BAM and machine stability at SXFEL

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Outline

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  - Work Review
  - Motivation
- **System Analysis and Optimization**
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  - Signal processing window
  - Temperature
- **Upgraded BAM system at SXFEL-UF**
- **Beam stability analysis**
- **Conclusion**

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Background

Introduction - SXFEL

Shanghai Soft X-ray FEL Test Facility

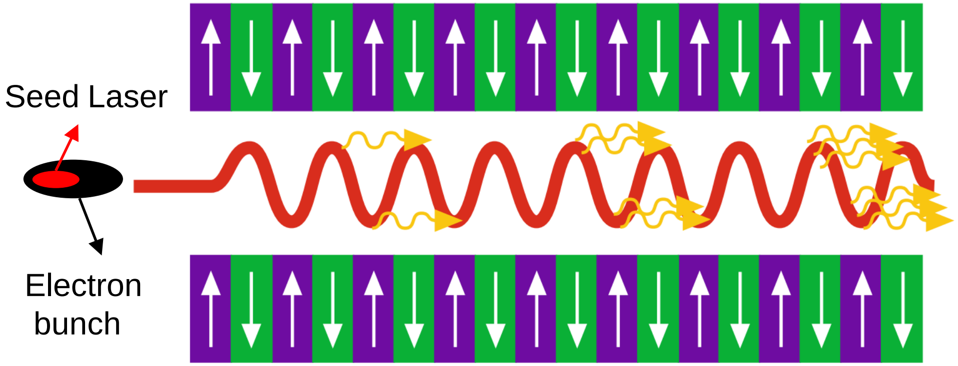
2021

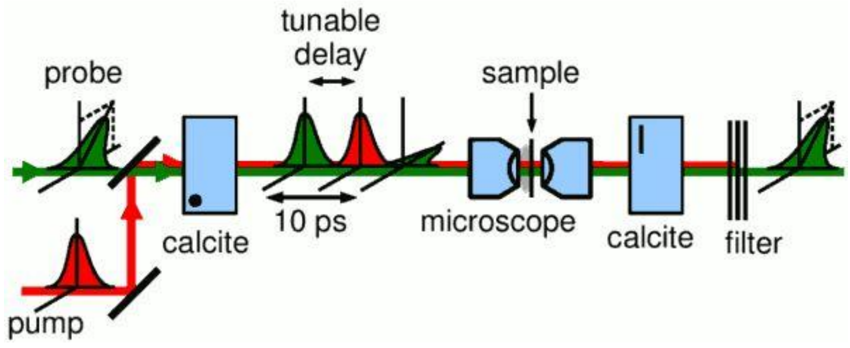
Shanghai Soft X-ray FEL User Facility

Parameters	Test Facility	User FEL-1	User FEL-2	Unit
FEL type	HGHG-HGHG HGHG-EEHG	SASE	HLSS EEHG	
Output Wavelength	8.8	2 ~ 10	1.2 ~ 3	nm
Bunch charge	0.5 ~ 1	~ 0.5	~ 0.2	nC
Pulse length (FWHM)	~0.5	0.3 - 1	0.3 - 1	ps
Peak current	~0.5	0.7	0.7	kA
Rep. rate	1 ~ 10	10 ~ 50	10 ~ 50	Hz

Introduction - BAM

- **To acquire ultra-short and high-brightness light :**
  - The precise synchronization between the electron bunches and the seed laser pulses in three-dimensional space
- **Time-resolved experiments：**
  - Require high temporal resolution & stability
  - Reduce the timing jitter of the electron bunch, correct timing drifts
- **Beam arrival time has to be measured !!!**
- **A temporal resolution better than 100 fs was required by SXFEL.**





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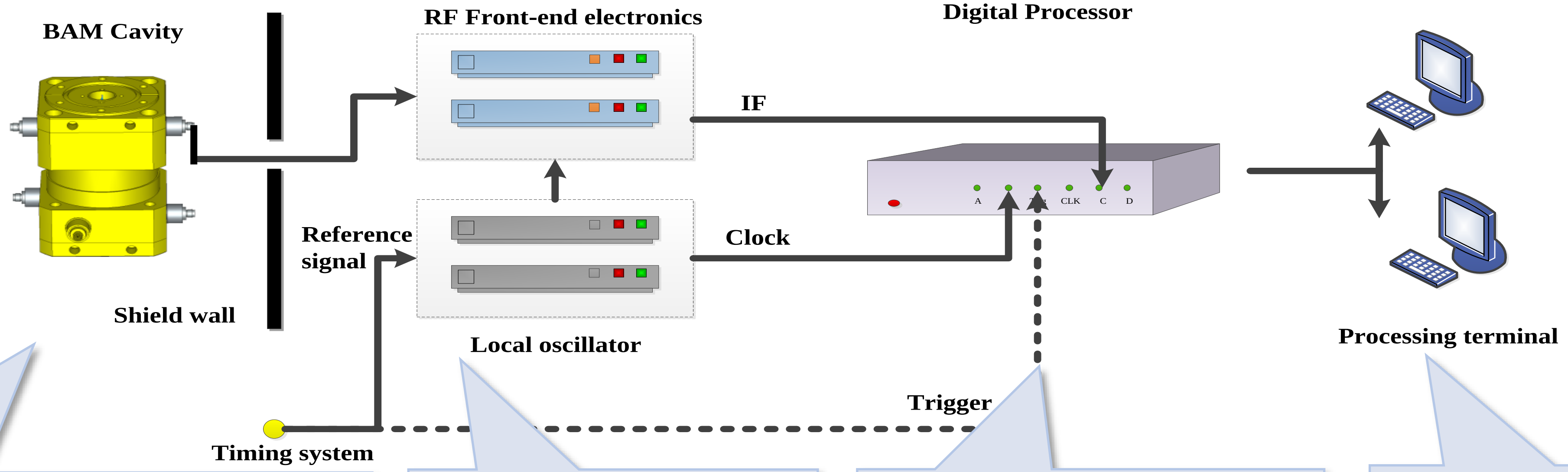
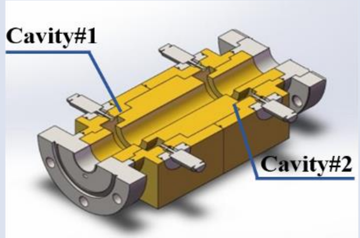
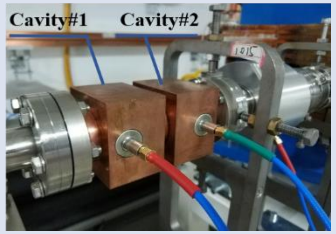
Work Review-Typical BAM system



Beam arrival time monitor





Parameters	Cavity #1	Cavity #2
Frequency/ GHz	4.685	4.72
Q_L	4671	4716
R over Q/Ohm	107.2	107.9
Bandwidth /MHz	1.002	1.025
τ /ns	318	318

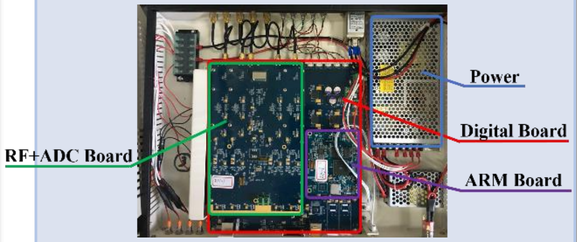
RFFE

LO

Front panel

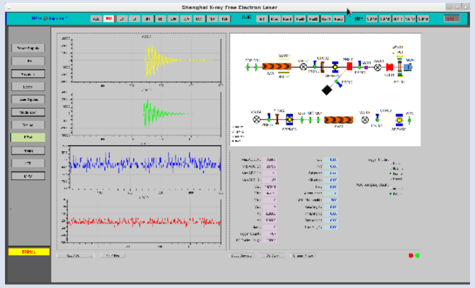
Back panel

DBPM



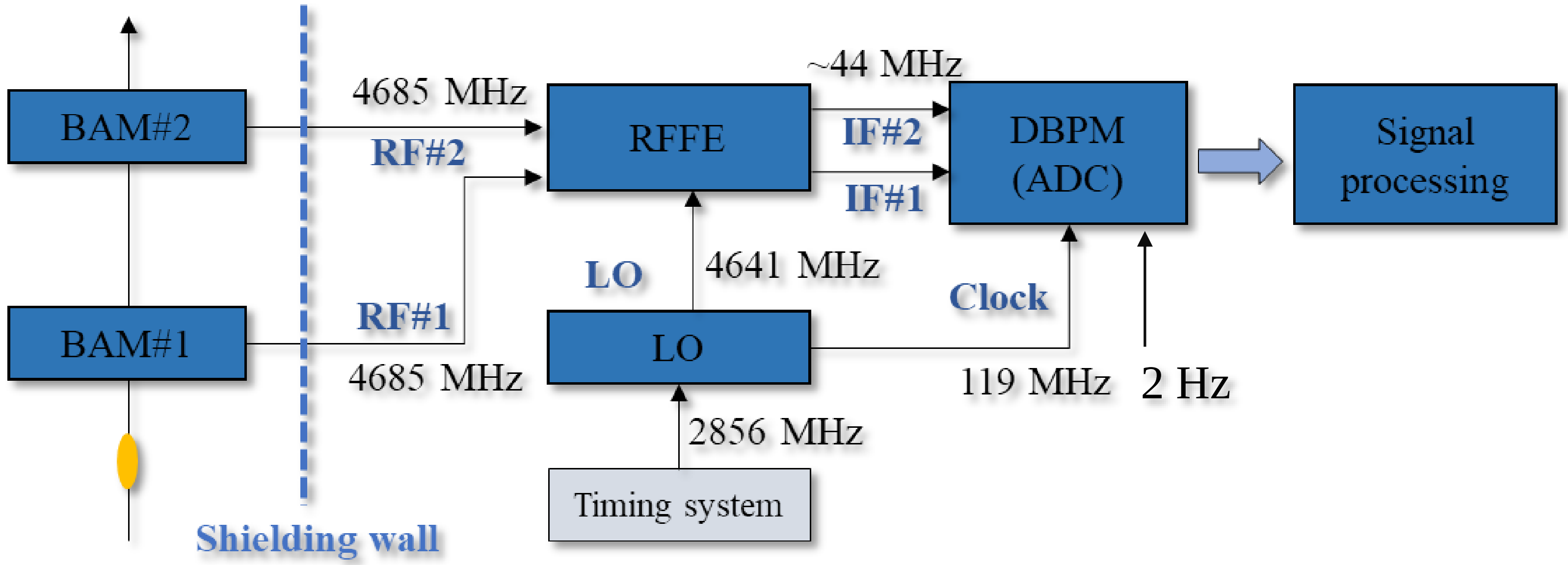
Para.	Value
Sampling rate	119 MHz
Number of bits	16
Channels	4

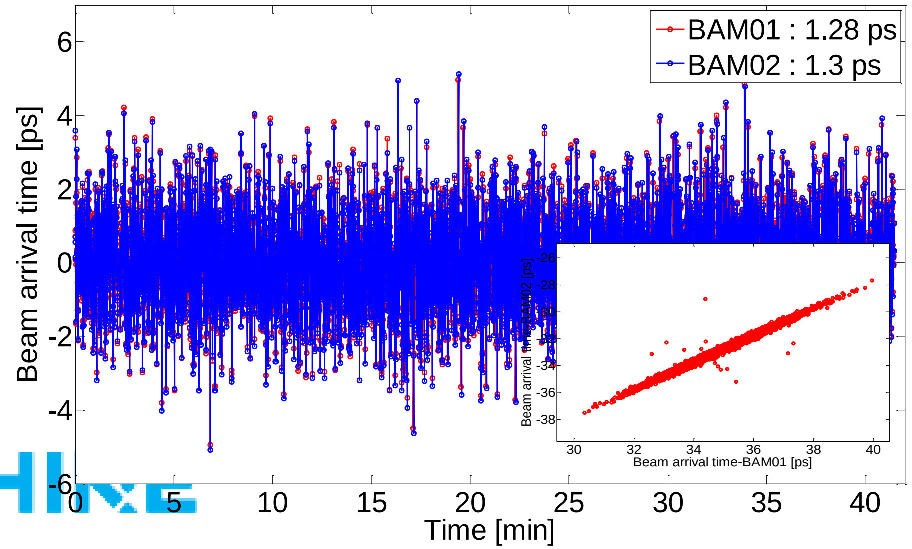
GUI



- Data acquire and publish;
- Real-time display ;
- Monitor and control

Work Review-Beam test results (IBIC2018)





- **Large** than **expected** measurement uncertainties :
  - 1.28 ps @ BAM01
  - 1.30 ps @ BAM02
- System issues should be checked firstly
- Beam stability also need to be evaluated

Motivation

Questions:

- **Why:** measurement uncertainties is large than expected?
- **What** can we do to improve the system performance**?**
- **How** to improve the system performance**?**

Motivation:

- Answer these questions
- Improve the system performance
- Analysis beam stability

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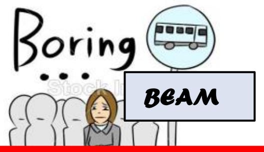
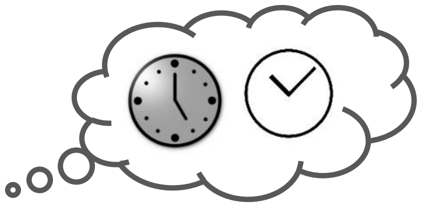
System Analysis and Optimization

Source analysis of measurement uncertainty





Total meansurement uncertainties

=

To be measured:

- Beam jitter
- Energy variation: amplitude fluctuations and phase jitter of the accelerating fields
- Noise of magnet current
- Timing jitter of the electron gun

+

To be improved:

- Poor stability of 2856-MHz reference signal;
- Poor performance of local oscillator
- Clock jitter
- Trigger jitter
- Environment disturbance: temperature, humidity etc.

Highly suspicious

- Error caused by phase extraction algorithm

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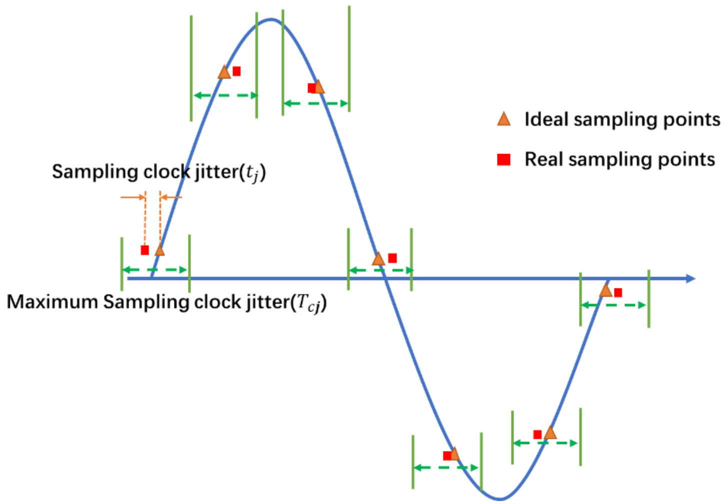
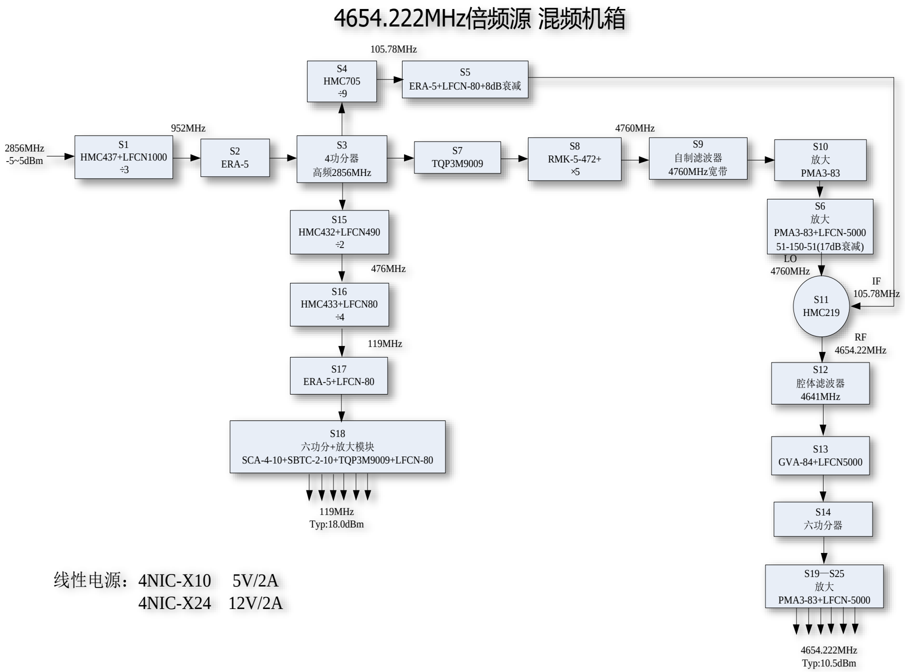
Fix problem of LO

- A signal source analyzer was used;
- The measured phase jitter (RMS) of 2856-MHz reference signal is in expectation.
- **Key issue**: Local Oscillator lost phase-lock -> Digital local oscillator
- **Solution**: Strictly phase-locked local oscillator -> Analog local oscillator
- The measured phase noise (RMS) of LO signal and clock signal have improved from ps to fs.





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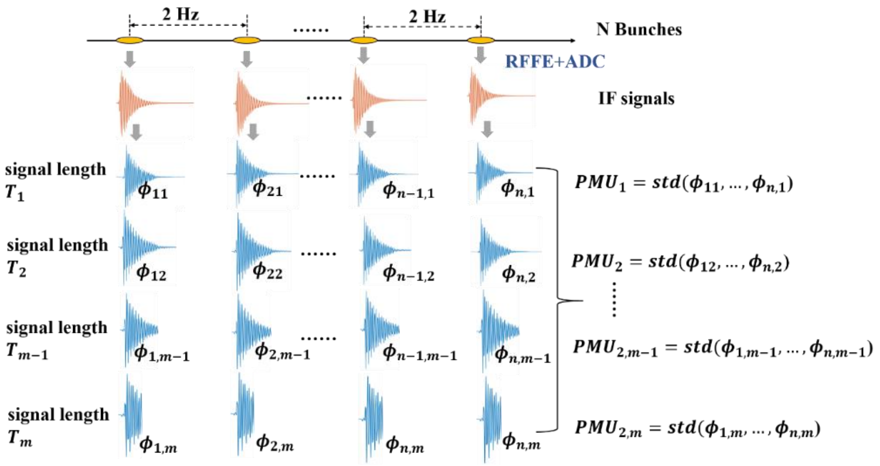
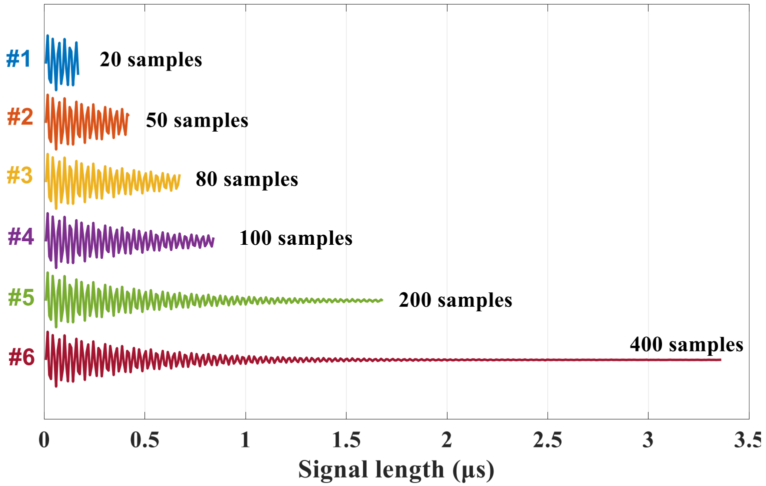
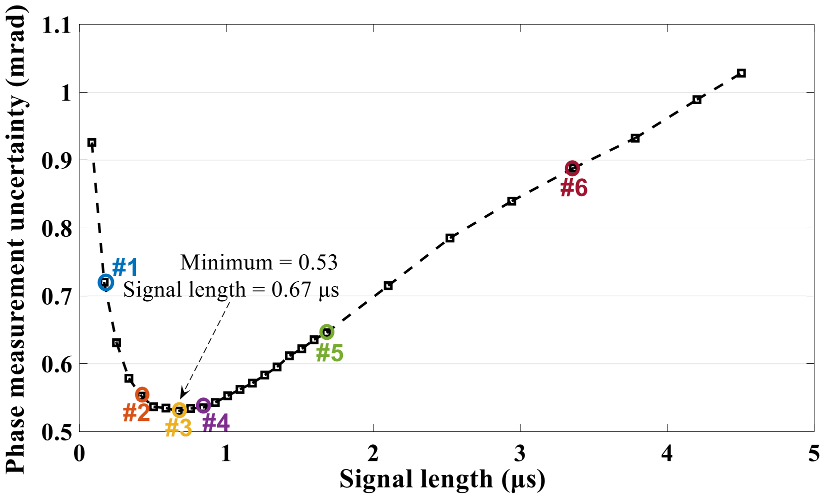
Analysis of the signal processing window

- Question: How to select the signal processing window?
- The phase measurement/extraction uncertainty (PMU) :
    - $PMU_n = std(\phi_1, \ldots, \phi_n)$
- Different PMU was found at different signal processing window, there is an **optimal** signal processing window with minimal PMU;
- For example, the PMU at the **optimal** signal processing window has improved by **41%** compared with the 6th signal processing window.







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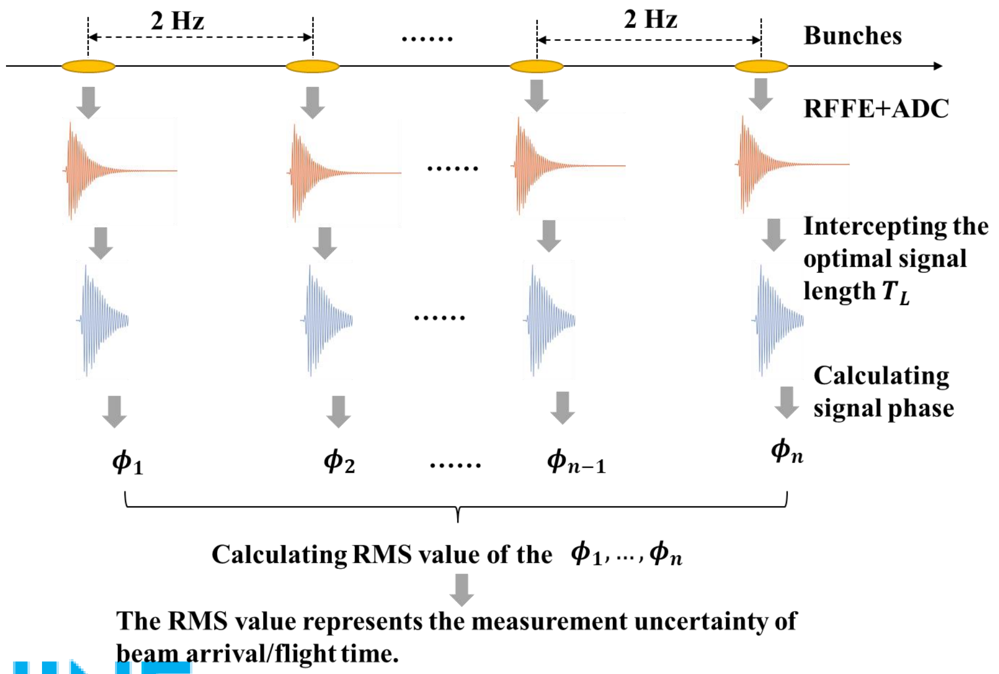
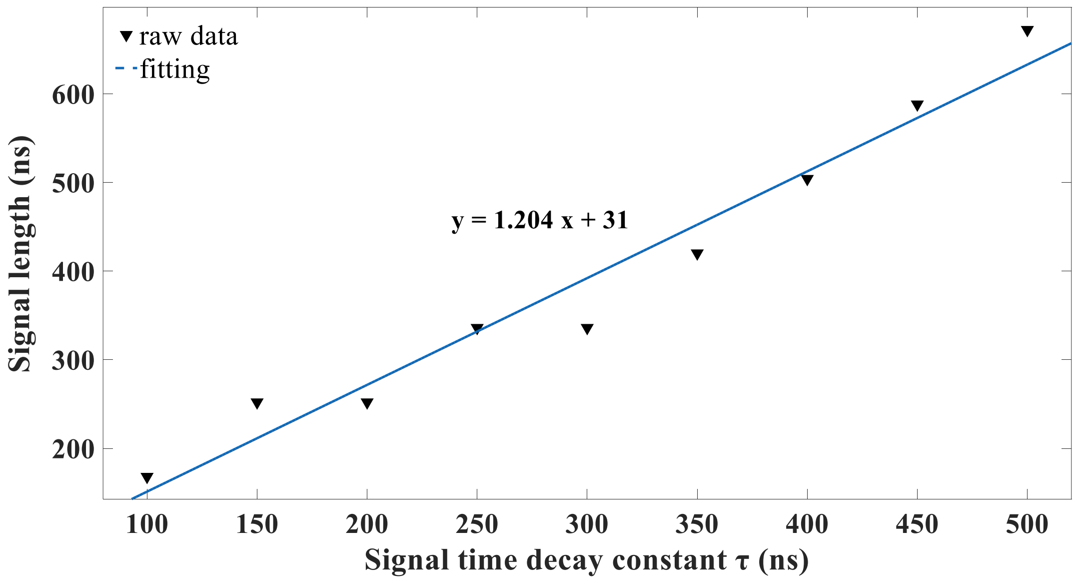
Cao S, Leng Y, Yuan R, et al. Optimization of beam arrival and flight time measurement system based on cavity monitors at the SXFEL[J]. IEEE Transactions on Nuclear Science, 2020, 68(1): 2-8.

Optimal signal processing window

- Furtherly, the relation between the signal damping time and the optimal signal processing window was studied;
- Simulation result reveals that they have a linear relation.
  - $optimal\ signal\ length = 1.204 * \tau + 31$





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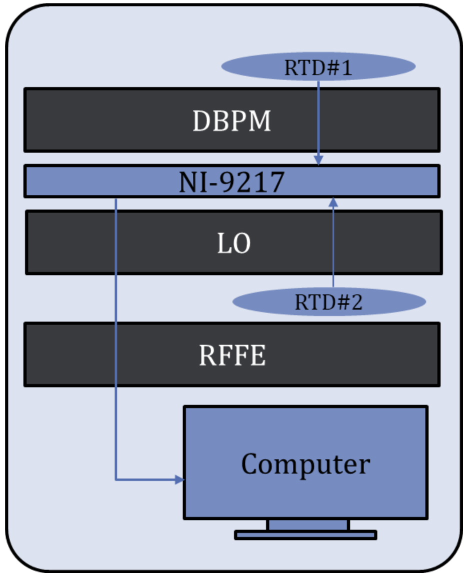
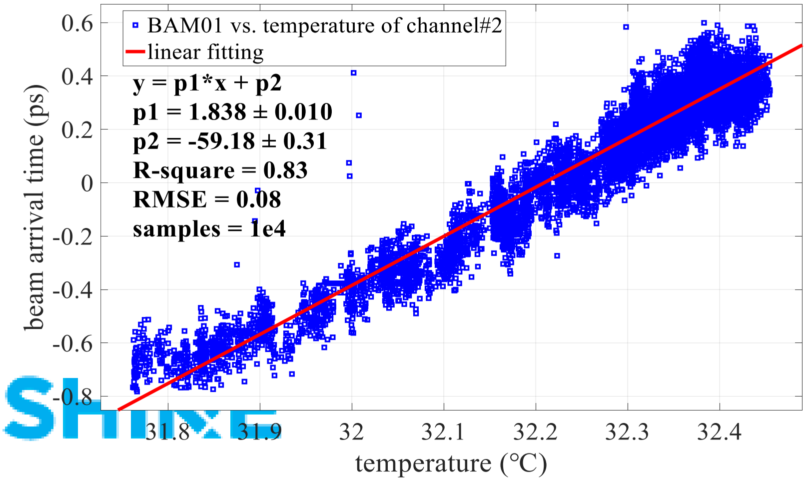
Cao S, Leng Y, Yuan R, et al. Optimization of beam arrival and flight time measurement system based on cavity monitors at the SXFEL[J]. IEEE Transactions on Nuclear Science, 2020, 68(1): 2-8.

Analysis of Temperature (electronic devices)

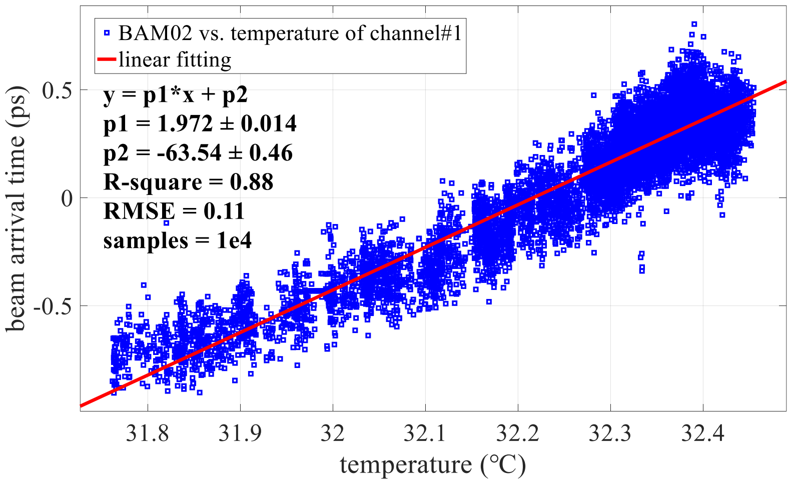


- Another experiment was conducted to verify the influence of the temperature around the electronic devices (RFFE, LO, DBPM) outside the tunnel.
- The test results show **an approximately linear** relationship between the temperature and the beam arrival time:
  - **1.838 ps/℃**@BAM01
  - **1.972 ps/℃**@BAM02
  - **1.781 ps/℃**@BAM03
- A high-performance thermostatic cabinet is required for long-term stability.

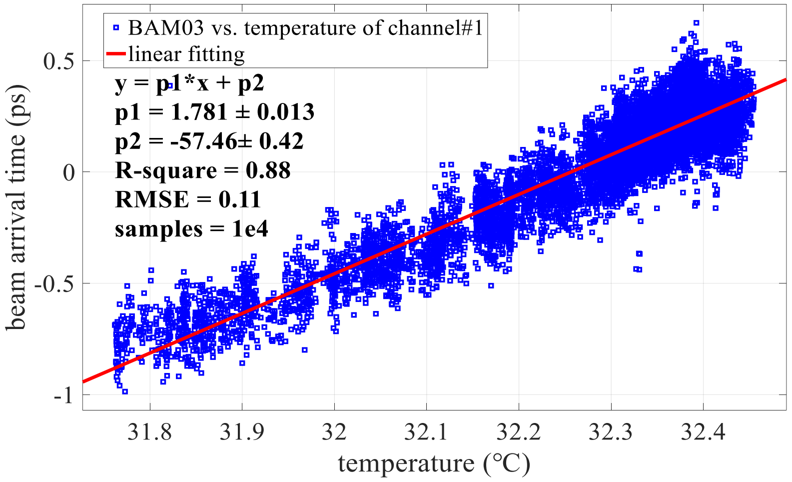
1.838ps/℃



1.972ps/℃



1.781ps/℃



Upgraded BAM system at SXFEL-UF

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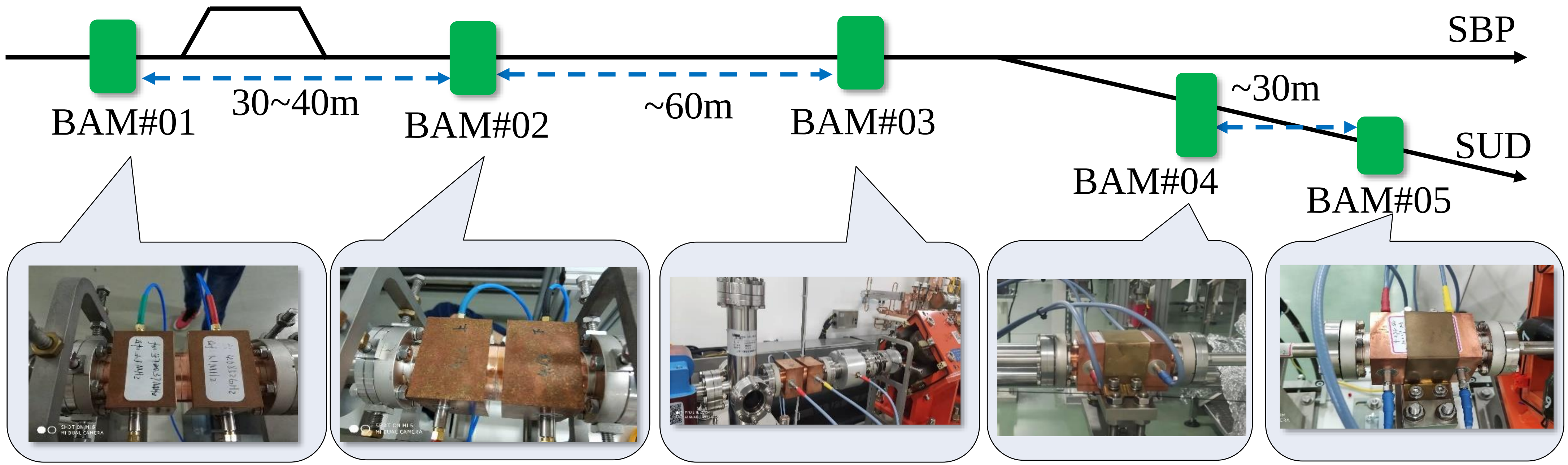
Layout of BAMs at SXFEL-UF

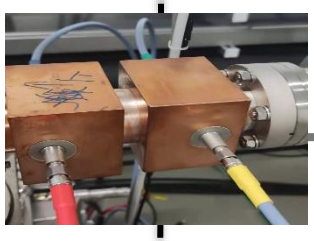


Parameter	BAM#01		BAM#02		BAM#03		BAM#04		BAM#05	
Freq./GHz	4.6852	4.7204	4.729	4.685	4.6872	4.7262	4.7224	4.6848	4.7232	4.6857
Bandwidth/ MHz	1.11	1.06	1.24	1.16	1.2	1.2	1.16	1.14	1.17	1.17
Qload	4221	4453	3814	4039	3906	3939	4057	4106	4046	4004

BAMs at LINAC

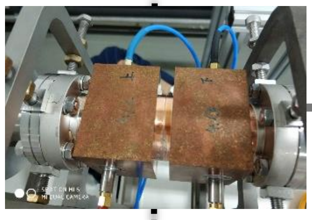
BAMs (3) | **Thermostatic cabinet** | **GUI**

BAM03



4.687 GHz

BAM02



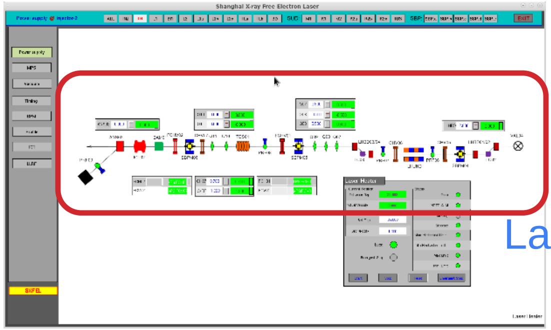
4.685 GHz

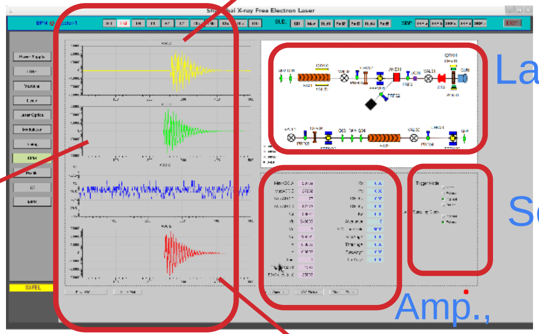
BAM01

4.685 GHz

Para.	Value
LO Freq	4654.2 MHz
Clock Freq.	119 MHz
Sampling rate	119 MHz
Channels of DBPM	4

LO Freq = 13.3 MHz * 350 = 4654.2 MHz





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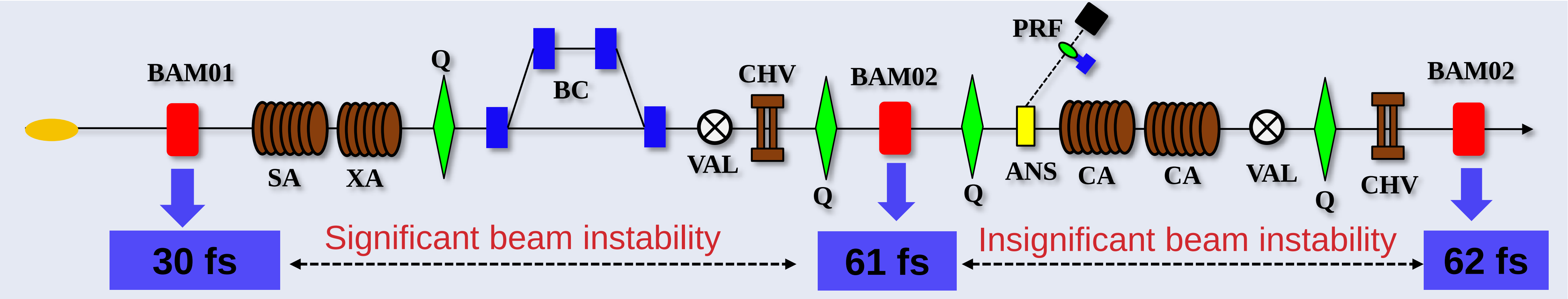
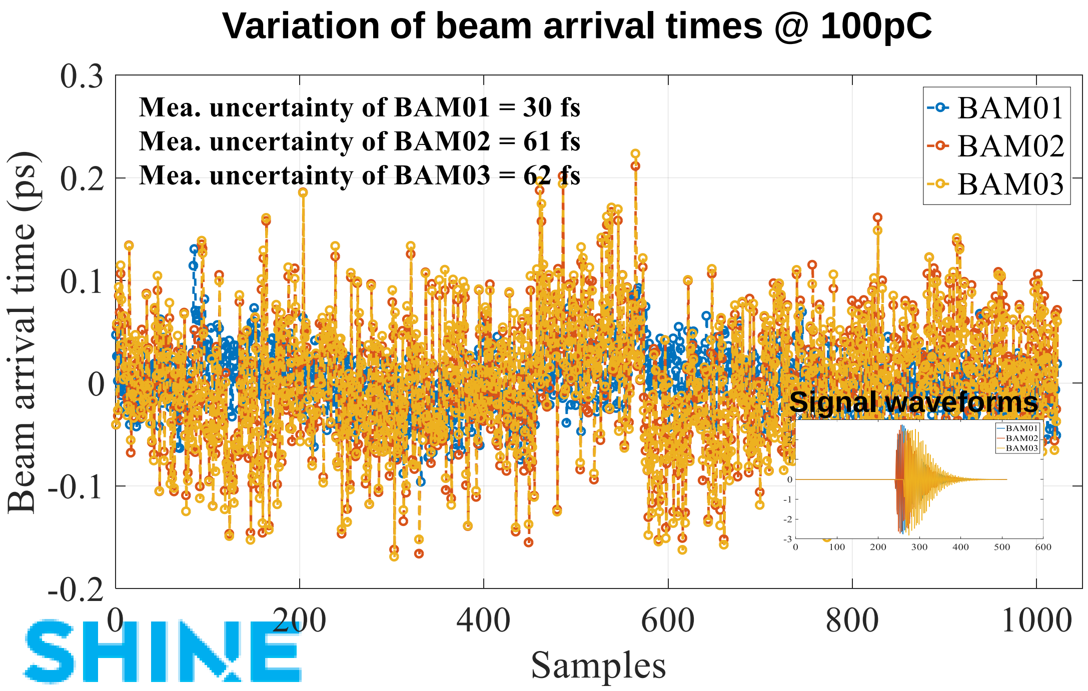
Beam test at LINAC





- Three upgraded BAMs system installed at SXFEL-UF's LINAC were tested.
- The measurement uncertainties of beam arrival time in short-term (about 10 min):
  - 30 fs @ BAM01
  - 61 fs @ BAM02
  - 62 fs @ BAM03
- The system performance has been significantly improved.

Beam stability analysis

- Beam energy jitter

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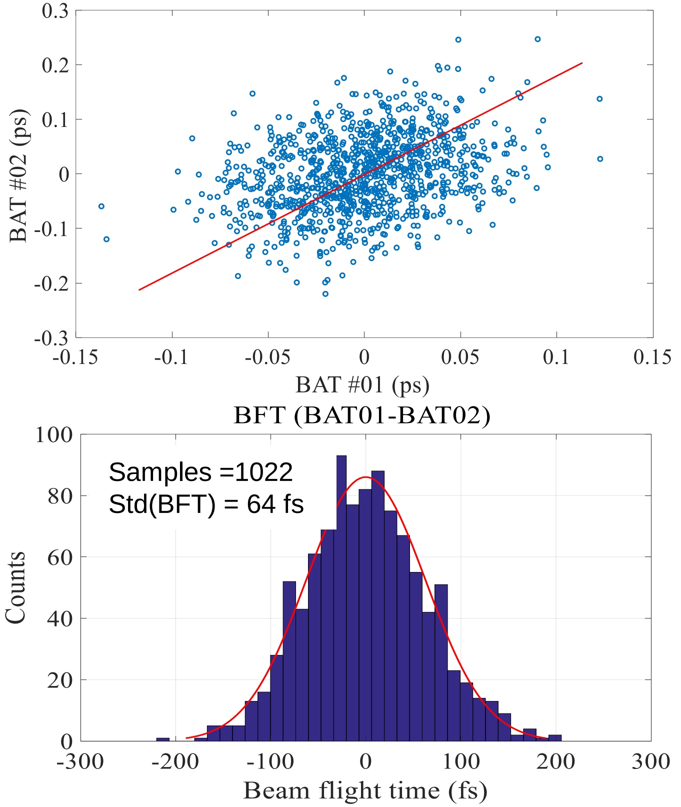
Beam instability

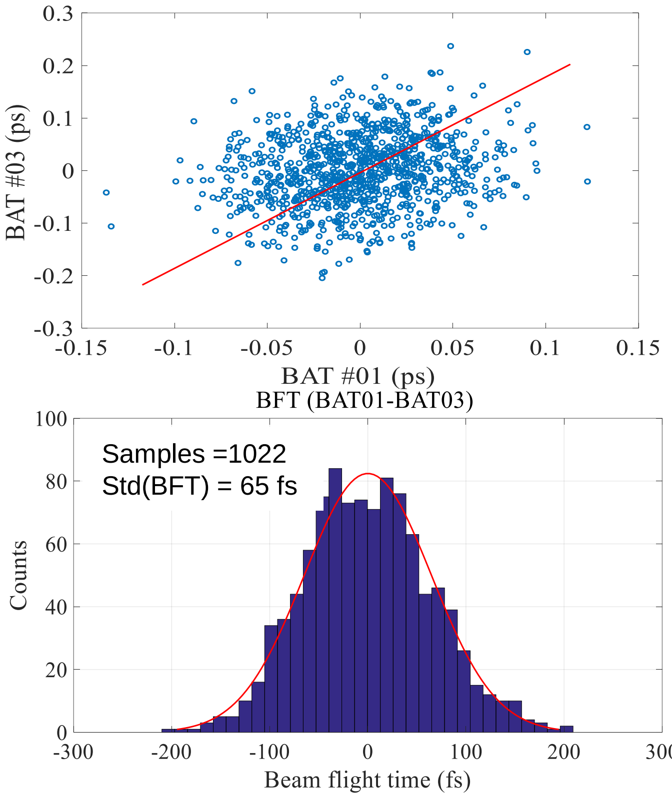
@ BAM02-BAM01



- BFT rms meas. uncertainty = **64** fs

Beam energy jitter

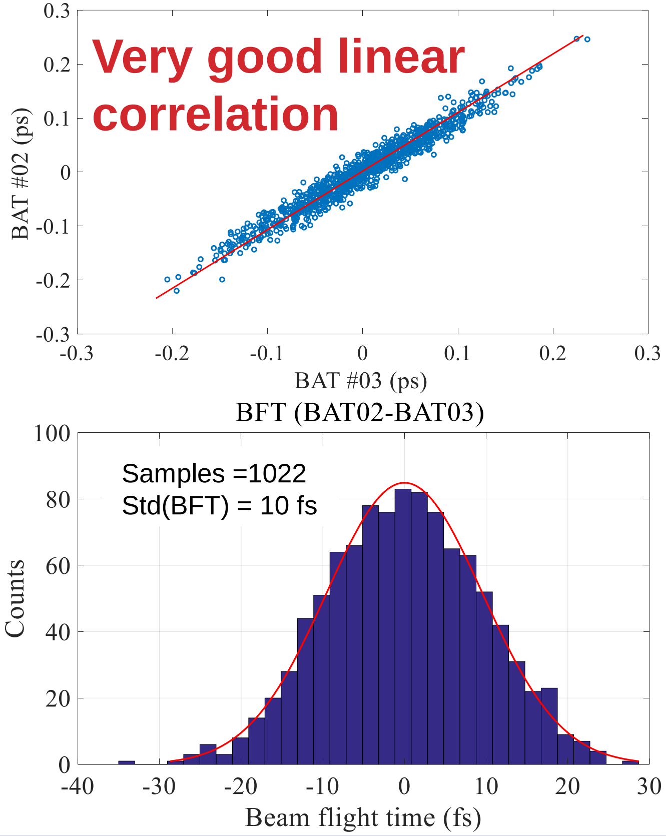
@ BAM03-BAM01



- BFT rms meas. uncertainty = **65** fs

Beam energy jitter

@ BAM03-BAM02



- BFT rms meas. uncertainty = **10** fs

System noise
Beam orbit fluctuation

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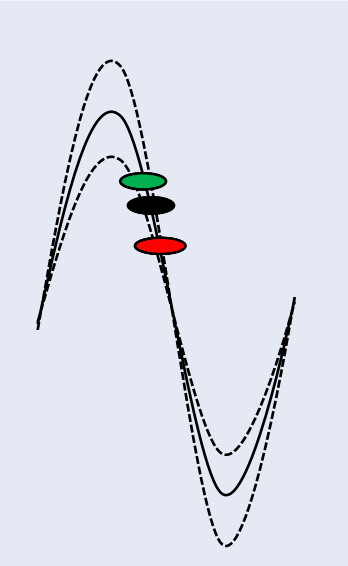
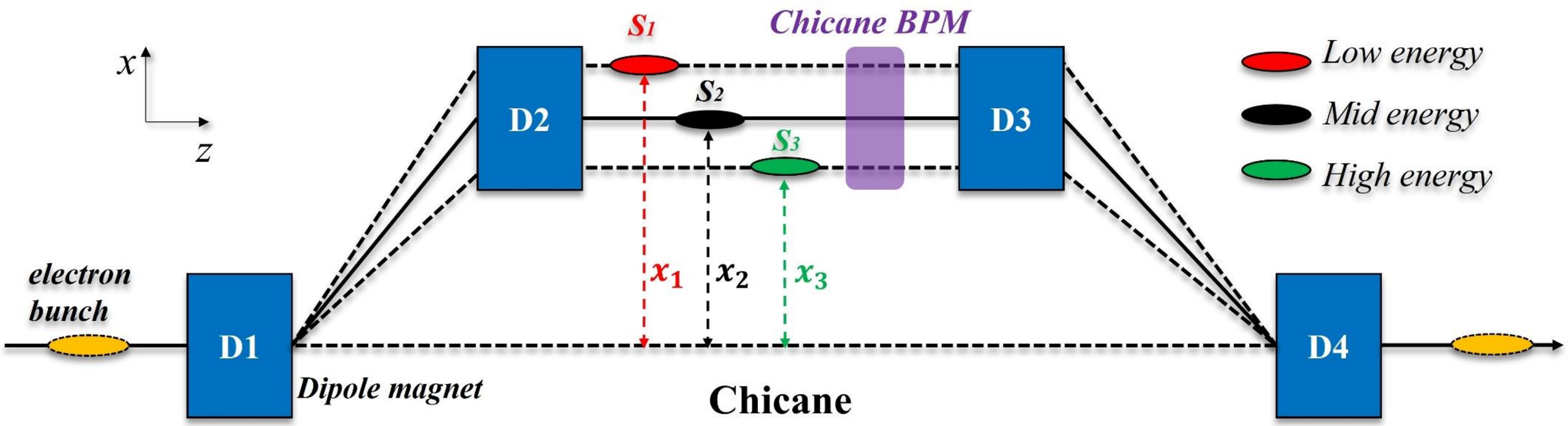
Study of beam energy jitter

- The amplitude fluctuations and phase jitter of the accelerating fields will cause energy jitter.
- The energy-dependent path leads to the conversion of beam energy jitter to beam arrival time jitter because of dispersive effects in the magnetic bunch compressor chicane.
- High-energy electron bunch travels a shorter path (green one) while low-energy bunches travel a longer path (red one).





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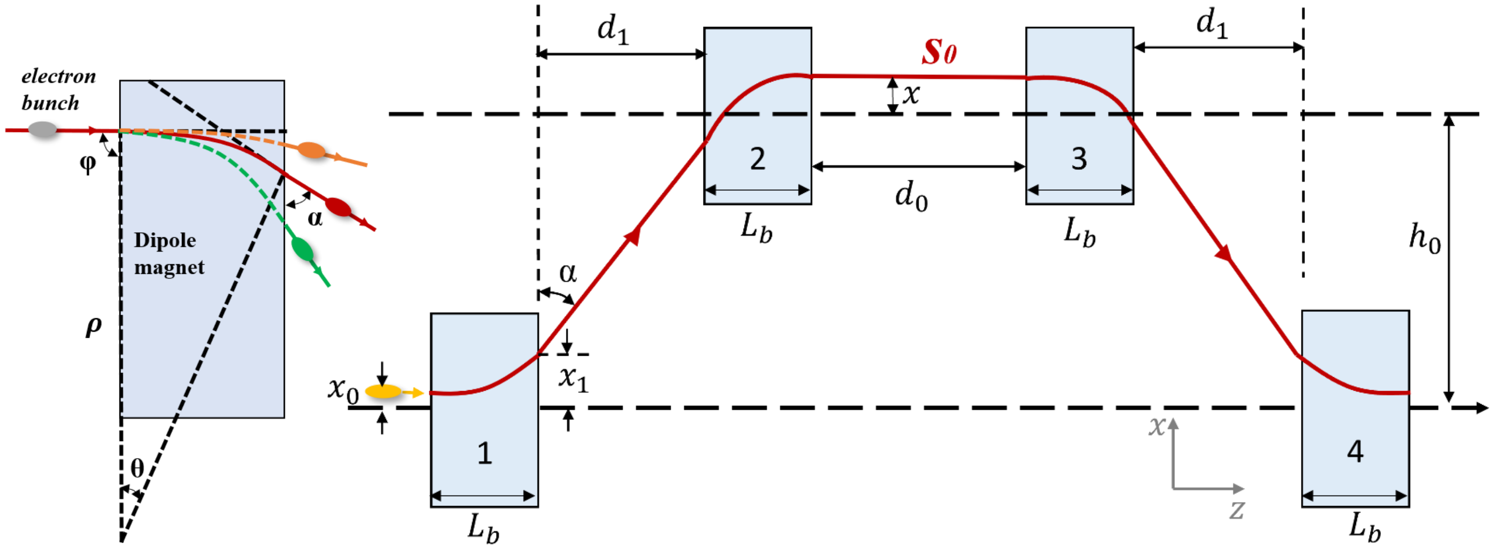
Relation between BFT/BAT and energy



Schematic of a chicane

Parameters of a chicane at SXFEL-UF

Symbol	Value	Unit
d_0	1.08	m
L_b	0.3	m
d_1	4.8	m
B	0.1577	T
h_0	0.33	m

- The relation between the beam energy and beam arrival/flight time:

$$t_{fly} = \left(\sum_{i=1}^{4} l_i + \sum_{1}^{3} l_{i,i+1} \right) \Big/ \beta c$$

$$l_1 = \rho \cdot \theta \qquad l_{12} = \frac{d_1}{\sin(\alpha)}$$

$$\cos(\alpha) + \cos(\varphi) = L_b/\rho$$

$$\theta = \pi - \alpha - \varphi \qquad \rho = \frac{m_0 c\sqrt{\gamma^2 - 1}}{eB}$$

- A special case: φ=90°

$$t_{fly}(\gamma) = \frac{[4\rho\theta + d_0 + 2\, d_1/\cos(\theta)]}{\beta c}$$

$$\theta = \arcsin\left(\frac{L_b}{\rho}\right)$$

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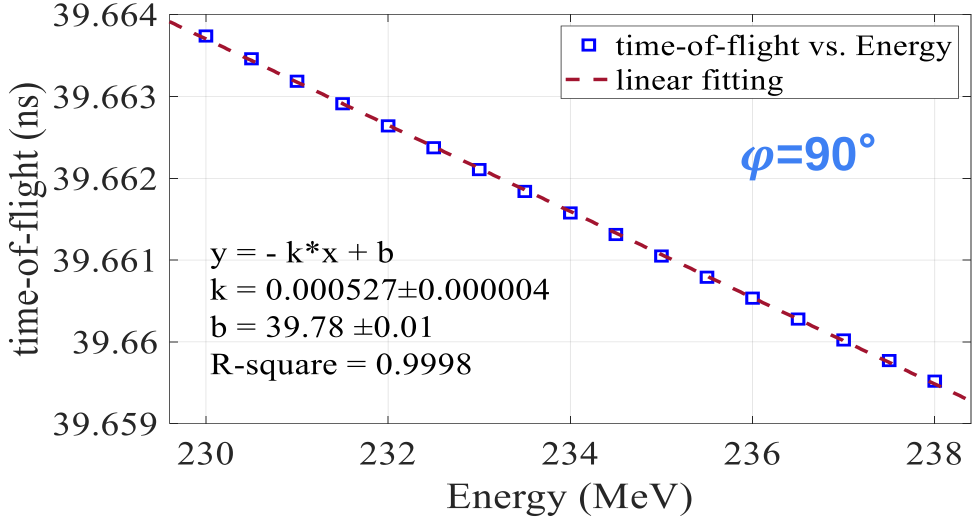
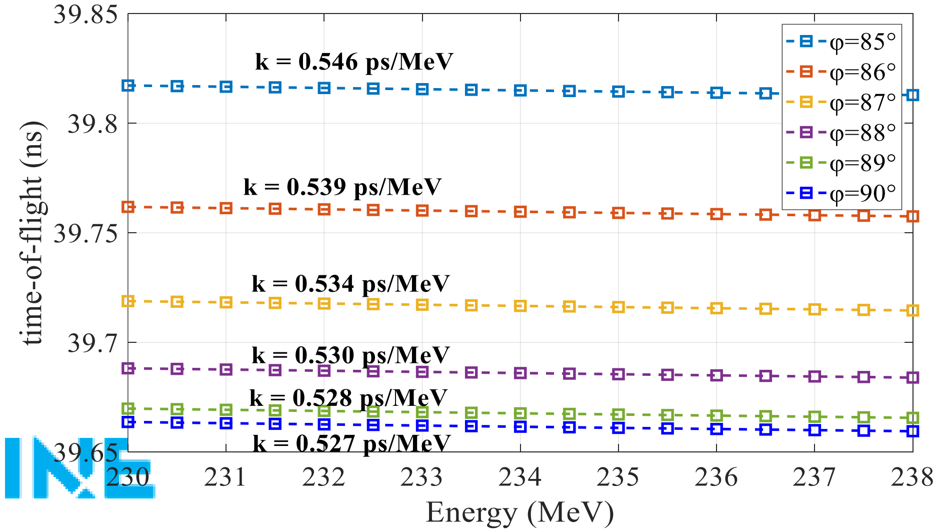
Relation between BFT/BAT and energy

Correlation between TOF and beam energy

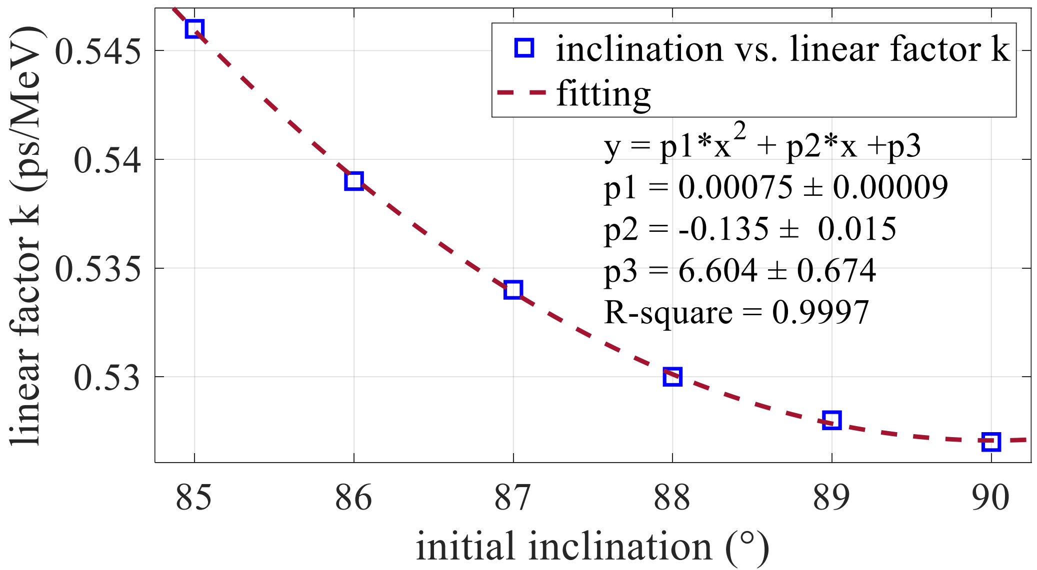


Correlation between TOF and beam energy



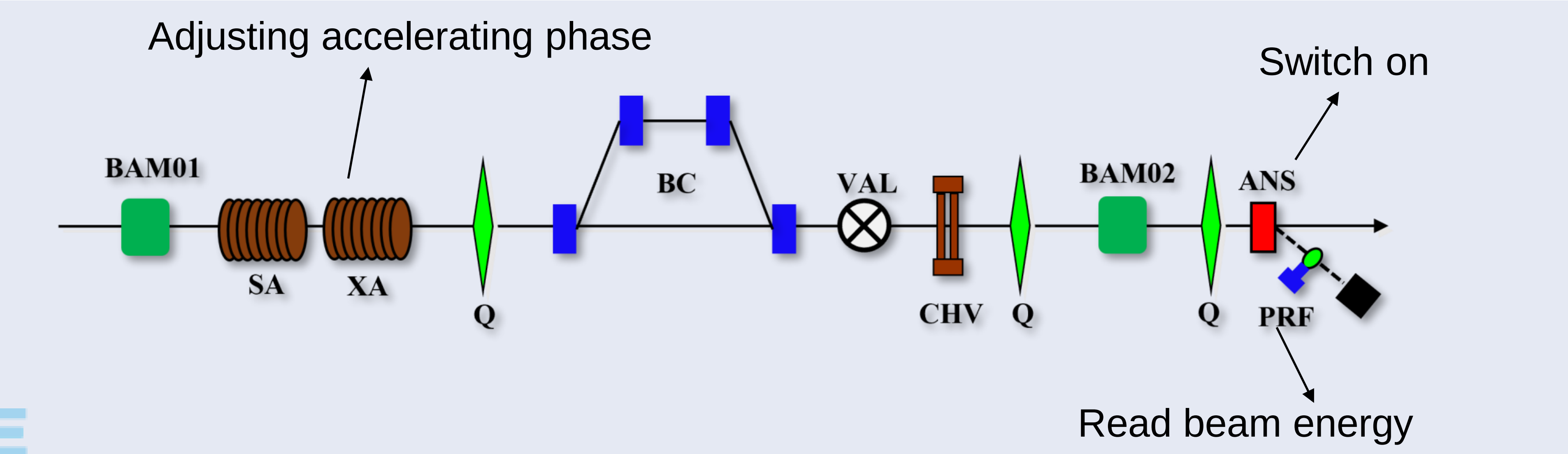
- The linear relation between the beam energy and beam arrival/flight time was obtained @ beam energy: 230 MeV to 238 MeV.
- The linear factor @ φ=90°
  0.546 ps/MeV
- The linear factor is related to the initial inclination (φ).

Relation between *k* and *φ*



Beam test for verification

- A beam test is performed to verify the relation between the beam energy and beam arrival/flight time.
- Two BAMs (BAM01 and BAM02) at LINAC are used.
- An analytical magnet and a profile behind BAM02 were utilized.
- Each adjusting the accelerating phase, the data of two BAMs and profile are recorded for multiple times.
- A total of 14 measurements are conducted.



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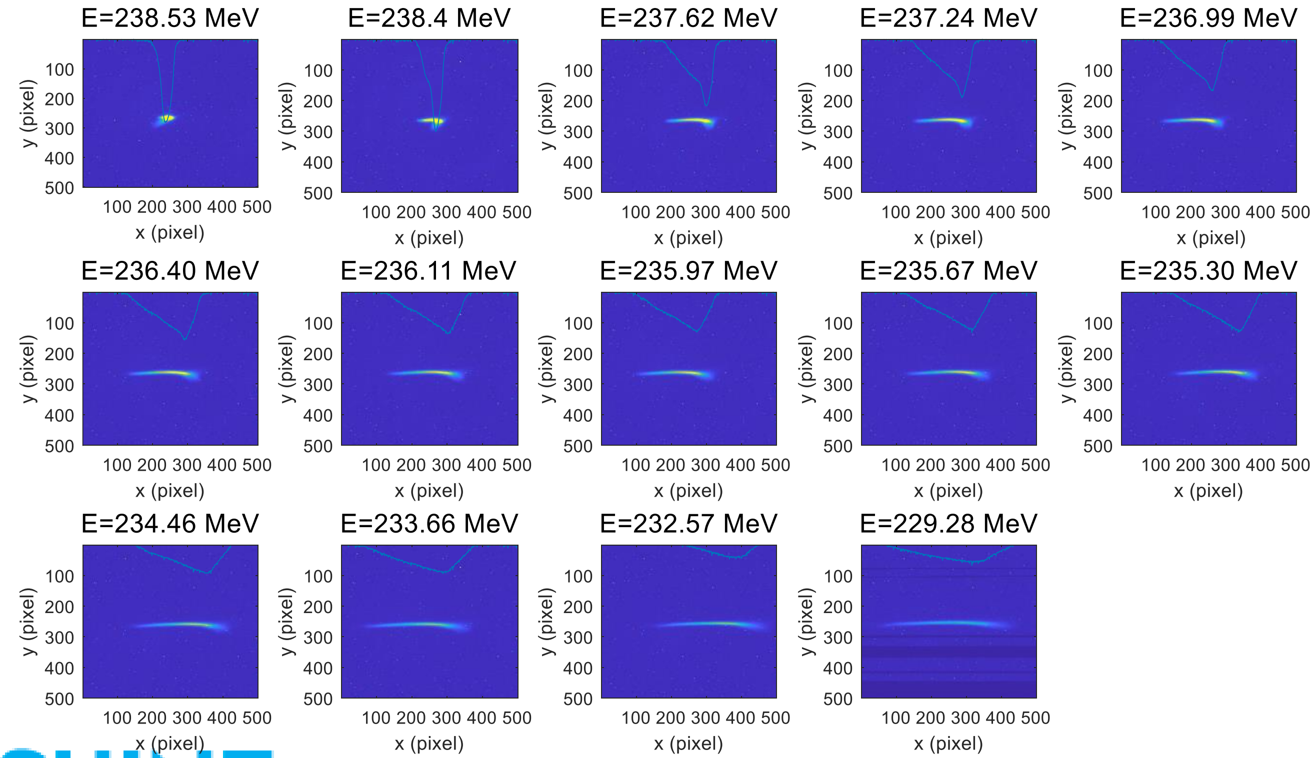
Measurement of beam energy

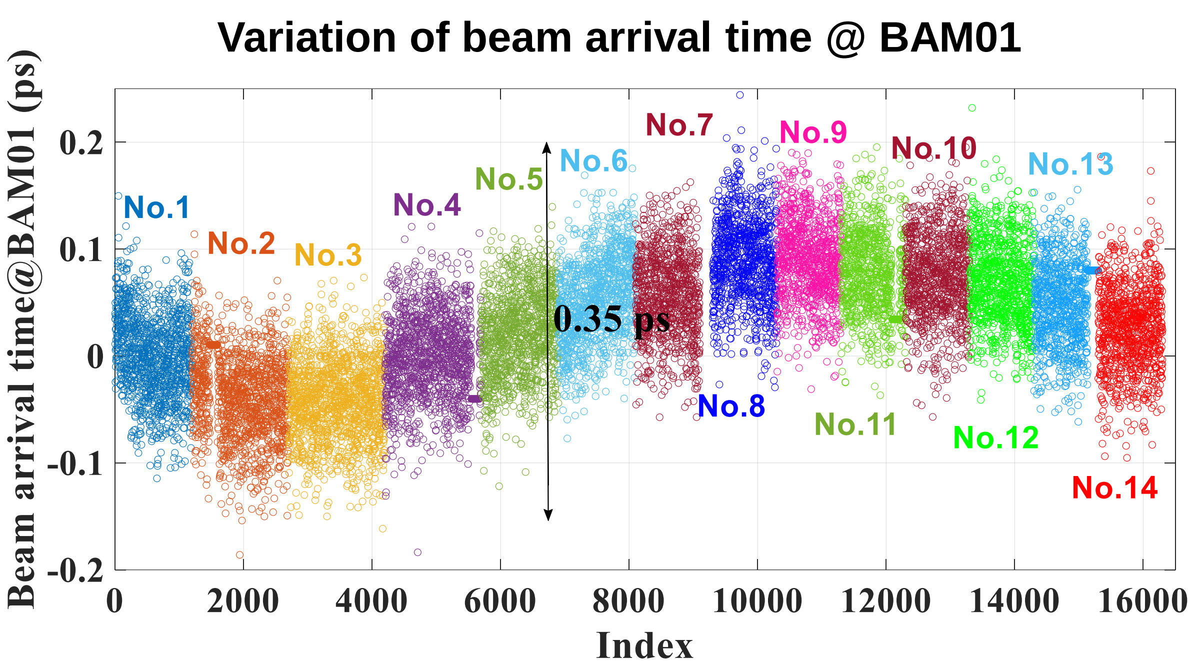
- The accelerating phase is gradually adjusted from -109° to -138°, the beam energy decreases, energy spread increases;
- The range of beam energy: 238.53 MeV to 229.28 MeV
- The range of energy spread: 0.07% to 0.55%
- Beam energy jitter: 0.02% ~ 0.04%

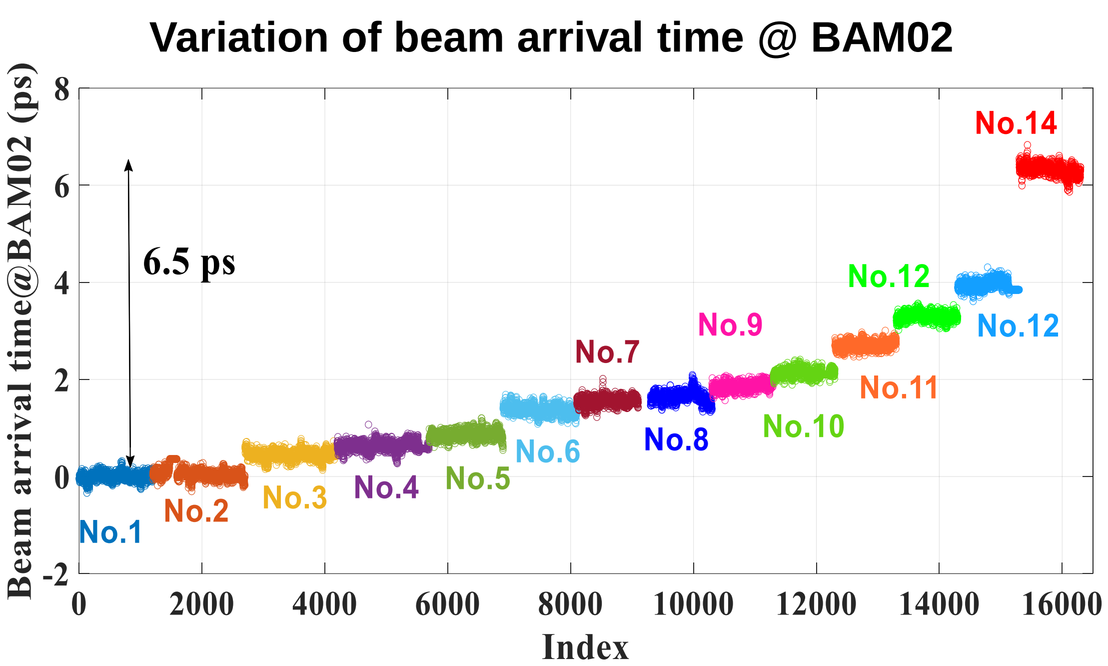


Meas. No.	Acc. Phase/°	Energy/MeV	Energy spread/%	Energy jitter/%
1	-109	238.53	0.07	0.03%
2	-113	238.40	~	~
3	-118	237.62	0.18	0.03%
4	-120	237.24	0.20	0.02%
5	-121	236.99	0.23	0.02%
6	-123	236.40	0.26	0.04%
7	-123.5	236.11	0.27	0.03%
8	-124	235.97	0.28	0.03%
9	-125	235.67	~	~
10	-126	235.30	~	~
11	-128	234.46	~	~
12	-130	233.66	0.40	0.03%
13	-132	232.57	0.44	0.03%
14	-138	229.28	0.55	0.03%

Measurement of beam arrival time

- More than 16000 samples (over 2 hours) were obtained;
- The variation of two beam arrival times are totally different;





- Beam arrival time @BAM01:
  - A small variation
  - peak-to-peak = 0.35 ps;

- Beam arrival time @BAM02:
  - A large variation;
  - peak-to-peak = 6.5 ps;

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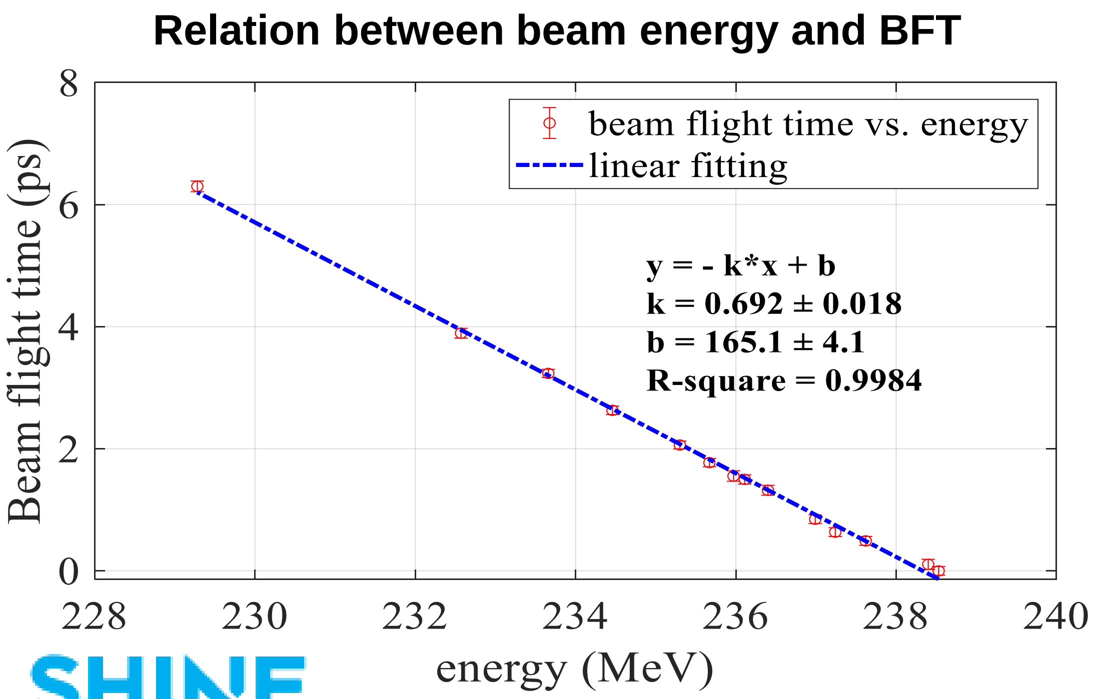
Relation between BFT/BAT and energy

➢ A linear relation between the beam energy and beam flight time is also proved by the beam test:

$$t_{BFT} = -k * E + b,$$
$$k = 0.692 \pm 0.018\ \mathrm{ps/MeV},\ \mathrm{b} = 165.1 \pm 4.1$$



Meas. No.	Acc. Phase/°	BFT/ps	Mea. Uncertainty/fs
1	-109	-0.001	71
2	-113	0.106	84
3	-118	0.491	73
4	-120	0.634	72
5	-121	0.846	72
6	-123	1.320	81
7	-123.5	1.498	75
8	-124	1.553	86
9	-125	1.772	68
10	-126	2.062	64
11	-128	2.630	70
12	-130	3.234	67
13	-132	3.893	80
14	-138	6.300	88

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Discussion

- Both formula-based calculation and beam test result show **the linear relation** between the beam flight time and beam energy (230MeV to 238 MeV)
- The linear factors obtained by formula-based calculation and beam test results are a bit different: **-0.546 ps/MeV** and **-0.692 ps/MeV**
    - Beam energy spread;
    - Beam profile;
    - Beam inclination;
- Given the beam energy rms jitter of 0.02% to 0.04% and the linear factor of 0.692 ps/MeV, the beam flight time rms jitter is expected to be **33 fs** to **65 fs**.

  -> **a little smaller** than the measured results (64 fs to 88 fs)
- Possible reasons:
    - Timing Jitter of reference signal
    - Not fully identical systems
    - Fluctuations of magnet current, environment, etc.

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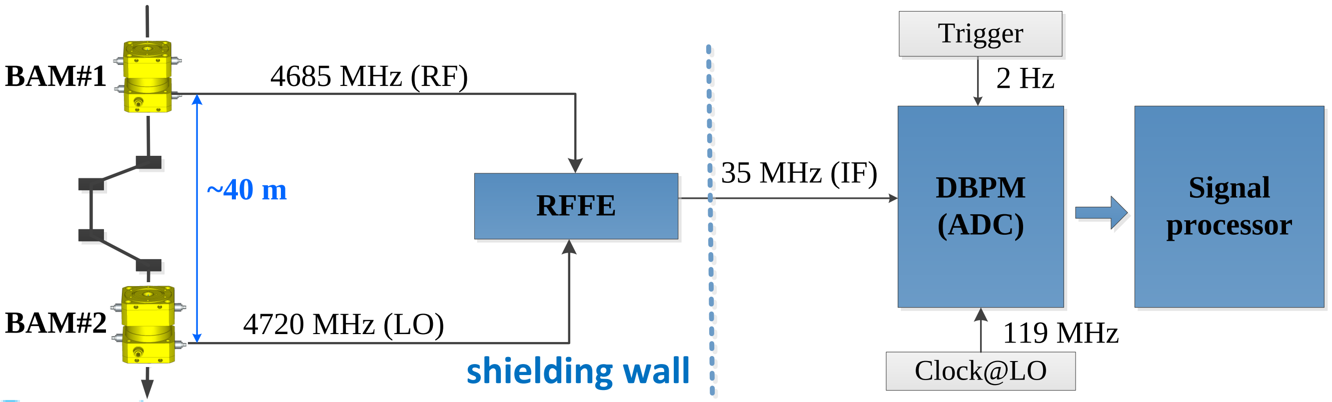
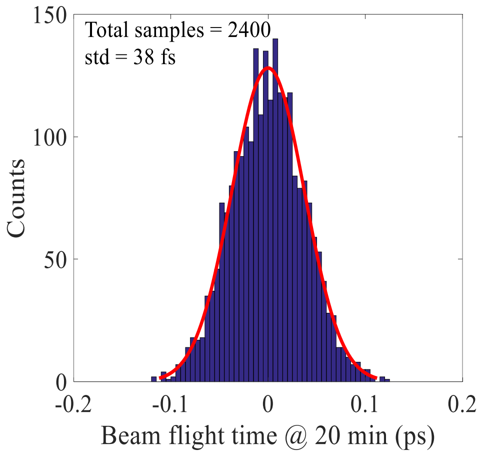
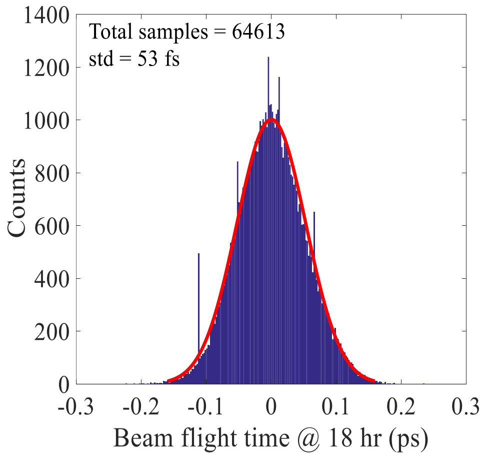
Discussion- new scheme

- Different from the typical scheme, dual-cavity mixing scheme uses the RF signal generated in a cavity as LO signal.
- Pros:
  - Independent of the performance of LO signal provided by LO
  - Place inside the tunnel: more stable temperature, humidity
  - Cost-effective for beam flight time measurement
- Beam test at SXFEL:
  - Meas. uncertainty (RMS) : **38 fs** over 20 min; -> **match well** with calculated results
  - Meas. uncertainty (RMS) : **53 fs** over 18 hours;







Conclusion

Conclusion

- The flawed cavity-based beam arrival time measurement systems at SXFEL-TF have been **analyzed** and **optimized** from several aspects;
- The **improved** beam arrival time measurement systems have been **utilized** at SXFEL-UF.
- The beam-based test reveal an obvious beam instability:
  - The beam flight time deviation with and without a magnetic chicane are 64 fs and 10 fs, respectively.
  - beam energy jitter was highly suspected.
- **Design and conduct an experiment to evaluate the contribution of beam energy jitter:**
  - **A linear relation** between the beam energy and the beam flight time traveling through a magnetic chicane is verified by formula calculation and beam test: -0.546 ps/MeV @ formula calculation & -0.692 ps/MeV @ beam test
  - The **energy jitter** can contribute 33 fs to 65 fs to the beam flight time rms jitter.
  - Match well with measurement results based on dual-cavity mixing scheme
- A promising application of the BAM system is used for **beam energy measurement**.
- Another promising scheme (dual-cavity mixing) is offered for beam flight time detection.

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What we can do next

- Further study beam stability and investigate other factors
- Further explore the possibility of using the BAM system to measure the beam energy
  - Analyze the impact of bunch profile, bunch length, beam inclination, and energy spread, as well as cavity distance on the measurement
  - Analyze the applicability of this approach @energy, energy spread
  - Compare the method with the SBPM-based scheme
- Further exploit and optimize the dual-cavity mixing scheme
  - Analyze the impact of damping time and signal amplitude of RF signals on the measurement
  - Analyze the temperature variation inside the tunnel and its impact on the measurement

Thank you!

Questions? Suggestions?

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