8th International symbosium on Negative Ions, Beams and Sources (NIBS' 22)
2nd – 7th October 2022, Orto Botanico, Padova, Italy

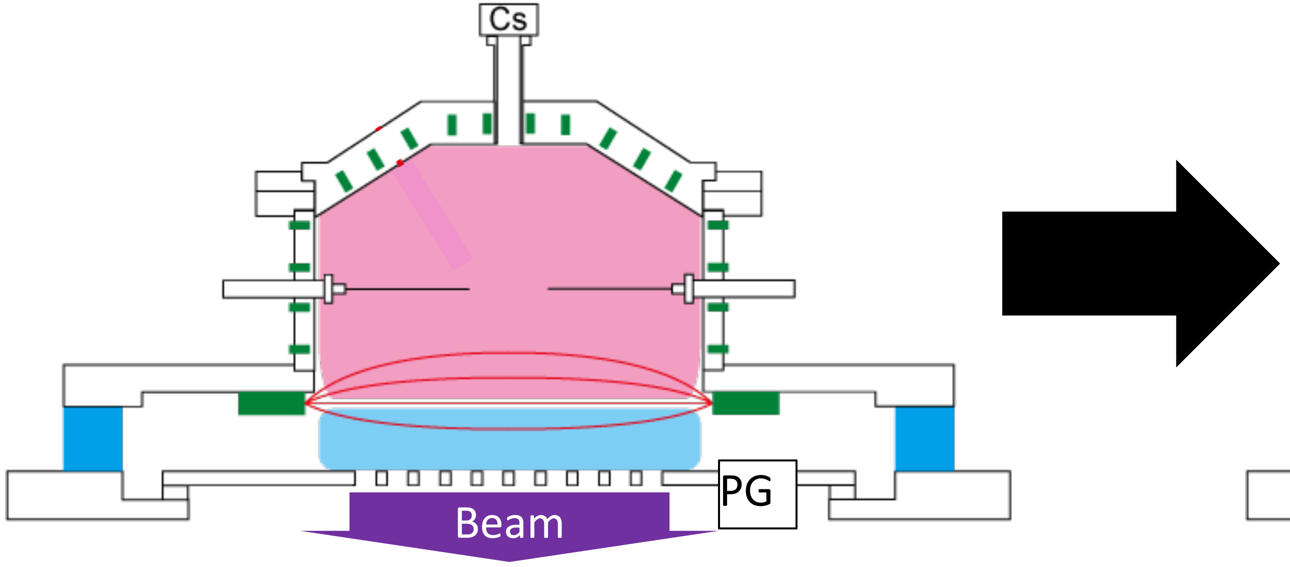
Negative and Positive Ion Density in front of Negative Ion Production Surface in Large-scaled Negative Ion Source for Fusion

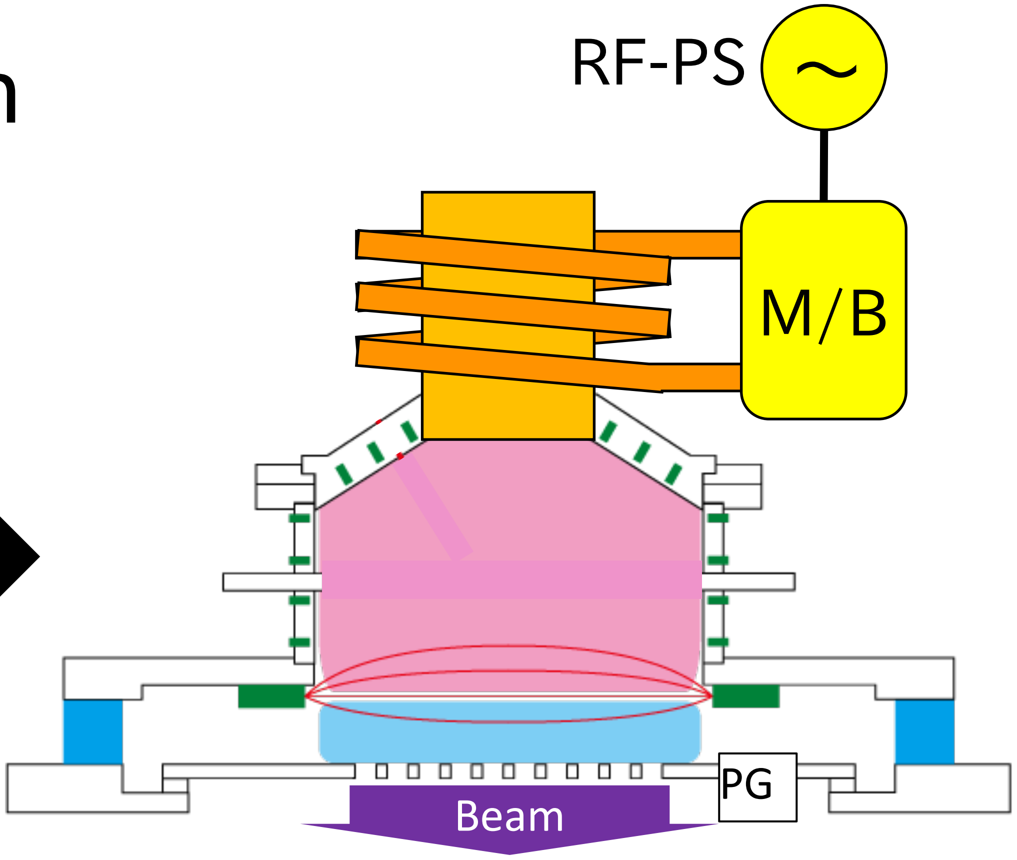
H. Nakano[1,2],

S. Masaki[3], K. Tsumori[1,3], M. Osakabe[1,3], Y. Takeiri[1], E Rattanawongnara[3], K. Ikeda[1], and K. Nagaoka[1,4]

[1]National Institute for Fusion Science, National Institutes of Natural Sciences
[2]Graduate School of Engineering, Nagoya University
[3]The Graduate University for Advanced Studies
[4]Graduate School of Science, Nagoya University

Negative ion source for fusion





Filament-driven Arc (FA) negative ion source

RF negative ion source

- The RF source is needed for CW operation, however there are tasks for applying actual NBIs.
- FA sources have been applied for actual NBIs on LHD and JT-60. The techniques and physics inside the FA source can contribute to the RF source development.

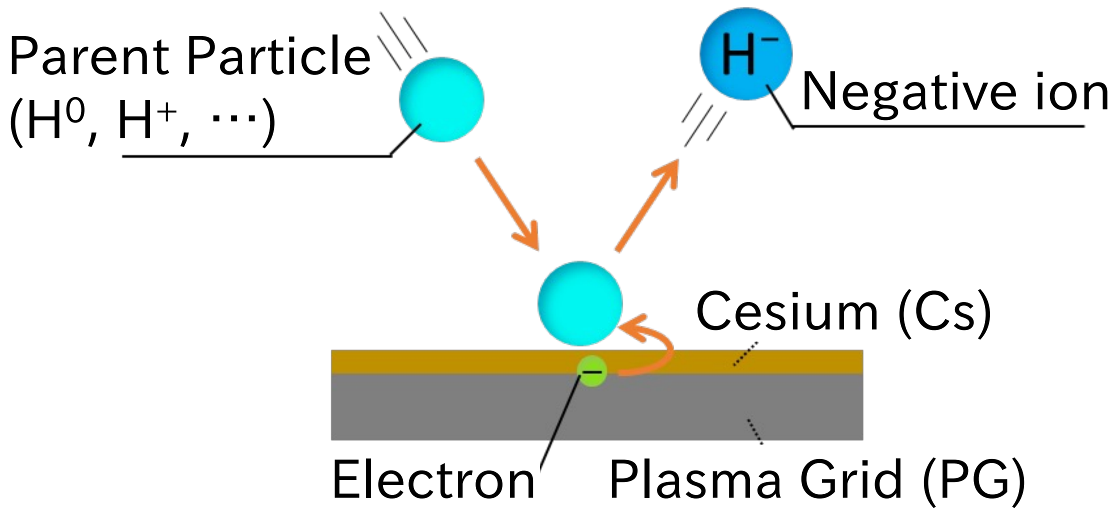
Objective

<Ion source for fusion>

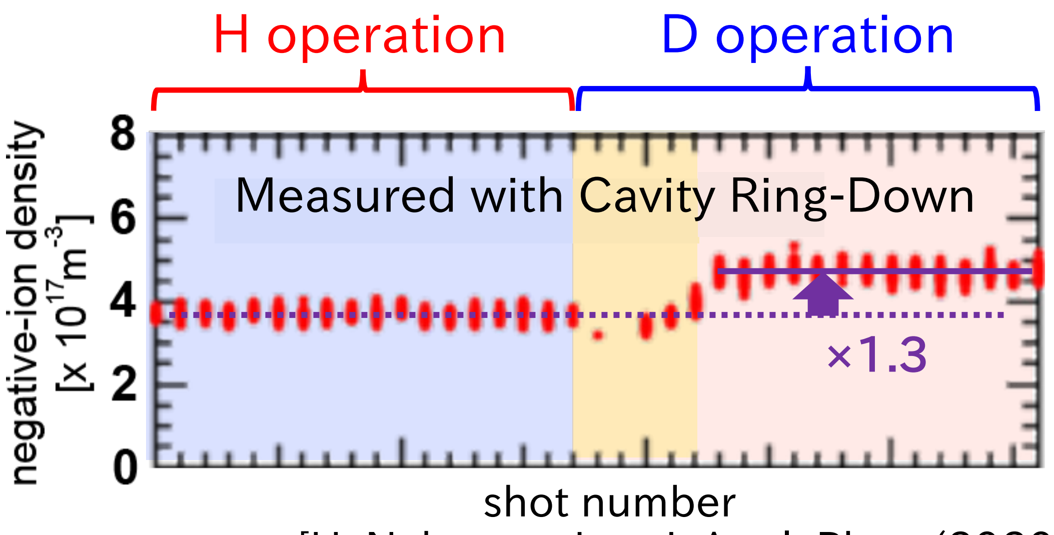
Large scale, cesium seeded, huge power, high energy, and cw (etc.) negative ion source

- Homogeniety, operation stability as well as high beam intensity and low divergence, etc.
- Surface negative ion production is dominat.
- Deuterium is utilized. Isotope effect exist.

Which is dominant parent particle?



Isotope effect on negative ion density

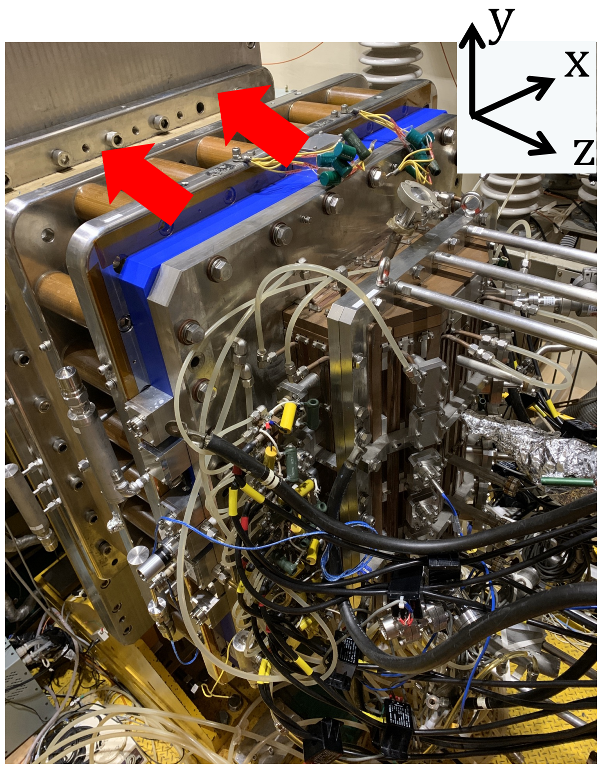


[H. Nakano+, Jpn. J. Appl. Phys. (2020)]

Objective

- Species of parent particle of surface produced negative ion production is identified.
- Understanding of the isotope effect on negative ion density is improved.

Experimental Setup (NIFS-RNIS)



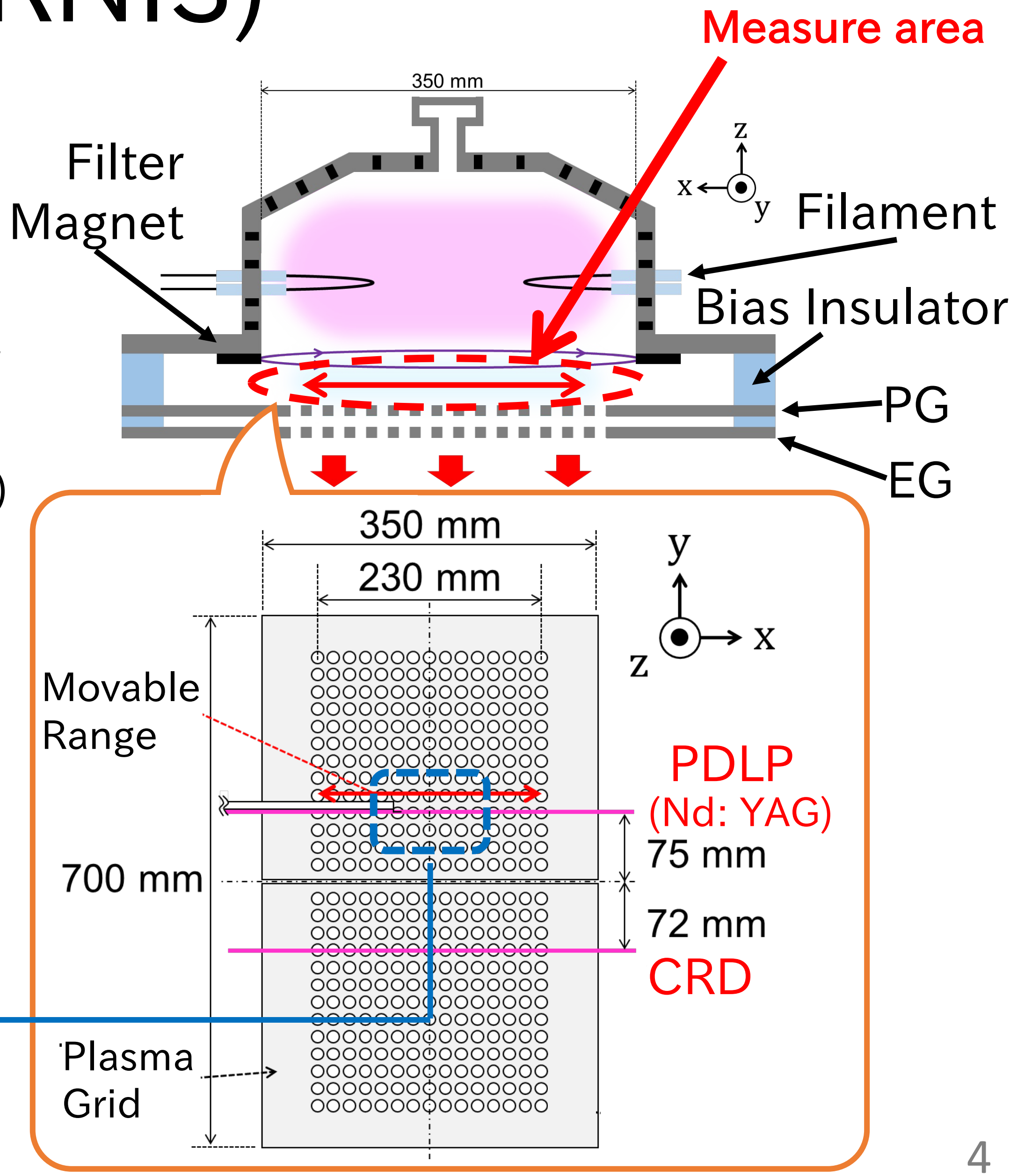
Research and development Negative Ion Source (NIFS-RNIS)

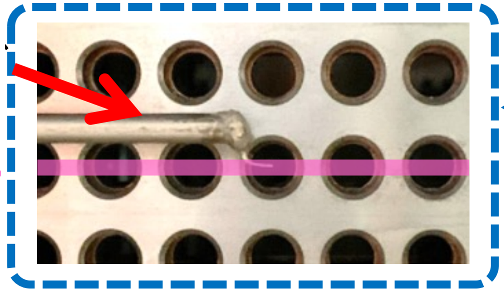
<Diagnostics>

- Cavity RingDown technique (CRD)
  - Line-averaged absolute negative ion density
- Photo-Detachiment with Langmuir Probe (PDLP)
  - Local negative ion density (n_-) (with CRD support)
  - Local positive ion density (n_+)

<Operation cond. >

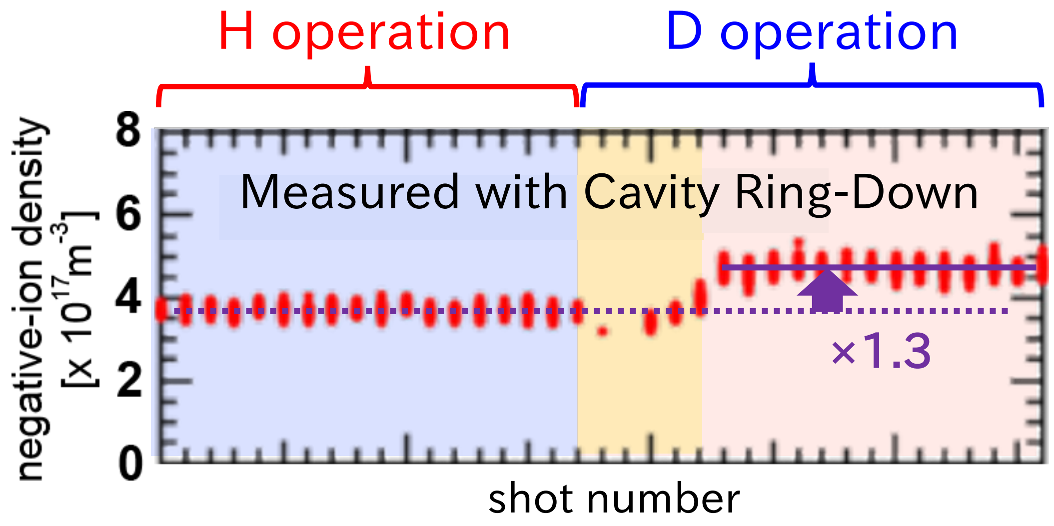
- Pressure: 0.3 Pa@H_2, D_2
- No beam extraction



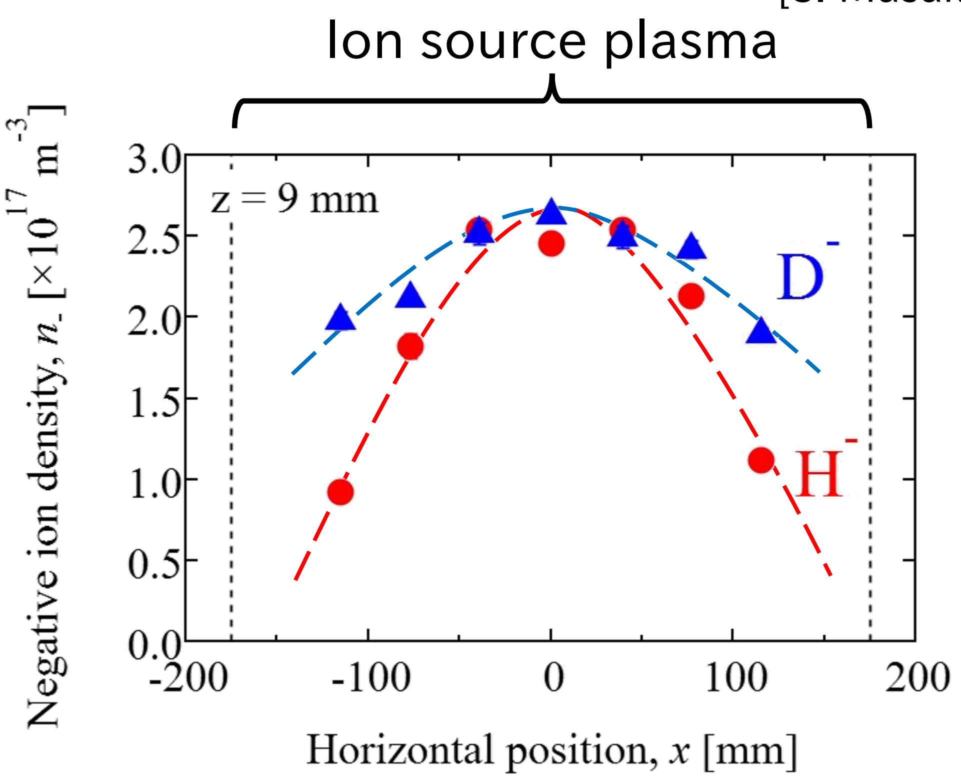


Isotope effect on negative ion density

[S. Masaki+, RS (2020)]



[H. Nakano+, Jpn. J. Appl. Phys. (2020)]



Line-averaged $n(H^{-})$ was 1.3 times higher than $n(D^{-})$.

Because peripheral $n(D^{-})$ is higher.

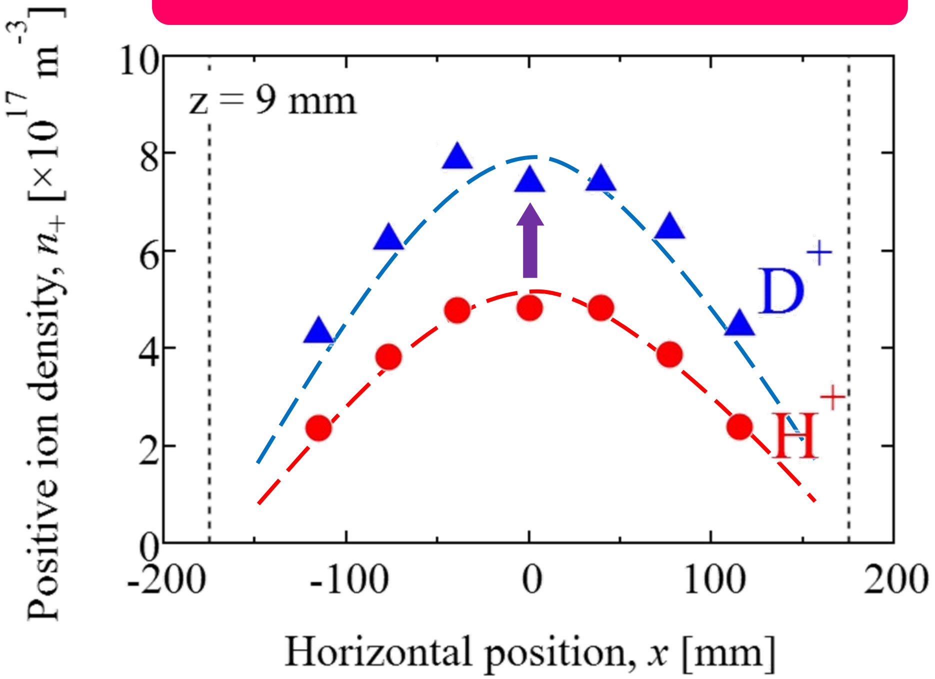
Different n_{-} was observed between D and H operations.

- Center: $n(D^{-}) \sim n(H^{-})$.
- Periphery: $n(D^{-}) > n(H^{-})$.

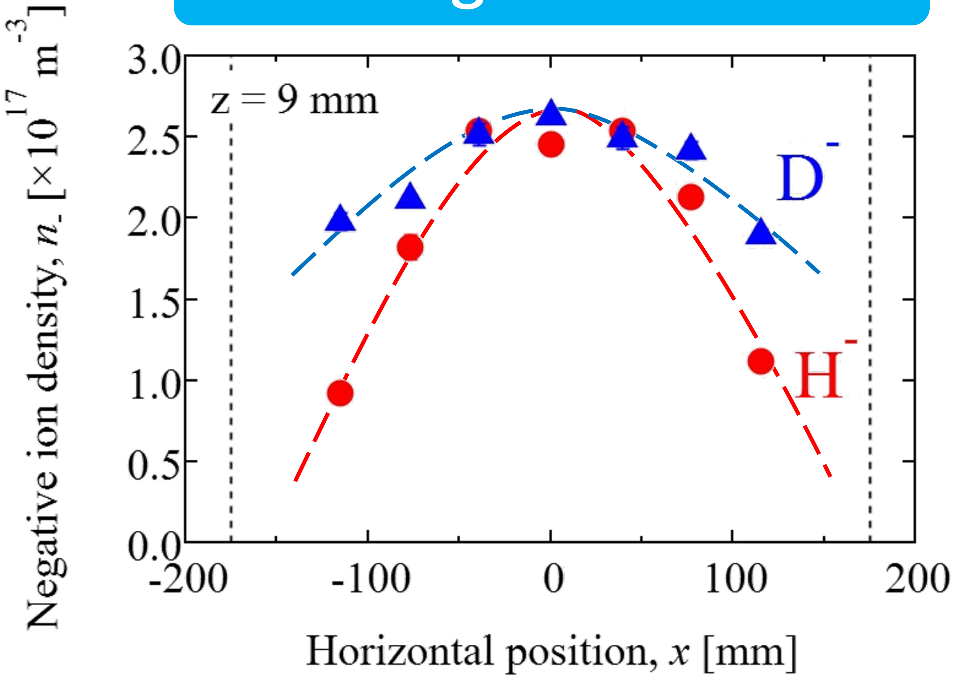
Positive ion density profile

[S. Masaki+, Rev. Sci. Instrum. (2020)]

Positive ion



Negative ion



$n(D^{+})$ is higher than $n(H^{+})$ with the same profile shape.

Different n_{-} was observed between D and H operations.

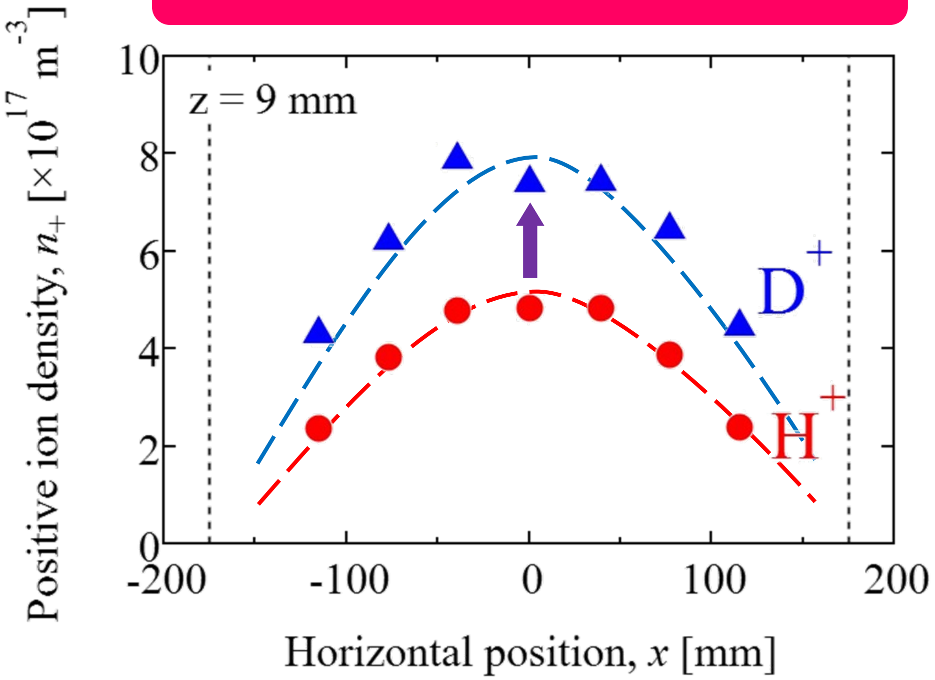
- Center: $n(D^{-}) \sim n(H^{-})$.
- Periphery: $n(D^{-}) > n(H^{-})$.

Why are n_{-} profile shapes different by isotopes?

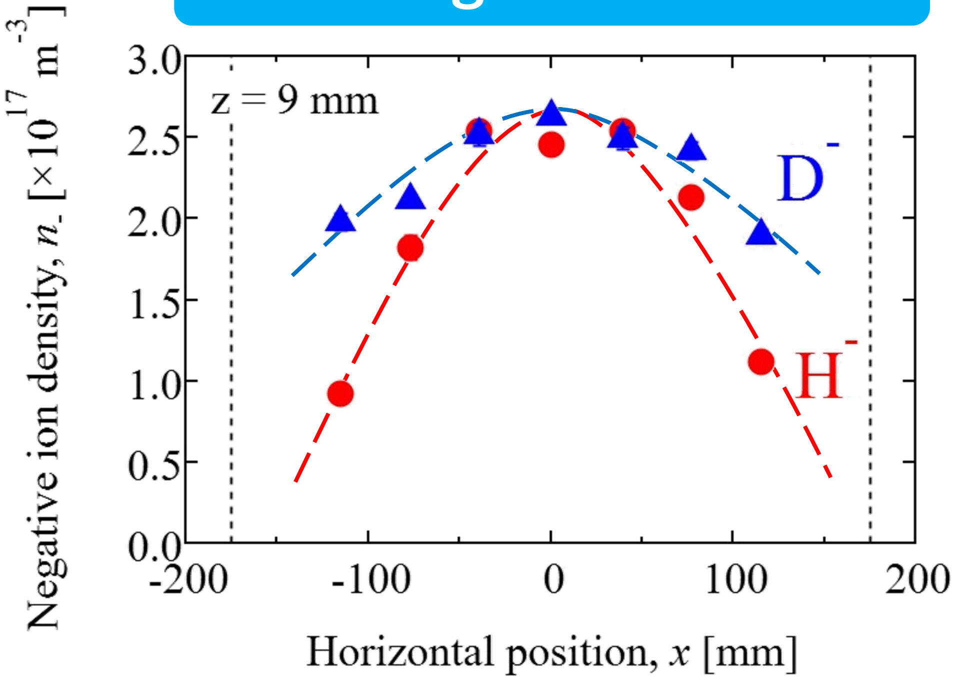
Positive ion density profile

[S. Masaki+, Rev. Sci. Instrum. (2020)]

Positive ion



Negative ion

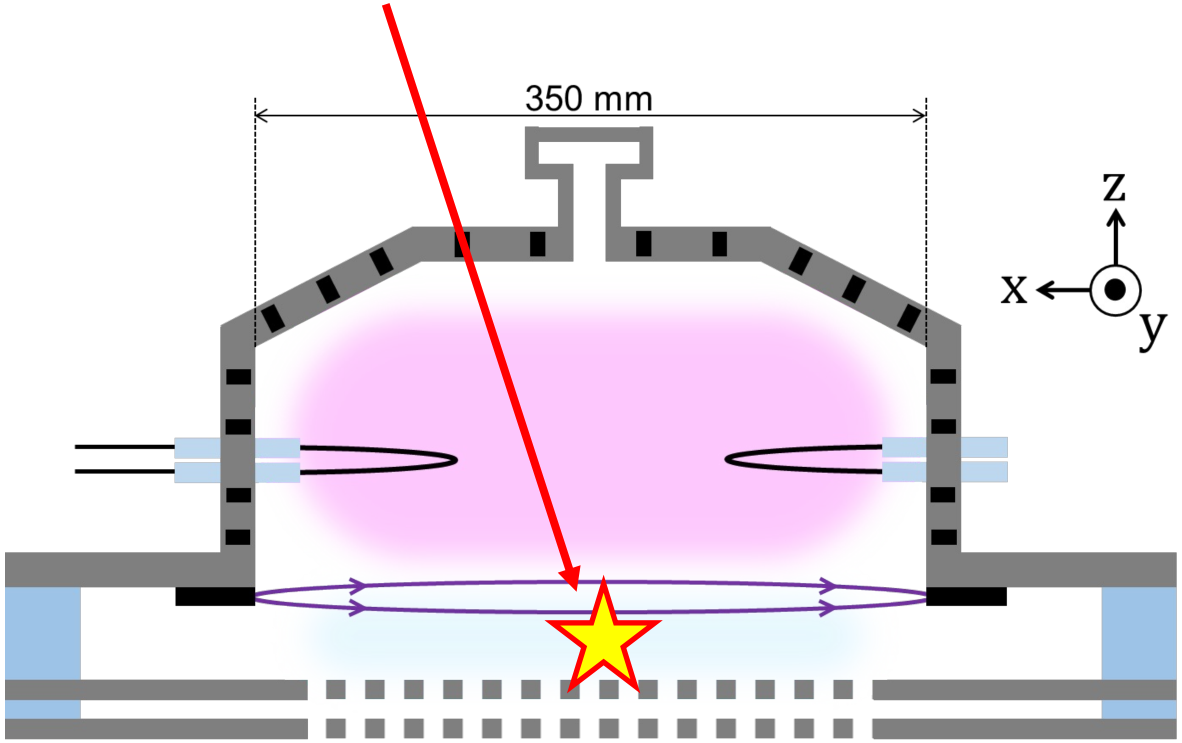


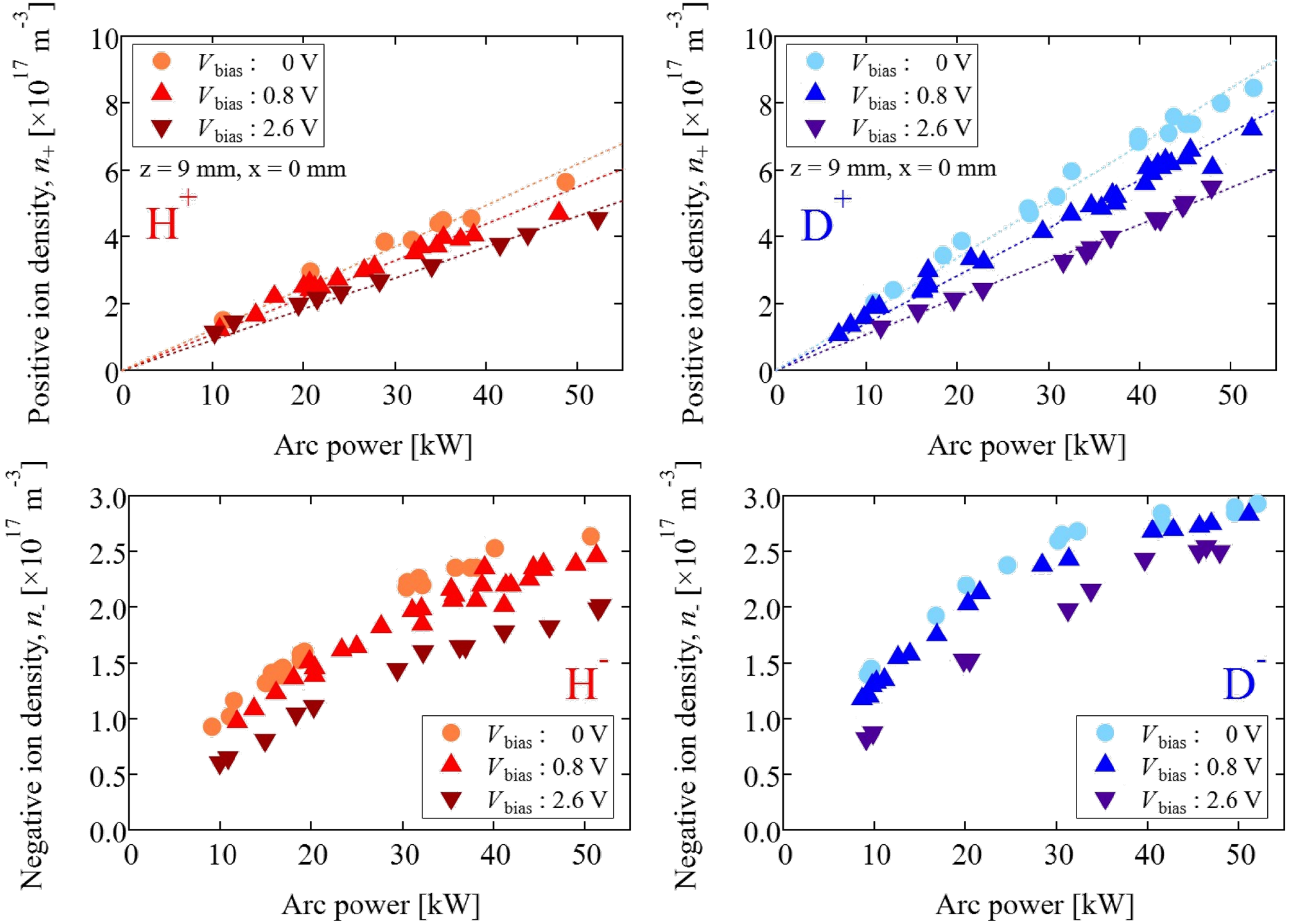
Why are n_- profile shapes different by isotopes?

1. Different atom profiles?
   → Local measurement of atom is not easy.
2. Different negative ion production yeild by isotopes?
   → Explore relation between positive and negative ions.

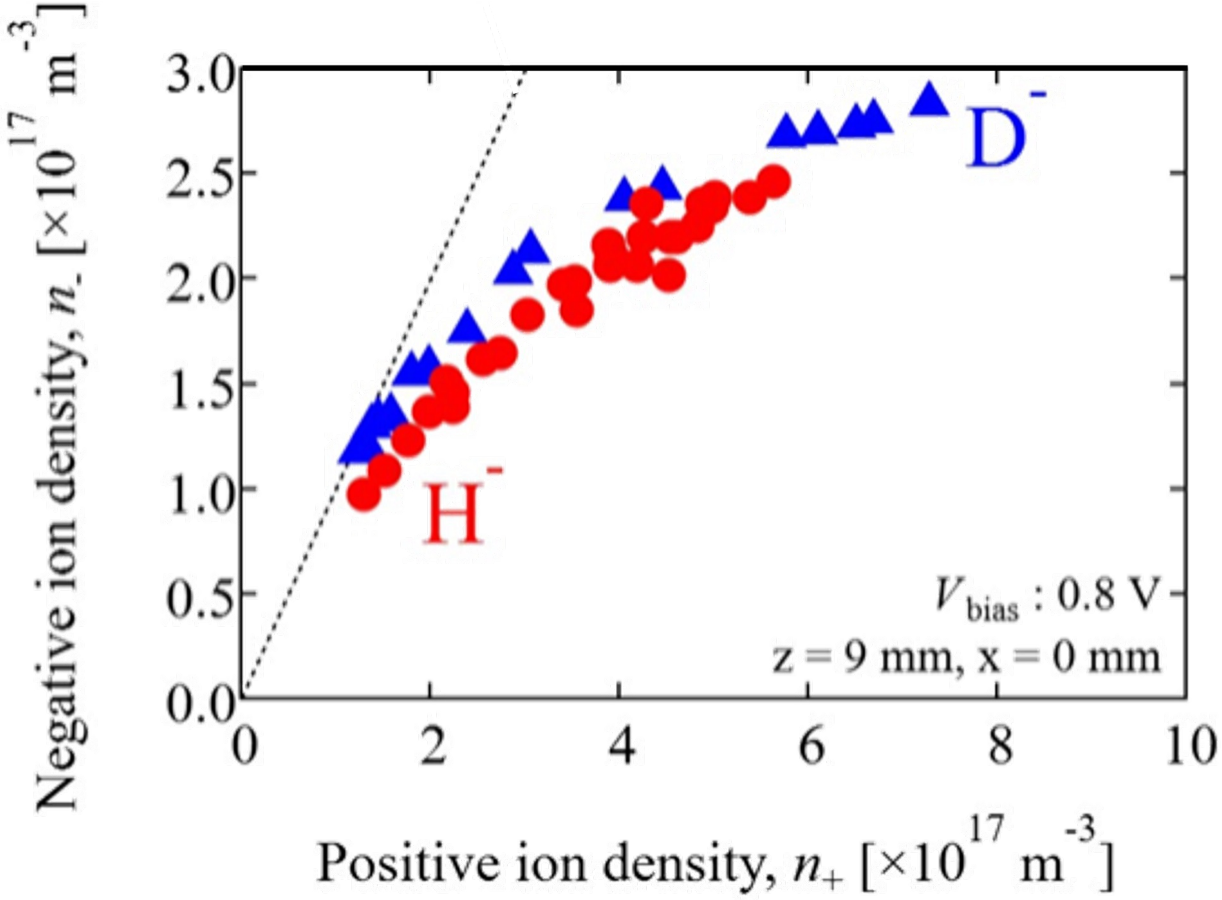
Positive and negative ion density as a function of discharge power at horizontal center

Measure density at the horizontal center.





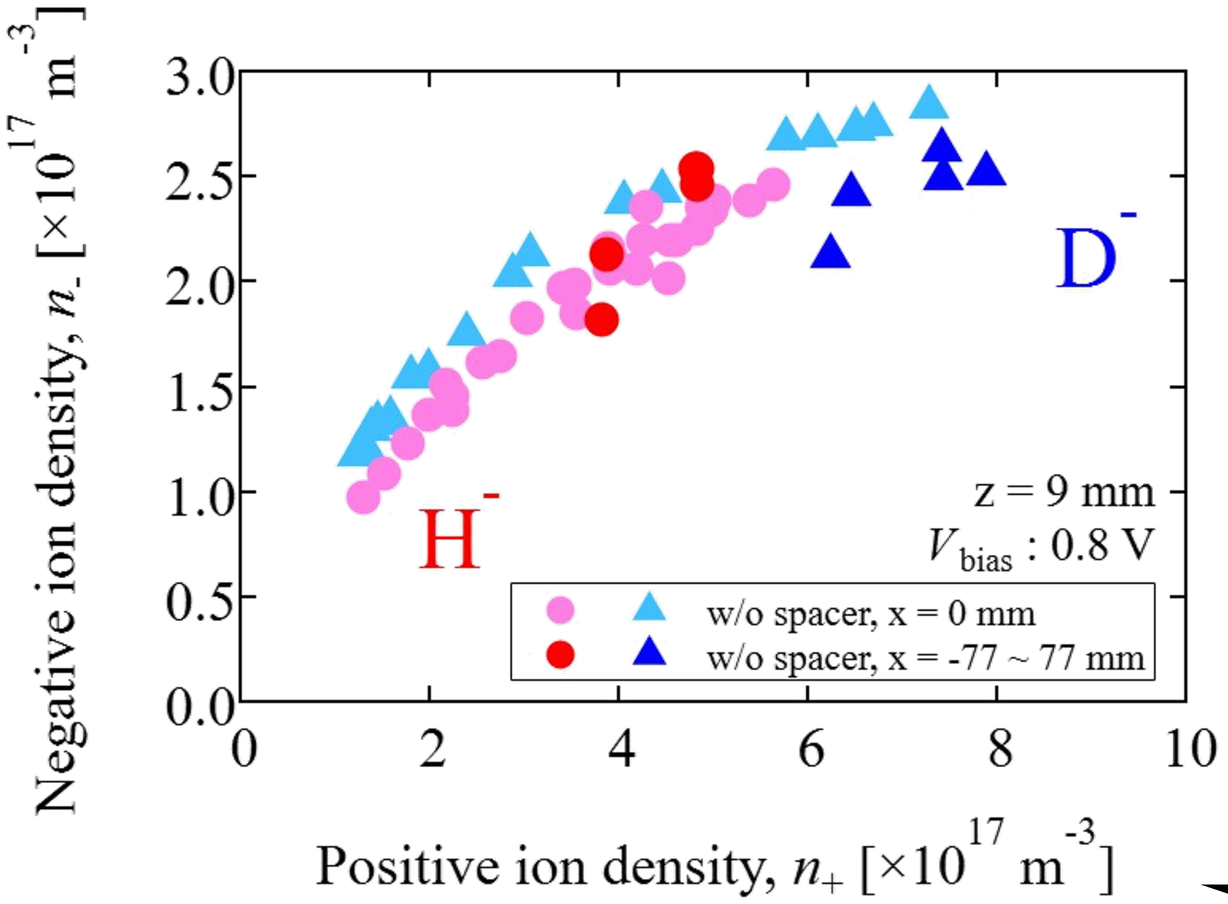
Negative ion ratio to positive ion at horizontal center



1) Increase of n_- degrades for n_+ in both isotope cases.

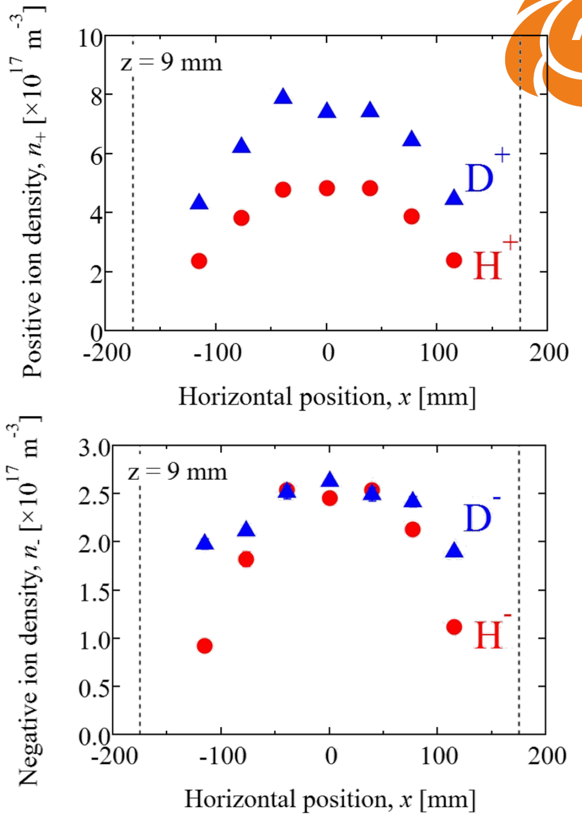
2) Absolute values n_- of the isotopes for n_+ are similar.

Negative ion ratio to positive ion



Combine

Density profile



Points of n_- as a function of n_+ from profile measuremets are ploted on the same trend evaluated from data at the center.

Local n_- seems to strongly depends on local n_+.

$n(D^-) \sim n(H^-)$ at the center caused by the n_- degradation as a function of n_+ in higher n_+.

Dominant parent particle of surface produced negative ion seems to be positive ion.

Why does the n_- degrade in high n_+?

Rate equation for negative ion density

$$\frac{\mathrm{d}n_-}{\mathrm{d}t} = S - n_-(n_+ R_{\mathrm{MN}} + n_{\mathrm{e}} R_{\mathrm{ED}} + n_{\mathrm{n}} R_{\mathrm{AD}}) - \frac{n_-}{\tau}$$

S : Negative ion production rate τ : Servibal time of negative ion

Destruction process	Reaction speed coefficient
➢ Mutual neutralization (MN)	$R_{\mathrm{MN}} = \int_0^\infty f_+(E)\sigma_{\mathrm{MN}}(E)v_+(E)dE$
➢ Electron impact destruction (ED)	$R_{\mathrm{ED}} = \int_0^\infty f_{\mathrm{e}}(E)\sigma_{\mathrm{ED}}(E)v_{\mathrm{e}}(E)dE$
➢ Atomic impact destruction (AD)	$R_{\mathrm{AD}} = \int_0^\infty f_{\mathrm{n}}(E)\sigma_{\mathrm{AD}}(E)v_{\mathrm{n}}(E)dE$

In stationary state $\left(\frac{\mathrm{d}n_-}{\mathrm{d}t} = 0\right)$, above equation becomes

Production Destruction

$$n_- = \tau\{S - n_-(n_+ R_{\mathrm{MN}} + n_{\mathrm{e}} R_{\mathrm{ED}} + n_{\mathrm{n}} R_{\mathrm{AD}})\}$$

Dominant negative ion destruction process

Production Destruction

$$n_- = \tau\{S - n_-(n_+R_{\mathrm{MN}} + n_\mathrm{e}R_{\mathrm{ED}} + n_\mathrm{n}R_{\mathrm{AD}})\}$$

Destruction FRQ: f_{MN}, f_{ED}, and f_{AD}

$f_{\mathrm{MN}} \sim 2\times10^4$ Hz $@n_+ \sim 5\times10^{17}\ \mathrm{m}^{-3}$, $T_+ \sim 0.3$ eV

$f_{\mathrm{ED}} \sim 2\times10^3$ Hz $@n_\mathrm{e} \sim 2\times10^{17}\ \mathrm{m}^{-3}$, $T_\mathrm{e} \sim 0.8$ eV

$f_{\mathrm{AD}} \sim 6\times10^3$ Hz $@n_\mathrm{n} \sim 5\times10^{18}\ \mathrm{m}^{-3}$, $T_\mathrm{n} \sim 0.3$ eV, Dissociation Rate: 0.7 in 0.3 Pa (H_2, D_2)

Dominant negative ion destruction process is the mutual neutralization (MN) by positive ion.

MN process makes the relation between n_- and n_+.

Production / Destruction

$$n_- = \tau\{S - n_-(n_+R_{\mathrm{MN}} + n_eR_{\mathrm{ED}} + n_nR_{\mathrm{AD}})\} \sim \tau\{S - n_-n_+R_{\mathrm{MN}}\}$$

If the parent particle of negative ion is positive ion, $n_-(\mathrm{Production}) \propto n_+$.

$$\tau S \equiv \eta n_+.$$

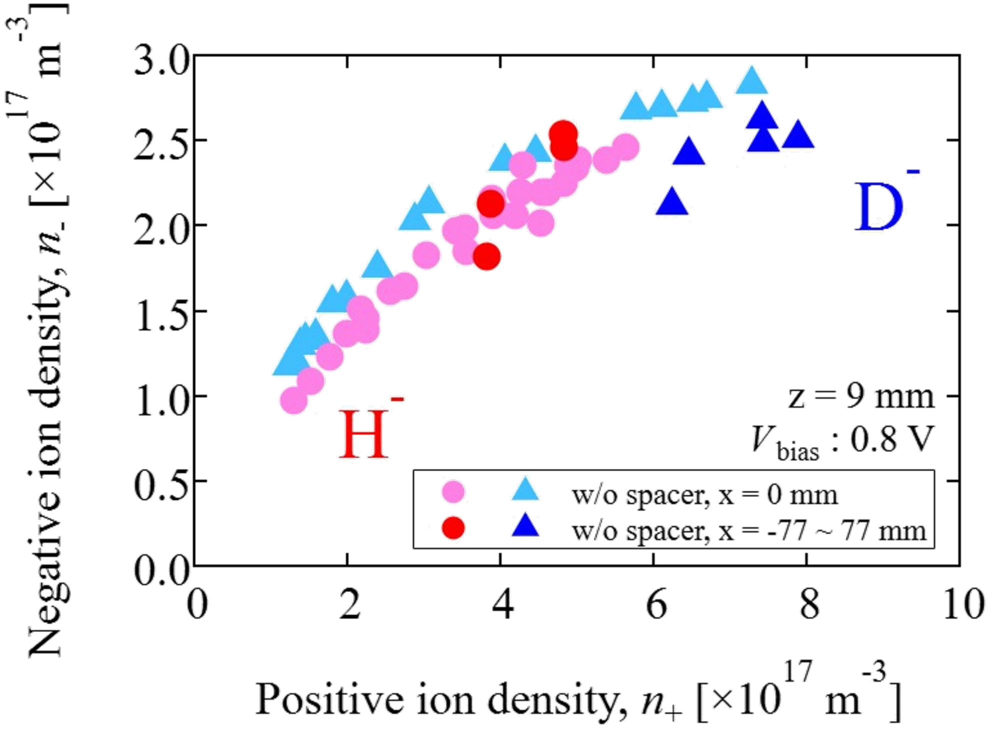
Destruction term can be written by

$$\tau R_{\mathrm{MN}} n_- n_+ = \tau R_{\mathrm{MN}}(\eta n_+)n_+ \equiv \kappa n_+^2.$$

Rate equation is modified by

$$n_- = \eta n_+ - \kappa n_+^2.$$

Production / Destruction



Degradation of n_- increase with n_+ is caused by mutual neutralization (MN) in high n_+ region if parent particle is positive ion.

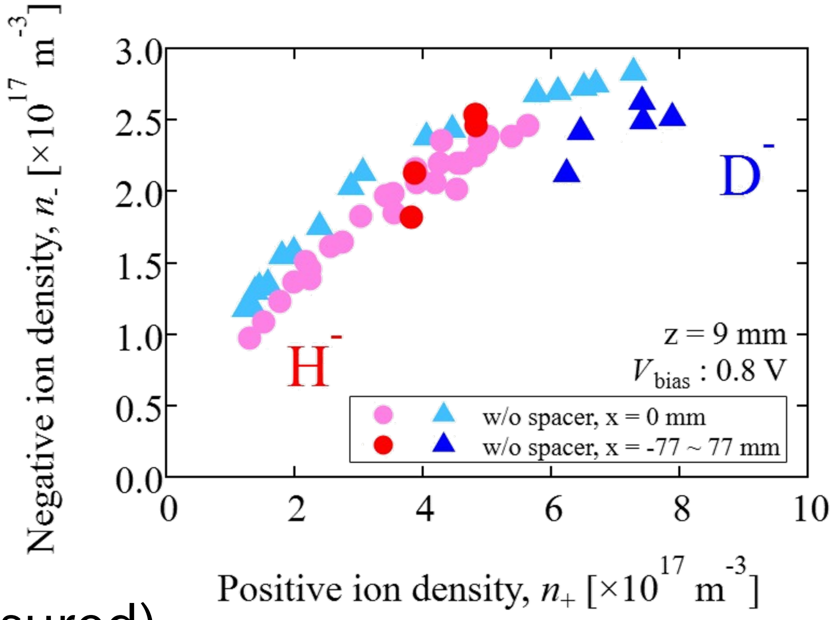
Characteristics length of negative ion mortion

$$\begin{cases} \tau S \equiv \eta n_+. \\ \tau R_{\mathrm{MN}}(\eta n_+) n_+ \equiv \kappa n_+^2. \end{cases}$$

Negative ion survibal time:

$$\tau = \frac{\kappa}{\eta R_{\mathrm{MN}}} \sim 2\times10^{-5}\ [s]$$

From curve fitting



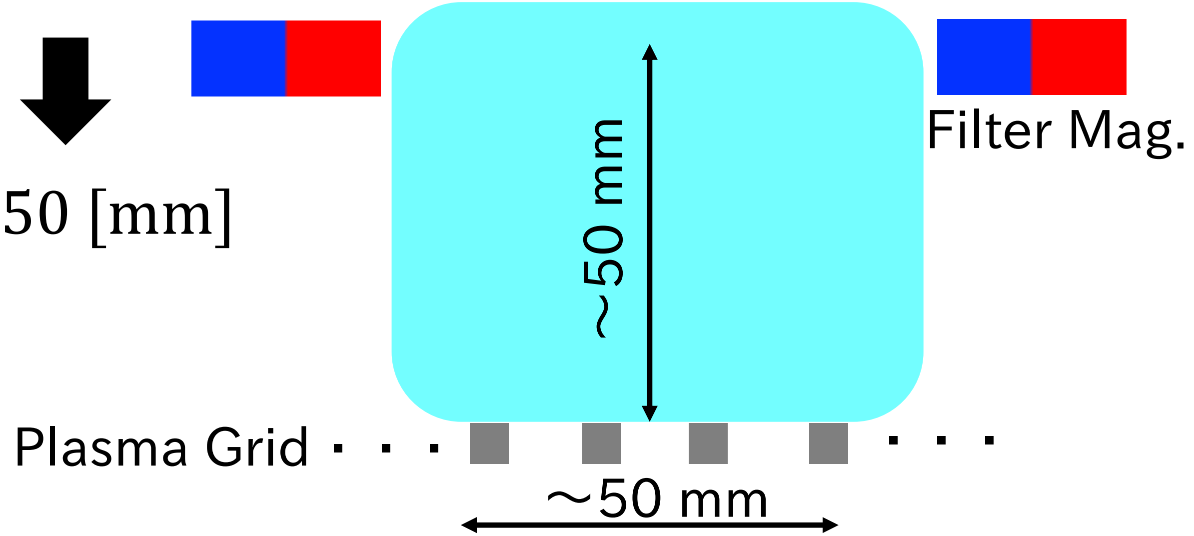
Negative ion survibal time can be also written by

$$\tau \equiv \frac{L}{v_{\mathrm{th-}}}$$

L : Characteristic langth of negative ion mortion

$v_{\mathrm{th-}}$: Negative ion thermal velocity, ~0.1 eV (measured)

$$L \sim 50\ [\mathrm{mm}]$$

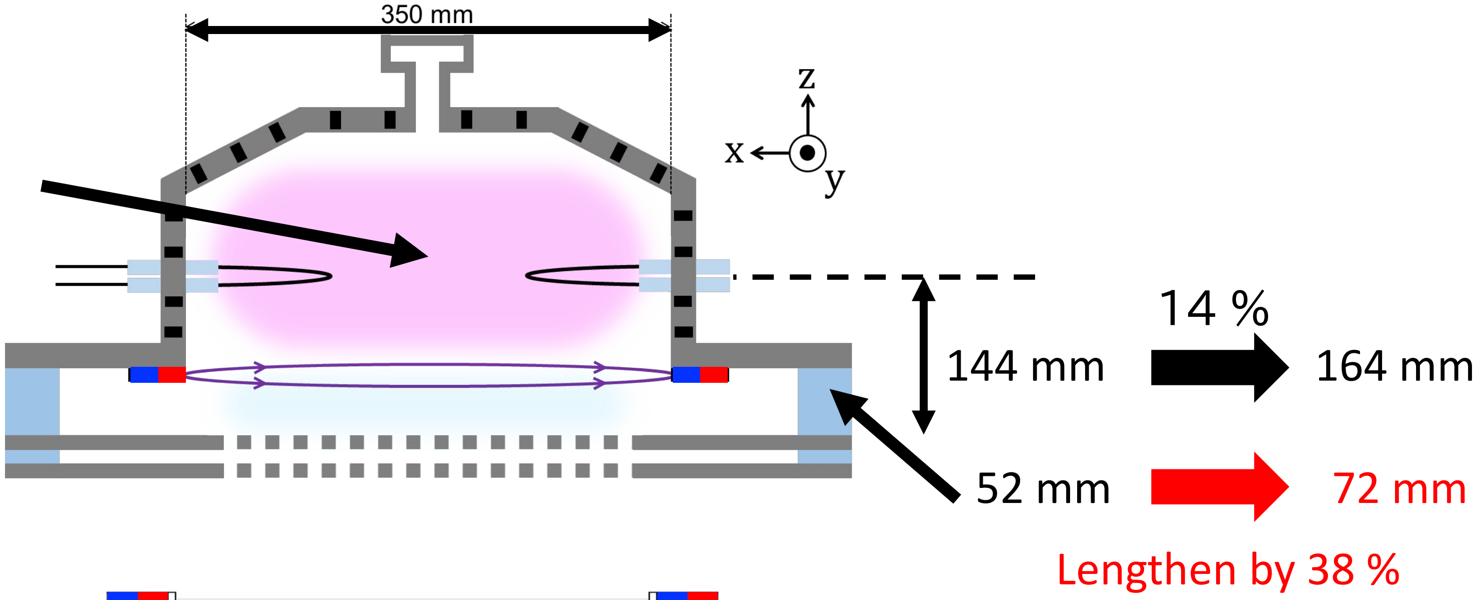


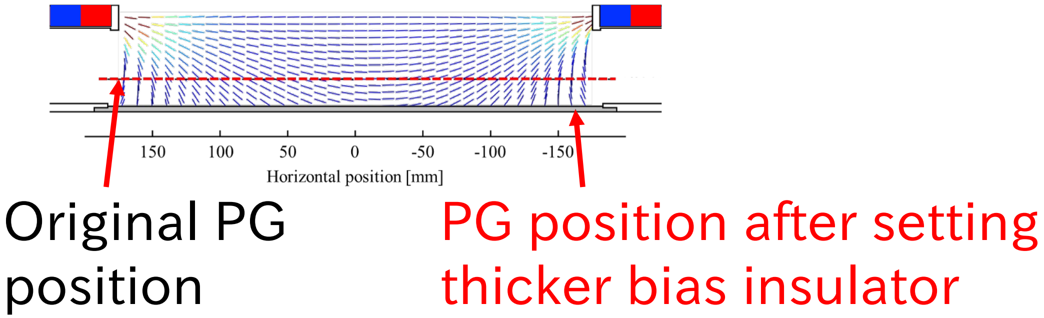
Local n_- dependence on local n_+ can be explained by assuming positive ion being dominant negative ion particle.

Reduction of n_+ with maintaining energetic atom flux

Energetic atom having potential of being nagative ion parent particle should be generated in plasma generation region with high T_e by Frank-Condon process.

Energetic atom flux to PG is not affected by the filter field.



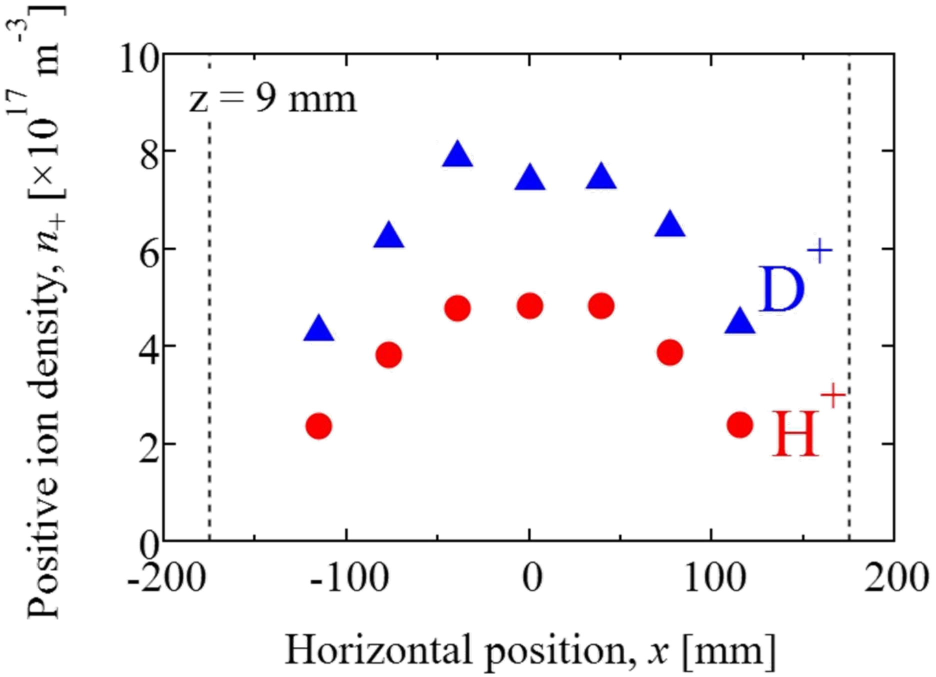


Reduction of n_+ near PG with maintaining energetic atom flux can be conducted.

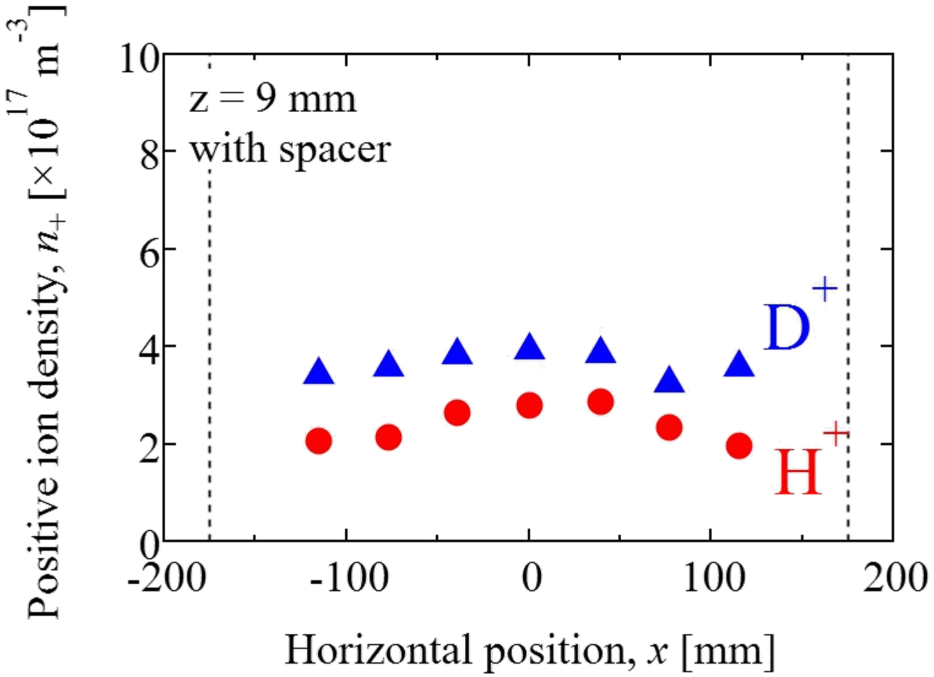
n_+, actually plasma density, is expected to decrease in the vinicity of PG.

Positive ion density profile with thicker bias flange

Original bias insulator



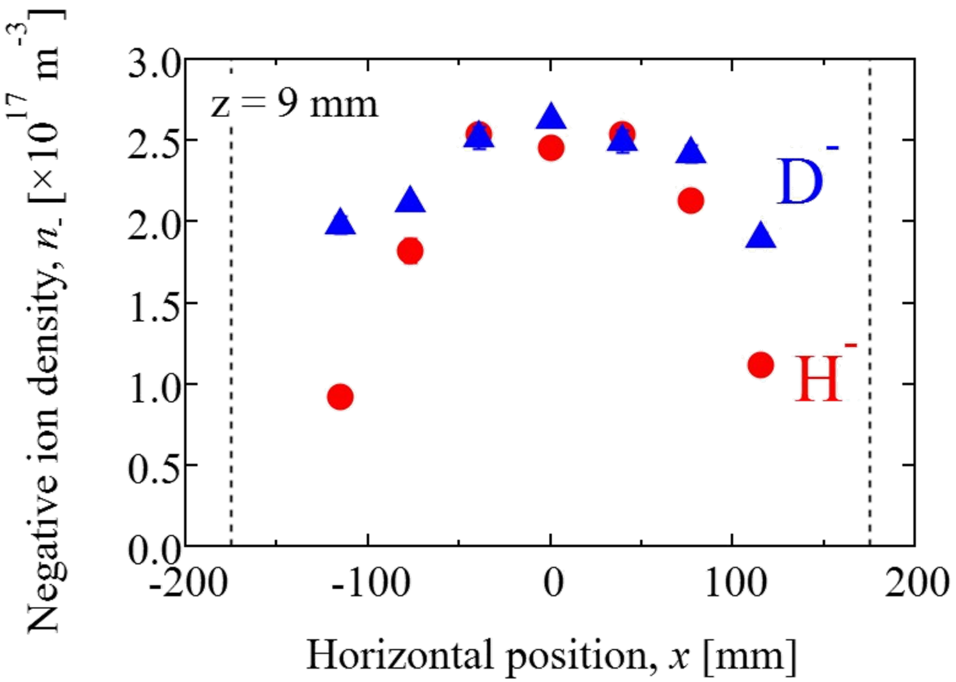
Thicker bias insulator



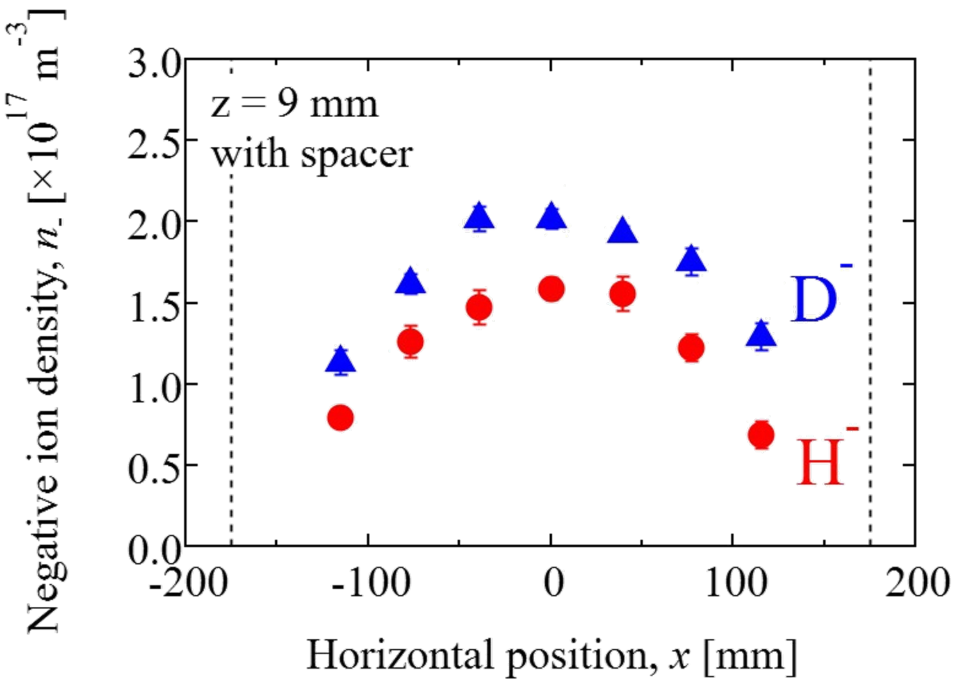
Both H and D positive ions density deccreased in the expectation.

Negative ion density profile with thicker bais flange

Original bias insulator



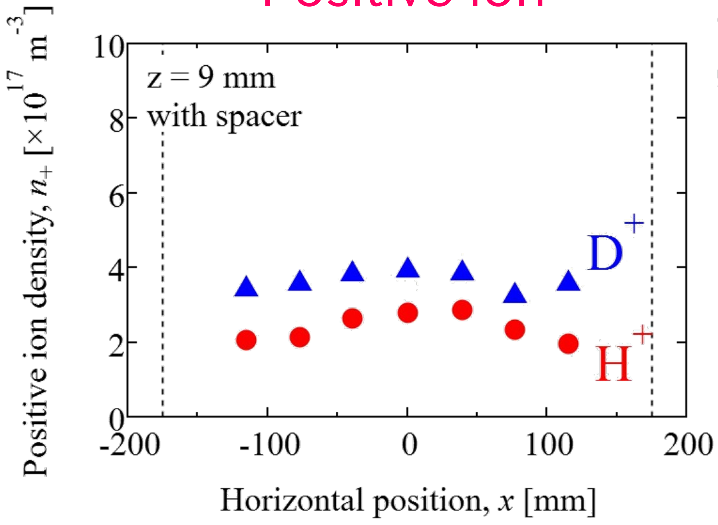
Thicker bias insulator



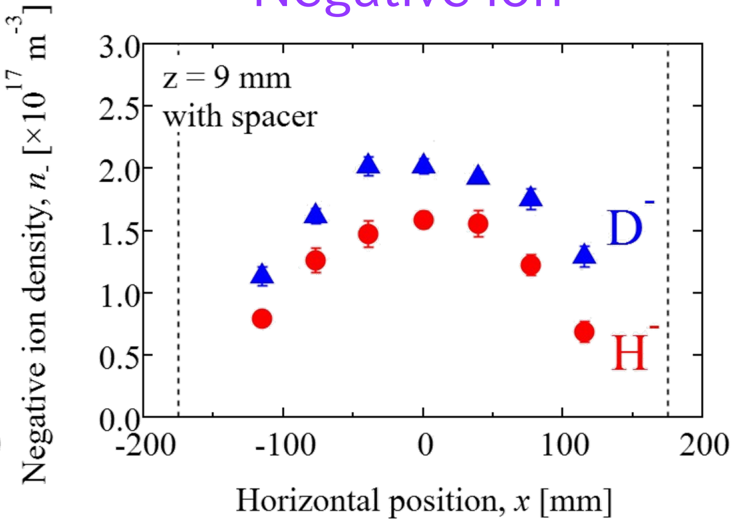
- Both H and D negative ions density decreased as well as positive ion density. Central density decreased by ~25 %, which corresponds to expected energetic atom flux density reduction by 14 % further distance of filament (plasuma production area) from the PG comparing with original.
- **But** both shapes of H and D negative ion profile were peak in thicker bias insulator case.

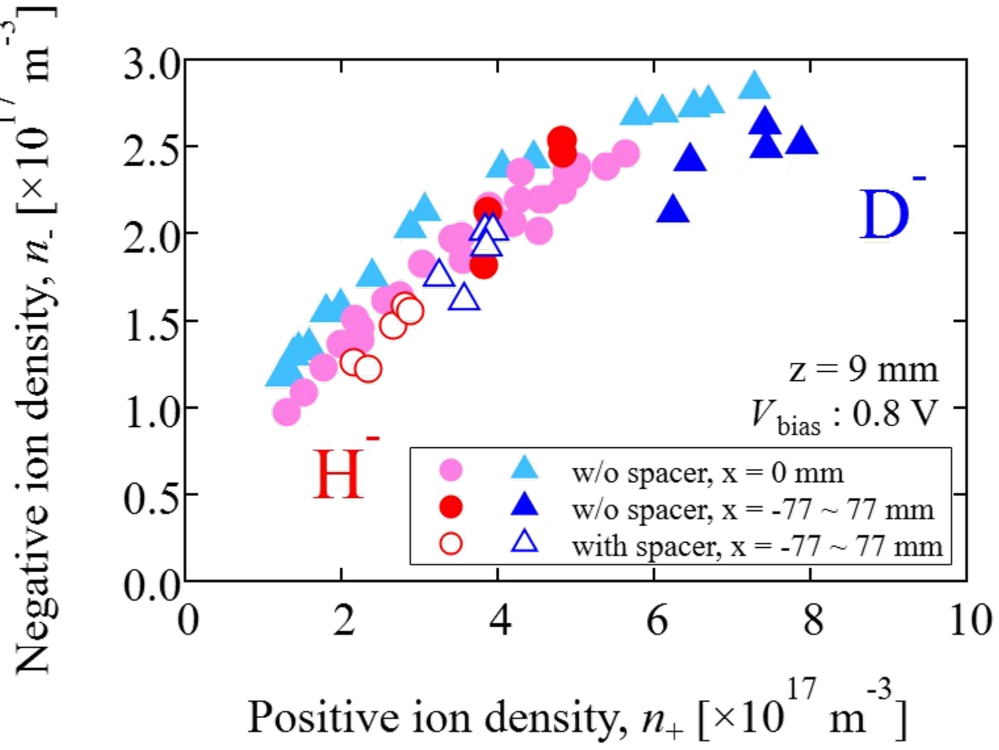
Relation between n_- and n_+

Positive ion



Negative ion





With the thicker bias insulator, the relation between n_- and n_+ is the same as other data.

Data in various experiment agree with the positive ion being the dominant parent particle for the surface produced negative ion.

Summary

Mutual neutralization is a main process of negative ion destruction.

- The n_- increase with n_+ degrades in high n_+ .
- Ratios of n_-/n_+ of the isotopes are similar values as a function of n_+.
- In local area, whose characteristic length is $\sim$ 50 mm, the n_- is limited by the n_+. This means n_- profile is affected by n_+ profile.

There is no inconsistensy in positive ion as the dominant parent particle of surface produced negative ion in NIFS-RNIS with condigion of 0.3 Pa in H and D operations.