Institute of Modern Physics
Chinese Academy of Sciences

High Intensity Heavy-ion
Accelerator Facility

FPGA-Based Digital IQ Demodulator Used in the Beam Position Monitor for HIAF BRing

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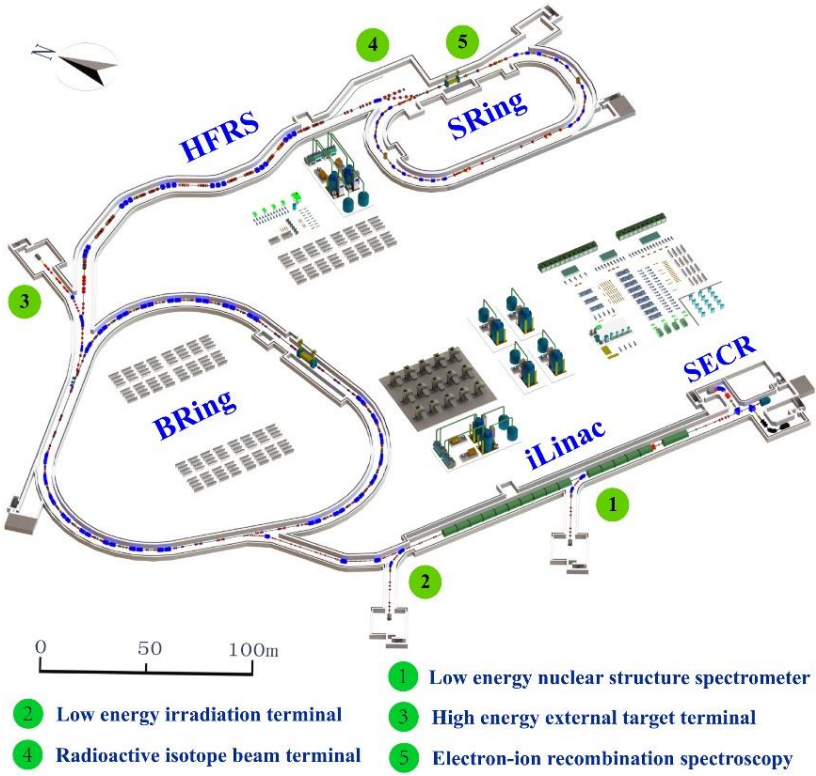
Outline

- Beam Position Monitors at BRing
- System Architecture
- Digital Signal Processing
- Beam test at HIRFL-CSRm & PREF
- Conclusion

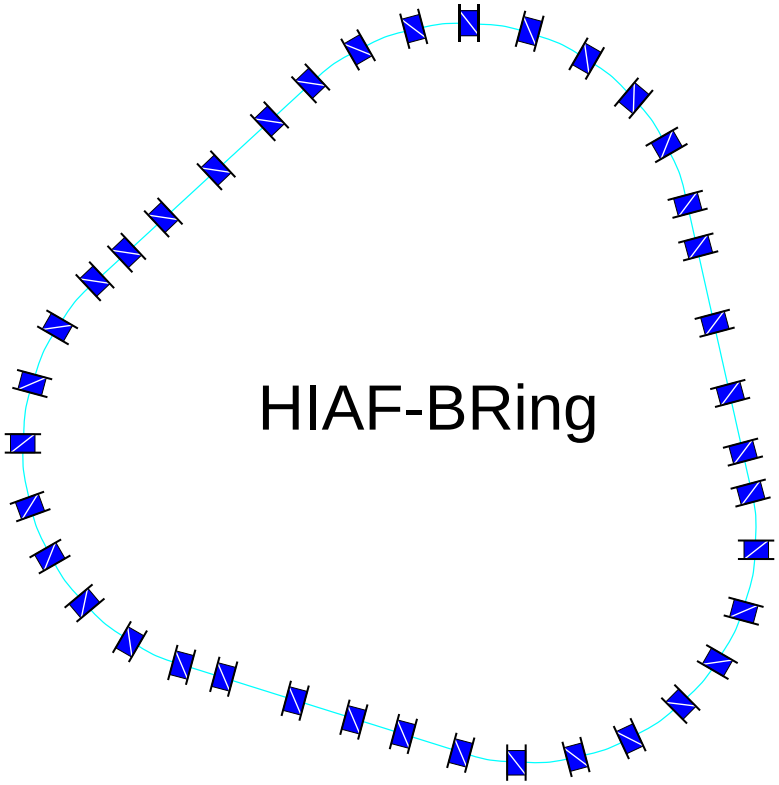


Beam Position Monitors at HIAF BRing

Main Parameters

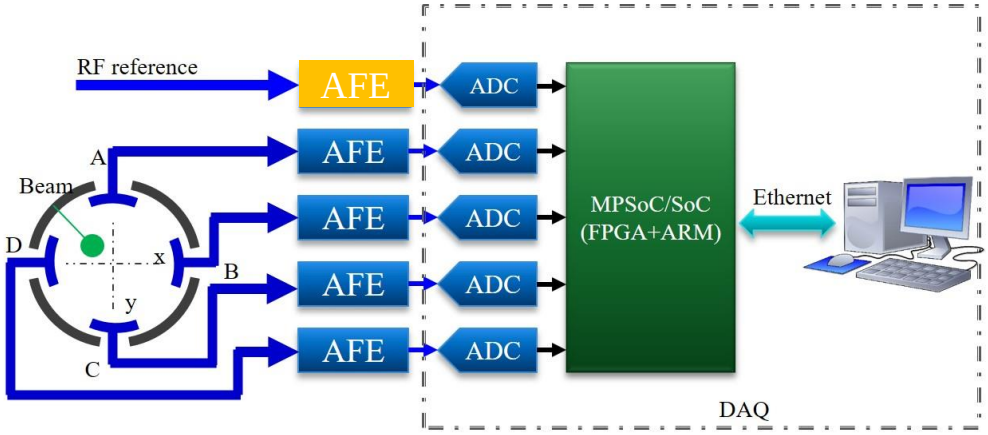
	BRing
Circumference (m)	569
Ion species	p – U
Harmonic number	4,2,1
Operation mode	fast ramping (12T/s, 3Hz)
Beam position resolution (mm)	0.1
Number of BPMs	40
Ramping time (ms)	< 300
RF range (MHz)	0.2 ~ 2.1

Beam commissioning, Closed orbit correction, Beam feedback system



The BPM distribution at HIAF-BRing

BPM System Architecture



Analog Front End : ~40 dB Amplifier

Radio Frequency : Set as Reference

Analog to Digital Convert : 250 Msps

System on Chip : ZYNQ UltraScale+(ZU15)

FPGA : Digital signal processing

ARM : Decoder FPGA data

Embedded the Linux systems

EPICS PVs over intranet

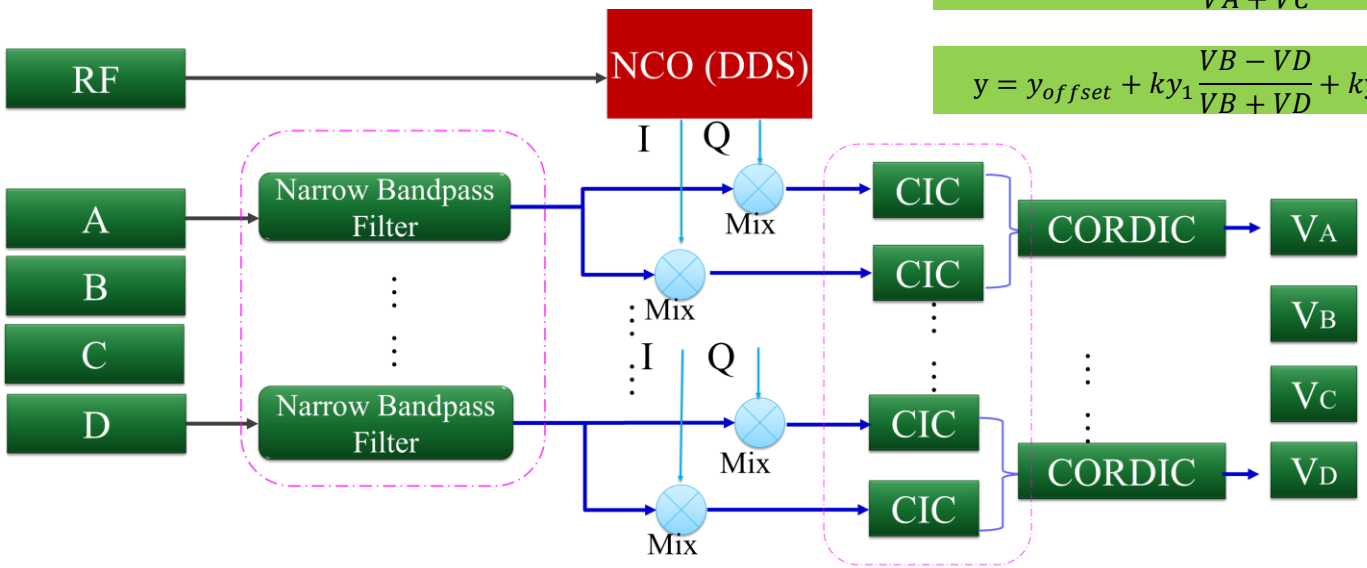
The Designed Electronics

Digital Signal Processing

- Narrow bandpass filter (IIR + FIR), bandwidth 0.2 ~ 2.5 MHz (@250 Msps)
- NCO realized by DDS, generates In-phase and Quadrature components (I,Q)
- CIC filter to decrease the data rates and get the DC component mixed signal (250 MHz →10 KHz)
- CORDIC (Coordinate Rotation Digital Computer) algorithm calculates the channel amplitude (VA,VB,VC,VD)
- Different over sum function to calculation the beam position, keeps quadratic term

$$x = x_{offset} + kx_1\frac{VA - VC}{VA + VC} + kx_2\left(\frac{VA - VC}{VA + VC}\right)^2$$

$$y = y_{offset} + ky_1\frac{VB - VD}{VB + VD} + ky_2\left(\frac{VB - VD}{VB + VD}\right)^2$$



Digital Signal Processing

IIR(Infinite Impulse Response) High-pass Filter (Direct II)

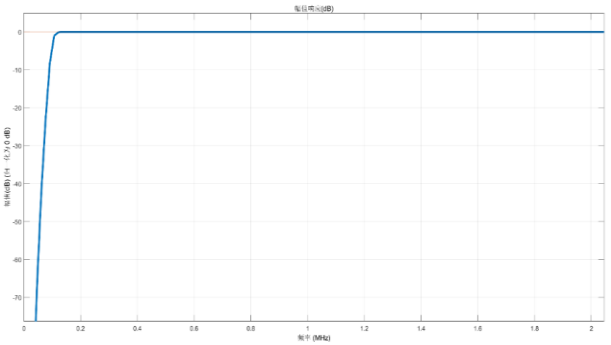
Pass band: 0.18 MHz; Stop band: 0.02 MHz

$$H(z) = \frac{\sum_{r=0}^{M} b_r z^{-r}}{1 - \sum_{k=0}^{N} a_k z^{-k}} \pi r^2$$

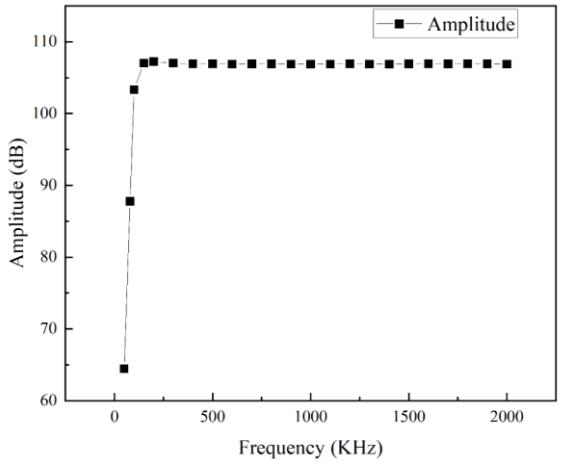
Matlab SOS matrix:

1 -2 1 1 -1.99920956185 0.9992158460333
1 -2 1 1 -1.99771971295 0.9977259924513
1 -2 1 1 -1.99645411851 0.9964603940366
1 -2 1 1 -1.99553561562 0.9955418882620
1 -2 1 1 -1.99505306895 0.9950593400748

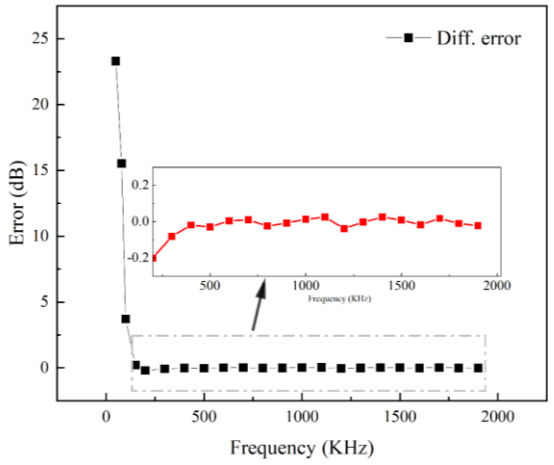
5 Stages Cascaded



Amplitude-frequency response in MATLAB



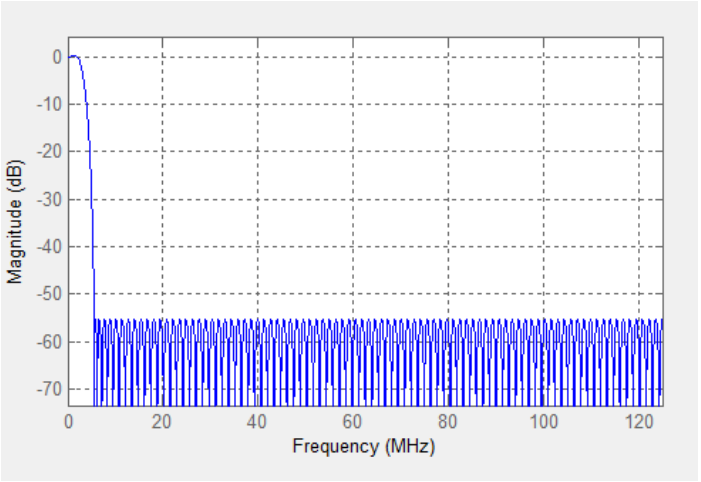
Amplitude-frequency response



Difference error

FIR Lowpass Filter

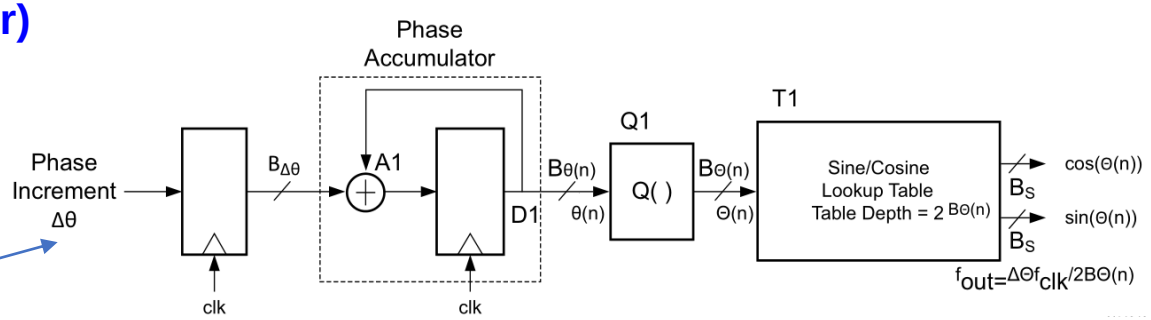
Pass band: 2 .5 MHz
Stop band : 5 MHz
Order : 278



FIR lowpass amplitude-frequency response

DDS (Direct Digital Synthesizer)

$$f_{out} = \frac{f_{clk}\Delta\theta}{2^{B_{\theta(n)}}}$$

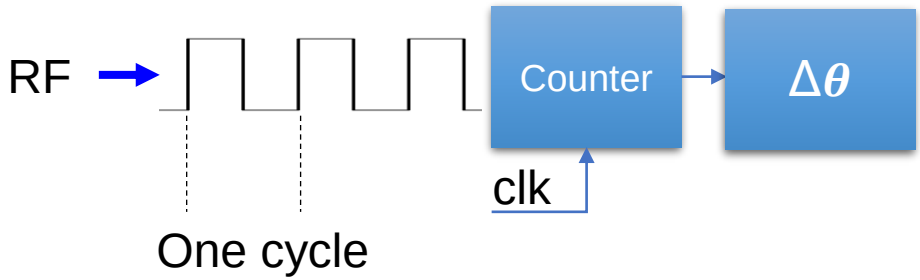


DDS Logic

fout: output frequency
fclk: sample frequency (FPGA)

Δθ： phase words
$B_{\theta(n)}$:number of bits in the phase accumulator

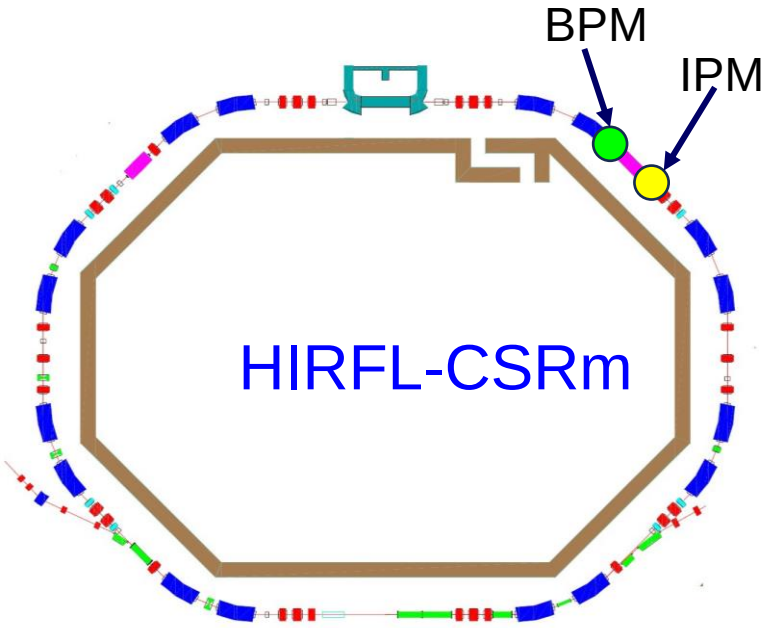
- **Real-time Frequency Monitor**



$$\Delta\theta = \frac{2^{B_{\theta(n)}}}{N}$$ ⇨ DDS

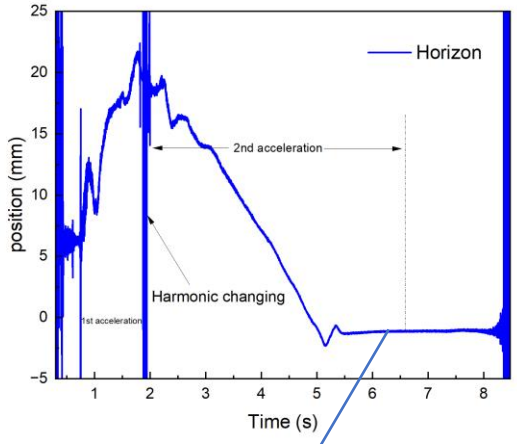
Beam test at HIRFL-CSRm

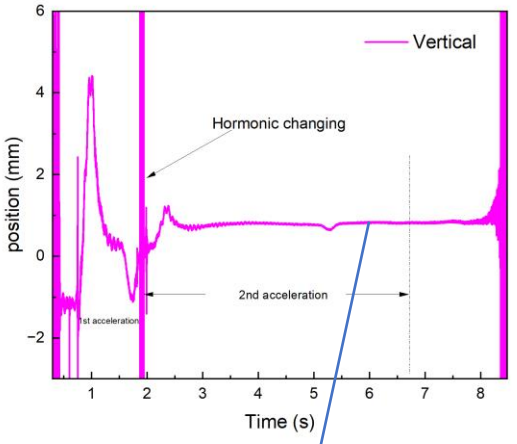
Ions: Fe, about 800 uA. The horizontal and vertical beam position measured, the resolution better 0.02 mm.

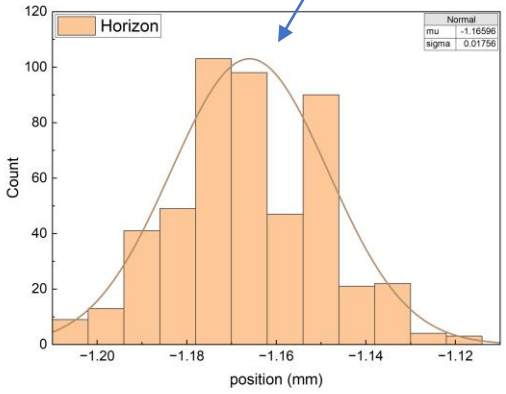


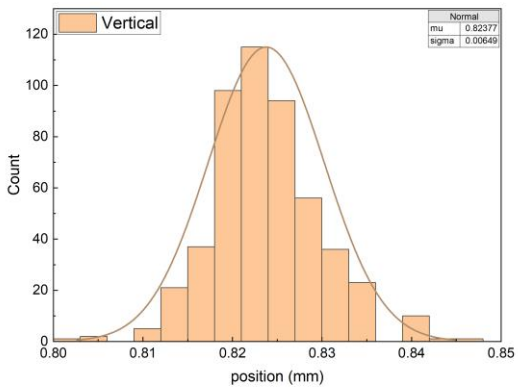
The Layout of CSRm

RF range 0.2 ~ 1.78 MHz





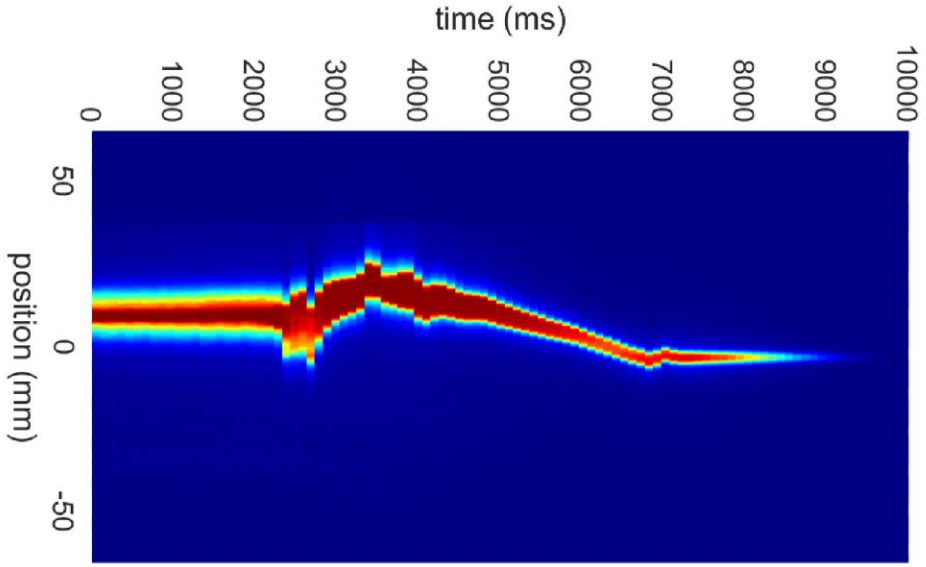




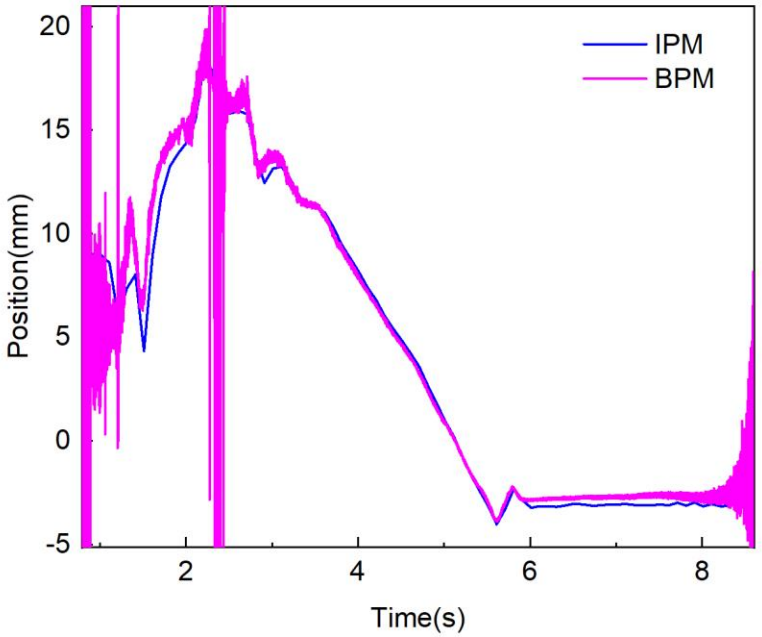
500 points selected

Beam test at HIRFL-CSRm

Compare with the noninvasive Ionization Profile Monitor (IPM)



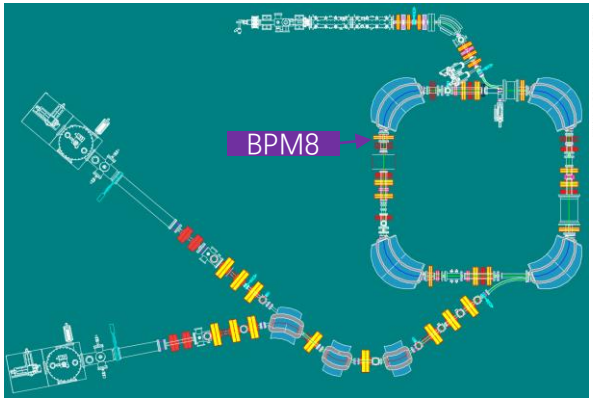
Waterfall diagram of IPM (10 Hz)



BPM and IPM position compare

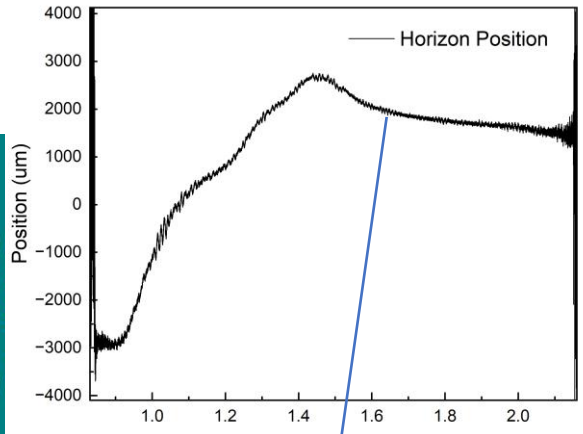
Beam test at PREF (*Proton Radiation Effects Facility*)

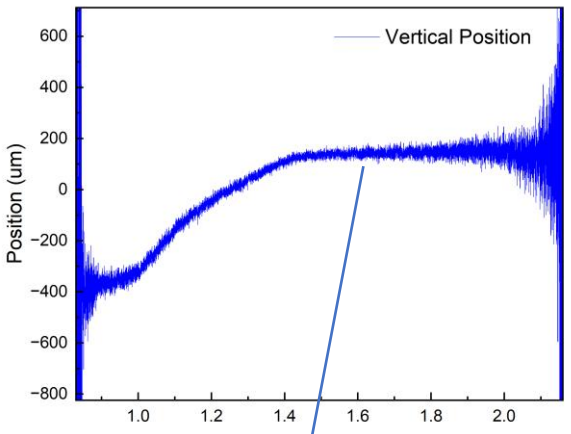
Horizontal and vertical beam position at PREF BPM08.(2023.09.12)
Ions: proton, 10 mA, without preamp. The resolution is 0.03 mm.

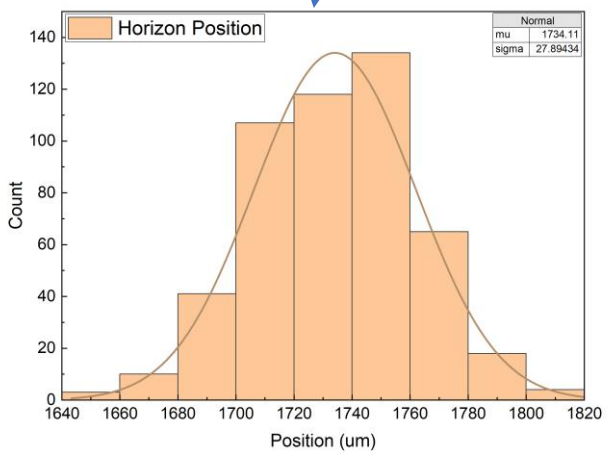


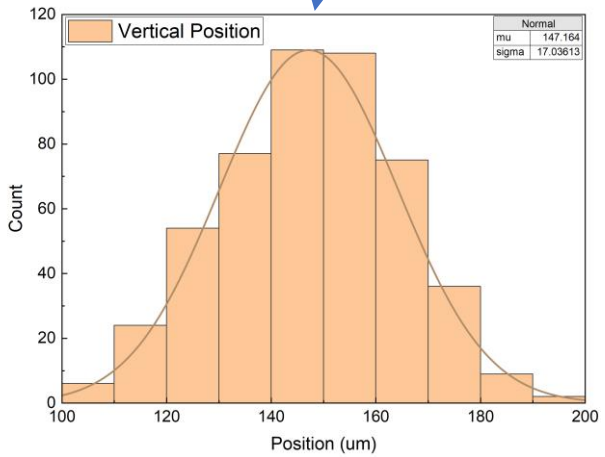
The Layout of PREF

RF range 1.2 ~ 5.8 MHz









500 points results

Conclusion

- ✓ A new BPM prototype for HIAF is developed.
- ✓ The HIRFL-CSRm and PREF tests show promising results.
- ✓ Current prototypes could achieve the required performance.

Acknowledgment

Many colleagues from the diagnostics and other groups have contributed directly or indirectly to this talk, by their work or through fruitful discussions.

Thank you