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TUOA04

Measurement and Reconstruction of a Beam Profile Using a Gas Sheet Monitor by Beam-Induced Fluorescence Detection in J-PARC

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Japan Proton Accelerator Research Complex (J-PARC)

J-PARC: **Intensity-frontier** proton accelerator

LINAC : ~ 400 MeV (50 mA, 500 us, 25 Hz)

Rapid-**C**ycling **S**ynchrotron : ~ 3 GeV => 8.3 x 10^{13} protons x 3 GeV x 25 Hz = 1 MW

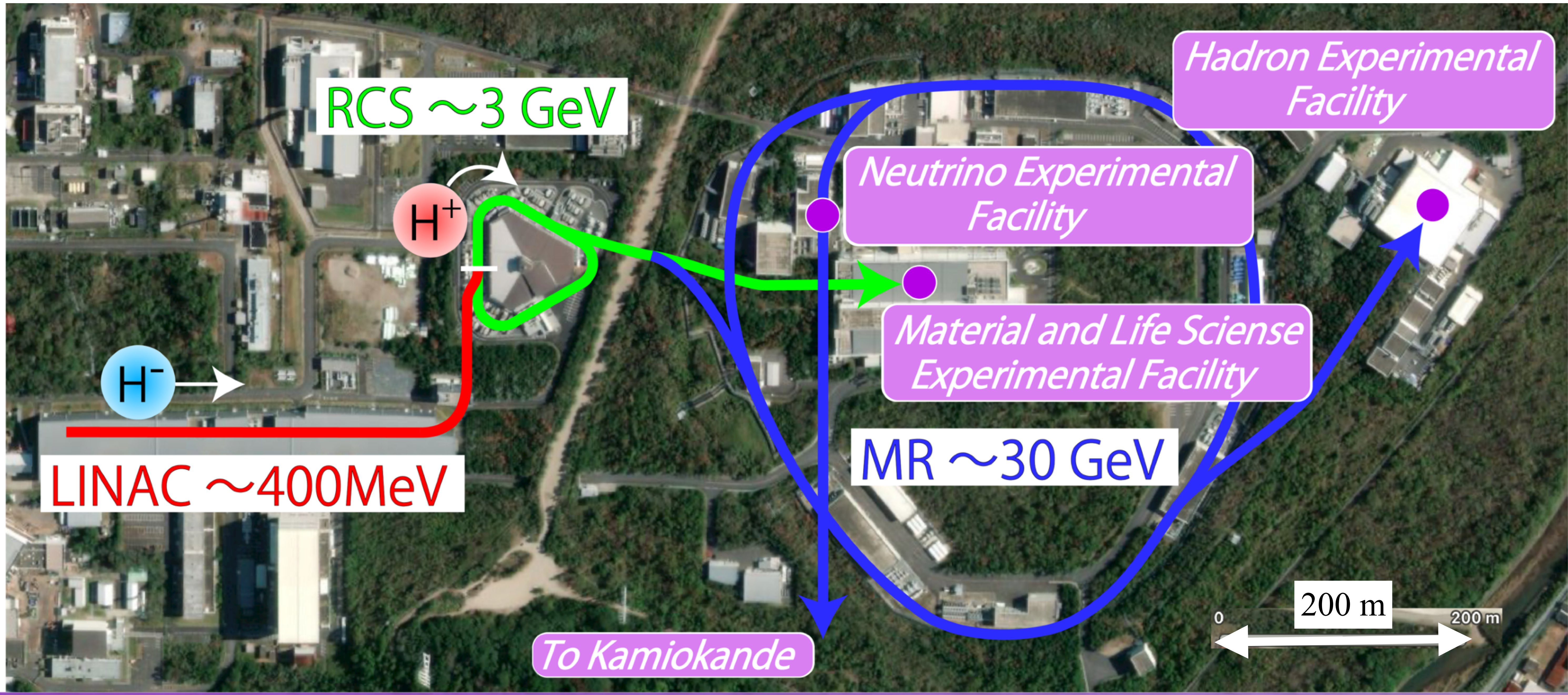
Main **R**ing : ~ 30 GeV => must keep beam loss less than 10^{-4}

Radiation dose is most important problem to operate accelerator

Destructive monitoring => inducing beam loss, radio-activating monitor, breaking monitor

Non-destructive monitor is strongly required

- to study high-intensity beam dynamics
- to operate accelerator with minimum loss



Non-destructive profile monitor: *Gas sheet monitor*

Gas Sheet Monitor (GSM)

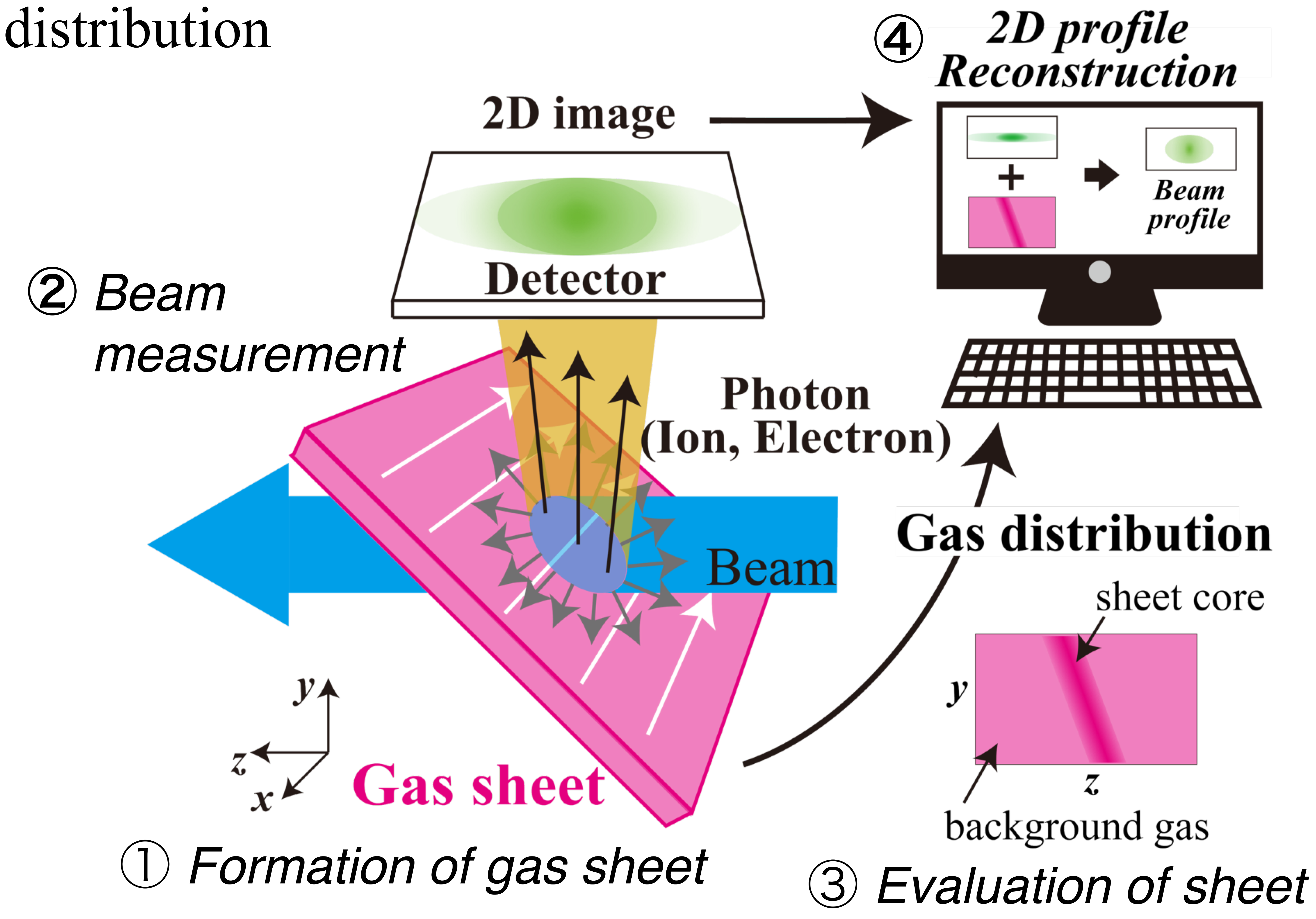
1. Injecting a **sheet-shaped gas**
2. Producing ions, electrons, and photons by beam-gas interaction
3. Detecting distribution of produced particles as **2D image**

Distribution of produced particles ∝ Beam profile × Gas distribution

=> **Non-destructive transverse profile monitor**

We discuss **fluorescence** detection in this contribution

Beam profile measurement system using Gas sheet monitor



Contents:

① Formation of gas sheet

② Measurement of high-intensity (J-PARC) beam

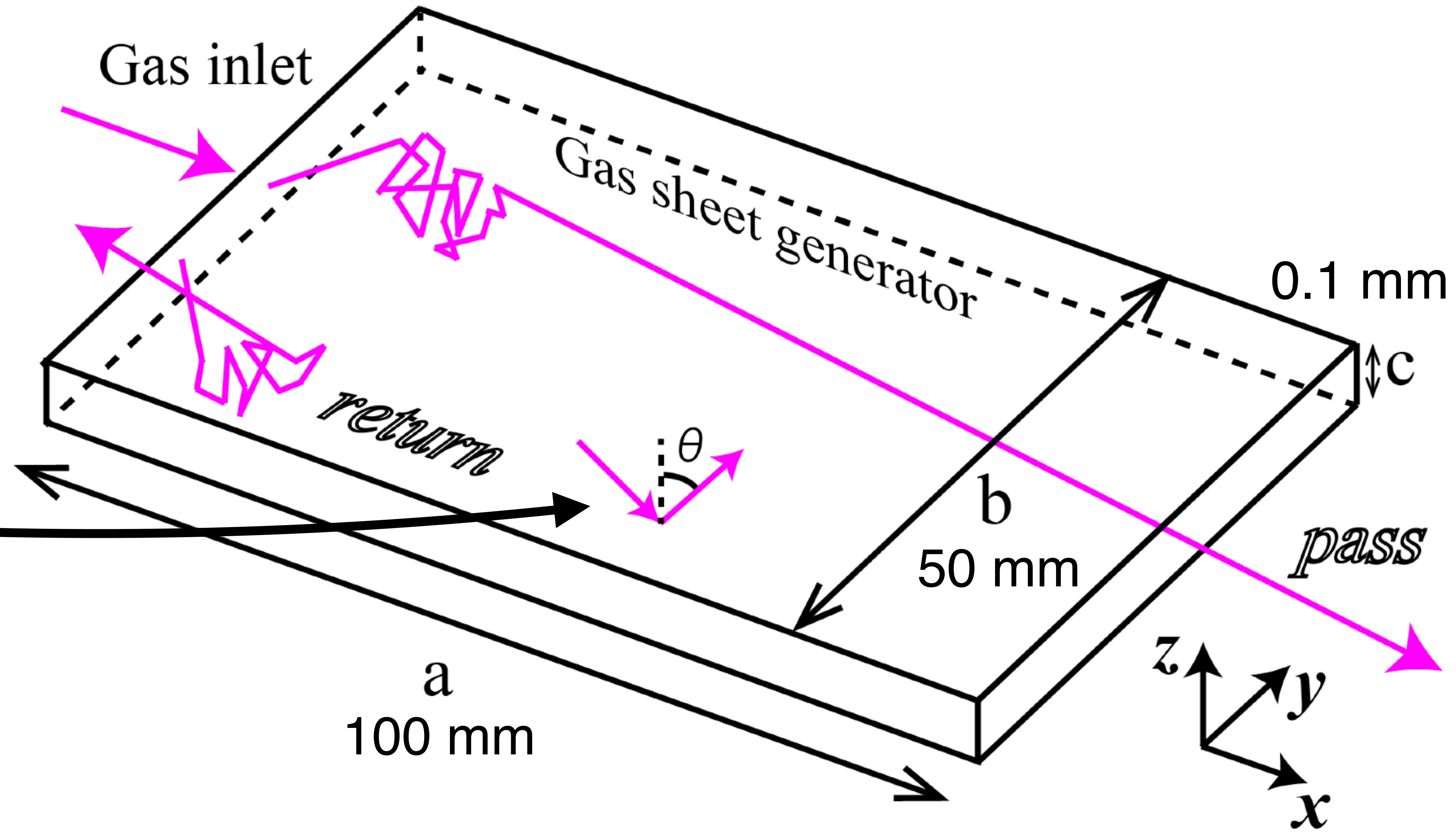
③ Evaluation of gas sheet distribution at off-line system

④ Reconstruction of 2D beam profile

Gas sheet generator: Principle

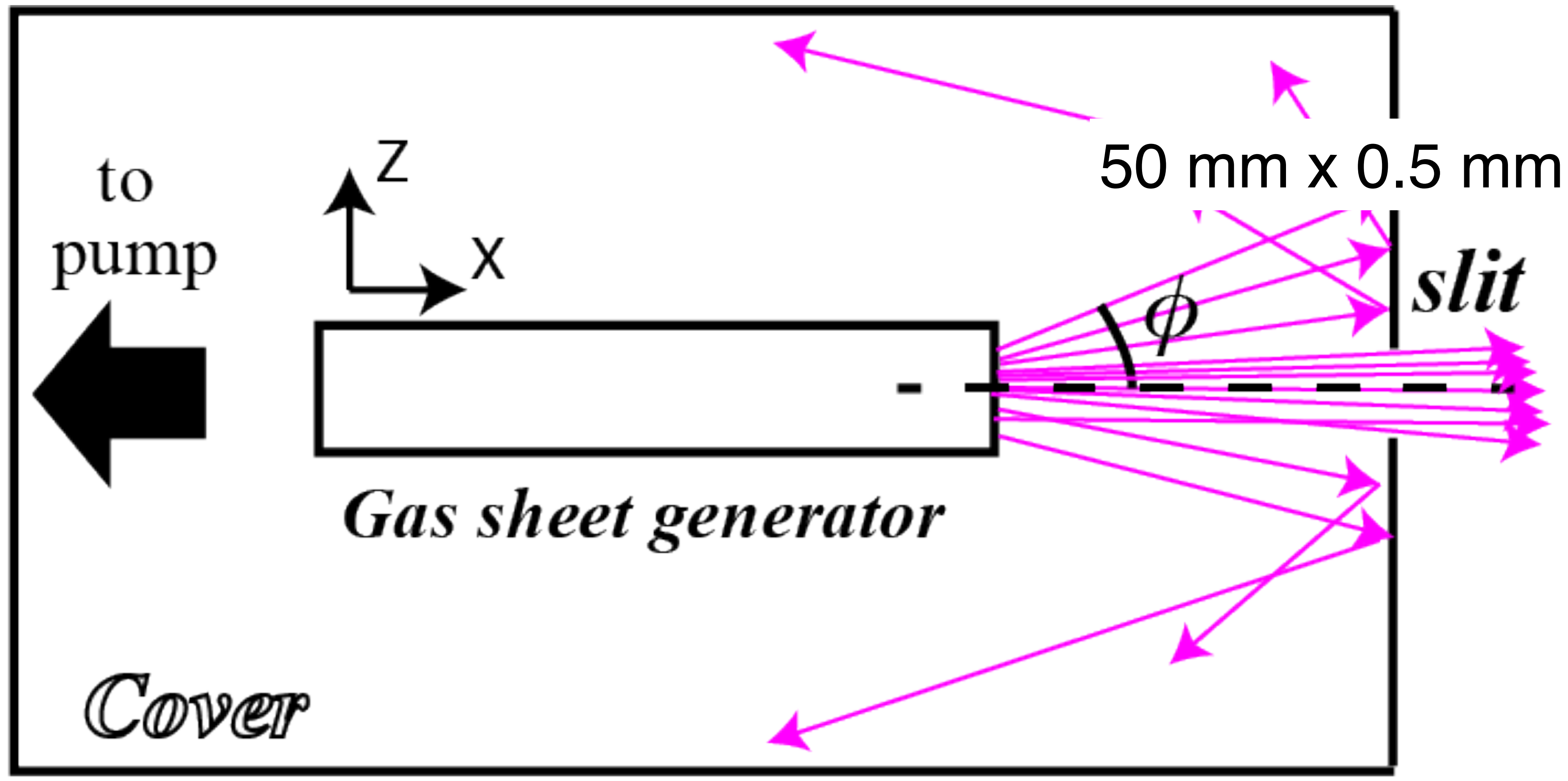
Gas sheet formation is based on ***rarefied gas dynamics****

- ***Collision-less approximation***
  Mean free path >> chamber size
  = intermolecular collisions are negligible
- ***Cosine law*** for reflection on wall
  Probability distribution function $p(\theta)$ of reflection angle θ
  => $p(\theta) \propto \cos\theta$ (with respect to normal direction of wall)



Gas molecules moving with thermal velocity enter
a long gas conduit with a thin cross section = *gas sheet generator*
=> Conduit increases the number of reflections in thickness (z) direction
=> Molecules obtaining large angle θ pass conduit and form gas sheet

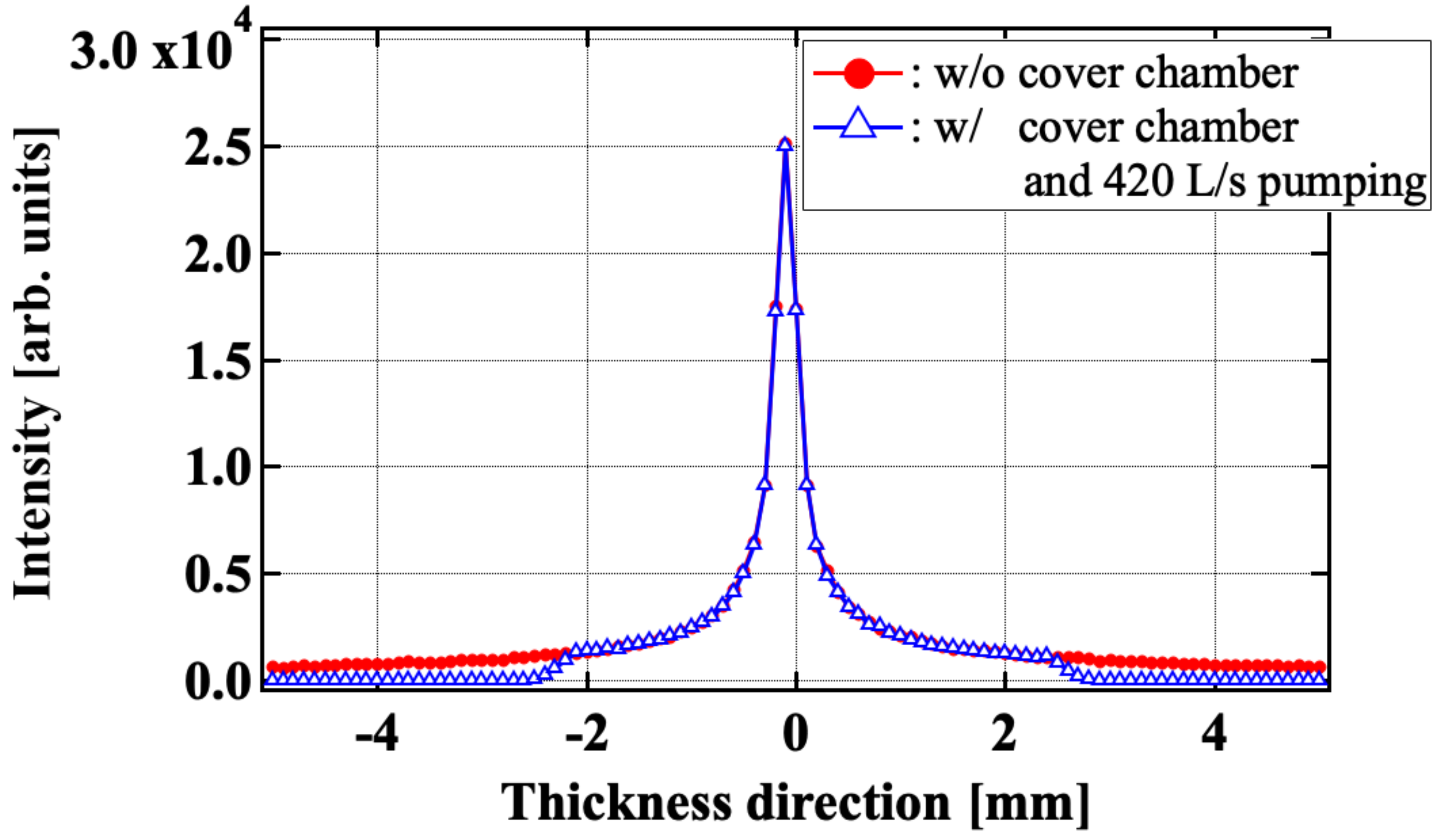
Cover chamber with slit to cut the tail part of sheet
=> keep background pressure low
(for high pressure,
more important because sheet spreads due to collisions)



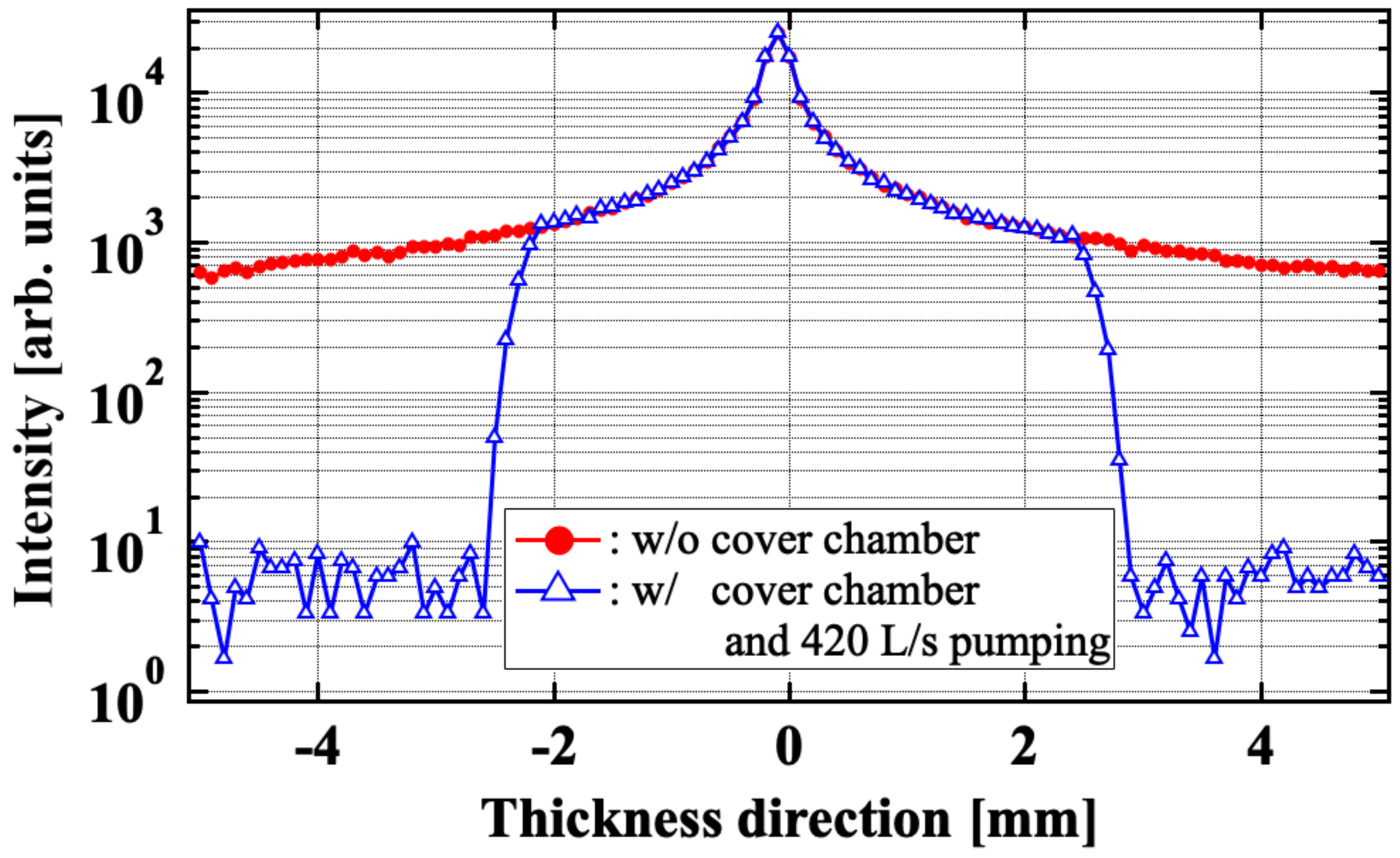
Gas sheet generator: Simulation

Gas flow can be calculated by

- individual motion with constant (thermal) velocity
- particular reflection on wall: *cosine law*



Intensity: Log scale



Monte-Carlo simulation (ex. Molflow+ code at CERN)

=> Calculating gas flux distribution along thickness direction

at beam-gas interaction point

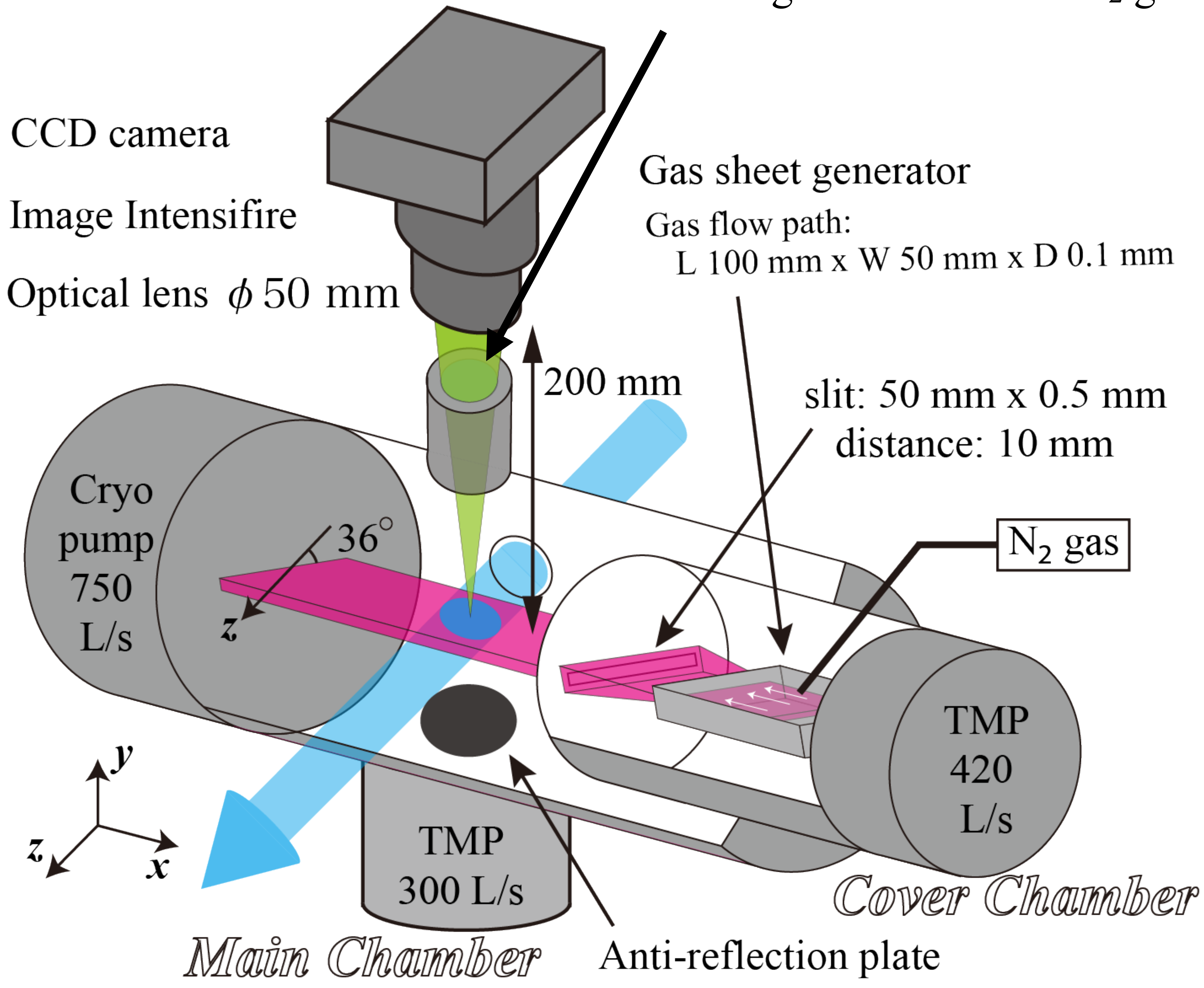
for Conduit of 100 mm × 50 mm × 0.1 mm

w/ and w/o slit of 50 mm × 0.5 mm

✓ Sheet-shaped distribution can be formed

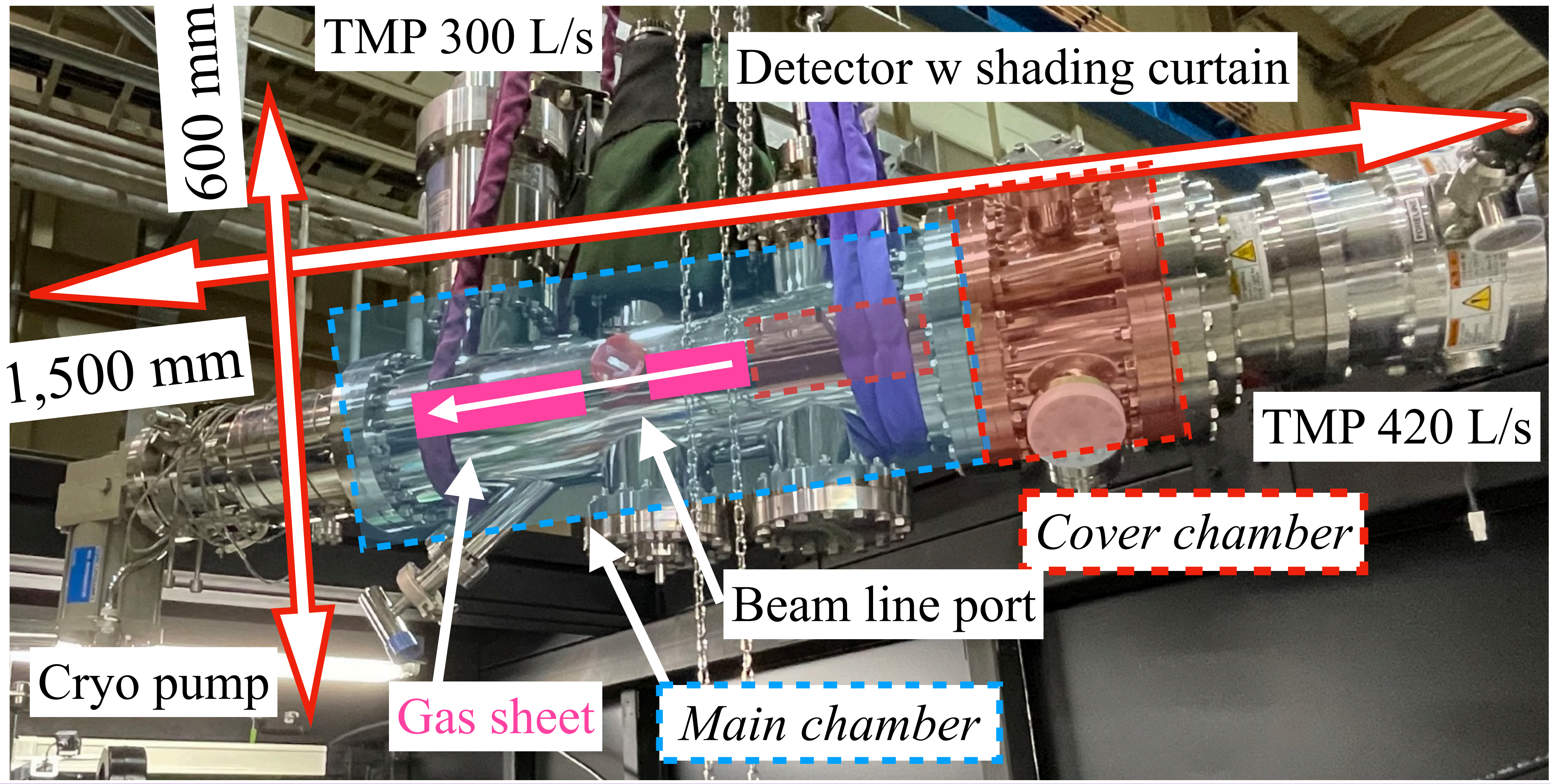
✓ Cover chamber cuts the tail part of the sheet

Developed gas sheet monitor system

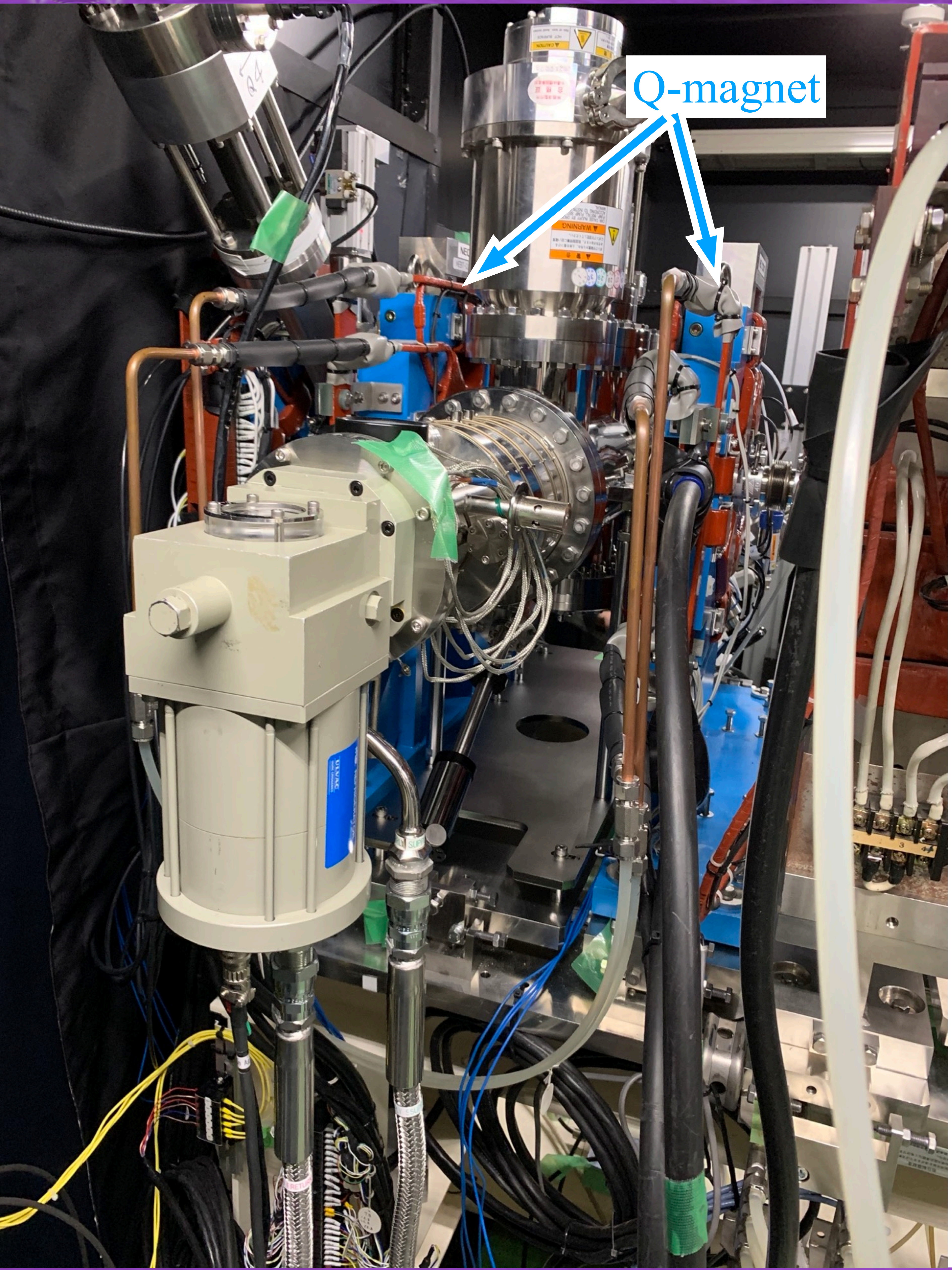


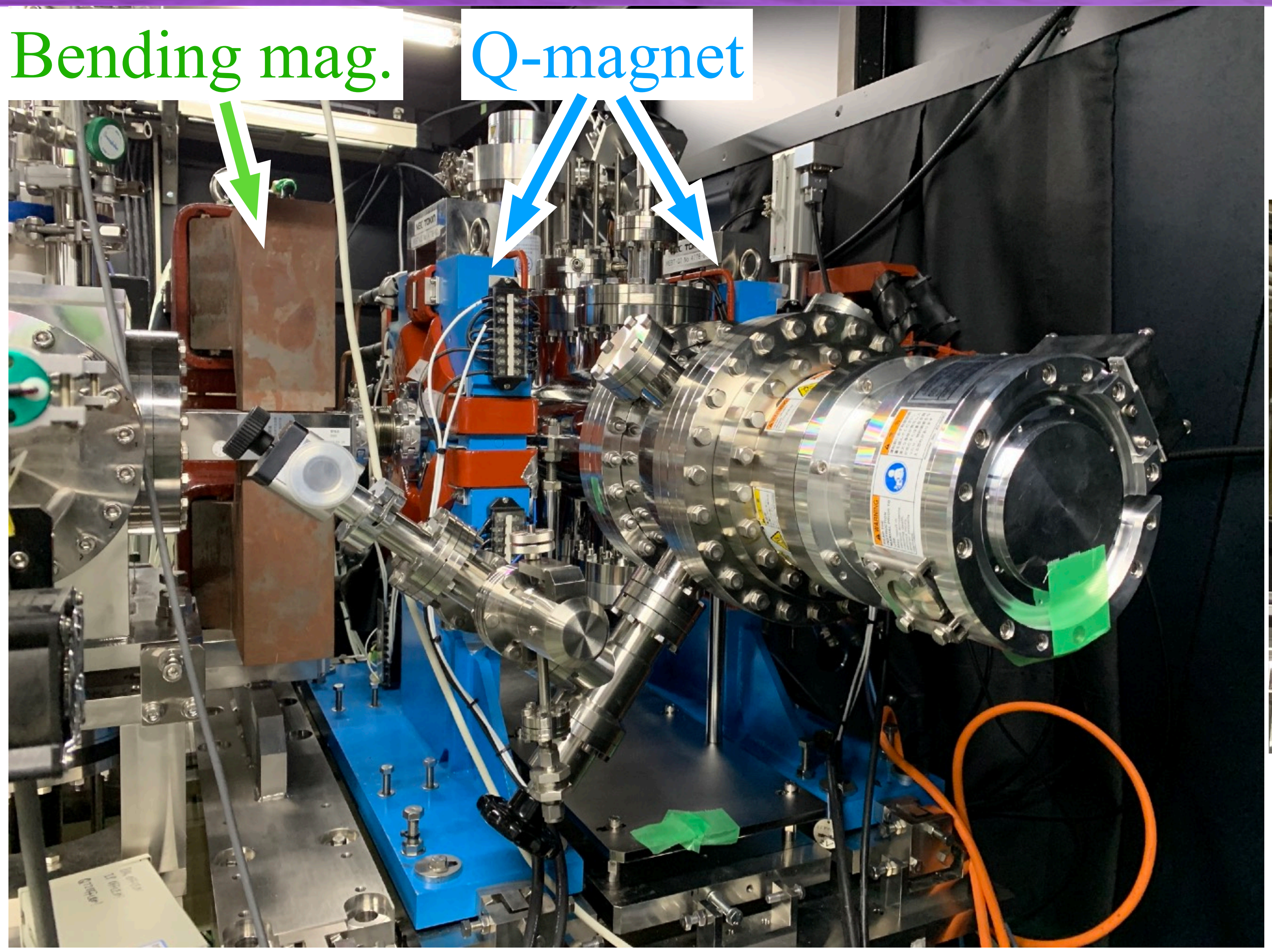
Photon detector system

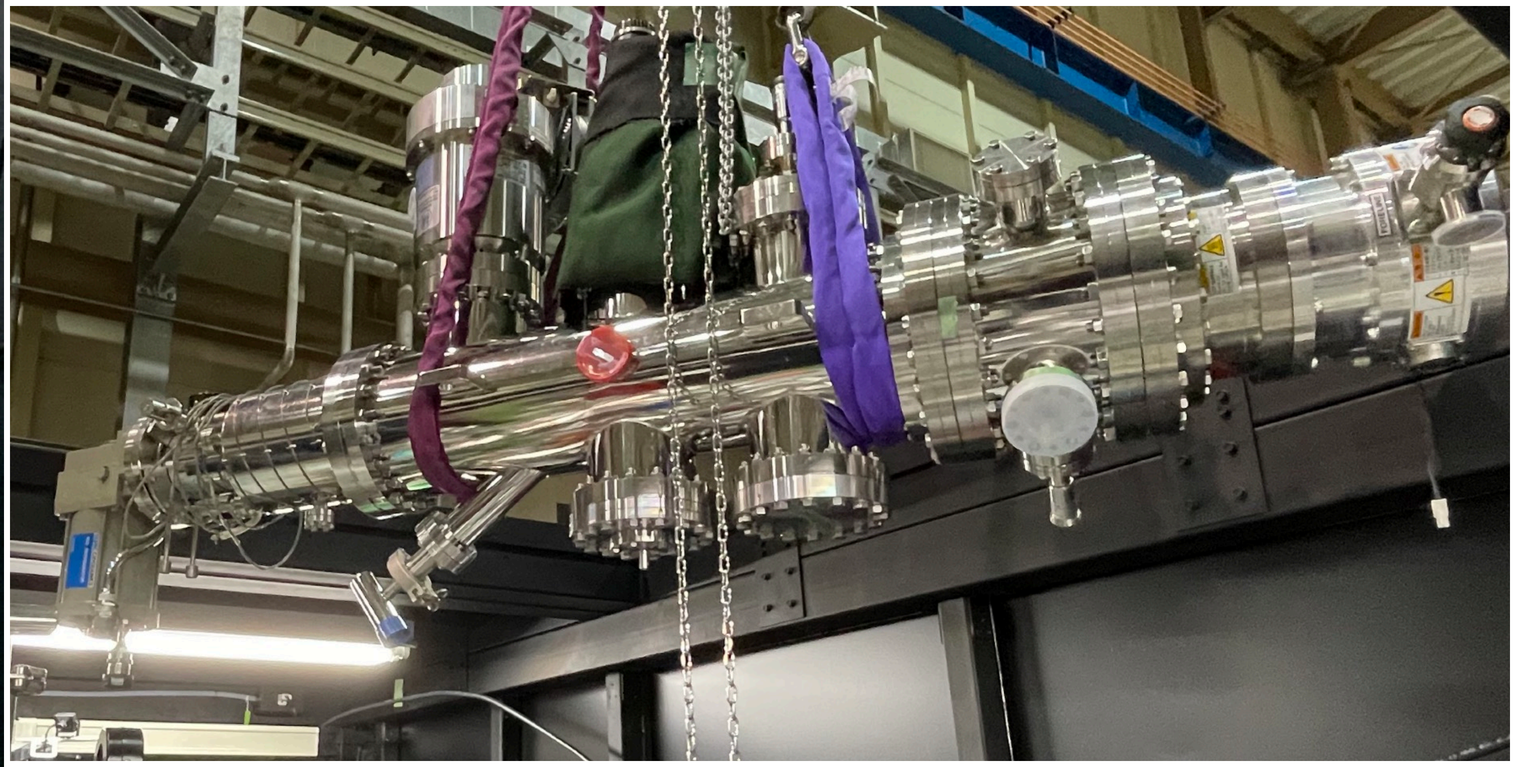
Image intensifier : Gain < 10^4
CCD camera : 16bit, 1920 x 1080 px
Solid angle : 0.05 sr (0.39% of 4π)

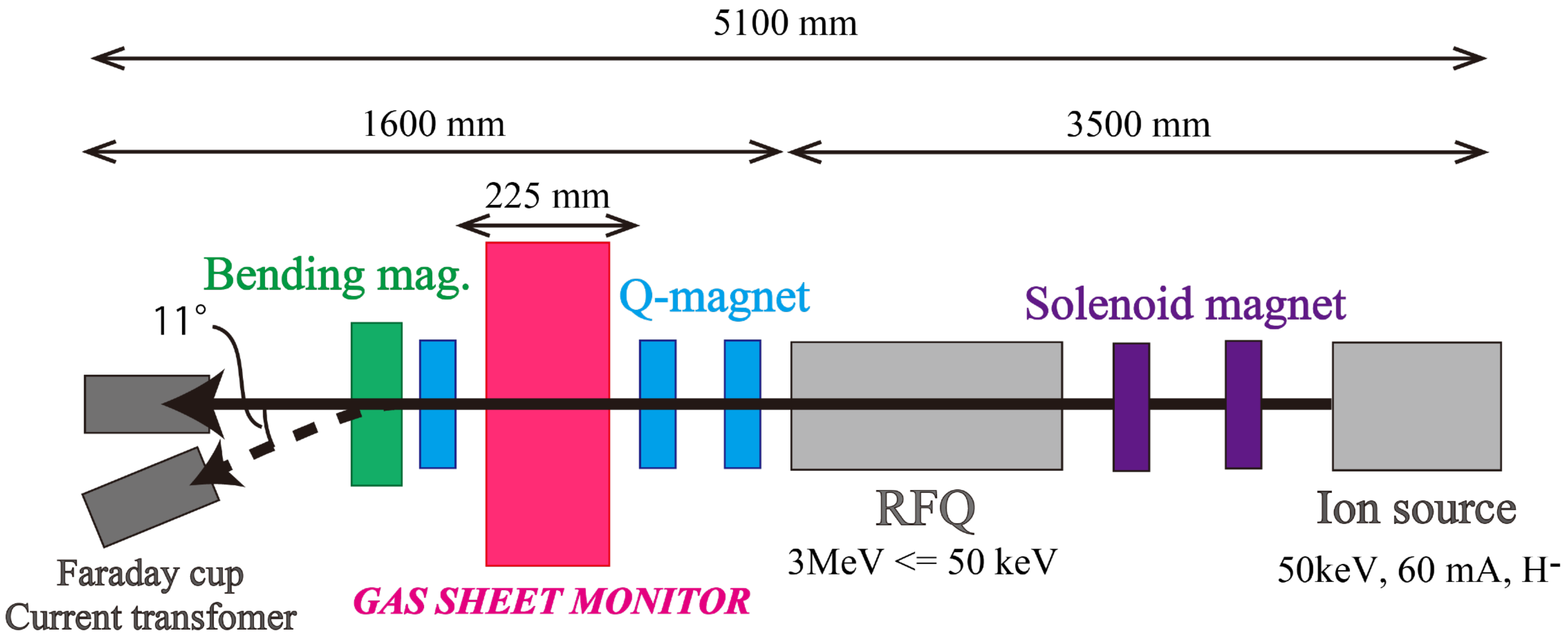


Installation in J-PARC MEBT test stand









H^- beam measurement (Raw data)

Conditions

Beam
- Current : 60 mA
- Pulse length : 50 us
- Species : H^-
- Repetition : 25 Hz

Photon detector
- Exposure time T : 20 s
- Image intensifier gate : 10 us

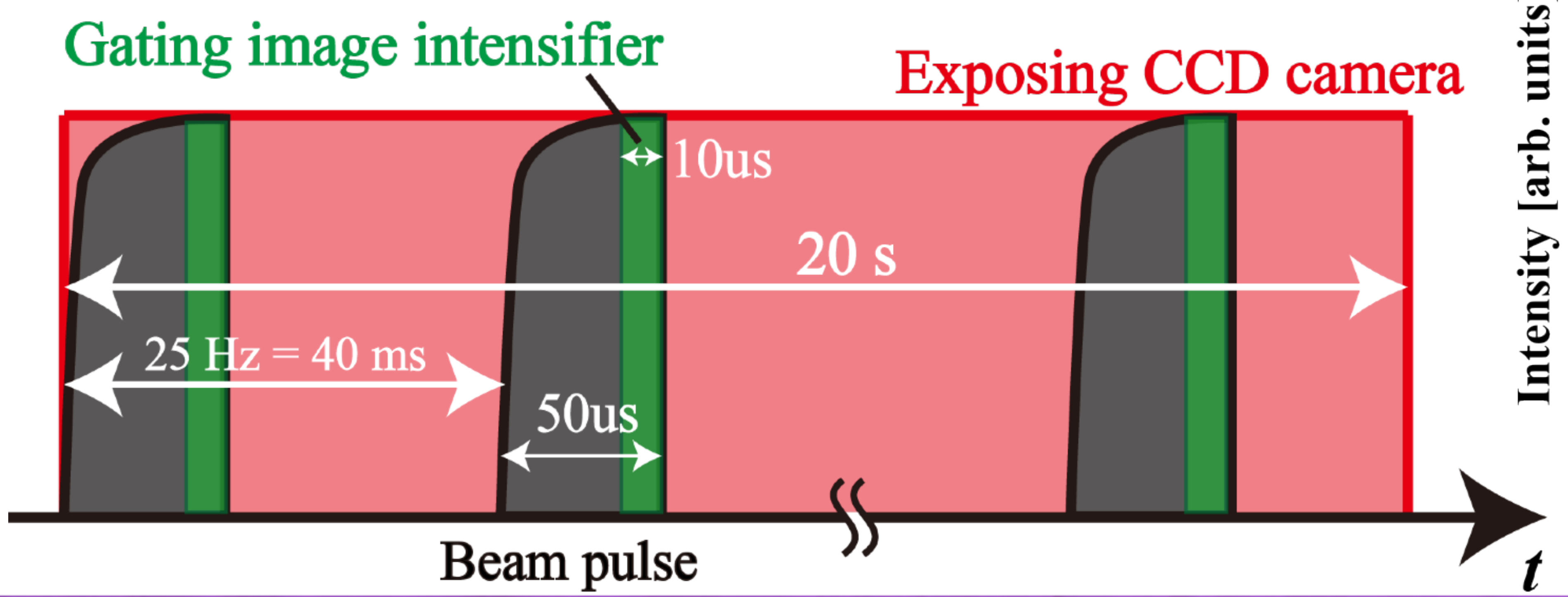
Gas sheet
- Inlet pressure : 100 Pa
- Background pressure (Main chamber) : 5.6×10^{-5} Pa

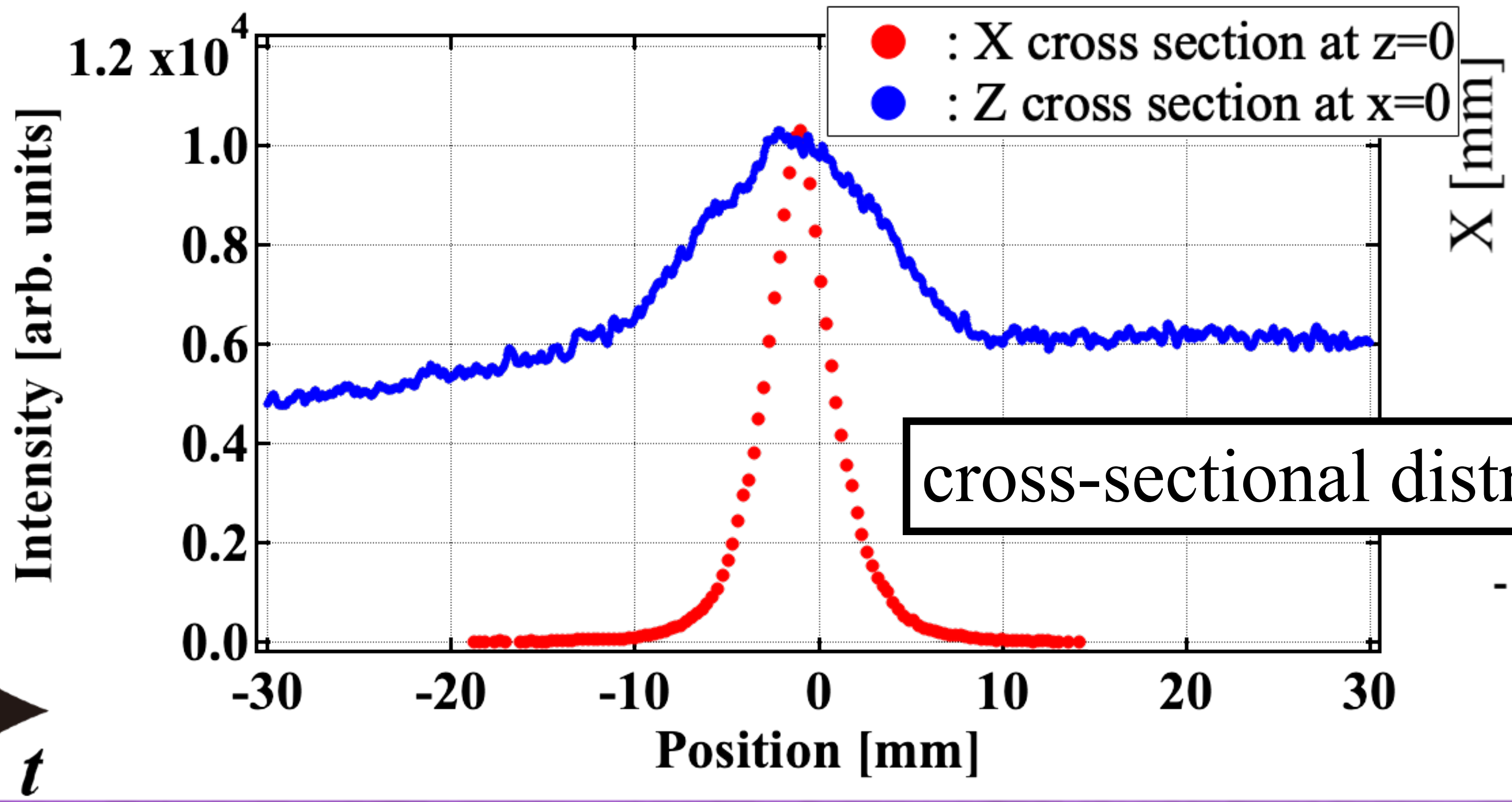
Image processing

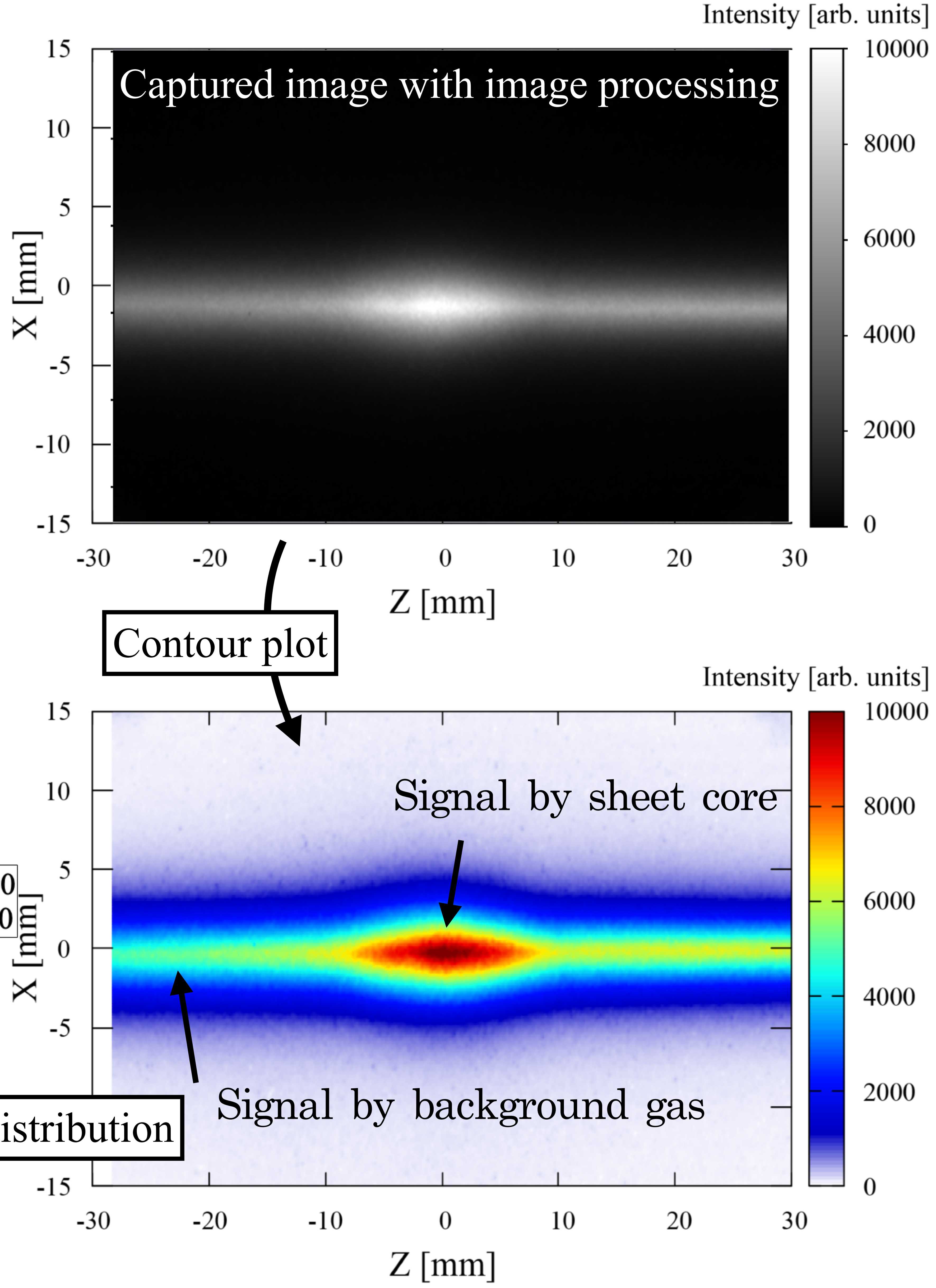
- Averaging : 80 frames
- Moving median : 5 x 5 px
- Moving average: 5 x 5 px (31 px = 1mm)
- Background subtraction
  Image w/ gas injection
  - Image w/o gas injection

✓ Fluorescence induced by beam-gas interaction can be detected.

Profile reconstruction considering gas distribution is necessary







Reconstruction: Principle

<u>Gas Sheet Monitor</u>

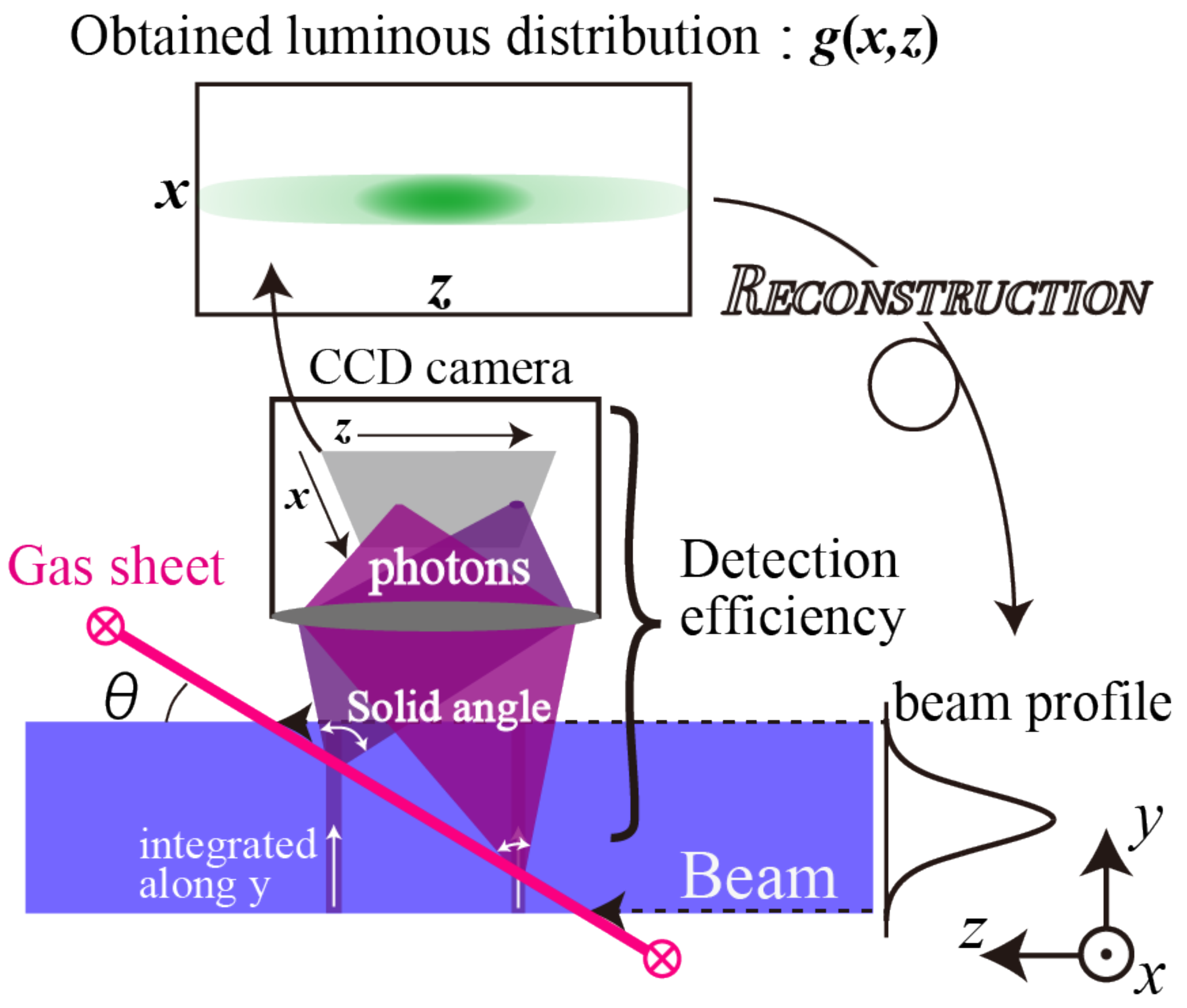
- Photons produced not only **by gas sheet** but also **by background gas**
- Photons are integrated along *y* axis
- and constructs luminous intensity distribution (captured image) : $g(x, z)$

$$g(x,z) = \int k(x,y,z)\ F(x,y)\ \mathrm{d}y$$

$F(x, y)$: Transverse beam profile

$k(x, y, z)$: ***Relative-sensitivity spatial distribution***

- Gas density spatial distribution
- Efficiency distribution of CCD image sensors
- Non-uniformity of solid angle along *y* axis
- Optical aberration, out of focus, …



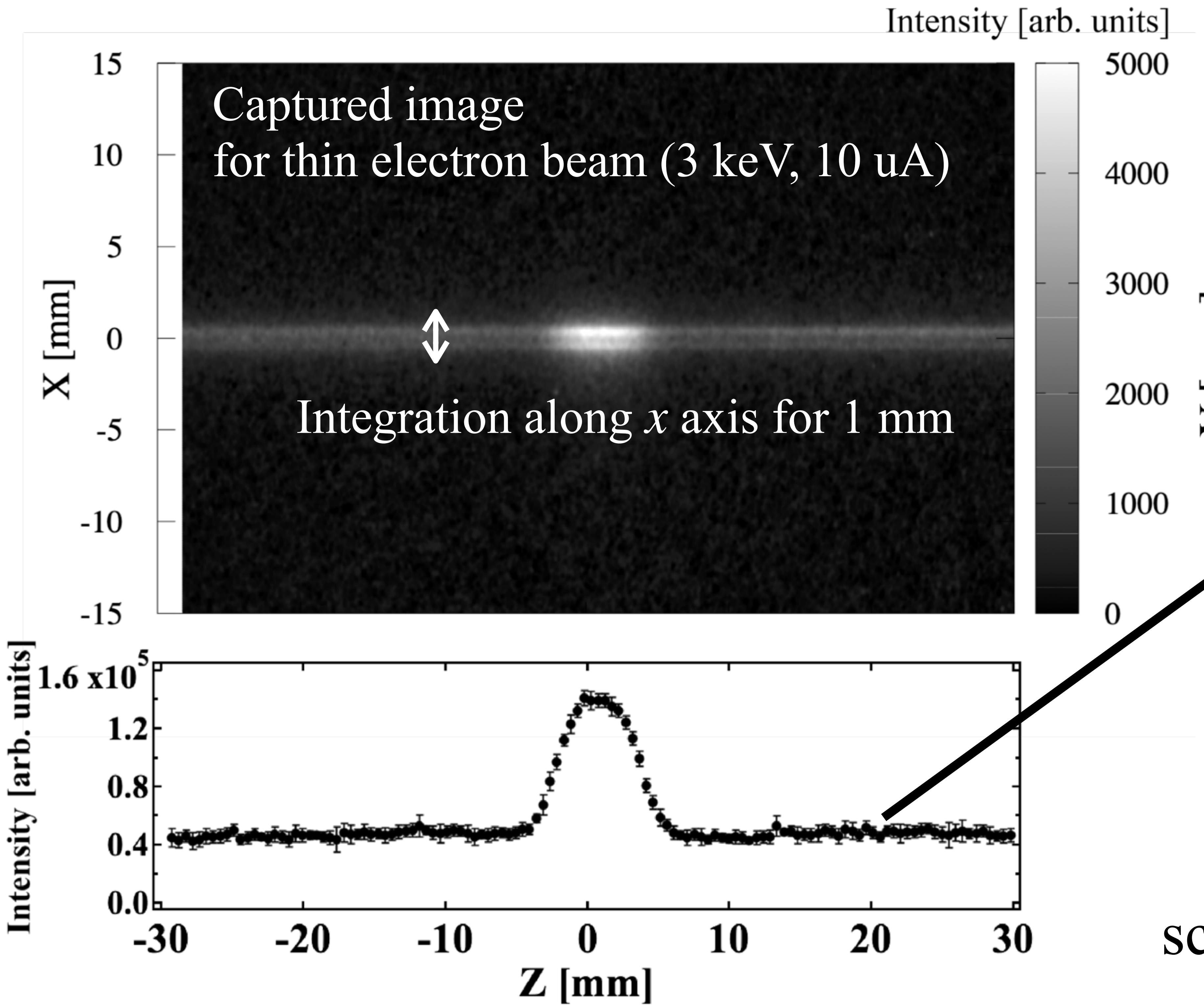
<u>2D beam profile can be reconstructed by giving $k(x, y, z)$</u>

<u>and solving integral equation</u>

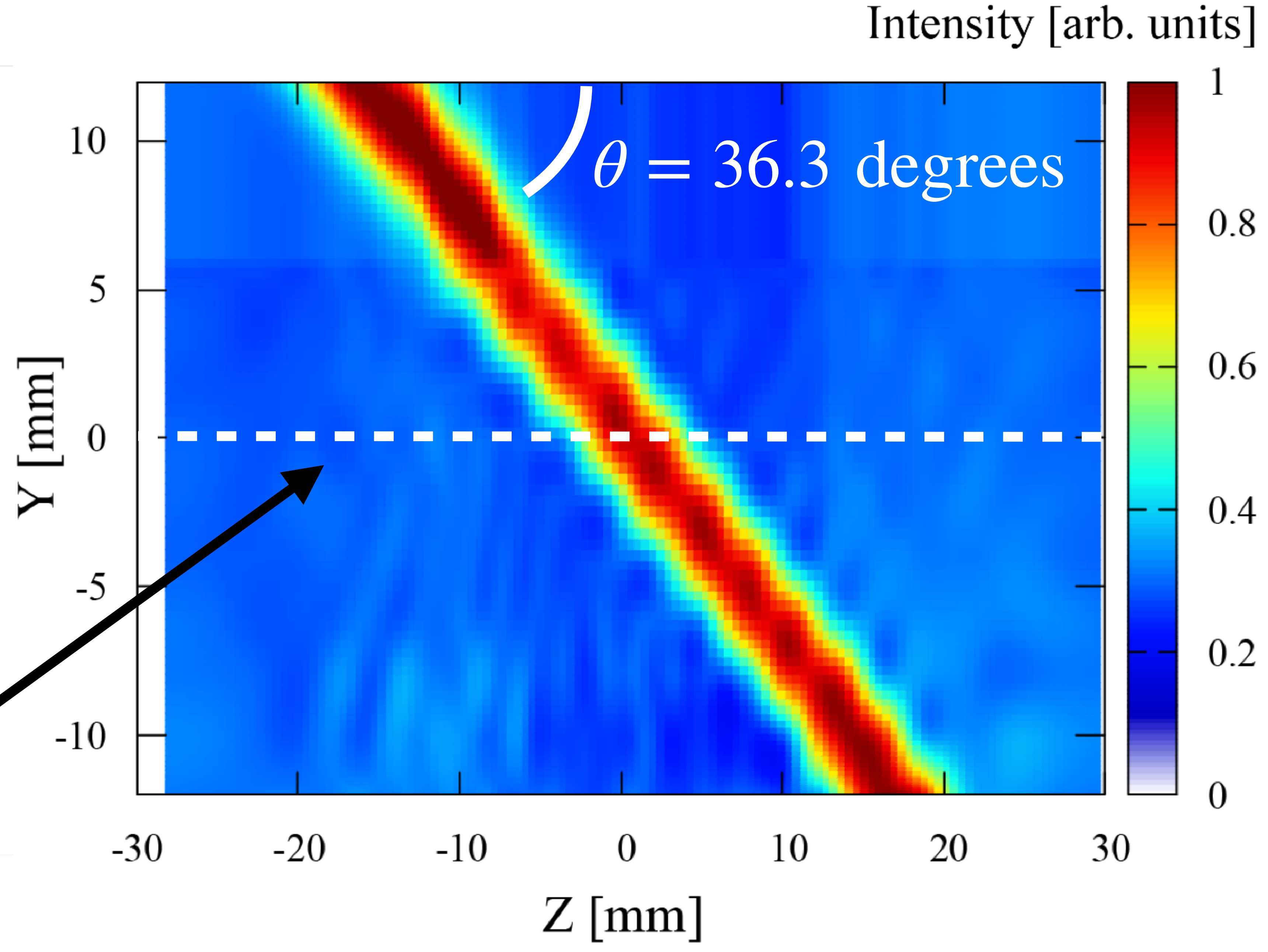
Reconstruction: Sensitivity distribution measurement

1. Injecting a **thin beam** instead of high intensity beam into gas sheet monitor
2. produces photons in a limited local volume = $k(x_0, y_0, z)$, (x_0, y_0): thin beam position
3. Scanning beam position and arraying the signal
   construct sensitivity distribution $k(x, y, z)$

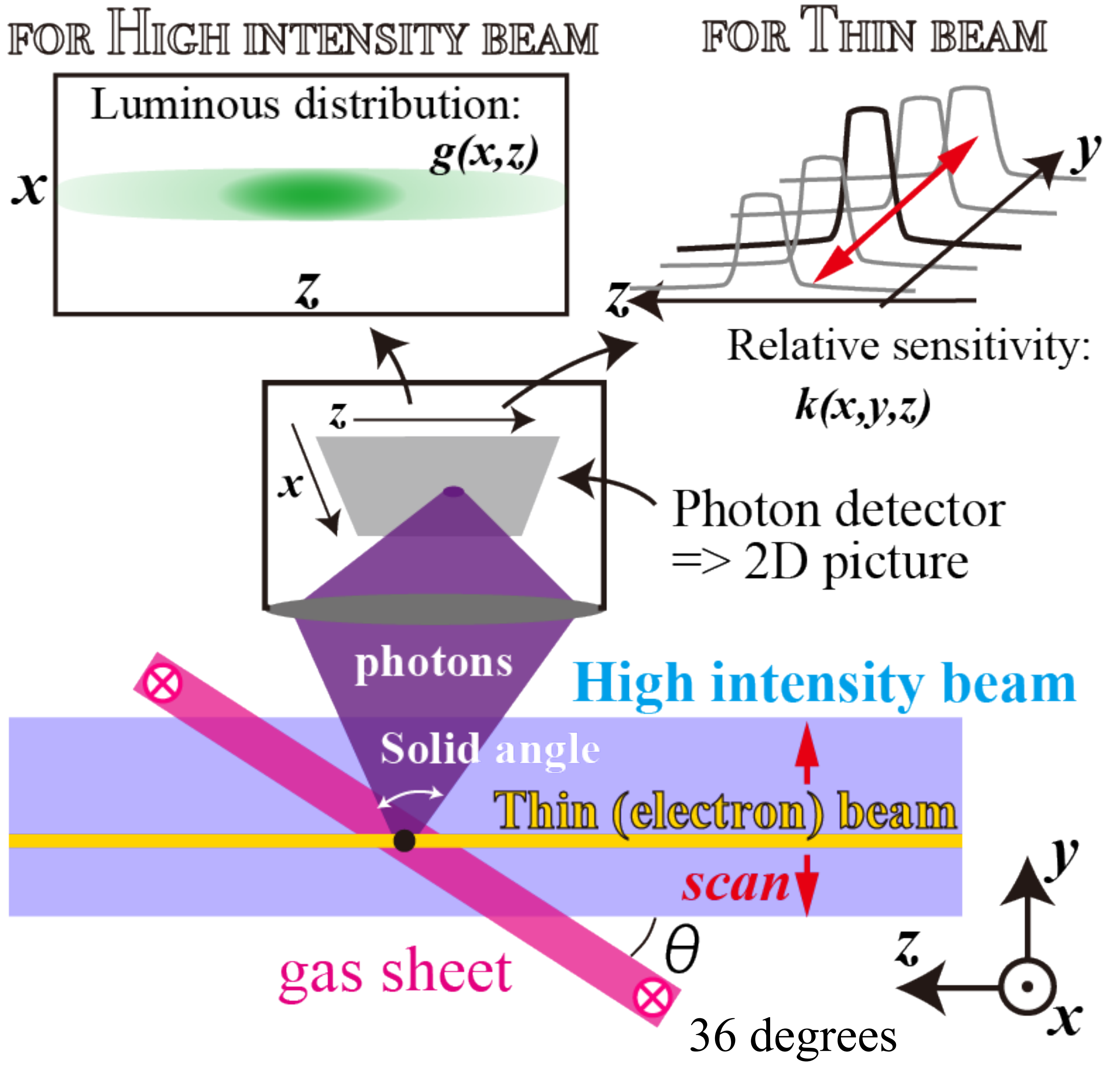
at off-line system



Integrated distribution = $k(x_0, y_0, z)$



scanning beam position and arraying the signal
=> 2D sensitivity distribution $k(x_0, y, z)$



Off-line system
= GSM + e$^-$ gun + Faraday cup

- ✓ Sensitivity distribution can be measured
- ✓ Gas sheet tilt can be recognized
- ☐ *Reconstructing beam profile*

Reconstruction: Analysis

1. Assuming beam profile as $F(x_0, y; \boldsymbol{a}, \boldsymbol{b}) = \frac{a_0}{2} + \sum_{k}^{10} \left\{ a_k \cos\left(k\frac{\pi y}{L}\right) + b_k \sin\left(k\frac{\pi y}{L}\right) \right\}$

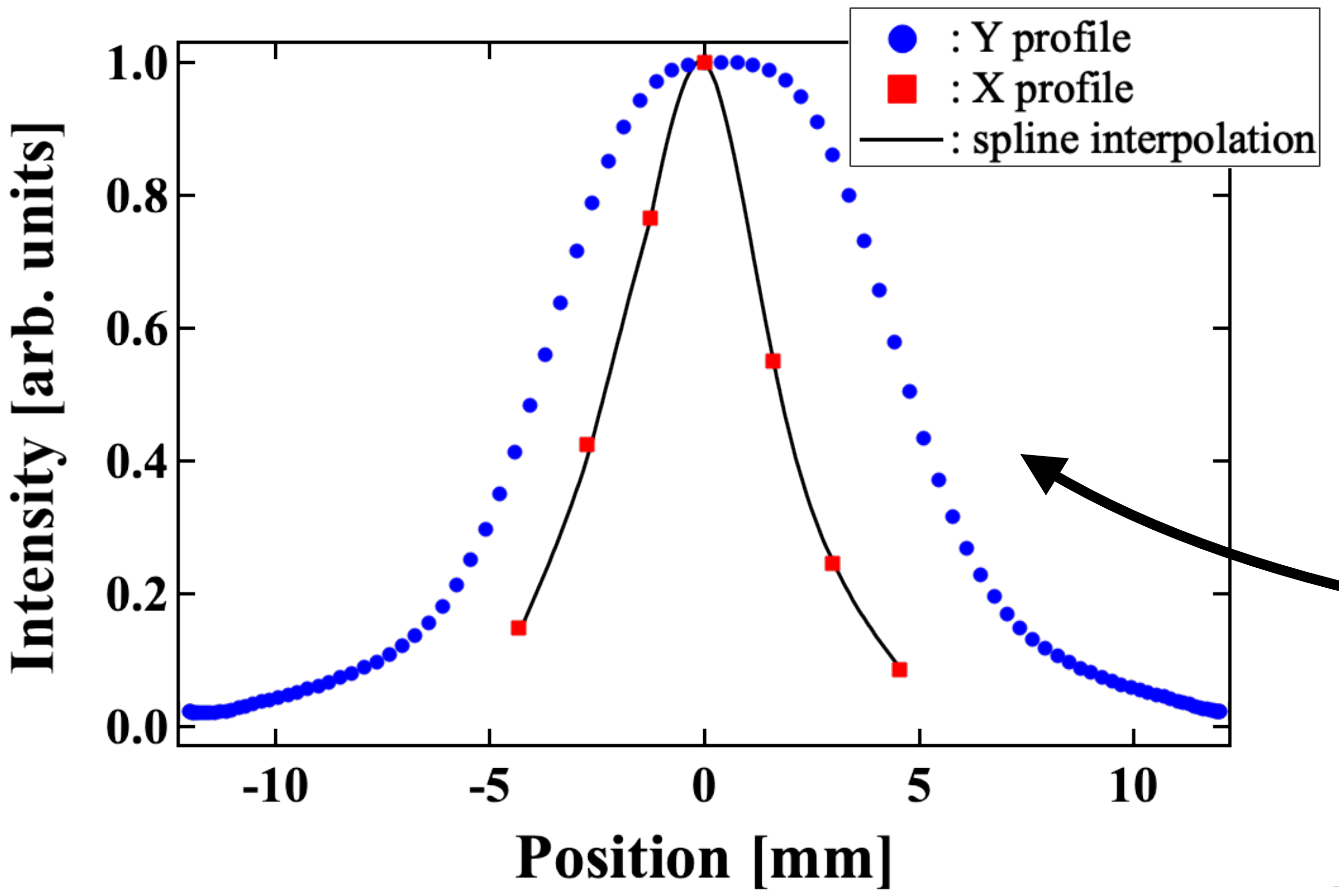
2. **Comparing** $g_{int}(x, z) = \int k(x, y, z)\ F(x, y, \boldsymbol{a}, \boldsymbol{b})\ \mathrm{d}y$

   $g_{int}(x, z)$: integral of <u>sensitivity distribution</u> × <u>assumed beam profile</u>

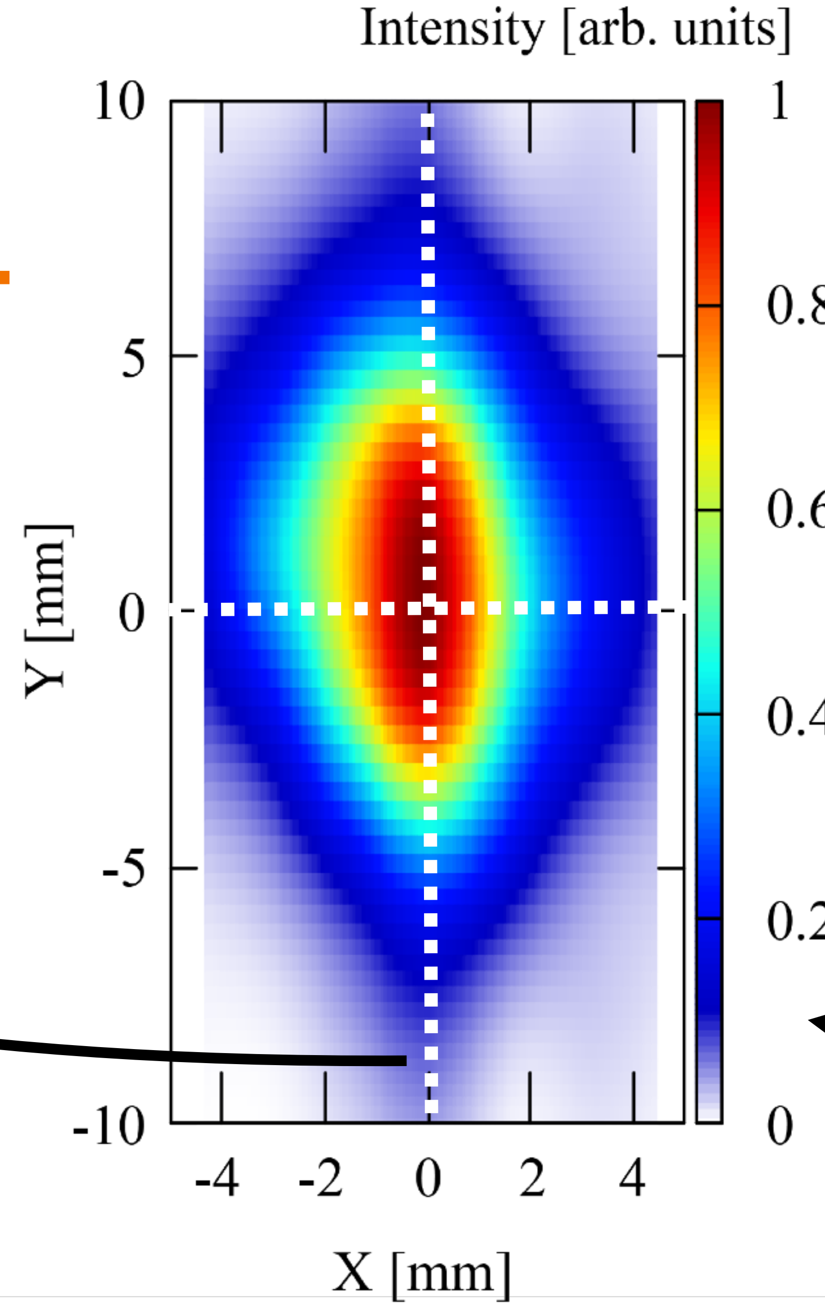
   $g_{H^-}(x, z)$: image captured by high-intensity-beam measurement

3. **optimizing** parameters $(\boldsymbol{a}, \boldsymbol{b})$ of the beam profile for fitting $g_{int}(x, z)$ to $g_{H^-}(x, z)$

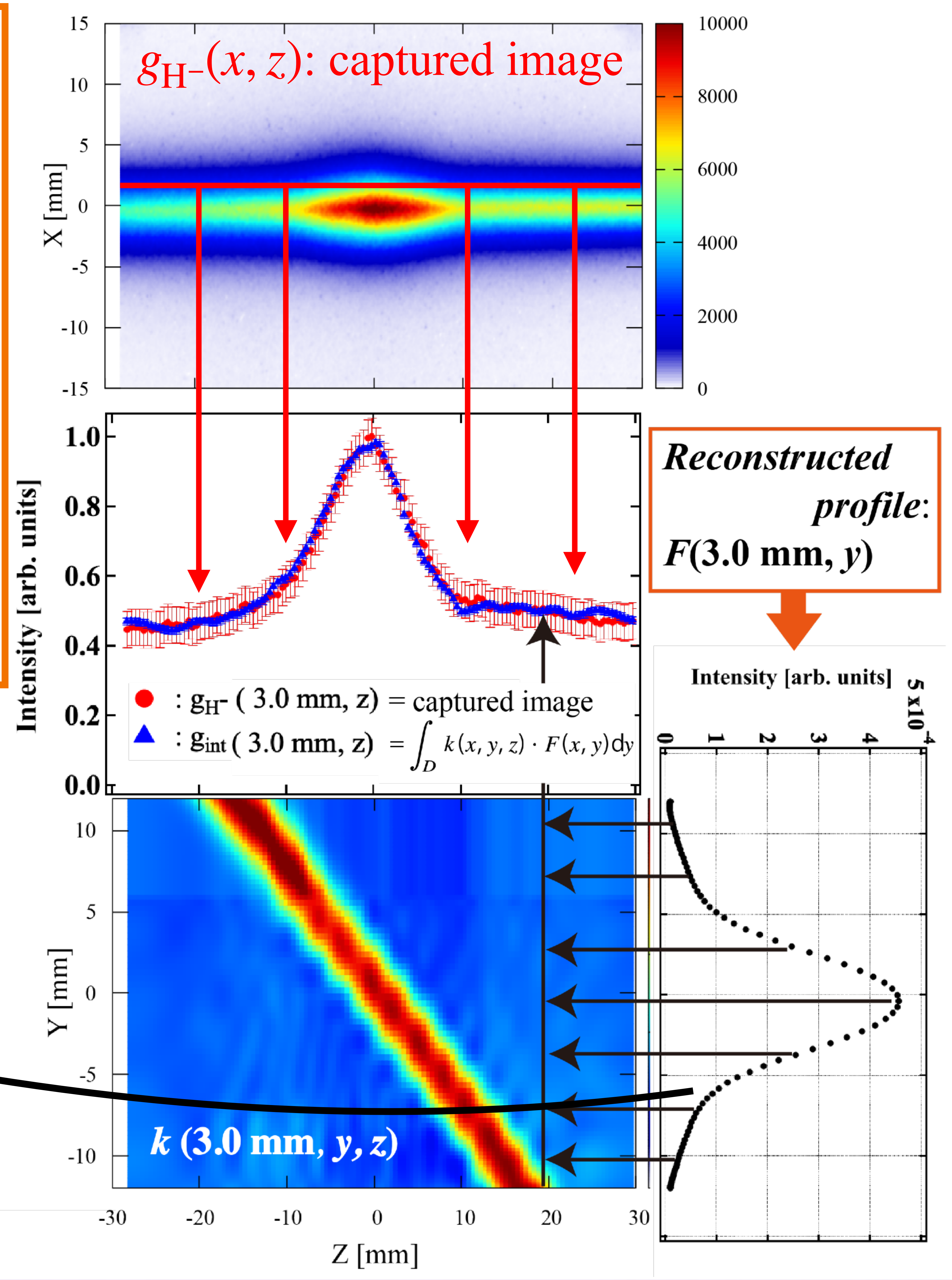
=> ***<u>2D transverse beam profile can be reconstructed !!</u>***



✓ Cross-sectional beam profile



✓ 2D transverse beam profile

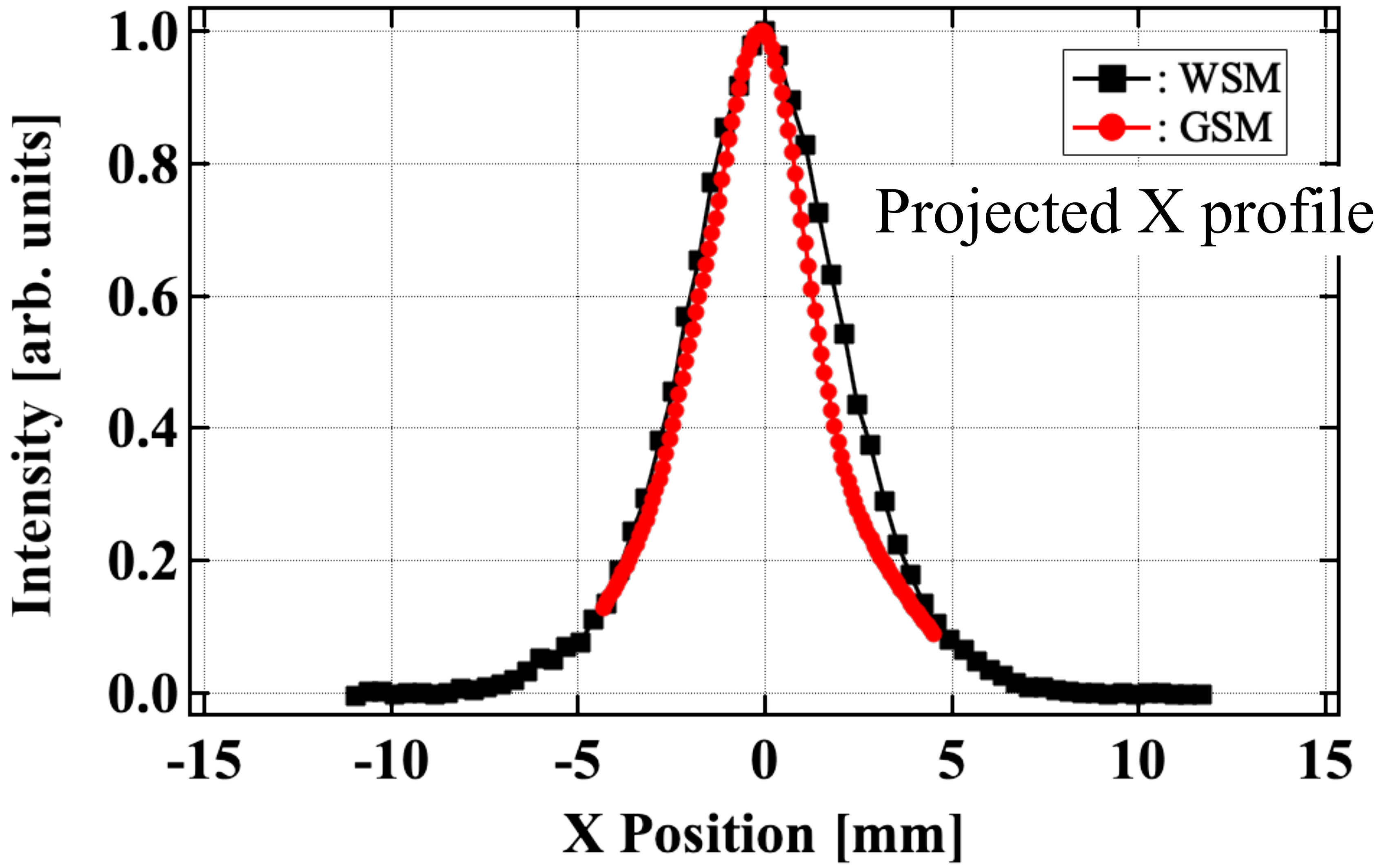


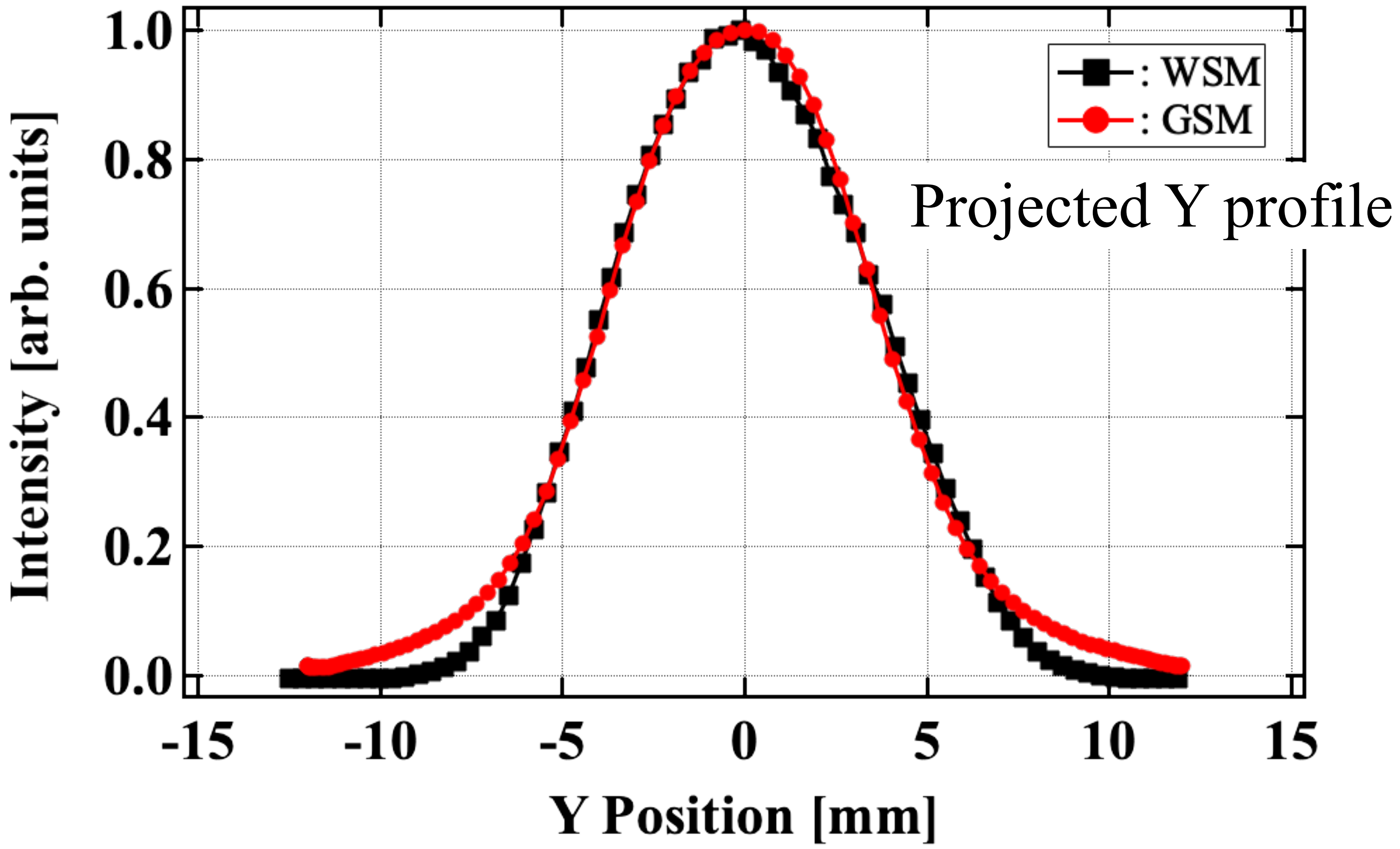
Evaluation of reconstructed beam profile

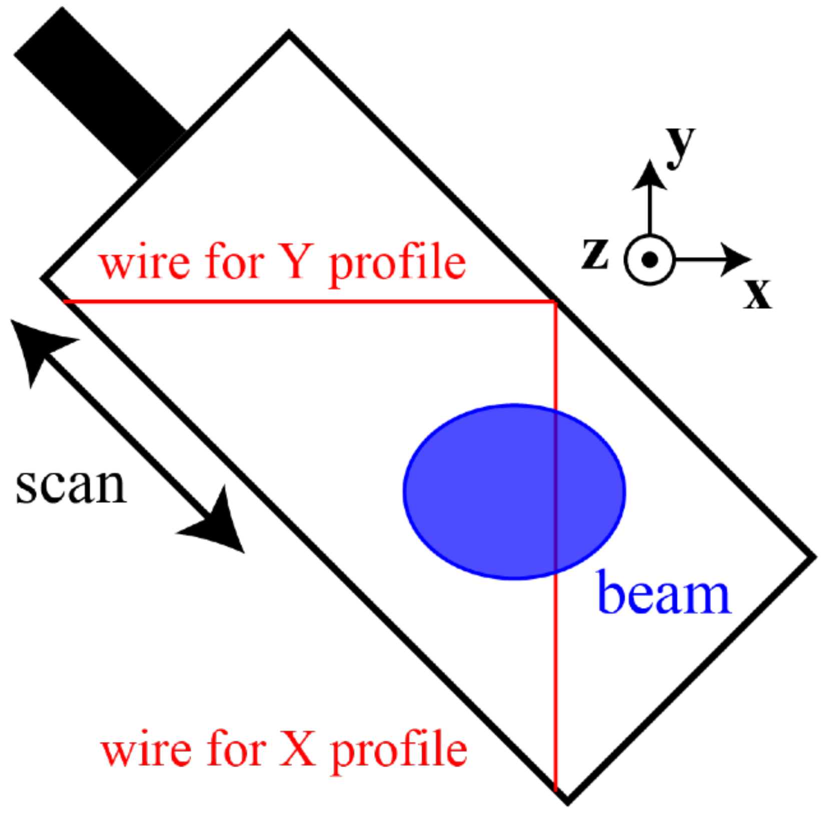
Comparison of Gas Sheet Monitor (GSM) and Wire Scanner Monitor (WSM)

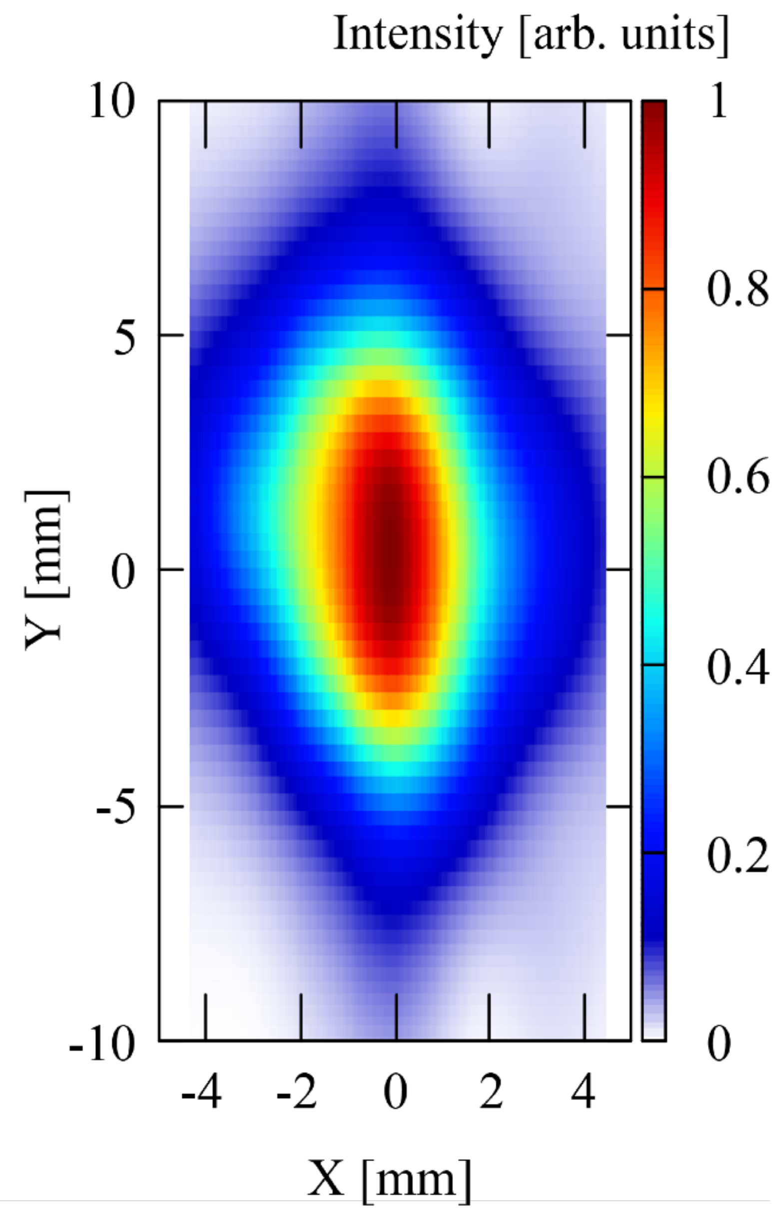
Wire scanner monitor => Destructive type, 1-dimensional (projected profile), utilized for operation in J-PARC

=> Projecting 2D profile measured by GSM into 1D profile









Accuracy of reconstructed profile:

- Standard deviation of profile and sensitivity distribution measurements
- Disagreement rate of distributions $g_{\mathrm{int}}(x, z)$ for $g_{\mathrm{H^-}}(x, z)$

=> Total 7% ± 2% on average

Various profile measurements (Beam : 3 MeV, 60 mA, 25 Hz, H^-)

100-pulse measurement

Gate width: 50 us

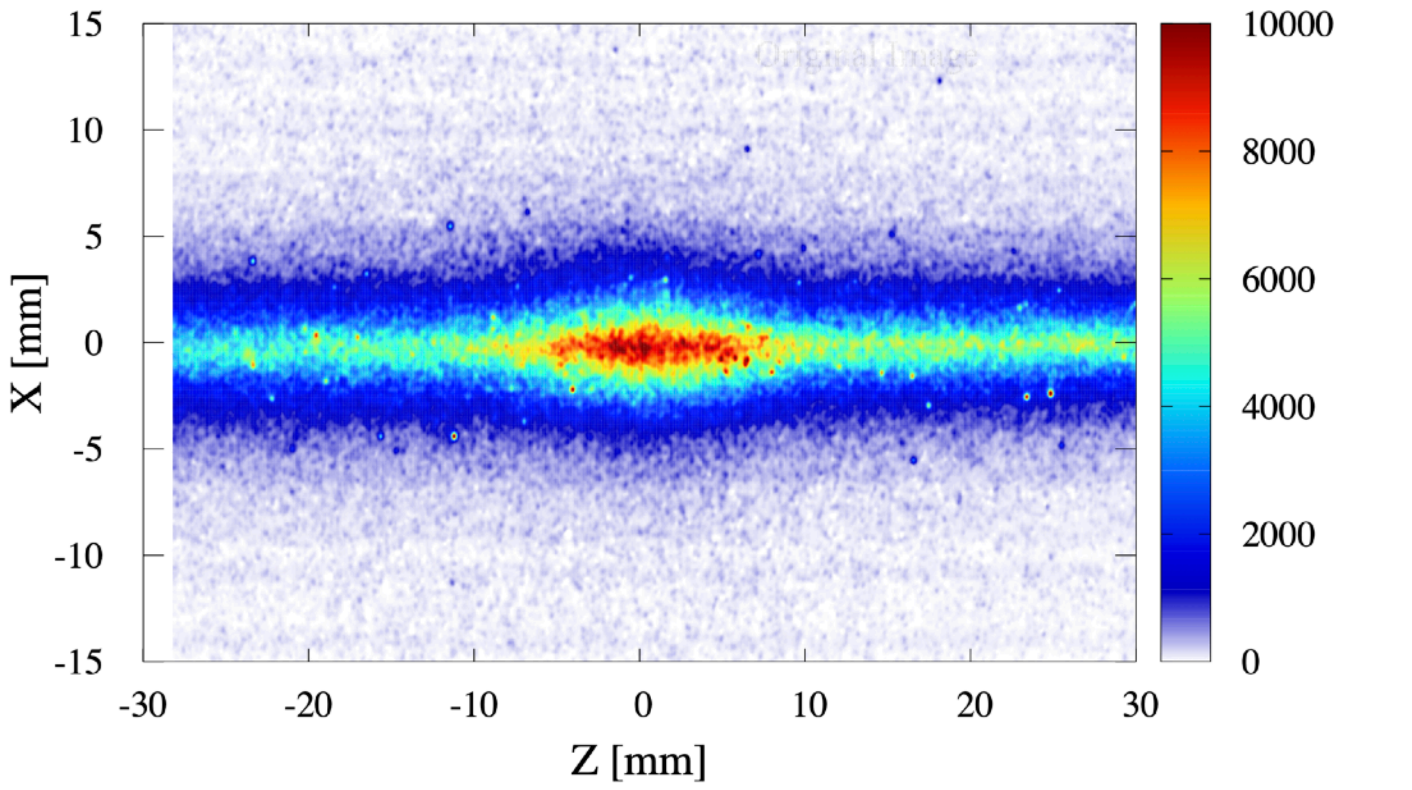
Exposure time: 4 s (x 25 Hz = 100 pulse)

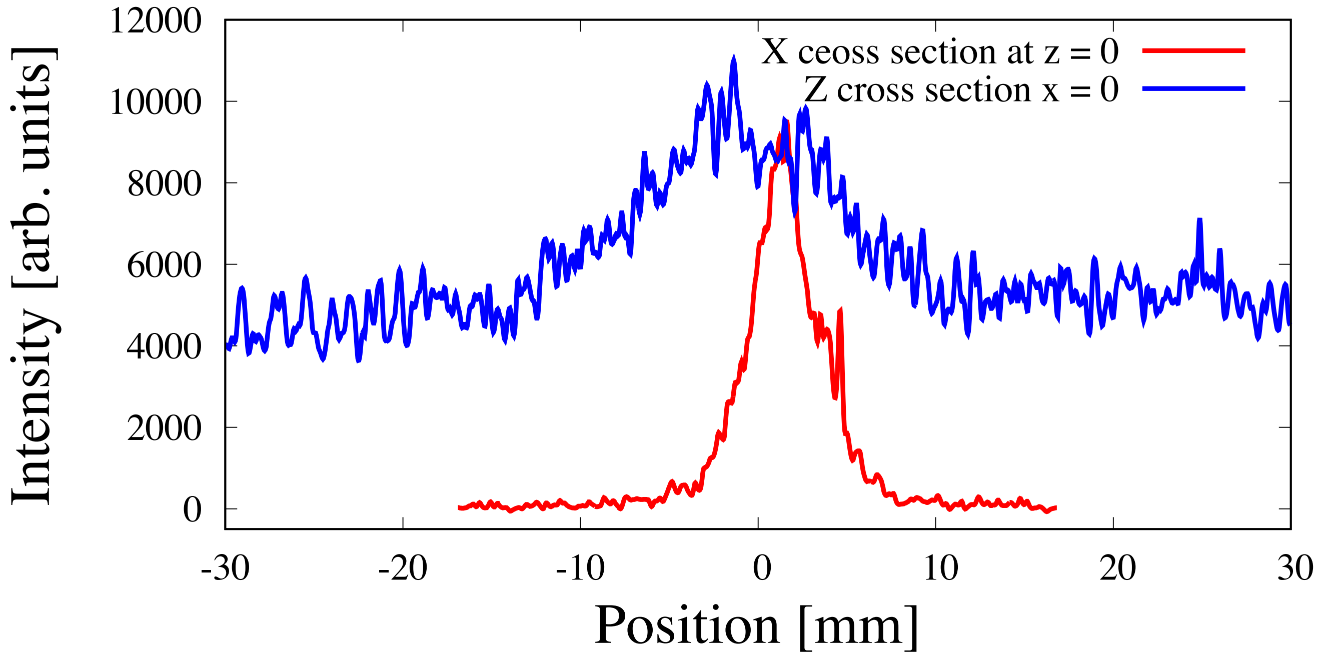
Averaging: 1 frame

Inlet pressure: 100 Pa

Main chamber: 5.6×10^{-5} Pa

Possibility of Pulse-to-pulse measurement





Low-pressure measurement

Gate width: 50 us

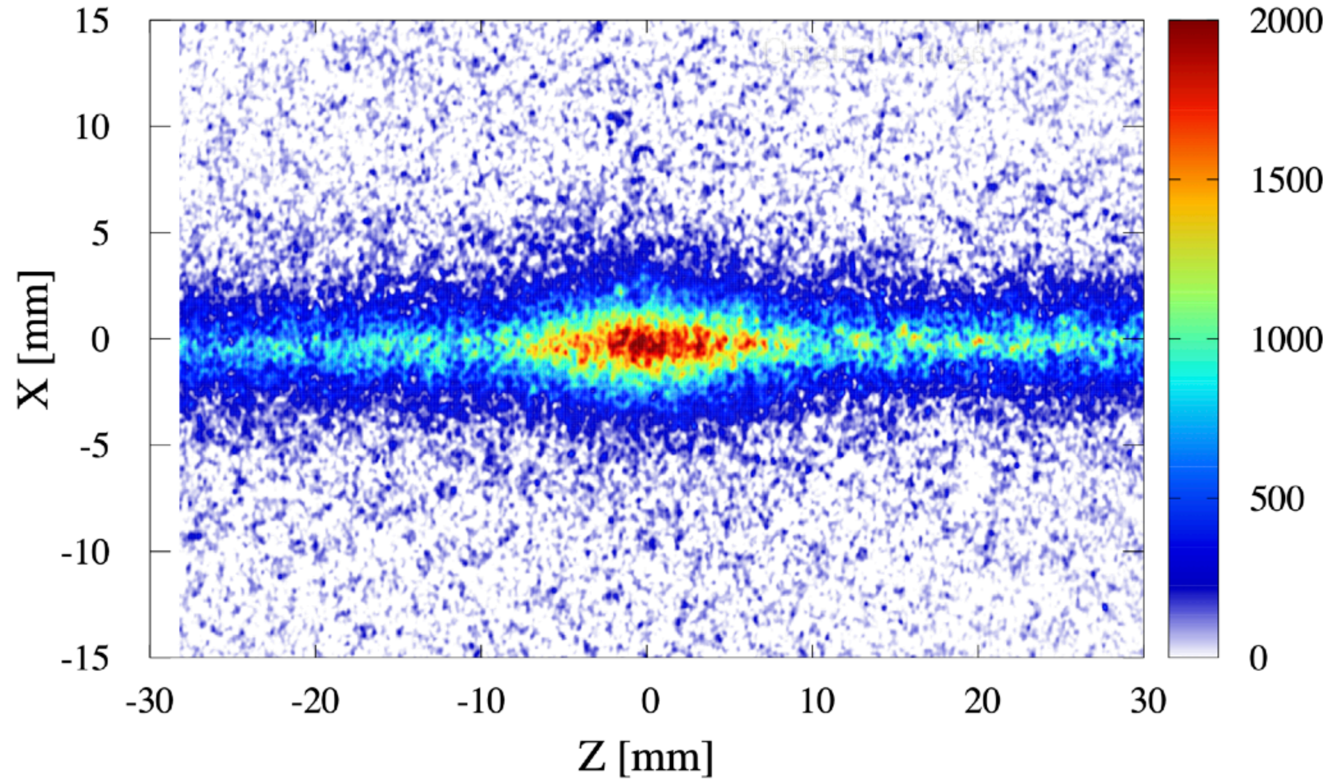
Exposure time: 200 s

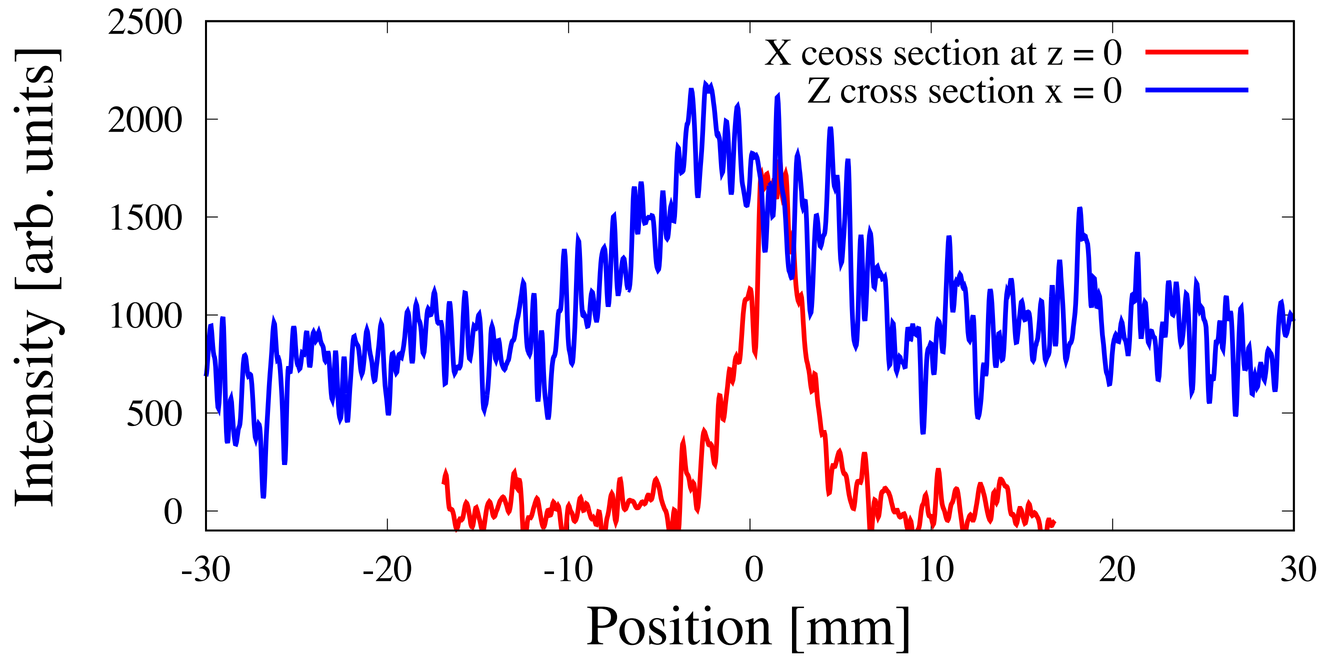
Averaging: 30 frame

Inlet pressure: 0.1 Pa

Main chamber: 1.4×10^{-6} Pa (Base: 1.2×10^{-6})

No-influence measurement on gas pressure





1us measurement

Gate width: 1 us

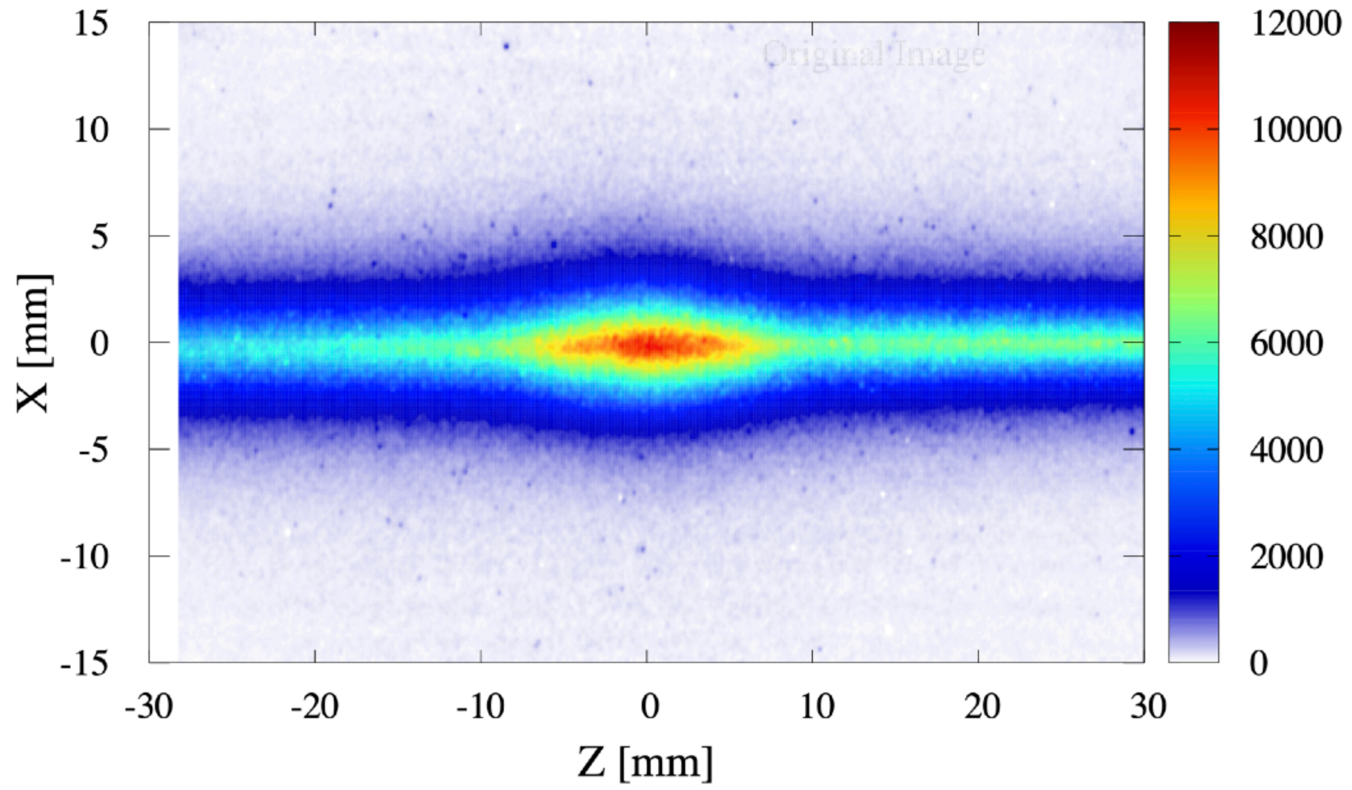
Exposure time: 200 s

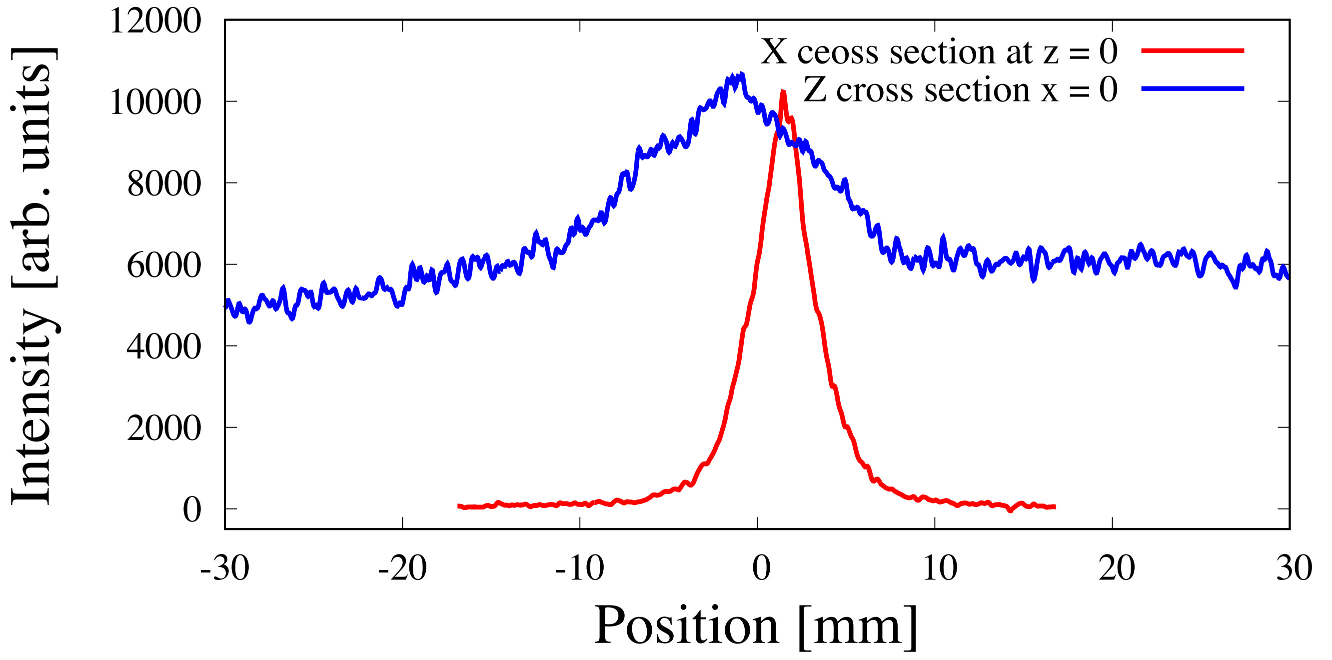
Averaging: 10 frame

Inlet pressure: 100 Pa

Main chamber: 5.6×10^{-5} Pa

Possibility of time-development measurement





Gas sheet monitor has wide-range parameters of *pressure*, *exposure time*, *number of frames*, *gate width*
=> Various kinds of profile measurements are possible

Summary & Next step

Summary

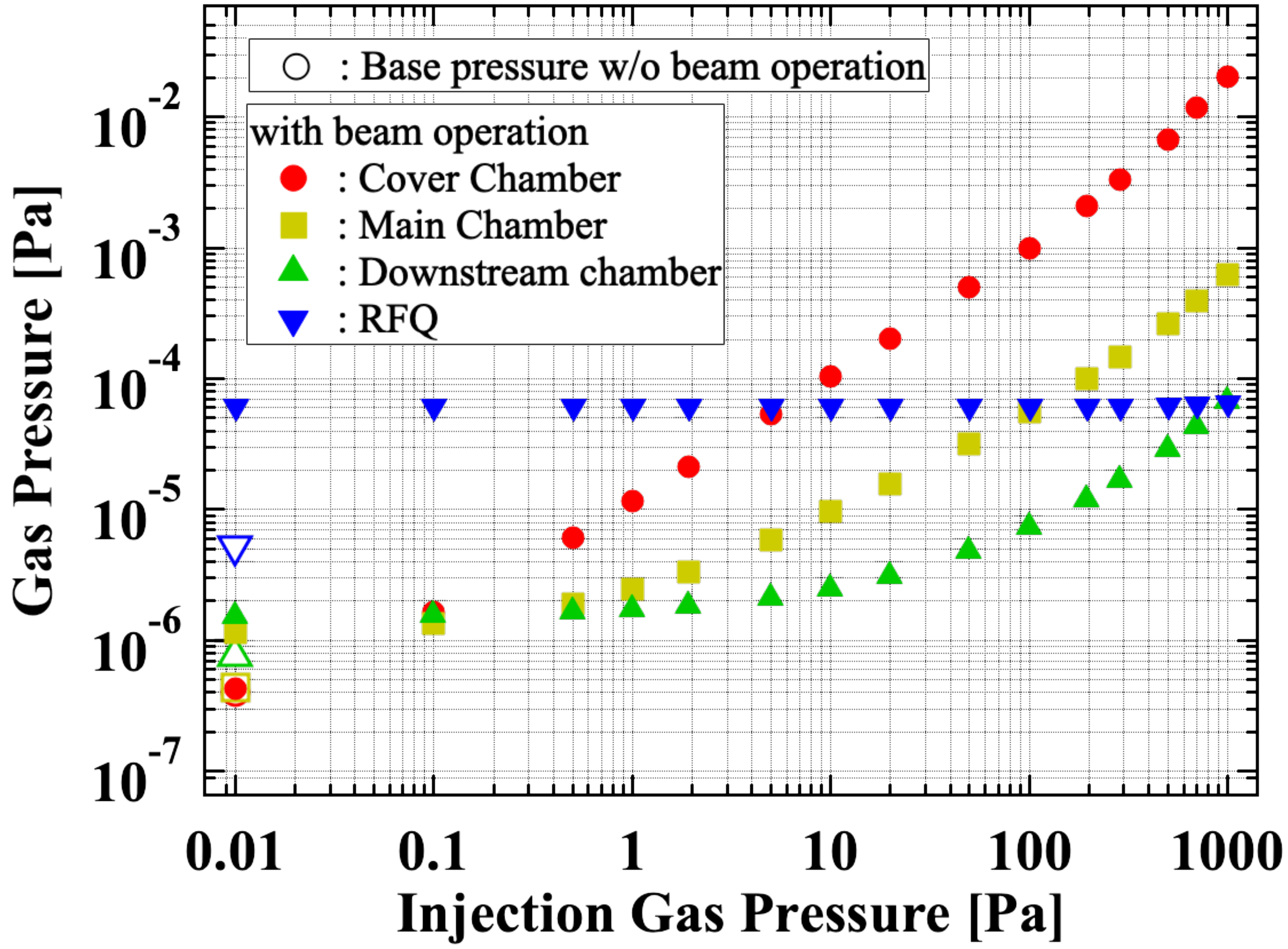
- ✓ Forming gas sheet based on rarefied gas dynamics and simulating gas flow using Monte-Carlo code
- ✓ Developing gas sheet monitor system and installing the monitor on J-PARC MEBT test stand
- ✓ Measuring J-PARC 3 MeV 60 mA H^- beam profile
- ✓ Formulating the gas sheet monitor's principle as integral equation to reconstruct beam profile
- ✓ Quantifying relative-sensitivity distribution by injecting thin beam into gas sheet monitor
- ✓ Reconstructing 2D transverse beam profile
- ✓ Applying gas sheet monitor for various profile measurement

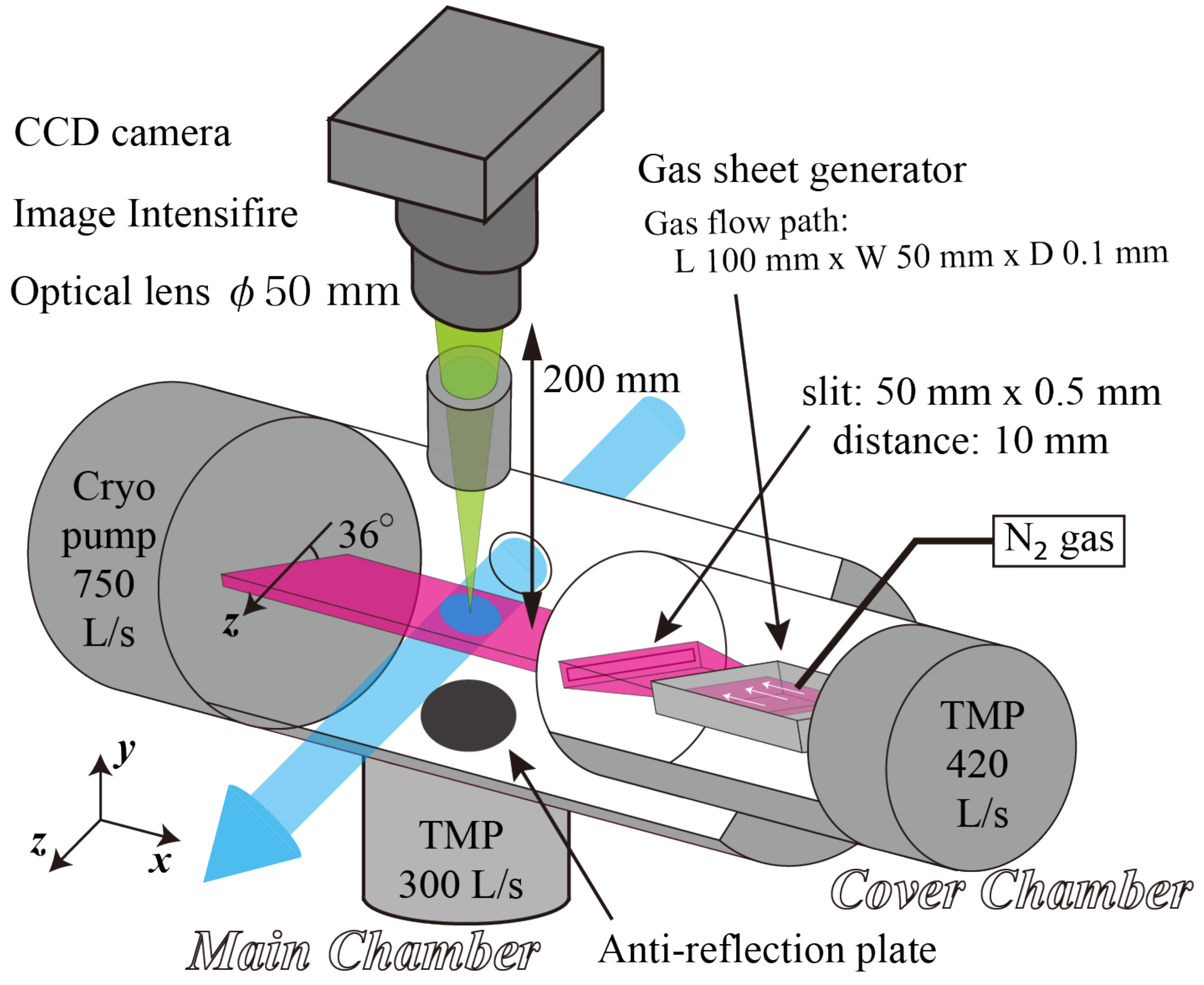
- ✦ Investigating time development of beam profile
- ✦ Investigating effect of gas sheet injection on beam (transportation)
- ✦ Introducing gas sheet monitor into J-PARC beam line for operation

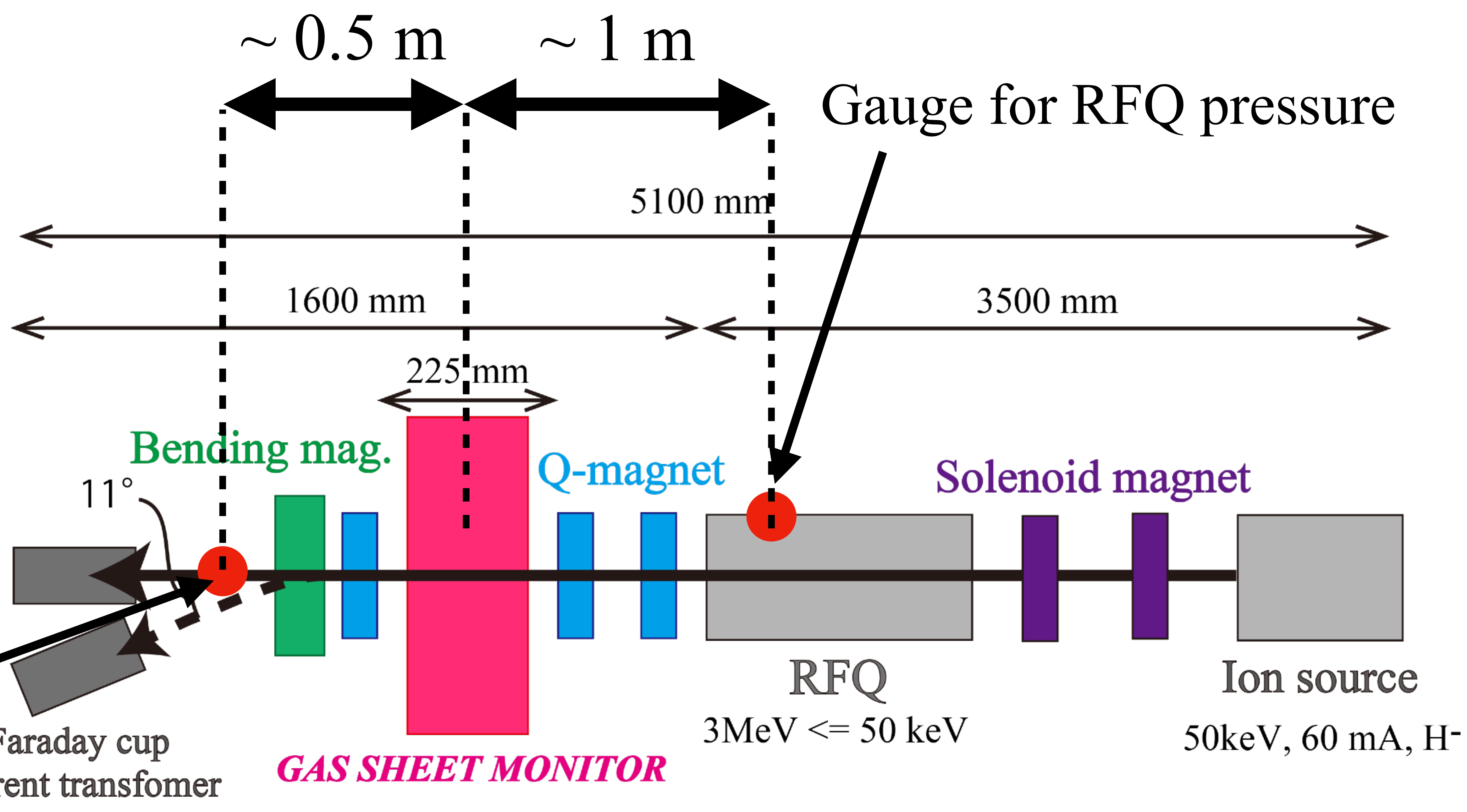
Appendices

Appendix 1: Gas Pressure at some points

There are little influences on beam-line gas pressure less than 1 Pa injection
(Beam operation has more strong influence)







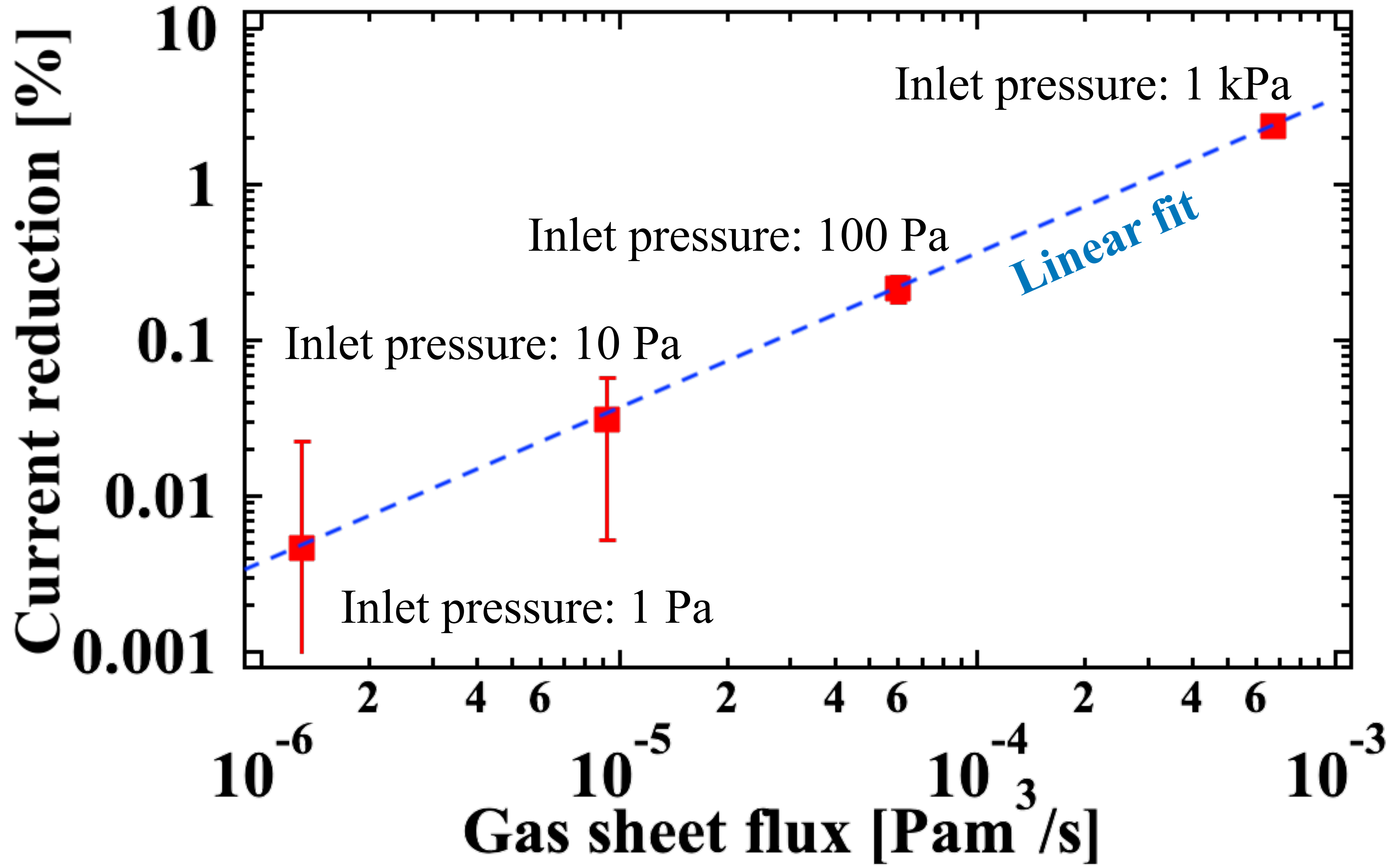
One of the effects of gas injection: charge stripping of beam

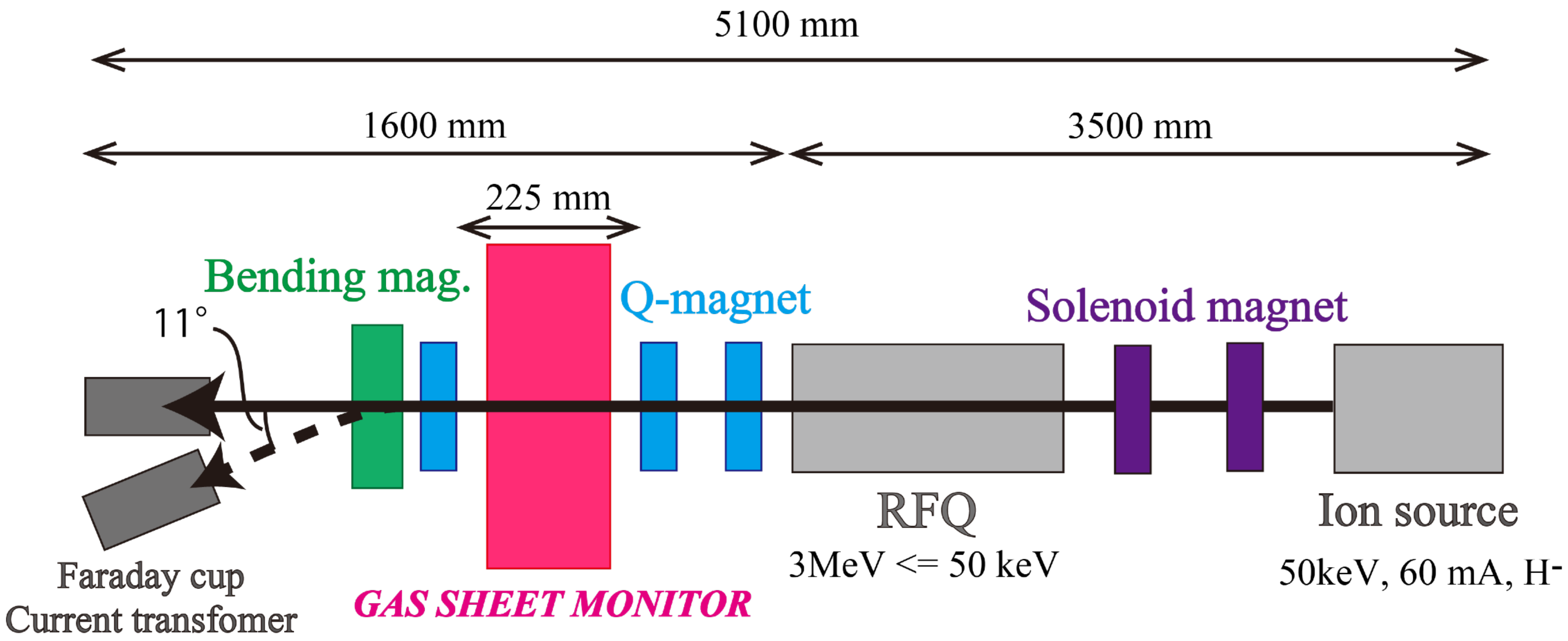
$H^- + N_2 \rightarrow H^0$ (or H^+) $+ N_2$ (or N_2^+)

H- and H^0 can be separated by bending magnet

=> H^- current reduction rate vs. gas sheet flux*

We are starting to investigate not only charge stripping but other effects of gas injection in more detail





Summary 1: Concept of Gas Sheet Monitor

High-intensity hadron accelerator (J-PARC)

=> Requires **non-destructive monitor** to avoid break of monitor and beam loss

=> Developing 2D transverse beam profile monitor based on beam-gas interaction: ***Gas Sheet Monitor***

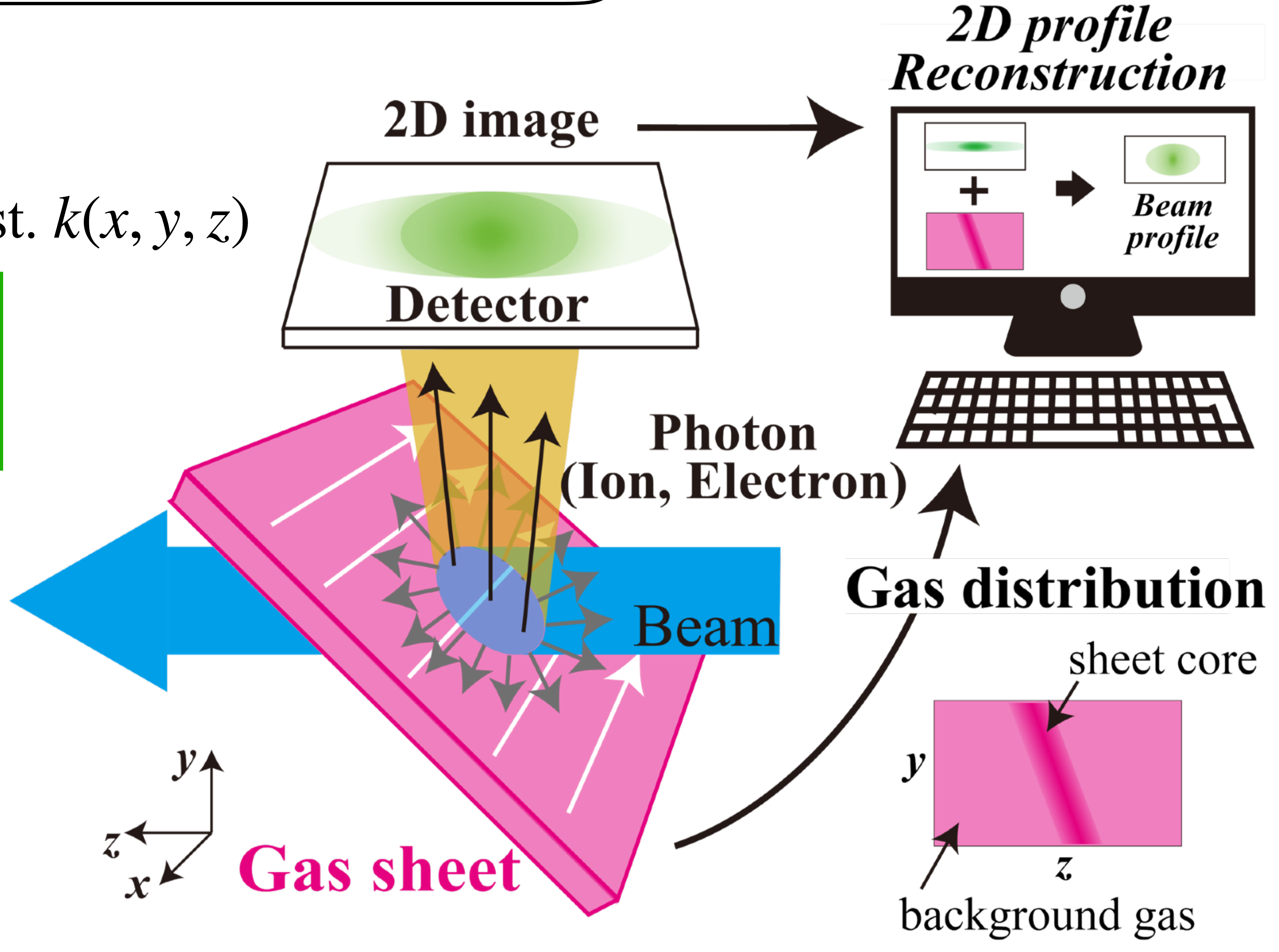
Gas sheet monitor (GSM)

- injects sheet-shaped gas
- produces photons (secondary particles)
- detects distribution of photons as a 2D image

=> Luminous intensity distribution $g(x, z)$, Beam profile $F(x, y)$, sensitivity dist. $k(x, y, z)$ are correlated by **integral equation**

$$g(x, z) = \int k(x, y, z)\ F(x, y)\ \mathrm{dy}$$

- Gas density distribution
- Efficiency distribution of imaging sensors
- …



Procedure of profile measurement

① Developing gas sheet monitor

② Evaluating sensitivity distribution at off-line system

③ Measuring high-intensity beam

④ Reconstructing 2D beam profile

Summary 2: Development of GSM

Gas sheet formation is based on ***Rarefied Gas Dynamics****

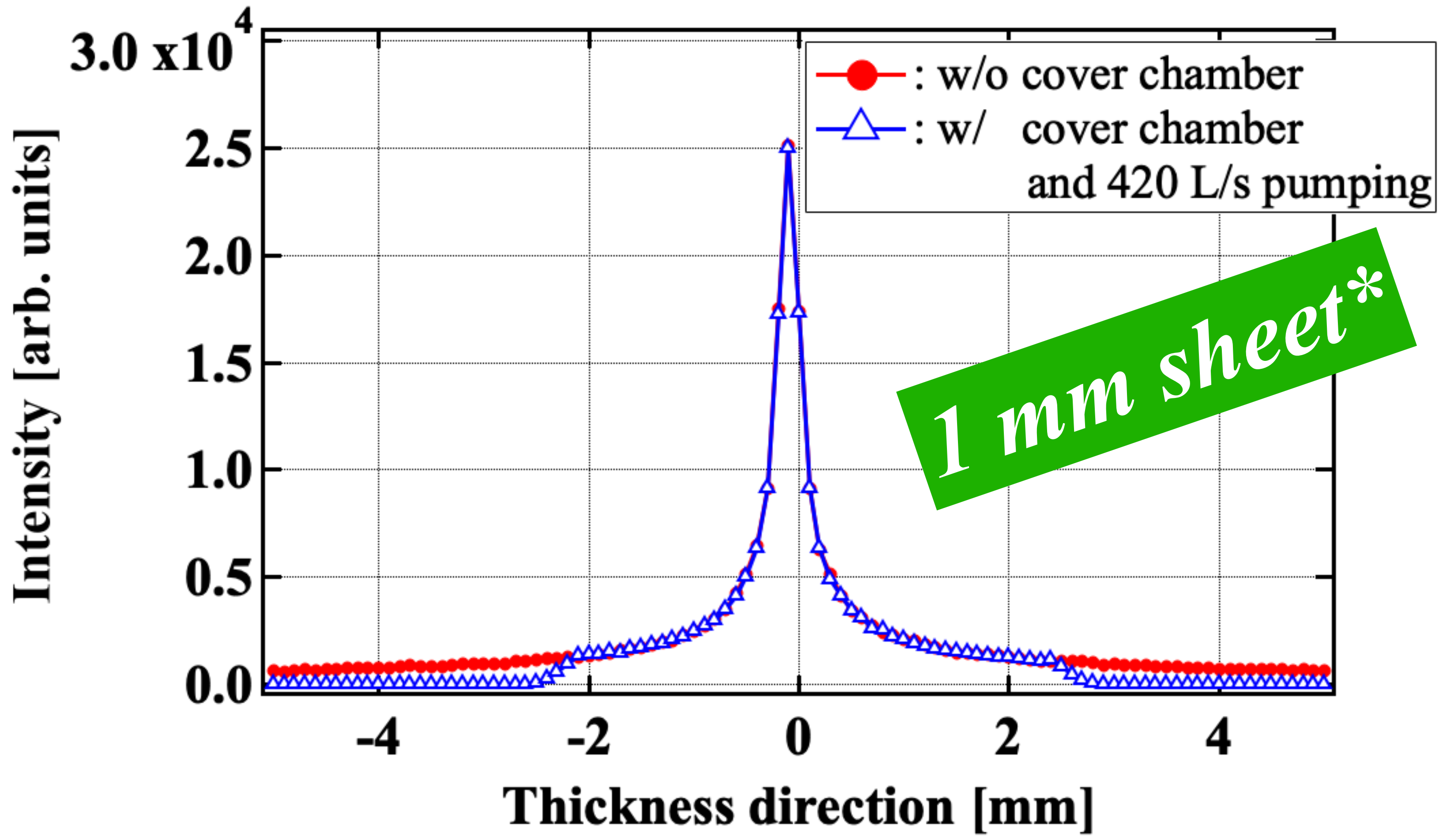
- **Collision-less approximation**

  Mean free path >> chamber size
- **Cosine law for reflection on wall**

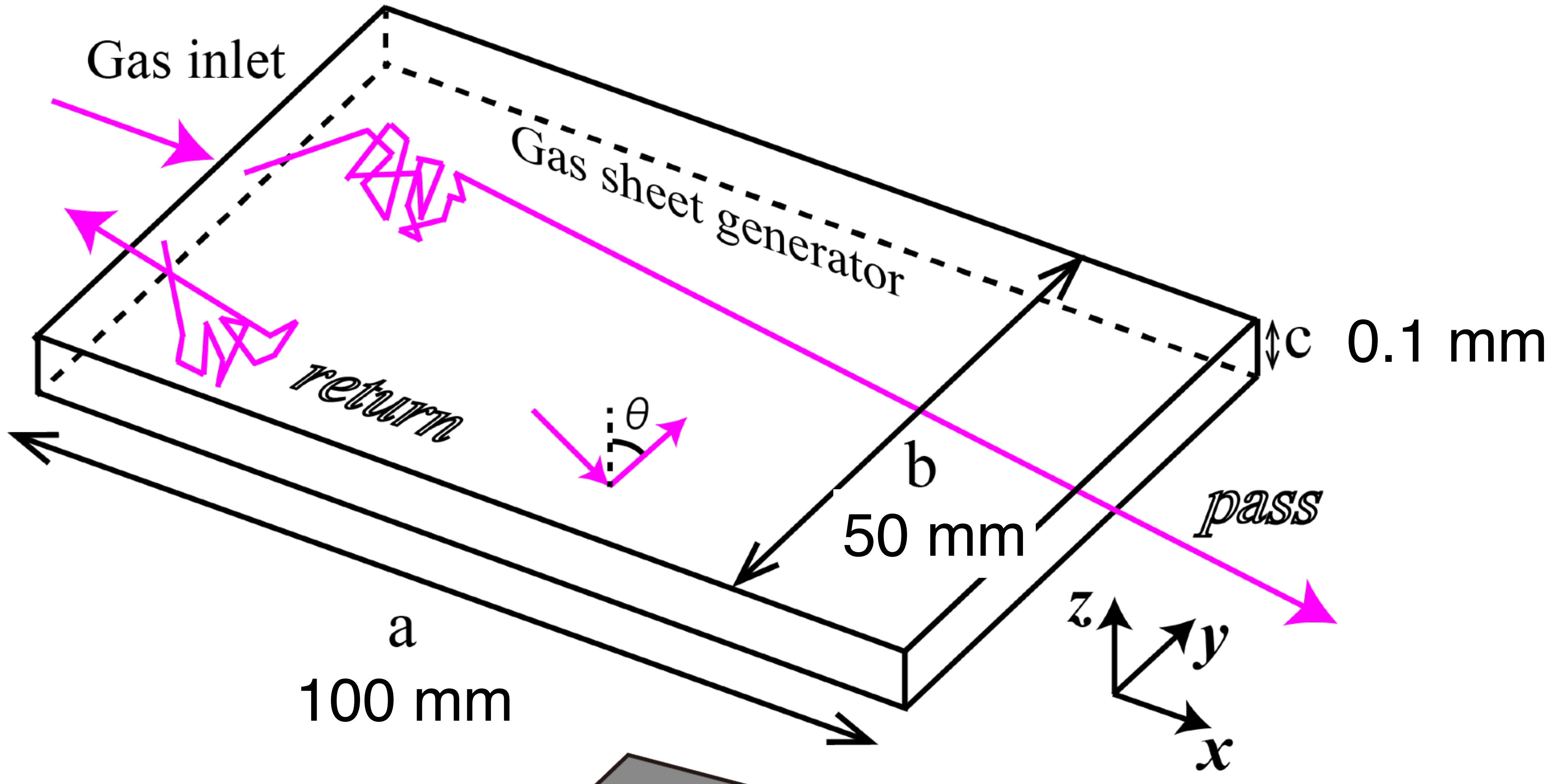
  Prob. dist. function $p(\theta)$ of reflection angle θ: $p(\theta) \propto \cos\theta$

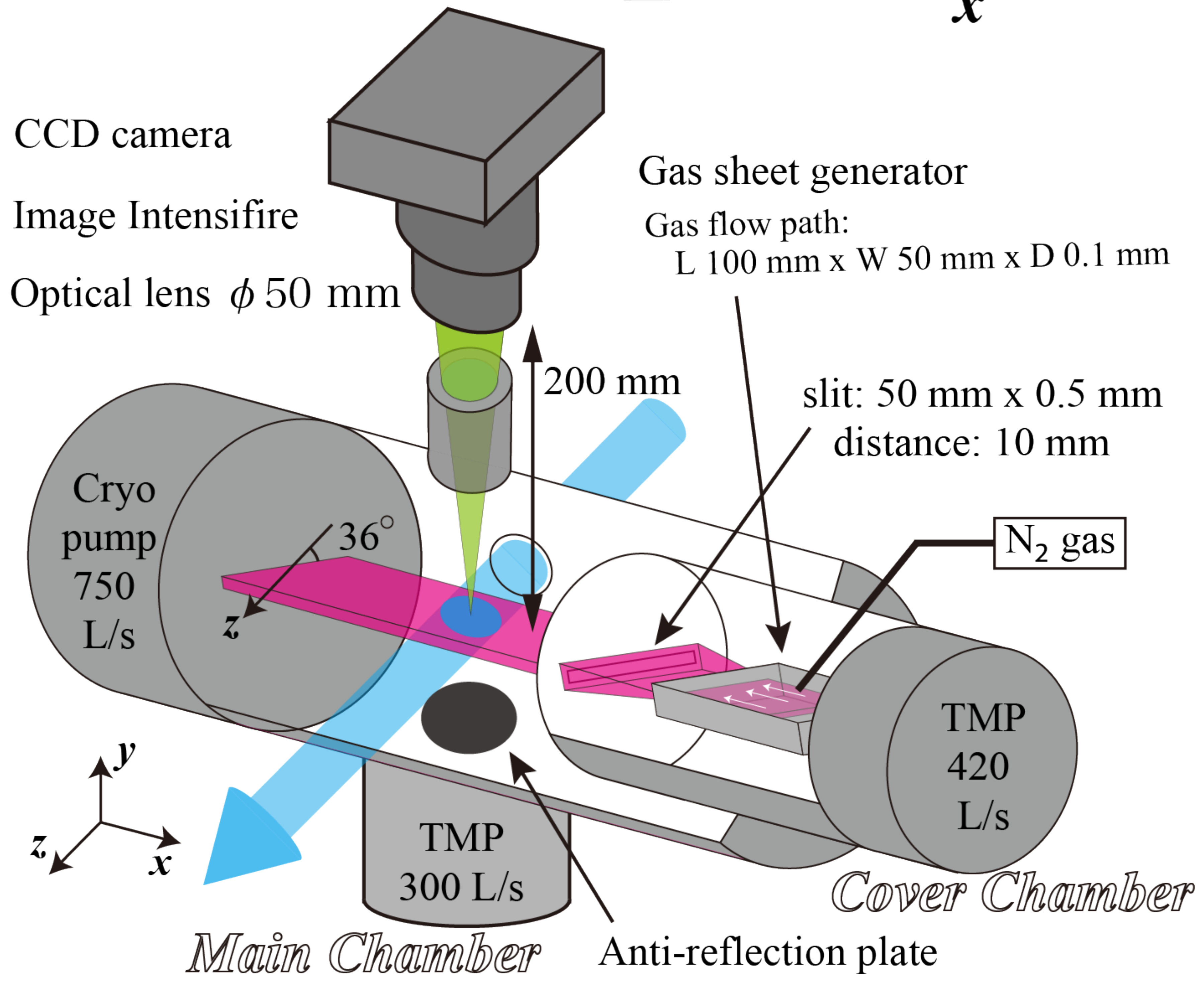
Thin and long gas conduit forms gas sheet

by increasing reflections in thickness direction



Estimated gas flux dist. by Monte-Carlo simulation





* N. Ogiwara, *Proc. of IPAC2016*, (Busan, Korea, 2016) WEOBB03.

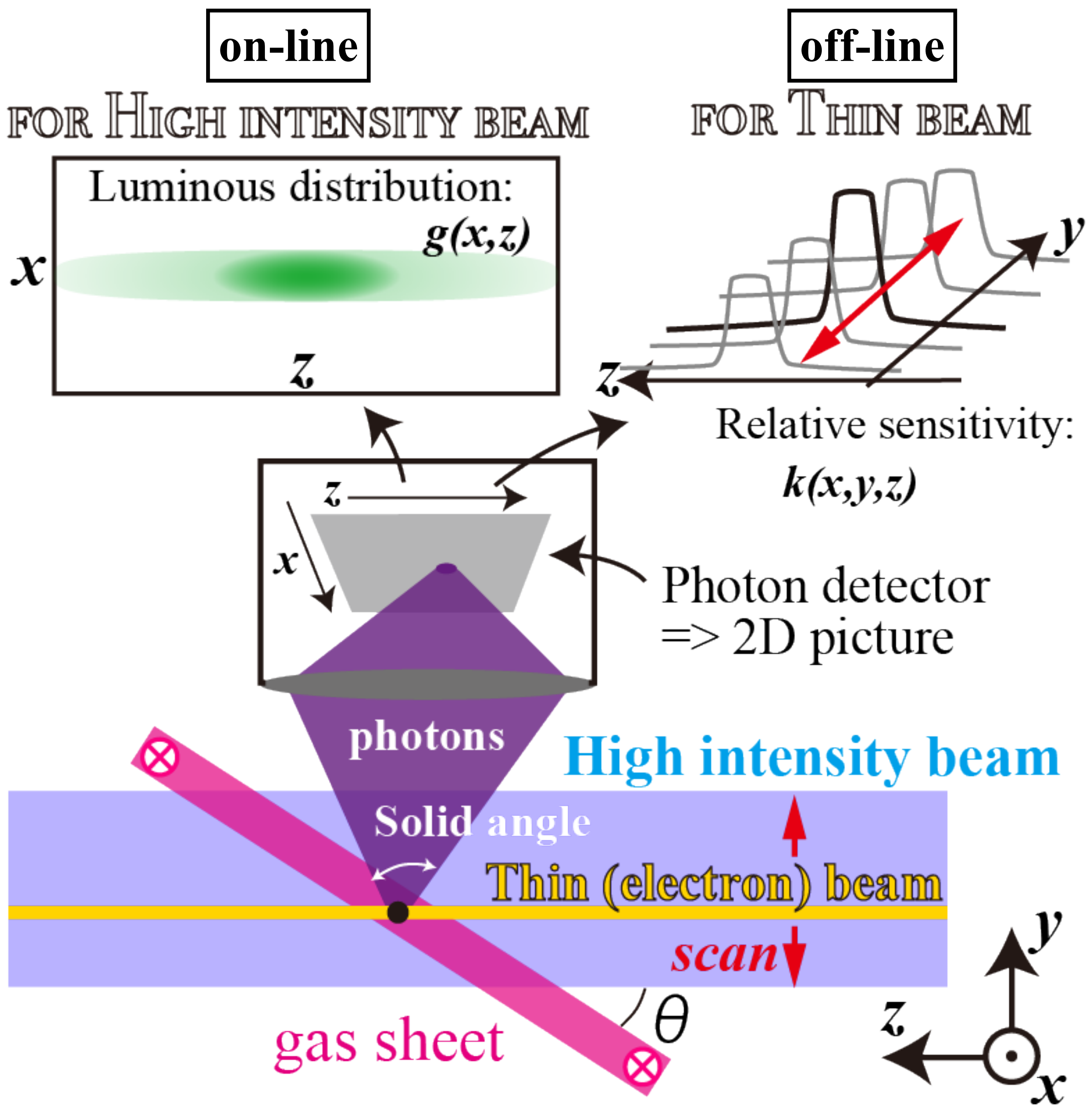
Summary 3: Evaluation of Sensitivity Dist. (off-line)

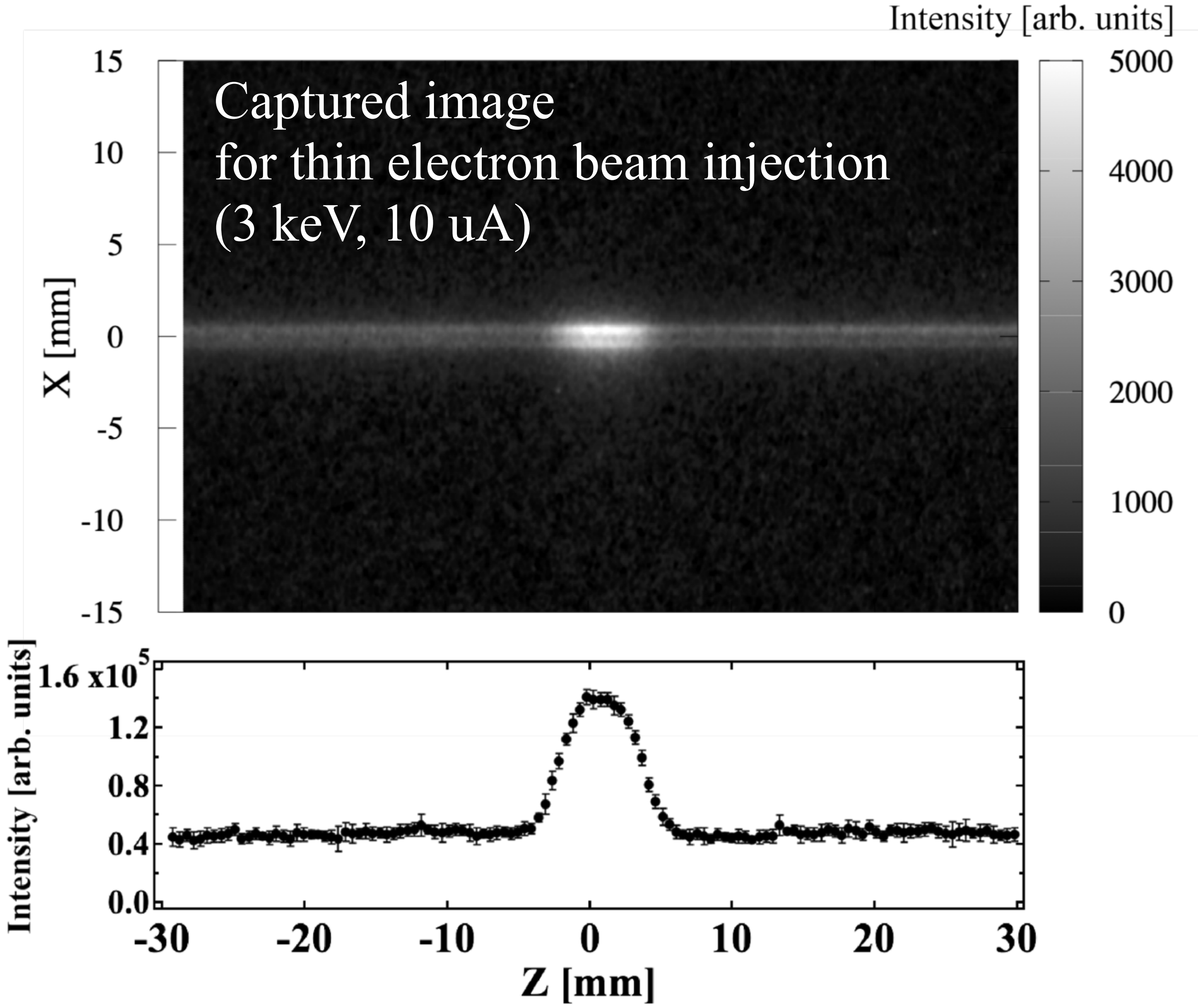
Evaluation of **relative-sensitivity distribution**

- Gas density distribution
- Efficiency distribution of CCD image sensors
- Non-uniformity of solid angle along *y* axis
- Optical aberration, out of focus, …

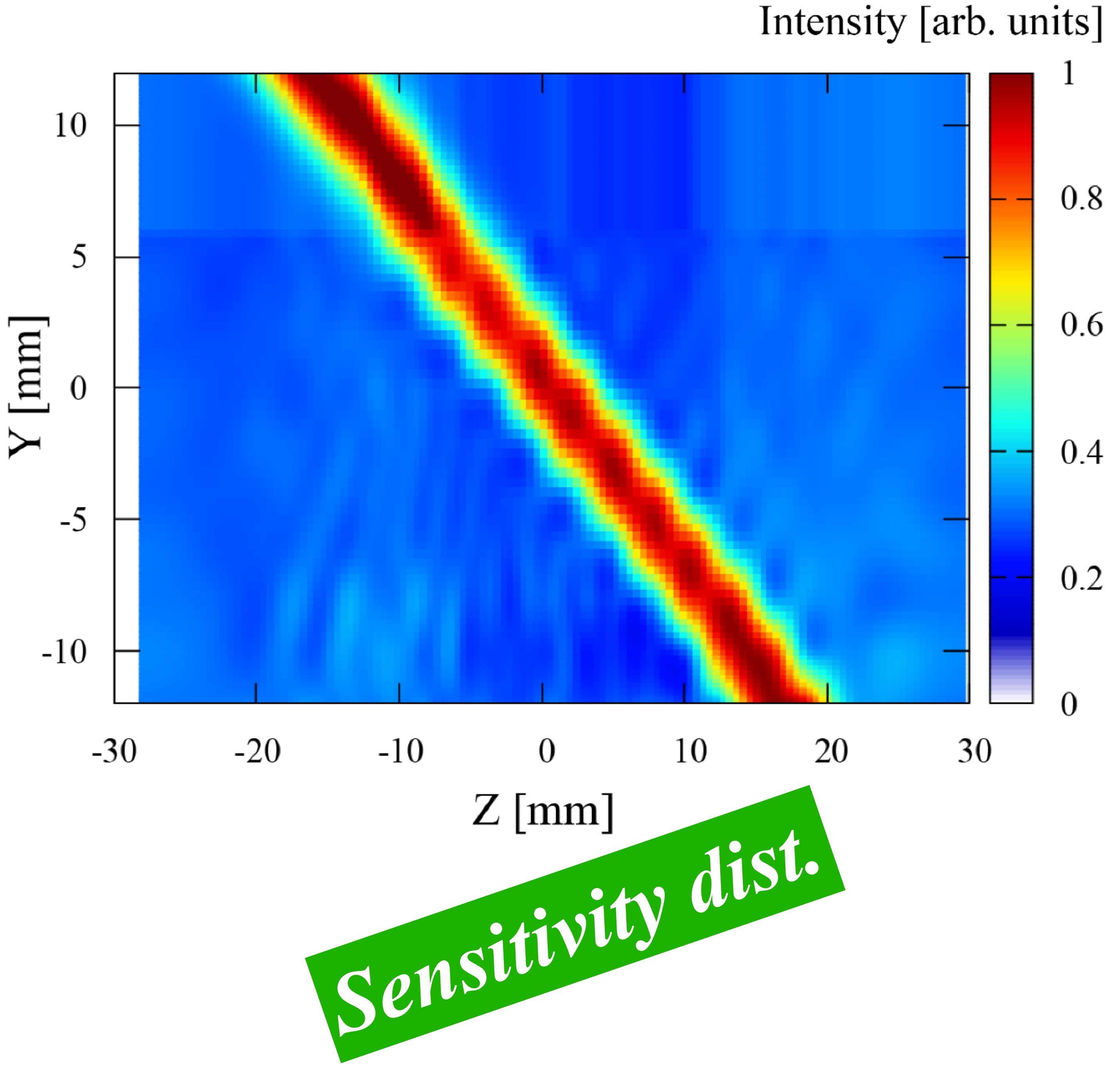
by injection of thin beam instead of high-intensity beam into GSM at off-line system

(GSM + e^- gun + Faraday cup)





Integrated distribution



Summary 4: Measurement of High-Intensity Beam

Conditions

Beam: J-PARC MEBT test stand

- Species : H^-
- Energy : 3 MeV
- Current : 60 mA
- Pulse length : 50 us
- Repetition : 25 Hz

Photon detector

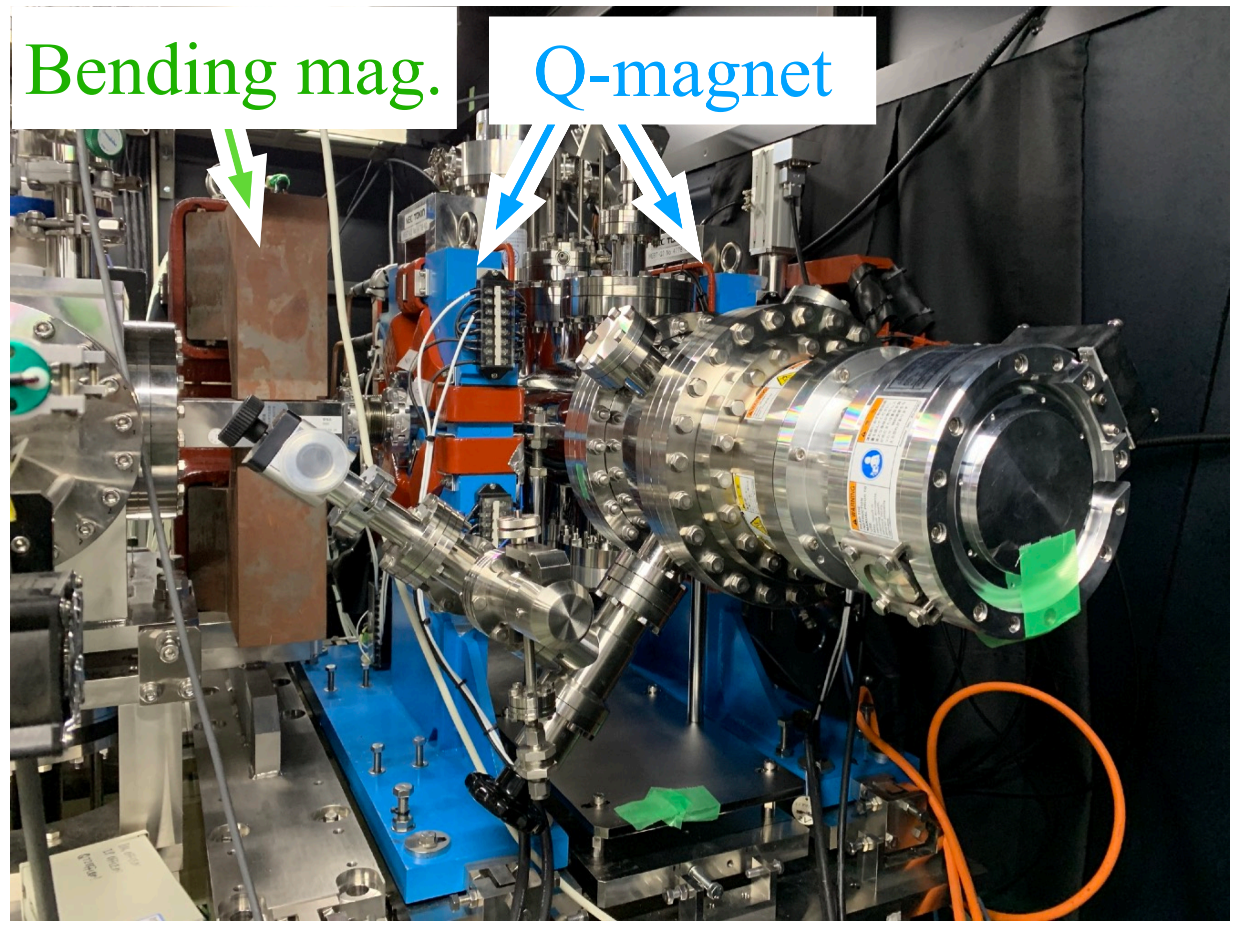
- Averaging : 1.5×10^{17} H^-

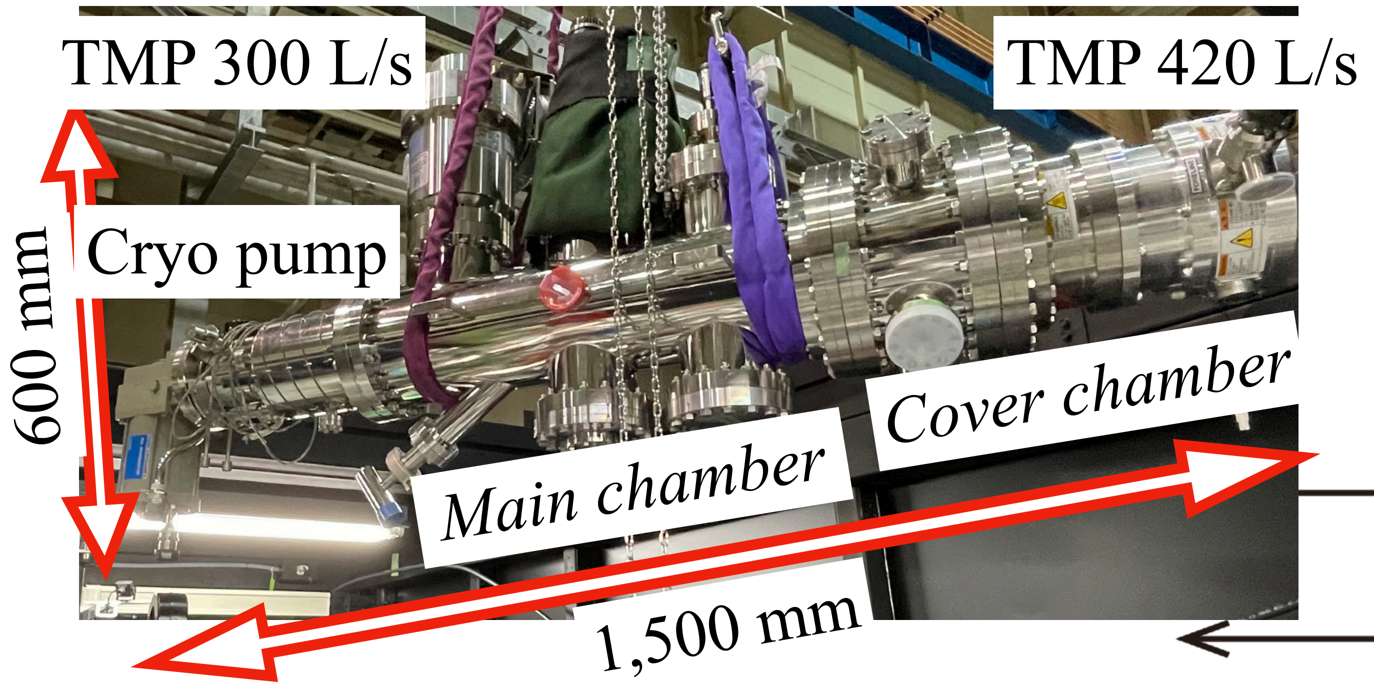
(= 60mA × 10 us × 25 Hz × 1600 s)

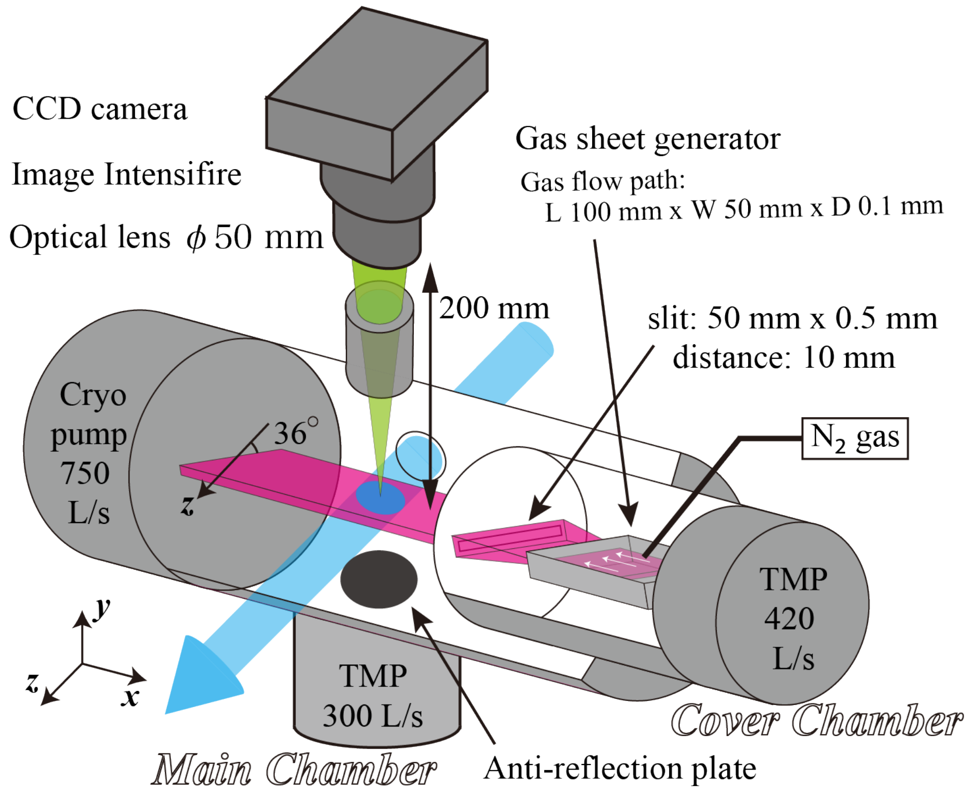
Gas sheet

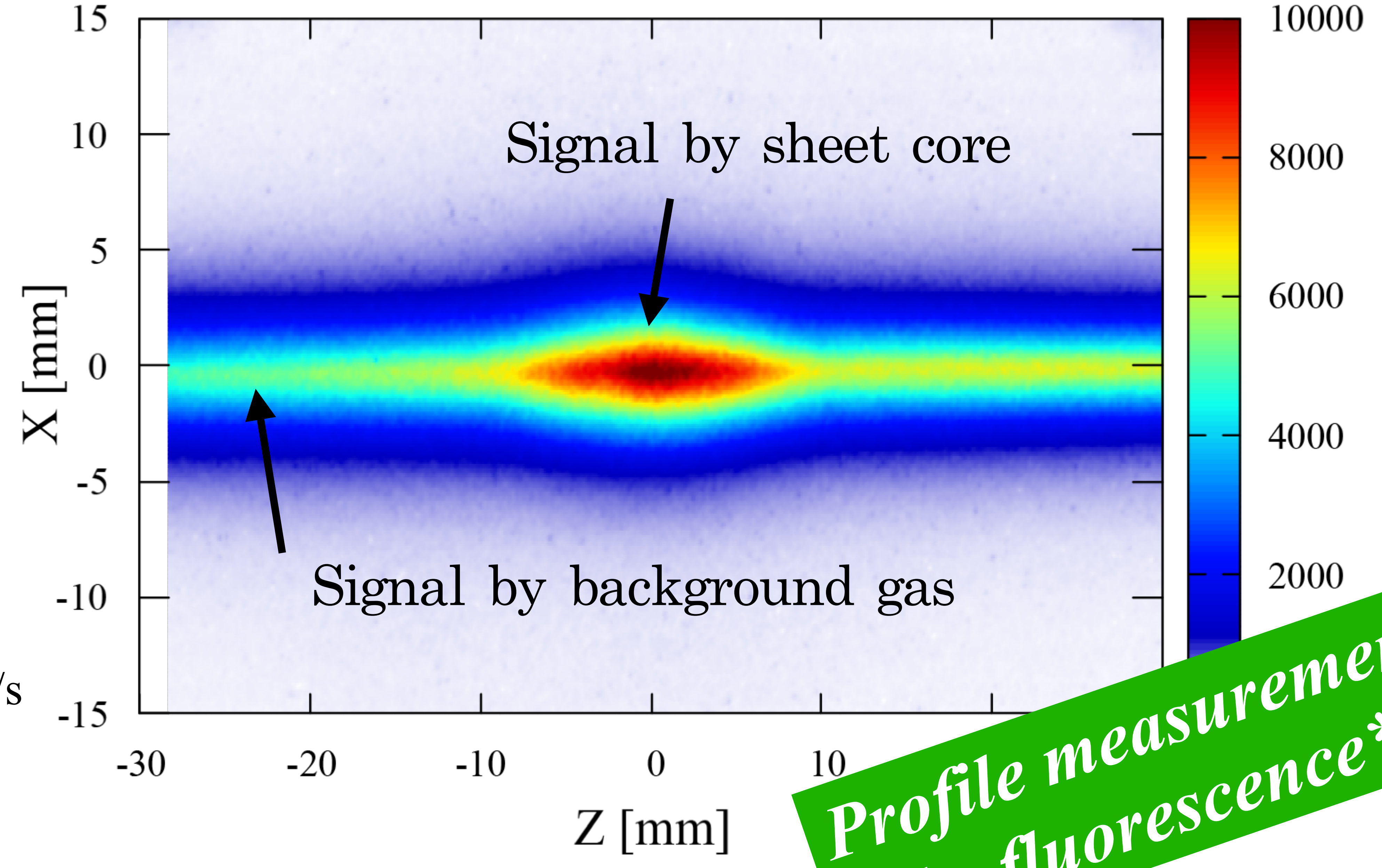
- Inlet pressure : 100 Pa
- Background pressure : 5.6×10^{-5} Pa (Main chamber)

In pre-recorded talk, we show results of other 3 conditions

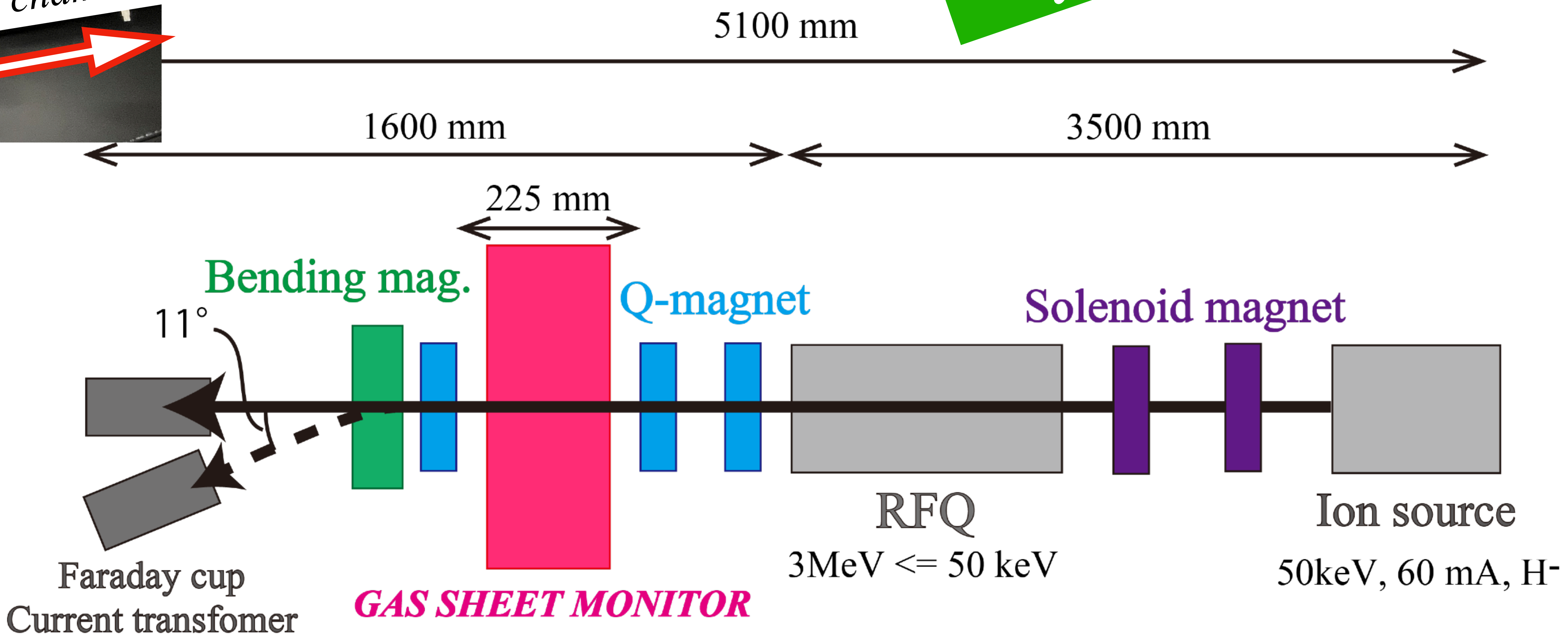








Profile measurement by fluorescence*

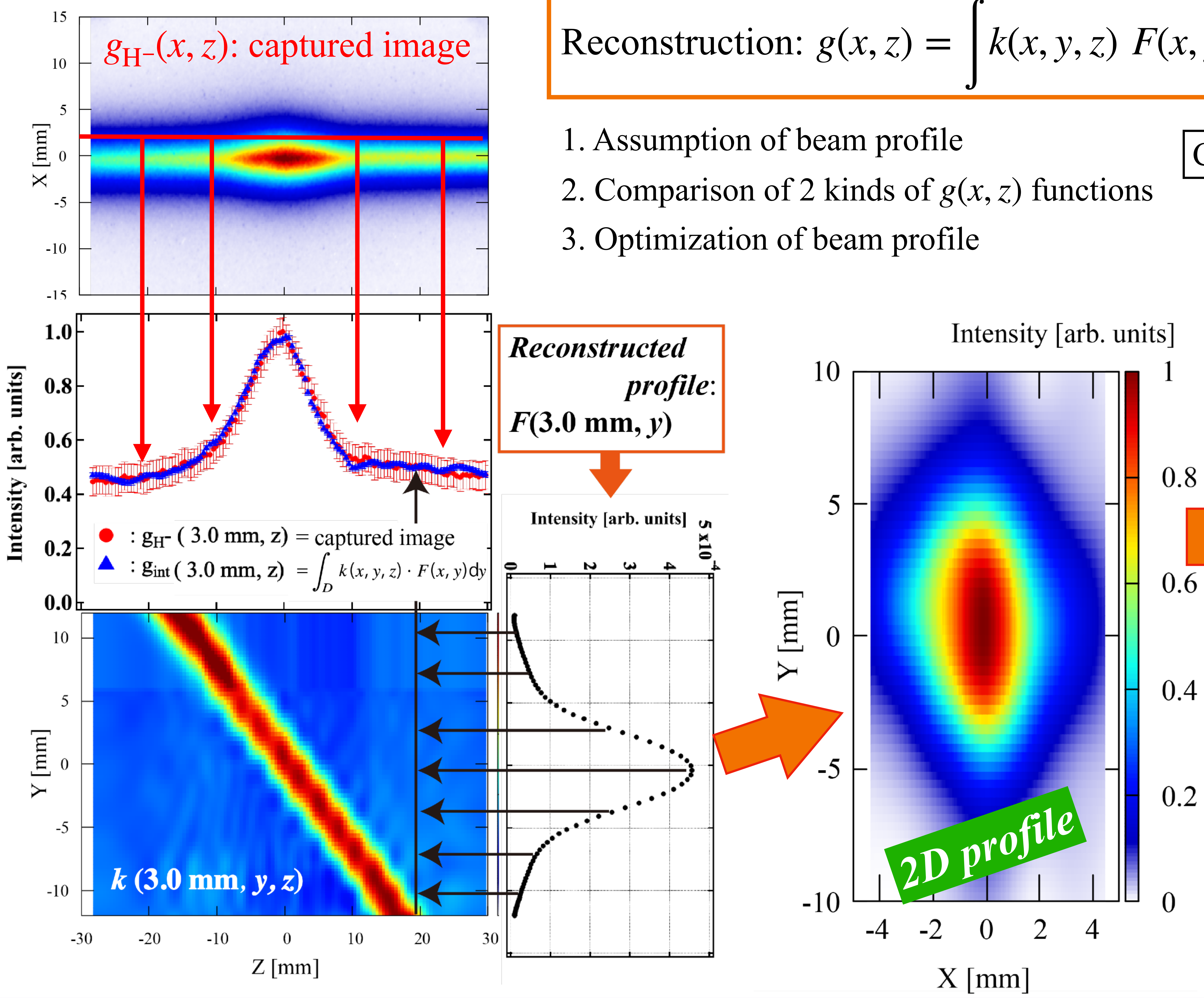


J-PARC MEBT test stand

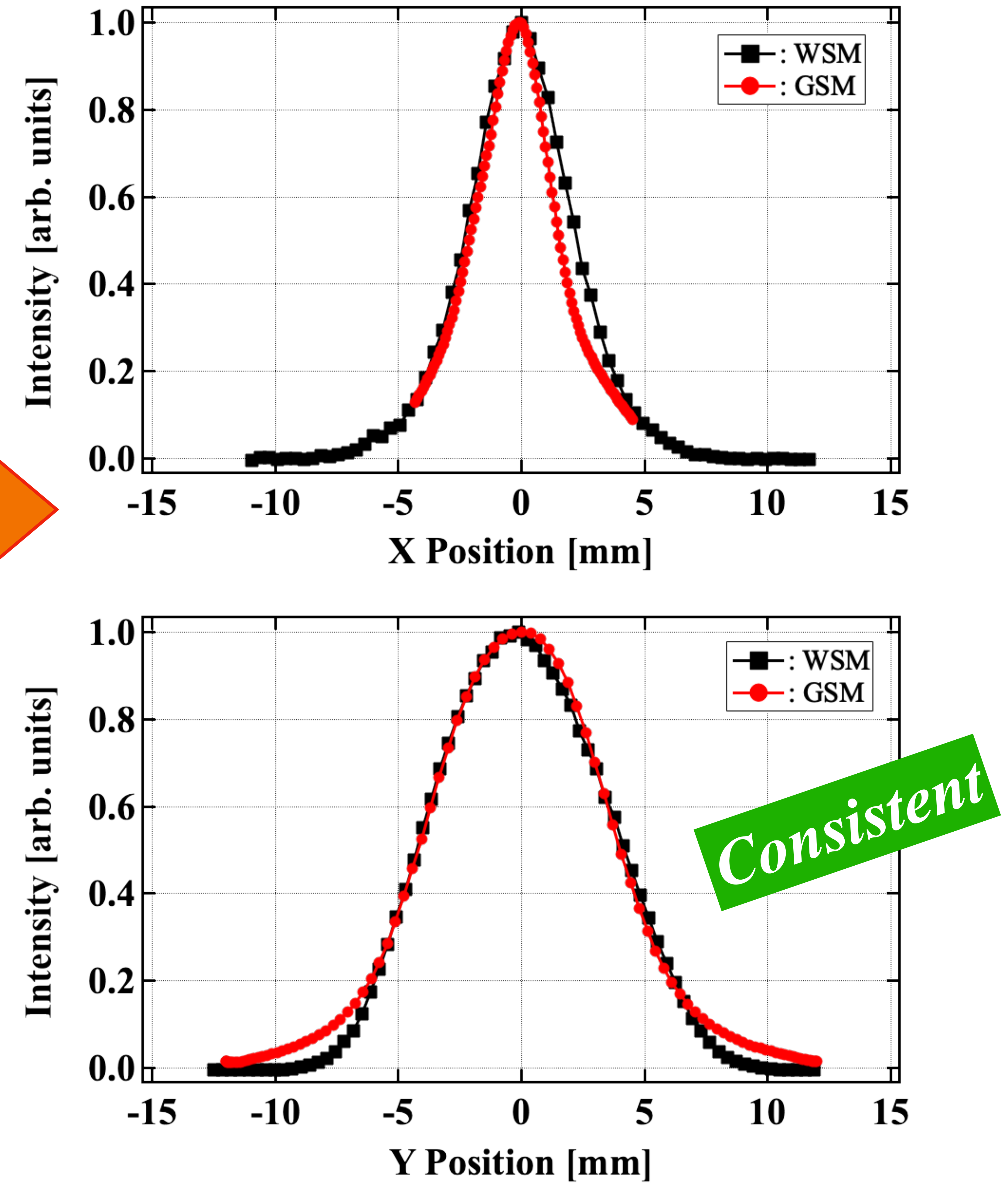
Summary 5: Reconstruction of Beam Profile

Reconstruction: $g(x,z) = \int k(x,y,z)\ F(x,y)\ \mathrm{d}y$

1. Assumption of beam profile
2. Comparison of 2 kinds of $g(x,z)$ functions
3. Optimization of beam profile

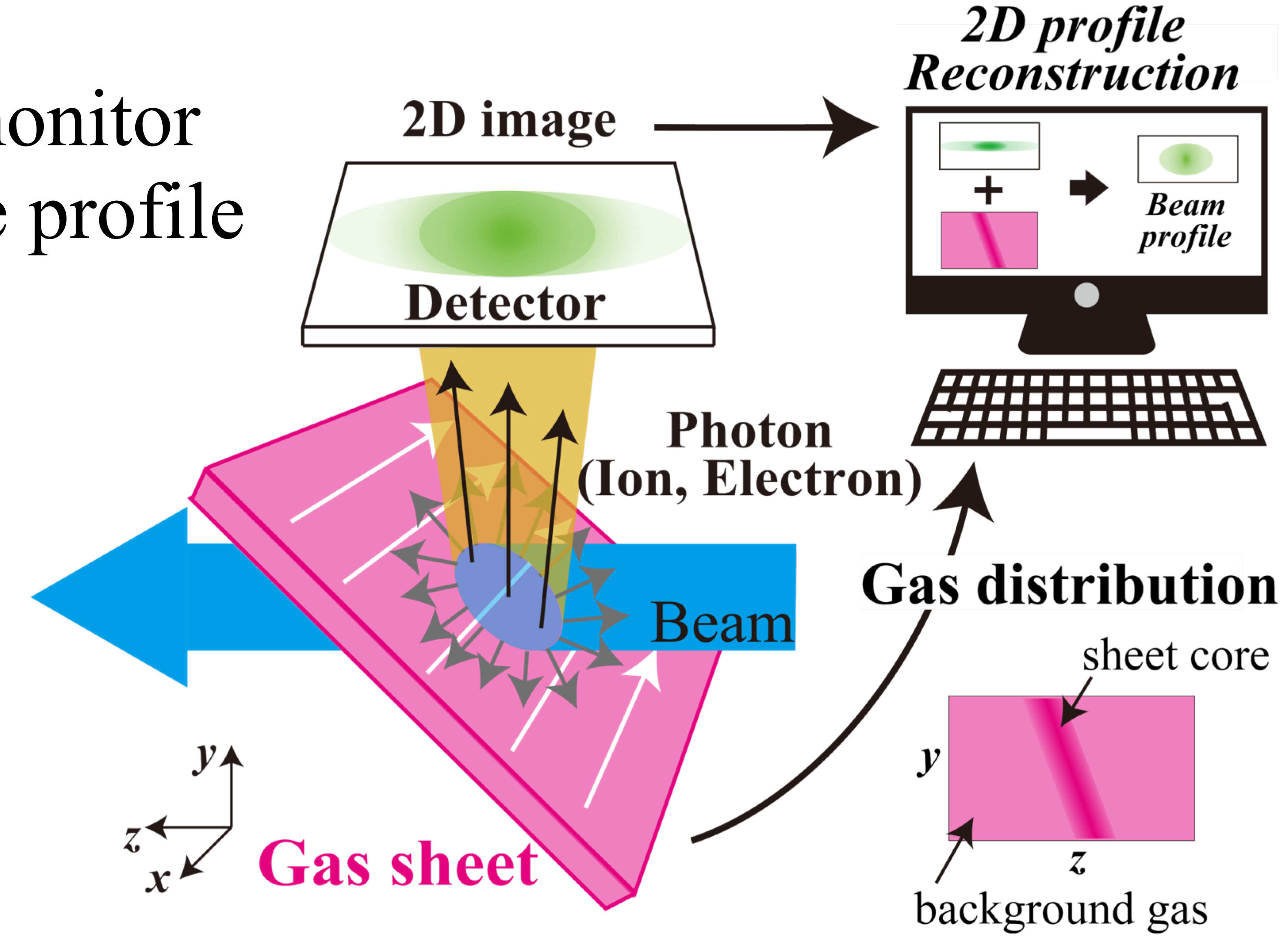


Comparison of projected profiles with Wire-Scanner Monitor



Measurement and Reconstruction of a Beam Profile Using a Gas Sheet Monitor by Beam-Induced Fluorescence Detection in J-PARC

Gas sheet monitor for transverse profile



Procedure of Beam Profile Measurement

① Formation of gas sheet

Gas sheet is formed based on Rarefied gas dynamics

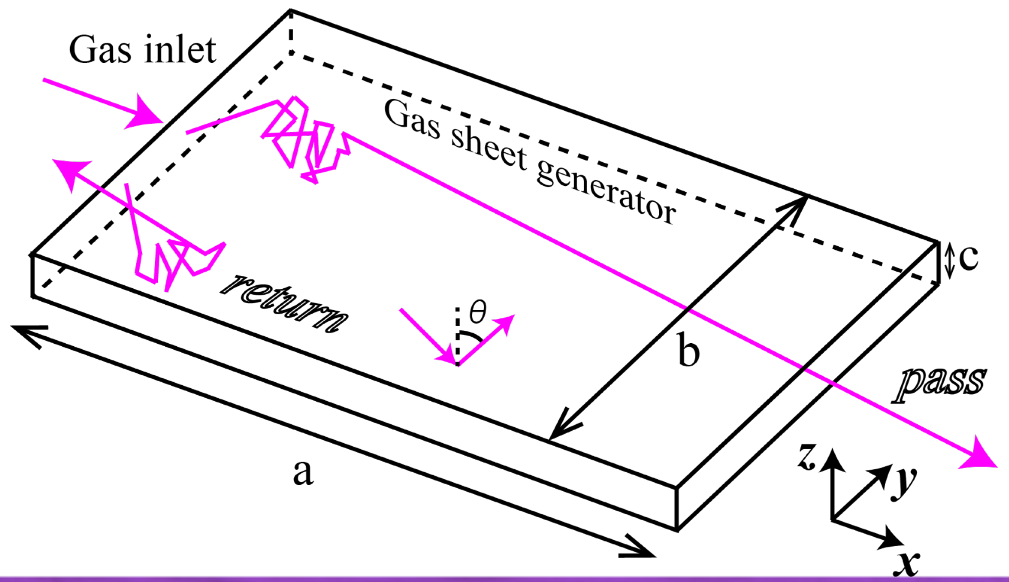
=> Negligible intermolecular collisions,

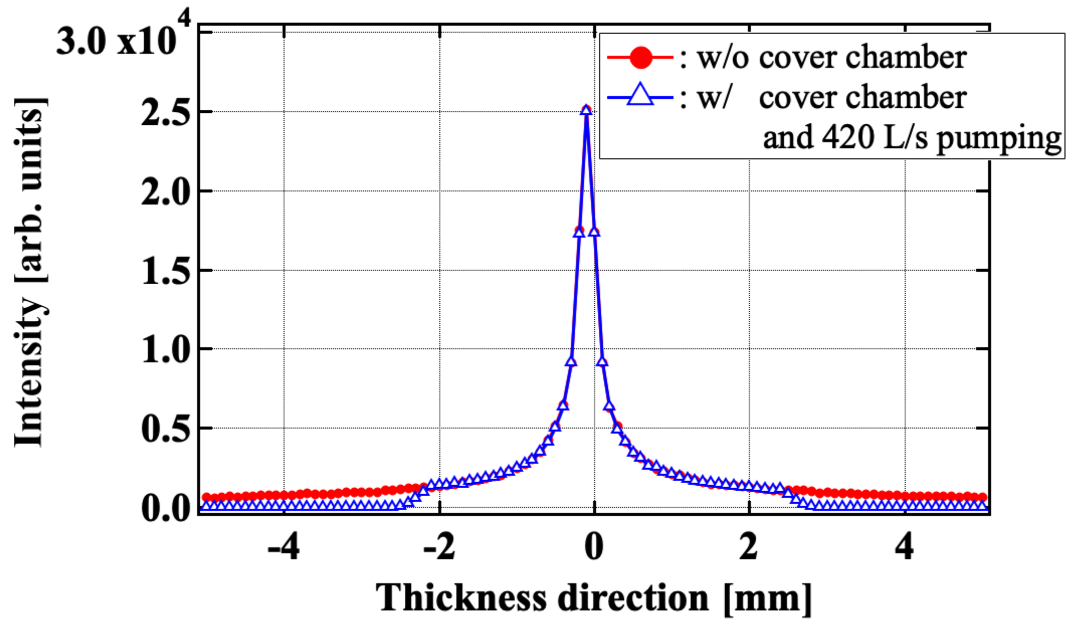
Reflection on wall based on *cosine law*

=> Sheet generator: Conduit of 100 mm × 50 mm × 0.1 mm

Gas flux distribution simulated by Molflow+ code

=> 1mm thickness sheet

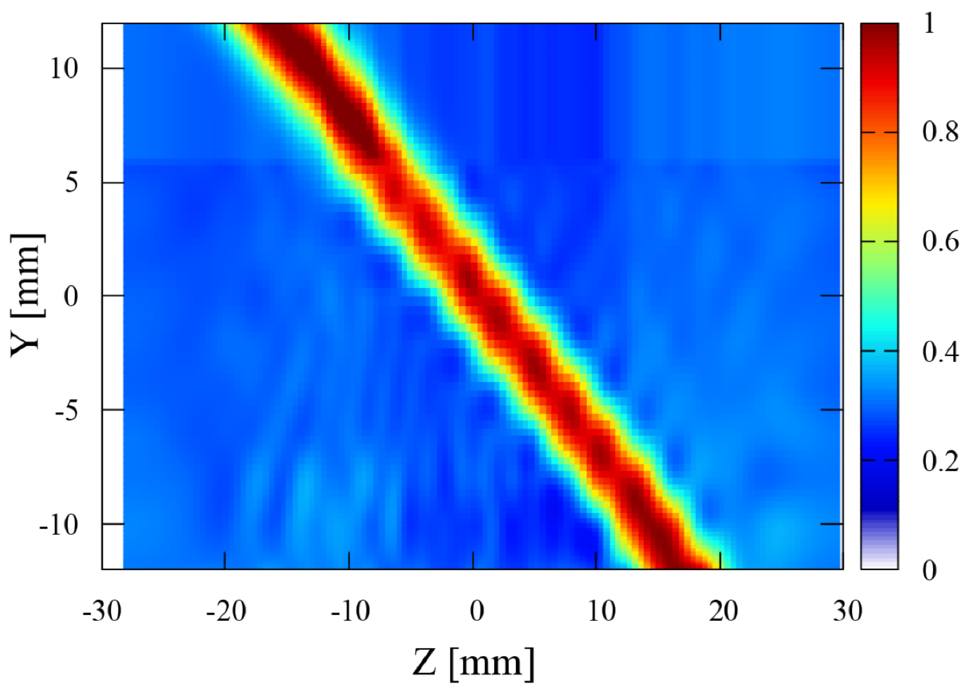




② Evaluation of sensitivity (gas) distribution $k(x, y, z)$

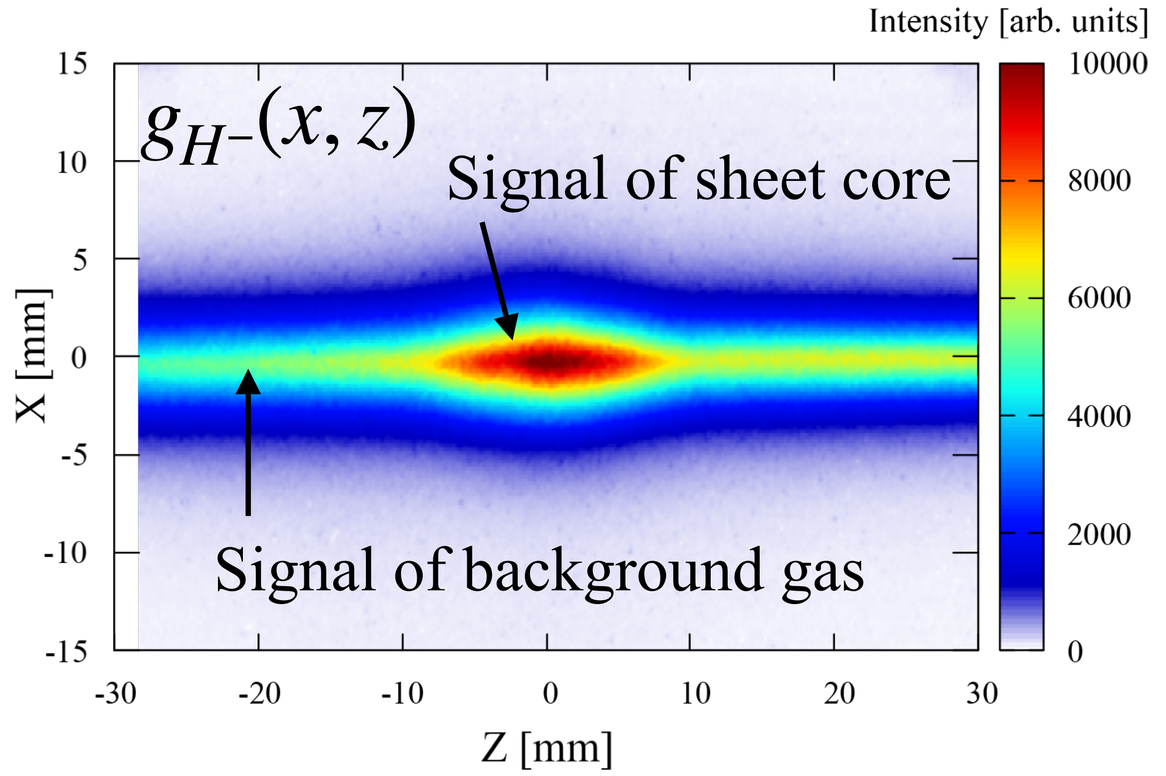
by injecting thin beam into the gas sheet monitor at off-line system

Sensitivity distribution $k(x_0, y, z)$



③ Measurement of J-PARC beam: $g(x, z)$

J-PARC 3 MeV, 60 mA H^- beam was detected with fluorescence



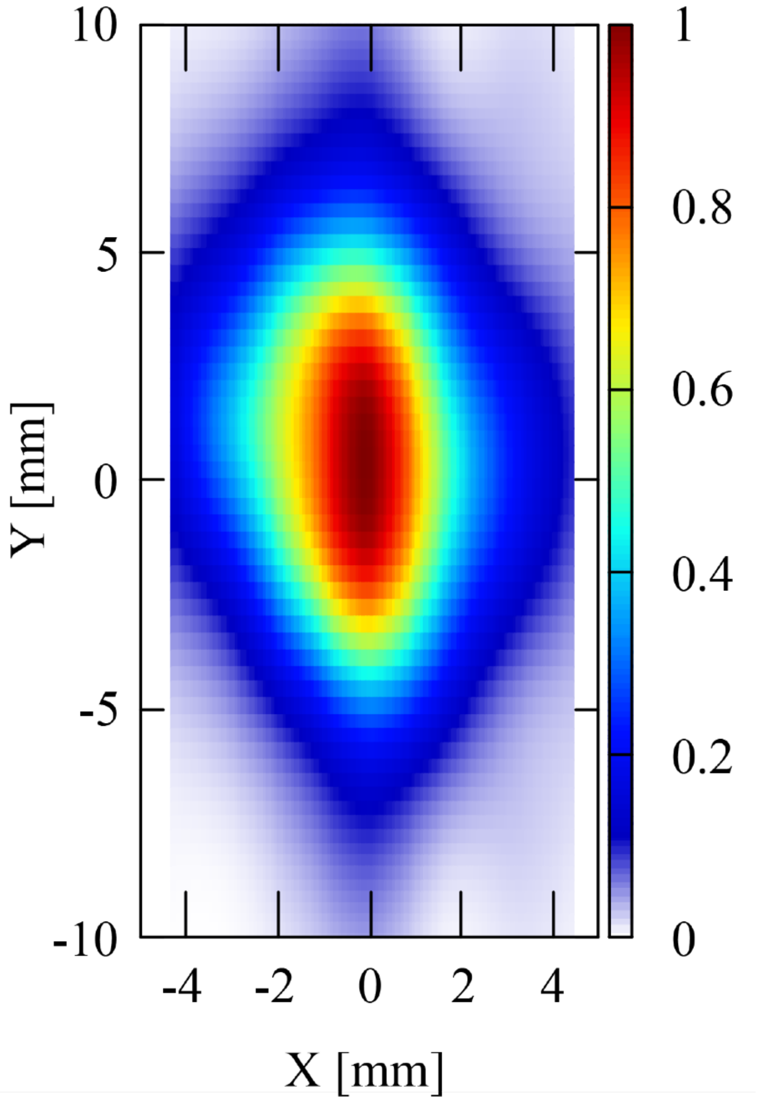
④ Reconstruction of 2D beam profile: $F(x, y)$

Luminous distribution of captured image $g(x, z)$ correlates with beam profile $F(x, y)$ through integral equation:

$$g(x, z) = \int k(x, y, z)\ F(x, y)\ \mathrm{d}y$$

Reconstructed profile corresponds to ordinary monitor's profile

Reconstructed 2D profile $F(x, y)$



I. Yamada, M. Wada, K. Moriya, J. Kamiya, M. Kinsho, 10th International Beam Instrumentation Conference, TUOA04