The 15th International Beam Instrumentation Conference
Whistler Canada, September, 2026

Experience with heavy ion beam instrumentation during HIAF commissioning

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On Behalf of The Beam Instrumentation Group at
Institute of Modern Physics, Chinese Academy of Sciences

❑ Content

➢ HIAF intro & commissioning progress

HIAF project introduction

Commissioning status and outcomes for now

➢ BI experiences during commissioning

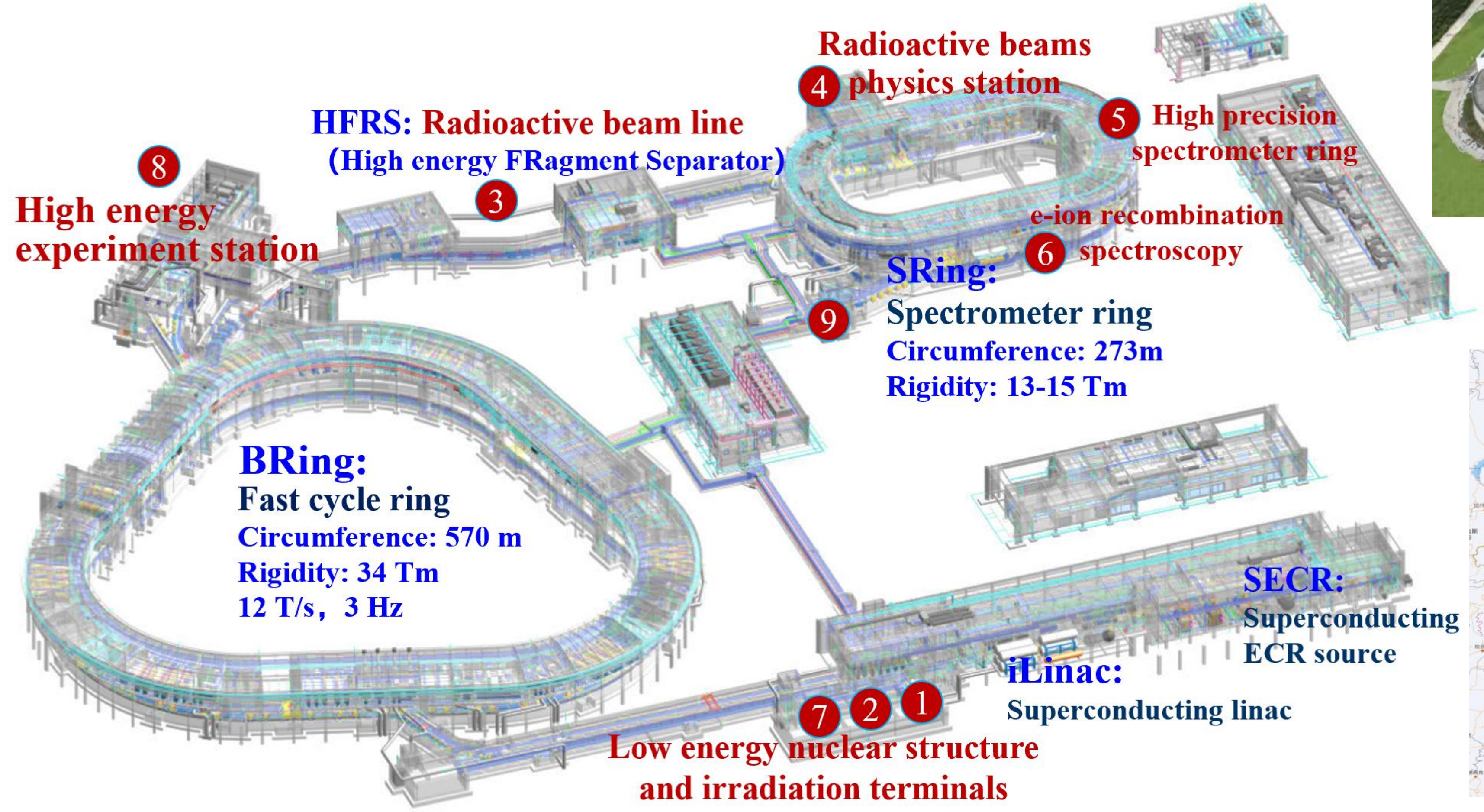
Super-conducting linac

Beam transfer-lines

Boost Ring & Spectrometer Ring

HIAF introduction

- **High Intensity heavy-ion Accelerator Facility (HIAF)**
- *2018-2025, Equipment costs ≈ 1.4 Billion CNY*
- *Fast ramping heavy ion synchrotron with 12 T/s, 3 Hz*
- *Deployed over 450 diagnostic monitors and 1500 electronics*



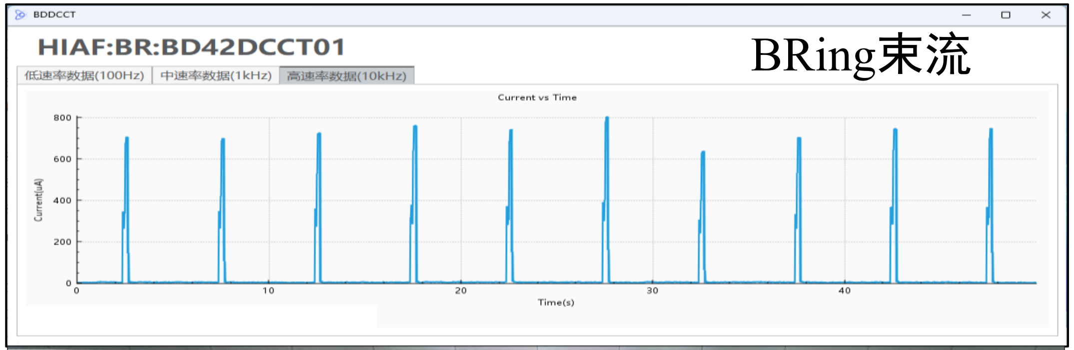
HIAF parameters

- **High Intensity heavy-ion Accelerator Facility (HIAF), the key design parameters:**

	SECR	iLinac	BRing	HFRS	SRing
Length / circumference (m)	---	114	569	192	277
Final energy (U^{35+}/H_2^+) **(MeV/u)**	---	17 / 48	835 /9300 (P)	835 (U^{92+})	835 (U^{92+})
Max. magnetic rigidity (Tm)	---	---	34	25	15
Max. beam intensity (U^{35+}/H_2^+) (emA)	1.7/1	1 /0.6	1×10^{11}ppp 6×10^{12}ppp (P)	-------	10^{10}ppp (U^{92+})
Operation mode	DC	CW or pulse	fast ramping (12T/s, 3Hz)	Momentum-resolution 1100	DC, deceleration
Emittance or Acceptance (H/V, π·mm·mrad, dp/p)		5 / 5/±0.2%	200/100, 0.5%	±30mrad(H)/±15 mrad(V), ±2%	30/30, 1.5% (normal mode)

First beam commissioning

- 2025.10.27, DCCT sees the first beam accumulated in BRing, **2h after SC-linac injection**
- And the beam successfully passes **through all the 2 km long beam lines within 16 hours**



Science journal reports & says:
Heavy-ion Accelerator Fires Up

Heavy-ion accelerator fires up

An accelerator that will produce the world's most intense pulses of heavy ions generated its first beam on 28 October. When fully operational, China's High Intensity heavy-ion Accelerator Facility (HIAF), nestled among the mountains of southern Guangdong province, will send pulses of exotic, short-lived ions into fixed targets or into a storage ring to support research on the properties of atomic nuclei and how stars forge heavy elements, as well as material sciences and biomedicine. The research center, which joins the ranks of similar facilities worldwide, represents a $420 million investment by the Chinese Academy of Sciences's Institute of Modern Physics. Institute officials say HIAF will be open to foreign researchers. —Dennis Normile

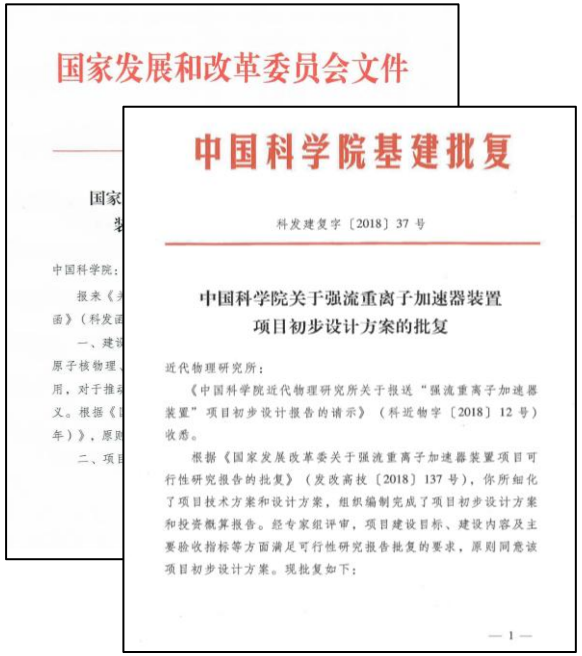
Acceptance commissioning

Mission 1: Three beam commissioning to meet the national acceptance indexes (*red terms in table*)

Mission 2: Accomplishment of 6 terminal experiments to pass whole accelerator tests @ 2026.07

National acceptance Ion species		Acceptance Index		Design Index		Commissiong Index	
		Energy (GeV/u)	Intensity (ppp)	Energy (GeV/u)	Intensity (ppp)	Energy (GeV/u)	Intensity (ppp)
Non-metal beams $^{18}O^{6+}$ / $^{78}Kr^{19+}$	$^{18}O^{6+}$	2.6	1.0×10^{10}	2.6	1.0×10^{11}		2.5×10^{11} √
	$^{18}O^{6+}$	4.25		4.25		4.299 √	
	$^{78}Kr^{19+}$	1.7	7.5×10^{9}	1.7	7.5×10^{10}		
Metal beams $^{209}Bi^{31+}$/$^{238}U^{35+}$	$^{209}Bi^{31+}$	0.85	3.0×10^{9}	0.85	3.0×10^{10}		3.17×10^{10} √
	$^{238}U^{35+}$	0.8	3.0×10^{9}	0.8	3.0×10^{10}		

Based on the original national approval document and index


国家发展和改革委员会文件

中国科学院基建批复

科发建复字〔2018〕37 号

中国科学院关于强流重离子加速器装置
项目初步设计方案的批复

近代物理研究所：

《中国科学院近代物理研究所关于报送"强流重离子加速器装置"项目初步设计报告的请示》（科近物字〔2018〕12 号）收悉。

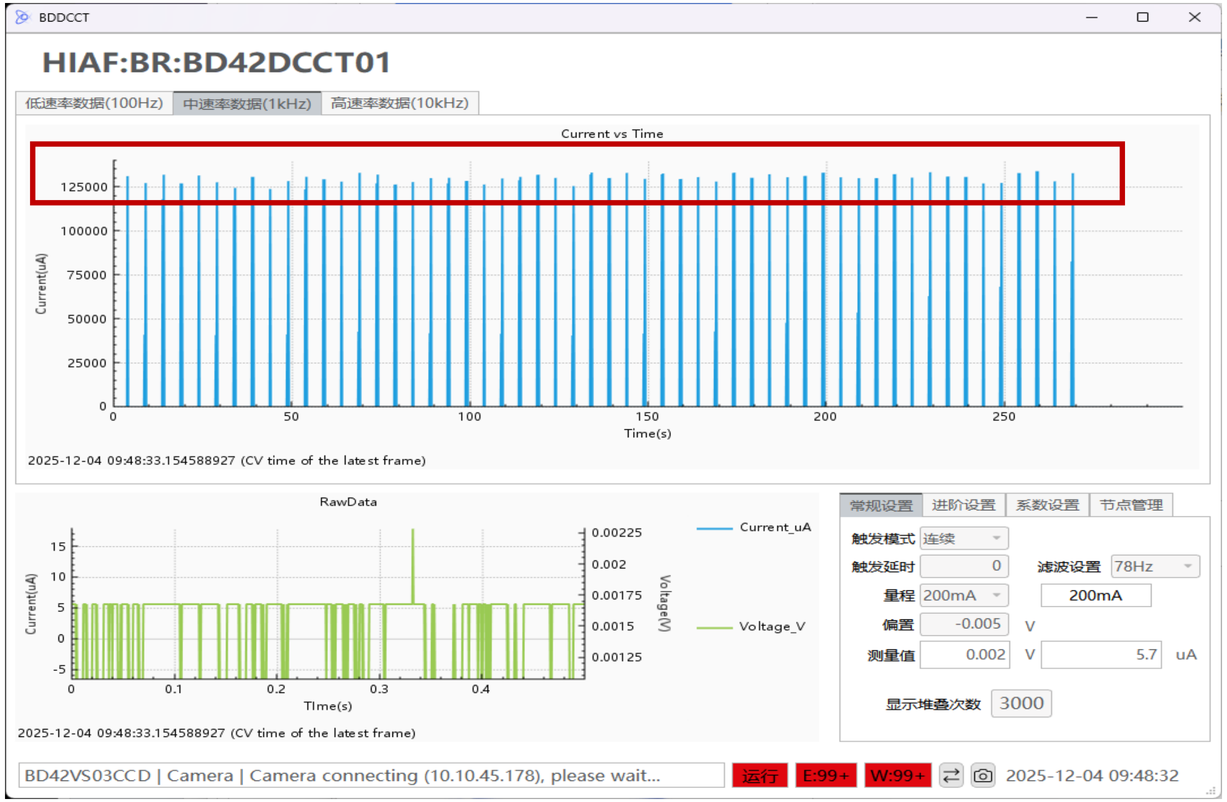
根据《国家发展改革委关于强流重离子加速器装置项目可行性研究报告的批复》（发改高技〔2018〕137 号），你所细化了项目技术方案和设计方案，组织编制完成了项目初步设计方案和投资概算报告。经专家组评审，项目建设目标、建设内容及主要验收指标等方面满足可行性研究报告批复的要求，原则同意该项目初步设计方案。现批复如下：

— 1 —

Acceptance commissioning

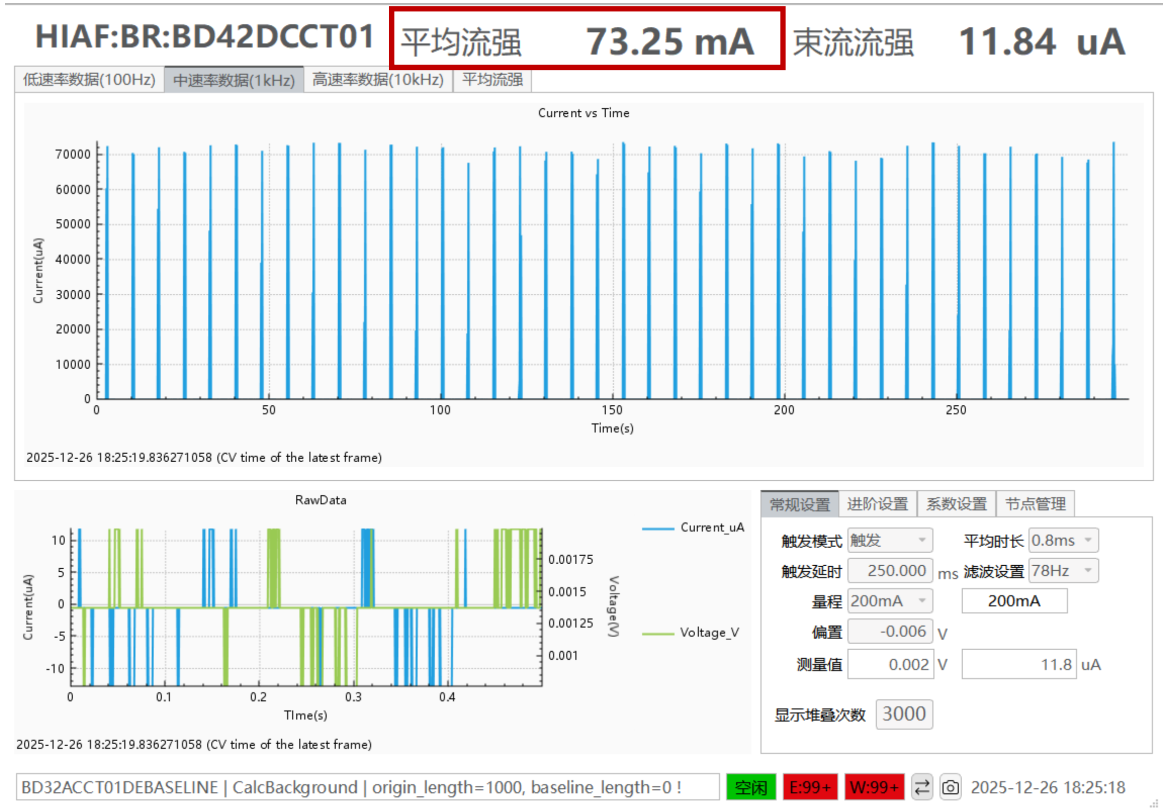
Acceptance beam commissioning Step 1:

$^{18}O^{6+}$ 2.6GeV/u 2.5e11 ppp @2025.12.12

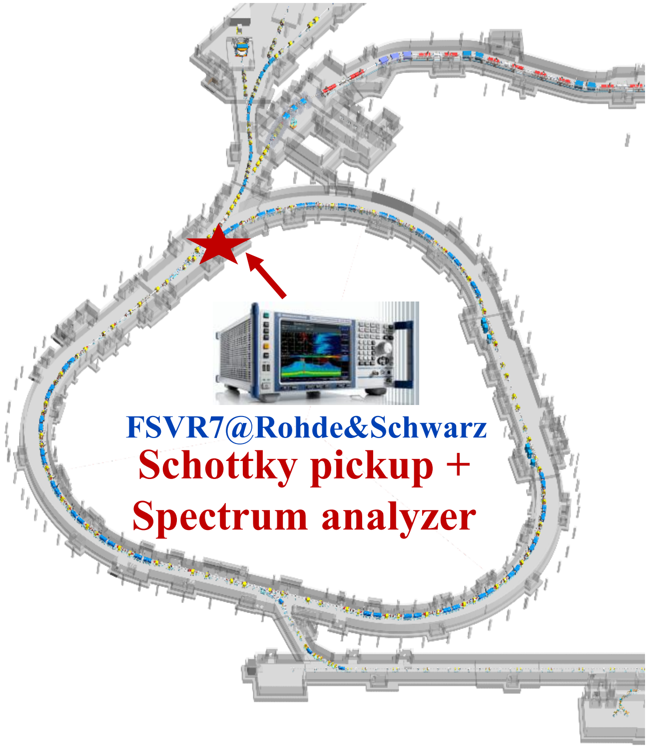


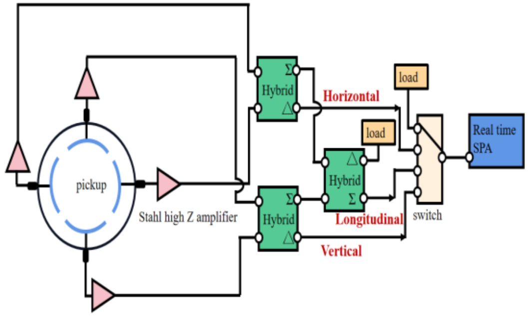
Acceptance beam commissioning Step 2:

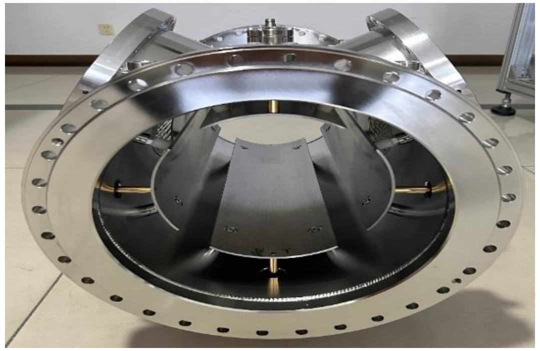
$^{209}Bi^{31+}$ 0.85GeV/u 3.17e11 ppp @2025.12.27



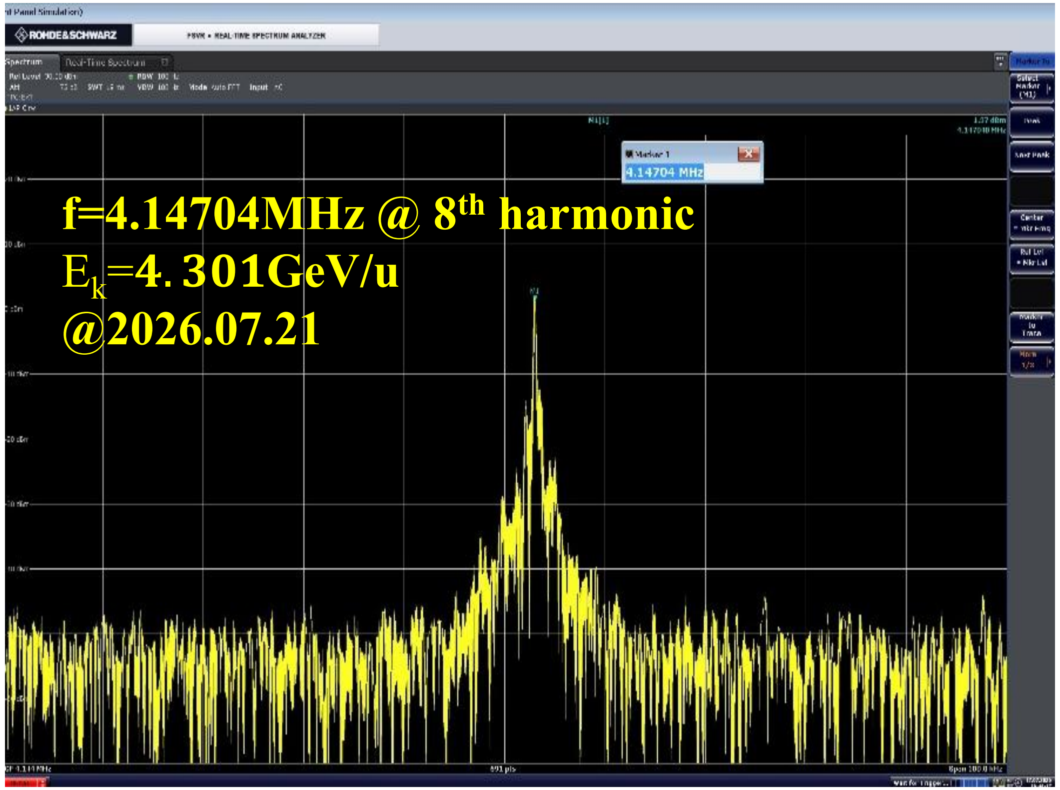
◆ Acceptance beam commissioning Step 3: $^{18}O^{6+}$, 4.3 GeV/u, @ 2026. 7. 18







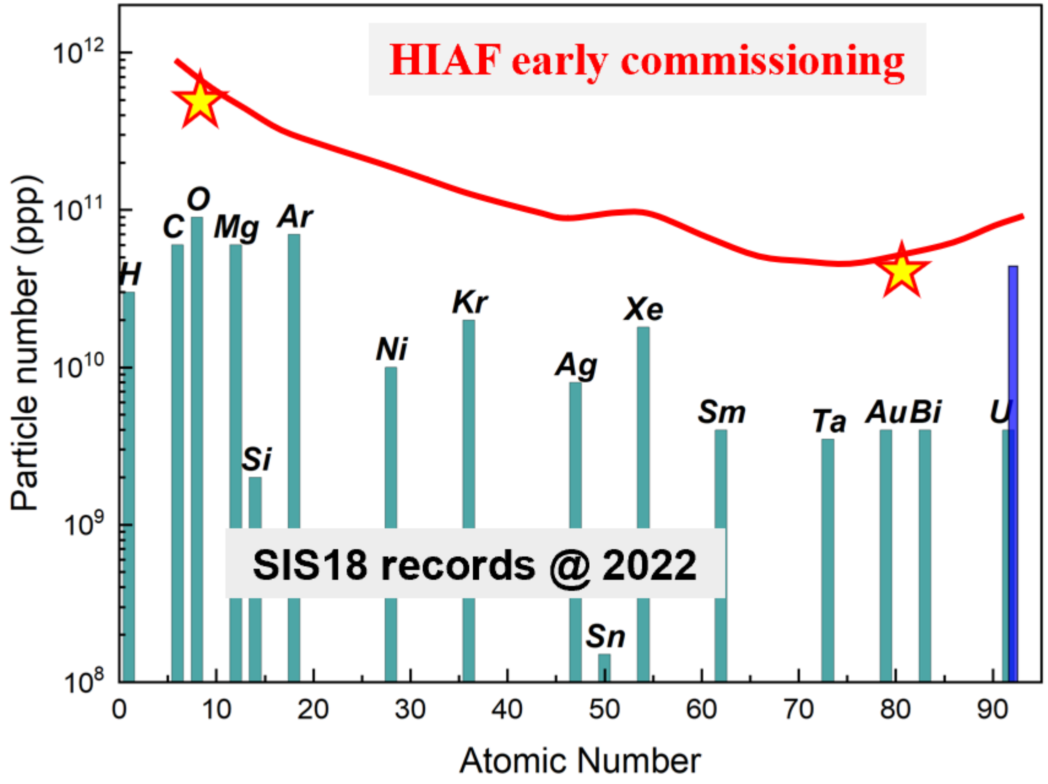
Capacitive Schottky pickup mounted in the BRing extraction point



Commissiong summary

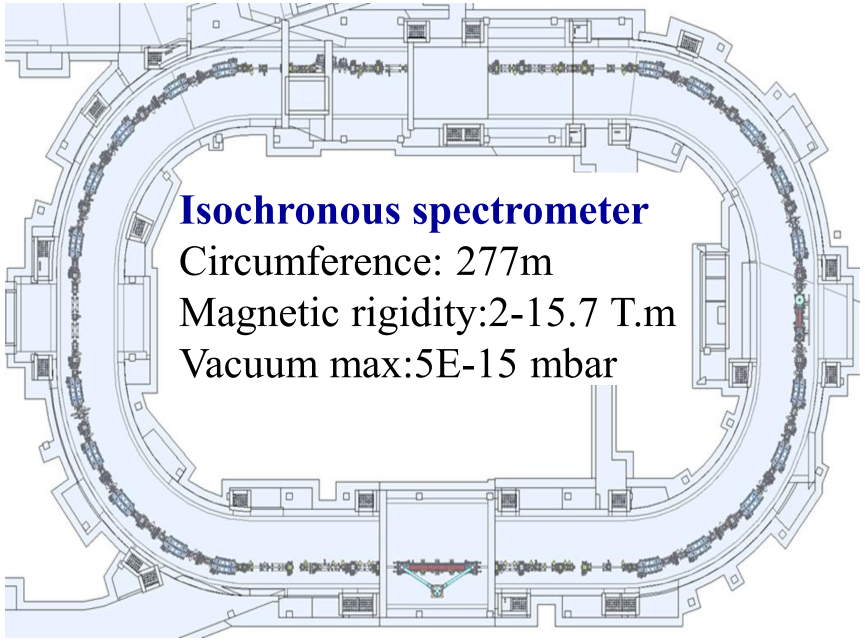
Test system	Test items	Status
Accelerator subsystems	11 subsystems including Beam Instrumentation	**2025.11.21 Accomplished √**
Accelerator beams (SC linac +Injection line +BRing +HFRS + SRing)	1.Typical non-metal beam $^{18}O^{6+}$	**2025.12.12 Accomplished √**
	2.Typical metal beam $^{209}Bi^{31+}$	**2025.12.27 Accomplished √**
	3.Highest energy beam $^{18}O^{6+}$	**2026.07.18 Accomplished √**
Terminal experiments (6 terminals constructed already on the stage-1)	1.Low energy nuclear structure Research spectrometer	**2026.05.24 Accomplished √**
	2.High intensity ion beam material irradiation terminal	**2026.05.24 Accomplished √**
	3.High energy FRagment Separator line/HFRS	**2026.04.28 Accomplished √**
	4.External target experiment terminal	**2026.04.28 Accomplished √**
	5.Electron-ion composite resonance spectrometer	**2026.06.28 Accomplished √**
	6.High-precision ring spectrometer/SRing	**2026.04.08 Accomplished √**

✓ **HIAF finished all national acceptance tests with some highest intensity in similar facilities**



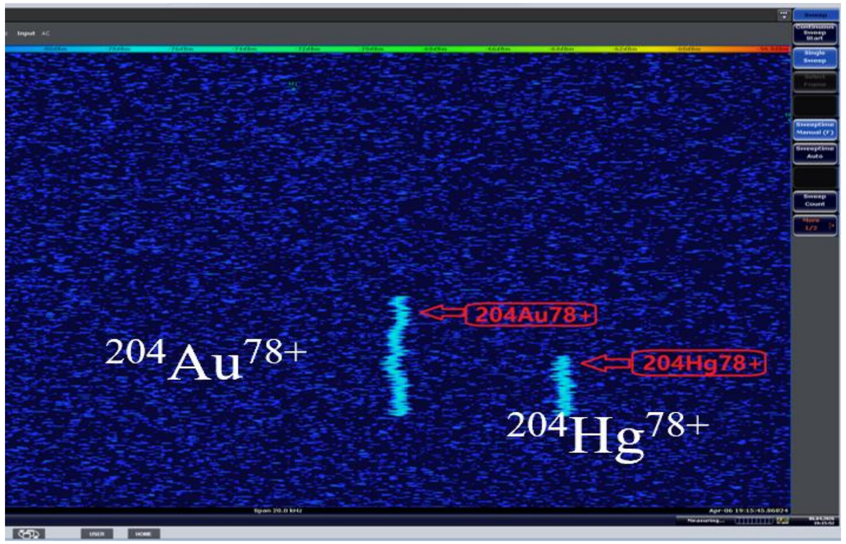
Fruits for now

✓ **1. Isochronous synchrotron (SRing) + Resonant Schottky pickup + Spectrum analyzer achieving the highest resolution (5.8E-8) mass measurement for short lifetime like ^{202}Au**



Resonant Schottky of high Q ≈ 1E4 and designed by BI group G,Y, Zhu

Resonant Schottky for the single particle determination in SRing

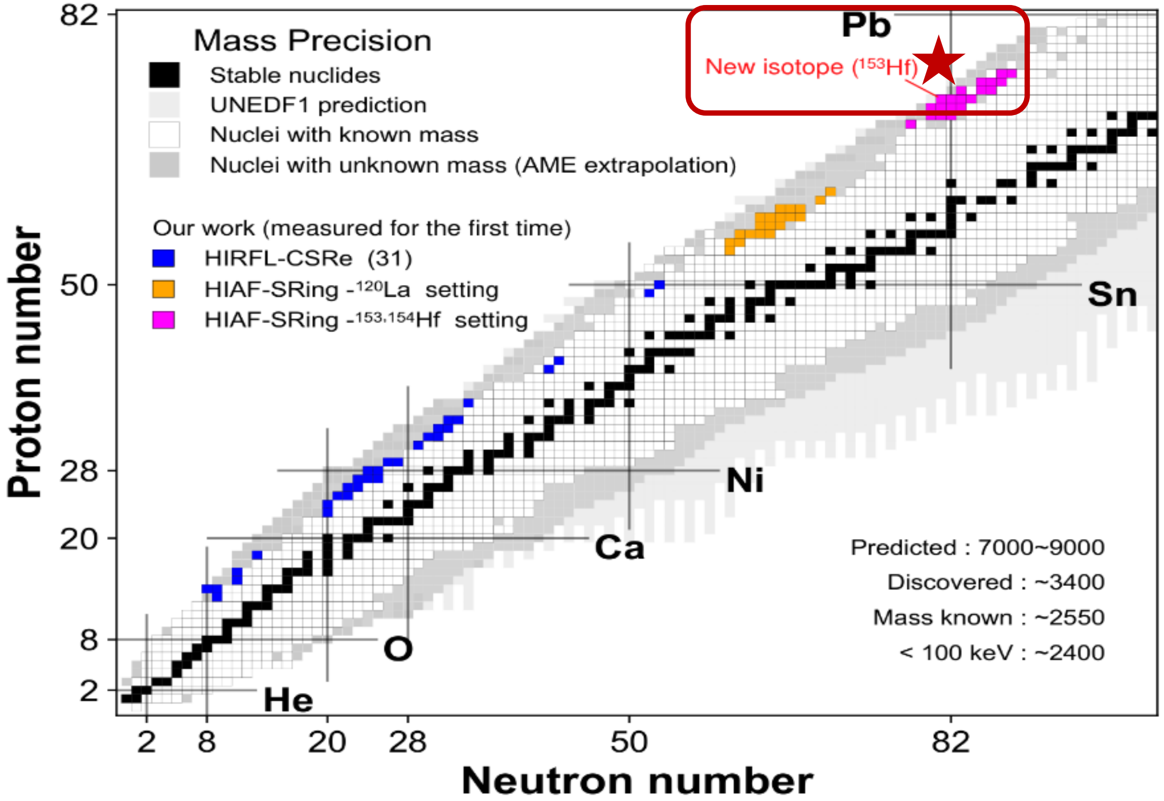


Fruits for now

✓ **2. Isochronous magnetic rigidity synchrotron (SRing) + TOF spectrometry**

first time finding a new nuclide ^{153}Hf by synchrotron in 12 hours experiments

3. ……



Science Bulletin

Discovery of isotope ^{153}Hf near the proton drip line via isochronous mass spectrometry: extending the nuclear landscape with HIAF

Hongfu Li[a], Min Zhang[a], Hongyang Jiao[a], Xing Xu[a,b,*], Chaoyi Fu[a,b,*], Jinyang Shi[a,b], Jiahao Lv[a,b], Xu Zhou[a], Yuanming Xing[a,b], Mingze Sun[a], Yuhu Zhang[a,b], Xiaohong Zhou[a,b], Yury A Litvinov[c,d], Qi Zeng[e], Wenjia Huang[f], Min Si[a], Peng Shuai[a], Houyu Hu[a,b], Xinliang Yan[a,b], Guodong Shen[a], Jie Liu[a], Lina Sheng[a], Weiping Chai[a], Fucheng Cai[a], Geng Wang[a], Wenwen Ge[a], Hang Ren[a], Youjin Yuan[a,b], Jiancheng Yang[a,b,*], Shitao Wang[a,b], Xueheng Zhang[a,b], Meng Wang[a,b,*] and Zhiyu Sun[a,b,*]

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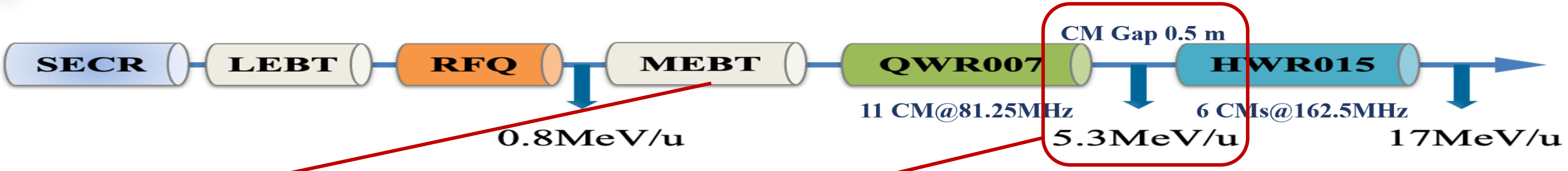
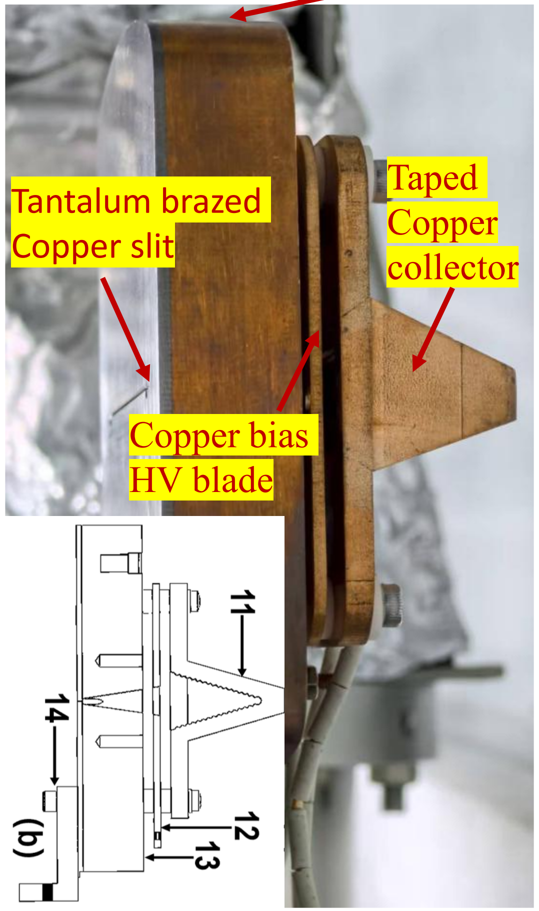
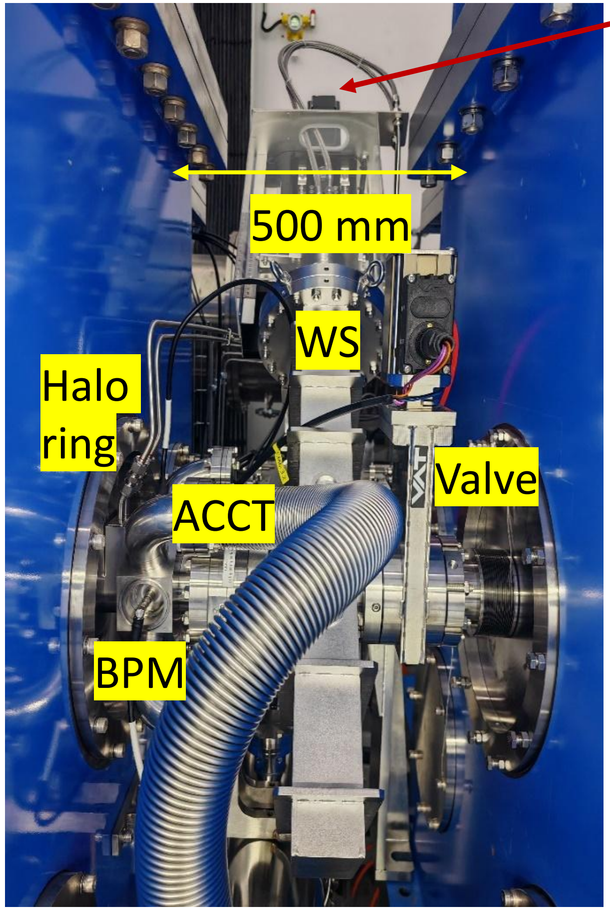
A R T I C L E I N F O

Article history:
Received : 18-May 2026
Revised : 08-Jun 2026
Accepted : 23-Jun 2026

Experiences in SC linac







Position/Device	LEBT& MEBT	CM007	CM gap	CM 015
DC&AC CT (MPS)	1+3		1	
Capacitive BPM (MPS)	5	5	1	11
Cold button BPM (MPS)	-	24	-	11
Slit & FC	1 Allison 4 Slit+1 FC	-	-	-
Brick scraper/ Halo ring (MPS)	4(Brick)	5(Ring)	1(Ring)	11(Ring)
Wire scanner	-	-	1(H&V)	-
FFC	1+1	-	-	-
BLM(MPS)	-	5	1	10

Experiences in SC linac

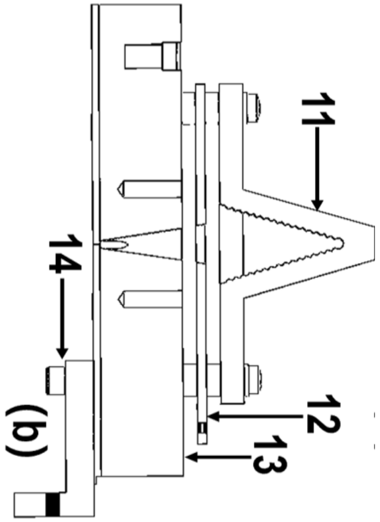
Issue 1:

e⁻ disturbance by slits for emittance measurements under nearly 1 mA

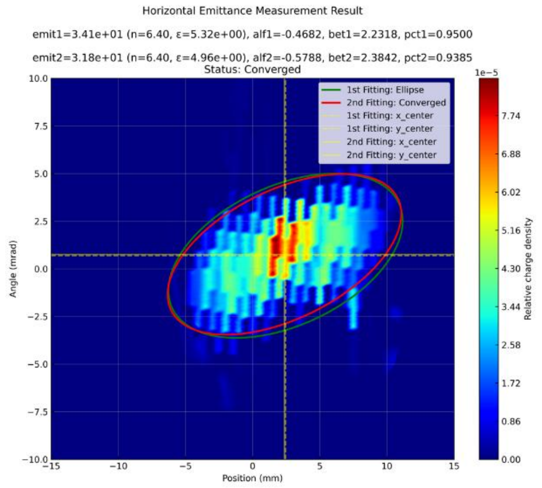
Even happening in another direction when it is not literally used

Solution: **By offline data correction for accuracy phase-reconstruction**

Plan: **Collector shielding; Bias-T amplifier; Magnet field suppression…**

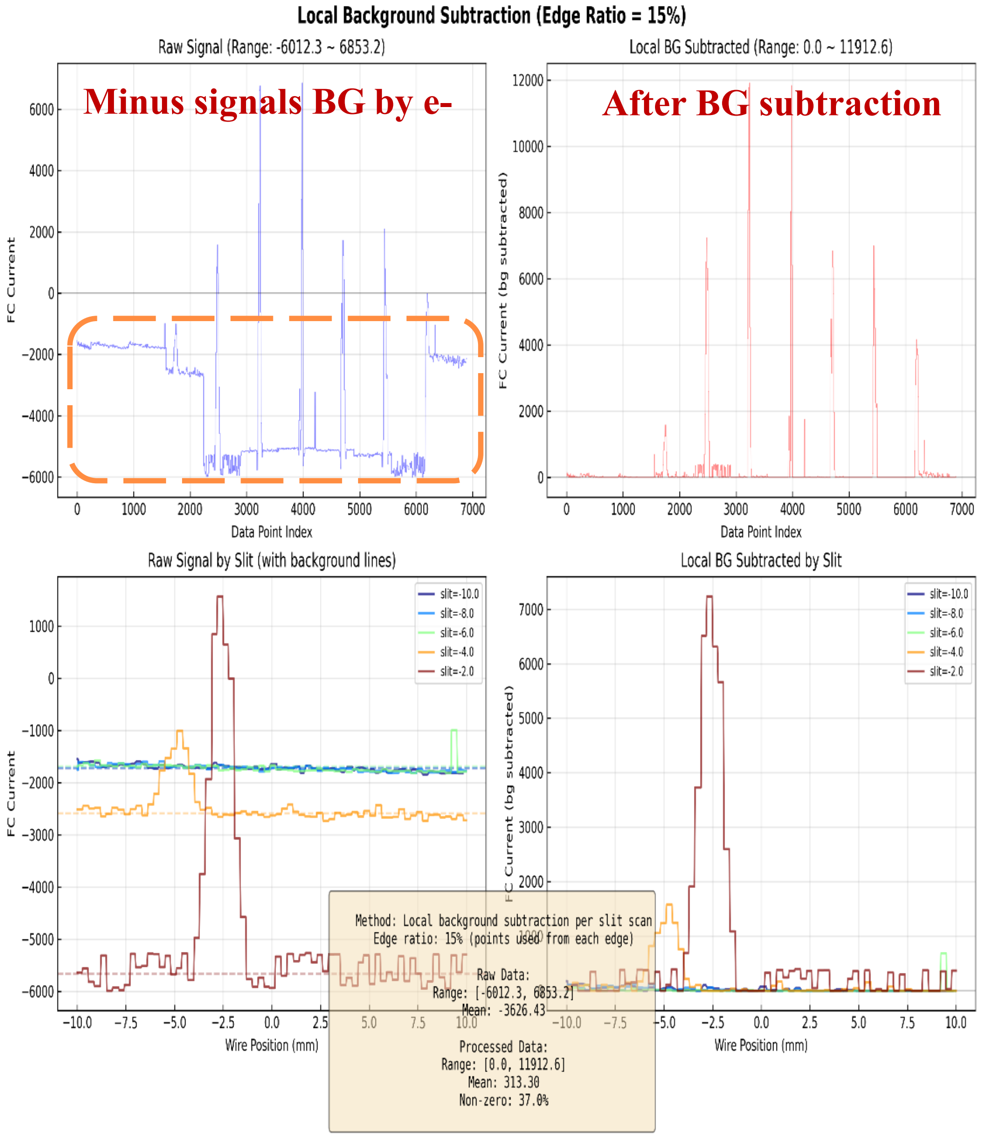


2nd slit with a sawtooth collector for the x' y'



$31.76\pi\ mm \cdot mrad\ @95\%$

$$\varepsilon_{rms,n} = \frac{31.76}{6} \cdot 0.042 = 0.22, \quad \beta = 2.38, \quad \alpha = -0.58$$



Experiences in SC linac

Institute Of Modern Physics

Issues 2:

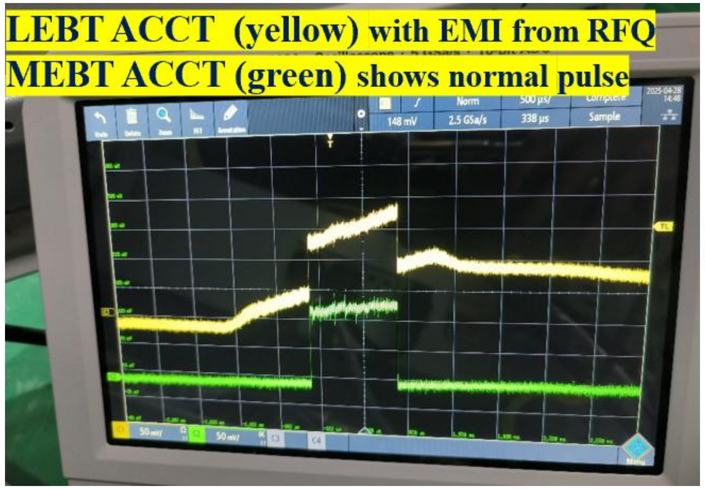
EMI problems to ACCT or BPM near RFQ

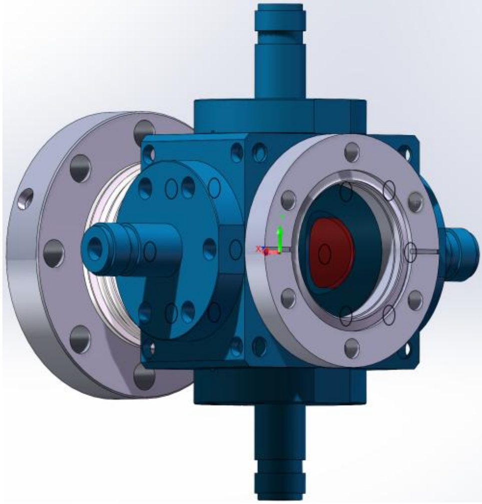
Solution:

Change connectors like BNC by screwed one;

Tin foil shielding for analog amplifiers;

BPM used in 2^{nd} harmonic acquisition…





Issues 3:

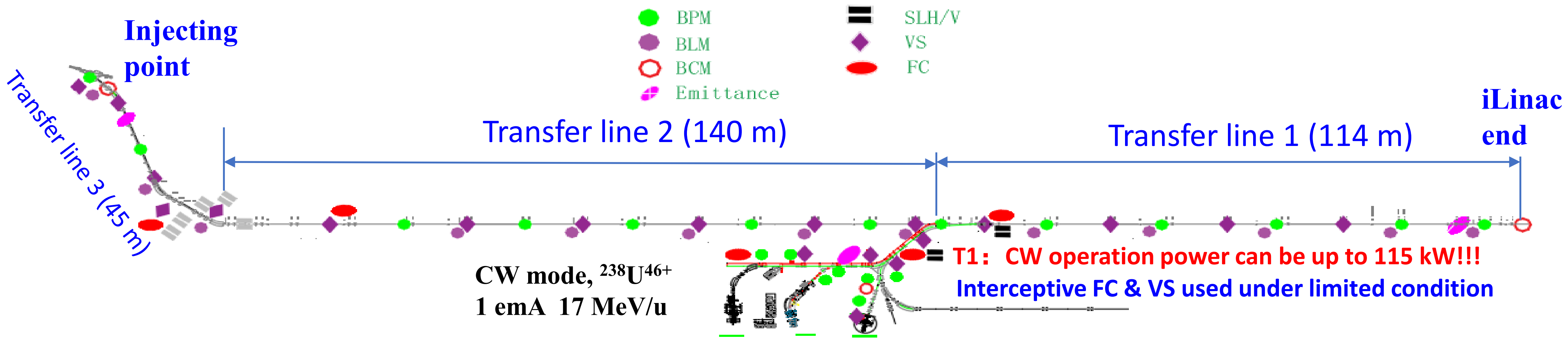
Pollution problems among SC-cryomodules, decreasing cavity performances deadly

1. From interceptive monitor like wire scanner (0.1mm tungsten) and halo ring (pure niobium with water cooling);
2. Main reason is vacuum leakage happening one time between CM06 and CM07 when installed and cooled down inside tunnel

Solution: Reducing the usage of destructive tors; None vacuum leakage is accepted for SC cryomodules

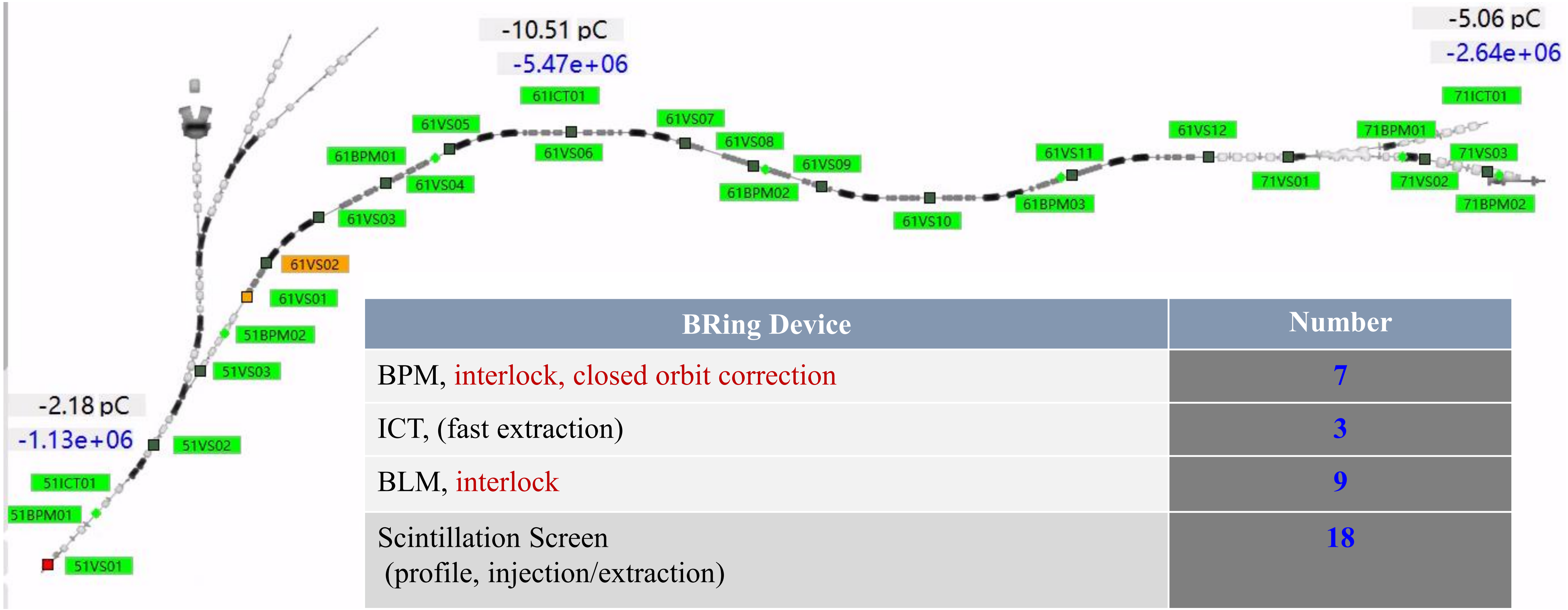
By the way, halo rings work perfectly to scrap stray particles for cavity safety, with normal few µA (around 1% of total current), and cold BPMs work stably with semi-rigid SiO_2 cables inside 4K CMs for the orbit corrections and cavity phase scanning.

Layout in injection-line



Parameters	Device/Position	Transfer line 1	Transfer line 2	Transfer line 3	Terminal 1
Current	ACCT(MPS)	2	1	1	1
Position, phase	BPM(MPS)	5	6	2	7
Emittance H/V, current, dump	Slit	4	0	4	4
	FC	1	1	1	5
Profile	Scintillation Screen	4	6	5	5
Beam scraping	Scraper		0	8	
Energy spread	Slit+FC		0	1	
Beam loss	BLM Scintillator(MPS)	6	5	3	6

Layout in transfer-line



BRing Device	Number
BPM, interlock, closed orbit correction	7
ICT, (fast extraction)	3
BLM, interlock	9
Scintillation Screen (profile, injection/extraction)	18

Current measurements

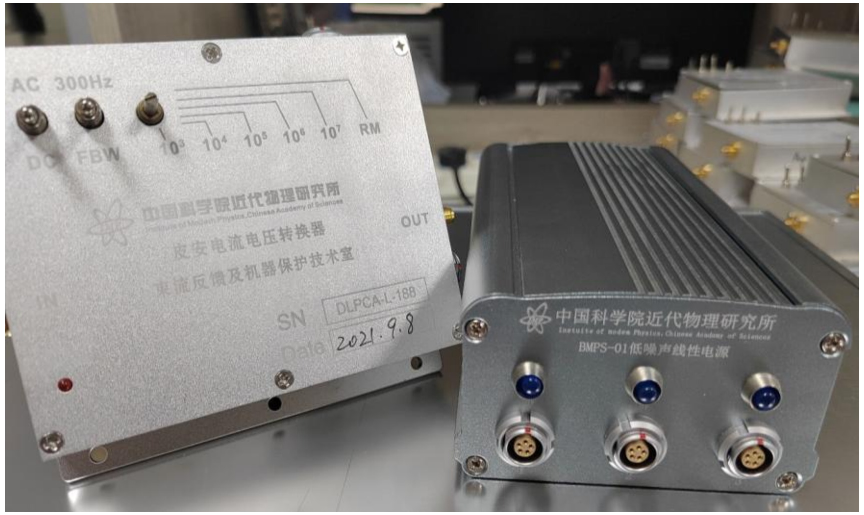
Case 1: **FC/Wire Scanner/CT… work with 6 magnitude range IV convertor and self-test design online for easy maintenances**

1. Detector like FC with 2 signal cables out; 2. IV can be remotely changed for range and status; 3. Self-test pulse generated in IV

Case 2: **EMI problem in FC from 50 Hz HV source happens, and is finally solved by a filter inserted the HV cable route.**

I/V convertor Bandwidth	Mode	Current Range	Noise Level
DC-700 kHz	Full bandwidth /Low noise mode; Self-test/ Normal mode	10 pA-10 mA	3 pA_{p-p}

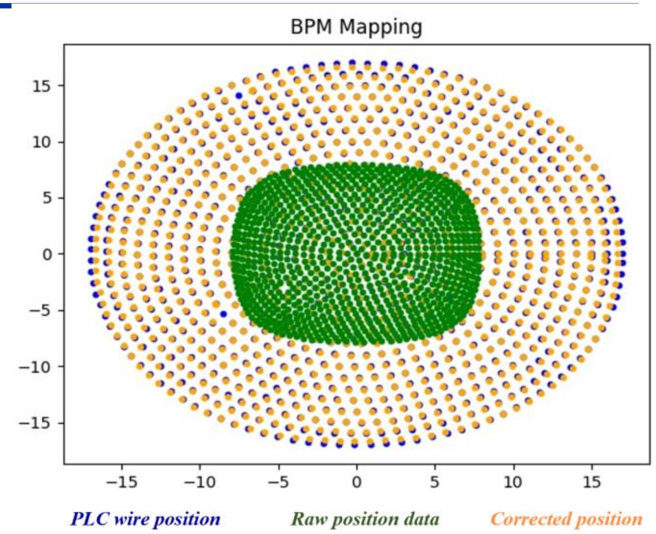
6/12CHs 20Msps sampling units with MPS



I/V convertor tested with 3 pA_{p-p} in lab and 6 magnitude range with remote control

1uA, 25ms test pulse from I/V convertor to check whole chains in real-time online

Experiences in BPMs



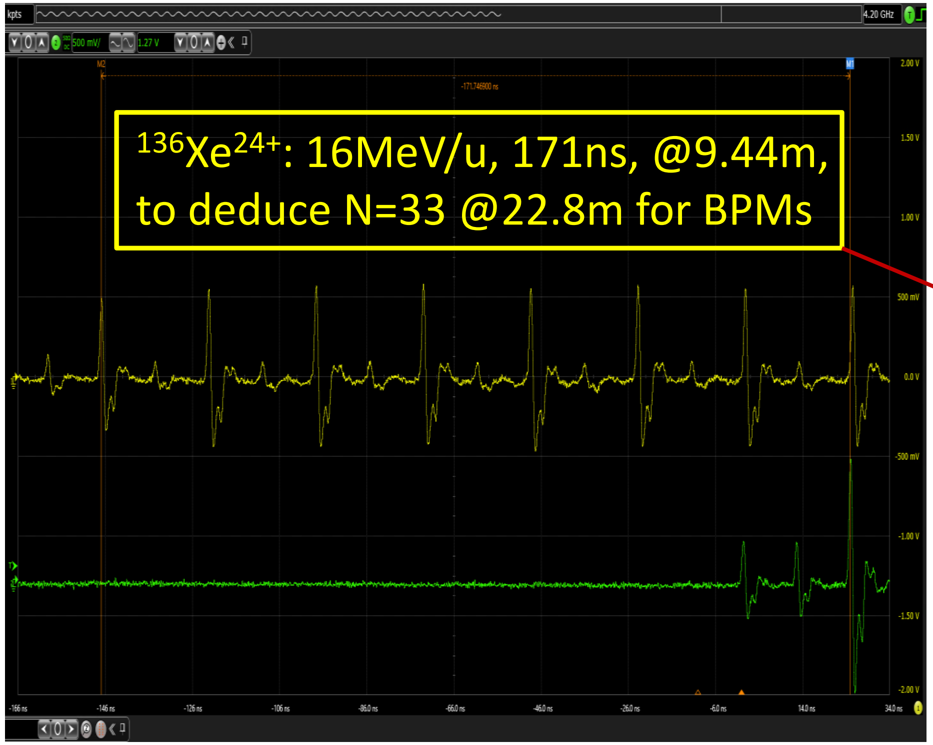
Case 1: Severe nonlinearity issues in position measurements for capacitive BPMs in linac

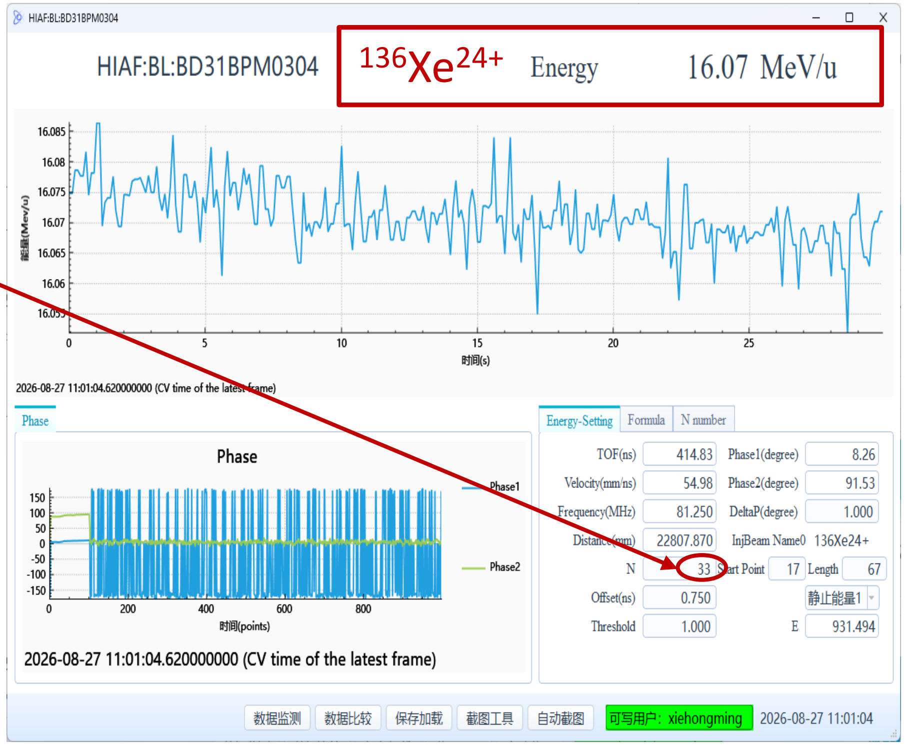
Solution: Using polynomial fitting implemented in FPGA to rapidly calculate the position

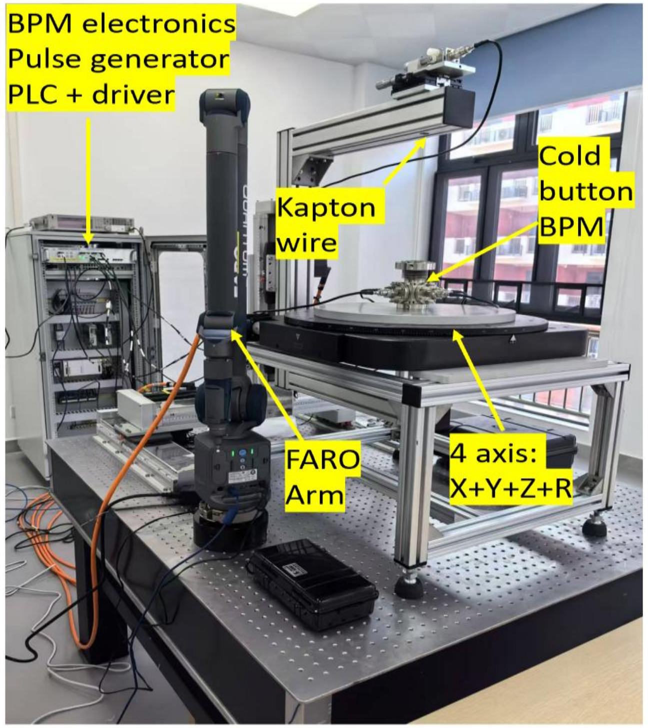
Wire scanning calibration to map and verify the fitting parameter's accuracy

Case 2: Using BPMs and splitter for both the oscilloscope and electronics phase in TOF

Oscilloscope works to verify the period N, and BPM phase allows real-time energy displays





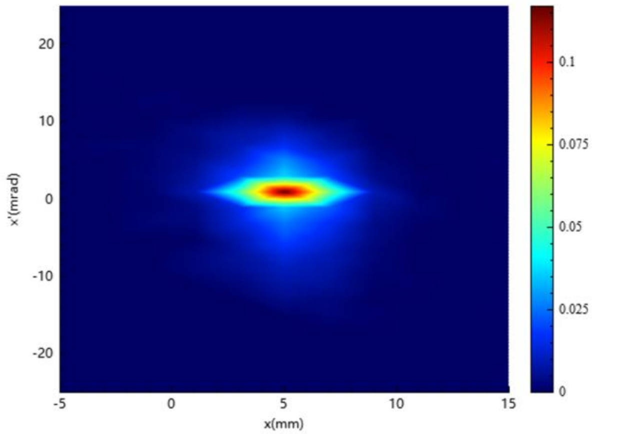


Emittances in injector

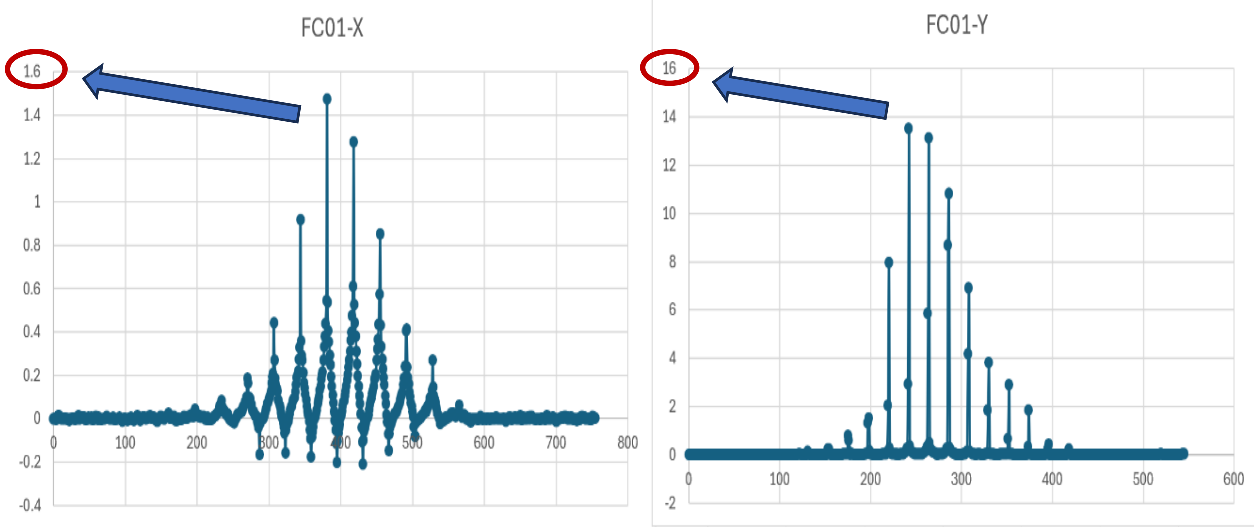
Issue 1: Poor SNR in emittance measurements probably by the slit misalignment

Phenomenon: The SNR in X 10 times less than Y, showing unexpected halos in phase

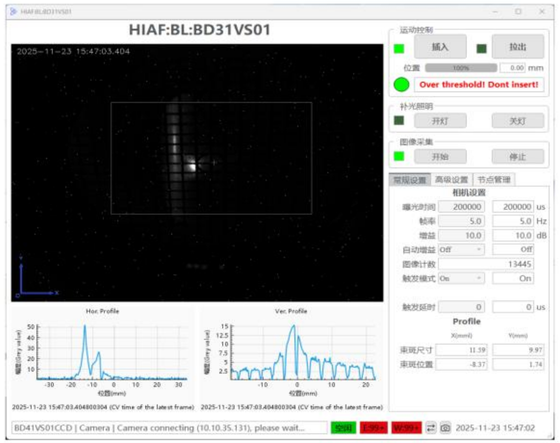
Check 1: Using an upstream view screen for checking and indeed confirmed it



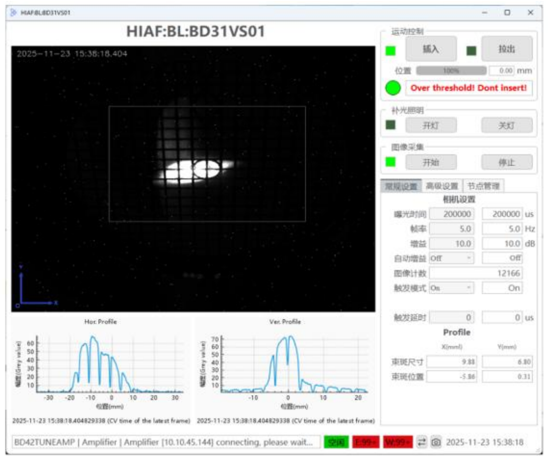
Measured emittance with stray halos



Bad SNR in X slit +slit +FC emittance measurements and Y is normal



束流经水平第一狭缝 SLIT01/H 后在 VS01 上成像



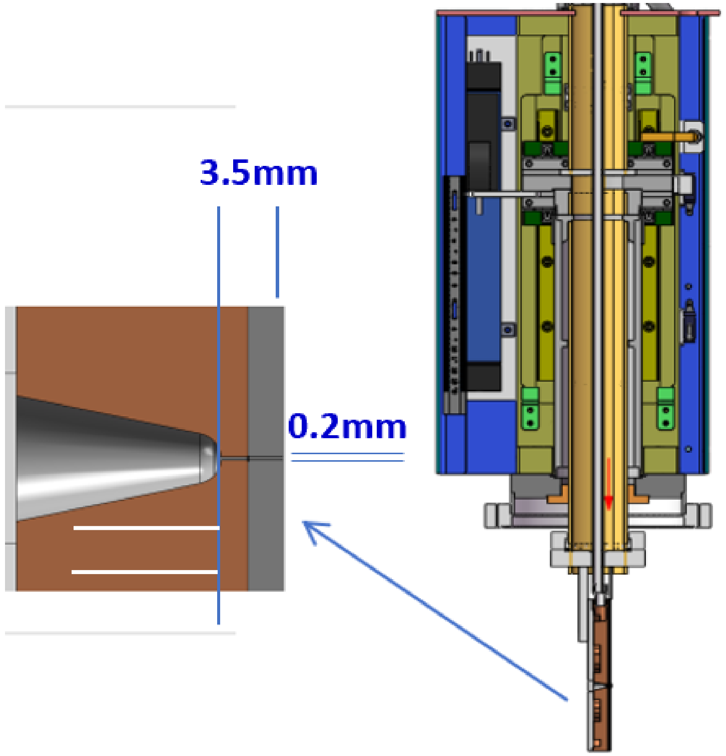
束流经垂直第一狭缝 SLIT01/V 后在 VS01 上成像

VS indeed confirms less beams through 1st H slit than the V one

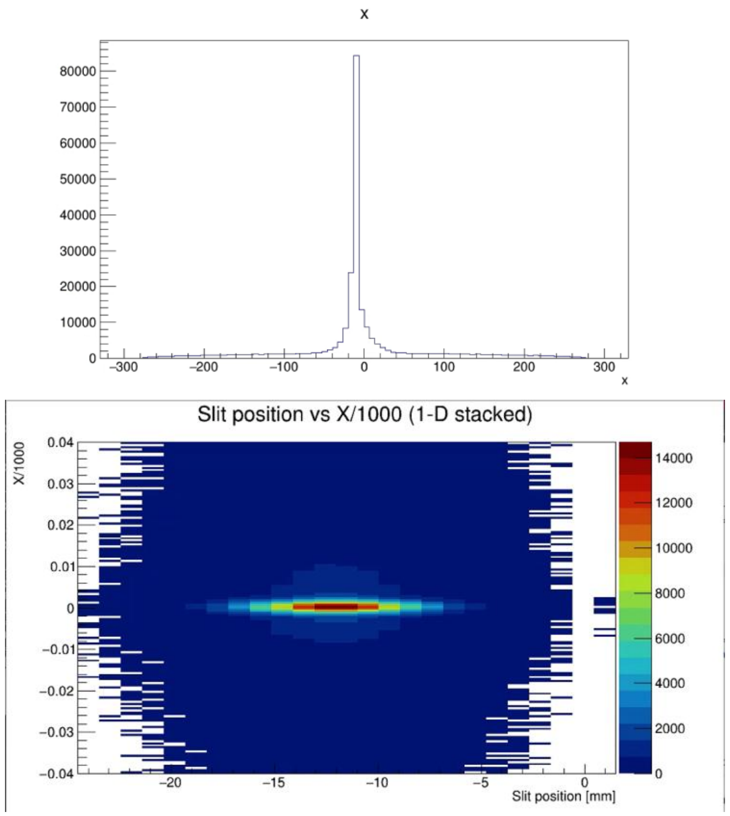
Emittances in injector

Check 2: Geant4 simulations are done and confirm the slit alignment is critical especially for intense heavy ion beams, which means that the slit has to be installed strictly orthogonal to the beam pipe.

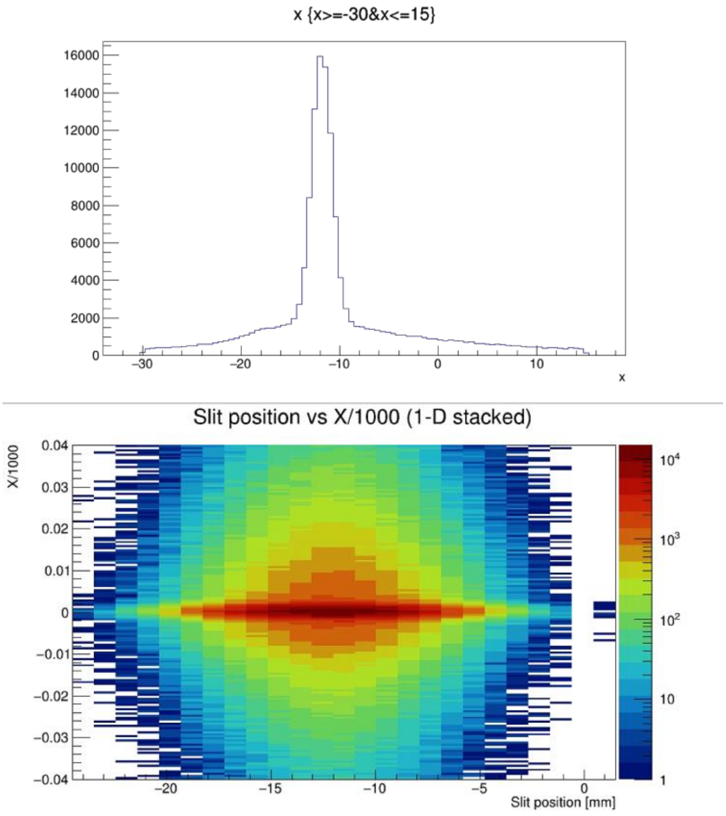
Solution: 1. Remount the 1st slit with errors ≤0.3mm; 2. Change the 2nd slit+ FC to wire scanners for higher SNR



Slit structure used in HIAF injection line



Slit is absolutely orthogonal to beams



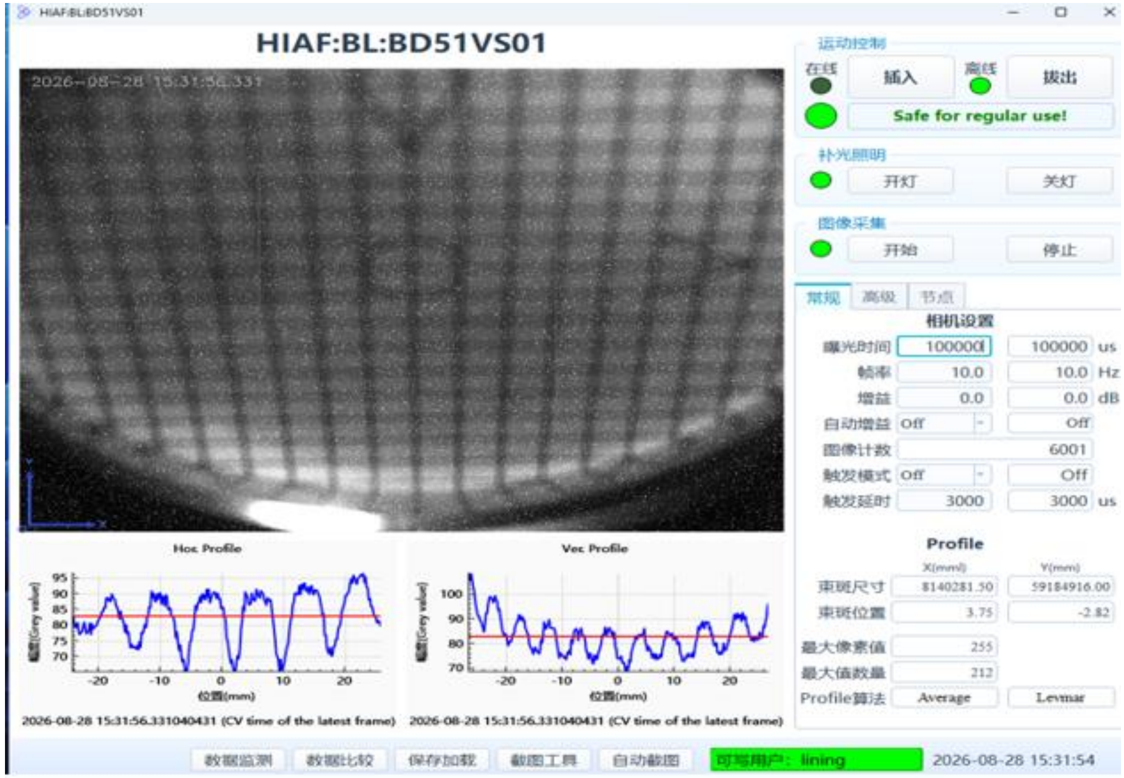
The slit rotates 2° with beams

View Screen issues

◆ Thin ceramic for high energy transfer lines, and powder coated target for injection line

1. Darkening happens in center area with more beams; 2. White noise occurs in cameras inside the tunnel

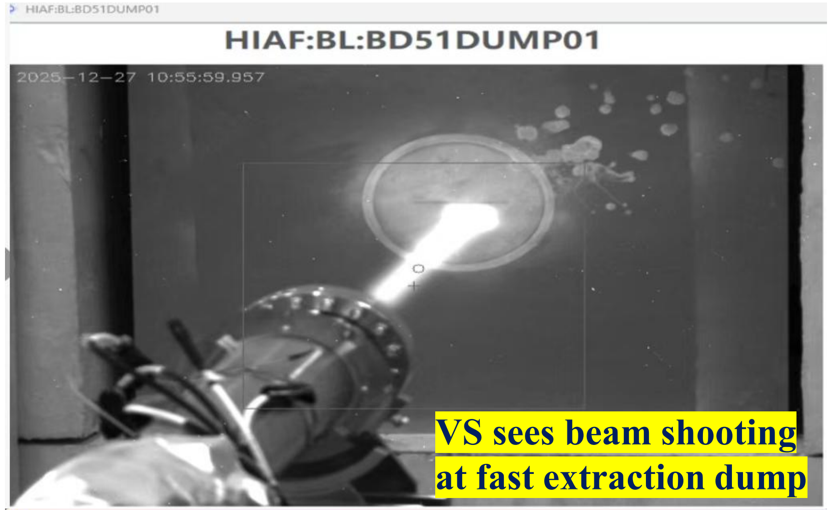
Coated powder VS darkening after a long-time beam shooting

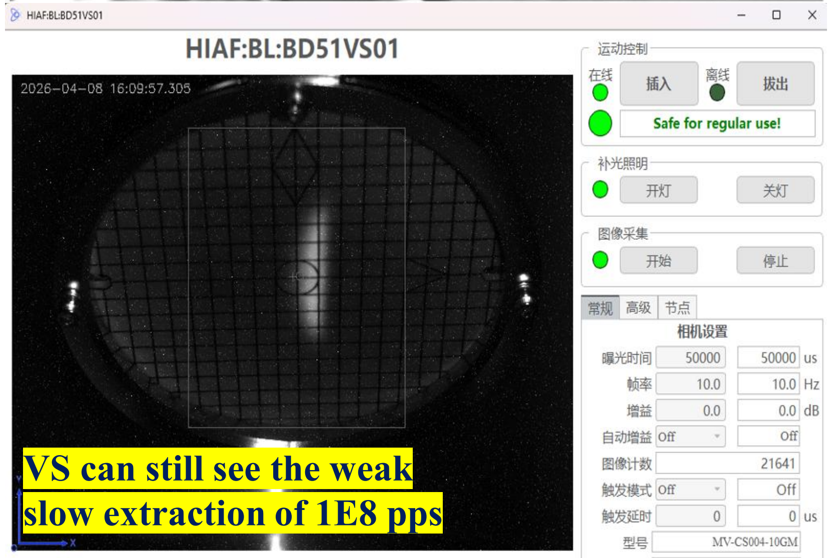


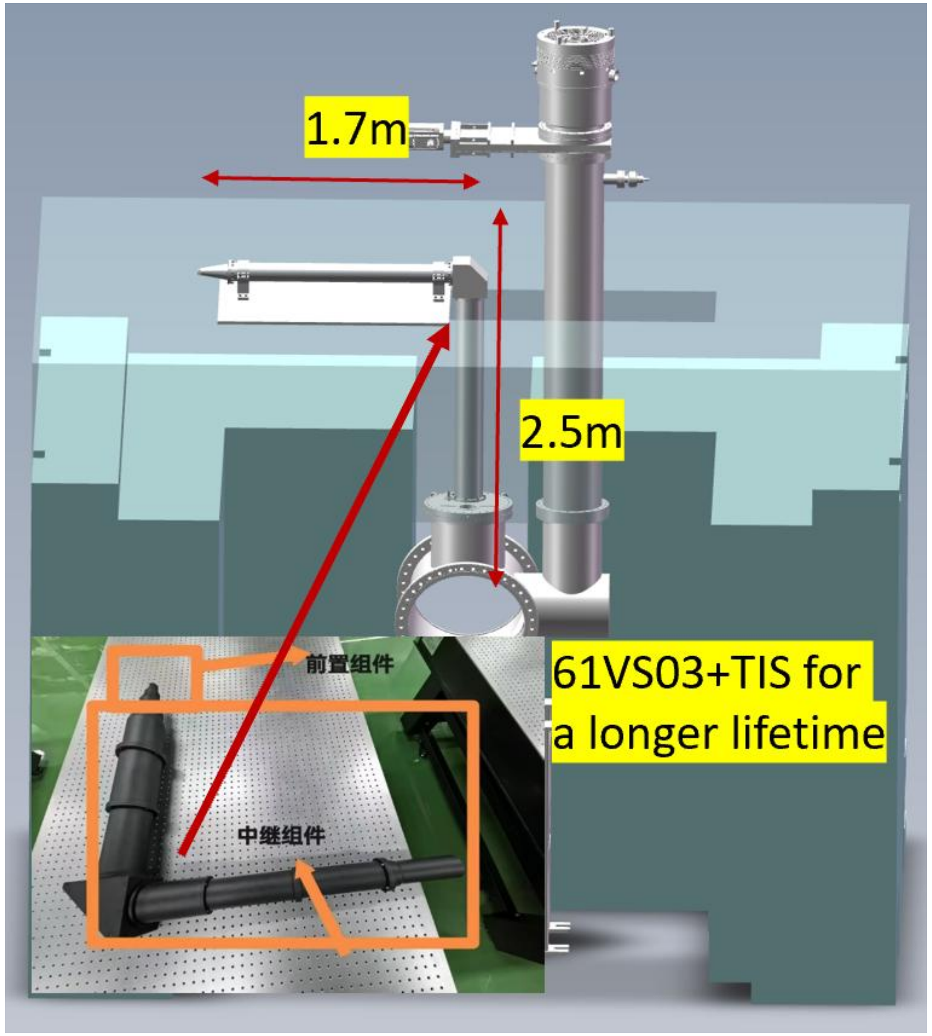
Thin ceramic sheet VS suffering severe camera degradations

VS applications

- Extended optics route acquisition designed in high adiation region for a longer life
- VS is practical for the commissioning like weak slow extraction or fast bombarding







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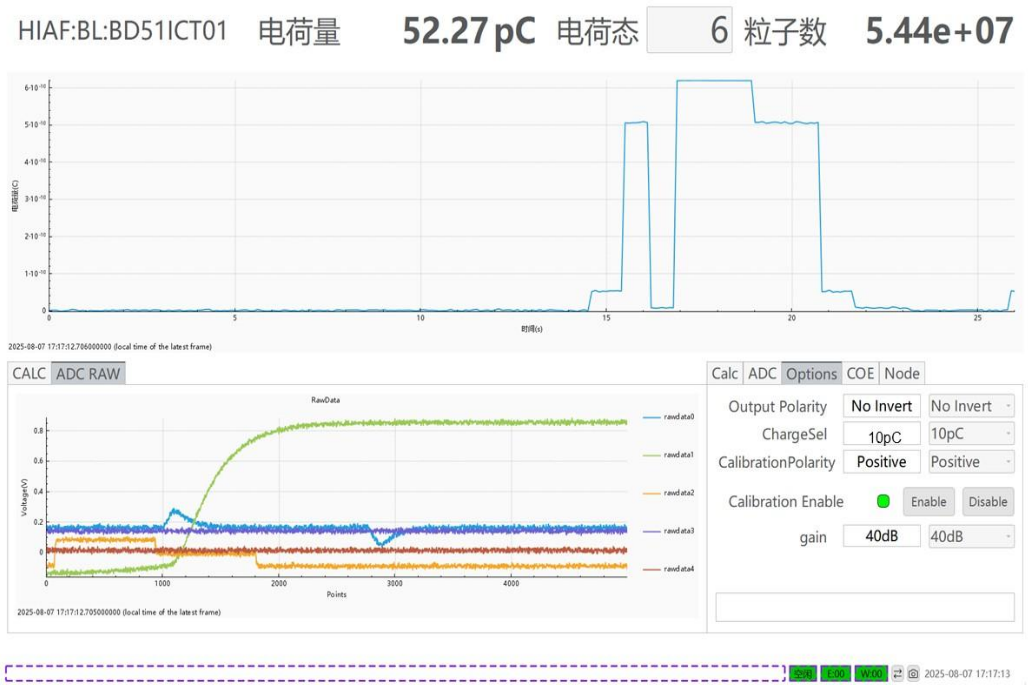
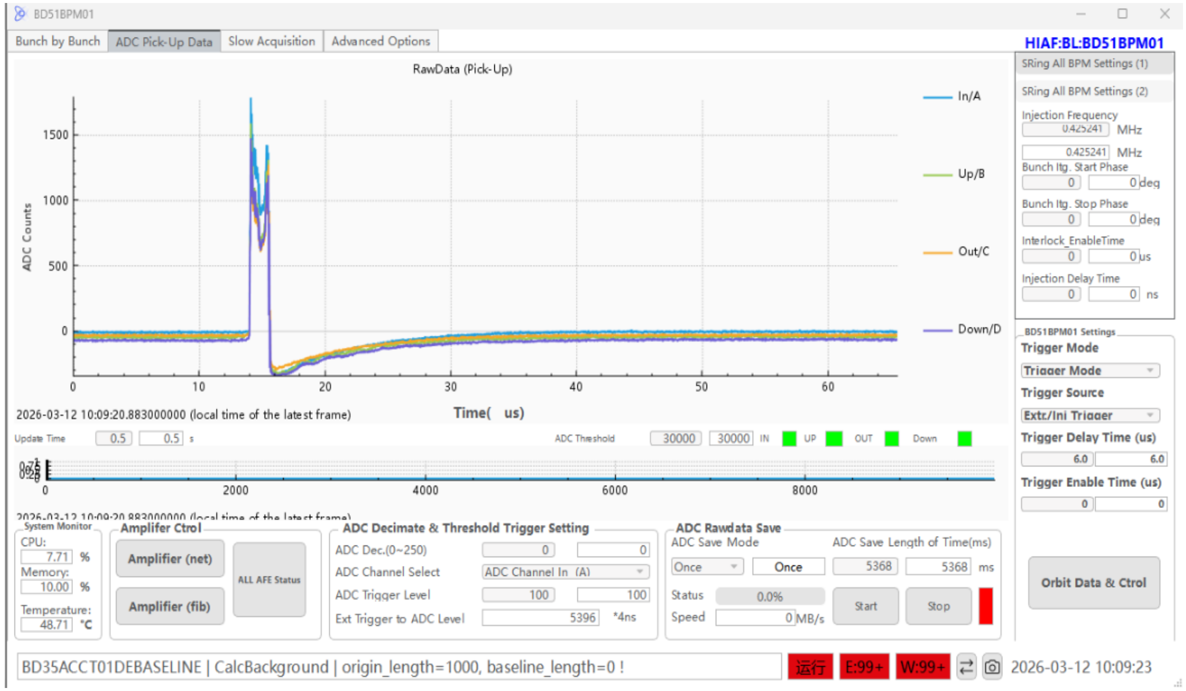
Fast extractions

- ➢ **ICT for the particle number and extraction efficiency determination.**
- ➢ **Big capacitive BPMs (300 mm max) for single short pulse monitoring**



ICT for fast extraction current and efficiency monitoring

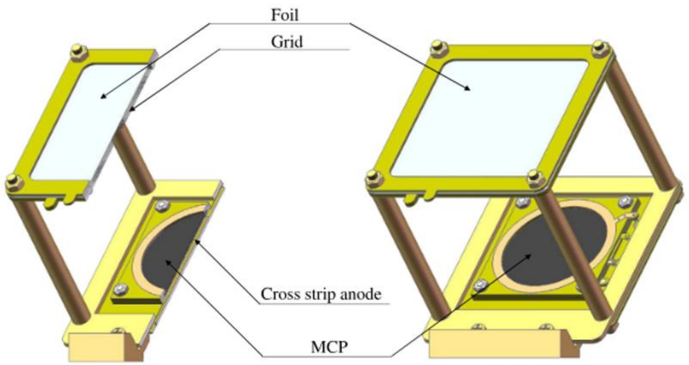


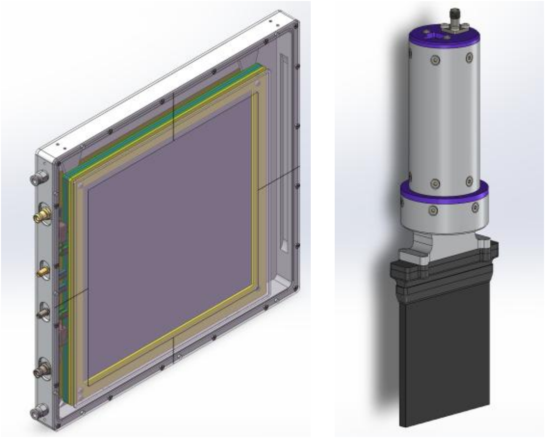
BPM single pulse position measurement during fast extraction

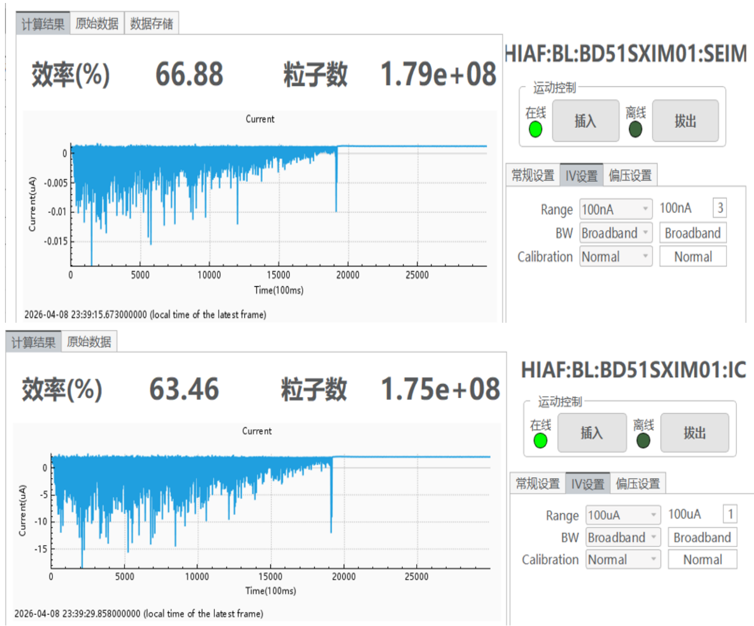
Slow extractions

- SC/IC/SEIM…
  for slow extraction current measurements

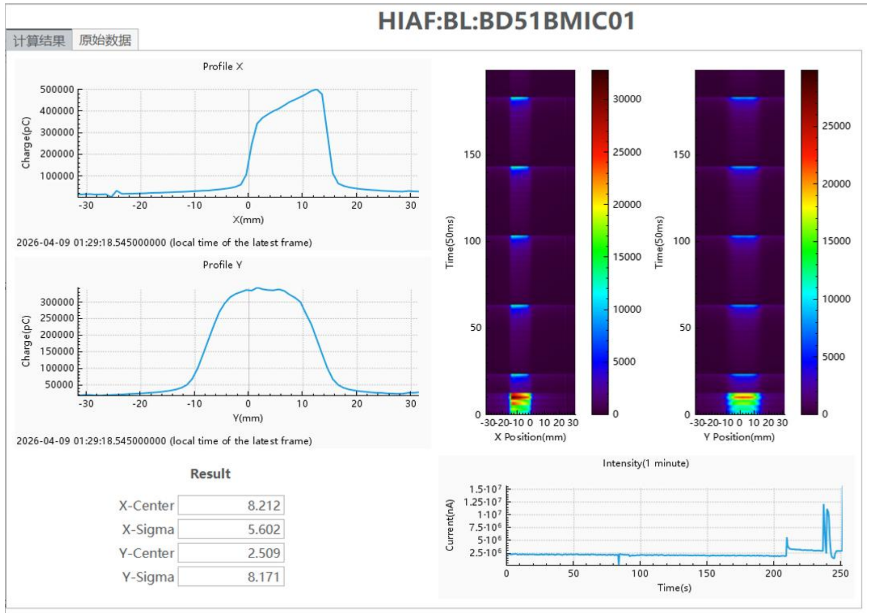
- MIC with gas for slow extraction profiles



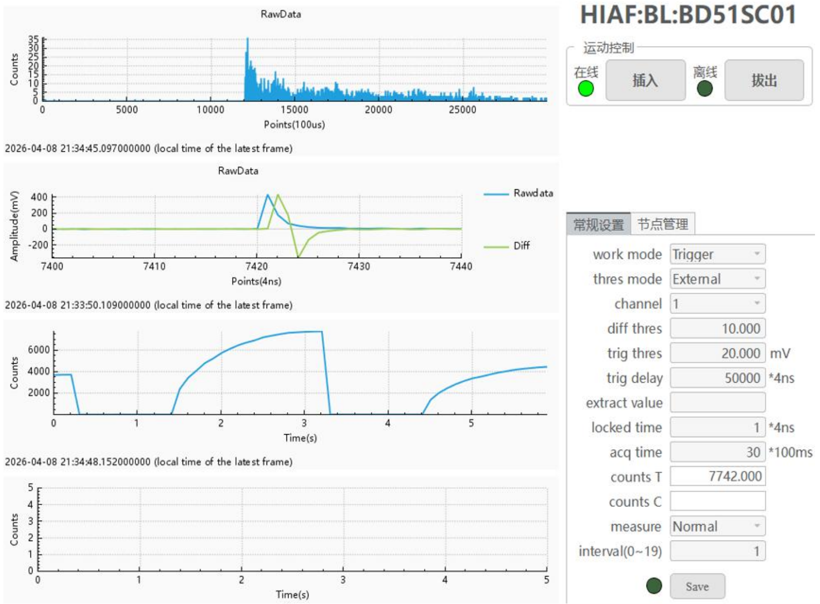




SEIM & IC for current in slow extraction



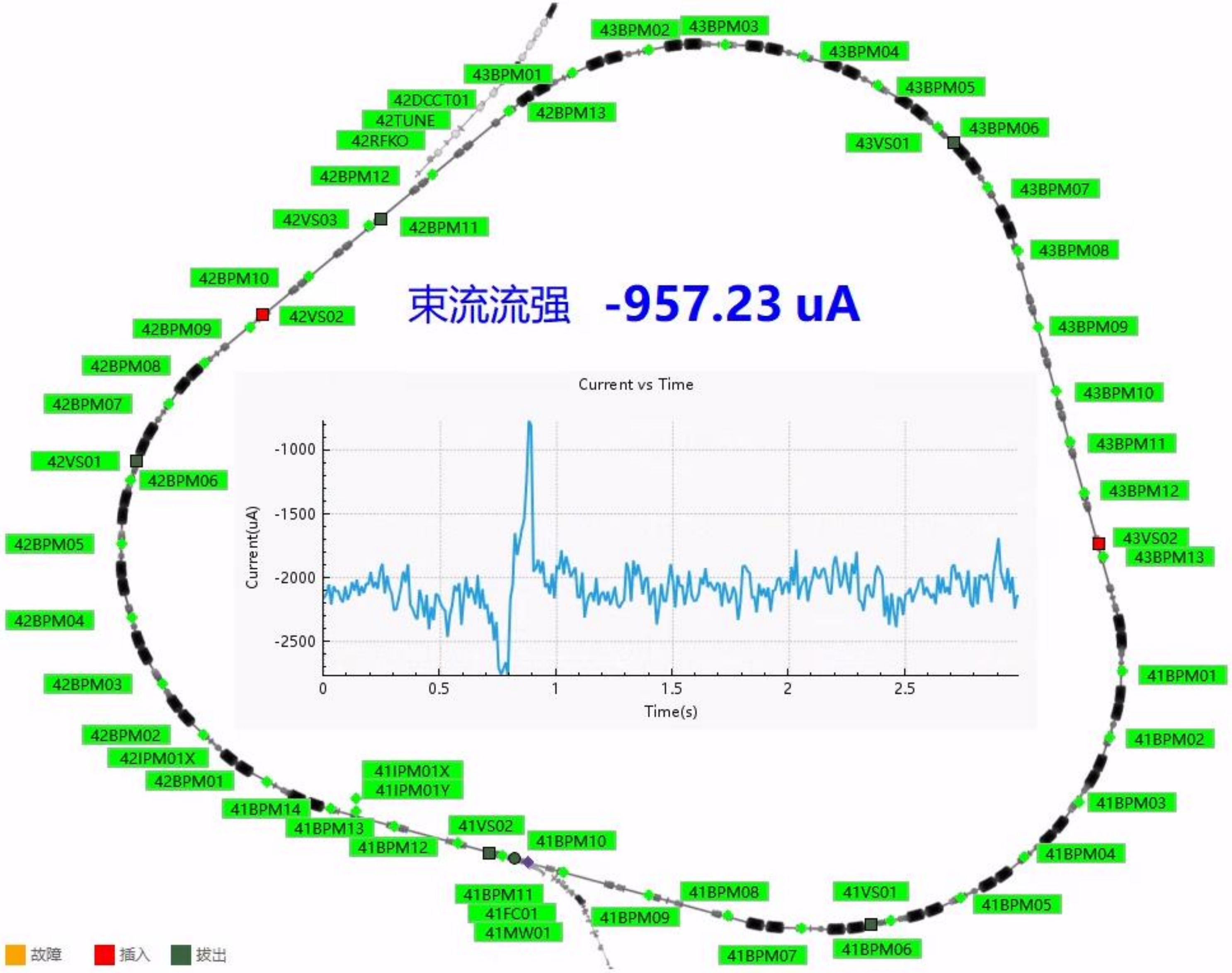
MIC for profile measurement in slow extraction



SC for weak current in slow extraction

BRing BI layout

BRing Device	Number
BPM, interlock, closed orbit correction	40
DCCT/ACCT	1/1
IPM H/V (profile)	3/1
Schottky H/V	1
Exciter+Schottky H/V (tune)	1
Wall current monitor	1
BLM, interlock	63
Feedback PU H/V	2
Feedback kicker H/V	2
RF knockout kicker, slow extraction	1
Scintillation Screen (profile, injection/extraction)	7
Faraday cup	1
Collimator	24
Emittance measurement(slit+grid)	1



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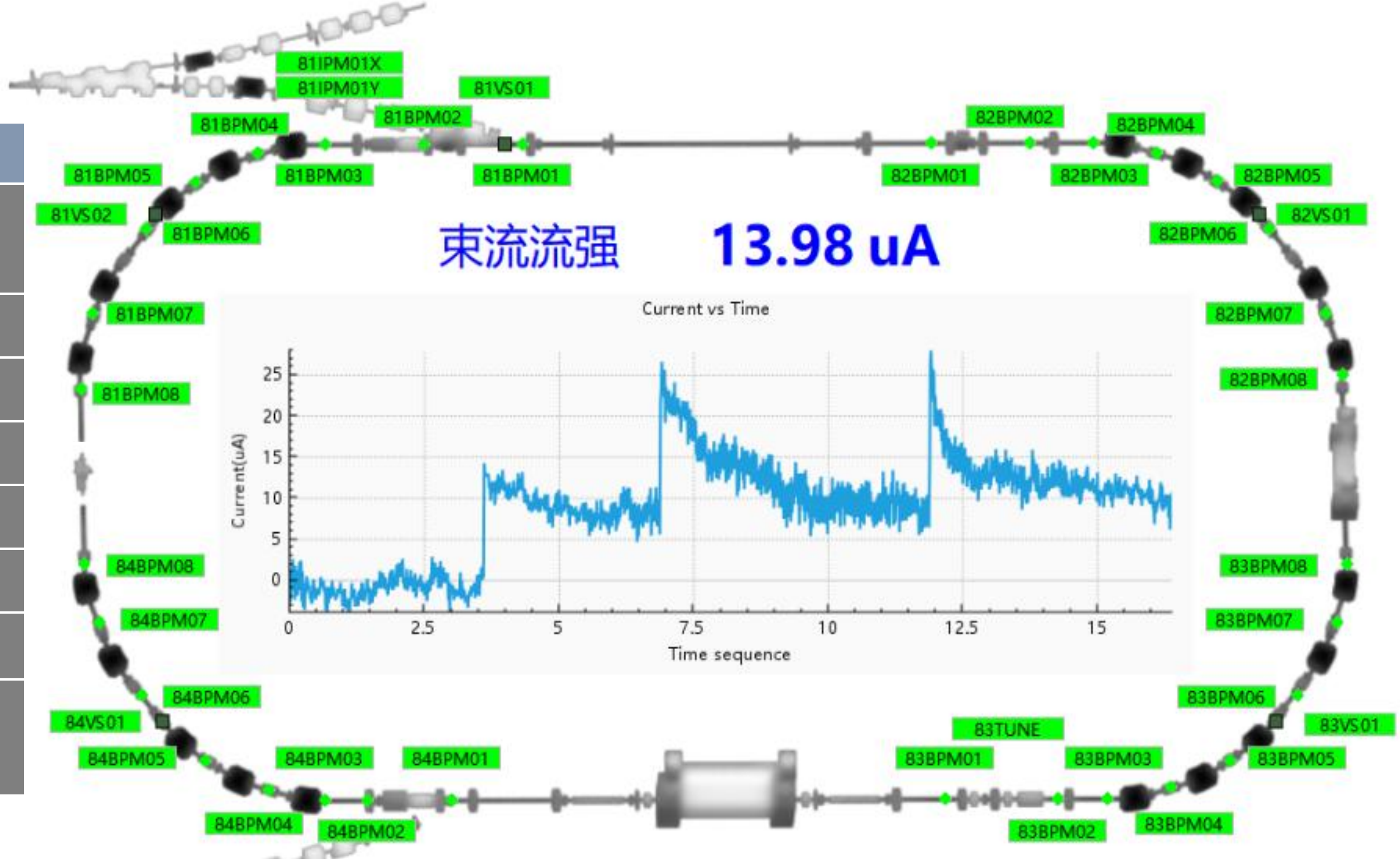
SRing BI layout

BRing Device	Number
BPM, interlock, closed orbit correction	32
DCCT/ACCT	1
IPM H/V (profile)	1/1
Schottky H/V	1
Exciter+Schottky H/V (tune)	1
Wall current monitor	1
BLM, interlock	32
Scintillation Screen (profile, injection/extraction)	6



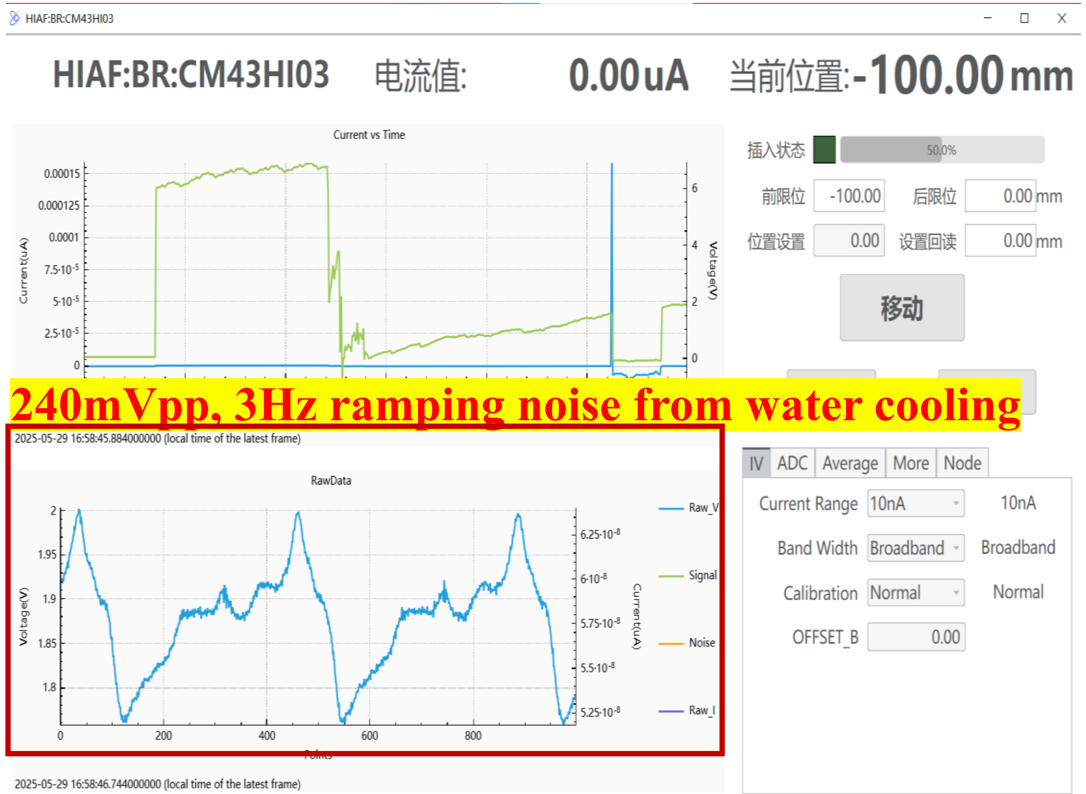
EMI issues in Rings

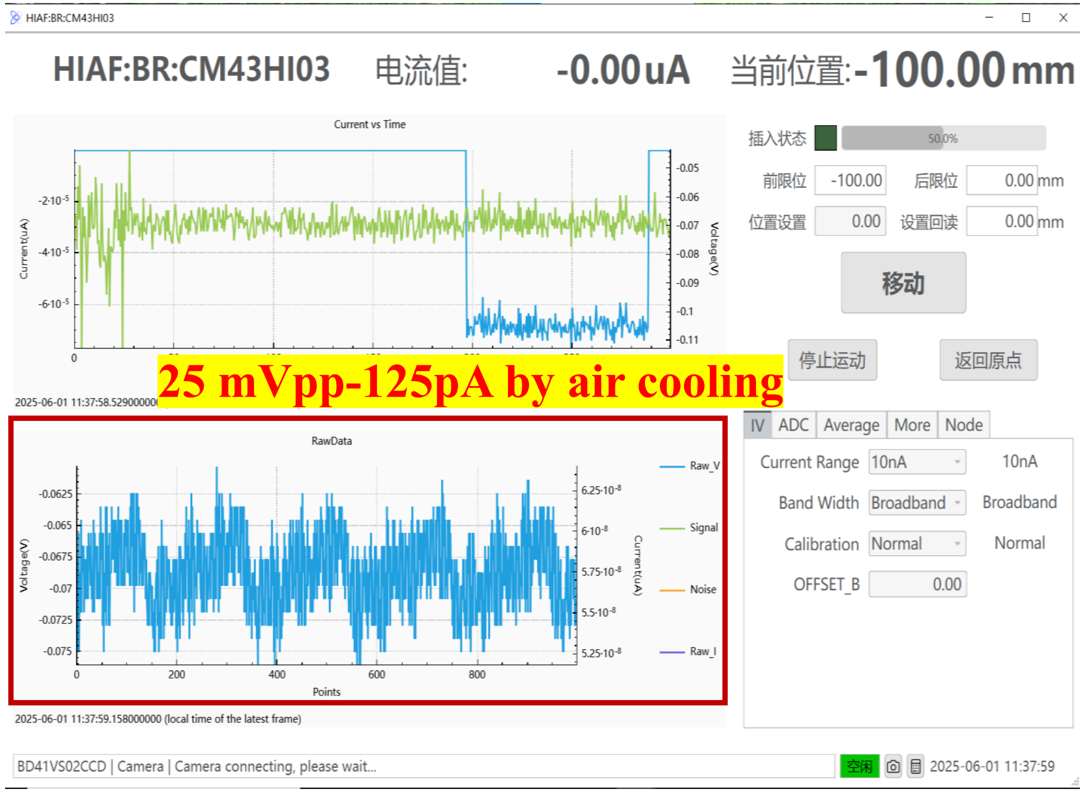
Issue: Noise comes from water cooling pipes into Collimators, which are designed to improve the dynamic vacuum

Solution: Changing water cooling into air cooling can decrease to **1 magnitude less around 100 pA**

Other EMI issues in WCM/DCCT… are correspondingly solved by E/M shielding for circumstances

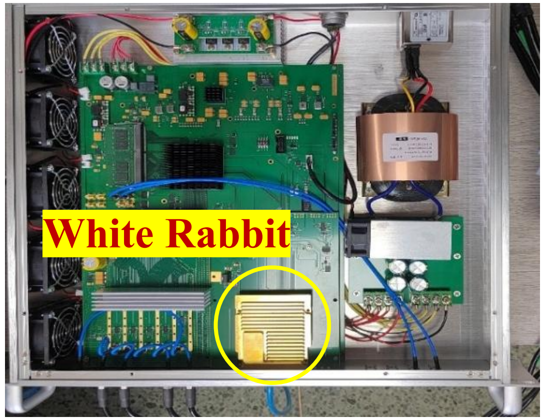
In addition, a special ACCT and BPM at the injection point are used when beams are injected to BRing





Ring BPM features

- Self-developed over 20 kinds and 1500 sets electronics for HIAF including Ring BPM electronics
- White rabbit + Self-calibration function + 2-stage controllable amplifier to satisfy 1E6 dynamics

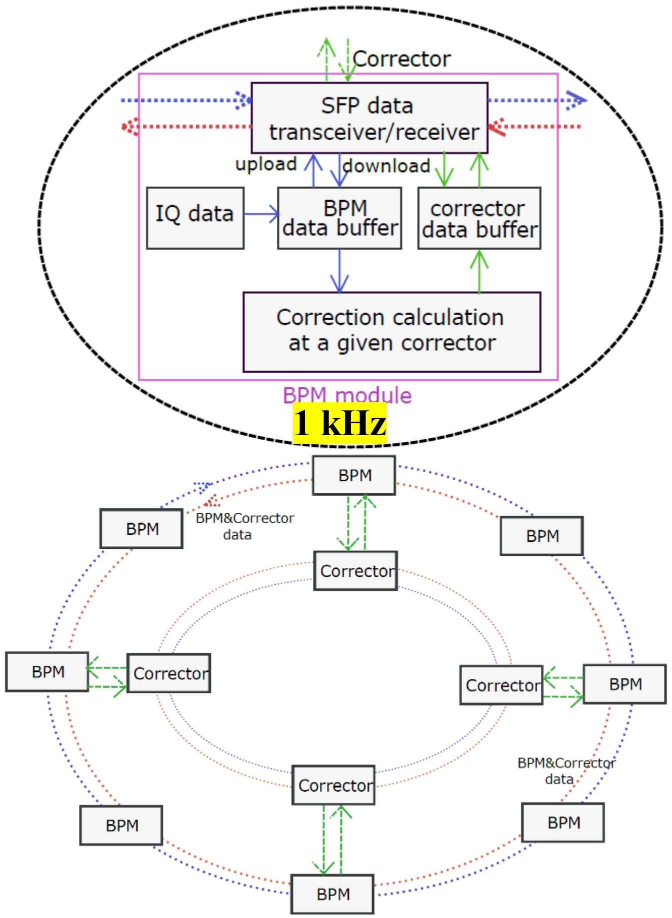


Customized Ring BPM electronics

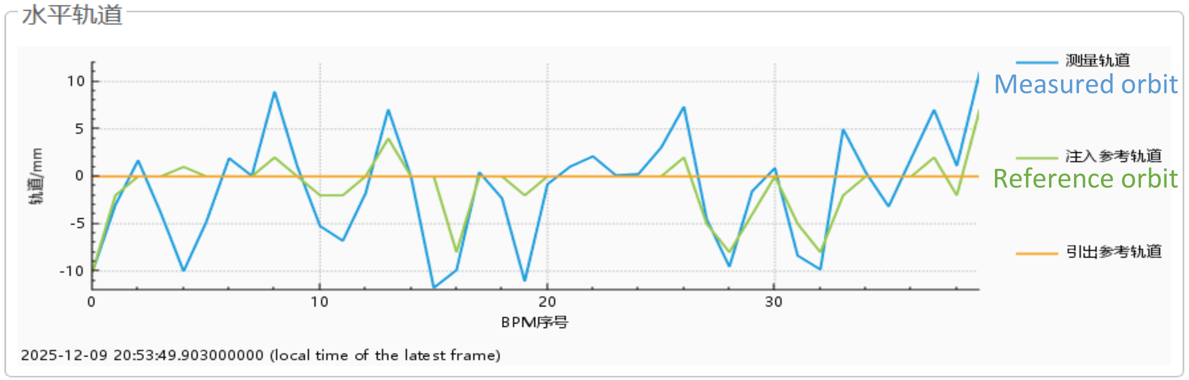
10MHz self-test signal from 2nd amplifier A to B,C,D
To check if the PU-cable-amplifier-electronics status

Ring BPM applications

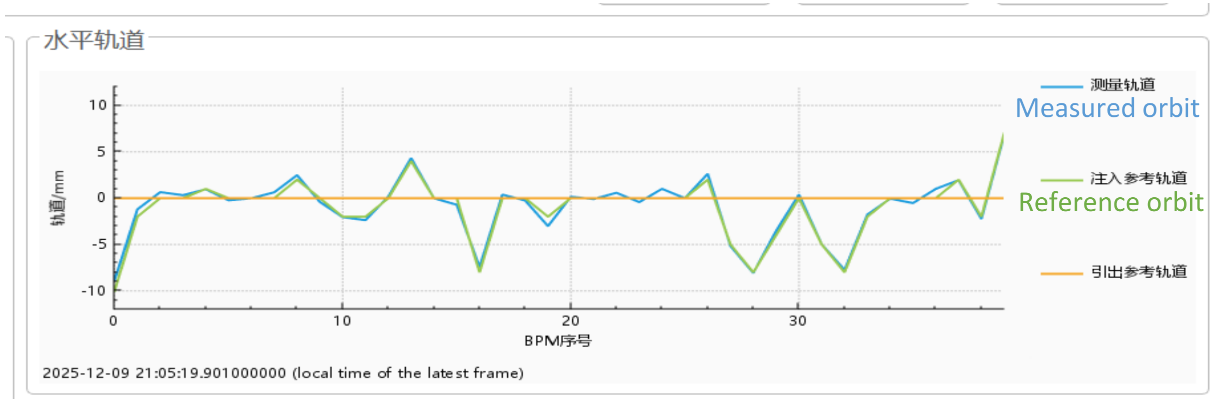
- RF generator + IQ modulation + SFP transmission for 1 kHz BPMs data for orbit correction
- Measurements showing orbit errors effectively decrease less than 1 mm after orbit correction



Data share by all BPMs through double-ring SFP link, coordinated with close orbit algorithm and magnets



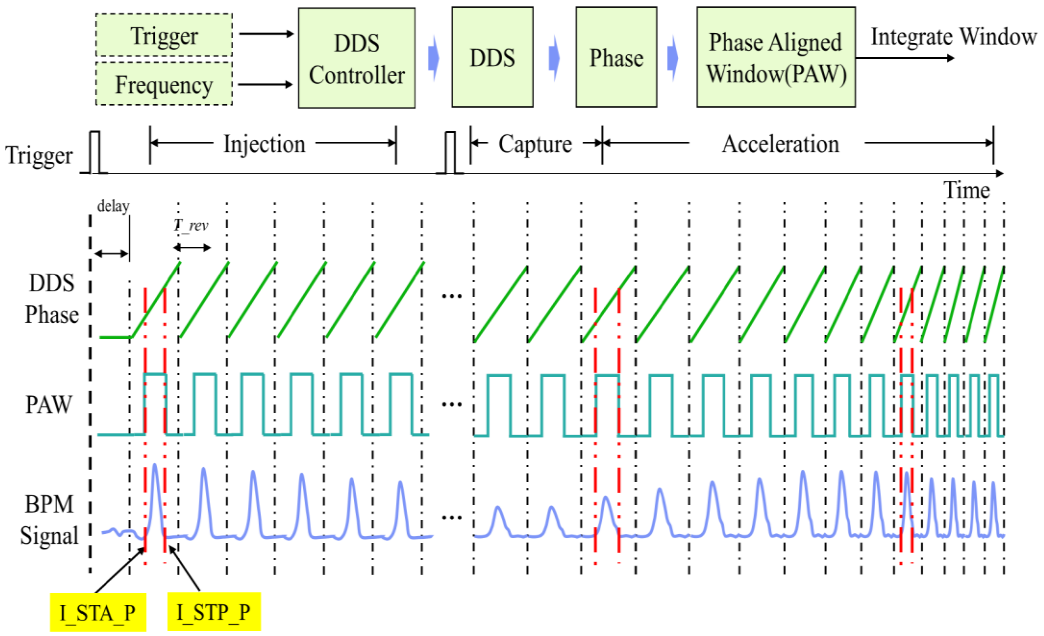
Error ≥ 10 mm between measured and reference orbits before correction



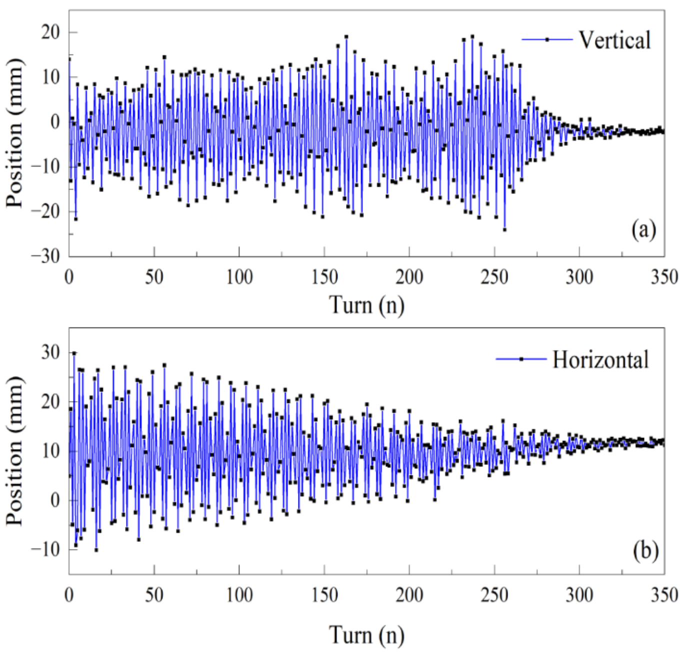
Error ≤ 1 mm between measured and reference orbits after correction

Ring BPM applications

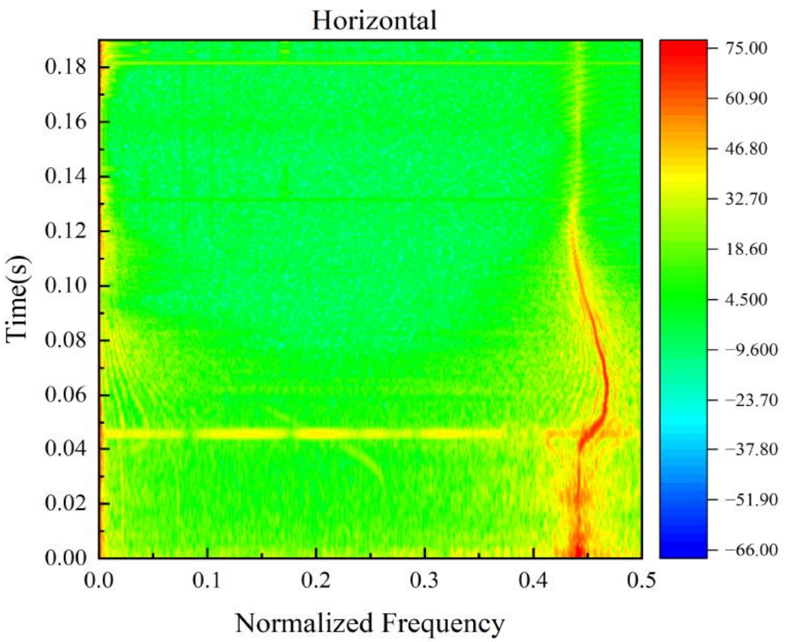
- ➢ **RF-waveform generator + White rabbit timing to achieve automatic PLL without RF reference**
- ➢ **Turn-by turn orbit makes real-time monitoring of beta oscillation, emittance and tune possible**



Automatic PLL during injection, capture and acceleration



β oscillations during injection process

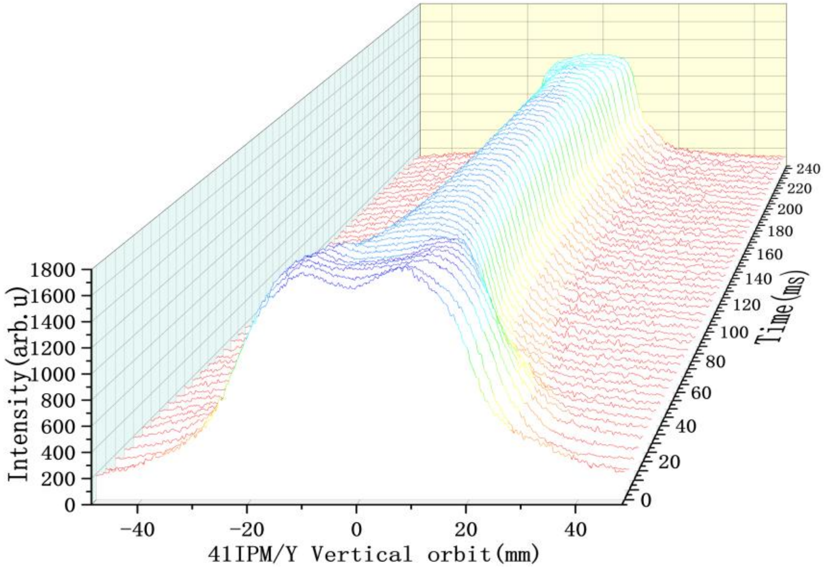


Tune monitoring by turn-by-turn data

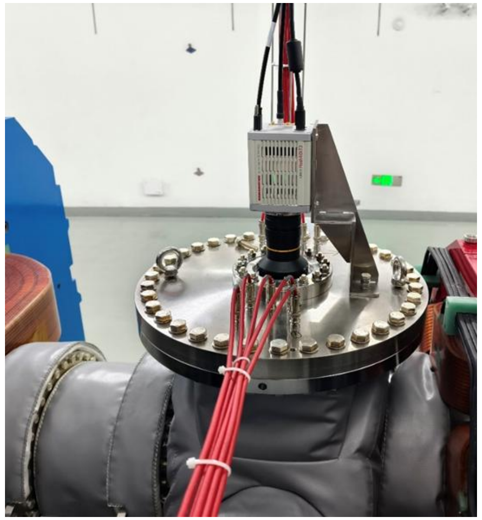
Ring IPM applications

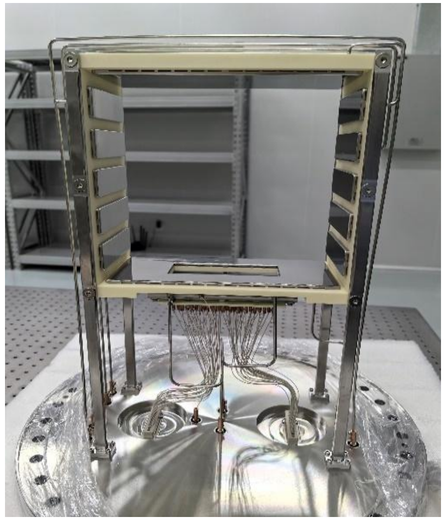
✓ **5 IPMs with optics acquisition work well for profiles fast up to 5ms in orbit/size monitoring during operation and e-cooling**

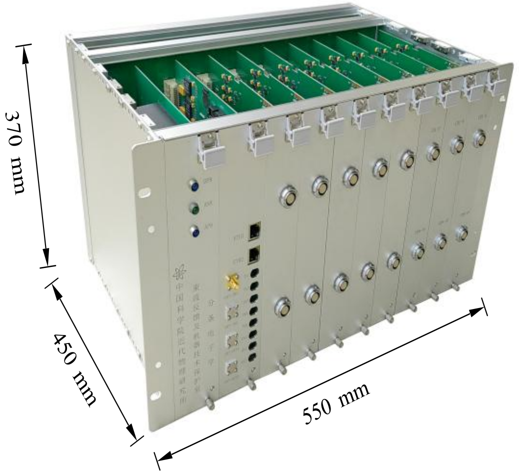
◆ **128 channels with 64 Msps electronics under tests for fast turn-by-turn profile measurements for future machine up**



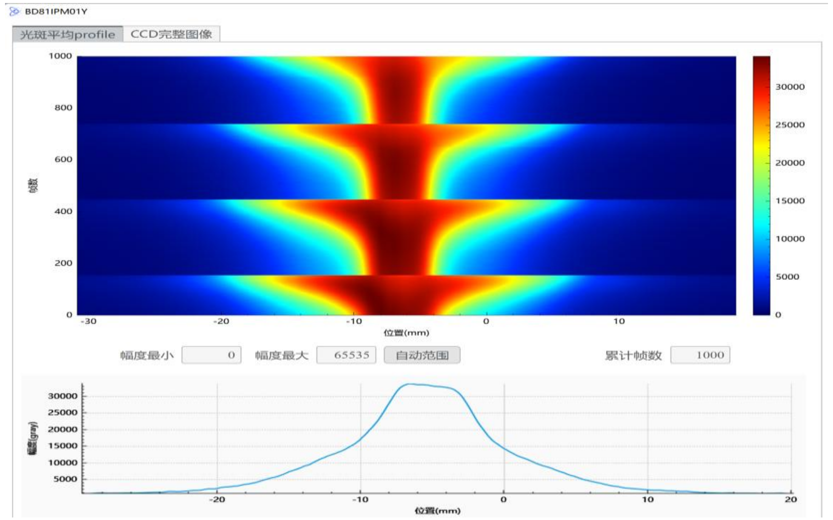
Profiles during injection, capture, acceleration







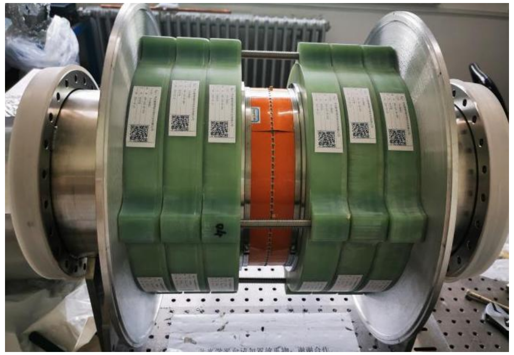
Optical IPM system view; Fast IPM with multi-channel anodes and electronics



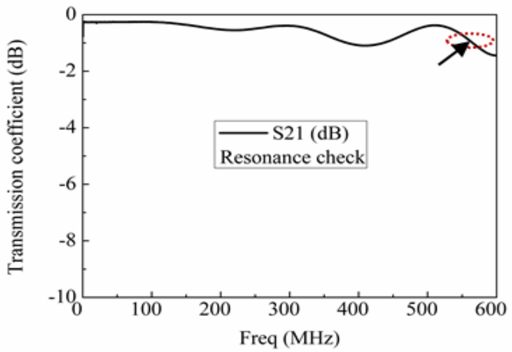
Profile variation during electron cooling cycles

WCM applications

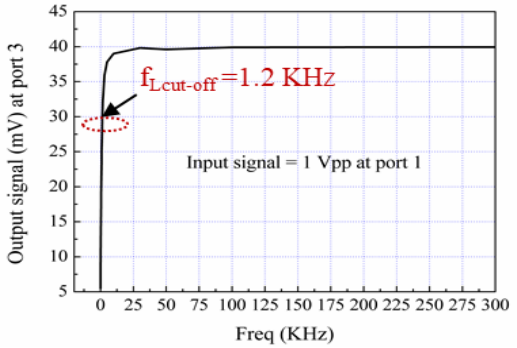
- WCM developed with printed resistor sheet to get a suitable bandwidth of 1.2 kHz-550 MHz
- Using FBP algorithm to reconstruct longitudinal emittance by bunch length data from WCM



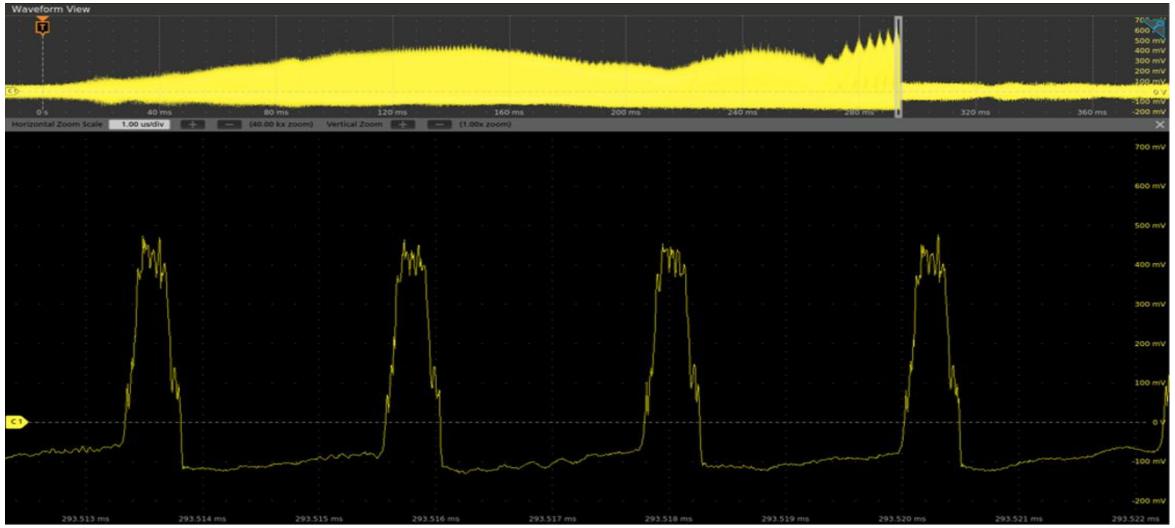
Wall current monitor



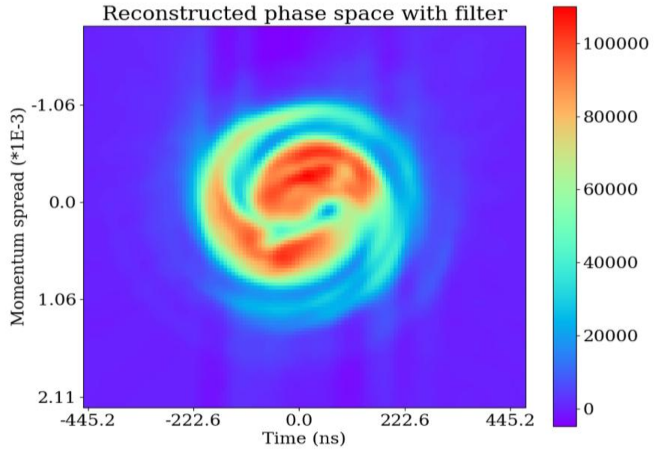
High cut-off frequency ≈ 550Mhz



Low cut-off frequency ≈ 1.2 khz



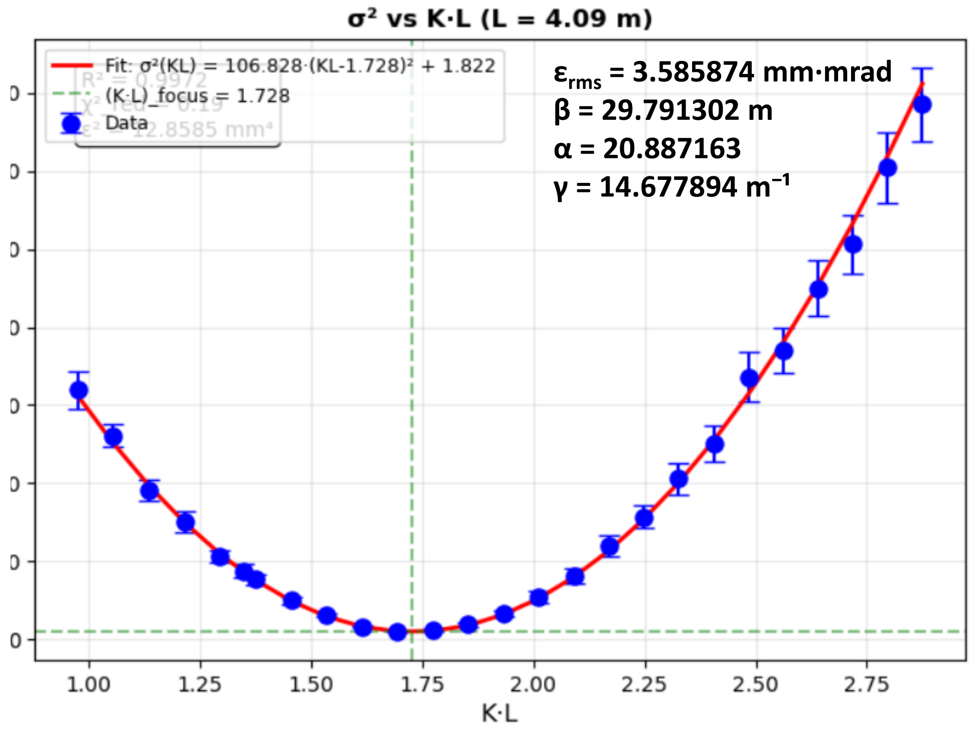
WCM raw data acquired by a high bandwidth oscilloscope



Longitudinal emittance reconstructed by WCM data

Prospective…

- Energy spread measurements by a dipole magnet and 2 slits + 1 FC are ready for the beam tests
- Transverse emittance by Multi-k scanning of Q-mag + a wire scanner has been tested and still proceed
- Trying to use BPM q values of σ^2x-σ^2y with Q-mag scanning for potential online emittance monitoring
- Fast turn-by-turn data researches by BPM or IPM for machine studies like mismatch optimizations
- 1D distributions with the tomography algorithm and deep learning exploration for precise 2D reconstruction
- ………



Multi-k scanning with 4.9MeV/u $^{40}Ar^{12+}$ beams for the transverse emittance measurements at injector

Summary

- HIAF has passed all the national acceptance beam commissioning, now moving to normal operations for experimental missions, and already achieving some big fruits like discovering new nuclides rapidly, due to its high intensity.

- During beam commissioning, over 450 instruments and 1500 self-developed electronics are deployed in different areas like linac or synchrotron, and in general they all work well and steadily.

- Some experiences especially in emittance measurements are learned, and also plenty of EMI problems are encountered and solved accordingly, such as RF interference to CT/BPMs and 50 Hz power supply noise for weak currents.

- In the future, more attention will be paid to non-destructive diagnostics for higher intensity upgrade, and explorations in the machine learning.