Nondestructive beam energy measurement using RF cavity beam arrival time monitors

Shanshan Cao

SARI BI Group

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SSRF 上海同步辐射光源 Shanghai Synchrotron Radiation Facility

Outline

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  - Motivation
- **Development of the BFT-BEM system**
  - Principles
  - Development
- **System performance evaluation**
- **Discussion**
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Background

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Introduction – SXFEL & SHINE

Shanghai Soft X-ray FEL Test Facility

2021

SXFEL： Shanghai Soft X-ray FEL User Facility

SHINE: Shanghai HIgh repetitioN rate XFEL and Extreme light facility

Key parameters

Parameters	SXFEL-TF	SXFEL-UF	SHINE
Output Wavelength/nm	9	2 ~ 10/ 1.2 ~ 3	0.4-25 keV
Bunch charge/nC	0.5 ~ 1	0.2~ 0.5	0.01~0.3
Pulse length (FWHM)/ps	~0.5	0.03 - 1	0.015~4
Peak current/kA	~0.5	0.7	0.5~2.5
Max Rep. rate/Hz	10	50	1e6

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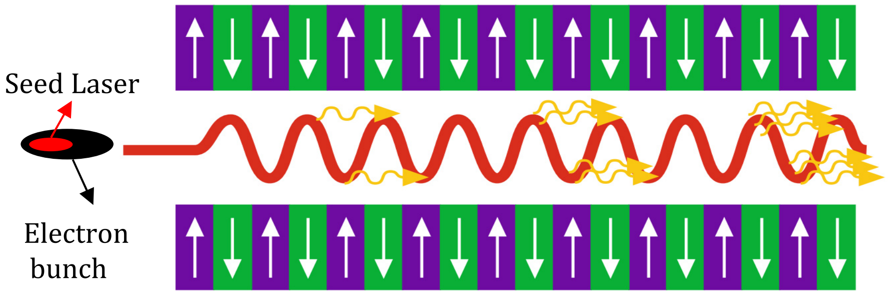
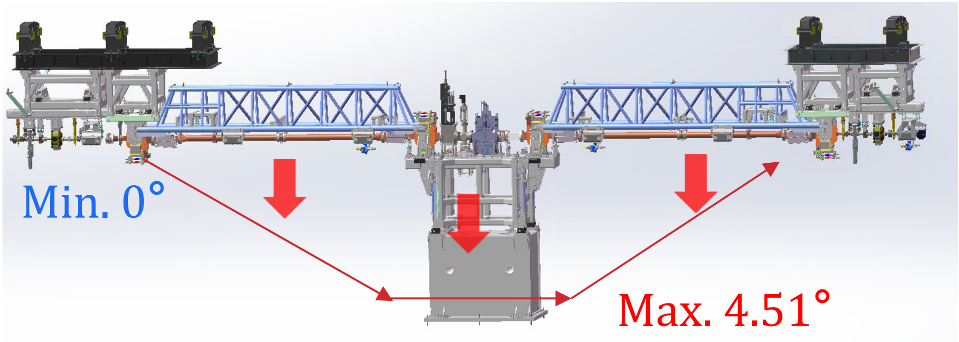
Introduction – *Why*

- **Beam energy:** one of the key parameters for FEL facilities
  - Beam energy determinate the radiation wavelength
  - The stability of beam energy determinate the stability of FEL radiation

$$\lambda_l = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{k^2}{2}\right)$$

- Accurate and precise beam energy measurement is crucial for the optimal performance of the facility
  - Used for radiation wavelength calibration
  - Used for **feedback** to stabilize the beam energy, maintain a constant output wavelength
  - An essential tool for the commissioning and acceptance of FEL facilities.
- **New demands from New facilities: e.g. SHINE**
  - BC1@SHINE: 200 MeV to 500 MeV (R56=-61mm@200MeV, aperture： 115mm×35mm)
- **A non-intercepting robust broad beam energy measurement system is necessary.**





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Introduction – *How*

■ Measuring the bunch/synchrotron radiation light position at the chicane is a commonly used method.

Synchrotron radiation monitor

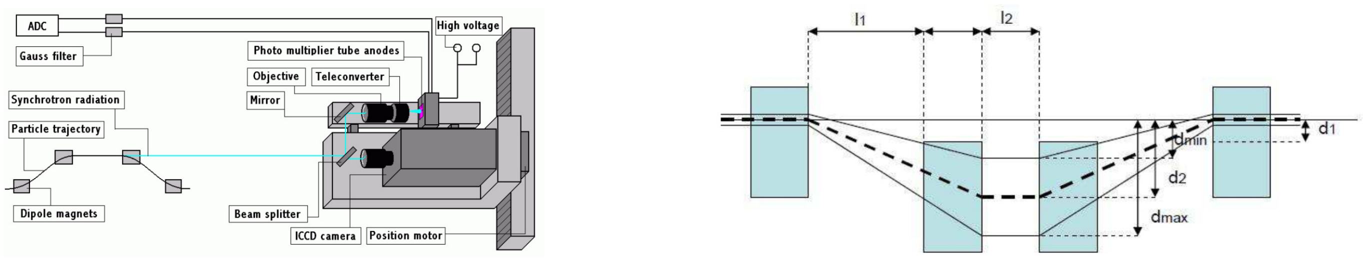


Fig.1 Synchrotron radiation monitor[1-2]

Intuitive and effective but expensive & complex

Chicane BPM

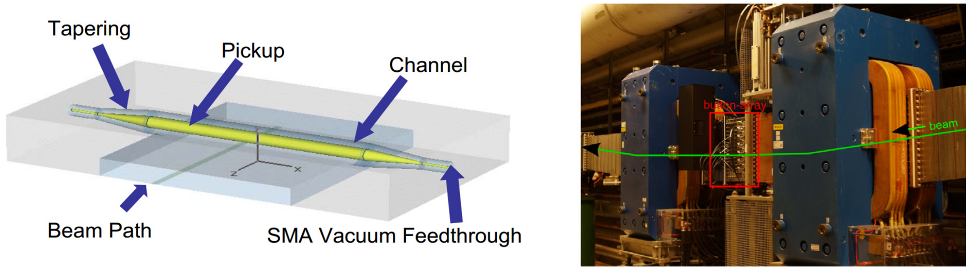
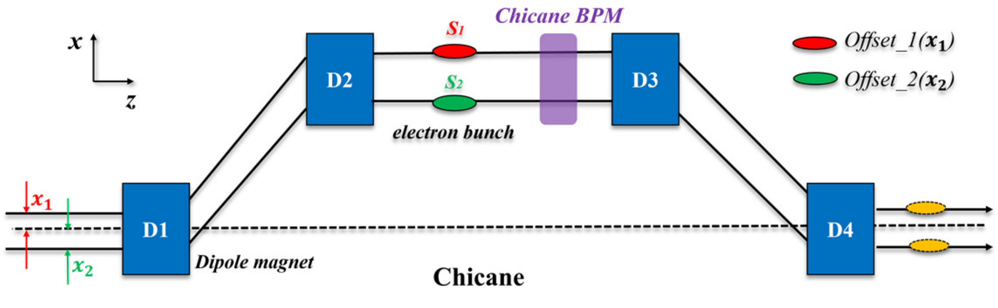


Fig.2 Chicane beam position monitor[3-4]

■ SXFEL: a stripline-BPM was utilized at the 1st BC of LINAC used for energy monitoring and feedback.

- ➢ Calibration of the initial position to obtain a more accurate measurement of beam position changes.
- ➢ Limited by the signal-to-noise ratio (SNR) of the electrode signal away from the beam(offset↑, SNR↓)
- ➢ Affected by the bunch profile inside the chicane



[1] Gerth C. Proceedings of DIPAC. 2007, 7.
[2] Wilhelm A, Gerth C, Proceedings of DIPAC. 2009.
[3] Lorbeer B, et al. Energy Beam Position Monitor Button Array Electronics for the European XFEL[J]. 2018
[4] Hacker K. Measuring the electron beam energy in a magnetic bunch compressor[R]. 2010.

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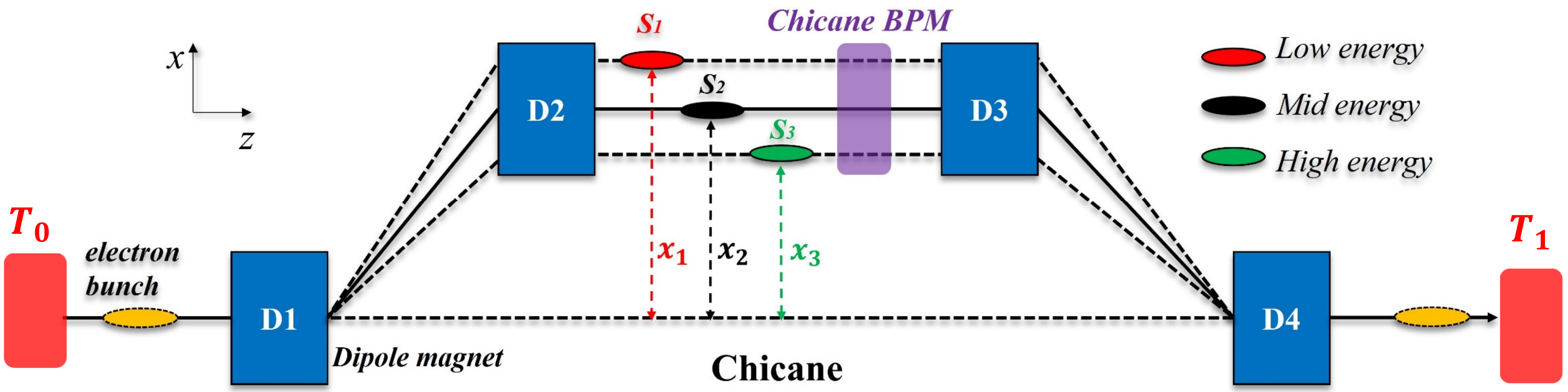
Introduction – *How*

- *Instead of measuring the beam position inside the chicane, can we determine the bunch energy by measuring certain parameters outside of the chicane?*



$$\Delta x = R_{16}\frac{\Delta E}{E}$$

bunch position

$$\Delta l = R_{56}\frac{\Delta E}{E}$$

the path length

$$\Delta t = R_{56}\frac{\Delta E}{E}/\beta c$$

bunch flight time

Also found a reference[4]

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Motivation

- **Questions:**
  - Can chicane-based beam flight time be used for beam energy measurement?
  - What is the performance like?
  - Which method is preferable for nondestructive beam energy measurement: BPM or BFT?

- **Motivation:**
  - Investigate this beam flight time-based beam energy measurement scheme
  - Establish an applicable system and evaluate the system performance
  - To learn and compare the two methods

Development of the BFT-BEM system

- Fundamental principles
- BEM system

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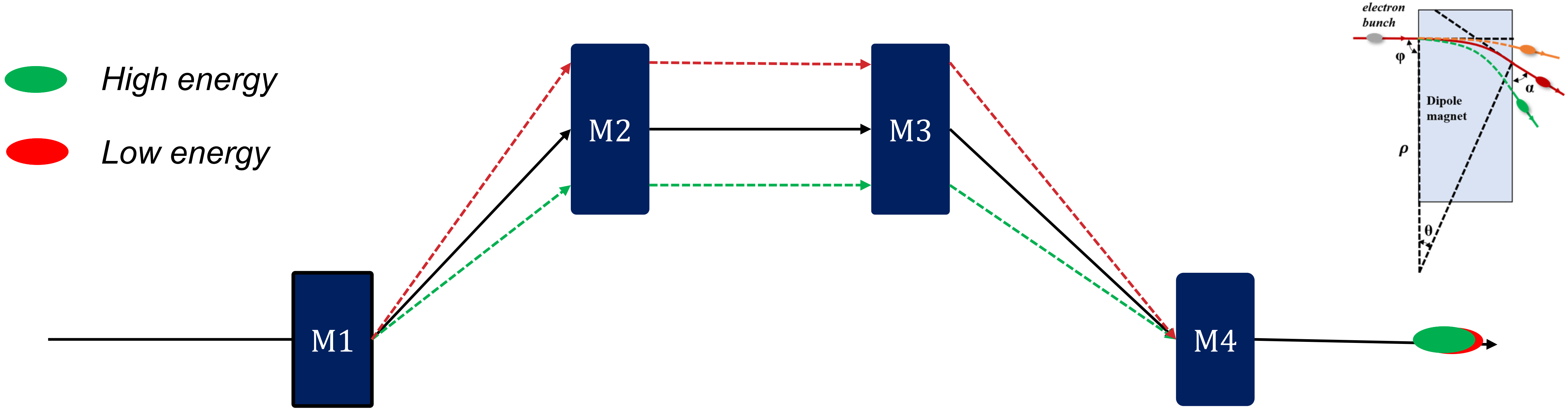
Fundamental Principle



- With an approximation, the bunch flight time (BFT) and bunch position at the chicane can be expressed as:

$$\Delta E \sim \Delta t_{bc} = R_{56} \cdot \Delta E/E\beta c, \Delta x_{bc} = R_{16} \cdot \Delta E/E$$

- Especially, given the bunch inclination, the relation between the beam energy and BFT can be determined:

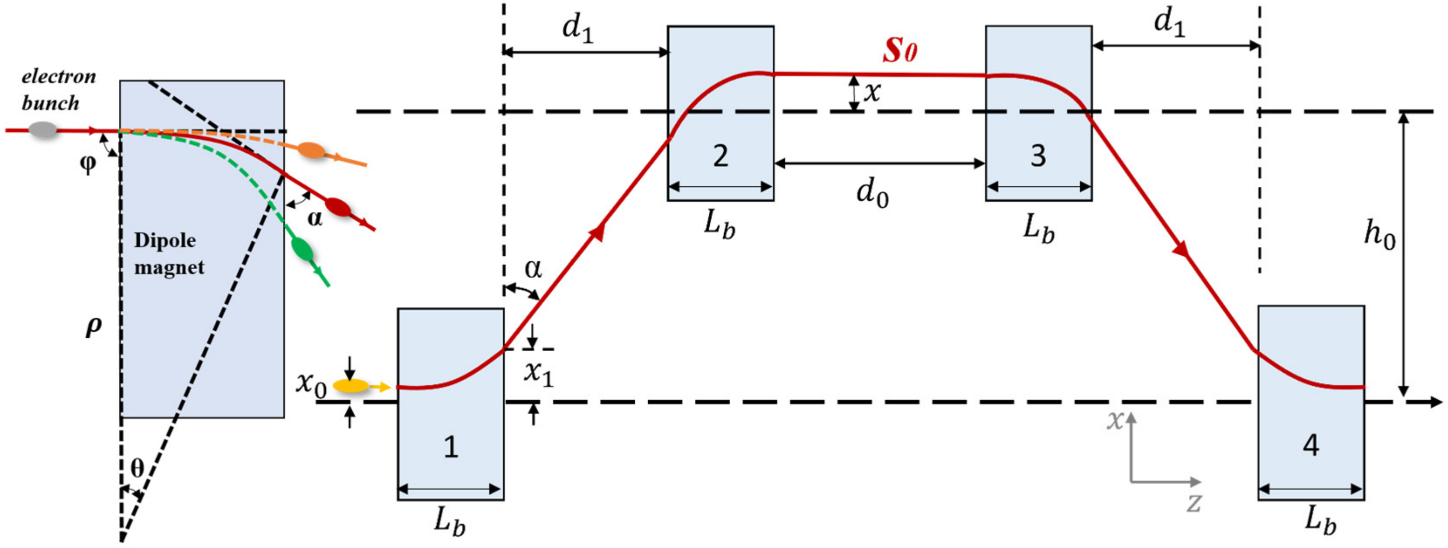
$$t_{fly} = \left(\sum_{i=1}^{4} l_i + \sum_{1}^{3} l_{i,i+1}\right) \Big/ \beta\, c$$

$$l_1 = \rho \cdot \theta$$

$$l_{12} = \frac{d_1}{\sin(\pi - \theta - \varphi)}$$

$$\cos(\alpha) + \cos(\varphi) = L_b/\rho \qquad \rho = \frac{\sqrt{\mathrm{W}(\mathrm{W} + \mathrm{e}_0)}}{ZcB}$$

Analysis of BC1@SXFEL



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	4.81	m
h_0	0.33	m
R_{56}	48	mm
R_{16}	351	mm

- Take the BC1@SXFEL-LINAC as an example, the relation between the BFT and beam energy is expected to be: (E=230MeV)

$$\frac{\Delta t_{bc}}{\Delta E} = 0.696\ ps/MeV$$

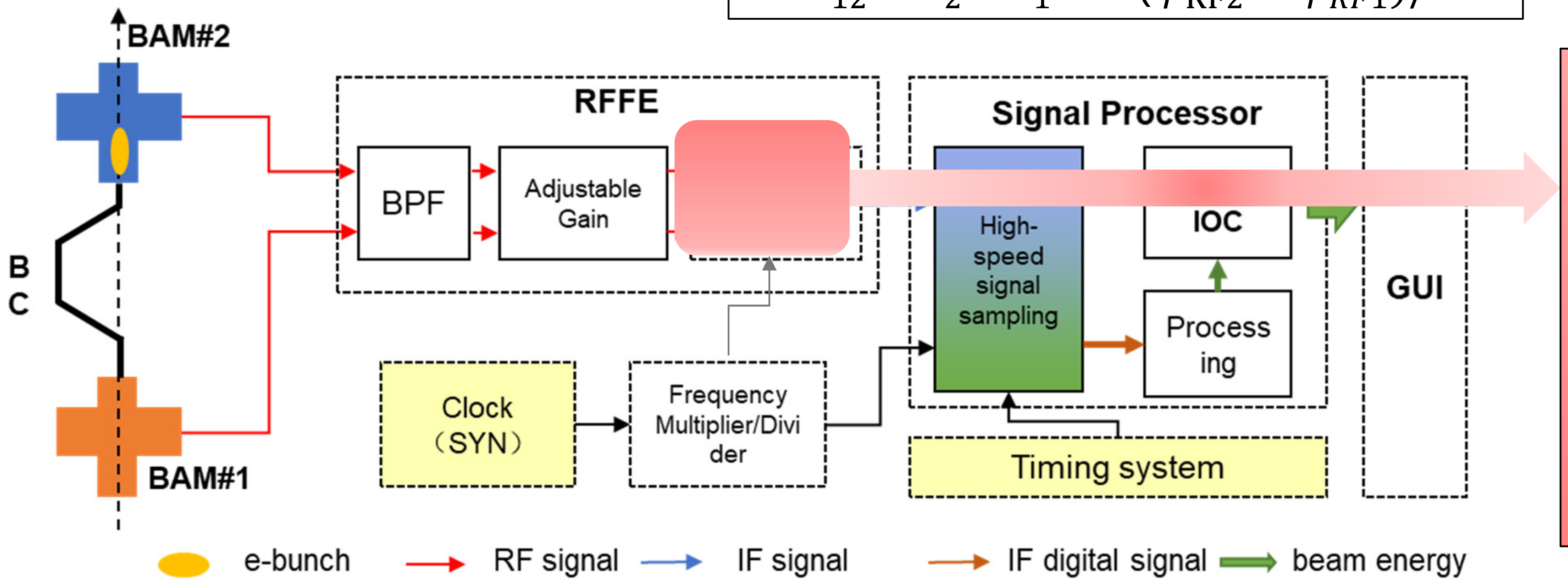
- Similarly, the relation between the beam position and beam energy is:

$$\frac{\Delta x_{bc}}{\Delta E} = 1.52\ mm/MeV$$

System scheme

- The system comprises the following components:
  - **Two cavities (BAMs):** Coupling out RF signal carrying the information of beam arrival time;
  - **RF front-end electronics (RFFE):** RF signal conditioning including filtering, amplifying, and mixing, etc.;
  - **Signal processor electronics**: signal acquisition and processing, BAT extraction

$$\Delta t_{12} = t_2 - t_1 = (\phi_{\mathrm{RF2}} - \phi_{RF1})/\omega$$



External-mixing IF scheme:

$$\Delta\phi_{\mathrm{RF}} = \phi_{RF2-LO} - \phi_{RF1-LO} = \phi_{IF2} - \phi_{IF1}$$

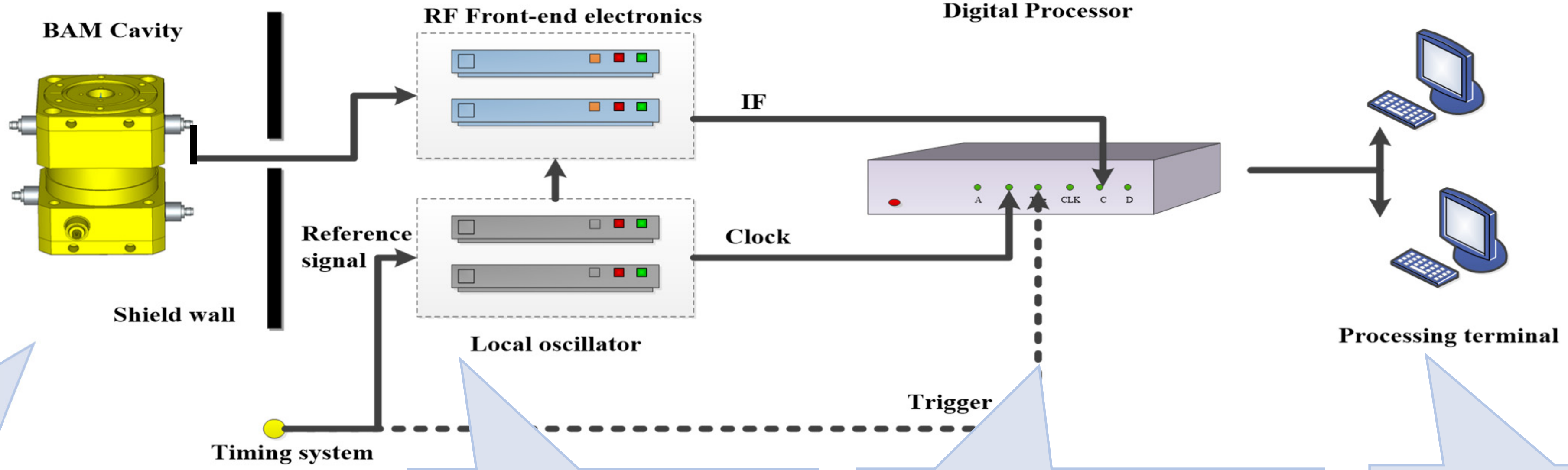
Self-mixing IF scheme:

$$\Delta\phi_{\mathrm{RF}} = \phi_{RF2} - \phi_{RF1} = \phi_{IF}$$

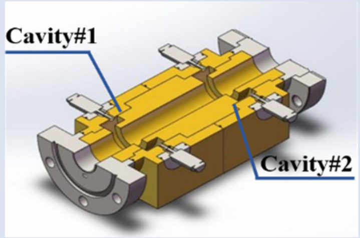
RF scheme：

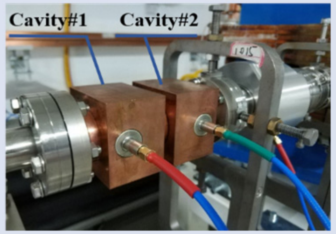
$$\Delta\phi_{\mathrm{RF}} = \phi_{RF2} - \phi_{RF1}$$

Typical External-mixing scheme



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

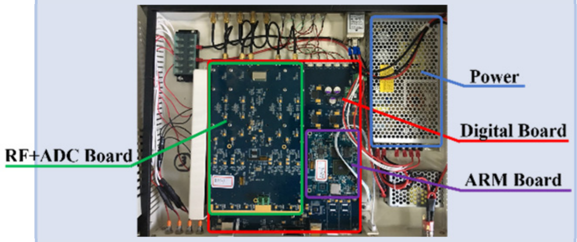
RFFE

LO

Front panel

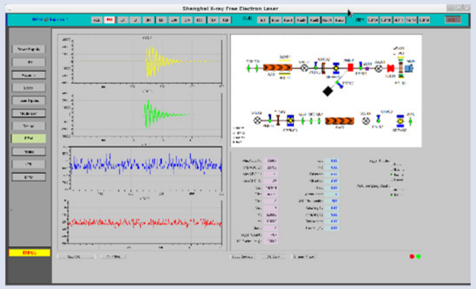
Back panel

DBPM



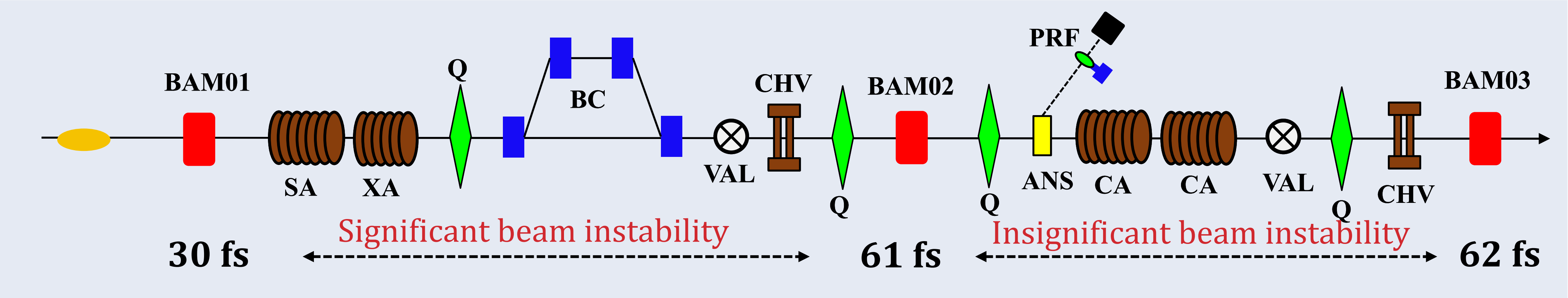
Para.	Value
Sampling rate	119 MHz
Number of bits	16
Channels	4

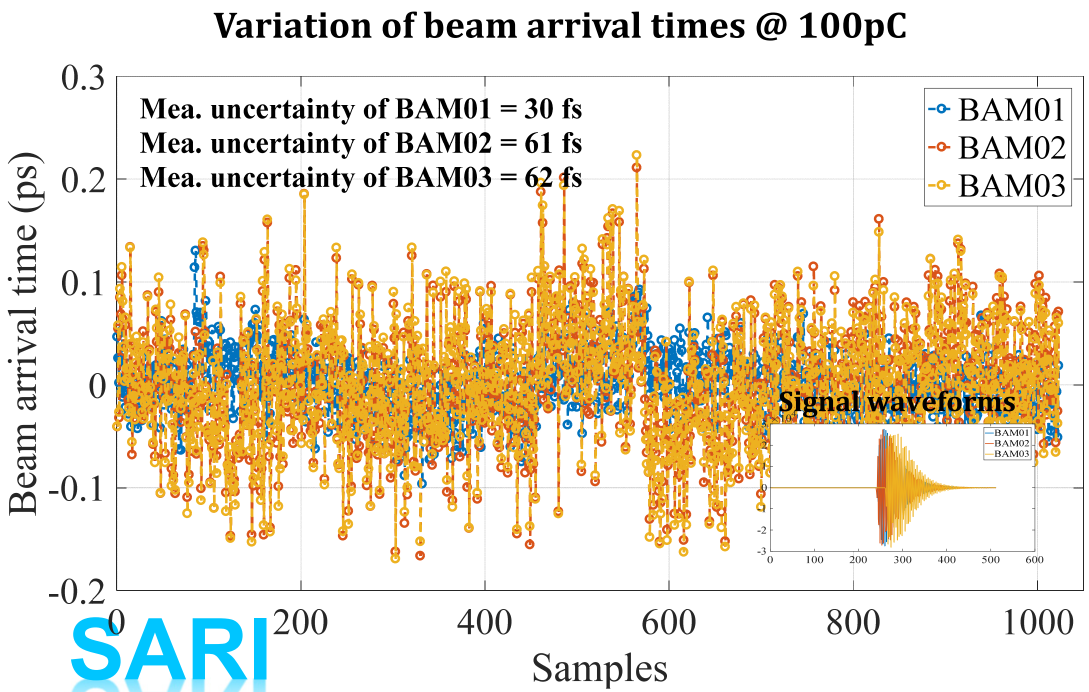
GUI



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

BFT measurement -External-mixing





- 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 (T1)
  - 61 fs @ BAM02 (T2)
  - 62 fs @ BAM03 (T3)
- The min. BFT rms. measurement uncertainty (T3-T2) = 10fs

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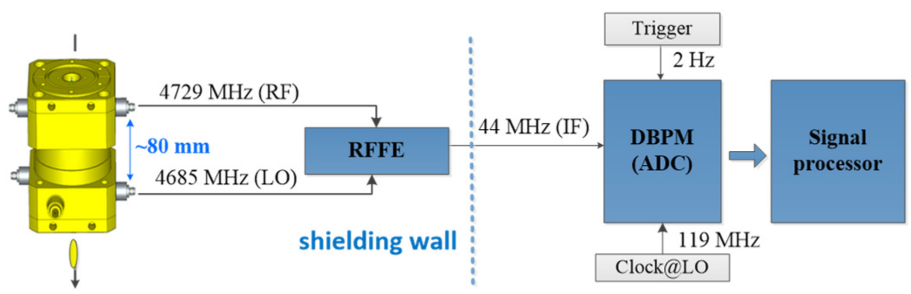
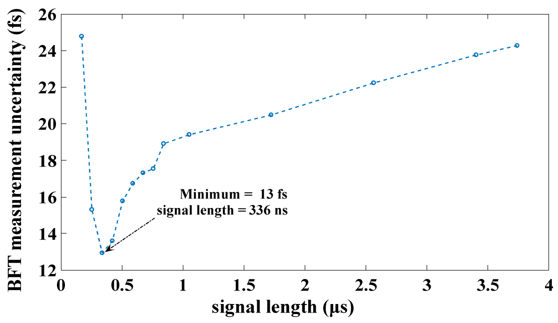
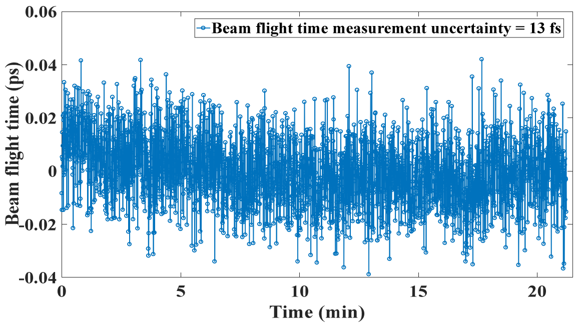
Self-mixing scheme

Short-distance measurement(~80mm)

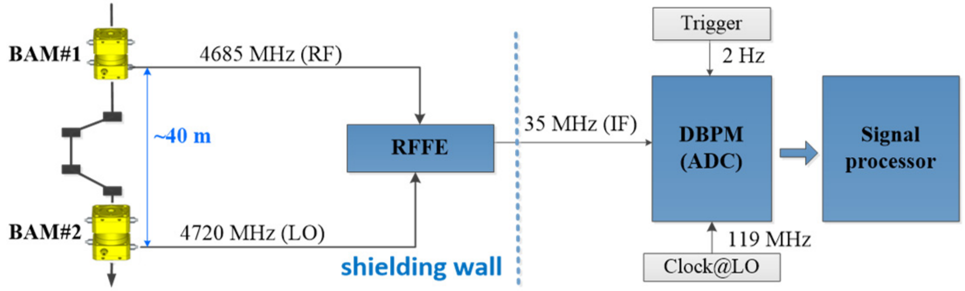


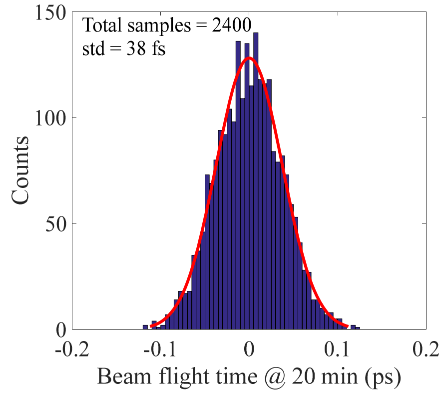


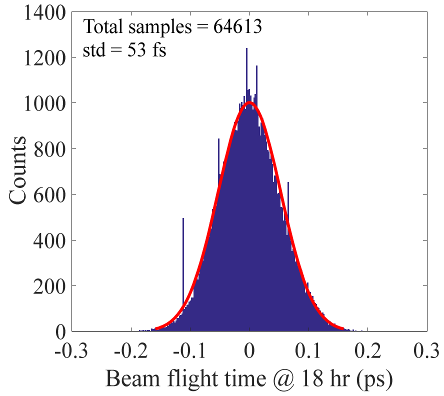


- Best result of measurement uncertainty (RMS): 13 fs over 20 min;
- Beam jitter and temperature drift can be ignored in this case, thus this measurement uncertainty describes the system resolution;

Long-distance measurement (~40m)



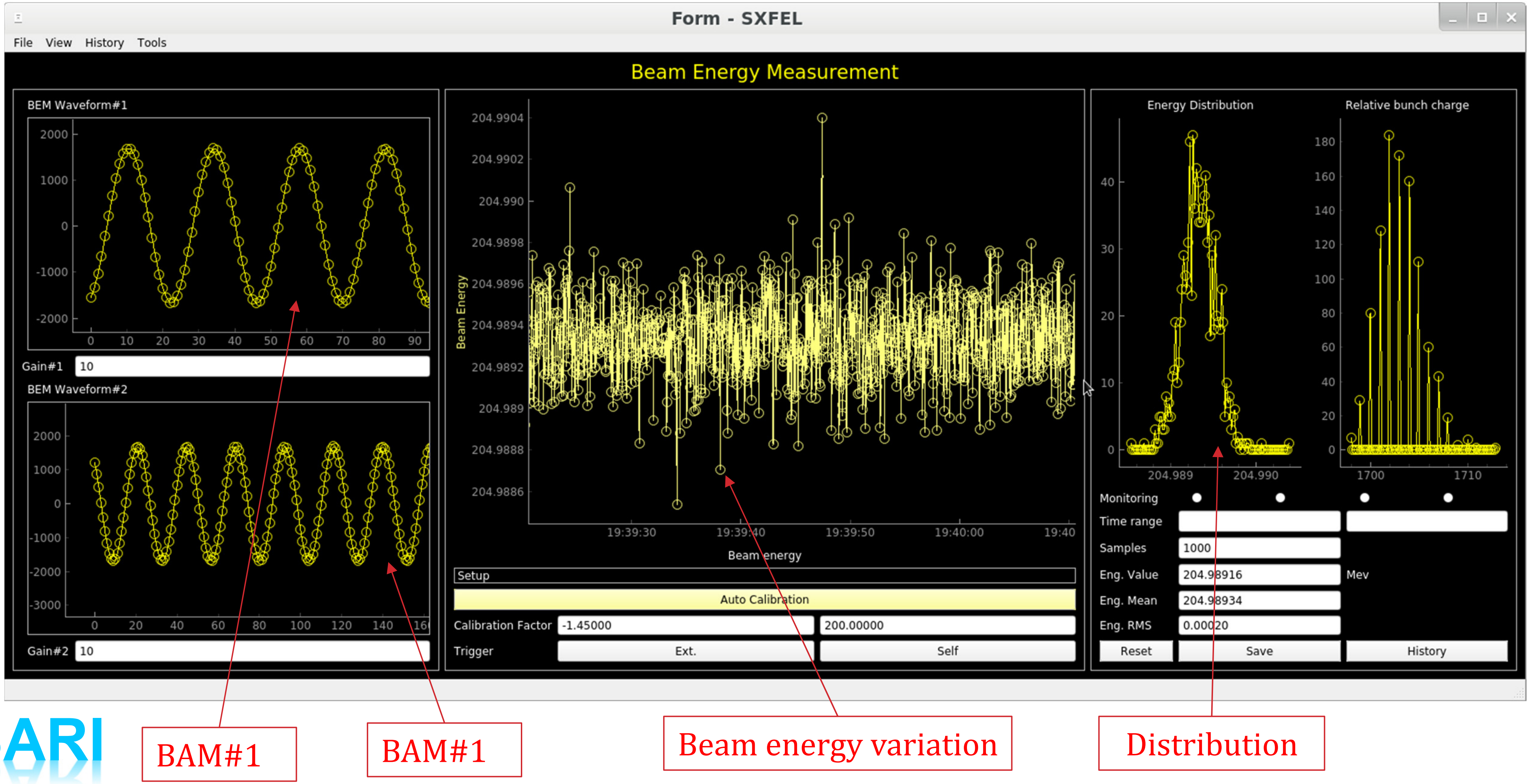




- Best result of measurement uncertainty (RMS) in short-term: 38 fs over 20 min;
- Best result of measurement uncertainty (RMS) in long-term: 53 fs over 18 hours;
- Beam jitter, temperature- and humidity-drift, and vibration contribute to this phase measurement uncertainty;

GUI for BFT-BEM

- A high-level graphic user interface (UI) for BFT-BEM has been designed and lab tested:



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System performance evaluation

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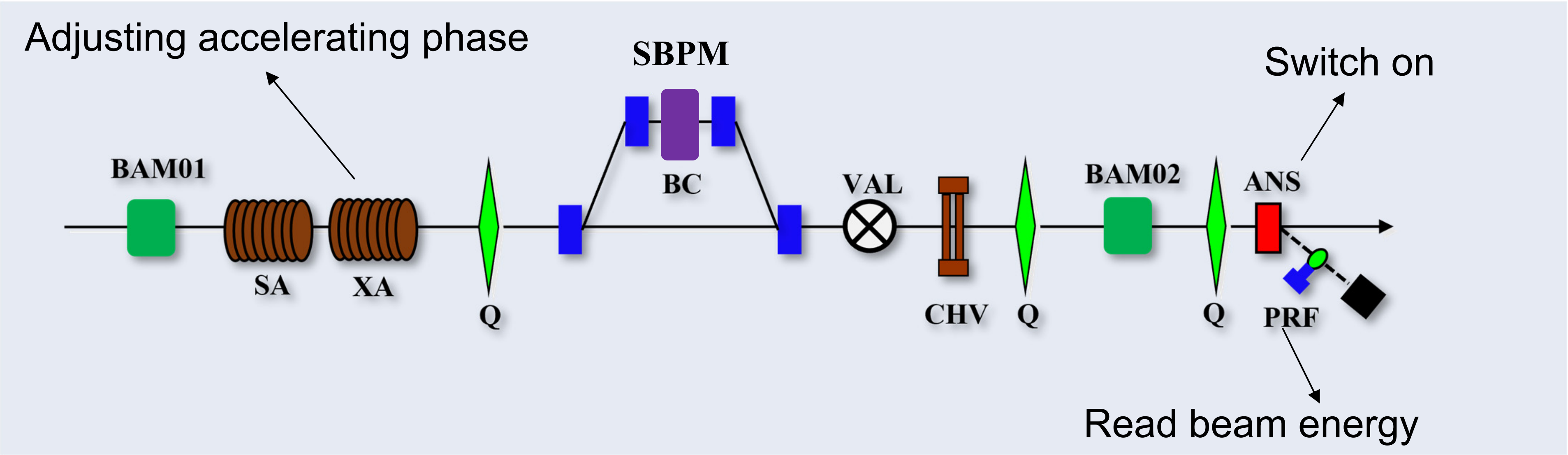
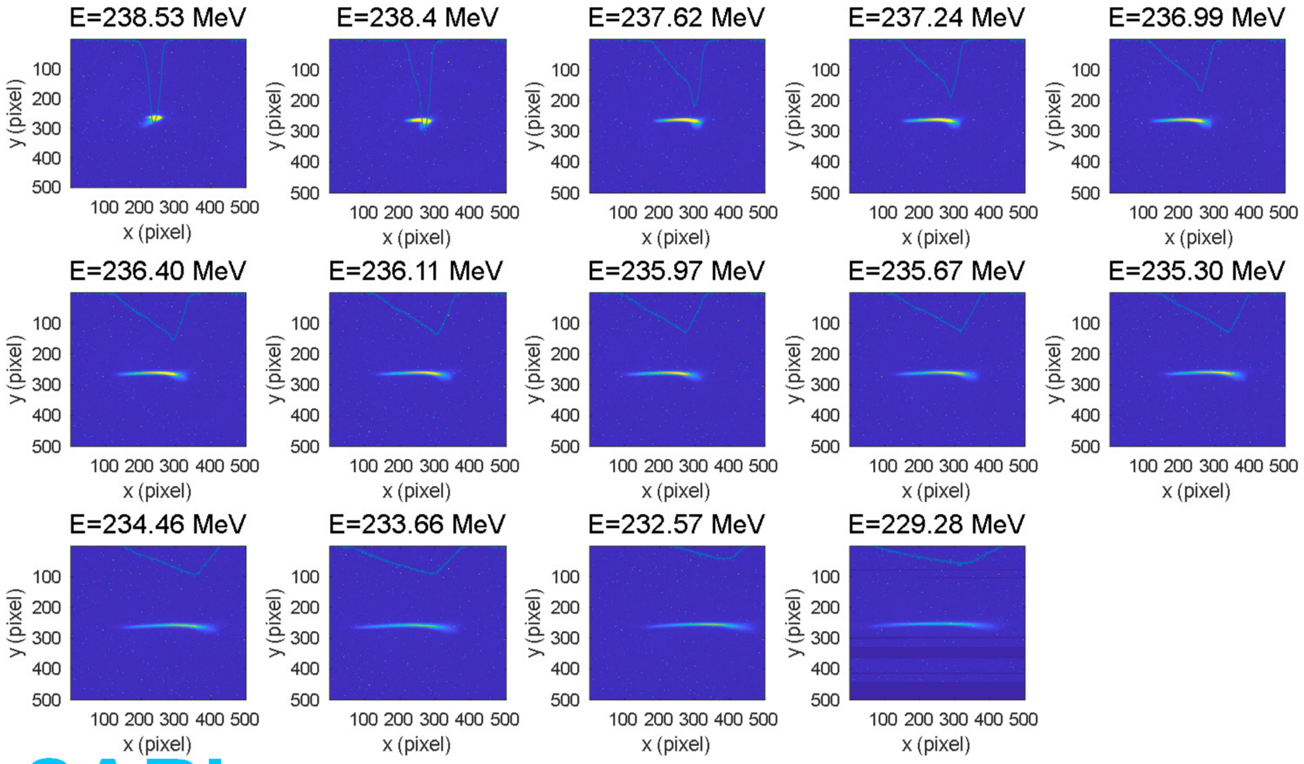
Beam test for evaluation

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



Measurement of beam energy

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

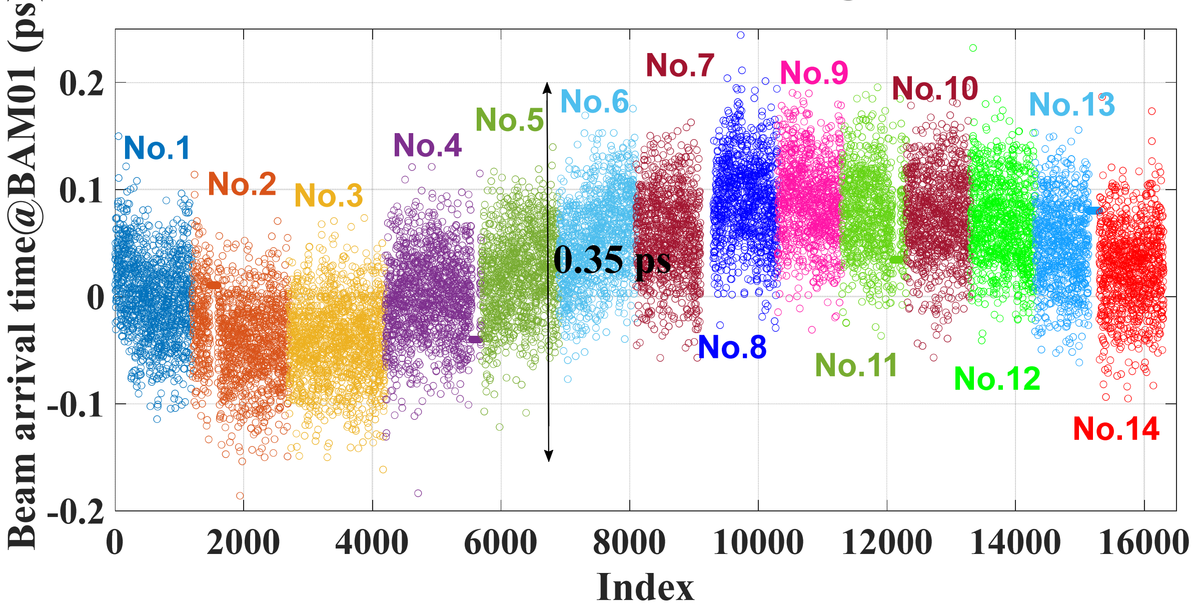


Meas. No.	Acc. Phase/°	Energy/MeV	Energy spread/%	Beam jitter
1	-109	238.53	0.07	0.03%
2	-113	238.40	~	~
3	-118	237.62	0.18	0.03%
4	-120	237.24	0.20	0.02%
5	-121	236.99	0.23	0.02%
6	-123	236.40	0.26	0.04%
7	-123.5	236.11	0.27	0.03%
8	-124	235.97	0.28	0.03%
9	-125	235.67	~	~
10	-126	235.30	~	~
11	-128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

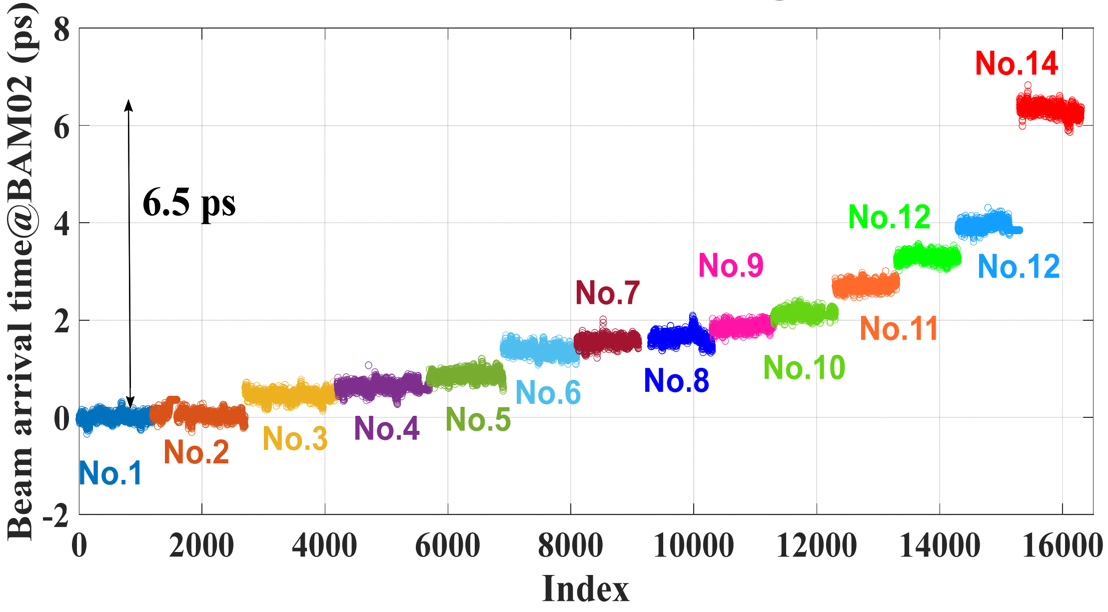
Measurement of beam arrival time

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

Variation of beam arrival time @ BAM01



Variation of beam arrival time @ BAM02



- 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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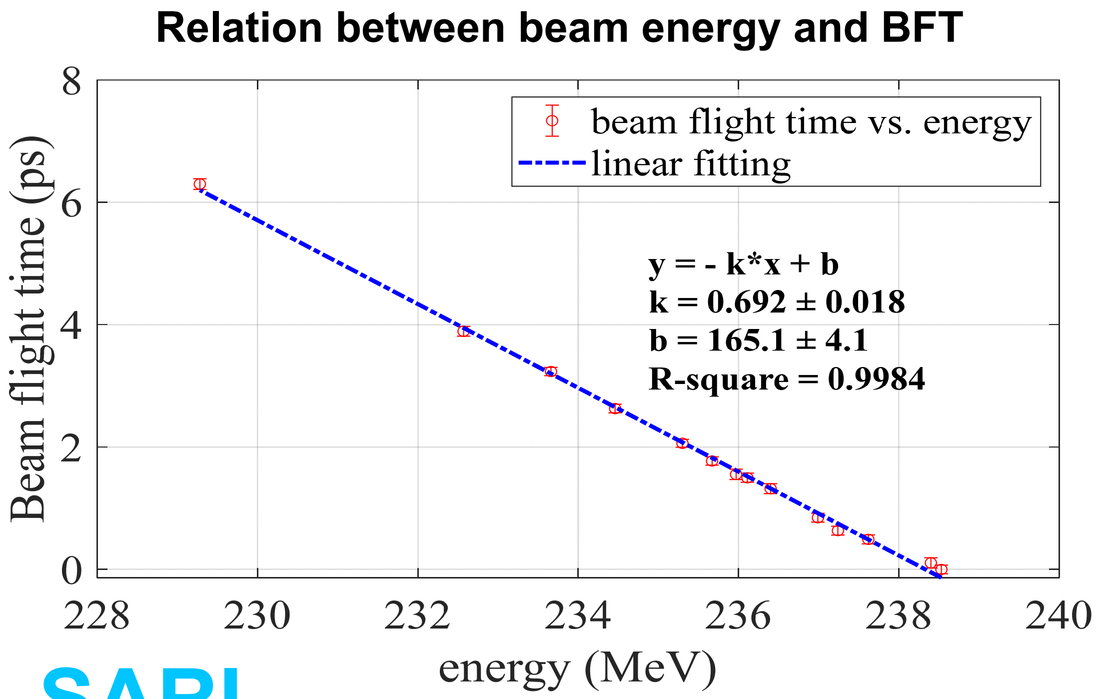
Relation between BFT and energy

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

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



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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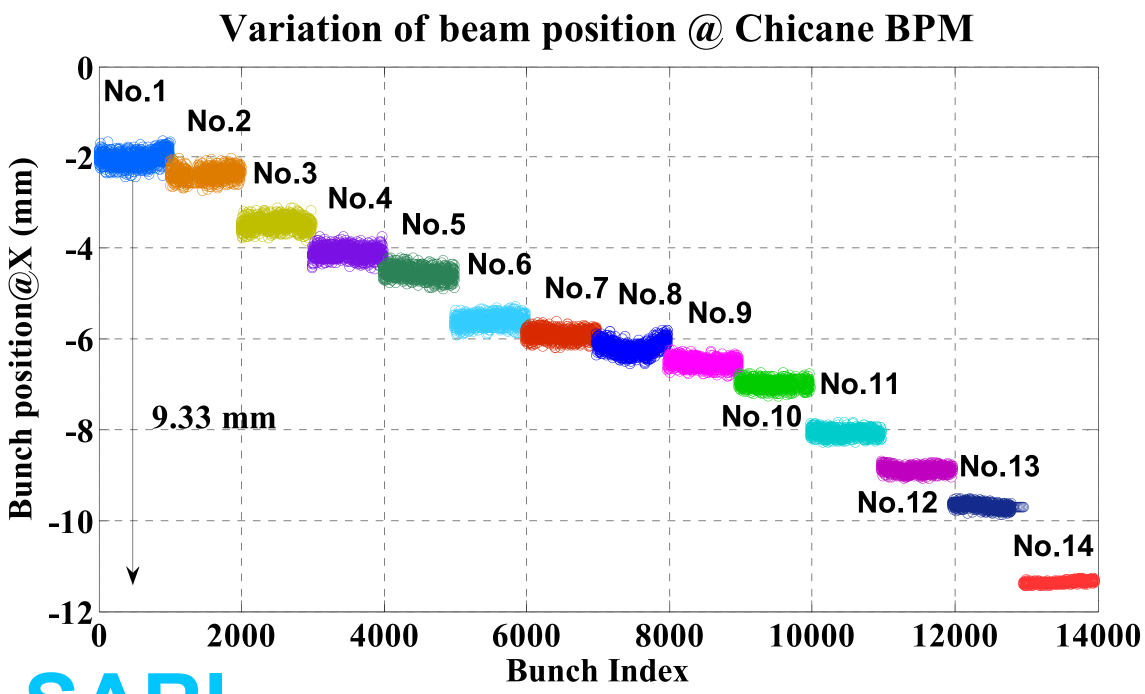
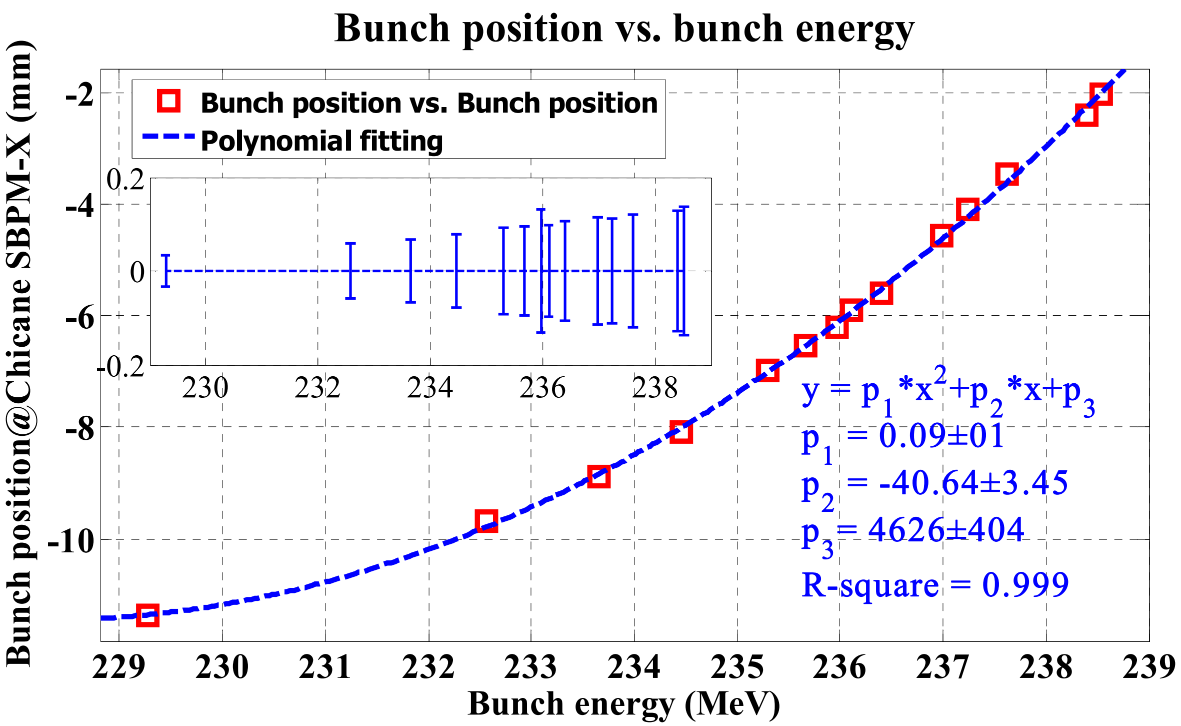
Relation between beam position and energy

- A quadratic polynomial relation between the beam energy and beam position is obtained via the beam test:

$$\boldsymbol{x = k * E^2 + b * E + c},$$
$$k = \mathbf{0.09} \pm 0.01\, mm/MeV^2, b = -\mathbf{40.64} \pm 3.45 mm/MeV, c = 4626 \pm 404 mm$$





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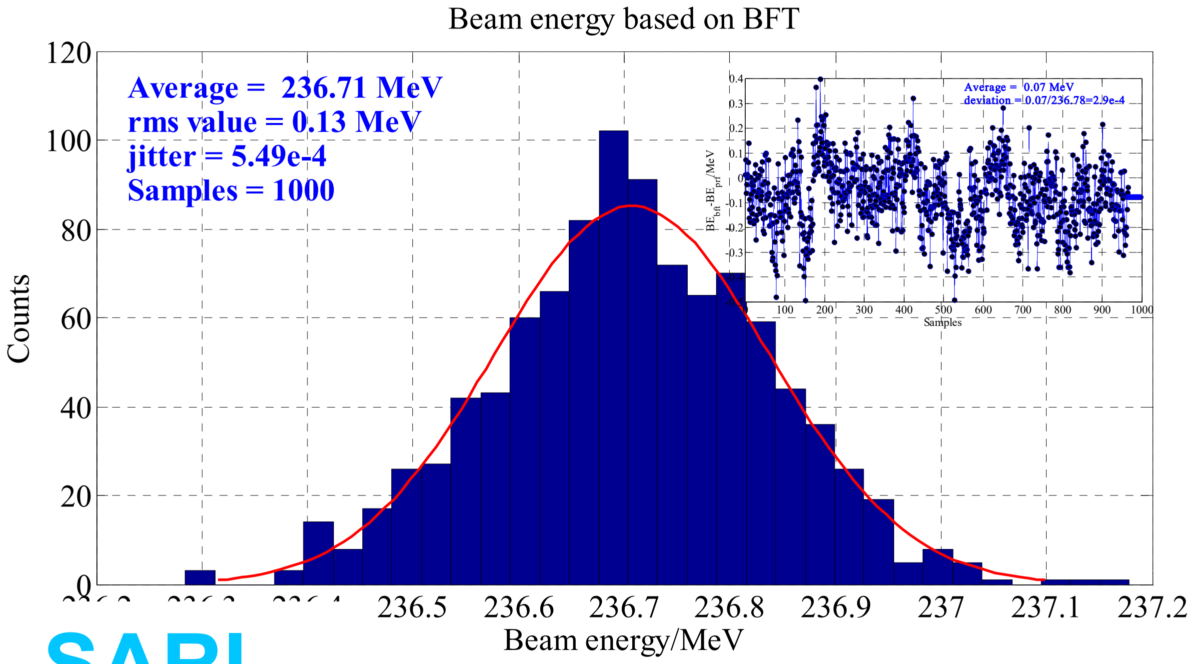
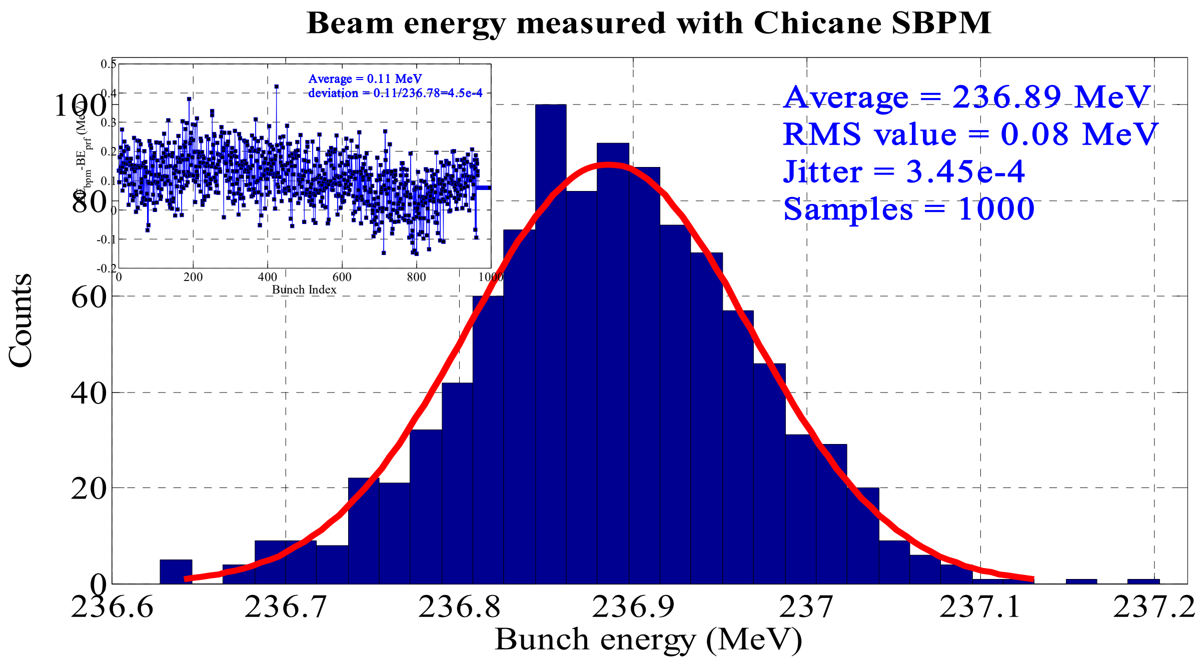
Analysis of BEM with BFT

Using above linear factor, the beam energy was measured with this system:

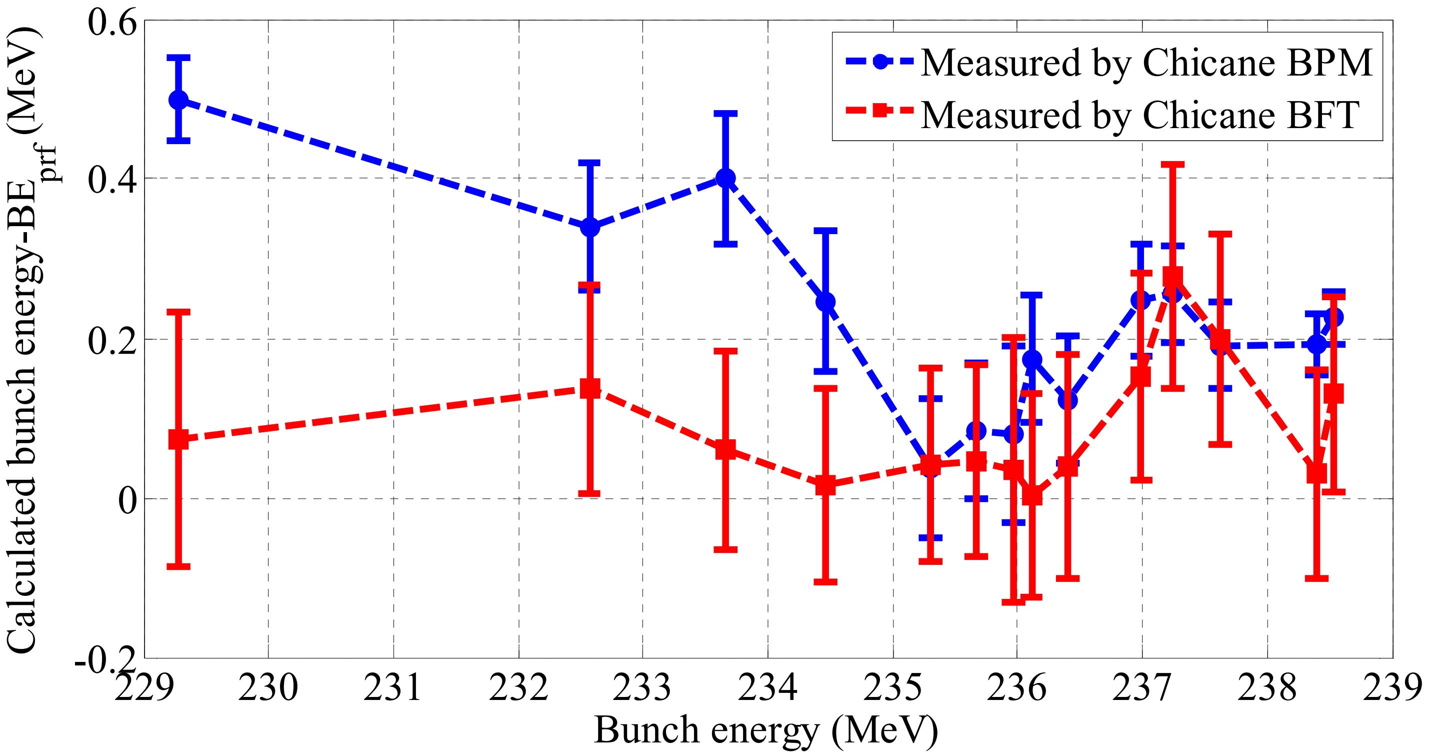
- For 1000 measurement (near 10min), the average energy measured by the profile is **236.78** MeV, the average energies by BFT-BEM and BPM-BEM are **236.71** MeV and **236.89** MeV, respectively.
- The energy jitters measured by BFT-BEM and BPM-BEM are **5.49e-4** and **3.45e-4**, respectively.
- The deviations compared to the PRF-BEM are **0.07 MeV** and **0.11 MeV**, respectively.





Analysis of BEM with BPM & BFT

- The beam energy measured by BFT has less deviation compared to the reference energy than the beam energy measured by BPM;
- However, the energy jitter obtained by BFT is larger than that measured by BPM;



Discussion

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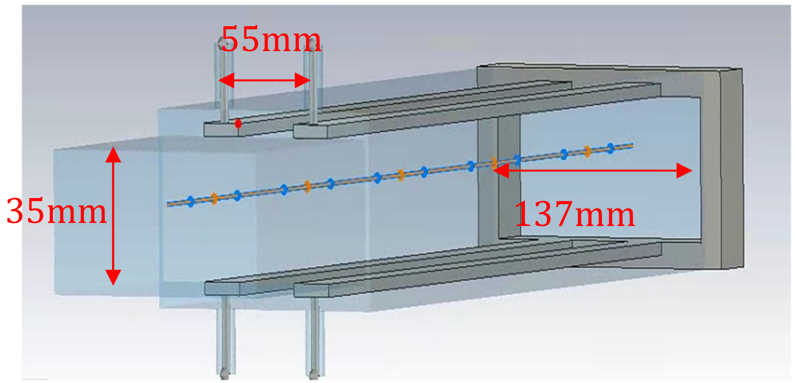
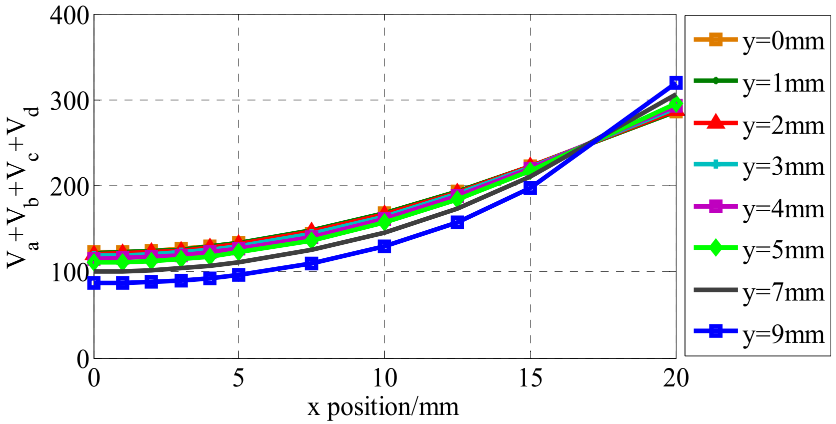
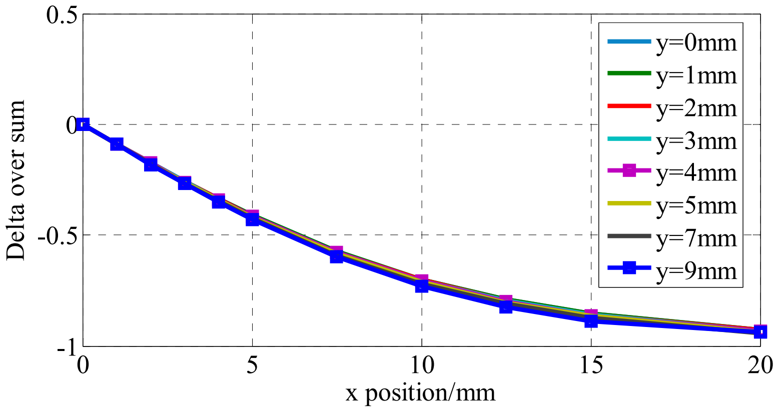
Discussion

***Why** is the relation between BP and BE nonlinear ?*

- The Chicane BPM is a rectangular four-electrode strip-line beam position monitor.
- As the beam offset increases, the relationship between the delta-over-sum and the beam position exhibits nonlinearity.
- Thus, the beam position obtained using the conventional delta-over-sum algorithm is smaller than the actual beam position;
- By applying the nonlinear algorithm, the beam position offset is found to be 13.9 mm for a beam energy change of 9.25 MeV, the result is nearly consistent with the formula-based calculation.







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Comparison of the two methods

- The beam test results of the two methods have been summarized in the table below.
- Overall, both have their own merits:
  - For beam energies with **small variations** (e.g. <3 MeV), **the BPM-BEM** is more suitable due to its higher precision. (Beam position should be calibrated or have a stabilized position before the Chicane).
  - For beam energies with **larger variations**, the **BFT-BEM** method is preferable because of its **larger linear region** and better accuracy;

Methods	BEM@BFT		BEM@BPM	
Analytic @230MeV	Linear	0.696 ps/MeV	Linear	1.52 mm/MeV
Beam test@230MeV	Linear	0.692 ps/MeV	quadratic polynomial	(0.09, -40.64) -> 1.76mm
Range @$\Delta E = 9.25MeV$	Analytic	6.44 ps	Analytic	14.06 mm
	Beam test	6.34 ps	Beam test	9.33 mm -> 13.9mm
Energy@237.78MeV	236.71 MeV	0.07 MeV	236.89 MeV	0.11 MeV
Energy jitter	0.13 MeV	5.49e-4	0.08MeV	3.45e-4

Conclusion

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Conclusion

- The bunch energy system, based on RF cavity-based bunch arrival time monitors, has been developed at SXFEL-UF, and the beam test results have verified its capacity for beam energy measurement..
  - A linear relationship between the beam energy and the beam flight time, as the beam travels through a magnetic chicane, is observed for energies ranging from 230 to 239 MeV.
  - Formula:-0.696 ps/MeV beam test: -0.692 ps/MeV
  - The system resolution should be better than 5.49e-4, linear range: over 9 MeV
- For beam energy with **larger variations (e.g. >3MeV)**, the **BFT-BEM** method is preferable.
- Next, we will continue to utilize valuable machine study time to learn the system's long-term stability and the impact of parameters such as bunch profile, bunch length, and energy spread on the measurements, and to further optimize the system.

Acknowledgement

Great appreciation to *Prof. Leng* for his valuable suggestions and support.

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Thank you!