

The Development and Application of the Digital **BPM** Signal Processor at SINAP

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BI, SSRF



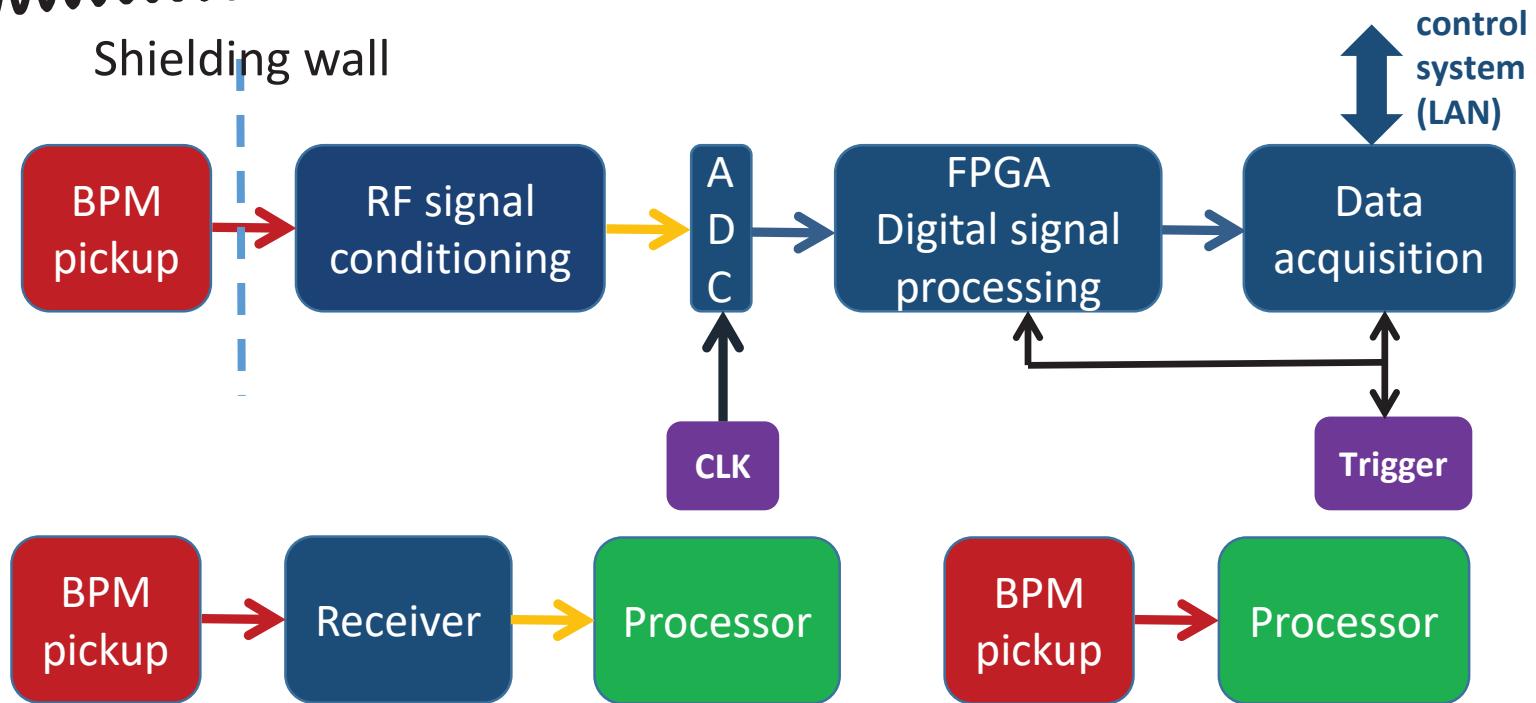
2018 March. 6



Outline

- Introduction of DBPM development
- Applications on FEL
- Applications on storage ring
- Other processors & Direct RF-Sampling DBPM
- Summary

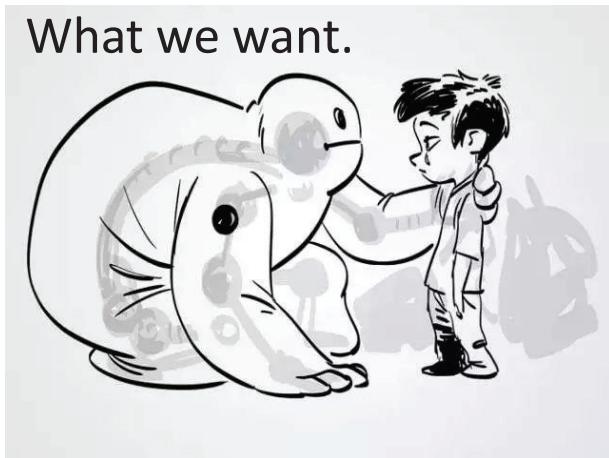
Objectives



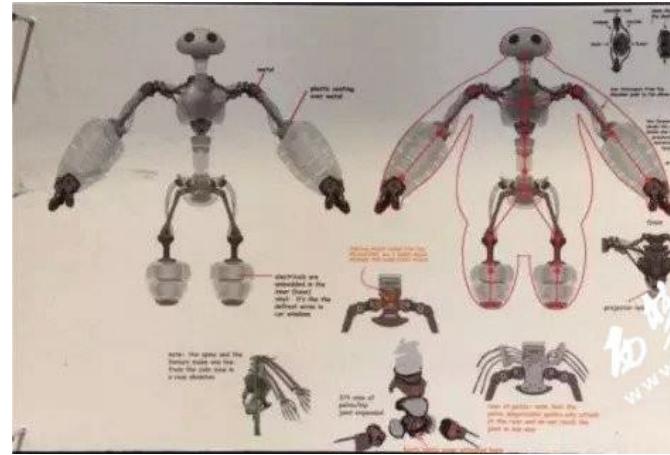
- BPM signal processing(SBPM,CBPM,BBPM).
- **General platform** for multi-parameters measurement.
- Research new applications and new algorithms.
- Stand-alone design and easy-to-use.

Develop Flow

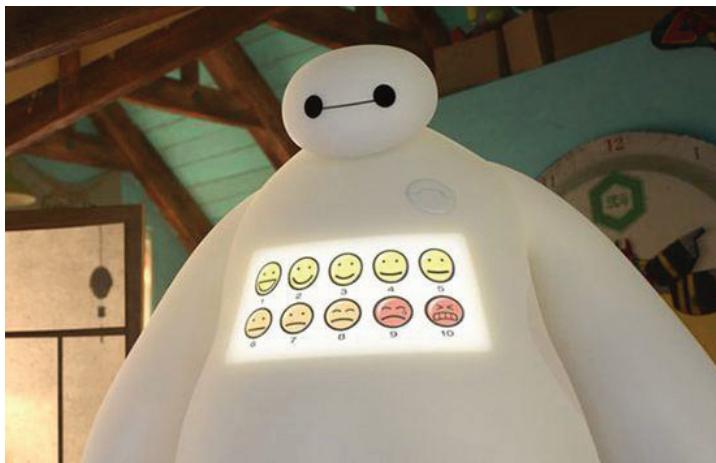
Conceptual Design:
What we want.



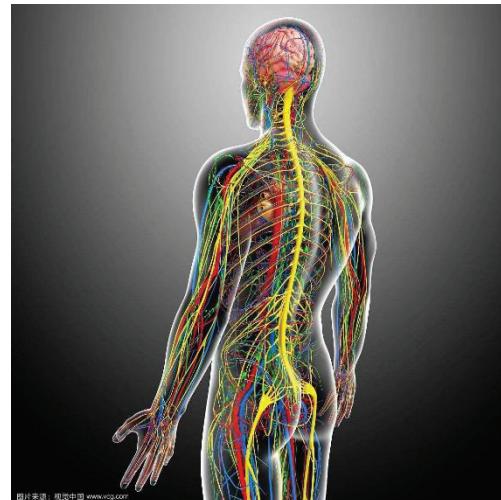
Hardware Design:



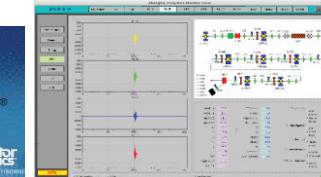
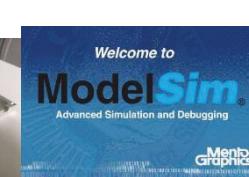
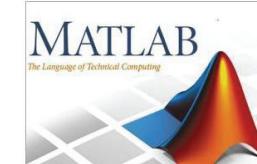
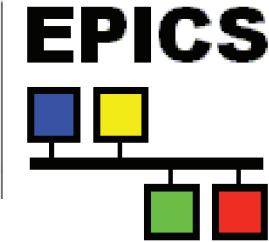
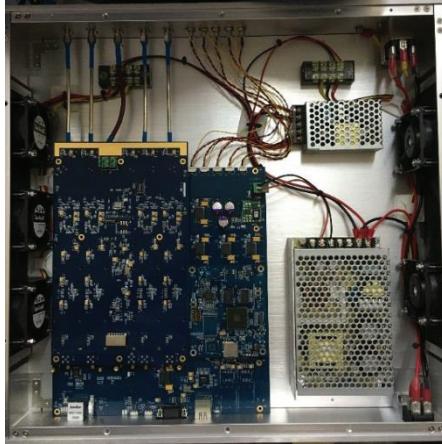
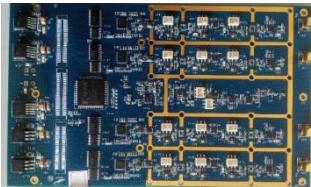
Software & OPI design



Firmware Design:



Included Techniques



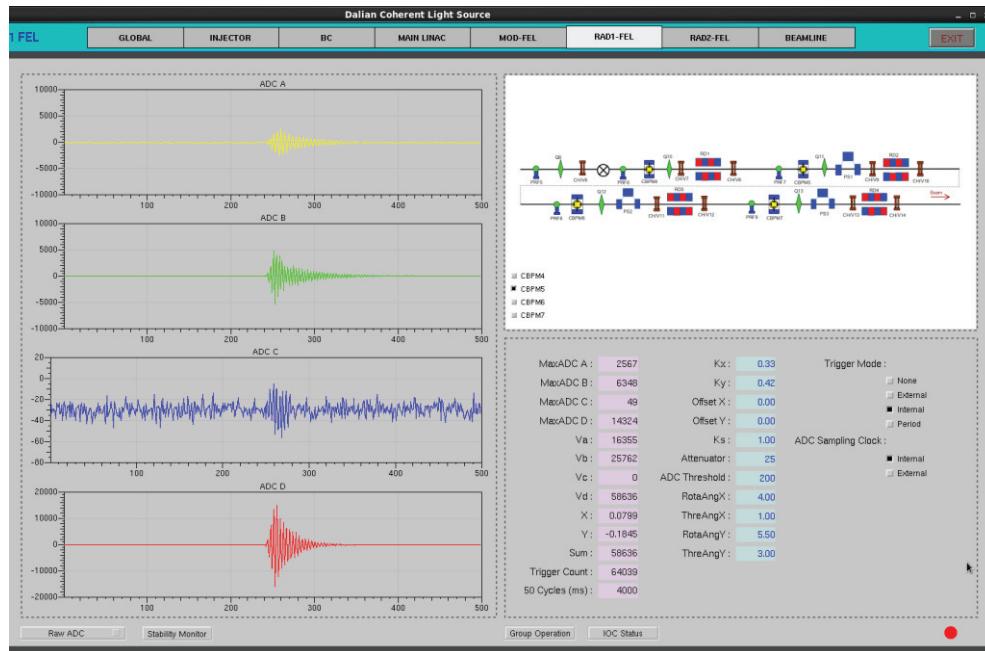
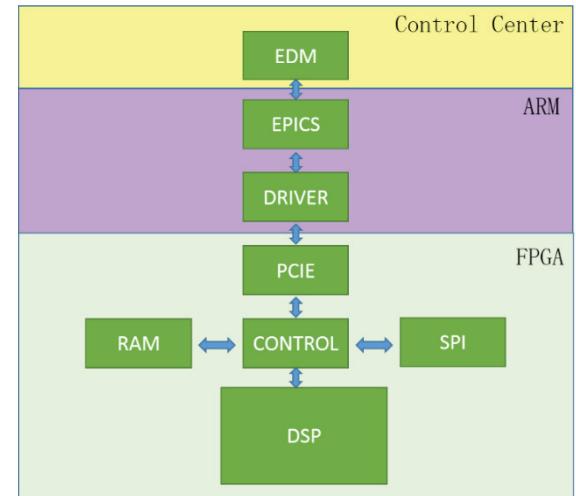
DBPM is an integration of various knowledge and techniques.
It takes a lot time.



Milestones

- **2009.9 Project Start**
- **2010.12 Principle Prototype: RF front-end and Digital Signal Processing**
 - Lai Longwei, Leng Yongbin*, Yi Xing, et al. DBPM signal processing with field programmable gate arrays[J], *NST* 22(2011), 129-133.
 - Yi Xing, Leng Yongbin*, Lai Longwei, et al. RF front-end for digital beam position monitor signal processor[J], *NST* 22(2011), 65-69.
 - 赖龙伟, 冷用斌*, 阎映炳, 杨桂森等, 数字BPM信号处理算法研究, 核技术, 2010年, 第33卷第10期, 734-739
- **2011.6 Version-I and Beam Tests**
 - 易星, 冷用斌*, 赖龙伟等. 基于软件无线电的新型数字束流位置处理器[J], 核技术, 2012年, 第35卷第5期
 - X. D. Sun, Y. B. Leng*, An DBPM Calibration Method Implemented on FPGA, IBIC 2012, Tsukuba, Japan
 - Leng Yongbin, Yi Xin, Lai Longwei, et al. Online Evaluation of New DBPM Processor at SINAP[C]// Prof of ICALEPCS2011,
 - 冷用斌, 易星, 赖龙伟等. 新型数字BPM信号处理器研制进展[J], 核技术, 2011年, 第33卷第5期, 326-330
 - X.D. Sun, Y.B. Leng. Implementation and integration of a systematic DBPM calibration [J], *NST* 25(2014), 020401-1-6.
 - X.D. Sun, Y.B. Leng. MATLAB Simulation of DBPM Digital Down Conversion [J] *AMM*, 333(2013), 680-683.
 - 赖龙伟, 冷用斌, 易星等. 数字束流位置信号处理算法优化[J], 强激光与粒子束, 2013年, 第25卷第1期, 109-113
- **2014.6 Small amount(5) tests**
- **2015.6 Optimization, Intelligent Trigger Application Development**
 - L.W. Lai, Y.B. Leng, AN INTELLIGENT TRIGGER ABNORMAL BEAM OPERATION MONITORING PROCESSOR AT THE SSRF, IPAC2015
 - 赖龙伟, 冷用斌等. 数字BPM信号处理器研制进展[J], 原子能科学技术, 2015
- **2016.6 Version-II, Mass Application on SXFEL and DCLS, Small Amount on SSRF**
 - L.W. Lai, Y.B. Leng, BATCH APPLICATIONS OF DIGITAL BPM PROCESSORS FROM THE SINAP, IBIC2016
 - L.W. Lai, Y.B. Leng, DESIGN AND PERFORMANCE OF DIGITAL BPM PROCESSOR FOR DCLS AND SXFEL, IPAC2017

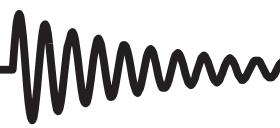
Design





Applications on FEL

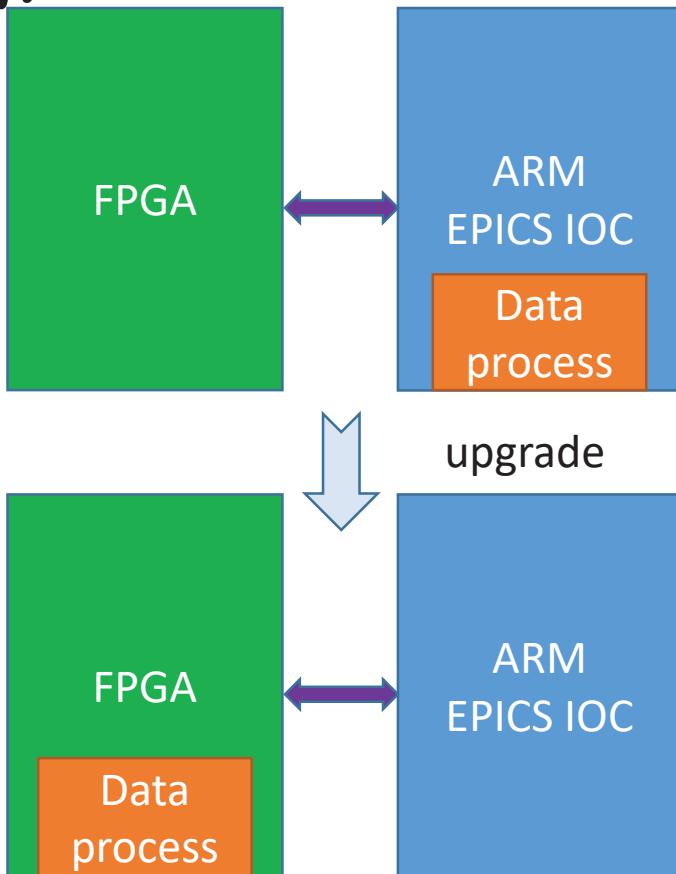
Stripline BPM Processor
Cavity BPM Processor



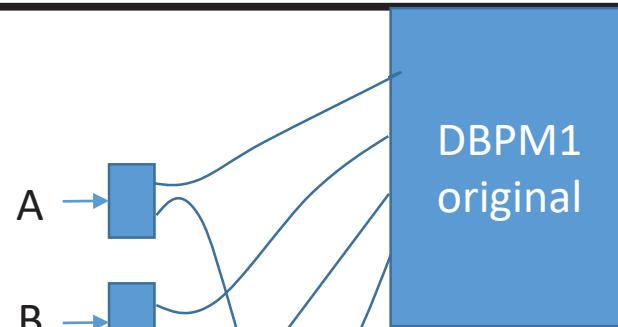
Mass Application on SXFEL/DCLS



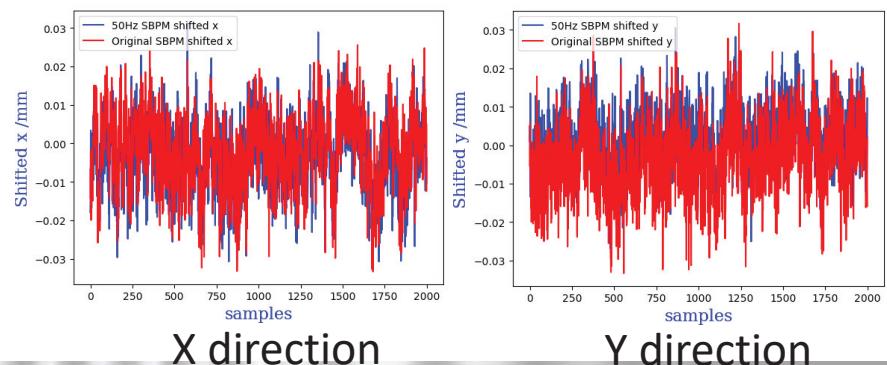
Firmware & Software Upgrade



Algorithms are moved from EPICS IOC to FPGA, speed upgraded from 10Hz to **more than 100Hz** in Dec. 2017.



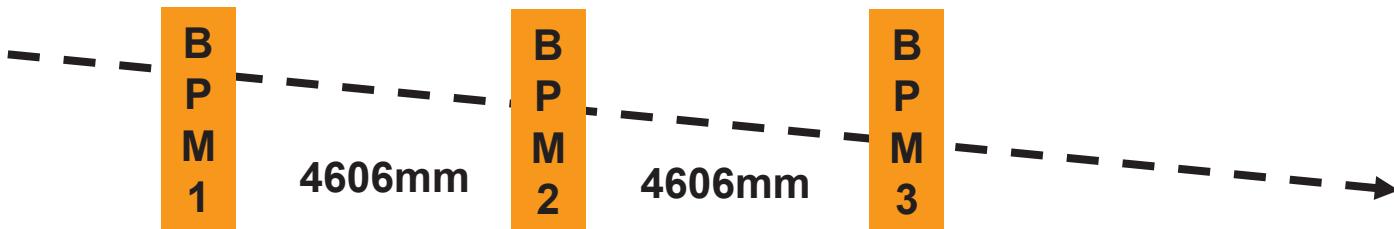
Accuracy Check setup block diagram



SBPM Tests@SXFEL

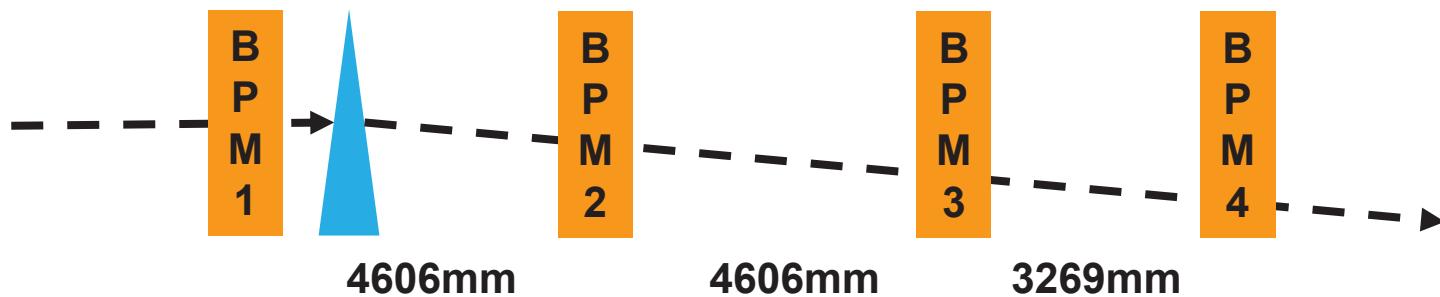
SBPM performance test,

$$\text{BPM2}' = (\text{BPM1} + \text{BPM3}) / 2, \text{std}(\text{BPM2}-\text{BPM2}') / \text{sqrt}(2)$$



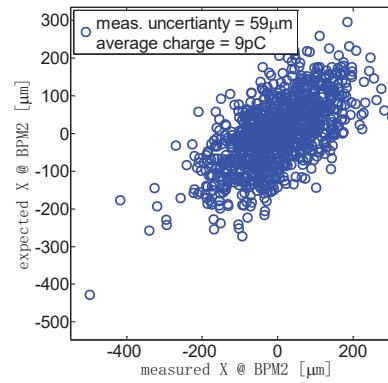
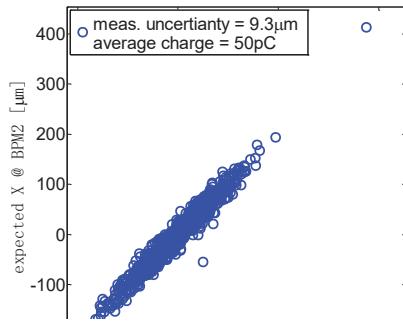
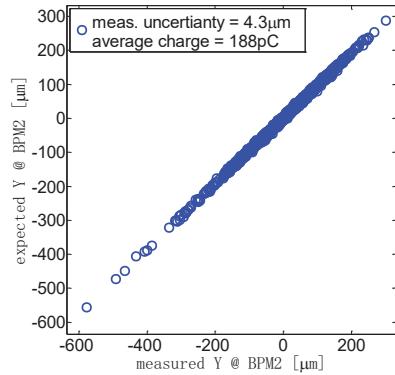
Long drift section on SXFEL LINAC.

Beam current measurement test with SBPM sum value.

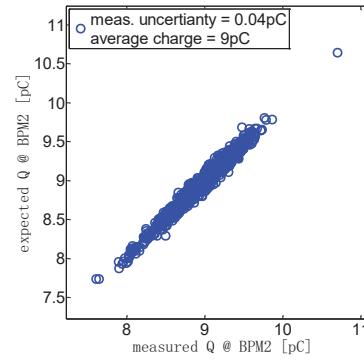
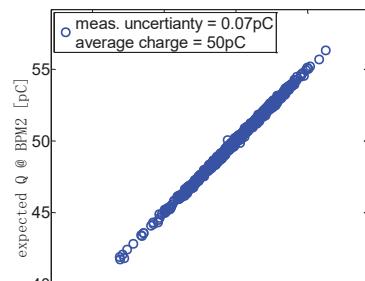
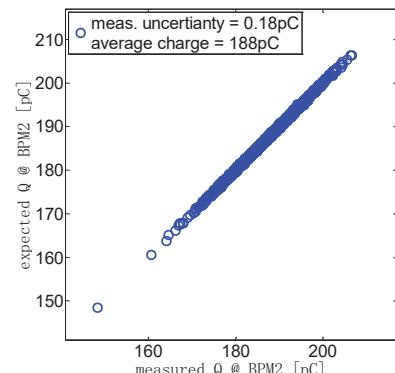


Q1 as reference, Q_i/Q_1 relative error introduced by beam displacement

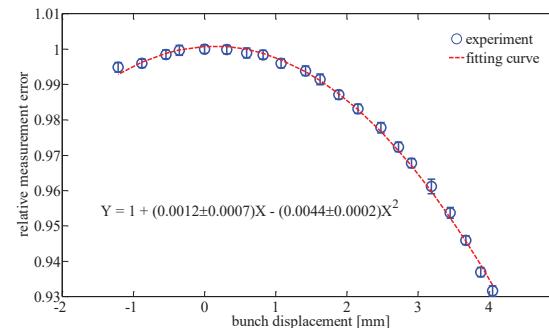
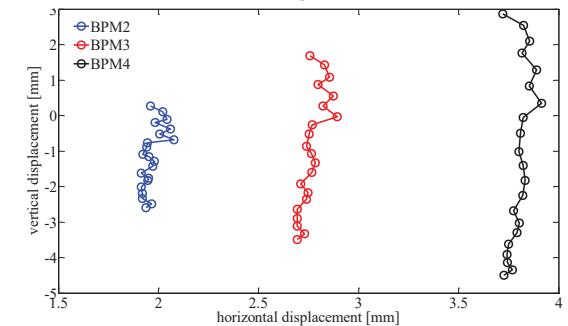
SBPM Evaluation@SXFEL



K=5.24, 4.3μm@188pC



K=5.24, 0.18pC@188pC

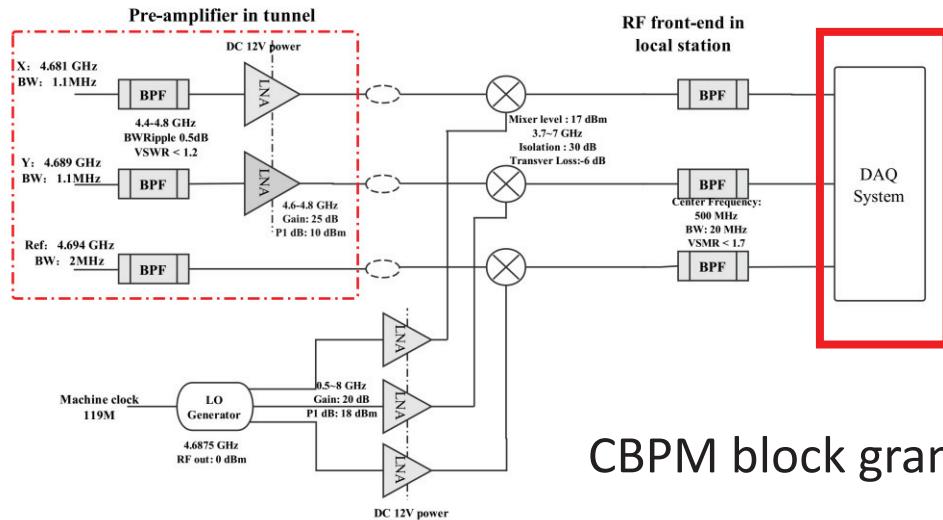


Vertical displacement is getting larger along the beam direction.

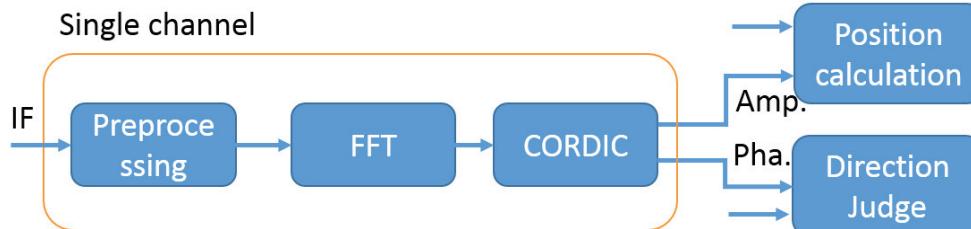
Charge measurement accuracy is getting worse when the beam moving from center.



Cavity BPM signal processing

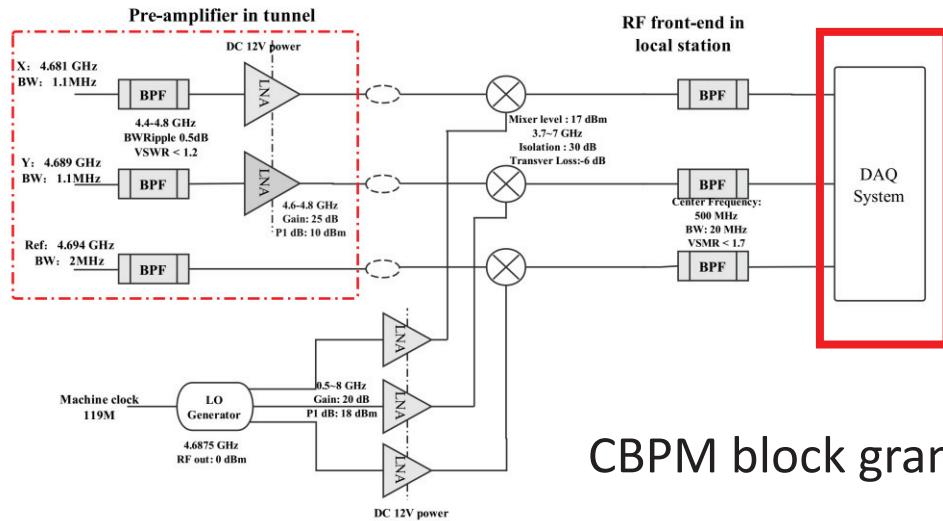


CBPM block gram

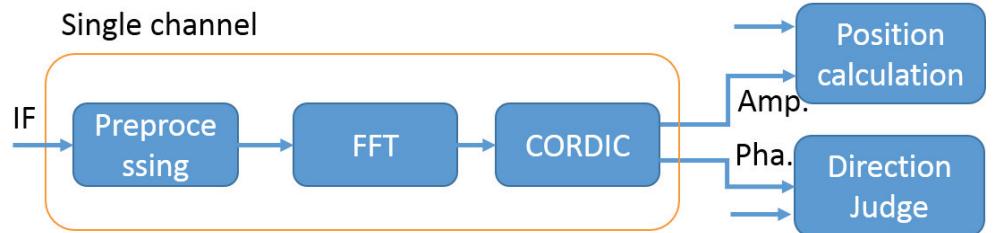




Cavity BPM signal processing

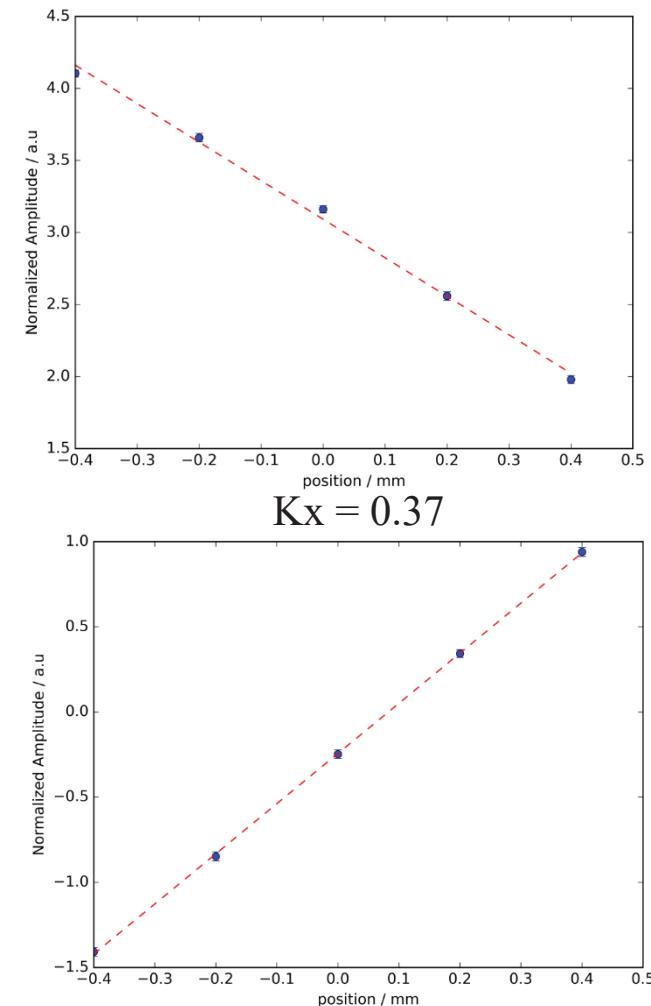
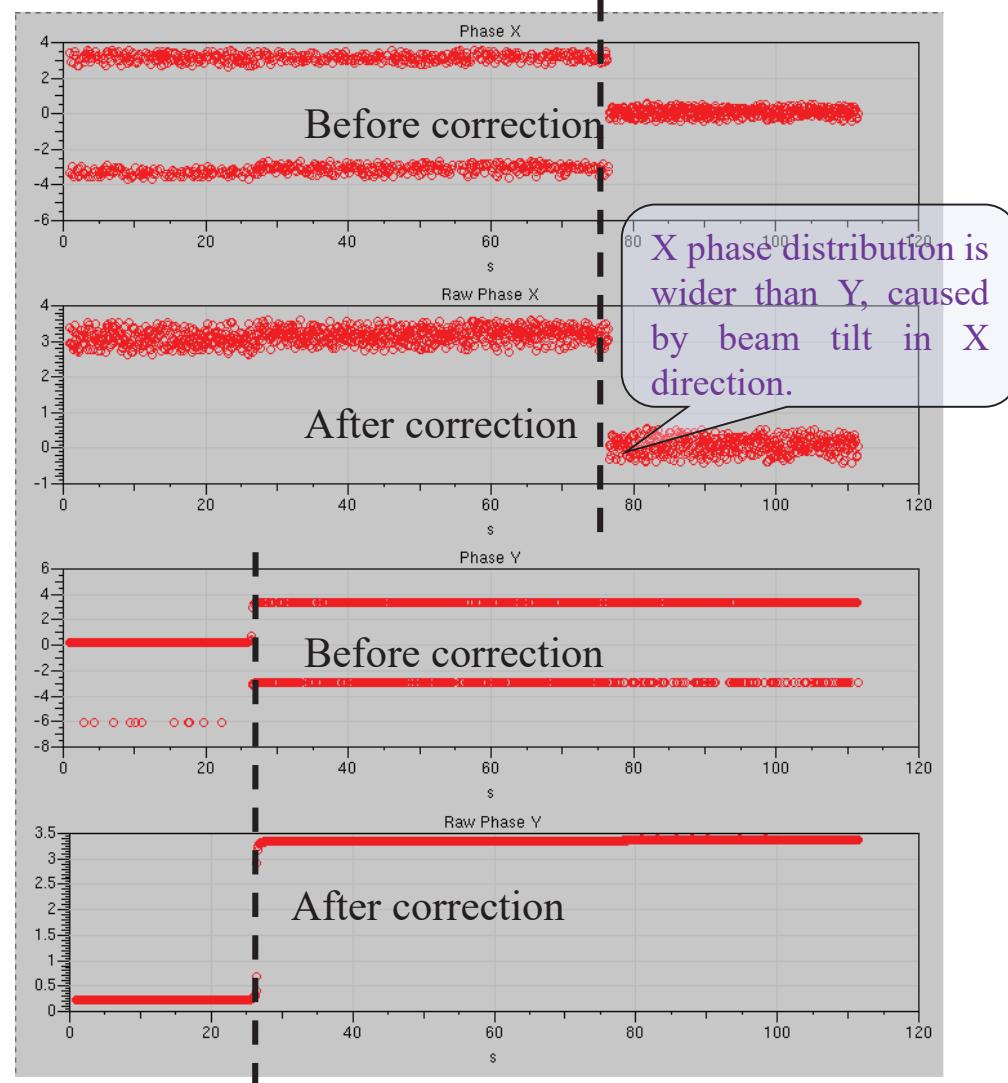


CBPM block gram



Algorithm

Phase and k Calibration @DCLS



K calibration tests.



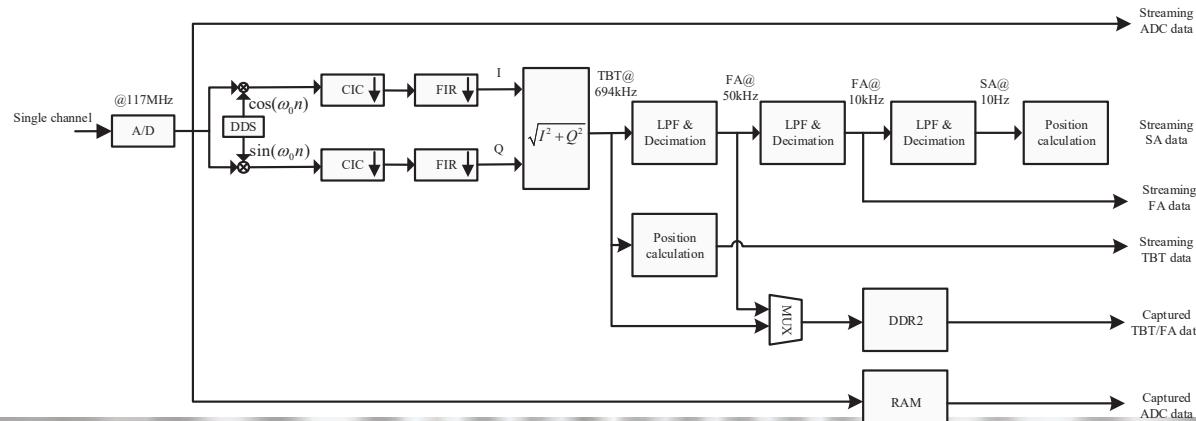
Applications on SSRF

Button BPM Processor

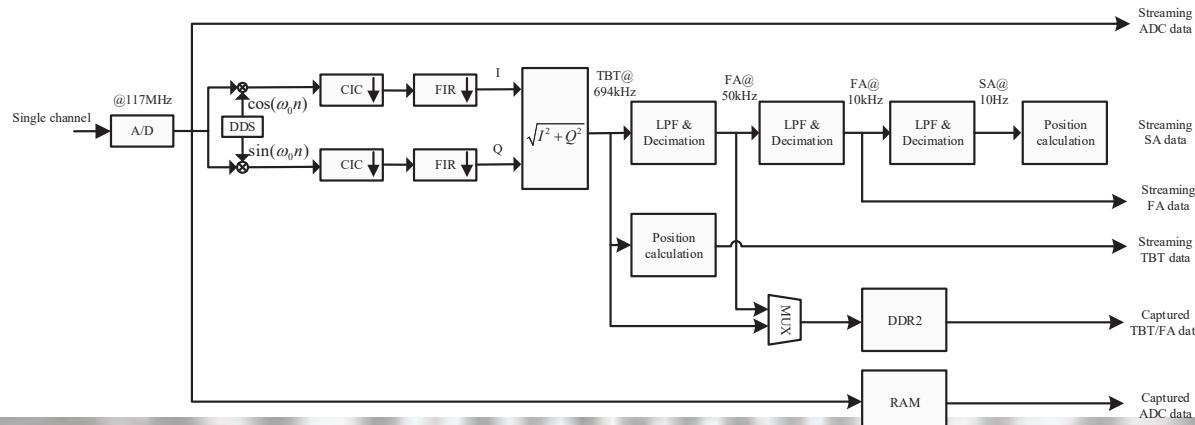
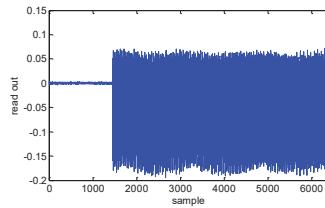
Operation Monitor

Bunch Charge Monitor

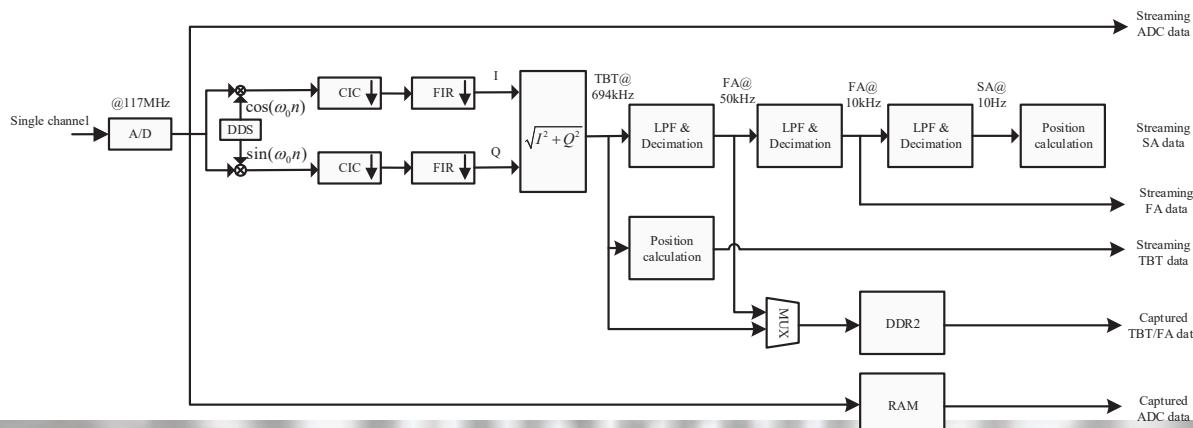
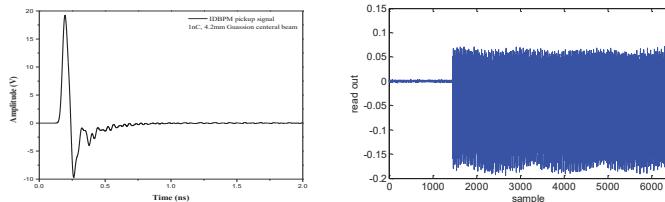
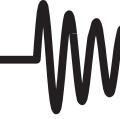
SSRF SR BPM Data Flow



SSRF SR BPM Data Flow

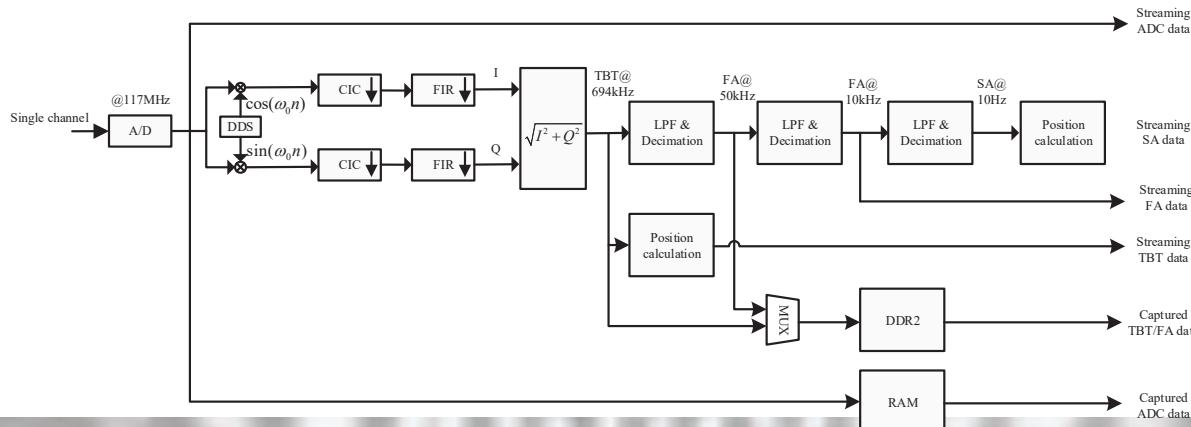
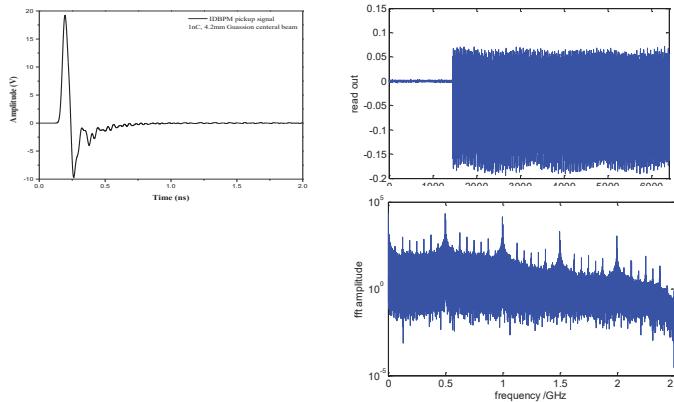


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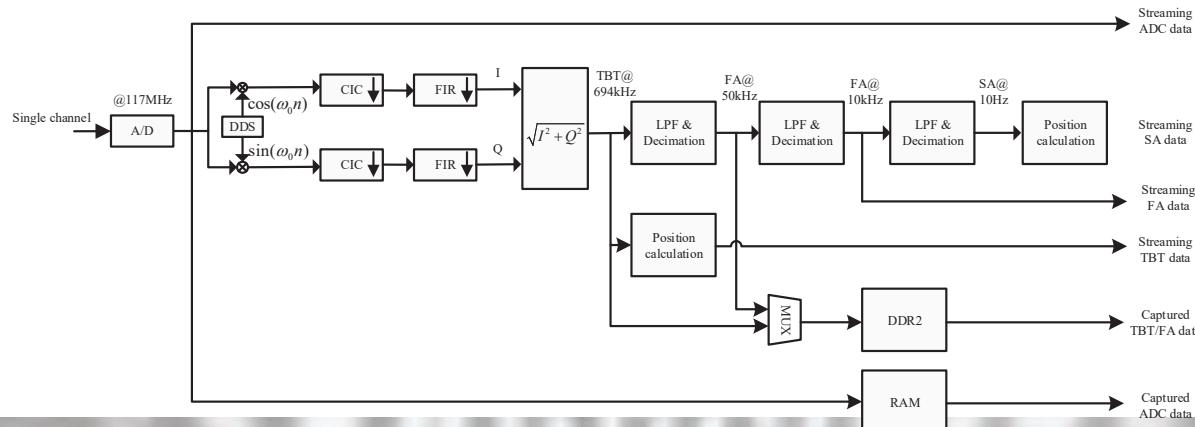
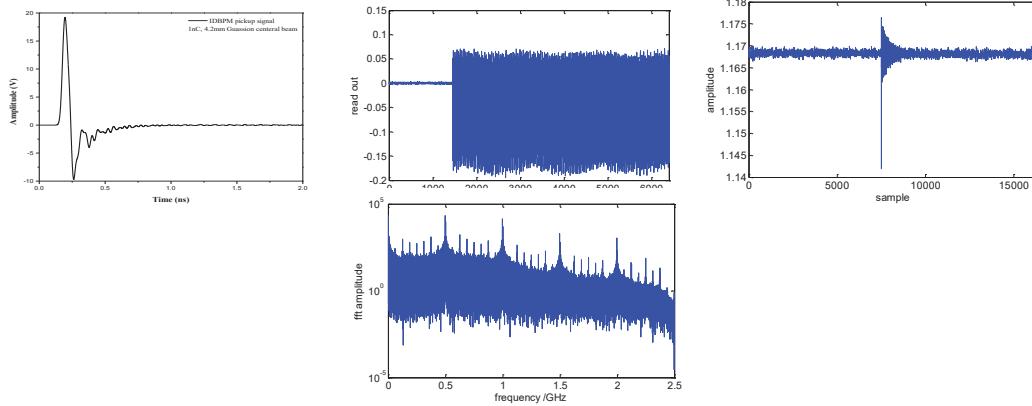
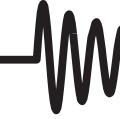




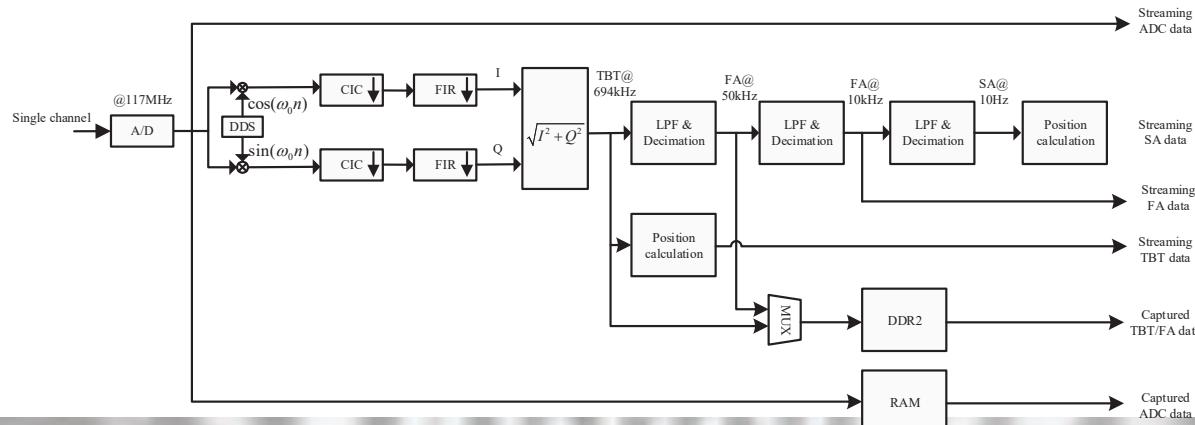
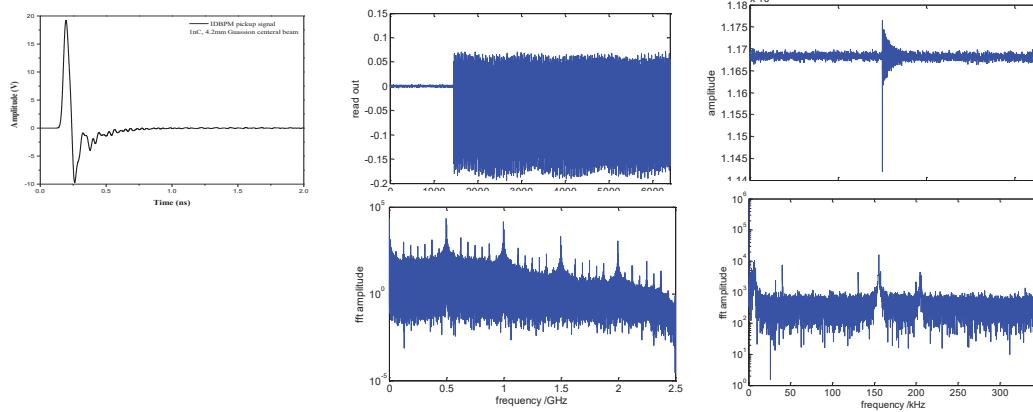
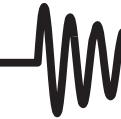
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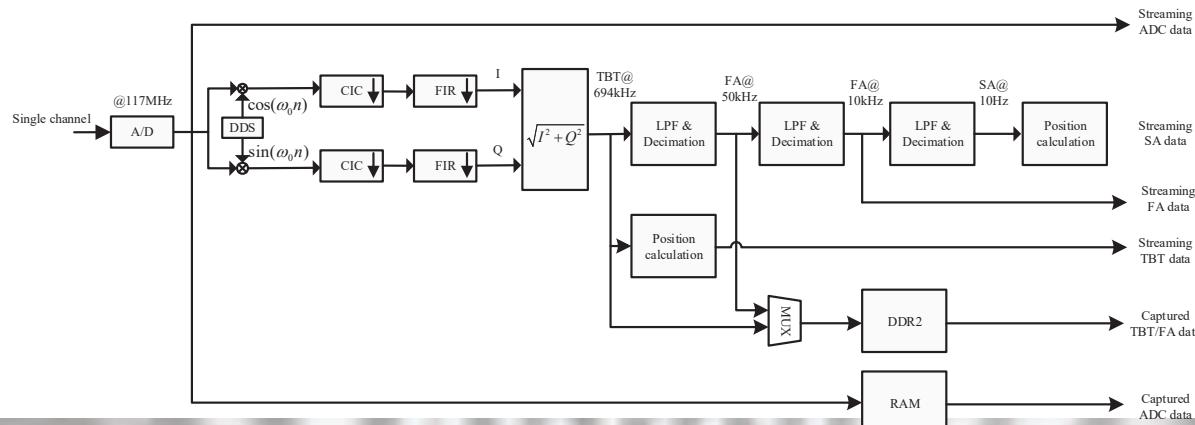
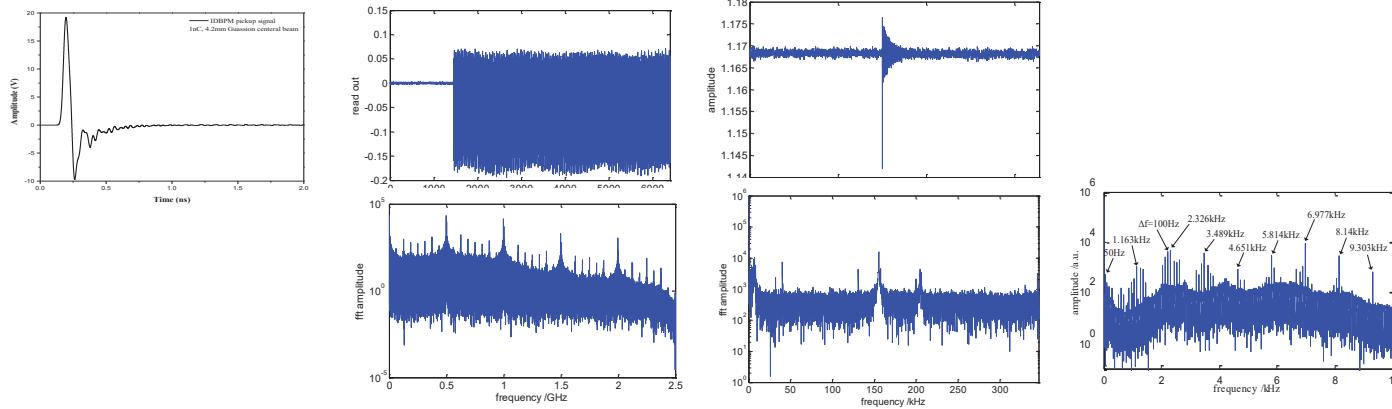
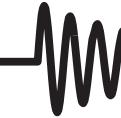
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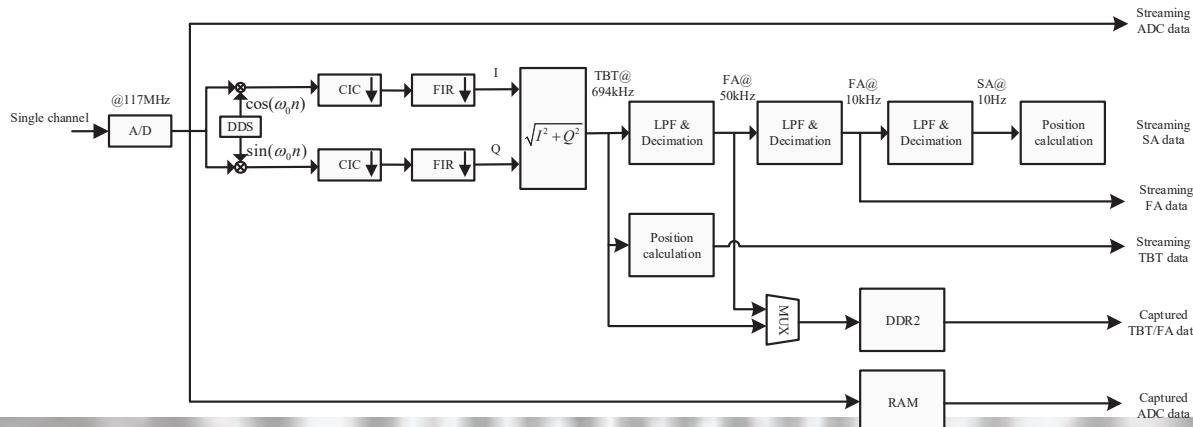
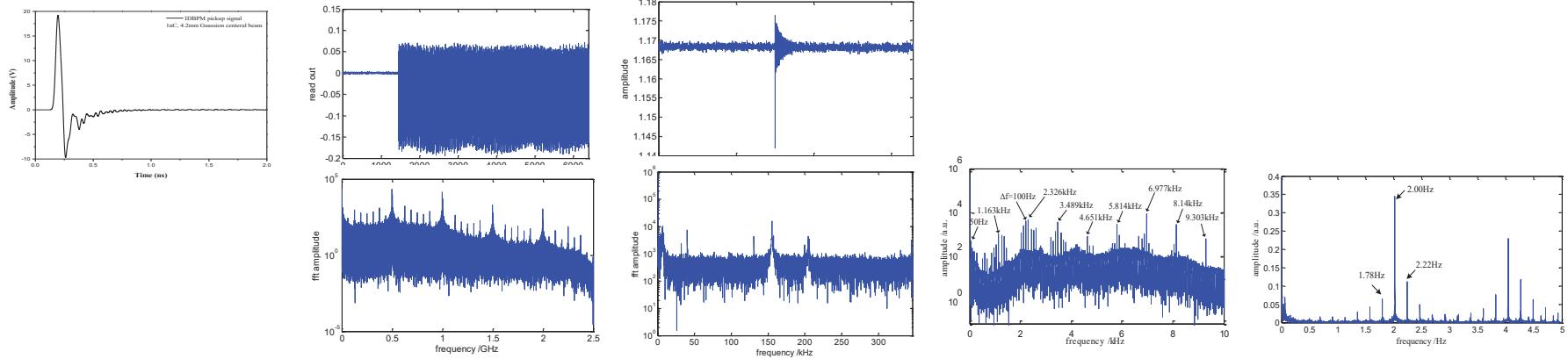
SSRF SR BPM Data Flow



SSRF SR BPM Data Flow

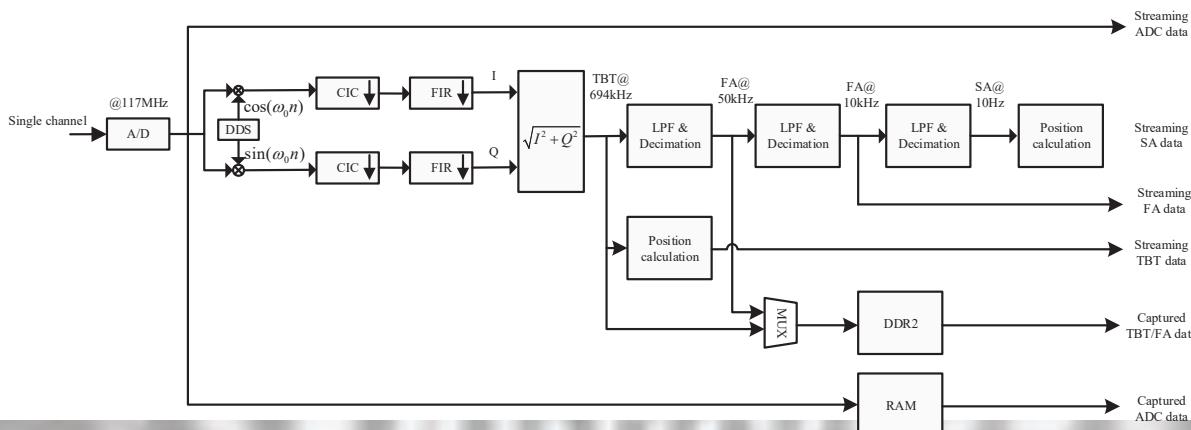
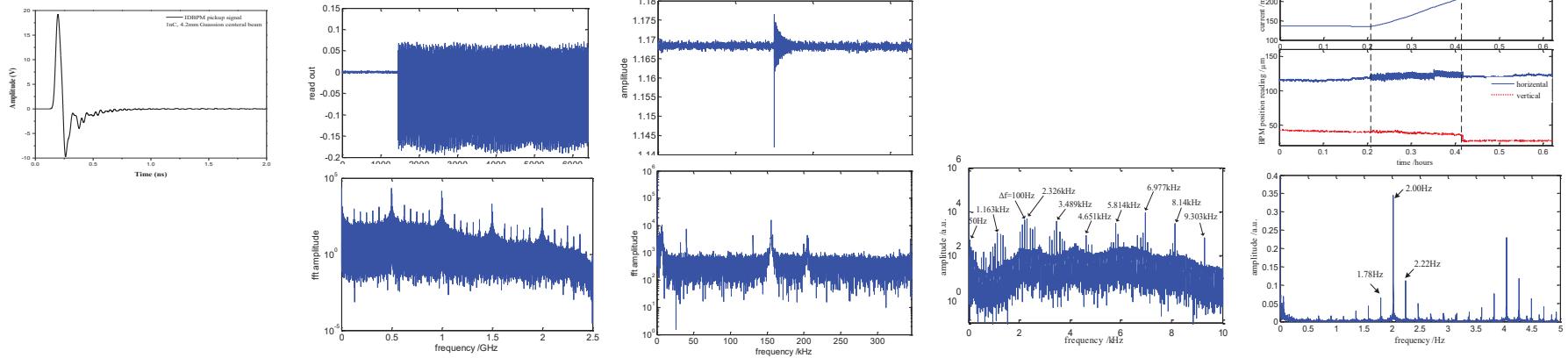
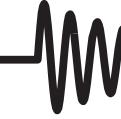


SSRF SR BPM Data Flow



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SSRF SR BPM Data Flow

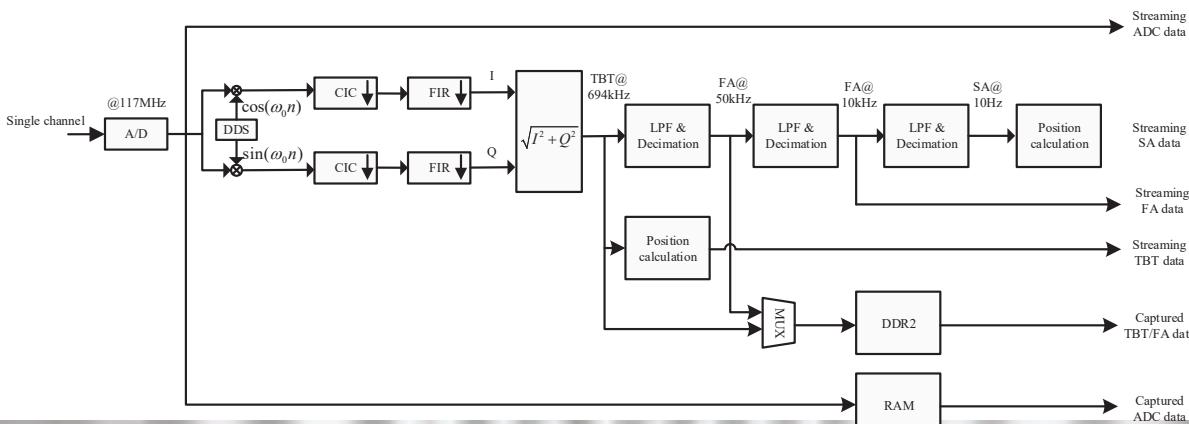
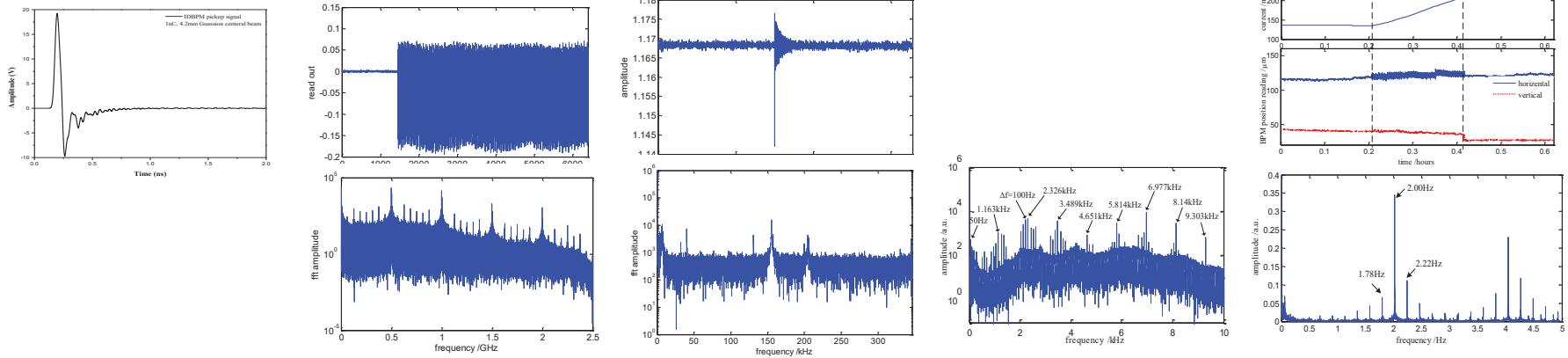


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SSRF SR BPM Data Flow



TBT data
processing
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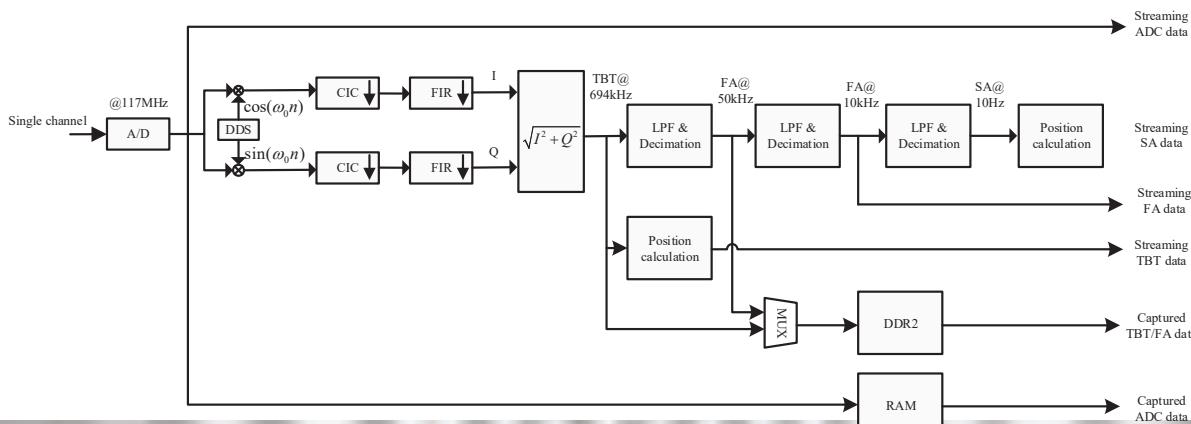
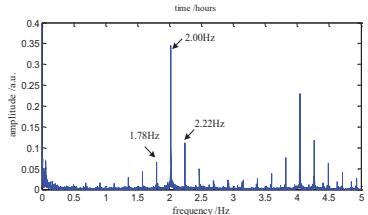
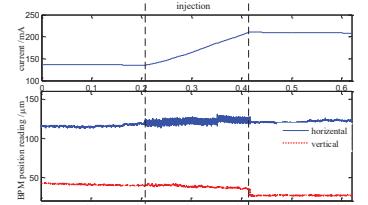
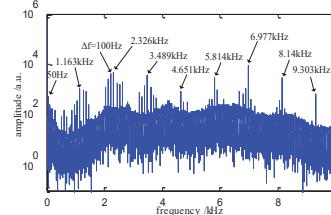
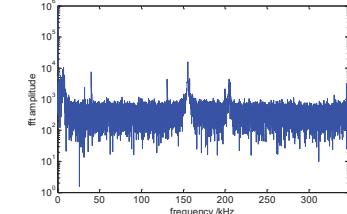
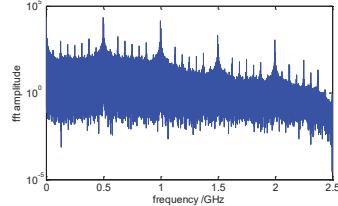
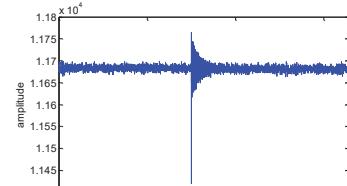
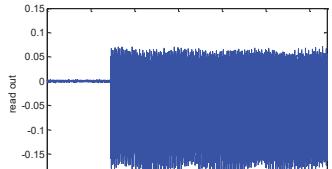
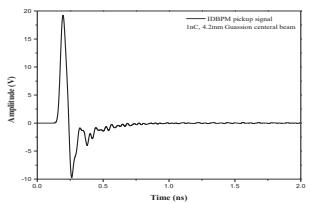


SSRF SR BPM Data Flow



TBT data
processing
1/169

FA data
processing
1/70(1/5,1/14)



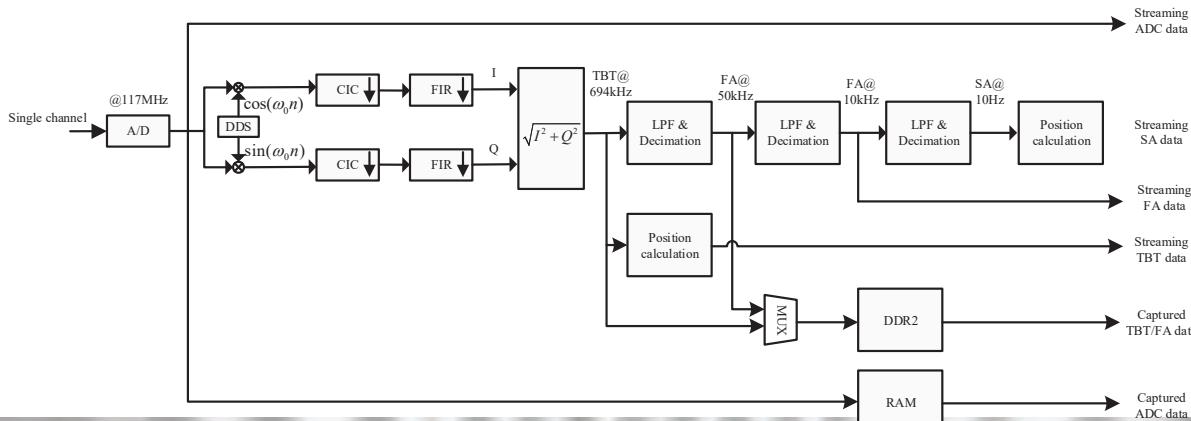
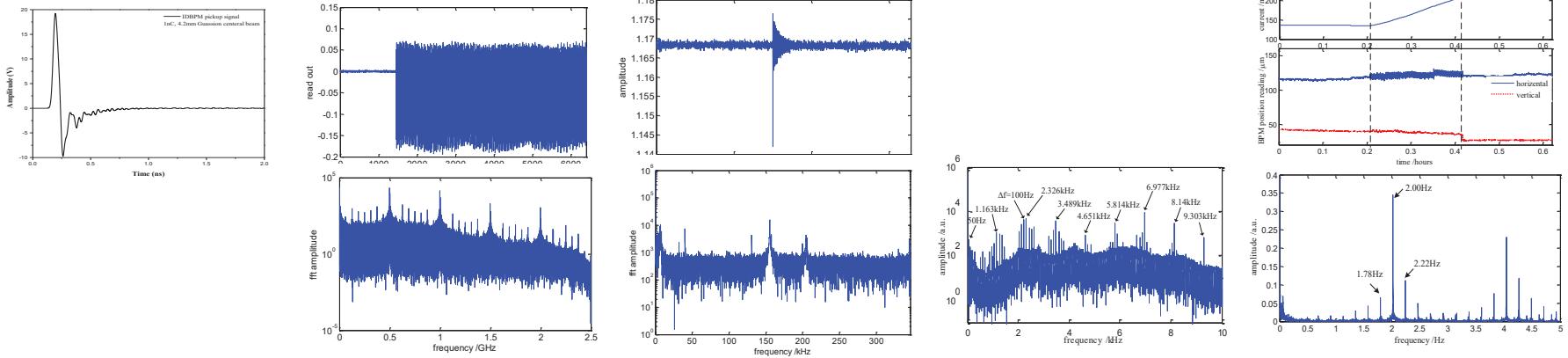
SSRF SR BPM Data Flow



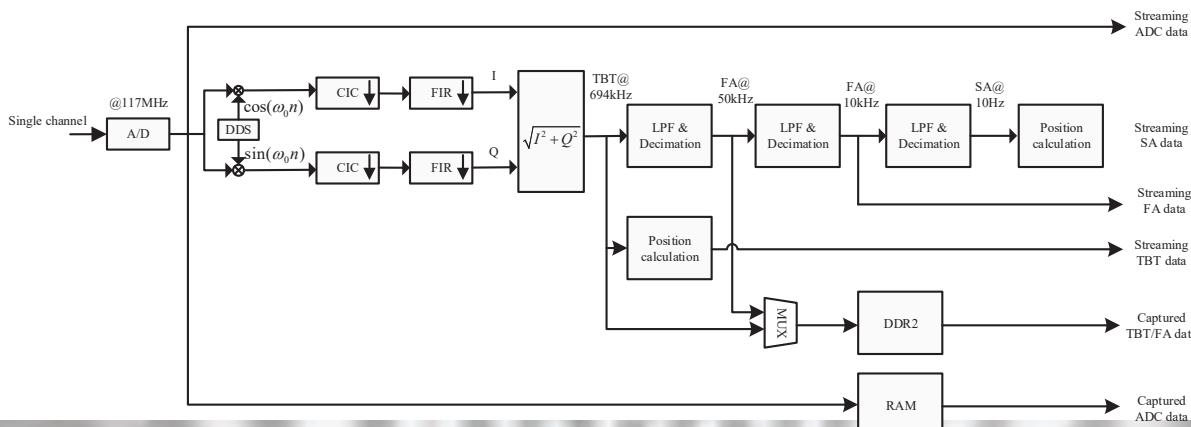
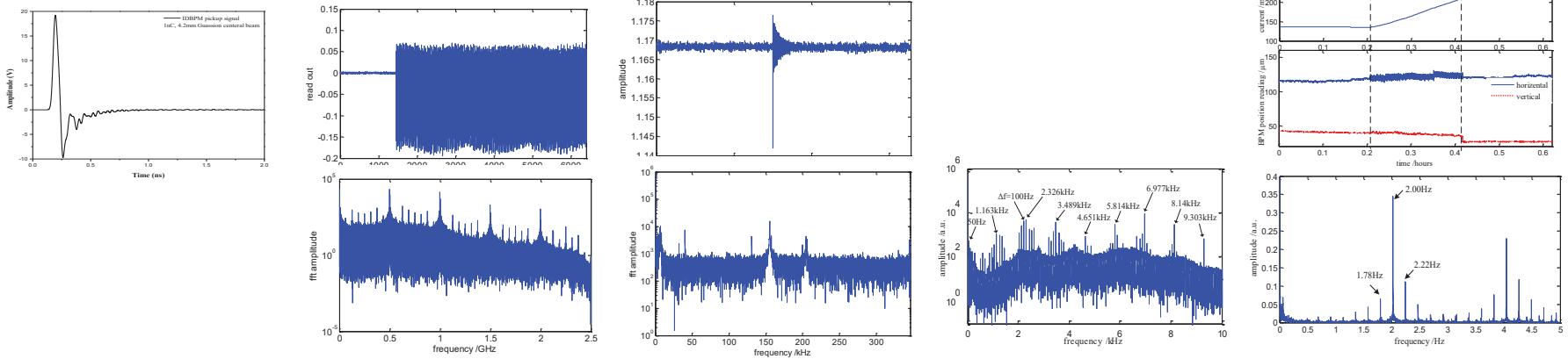
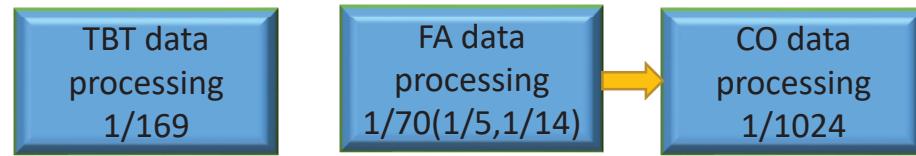
TBT data
processing
1/169

FA data
processing
1/70(1/5,1/14)

CO data
processing
1/1024



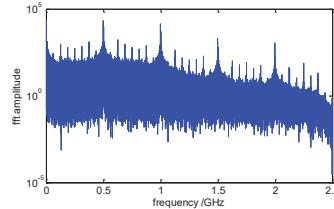
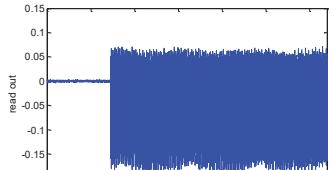
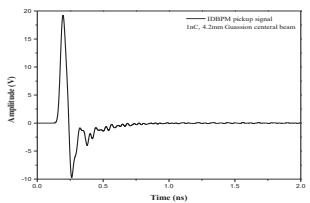
SSRF SR BPM Data Flow



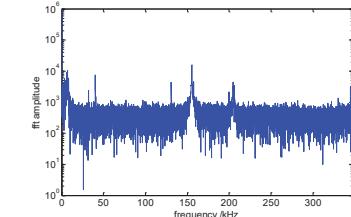
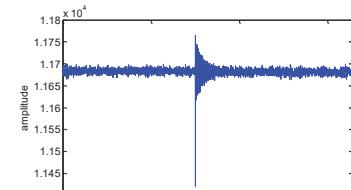
SSRF SR BPM Data Flow



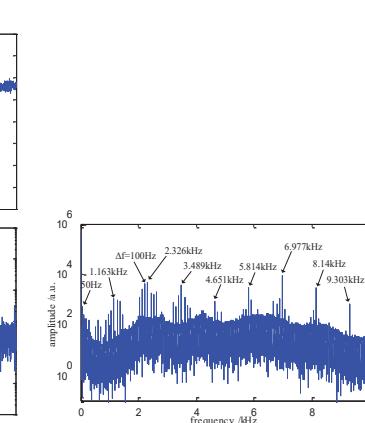
BPM pickup



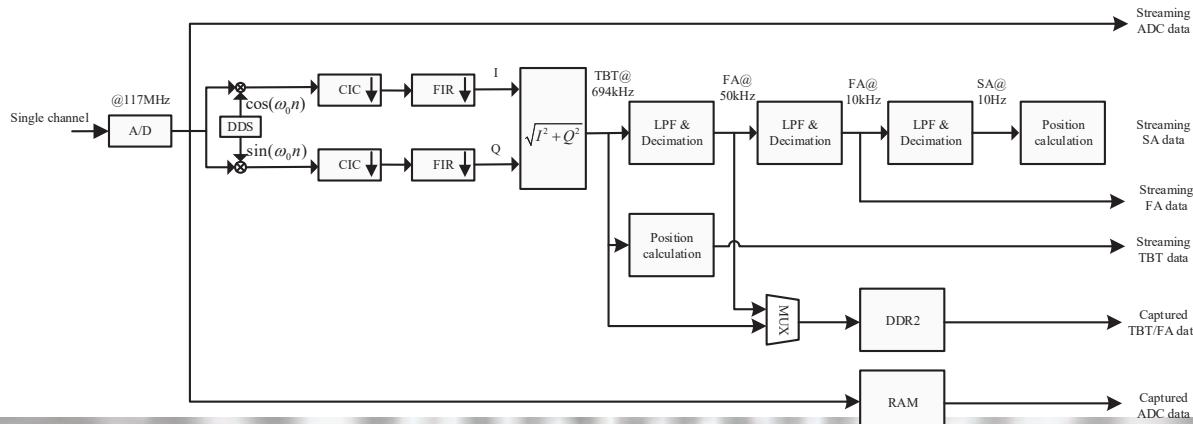
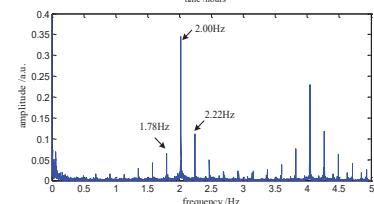
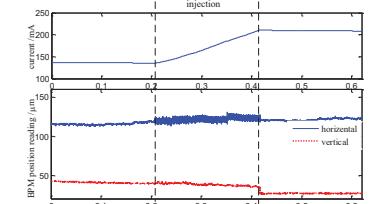
TBT data processing
1/169



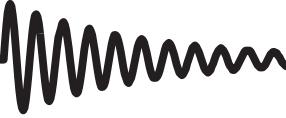
FA data processing
1/70(1/5,1/14)



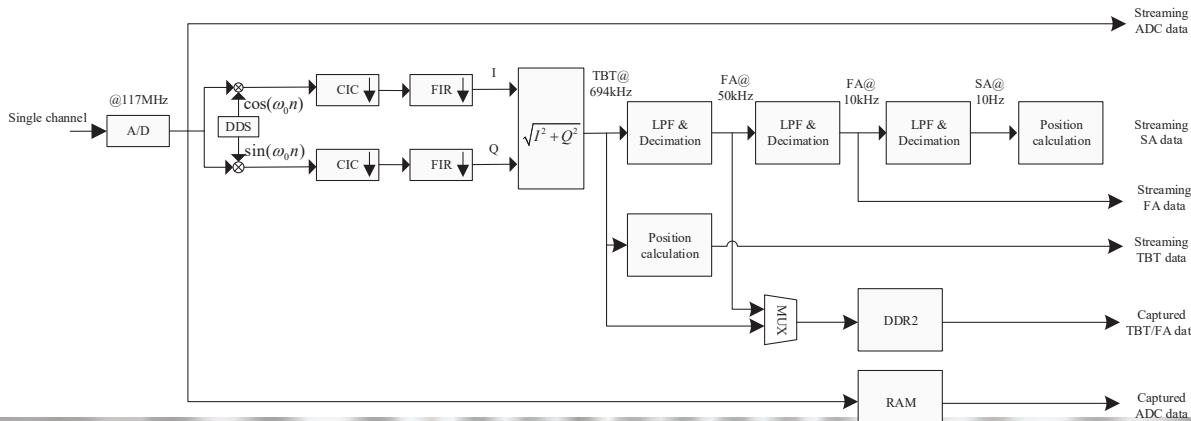
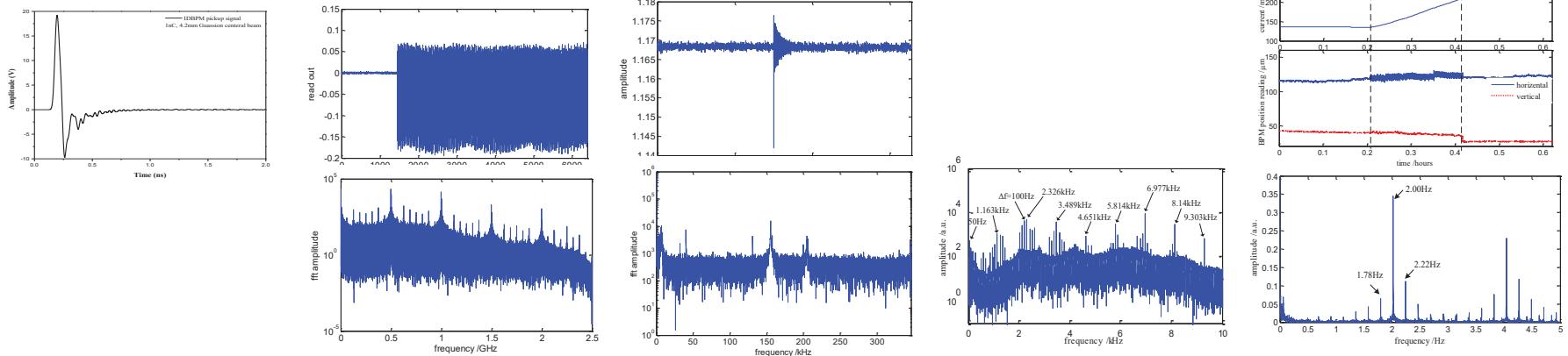
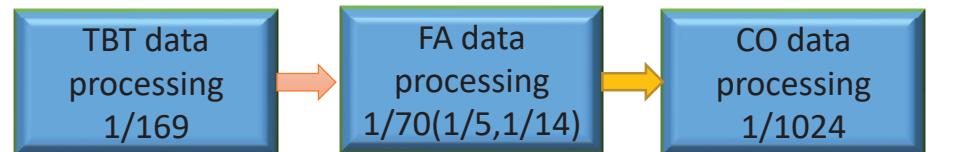
CO data processing
1/1024



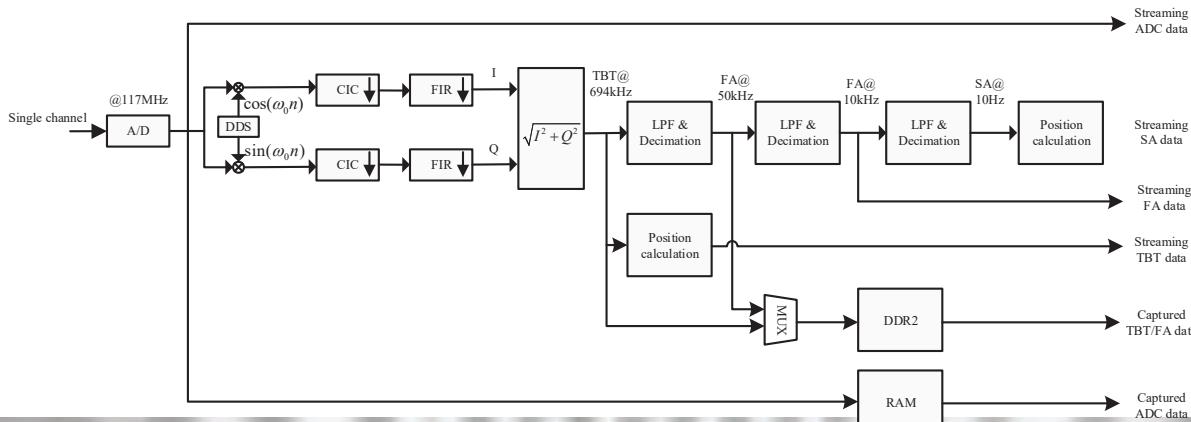
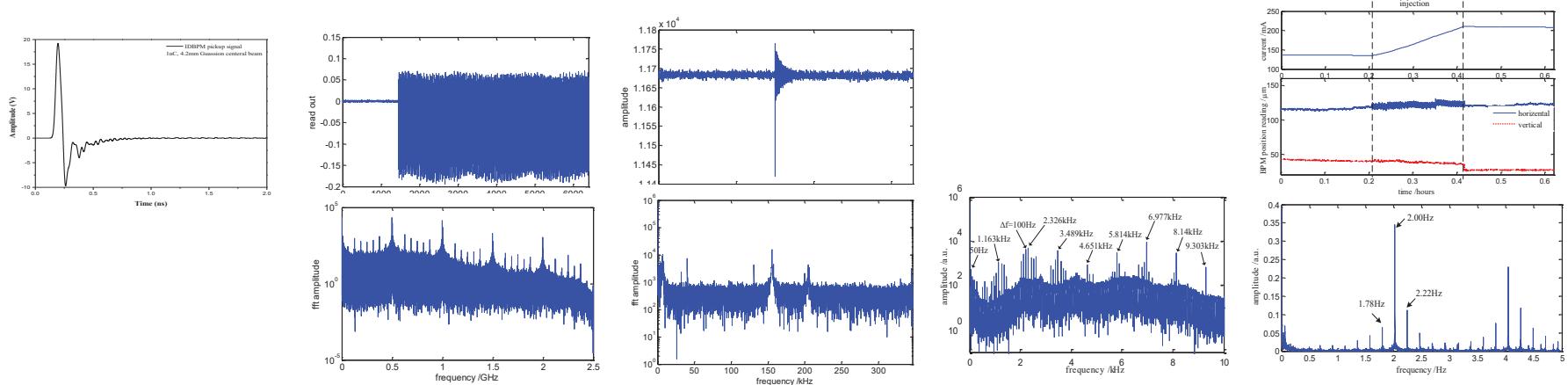
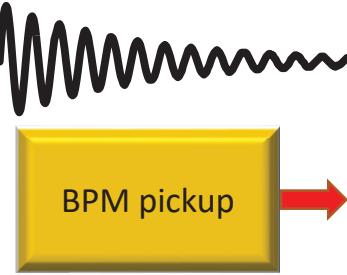
SSRF SR BPM Data Flow



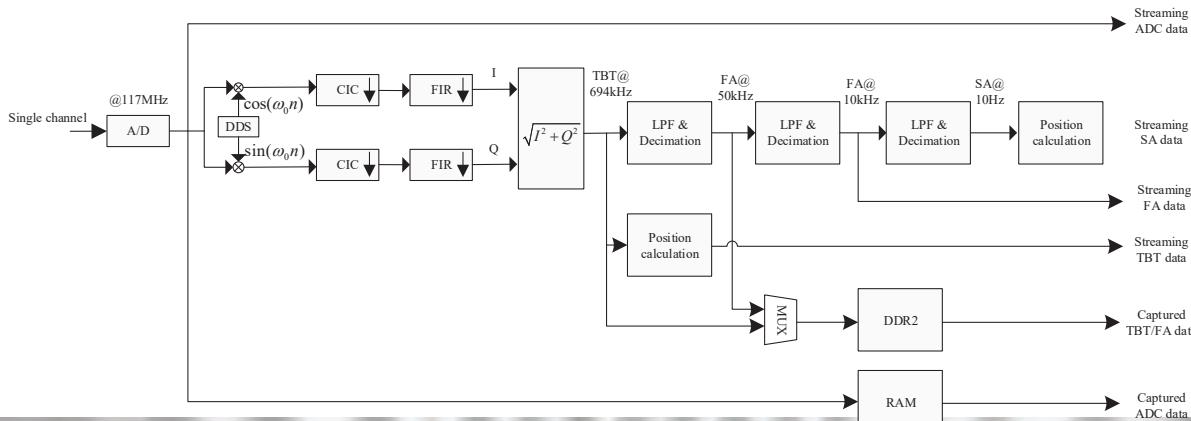
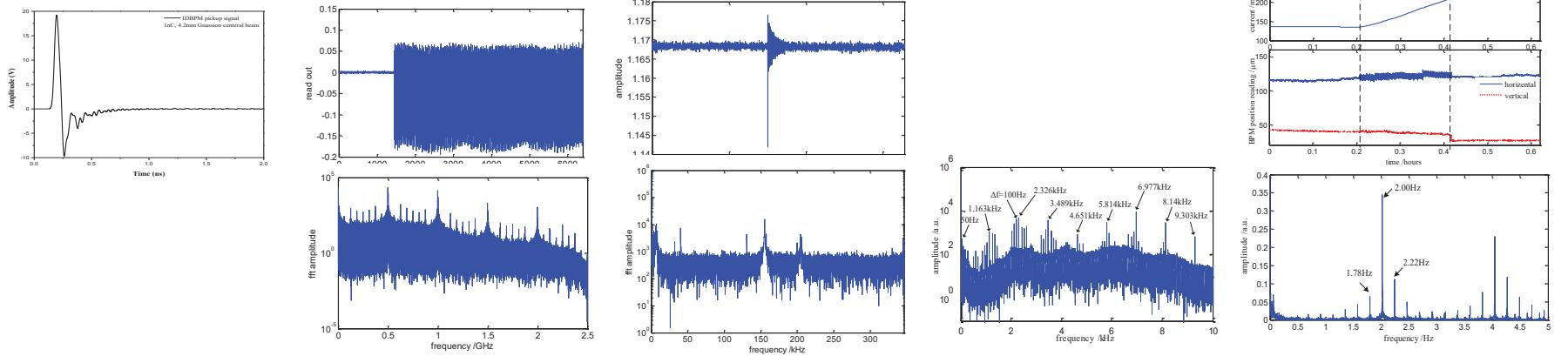
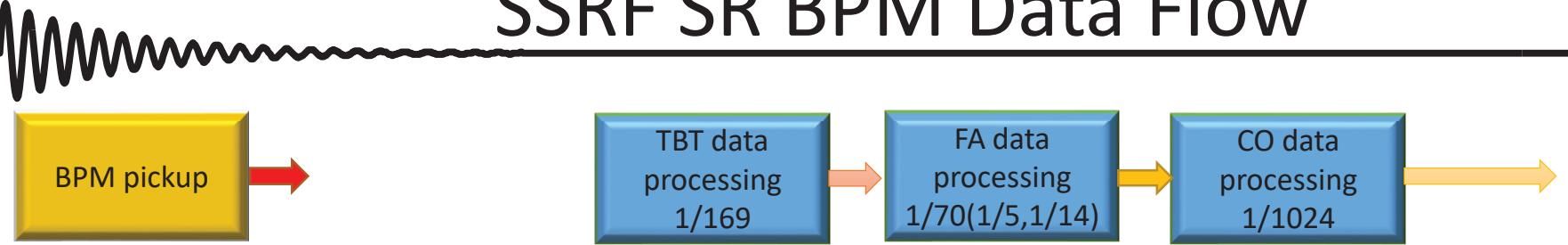
BPM pickup



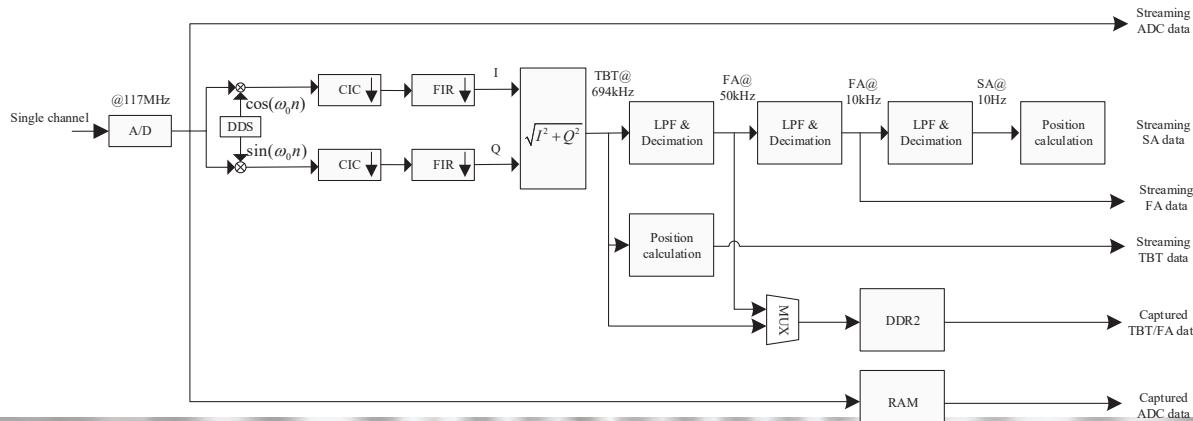
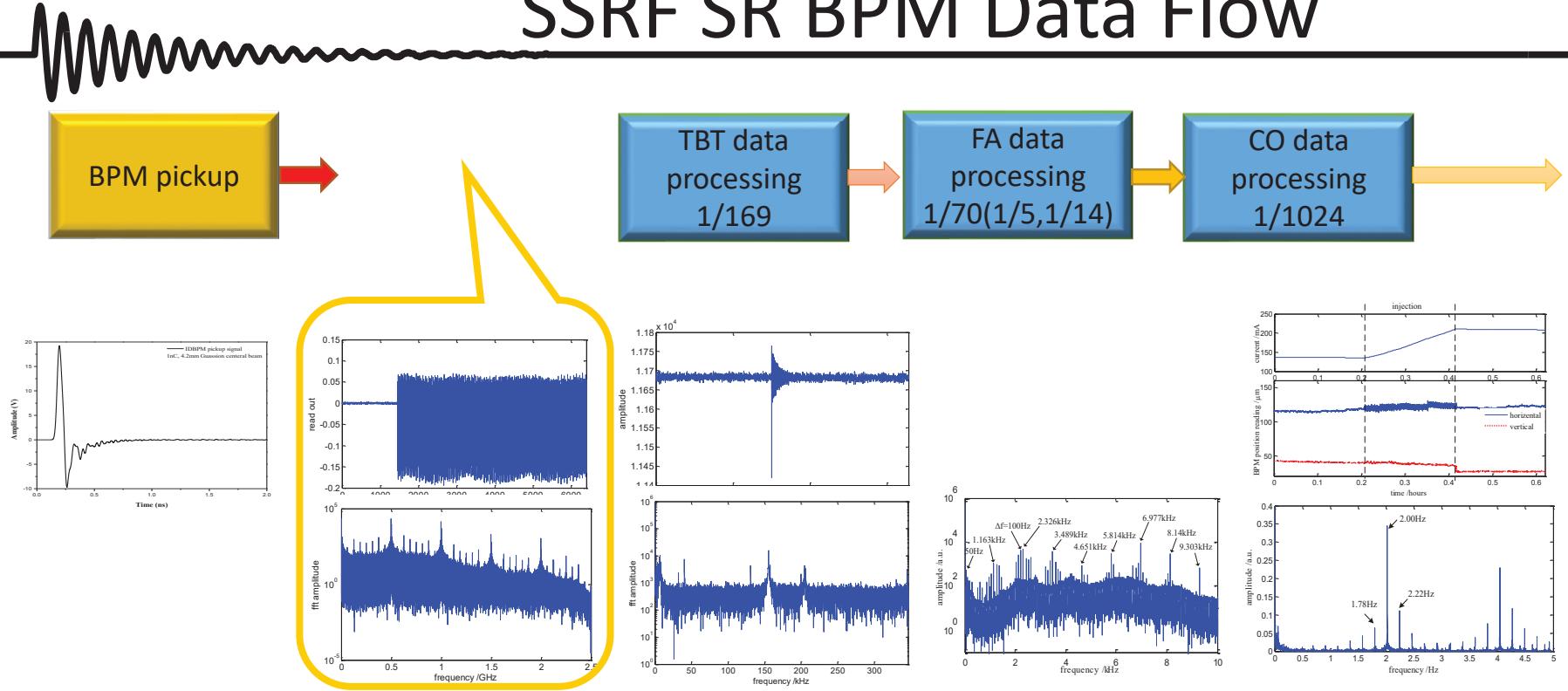
SSRF SR BPM Data Flow



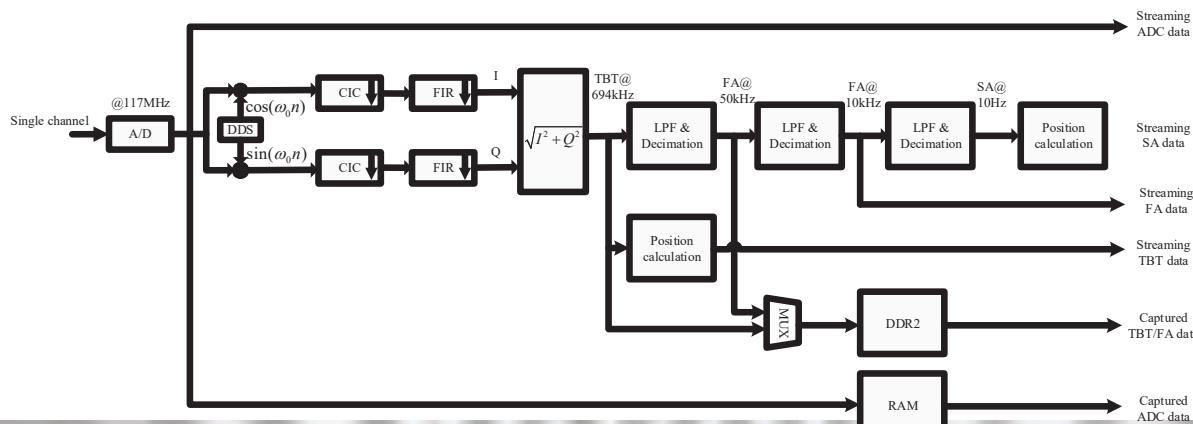
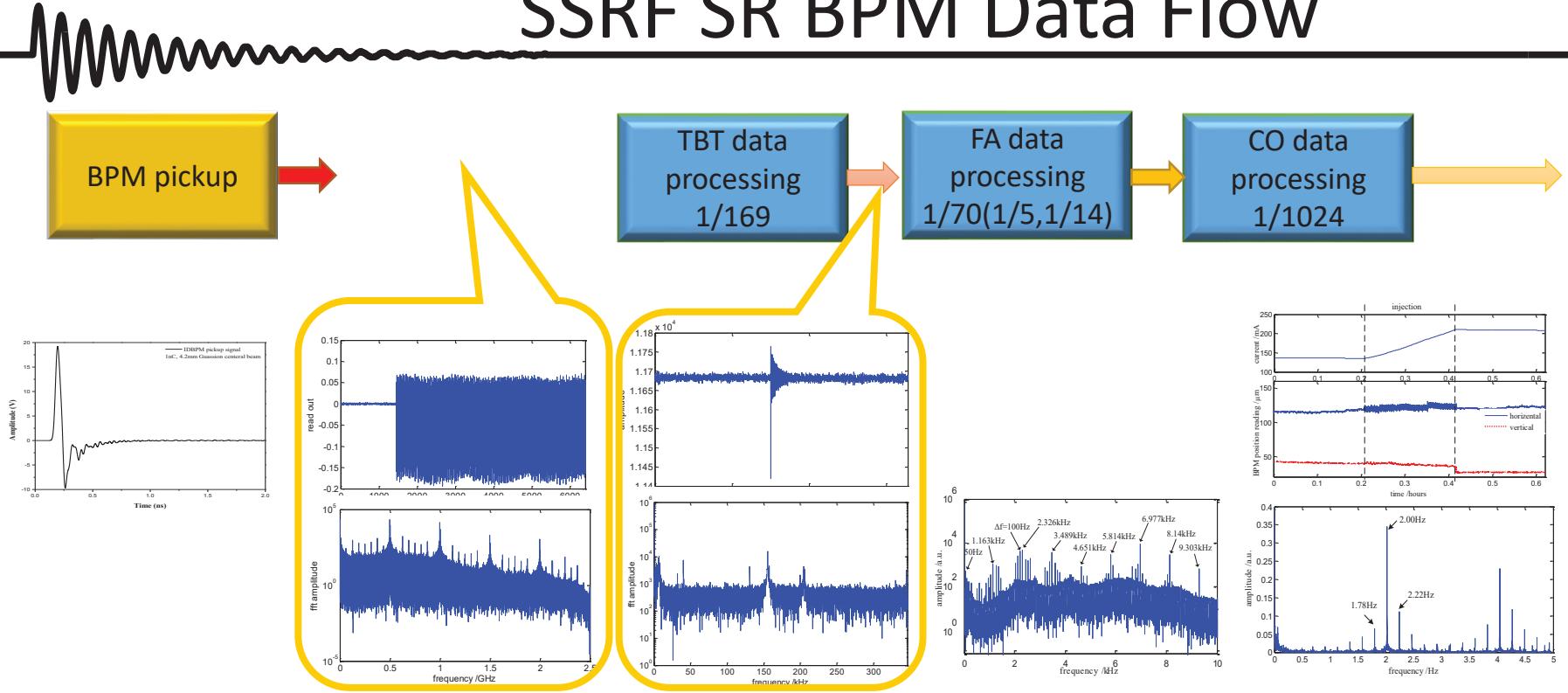
SSRF SR BPM Data Flow



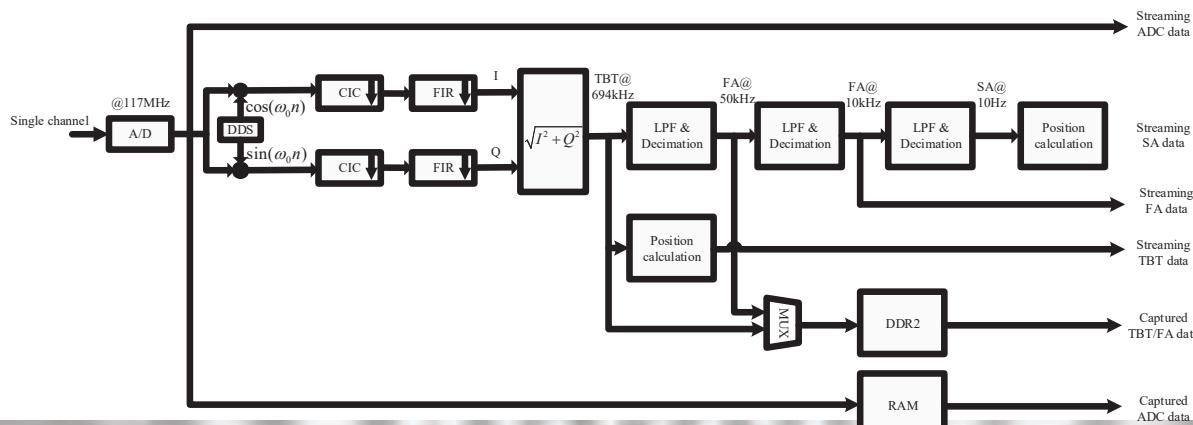
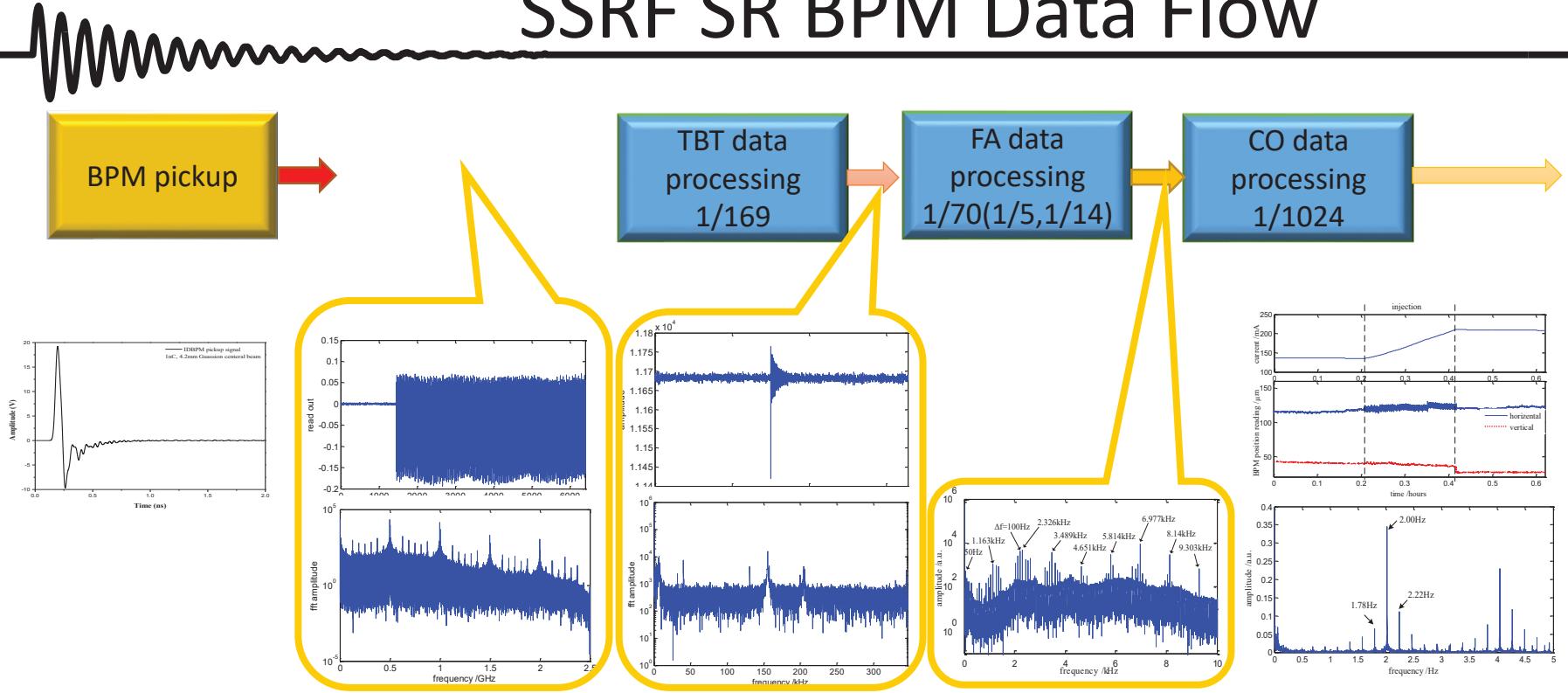
SSRF SR BPM Data Flow



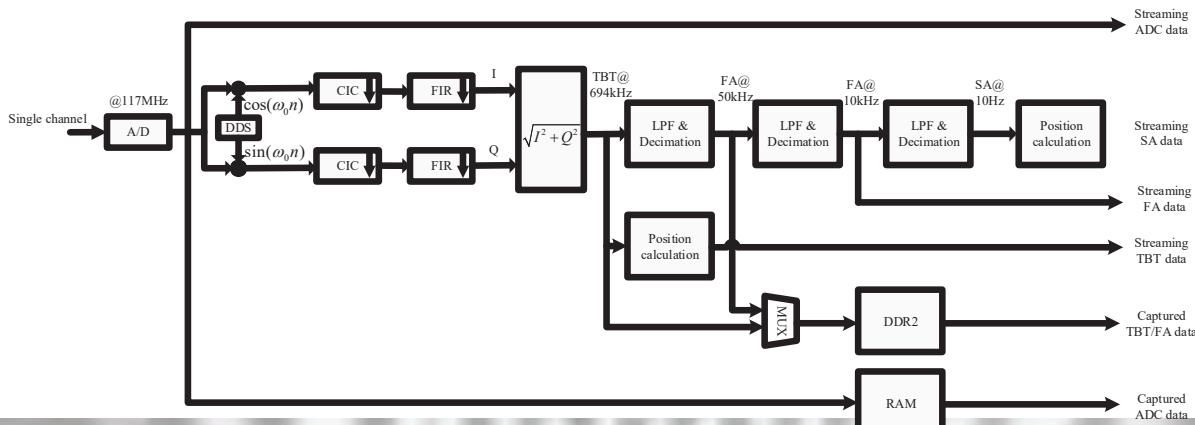
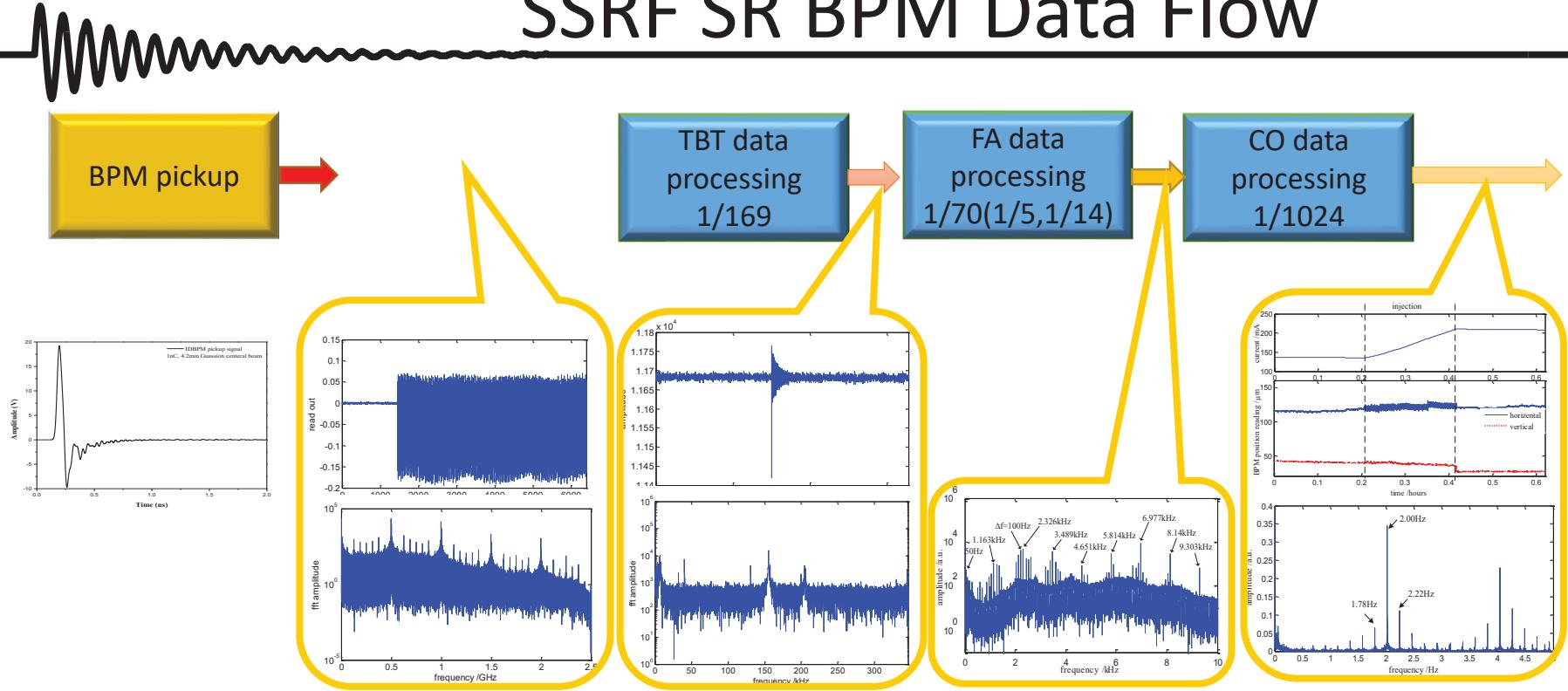
SSRF SR BPM Data Flow



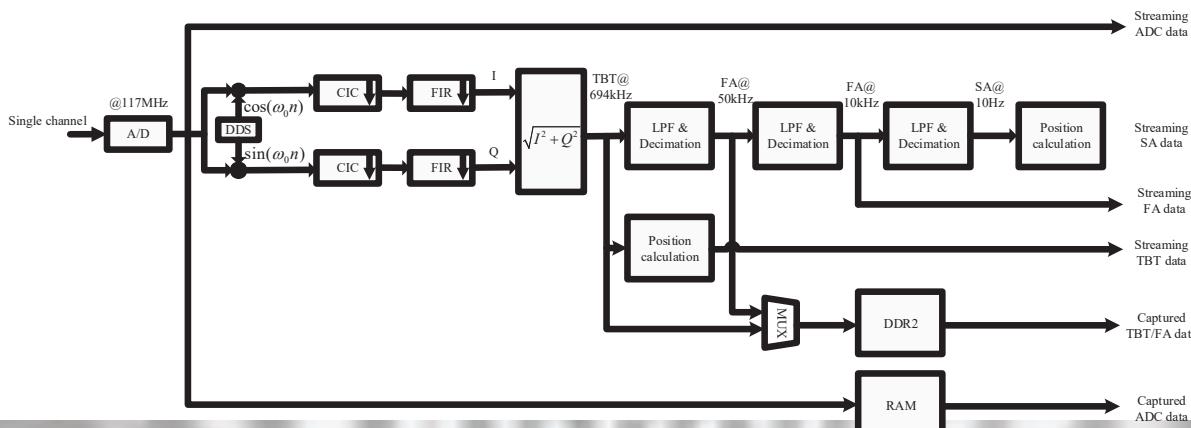
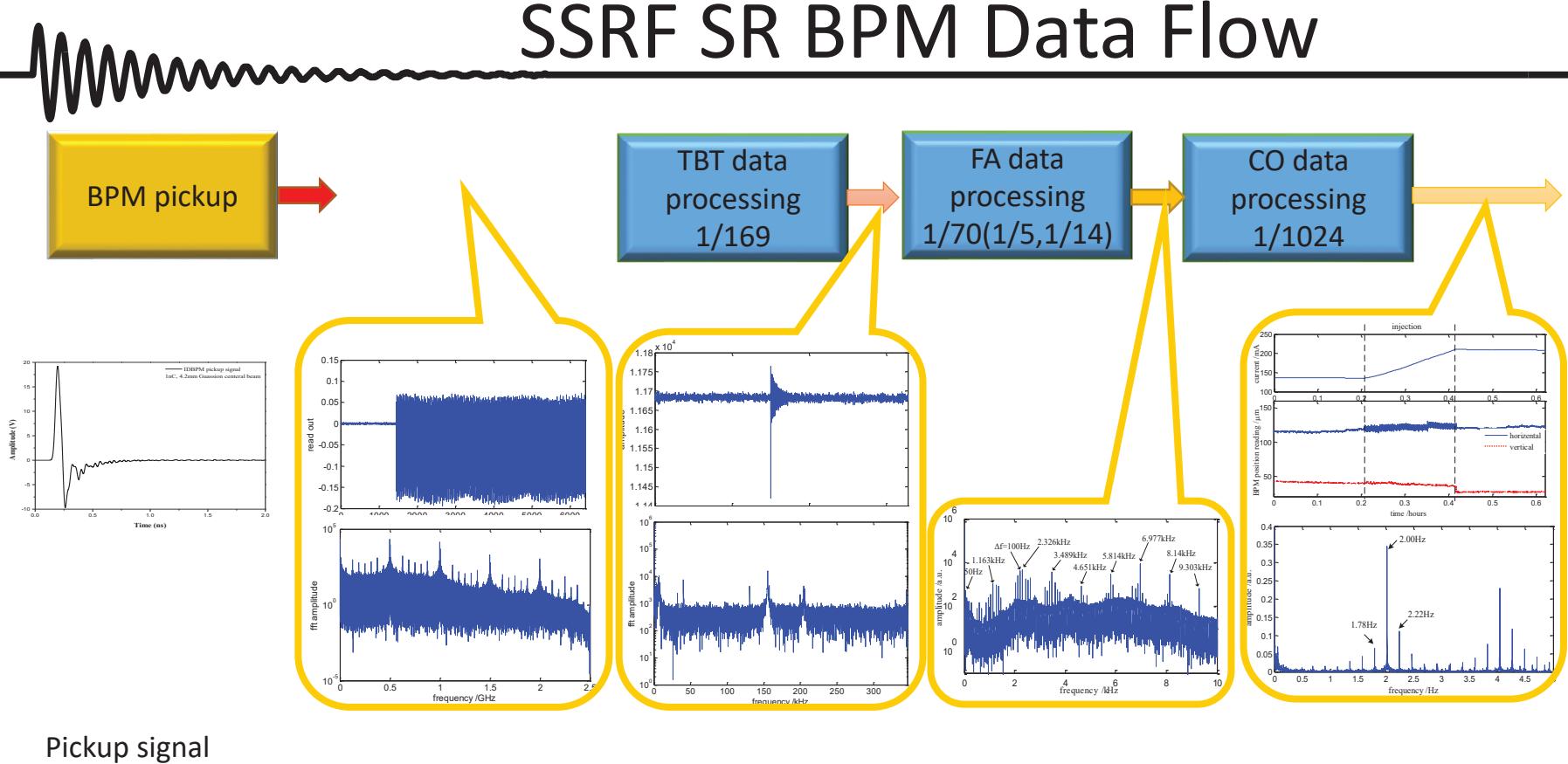
SSRF SR BPM Data Flow



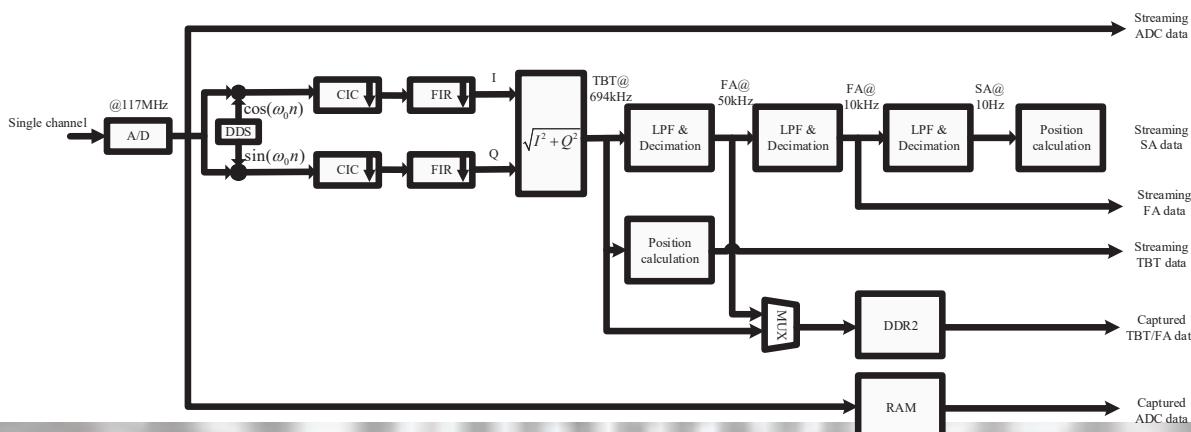
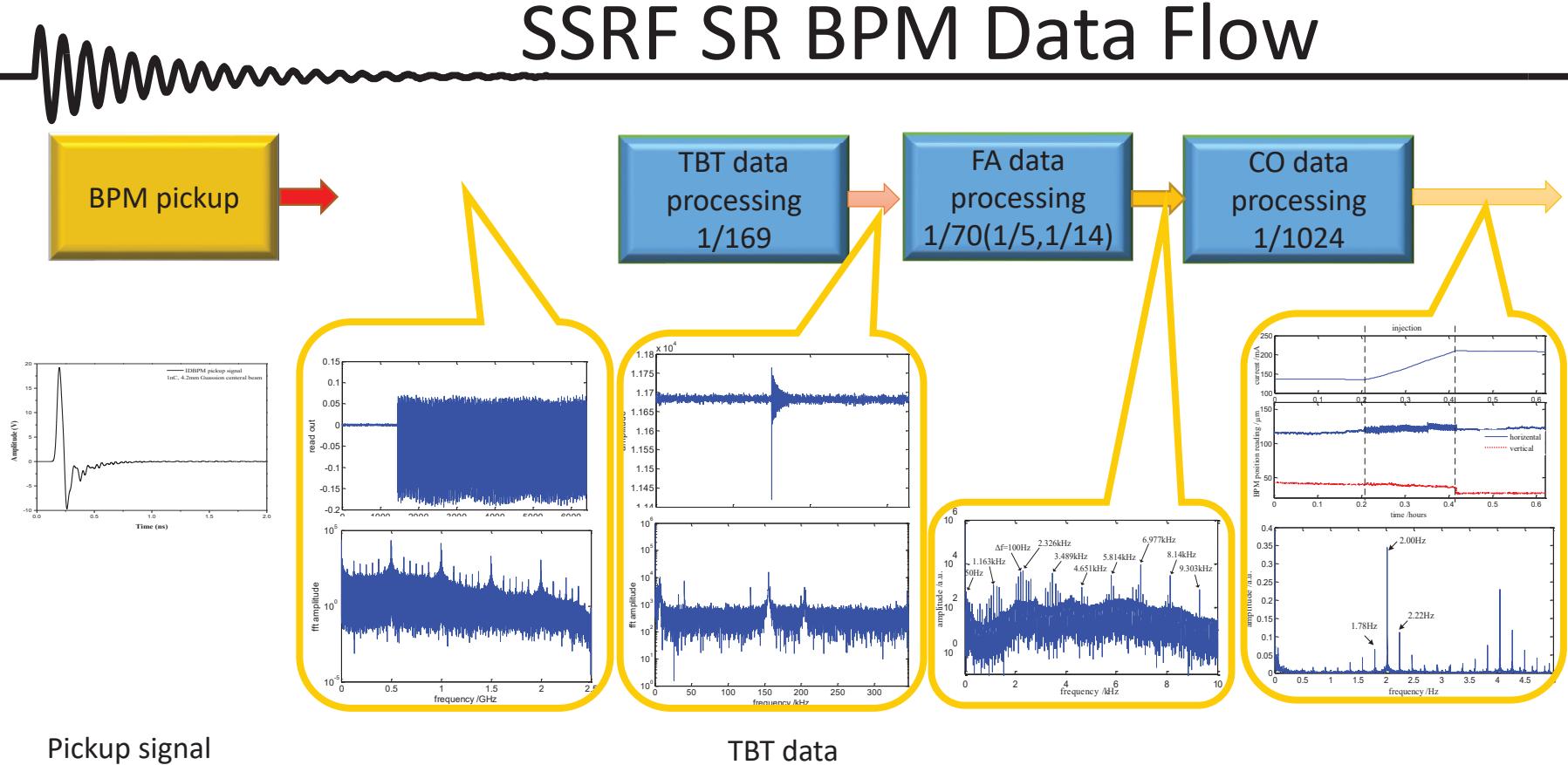
SSRF SR BPM Data Flow



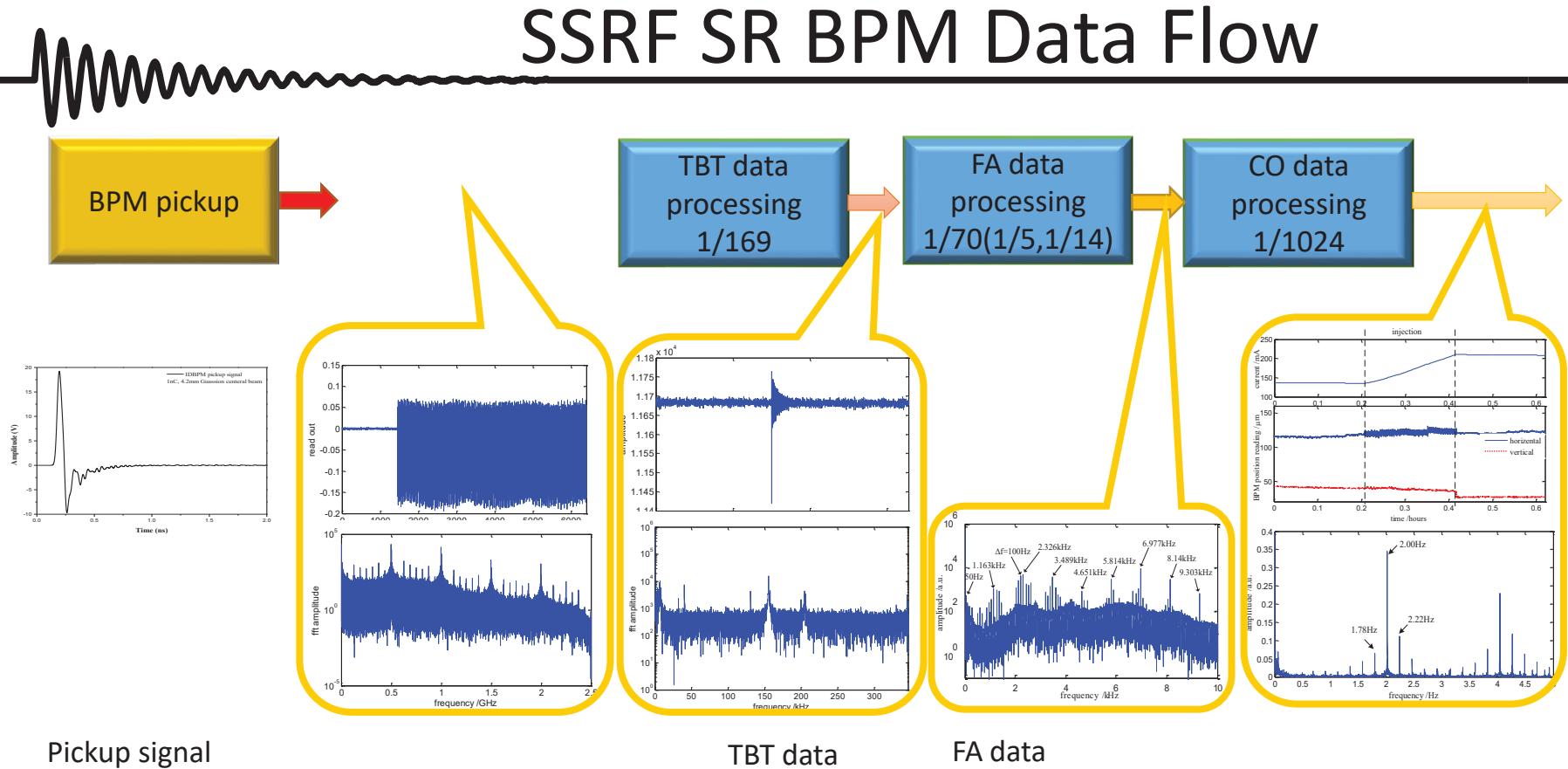
SSRF SR BPM Data Flow



SSRF SR BPM Data Flow



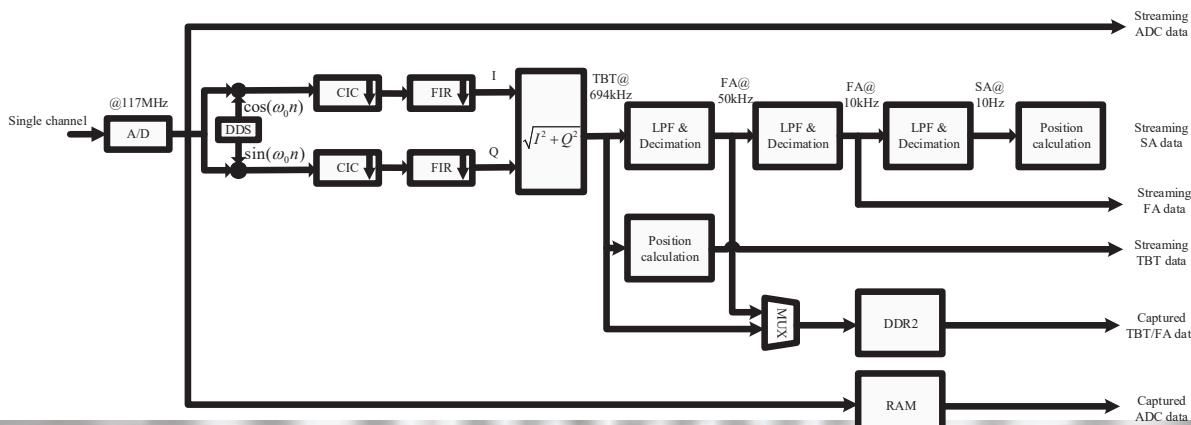
SSRF SR BPM Data Flow



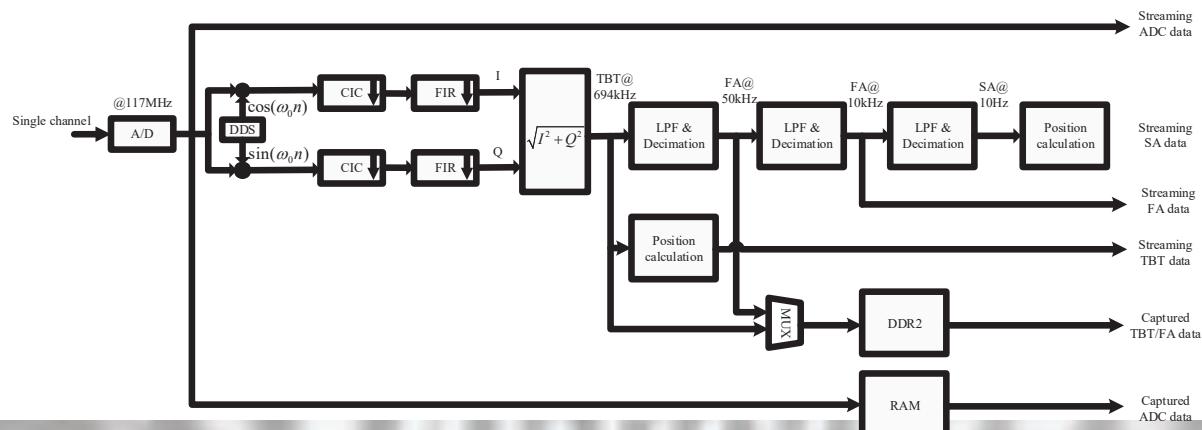
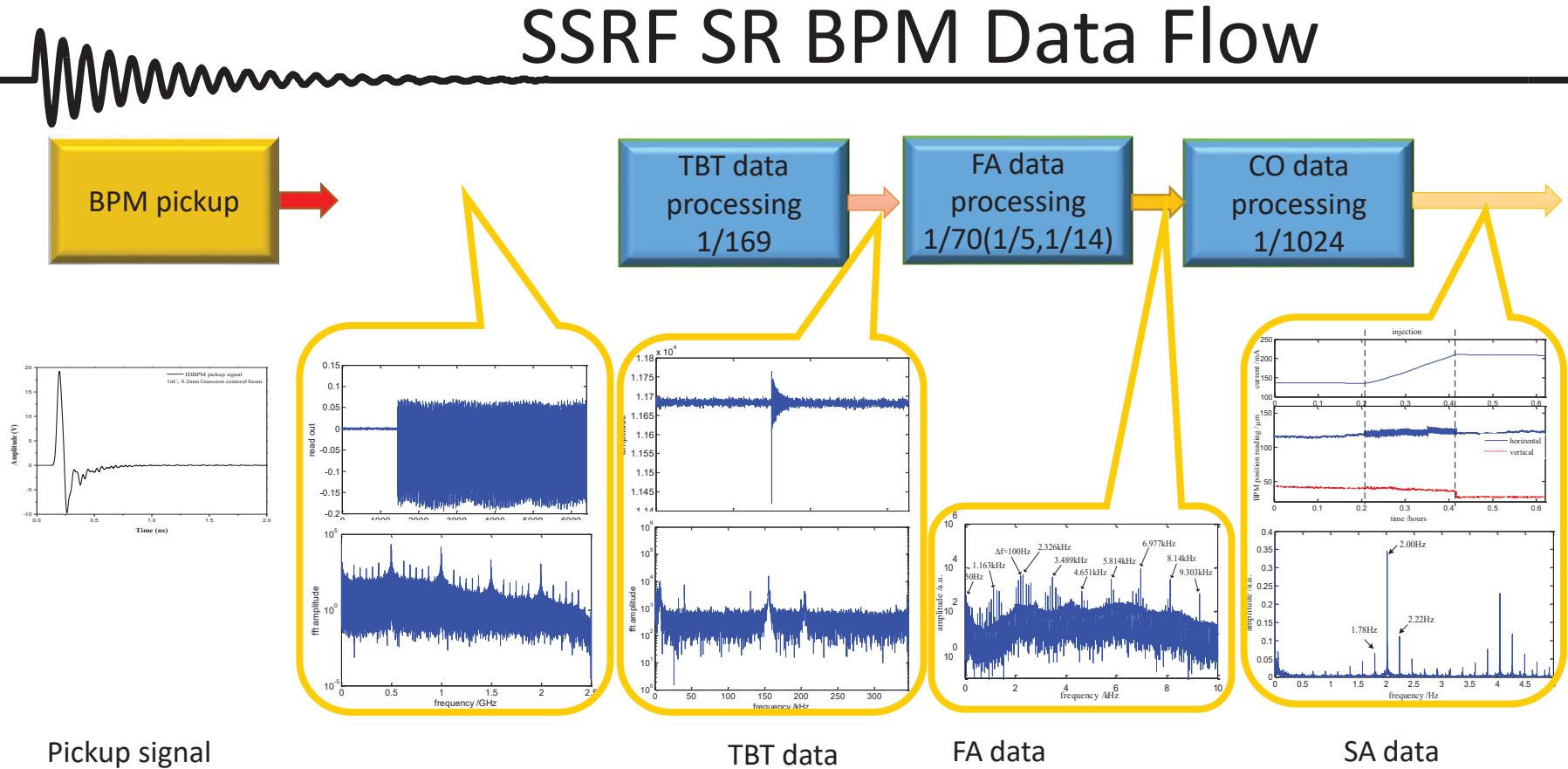
Pickup signal

TBT data

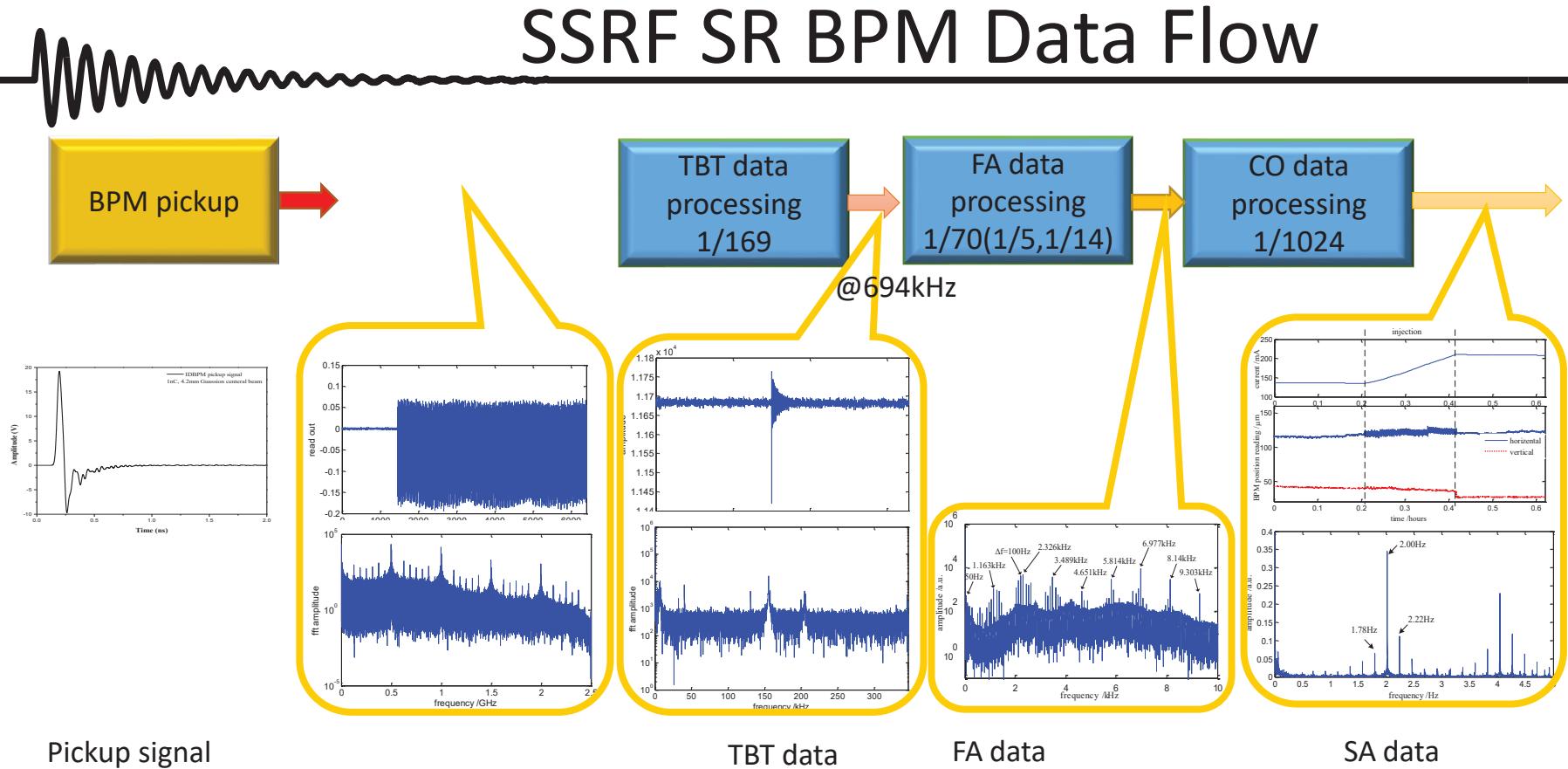
FA data



SSRF SR BPM Data Flow



SSRF SR BPM Data Flow

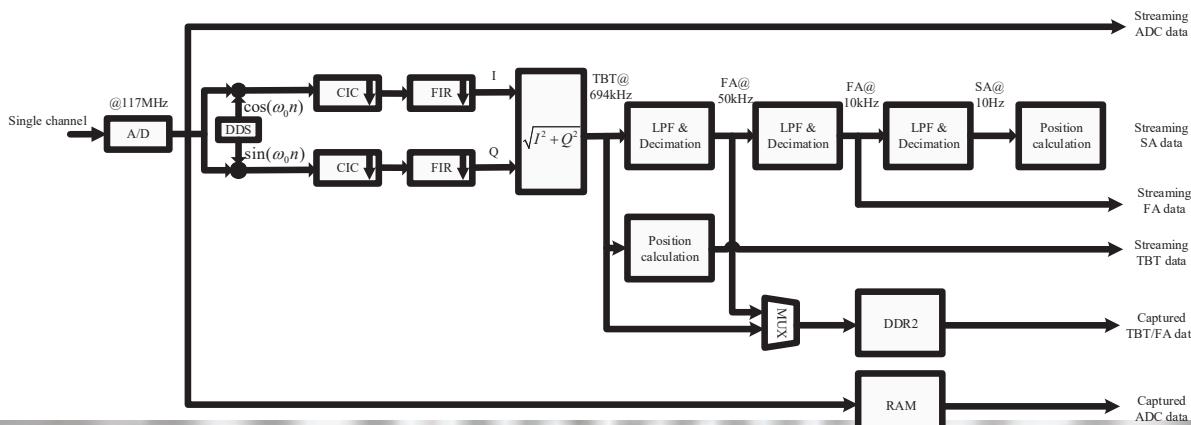


Pickup signal

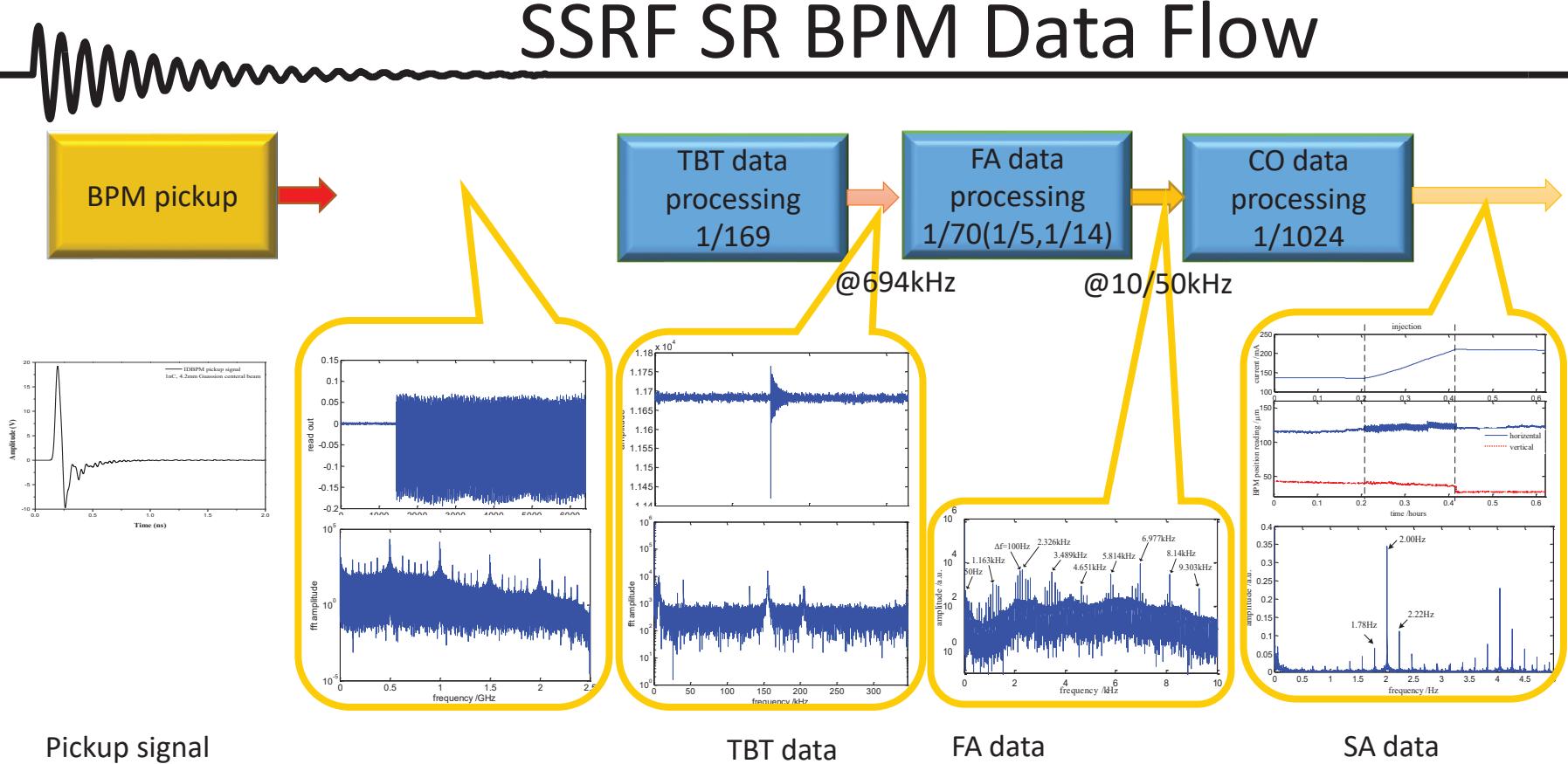
TBT data

FA data

SA data



SSRF SR BPM Data Flow

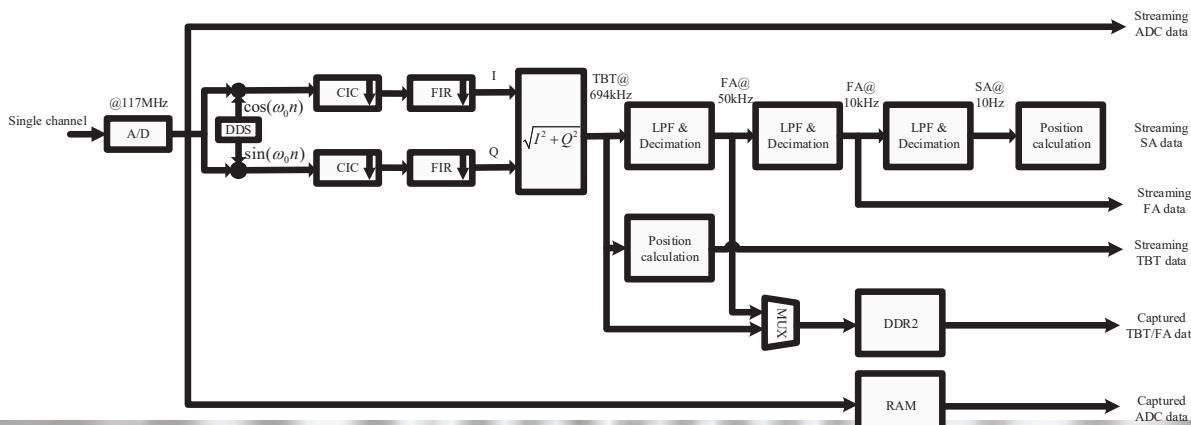


Pickup signal

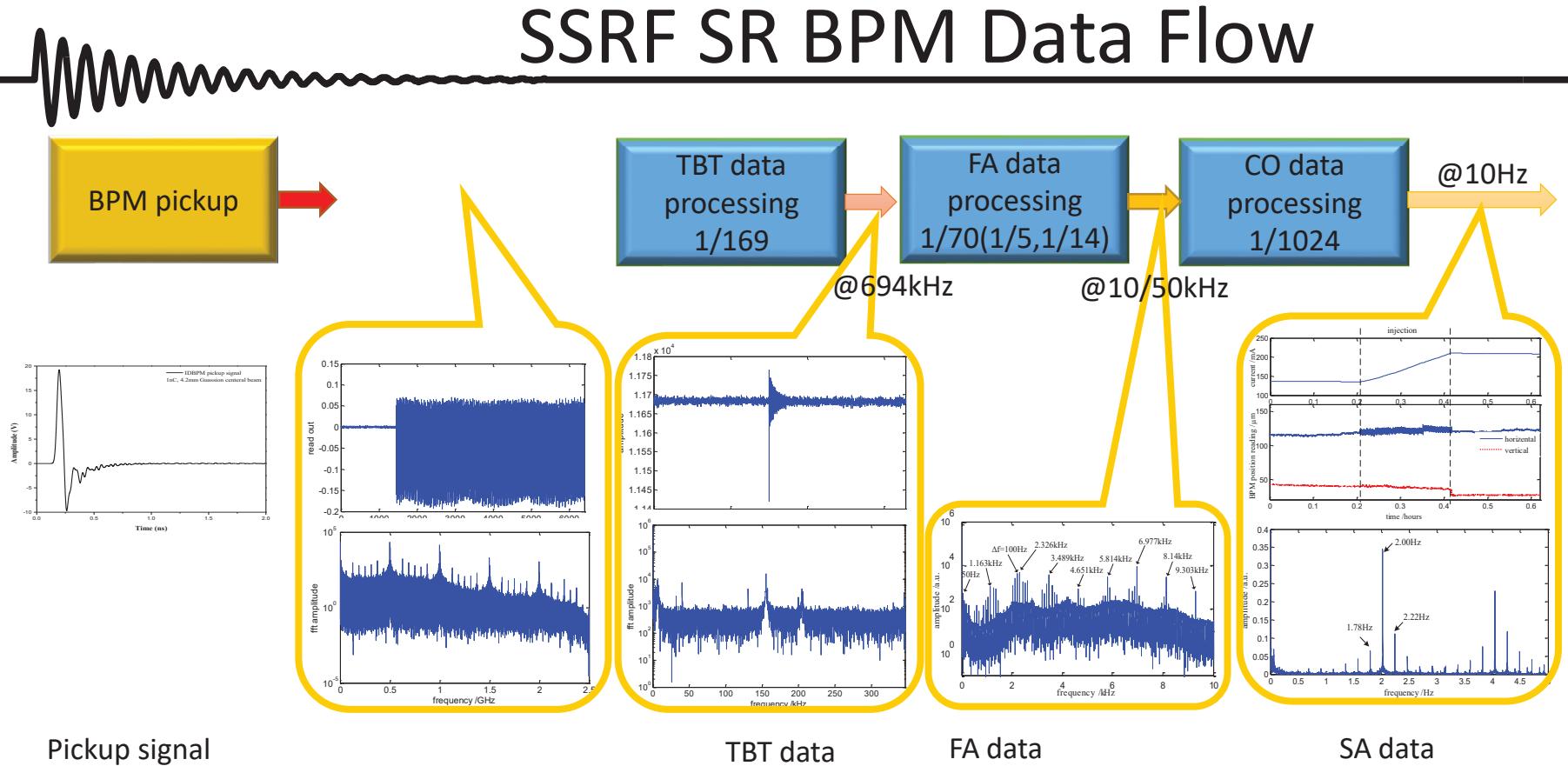
TBT data

FA data

SA data



SSRF SR BPM Data Flow

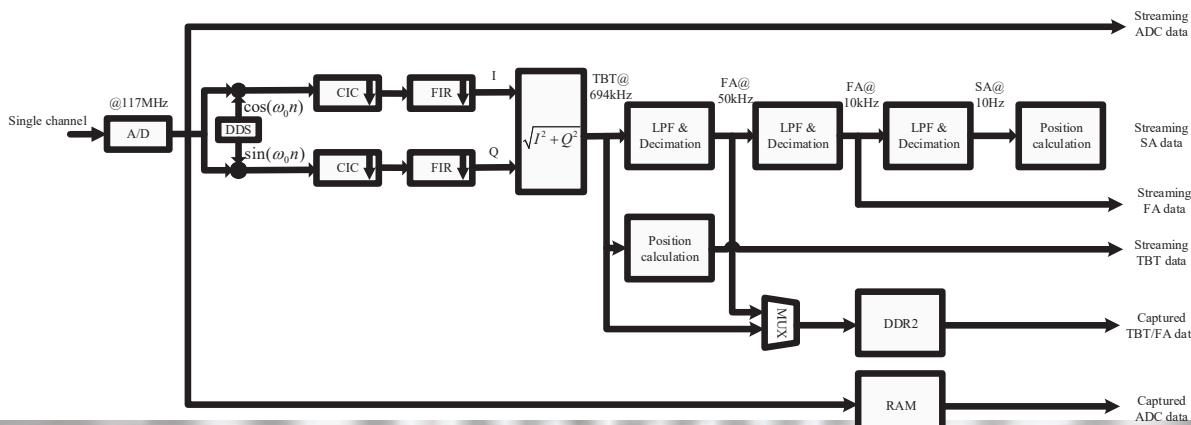


Pickup signal

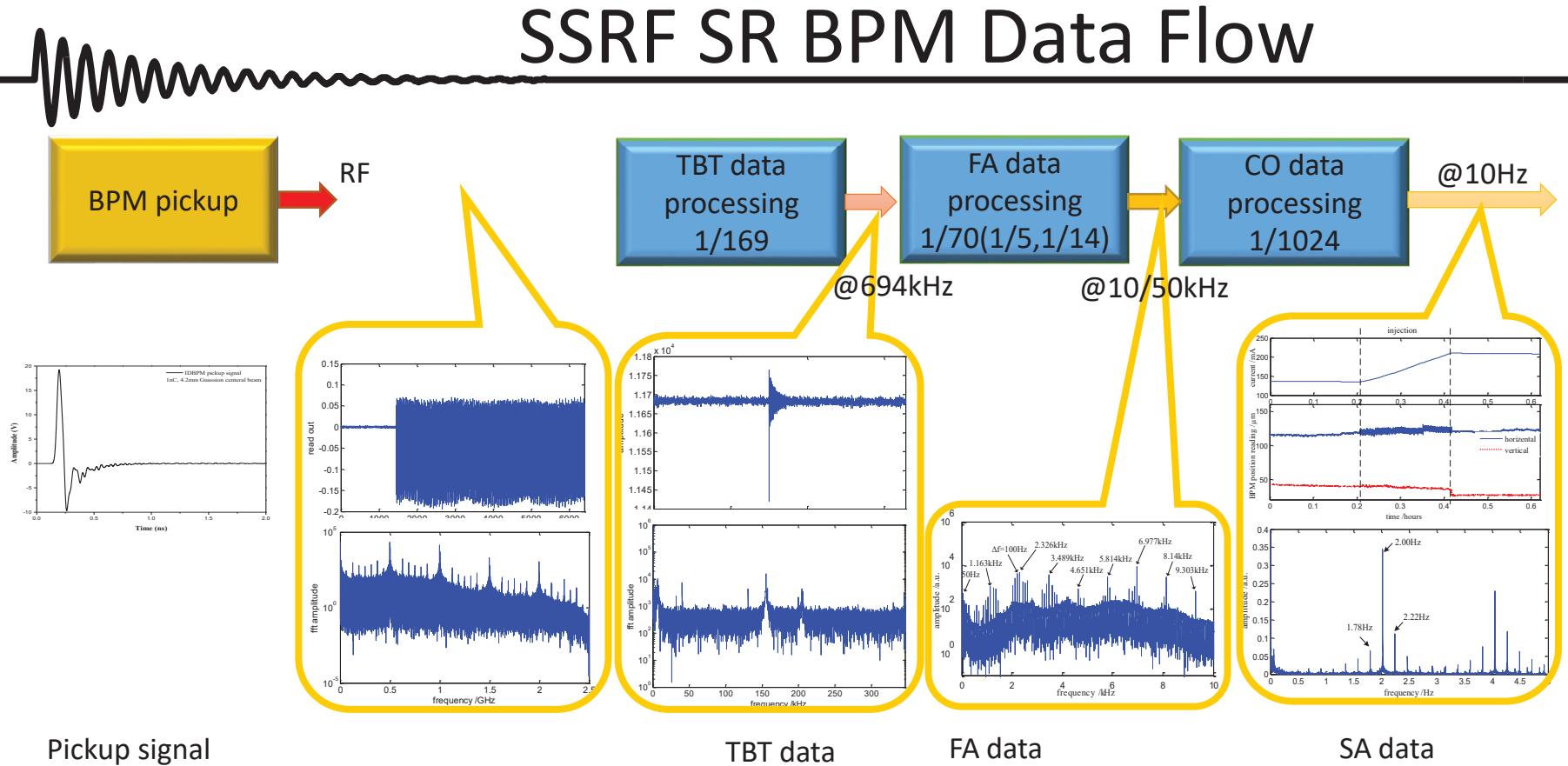
TBT data

FA data

SA data



SSRF SR BPM Data Flow

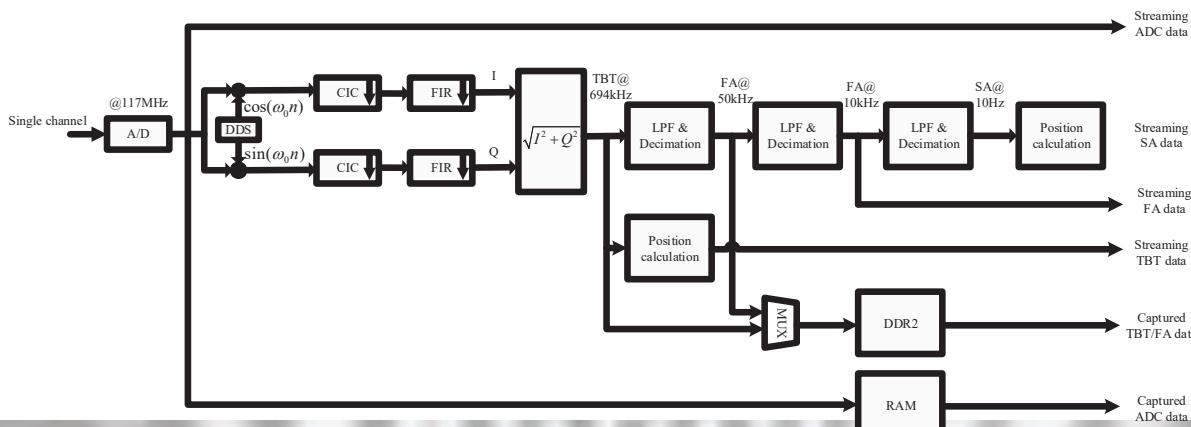


Pickup signal

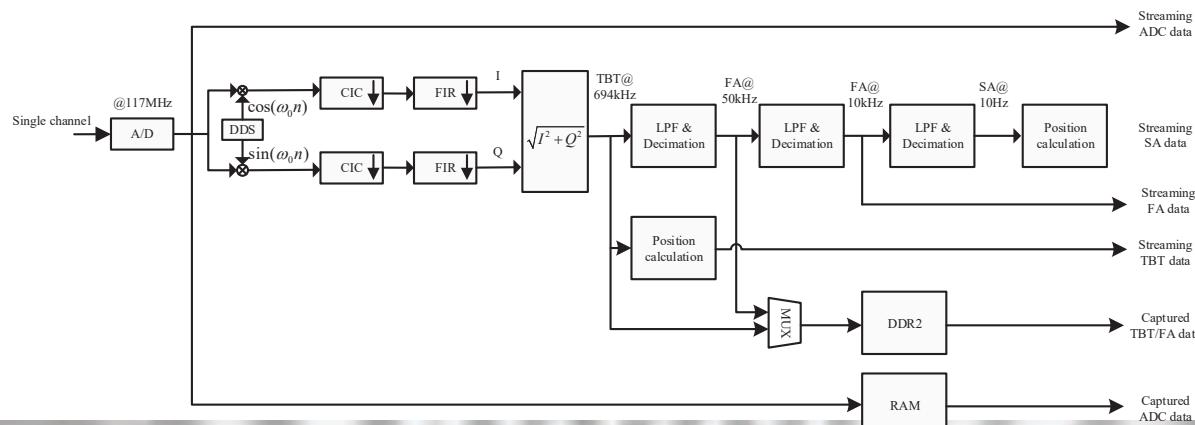
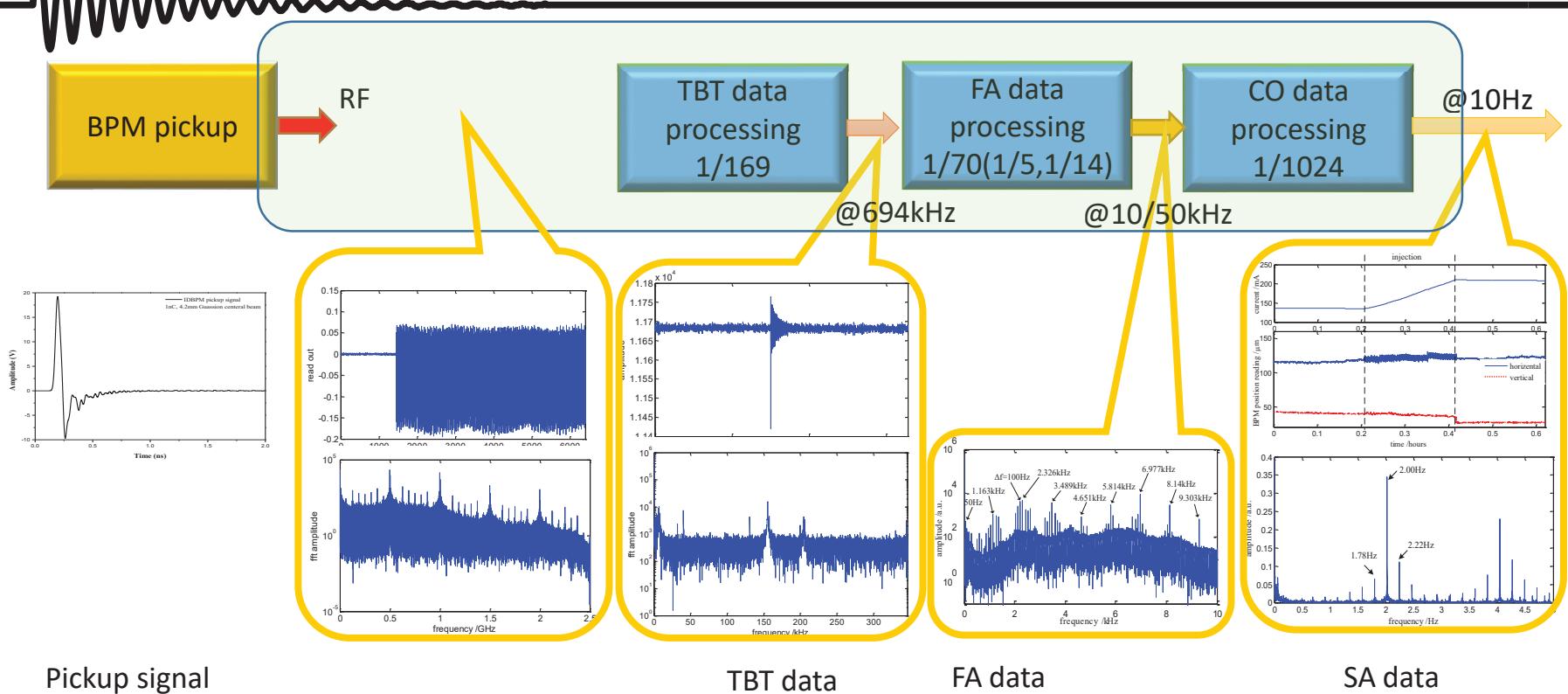
TBT data

FA data

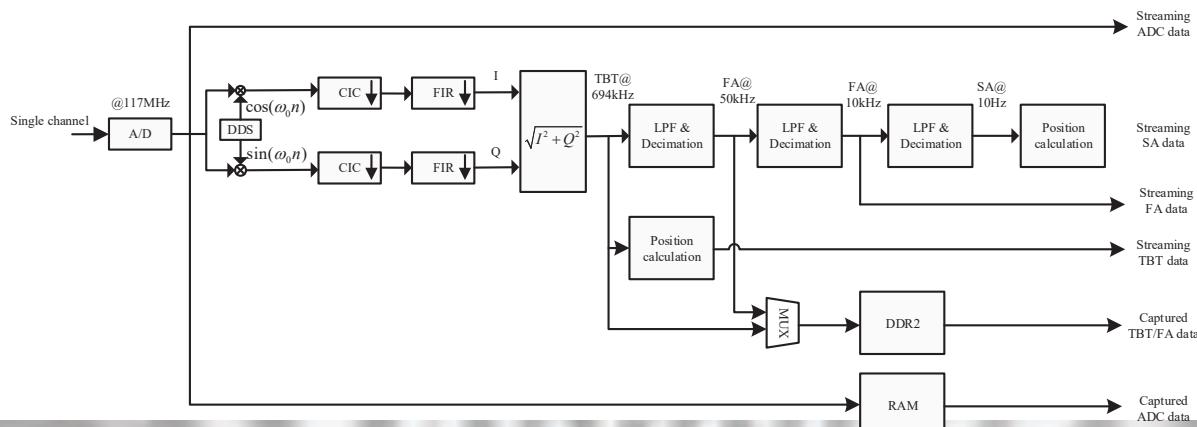
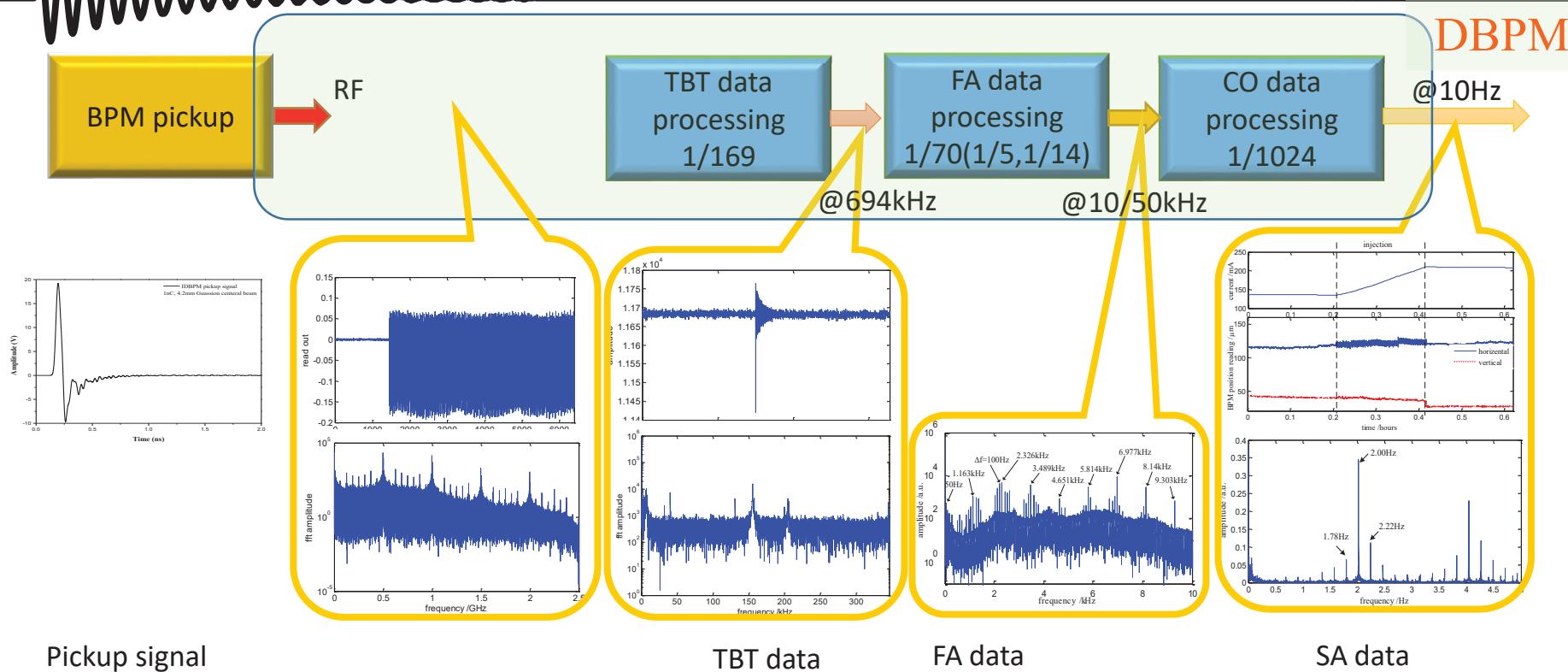
SA data



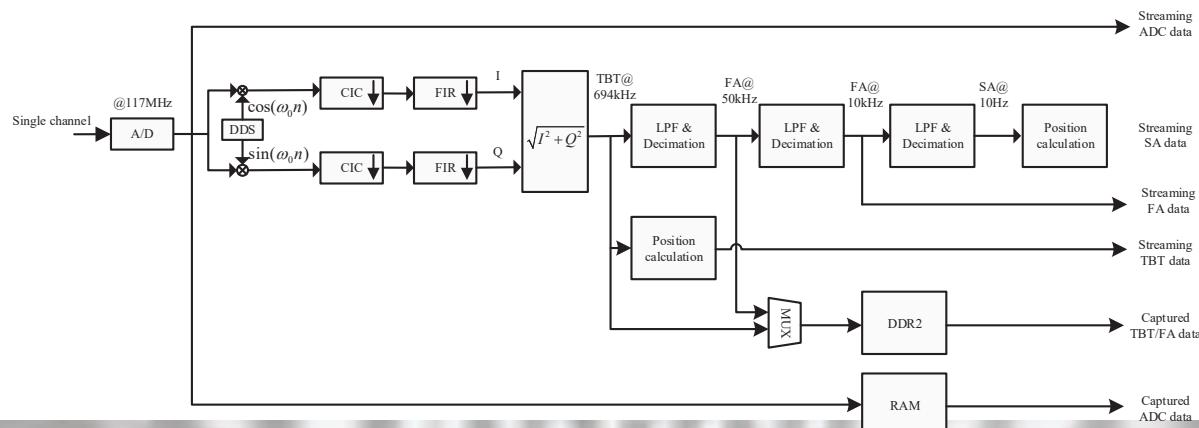
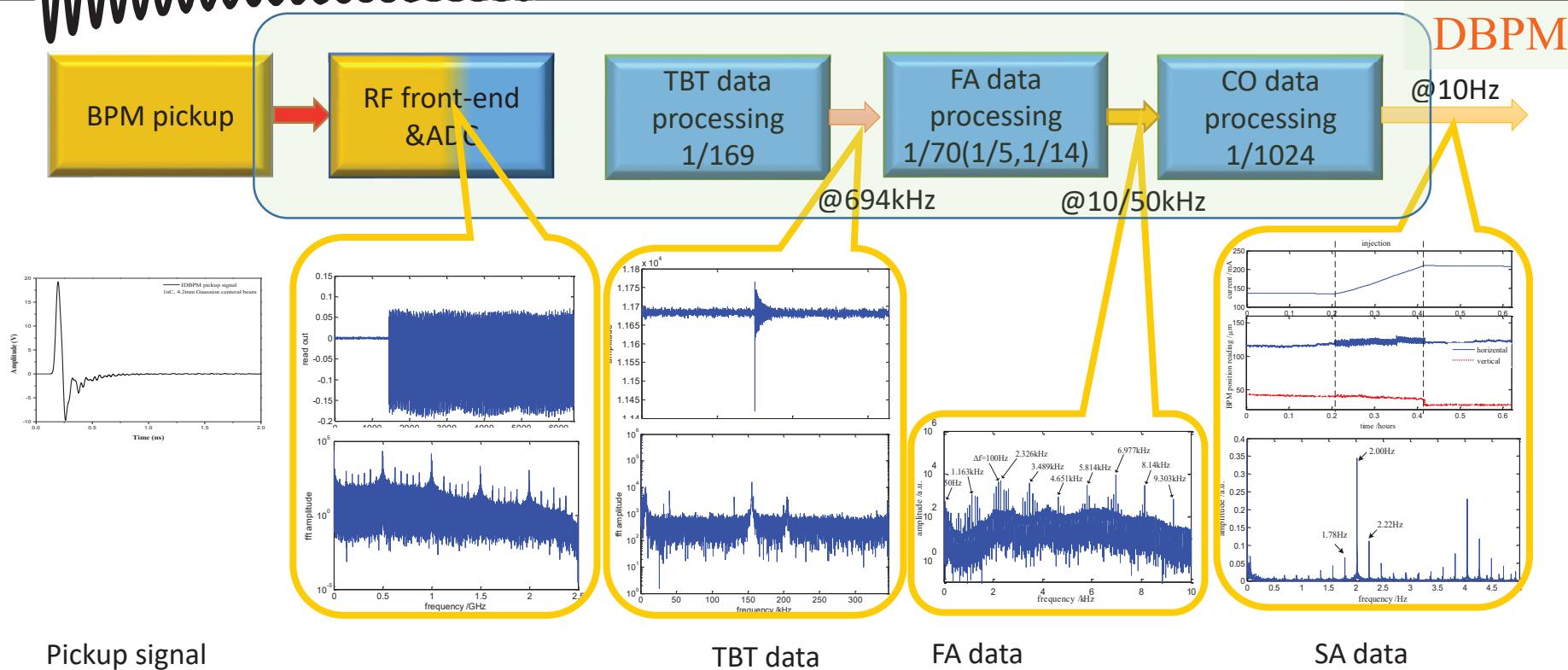
SSRF SR BPM Data Flow



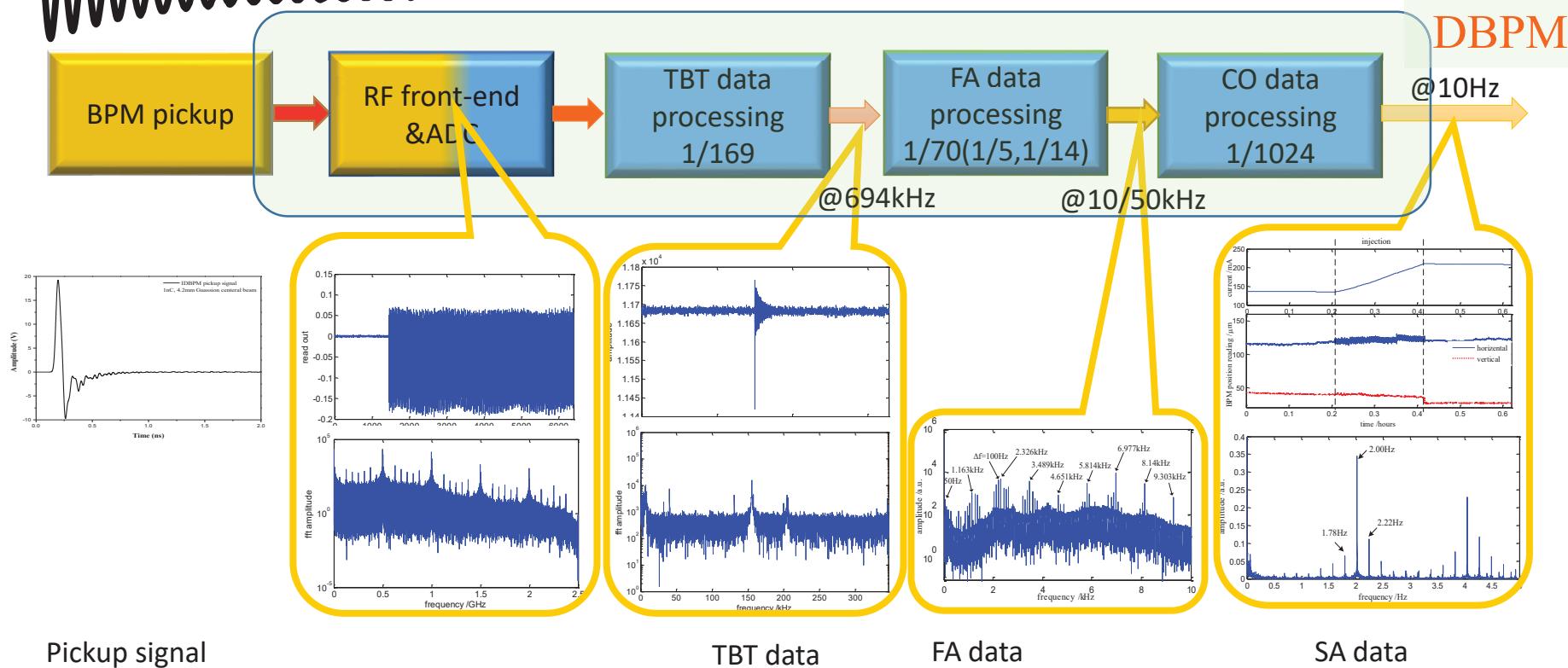
SSRF SR BPM Data Flow



SSRF SR BPM Data Flow



SSRF SR BPM Data Flow

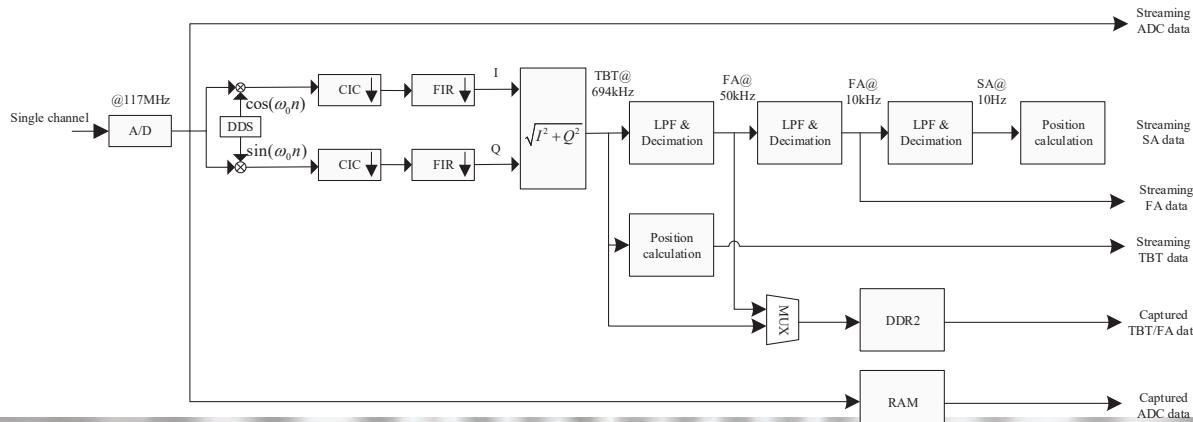


Pickup signal

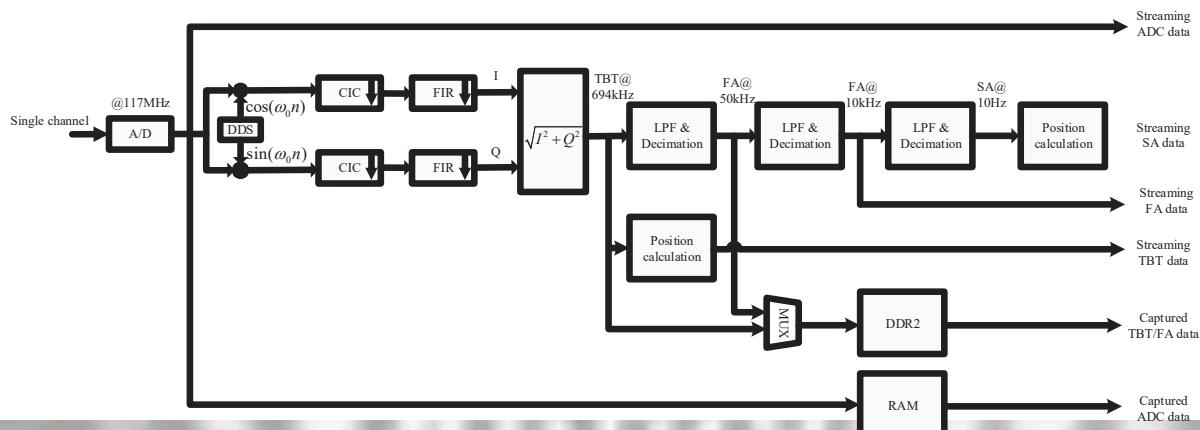
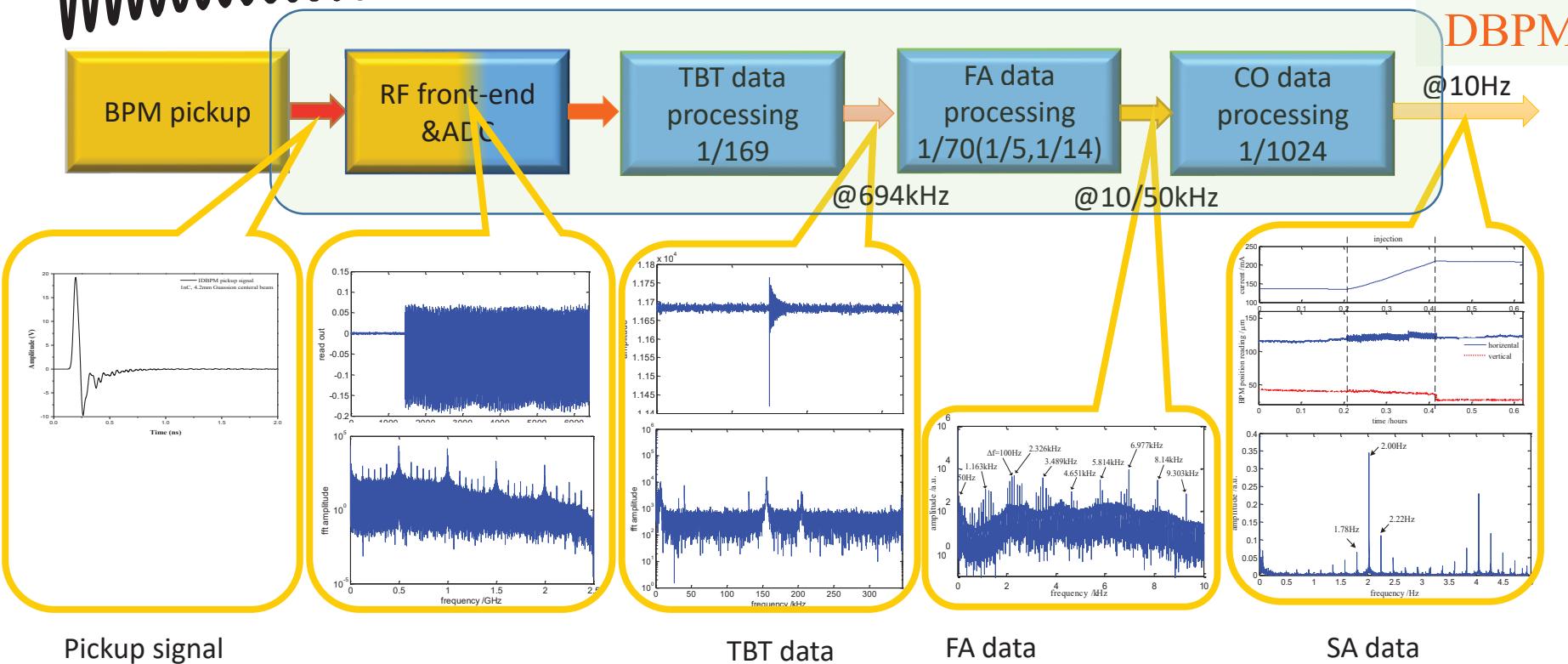
TBT data

FA data

SA data

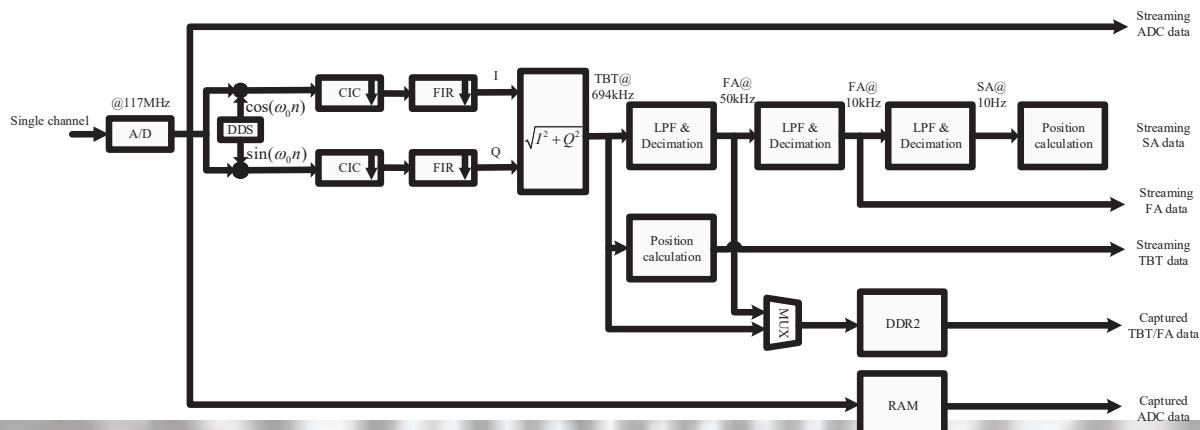
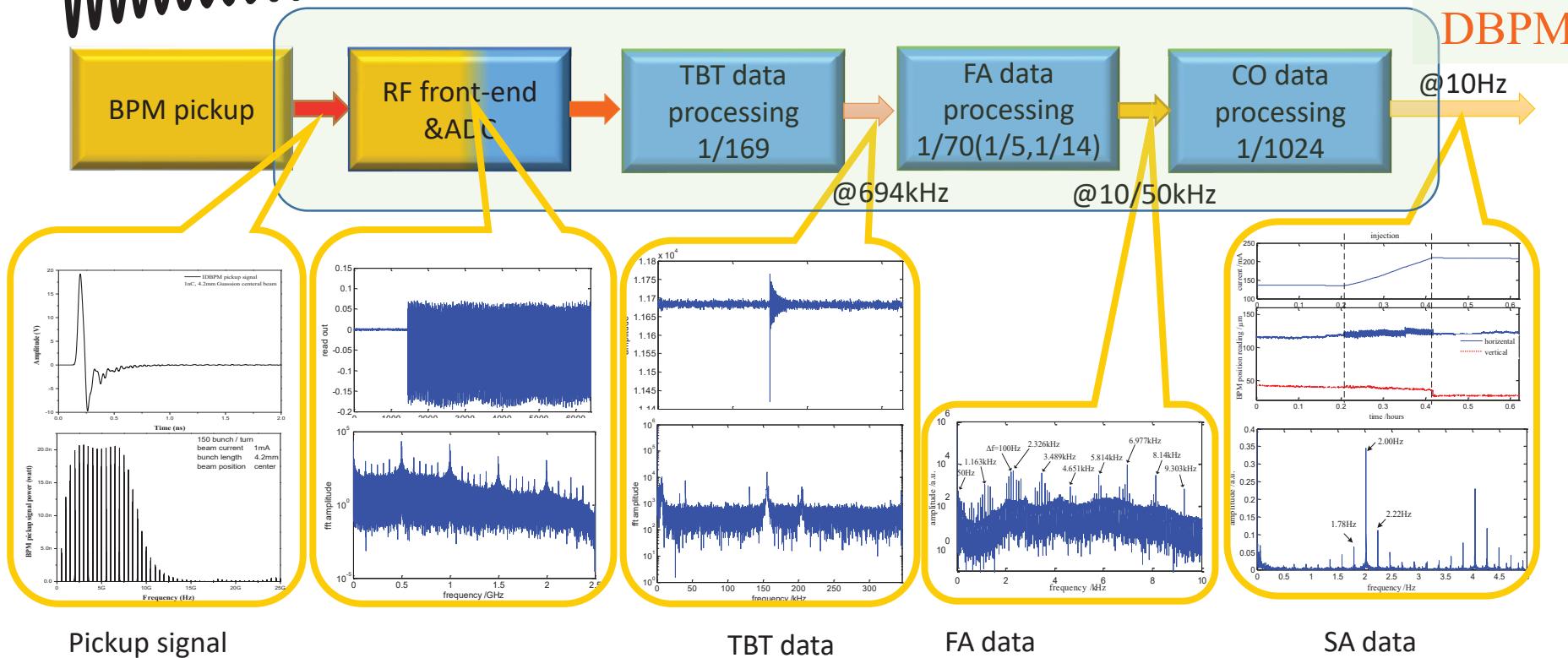


SSRF SR BPM Data Flow



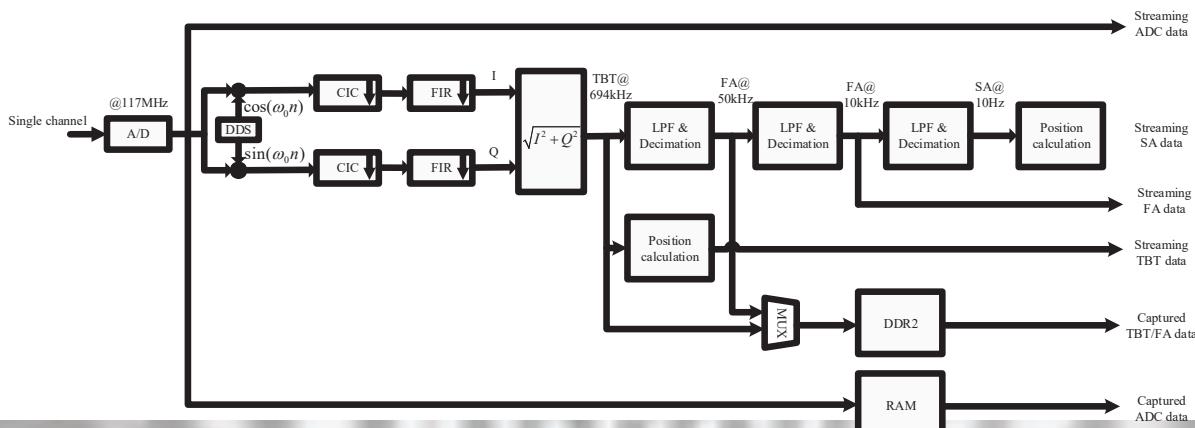
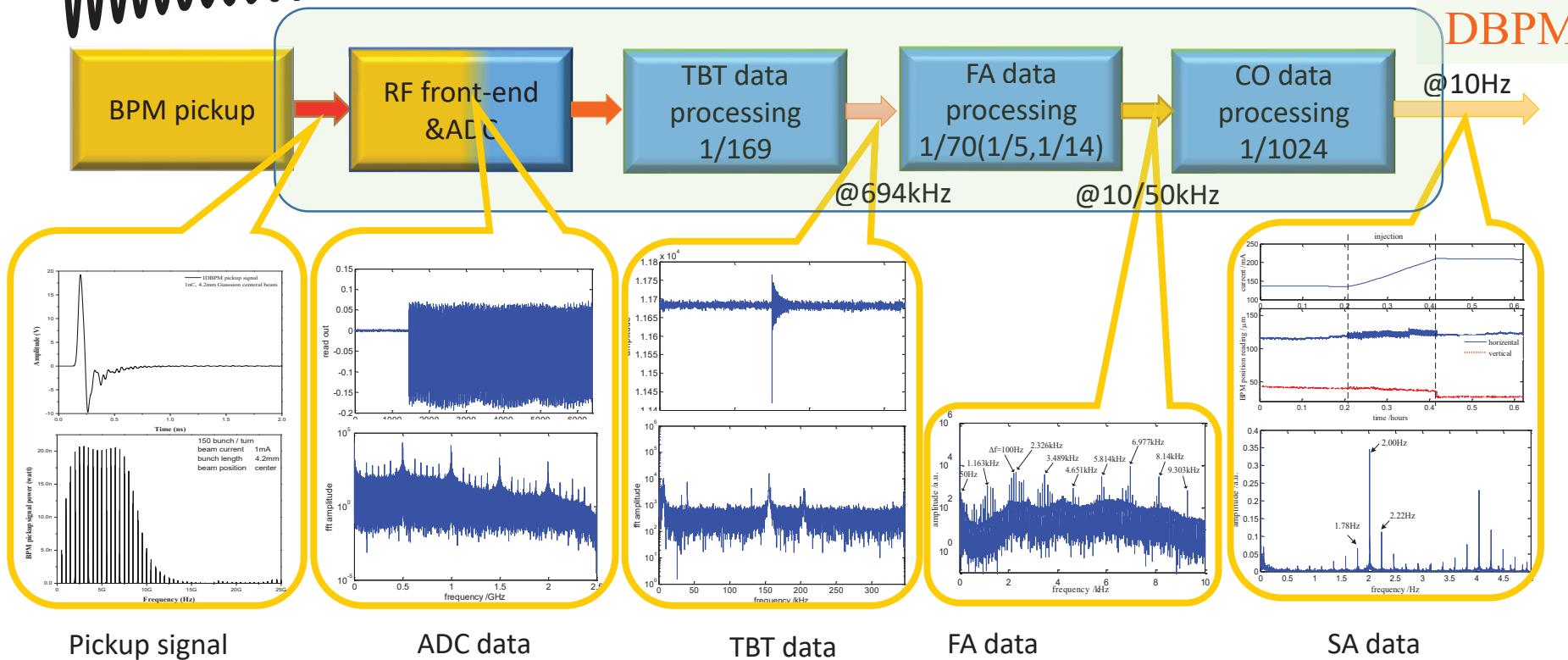
Longwei Lai, BI, SSRF

SSRF SR BPM Data Flow



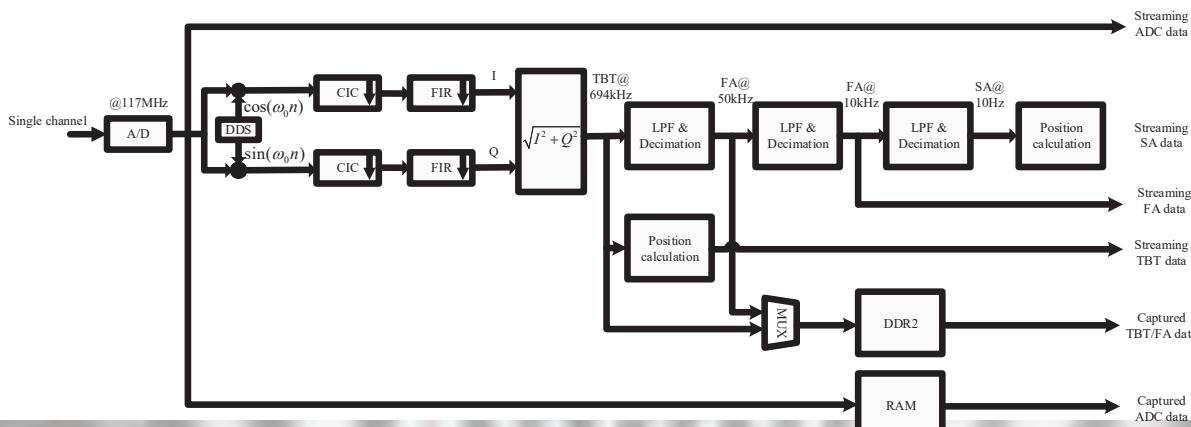
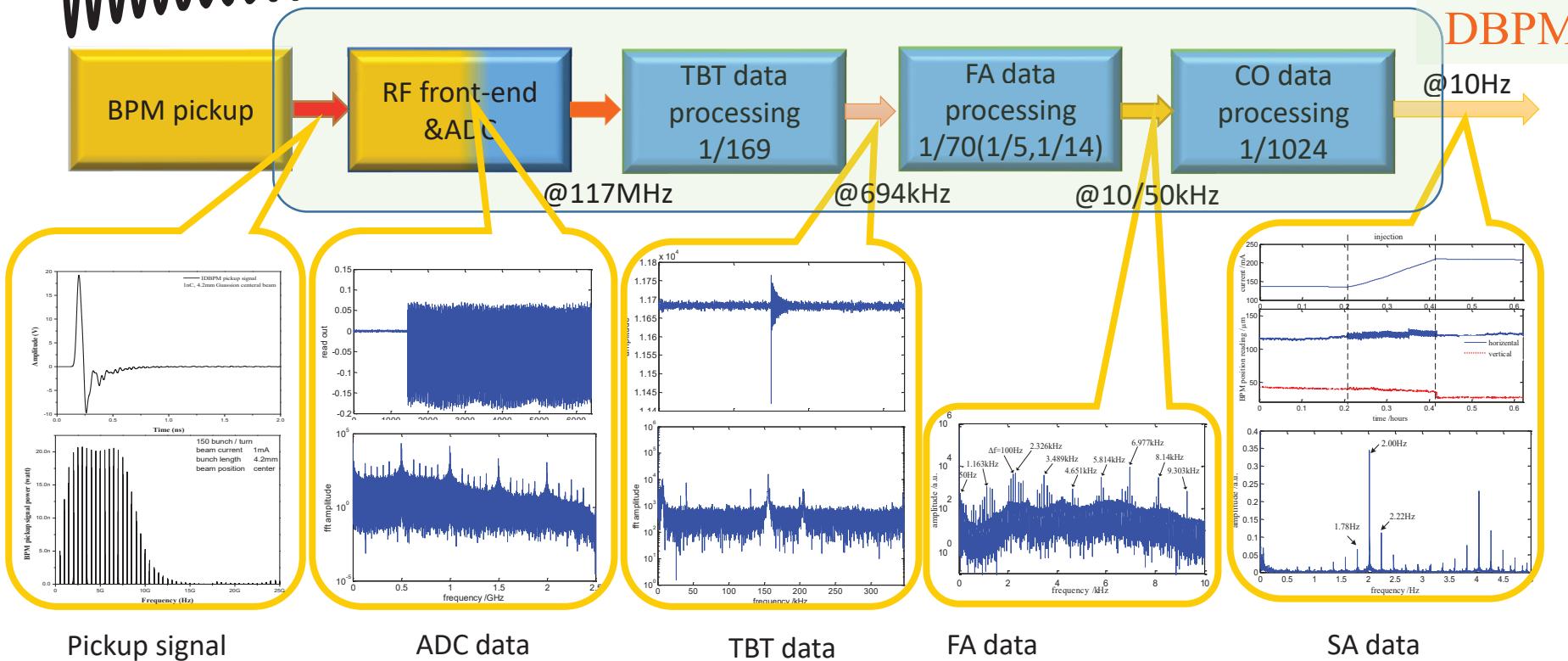
Longwei Lai, BI, SSRF

SSRF SR BPM Data Flow



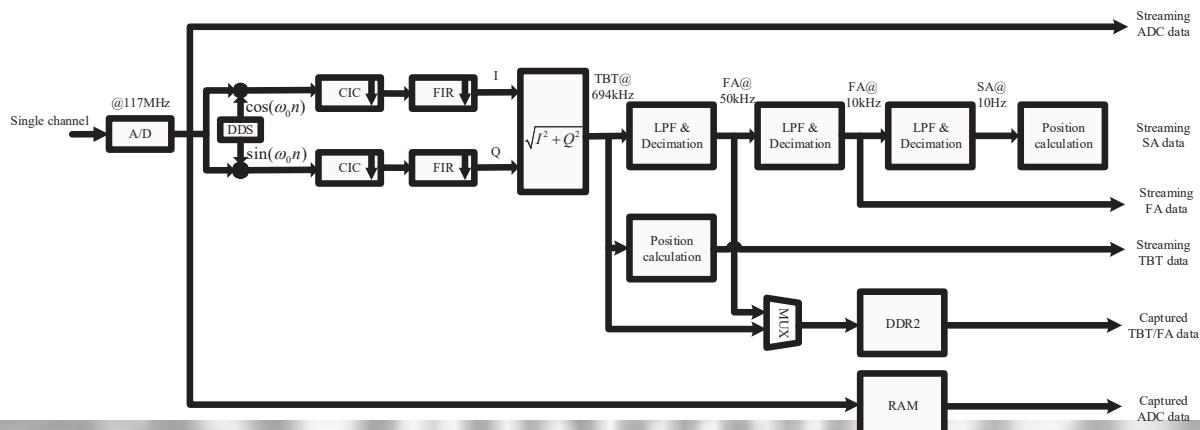
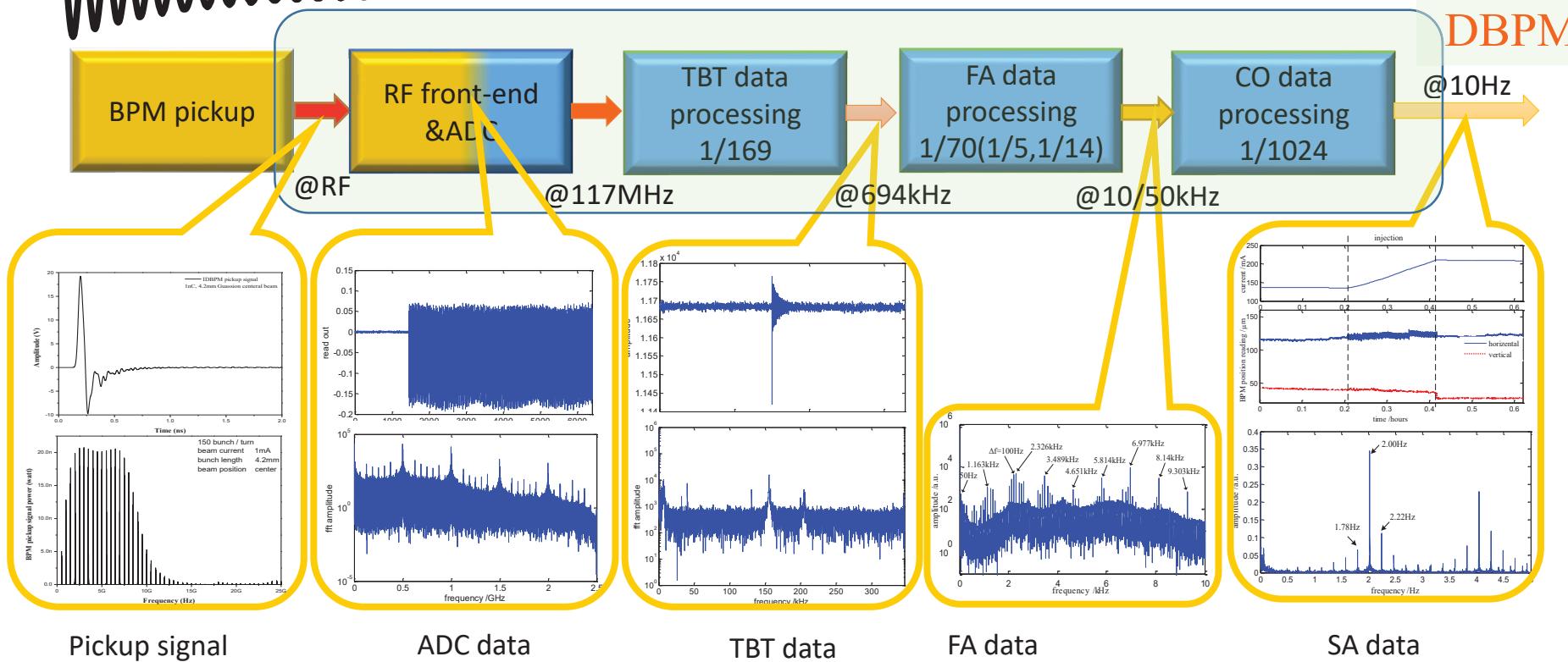
Longwei Lai, BI, SSRF

SSRF SR BPM Data Flow



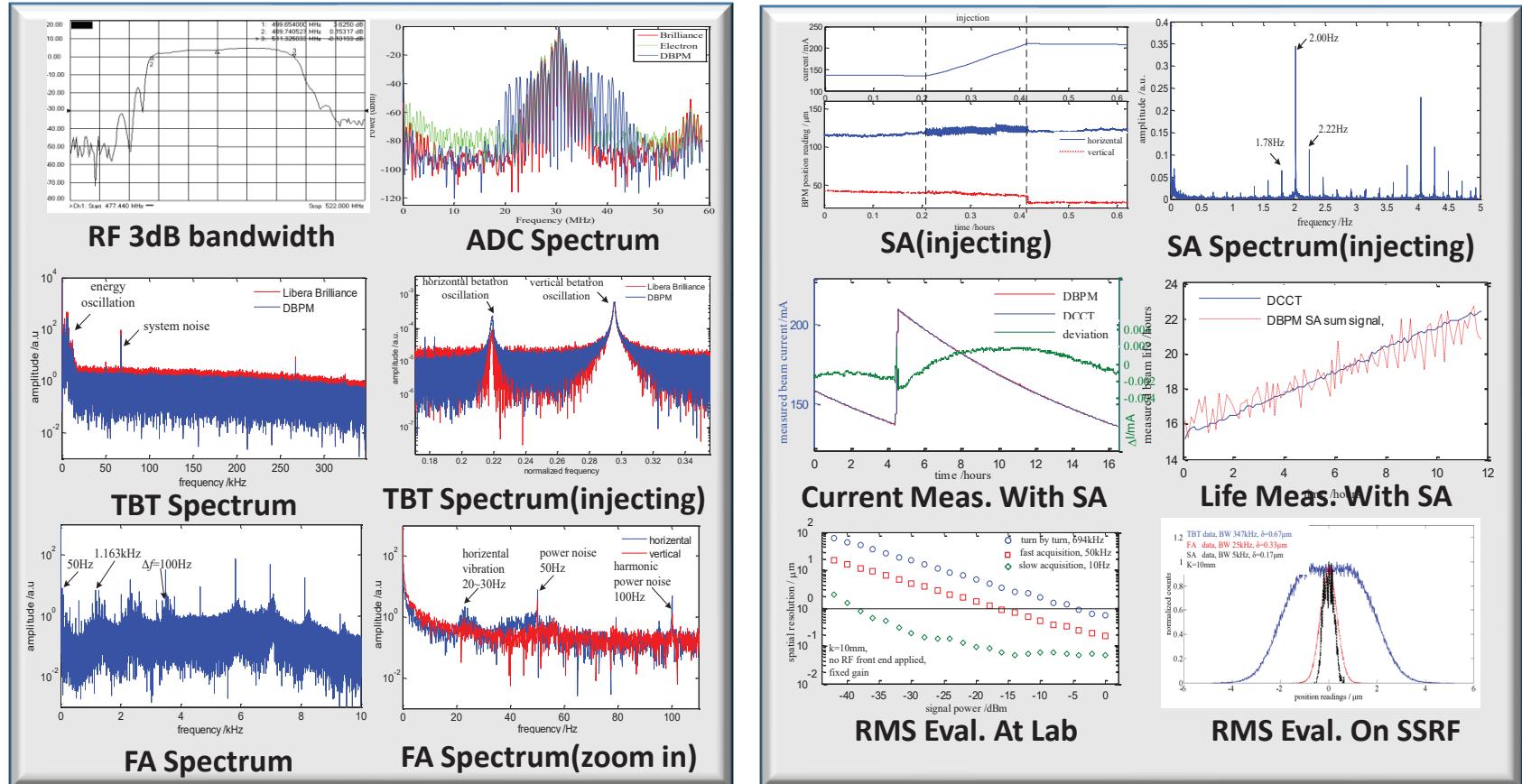
Longwei Lai, BI, SSRF

SSRF SR BPM Data Flow

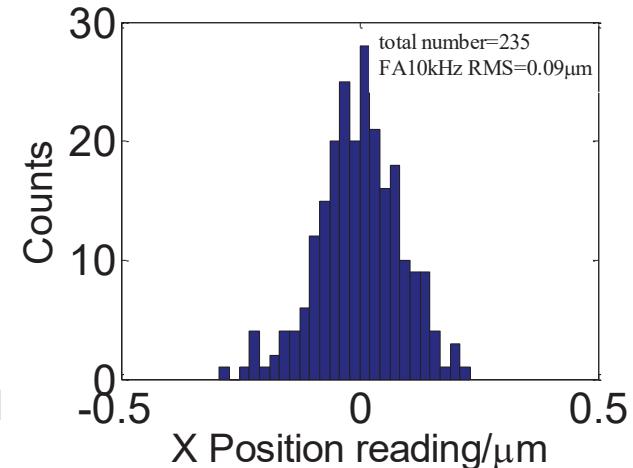
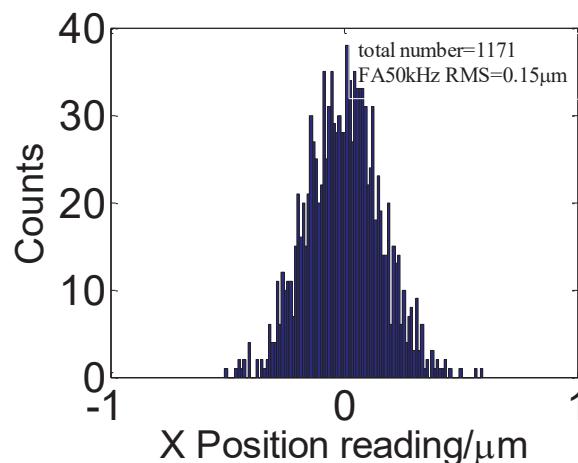
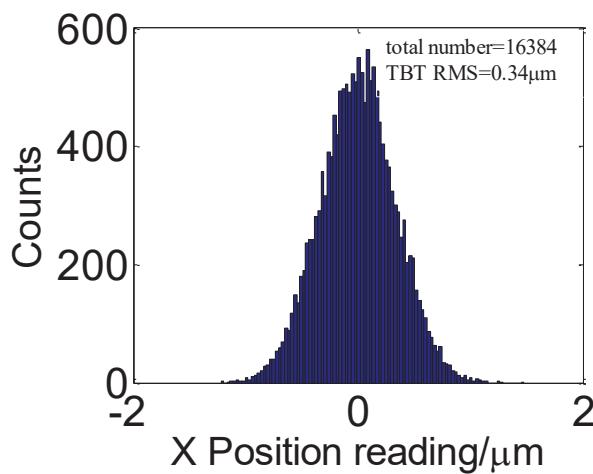
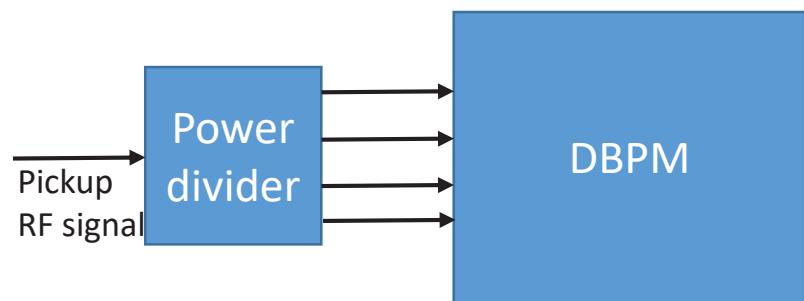


Longwei Lai, BI, SSRF

Version-I DBPM Beam Tests@2012

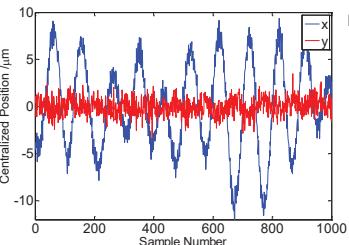
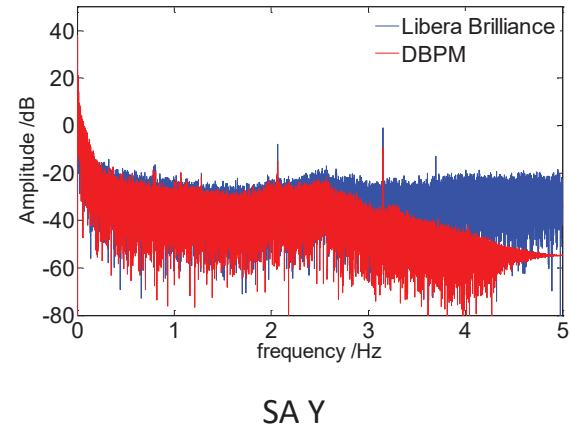
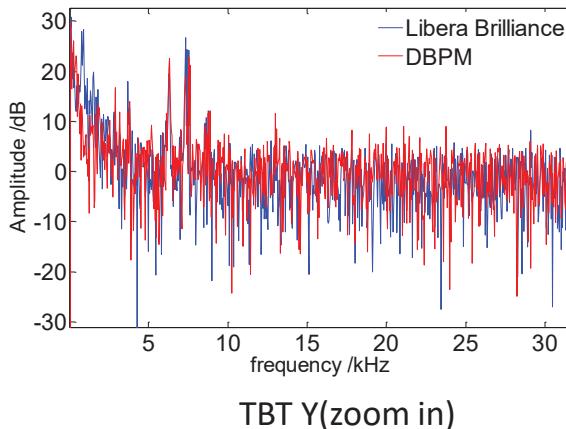
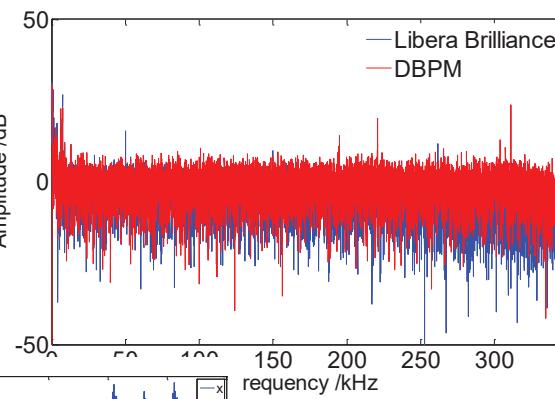
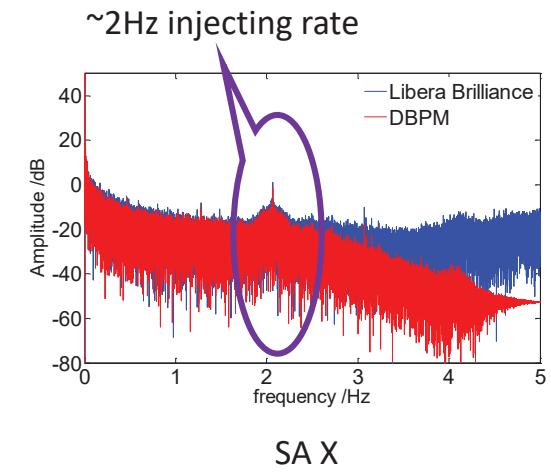
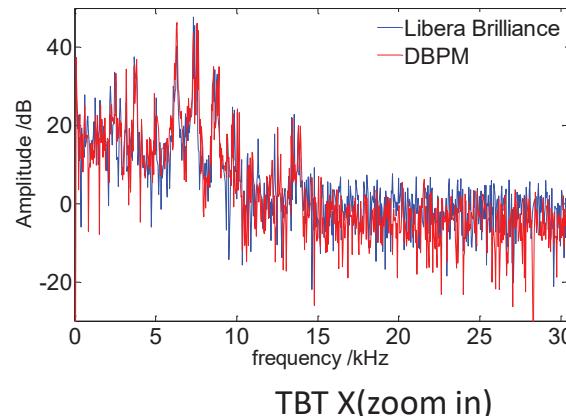
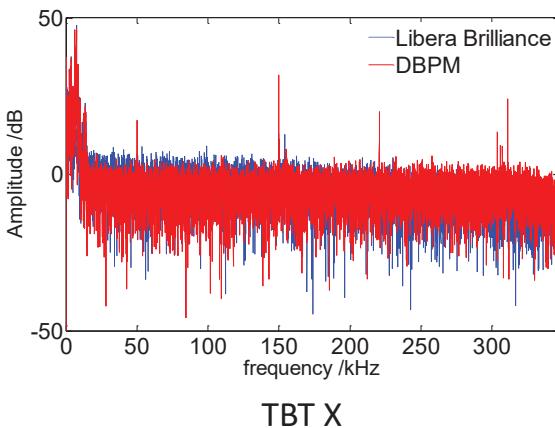


Version-II DBPM Beam Tests @Jan. 2018



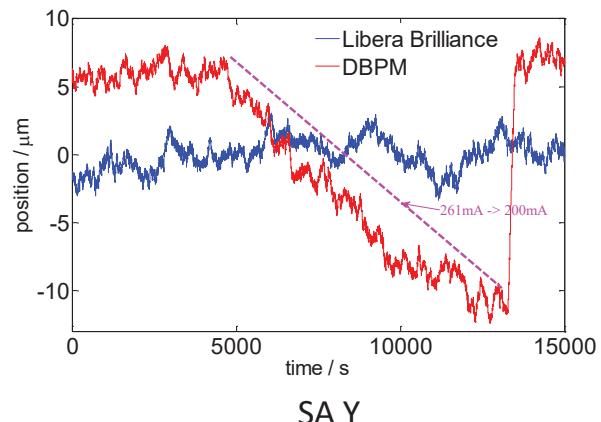
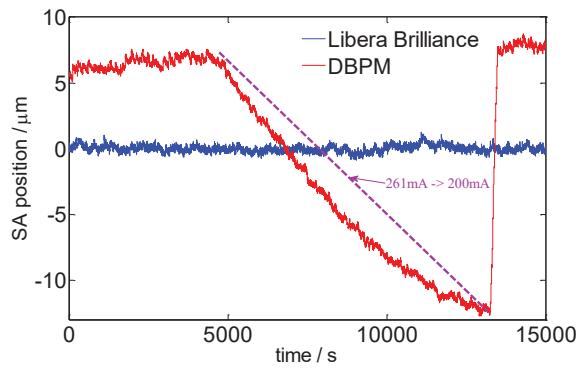
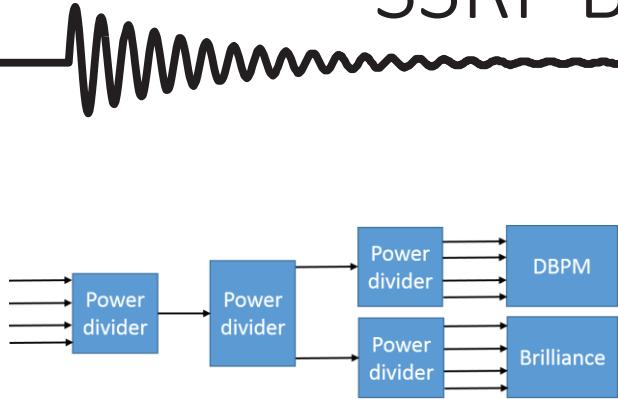
K=10mm, Turn-by-turn resolution:0.34 μ m

SSRF Beam Test—Check With Brilliance



Assuming the Brilliance results are correct.
Data spectrums show they fit quite well.

SSRF Beam Test—Current Dependency

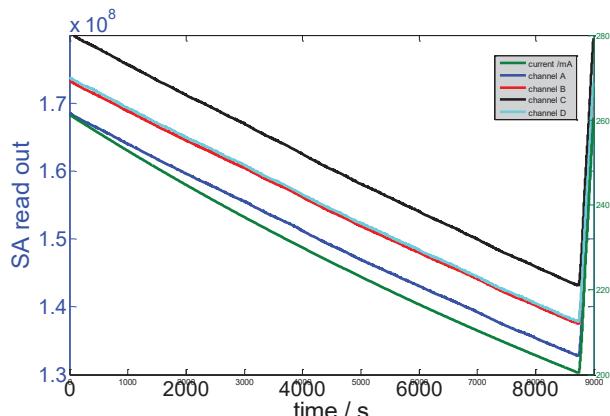


BPM pickup sum signal is divided into 8 channels and put into DBPM and Brilliance, similar to beam passing through BPM center. The output position value should be stable.

The DBPM output is **drifting when beam current decays from 260mA to 200mA**.

Brilliance output is stable when crossbars are switched off.

The main reason is the **inconsistency between the four channels**.



Fit polynomial to data.

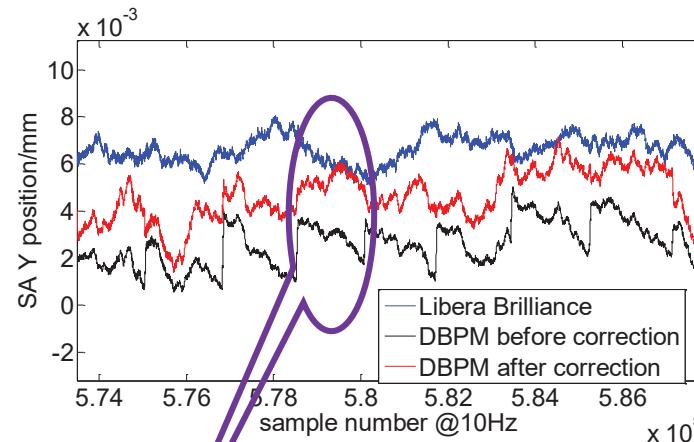
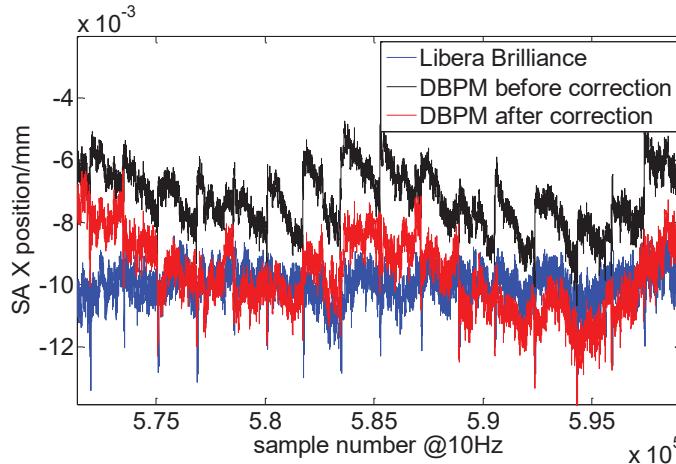
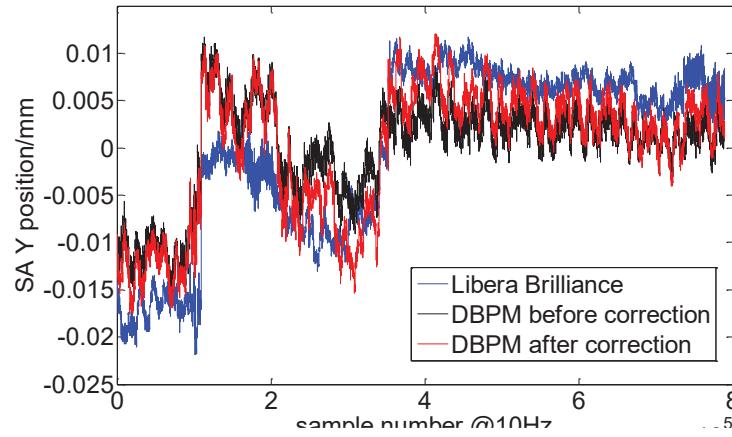
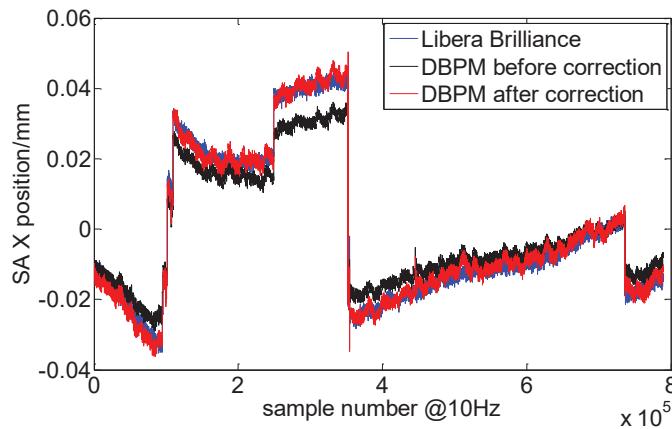
$$P = \text{POLYFIT}(X, Y, N), N=3$$

X: SA channel read out

Y: current, mA

$$Y = P(1)*X^3 + P(2)*X^2 + P(3)*X + P(4)$$

SSRF Beam Test—Correction

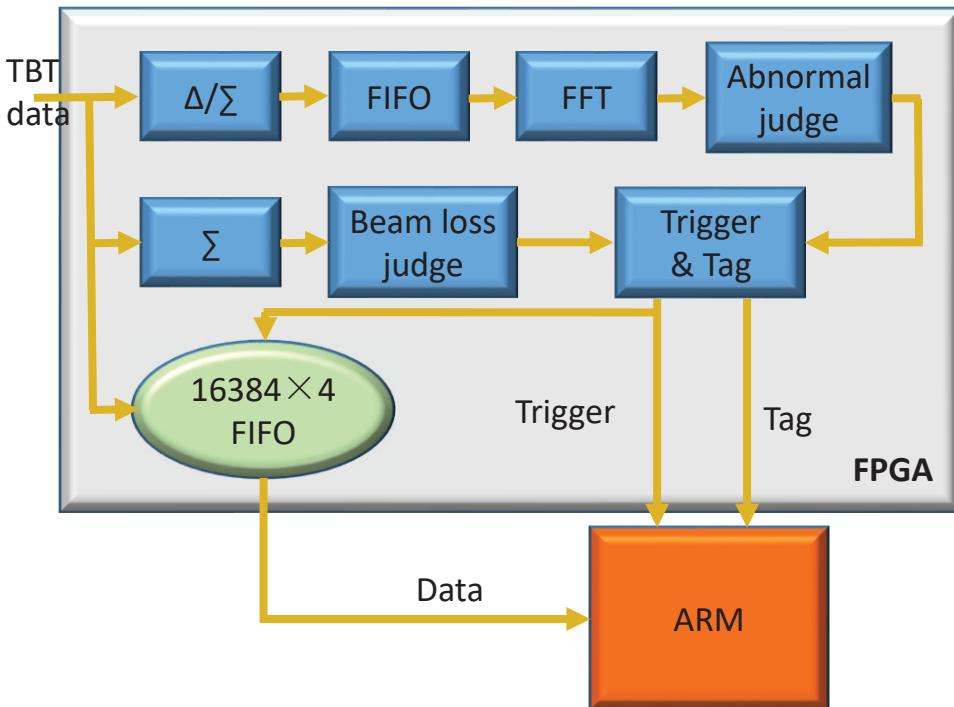


X fits well after correction.

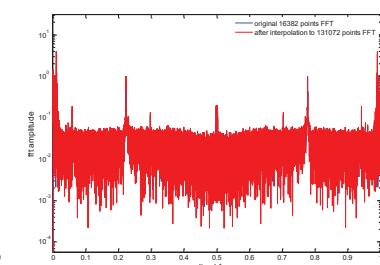
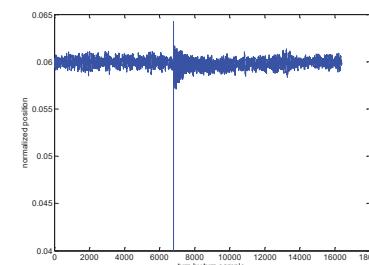
Y not very good.

Correction effect is obvious during injection.

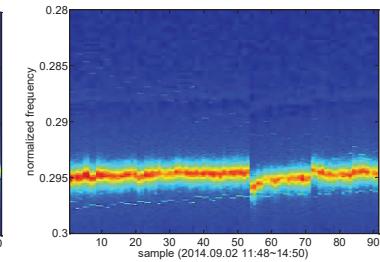
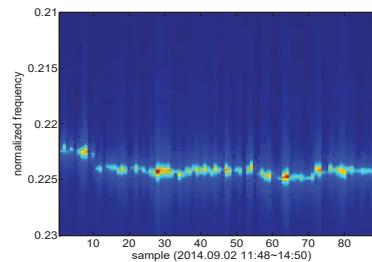
SSRF Operation Monitor



Monitoring beam status and capture data when abnormality is detected.
Optimization is ongoing.



TBT data waveform and spectrum during injecting.(Hor.)



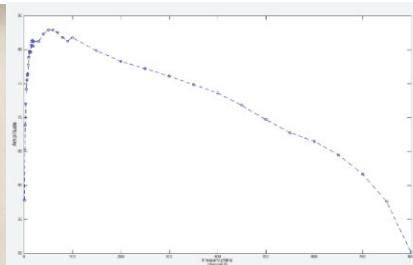
Tune tracking.

L.W. Lai, Y.B. Leng, Y.B. Yan, Z.C. Chen, An Intelligent Trigger Abnormal Beam Operation Monitoring Processor at the SSRF, IPAC2015

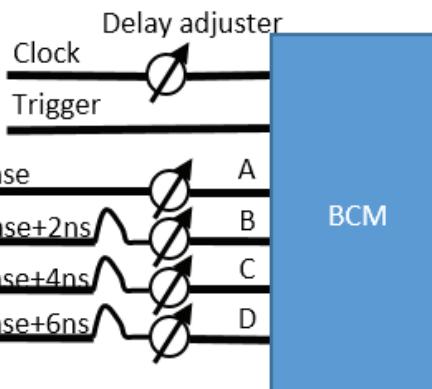


Bunch Charge Monitor

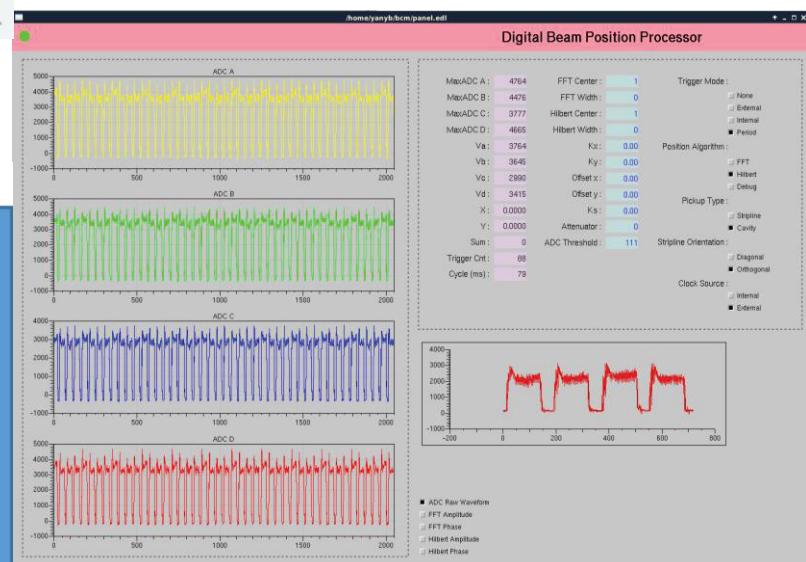
4 ADCs on wideband RF board make bunch-by-bunch charge measurement with interleaved sampling.
Optimization is ongoing.



Wideband ADC board



Interleaved Sampling





Other processors

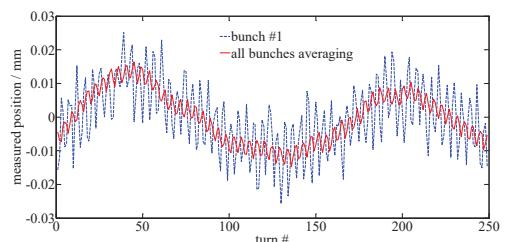
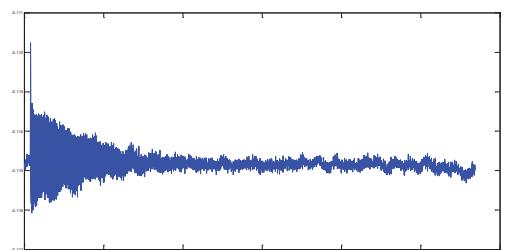
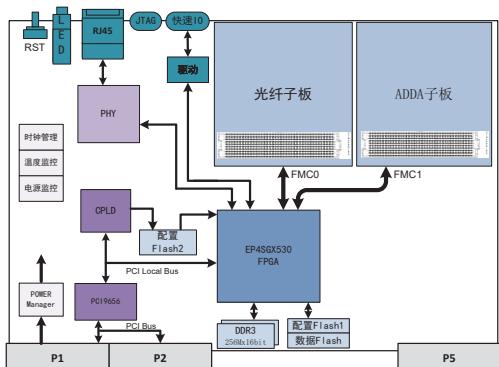
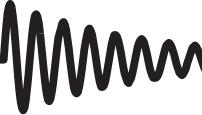
SR Bunch-by-bunch BPM Processor.

Proton Therapy Accelerator BPM Processor.

Transverse Feedback Processor.

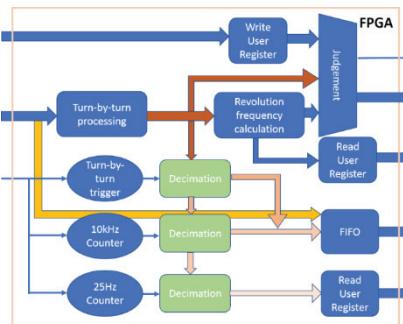
Hard X-ray FEL General Processor.

BxB DBPM & PT Acc. BPM Processor

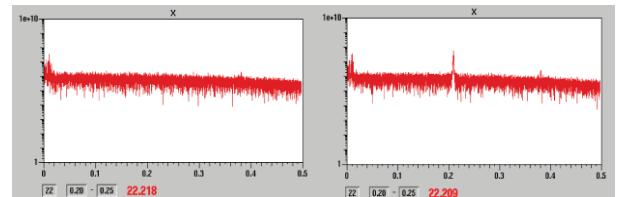
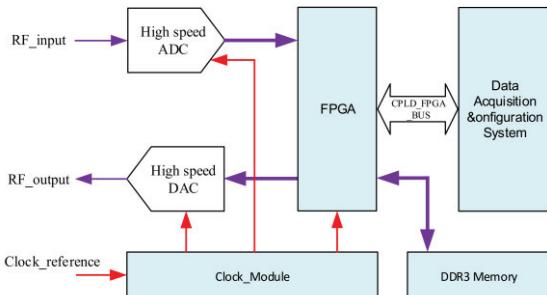


500M bunch-by-bunch
BPM processor

SP Device PXI board.

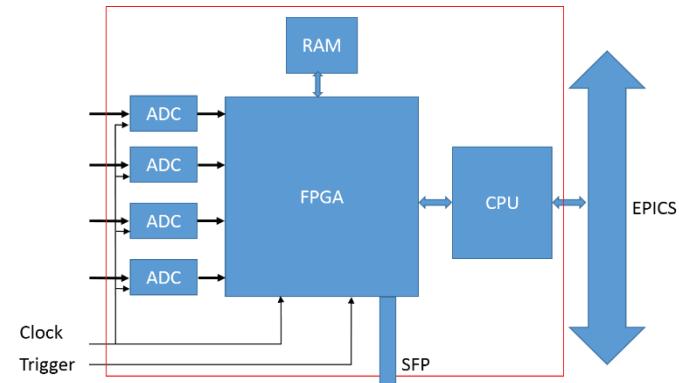
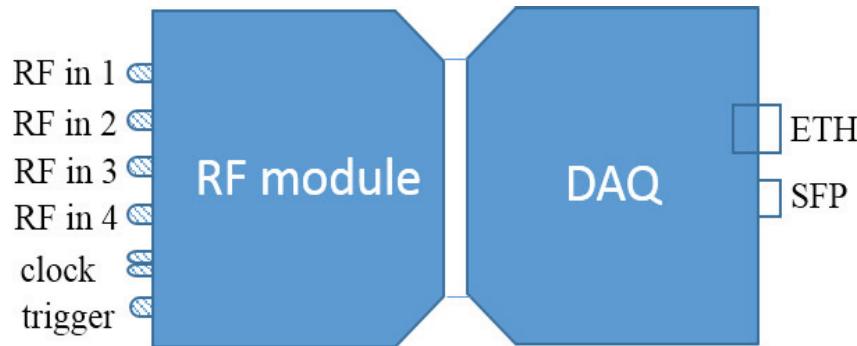


BPM Processor on
Proton Therapy
Accelerator.
On-line.



Bunch-by-bunch
transverse feedback
processor.
Tested on SSRF.

Shanghai Hard X-ray FEL General Processor



Support 1MHz bunch rate.

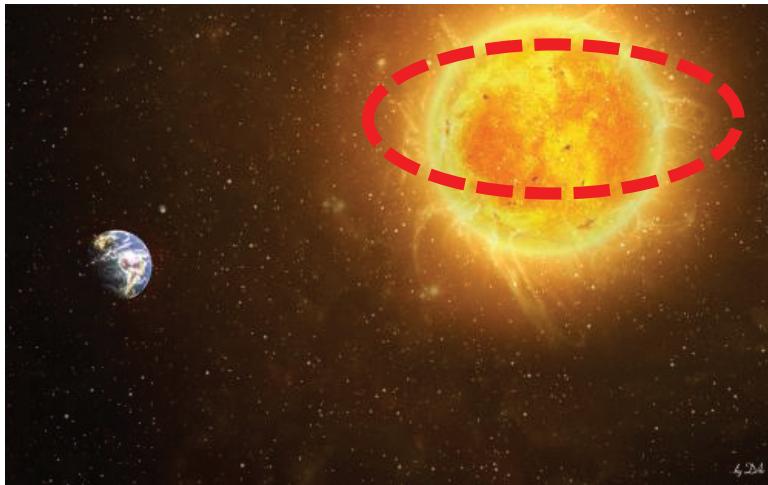
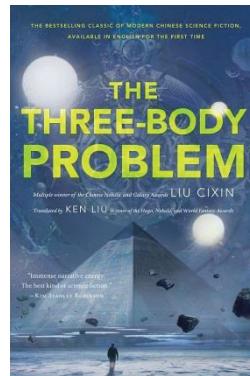
- Narrow band RF(EGU-FRE500W)
- Wide band RF(EGU-FRE500B)
- **500MHz** DAQ(EGU-DAQ500)
- WhiteRabbit Timing Board

Applications

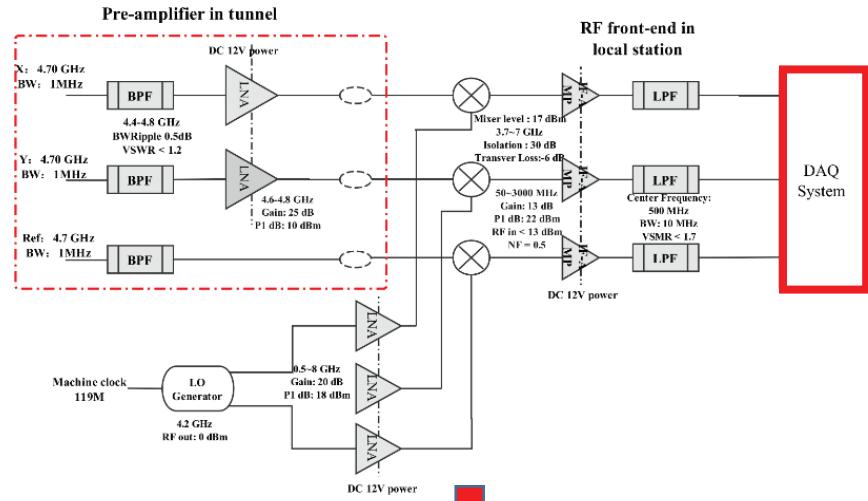
- BPM
- Profile(wire scanner)
- Beam loss
- Bunch charge
- Beam arrival time



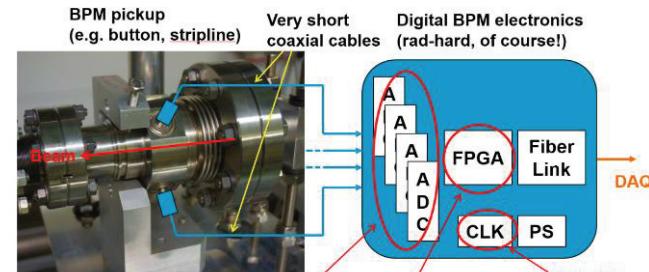
“Future” DAQ



“Future” Accelerator around the Sun.



The Ideal BPM Read-out Electronics!?



- Time multiplexing of the BPM electrode signals:
 - Interleaving BPM electrode signals by different cable delays
 - Requires only a single read-out channel!

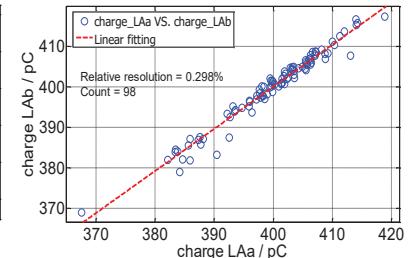
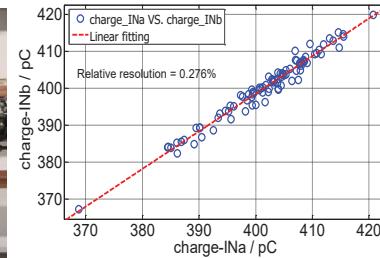
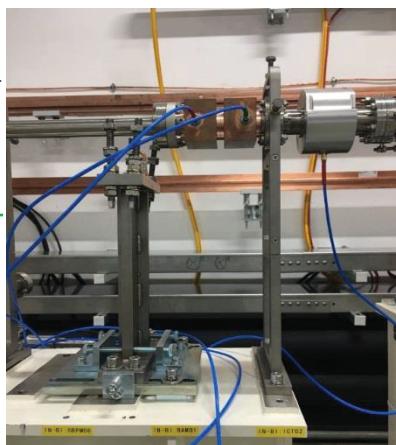
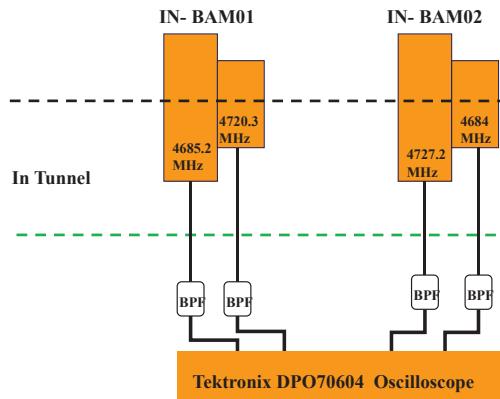
September 17, 2014 – IBIC 2014 – M. Wondt

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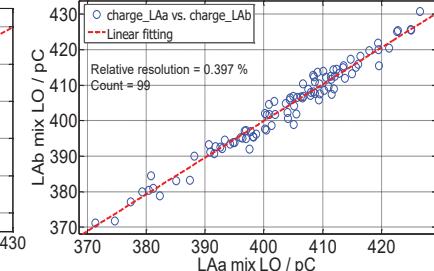
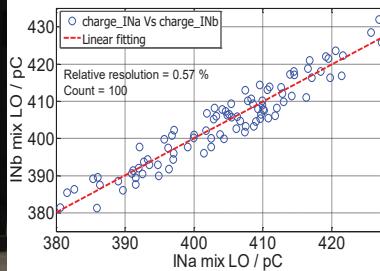
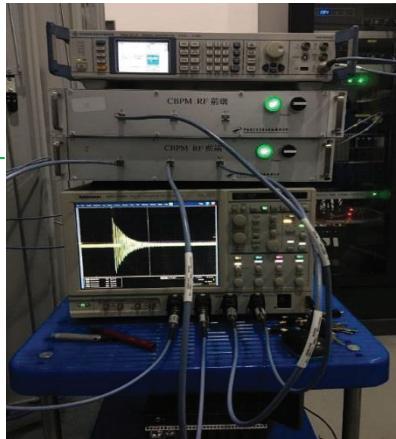
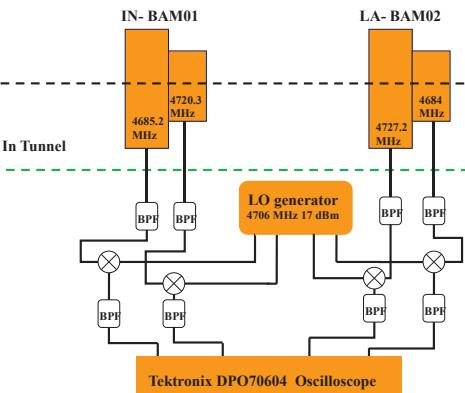
Courtesy of Hermann Schmickler, CERN, IBIC 2015

Longwei Lai, BI, SSRF

RF-Sampling tests



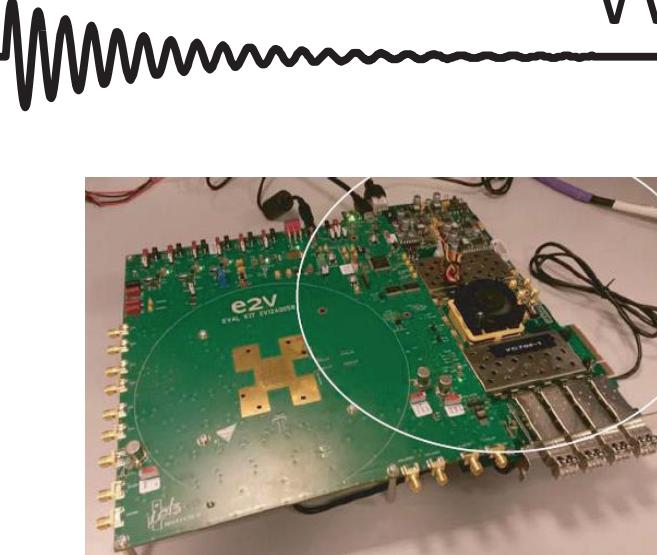
Relative RMS 0.27%, 0.29%



Relative RMS 0.57%, 0.40%

SXFEL BAM tests with 6G bandwidth Oscilloscope

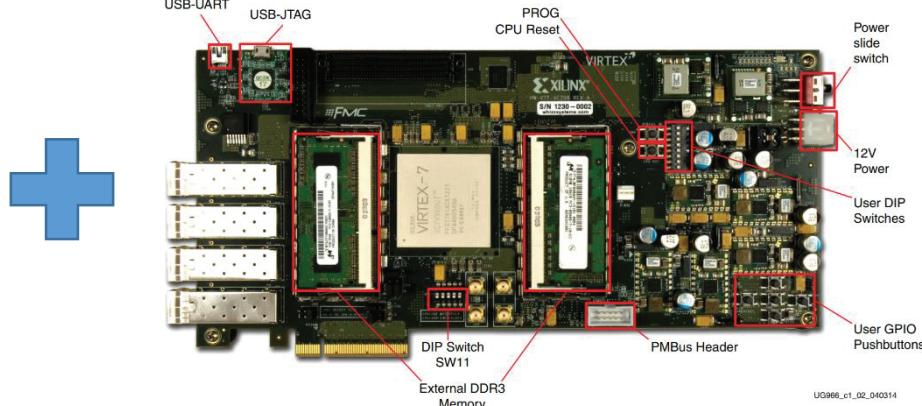
We are on the way.



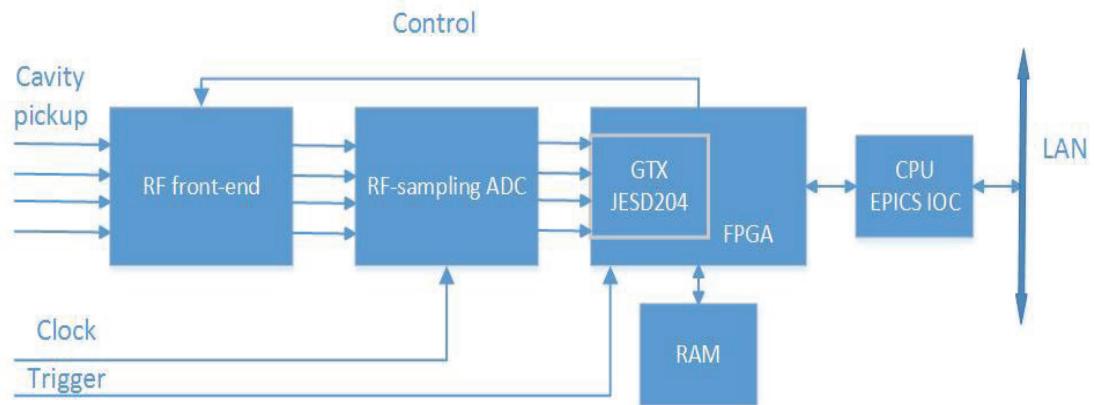
E2V EV12AD500A
Dual 12-bit ADC
Bandwidth up to 5.2GHz,
1.5GHz sampling rate

Texas Instruments ADC12DJ2700

Input bandwidth 8GHz
5.4GSPS in single channel /
2.7GSPS in double channel
12-Bits
ENOB: ~8.5@fin=4.7GHz

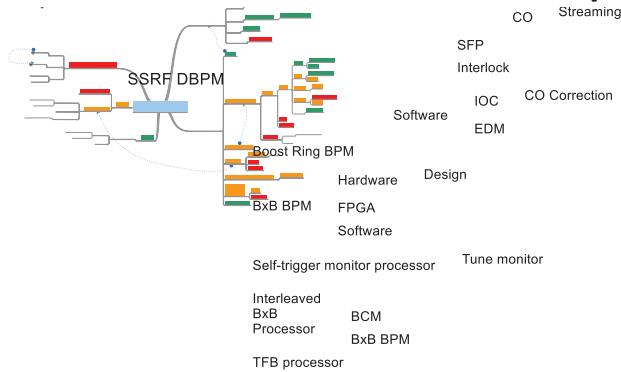


XILINX VC709, FMC connector
Virtex-7 XC7VX690T FPGA
2× 4GB DDR3 memory, 8-lane
PCIE



Summary

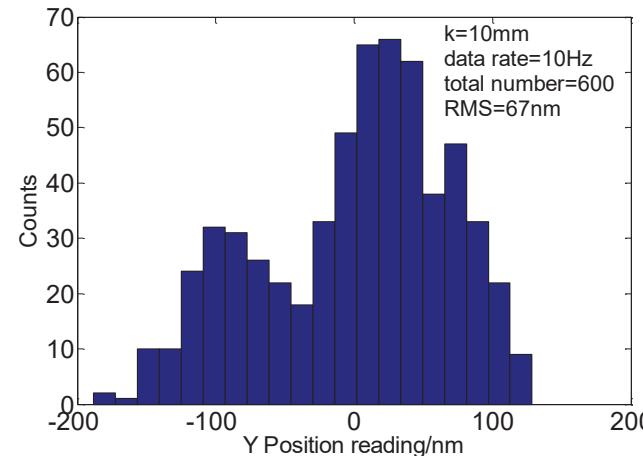
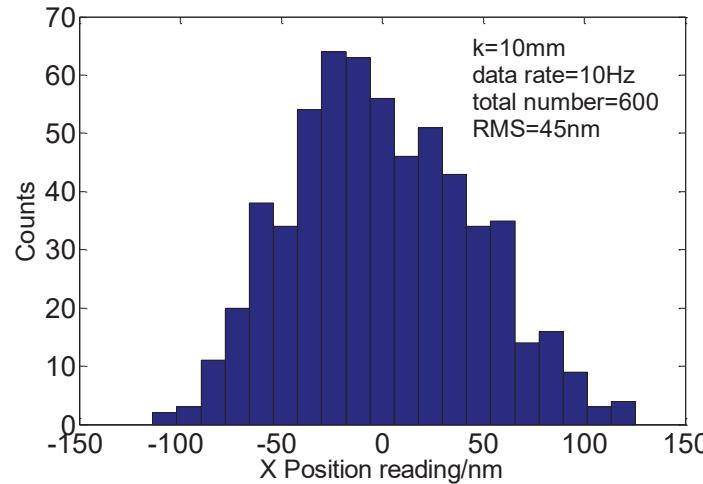
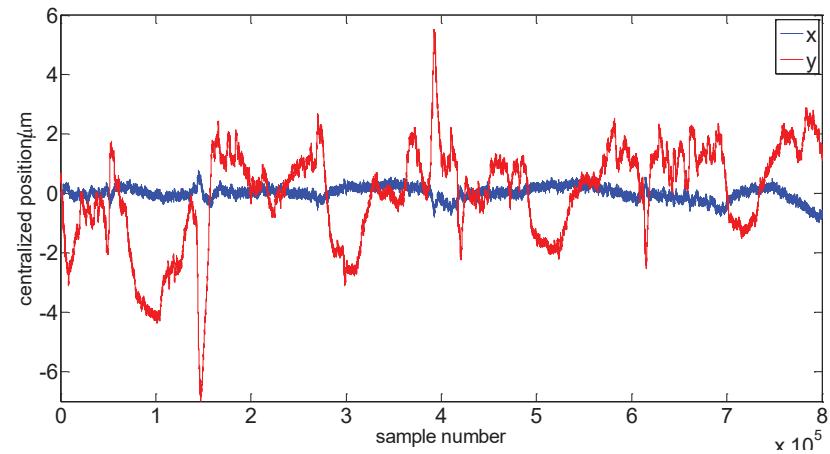
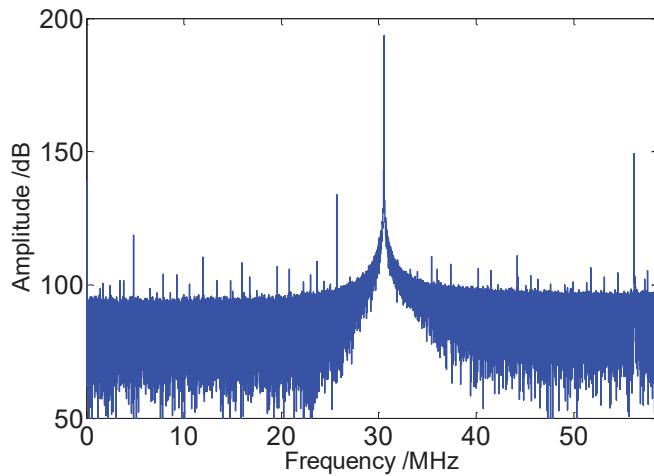
- Mass application on SXFEL&DCLS, 100Hz rate capability, SBPM RMS 2.7μm, CBPM RMS 0.54 μm@500pC.
- On-line tests on SSRF, **TBT RMS 0.34 μm**.
- Several processors have been developed, higher performance processors are under developing.





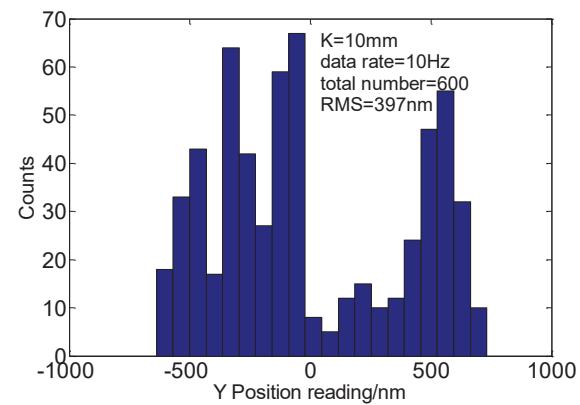
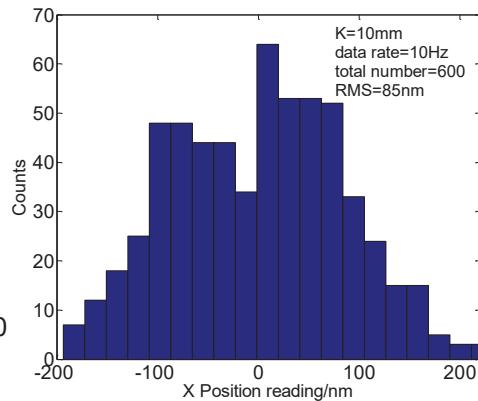
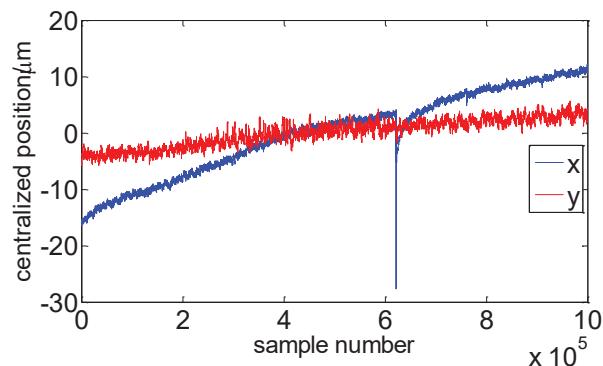
Thanks for your attention

DBPM RF SA Tests

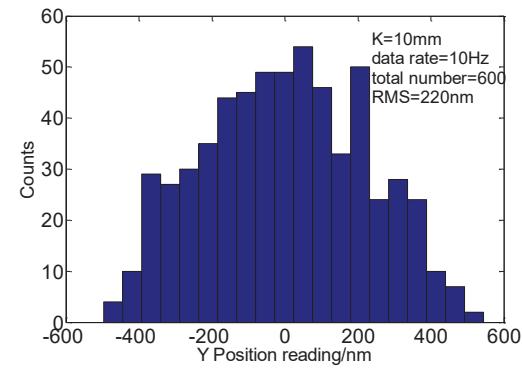
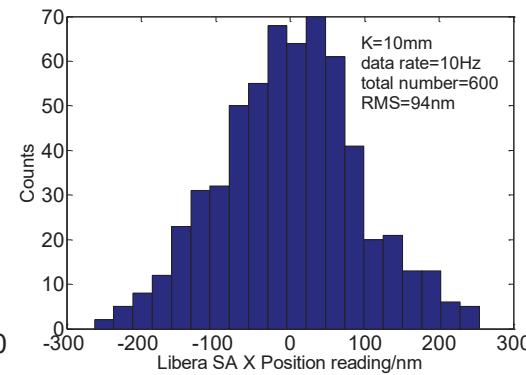
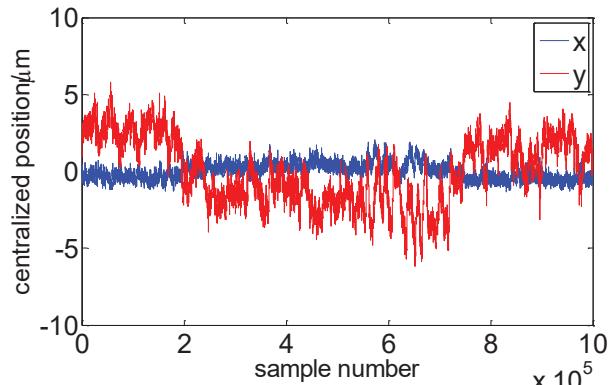




DBPM



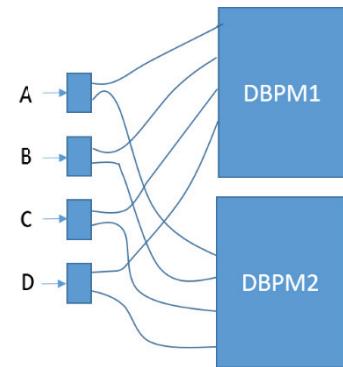
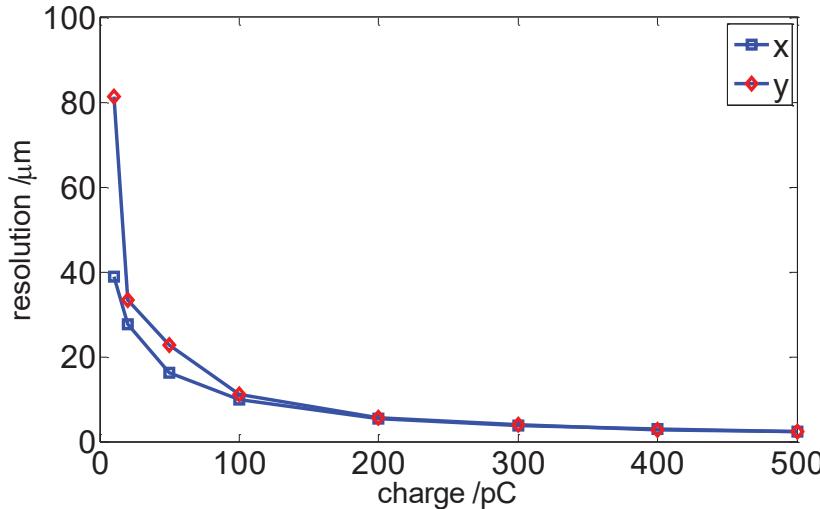
Libera Brilliance



Performance Tests On DCLS

Stripline BPM

- 500pC [2.39, 2.27]
- 400pC[2.92,2.83]
- 300pC[3.77,3.93]
- 200pC[5.47,5.63]
- 100pC[9.91,11.08]
- 50pC[16.19,22.69]
- 20pC[27.69,33.31]
- 10pC[38.79,81.33]



Cavity BPM

- 500PC[1.99 0.54]
- 400PC[2.31 0.57]
- 300PC[2.94 0.84]
- 200PC[4.31 1.20]
- 100pC[7.34 2.16]
- 50pC[12.77 4.20]
- 20pC[28.30 8.32]
- 10pC[49.10 14.42]

