Fourth IAEA Technical Meeting
on **"Negative Ion Based Neutral Beam Injectors"**
May 9-11 2005, Padova - Italy

Modeling of Negative Ion Transport in Cesium-Seeded Volume Negative Ion Sources

Osamu Fukumasa and Ryo Nishida

Department of Electrical and Electronic Engineering
Faculty of Engineering, Yamaguchi University,
Ube 755-8611, Japan

CONTENTS

Background

Two-step process of H^- volume production

(1) $H_2(v''=0) + e_{fast}\ (E_{fe}>20\sim30eV) \rightarrow H_2(v'')$

(2) $H_2(v''>5) + e_{slow}\ (T_e=1eV) \rightarrow H^- + H$

Optimization (Enhancement)

Tandem two-chamber system

magnetic filter/plasma grid → f(E), n_e, T_e

Introduction of cesium

enhancement of H^- production → cesium effect (surface)

Extraction of negative ions

probability, beam optics

→ **Source Modeling**

Yamaguchi Univ.
Plasma Lab.

Objectives

(1) Optimization of H^- volume production

→ plasma parameter dependence

(2) Modeling cesium effects

→ surface effect, volume effect

→ enhancement of H^- production

(3) Estimation of extracted H^- current

→ pressure dependence of extraction probability

→ average energy of extracted H^- ions

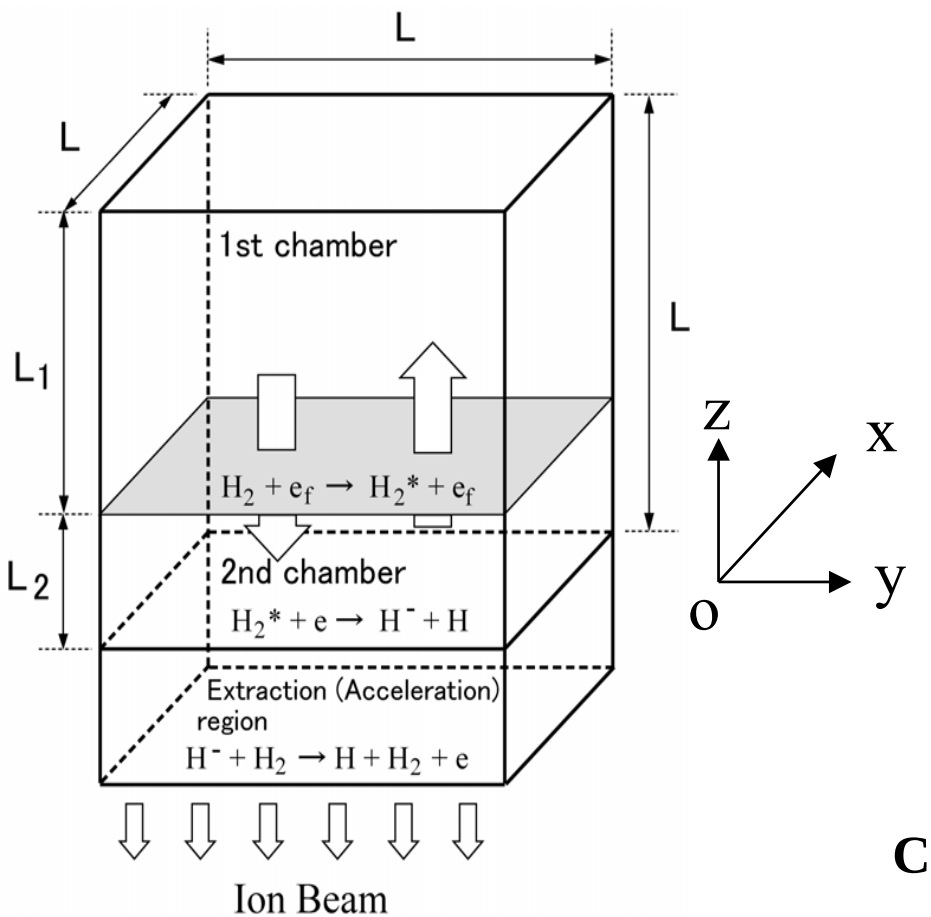
→ pressure dependence of extracted H^- current

(4) Modeling D^- production, isotope effect

Numerical Model

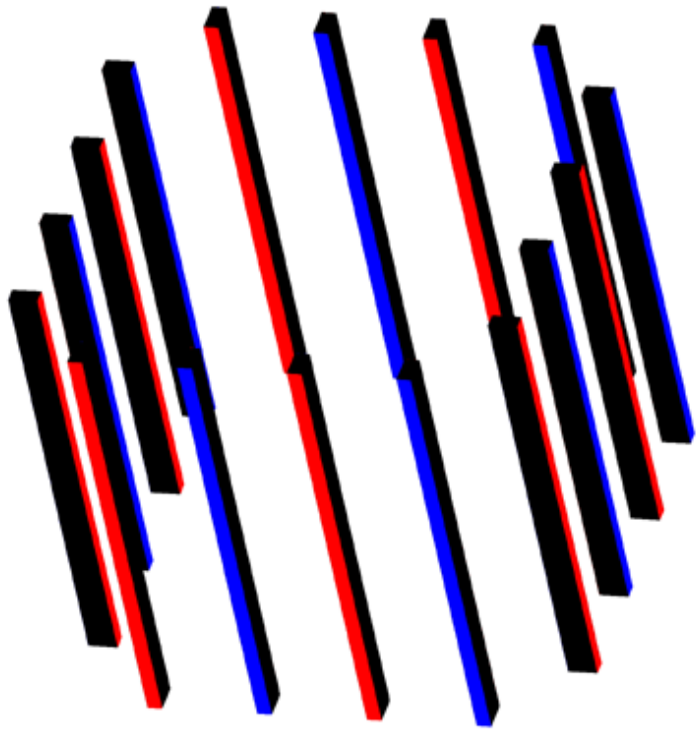
Motion equation

$$M\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{dt}} = q(\boldsymbol{v}\times\boldsymbol{B}) + \boldsymbol{F}_{col}$$



Magnetic filter

$$B_y = B_0 \exp\left[-\left(\frac{z-z_0}{l_B}\right)^2\right]$$

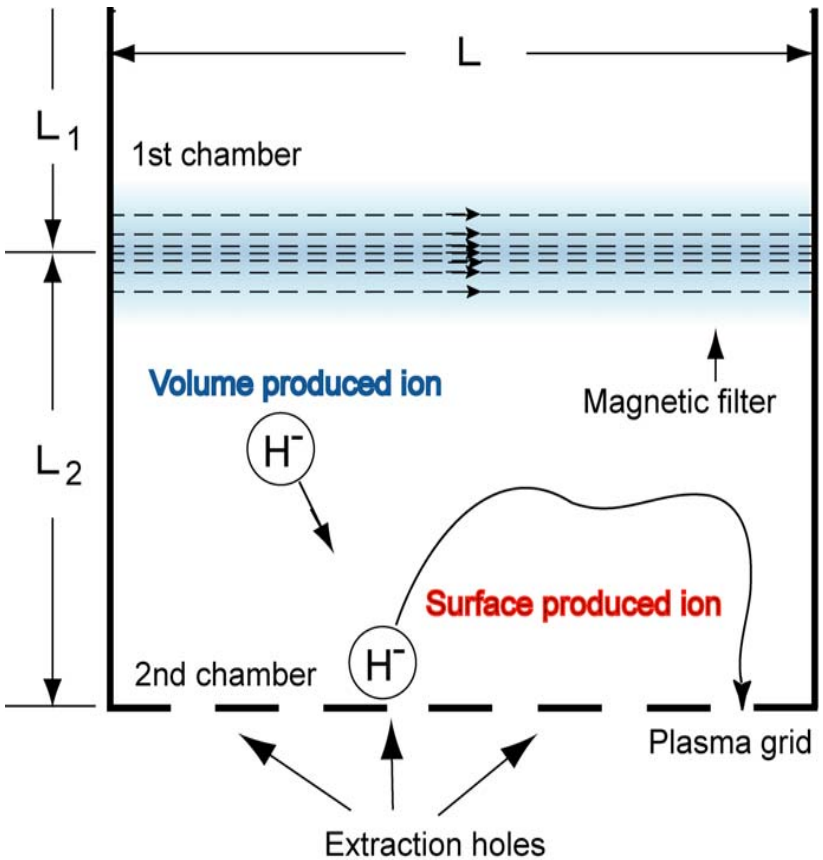


Construction of line-cusp magnetic field

Cross-sectional view of the model geometry for the second chamber

Motion equation

$$M\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{dt}} = q(\boldsymbol{v}\times\boldsymbol{B}) + \boldsymbol{F}_{col}$$

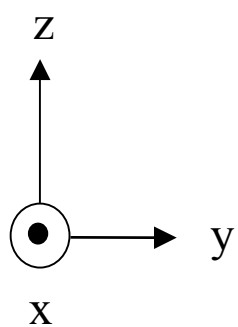


Magnetic filter

$$B_y = B_0 \exp\left[-\left(\frac{z-z_0}{l_B}\right)^2\right]$$

$B_0 = 120$ (Gauss)
$z_0 = 2$ (cm)
$l_B = 4$ (cm)

Geometrical transparency 40%



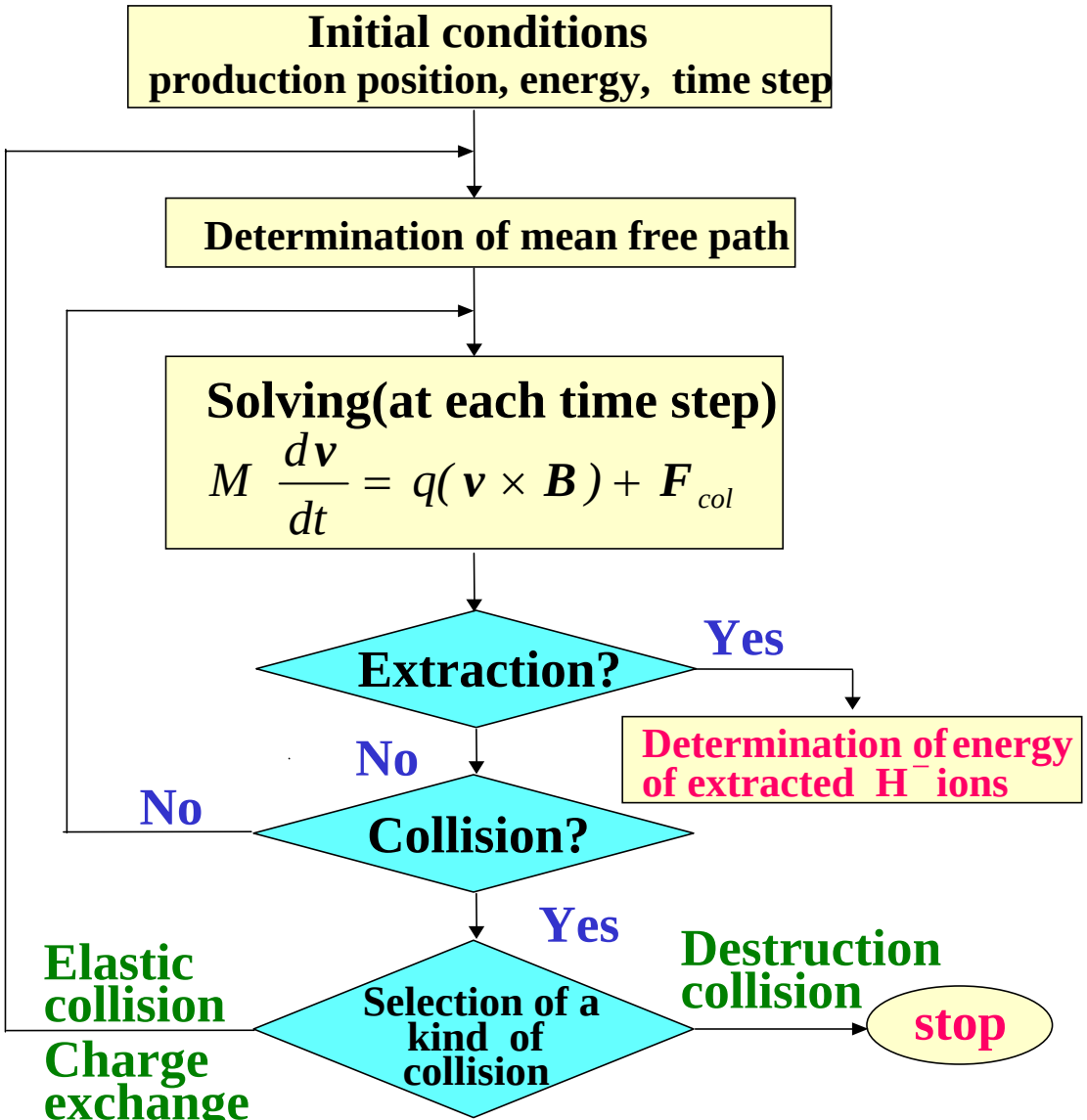
Yamaguchi Univ.
Plasma Lab.

Collisional processes （2nd, Pressure = 5mTorr with Cs）

Collisional processes	Surface produced H^- ions		Volume produced H^- ions	
	mfp [cm]	Collision probability [%]	mfp [cm]	Collision probability [%]
$H^- + e \rightarrow H + 2e$	141.82	0.39	93.18	0.47
$H^- + H^+ \rightarrow 2H$	41.82	1.31	27.48	1.59
$H^- + H_2^+ \rightarrow H + H_2$	57.59	0.95	37.82	1.15
$H^- + H_3^+ \rightarrow 2H + H_2$	102.9	0.53	67.43	0.65
$H^- + H \rightarrow H_2 + e$	29.88	1.83	19.64	2.22
$H^- + H_2 \rightarrow H + H_2 + e$	18.78	2.91	12.33	3.54
$H^- + Cs^+ \rightarrow Cs + H$	17.08	3.20	34.16	1.28
$H^- + Cs \rightarrow Cs + H + e$	113.26	0.48	113.26	0.39
$H^- + H^+$ (elastic collision)	2.26	24.16	1.47	29.70
$H^- + H$ (charge exchange)	0.85	64.24	0.74	59.01

Yamaguchi Univ.
Plasma Lab.

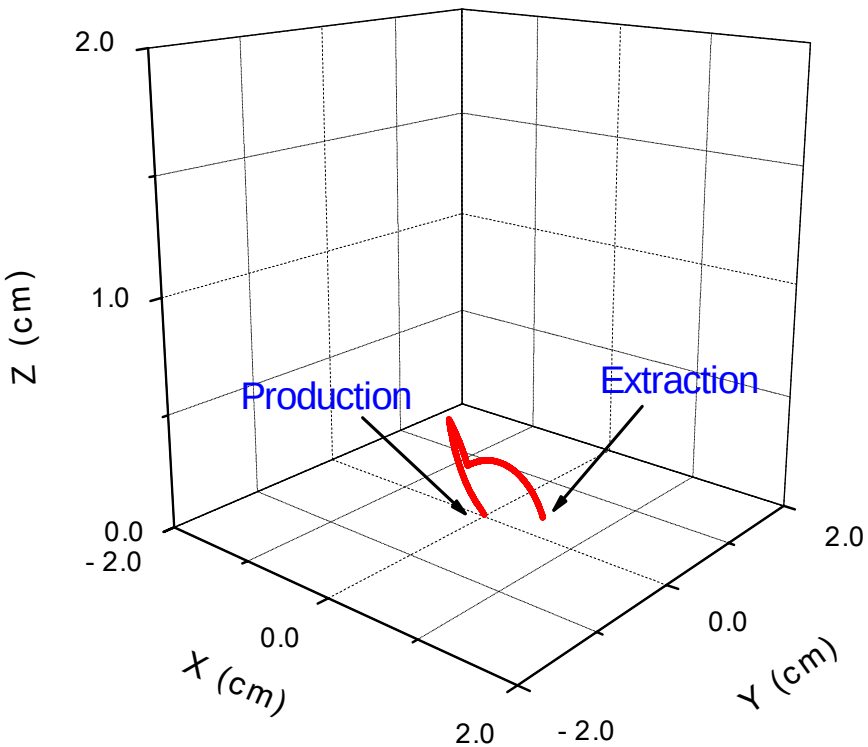
Flow chart



Yamaguchi Univ.
Plasma Lab.

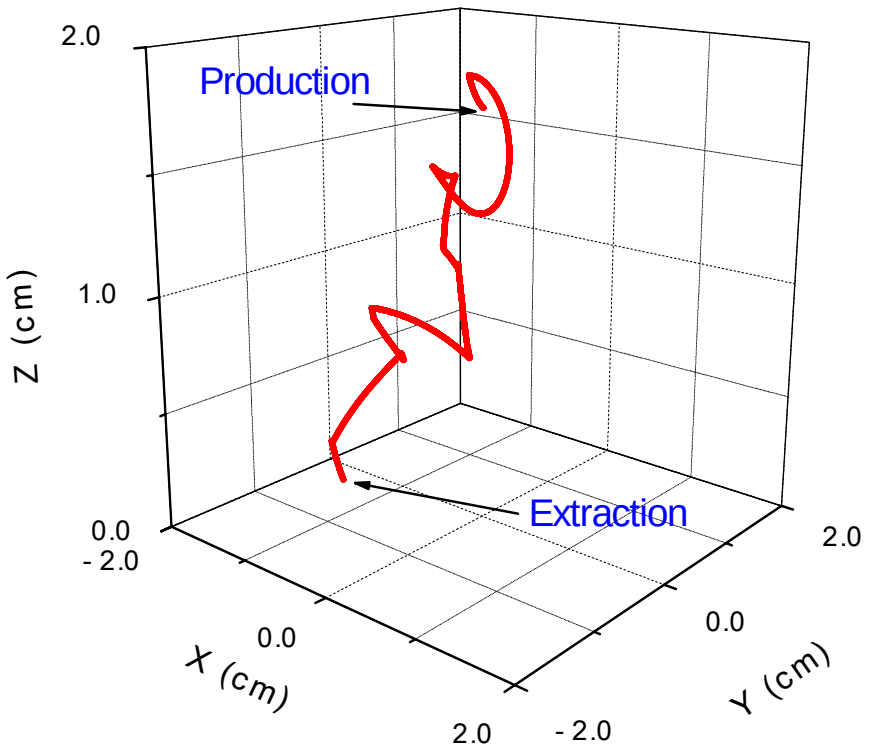
H^- ion trajectories in the second chamber

Surface produced H^- ions



Initial energy : 1.0 eV
Birth point (x, y, z) = (0, 0, 0) cm

Volume produced H^- ions



Initial energy : 0.5 eV
Birth point (x, y, z) = (0, 0, 1.75) cm

Numerical results of H^- transport

(B_0=120G, l_B=4cm)

Yamaguchi Univ. Plasma Lab.

H^- ions / Collisions		Surface produced H^- ions	Volume produced H^- ions, Birth point from the PG [cm] 0.25	0.75	1.25	1.75
Wall loss		29	54	71	77	68
Collsional destruction	e	20	59	117	185	346
	H^+	36	98	130	129	118
	H_2^+	20	41	54	56	55
	H_3^+	1	9	11	11	6
	H	13	54	64	88	80
	H_2	23	63	99	83	56
	Cs^+	88	161	242	230	203
	Cs	10	37	49	59	43
Total		211	522	766	841	907
Elastic collision	H^+	1043	3047	3992	3992	2942
Charge exchange	H	428	1199	1678	1865	2212
H^- ions reach the PG		760	424	163	82	25
Average energy of the above H^- ions [eV]		0.69	0.46	0.42	0.44	0.49
Extraction probability [%]		30.4	17.0	6.5	3.3	1.0

P=1mTorr （Mean value 7.0%）

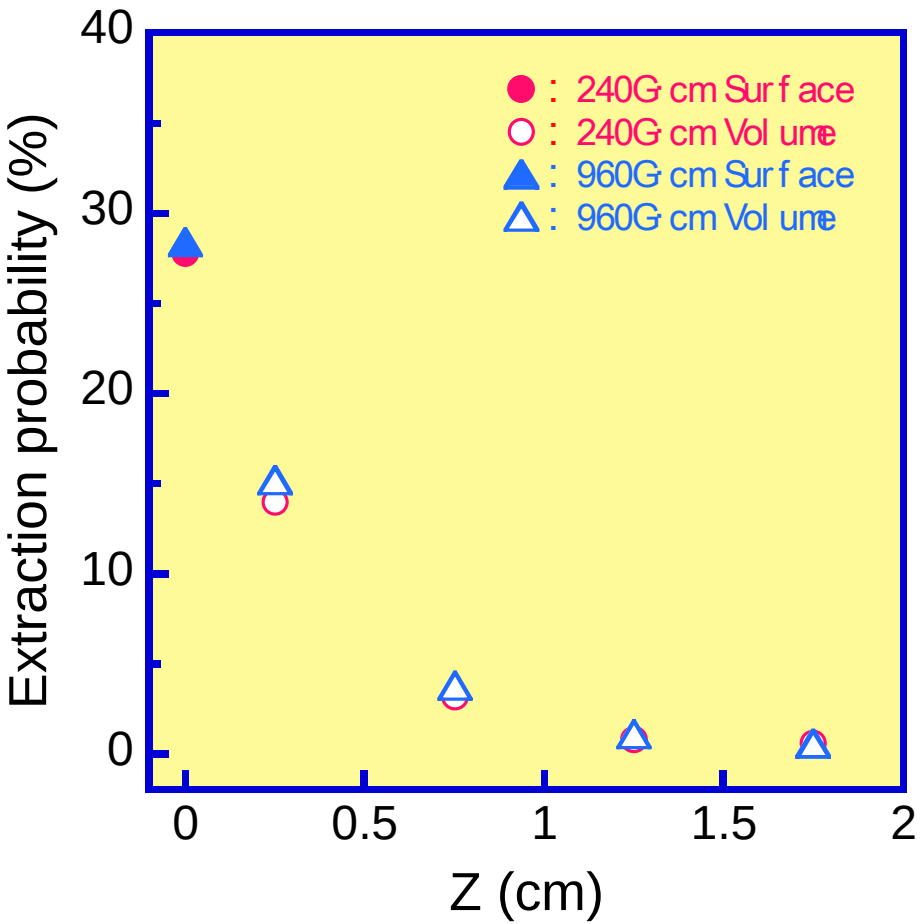
H^- ions / Collisions		Surface produced H^- ions	Volume produced H^- ions, Birth point from the PG [cm] 0.25	0.75	1.25	1.75
Wall loss		16	31	51	53	57
Collsional destruction	e	13	24	65	127	258
	H^+	33	83	113	127	103
	H_2^+	26	68	87	79	70
	H_3^+	11	31	46	33	33
	H	44	115	165	162	145
	H_2	80	186	242	257	196
	Cs^+	57	55	103	99	97
	Cs	10	28	33	36	27
Total		274	590	854	920	929
Elastic collision	H^+	682	1494	2161	1999	1517
Charge exchange	H	1464	3007	4416	4389	3776
H^- ions reach the PG		710	379	95	27	14
Average energy of the above H^- ions [eV]		0.66	0.46	0.42	0.44	0.48
Extraction probability [%]		28.4	15.2	3.8	1.1	0.6

P=5mTorr （Mean value 5.2%）

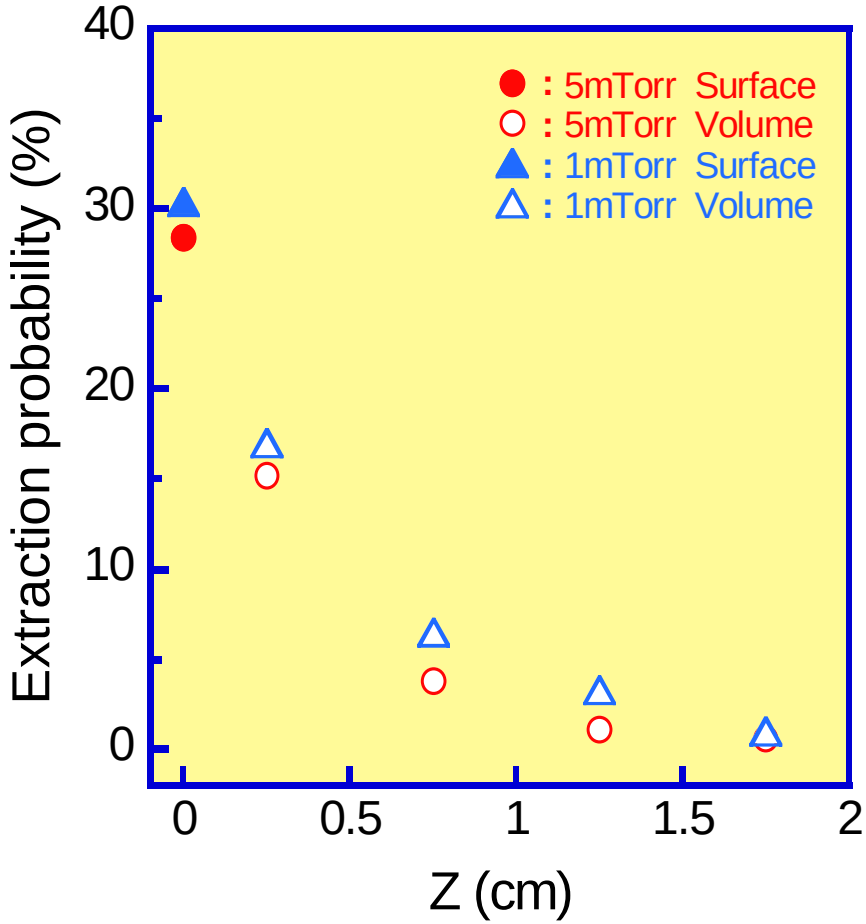
Yamaguchi Univ.
Plasma Lab.

Extraction probability as a function of z

(a) Effect of magnetic filter intensity

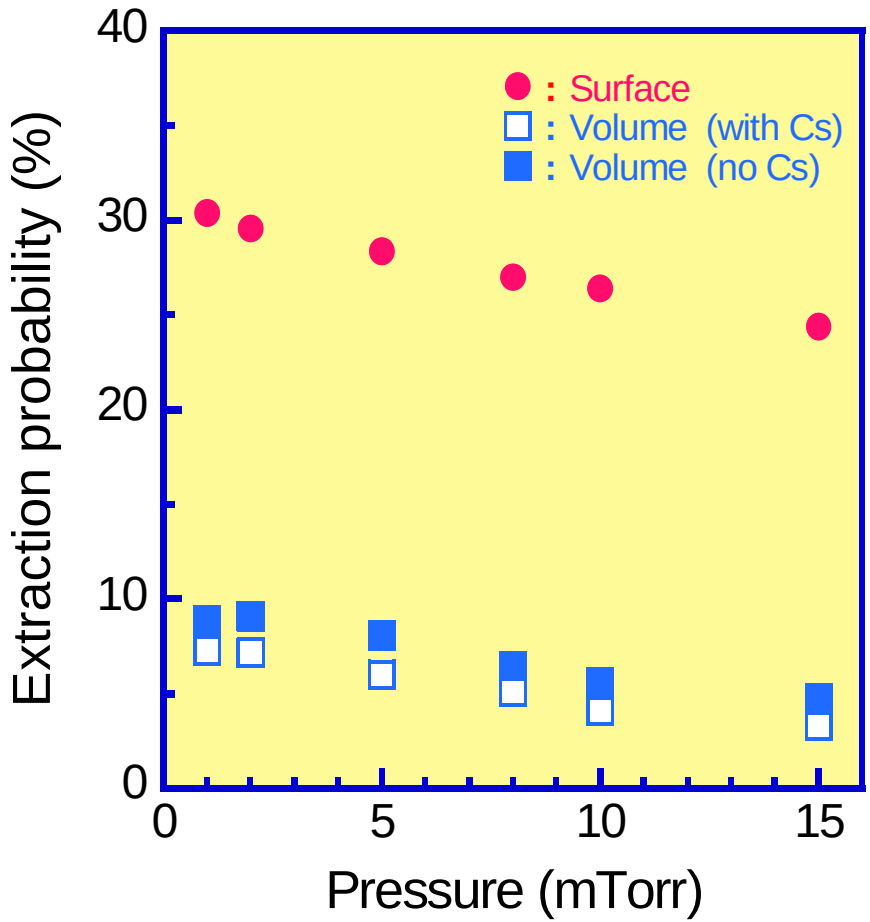


(b) Effect of hydrogen gas pressure



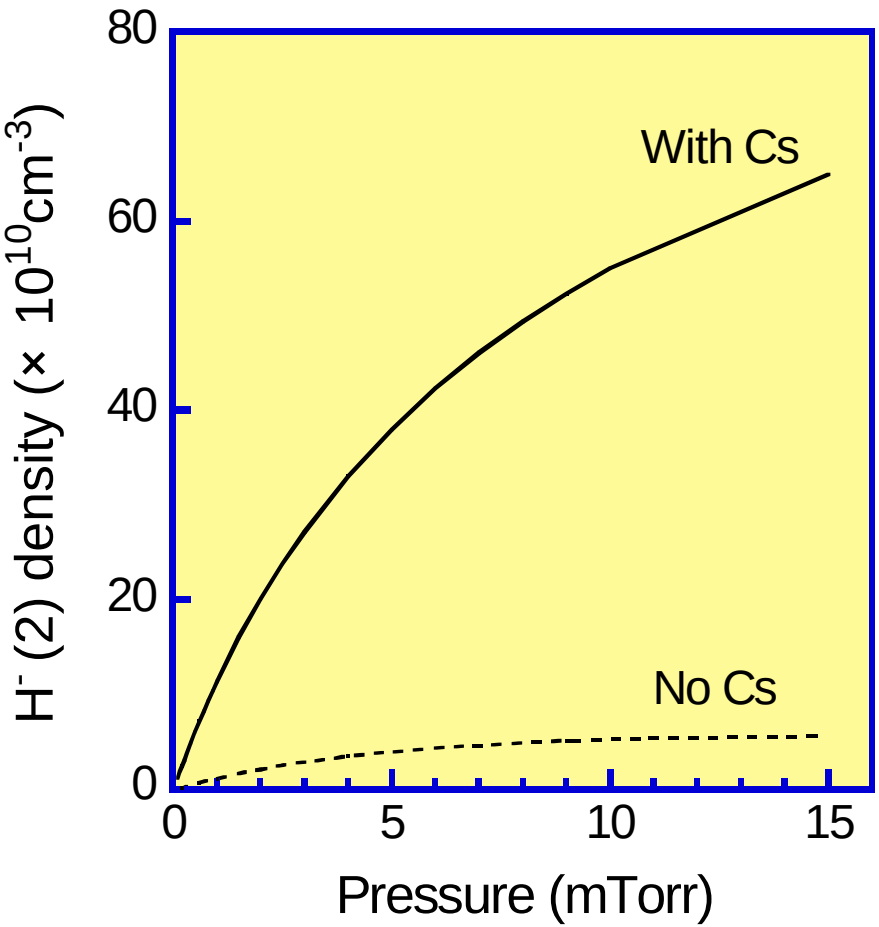
Yamaguchi Univ.
Plasma Lab.

Pressure dependence of extraction probability



Yamaguchi Univ.
Plasma Lab.

Pressure dependence of H^- (2) density



Yamaguchi Univ.
Plasma Lab.

Rate equation for H^- in the second chamber

H^-

$$N_{2[2]} n_{e[2]} \alpha_{11[2]} + \Sigma N_2(v'')_{[2]}\, n_{e[2]} \alpha_{12}(v'')_{[2]} + n_{2[2]} n_{e[2]} \alpha_{13[2]}$$

Volume production term

$$+ P_{Cs} \gamma_1 \frac{N_{1[2]}}{T_{1[2]}} \left(1 - \frac{S_f}{S_{t[2]}}\right) + P_{Cs} \frac{n_{1[2]}}{\tau_{1[2]}} \left(1 - \frac{S_f}{S_{t[2]}}\right) + P_{Cs} \frac{n_{2[2]}}{\tau_{2[2]}} \left(1 - \frac{S_f}{S_{t[2]}}\right) + 2 P_{Cs} \frac{n_{3[2]}}{\tau_{3[2]}} \left(1 - \frac{S_f}{S_{t[2]}}\right)$$

Surface production term

$$- n_{-[2]} (n_{e[2]} \alpha_{14[2]} + n_{fe[2]} \alpha_{f14[2]} + n_{1[2]} \alpha_{15[2]} + n_{2[2]} \alpha_{16[2]} + n_{3[2]} \alpha_{17[2]}$$

$$+ N_{1[2]} \alpha_{18[2]} + N_{2[2]} \alpha_{19[2]} + n_{Cs[2]} \alpha_{33[2]} + N_{Cs[2]} \alpha_{34[2]})$$

$$+ n_{-[1]} \frac{v_-}{4L_2} - n_{-[2]} \frac{v_-}{4L_2} - \left(1 - \frac{S_f}{S_{t[2]}}\right) \frac{n_{-[2]}}{\tau_{-[2]}} = 0$$

Yamaguchi Univ.
Plasma Lab.

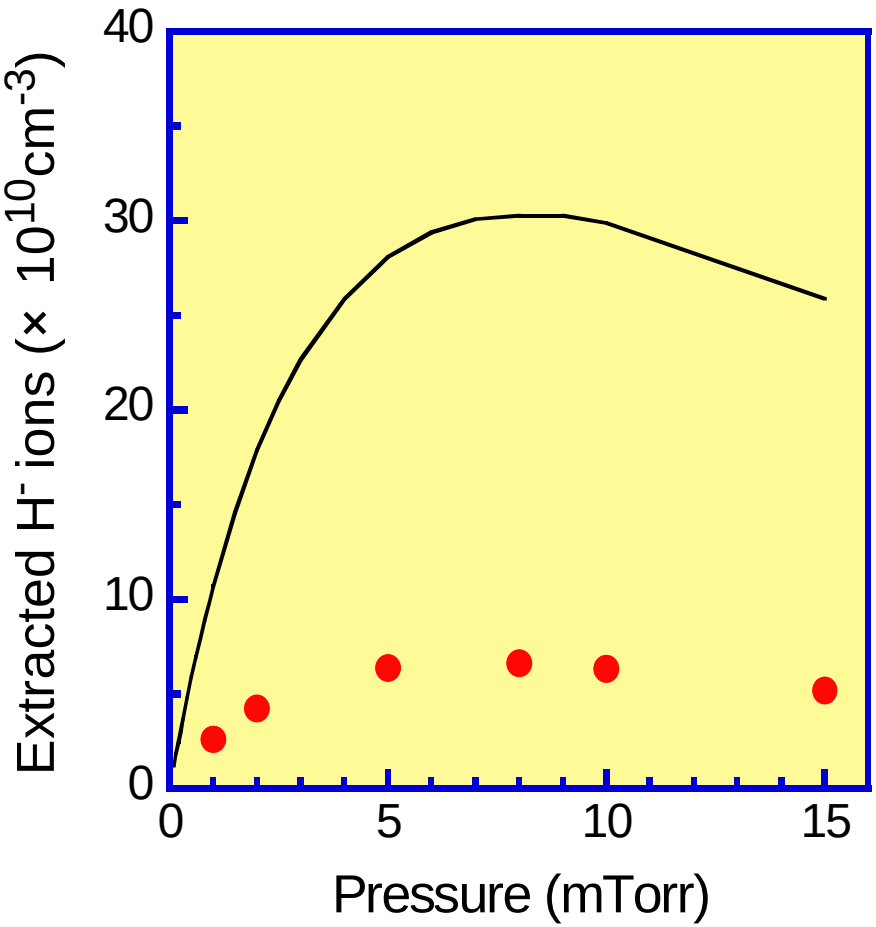
Procedure for estimation of extracted H^- ions

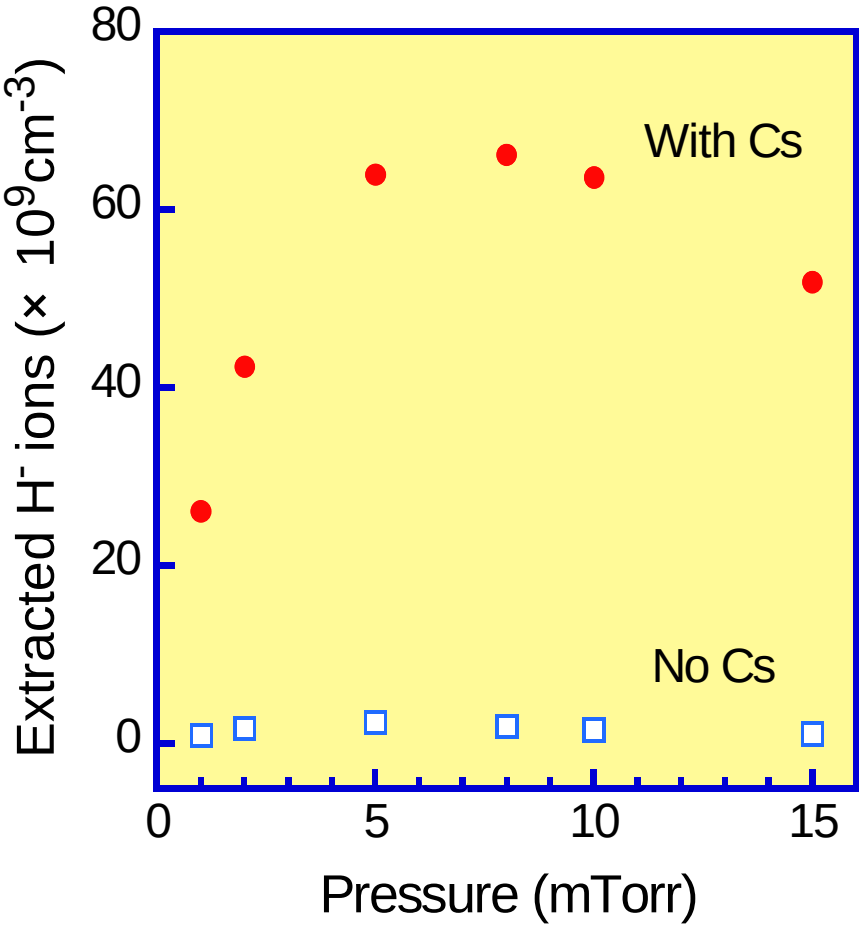
		Pressure [mTorr]					
		1	2	5	8	10	15
$H^-(2)$ ion density [$\times 10^{10} cm^{-3}$]		11.4	20.2	38.1	49.5	55.1	65.0
A rate of H^- formation [%]	SP	73.6	73.4	74.1	74.9	75.5	76.9
	VP	26.4	26.6	25.9	25.1	24.5	23.1
Estimated H^- ions [$\times 10^{10} cm^{-3}$]	SP	8.39	14.8	28.2	37.1	41.6	50.0
	VP	3.01	5.36	9.87	12.4	13.5	15.0
Extraction probability of H^- ions [%]	SP	30.4	29.6	28.4	27.0	26.4	24.4
	VP	7.3	7.2	6.0	5.1	4.1	3.3
H^- ions reach the PG [$\times 10^{10} cm^{-3}$]	SP	2.55	4.39	8.01	10.0	10.9	12.2
	VP	0.22	0.38	0.59	0.63	0.55	0.49
H^- ions reach the PG (total) [$\times 10^{10} cm^{-3}$]		2.77	4.77	8.60	10.6	11.5	12.7
Survival factor F against the stripping loss [%]		94.2	88.8	74.3	62.2	55.2	40.9
Extracted H^- ions from the ion source [$\times 10^{10} cm^{-3}$]		2.61	4.24	6.39	6.62	6.36	5.19

SP : Surface Production , VP : Volume Production

Yamaguchi Univ.
Plasma Lab.

Pressure dependence of extracted H^- ions





Yamaguchi Univ.
Plasma Lab.

Summary

(1) The probability for H^- ions to reach the plasma grid is estimated.

→ For surface-produced H^- ions

- The extraction probability is weakly decreased with pressure. (24~30%)

→ For volume-produced H^- ions

- The extraction probability is decreased markedly with the upstream distance from the extraction grid. (~within 2cm)
- The averaged extraction probability is much lower than that for surface-produced H^- ions. (3~8%)

(2) The kinetic energy of the extracted H^- ions is reduced mainly through charge exchange collisions with H and elastic collisions with H^+.

(3) Although the kinetic energy of surface-produced H^- ions is reduced due to collisions, the value is slightly higher than that of volume-produced H^- ions.

(4) Extracted H^- current is estimated by using the present extraction probability and the result of model calculation.

Yamaguchi Univ.
Plasma Lab.

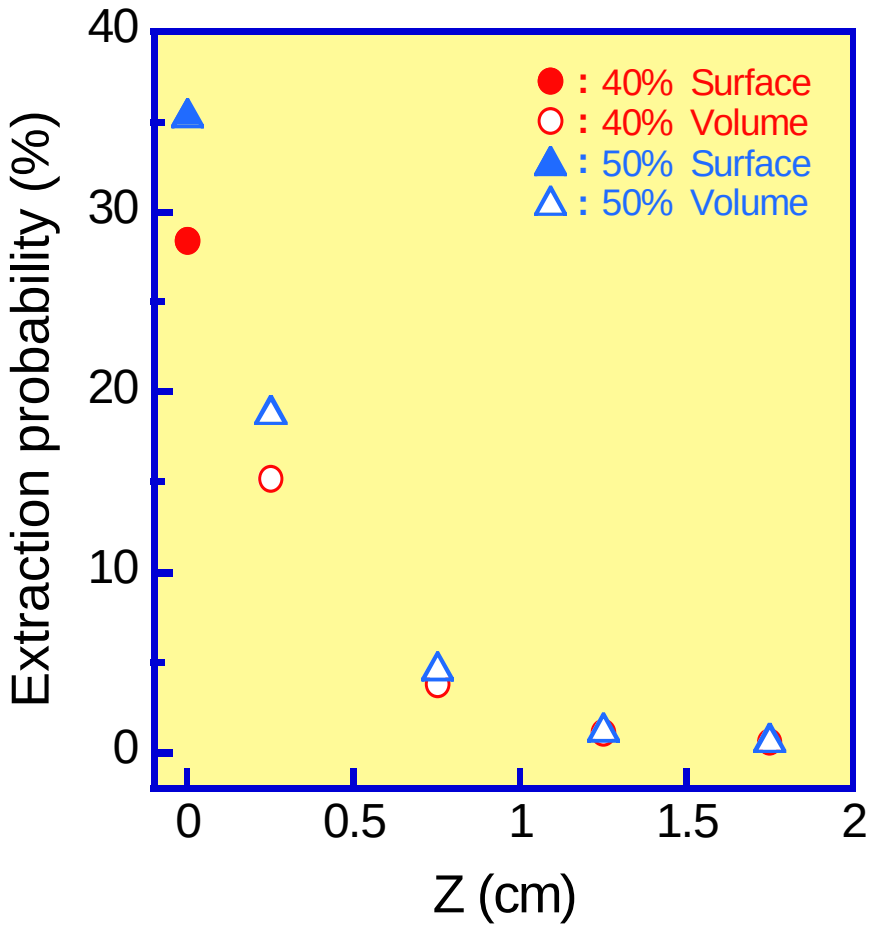
Plasma parameters obtained from the model calculation
(gas pressure p = 5mTorr)

n_{H^-}	H^- ion density	3.81×10^{11} cm^{-3}
n_e	Electron density	1.00×10^{12} cm^{-3}
n_H	H atom density	5.22×10^{13} cm^{-3}
n_{H_2}	H atom density	8.31×10^{13} cm^{-3}
n_{H^+}	H^+ ion density	3.73×10^{11} cm^{-3}
$n_{H_2^+}$	H^+ ion density	2.71×10^{11} cm^{-3}
$n_{H_3^+}$	H^+ ion density	1.52×10^{11} cm^{-3}
n_{Cs^+}	Cs^+ ion density	5.85×10^{11} cm^{-3}
n_{Cs}	Cs atom density	4.41×10^{12} cm^{-3}
T_e	Electron temperature	1.0 eV
T_H	H atom temperature	0.5 eV
T_{H^+}	H^+ ion temperature	0.5 eV

Yamaguchi Univ.
Plasma Lab.

Extraction probability as a function of z

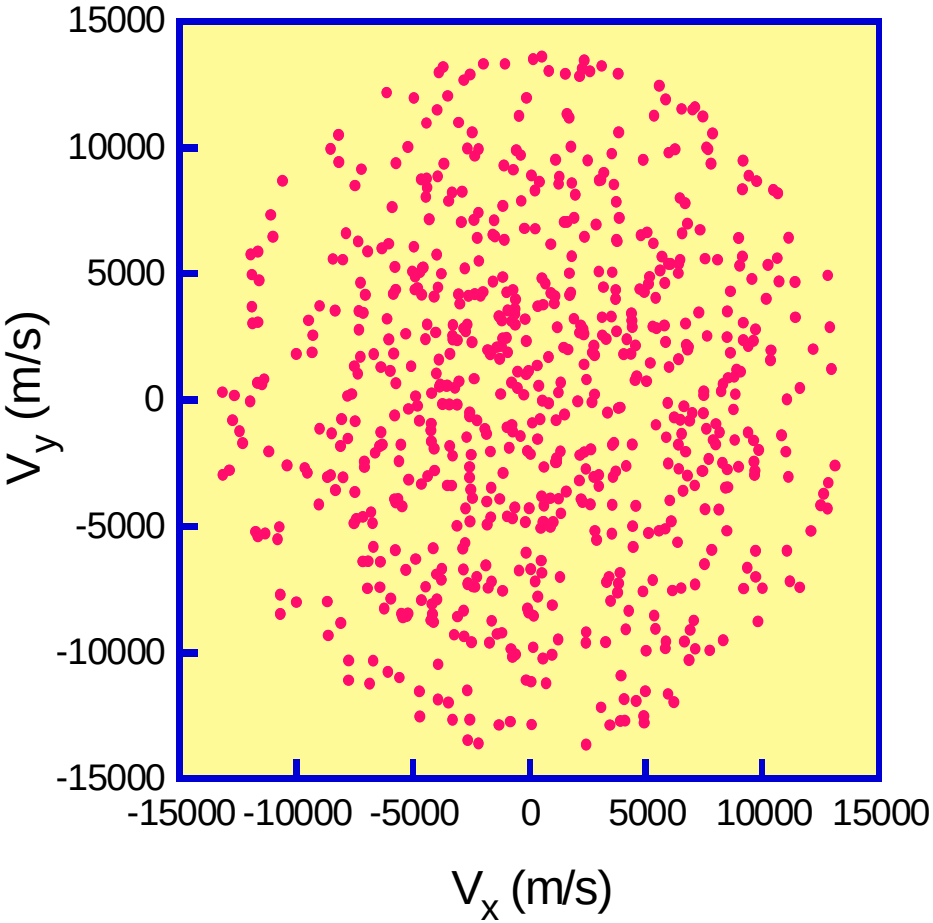
(parameter is geometrical transparency)



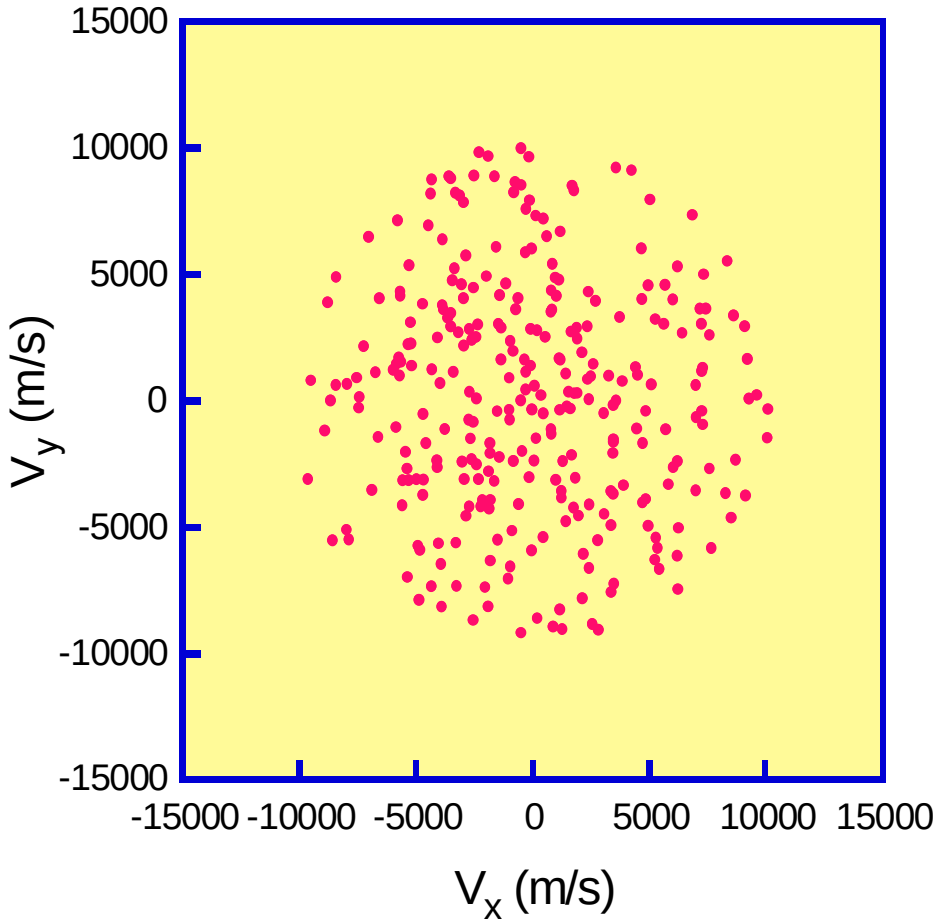
Yamaguchi Univ.
Plasma Lab.

Two dimensional velocity distribution of H^- ions (V_x-V_y)

Initial energy : surface 1.0 eV
volume 0.5 eV



Surface produced H^- ions



Volume produced H^- ions