Design and Commissioning of HEPS Instrumentation

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HEPS Beam Diagnostics Group

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Beijing, China

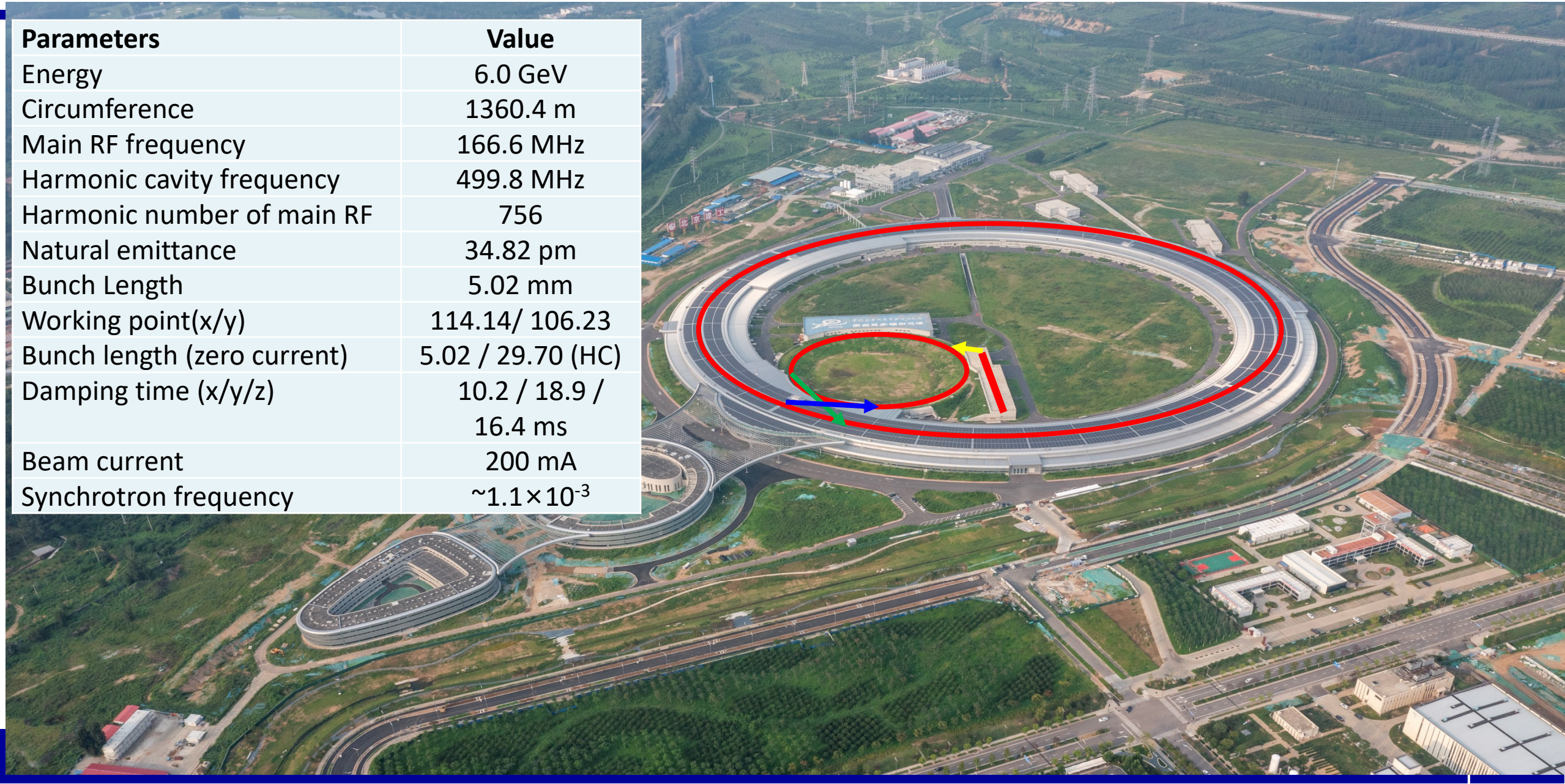
Content

- Introduction of HEPS
- HEPS beam instrumentation design
- Commissioning of beam instrumentation
- Summary

High Energy Photon Source （HEPS）

High Energy Photon Source （HEPS)

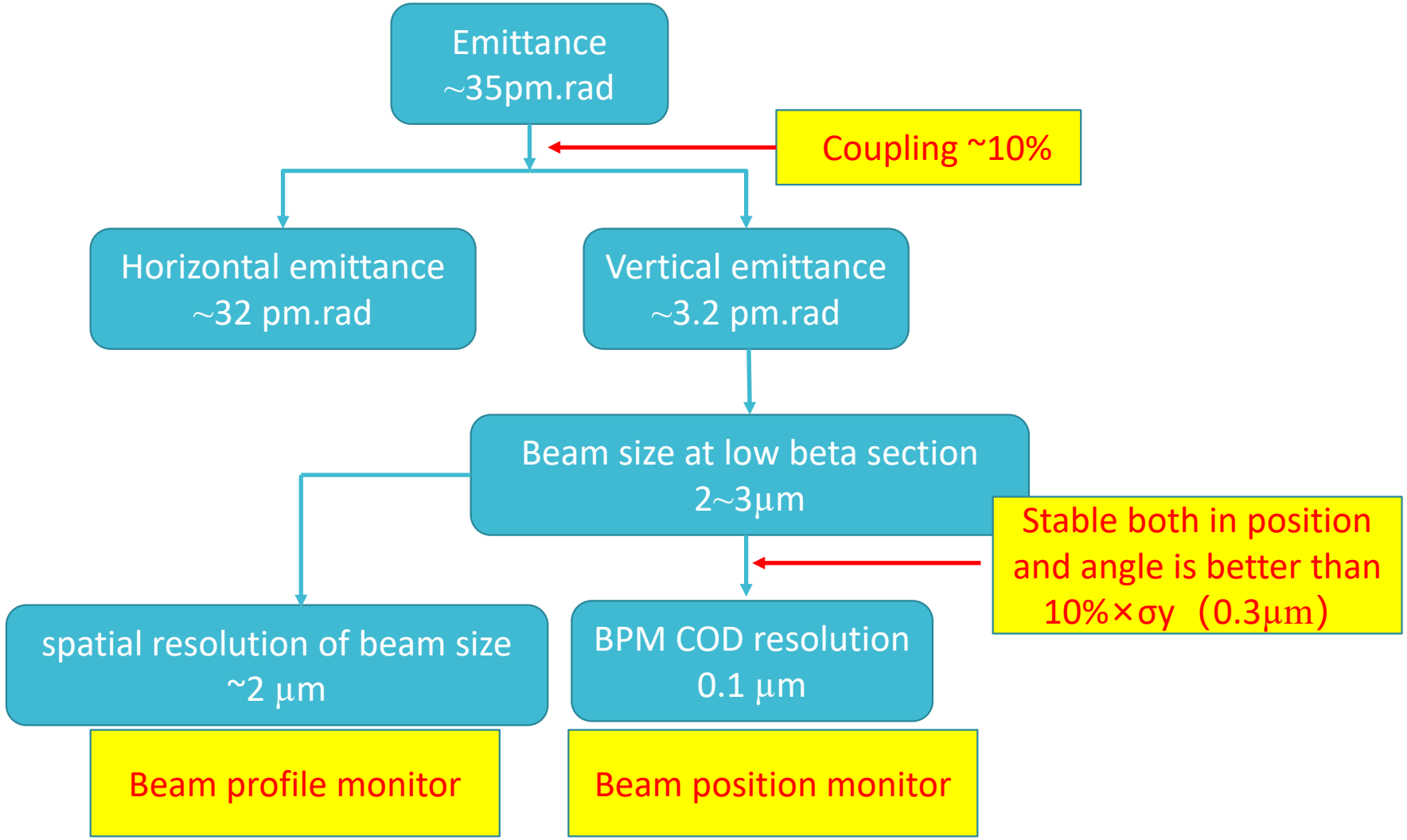
Parameters	Value
Energy	6.0 GeV
Circumference	1360.4 m
Main RF frequency	166.6 MHz
Harmonic cavity frequency	499.8 MHz
Harmonic number of main RF	756
Natural emittance	34.82 pm
Bunch Length	5.02 mm
Working point(x/y)	114.14/ 106.23
Bunch length (zero current)	5.02 / 29.70 (HC)
Damping time (x/y/z)	10.2 / 18.9 / 16.4 ms
Beam current	200 mA
Synchrotron frequency	~1.1×10^{-3}



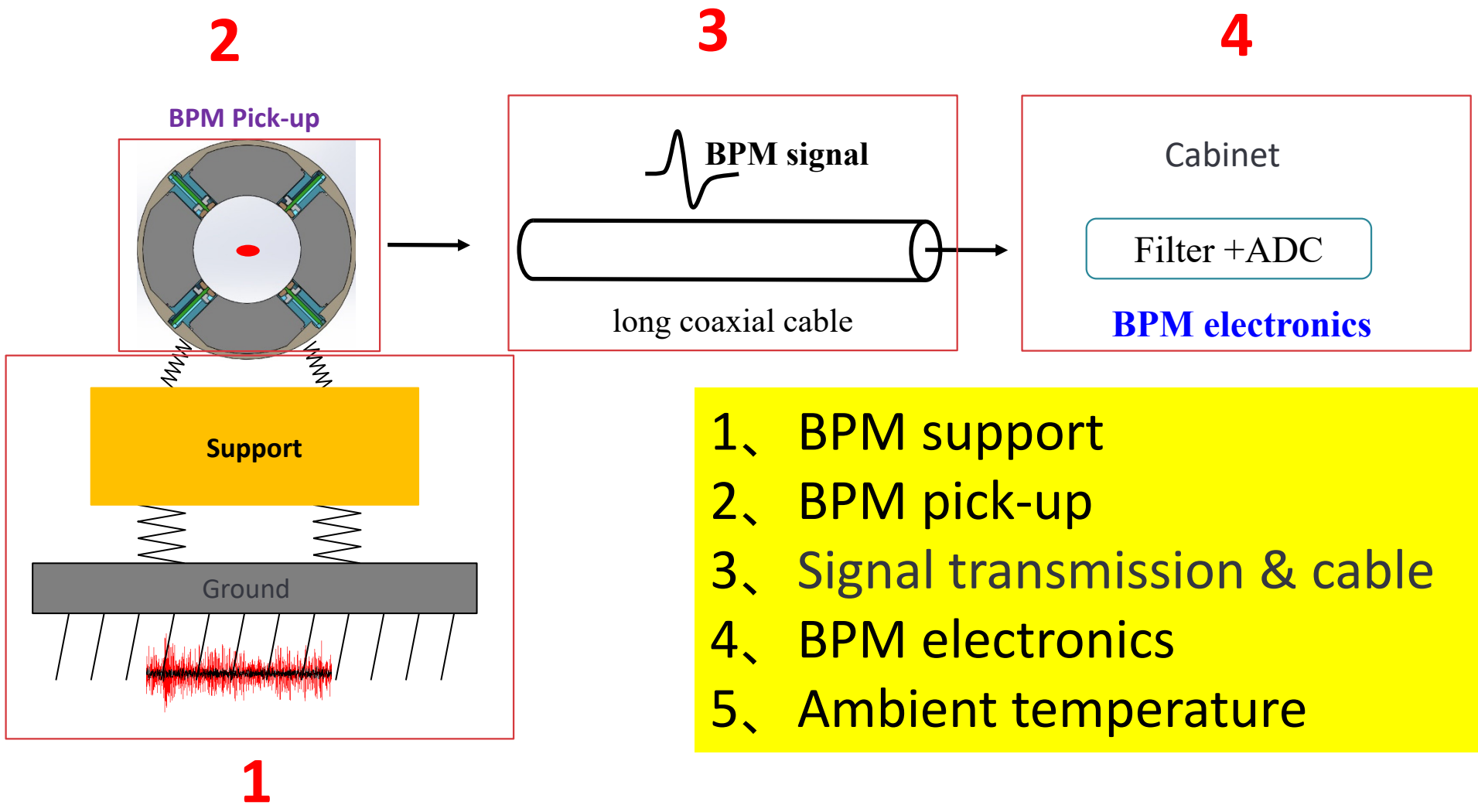
Beam Instrumentation in HEPS

Beam instrumentations	Purpose	Linac	LB	Booster	BR	RB	Ring
BPM	Position	8	8	80	11	11	576+24
ICT	Bunch charge	7	2	-	2	2	-
DCCT	Beam average current	-	-	2	-	-	2
Bunch Current Monitor	Bunch current	-	-	1	-	-	1
OTR/YAG	Beam profile	7	2	-	2	2	-
Synchrotron Light Monitor	Beam size	-	-	2	-	-	1
Pilot tune/3D Frequency sweeping/FFT	Tune	-	-	1	-	-	1
Beam loss monitor	Beam loss	-	-	4	-	-	192
Bunch-by-bunch feedback system	Instability mitigation	-	-	3	-	-	3
High-resolution displacement monitor	Chamber displacement	-	-	-	-	-	8
Streak camera (visible light beam line)	Bunch length	-	-	-	-	-	1
Bunch cleaning system	Obtain high bunch purity	-	-	-	-	-	1
Energy analyze station	Energy measurement	2					
Emittance	Emittance measurement	2					

HEPS beam instrumentation design

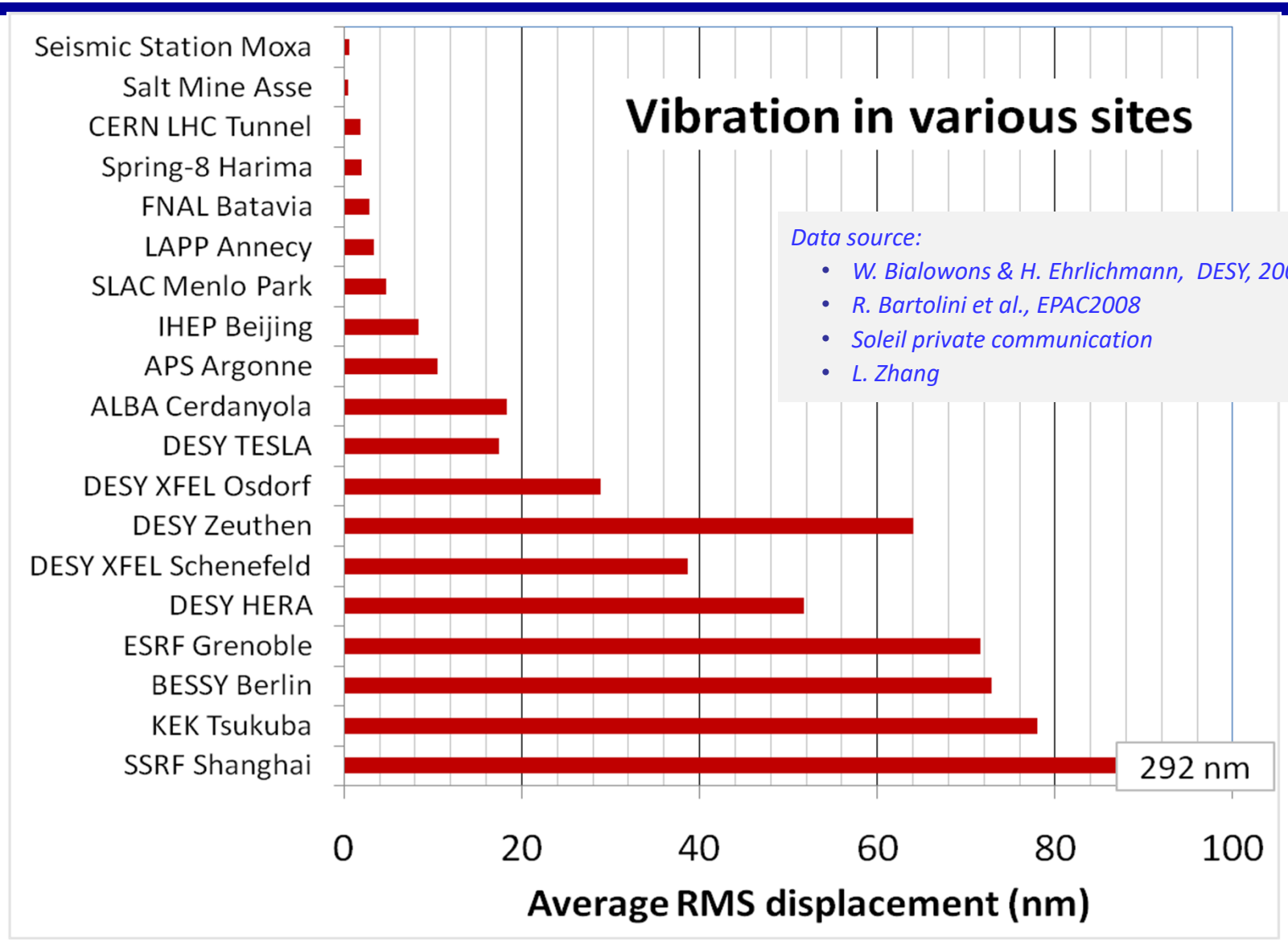


Factors affecting BPM resolution



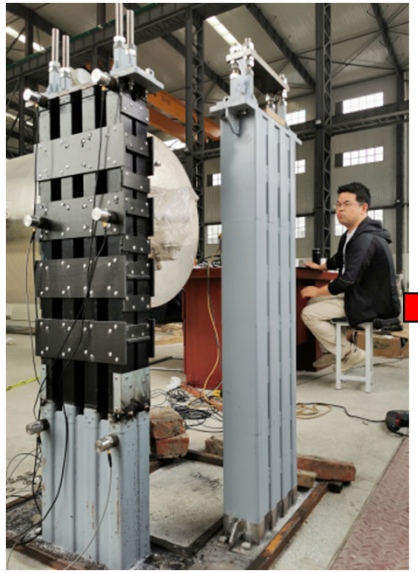
1、BPM support
2、BPM pick-up
3、Signal transmission & cable
4、BPM electronics
5、Ambient temperature

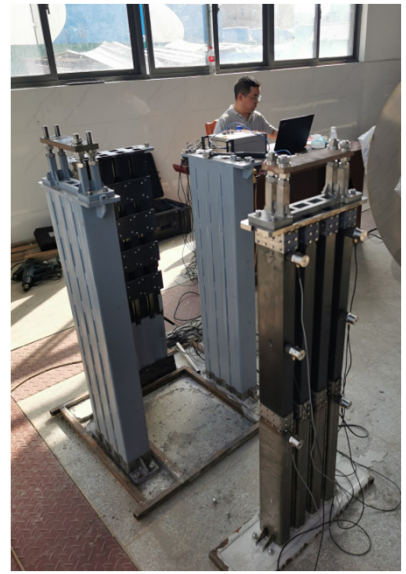
Ground vibration



High stability low expansion BPM support







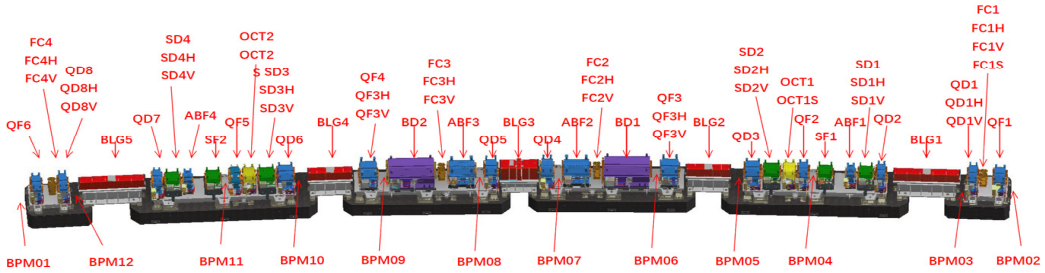
Support	1st-order frequency (Hz)	2nd-order frequency (Hz)	vibration amplification factor (H)	vibration amplification factor (V)
Invar (simulation)	61.42	120.99	----	----
Invar(test)	**55.35**	**109.64**	**1.006**	**1.034**
Composite (simulation)	84.702	154.69	----	-----
Composite4 (test)	**64.86**	**127.735**	**1.124**	**1.021**
Composite5 (test)	**66.23**	**88.75**	**1.05**	**1.03**

Thermal stability： **±20nm**； **μ < 1.02** (No magnetic field within 670mm of the beam)

BPM system

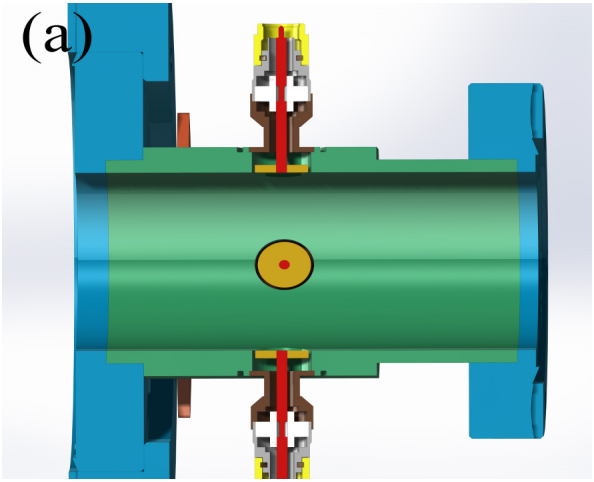
Number and distribution of the HEPS BPMs.

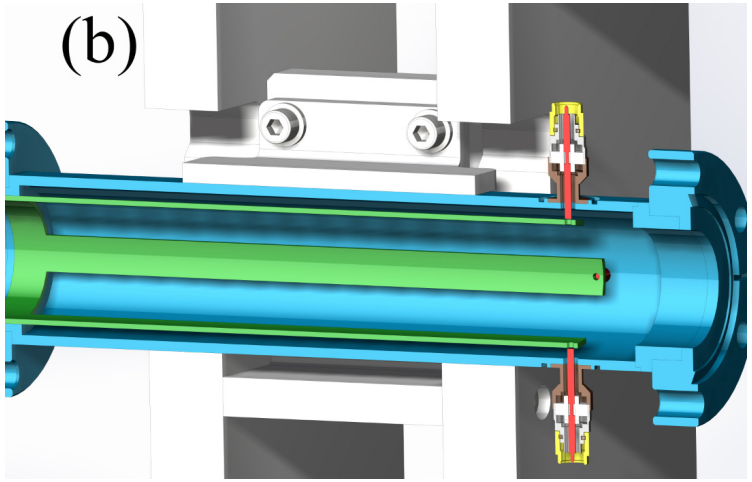
Instruments		LINAC	LTB	BTS	STB	Dump line	Booster	Storage ring
BPM	Button	2	-	-	-	-	79	578
	Stripline	6	8	11	11	2	1	-



LINAC button and Stripline BPMs

Each 7BA unit is equipped with 12 BPMs





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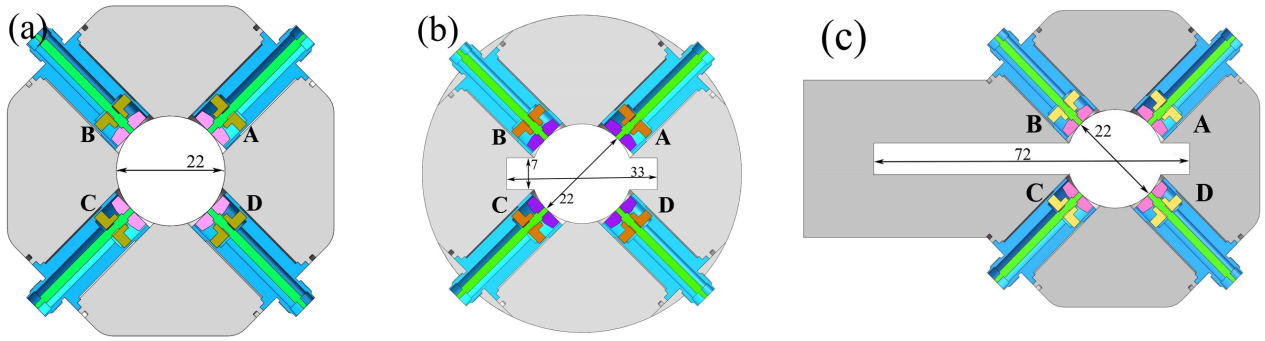
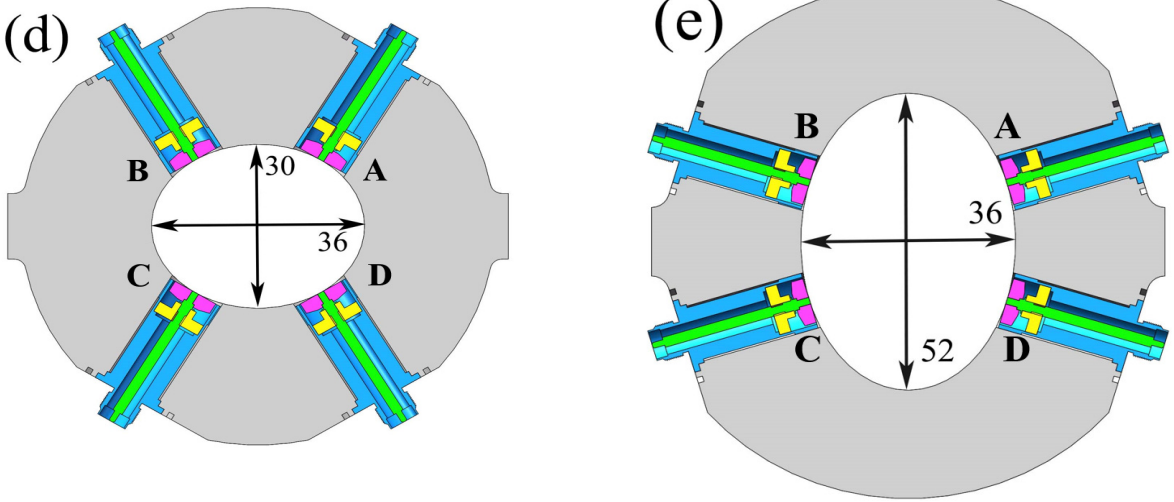
BPM pick-up

Storage ring BPMs.



Booster BPMs.



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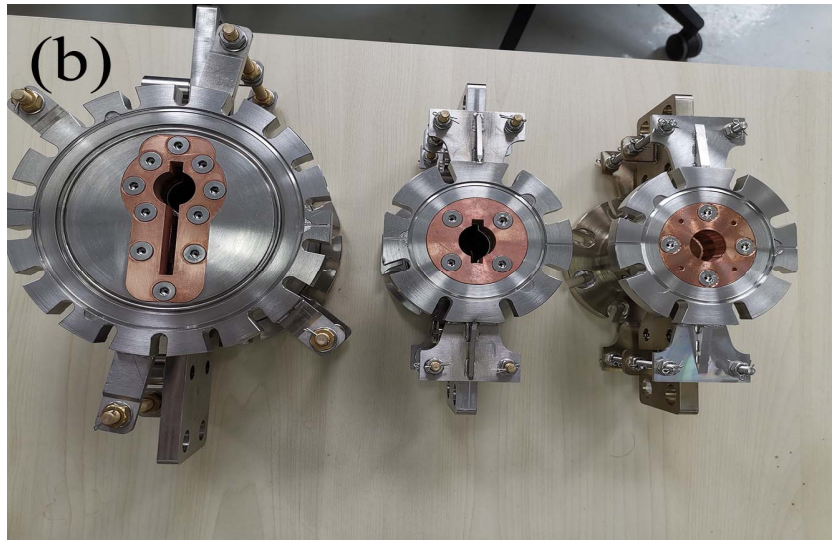
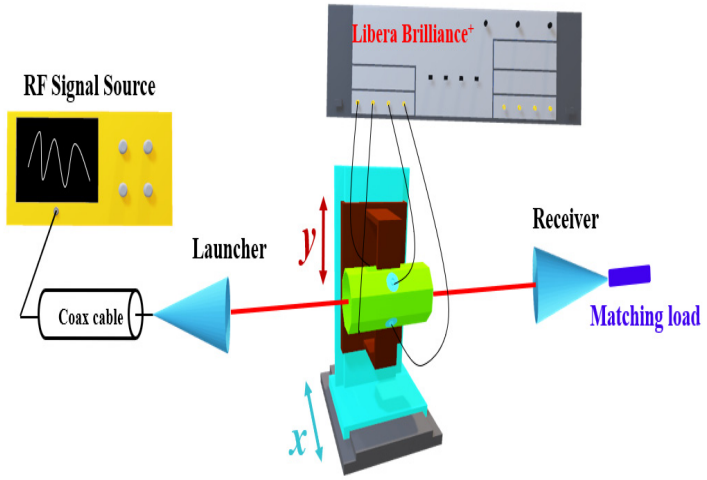
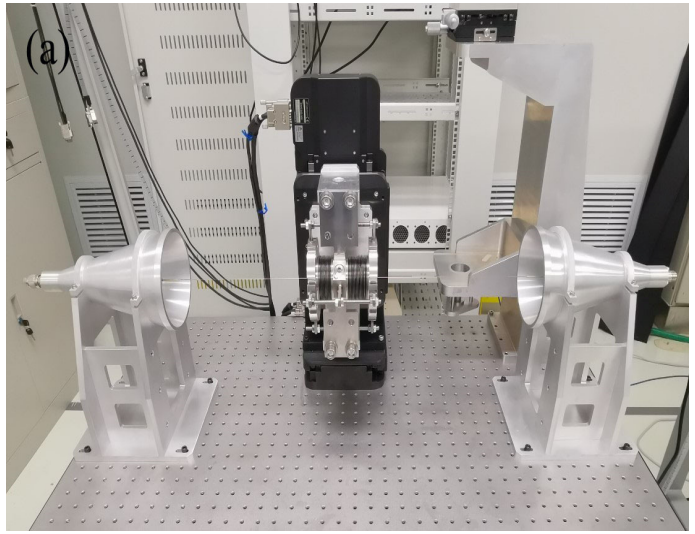
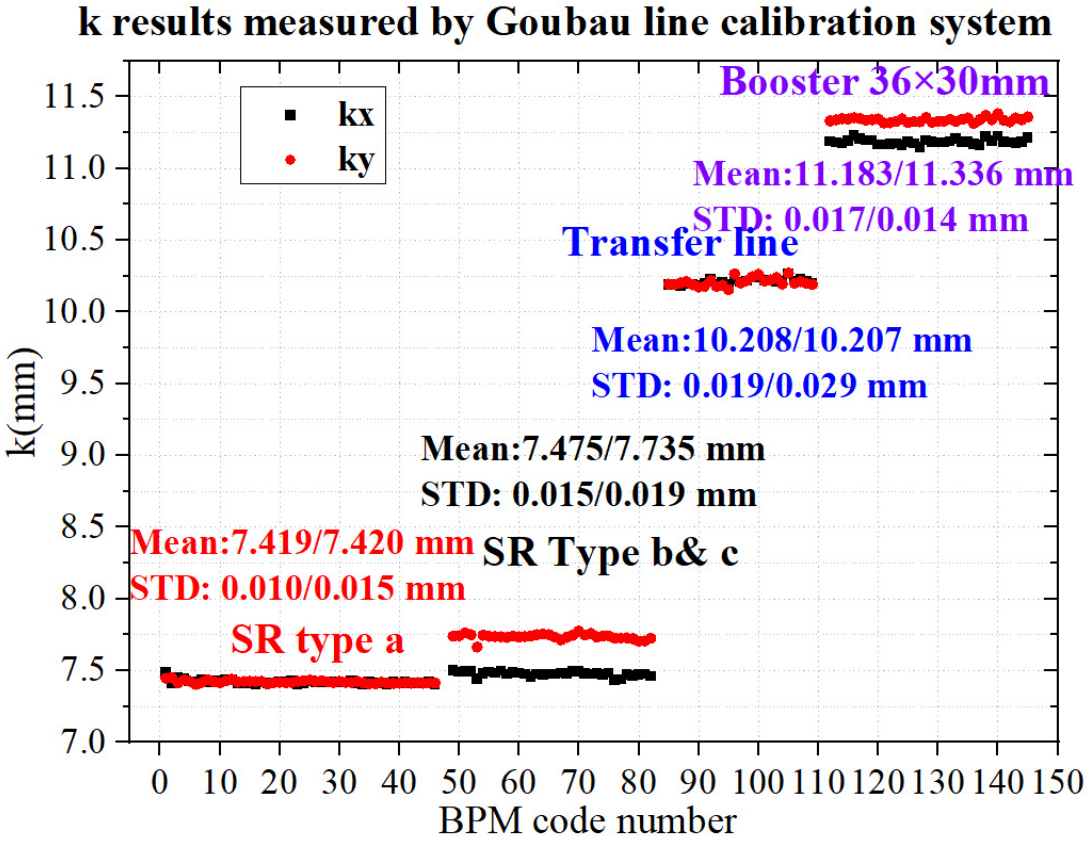


BPM calibration

- A new calibration system based on Goubau line is used for BPM calibration.







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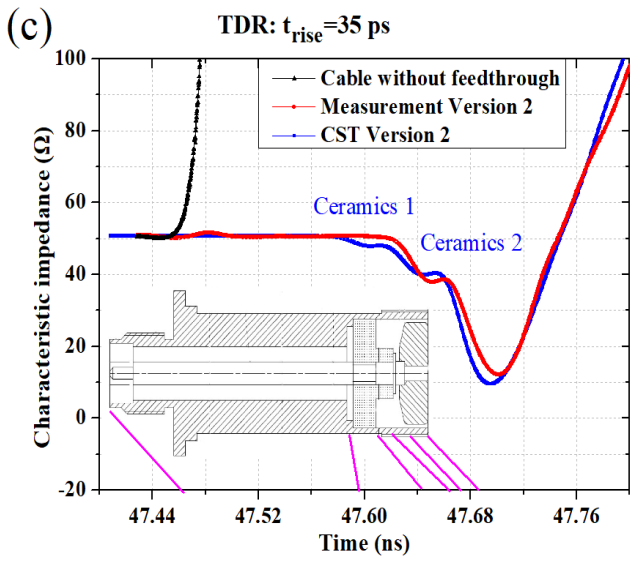
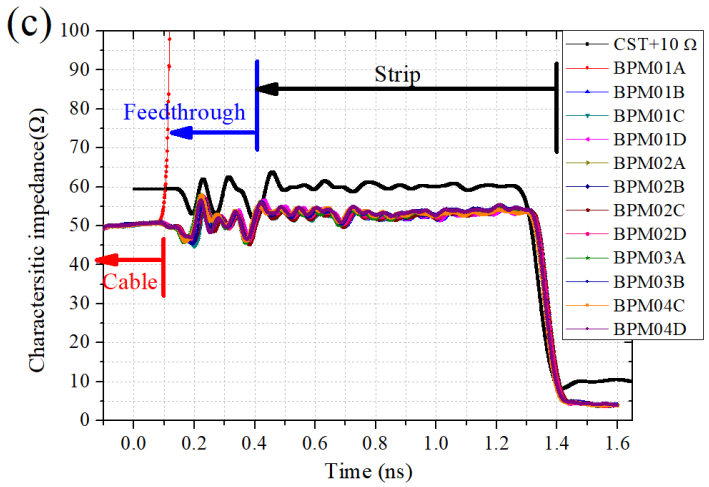
Feedthroughs research and process Improvement

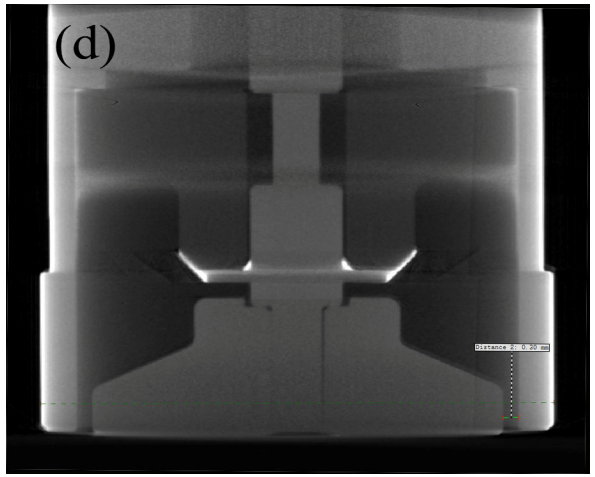


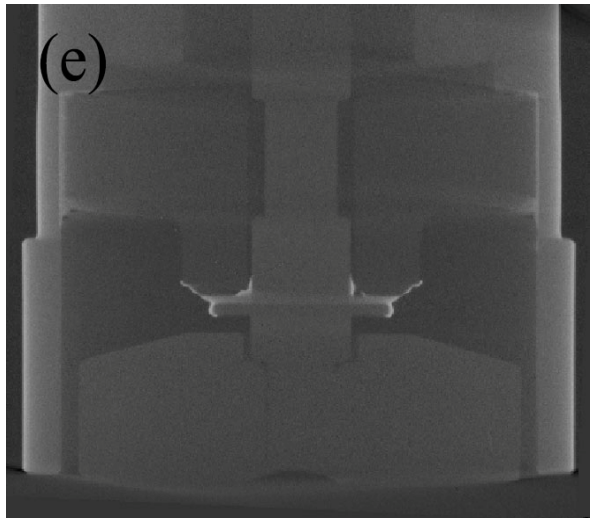
Feedthrough characteristic impedance measured by TDR



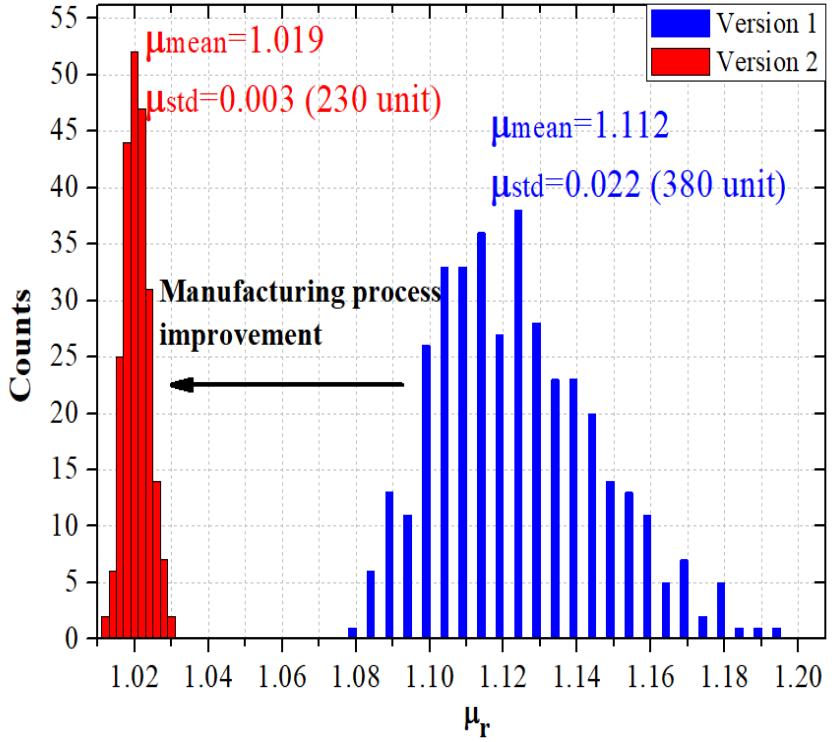
Stripline characteristic impedance measured by TDR

Structural optimization





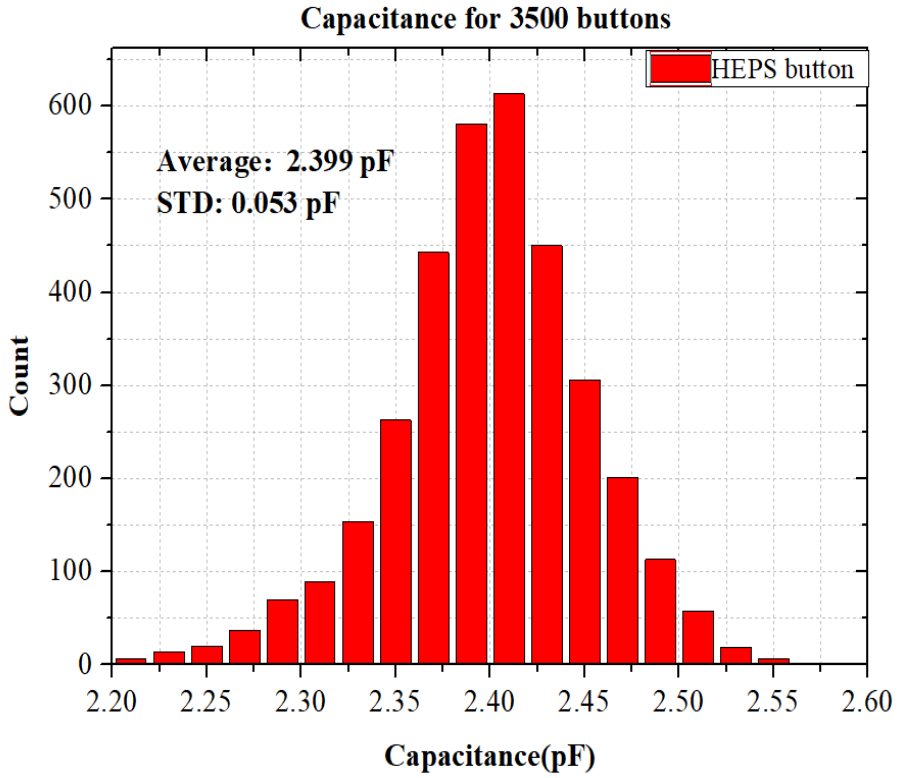
x-ray tomography results for two feedthrough prototypes.

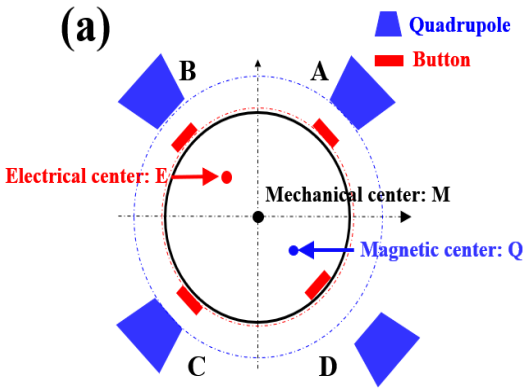


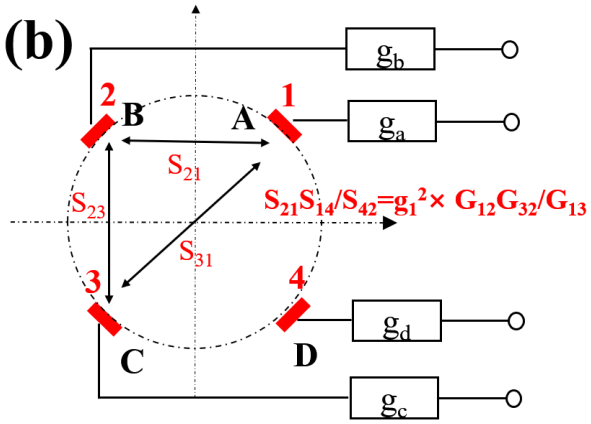
Reducing permeability

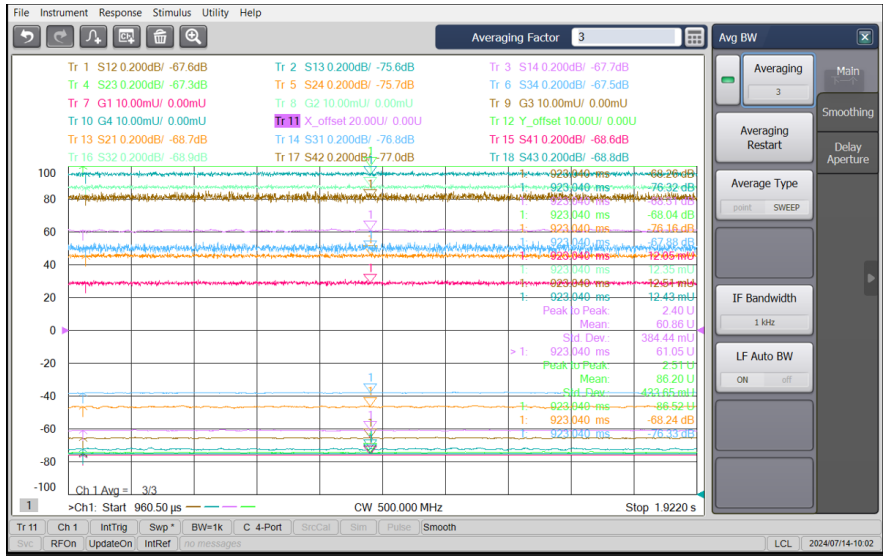
Feedthrough sorting and Electro-mechanical offset measured by VNA

- Capacitance measued by TDR(risetime)









Summary of BPM characterization

Measurement object	Parameters	Standard value	Amount	Average	STD
Stripline	Characteristic impedance	50 Ω	152	51 Ω	0.7 Ω
Feedthrough with button	Radius	4 mm	500	3.991 mm	6 μm
	Distance between the button and welding point	20 mm	500	19.969	6 μm
	Capacitance	2.2 pF (CST)	500	2.385 pF	0.044 pF
	Permeability	<1.03	380	1.112	0.022
	Permeability	<1.03	230	1.019	0.003
Button-type BPM	Distance between the button and pipe axis	16.098 mm	280	16.156 mm	43 μm
	Electro-mechanical offset X/Y	0	578	2.7/3.5 μm	53 /52 μm
	Calibration coefficient Offset X/Y	<1 μm (CST)	62	1 /21 μm	7 /13 μm
	Calibration coefficient k X/Y	11.406 mm/ 11.597 mm (CST)	62	11.182/11.336 mm	20/14 μm
	Calibration coefficient $A_{0,1}/B_{1,0}$	<1 μm (CST)	62	-74/-75 μm	63/60 μm

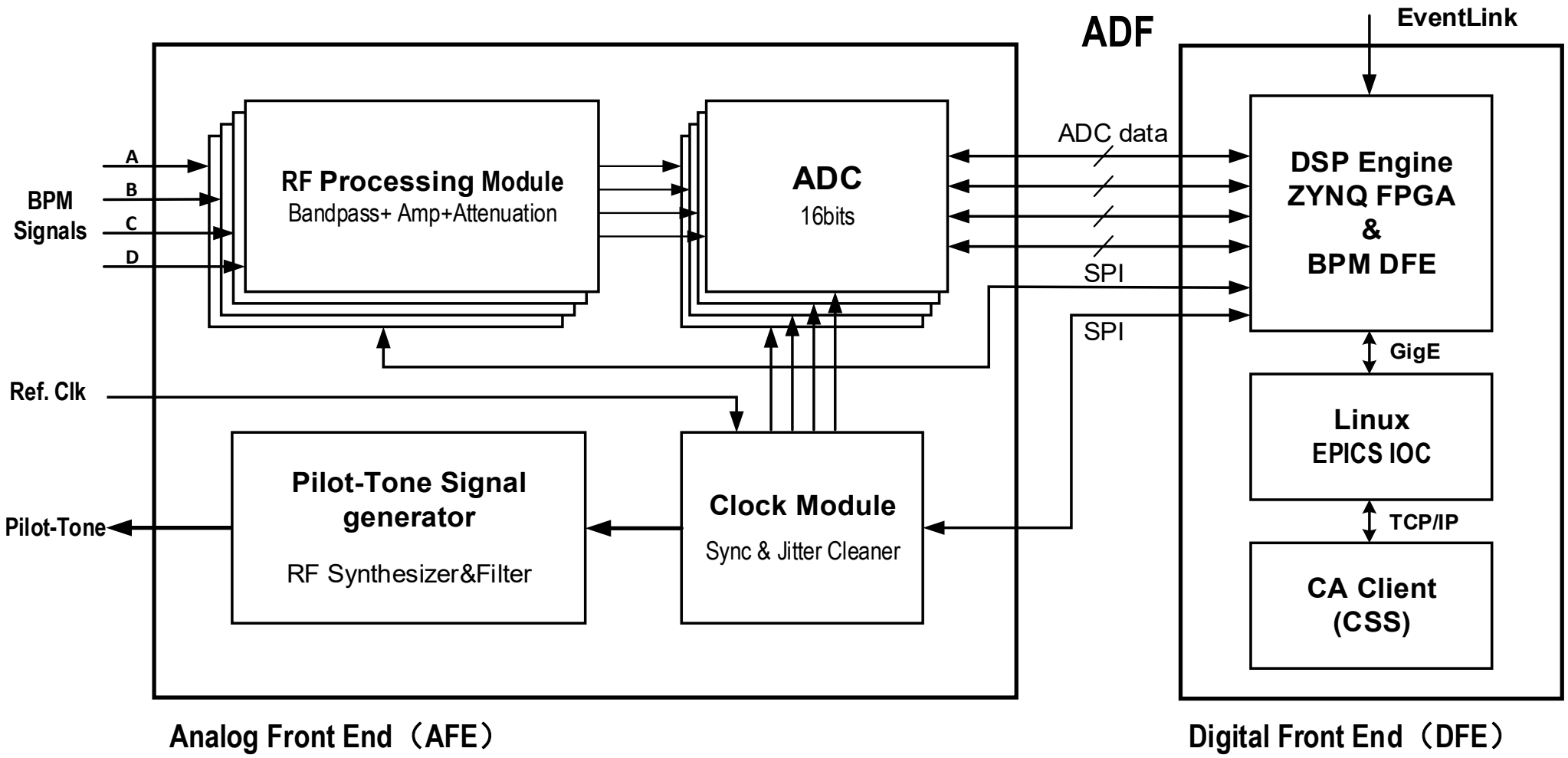
BPM blocks summary

Beam position monitors for the HEPS (TUP11)

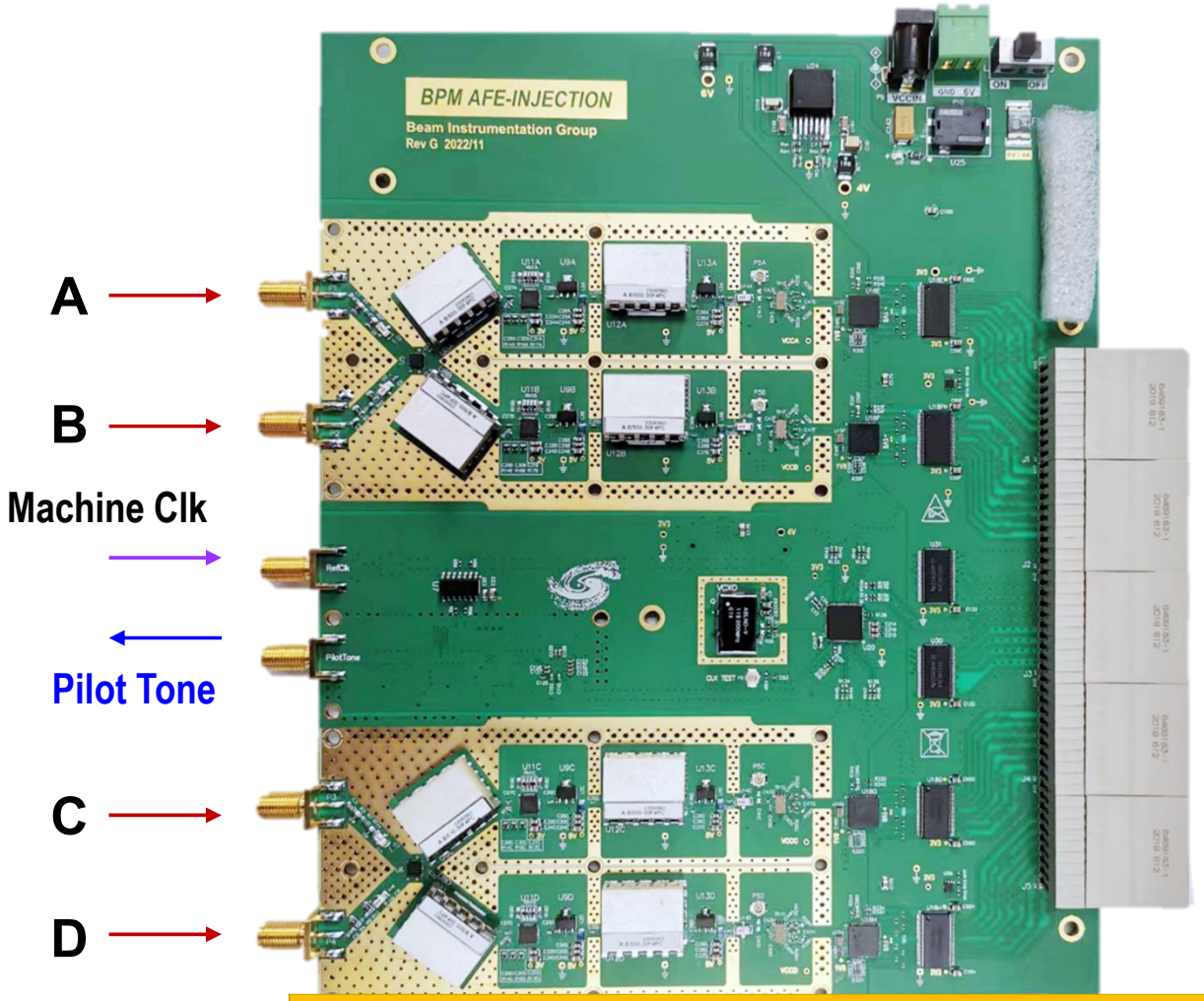
- More detail about BPM can be found in reference

J. He, Y. F. Sui, J. H. Yue, J. S. Cao et al. TUP11 This conference.
J. He, Y. F. Sui, J. H. Yue, J. S. Cao et al. Electro-mechanical offset measurements of beam position monitors. Radiation Detection Technology and Methods (2023) 7:288–296
J. He, Y. F. Sui, J. H. Yue, J. S. Cao et al. Beam position monitor design for the High Energy Photon Source. Meas. Sci. Technol. 2022, 33, 115106.
J. He, Y. F. Sui, J. H. Yue , J. S. Cao et al. Design and fabrication of button-style beam position monitors for the HEPS synchrotron light facility, NUCL SCI TECH (2022) 33:141
J. He, Y. F. Sui, J. H. Yue, J. S. Cao et al. Design and optimization of a Goubau line for calibration of BPMs for particle accelerators. Nucl. Instrum. Methods Phys. Res. A 2023, 1045, 167635
J. He, Y. F. Sui, J. H. Yue, J. S. Cao et al. Preliminary Analysis of Beam Position Monitor Accuracy. Symmetry 2024, 16, 566.
J. He, Y. F. Sui, J. H. Yue, J. S. Cao et al. Beam Position Monitor Characterization for the High Energy Photon Source Synchrotron. Symmetry 2023, 15, 660.
J. He, Y. F. Sui, J. H. Yue, J. S. Cao et al. Development of BPM feedthroughs for the High Energy Photon Source. Radiation Detection Technology and Methods (2022) 6:460–469

BPM electronics



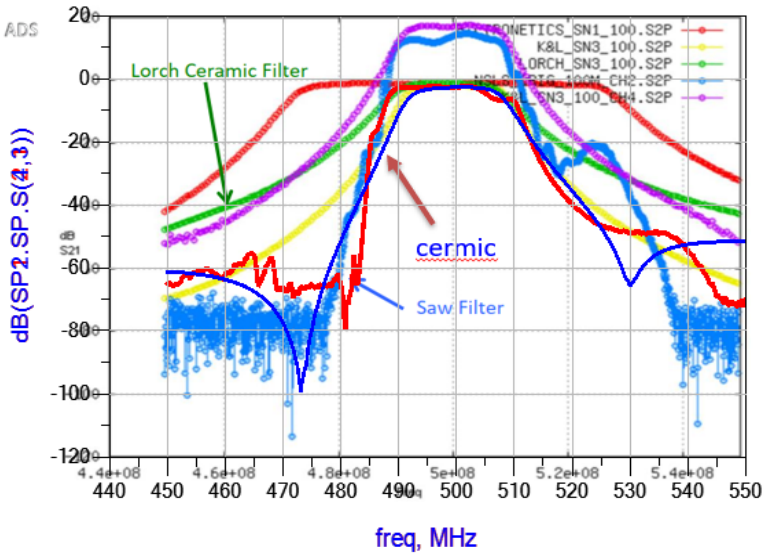
Analog Front End Board (AFE)



Low noise & Impedance matching

Performance Features

- ☑ P1dB = +18.5dBm (at ADC Input)
- ☑ IP3 = +39 dBm (at ADC input)
- ☑ NF =6.0dB (LPF and SAW Filter)
- ☑ Channel to Channel Isolation > 40dB
- ☑ Phase difference < 10°
- ☑ Amplitude difference < 5%
- ☑ -3dB Bandwidth ≈ 20MHz



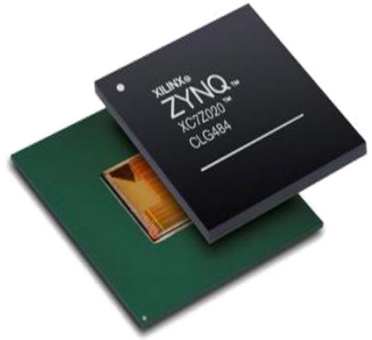
Receiver S-Parameter Characterization

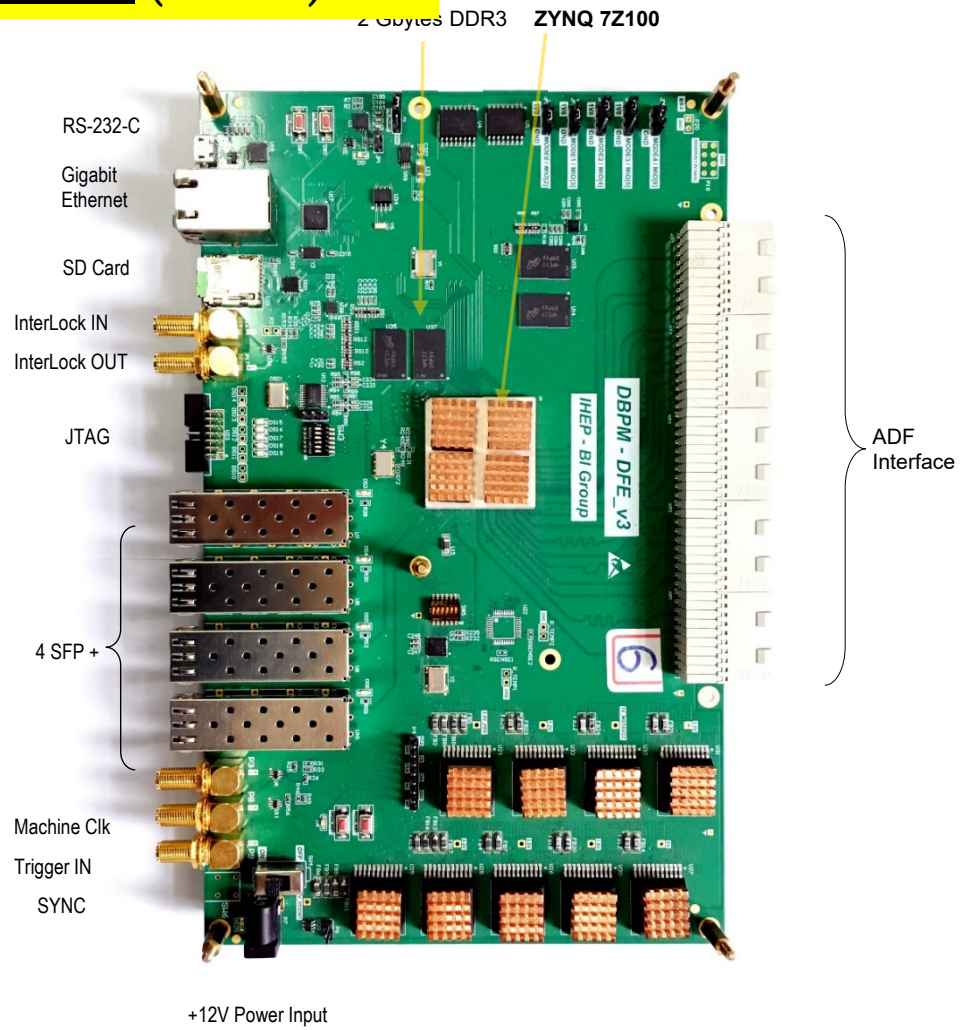
Digital Front End Board (DFE)

Development of digital beam position monitor for HEPS (TUP24)

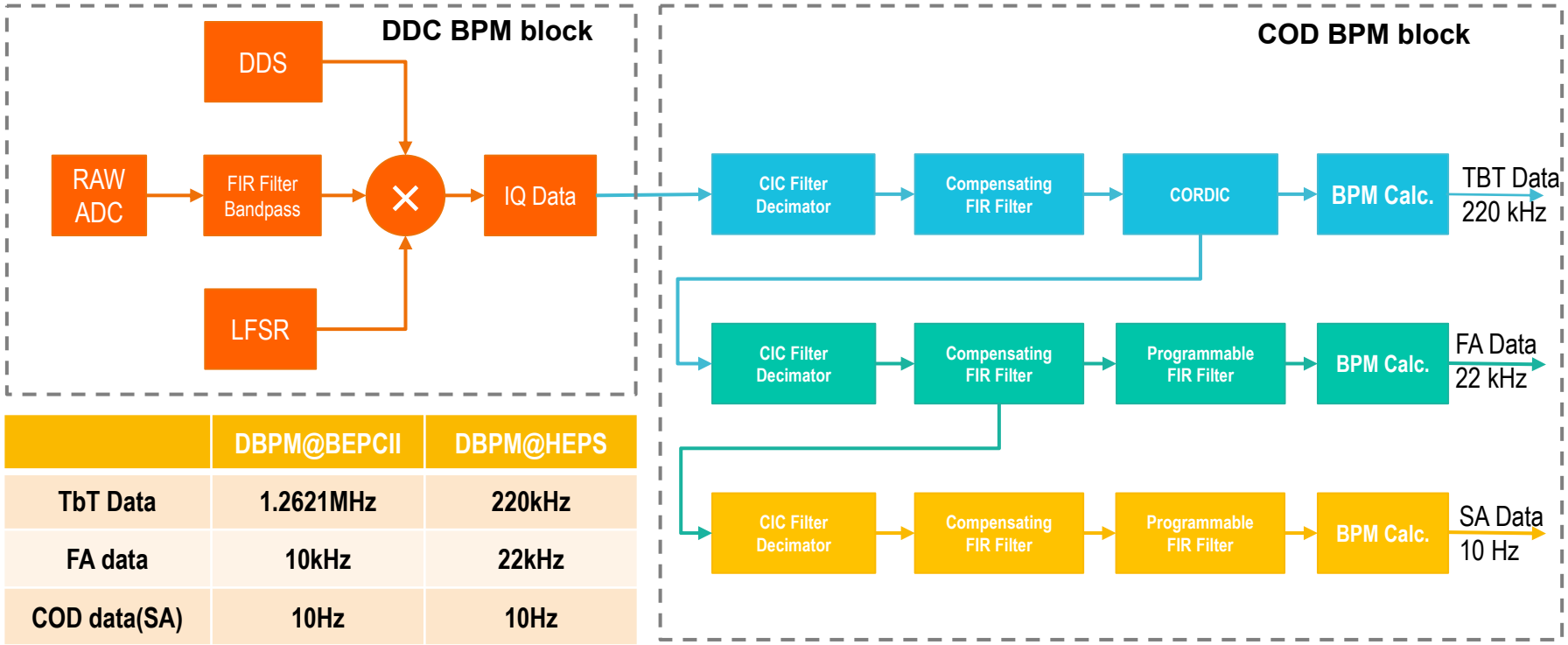
Features::

- Xilinx ZYNQ FPGA (XZ7100)
- Hard dual-core ARM A9 processor
- Beam signal processing with DDC+CIC+FIR
- Runs standard Debian based Linux Operating System
- Embedded IOC
- Boot via 32Gbyte micro SD-Card
- Gigabit Ethernet
- 2Gbyte DDR3 Memory (SO-DIMM Module)
- Four 6.6Gbps SFP modules
- Embedded Event Receiver
- Fast Orbit Feedback
- 32Mbit FLASH memory





Digital Signal Processing Block

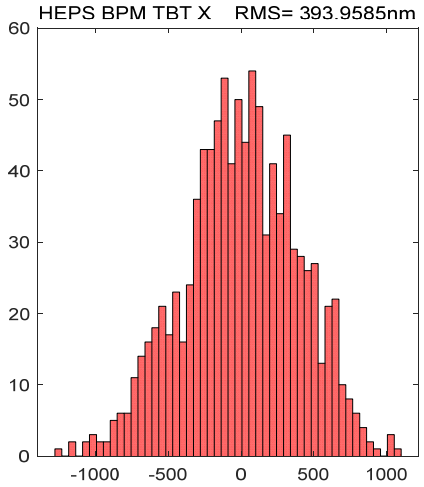


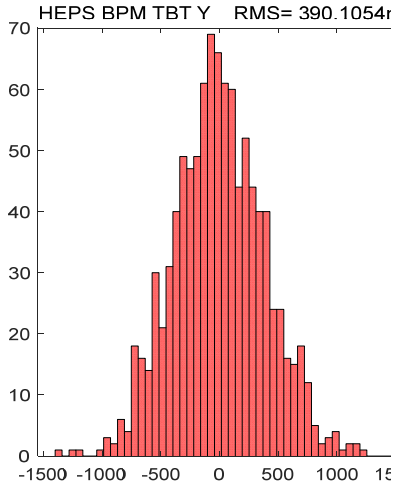
	DBPM@BEPCII	DBPM@HEPS
TbT Data	1.2621MHz	220kHz
FA data	10kHz	22kHz
COD data(SA)	10Hz	10Hz

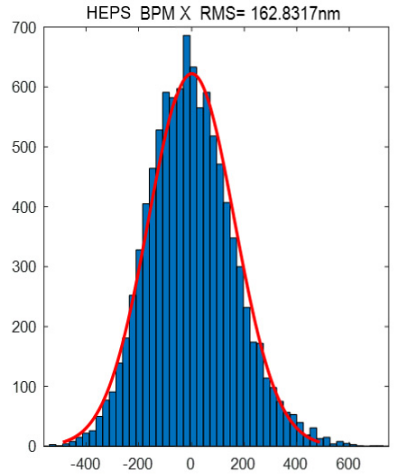
LFSR: Linear Feed-back Shift-Register
FIR filter : Finite Impulse Response filter
CIC filter : Cascaded Integrator-Comb filter
DDS : Direct Digital Synthesis

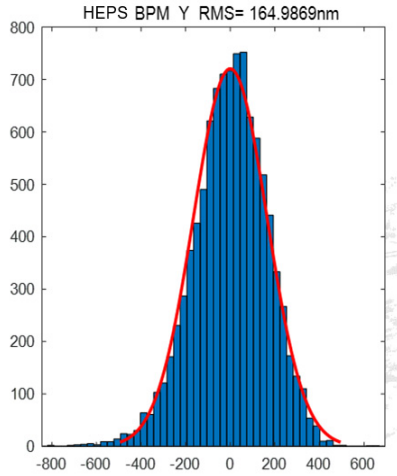
DDC BPM Block generates IQ data with NCO&ADC The purpose of band-pass filter is to remove the baseline of ADC;
COD BPM Block generates TbT, and SA data.
DSP filter = CIC+FIR for LowPass Filter and Decimator;

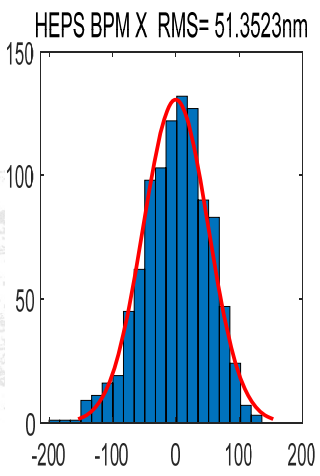
Resolution of BPM

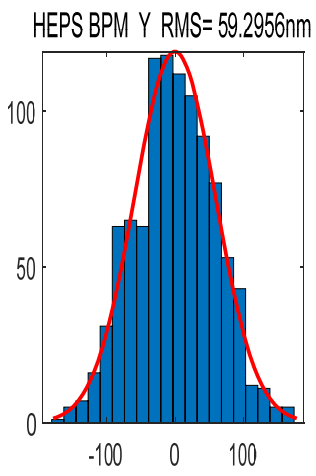










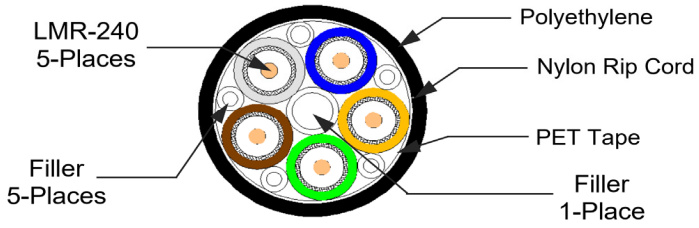


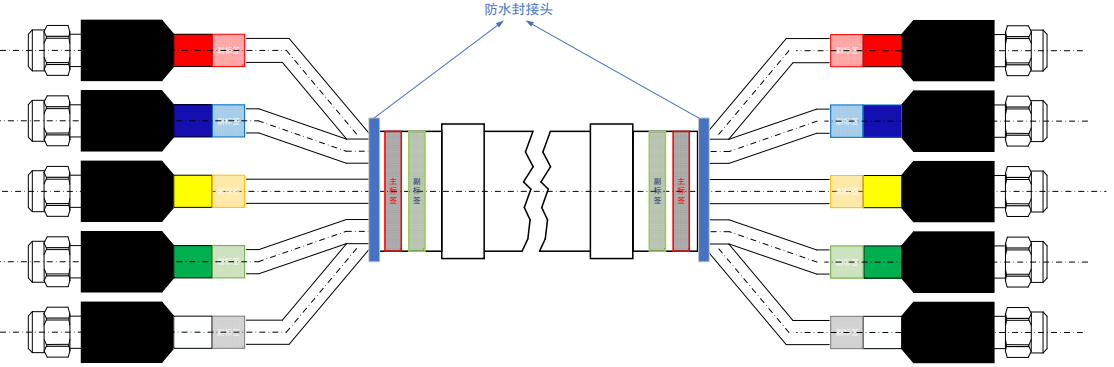
- **tbt x rms ≈ 393 nm**
- **tbt y rms ≈ 390 nm**

- **FA x rms ≈ 162 nm**
- **FA y rms ≈ 164 nm**

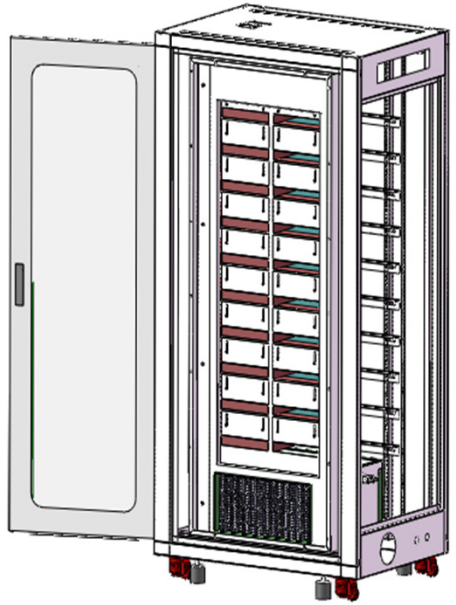
- **SA x rms ≈ 51 nm**
- **SA y rms ≈ 59 nm**

Bundle cable & thermal stability cabinet

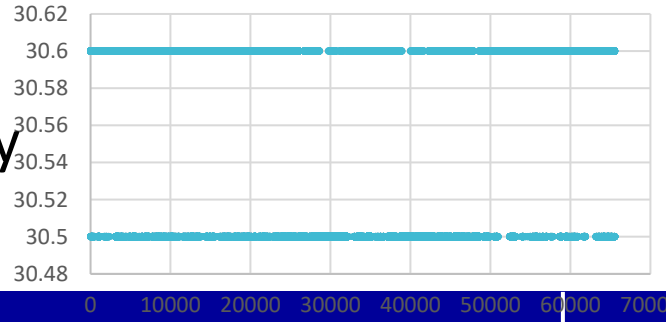




Bundle cables



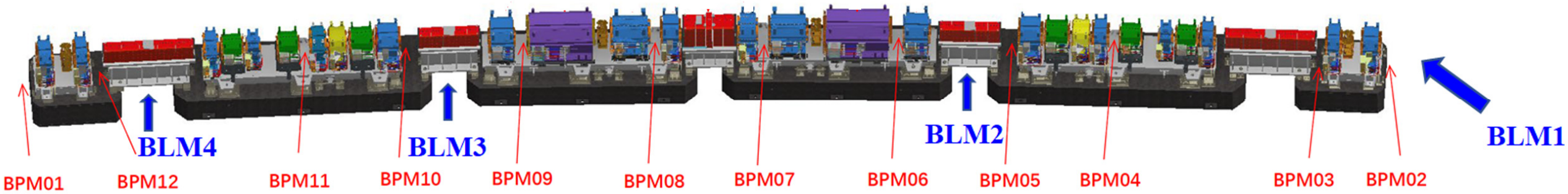
Channel 26(℃)



Temperature control accuracy
±0.1℃

Beam loss monitor

THP28 & WEP54

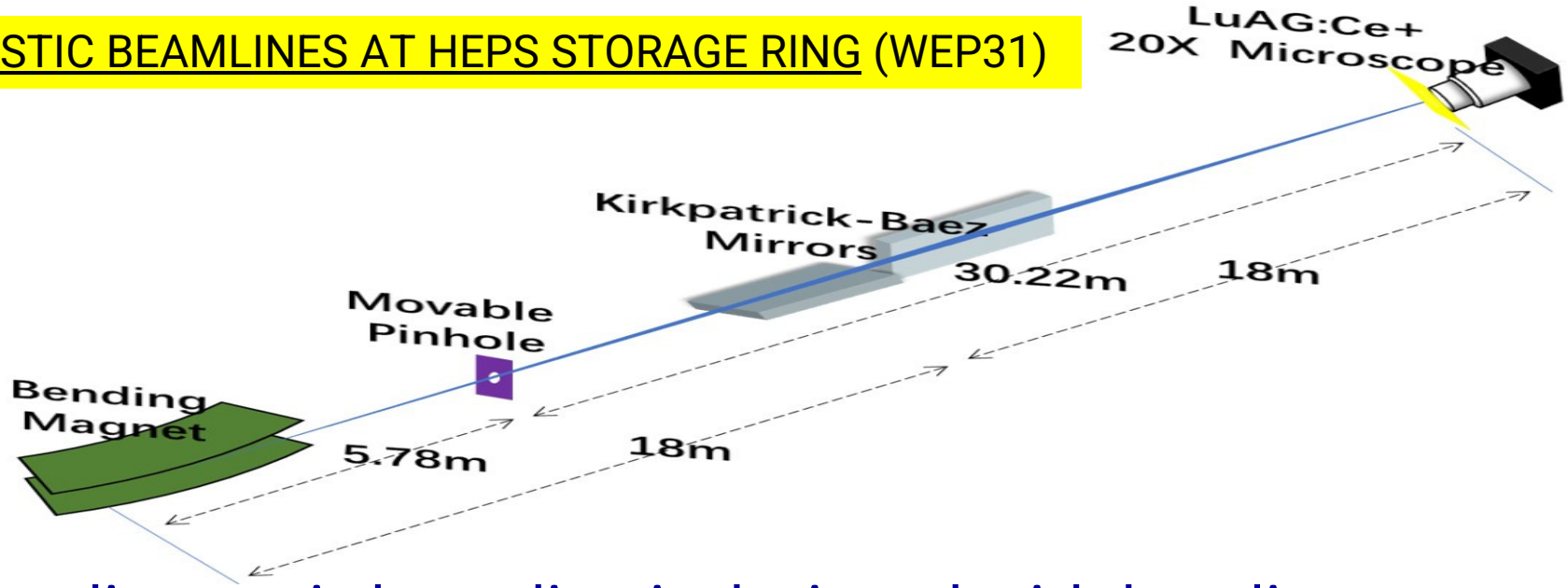


BLM(Beam Loss Monitor)

- 4 beam loss monitors （BLM） have been installed in each of the 48 HEPS cell
- 1 BLM is located on the inner side of straight section, the other 3 BLMs are located on the inner side part of bending magnets
- Data acquisition based on open hardware-RedPitaya , can give turn by turn beam loss data

Synchrotron Radiation Based Beam Diagnostics

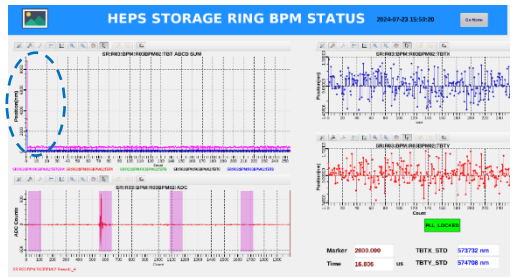
BEAM DIAGNOSTIC BEAMLINES AT HEPS STORAGE RING (WEP31)



- X-ray beam diagnostic beamline is designed with bending magnet as source point.
- X-ray diagnostic beamline (XBL) is dedicated to capturing beam image and measuring beam sizes using X-ray pinhole and KB mirror imaging.
- Pinhole and KB mirrors share the same source point and also the same X-ray camera, and they are both movable by remote control.

Commissioning of beam instrumentation

HEPS Commissioning Time-Line

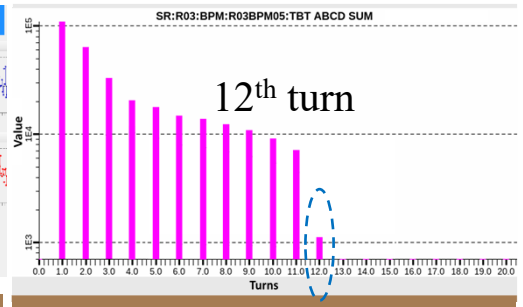


First injection

07.23

07.23

First turn

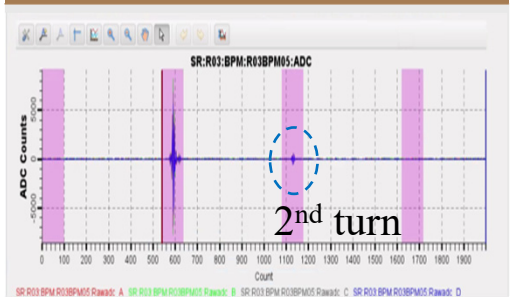


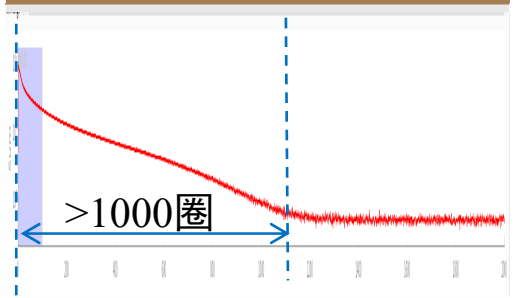
10 turns

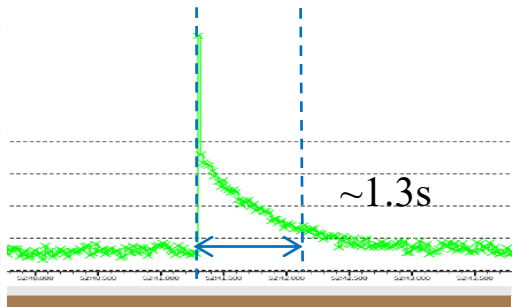
07.29

08.04

1000 turns





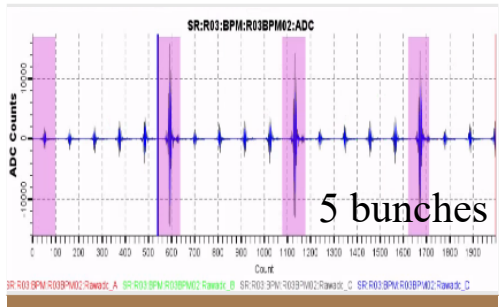


Beam stored

08.06

08.06

60uA



Multi-bunch

08.08

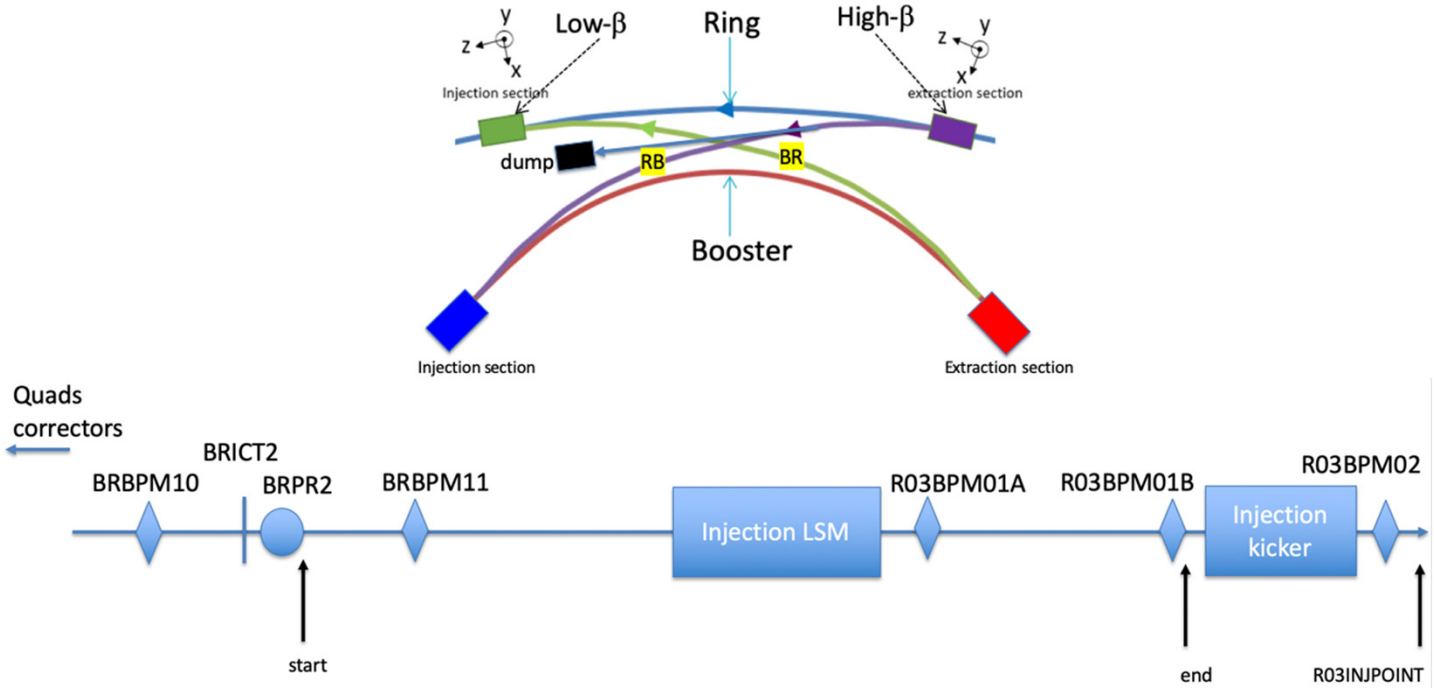
08.15

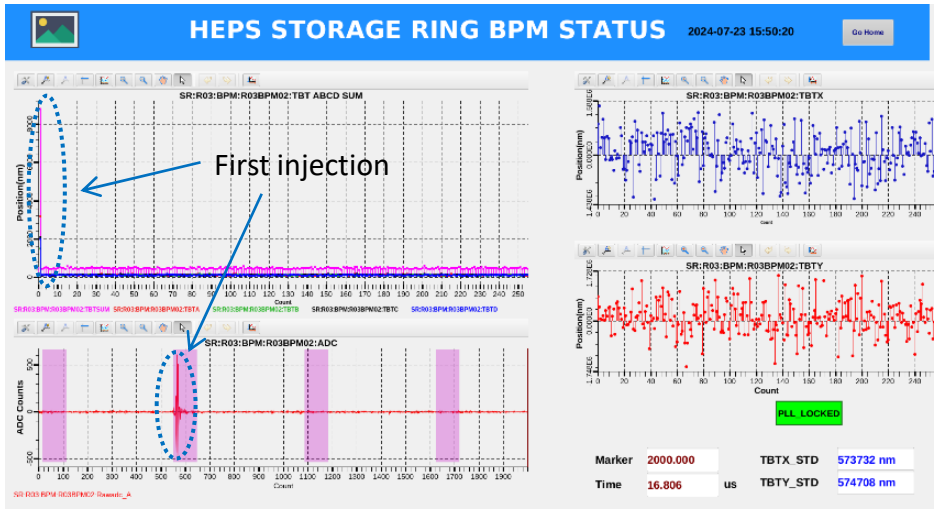
7 mA

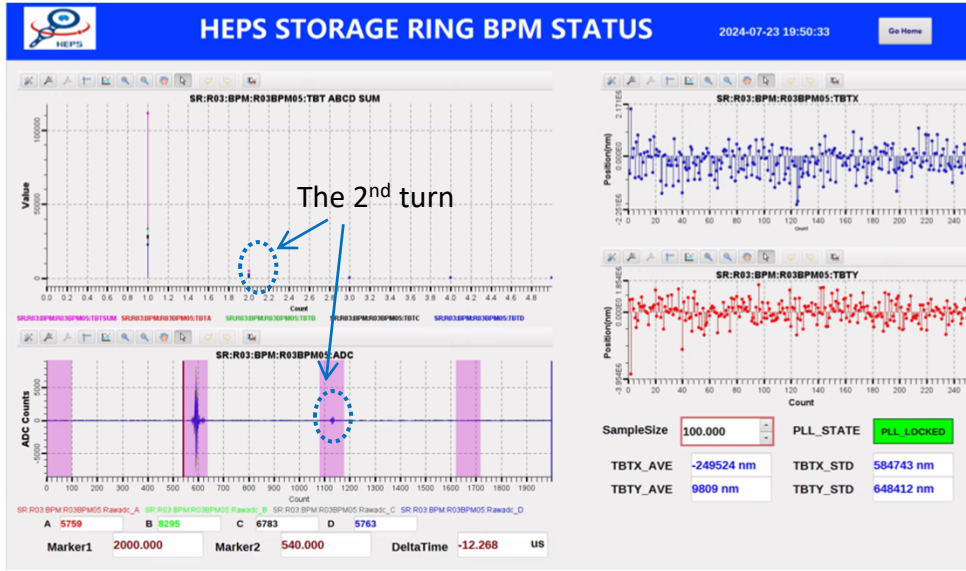
10 mA

08.18

First injection





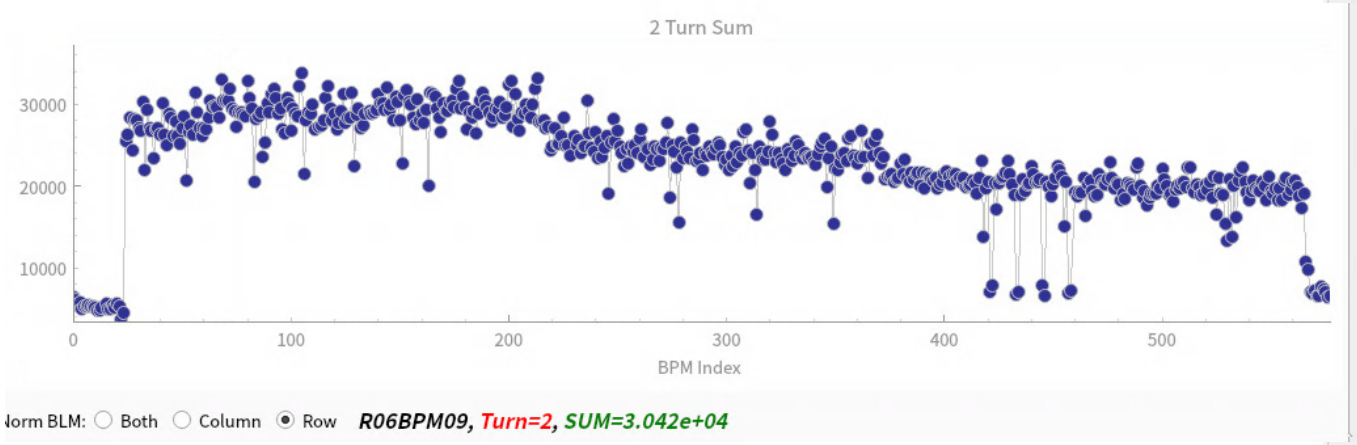


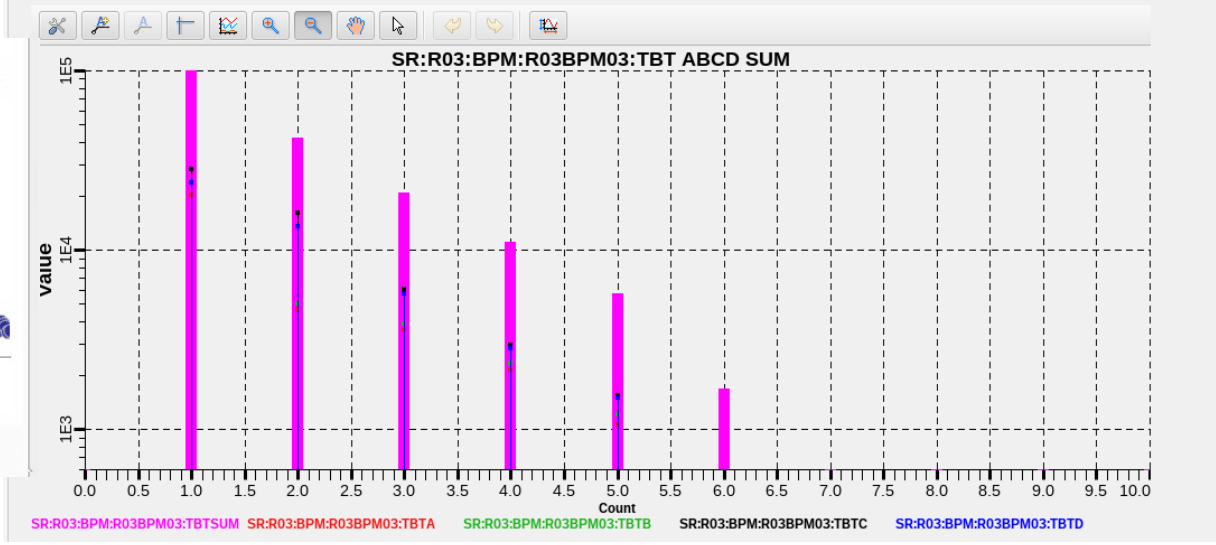
13:20, Beam transport from the booster to the end of the high-energy transport line

15:10, First injection;

19:50, Based on TBT orbit, automatic closed-orbit correction achieves First Turn!

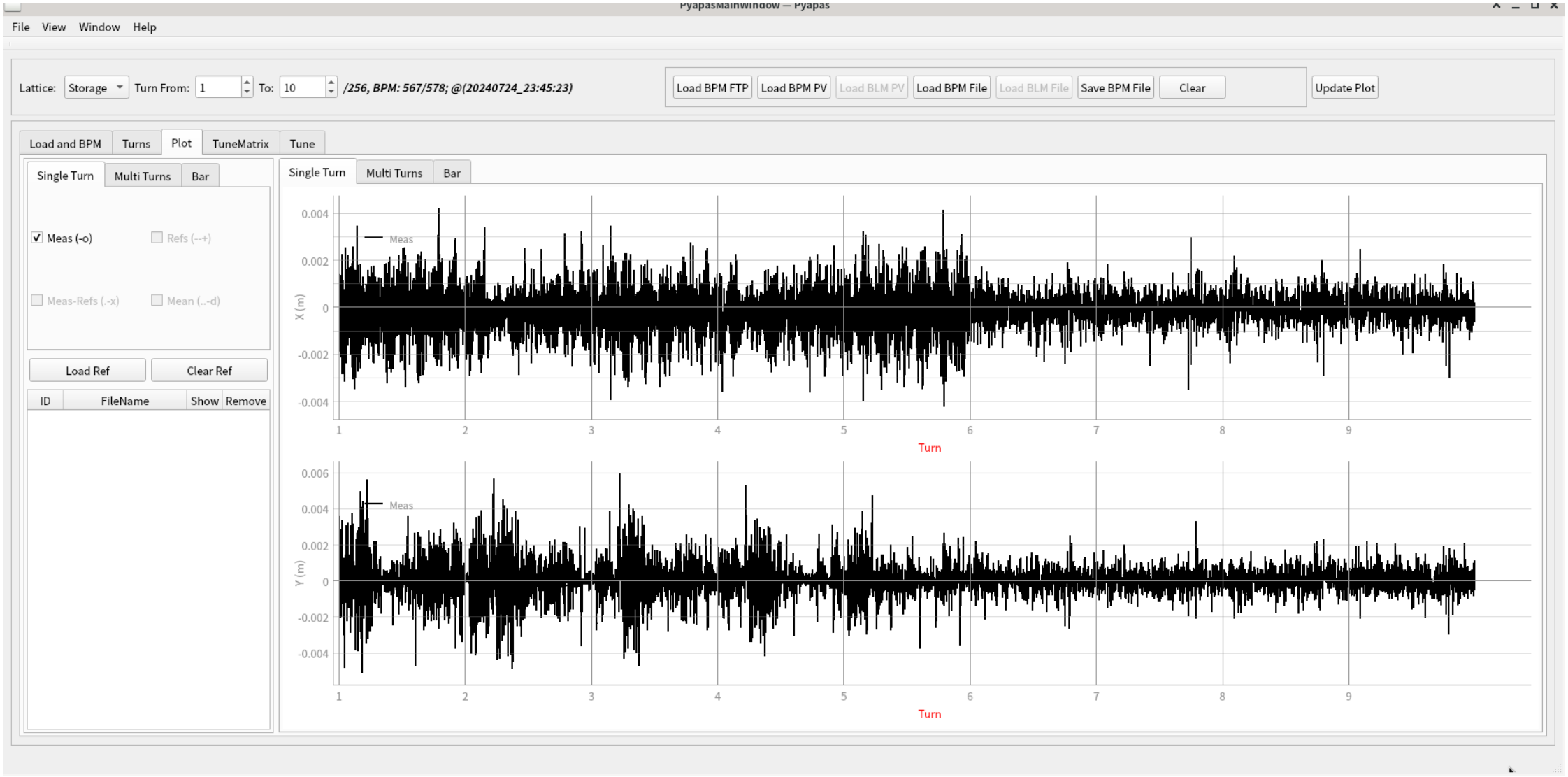
Sum signal of BPM



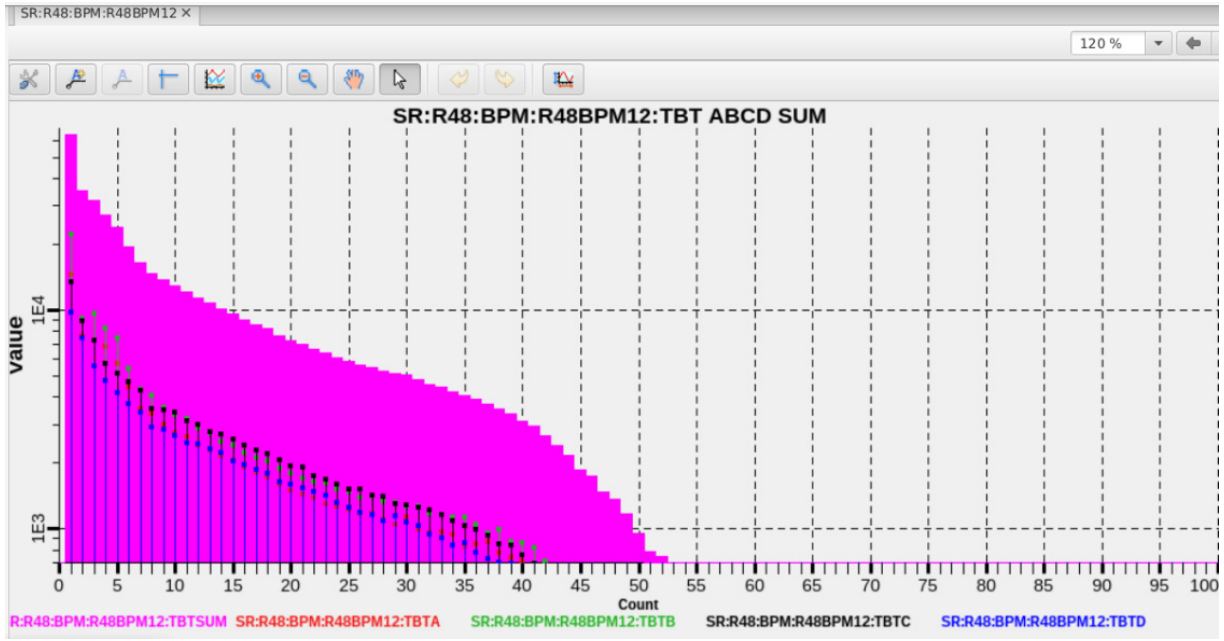


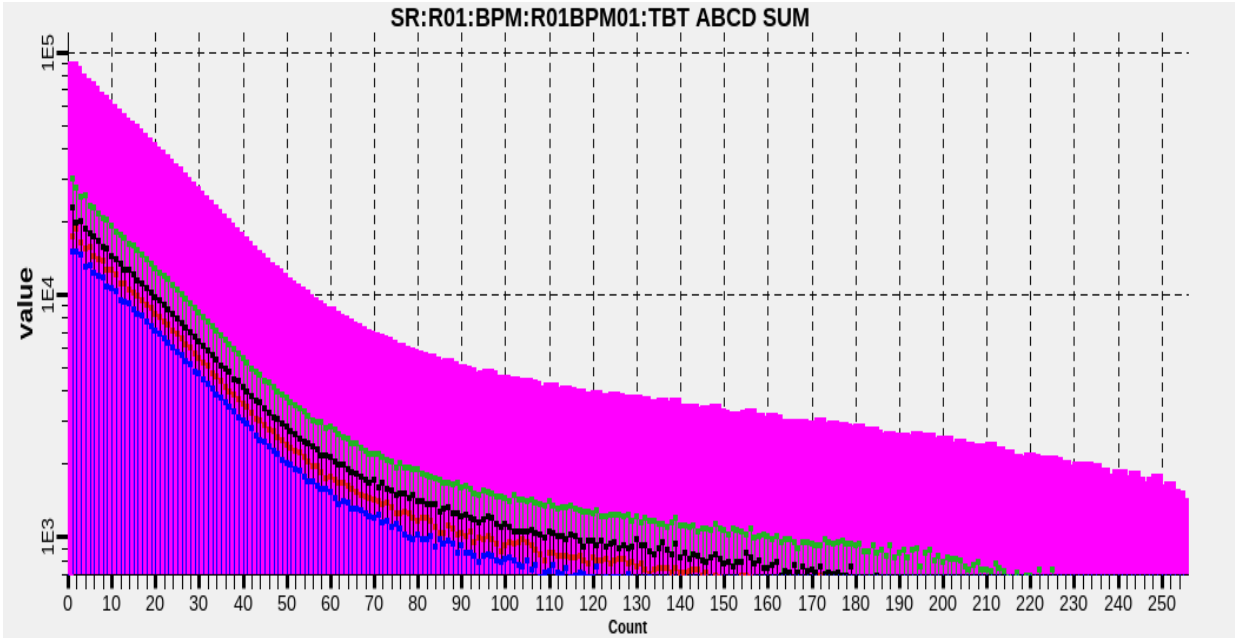
- To display the state of the beam along the ring
- To show number of turns
- To check injected current (sum is proportional to current)
- To find orbit mismatch or spot obstacles (signal drop)

TBT orbit


PyapasMainWindow — Pyapas
File View Window Help
Lattice: Storage Turn From: 1 To: 10 /256, BPM: 567/578; @(20240724_23:45:23)
Load BPM FTP
Load BPM PV
Load BLM PV
Load BPM File
Load BLM File
Save BPM File
Clear
Update Plot
Load and BPM
Turns
Plot
TuneMatrix
Tune
Single Turn
Multi Turns
Bar
Meas (-o)
Refs (--+)
Meas-Refs (.-x)
Mean (..-d)
Load Ref
Clear Ref
ID
FileName
Show
Remove
Meas
X (m)
Y (m)
Turn

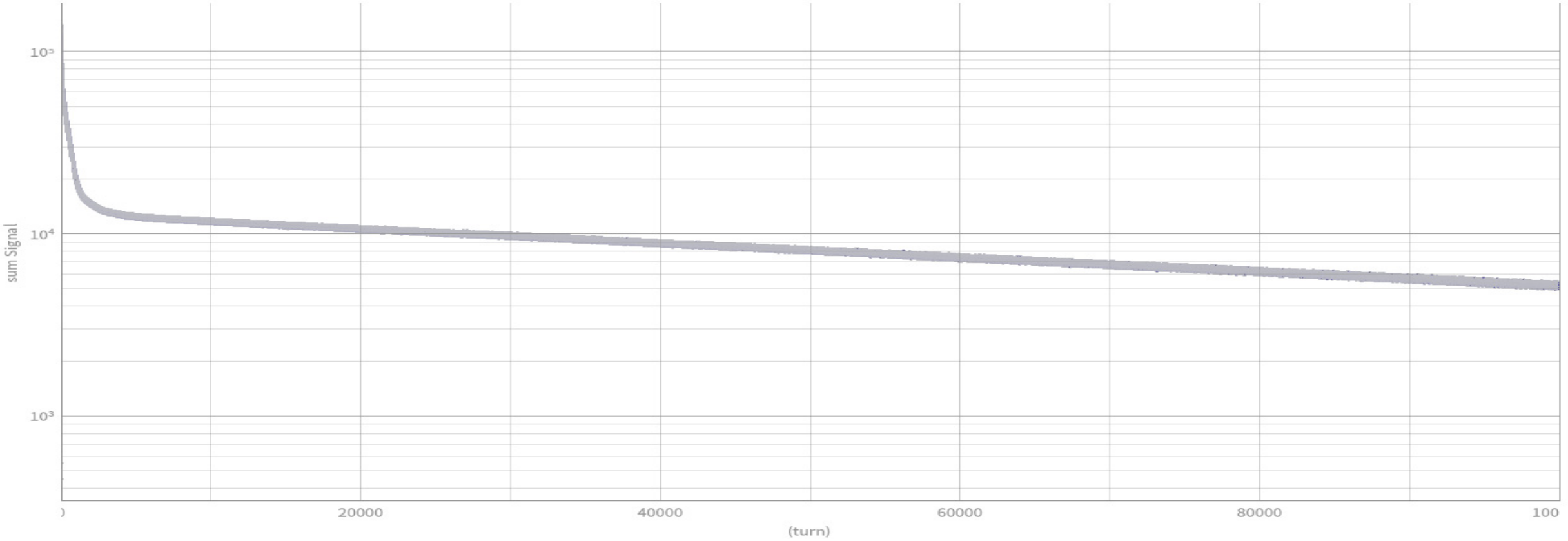
Sum data of BPM





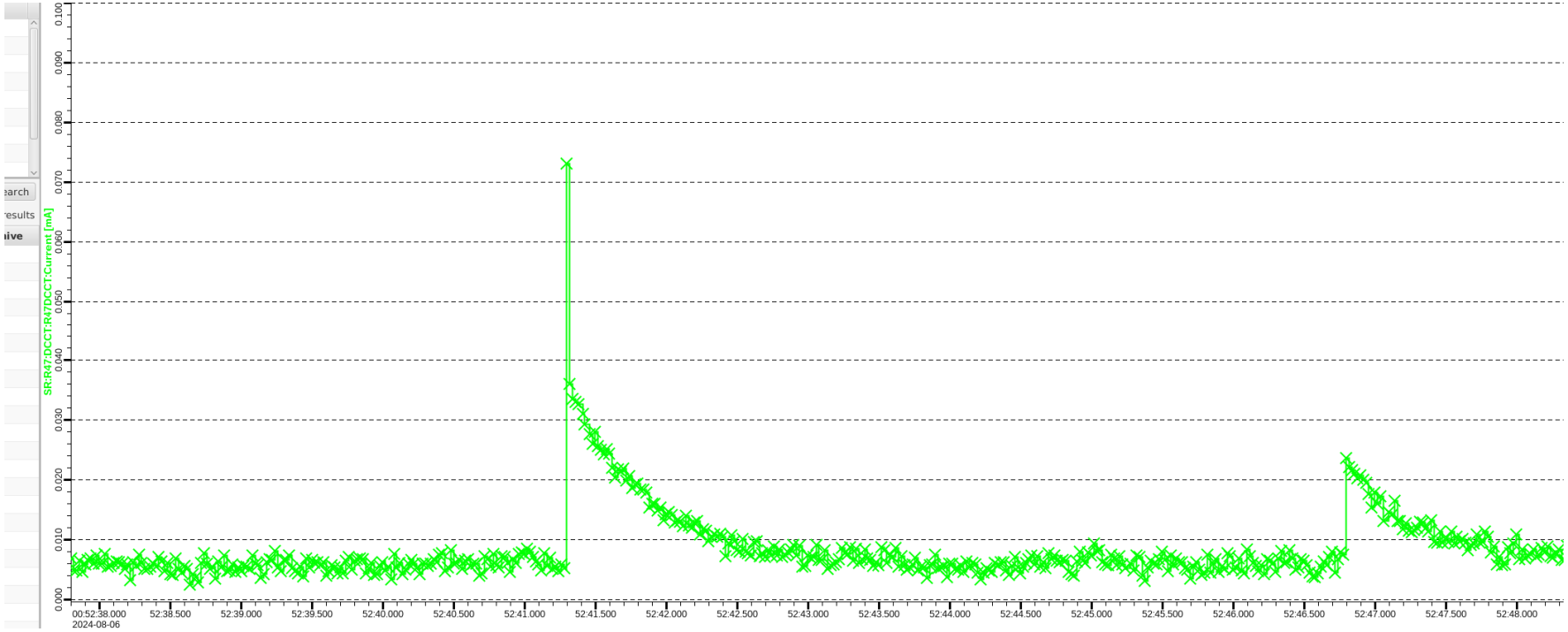
- Open RF cavities
- Increase the strength of the sextupoles setting, approaching the theoretical value

Multi-turns sum data



- 30000 turns

Beam stored

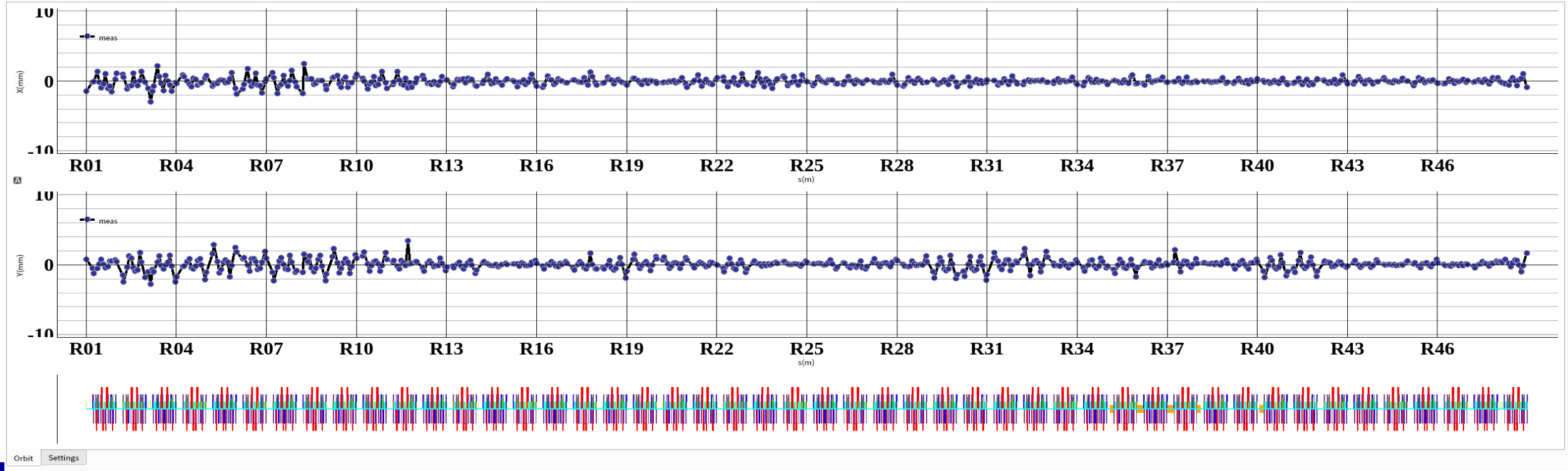


- Beam stored! From NPCT data, we can see the beam stored and the beam life is about ~1.3 s.
- The experiment can be repeated, and we are sure that the beam has been stored.

Beam orbit -SA

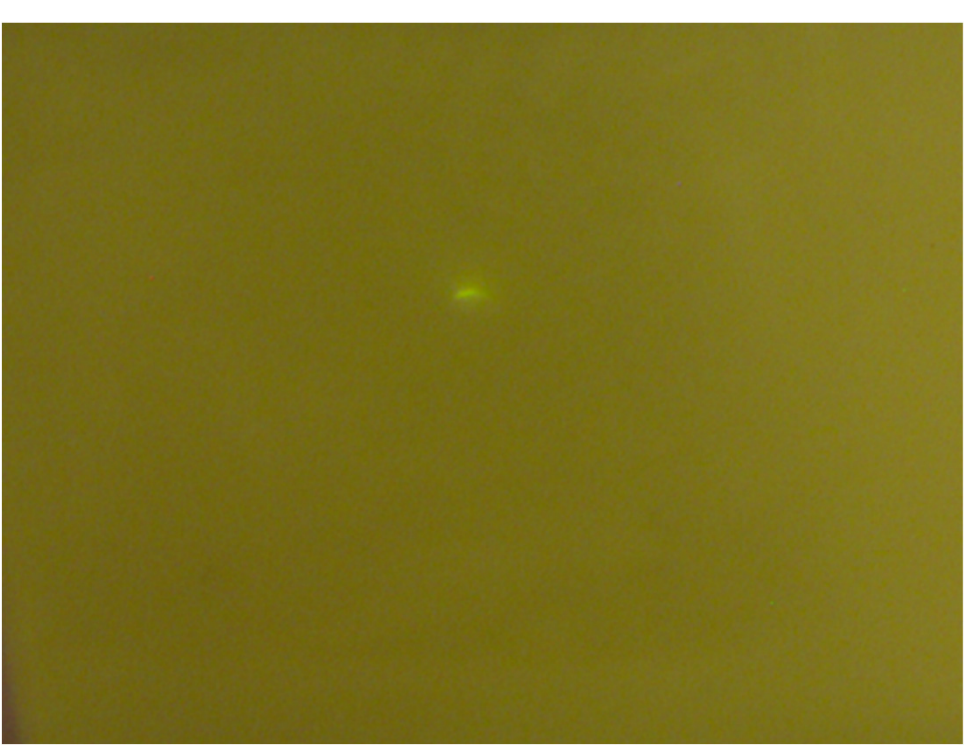
Orbit Display

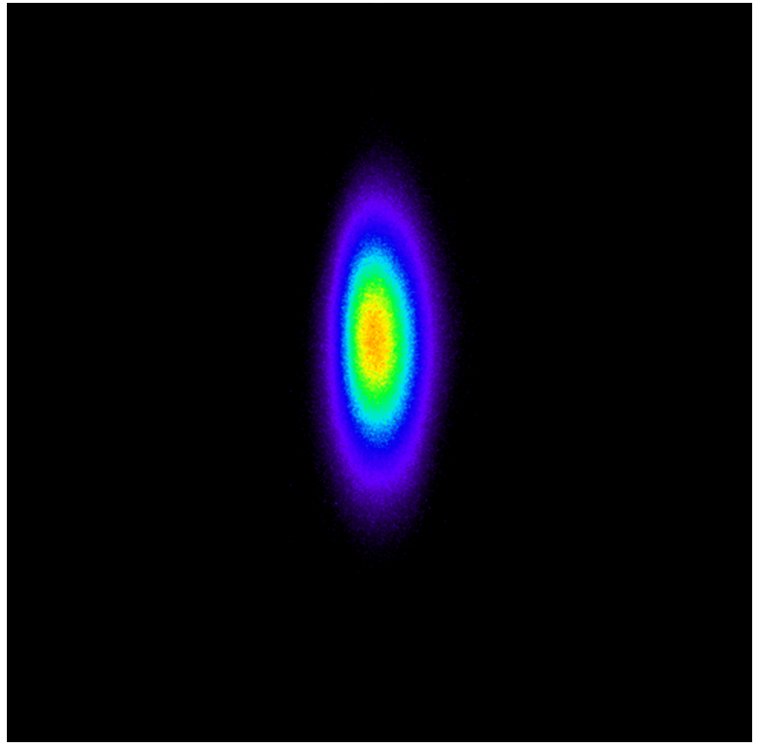
Horizontal	Peak	2.94	mm	Vertical	Peak	3.39	mm
	Rms	0.51	mm		Rms	0.73	mm
	Avg	-0.02	mm		Avg	0.052	mm



Synchrotron Radiation Based Beam Diagnostics

X ray beam line





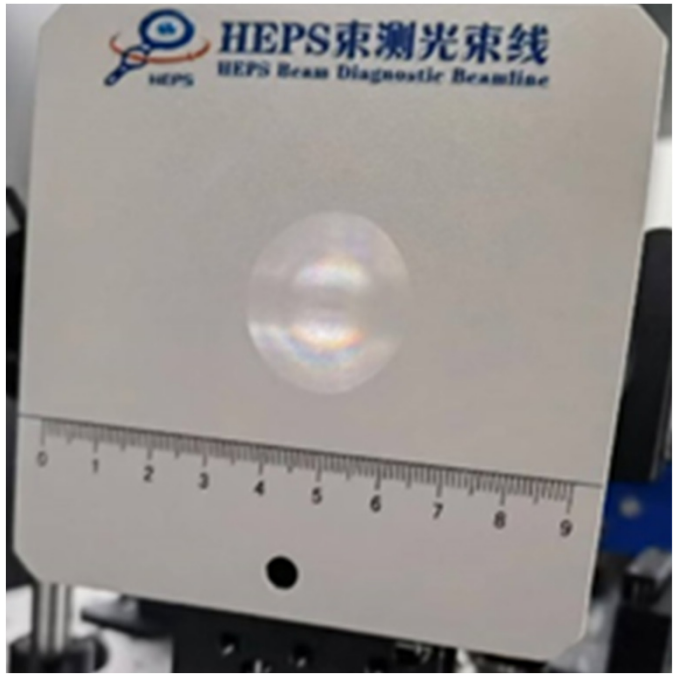
No pinhole

The First synchrotron light was observed when the beam stored(Left)

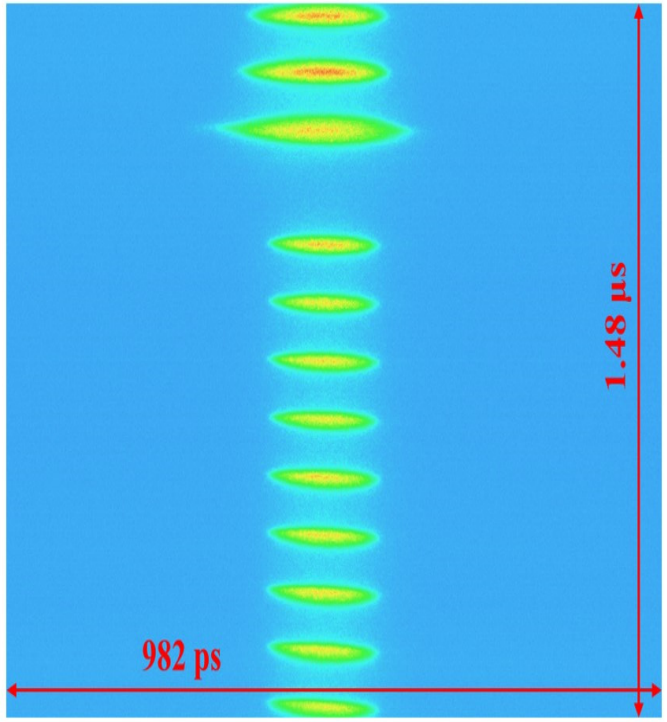
Pinhole
10mA

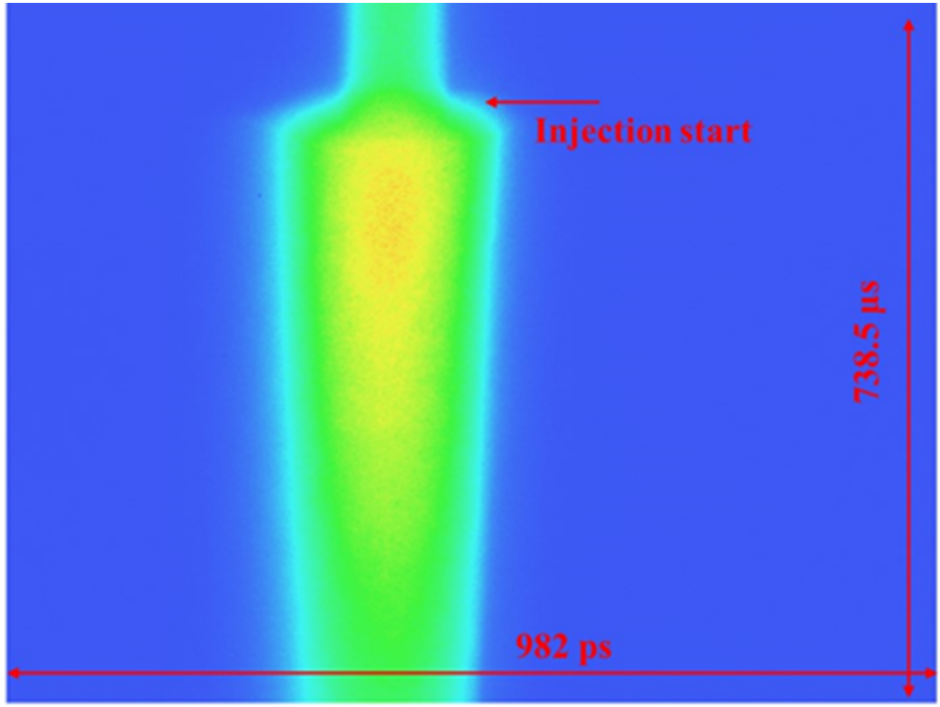
Synchrotron Radiation Based Beam Diagnostics

Visible light beam line



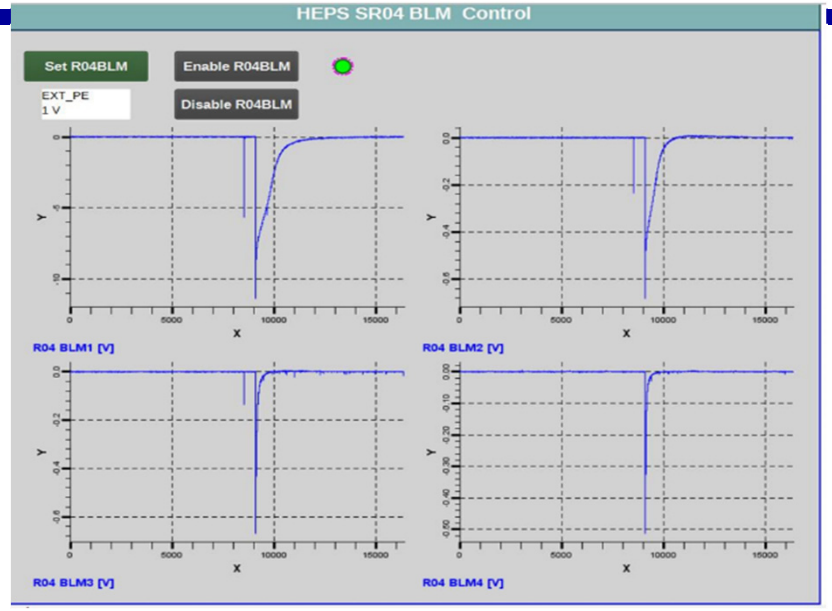
First visible light observed when beam stored



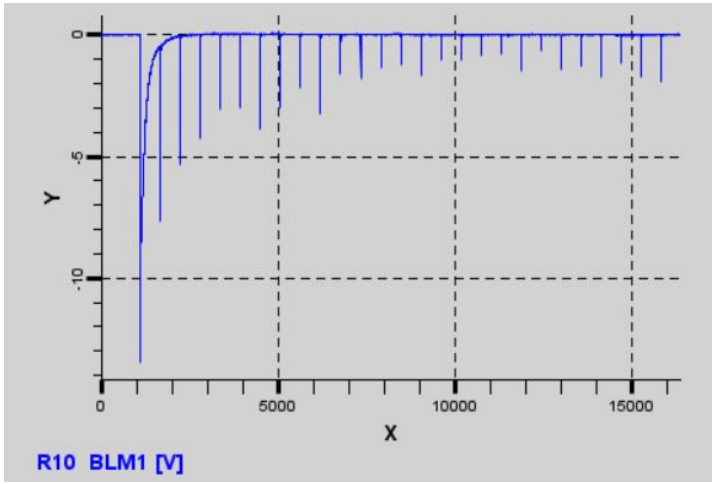


Bunches image captured by streak camera

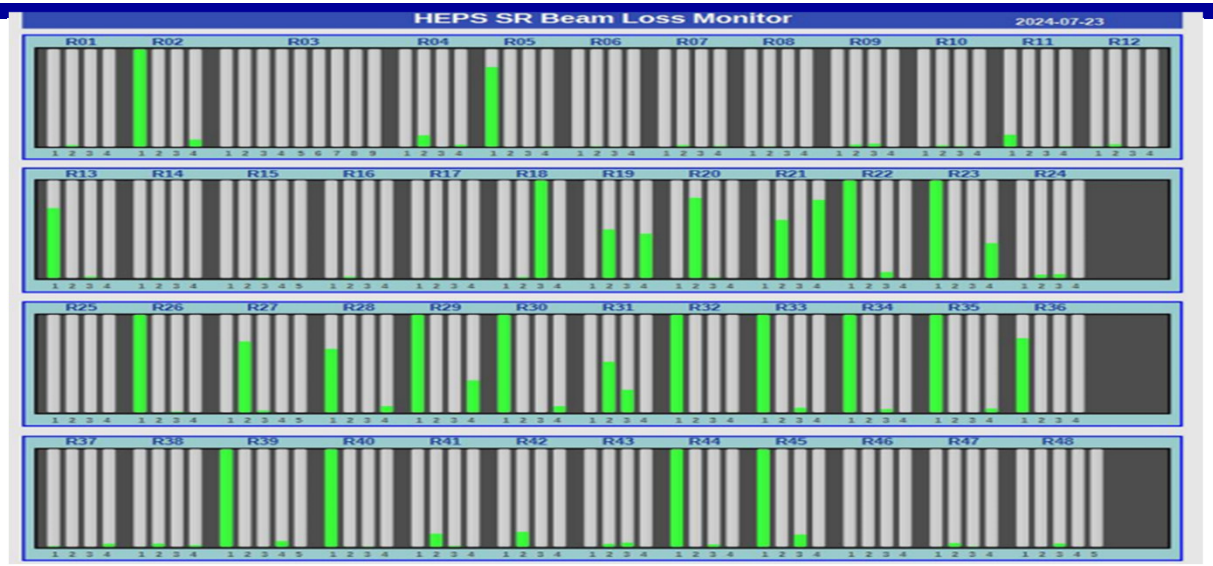
Beam loss data



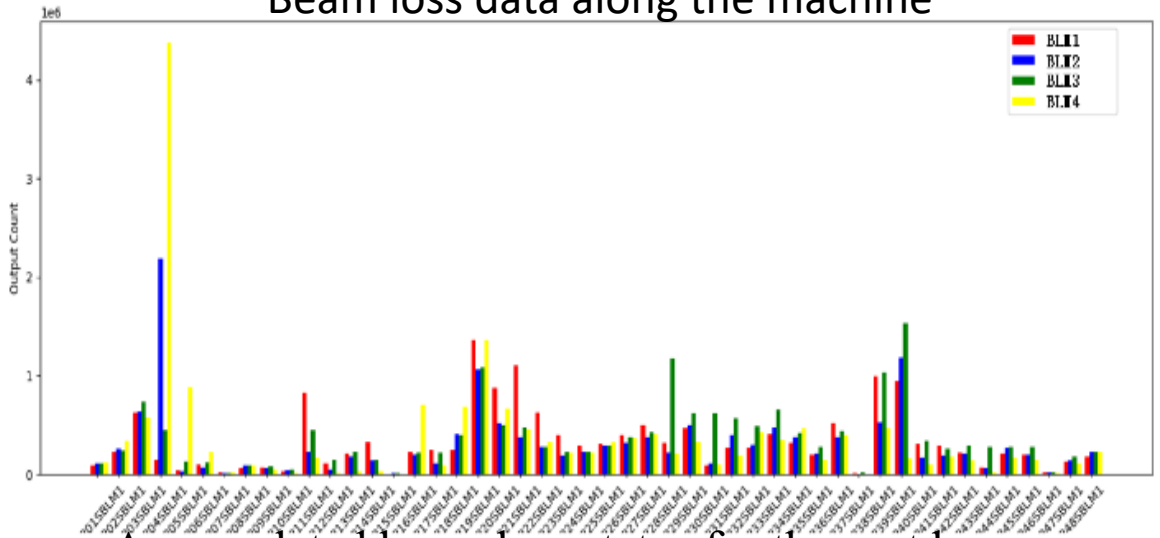
First turn beam loss data



28 turns beam loss data



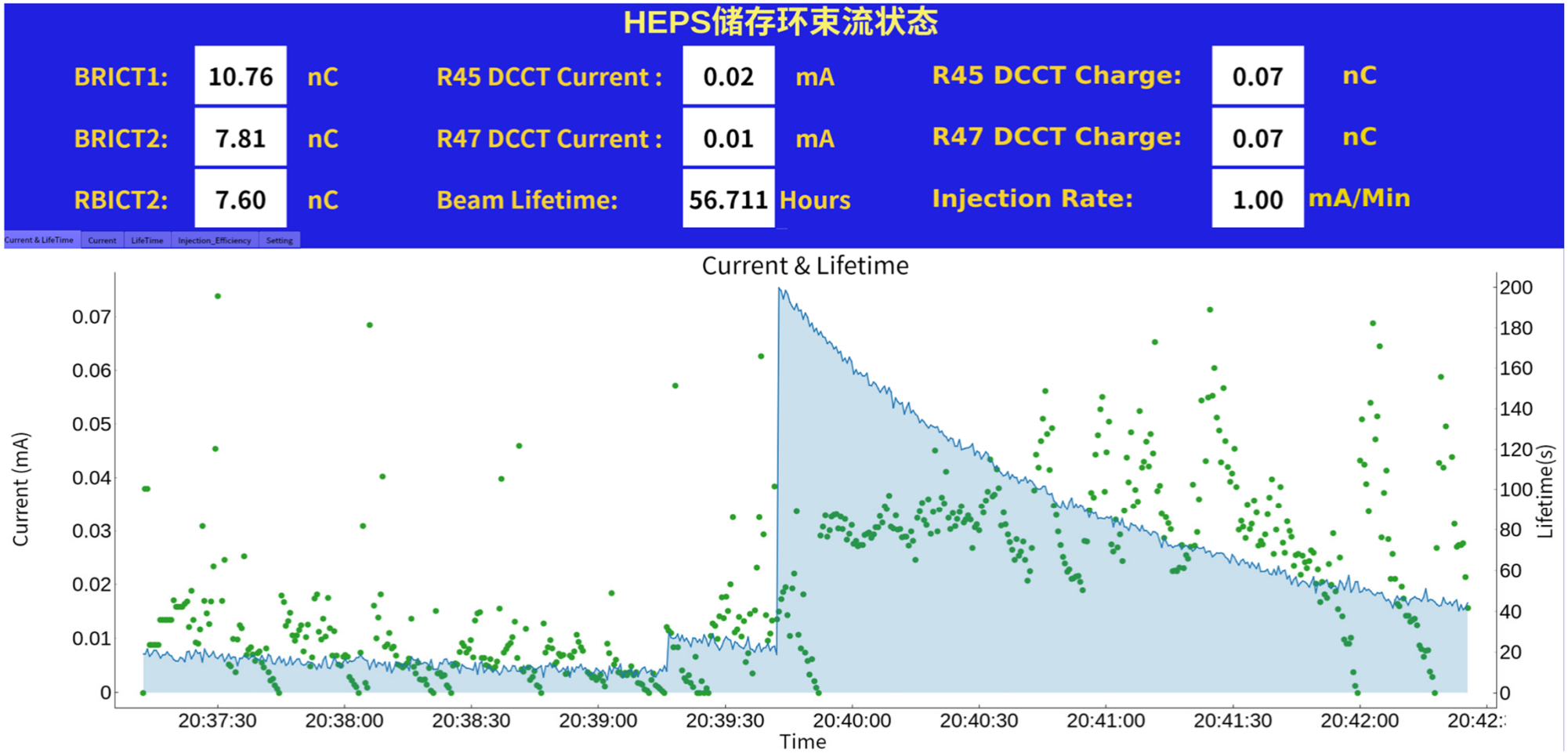
Beam loss data along the machine



Accumulated beam loss status for the past hour

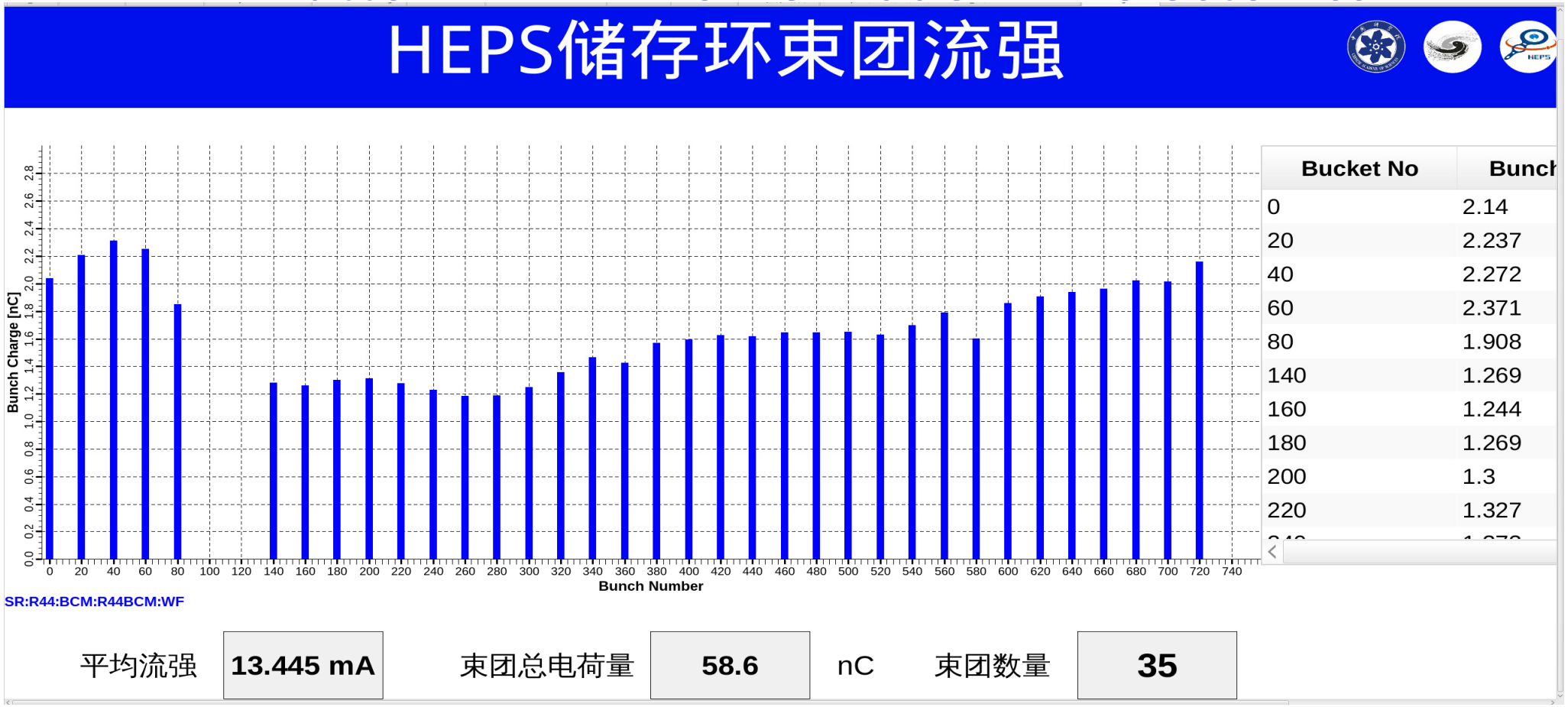
Beam current and life ~1min @ 70 μA

NPCT+Data acquisition



Bunch current monitor

Button BPM + Home made BBB electonics

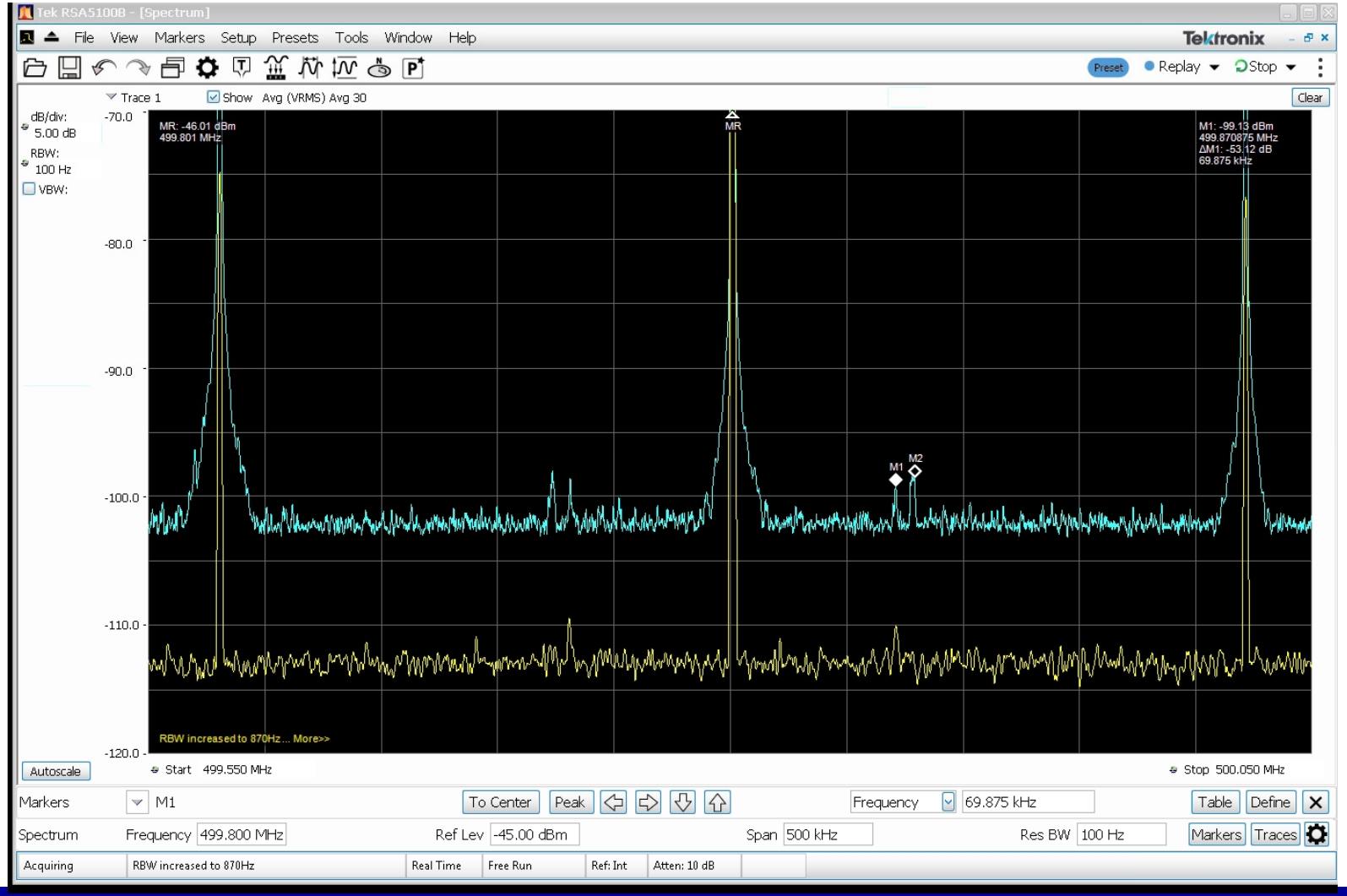


Bucket No	Bunch
0	2.14
20	2.237
40	2.272
60	2.371
80	1.908
140	1.269
160	1.244
180	1.269
200	1.3
220	1.327

Development of bunch-by-bunch beam charge monitor for High Energy Photon Source (THP05)

Tune

Tune kicker + button BPM+ spectrum analyzer



Summary

- HEPS, being a fourth-generation ring with ultra low emittance of less than 50 pm rad, presented significant challenges during commissioning.
- The successful beam commissioning of the HEPS storage ring is partly attributed to the reliable beam measurement system providing diverse and customized observation methods.
- The self-developed digital BPM and BLM electronics contributed more in first turn and day one commissioning.

Thank You for Your Attention!