

Current status of Tomography and WCM



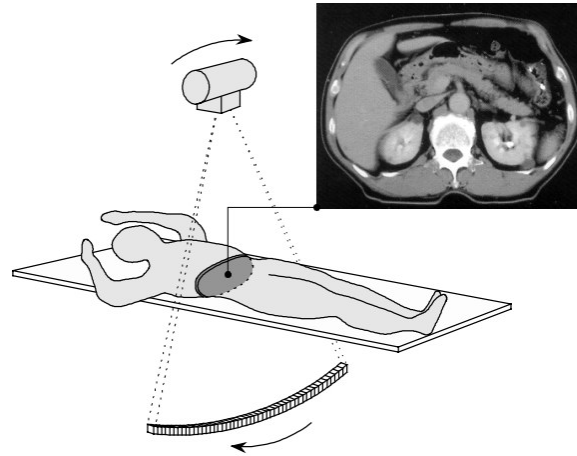
25. 11. 07.

.Geunwoo Kim
DANE, POSTECH

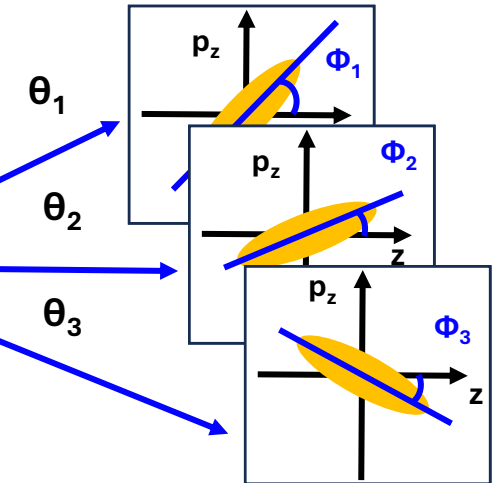
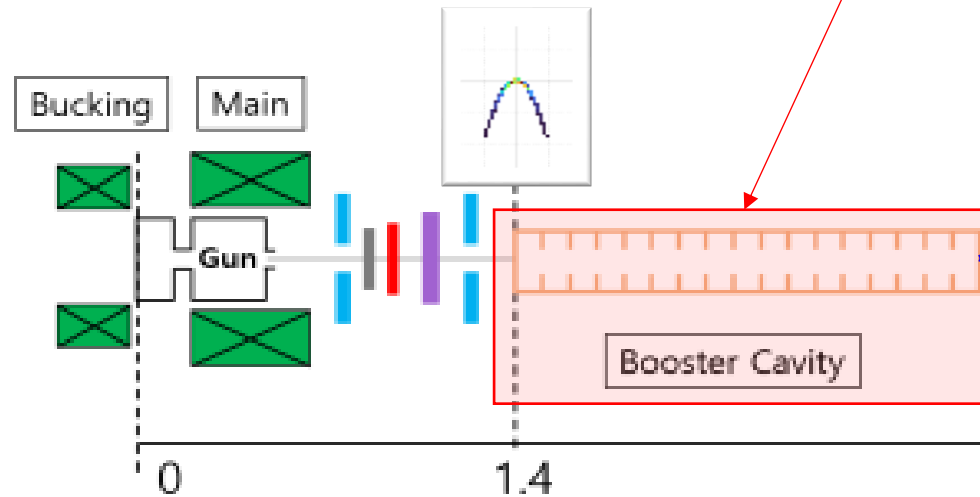
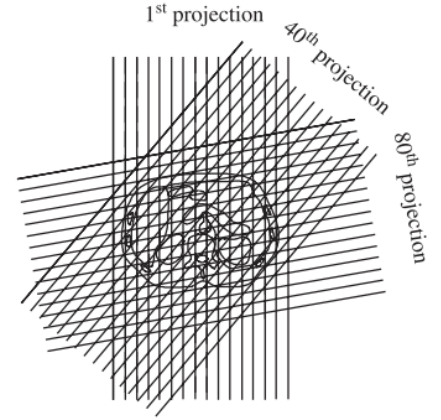
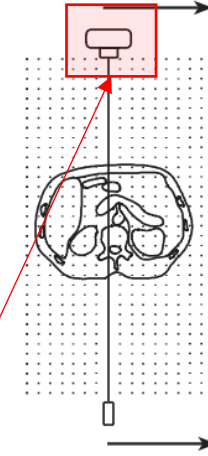
Review

- Basic principle of tomography

- 1D distribution
- Projection angle

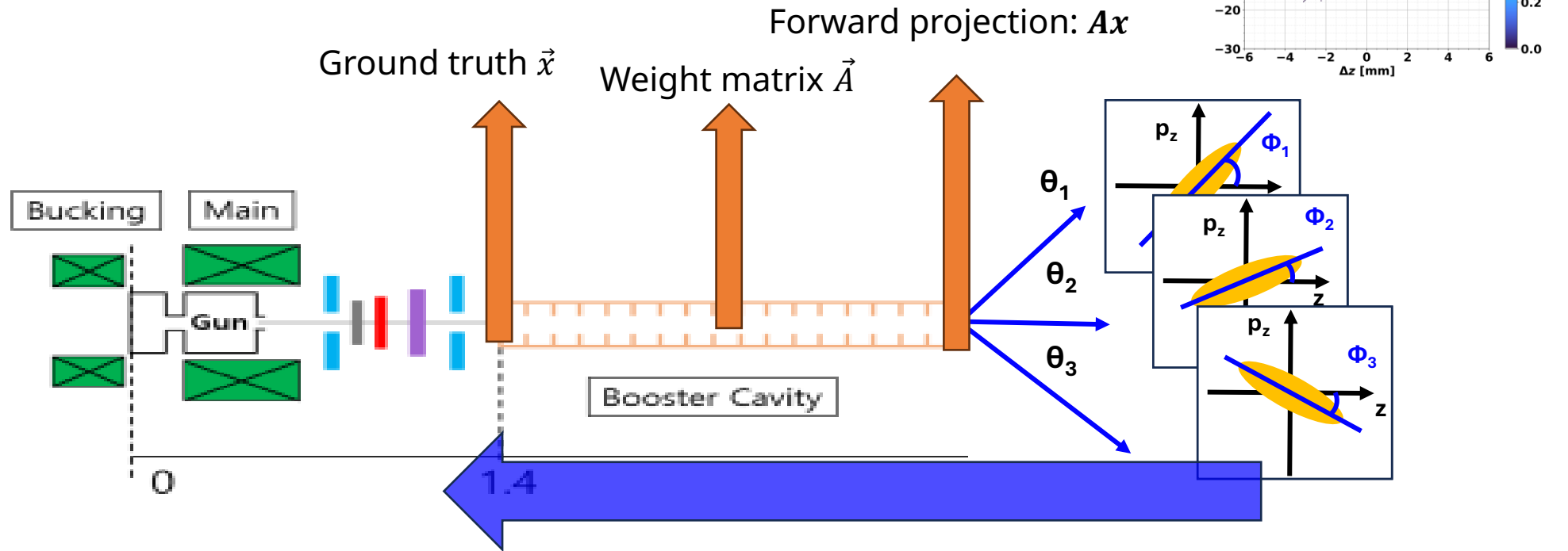


Scanner



Review

- Using different method to suppress stripe artifacts



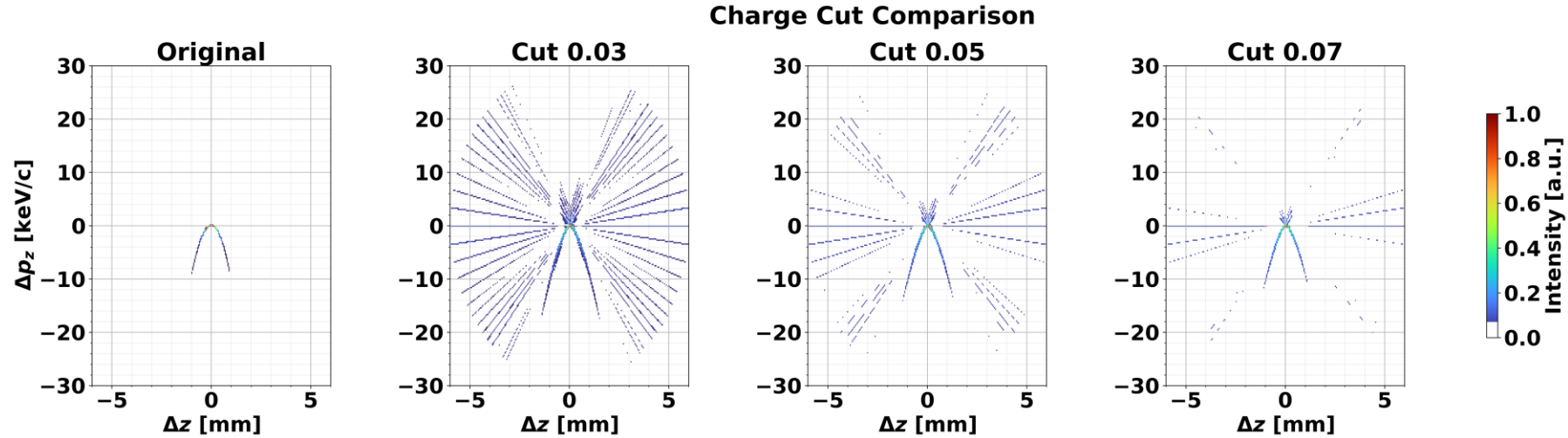
Iterative reconstruction algorithm

Backward projection

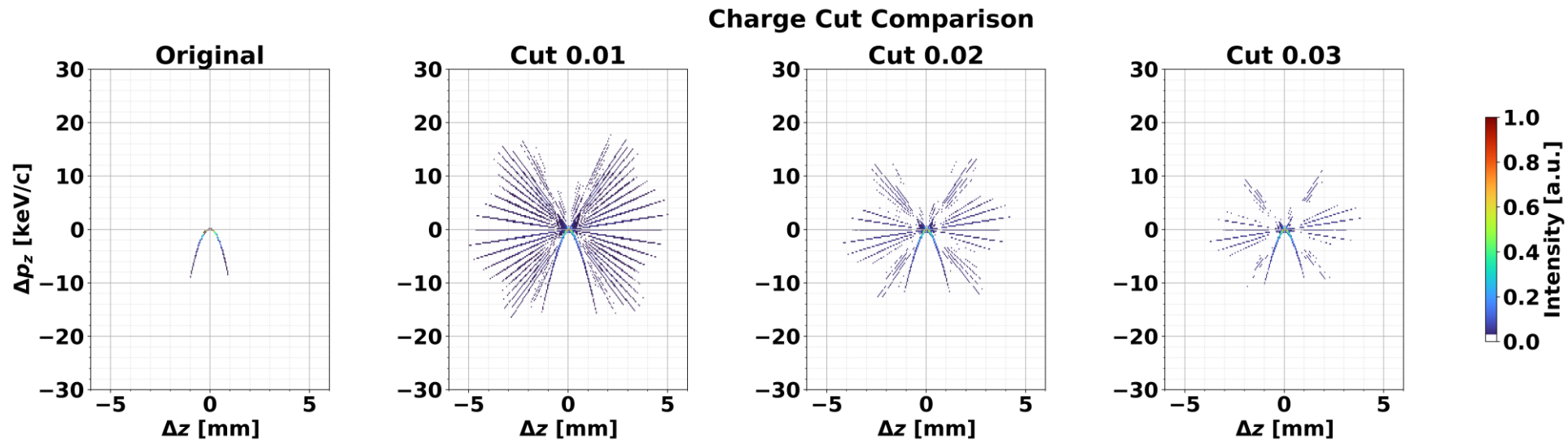
1. $\vec{x}^{k+1} = \vec{x}^k + \frac{1}{\vec{A}^T \vec{1}} \cdot \frac{\vec{A}^T (\vec{m} - \vec{A}^T \vec{x}^k)}{\vec{A}^T \vec{1}}$ (SART) Determine \vec{A} representing the extent of the beam's physical location.
2. $\vec{x}^{k+1} = \vec{x}^k \cdot \frac{\vec{A}^T \vec{m}}{\vec{A}^T \vec{A} \vec{x}^k}$ (ISRA)

Recall the previous results: Python library [Done]

- Filtered Back Projection (FBP):** Direct, fast, non-iterative reconstruction.



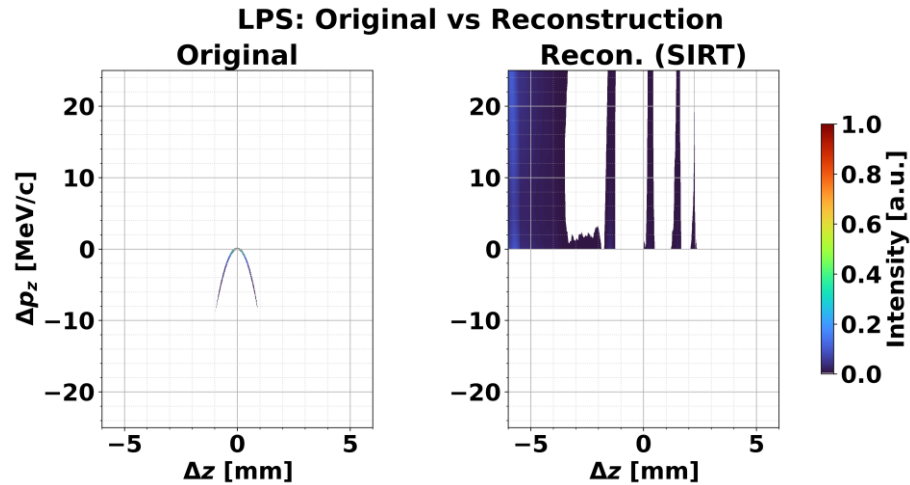
- Simultaneous algebraic reconstruction technique (SART):** Iterative, weighted matrix, quality improvement.



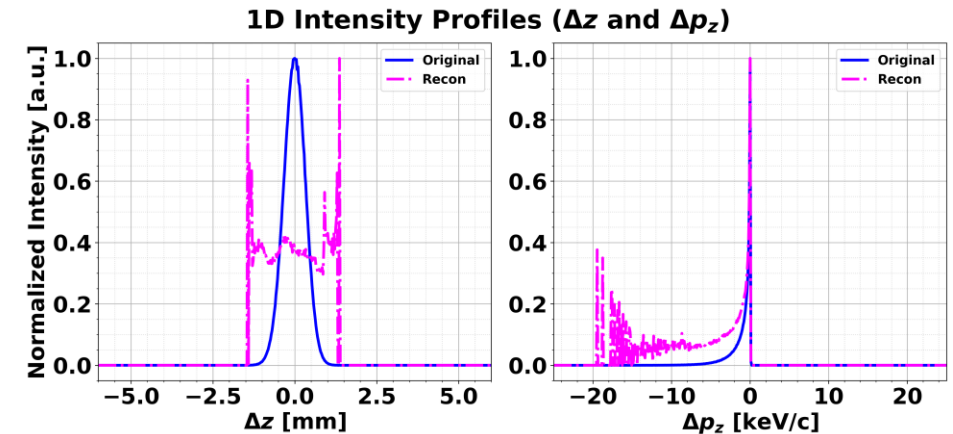
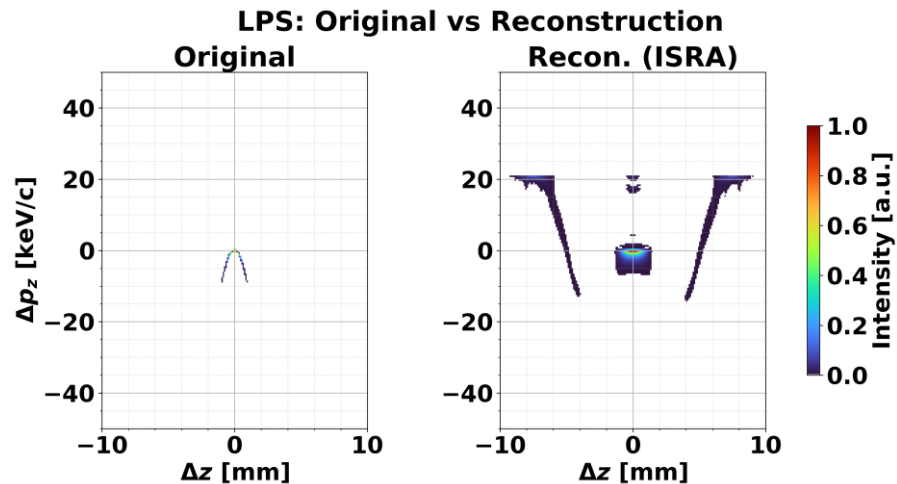
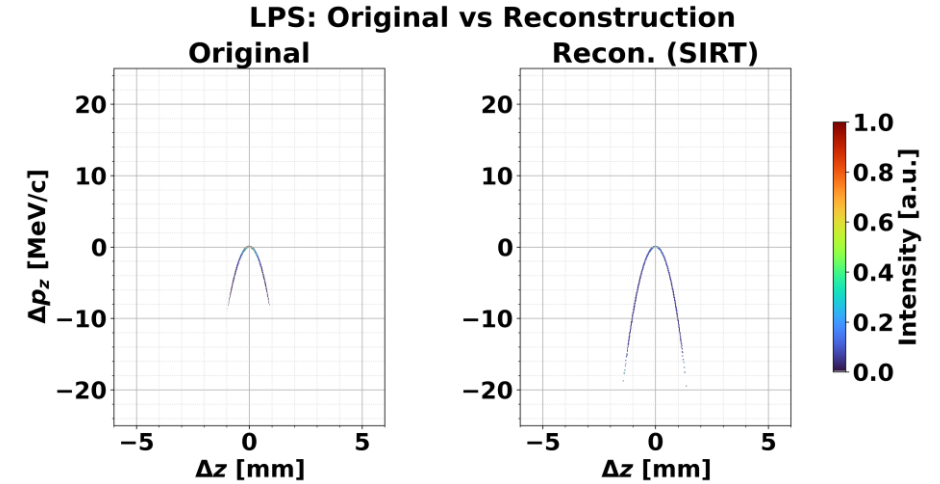
Recall the previous results: construction \vec{A} [On-going]



x^1 : Uniform



x^1 : Ground truth



Algorithm of weight matrix \vec{A}

- Key parameters

1. $z(t)$: Not bunch length.
2. p_{\min}^{boo} : Not min of measured value.

Algorithm 1: Weight matrix for LPS Reconstruction

input : $\varphi, p_z^{\text{gun}}, V, z$

output: *WeightMatrix* (consists of 1s and 0s)

1 **Function** Loop(*A*)

2 $N_\varphi \leftarrow \text{length}(\text{booster phases})$

3 $N_s \leftarrow \text{length}(\text{momentum bins})$

4 $N_t \leftarrow \text{length}(\text{longitudinal bins})$

5 **for** $i \leftarrow 1$ **to** φ_{\max} **do**

6 **for** $s \leftarrow 1$ **to** N_s **do**

7 **for** $t \leftarrow 1$ **to** N_t **do**

8 $p_{\text{cal}}^{\text{boo}} \leftarrow p_z^{\text{gun}}(s) + V \cos(\varphi(i) + z(t))$

9 $j \leftarrow \frac{p_{\text{cal}}^{\text{boo}} - p_{\min}^{\text{boo}}}{\Delta p_{\text{boo}}}$

10 $W(j + N_s(i - 1), t + N_t(s - 1)) \leftarrow 1$

11 **return** *WeightMatrix*



Algorithm verification

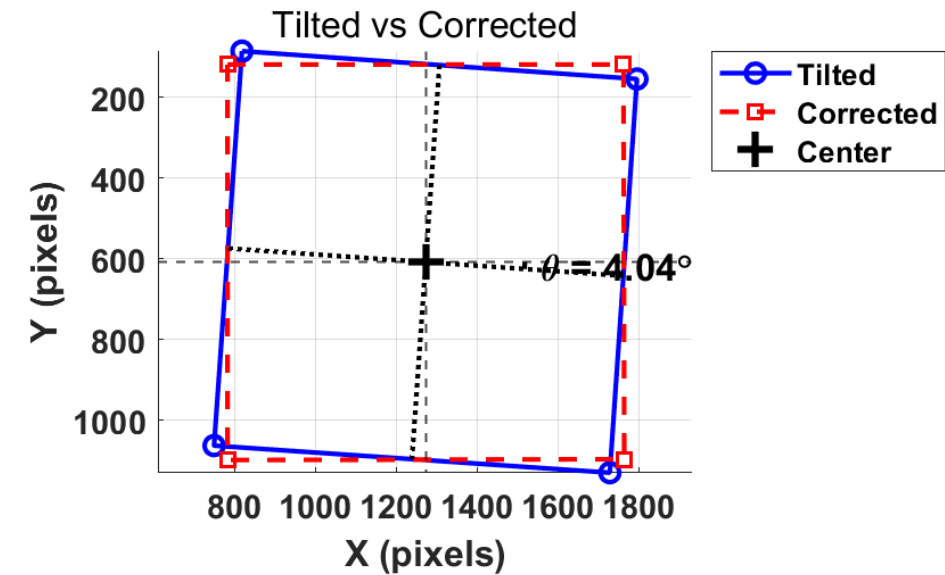
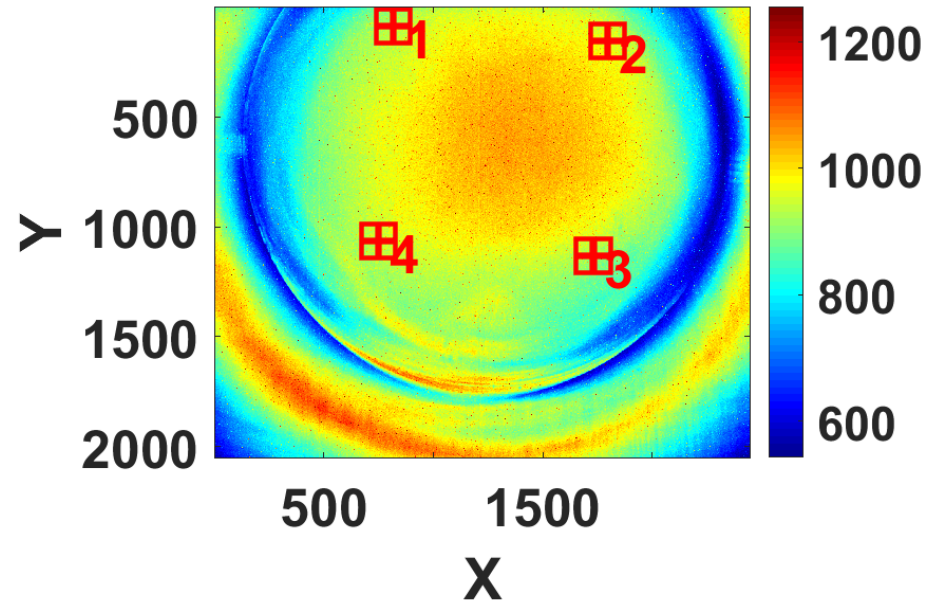
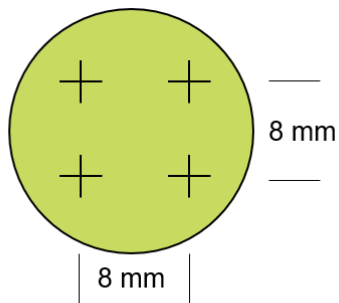
$$p_{cal}^{boo} \leftarrow p_z^{gun}(s) + V \cos(\varphi(i) + \mathbf{z}(t))$$



1. $z(t)$: Not bunch length. → Calculated as **(Screen pixels) x (Screen resolution mm/pixels)**
 - It is not significant element in my situation (simulation).

SCM04

- 4도 기울어짐
- 중심: (0.35, 3.38)



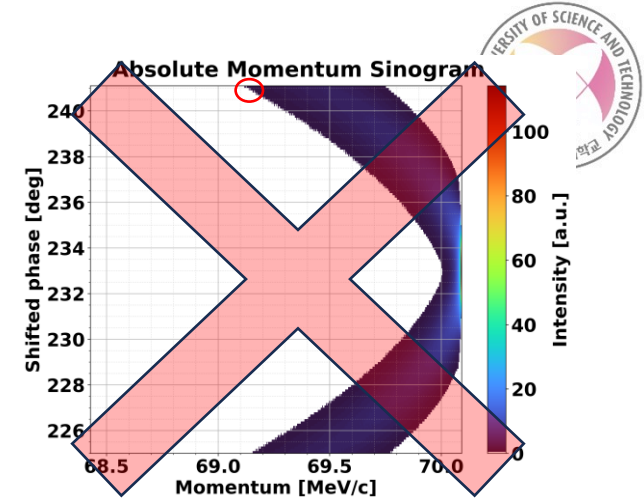
- **X Resolution : 8.16 um/pixel**
- Y Resolution: 8.18 um/pixel

Algorithm verification

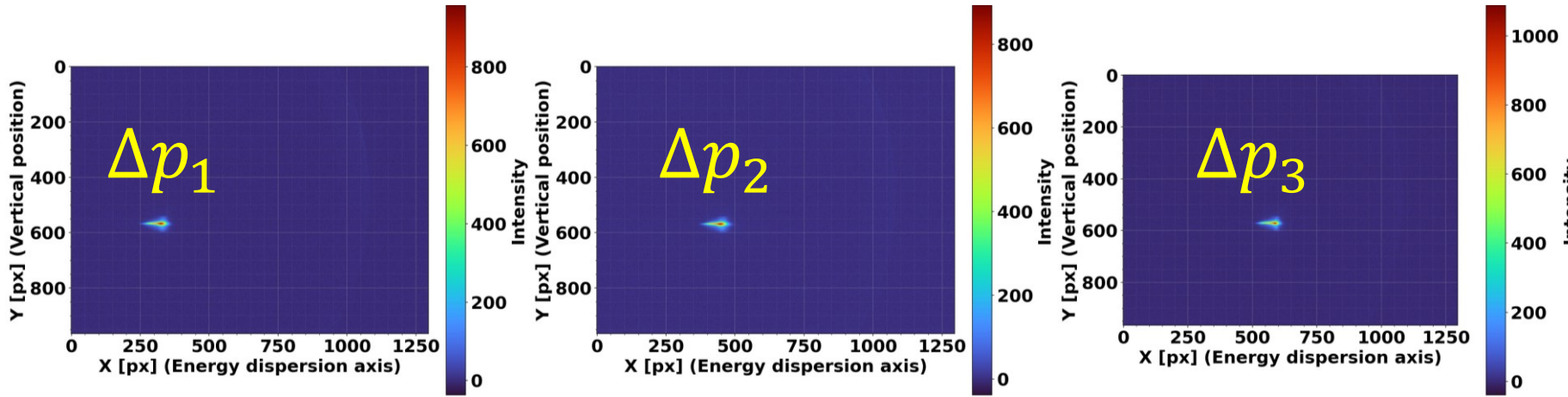
$$j \leftarrow \frac{p_{cal}^{boo} - p_{min}^{boo}}{\Delta p_{boo}}$$

2. p_{min}^{boo} : Minimum measurable momentum on screen.

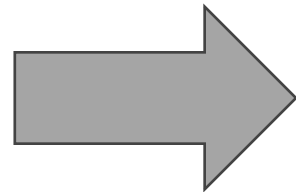
- $X(s) = x_{\beta}(s) + D(s) \cdot \left(\frac{\Delta p}{p}\right)$



In elabs case,



phase_deg	all_within
220	FALSE
222	FALSE
224	TRUE
226	TRUE
228	TRUE
230	TRUE
232	TRUE
234	TRUE
236	TRUE
238	TRUE
240	TRUE
242	FALSE
244	FALSE
246	FALSE



$p_{min}^{boo} : 68.396 \text{ MeV/c}$

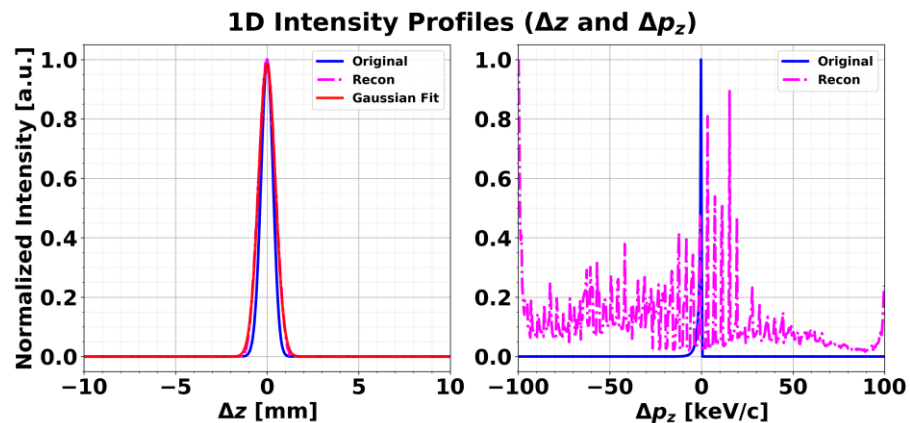
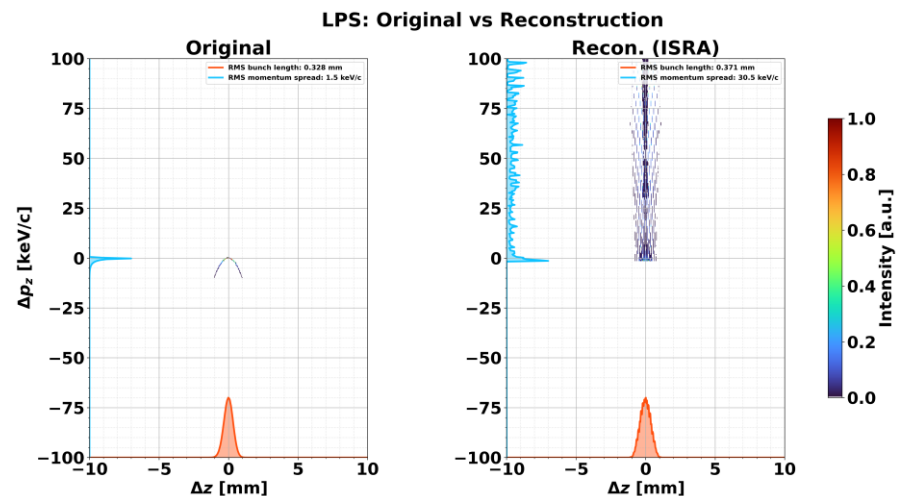
Results

$$\vec{x}^{k+1} = \vec{x}^k \cdot \frac{\vec{A}^T \vec{m}}{\vec{A}^T \vec{A} \vec{x}^k} \text{ (ISRA)}$$

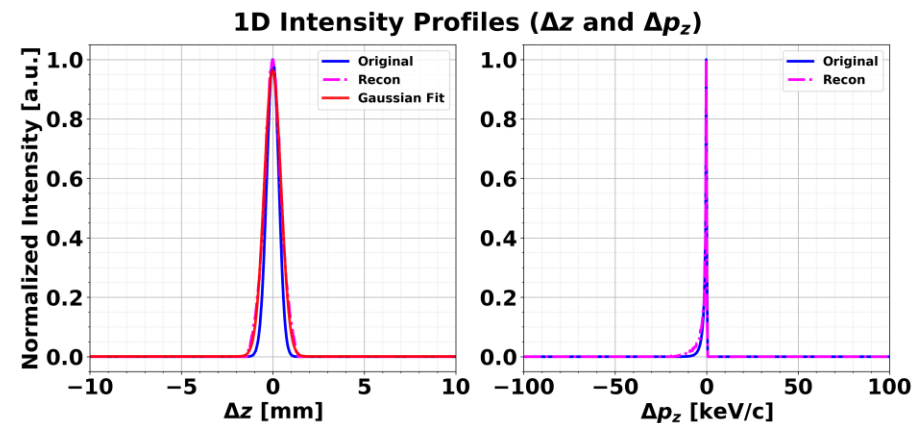
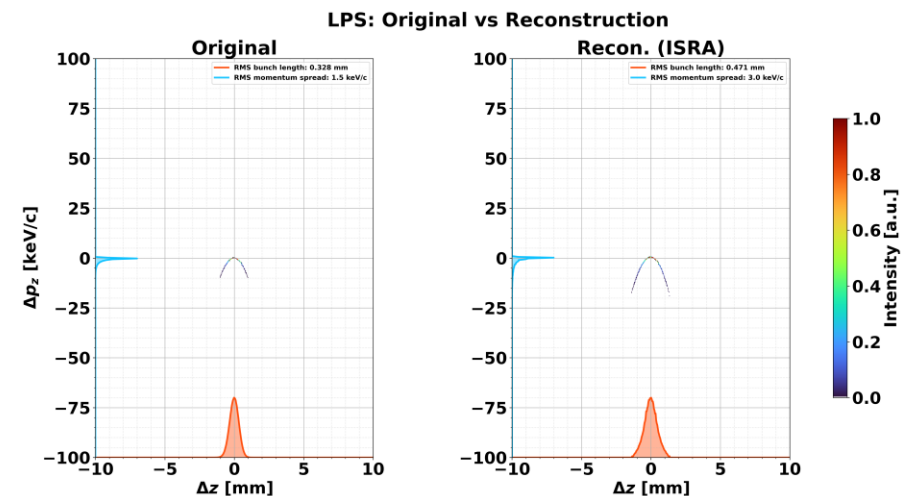


Good agreement to $z(t)$, but, obtained worse Δp results.

x^1 : Uniform

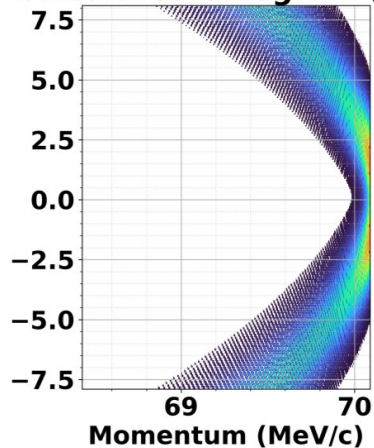


x^1 : Ground truth



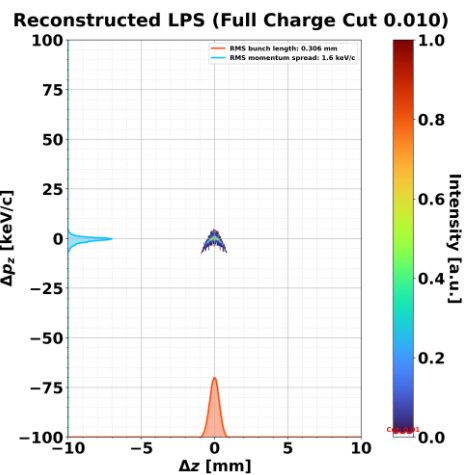
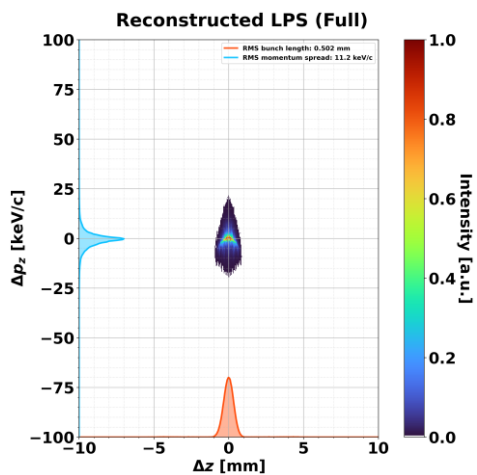
Finding issues

Calculated Sinogram (Ax)

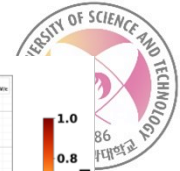
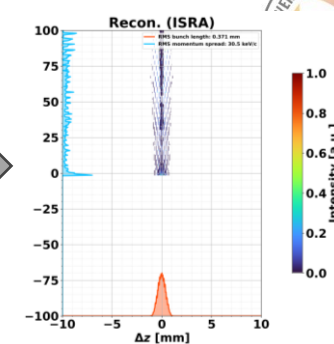
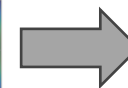
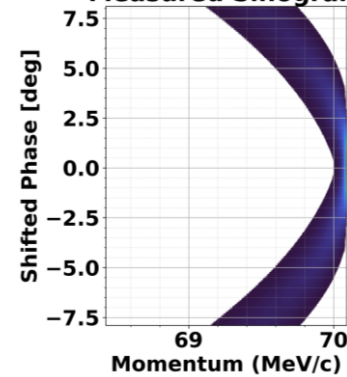


$$\vec{x}^{k+1} = \vec{x}^k \cdot \frac{\vec{A}^T \vec{m}}{\vec{A}^T \vec{A} \vec{x}^k} \Rightarrow \vec{x}^k \cdot \frac{\vec{A}^T \vec{A} x^{True}}{\vec{A}^T \vec{A} \vec{x}^k}$$

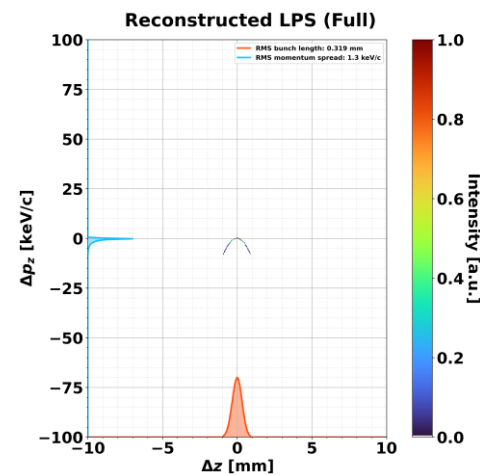
x^1 : Uniform



Measured Sinogram

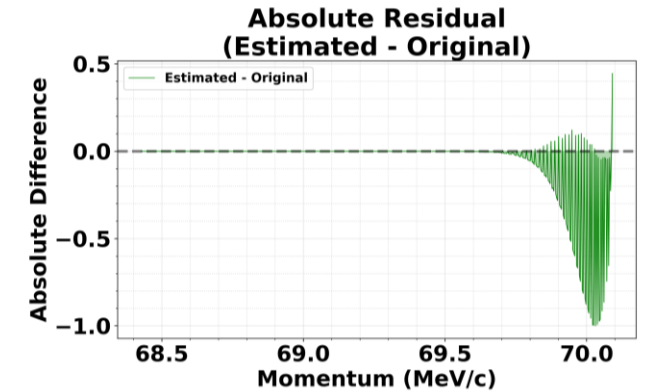
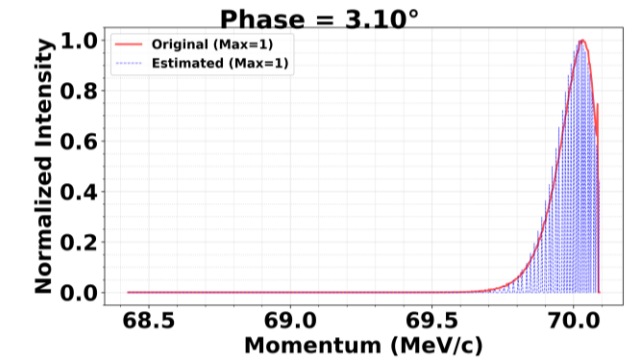
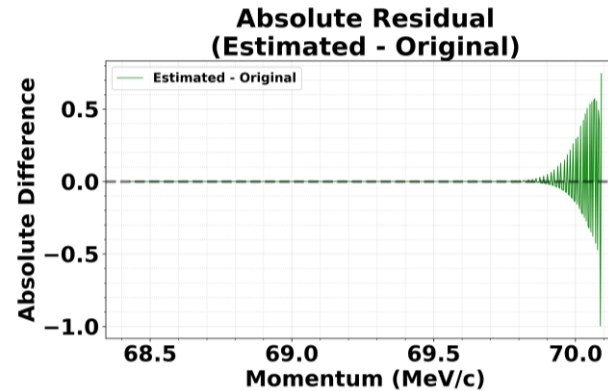
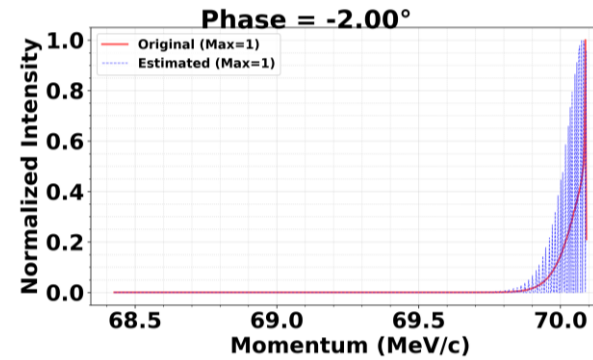
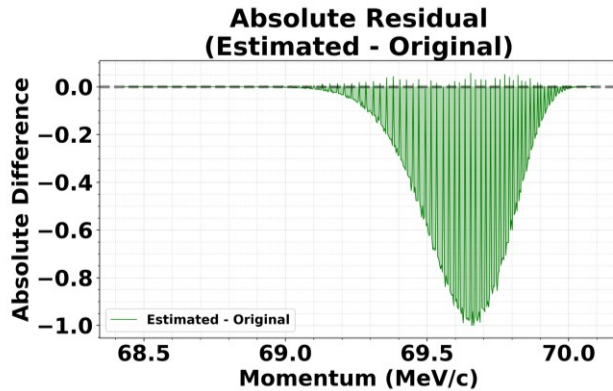
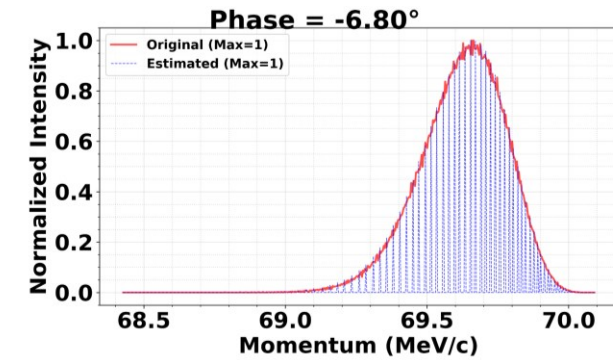


x^1 : Ground truth



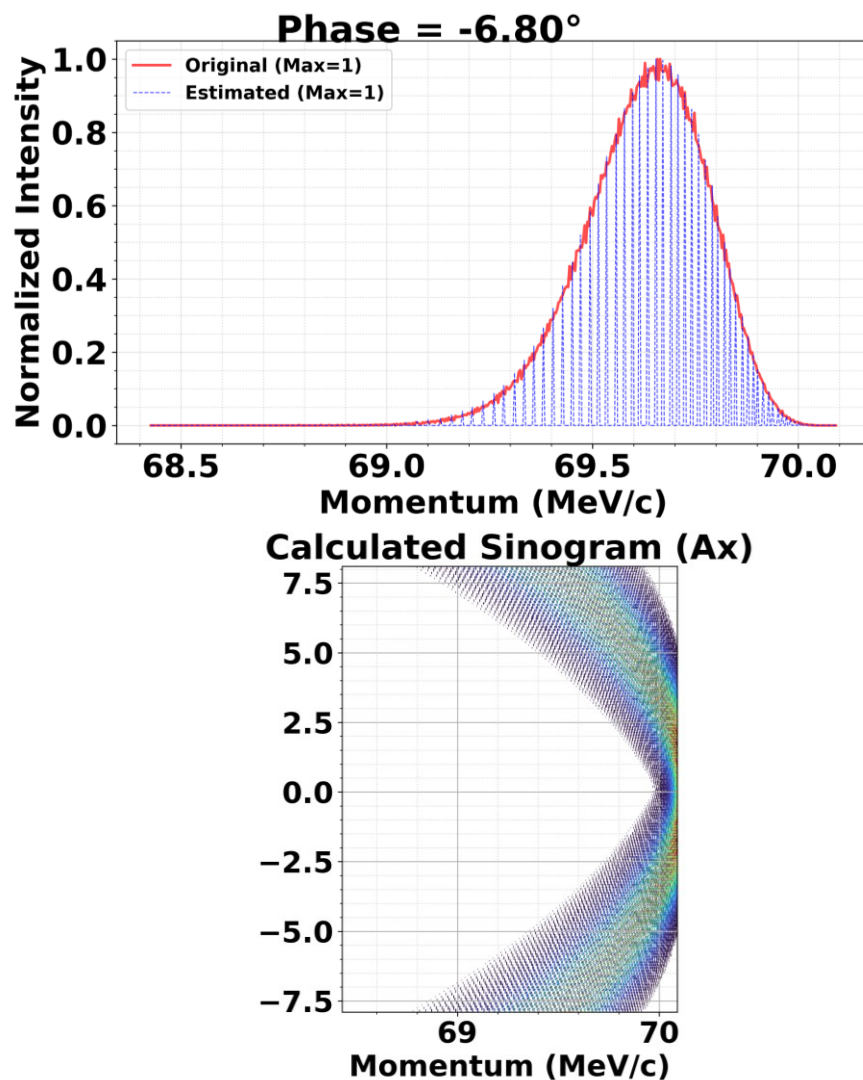
Bilinear interpolation

Constructed \vec{A} (Simple binning) vs simulated momentum distribution

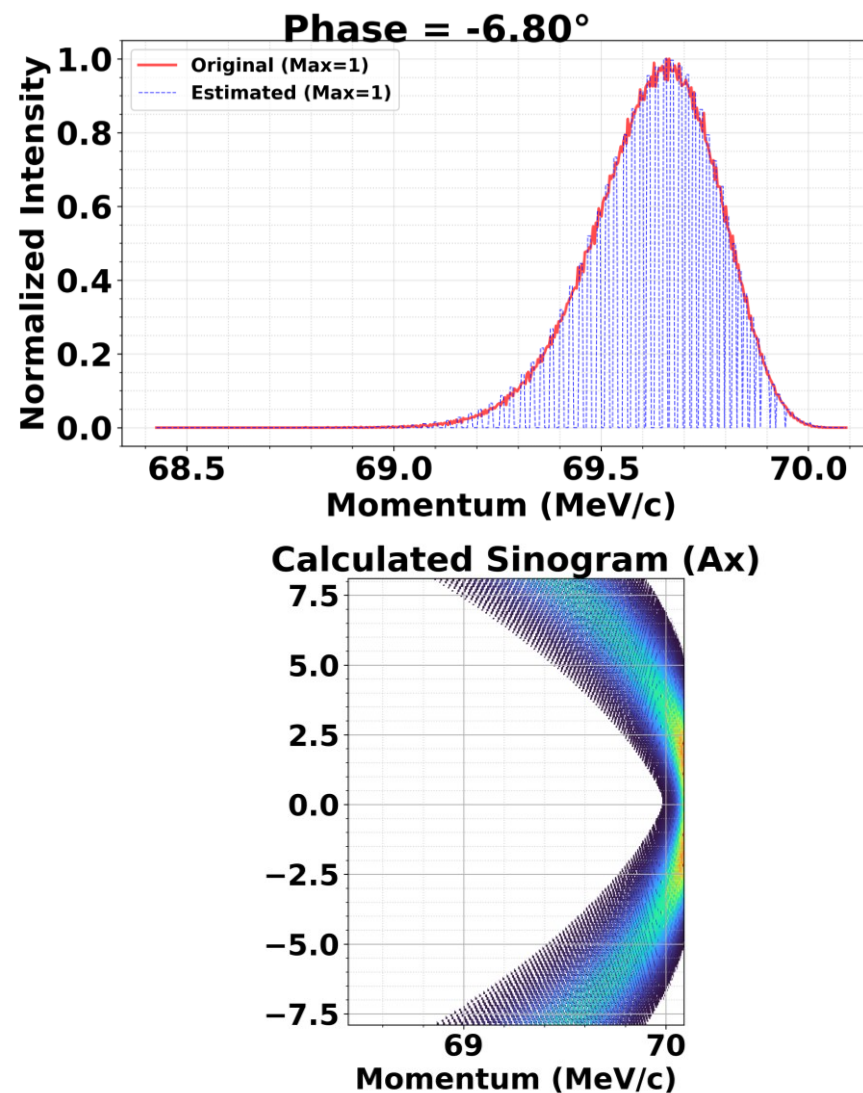


Bilinear interpolation

Simple binning



Bilinear interpolation

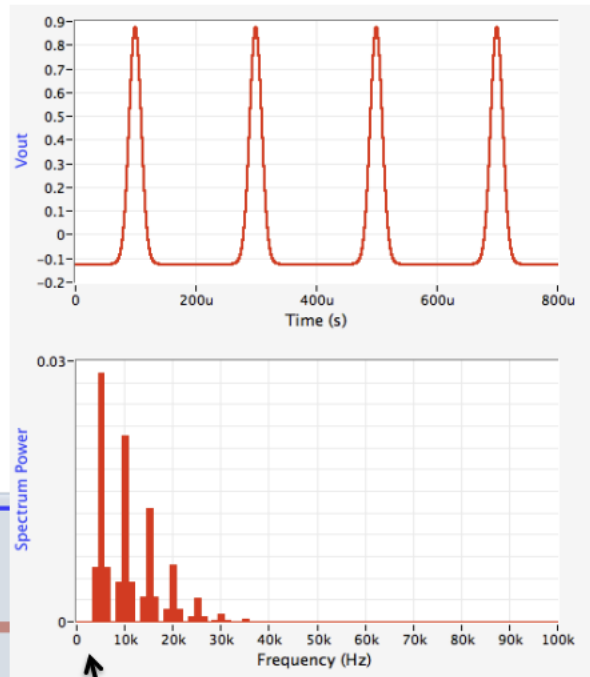
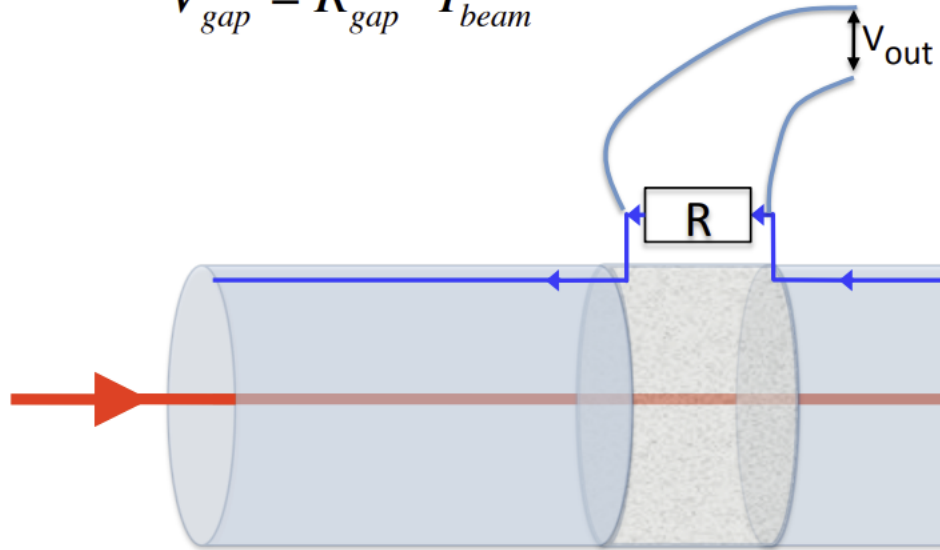


Energy spread measurement

Wall Current Monitor

- Put a resistor over the gap and measure its voltage.

$$V_{gap} = R_{gap} \cdot I_{beam}$$



No DC in image current

The Study Of The Energy Spread Measurement At Linac of CSNS
Yanliang Han*, Jun Peng, Zhiping Li
CSNS, IHEP, CAS, Dongguan, China

Abstract
In accelerator-based spallation neutron sources, which include a rapid cycling synchrotron (RCS), the energy spread at the end of the linac is a crucial parameter that significantly impacts the operational efficiency of the downstream RCS ring. However, in recent years, the energy spread at the linac of the Chinese Spallation Neutron Source has been inadequately measured due to limited methods for longitudinal phase space measurement. This paper presents a study on measuring the energy spread using wall current monitors at the linac. The results indicate that the energy spread is at the 10^{-3} level, consistent with simulations. Nevertheless, the uncertainty remains relatively high, necessitating further efforts to improve measurement accuracy in the future.

The principle of measurement
There are 3 WCMs installed in LRBT which can give the bunch length information in the linac, as shown in Fig. 2.

Data taking & Processing
Bunch length measurements were conducted on the linac of CSNS under various conditions using WCM1 and WCM2 during the machine study period. The pulse length was set to 100 μ s. The data were collected for different peak currents, with a maximum of 20mA.

Simulation
The simulation covers the linac from the MEBT to the end of the LRBT. It shows that rms momentum spread is in the level of less than 1.0‰ and the correlation between the momentum spread and longitudinal position is non-linear due to the space charge effect. This means the $\delta p/p$ has a dependence on the peak current and large peak current beam will lead to larger $\delta p/p$.

Introduction
The China Spallation Neutron Source (CSNS) is an accelerator-based pulsed neutron source located in Guangdong Province, southern China. Construction began in 2011 and was completed in 2018, shown in Fig. 1. The design beam power is 100 kW with plans to upgrade it to 500 kW in the next few years.

Several types of instrumentation equipment are installed along the linac, such as BPM, CT, FCT, and wire scanners. However, some longitudinal beam properties, such as bunch length and energy spread, have not been measured. An energy spread study based on the wall current transformer (WCM) in the RCS for the accumulated initial beam in the RCS indicates an energy spread of 0.17‰. In contrast, simulations in the linac suggest a momentum spread of around 0.1‰. This discrepancy underscores the importance of directly measuring the energy spread at the end of the linac.

Figure 1: The layout of the CSNS facility

Figure 2: The layout of three WCMs in the LRBT

Figure 3: The evolution of $\delta p/p$ along the linac @ 15mA

Figure 4: A sample of measured bunch length @ 20mA

Figure 5: Measured energy spread for different current

Summary
The energy spread at the end of the linac is a key beam parameter that significantly affects the operational efficiency of the RCS ring. This paper investigates the energy spread at the CSNS linac using wall current monitors in the LRBT transfer line. The study reveals that the momentum spread is at the level of 10^{-3} , which is consistent with simulation results. However, the uncertainty remains relatively large.

Peak current [mA]	Momentum spread [%]
5	0.46
10	0.56
15	0.60
18	0.63
20	0.63
40	0.83

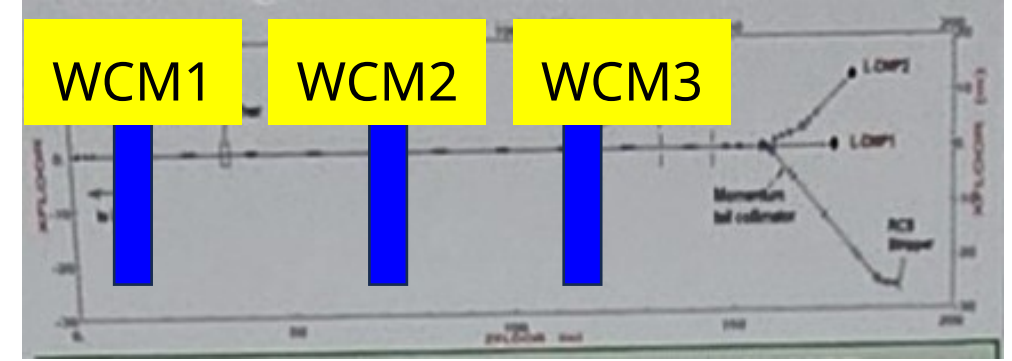
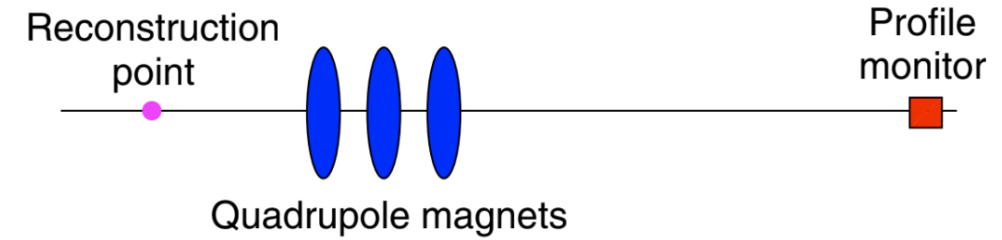
Energy spread measurement

- Unknown: $\sigma_{z,0}^2, \sigma_{\delta,0}^2, \sigma_{z\delta,0}$

- $\Sigma_0 = \begin{pmatrix} \langle z^2 \rangle & \langle z\delta \rangle \\ \langle z\delta \rangle & \langle \delta^2 \rangle \end{pmatrix} = \begin{pmatrix} \sigma_{z,0}^2 & \sigma_{z\delta,0} \\ \sigma_{z\delta,0} & \sigma_{\delta,0}^2 \end{pmatrix}$

- $\Sigma_i = R_i \Sigma_0 R_i^T$

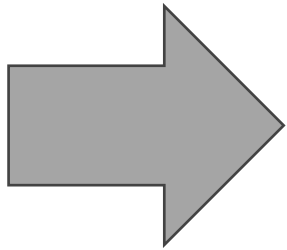
- $\sigma_{z,i}^2 = (R_{i,55})^2 \cdot \sigma_{z,0}^2 + (R_{i,56})^2 \cdot \sigma_{\delta,0}^2 + 2(R_{i,55}R_{i,56}) \cdot \sigma_{z\delta,0}$



WCM 1: $\sigma_{z,1}^2 = (R_{1,55})^2 \cdot \sigma_{z,0}^2 + (R_{1,56})^2 \cdot \sigma_{\delta,0}^2 + 2(R_{1,55}R_{1,56}) \cdot \sigma_{z\delta,0}$

WCM 2: $\sigma_{z,2}^2 = (R_{2,55})^2 \cdot \sigma_{z,0}^2 + (R_{2,56})^2 \cdot \sigma_{\delta,0}^2 + 2(R_{2,55}R_{2,56}) \cdot \sigma_{z\delta,0}$

WCM 3: $\sigma_{z,3}^2 = (R_{3,55})^2 \cdot \sigma_{z,0}^2 + (R_{3,56})^2 \cdot \sigma_{\delta,0}^2 + 2(R_{3,55}R_{3,56}) \cdot \sigma_{z\delta,0}$



Summary

- Checked Algorithm element ($z(t)$, and p_{min}^{boo})

Algorithm 1: Weight matrix for LPS Reconstruction

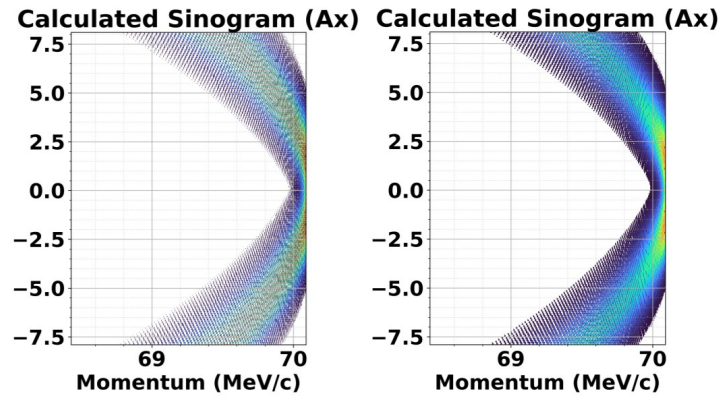
input : φ, p_z^{gun}, V, z
output: *WeightMatrix* (consists of 1s and 0s)

```

1 Function Loop(A)
2    $N_\varphi \leftarrow \text{length}(\text{booster phases})$ 
3    $N_s \leftarrow \text{length}(\text{momentum bins})$ 
4    $N_t \leftarrow \text{length}(\text{longitudinal bins})$ 
5   for  $i \leftarrow 1$  to  $\varphi_{max}$  do
6     for  $s \leftarrow 1$  to  $N_s$  do
7       for  $t \leftarrow 1$  to  $N_t$  do
8          $p_{cal}^{boo} \leftarrow p_{gun}^{gun}(s) + V \cos(\varphi(i) \cdot z(t))$ 
9          $j \leftarrow \frac{p_{cal}^{boo} - p_{min}^{boo}}{\Delta p_{min}}$ 
10         $W(j + N_s(i - 1), t + N_t(s - 1)) \leftarrow 1$ 
11  return WeightMatrix

```

- \vec{m} dependency



- $\sigma_{z,i}^2 = (R_{i,55})^2 \cdot \sigma_{z,0}^2 + (R_{i,56})^2 \cdot \sigma_{\delta,0}^2 + 2(R_{i,55}R_{i,56}) \cdot \sigma_{z\delta,0}$