MOAO05

Beam Instrumentation System for Shanghai Soft X-ray FEL Test Facility

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Outline

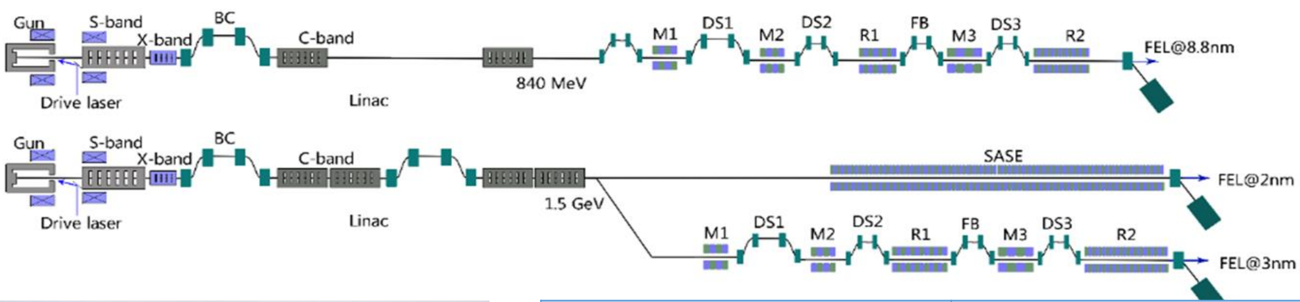
- Shanghai Soft X-ray FEL Facility (SXFEL) introduction
- Beam diagnostic system for SXFEL-TF
  - System Overview
  - Bunch charge measurement
  - Transvers measurement
    - Beam profile measurement
    - Stripline BPM system(SBPM)
    - Cavity BPM system(CBPM)
  - Longitudinal measurement
    - Beam arrival time(BAM), time-of-flight(TOF)
    - CSR bunch length measurement(BLM)
    - Deflector cavity
- Summary

SXFEL：Shanghai Soft X-ray FEL Facility

- **SXFEL Facility** consists of two projects independently funded, SXFEL test facility (SXFEL-TF) + SXFEL user facility (SXFEL-UF), located at the SSRF campus;
- **SXFEL-TF** was initiated in 2006 and founded in 2014, its 0.84GeV linac and undulators was installed through 2016 to 2018, it is for testing the cascaded seeding schemes; passed formal acceptance in this year.
- **SXFEL-UF** was founded to upgrade the linac energy to 1.5 GeV for driving 2 undulator lines (SASE+HGHG/EEHG) with 5 experimental stations in the water window region.

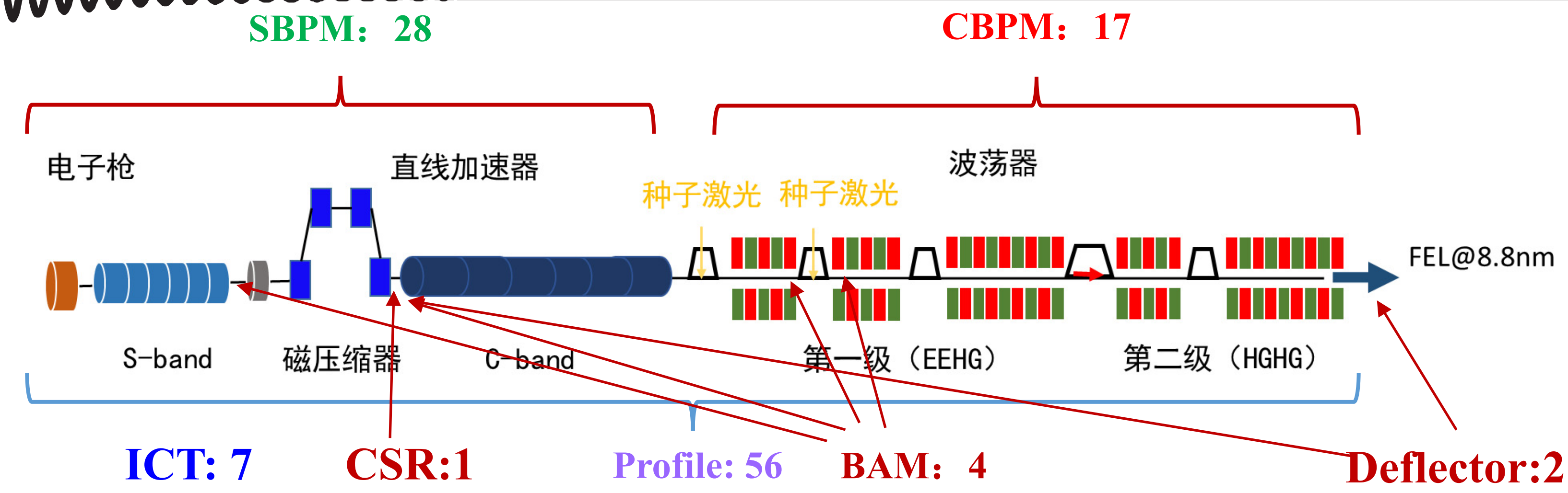
SXFEL-TF

SXFEL-UF



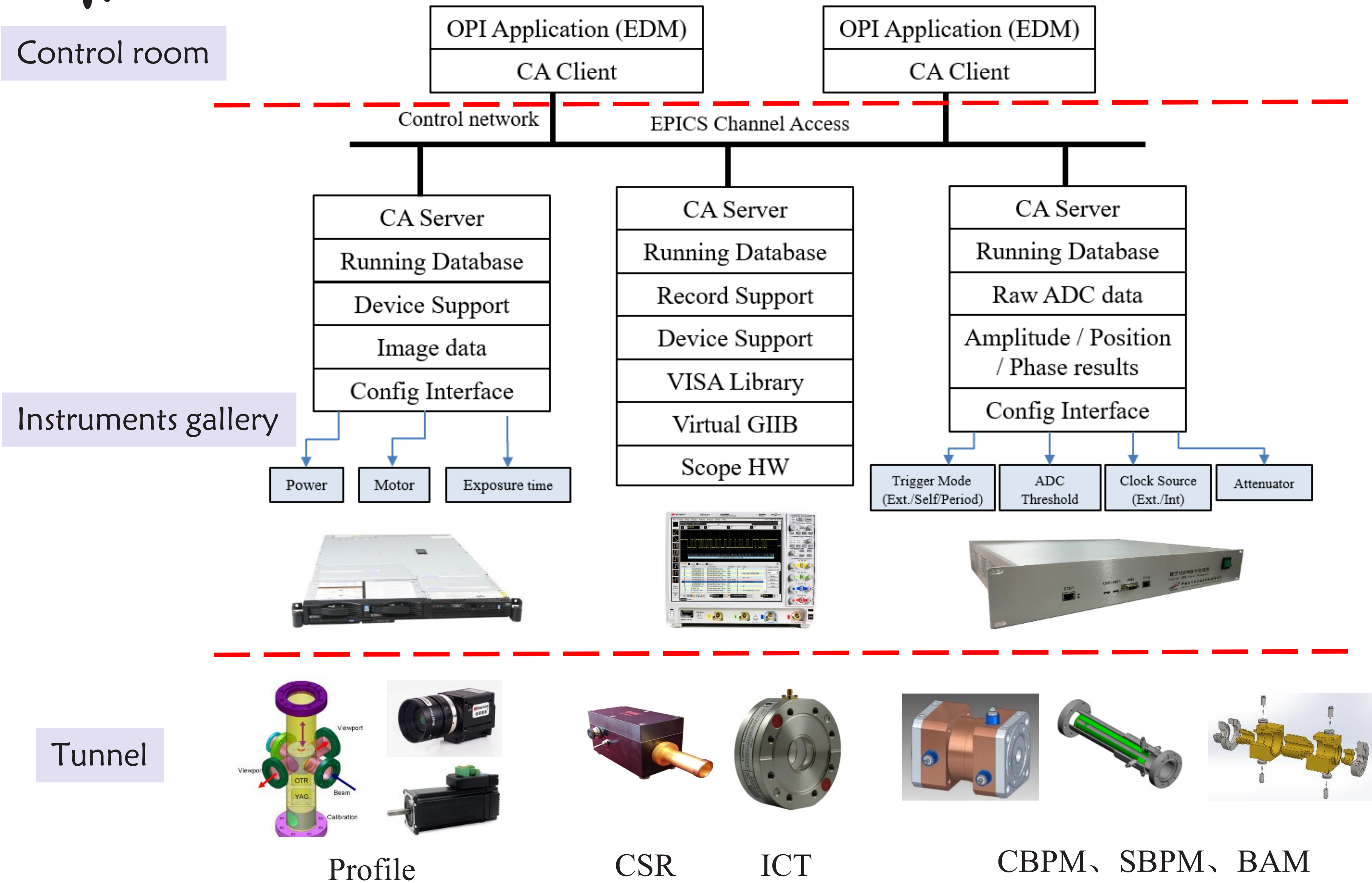
Total length	293-532m
Photon energy	0.2 – 0.6 keV
Pulse length	>10 fs
Repetition rate	10 - 50 Hz
Peak photon power	1 GW
Electron energy	0.8 - 1.5 GeV

Beam Instrumentation system for SXFEL-TF



	Sensors	Electrics	DAQ/control	Number	Resolution
Beam Profile	YAG / OTR	CCD / Motor	TCP / IP	56	< 20μm@0.5nC
Bunch Charge	ICT	Oscilloscope	Windows embedded IOC	7	< 1%@0.5nC
Beam position	SBPM	DBPM	Linux embedded IOC	28	< 10μm@0.5nC
Beam position	CBPM	DBPM	Linux embedded IOC	17	< 1μm@0.5nC (DR: ±0.5 mm)
BAM, TOF	Dual cavity	DBPM	Linux embedded IOC	4	< 100 fs@0.5nC
Bunch length	CSR	NI PXI-5122	Linux embedded IOC	1	<100fs@0.5nC
	Deflection cavity	CCD / Motor	TCP / IP	2	<100fs@0.5nC

DAQ structure

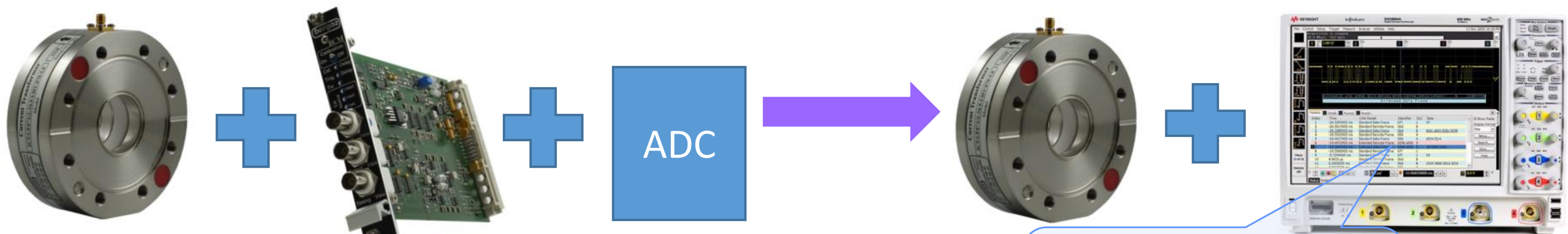


Bunch charge measurement

Bunch charge measurement system

- Traditional solution
- SXFEL solution

Embedded Soft-IOC



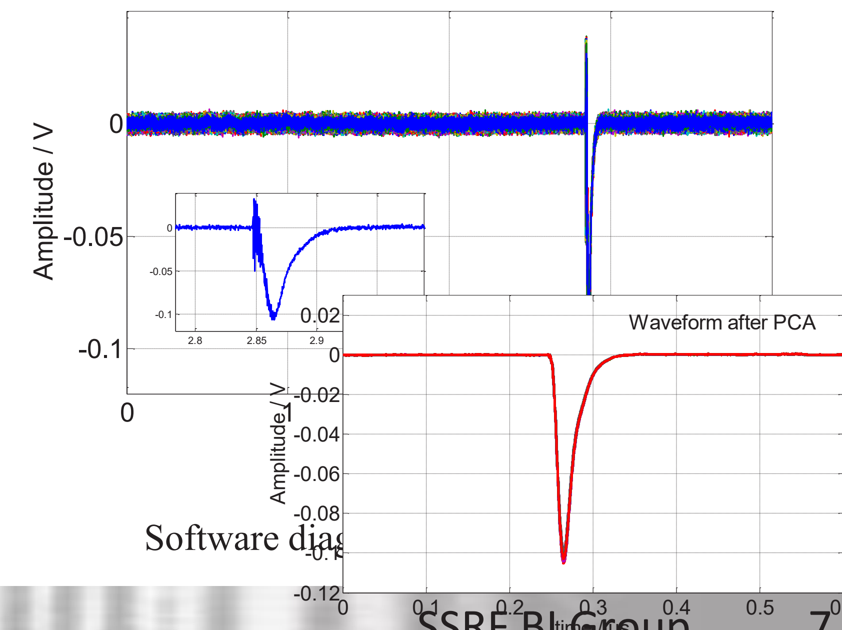
Bergoz ICT

BCM-IHR-E

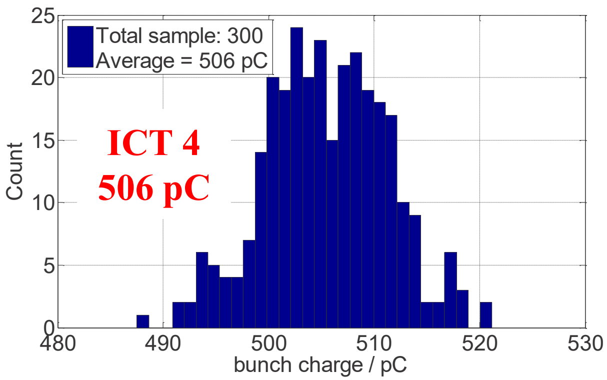
- Bandwidth: 600MHz
- Sampling rate: 5GSA/S
- Resolution: 10 bit

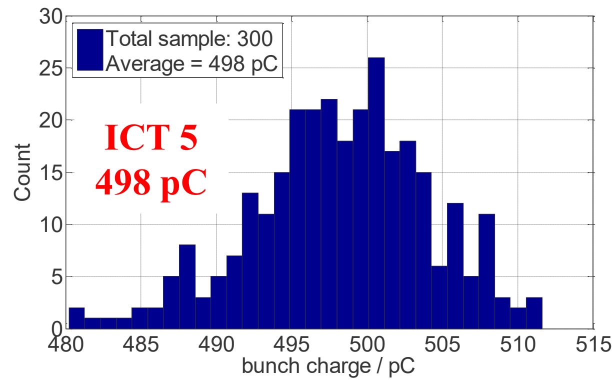
Advantages:

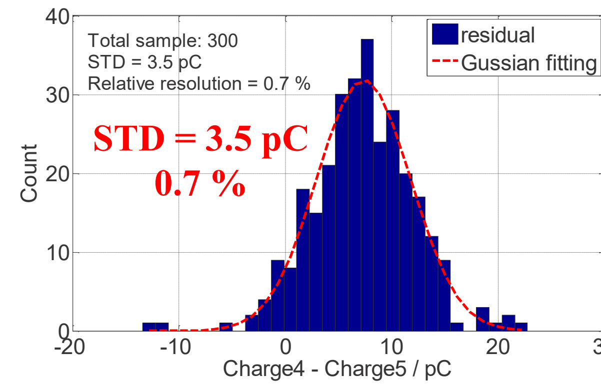
- avoiding noise interference into analog electronics
- flexible digital signal processing algorithms(PCA) to improve performance



On-line performance evaluation

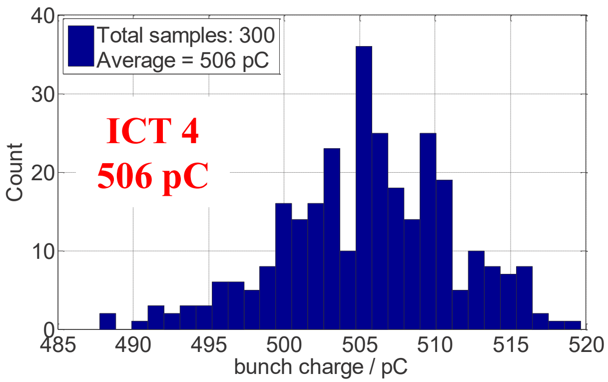


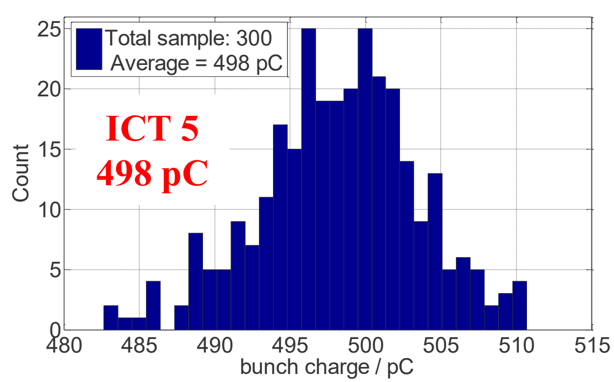


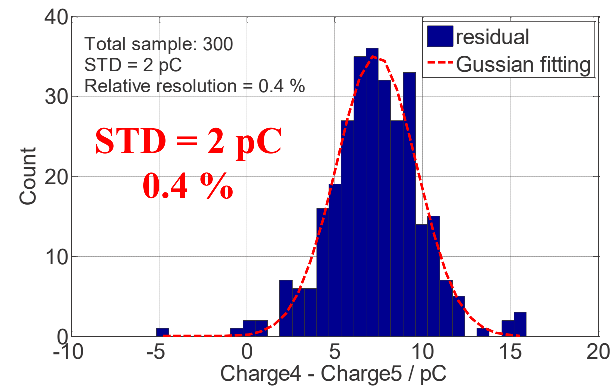


Direct integration:

- Relative resolution = 0.7 %
- Transfer efficient from LINAC to Undulator about: 498 / 506 = 98.5 %







PCA before integration:

- Relative resolution = 0.4 %
- Transfer efficient from LINAC to Undulator about: 498 / 506 = 98.5 %

More info. pls. refer to talk “Precise Bunch Charge Measurement Using BPM Pickup” by Dr. Jian Chen on Tuesday.

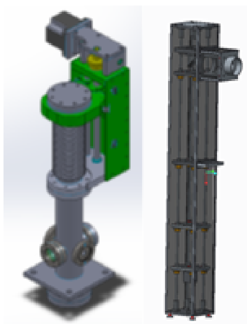
Transverse measurement

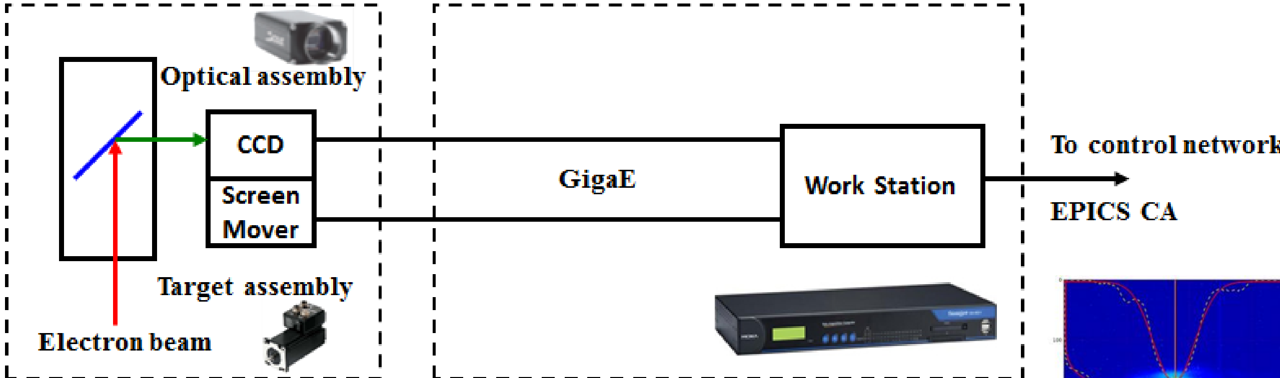
- Beam profile measurement
- Stripline BPM system(SBPM)
- Cavity BPM system(CBPM)

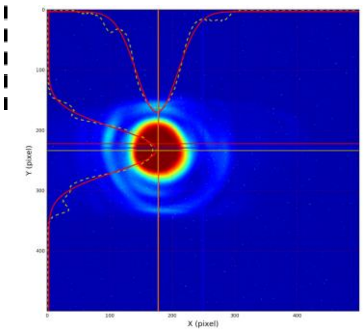
Beam Profile Measurement System

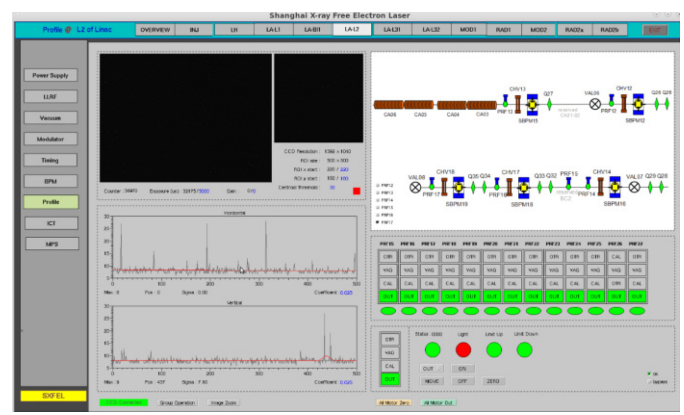
In tunnel

In Diagnostics station



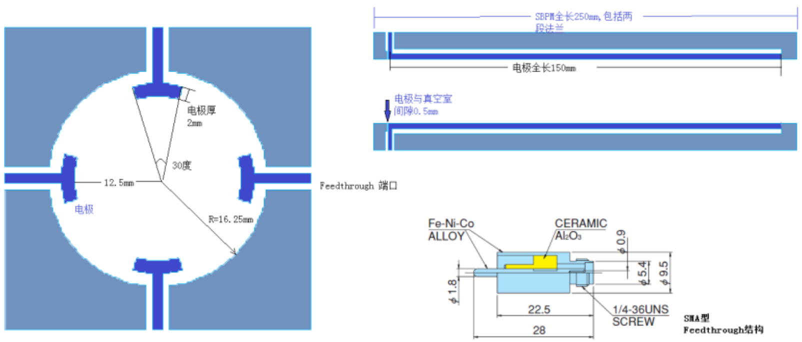


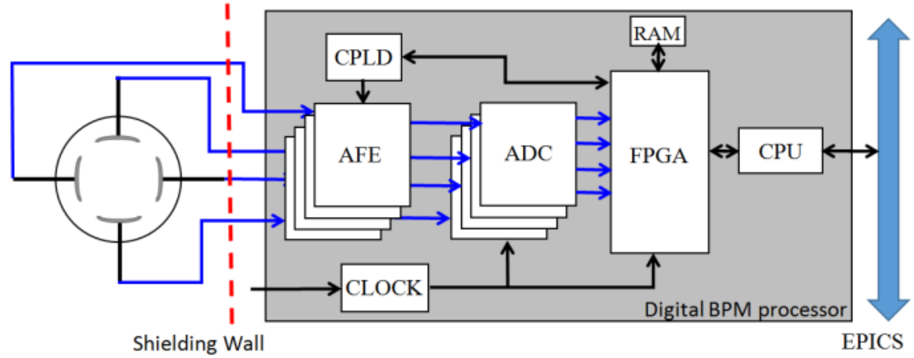




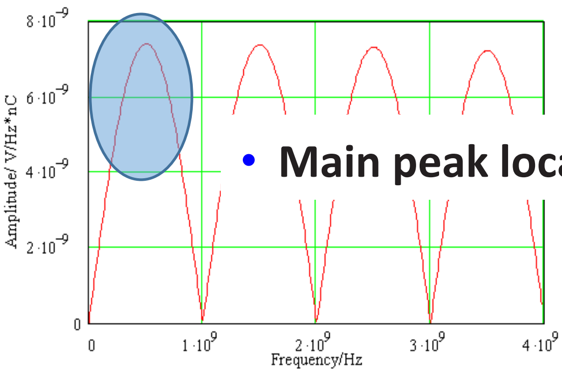
- **CCD and motors are controlled via TCP/IP protocol.**
- **Horizontal and vertical RMS resolution is13μm@41μm, 15μm@50μm respectively.**
- **One of the most useful instrumentations during commissioning**

Stripline BPM System





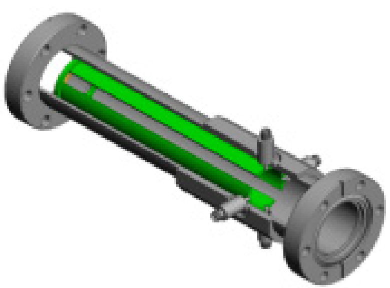
Stripline BPM pickup

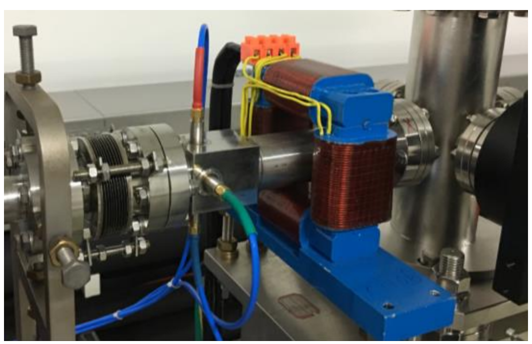


- **Main peak locates at 500MHz**

DBPM

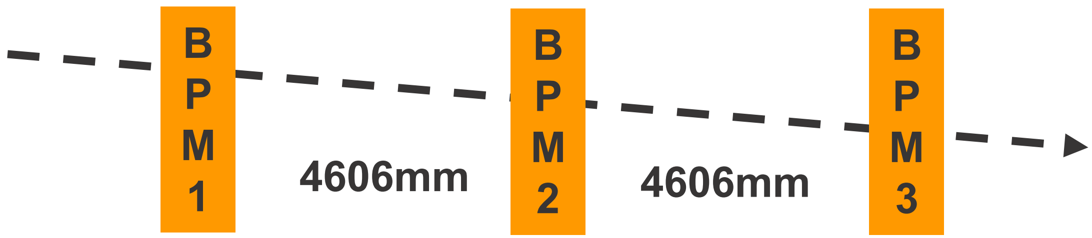
Parameters	value
Channels	4
Central Frequency	500MHz
Bandwidth	~20MHz
Dynamic range	31dB
ADC bits	16
Max ADC rate	125MSPS
FPGA	Xilinx xc5vsx50t
Clock	Ext./Int.
Trigger	Ext./Self/Period
Software	Arm-Linux/EPICS





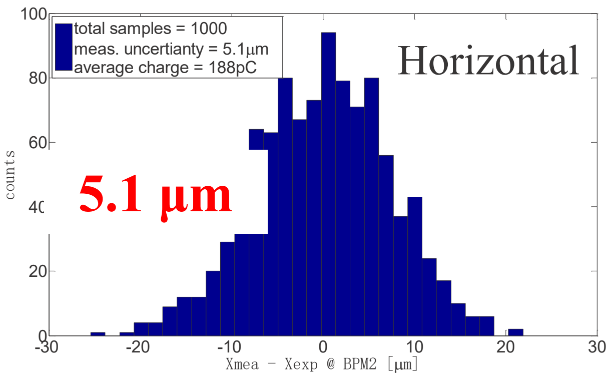
SBPM Performance Evaluation

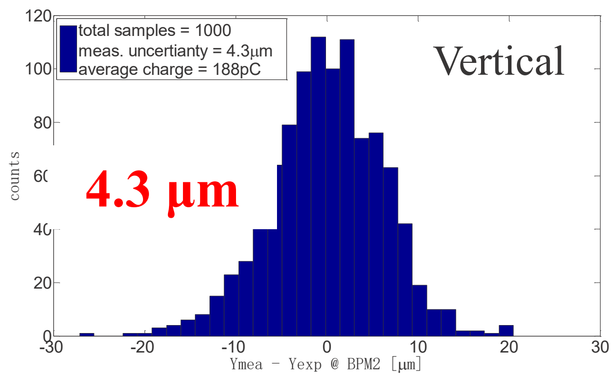
Linac drift section



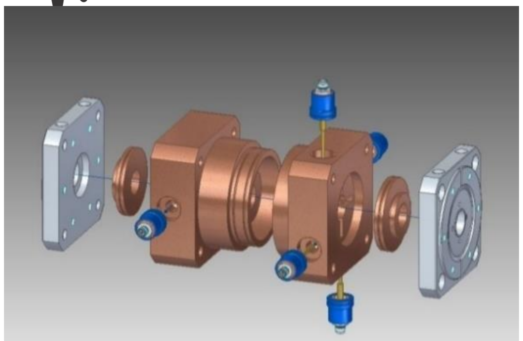
BPM2’ = （BPM1 + BPM3）/ 2
Resolution = std(BPM2-BPM2’) / sqrt(2)

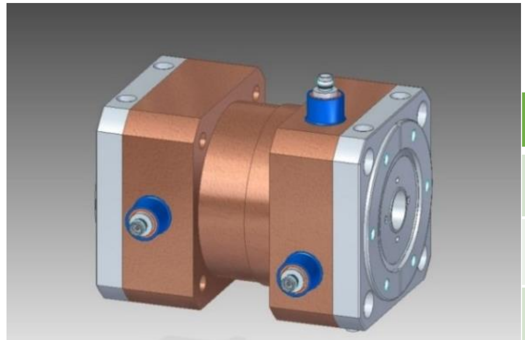
- Average beam charge: 188pC
- K = 5.24



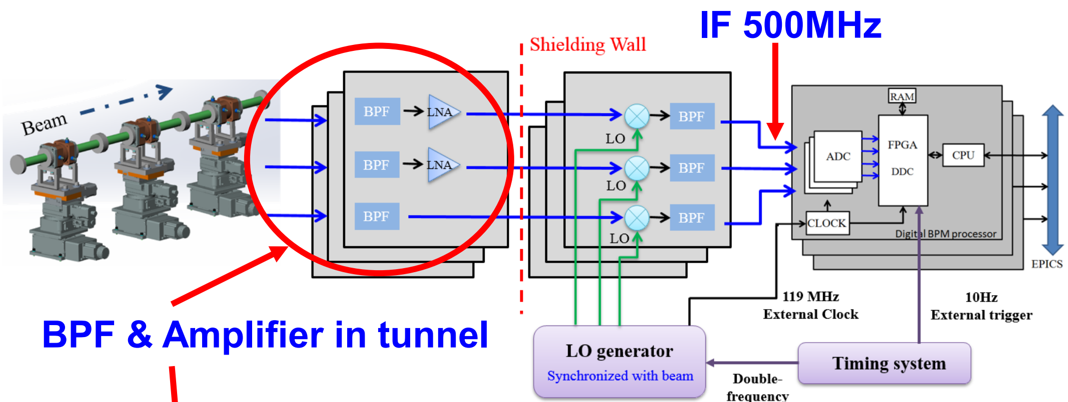


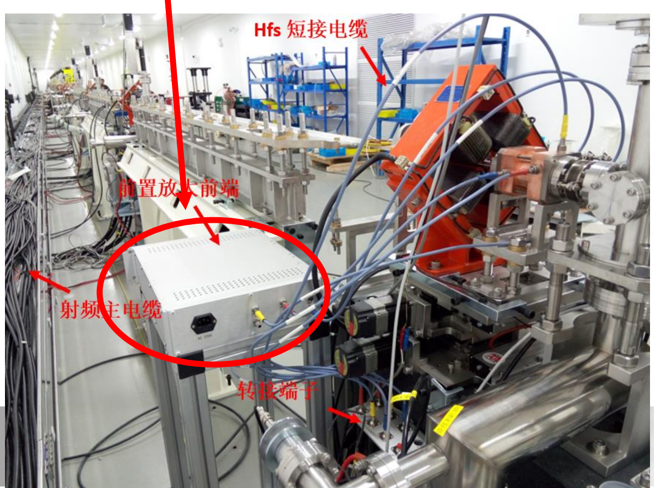
Cavity BPM System





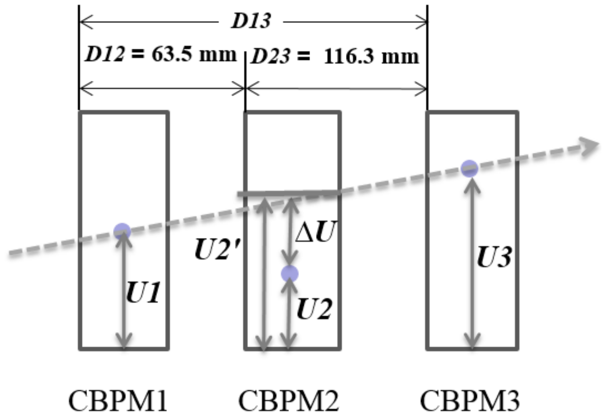
	Frequency	Q Value
Reference cavity	4693 ± 3MHz	2250 +-10%
Horizontal	4681 ±3MHz	4500 +-10%
Vertical	4688 ± 3MHz	4500 +-10%

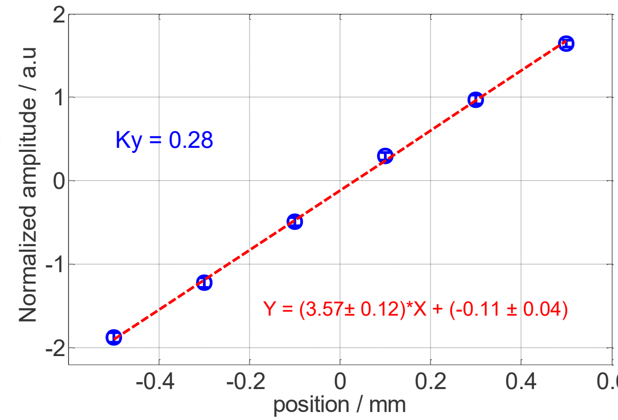


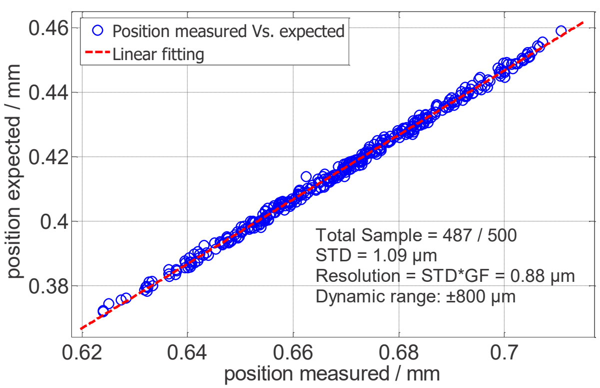


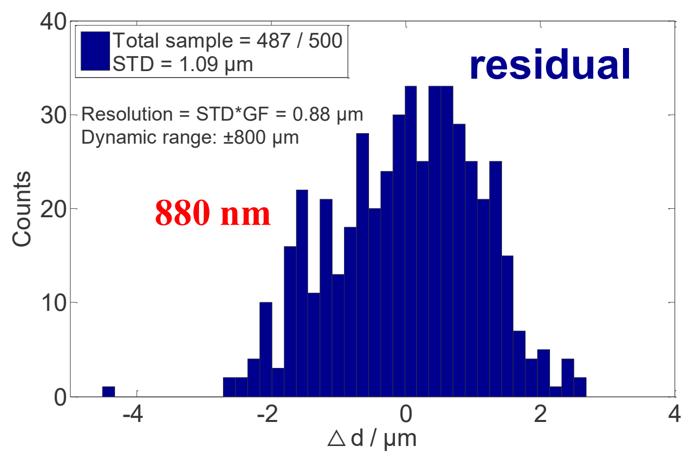
CBPM performance evaluation

- BPM2 Expt.: $U_2' = \dfrac{D_{12} \cdot U_3 + D_{23} \cdot U_1}{D_{13}}$
- Residual: $\delta_{CBPM} = GF \cdot std_{\Delta d}$
- GF: $GF = \dfrac{1}{\sqrt{(\frac{D_{23}}{D_{13}})^2 + (\frac{D_{12}}{D_{13}})^2 + 1}}$



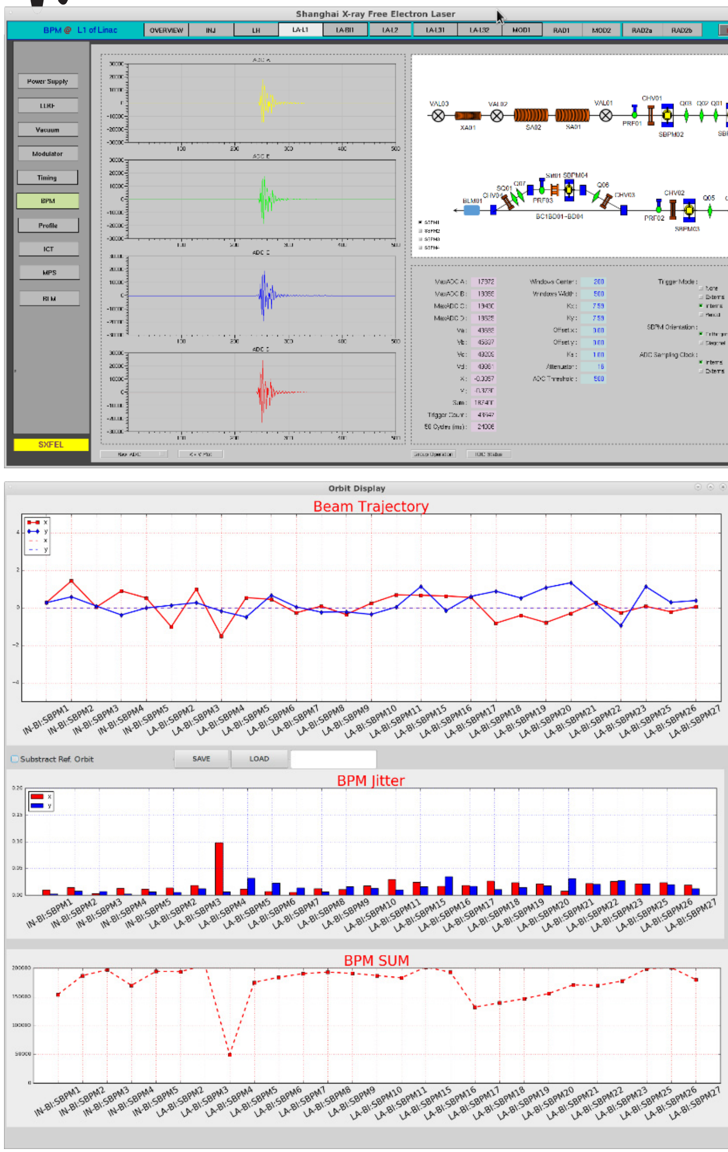




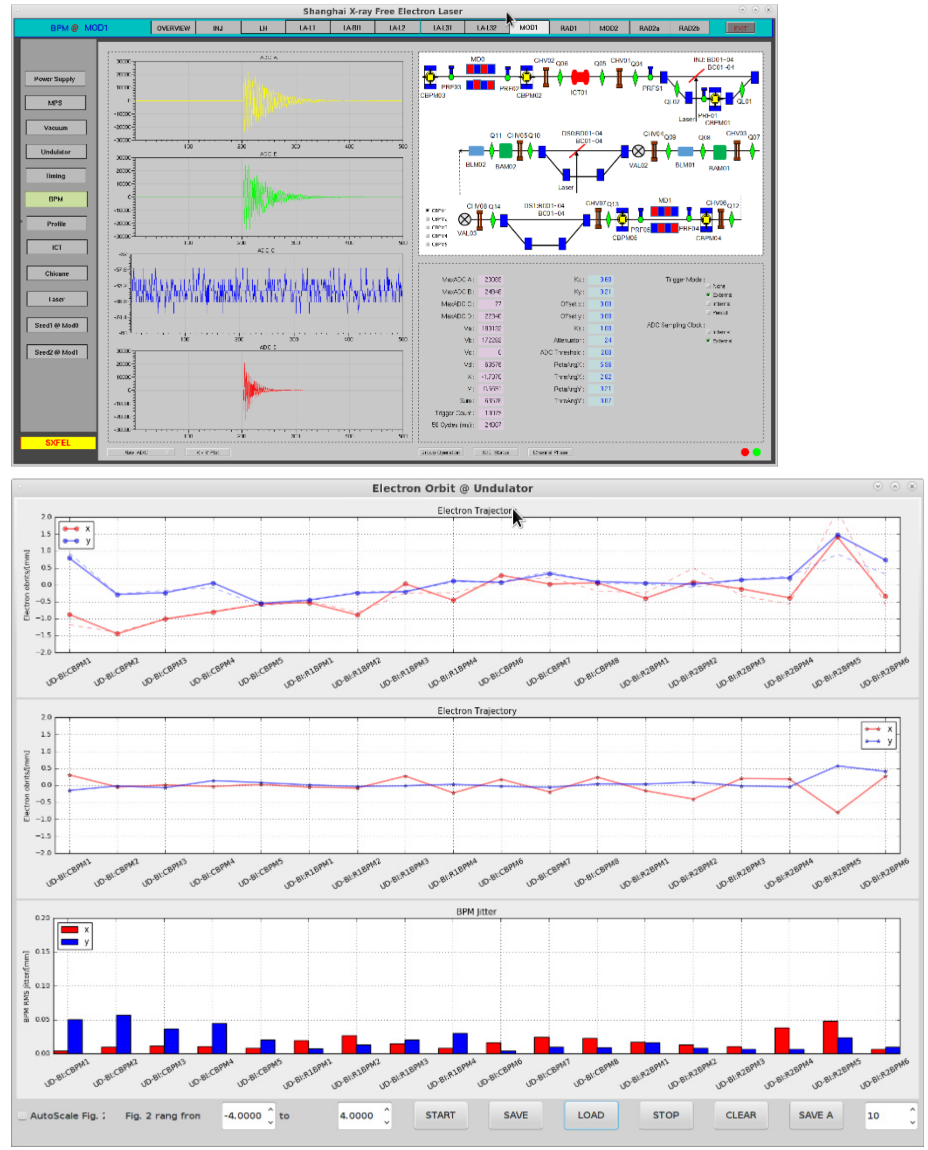


880 nm @ 500pC, ±800μm

BPM OPI Panel



SBPM

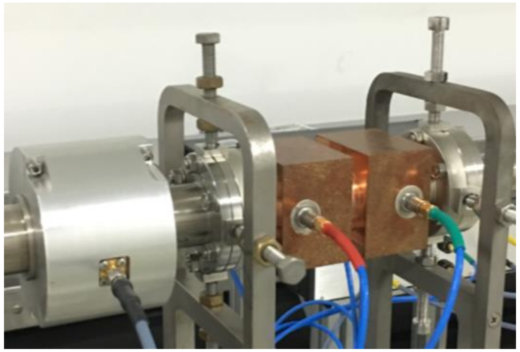


CBPM

Longitudinal measurement

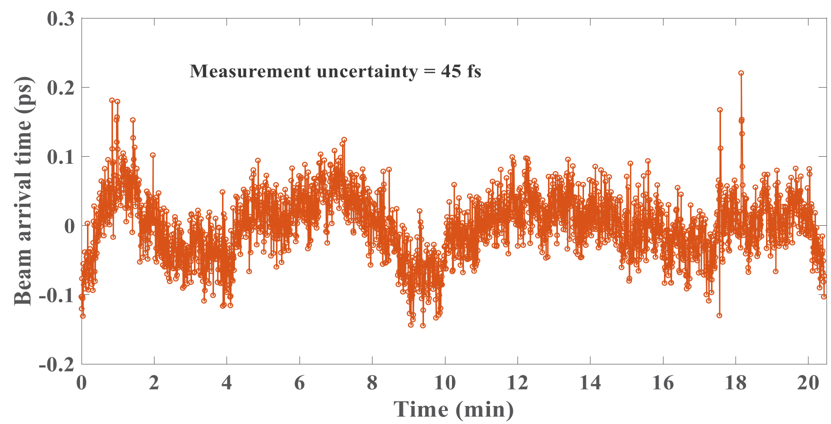
- Beam arrival time(BAM), time-of-flight(TOF)
- CSR BLM
- Deflector cavity

Beam Arrival Time Measurement System



Dual-cavity BAM pickup

Parameters	Cavity #1	Cavity #2
Frequency/MHz	4685	4720
Bandwidth/MHz	1	1
Decay time/ns	318	318
Q_{load}	4671	4716

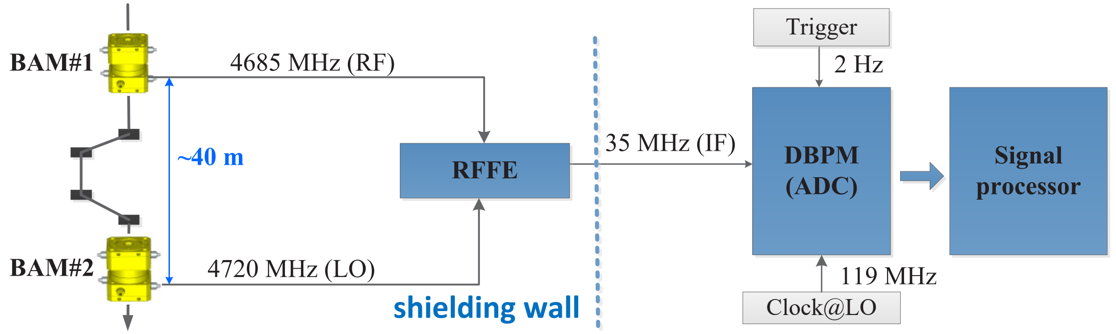


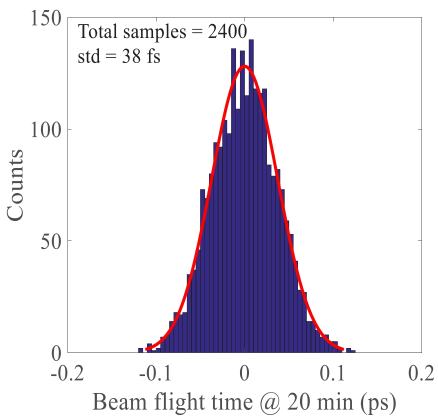
LO mixing down conversion

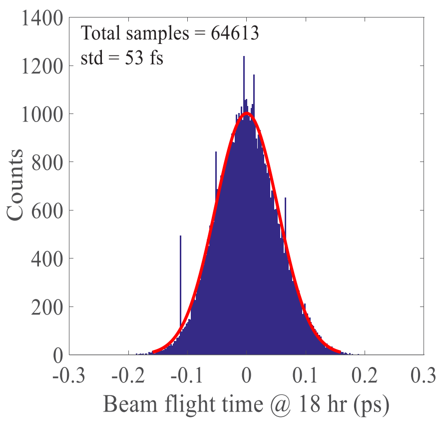
Best uncertainty (RMS) : 45 fs over 20 min;

More info. pls. refer to paper "BEAM ARRIVAL TIME MEASUREMENT AT SXFEL" by Dr. S.S.Cao in IBIC2017.

Time-Of-Flight measurement system







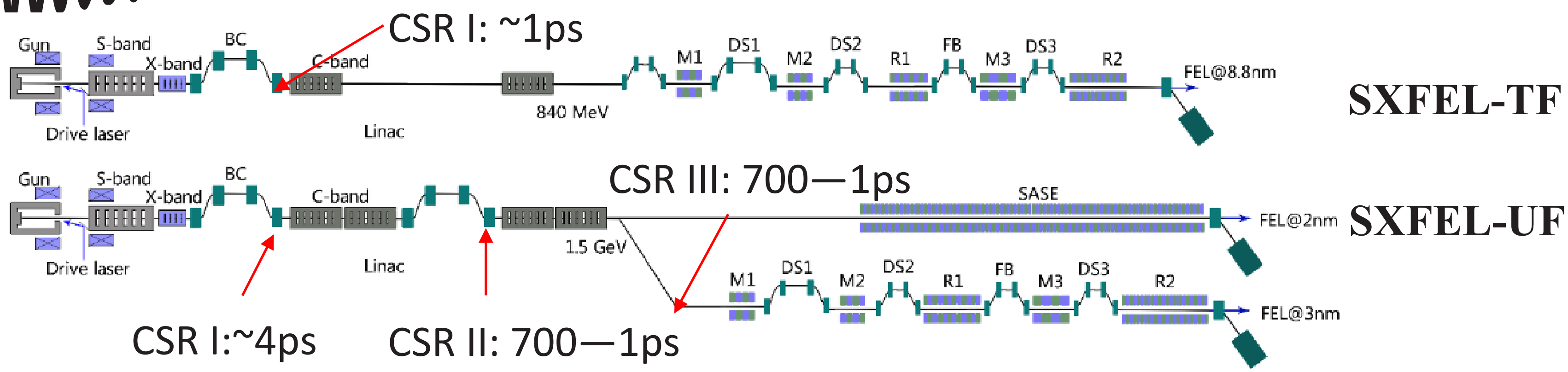
- **Best result of measurement uncertainty (RMS) in short-term: 38 fs over 20 min;**
- **Best result of measurement uncertainty (RMS) in long-term: 53 fs over 18 hours;**
- **Beam jitter, temperature- and humidity-drift, and vibration contribute to this phase measurement uncertainty;**

Time -> Energy

- $t_{flt} = f(E) = \frac{4R\theta + \frac{2L_1}{\cos\theta} + L_2}{c}, and\ R = \frac{mv}{eB}, \theta = \arcsin\left(\frac{L_0}{R}\right)$

$$\boldsymbol{E = f^{-1}(t_{ref})}$$

CSR Bunch Length Measurement System



- 1 CSR_BLMs on SXFEL-TF, 3 on SXFEL-UF
- Pyroelectric detector used to detect radiation
- BAM used to detect charge change of electron bunches and use this signal to normalize the output of Pyroelectric detector
- TDS used to calibrate the system

measurement uncertainty
30 fs@1ps bunch length

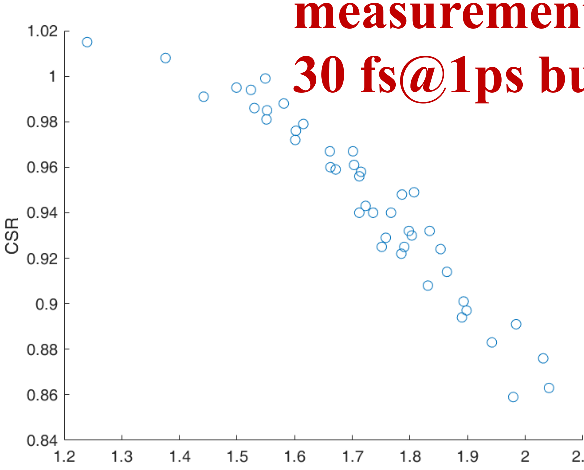
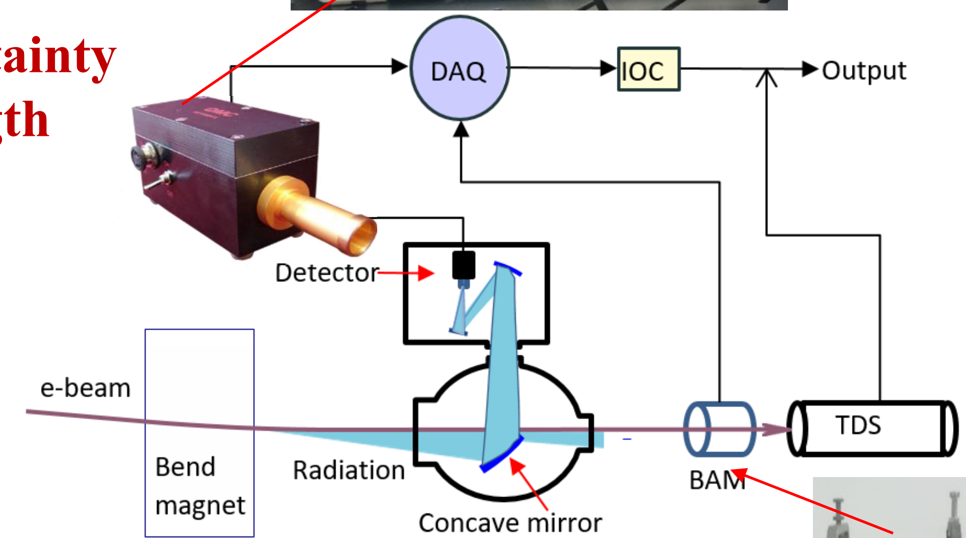


Figure1. Calibration results of TDS and normalized CSR



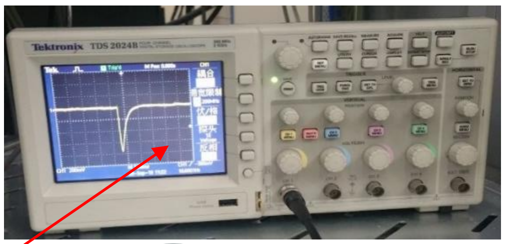
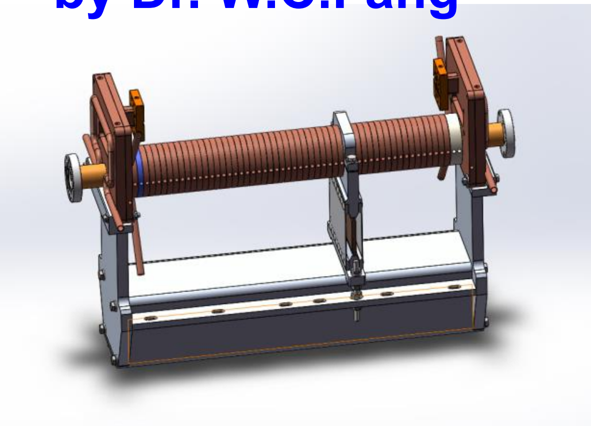


Figure 2. Layout of CSR_BLM used in SXFEL

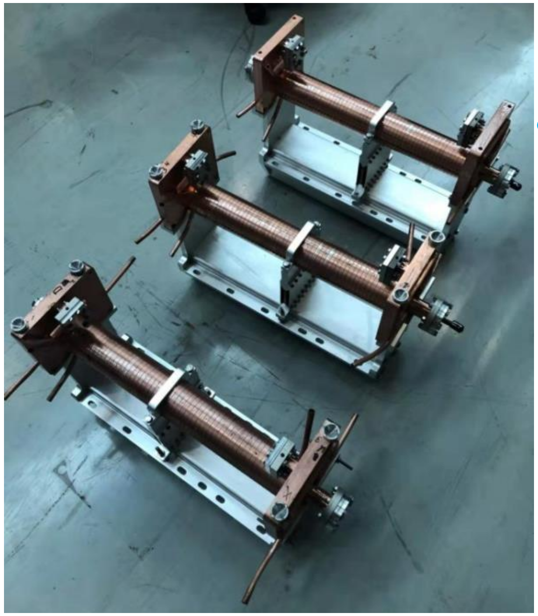
X-band Deflector

-- by Dr. W.C.Fang



2 units located in the end of undulator on SXFEL-TF
3 units of deflecting structures will used on SXFEL-UF.
One unit located in the end of linac, power feeded by one klystron.
Two units located in the end of undulator, feeded by one klystron

Parameters	Value	Units
Frequency	11.424	GHz
Phase advance	120	Deg
Maximum power	20	MW
Transverse voltage	0~30	MV
Total length	0.6	meter
Filling time	60	ns
Repetition frequency	50	Hz



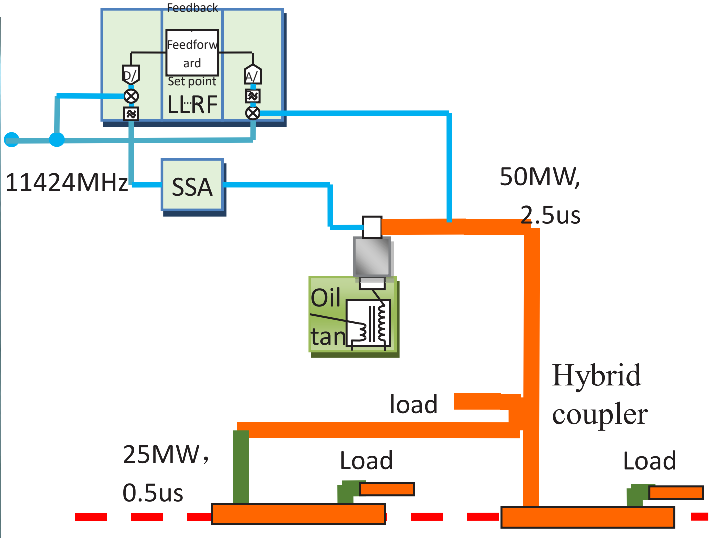
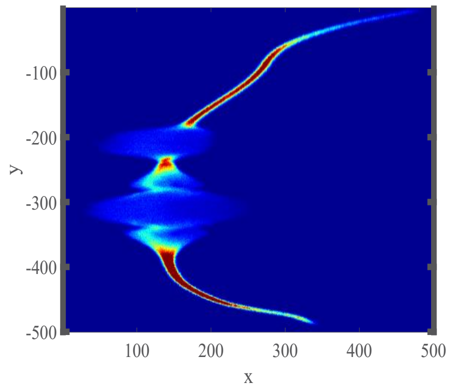


Figure. Layout of x-band deflector unit in the end of linac

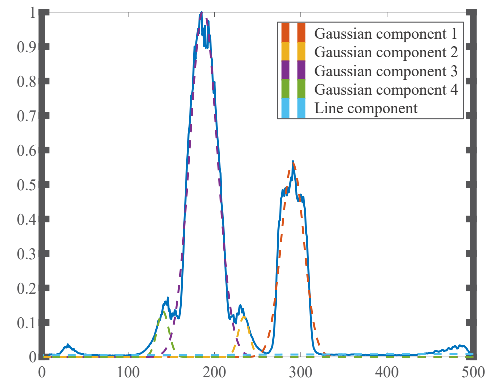
Single FEL Pulse Reconstruction

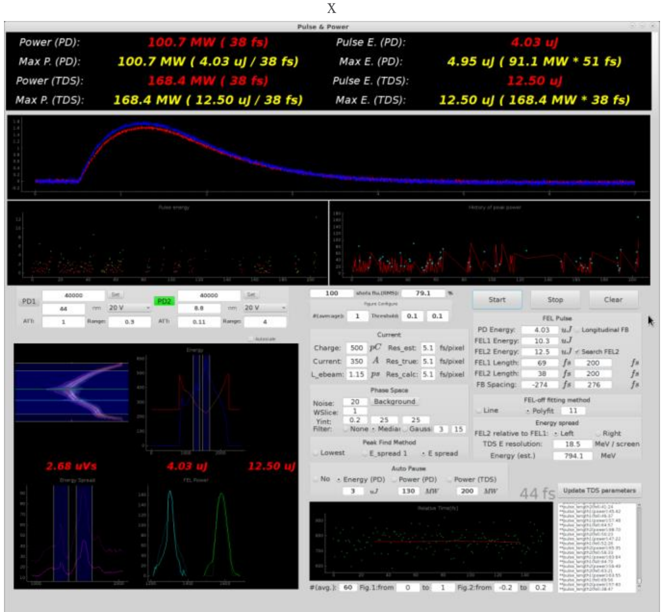
-- by Dr. C.Feng

Electron beam longitudinal phase space
After lasing of a seeded FEL



Single pulse reconstruction for FEL





Now we can get following information:

- ☐ **FEL profile**
- ☐ **FEL pulse energy**
- ☐ **Relative timing jitter**
- ☐ **Correlation between two stages FEL pulses**

Plays an important role in the commissioning

Summary

	Sensors	Resolution	Results
Beam Profile	YAG / OTR	< 20µm@0.5nC	13µm@0.5nC
Bunch Charge	ICT	< 1%@0.5nC	0.4%@0.5nC
Beam position	SBPM	< 10µm@0.5nC	4.3µm@0.5nC
Beam position	CBPM	< 1µm@0.5nC (DR: ±0.5 mm)	0.88µm@0.5nC (DR: ±0.5 mm)
BAM, TOF	Reference/Double cavity	< 100 fs@0.5nC	45 fs@0.5nC, 20min
Bunch length	CSR	<100fs@0.5nC	30fs@0.5nC
	Deflection cavity	<100fs@0.5nC	30fs@0.5nC

- BI system performance is better than the requirements. It helps SXFEL-TF commissioning successfully.
- Some lessons learned:
  - The center frequencies of the CBPM's three cavities are designed inconsistent and DBPM is narrow band width at about 500M, both limits lead to the complex design of down conversion RF front-end module.
  - High dose radiation in tunnel during commissioning caused a large number of CCD be damaged. Radiation protection on CCD is added later.
- Experience and lessons learned from SXFEL-TF are very helpful. System will be upgraded for SXFEL-UF.

Thanks for your attention