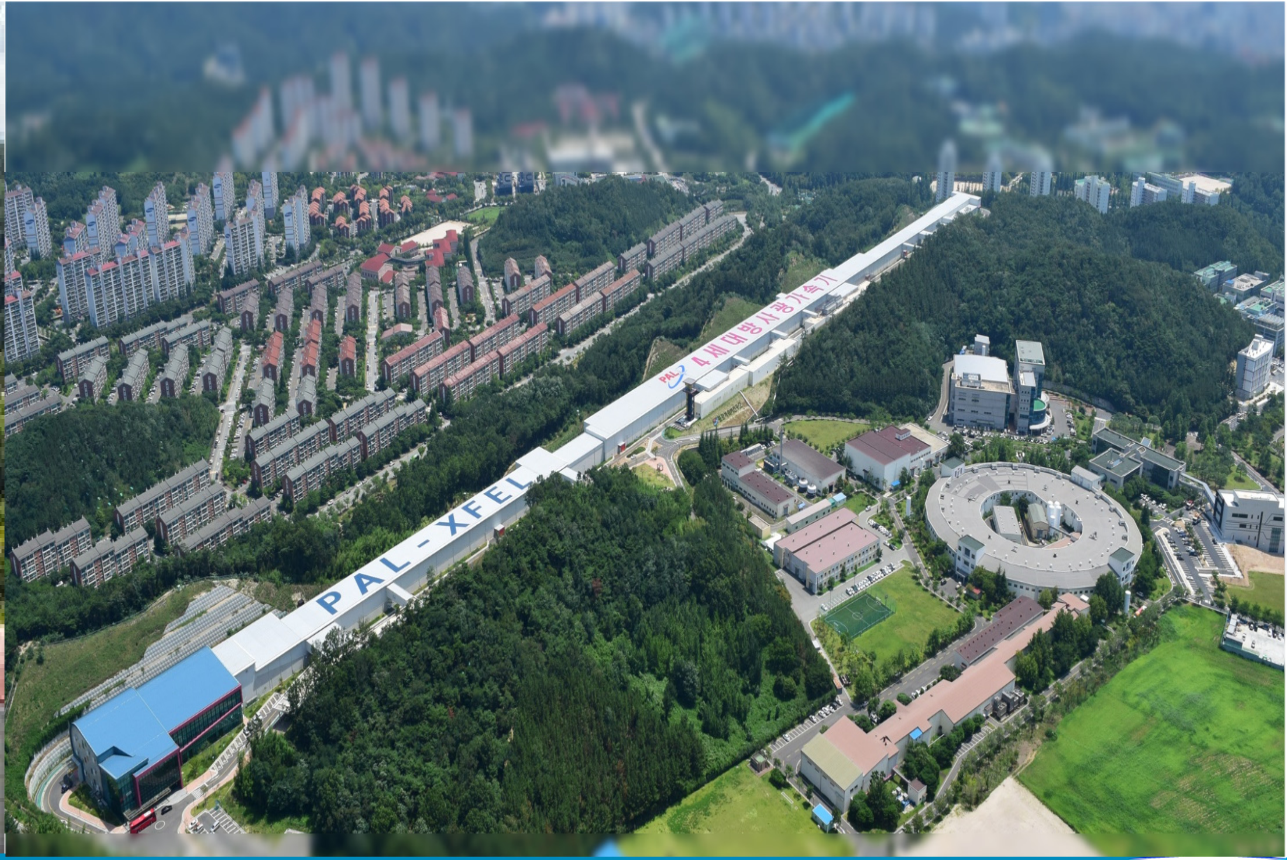

Design and experimental validation of high-resolution single-shot emittance diagnostics for heavy-ion beams

IBIC2024
Sept. 9-13, 2024 · Beijing, China

Ji-Gwang Hwang, Gangneung-Wonju Nat'l Univ. (GWNU)

Garam Hahn, Pohang Accelerator Laboratory (PAL), Rep. of Korea

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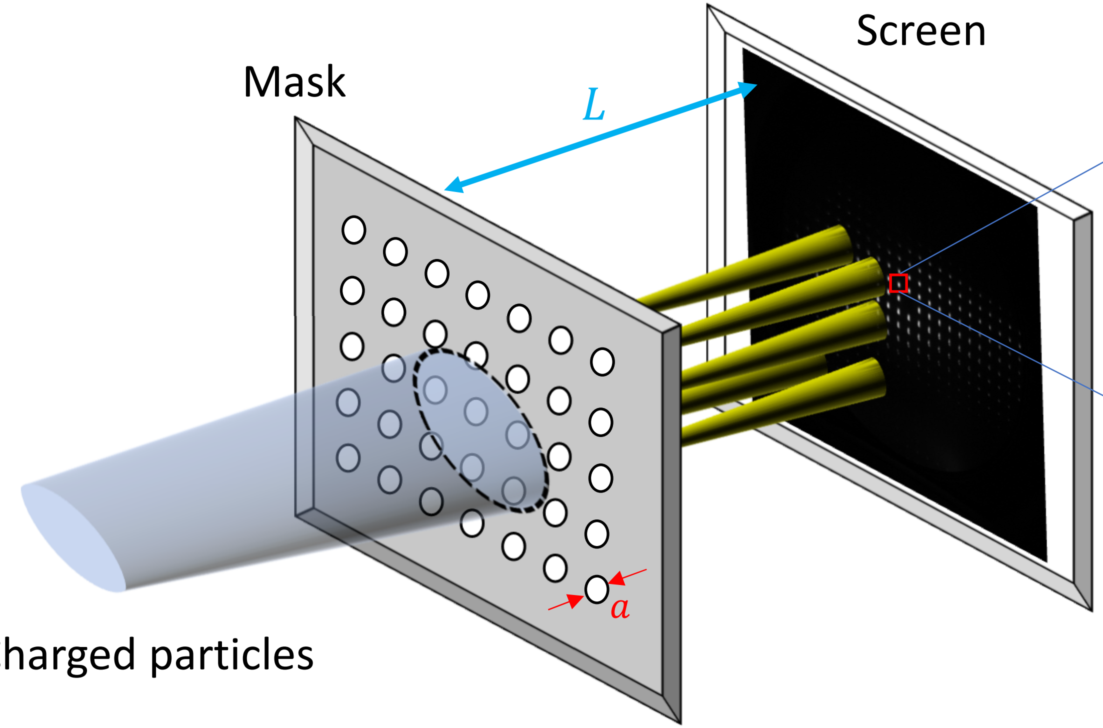
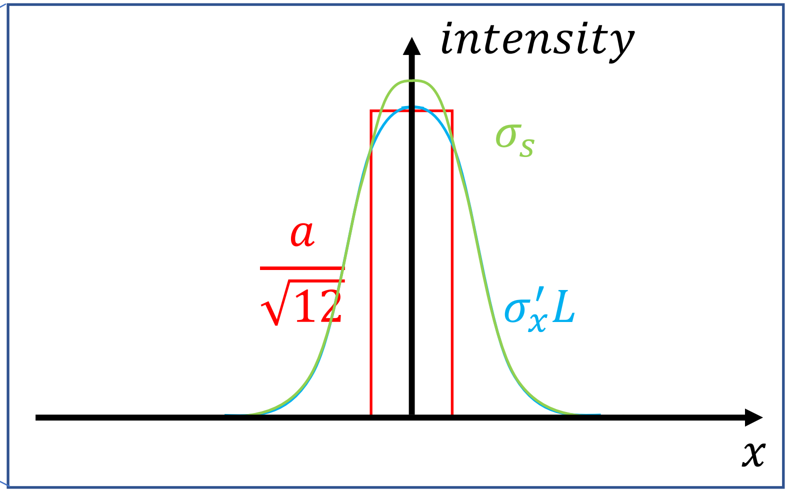
Principle of Pepper-pot device





The rms spot size on the screen σ_s is given by

$$\sigma_s = \sqrt{\left(\frac{a}{\sqrt{12}}\right)^2 + (\sqrt{\varepsilon\gamma}L)^2},$$

where ε denotes the emittance and γ is the Twiss parameter. The factor $1/\sqrt{12}$ comes from considering the rms of the flattop distribution created by the slit projection.

High resolution → Small hole → Low intensity
↓
Limited resolution ← Noise ← Micro-Channel Plate

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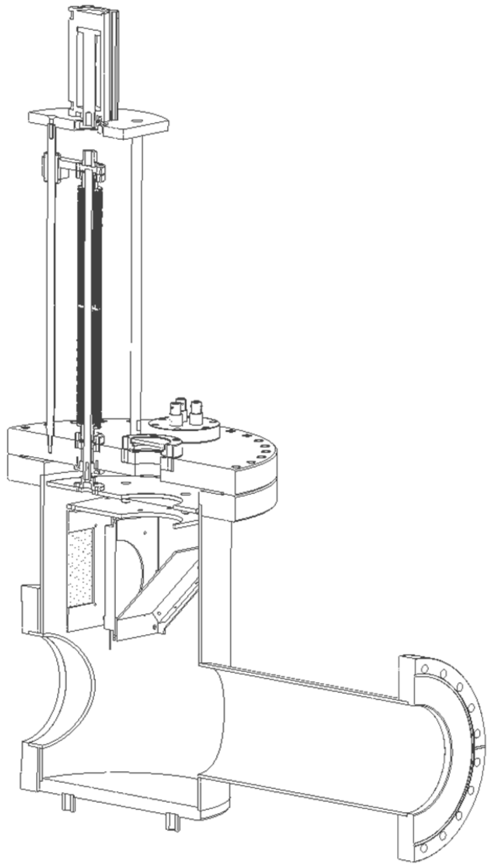
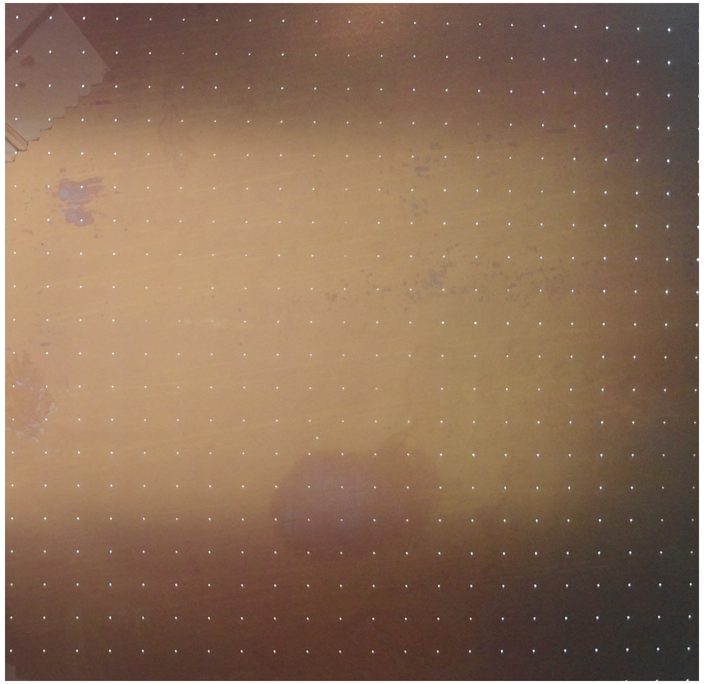
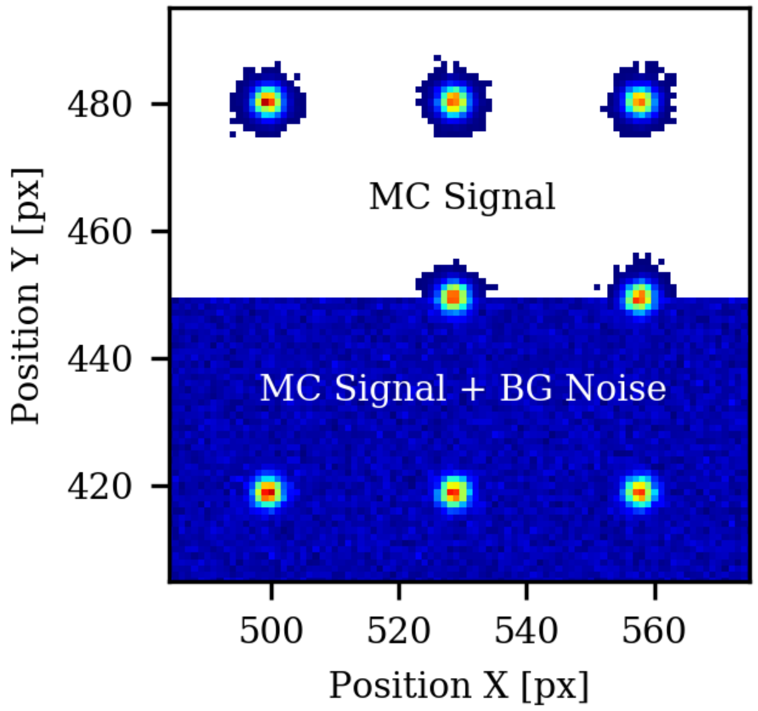
Design considerations and issues



Design recipe
(hole size, distance,...)



Mask manufacturing
(Laser, Etching,...)



Noise subtraction
(Floor cut, + extrapolation
sophisticated filters, ...)

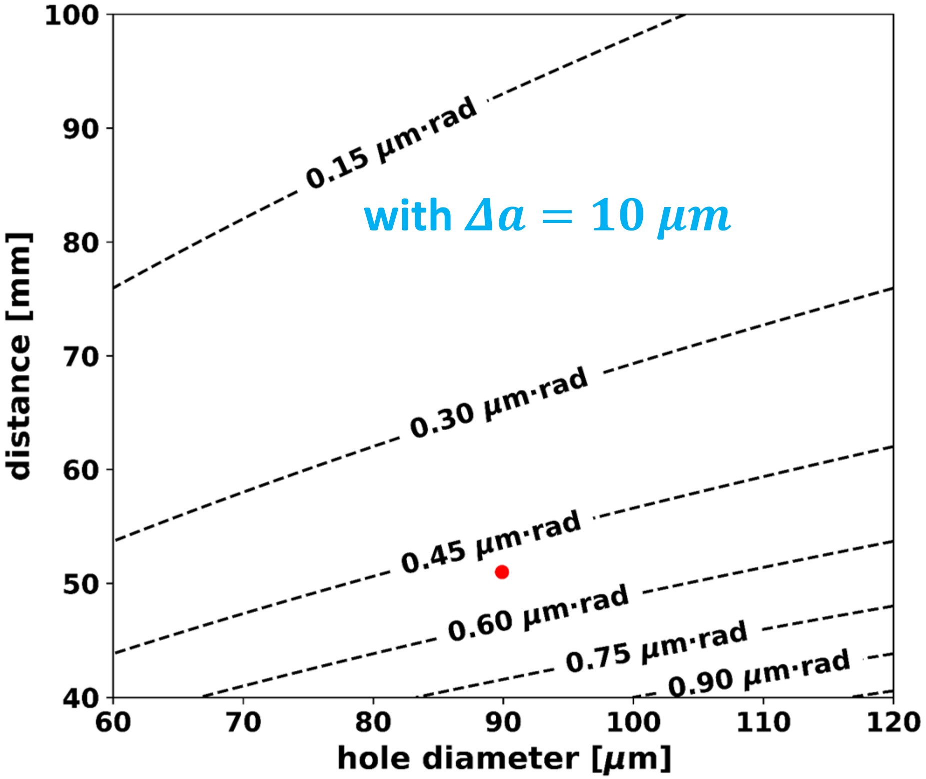
Design considerations

- Resolution calculation with hole size inaccuracy

$$\Delta\varepsilon = \frac{2\Delta a}{\gamma L^2}\left(2\sigma_s \frac{\partial \sigma_s}{\partial a} - \frac{2a}{\sqrt{12}}\right)$$

  - hole size inaccuracy Δa (?)
  - hole diameter a ($60\sim150\mu m$)
  - MCP-to-mask distance L ($40\sim150\ mm$)
  - γ are the Twiss parameters

- For our beamline, the installation space is limited (less than 10 cm total)
- LEBT emittance: ~ 30 nm-rad

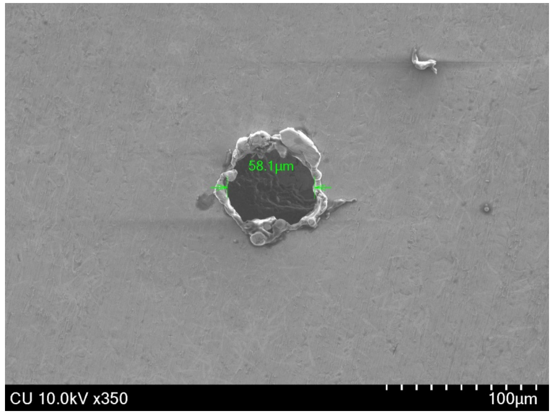


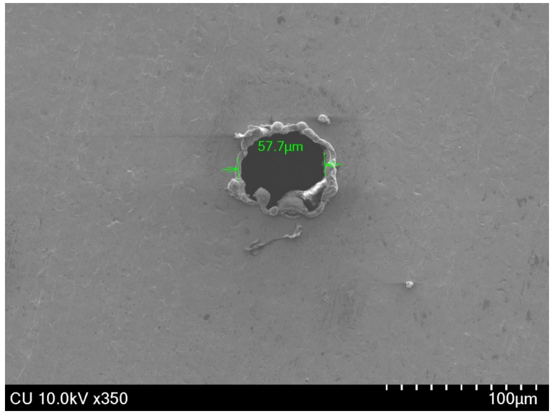
MAIN SPECIFICATIONS OF THE DESIGNED PEPPER-POT DEVICE

Name	Value	Unit
Dimension of mask hole-array	75 × 75	mm
Mask hole configuration	25 × 25-1	–
Mask hole-to-hole distance	3.0	mm
Mask hole diameter	89.9 ± 1.3	μm
Mask to MCP distance	51	mm
MCP active radius	37.5	mm

Mask production

Laser-cutting





Small and irregular holes

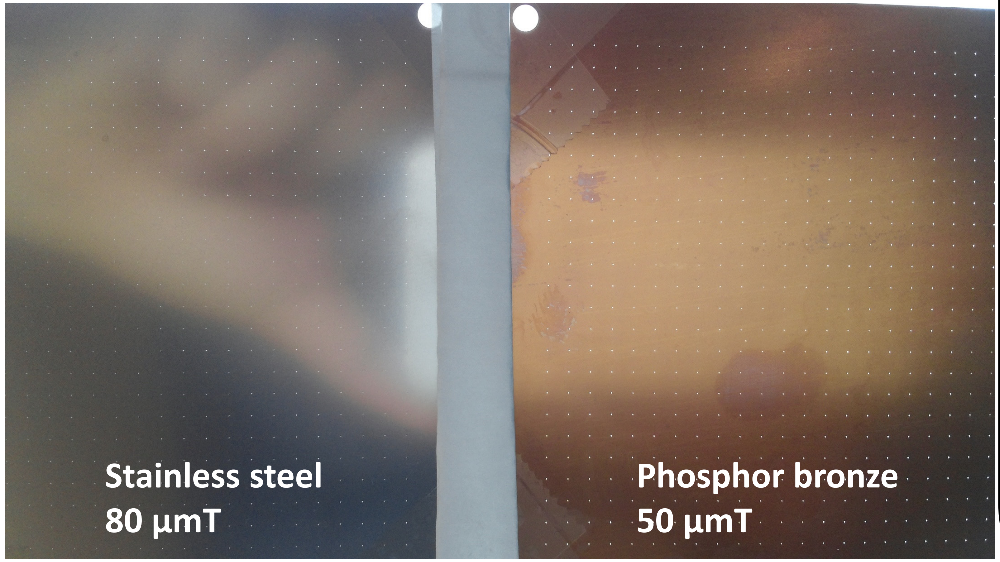
Requirements

Diameter: less than $90\mu m$

Mask size: $8.5\ cm\ \times 8.5\ cm$

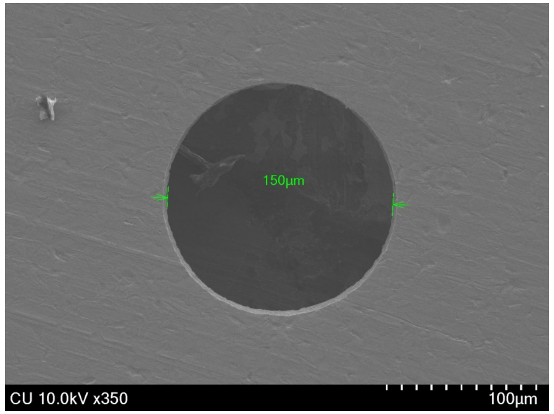
# of holes: 25 x 25 – 1 (*at center)

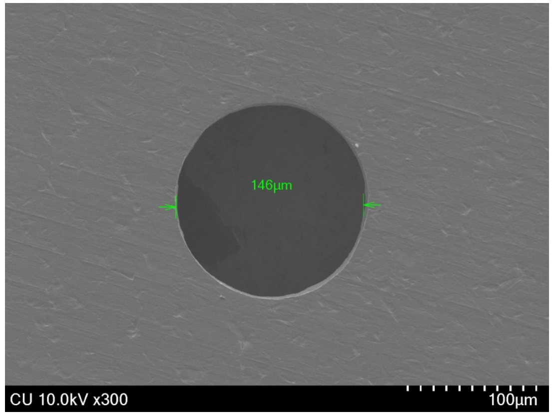
Laser-cutting **Photolithography**



$\langle a \rangle = \mathbf{58}\boldsymbol{\mu m}$ $\langle a \rangle = \mathbf{150}\boldsymbol{\mu m}$

Lithography





Large diameter but clean

Controllable by Manufacturing procedure

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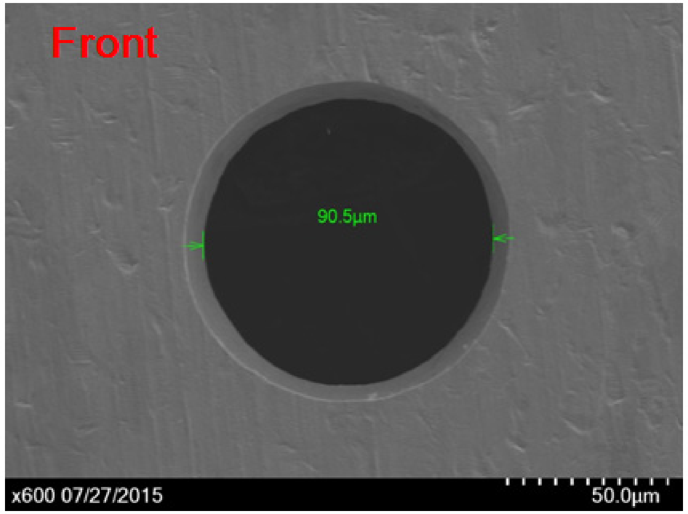
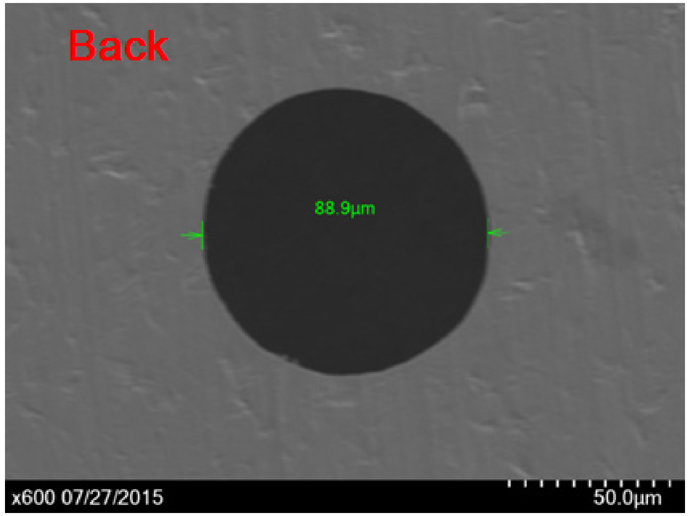
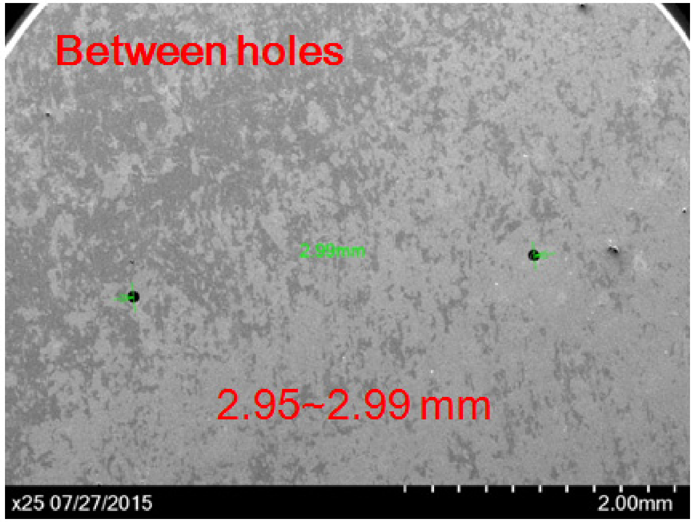
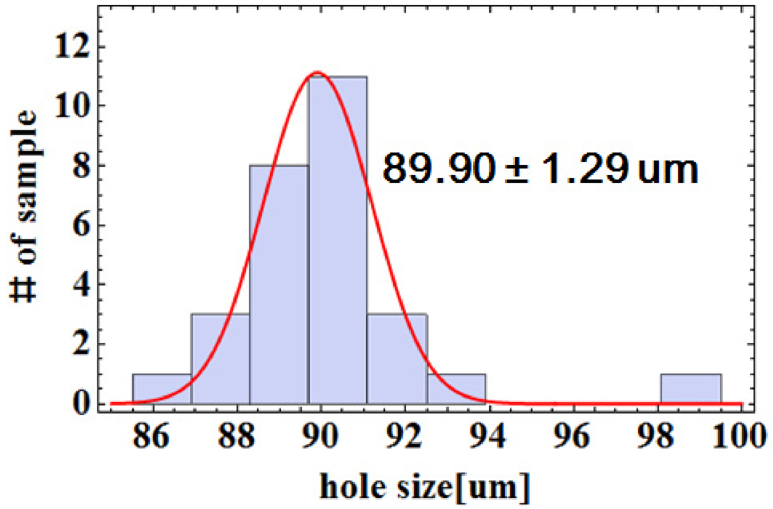
Mask production

Scanning Electron Microscope
- 5 cm x 5 cm sample

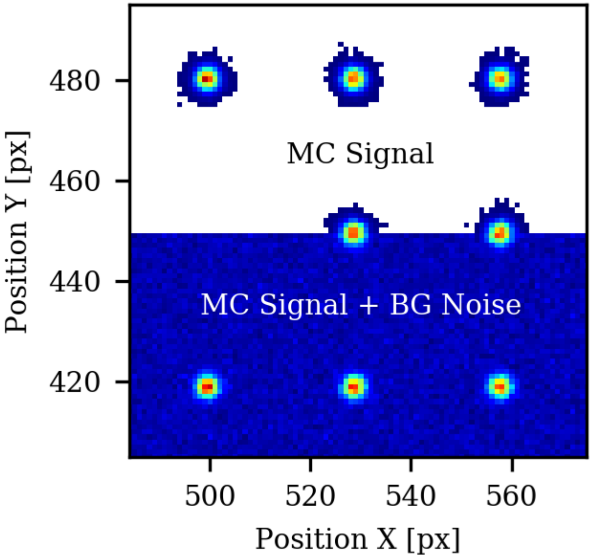


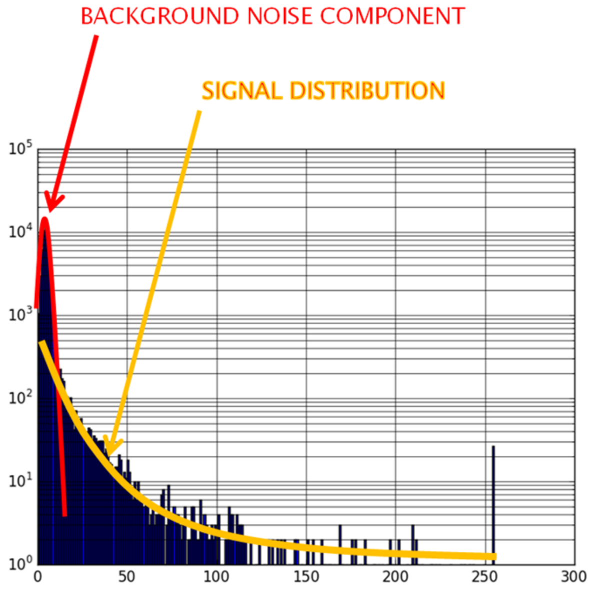






Background + noise subtraction



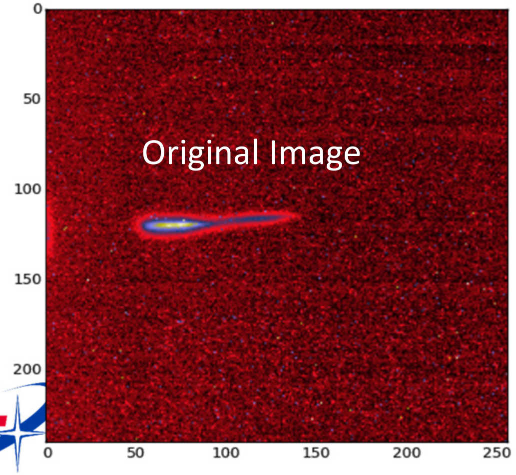


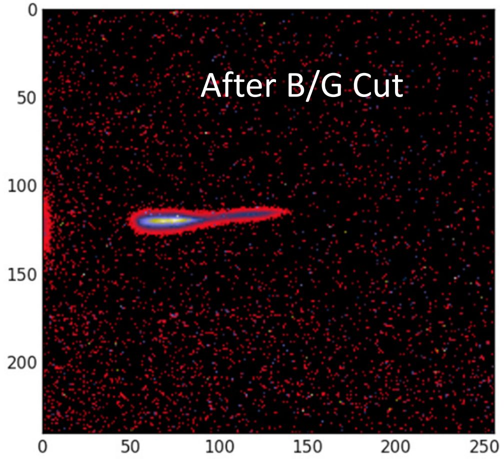
ALGORITHM WORK-FLOW

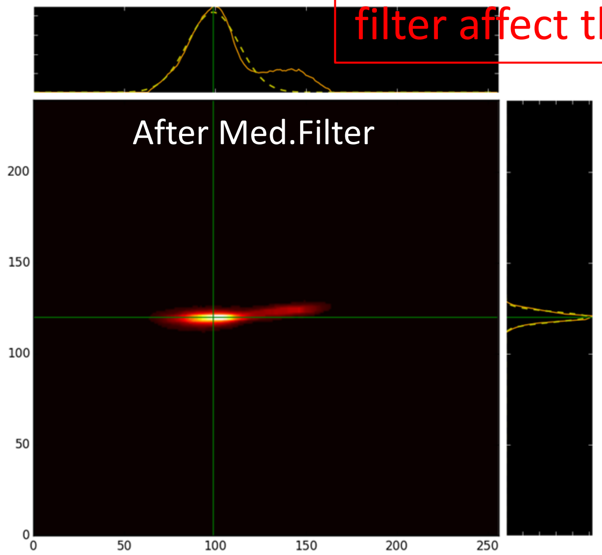
For the spectrum analysis

1. find the lowest peak
2. Pick a sample point for fitting
   around hilltop
3. make a curve fit
   → get std. deviation
4. subtract the threshold (~ 2.5σ)
5. Apply median filter (with a kernel of 5 pixels)

BG noise cut and median filter affect the real signal





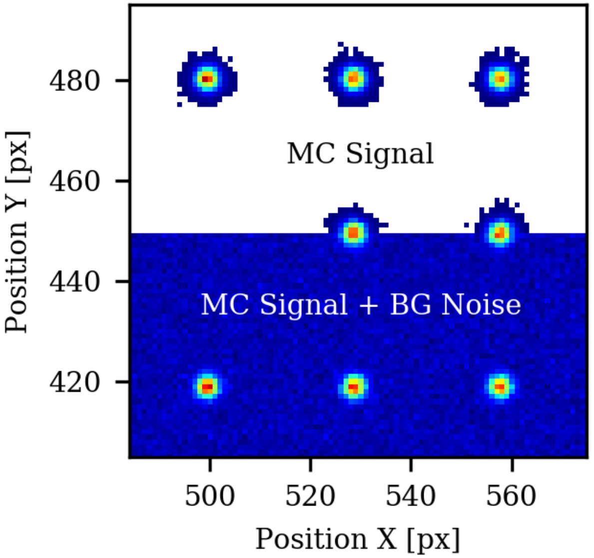


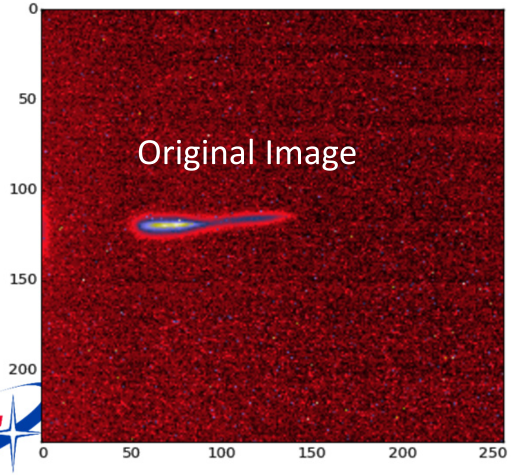
Background + noise subtraction

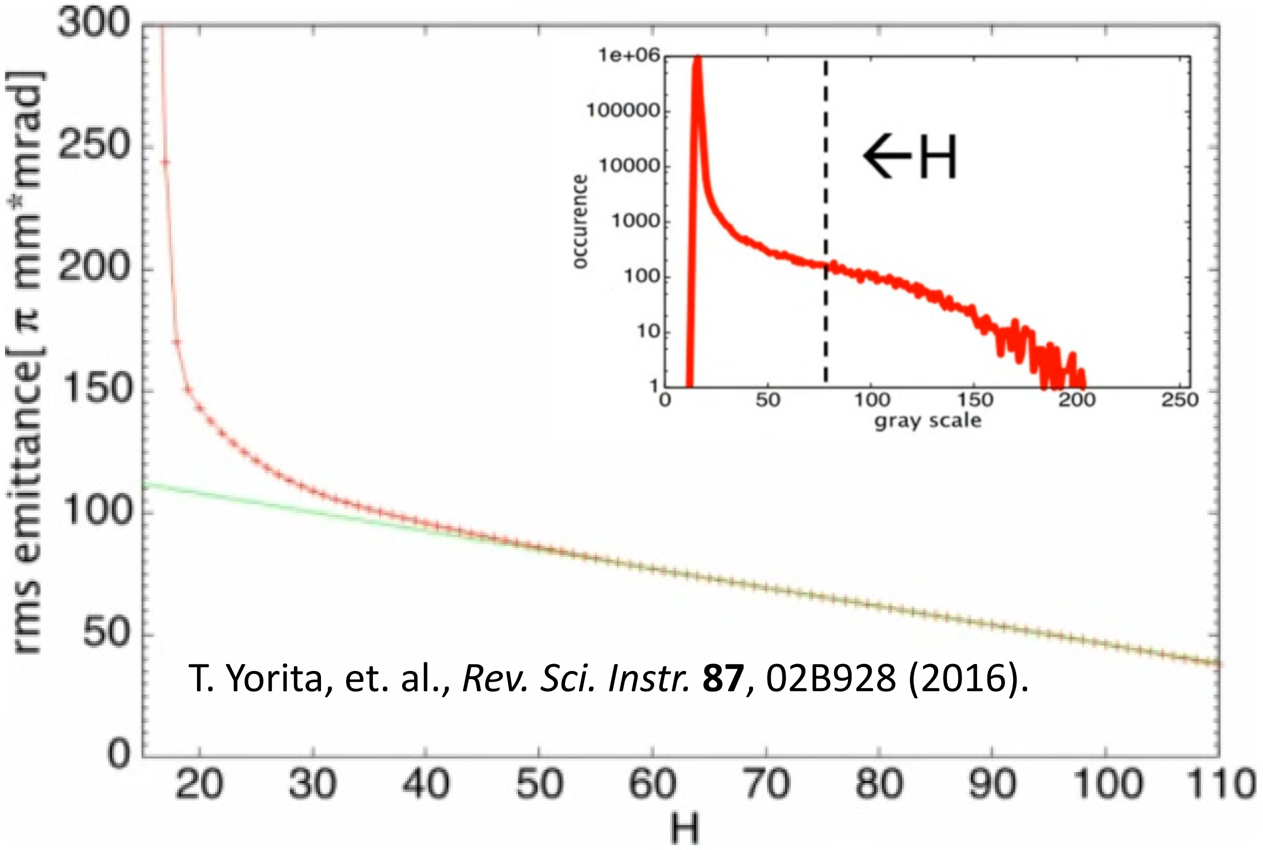
BACKGROUND NOISE COMPONENT

SIGNAL DISTRIBUTION

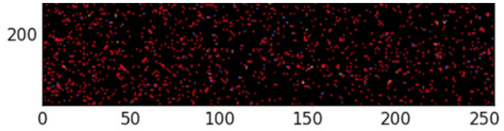
ALGORITHM WORK-FLOW







T. Yorita, et. al., *Rev. Sci. Instr.* **87**, 02B928 (2016).

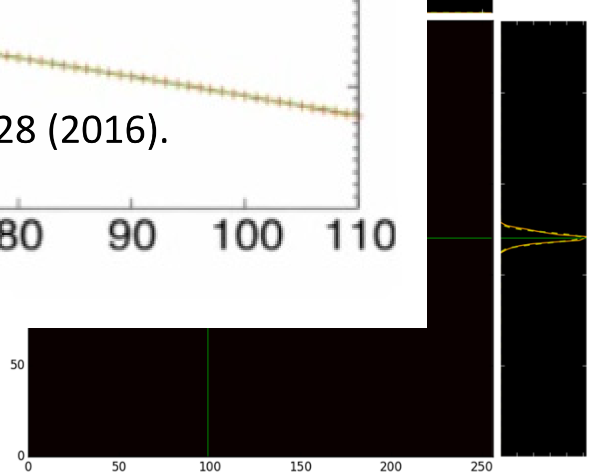


5)

rnel of 5 pixels)

noise cut and median

r affect the real signal



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Algorithm test with virtual image

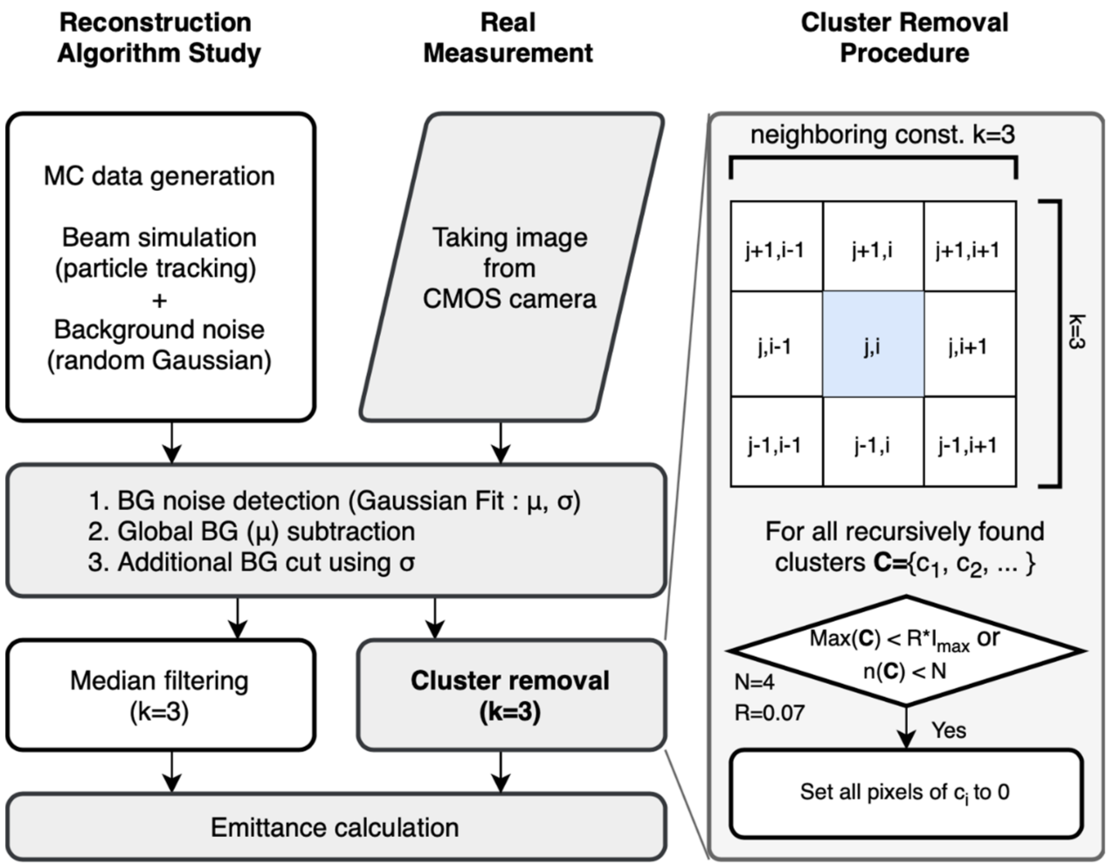
- MC-GEN – MonteCarlo event generator
  Gaussian Twiss beam Gen.
  * Misalignment error + Dist. error
- SIM-DIGI – Transform and Digitization
  Convert to a bitmap image
  * MCP and CCD resolution-related error

intensity level of each pixel

$$n(\vec{X}_{i,j}) = \left\lfloor A e^{-\frac{(x-x_i)^2}{2\epsilon_x \beta_x}} e^{-\frac{(y-y_j)^2}{2\epsilon_y \beta_y}} \right\rfloor$$

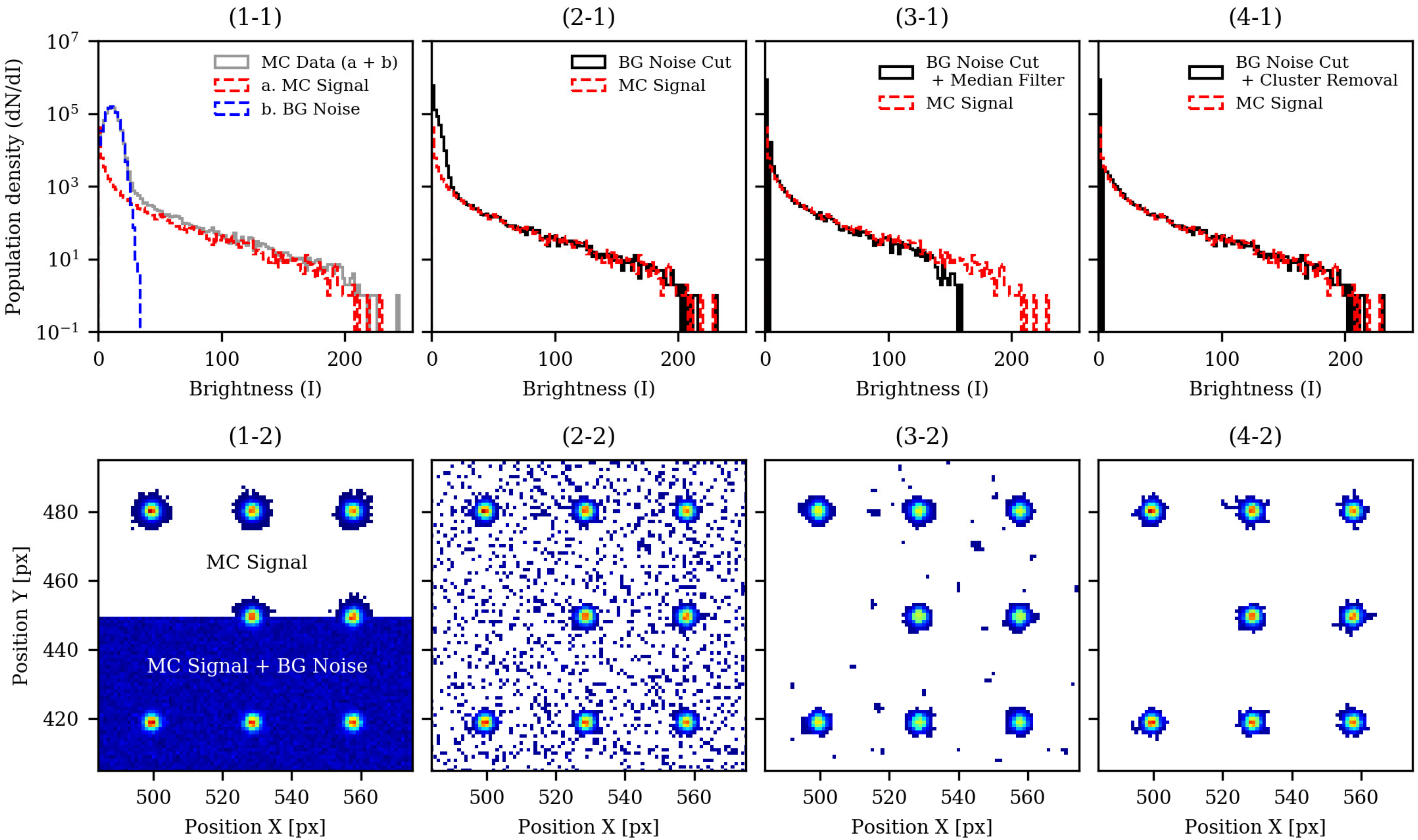
Gaussian beam distribution model
applying Twiss parameters

$$x'_i, y'_j = G_r\left(-\frac{\alpha_x}{\beta_x} x_i, \sqrt{\frac{\epsilon_x}{\beta_x}}\right), G_r\left(-\frac{\alpha_y}{\beta_y} y_j, \sqrt{\frac{\epsilon_y}{\beta_y}}\right)$$

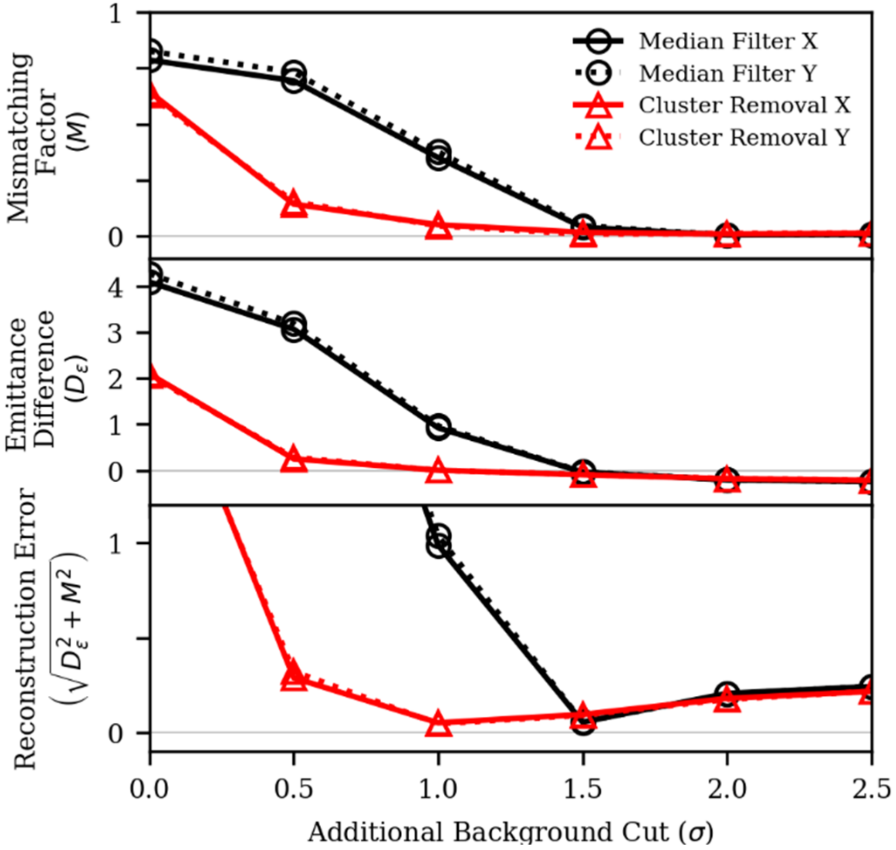


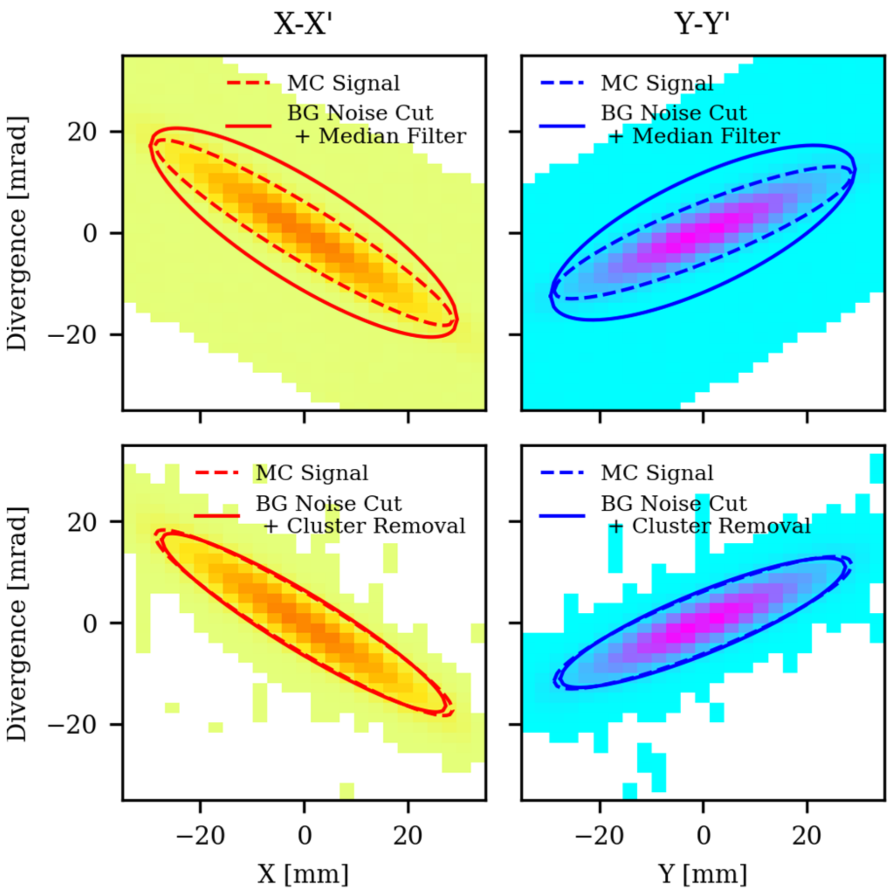
- RECO – Reconstruction toolkit
  - Mc level : comparing RECO to MC, Def. error bars
  - RECO level : making production GUI console

Cluster removal algorithm



Cluster removal algorithm

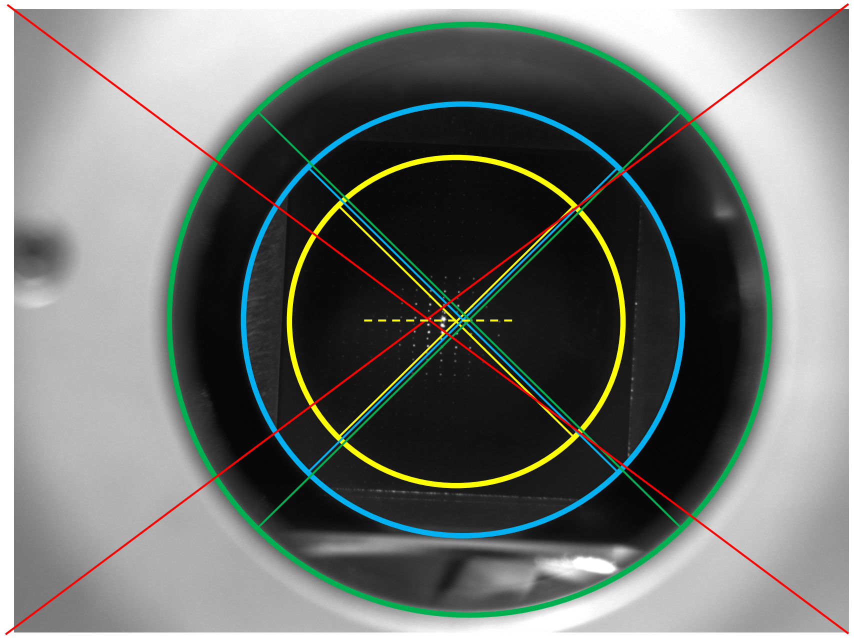


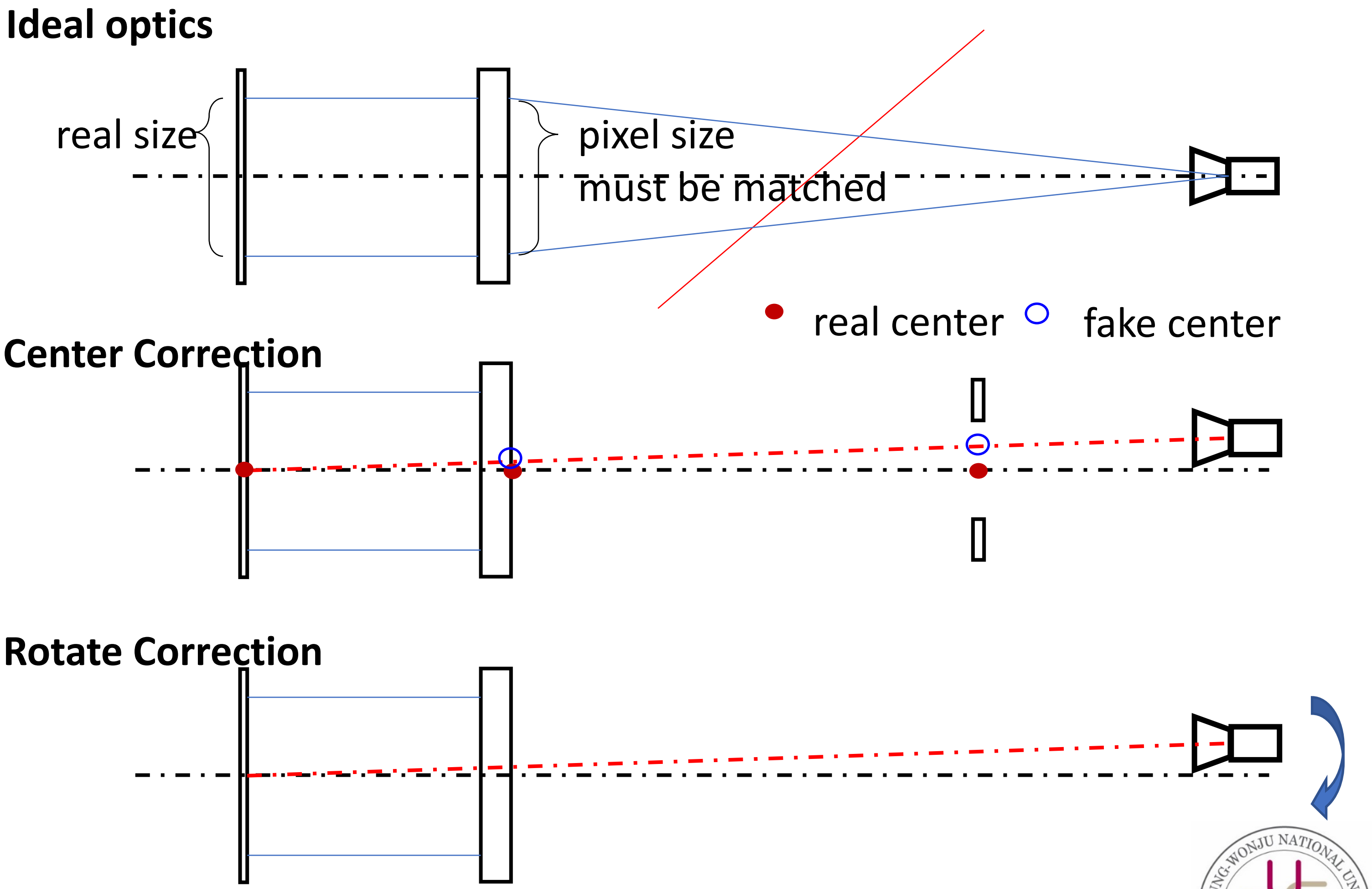


The additional background cut (1.0σ) is necessary and the level was investigated to minimize the mismatching factor ($M = \sqrt{(R + \sqrt{R^2 - 4}/2 - 1}$) and emittance misreading $D_\varepsilon = (\varepsilon_r - \varepsilon_m)/\varepsilon_m$.

$R = \beta_r\gamma_m + \beta_m\gamma_r - 2\alpha_m\alpha_r$ G. Hahn, J.-G Hwang, et. al., *IEEE Tras. Instr. and Mea.* **70**, 5015507 (2021).

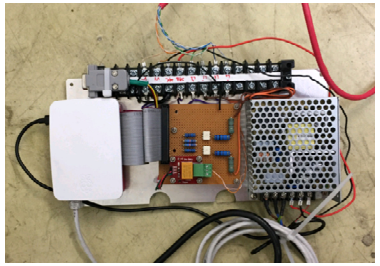
Perspective correction

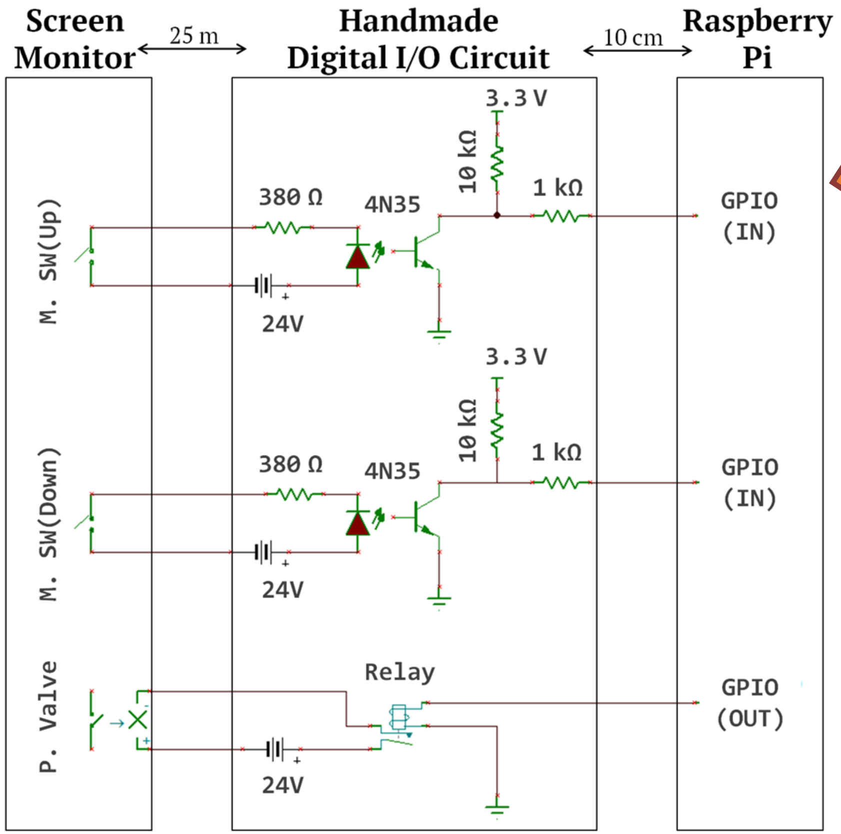


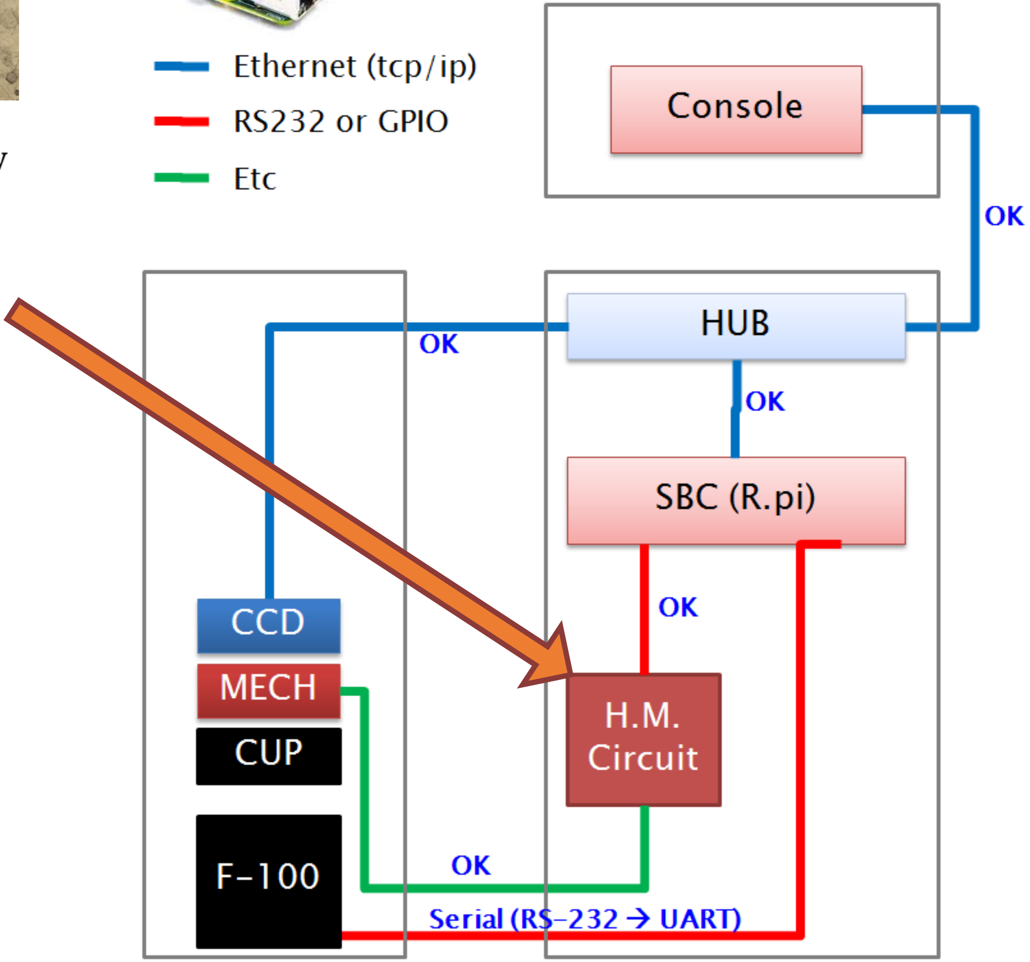


Control system

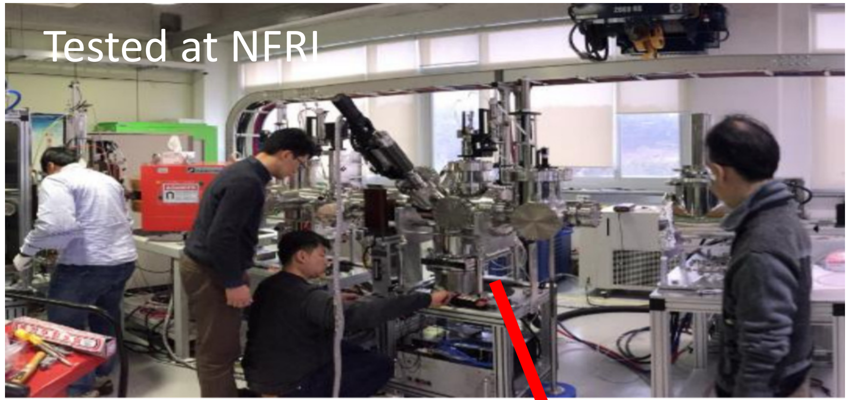
To save budget,
Handmade Circuit
was used
instead of PLC

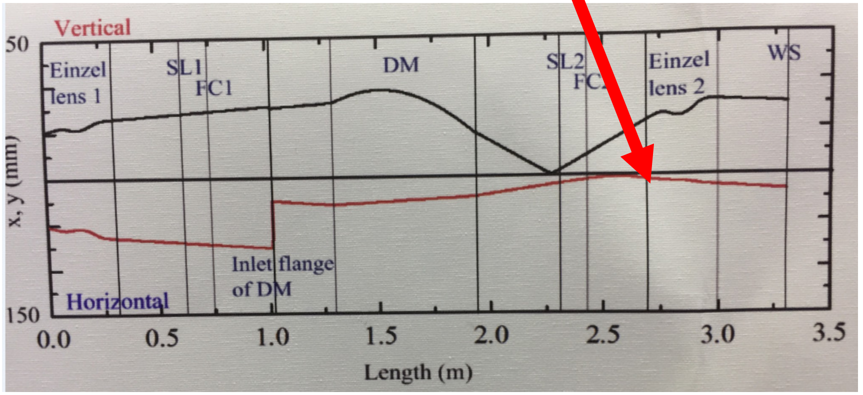


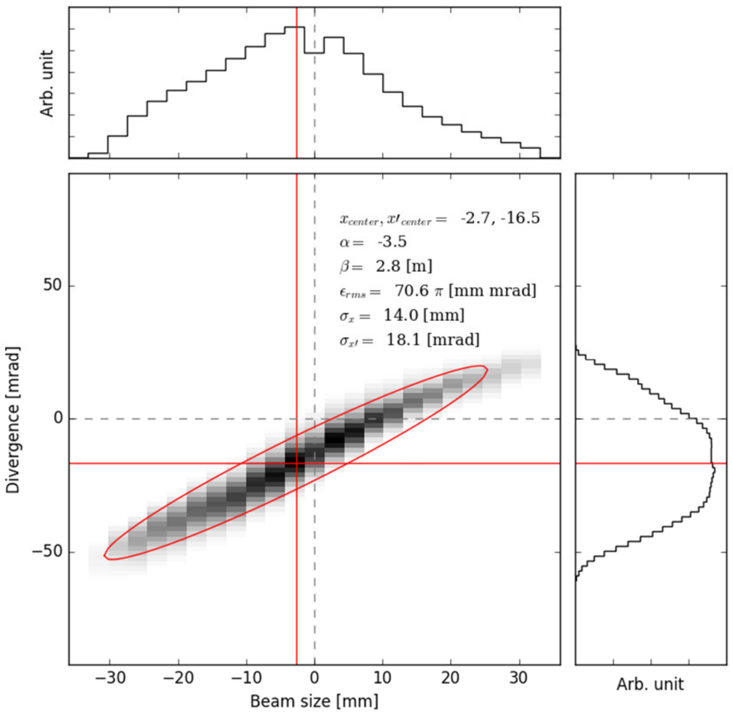


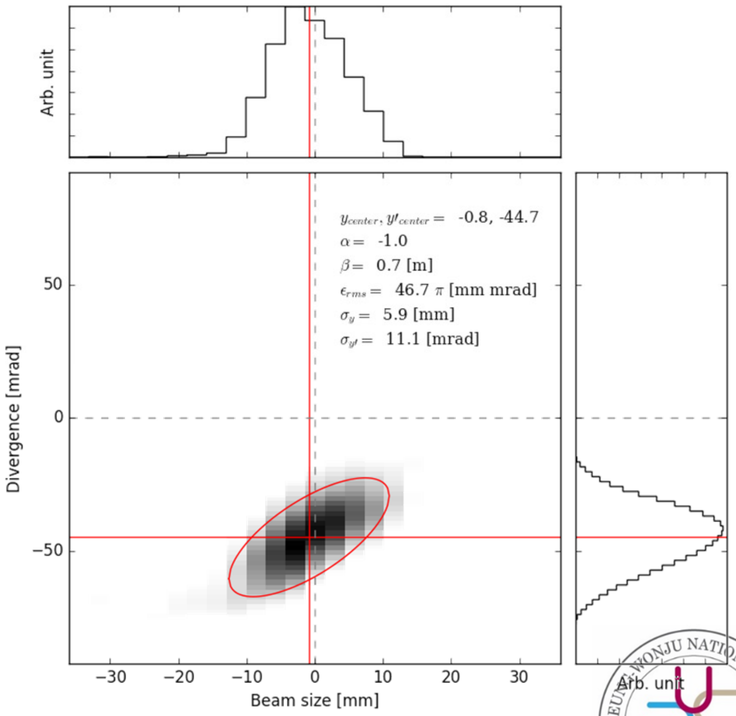


Beam experiments

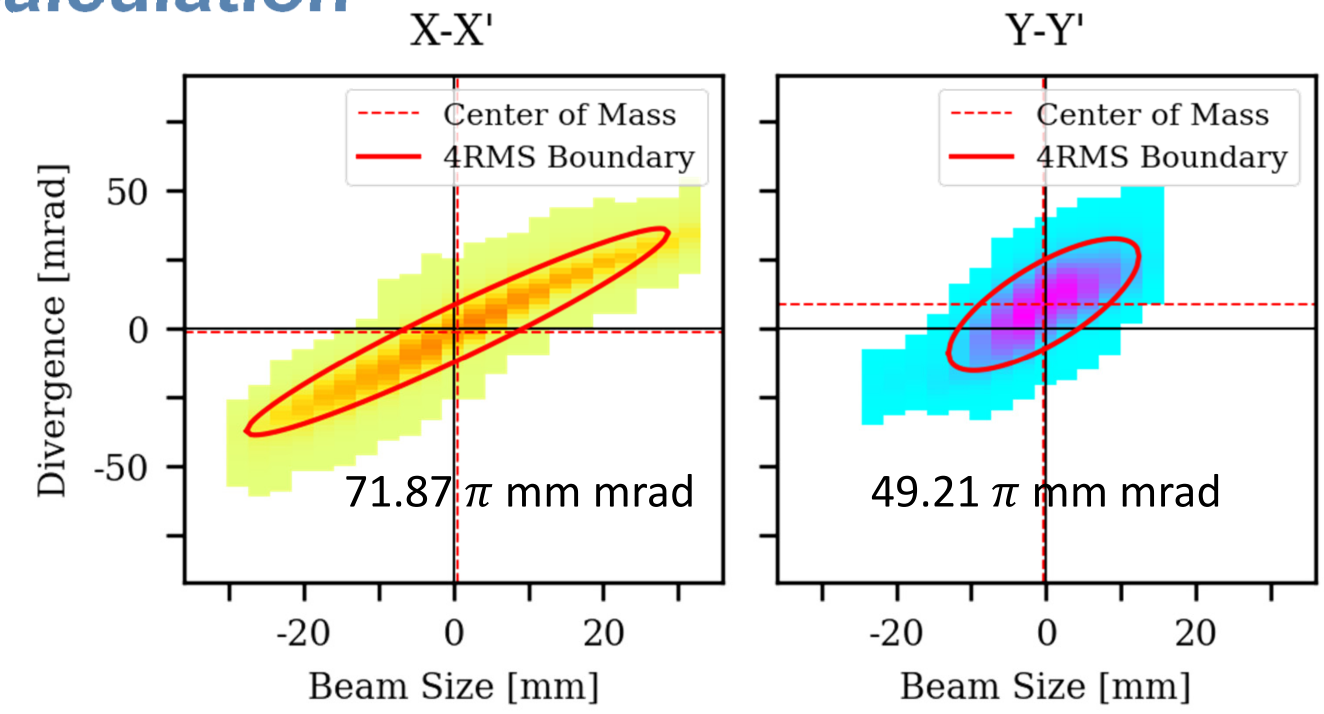








4D emittance calculation



RMS emittance

$$\varepsilon_\mu = \sqrt{\langle \mu\mu \rangle \langle \mu'\mu' \rangle - \langle \mu\mu' \rangle^2}$$

$$C = \begin{bmatrix} \langle xx \rangle & \langle xx' \rangle & \langle xy \rangle & \langle xy' \rangle \\ \langle x'x \rangle & \langle x'x' \rangle & \langle x'y \rangle & \langle x'y' \rangle \\ \langle yx \rangle & \langle yx' \rangle & \langle yy \rangle & \langle yy' \rangle \\ \langle y'x \rangle & \langle y'x' \rangle & \langle y'y \rangle & \langle y'y' \rangle \end{bmatrix} = \begin{bmatrix} 181.41 & 231.83 & 31.55 & 13.51 \\ 231.83 & 324.85 & 44.63 & 24.00 \\ 31.55 & 44.63 & 36.48 & 50.37 \\ 13.51 & 24.00 & 50.37 & 135.30 \end{bmatrix}$$

Statistical Twiss parameter

$$\alpha_\mu = -\frac{\langle \mu\mu' \rangle}{\varepsilon_\mu}, \qquad \beta_\mu = \frac{\langle \mu\mu \rangle}{\varepsilon_\mu}$$

$$\langle \mu\nu \rangle = \frac{\sum_i \sum_j \iint W_{i,j}(x', y')\mu\nu dx'dy'}{\sum_i \sum_j \iint W_{i,j}(x', y') dx'dy'}$$

Summary

The pepper-pot instrument is widely used at low-energy beams since it is capable of a single-shot measurement of 4D emittance + coupling terms.

For gauging a beam emittance accurately, pepper-pot diagnostics have to be carefully designed in terms of

- Precise mask production (**lithography + SEM**)
- Noise subtraction algorithm (**cluster removal**)
- Rotation correction (**perspective correction**)

In this study, we validated the mask fabrication process by SEM and the effectiveness of the cluster removal algorithm by virtual images as well as beam experiments. Contrary to other filters, the cluster removal algorithm is able to suppress noise without distortion on the signal.

Thank you for your attention

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