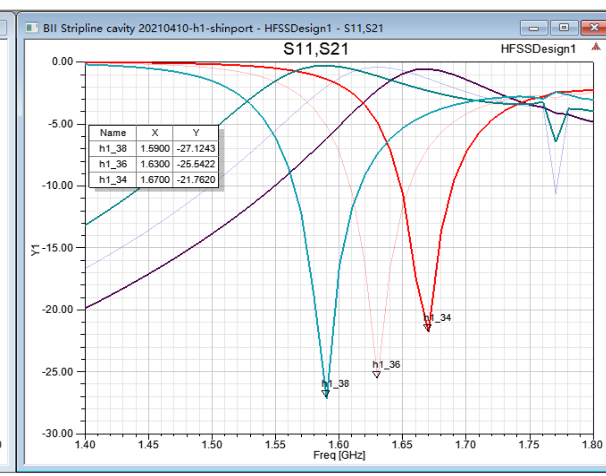
Rs VS a2
60mm->66mm



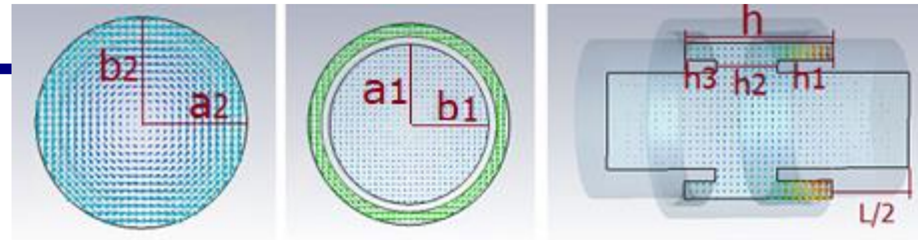


Rs VS h1
34mm->38mm



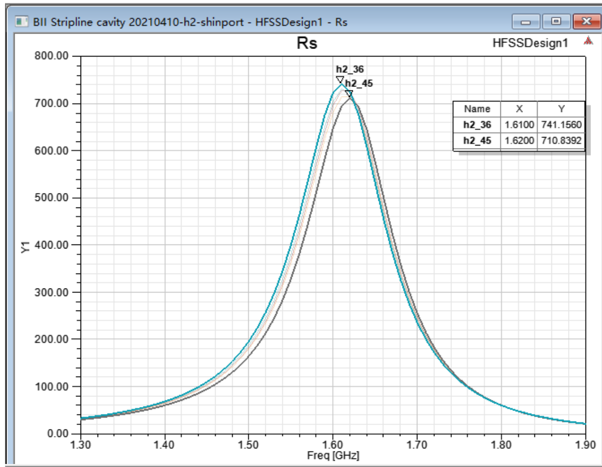


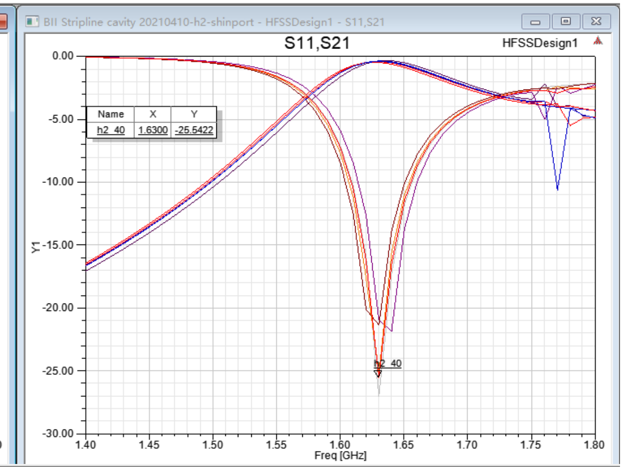
Sweep the geometric parameters to maximum RS



Rs VS h2

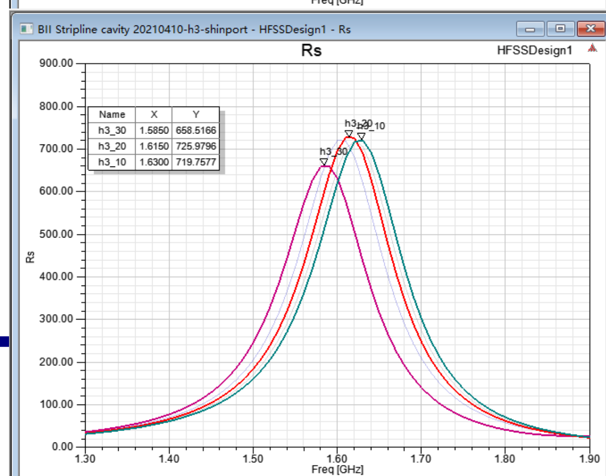
36mm->45mm

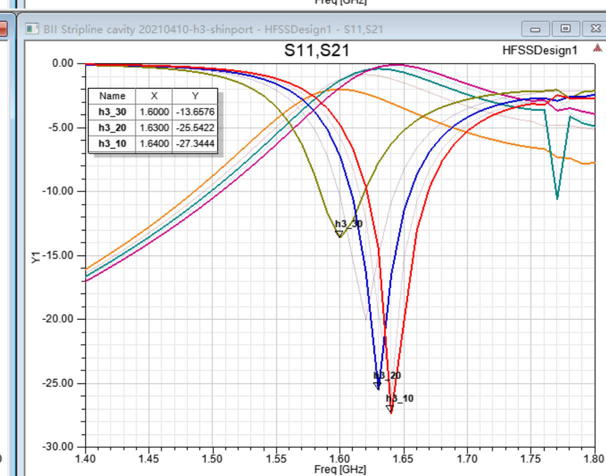




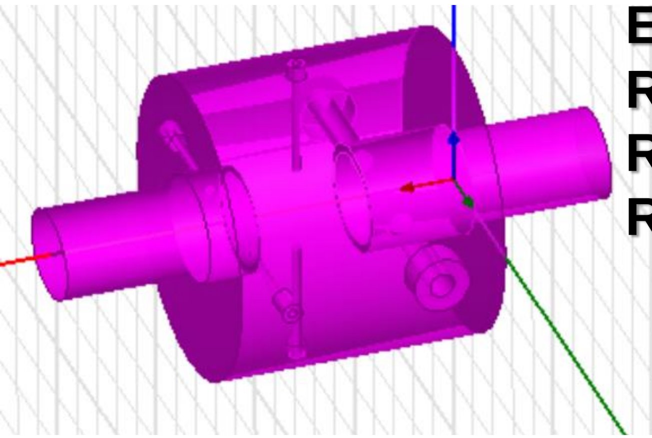
Rs VS h3

10mm->30mm





Study of LFB kicker

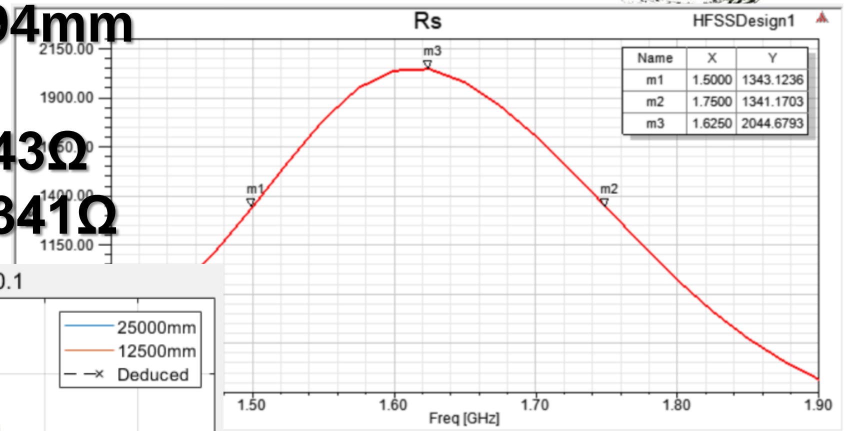


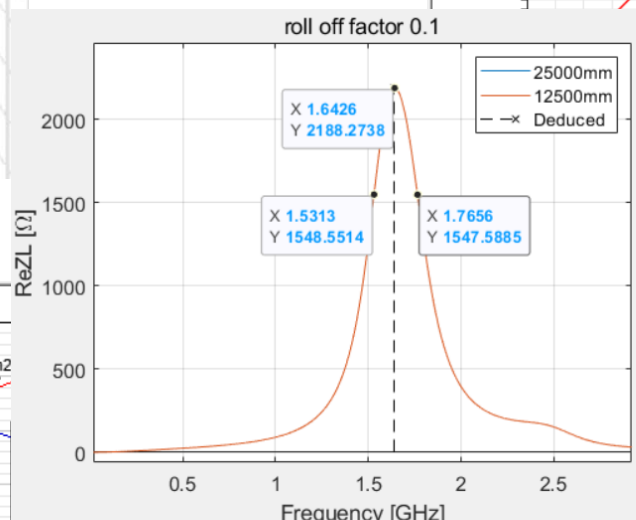
Effective length:94mm

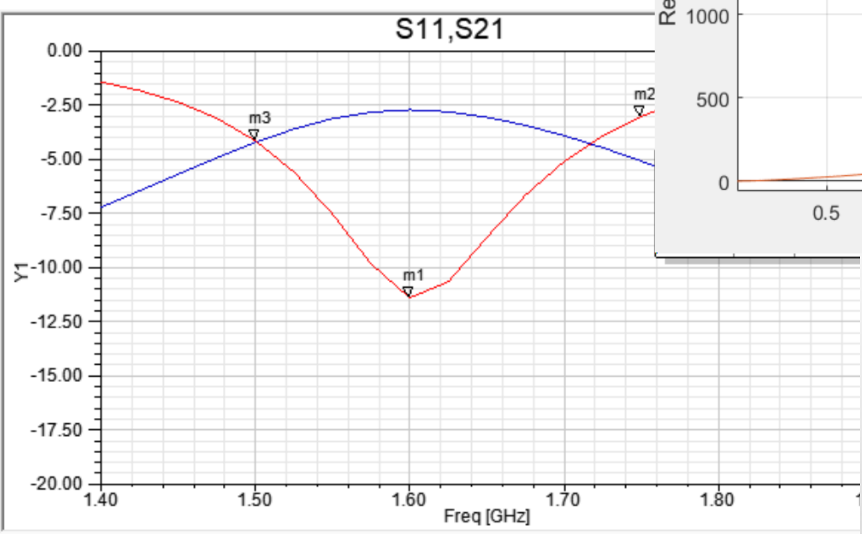
Rs max=2044Ω;

Rs @1.5GHz=1343Ω

Rs @1.75GHz=1341Ω







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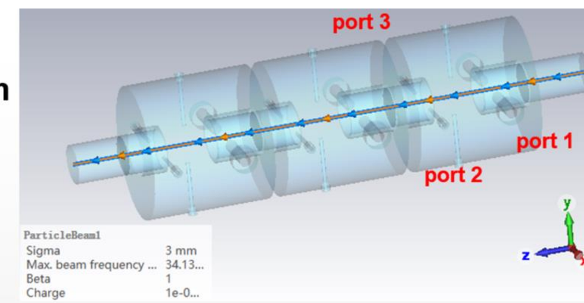
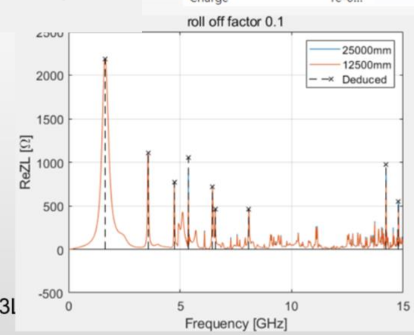


1	1.6426	2.1883e+03
2	3.5611	1.1046e+03
3	4.7426	770.3831
4	5.3726	1.0514e+03
5	6.4543	715.6862
6	6.5712	463.6951
7	8.0852	456.3905
8	14.2265	975.3146
9	14.7885	550.9255



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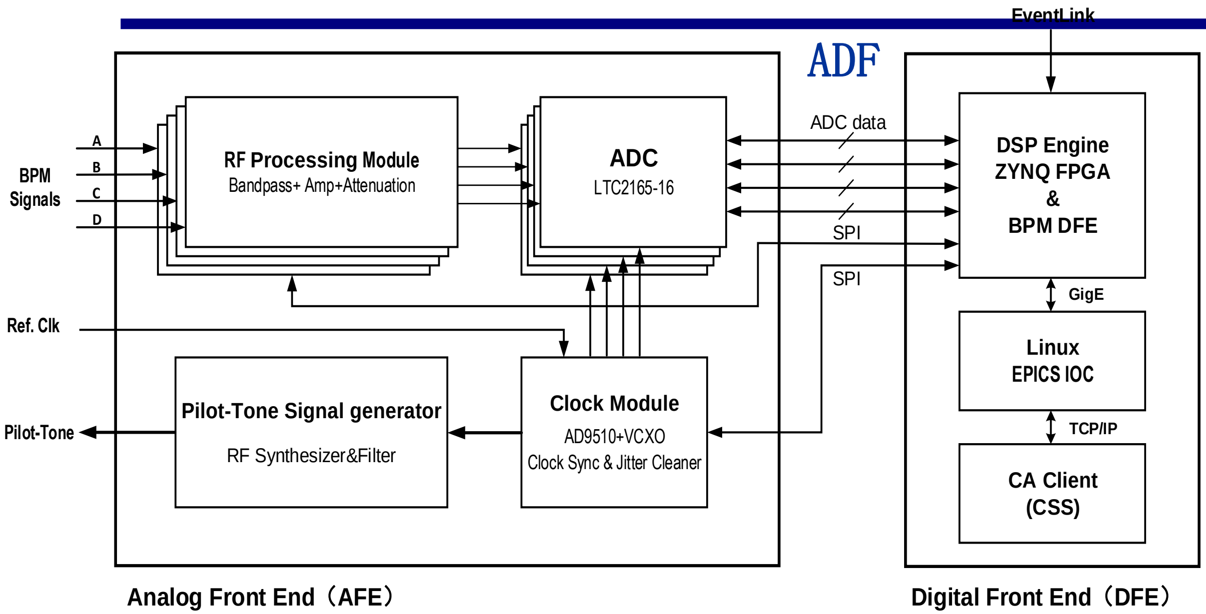
R&D Motivation

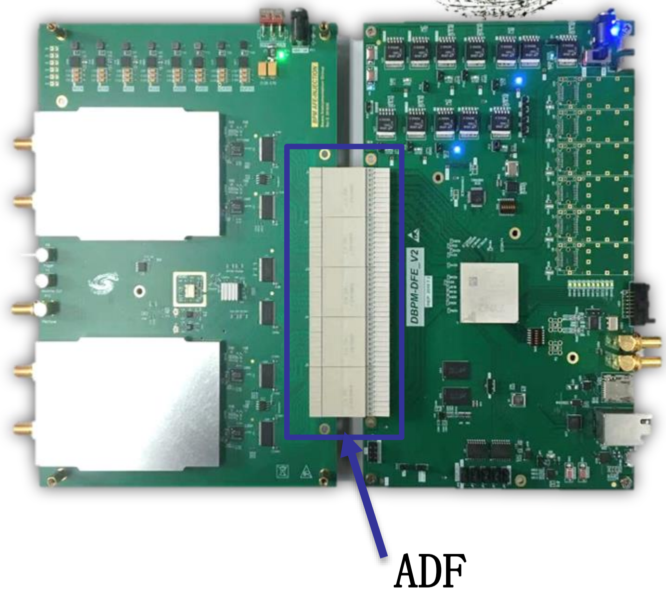
- To reduce the budget of BI system, due to a large number of monitors and the high price of commercial products.
- To grasp key technologies of beam diagnostics.
- To make the whole system easy to maintain and upgrade

Overview of the BPM electronics R&D

- The R&D of BPM electronics founded by seed money of IHEP and other funding（HEPS-TF etc.）
- Kicked off in the start of 2015
- The first version(V1.0) of the electronics was finished in 2018.
- The second version(V2.0) was finished in middle of 2019. Modification was done to improve the performance of the electronics. 8 versions have been tested in the past six years.
- In 2019, self-developed electronics were put into use in the BEPCII.

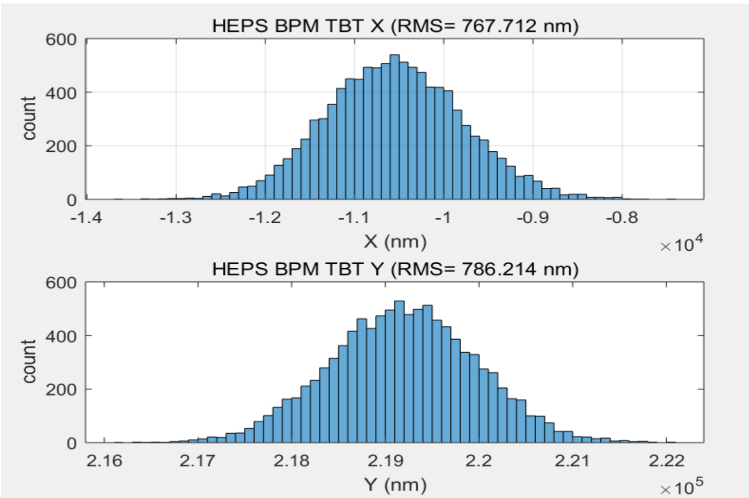
Overview of the BPM Electronics



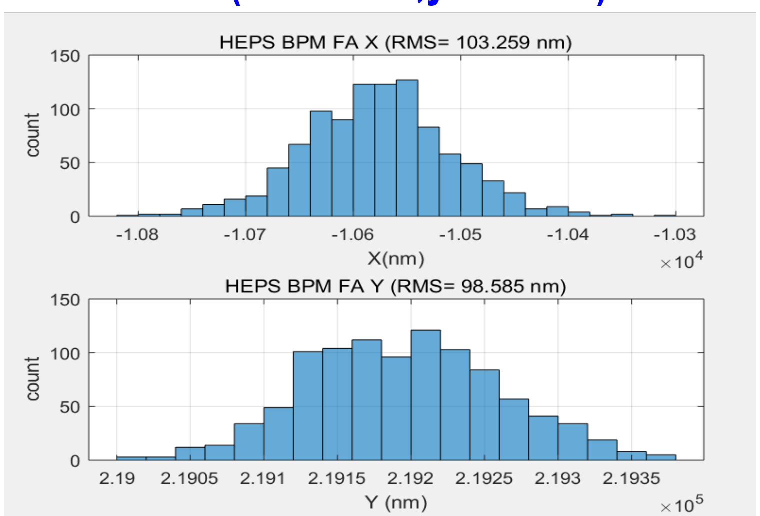


- Since of ADF interface is not suitable for RF signal transmission, so we developed new hardware, ADC&CLK in AFE board.
- AFE board： RF Processing+ ADCs + Clock + Pilot tone;
- DFE board： FPGA(ZYNQ) + DDR3 memory + SFPs + Ethernets;
- EPICS IOC： In ZYNQ FPGA, Increase the convenience of the BPM system;

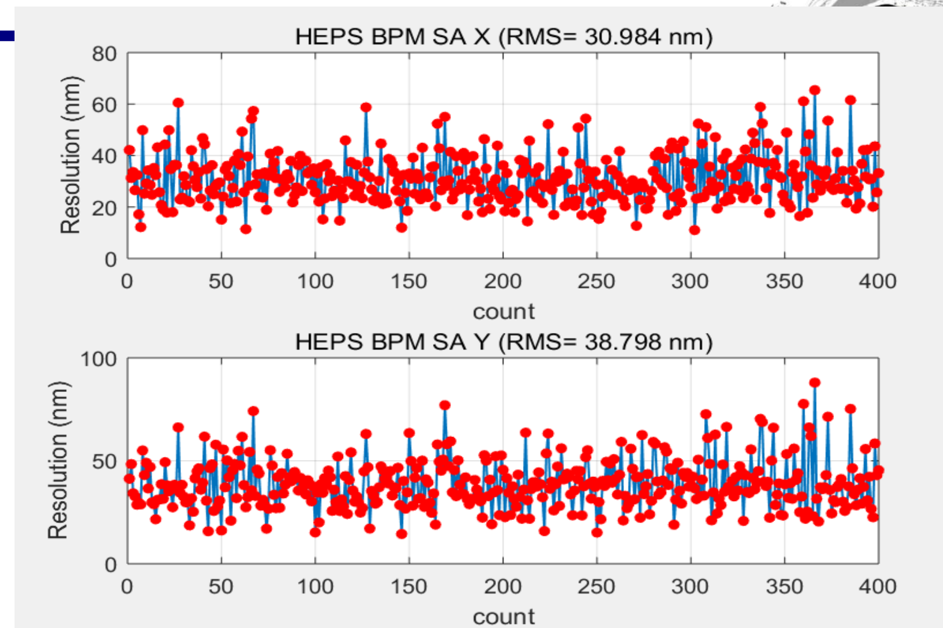
BPM TbT/FA/SA Resolution Test in Lab



TBT RMS (X=767nm,y=786nm)



FA RMS (X=103nm,y=98nm)

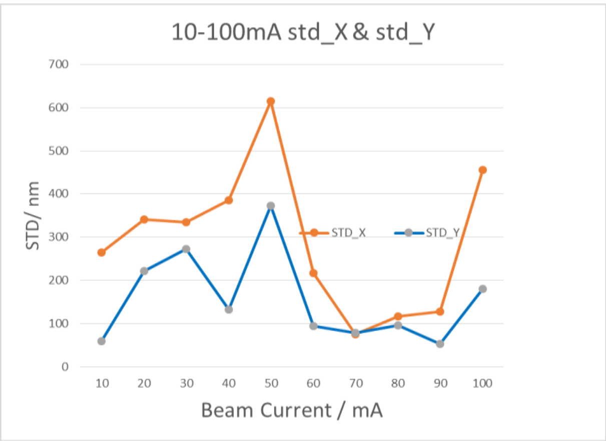


SA RMS(X=30nm,Y=38nm) 10points STD

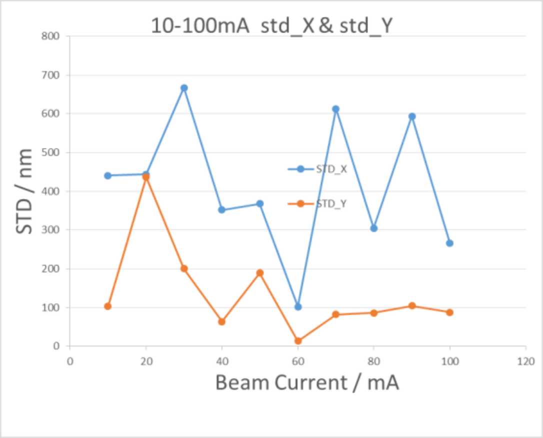
- We test the performance of DBPM in house
- RF frequency is 499.8MHz(-15dBm) from R&S SMA100
- TBT data rms xpos ≈767nm, ypos ≈786nm;
- FA data rms xpos ≈103nm, ypos ≈98nm;
- SA data rms xpos ≈30nm, ypos ≈38nm;
- Kx=Ky=8.26mm;

Beam test in BEPCI

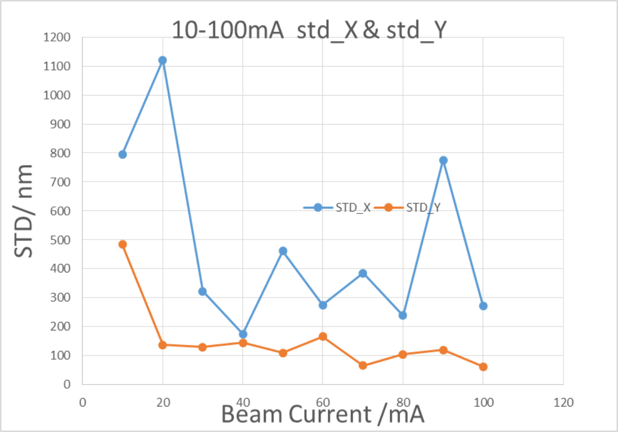
- Resolution of BPM electronics（**110 bunches, 1/3**）



BPM3



BPM4

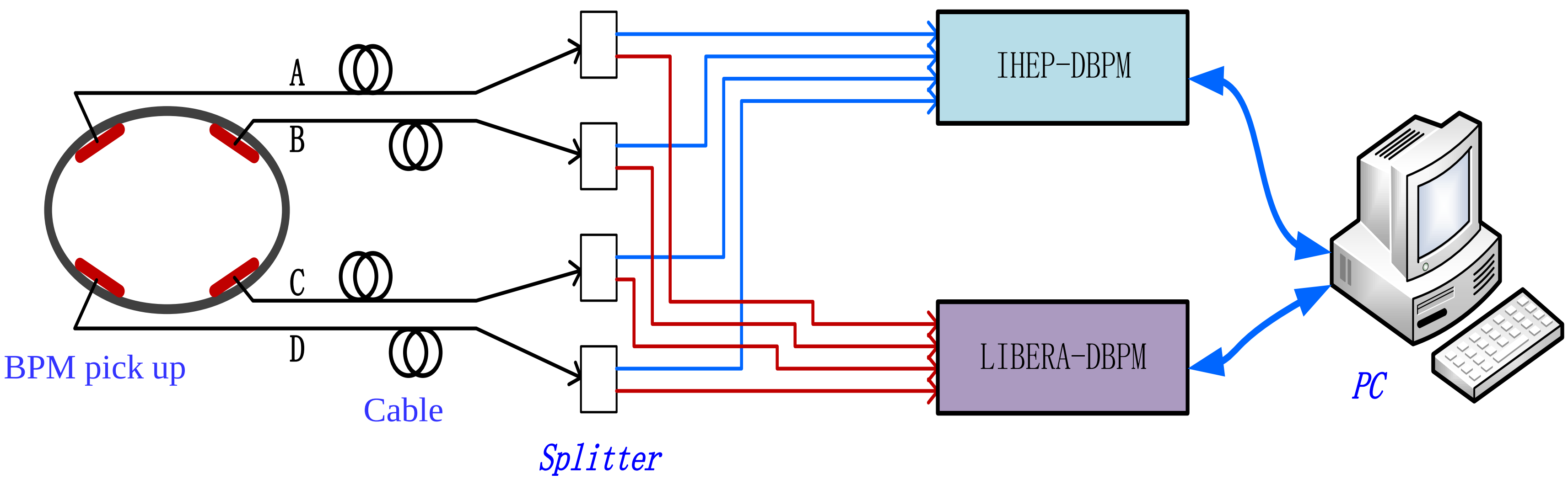


BPM5

BPM electronics NO.	Beam current（10-20mA）		Beam current（20-818mA）	
	ΔX(um)	ΔY(um)	ΔX(um)	ΔY(um)
Commercial product	-	-	6	7
BPM1	-	-	10	17
BPM3	22	11	29	11
BPM4	71	61	11	36
BPM5	5	17	4	31

Beam current dependence of BPM electronics

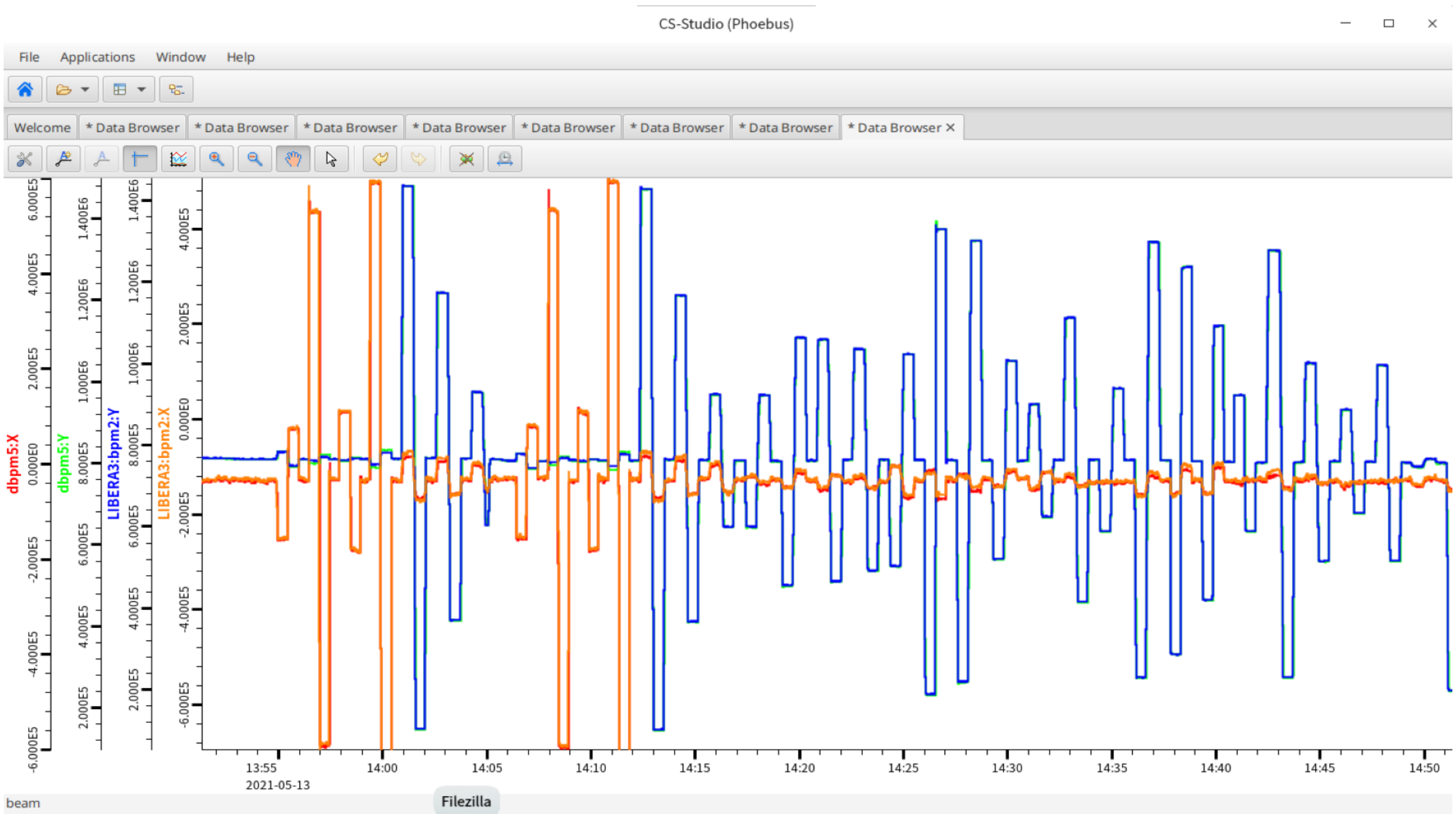
Home made products VS commercial products



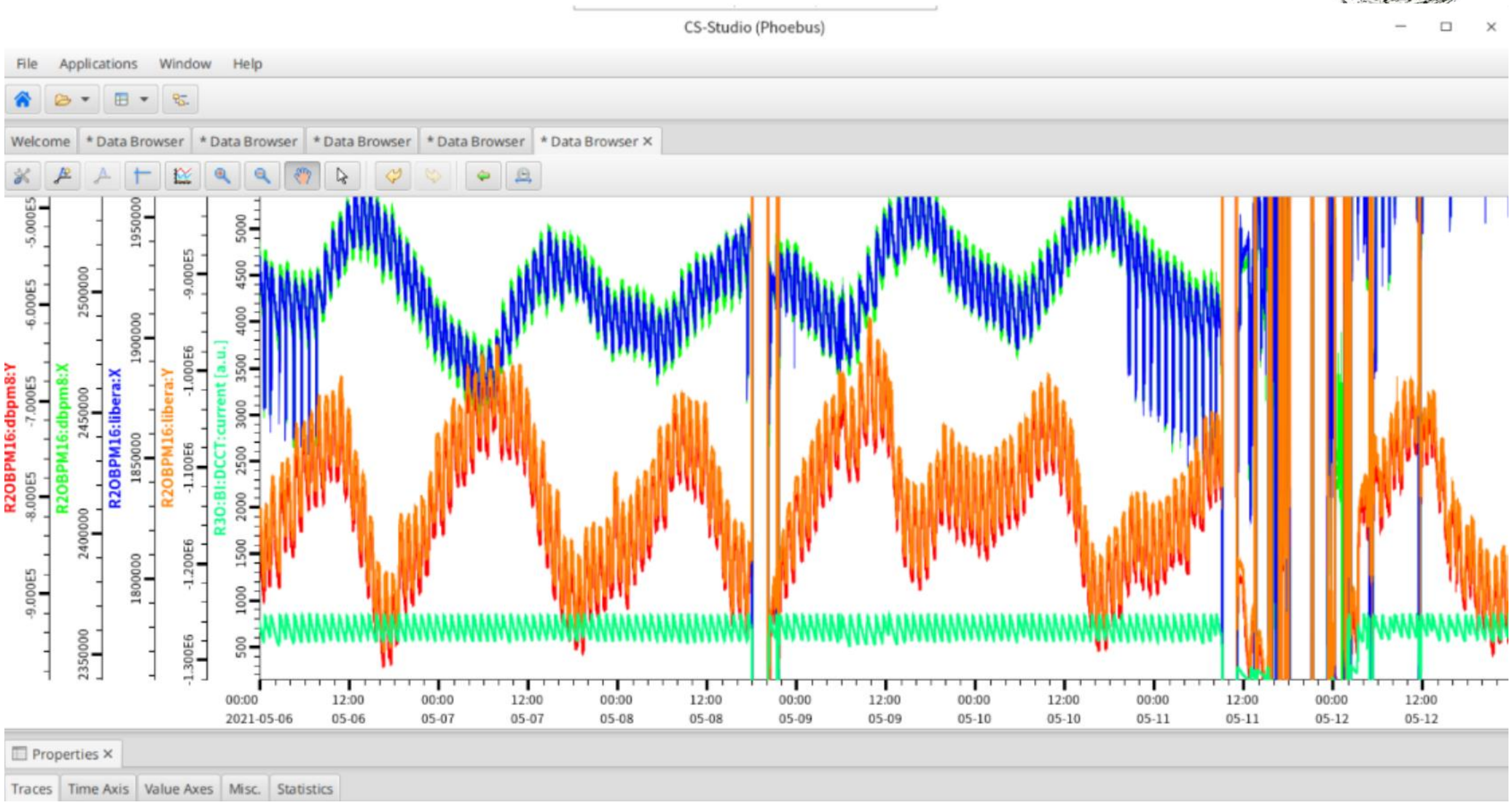
Comparative test of self-developed product and commercial product

- Libera brilliance+ VS Home-made BPM
- Both are the same pick-up signal from button-> splitter

Long time stability (1 hour)



Long time stability (7 days)



Application of home-made BPM electronics

- There are 20 singal-pass BPM electronics were installed and operating in BEPCII Linac in 2019.
- All Bergoz type BPM electronics had been upgraded to home-made electronics by the end of last year. Totally ,92 sets of electronics running online now.
- There will be 700+ sets electronics in the new project -HEPS

Summary

- The BPM pick-ups and the feedback systems are refined based on latest parameters and suggestion of IARC.
- We clearly understand the CEPC beam position measurement requirements. Based on that, BPM electronics have been developed in house in the past 6 years.
- 112 sets of home-made electronics running online in BEPCII. More than 700 units will be used on both injector and storage ring in HEPS.
- The application of electronics is conducive to improving the performance of electronics and accumulating experience , which is helpful for the CEPC BPM electronics R&D.

Thanks for your attention !