#17 Study of negative ion beam emittance characteristics using 3D PIC-MCC simulation

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Introduction

A negative ion source of the neutral beam injection system for nuclear fusion is required to produce a negative ion beam with good optics.

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It is reported from the measurement of a negative ion beamlet emittance that the characteristic three-Gaussian components are observed in the emittance diagram [1]. These components can be identified as a combination of three beam components with different beam axes.

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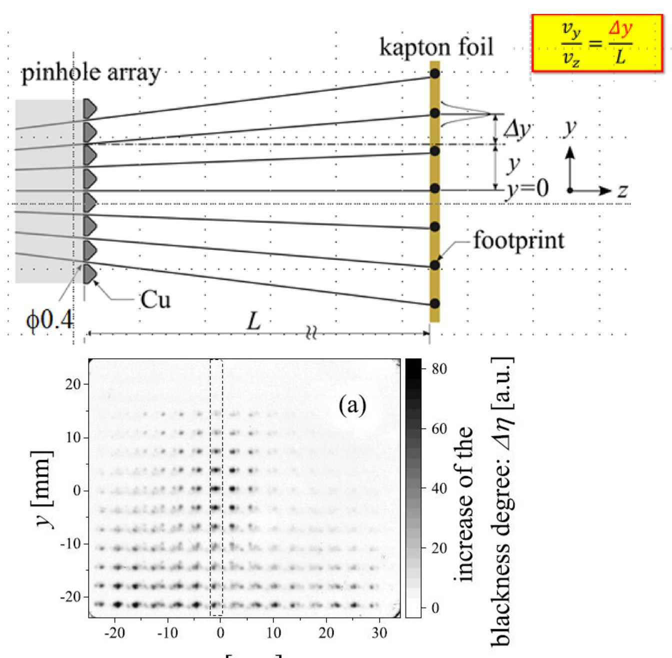
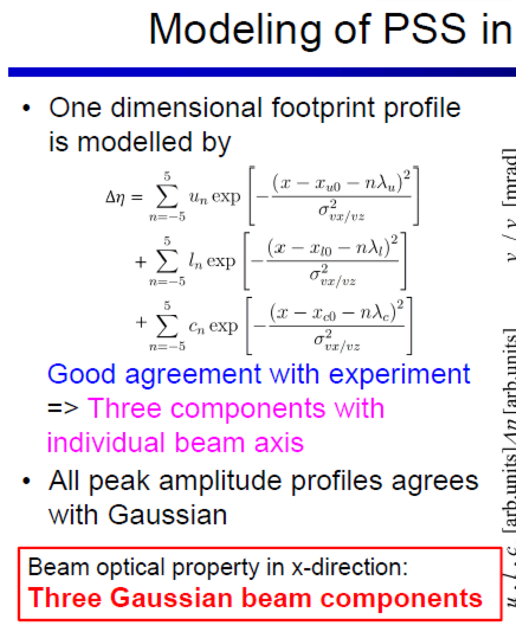
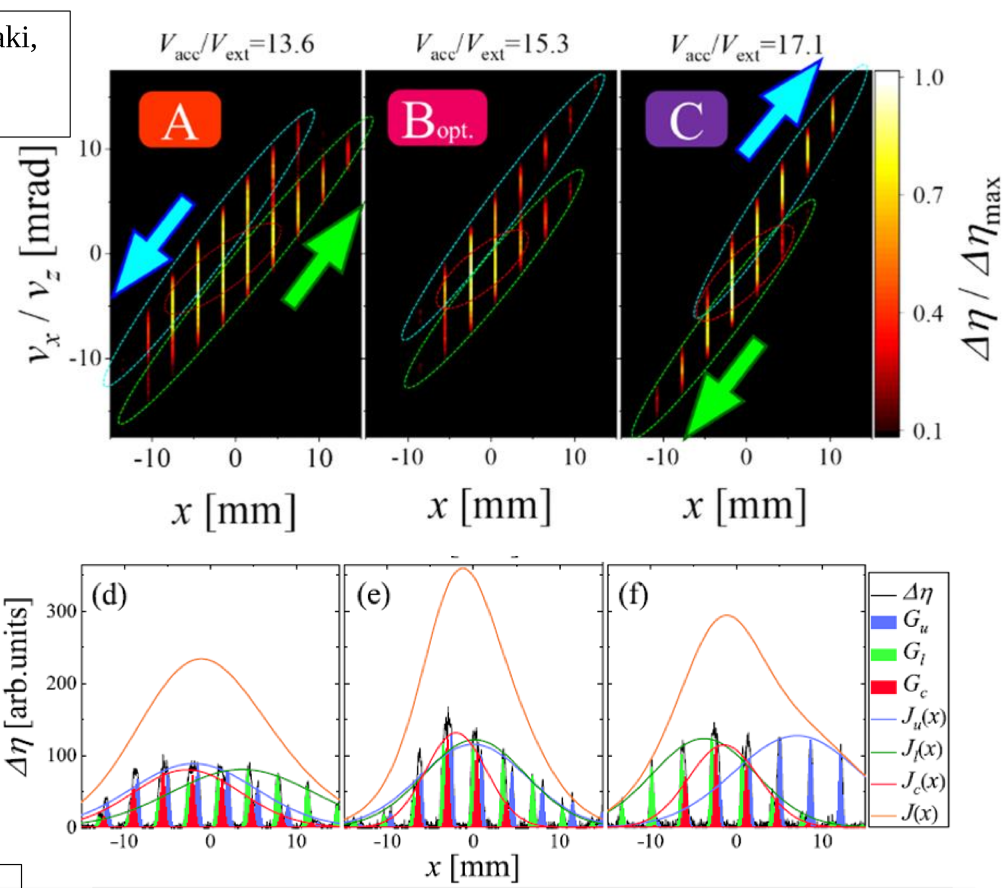
In order to clarify the origin of this complicated phase space structure and underlying physical mechanism, potential structure and particle dynamics including the negative ion trajectories have been calculated self-consistently in a 3D model geometry.

Measurement of negative ion beam emittance

[1] Y. Haba, K. Nagaoka, K. Tsumori, M. Kisaki, H. Nakano, K. Ikeda, and M. Osakabe, *New J. Phys.*, **22**, 023017 (2020).



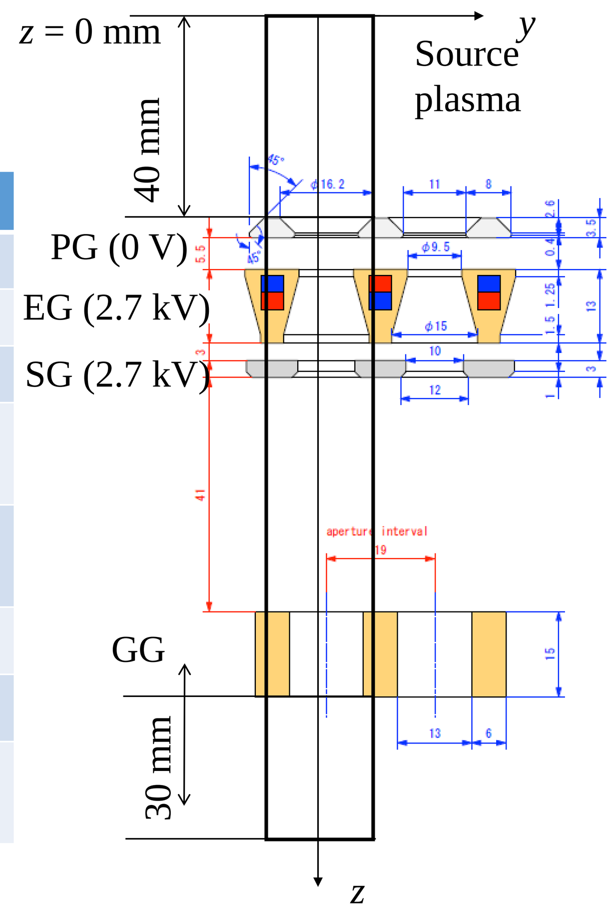


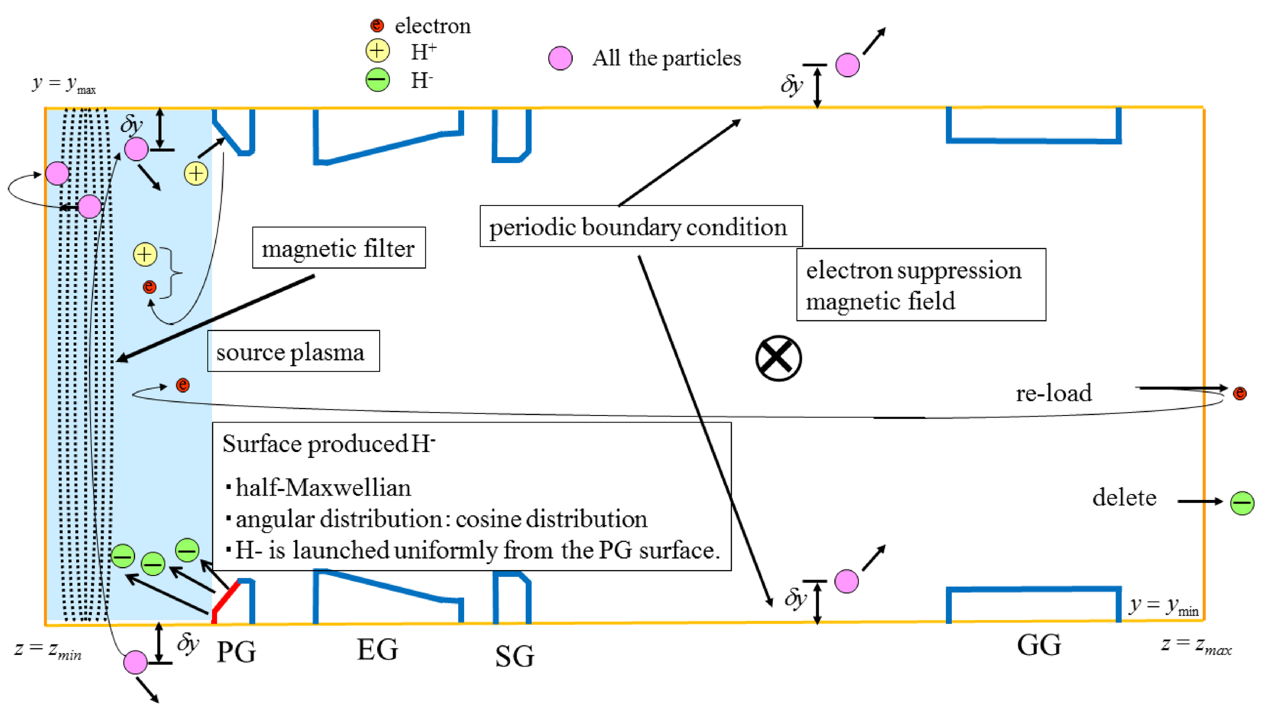


PIC simulation model

Main physical parameters

Physical quantity	value
Electron density	1.8×10^{17} m^{-3}
Electron temperature	0.8 eV
H^+ ion temperature	0.3 eV
H^- ion temperature	0.1 eV (volume produced) 1 eV (surface produced)
H_2 molecular density	1.88×10^{19} m^{-3} (at 0.3 Pa)
H_2 molecular temperature	0.1 eV
H atomic temperature	0.3 eV
Ratio of H atomic density to H_2 molecular density	0.5





The following collision processes are taken into account for the H^- ions:

Coulomb collision : H^-—H^+, H^- — H^-

Charge exchange :
H^- (fast) + H(slow) → H^- (slow) + H(fast)

Elastic collision with neutrals : H^-—H, H^- — H_2

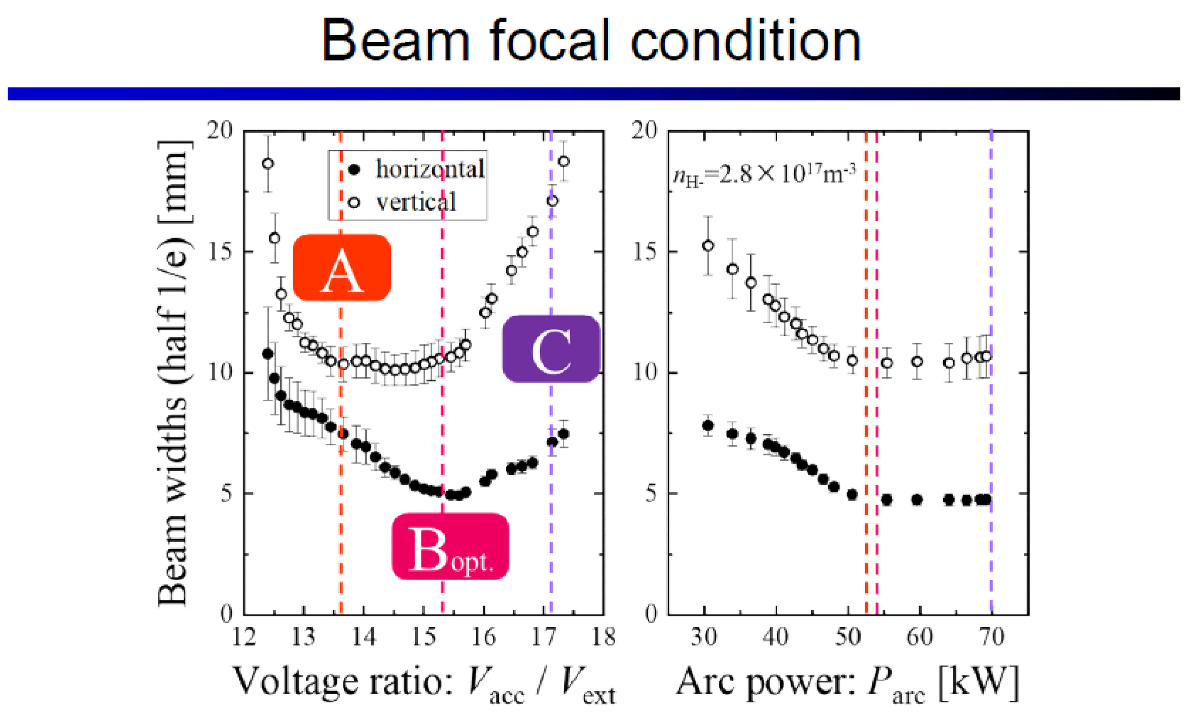
Mutual neutralization : H^- + H^+ → H + H

Other simulation conditions

- particle : e, H^+, H^-
- Neutral are assumed to be the background particles.
- Initial particle number ratio : e : H^+ : H^- = 3 : 10 : 7
- V_{ext} = 2.7 kV
- V_{acc} / V_{ext} = 13, 14, 15, 16, 18, 20, 22, 24, 26

Dependence of negative ion beam optics on the voltage ratio V_{acc}/V_{ext}

Experimental result

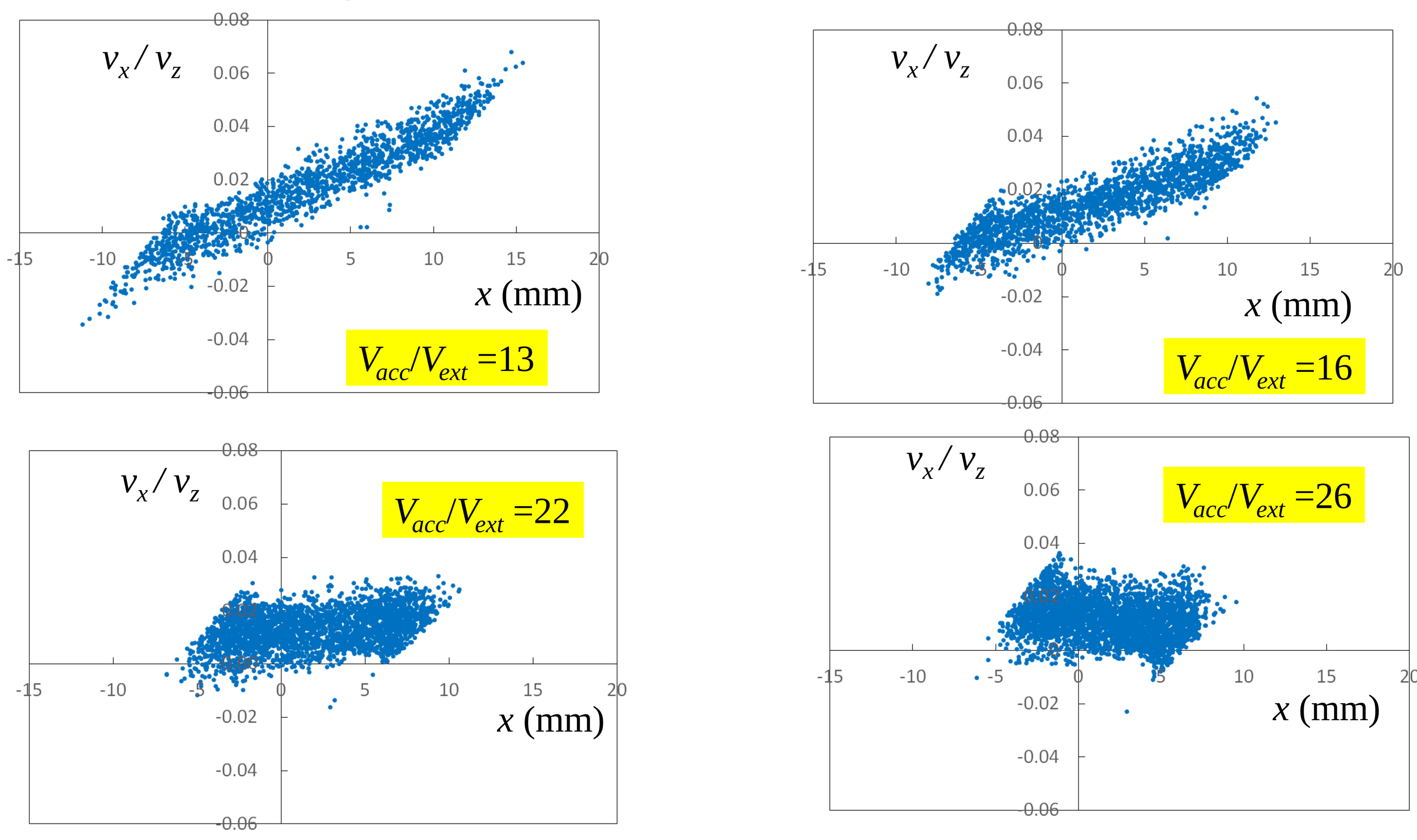


- Beam width shows the minimum in V_{acc}/V_{ex} scan
- Beam width also changes with arc power (perveance)

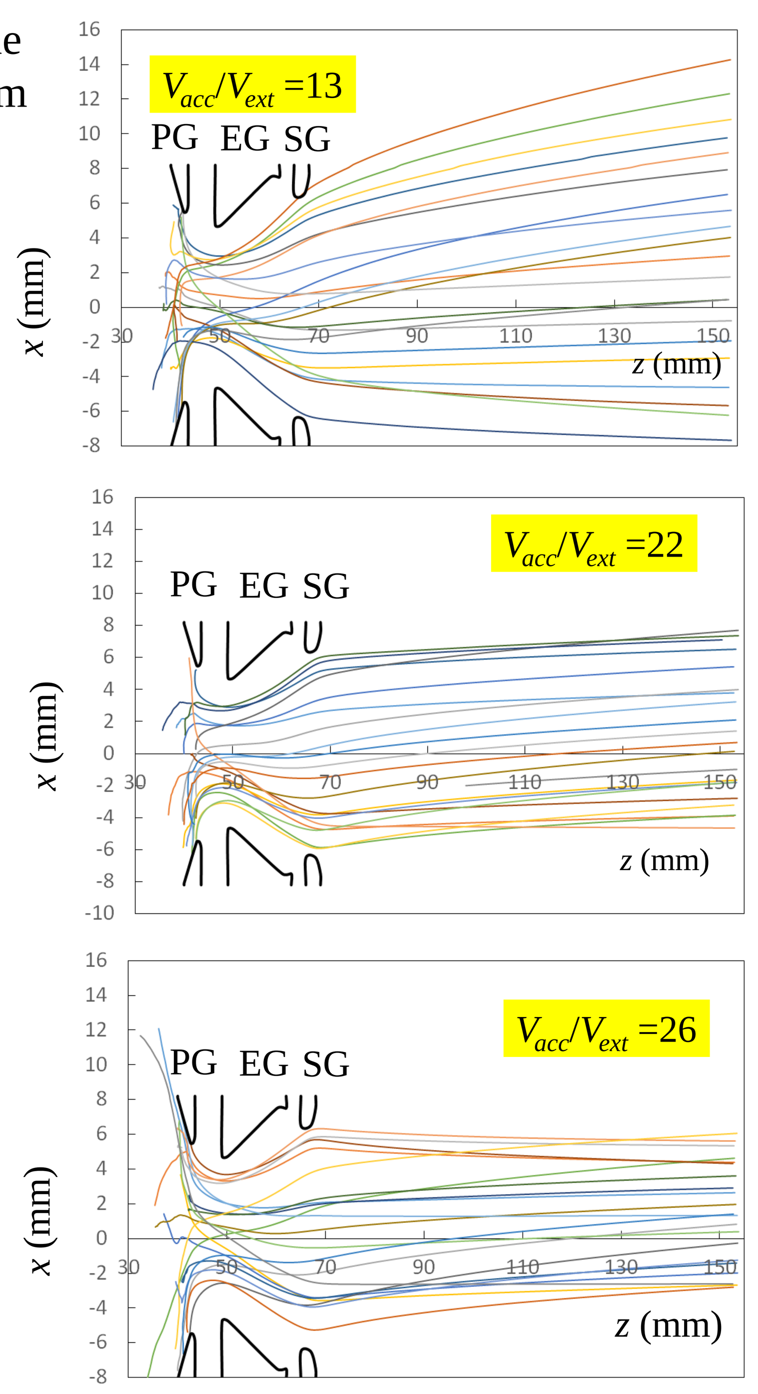
Simulation result

The negative ion beam changes from a diverging beam to a converging beam due to an electrostatic lens effect as the voltage ratio V_{acc}/V_{ext} increases.

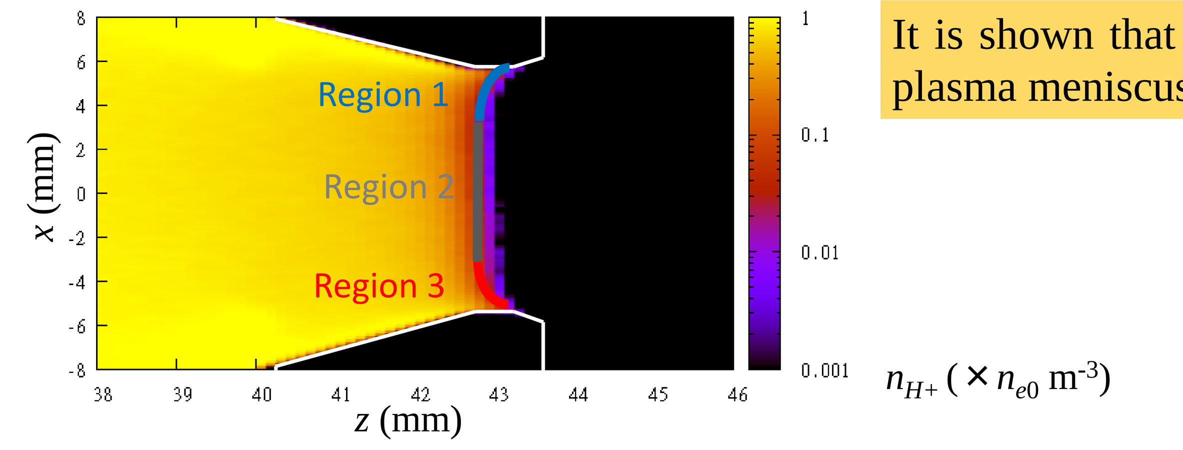
(1) Emittance diagram at a location of 30 mm downstream from the exit of GG



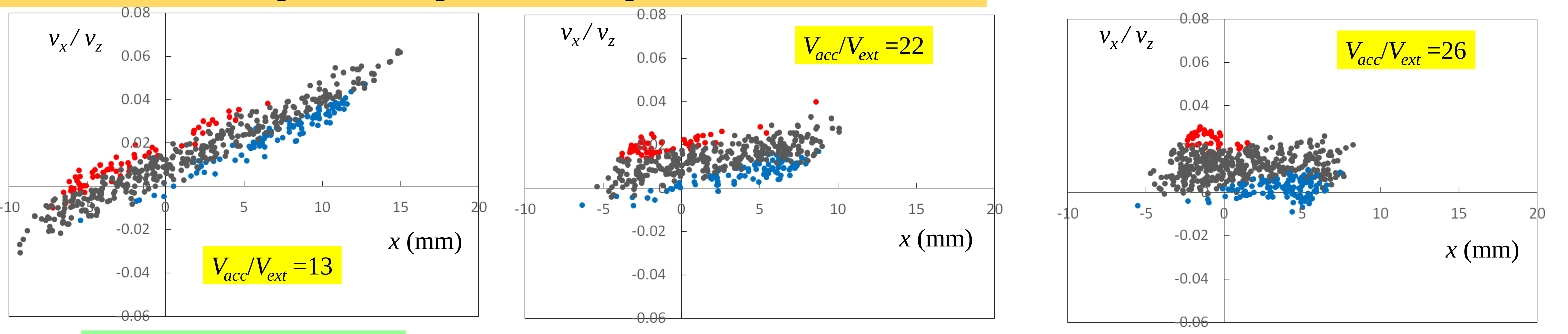
(2) Trajectories of the negative ion beam



Relation between the location of the negative ion extraction along the plasma meniscus and the emittance diagram

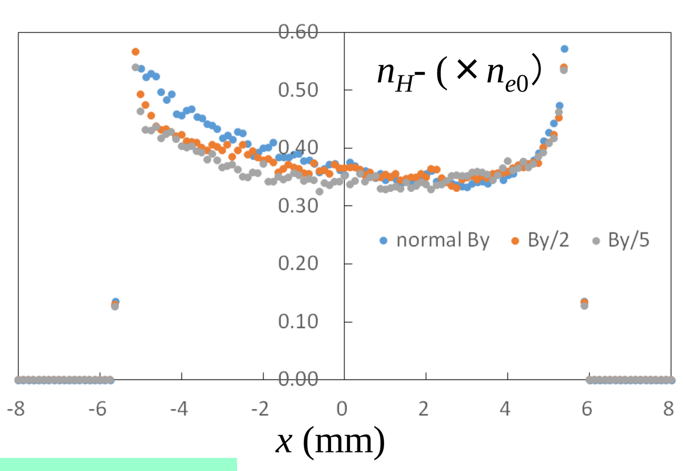


It is shown that the Gaussian components are caused by the negative ions extracted from the different plasma meniscus region, that is, the central region or the region near the edges of the meniscus.

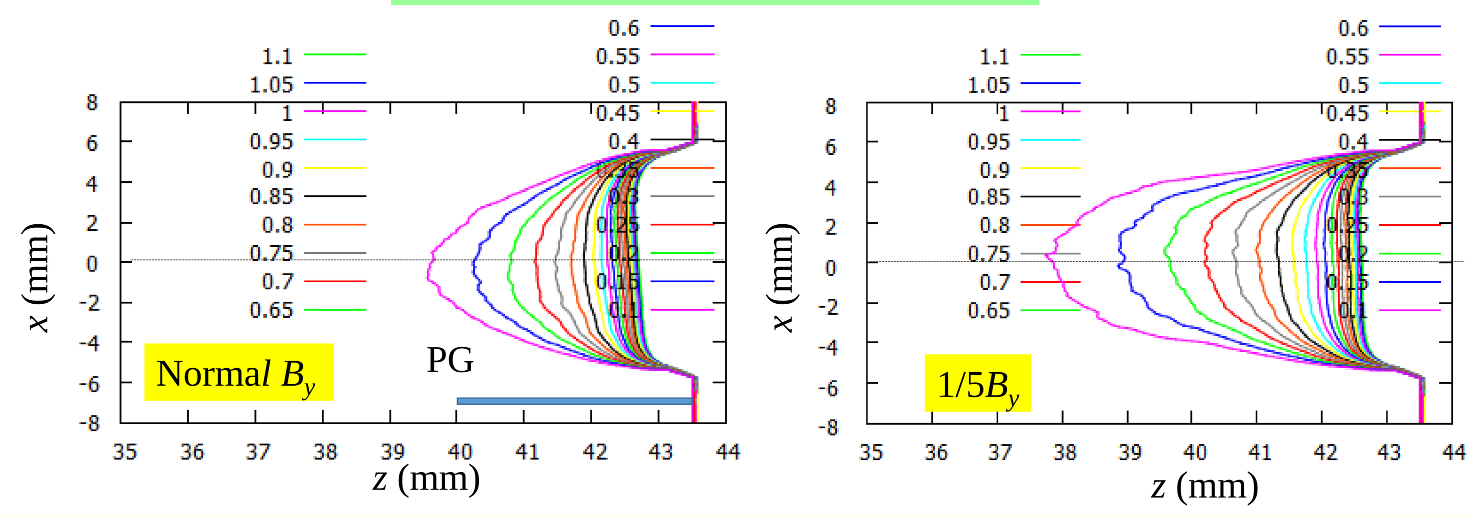


	V_{acc}/V_{ext} =13	V_{acc}/V_{ext} =22	V_{acc}/V_{ext} =26
Total number of the negative ion beam trajectories in the analysis	515	421	505
A number of the negative ion beam trajectories extracted from the region 1	100	87	107
A number of the negative ion beam trajectories extracted from the region 2	353	278	359
A number of the negative ion beam trajectories extracted from the region 3	62	56	39

H^- density profile (z = 42 mm)



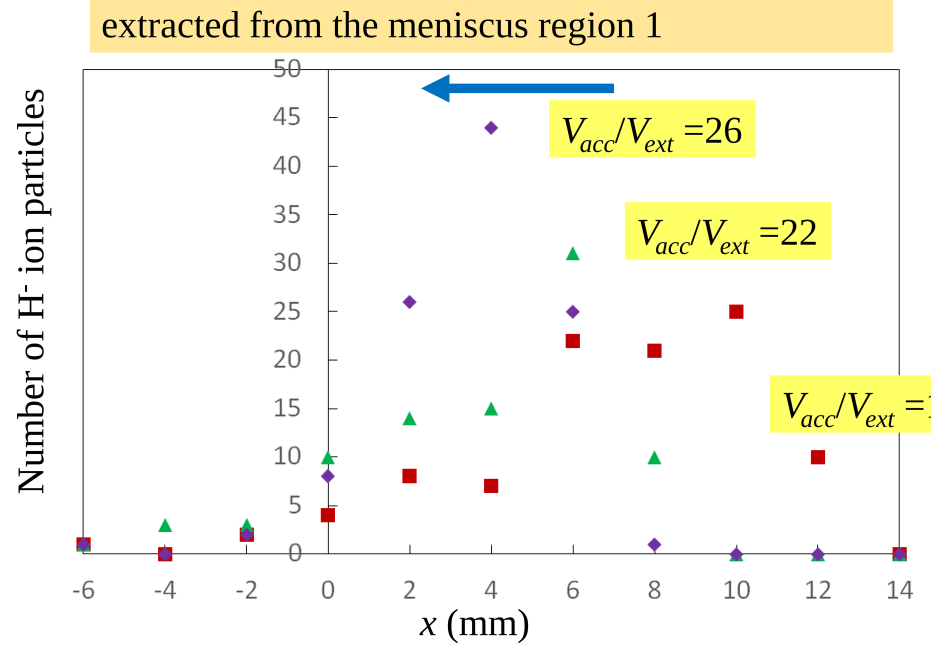
Contour map of equipotential around PG



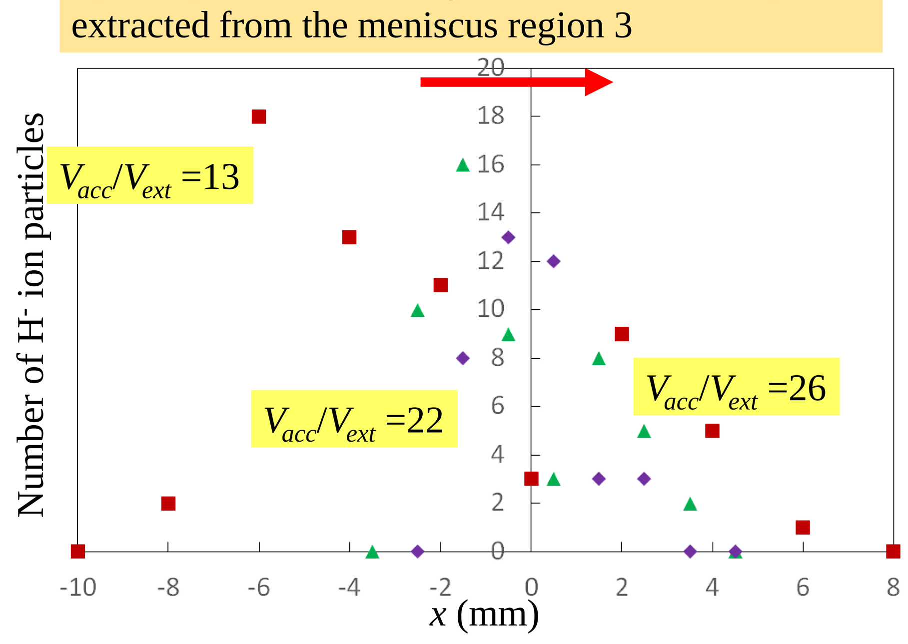
Dependence of the peak shift of the negative ion beam component profile on V_{acc}/V_{ext}

The peaks of the negative ion beam components extracted from the meniscus region 1 and 3 shift in the opposite direction each other as the voltage ratio V_{acc}/V_{ext} increases.

Spatial profile of the negative ion beam component extracted from the meniscus region 1



Spatial profile of the negative ion beam component extracted from the meniscus region 3



Summary

1) It is verified that the negative ion beam changes from a diverging beam to a converging beam due to an electrostatic lens effect as the voltage ratio V_{acc}/V_{ext} increases.

2) It is shown that the Gaussian components are caused by the negative ions extracted from the different plasma meniscus region, that is, the central region or the region near the edges of the meniscus.

3) The peaks of the negative ion beam components extracted from the upper and lower meniscus region shift in the opposite direction each other as the voltage ratio V_{acc}/V_{ext} increases, which corresponds that the negative ion beam changes from the diverging beam to the converging beam .

4) The number of the negative ion trajectories extracted from the upper meniscus region is not the same as that extracted from the lower meniscus, which reflects that the negative ion density spatial profile is not symmetry with the axis.

5) It is considered that the asymmetry of the plasma meniscus results from that of the negative ion density spatial profile.