



Development of a new beamlet monitor system: time resolution and phase space structure

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1. Introduction

2. Diagnostics

- A new beamlet monitor system
- Pepper-pot-type Phase Space Analyzer (PPSA)
- Fast Beamlet Monitor (FBM)

3. Results

- FBM
- PPSA

4. Discussion

5. Summary

Negative ion source is inevitable in nuclear fusion

ITER neutral beam system requirements:

- 16.7 MW, 3600 s,

- 230 A/m²

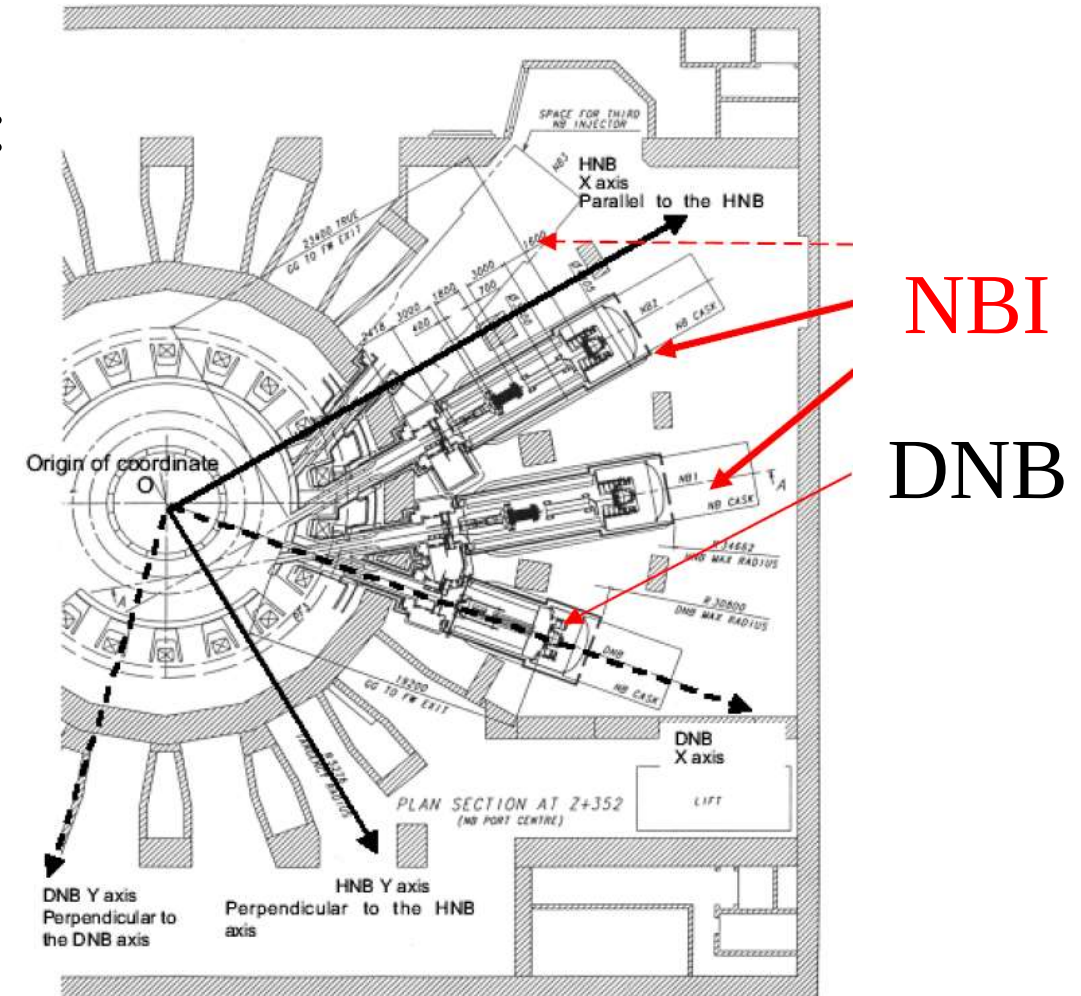
(achieved 330 A/m², P. Franzen 2011)

- 1 MeV

(achieved 0.98 MeV, M. Taniguchi 2012)

- < 7 mrad:

(experimentally unknown)

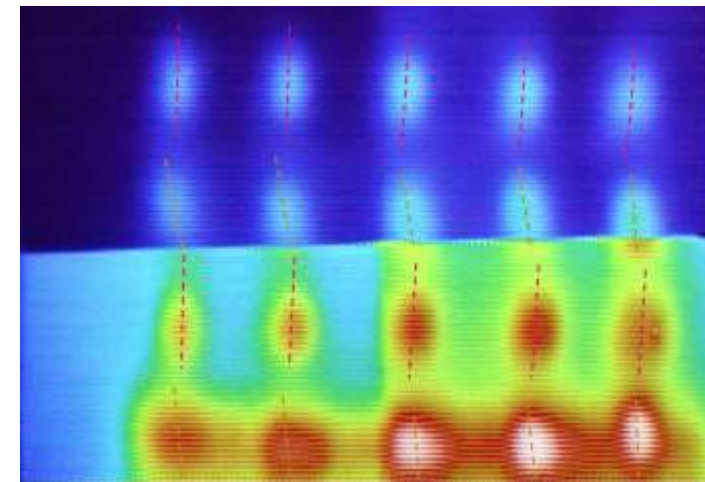
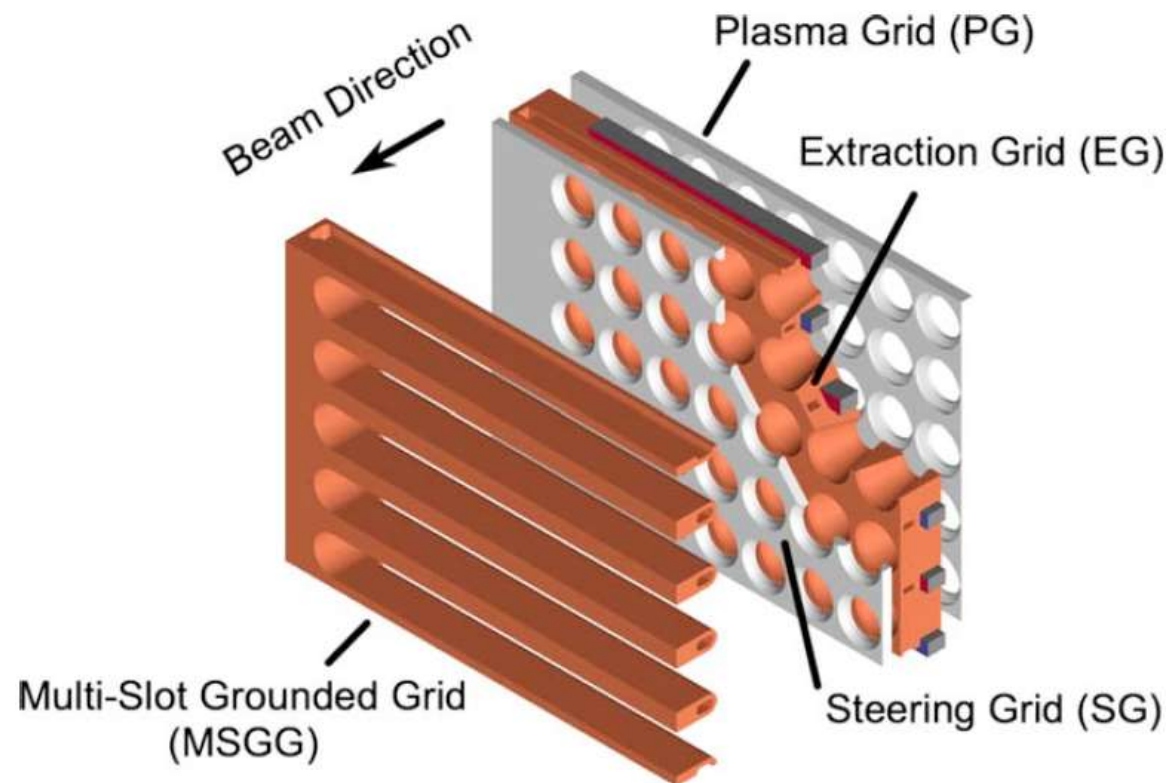


The optimization of beam optics is one of the most important subjects.

LHD negative-ion-based NBI typical parameters

(Filament-arc source)

$P = 6.4 \text{ MW}$, $V = 190 \text{ kV}$



- Image of negative ion beamlets obtained with IR camera

divergence: $\theta_h = 4.1 \text{ mrad}$, $\theta_v = 6.1 \text{ mrad}$

(Filament-arc source)

(K. Tsumori 2010)

Divergence for RF sources $\rightarrow ?$

We should study beam characteristics in more detail.

We propose here that

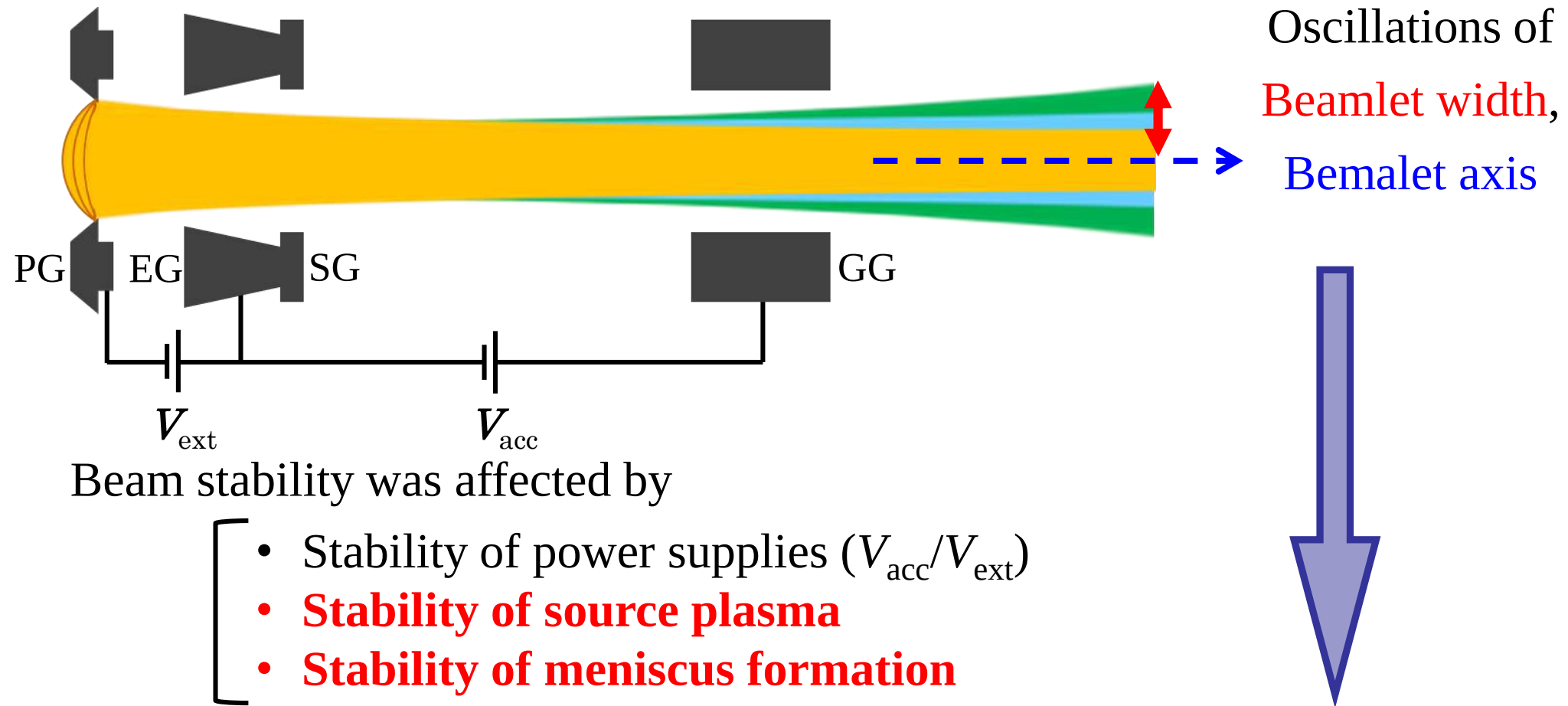
(1) the beamlet stability

(2) the phase space structure of negative ion beamlet
should be measured in more detail.

(1) Beam stability

Why should the beamlet stability be studied ?

Because the beamlet stability may degrade the beam optics.



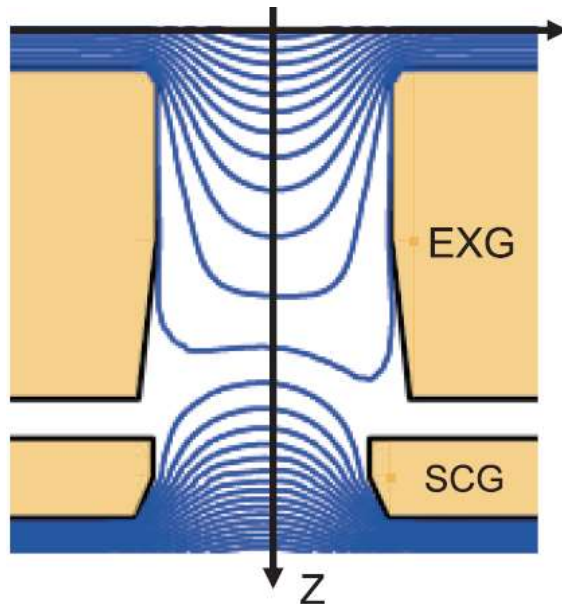
We focus on the time evolution of the “**beamlet width**” and “**beamlet axis**”.

(2) Phase space structure

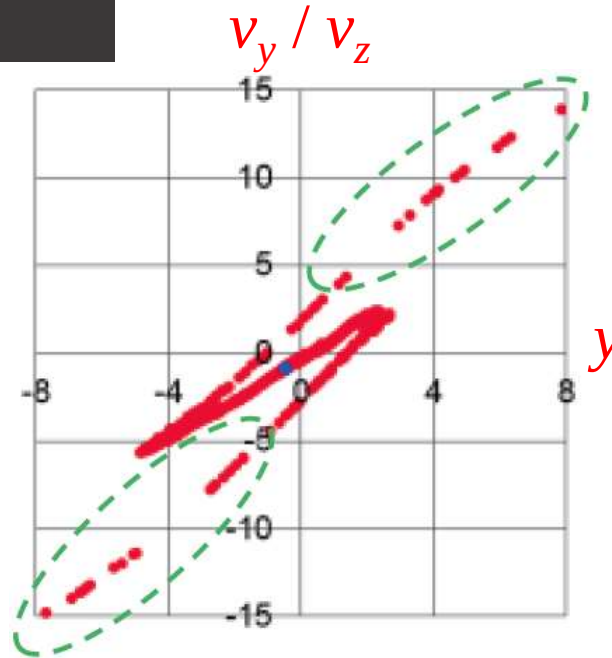
Why should the phase structure be studied ?

- Because, the phase space has much information on beam optics

Numerical study



Equipotential lines
in the extractor



Phase space structure
at the acceleration grid
(J. Hiratsuka 2015)

Experimental study

- Evaluation of beam emittance
 - 0.59 mm mrad (S. K. Guharay 1996)
 - 0.54 mm mrad (B. Klump 2014)
 - 0.82 mm mrad (Ueno, Shinto 2018)
- **Phase space structure** is not discussed in detail.

We should evaluate the phase space structure of negative ion beamlet in experiment.

Purpose of a new beamlet monitor system

- (1) Measurement of the **time evolution of the beamlet width and beamlet axis**
- (2) Measurement of the **phase space structure** of negative ion beamlet

➤ We aim to understand the beam optics in more detail. In particular, we want to elucidate the difference of the beam optical properties **between rf source and filament arc source**.

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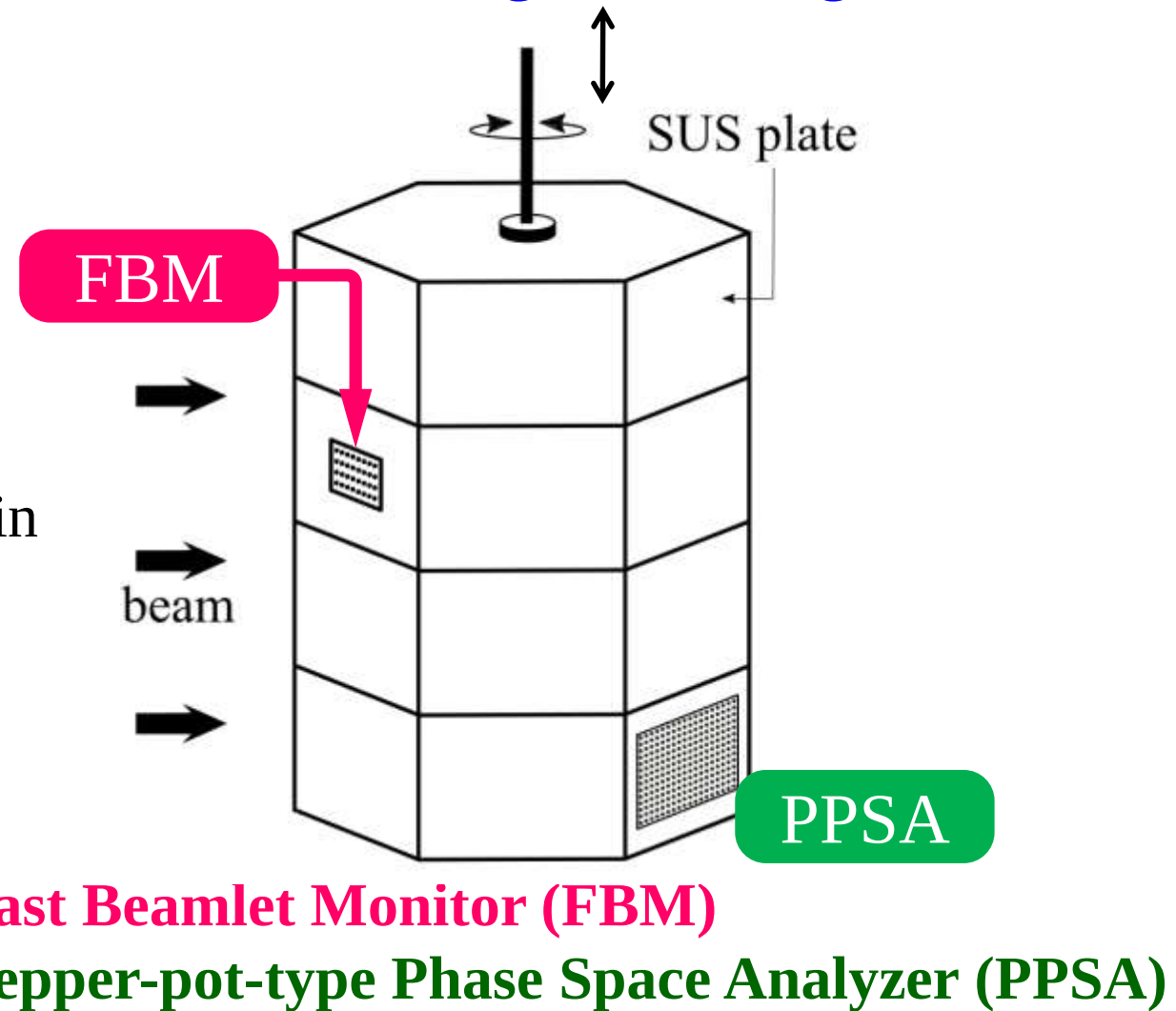
5. Summary

A new beamlet monitor system

A new beamlet monitor system is a hexagonal box mounting multi-diagnostics.



- Multi-diagnostics
- Rotatable
- Vertically moved in vacuum chamber



The diagnostics can be switched for shots interval by rotating or vertical motion.

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Pepper-pot-type Phase Space Analyzer

PPSA

: Diagnostic for measuring the phase space structure of a beamlet

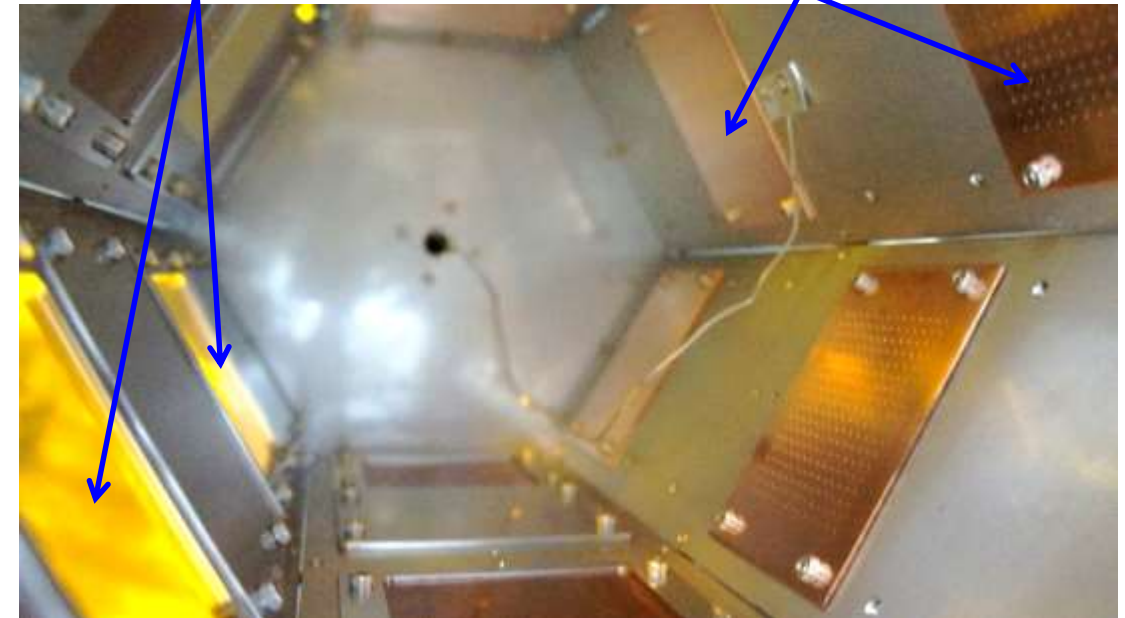
pinhole array kapton foil



- PPSA consists of a pinhole array and kapton foil.

kapton foil

pinhole array

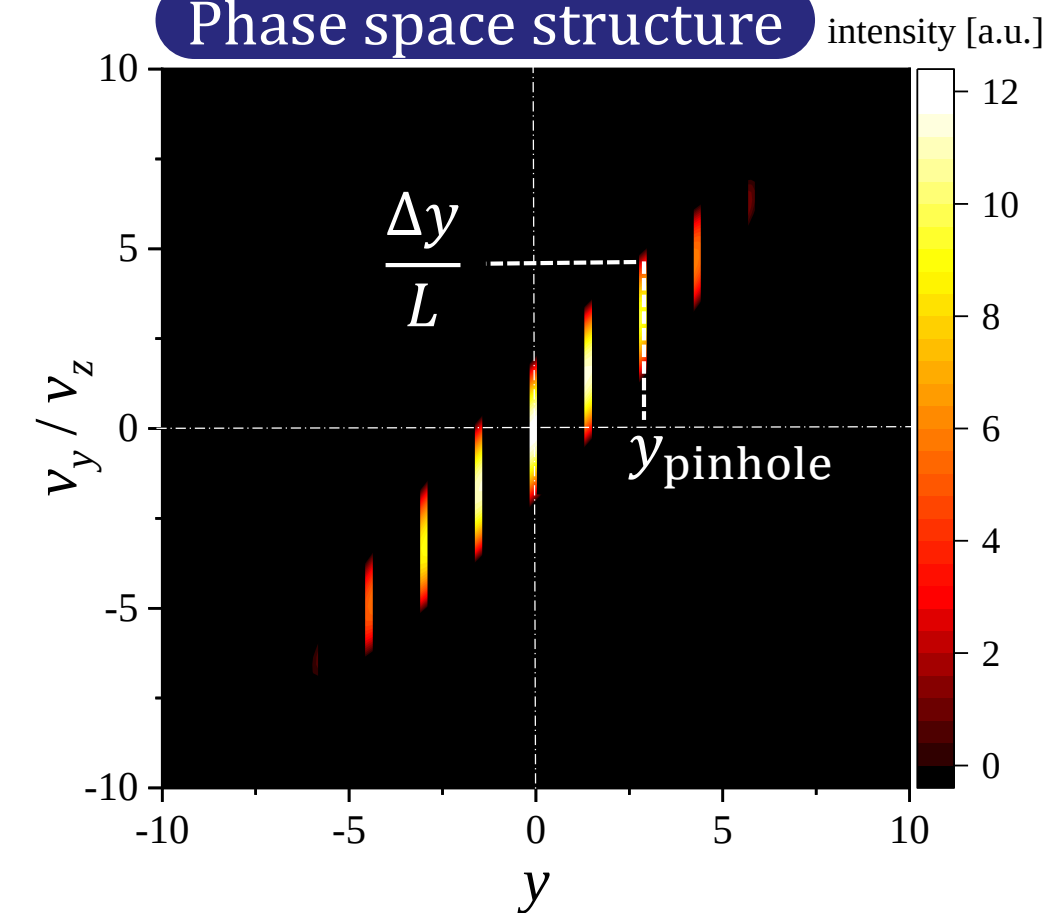


- Several sets of PPSAs were mounted on the hexagonal box.

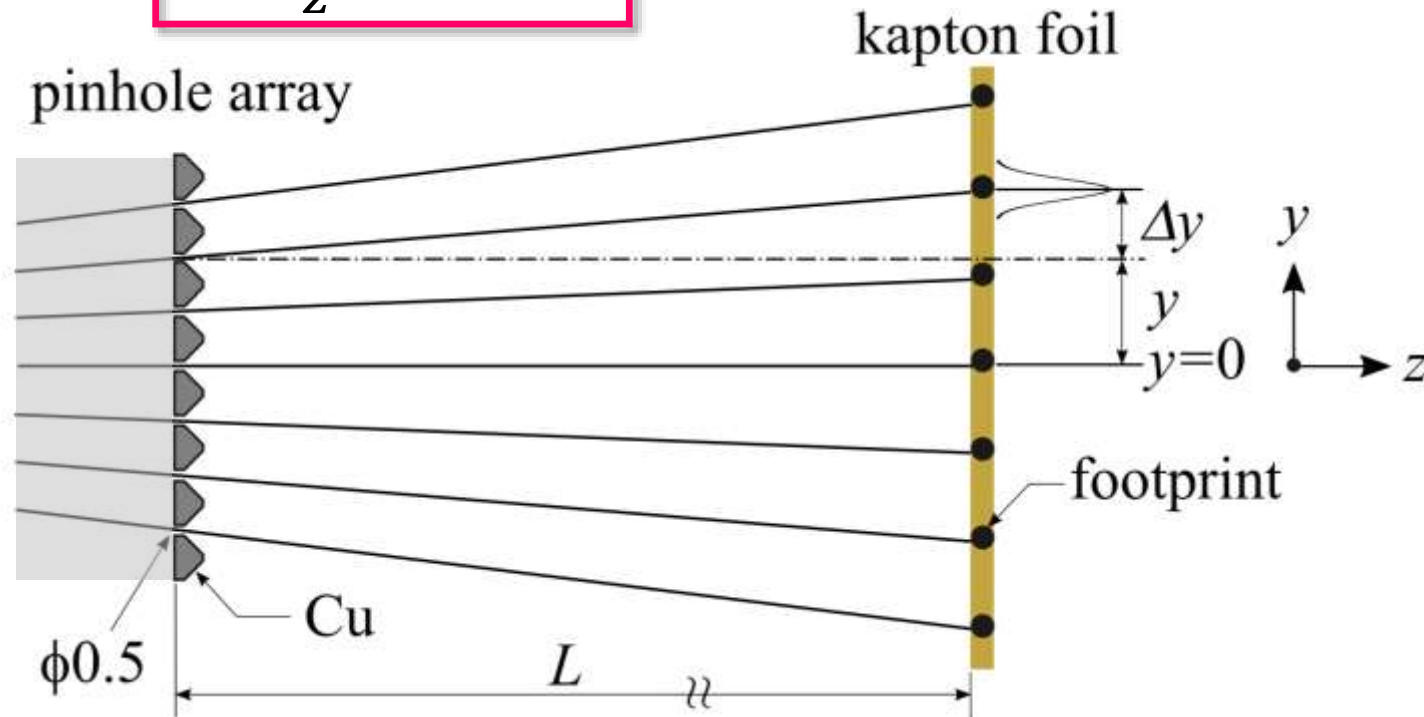
Concept of measurement using PPSA

PPSA

Phase space structure



$$\frac{v_y}{v_z} = \frac{\Delta y}{L}$$



- Many partial beamlets passing through each pinhole reach the surface of the kapton foil, and make burn pattern.
- The deviation of footprint from the pinhole position, Δy , corresponds to the vertical velocity at the pinhole position.

- The horizontal and vertical axes show the measuring point y and normalized velocity v_y/v_z , respectively.
- We obtain the distribution function: $f(y, v_y)$.

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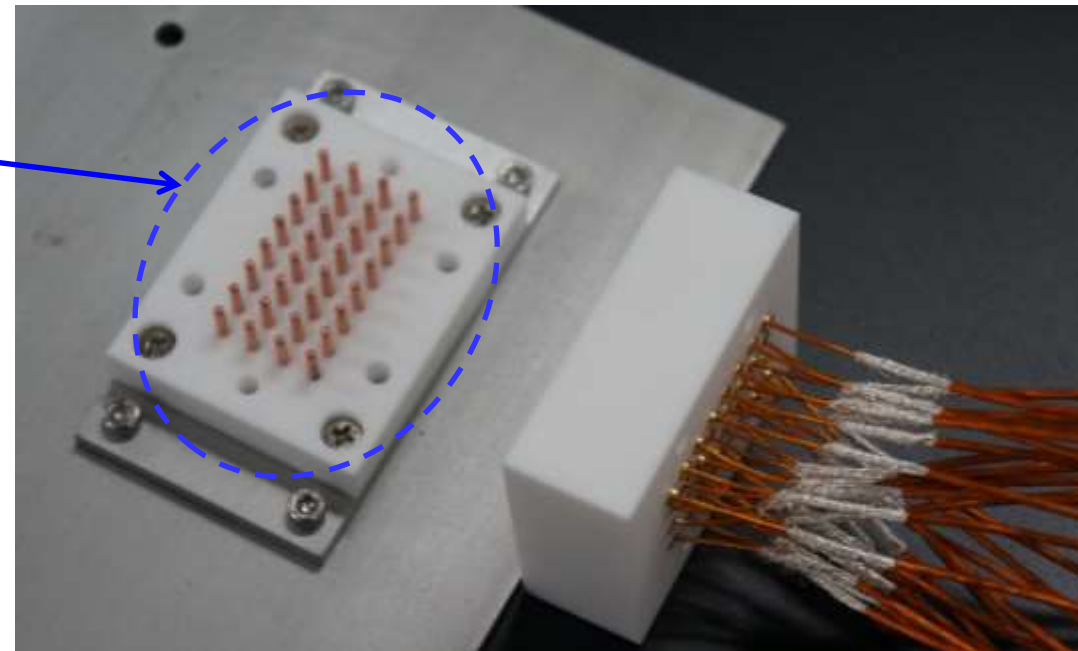
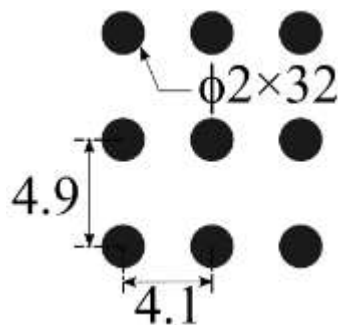
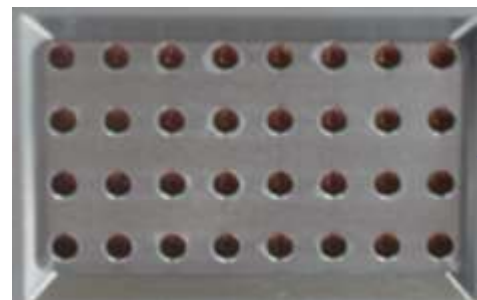
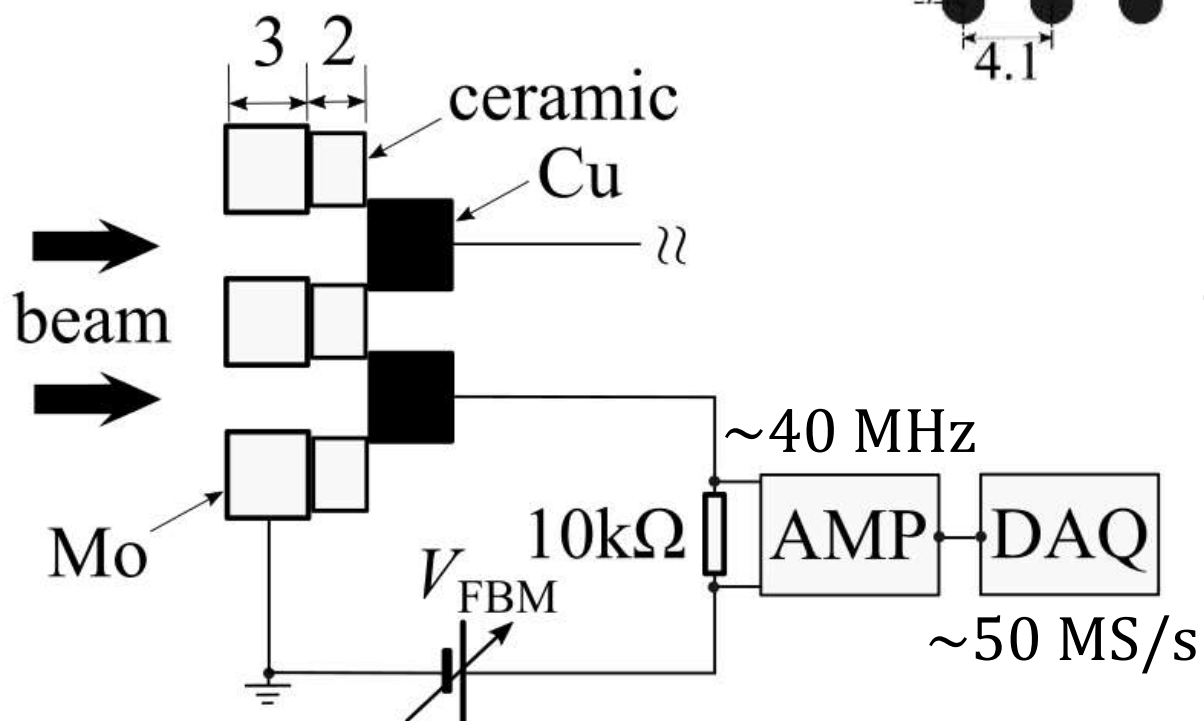
- A new beamlet monitor system
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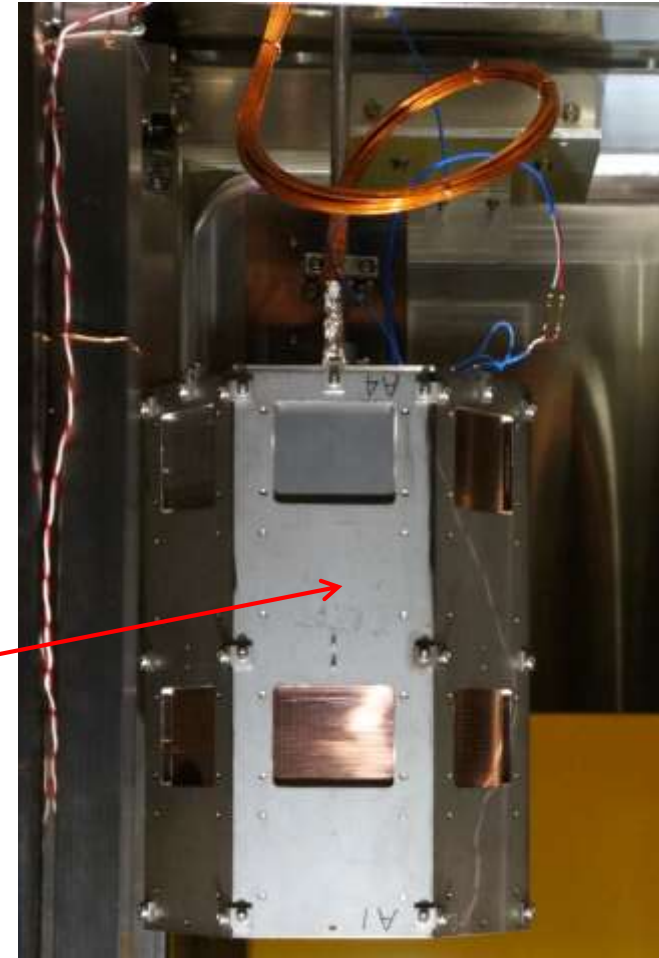
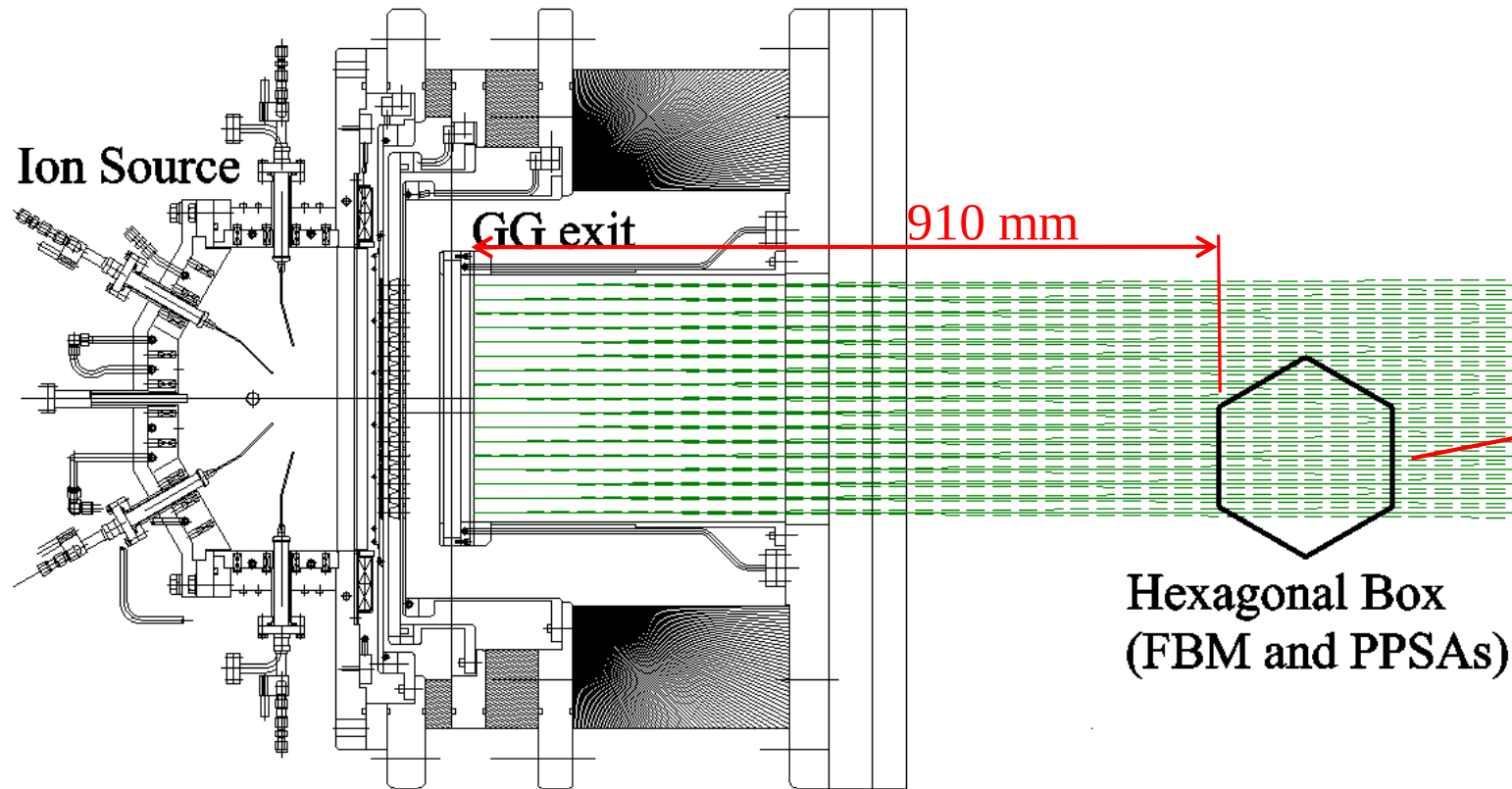
FBM**Fast Beamlet Monitor:****Faraday-cup-type 32-channel
electrode array for beam
current profile monitor**

- Two-grid system to suppress secondary electrons
- Wide frequency range of DC~40 MHz
- The spatial resolutions are 4.1mm and 4.9 mm

Experimental configuration

The measurement of negative ion beamlet was carried out

- Neutral beam test stand at NIFS (NIFS-NBTS)
- **Filament arc source**: R&D negative ion source (NIFS-RNIS)



- The beam accelerator is identical to those of the working beam injector in LHD plasma experiment.

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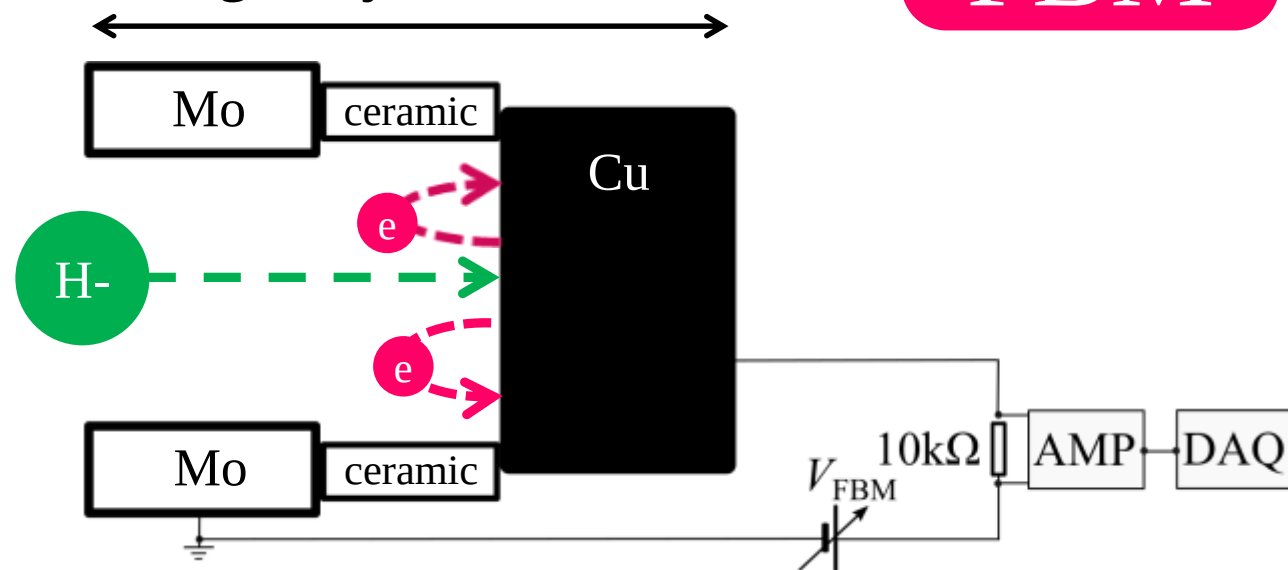
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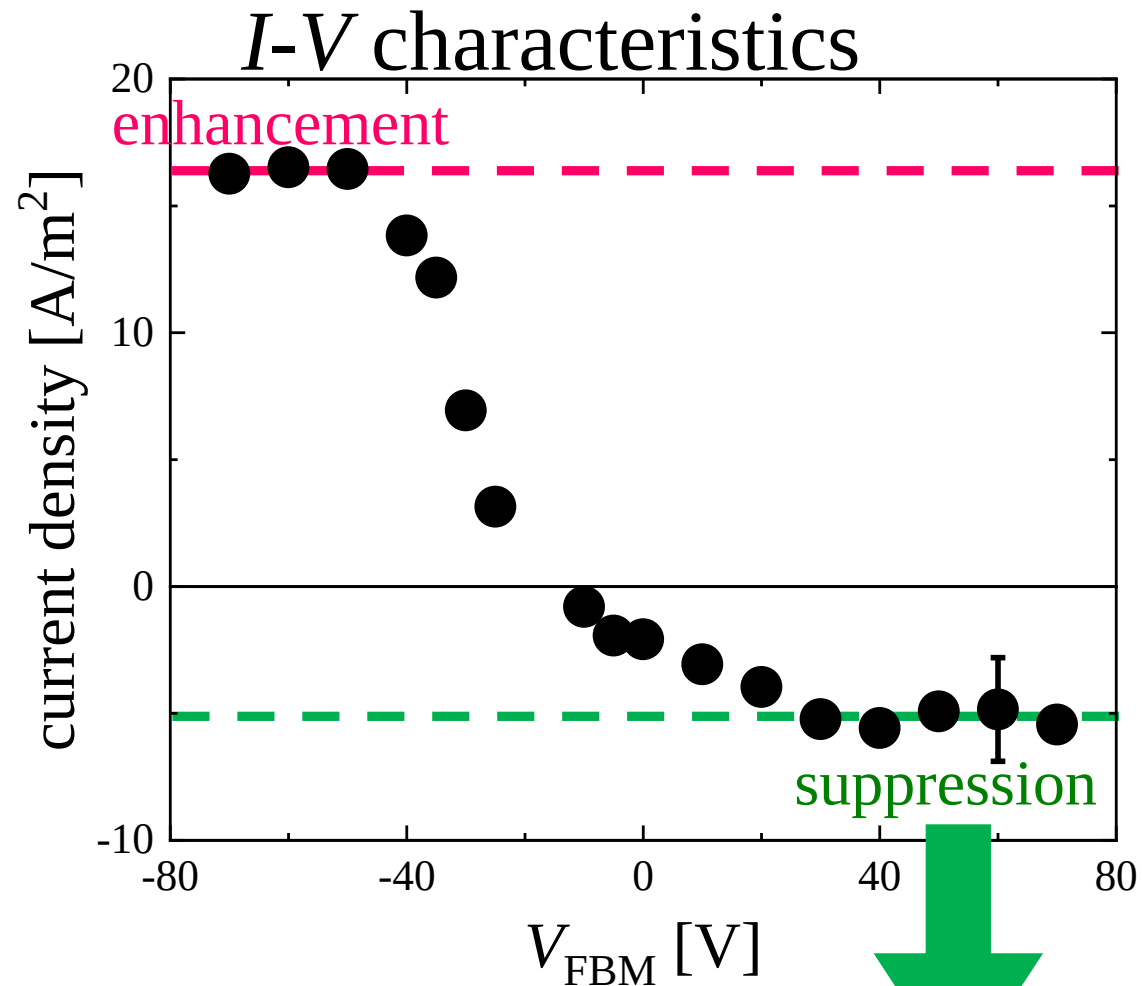
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Two-grid system of FBM

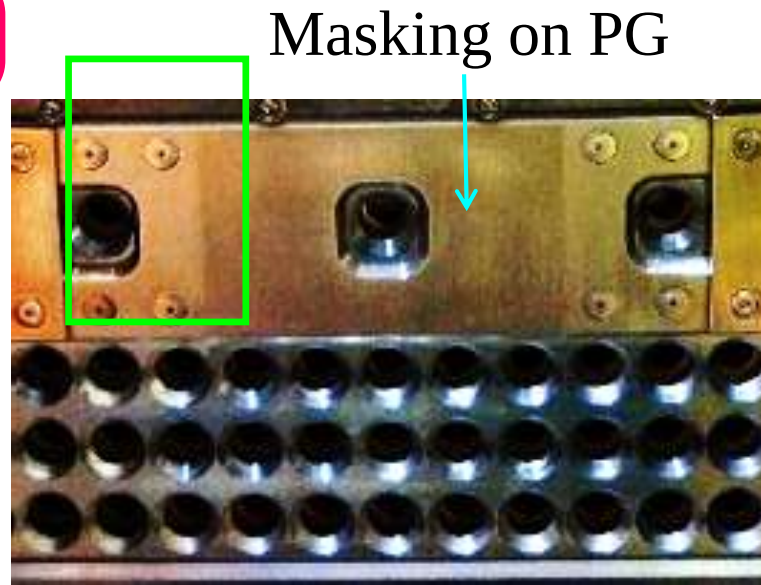
FBM



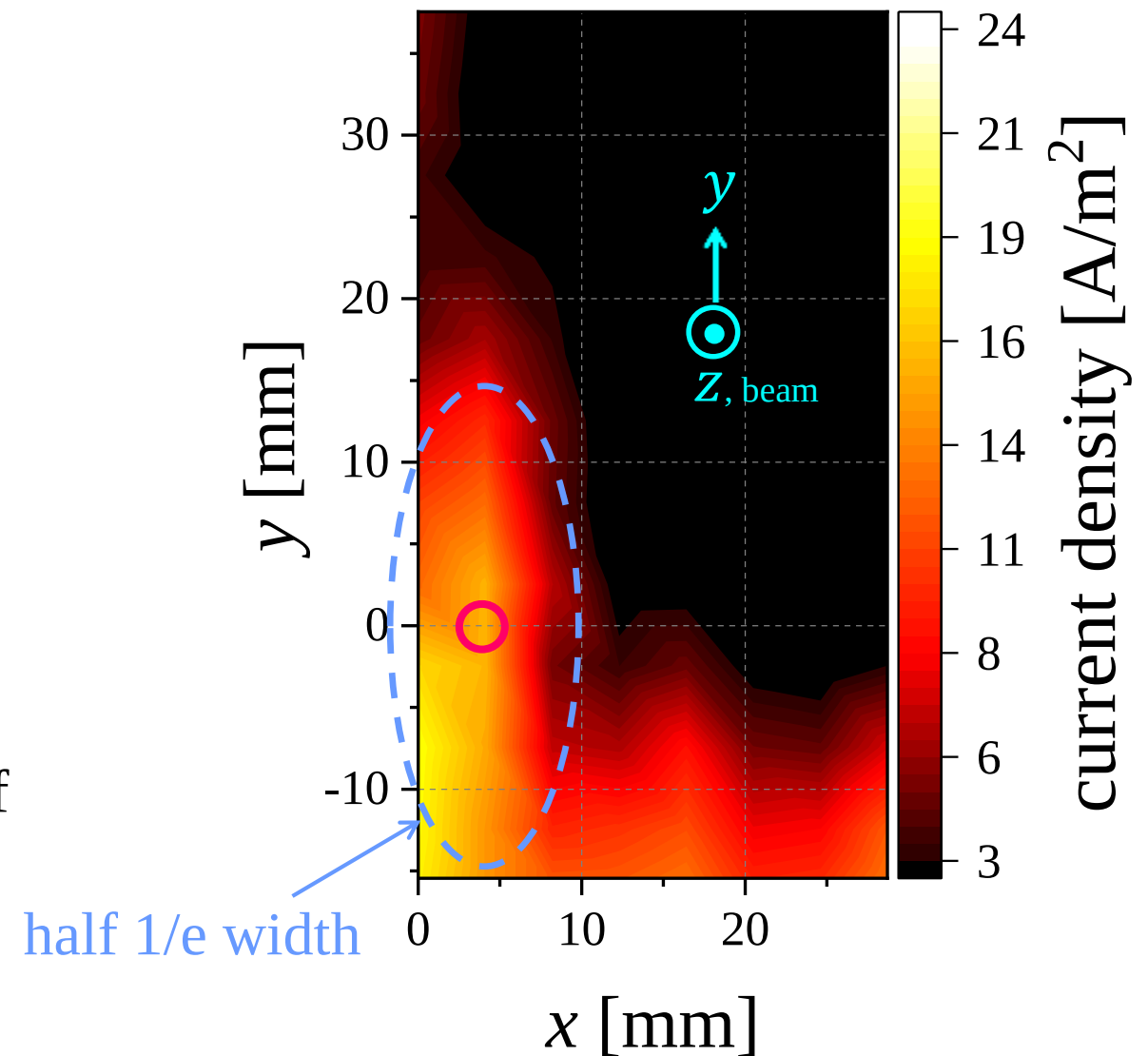
- V_{FBM} : Collection voltage for secondary electrons
- The saturation of negative ion current was observed when the suppression voltage is positively higher than 40V.



The absolute value of the negative ion current was obtained.

FBM

- Observation was carried out on shot by shot basis.
- Isolated beamlet due to masking of the neighboring apertures on PG

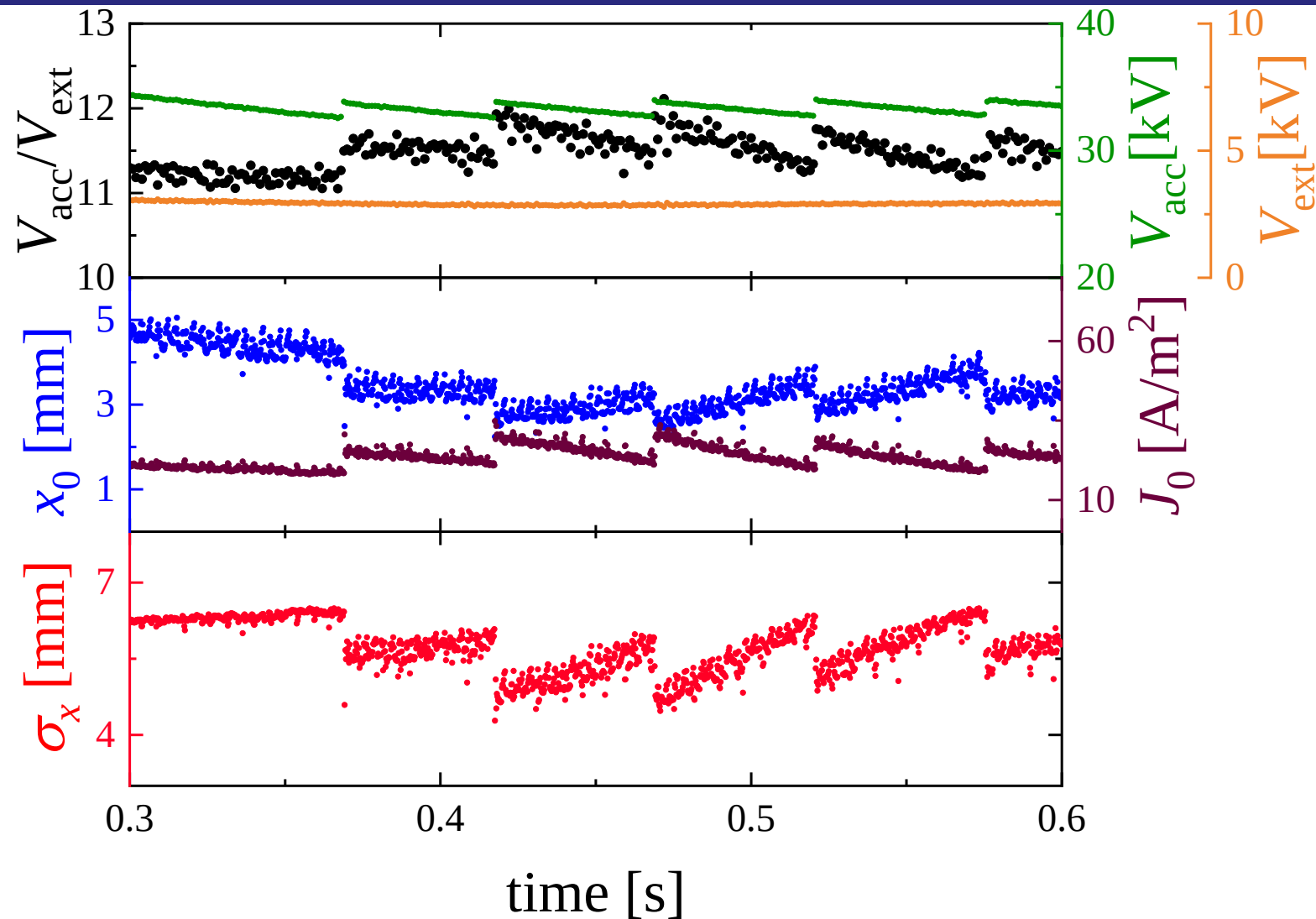


Two-dimensional beam profile was obtained by FBM.

FBM

- V_{acc} : acceleration voltage
- V_{ext} : extraction voltage
- J : current density written by

$$J = J_0 \exp \left[- \left(\frac{x - x_0}{\sigma_x} \right)^2 \right] + C$$
- x_0 : beamlet axis
- σ_x : beamlet width (half 1/e)
- J_0 : current amplitude
- C : background level



The **beamlet width** and **beamlet axis** are strongly depended on $V_{\text{acc}}/V_{\text{ext}}$.

FBM has the ability to observe the time evolution of the beamlet width and beamlet axis.

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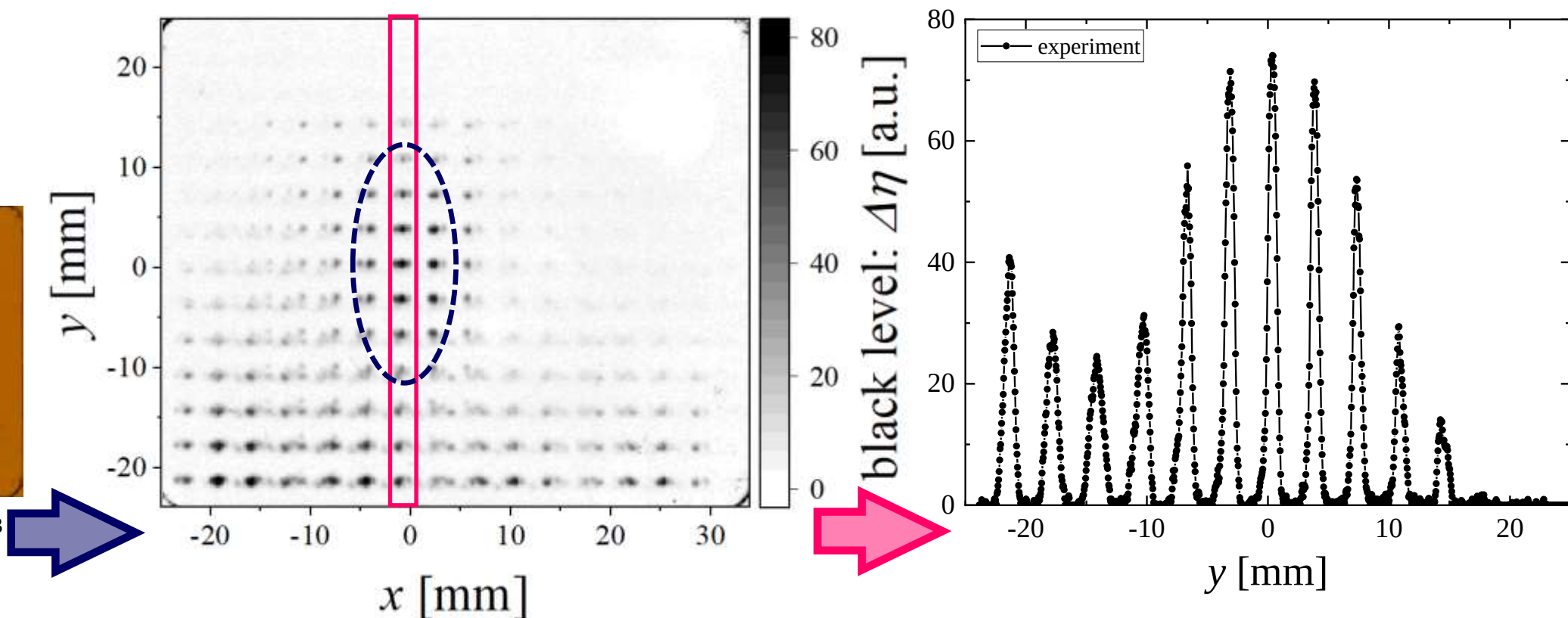
PPSA

Beam burn pattern
on the kapton foil



$$n_{H^-} = 2.78 \pm 0.15 \times 10^{17} \text{ m}^{-3}$$

$$P_{\text{arc}} = 54.2 \pm 4.5 \text{ kW}$$



- The burn pattern was digitized by a scanner with a gray scale depth of 8 bit and spatial resolution of 0.042 mm/pixel.
- In this analysis, it is assumed that the increase of **black level** ($\Delta\eta$) of the kapton foil is proportional to the time integral of the beam current density.

$$\Delta\eta \propto \int J dt$$

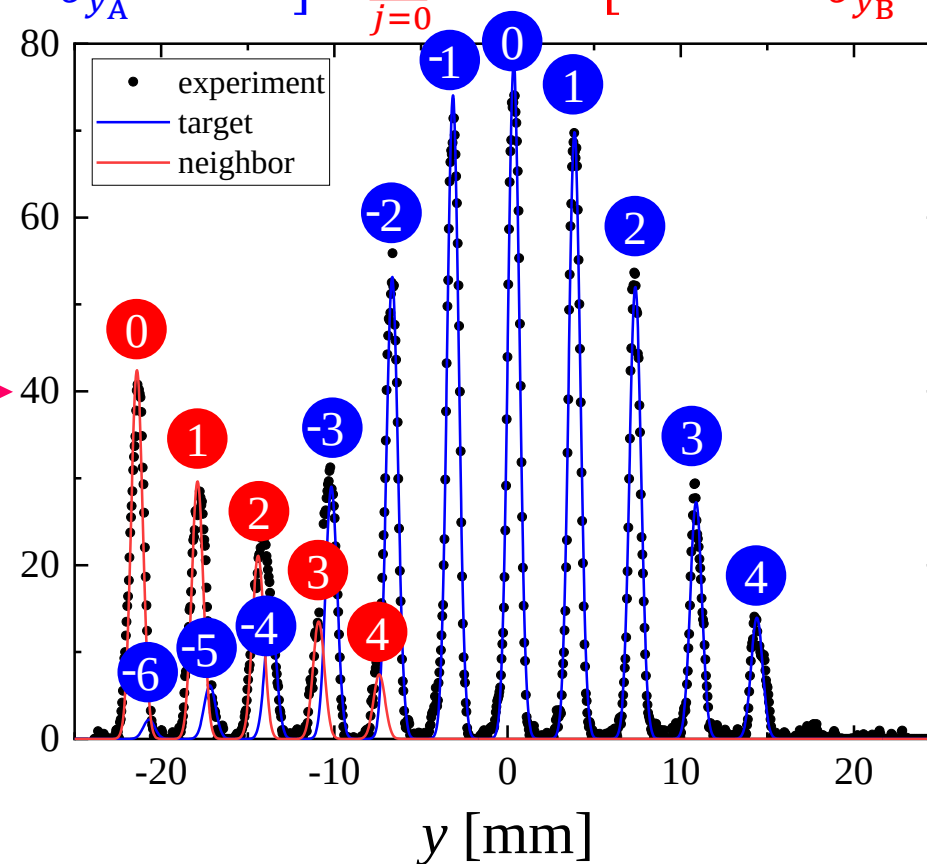
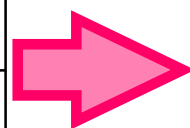
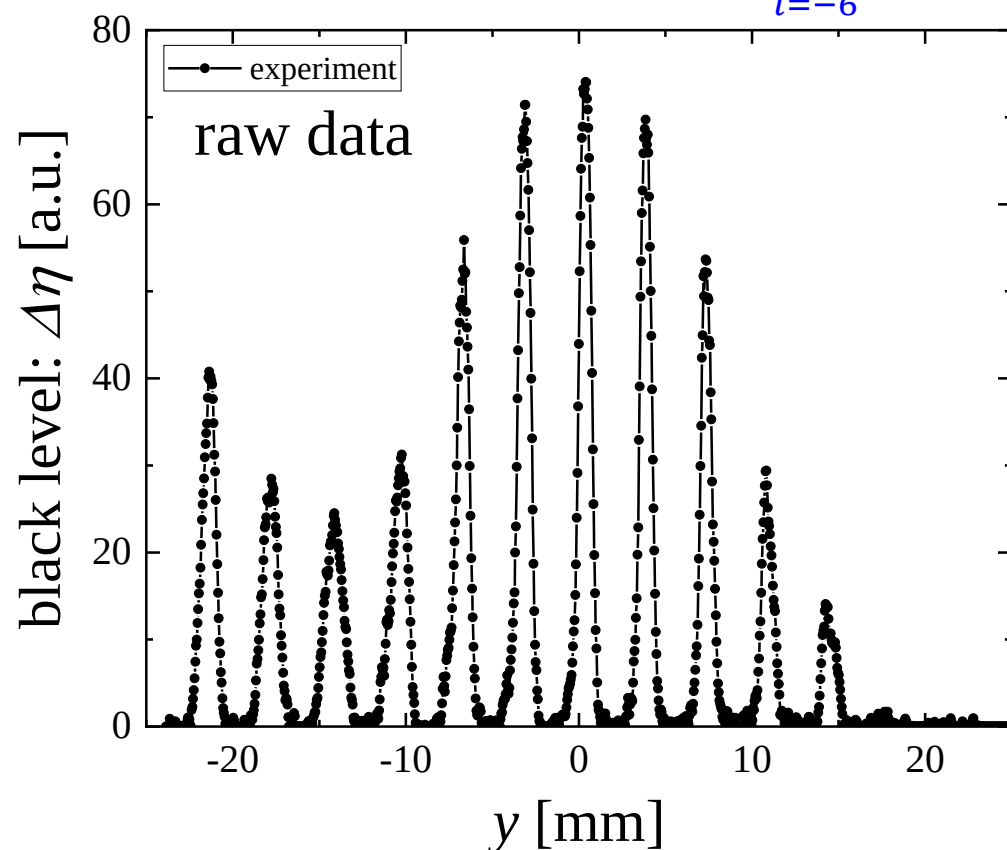
Procedure to distinguish two beamlets

PPSA

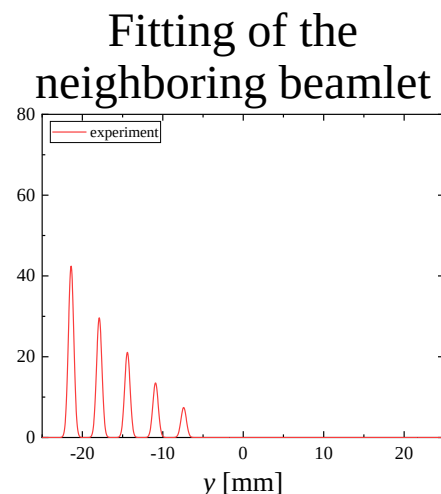
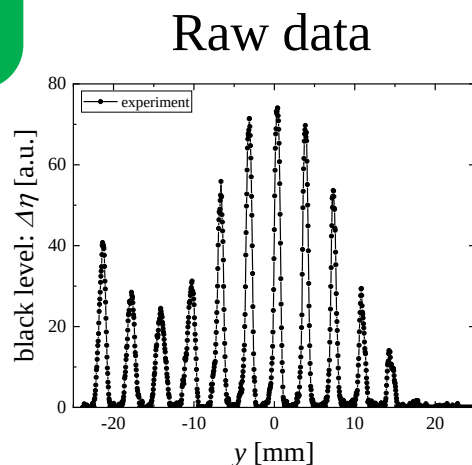
In order to distinguish the target beamlet (**A**) from the neighboring one (**B**), we put two conditions as follows:

1. The footprint width (σ) is constant for the same beamlet.
2. The interval of footprints (δy) is constant for the same beamlet.

Model eq.
$$\Delta\eta = \sum_{i=-6}^4 \alpha_{Ai} \exp \left[-\frac{(y_A - y_{A0} - i\delta y_A)^2}{\sigma_{y_A}^2} \right] + \sum_{j=0}^4 \alpha_{Bj} \exp \left[-\frac{(y_B - y_{B0} - j\delta y_B)^2}{\sigma_{y_B}^2} \right]$$

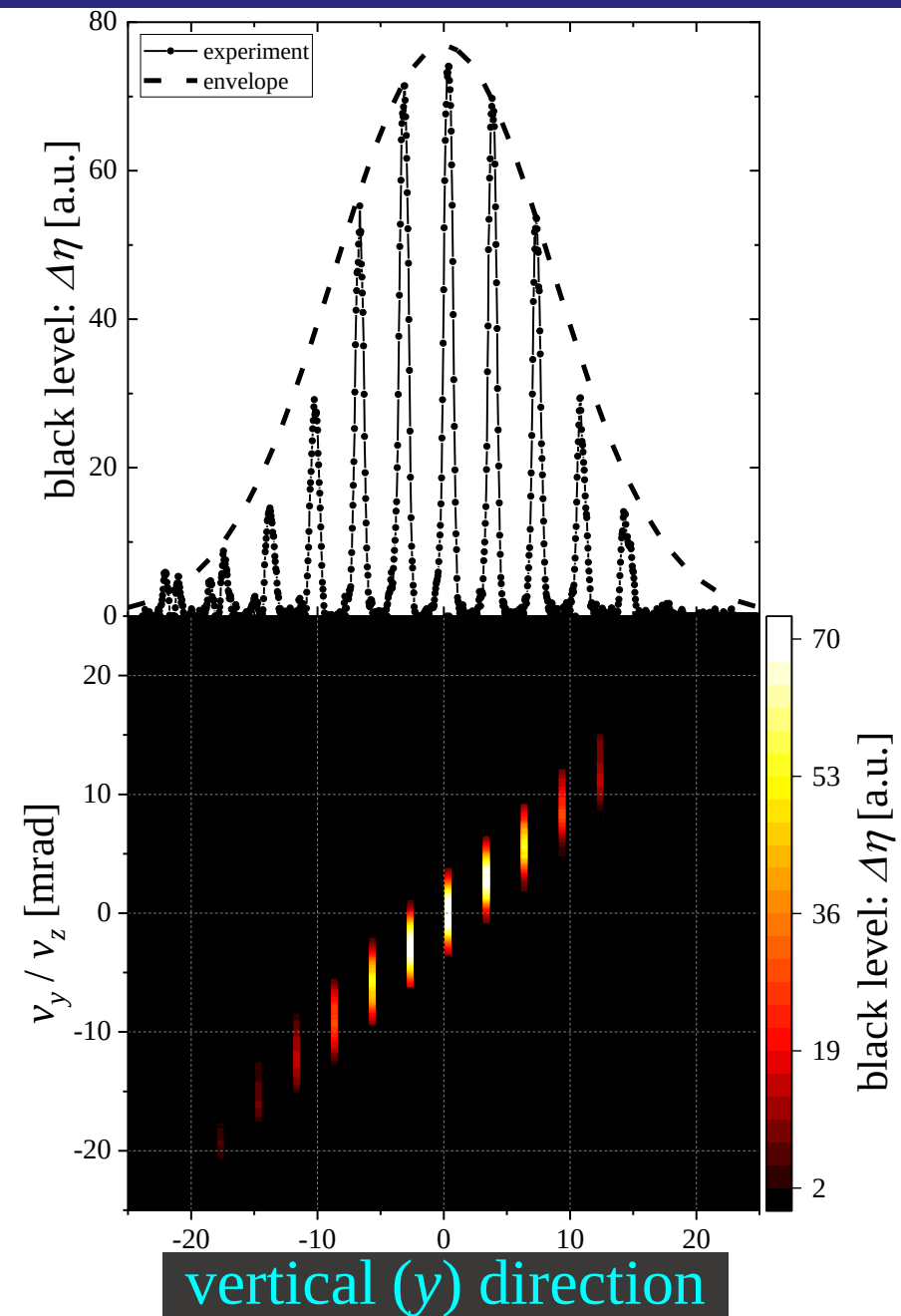


PPSA



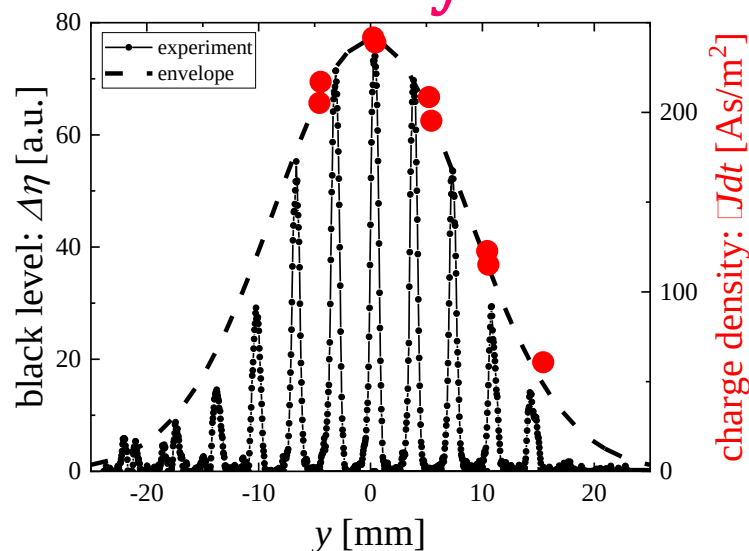
- The negative ion beamlet profile in the vertical direction was obtained.
- The envelope of the target beamlet profile shows a good agreement with Gaussian distribution.

The phase space structure of the negative ion beamlet can be successfully measured by PPSA.

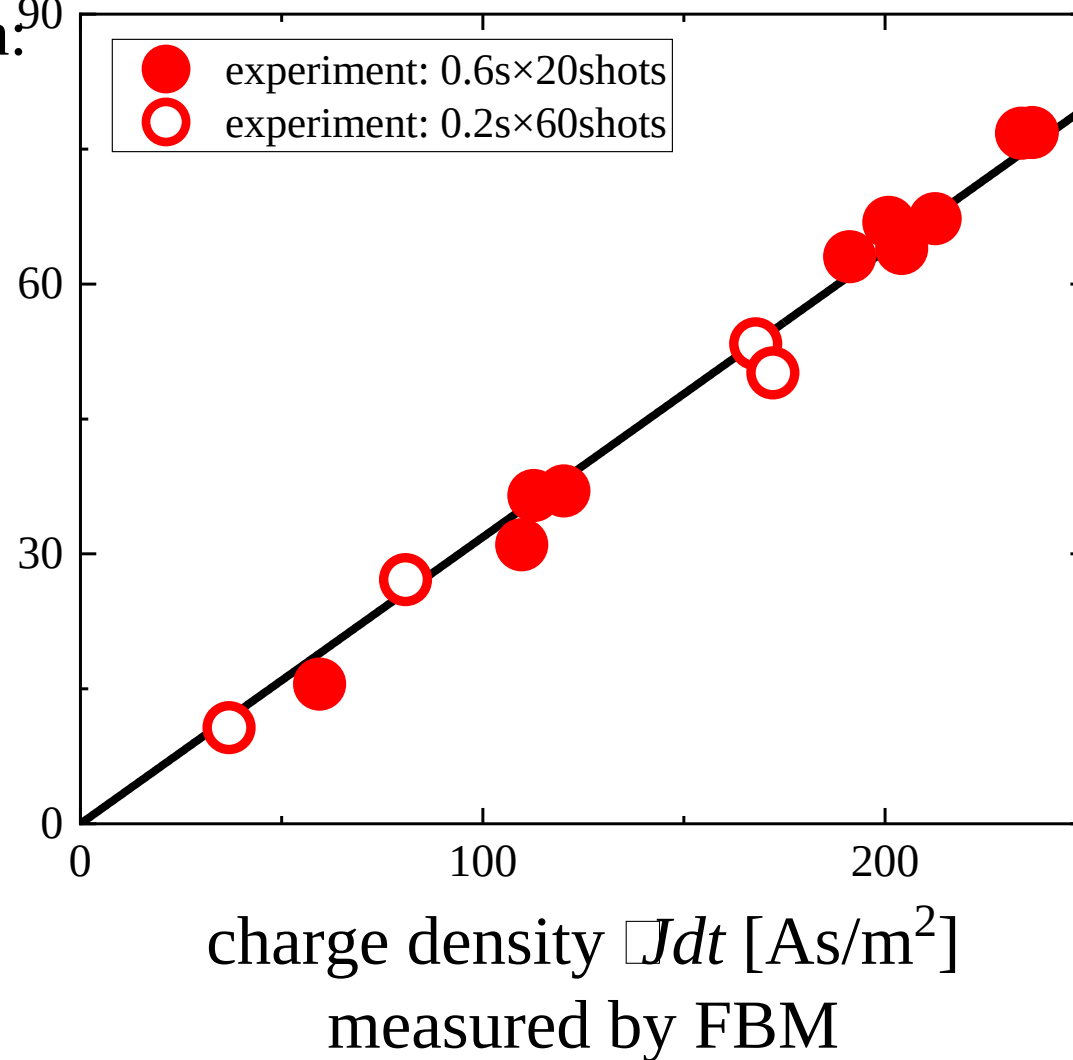


We discuss about the applicability of our assumption.⁹⁰

PPSA $\Delta\eta \propto \int J dt$ FBM



black level: $\Delta\eta$ [a.u.]
measured by PPSA



- We changed single shot beam duration, but total beam duration is constant.
- Linearity

The black level is proportional to the charge density, and this linear relationship is applicable to the evaluation of the phase space structure for the fixed beam energy.

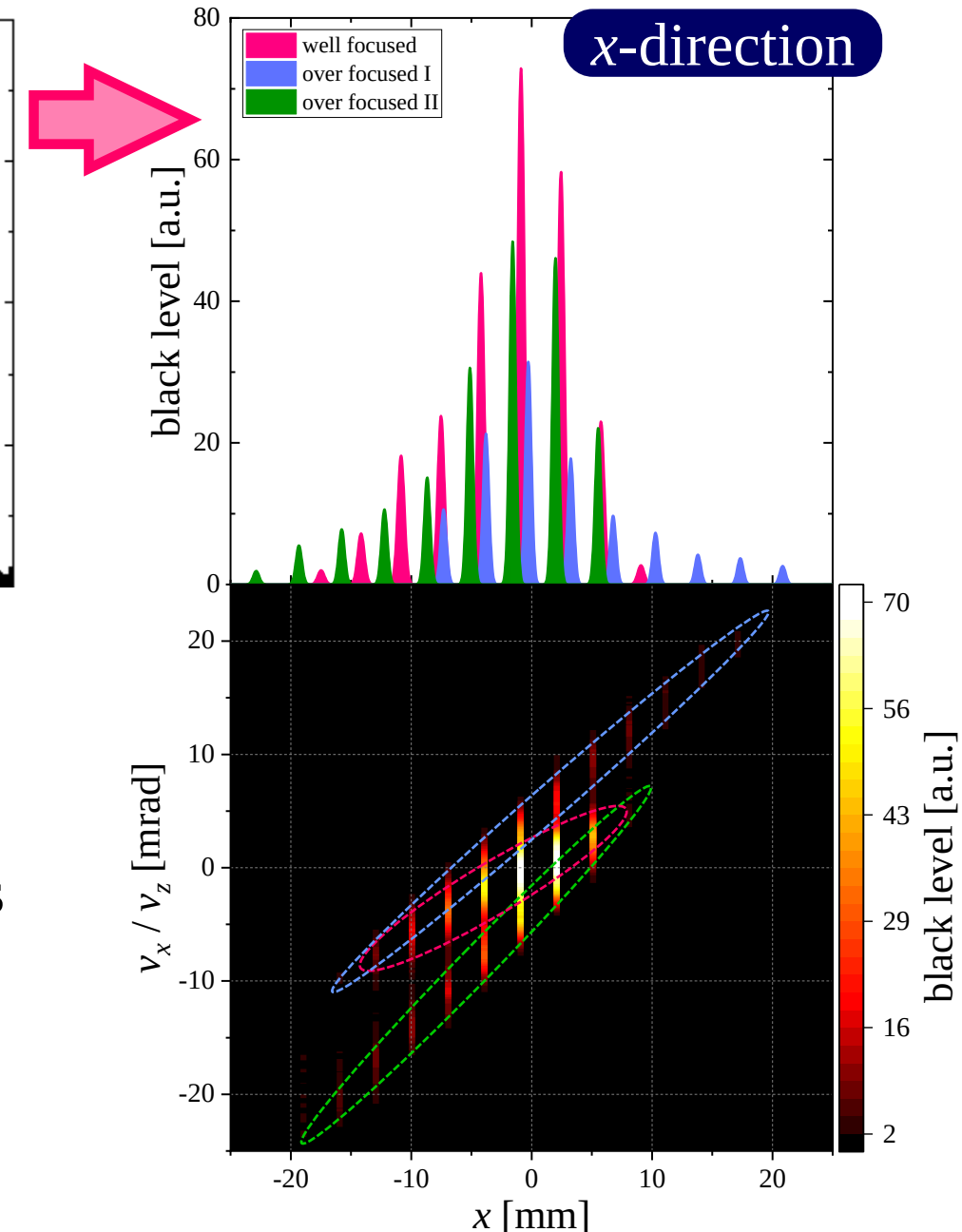
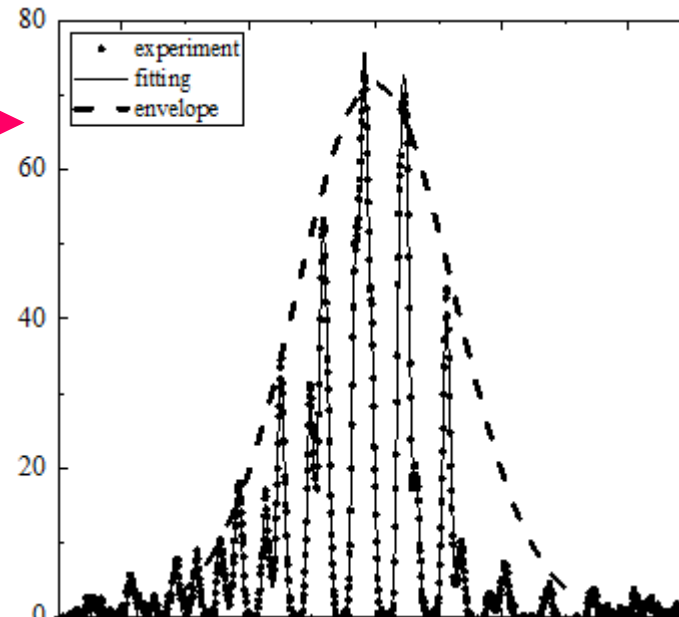
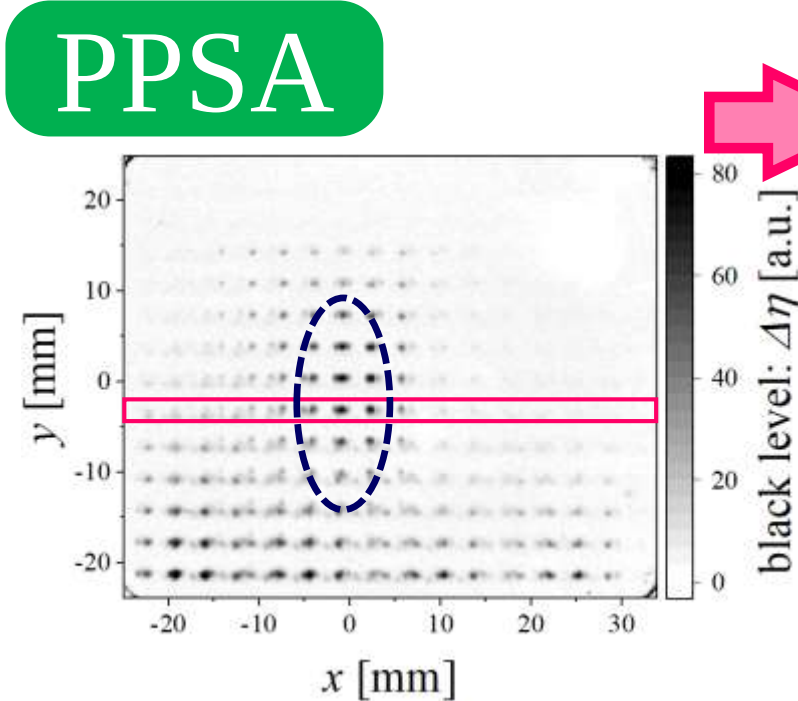
In the previous session,
We have successfully demonstrated that
FBM and **PPSA** work well.

In this session, I will show you
two important observations.

I discuss about the strategy for future study related to

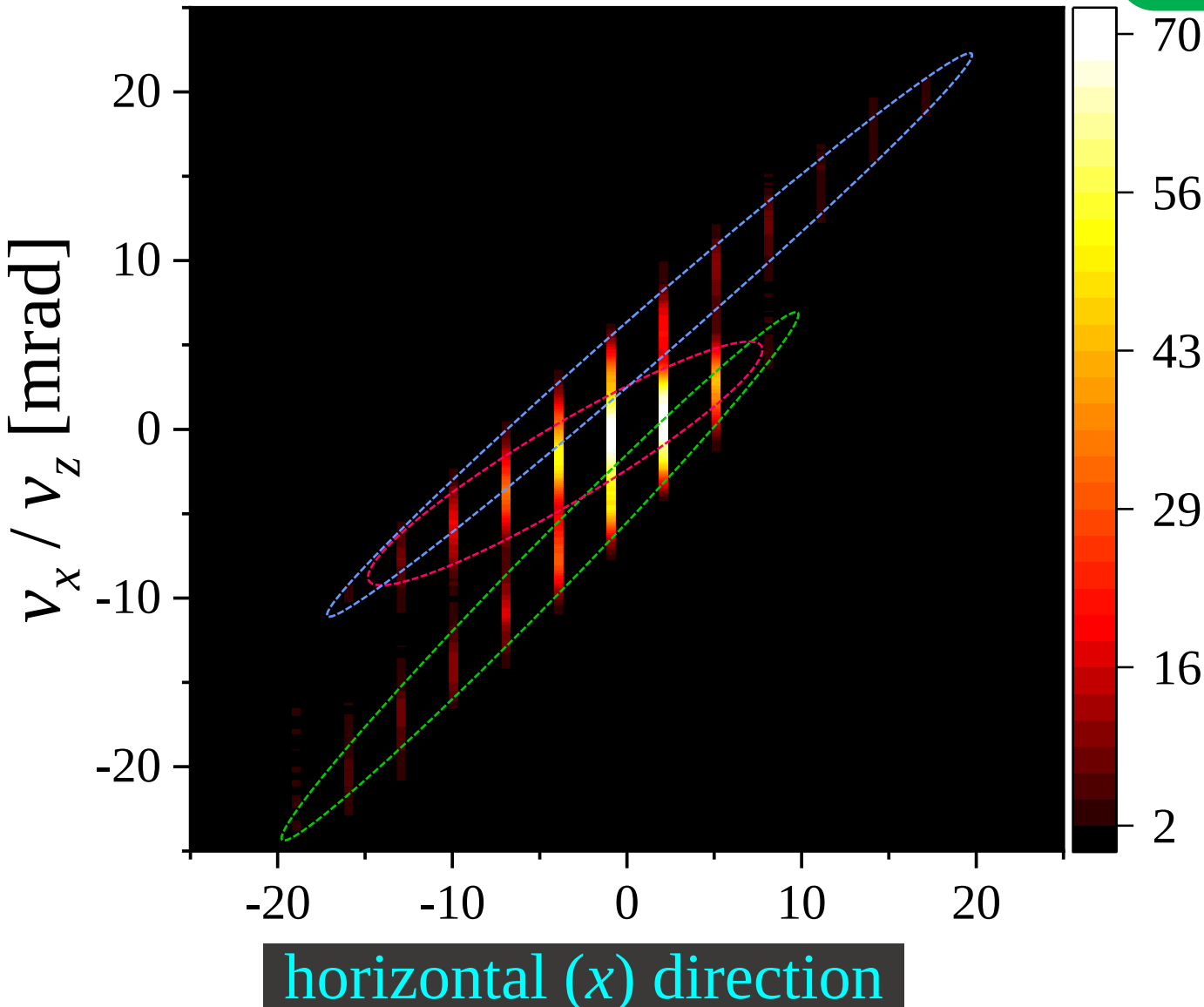
- Phase space structure
- Beamlet stability

PPSA



- In this case, no overlap of neighboring beamlet was observed.
- The phase space structure in the horizontal direction is more complicated than that in the vertical direction.
- The black level profile can be decomposed to **three components** by the same model based on σ and δy .

PPSA



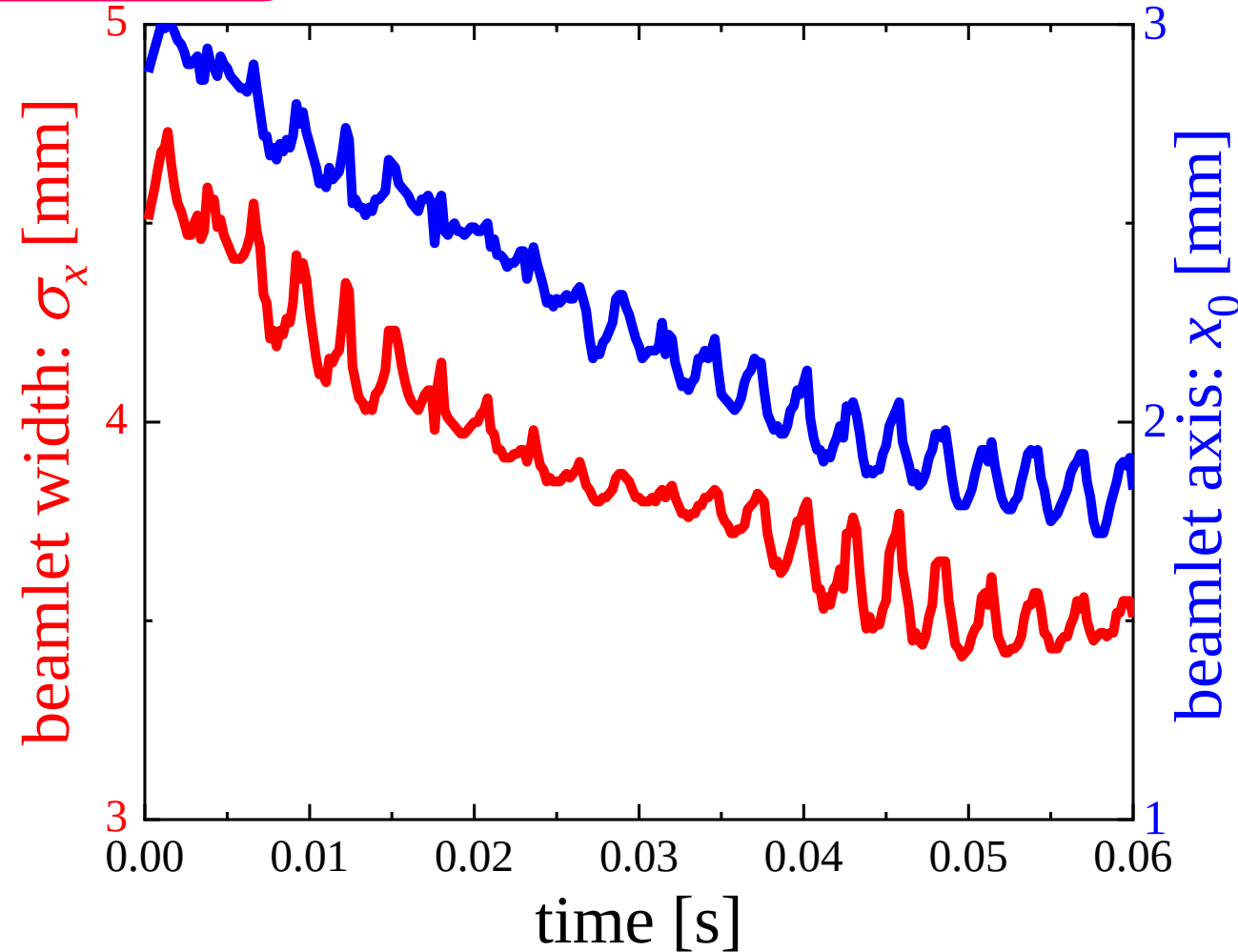
Multi-velocity components were observed in x -direction.

We will try to

- reveal the *perveance dependence*
- compare with *numerical model*

The phase space structure of negative ion beamlet will be studied for further understanding of beam optics.

FBM



The oscillations of the beamlet width and beamlet axis due to source plasma fluctuation were observed.

We try to investigate the linkage between the oscillations and the stability of

- source plasma
- meniscus formation

→ ??

Further study of the beamlet stability is required for understanding of beam optics.

A new beamlet monitor system with the combination of FBM and PPSAs has been developed for measurements of negative ion beamlet.

Using **FBM** we have measured

- the absolute value of negative hydrogen ion beam
- two-dimensional current profile
- the time evolution of the beamlet width and beamlet axis

Using **PPSA** we have demonstrated

- subtraction of the overlapped components coming from the neighboring beamlet
- construction of the phase space structure
- confirmation of the linearity between black level and the charge density

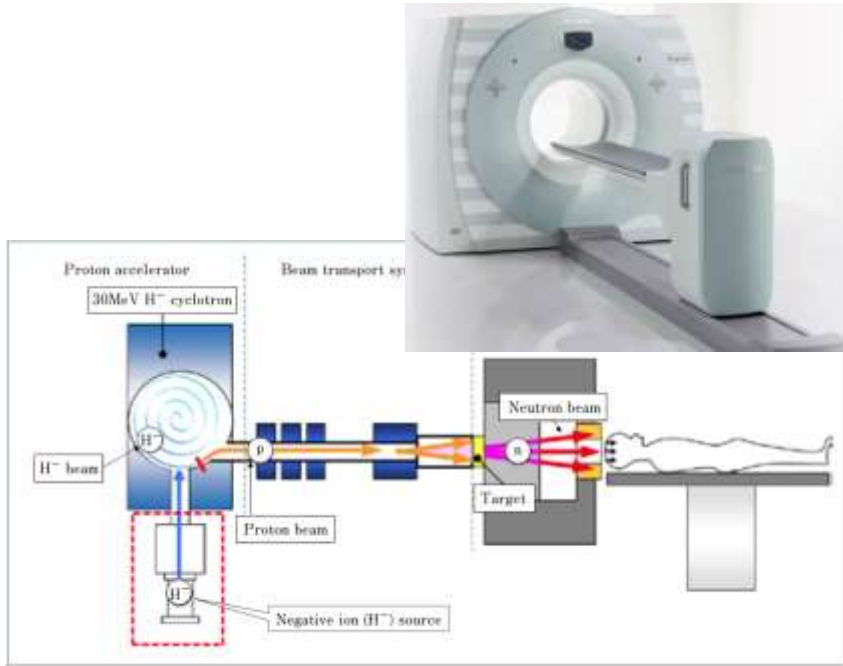
In future, we will study

- beamlet stability and the relation to the source plasma and meniscus stabilities
- phase space structure due to perveance dependence and comparison with numerical model

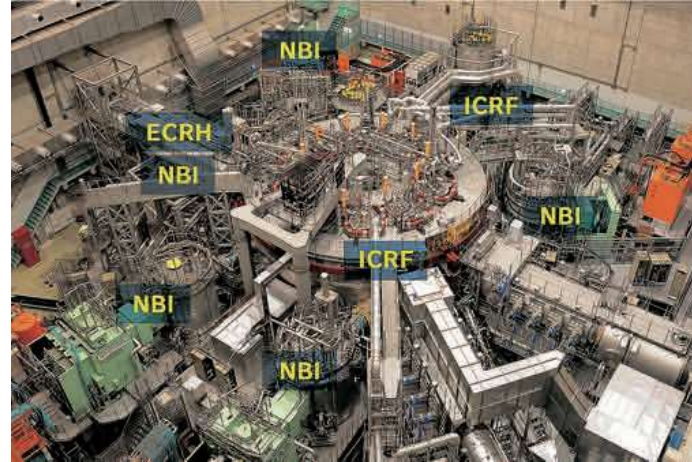
Thank you for your attention.

Negative ion beam production

Medical applications



Nuclear physics



LHD

Large-scale nuclear fusion experiments

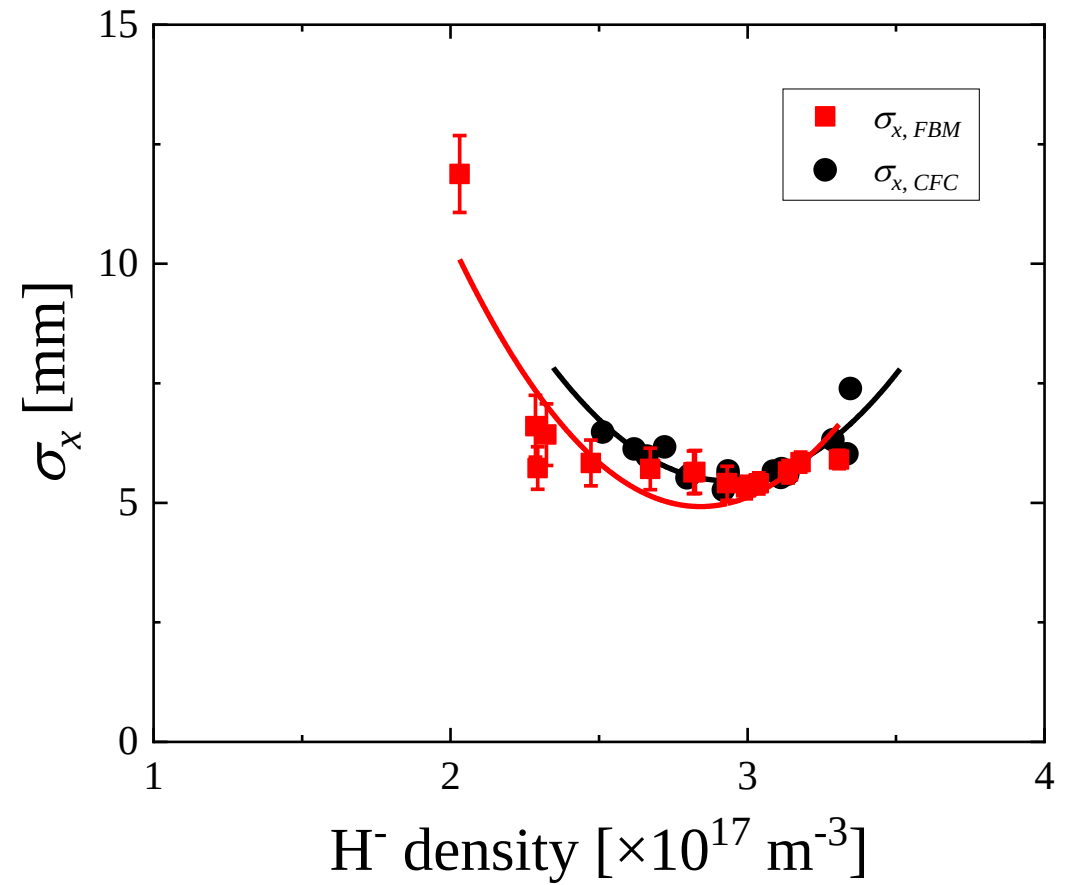
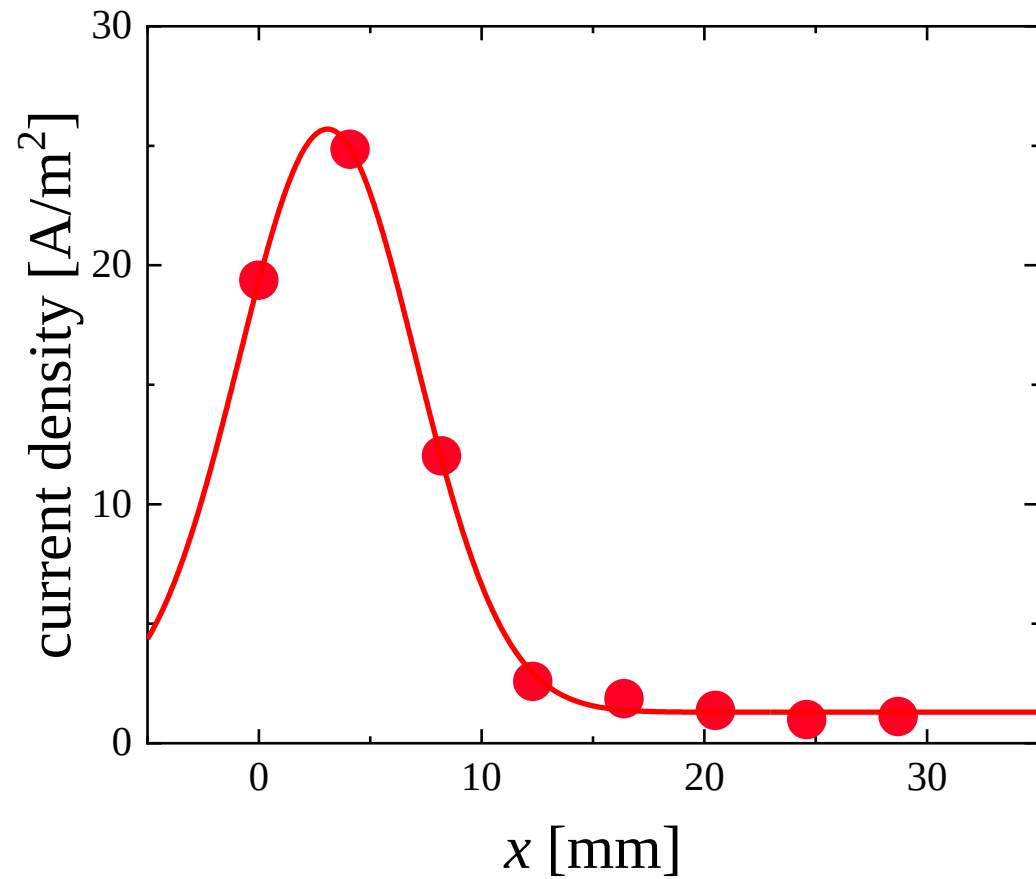


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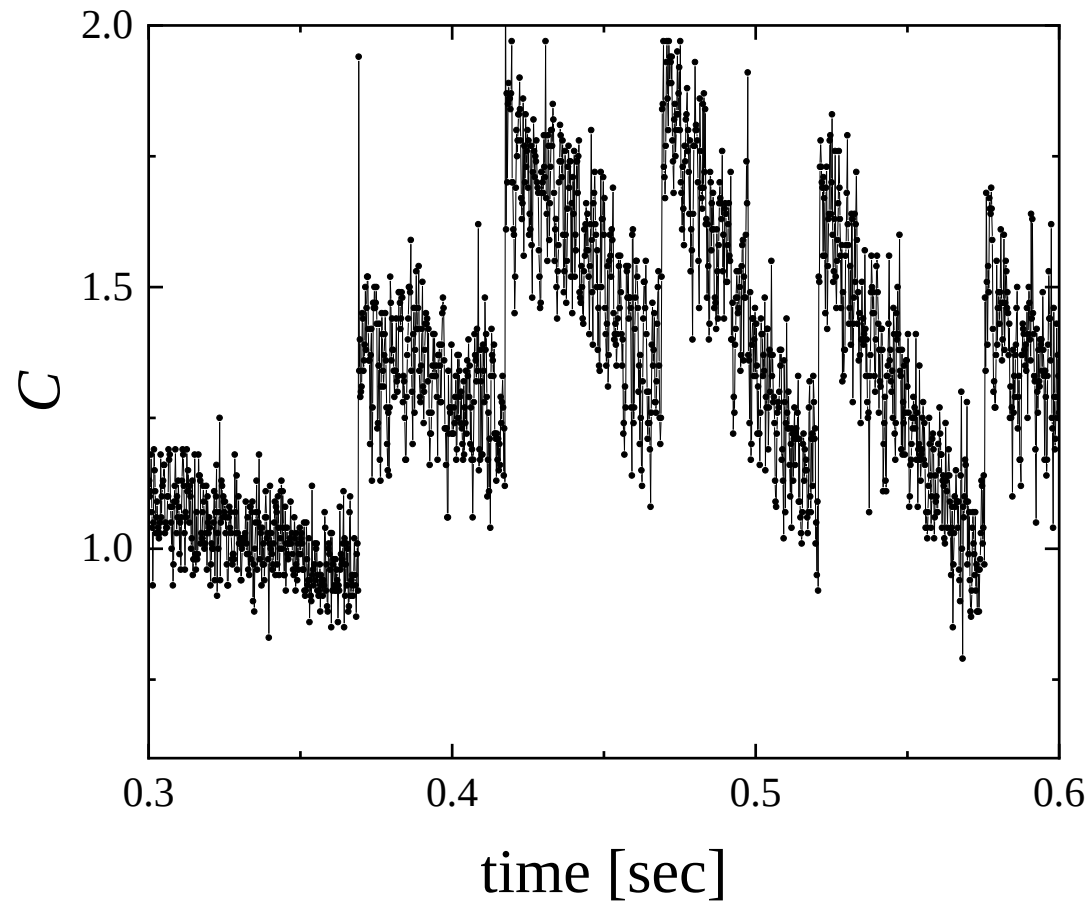
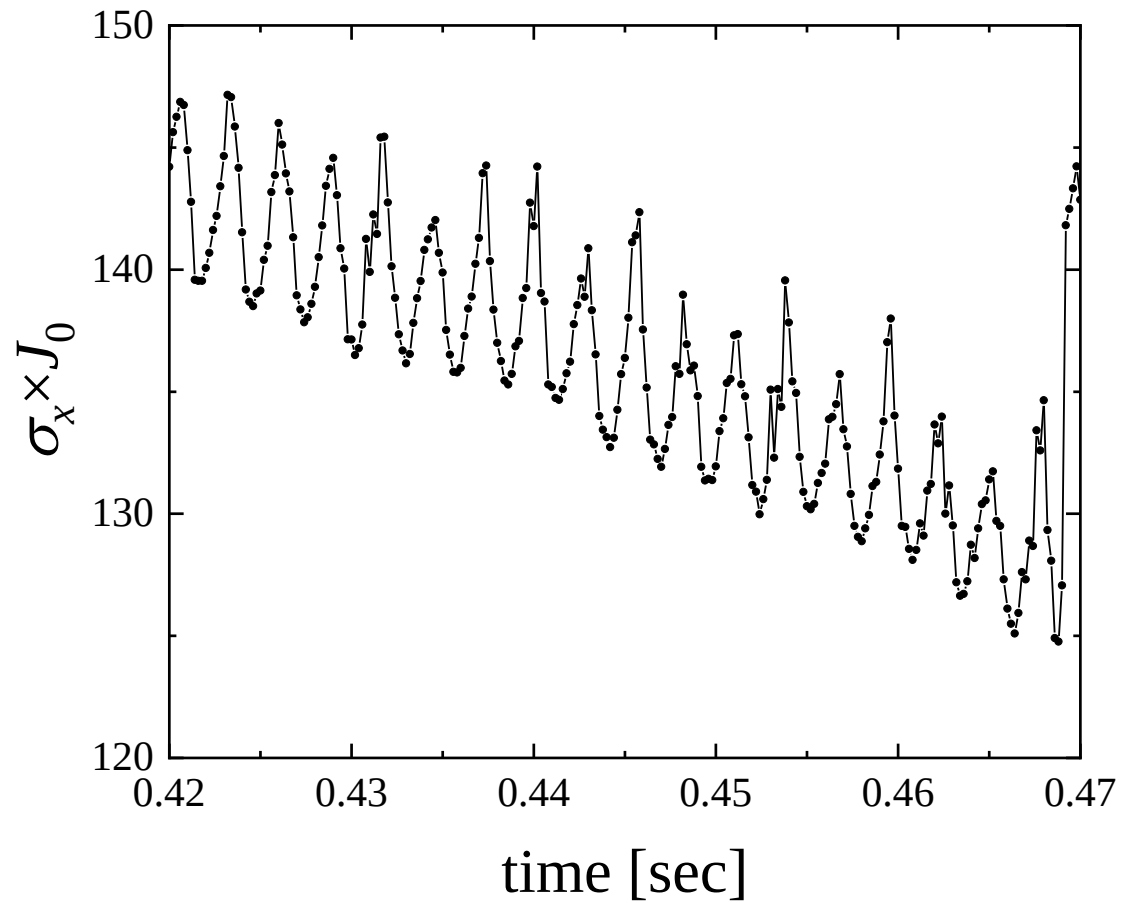
In nuclear fusion, negative-ion-based neutral beam injectors (NNBI) are an effective method to heat magnetically confined plasmas.

Common requirements of these negative ion beam productions are to produce the high current negative ion beam with good optics.

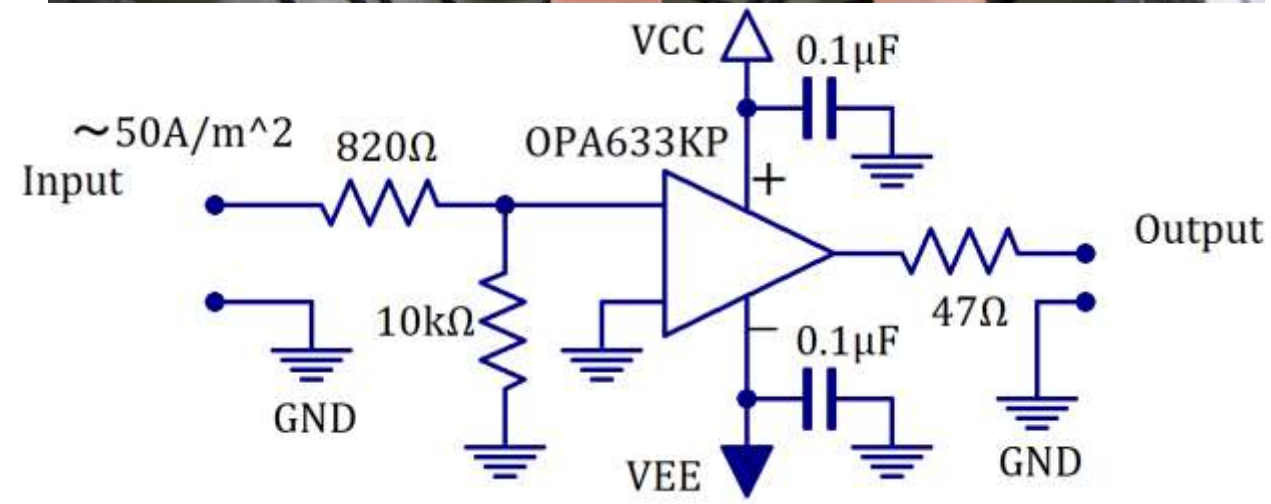
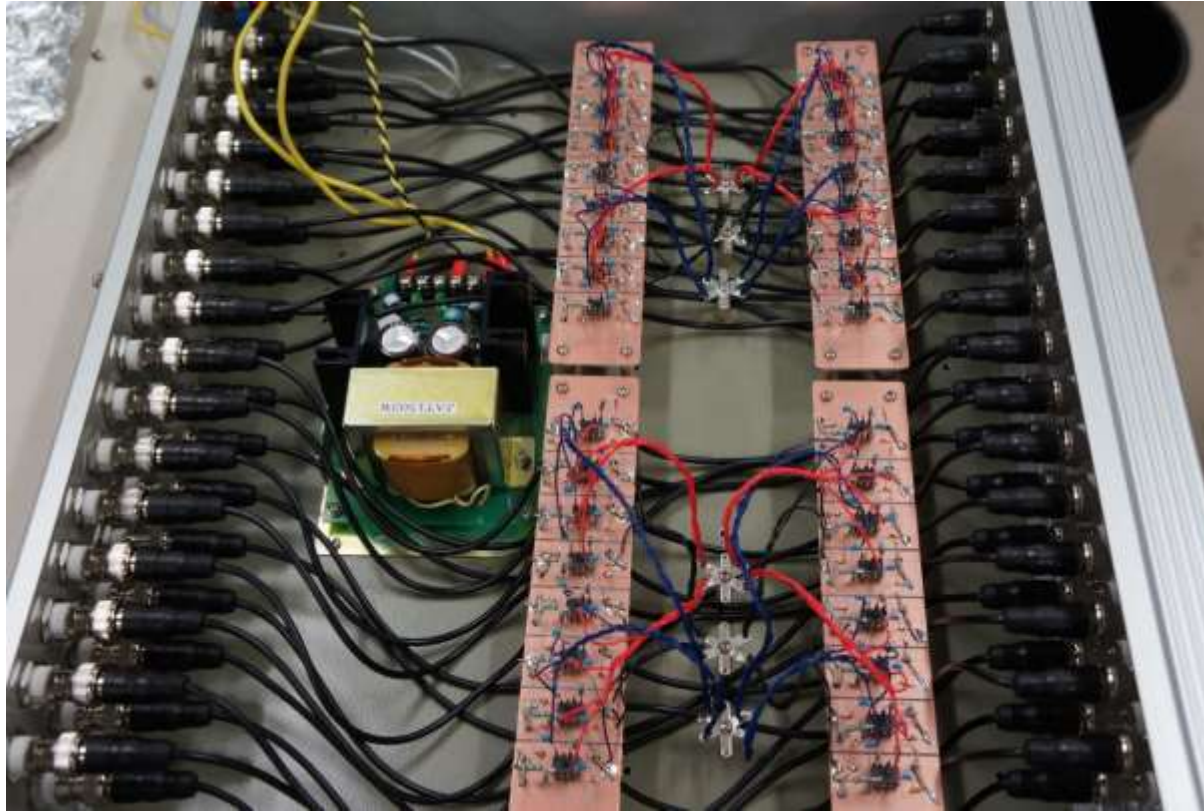
Beam width depended on the H⁻ density



Time evolution of $\sigma_x \times J_0$

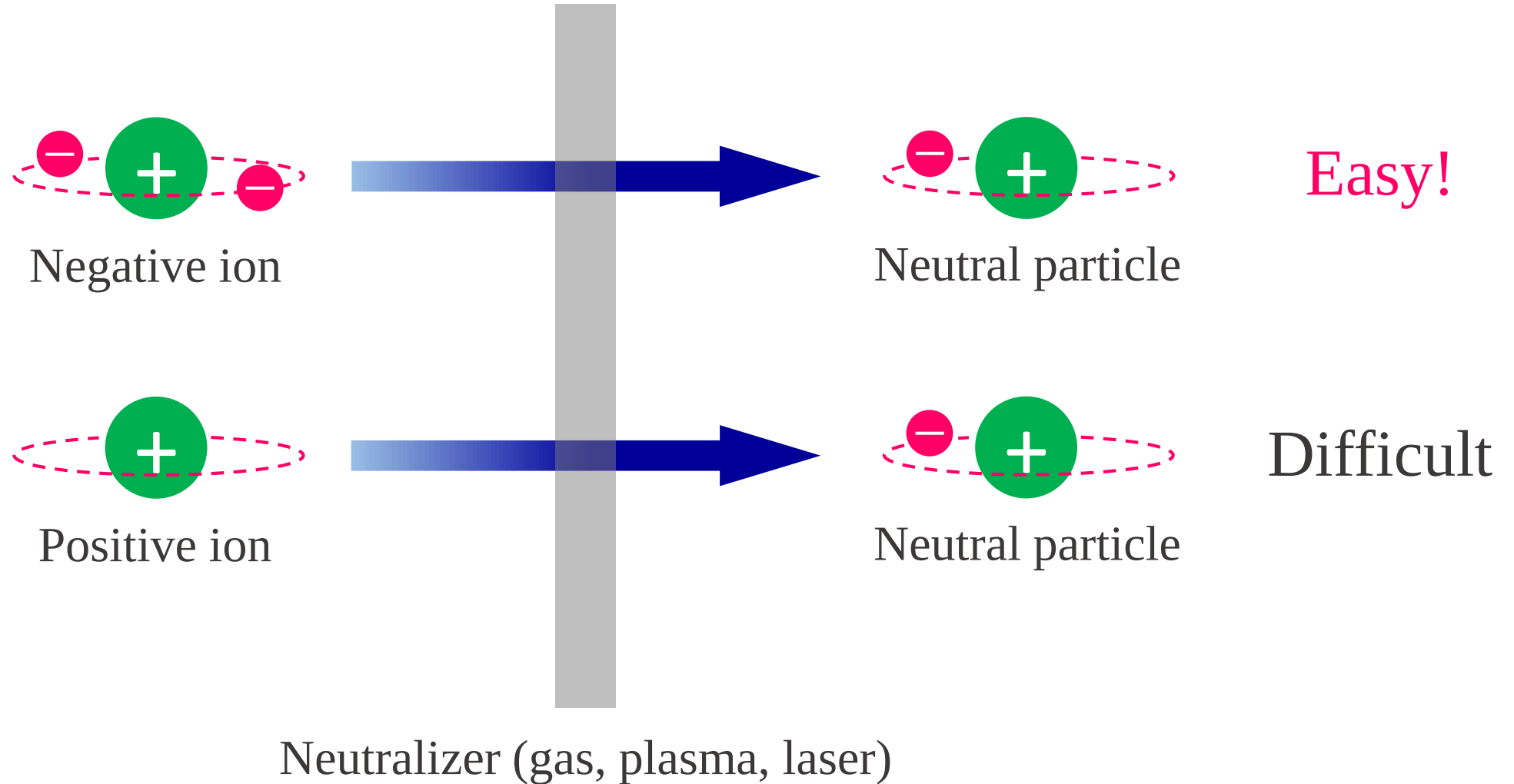


Current amplifier of FBM



Charge exchange of negative ions

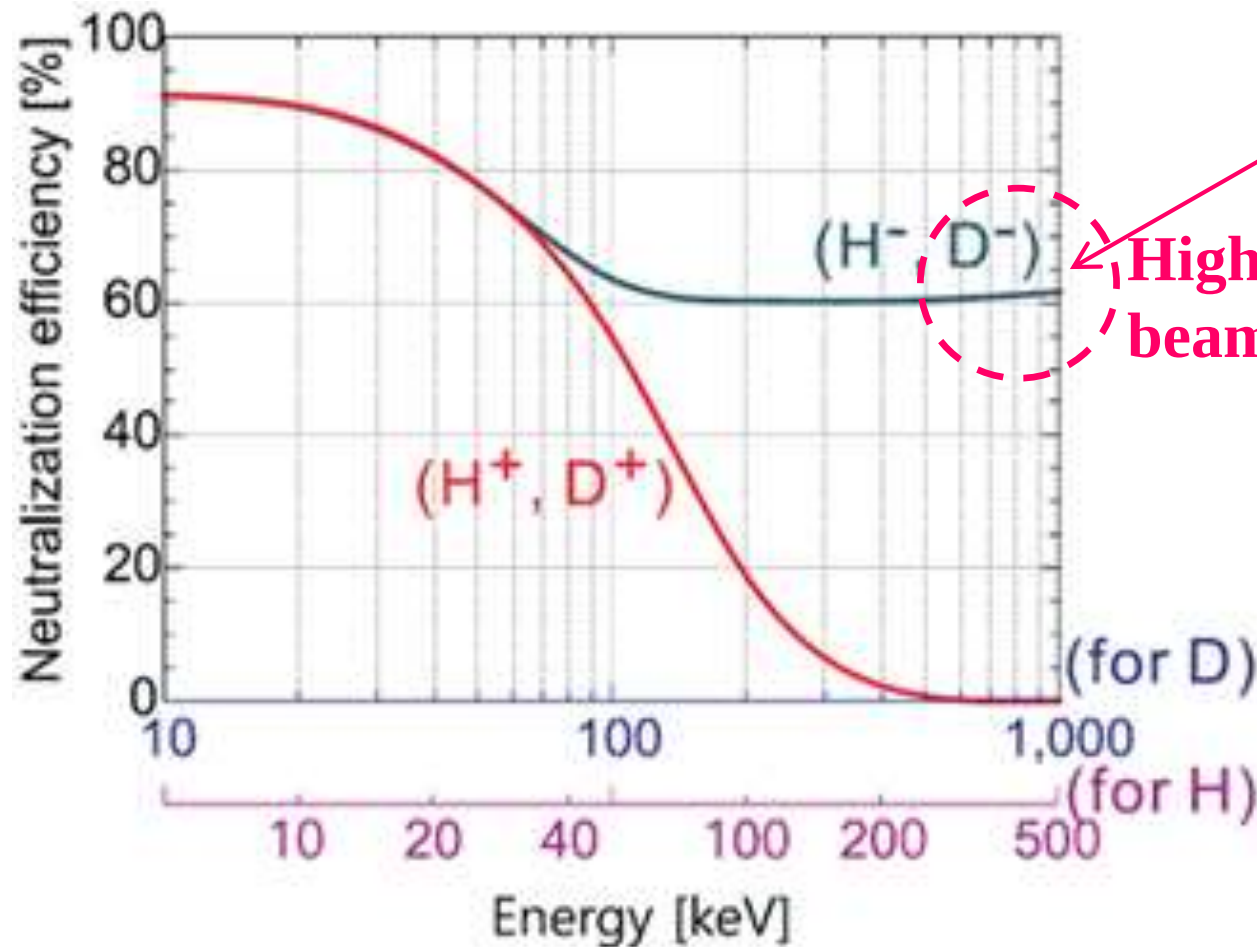
Charge exchange of negative ions is easier than that of positive ions.



Negative ions are useful for neutral beam injections.

Neutralization efficiency of negative ions

Negative-ion-based neutral beam injection (negative-NBI) is an effective method to heat magnetically-confined plasmas because of **high fraction of beam neutralization in high energy regime** (180~190 keV for LHD, 1 MeV for ITER).

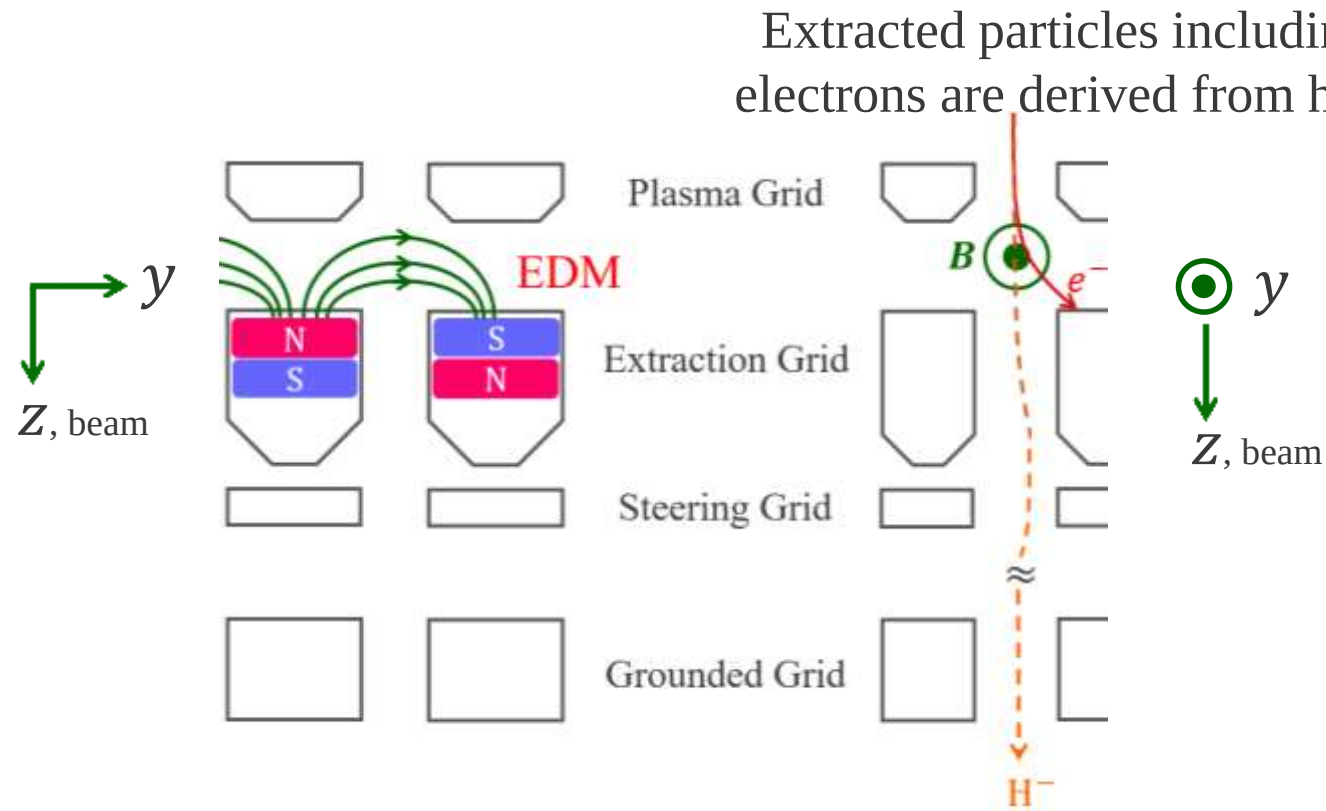


Higher than 60% even the beam energy reaches 1 MeV!

Maximum neutralization efficiency depended on the beam energy in the case of using the gas neutralizer

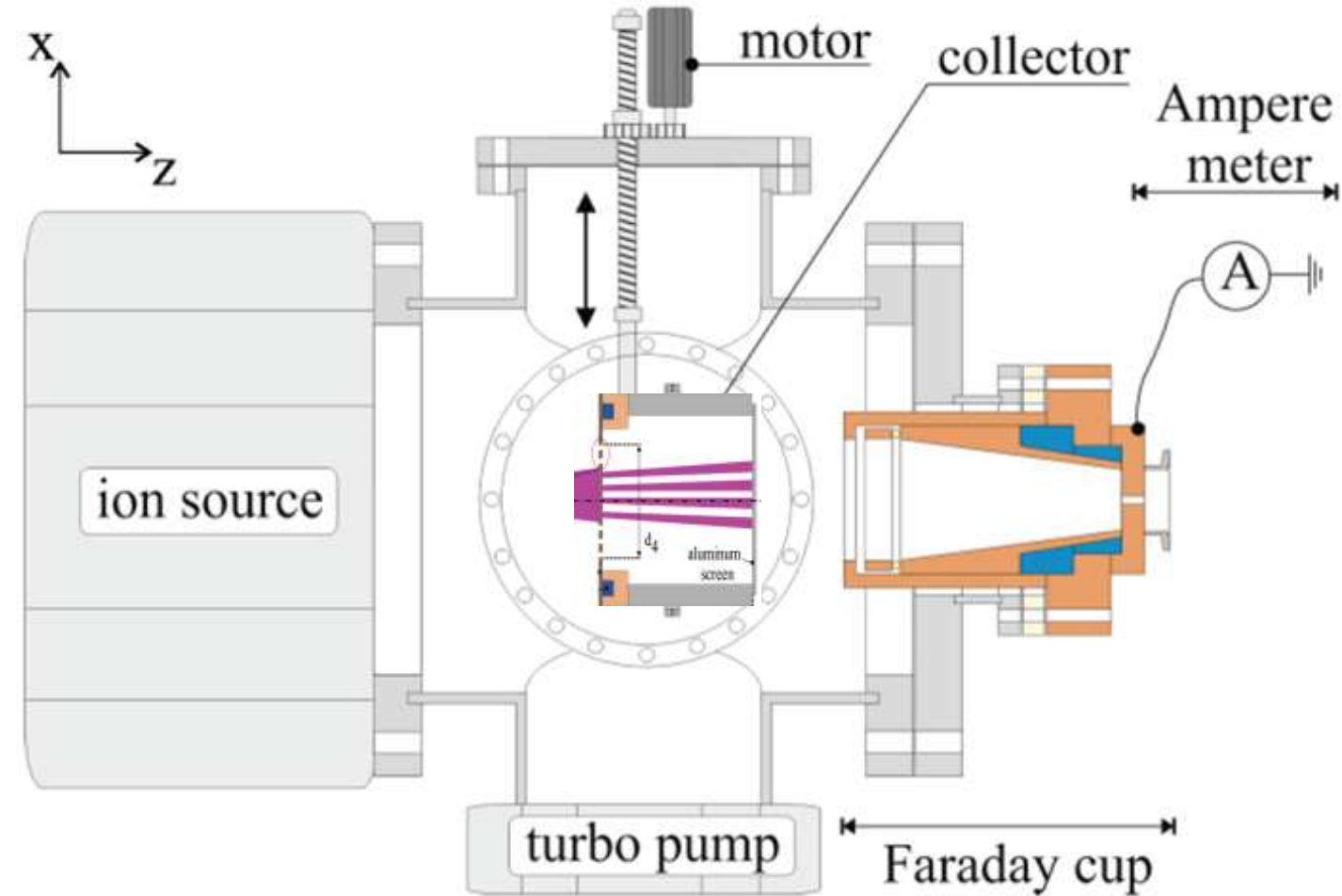
Difficulty of negative ion beam production and extraction

- Negative ion beam production itself is not so easy.
- Co-extracted electrons are useless for neutral beam, so it is required to remove the electrons from the extracted particles using a series of electron deflection magnets (**EDM**).



A steering grid (SG) is also installed for correction of the beam axis z .
 H^- ions are slightly changed their orbits due to EDM and SG.

Previous study (idea of the device development)



Proceedings of LINAC 2014, Geneva, Switzerland
B. Klump, U. Ratzinger, W. Schweizer, and K. Volk

The ion beam penetrates from the left side through a pinhole array, which made of wolfram-copper. Partial beams hit the aluminum screen.

This collector was build and installed in a diagnostic chamber, which also contains a Faraday cup, the vacuum system and a viewing window.

The system can be moved into the beam by a motor drive. For the investigations, the ion beam of the FRANZ ion source was used.

- **Collector based on the pepper-pot method** for evaluation of phase space structure of ion beams
- **Faraday cup** for measuring beam current profiles

What can we do for the combination of these two diagnostics?

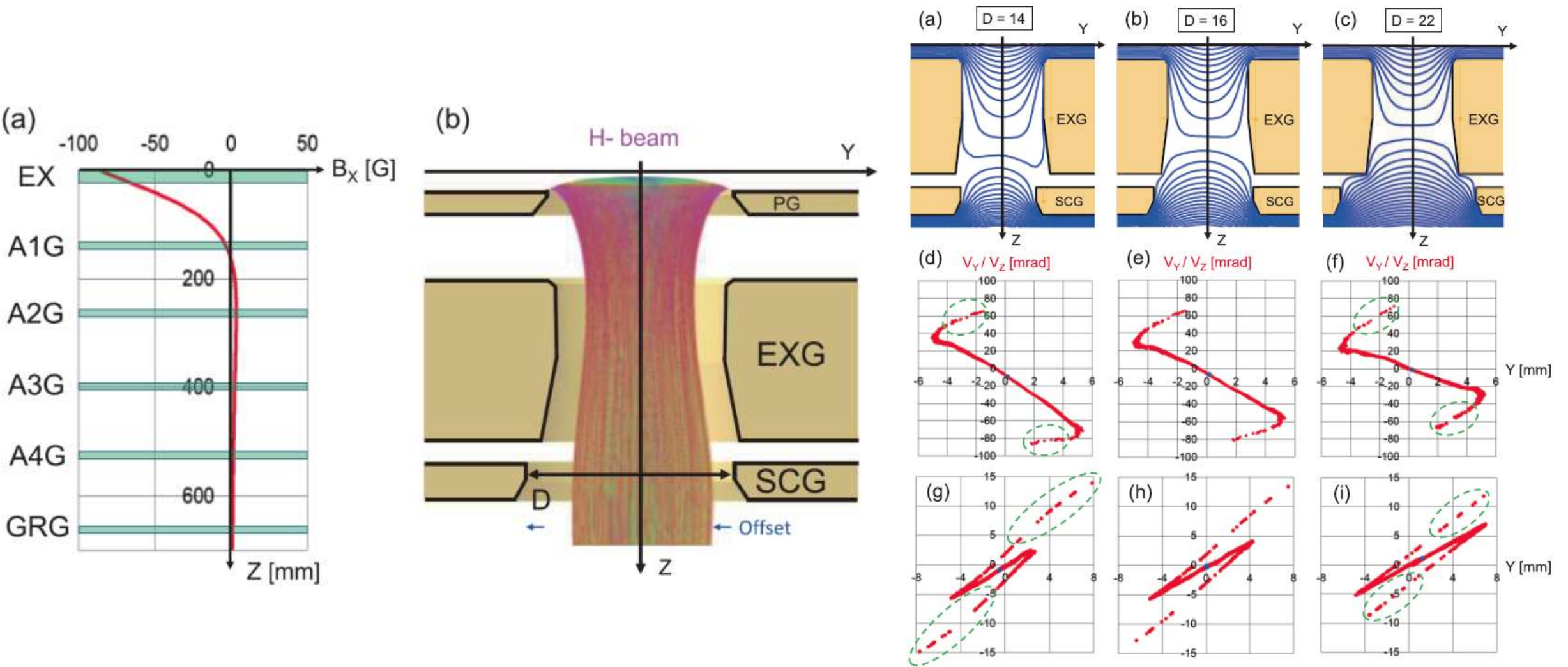


Fig. 2 Equipotential lines in the extractor (a-c). Emittance diagram of ion beam at SCG (d-f) and GRG (g-i) with three different aperture diameters of SCG ($D = 14, 16, 22$ mm).