Bunch-resolved 3D beam position measurement system and its application in FELiChEM

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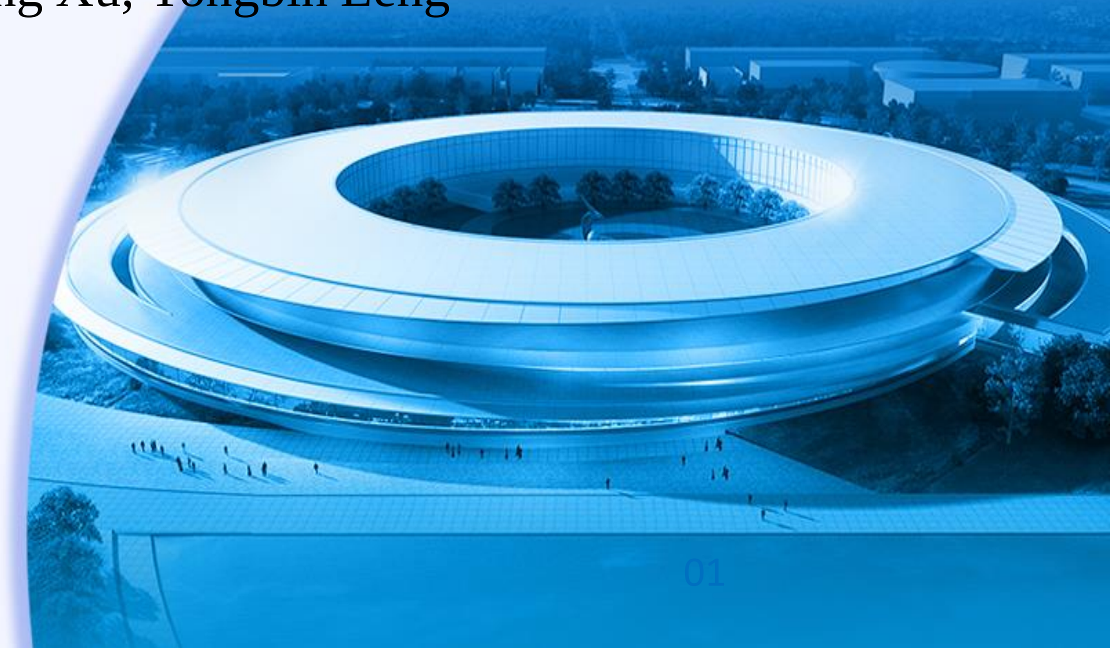


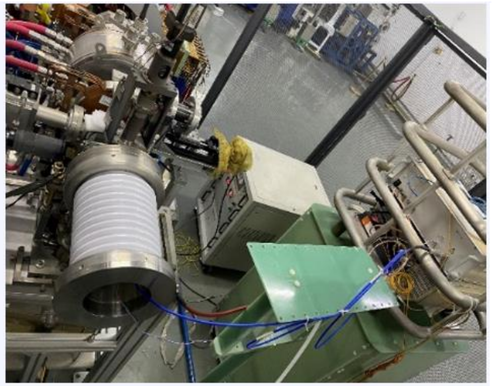
Outline

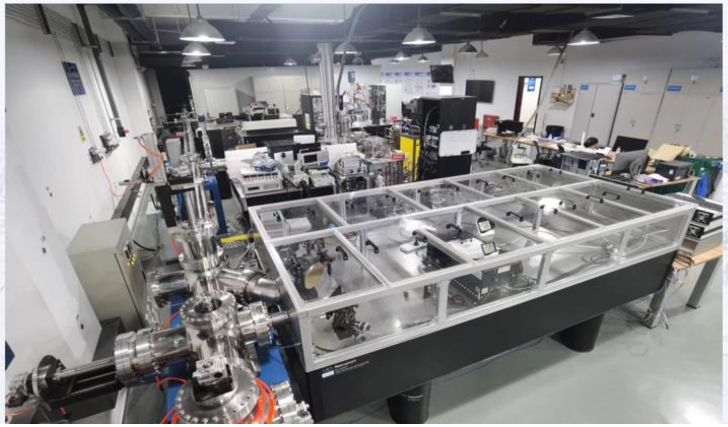
- Introduction
  - Facility overview
  - Motivation to upgrade BPM (bunch-by-bunch capability)
- Bunch-resolved 3D BPM system setup
  - Key issue: response function reconstruction in LINAC
  - Signal conditioning to improve resolution
- Application
- Summary

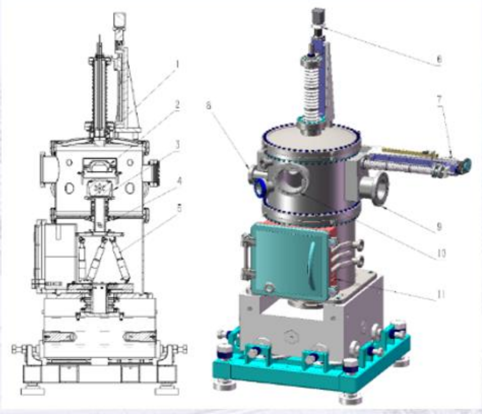
Introduction

What is FELiChEM

FELiChEM is an experimental facility at the University of Science and Technology of China (USTC). Its core device is two free electron laser oscillators generating middle-infrared and far-infrared laser and covering the spectral range of 2.5–200 μm. It is a dedicated infrared light source aiming at energy chemistry research.



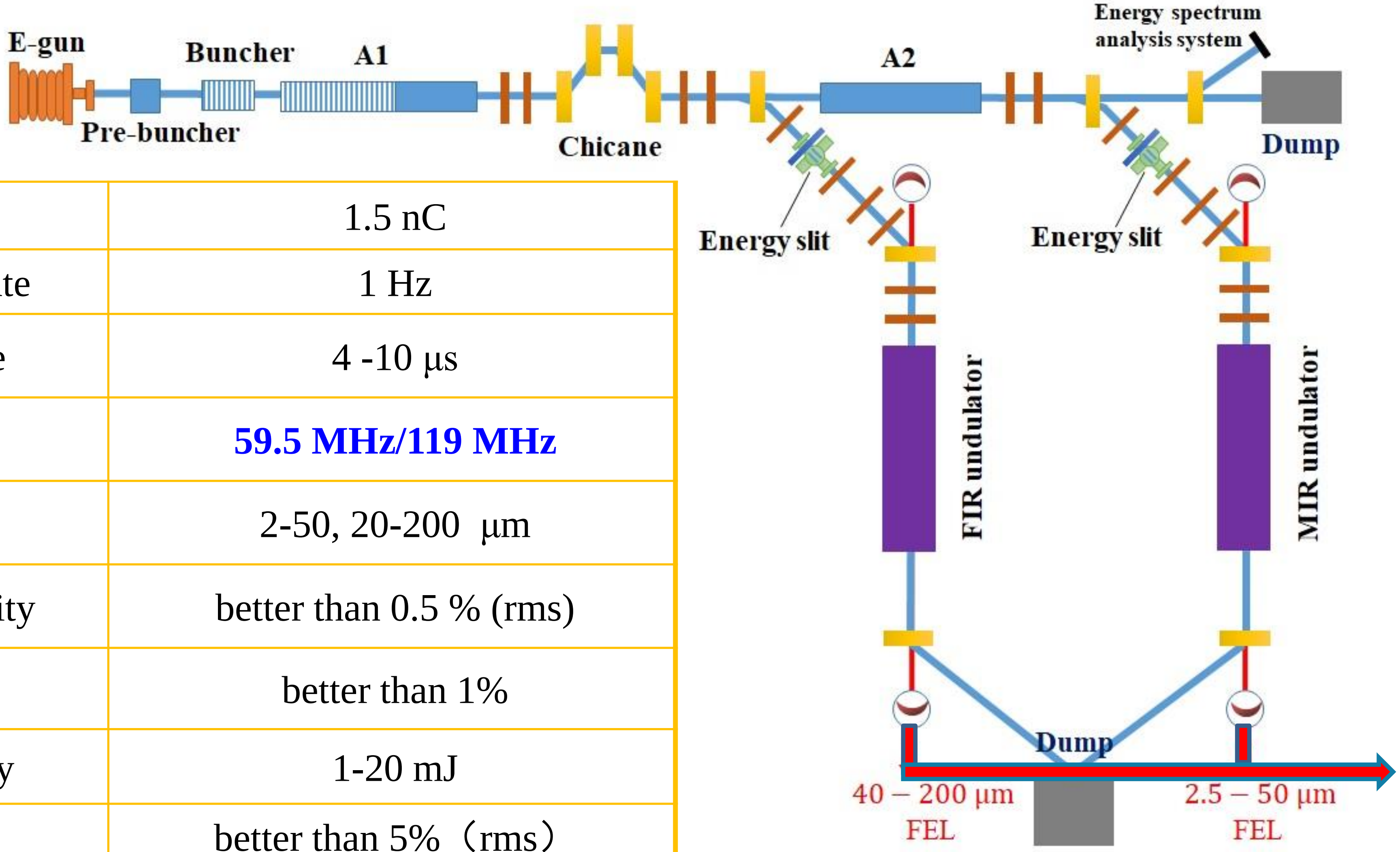




Energy	30-50MeV
Type	Undulator
Range	2.5~200 μm (4000~50 cm^{-1})
middle-infrared	2.5~40 μm (4000~50 cm^{-1})
far-infrared	20~200 μm (4000~50 cm^{-1})
Monochromaticity	~1%
Polarization type	Horizontal
Structure	Macro + micro pulse
Macro pulse	Repetitive: 10Hz Length: 5~10 μs Peak Power ~5kW (Energy: ~100 mJ)
Micro pulse	Repetitive: 2856 MHz adjustable Length: 5~10 ps Peak Power ~5MW (Energy: ~20μJ)

Machine parameters

Users require better radiation, need to find a way to improve FEL performance



Charge	1.5 nC
Macro pulse repetitive rate	1 Hz
Macro pulse length rate	4 -10 μs
Micro repetitive	**59.5 MHz/119 MHz**
Wave length range	2-50, 20-200 μm
Center wavelength stability	better than 0.5 % (rms)
Monochromaticity	better than 1%
FEL Macro pulse energy	1-20 mJ
FEL energy stability	better than 5%（rms）

How to improve radiation performance

Electron Beam + Undulator + Resonant cavity + Waveguide → FEL performance

Single pass gain
FEL basic parameters

Multi-pass gain to reach saturation

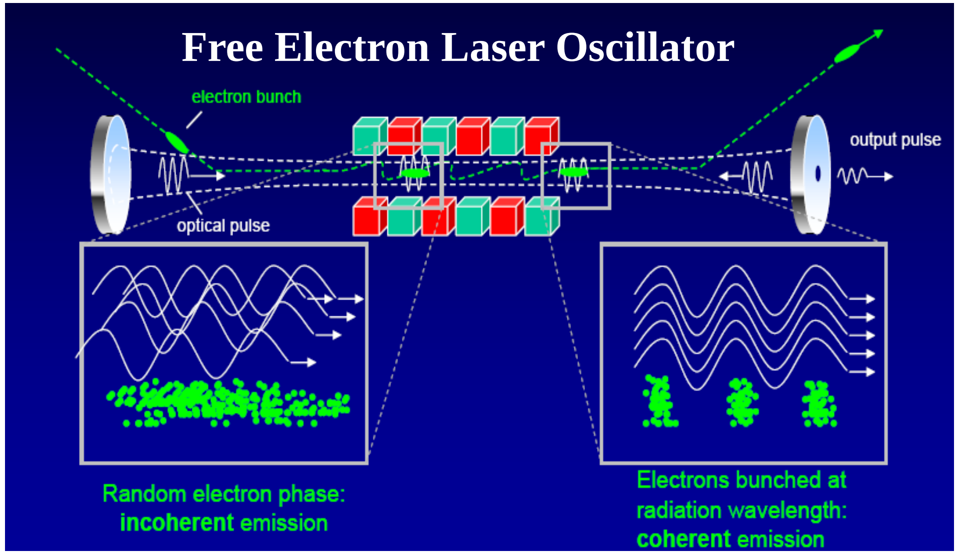
Reduce diffraction loss

Single pass gain $g = f_{\sigma_r} f_{\varepsilon_n} f_{\mu_c} g_s$

Energy spread Emittance Diffraction Small signal gain

Multi-pass power $P_m = P_0(1-\alpha)^{m-1}\prod_{i=2}^{m}(1+g_i)$

Cavity loss



- Electron beam should have a good quality for achieving enough gain to overcome single-pass loss

$$\varepsilon_n < \frac{\gamma\lambda_s}{4\pi} \qquad \frac{\Delta\gamma}{\gamma} < \frac{1}{4N_u} \qquad g_s = 3.74\pi^2 N_u^2 \frac{1}{\gamma}\frac{a_u^2}{1+a_u^2}\frac{I_p}{I_A}[JJ]^2$$

- Cavity must strictly match the beam repetitive frequency to ensure the multi-pass gain

$$T_e = M\frac{2L_c}{c}$$

- Good balance between output coupling and cavity loss to optimize the saturation output power

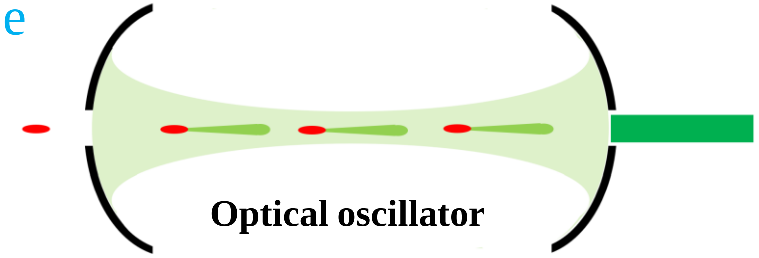
$$g \gg \alpha > Threshold$$

- Waveguide modes should match the radiation wavelength to avoid the “spectrum gap”
- Optical axis must strictly match beam axis to maintain interaction between FEL and beam along undulator

Bunch resolved 3D BPM required

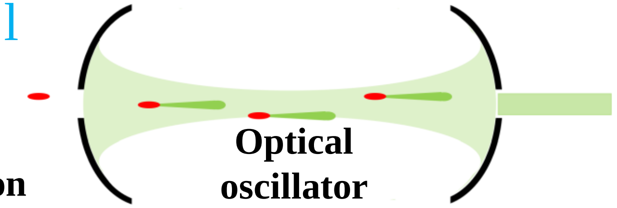
Optical axis must strictly match beam axis to maintain interaction between FEL and beam along undulator

Ideal case

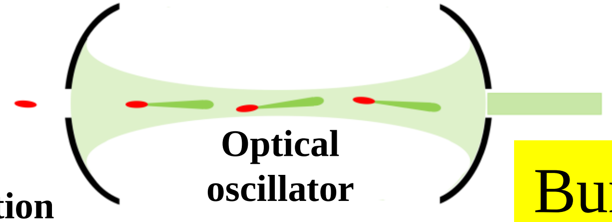


To get the best coherent radiation
all bunches need to go through optical oscillator with
- **Right (same) transverse position**
- **Right (same) trajectory**
- **Right (same) energy**

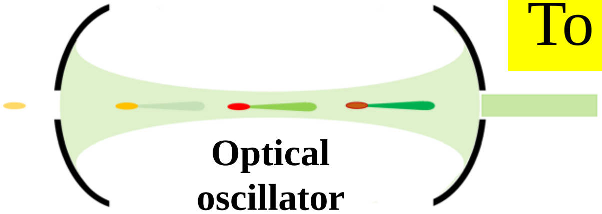
In practical



Position deviation



Trajectory deviation



Energy deviation

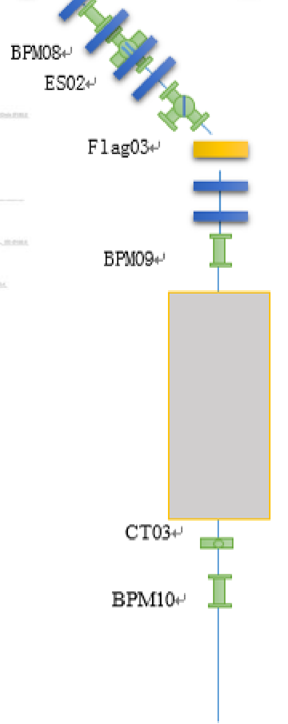
Impossible to get perfect uniform bunch train
- **Position: 0.3mm deviation introduce 20% power loss**
- **Trajectory: 0.2mrad deviation introduce 20% power loss**
- **Energy: 0.2% deviation introduce 20% power loss**

Bunch-resolved diagnostics tool required
To monitor and guide to tuning individual bunch parameters

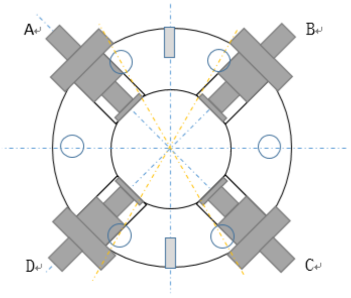
Present beam instrumentation system

- **Charge:** ICT + FCT + scope
- **Profile:** YAG/OTR + normal CCD (~Hz)
- **Position:** Button + Libera Single Pass

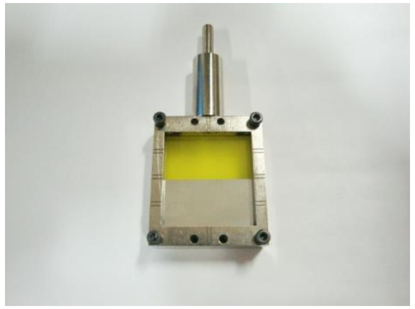
- **Bunch train average measurement only**
- **Not good enough for FEL performance improvement**
- **New bunch-resolved diagnostics tools required**



Libera Single Pass



10 BPM



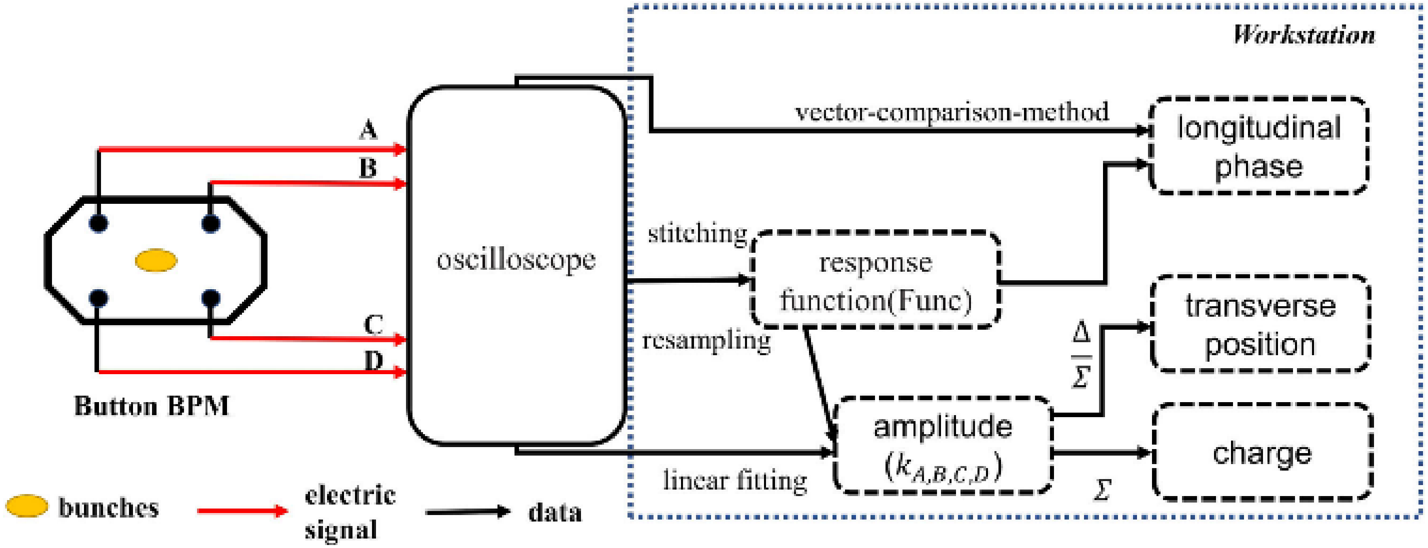
3+1 Flag

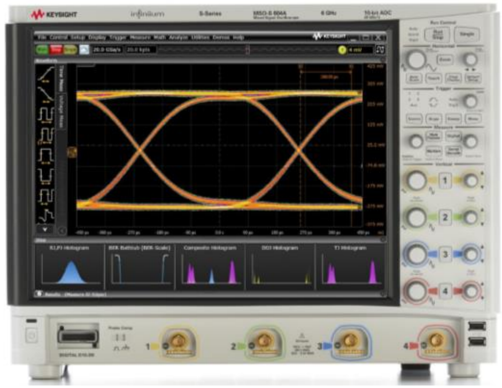
3 ICT

1 FCT

3D BPM system setup

HOTCAP





Source: ⟹ **Hardware:** ⟹ **Data processing:**

Button BPM

$$V_b(t) = \frac{-Z}{\beta c} \cdot \frac{t - t_0}{\sigma^2} \cdot I(t) \cdot F(\delta, \theta)$$

Longitudinal phase (t_0), Charge ($I(t)$), Transverse position ($F(\delta, \theta)$)

Keysight MSOS604A	
Sampling rate	10 GS/s
Bandwidth	4.2 GHz
ENOB	10 bit
Memory depth	103 M/channel

Correlation coefficient-based methods

- Construction of ultra-high time-resolved response functions
- 3D position information extraction

- **Experimental Verification and Analysis of Beam Loading Effect Based on Precise Bunch-by-Bunch 3D Position Measurement, IBIC2022**
- **Non-Invasive Machine Parameters Measurement in a Storage Ring Based on Bunch-by-Bunch 3D Position Data Correlation Analysis, IBIC2021**
- **Beam Coupling Impedance Analysis Using Bunch-by-Bunch Measurement, IBIC2020**
- **Injection transient study using 6-dimensional bunch-by-bunch diagnostic system at SSRF, IBIC2018**

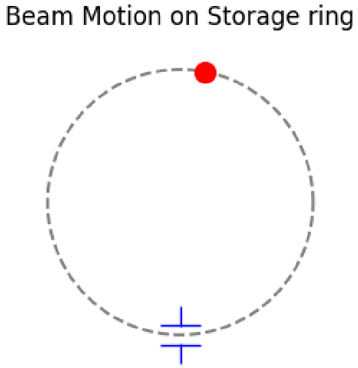
HOTCAP for LINAC: key issue

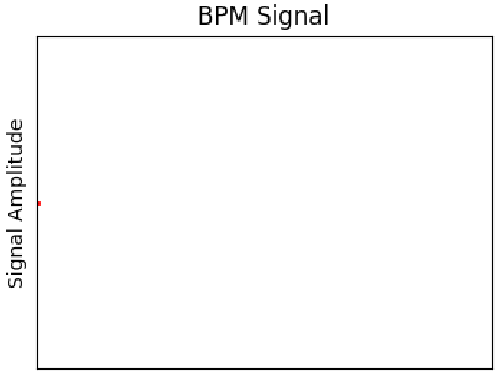
NSRL National Synchrotron Radiation Laboratory

System response function in a ring can be built with equivalent sampling method

Single bunch signal in a Ring

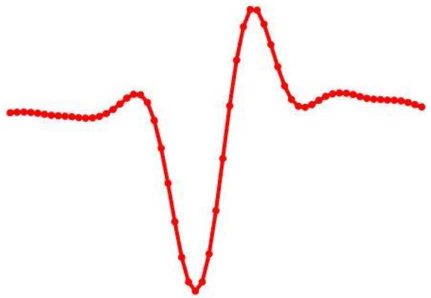
Same bunch passes through pickup many turns





Multi turns data

Equivalent sampling

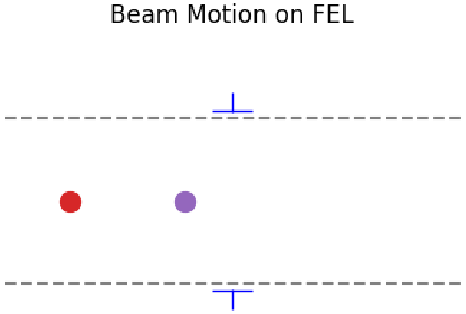


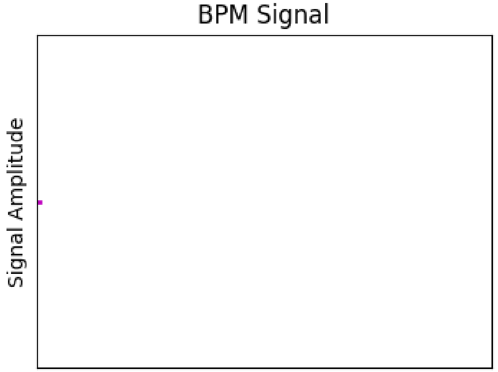
Response function

Similar method can be used in a LINAC (with uniform bunch train condition)

Bunch train signal in a LINAC

Many bunches pass through pickup once





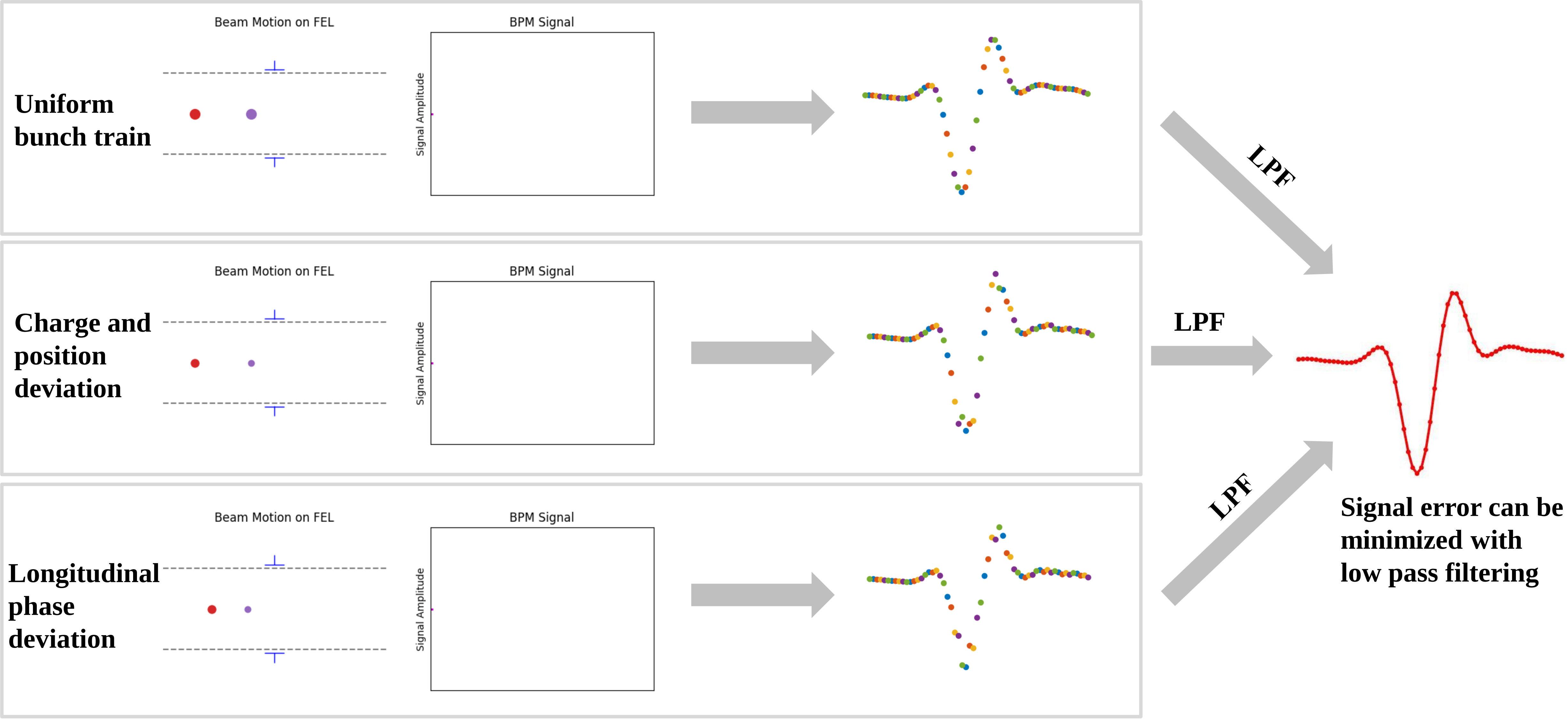
Multi bunches data

Equivalent sampling

Response function

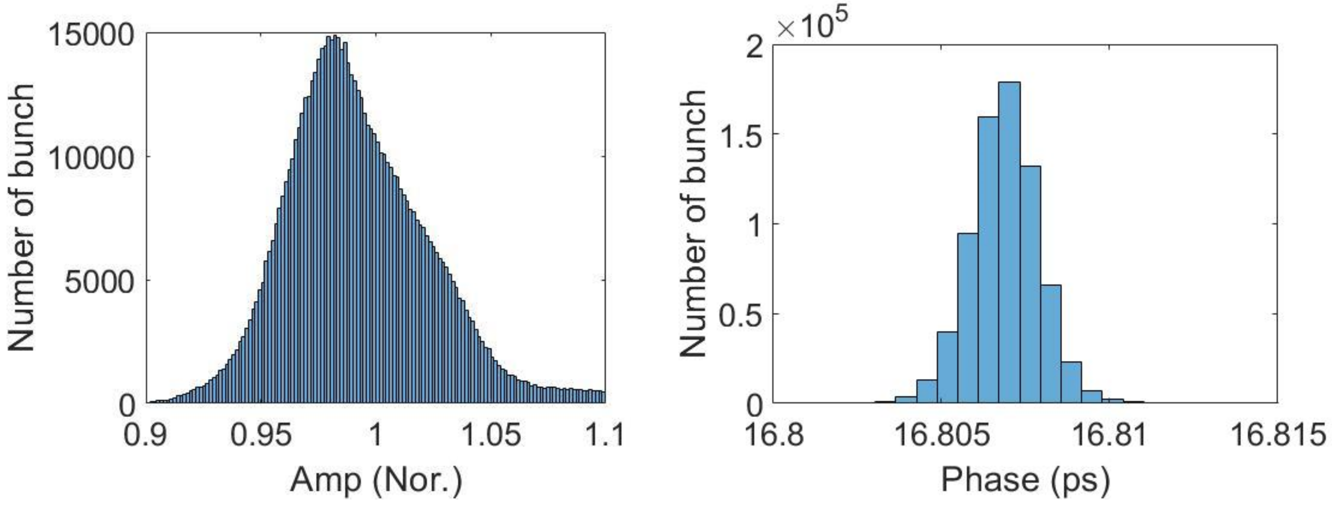
HOTCAP for LINAC: key issue

Measurement error is acceptable with small charge, position and phase deviation

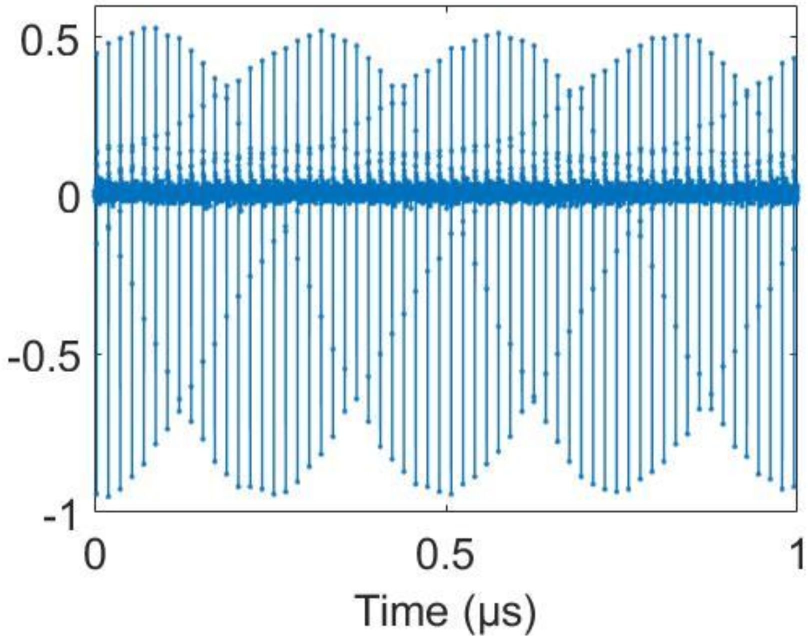


HOTCAP for LINAC: FELiChEM case

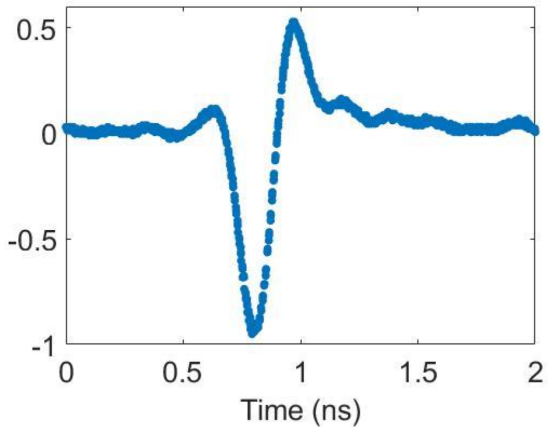
In FELiChEM case, bunch train charge, position and phase deviation is small enough



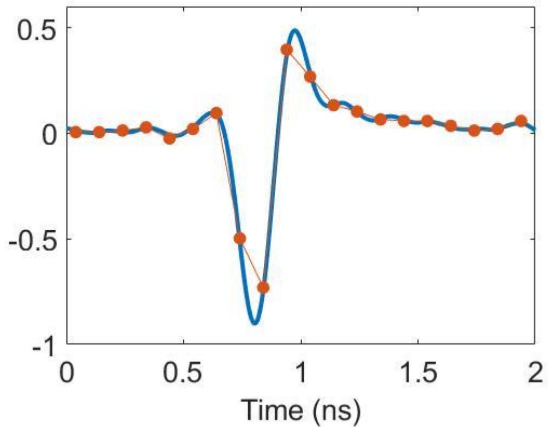
Varied Amp & Phase
Close to the normal distribution



Original Signal (local)



Response Function



Matched Amp & Phase by correlation coefficient
(phase = -6 ps amp = 0.95)

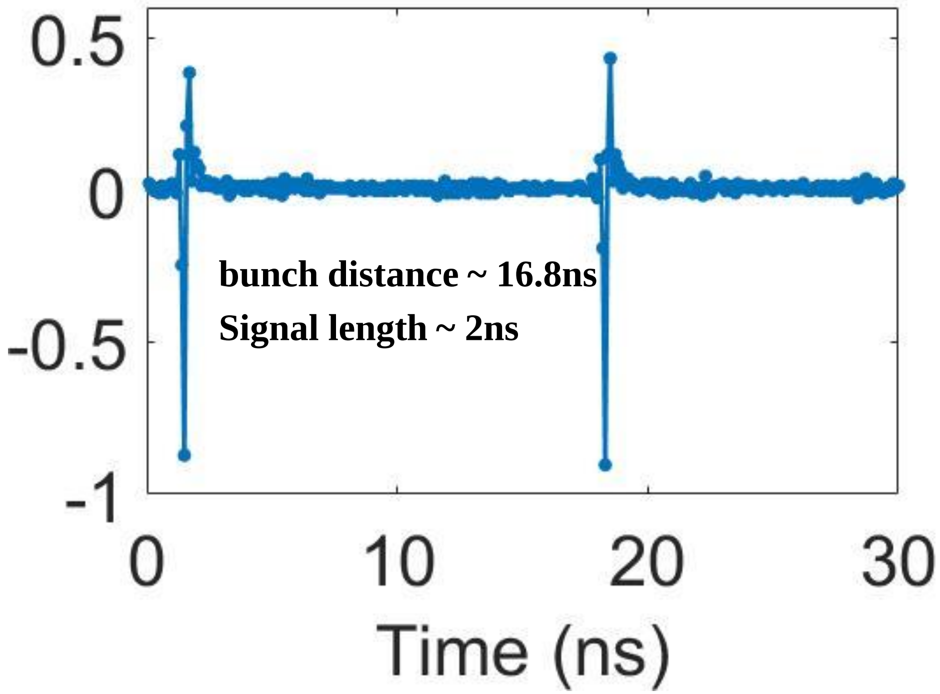
Performance improvement: signal conditioning

Raw signal direct sampling

Charge resolution: ~0.2%

Hori. resolution: 9μm

Vert. resolution: 13μm



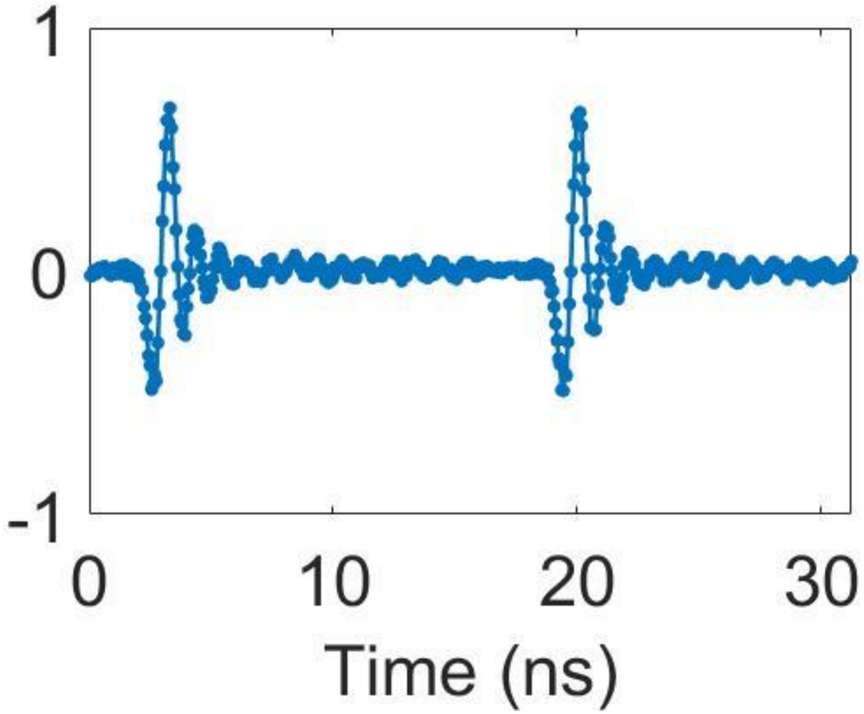
- **Only 12% samples carried beam information**
- **Narrow band signal conditioning can be used to improve SNR**

900MHz LPF applied

Charge resolution: ~0.1%

Hori. resolution: 8μm

Vert. resolution: 12μm



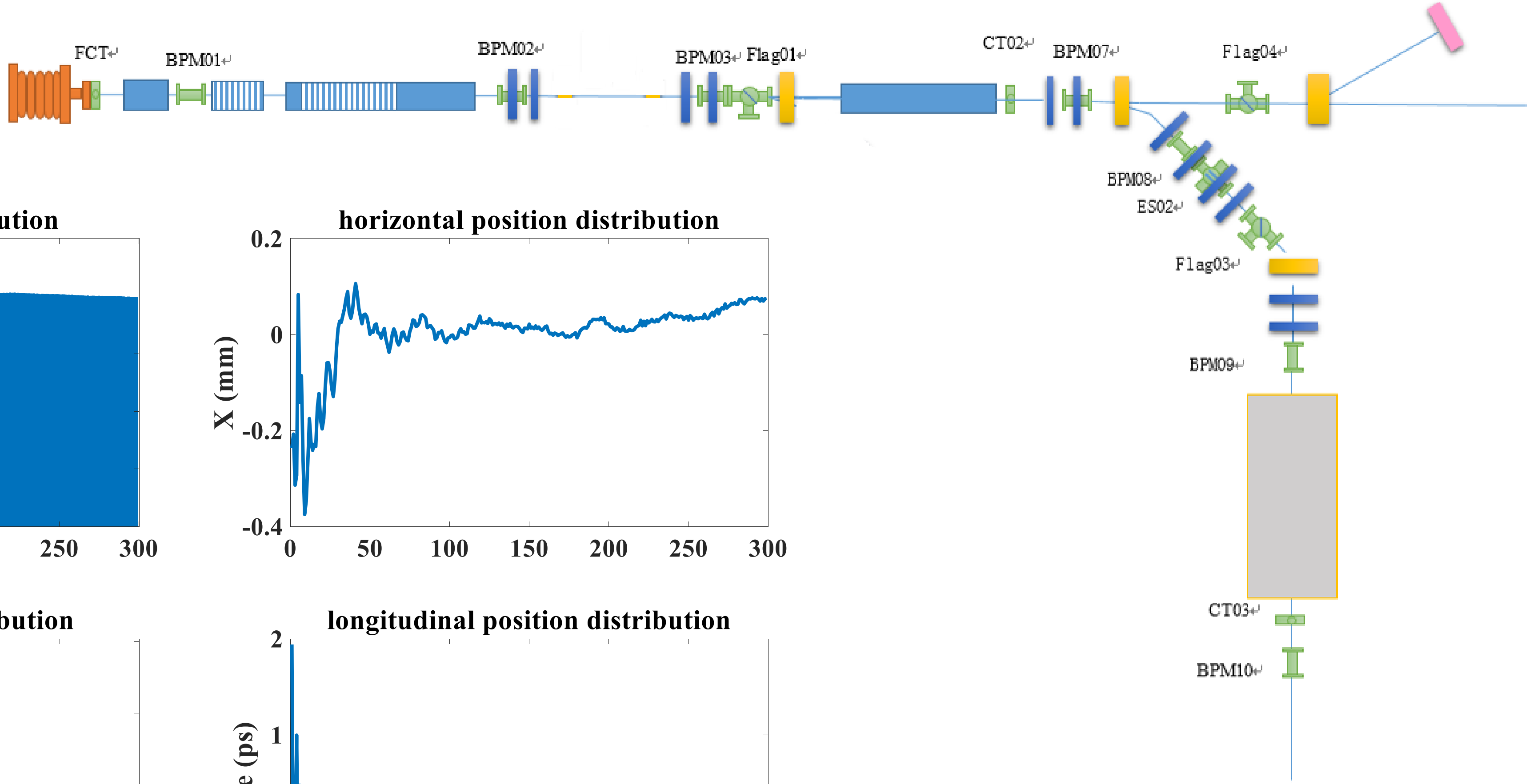
- **More samples useful for amp and phase calculation**
- **Balance between SNR and bunches signal overlap**

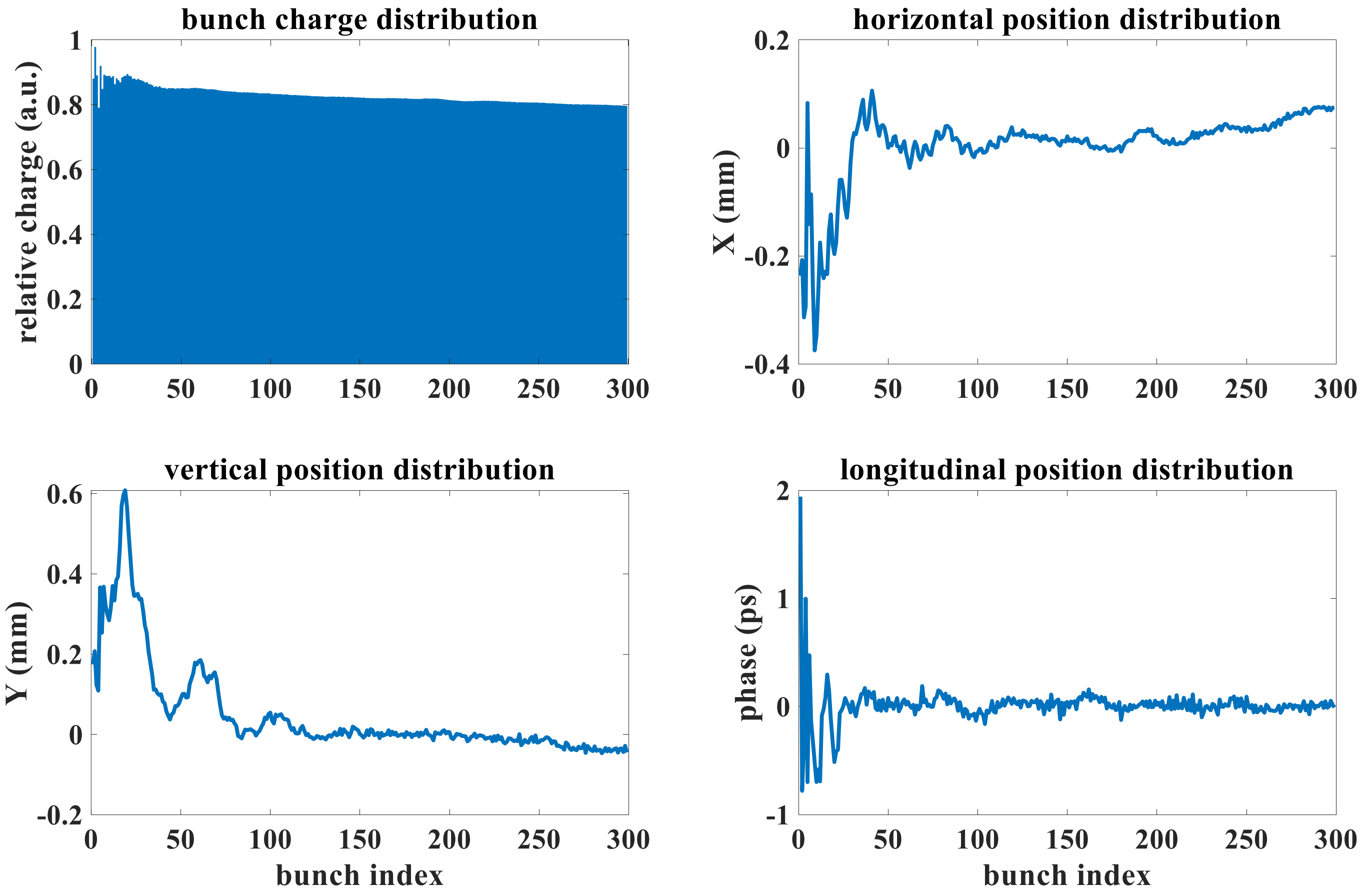
Application

3D position + Charge measurement

3D position + charge measurement can be performed at every BPM

Transfer efficiency, trajectory and energy distribution can be derived by multi-BPMs correlation analyze

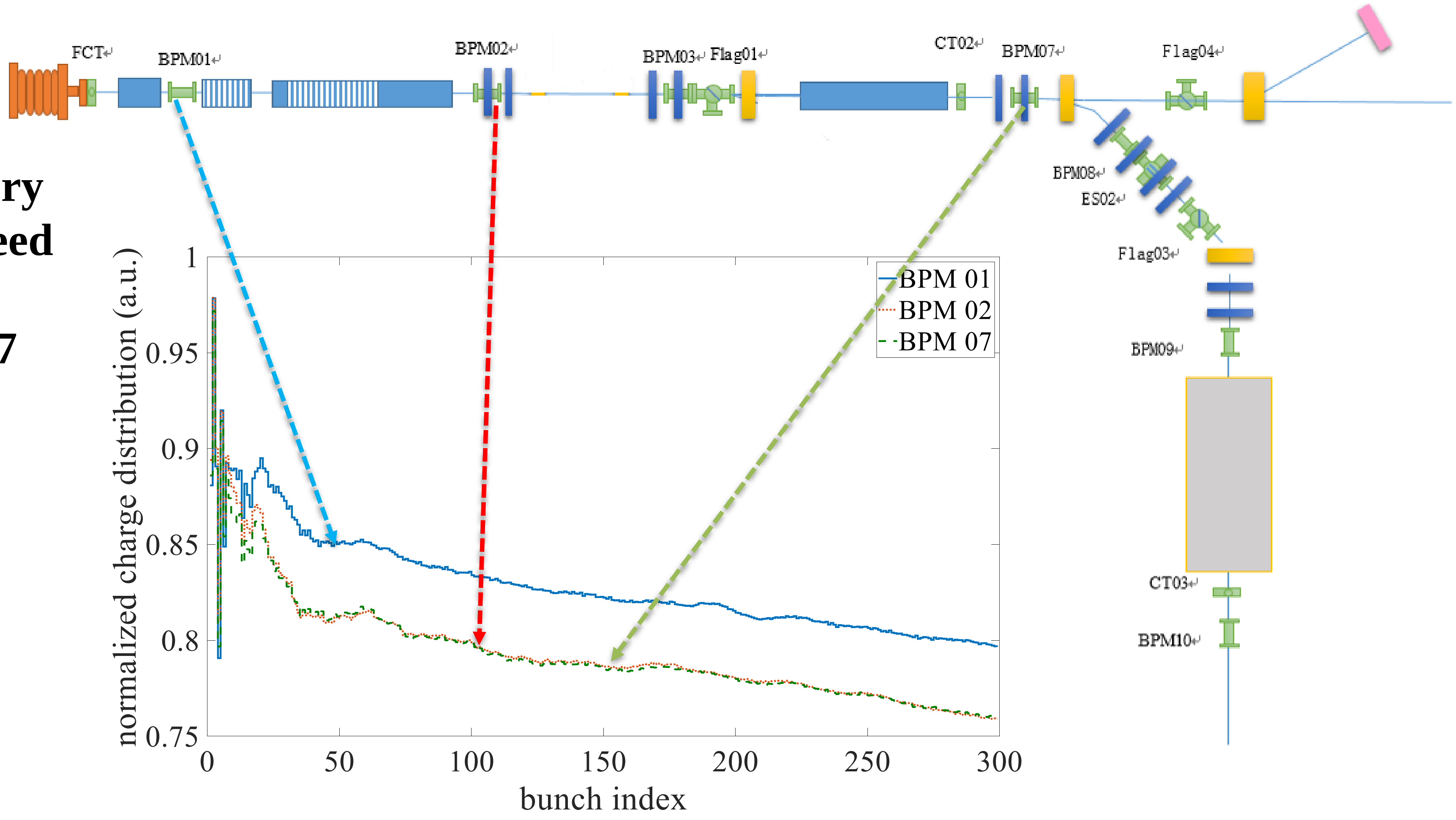




Bunch charge

Bunch Charge: LINAC section, transfer efficiency

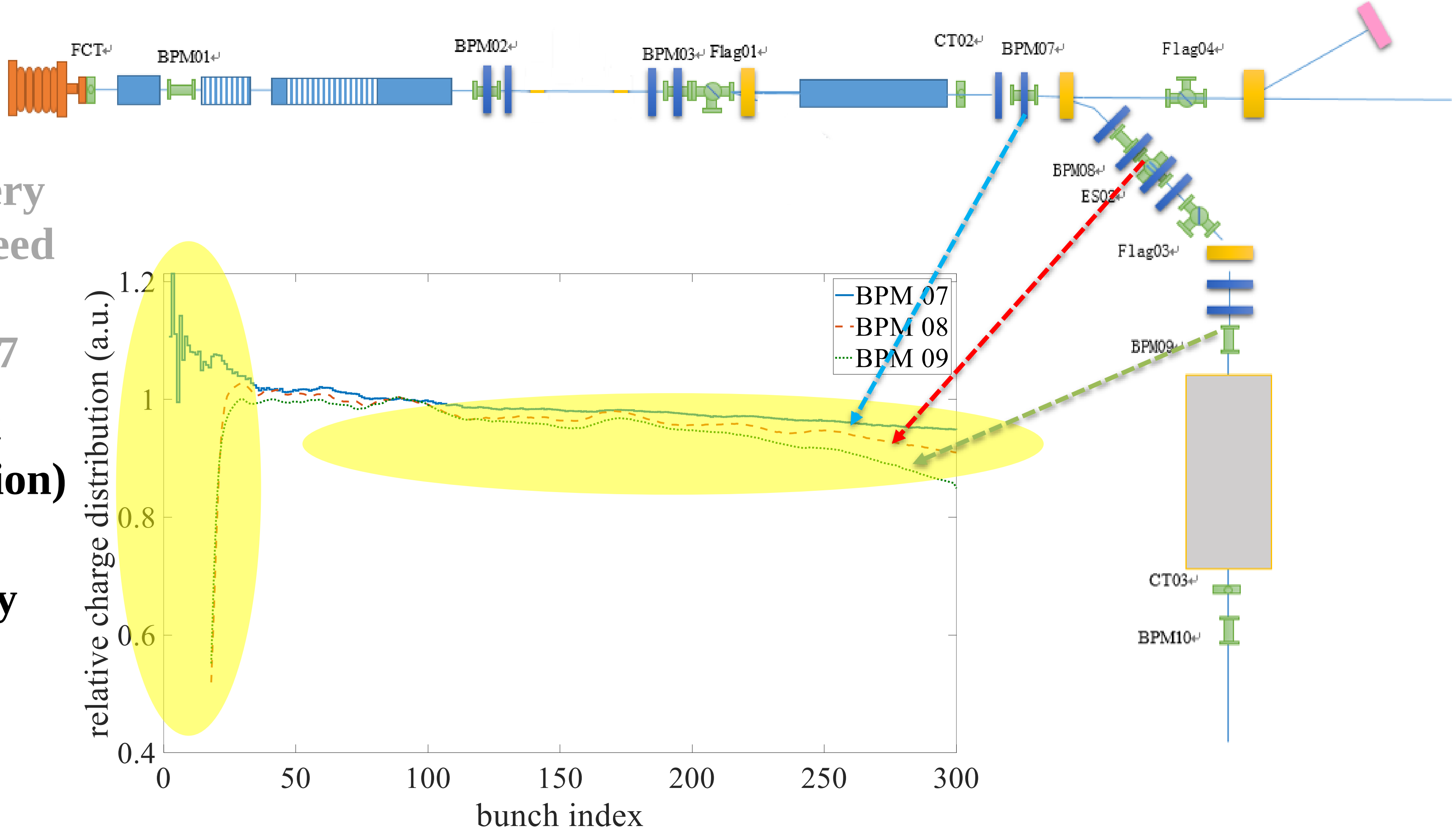
- 15% charge loss for almost every bunch in bunching section agreed with simulation
- No charge loss, BPM2 -> BPM7



Bunch charge

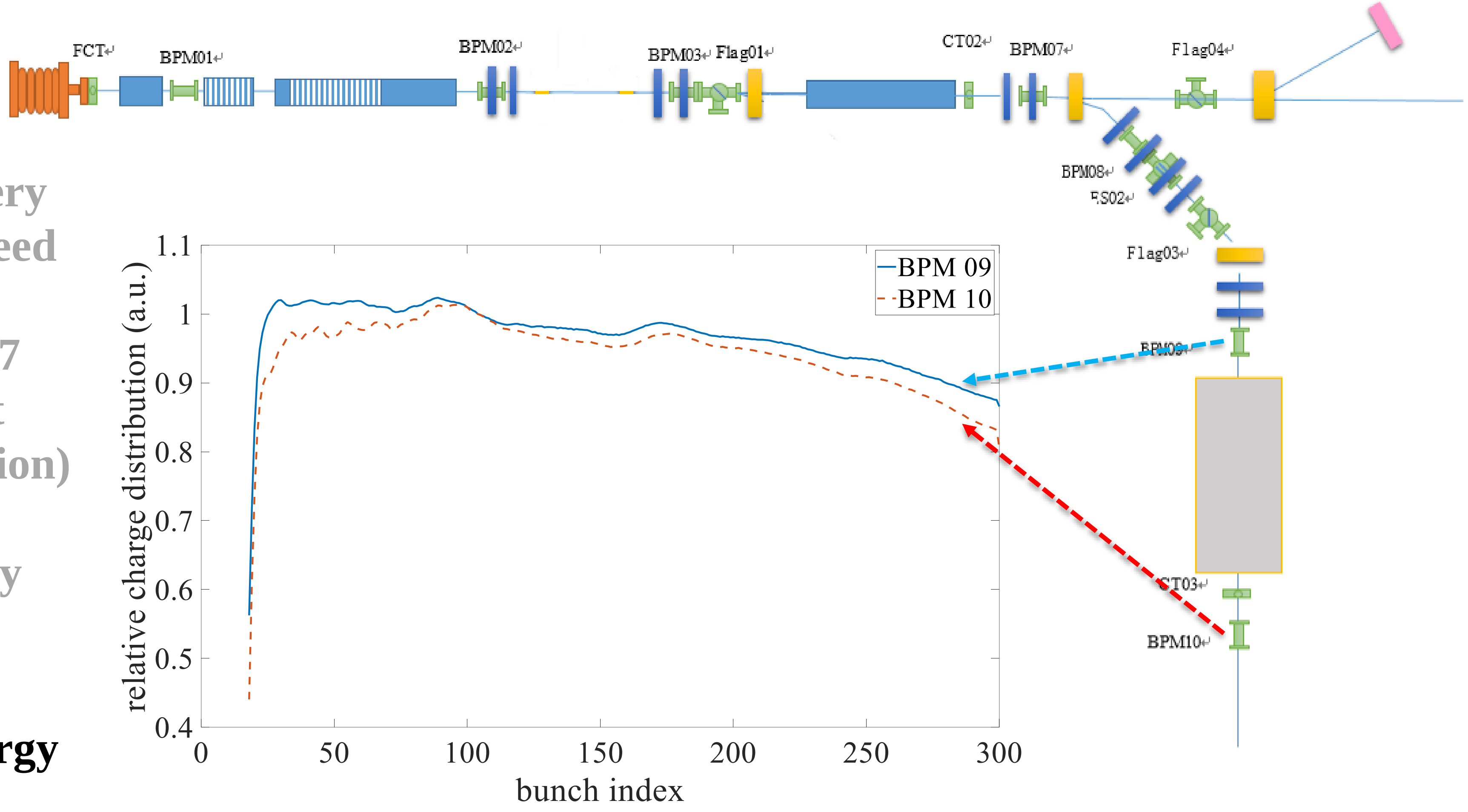
Bunch Charge: bending section, train head lost

- 15% charge loss for almost every bunch in bunching section agreed with simulation
- No charge loss, BPM2 -> BPM7
- **Train head (20 bunches) lost at bending section (energy deviation)**
- **Unexpected charge loss intra-train at bending section (energy deviation too?)**



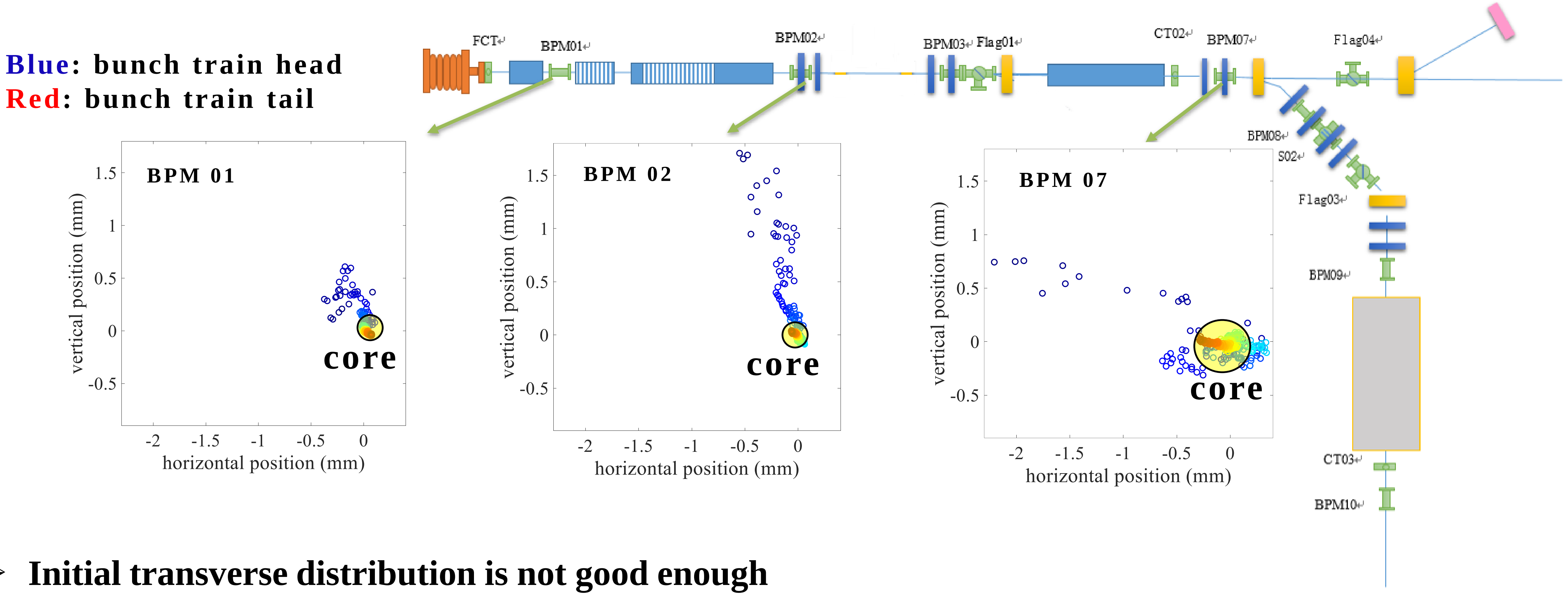
Bunch Charge: undulator section, unexpected beam loss

- 15% charge loss for almost every bunch in bunching section agreed with simulation
- No charge loss, BPM2 -> BPM7
- Train head (20 bunches) lost at bending section (energy deviation)
- Unexpected charge loss intra-train at bending section (energy deviation too?)
- **Unexpected charge loss intra-train at undulator section (energy deviation too?)**



Transverse position

Transverse position: LINAC section, orbit need to be optimized

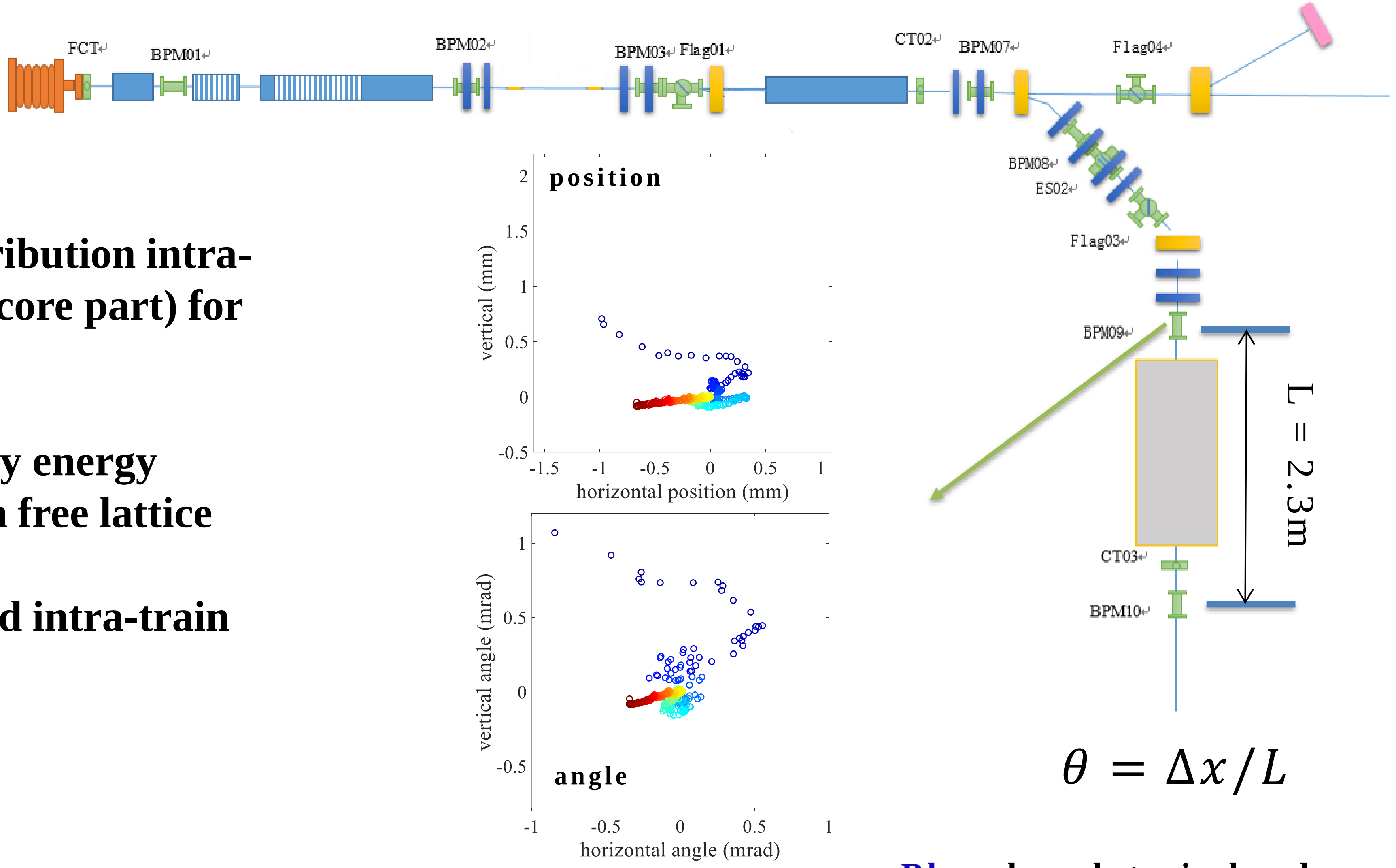


- Initial transverse distribution is not good enough
- Bunch train core (#101 - #300, yellow circle) can be defined with transverse position distribution
- Transverse position deviation getting worse and worse after bunching section
  - Could be introduced by dispersion
  - Off-center orbit introduced transverse kick in accelerating structure

Transverse position and trajectory

Bunch position and angle: undulator section

- ➢ Poor position and angle distribution intra-train (not just head but also core part) for FEL radiation
- ➢ Highly possible introduced by energy deviation and non-dispersion free lattice
- ➢ Energy chirp can be observed intra-train



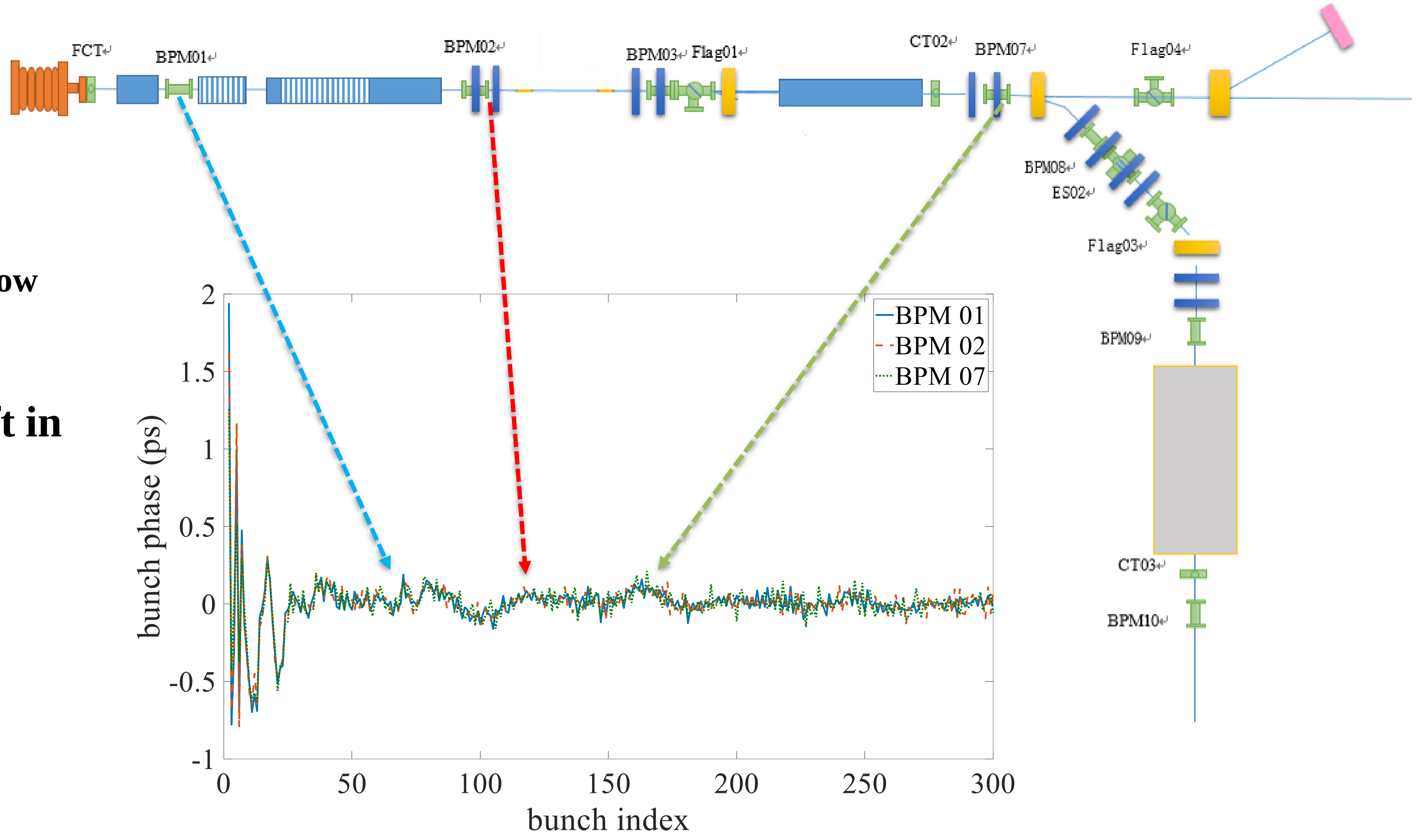
$$\theta = \Delta x / L$$

Blue: bunch train head
Red: bunch train tail

Bunch phase distribution

Bunch phase: LINAC section

- Bunch phase variation can be observed from train head part
  - Could be beam loading effect at low energy region
- No any other bunch phase shift in LINAC section as expected



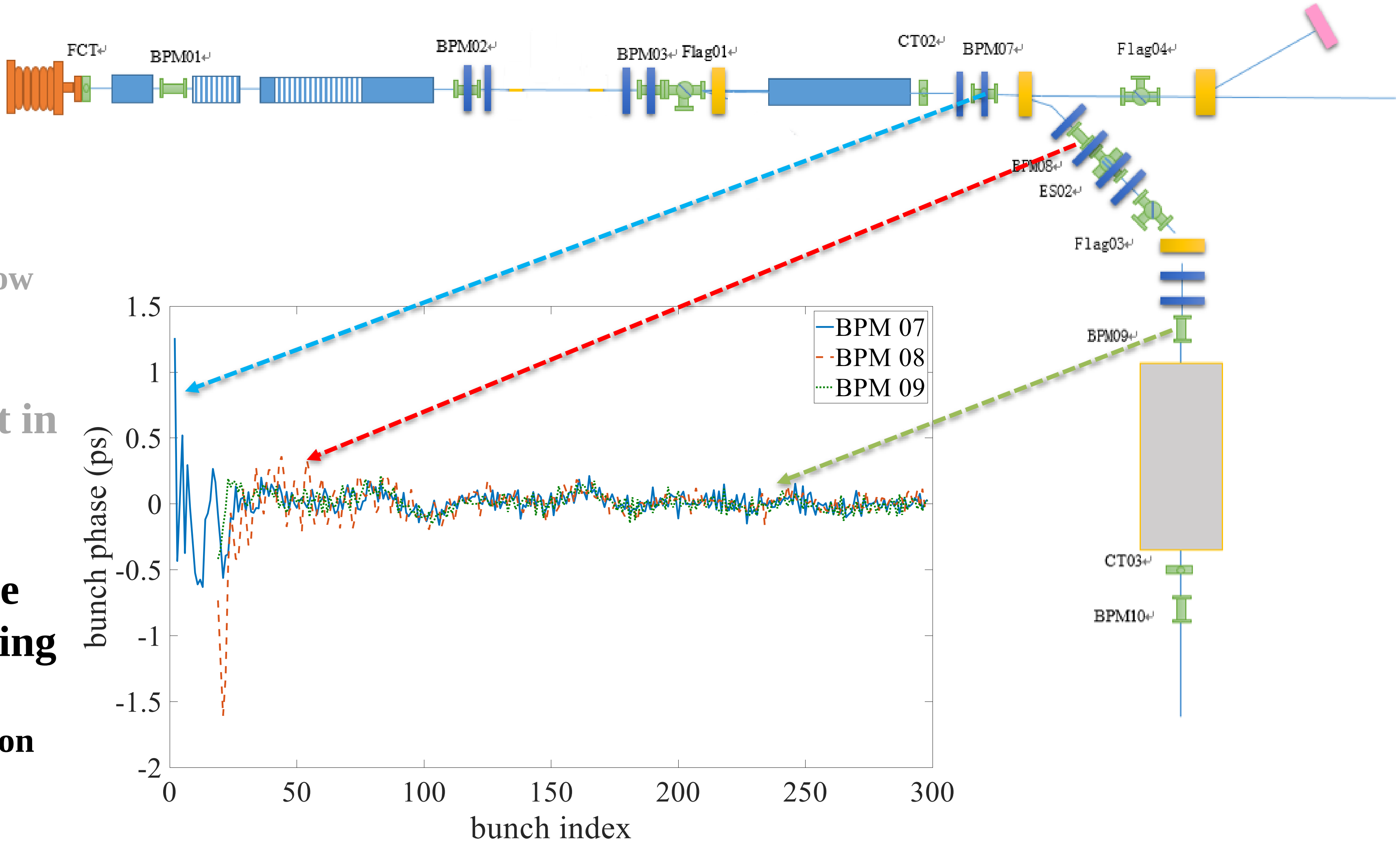
Bunch phase distribution

Bunch phase: bending section, longitudinal position variation due to dispersion orbit

- Bunch phase variation can be observed from train head part
  - Could be beam loading effect at low energy region

- No any other bunch phase shift in LINAC section as expected

- **Bunch phase modulation can be observed at the middle of bending section**
  - **Energy deviation + large dispersion**

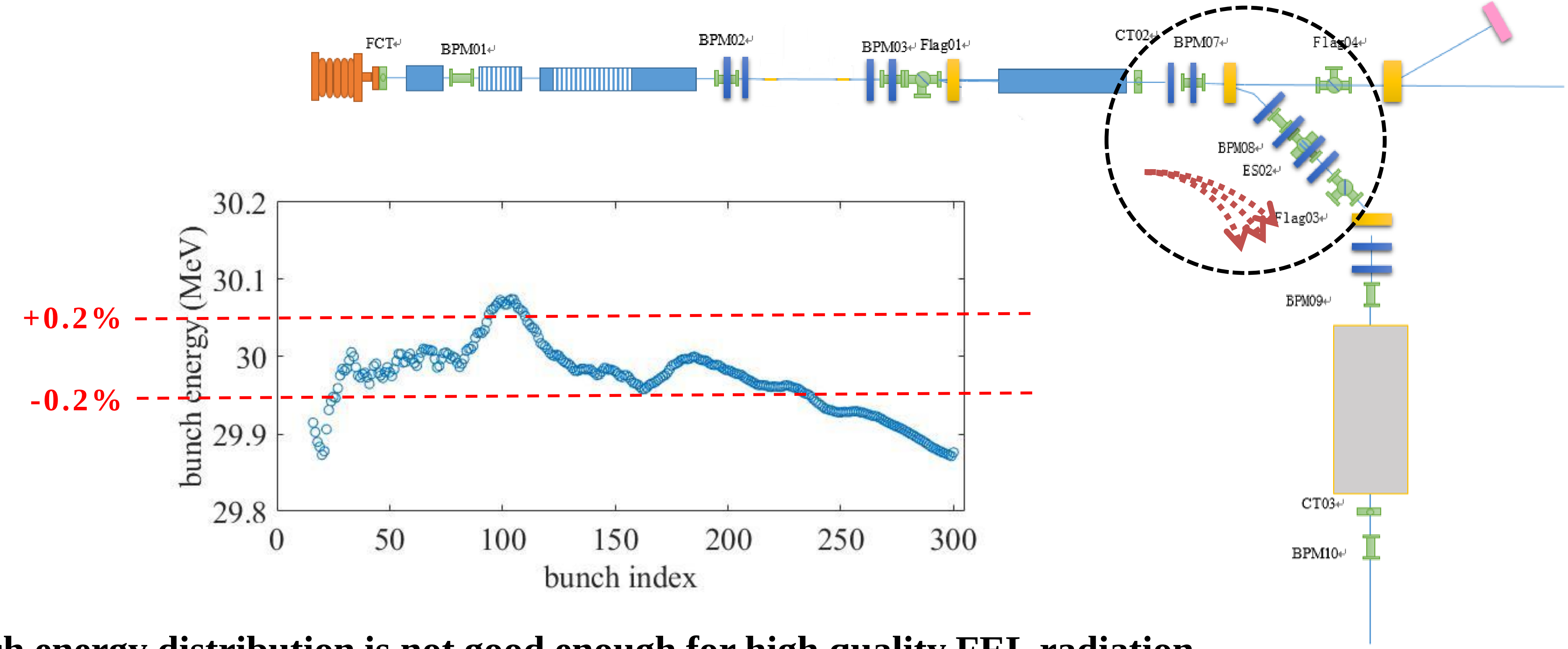


Bunch average energy distribution

Energy measurement

Bending section: BPM7 + BPM9

$$\Delta x = \eta_x \frac{\Delta E}{E_0} \quad \eta_x = 0.9m \quad E_0 = 30MeV$$

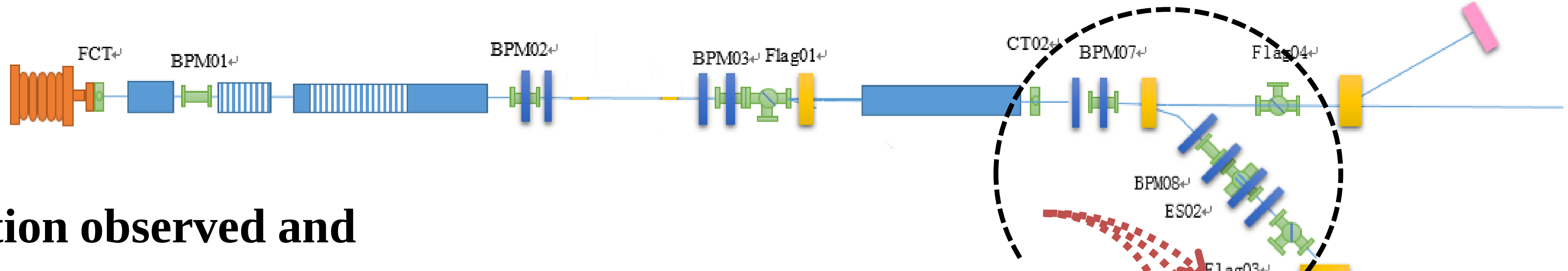


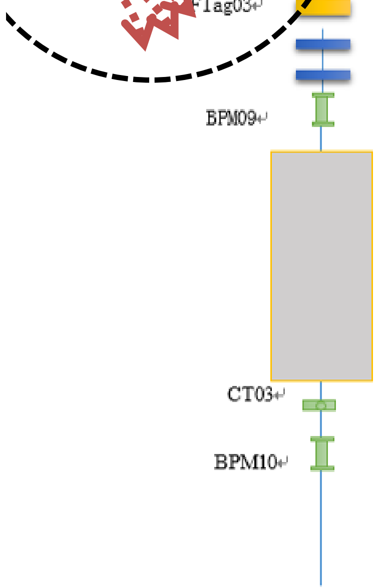
- ➢ **Bunch energy distribution is not good enough for high quality FEL radiation**
- ➢ **A lot of radiation power should be lost due to this poor energy deviation**

Beam energy variation

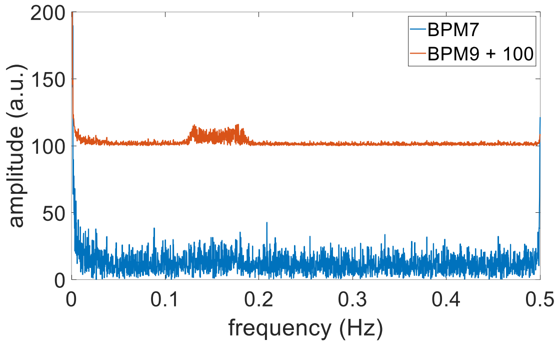
Energy measurement
Bending section: BPM7 + BPM9

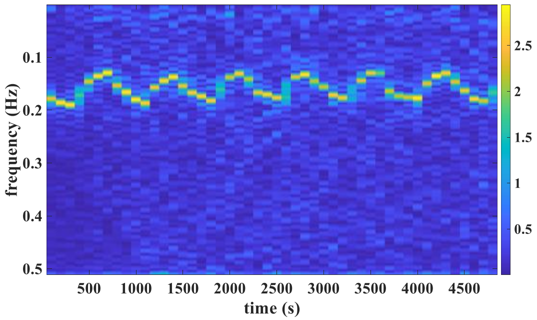
$$\Delta x = \eta_x \frac{\Delta E}{E_0} \quad \eta_x = 0.9m \quad E_0 = 30MeV$$



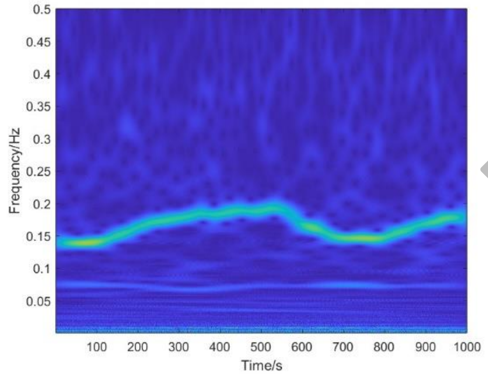


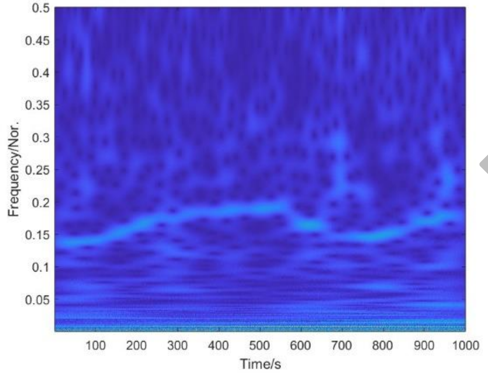
- Pulse to pulse energy oscillation observed and recorded
- Energy measurement data can be used to identify noise source, which is Klystron high voltage power supply in this case





trace back





Klystron HV PS

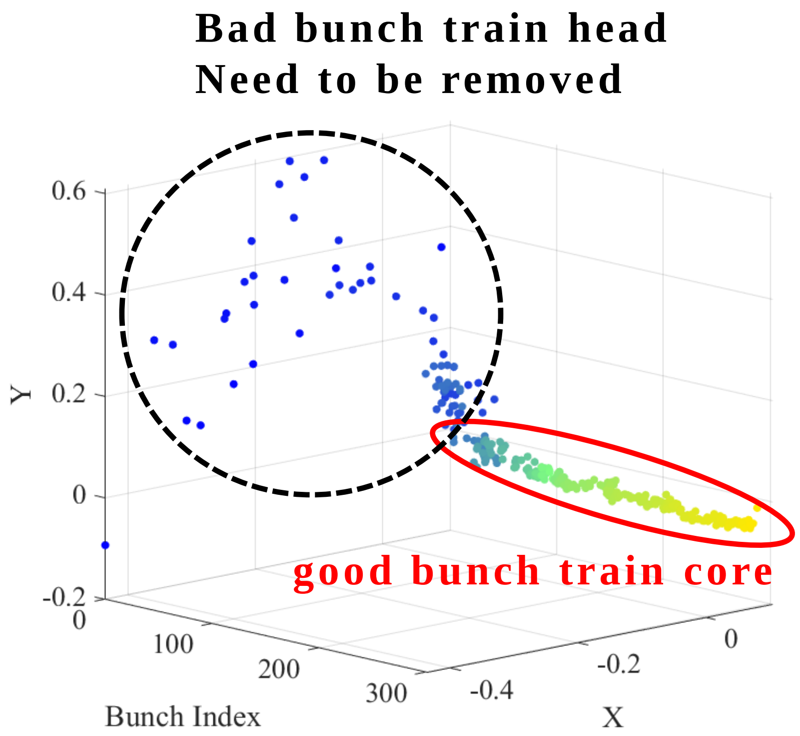
Klystron output

Energy oscillation (0.13-0.20 Hz) observed
Oscillation frequency modulated by cooling water cycle

Final finding and Actions

Finding

- ➢ A lot of radiation power has been lost due to poor bunch train uniformity.
- ➢ Bunch train head (around 100 bunches) has huge transverse position deviation due to heavy beam loading effect at the very beginning, no way to compensate it.
- ➢ Train body and tail have much better performance than head, which can be defined as 'good core' for radiation.



Actions

- ➢ An energy slit will be added to remove low energy bunches (charges)
- ➢ Lattice will be optimized targeting bunch train core
- ➢ RF system needs to be upgraded to improve intra-train uniformity and pulse to pulse stability
- ➢ All BPMs will be upgrade to bunch-by-bunch mode online to provide a powerful tuning tools for the next run

Summary

Summary

- Bunch-resolved diagnostics tools required in FELiCHeM facility for bunch train uniformity analyze.

- Bunch-by-bunch software package (HOTCAP) developed for ring was modified and implemented in LINAC, which successfully retrieved multi parameters (charge, transverse position, longitudinal phase, trajectory and energy) for every bunch.

- Facility upgrade plan has been made based on bunch-by-bunch diagnostics result.

- Better radiation performance can be expected for the next run.

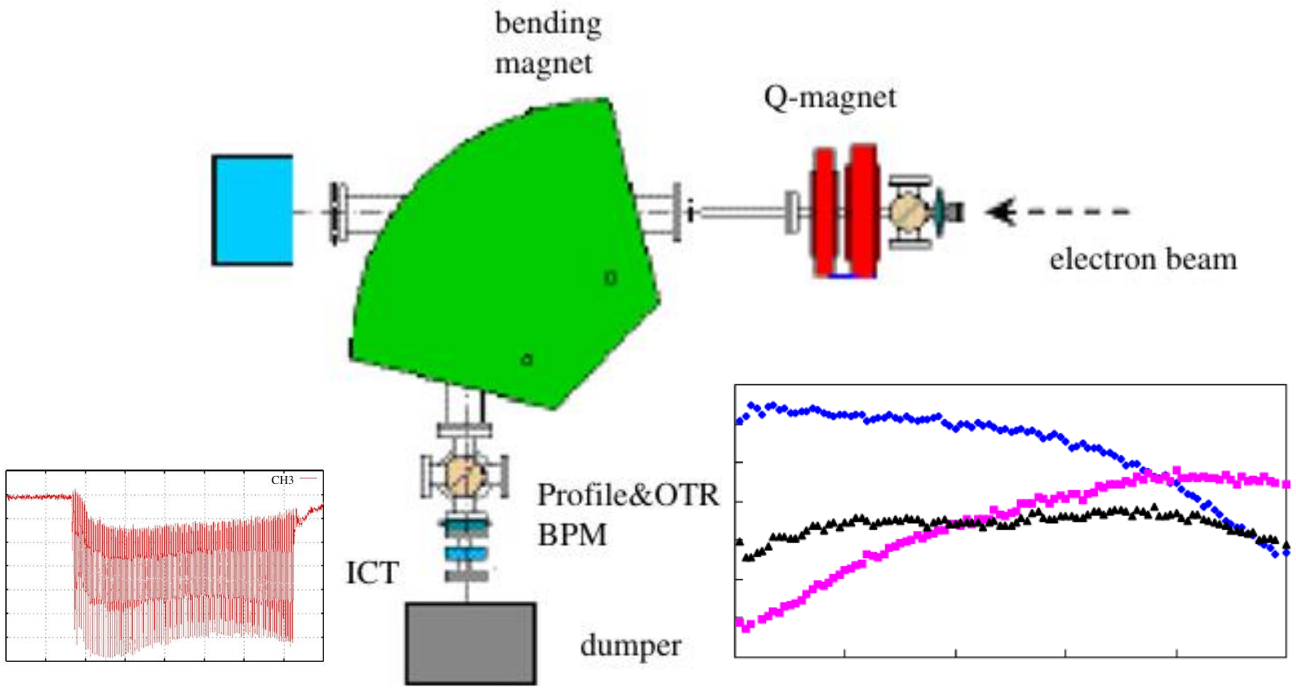
Thanks for your attention

USTC NSRL
NSRL
National Synchrotron Radiation Laboratory

Contact: yangxingnsrl@ustc.edu.com

Previous work done in other facilities

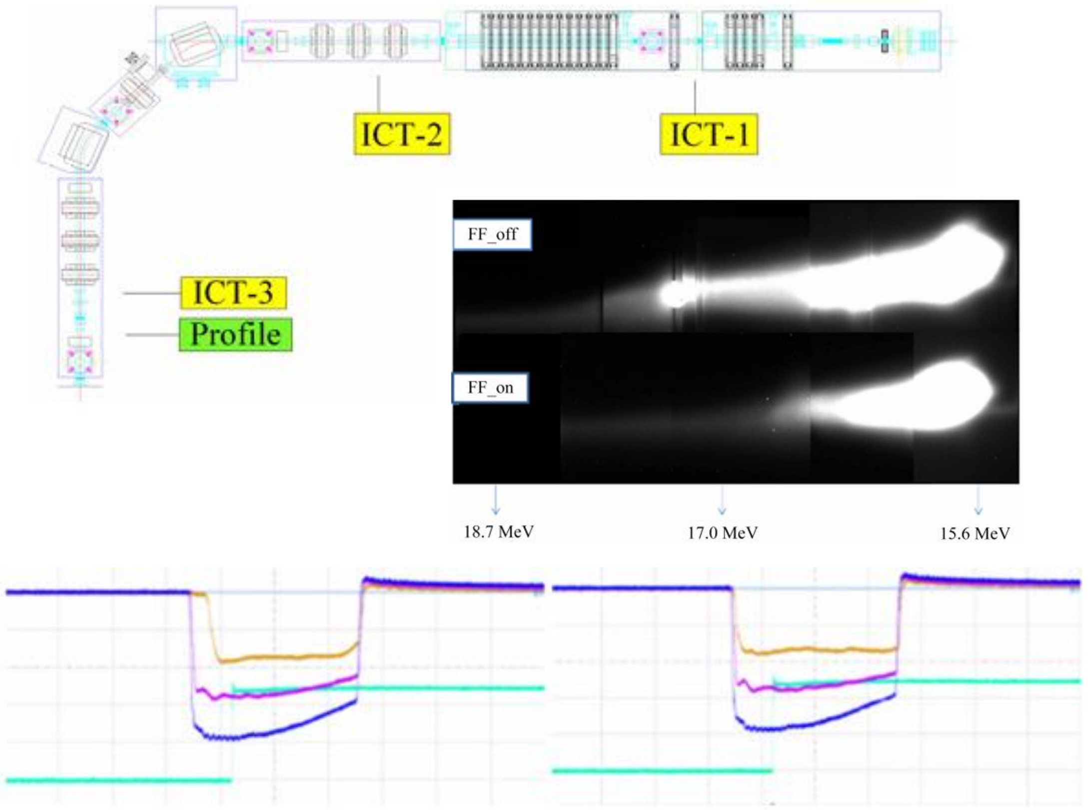
KEK



Bunch-resolved BPM (pickup + scope)

- Beam loading compensation for acceleration of multi-bunch electron beam train, **NIMA**, **2008**
- Development of a new initial-beam-loading compensation system and its application to a free-electron-laser linac, **PRST 2009**

SINAP (TDSN1)



ICT + screen (indirect diagnostics)

S. Li, **Nuclear Techniques**, 39(7), **2016**