The 5th JKPS title:

Electron beam transverse phase space tomography using nanofabricated wire scanners with submicrometer resolution

Geunwoo Kim
Div. of Advanced Nuclear Engineering, DANE
POSTECH

Introduction

Why this paper?

1. Wire scanner (WS) is a crucial instrument to get transverse beam profile, even if it is an old technology.
2. Well-written about recent research trends of WS, including lots of previous research, and related equipment.
3. Show how to measure transverse phase space (TPS) via wire scanners with novel method.

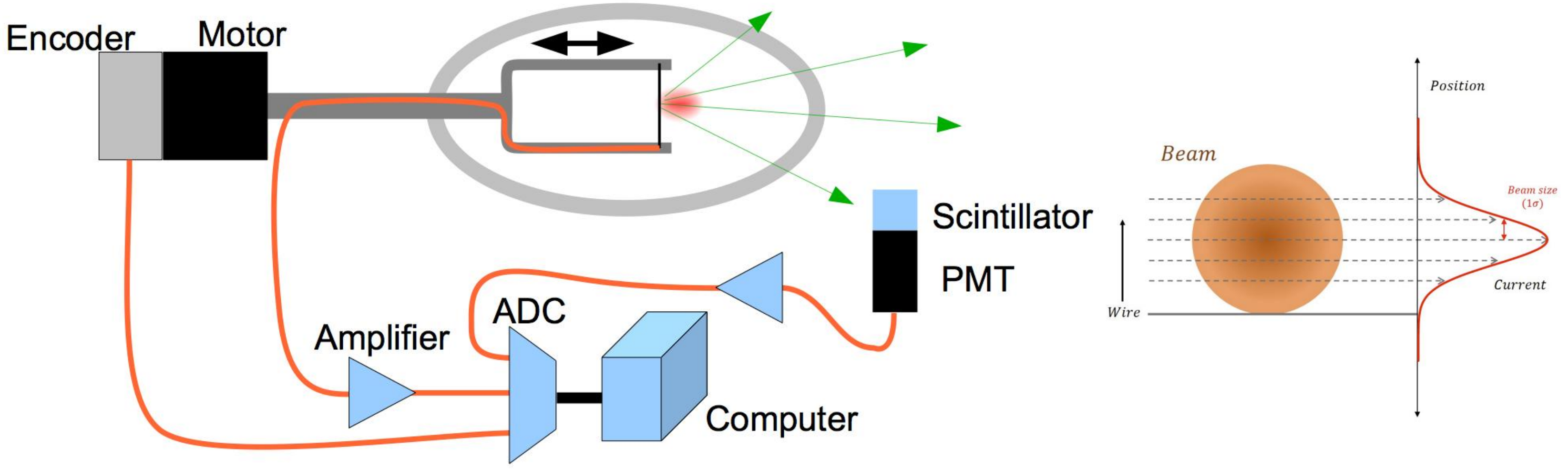
Let's remember title…

~~Electron beam~~ transverse phase space tomography

~~using~~ nanofabricated wire scanners ~~with submicrometer resolution~~

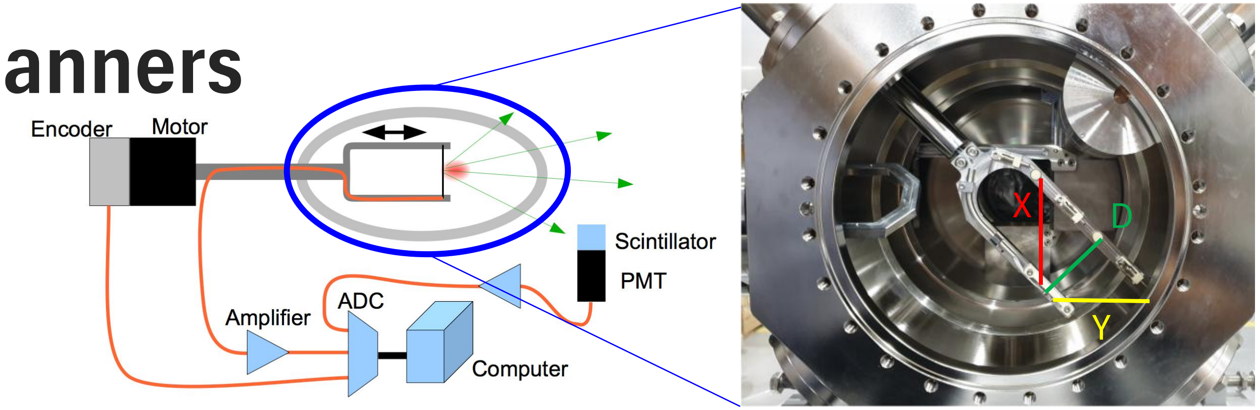
Principal of wire scanners

- What is wire scanner (WS)?
  - One of beam profile monitor
  - Can measure transverse beam size and emittance.



<Schemetic of wire scanners>

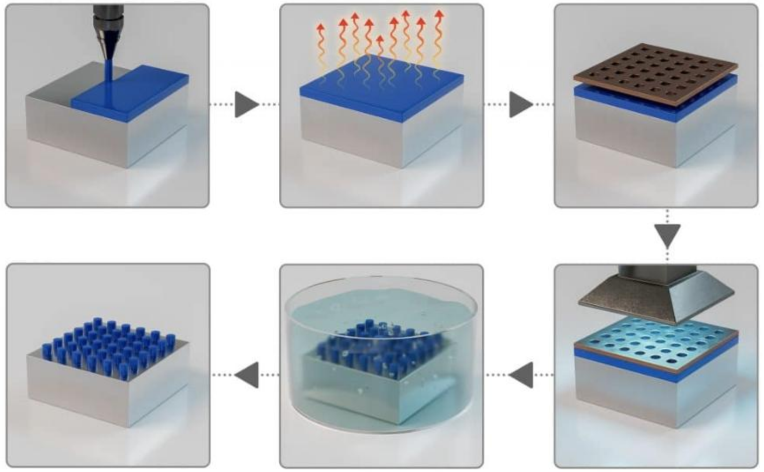
Limitations of conventional wire scanners



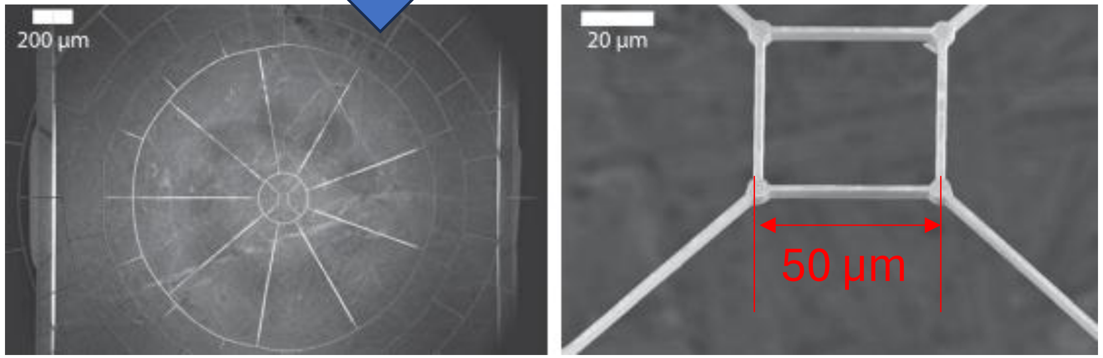
1. Fork wire scanners (Conventional)
   - Thin wires stretched across a fork structure.
   - Wire materials and diameters:
     - Tungsten (5 µm), Al:Si (12.5 µm)
   - **Further size reduction limited by physical constraints (mechanical, thermal, tension)**
2. Resolution σ ~ D/4
   - Target: 400-500 nm beam size at SwissFEL.
   - **Current limitation: σ ~ 1.25 µm** with conventional method.
   - Solution: New approach using electron beam lithography.

3. Nanofabricated wire scanners (Novel)

- Nine free-standing 1 µm Au stripes. (σ ~ 250 nm)
- Nine radial wires



<Electron lithography process>

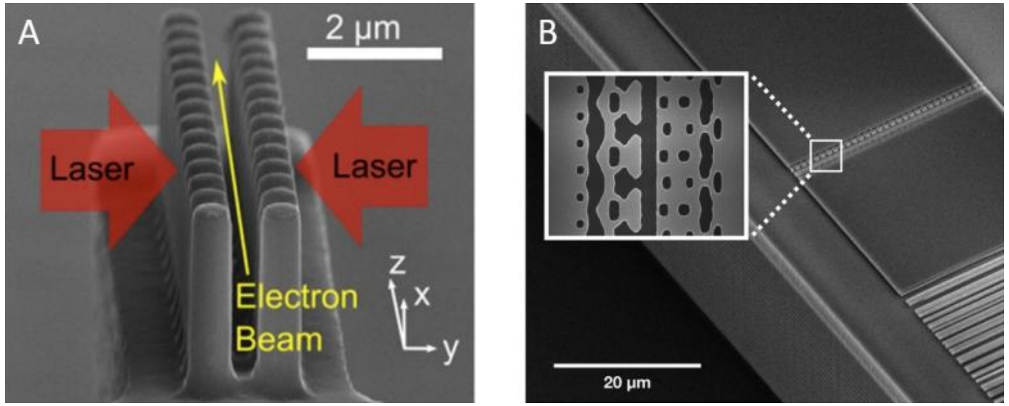


Why need a new-type wire scanner?

- Requirements of next-generation accelerator.
    - Plasma accelerator, and dielectric laser accelerator (DLA)

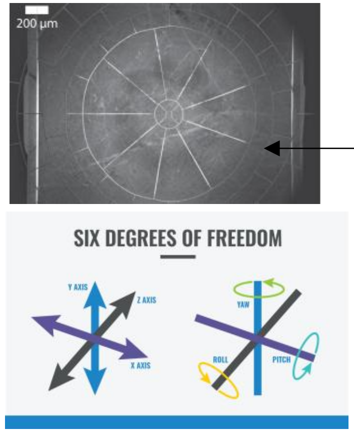
  : ~**a few tens of μm** structure **apertures**

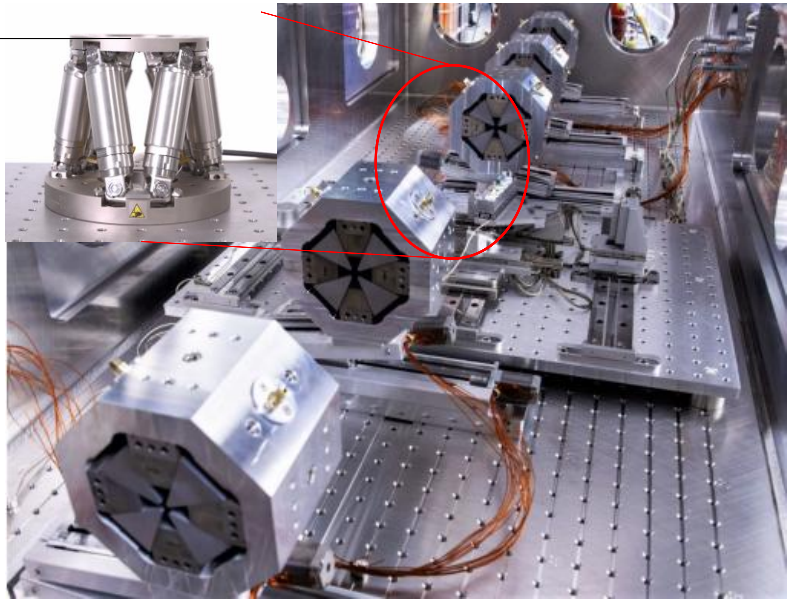
  : Suitable **sub-μm beam tests have to be characterized** in advance.



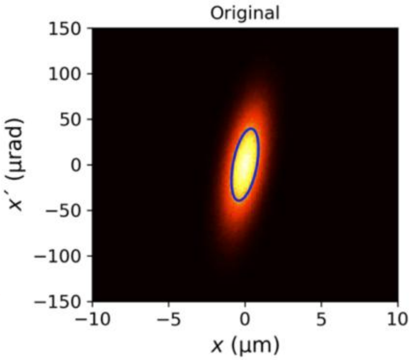
<Dielectric laser accelerator structure>

<Accelerator on a Chip International Program (ACHIP)>





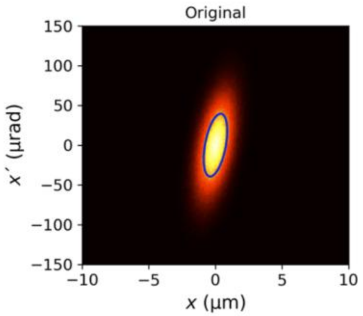
- Designed for DLA research at SwissFEL.
- Two quadruple triplets. (Six magnets in total)
- **Hexapod mounted in the center.**
    - Wire scanner is mounted on hexapod.



~~**Electron beam**~~ **transverse phase space tomography**

~~**using**~~ **nanofabricated wire scanners** ~~**with submicrometer resolution**~~

Reconstruction method

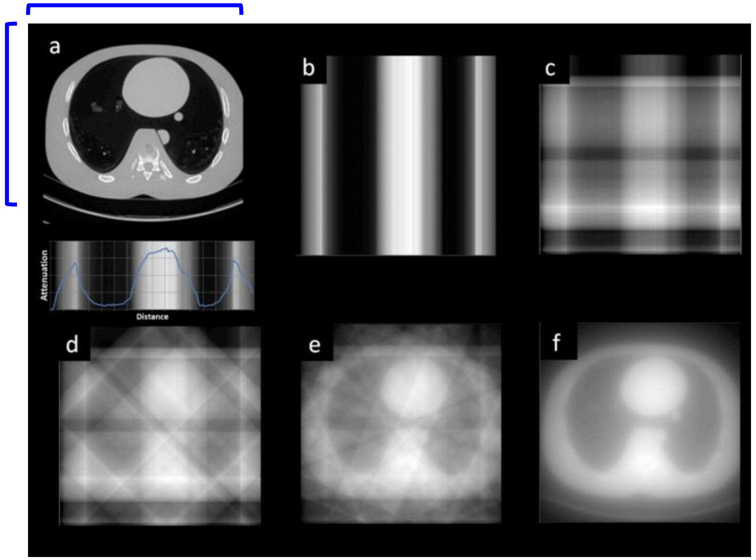


1. Grid-based reconstruction (Standard)
   - Using intensity on each pixel for reconstruction.
   - **Complexity O(n^k)** → Not suitable to reconstruct 4D phase space (x, x', y, y').

Method 1

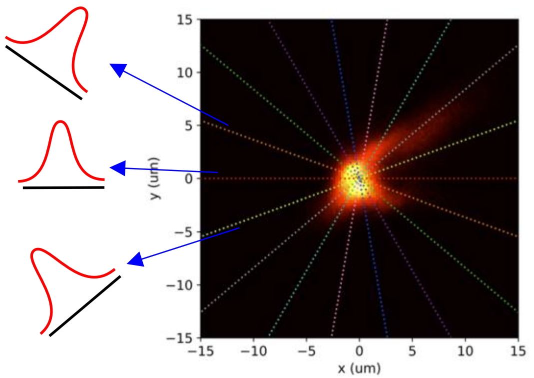
# of pixels (=n)

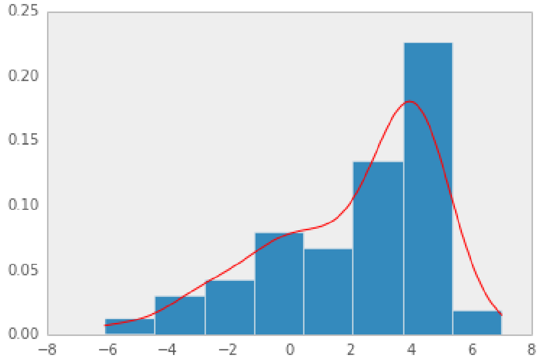
k-axes → k-dimension

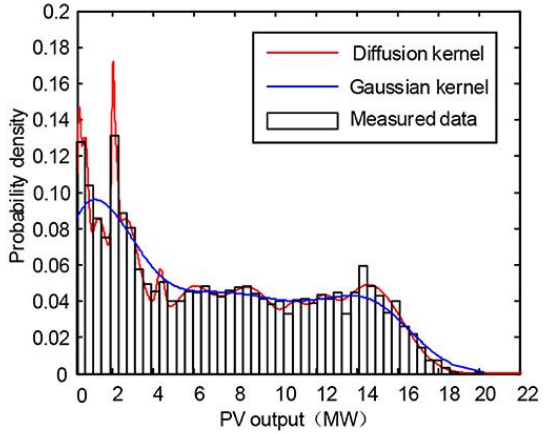


<Reconstruction procedure example>

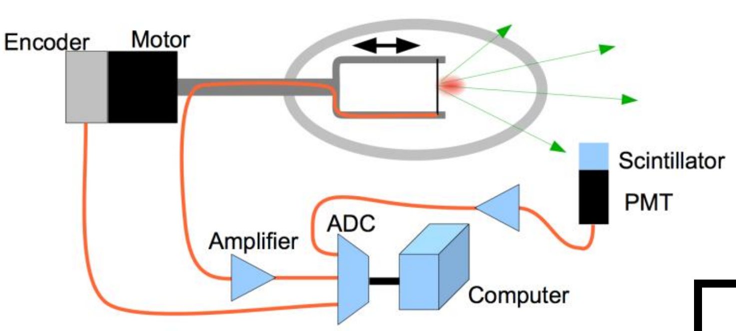
2. <u>Macroparticle-based method (Suggested)</u>
   - Based on Kernal Density Estimation (KDE) similar to Probability Density Estimation
   - Gaussian kernel function $G_k = \frac{1}{\sqrt{2\pi}\rho_\kappa}\exp[-\frac{\kappa^2}{2\rho_\kappa^2}]$ $\kappa \in \{x, x', y, y'\}$
   - **Complexity O(n$_p$)** where n$_p$ is # of macroparticles (***<u>Independent on dimension!</u>***)

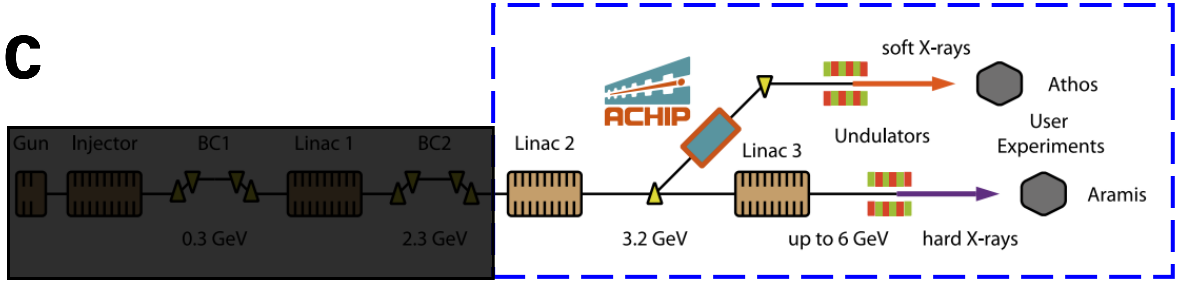






Experimental schematic

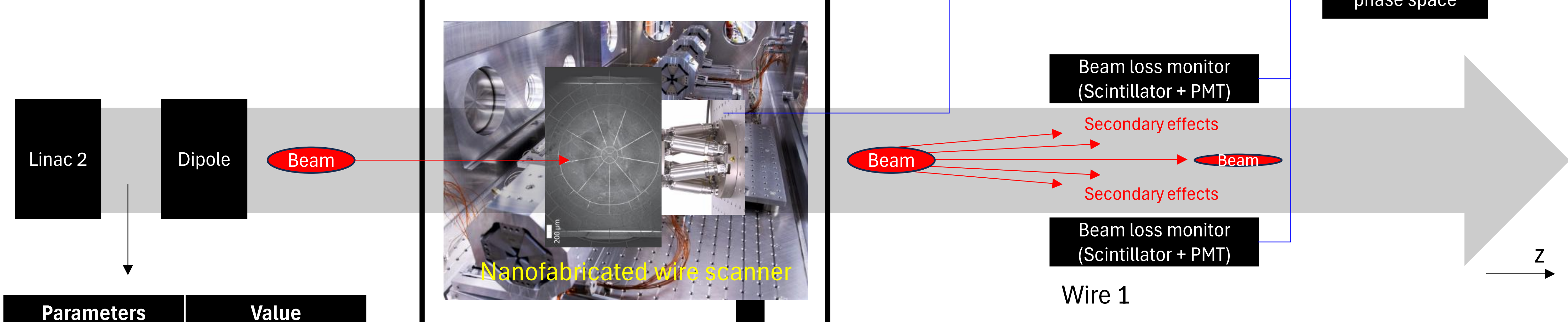




SwissFEL beamline

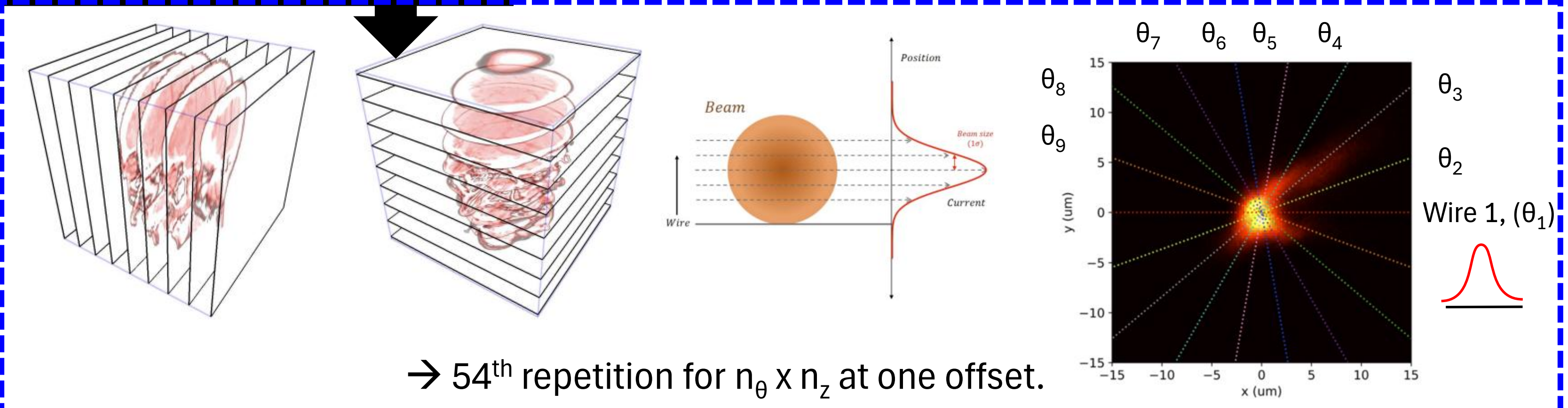
Data processing

<Computer>
Reconstruction
transverse
phase space



ACHIP chamber

Parameters	Value
β_x, β_y	1, 1.8 cm
Energy	3.2 GeV
ΔE/E	1.4×10^{-5}
Charge	1 pC
ε_{nx}, ε_{ny}	93, 157 nm rad



→ 54^{th} repetition for n_θ x n_z at one offset.

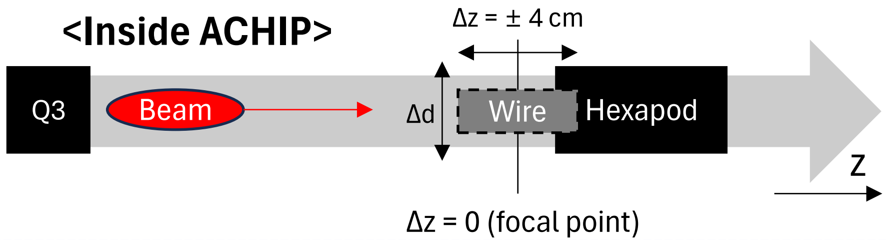
Reconstruction procedure of 4D phase space reconstruction

Eq. (5): $\Delta_{z,\theta}(\xi) = \frac{P^m_{z,\theta}(\xi) - P^r_{z,\theta}(\xi)}{\max P^r_{z,\theta}(\xi)}$ ::

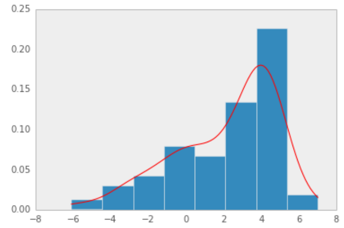
Eq. (6): $\Delta^i = \frac{1}{n_\theta n_z} \Sigma_{\theta,z} \Delta^i_{z,\theta}$ :: Avera

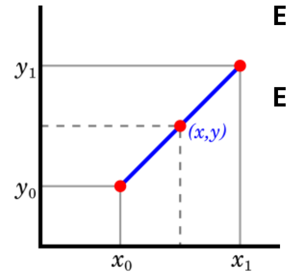
Eq. (B1): $p_k = \frac{1}{n_p n_\theta n_z} \Sigma_{i,\theta,z} \left| \Delta^i_{z,\theta} \right|$

Eq. (B2): $\frac{|p_k - p_{k-1}|}{|p_k|} < \tau = 0.005$ ::



$$G_\kappa = \frac{1}{\sqrt{2\pi}\rho_\kappa} \exp[-\frac{\kappa^2}{2\rho_\kappa^2}] \;\; \kappa \in \{x, x', y, y'\}$$





[A] Reference data

1_{-1}.Generating test signal

1_{-2}.
Data acquisition
(Wire scanner.
Beam Loss Monitor)

2. Transport
$T = \begin{bmatrix} 1 & z \\ 0 & 1 \end{bmatrix}$

3. Rotation
$R = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}$

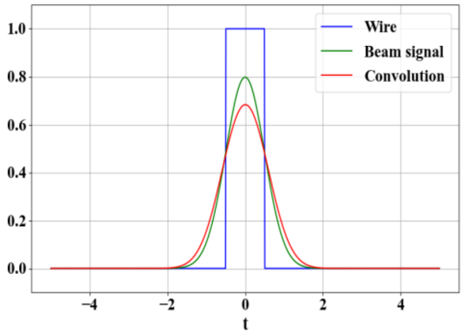
4. Histogram of converted coordinates

5. Interpolation to measured wire positions

[B] Reconstructed data

6. Comparison
Ref. vs reconstructed

7. Redistribution

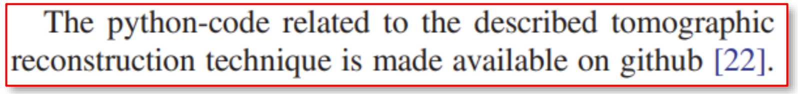


Eq. (5): $\Delta_{z,\theta}(\xi) = \frac{P^m_{z,\theta}(\xi) - P^r_{z,\theta}(\xi)}{\max P^r_{z,\theta}(\xi)}$ :: Error (measured vs reconstructed)

Eq. (6): $\Delta^i = \frac{1}{n_\theta n_z} \Sigma_{\theta,z} \Delta^i_{z,\theta}$ :: Averaged error for i^{th} macroparticles

Eq. (B1): $p_k = \frac{1}{n_p n_\theta n_z} \Sigma_{i,\theta,z} \left| \Delta^i_{z,\theta} \right|$ :: Averaged error for whole macroparticles

Eq. (B2): $\frac{|p_k - p_{k-1}|}{|p_k|} < \tau = 0.005$ :: Stable convergence condition

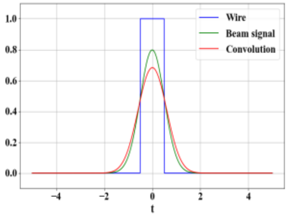

The python-code related to the described tomographic reconstruction technique is made available on github [22].

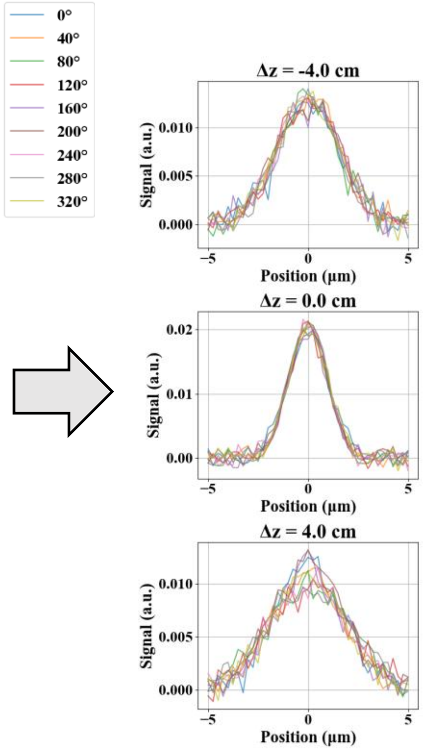
Reconstruction of a simulated measurement

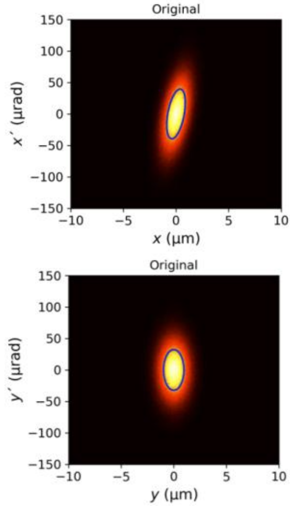
$\chi^i < \frac{|\Delta^i|}{s_{max}}, \chi \in [0,1]$ for each macro particle

[A] Reference data

Signal → **2. Transport** → **3. Rotation**





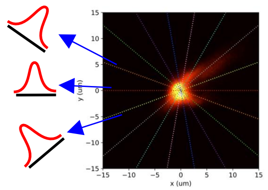


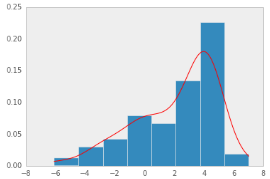
Projection to phase space

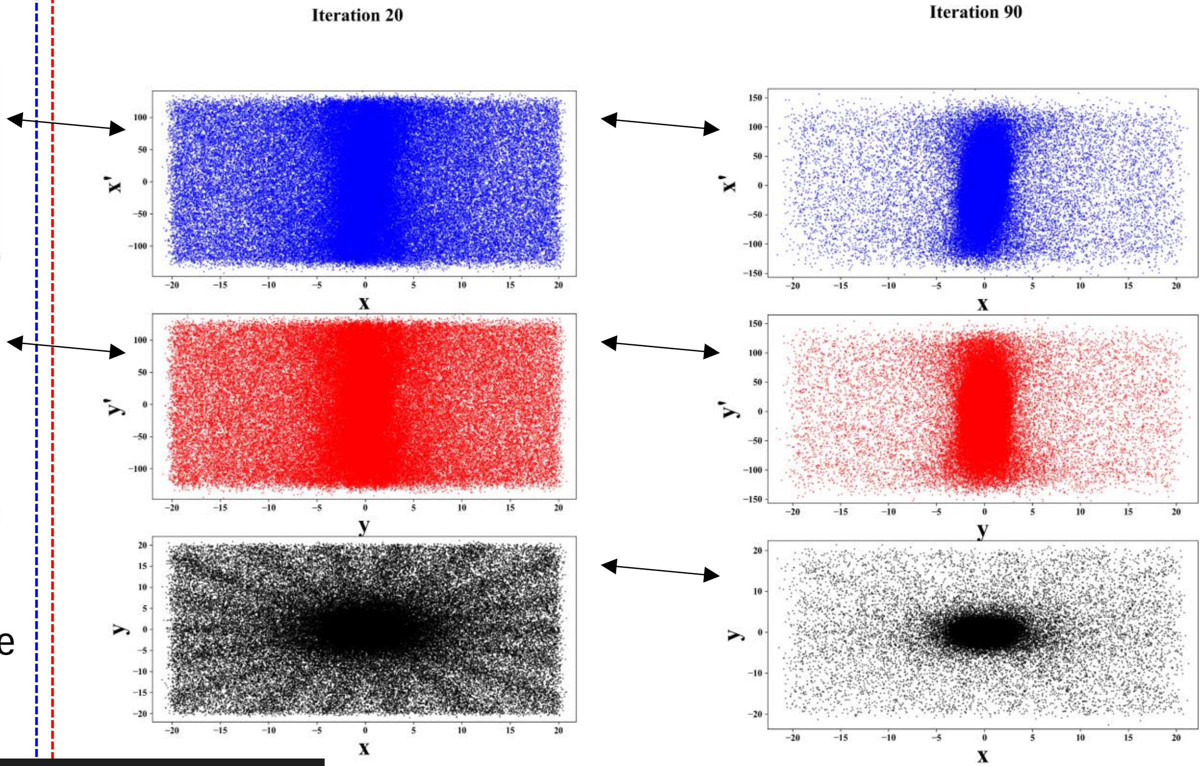
[B] Reconstructed data

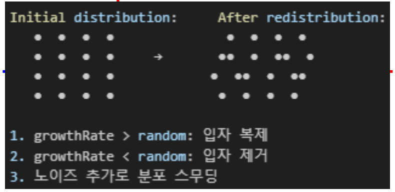
Kernel size $\rho_{x,y}$ = 80 nm

4. Histogram of converted coordinates → **5. Interpolation**









```
Initial distribution:    After redistribution:
   ● ● ● ●                ● ● ● ●
   ● ● ● ●      →       ●● ● ●● ●
   ● ● ● ●             ● ●● ● ●●
   ● ● ● ●               ● ● ● ●

1. growthRate > random: 입자 복제
2. growthRate < random: 입자 제거
3. 노이즈 추가로 분포 스무딩
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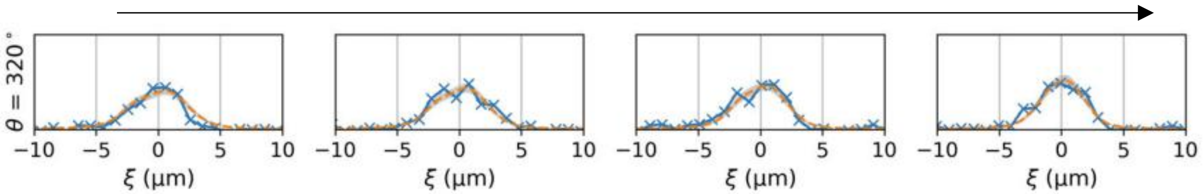
6. Comparison → **7. Redistribution**

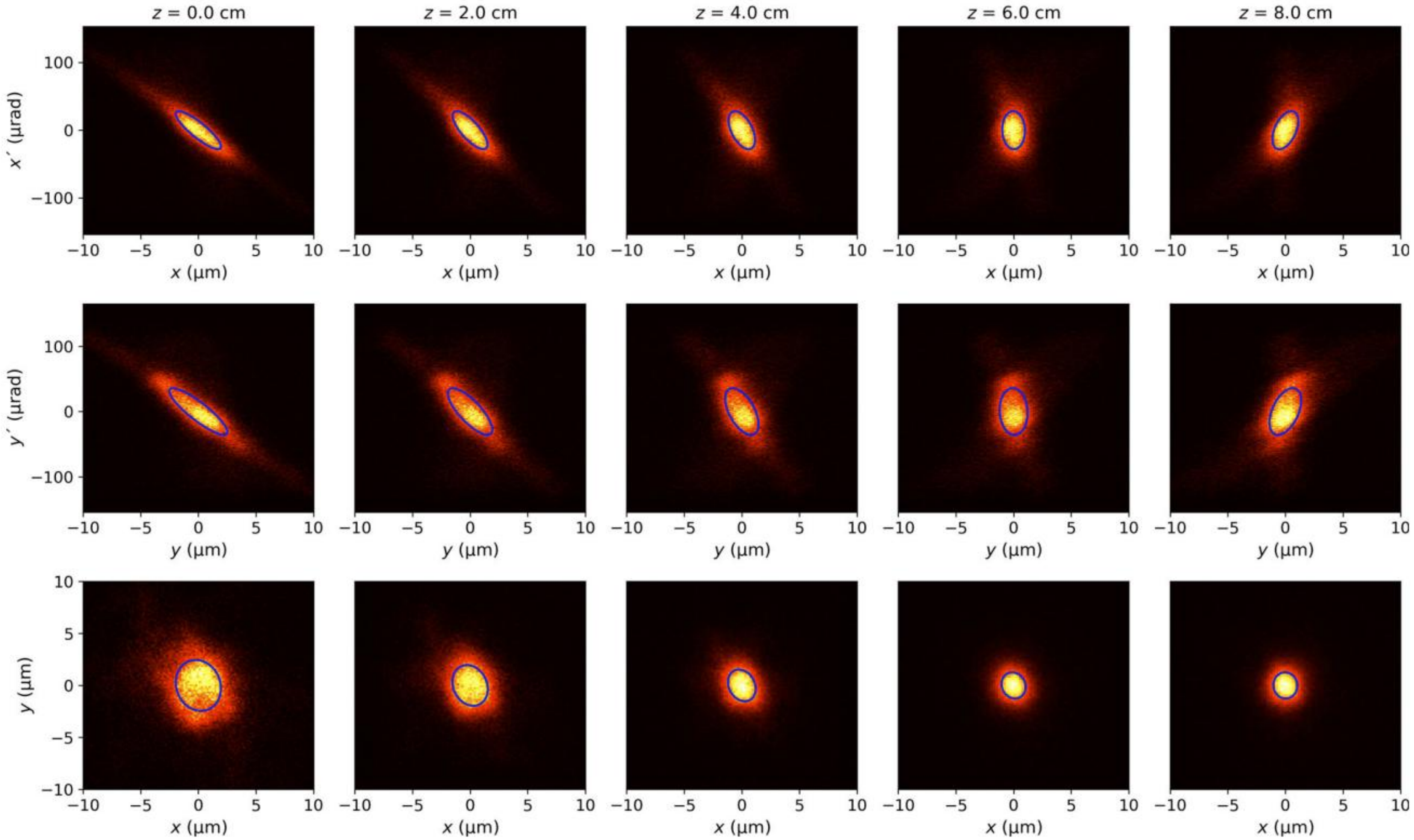
t ~ 2 min

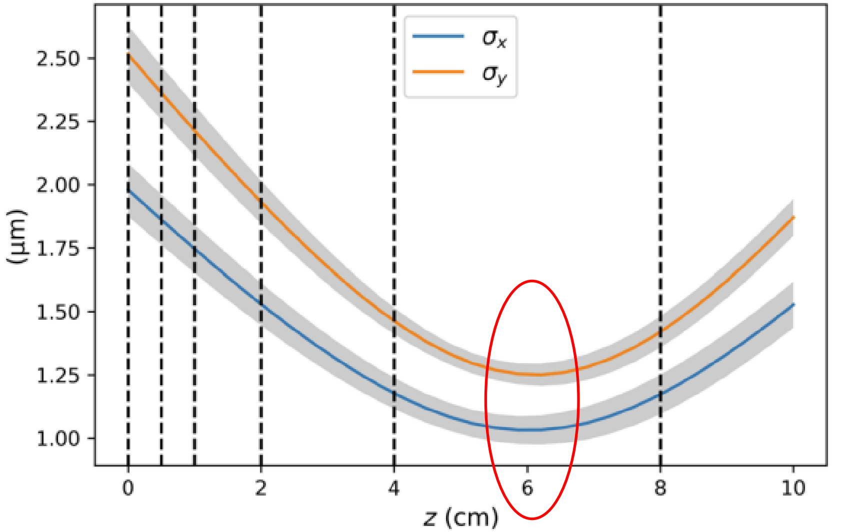
Results

Results for each z step



1. Well-matched BLM signal vs reconstruction
2. To reconstruct 4D phase space, x-y’, x’-y need to be assessed.





Measured focal point = 6.2 m

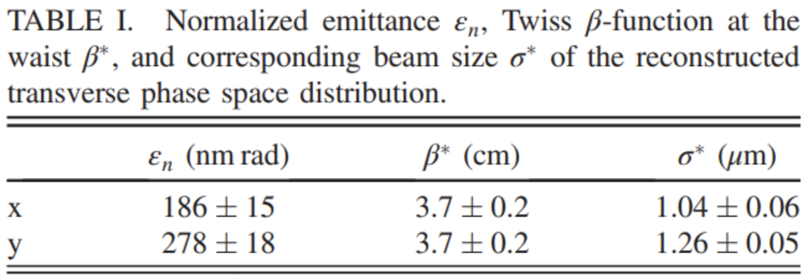
TABLE I. Normalized emittance ε_n, Twiss β-function at the waist β^*, and corresponding beam size σ^* of the reconstructed transverse phase space distribution.

	ε_n (nm rad)	β^* (cm)	σ^* (μm)
x	186 ± 15	3.7 ± 0.2	1.04 ± 0.06
y	278 ± 18	3.7 ± 0.2	1.26 ± 0.05

Discussion

1. Expected waist is located in the center (z= 0), but measured at z = 6.2 m
   - A. Variation of Twiss parameters (Designed optics β_x^*= 1 cm, β_y^*= 1.8 cm)
     - Could be mismatched ACHIP along with beamline.
   - B. ε_n was reconstructed as up to a factor of two larger.
     - Chromatic effects
     - Transverse offsets
     - Lecking dispersion
   - C. Shot-to-shot jitter and non-gaussian beam distribution

→ The **priority** was **to validate a new method** for transverse phase space characterization



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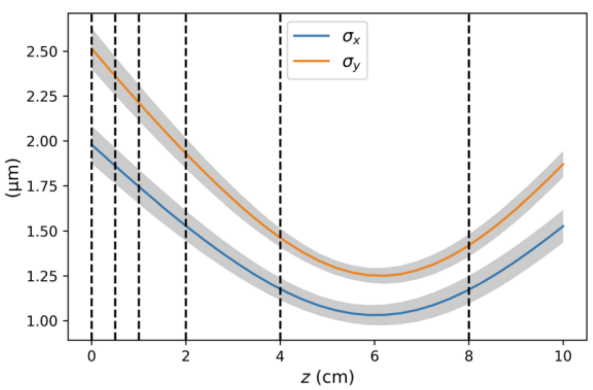
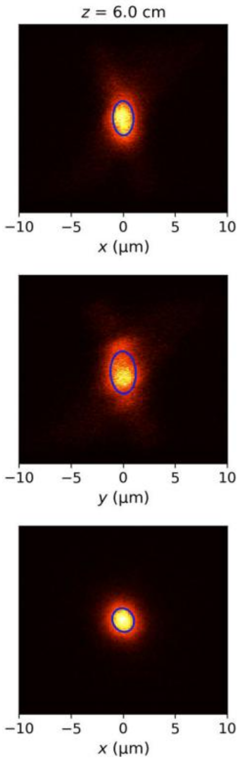
<Reconstructed parameters>

Parameters	**Value**
β_x, β_y	1, 1.8 cm
Energy	3.2 GeV
ΔE/E	1.4×10^{-5}
Charge	1 pC
ε_{nx}, ε_{ny}	93, 157 nm rad

<Designed optics parameters>

Conclusion





1. Presented and validated a novel phase space reconstruction technique.

2. Series of wire scan at different angle, positions along the beam waist.

3. The method could be applied to other facilities and experiments

   e.g. plasma accelerator or DLA experiments. (future compact low-emittance FEL)

However, the damage threshold of the nanofabricated gold wire should be identified.

1. The authors did not include the computing time comparison with old reconstruction method.

2. I’m not sure they identified Δθ or a certain angle.