Effect of positive ions incident on the caesiated converter of a negative ion source with energy of tens of eV

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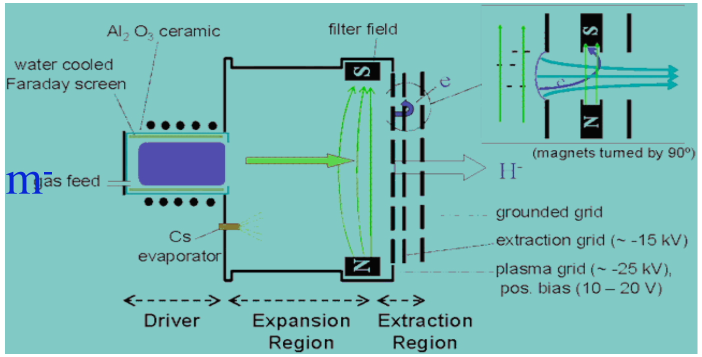
Negative ion sources for fusion

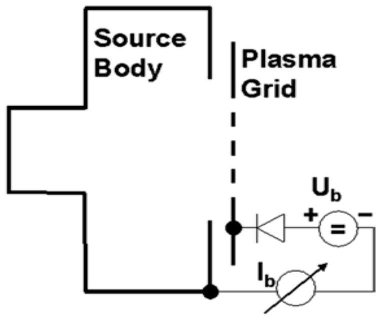
IPP prototype
(Speth et al., Franzen et al)

- RF discharge divided into two regions by magnetic filter field



- Driver region
  - pressure ~ 0.3Pa, T_e~ 8eV, n_e~ 5 x 10^{18} m^{-3}
  - production of vibrationally excited molecules

$$e + H_2 \_ H_2(v^*) + e$$

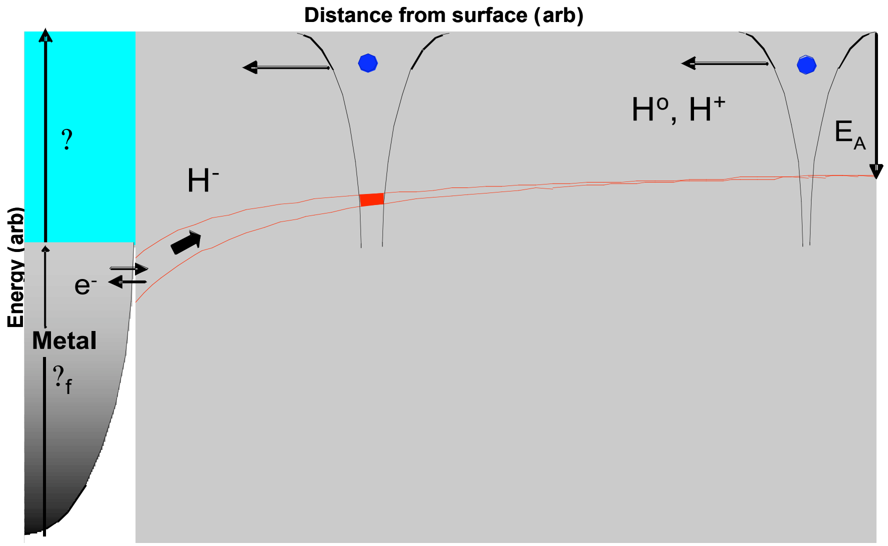


- Extraction region
  - T_e~2 eV, n_e ~ 5 x 10^{17} m^{-3}, n_{H-} ~ 10^{16} - 10^{17} m^{-3}
  - produce negative ions by dissociative attachment

$$e + H_2(v^*) \_H^- + H$$

Surface production of negative ions

- For ions, Auger neutralisation takes place first. Molecules are dissociated into atoms
- Affinity level is shifted down and broadened as neutral approaches surface
- Overlap with metal states leads to electron tunnelling and negative ion formation
- The lower the work function the greater probability of negative ion formation
- Enhancements of x2 - 8



$$E_{thr} = \phi - E_A$$

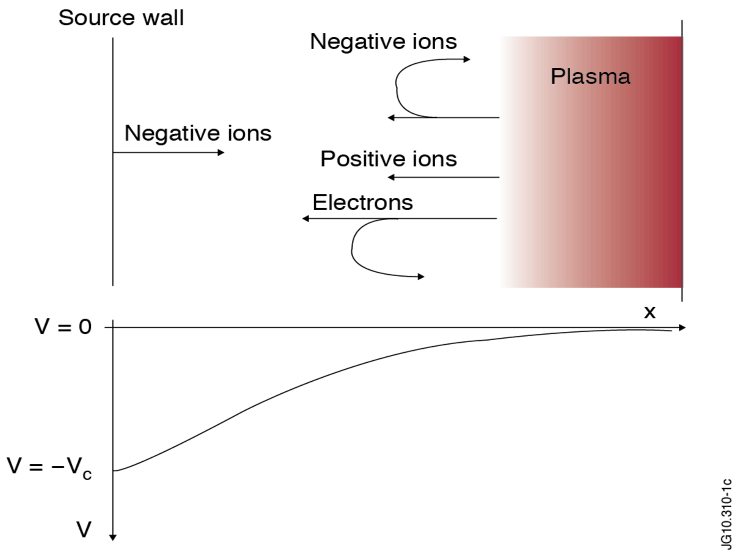
For Cs $\phi \geq 1.5$eV, $E_A = 0.75$eV
$E_{thr} \geq 0.75$eV

- For the plasma conditions in the source, surface negative ion production is dominated by hydrogen atoms and not positive ions (this is a view currently accepted until now, to be revised following the present report)
- This has implications for the conditions in the sheath between the wall and the plasma
- It affects how many of the negative ions can be transported across the sheath and hence be extracted

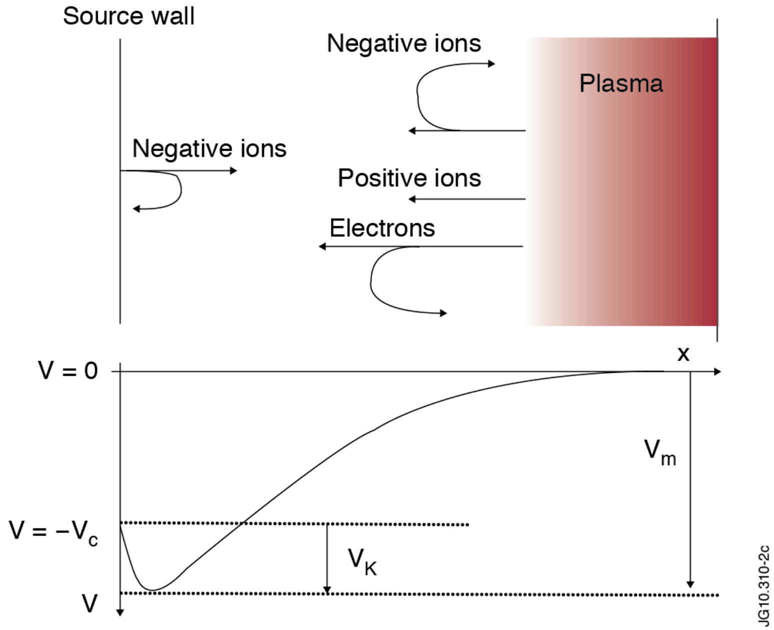
Formation of a virtual cathode

- Field at cathode decreases as emission of negative ions increases
  - space charge limit is reached when field is zero

- As emission increases further the field is negative and a virtual cathode is formed



Increased production by atoms

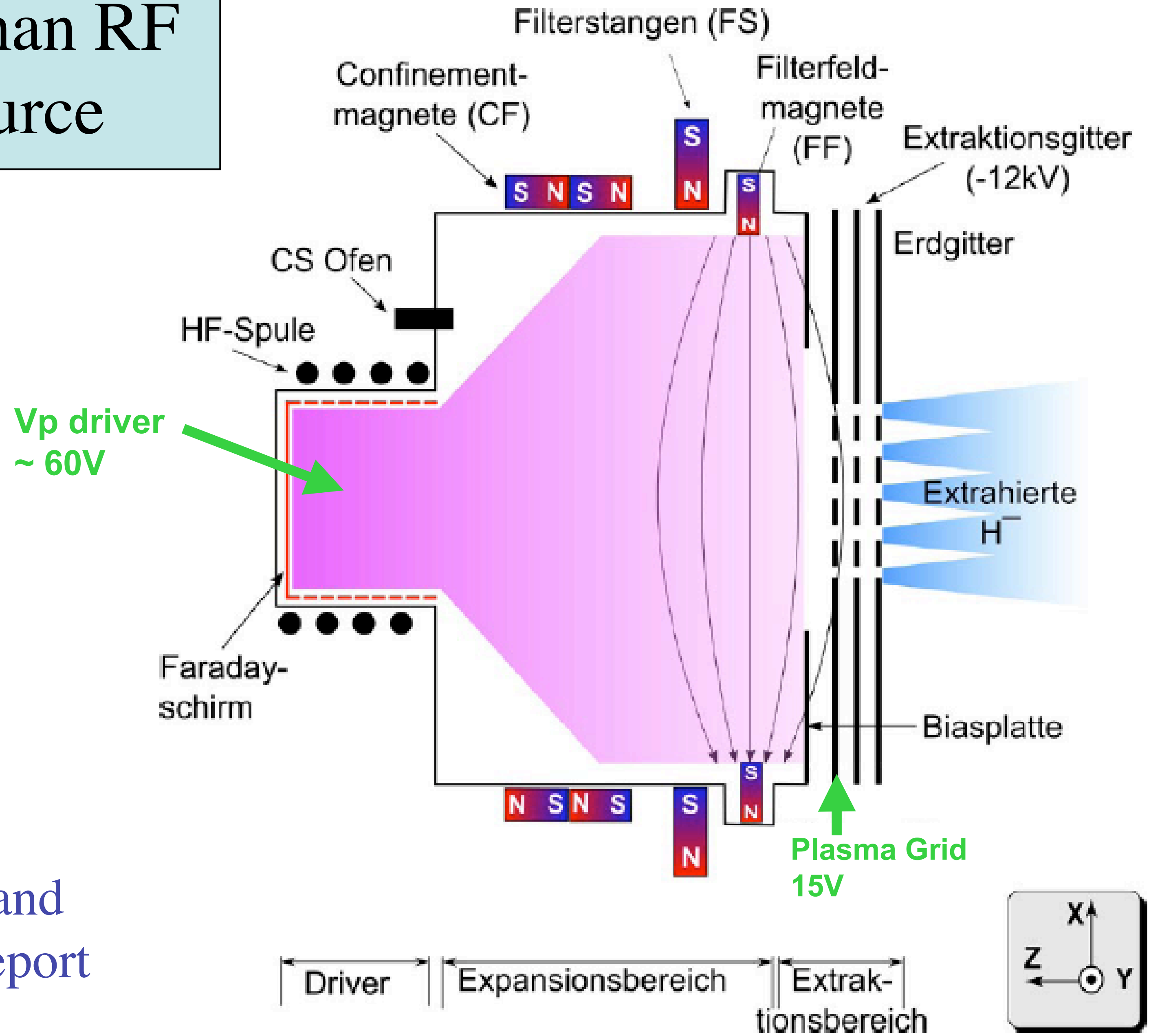


INTRODUCTION

In most negative ion source simulations it is assumed that the positive hydrogen ions enter the extraction region with low energy.
In the case of the RF caesium seeded negative ion source studied in IPP Garching for fusion applications, a positive ion temperature of 0.8 eV is ascribed to these positive ions (Wünderlich *et al*, PSST, **18**, 045031(2009)).

However, in this source, the plasma potential in the driver in pure hydrogen operation at 0.3 Pa is positive by 45 to 60 V with respect to the source walls, when the RF power is varied from 40 to 80 kW (McNeely *et al*, PSST, **18**, 014011 (2009))

IPP Batman RF ion source



Christ-Koch and Fantz, IPP Report 4/287 (2008)

Requirements for ITER

Criteria	Required by ITER	Demonstrated at IPP
H^- current density ($mA\,cm^{-2}$)	30	33/15[a]
D^- current density ($mA\,cm^{-2}$)	20	23/12[a]
Co-extracted electron to ion ratio	<1	$<1/<1.5$[a]
Operating pressure (Pa)	0.3	0.3
Plasma uniformity	$\pm 10\%$	To be shown
Pulse length (s)	3600	3600[b]

Present operation parameters of a 1/8 model:

Density of caesium neutral atoms:

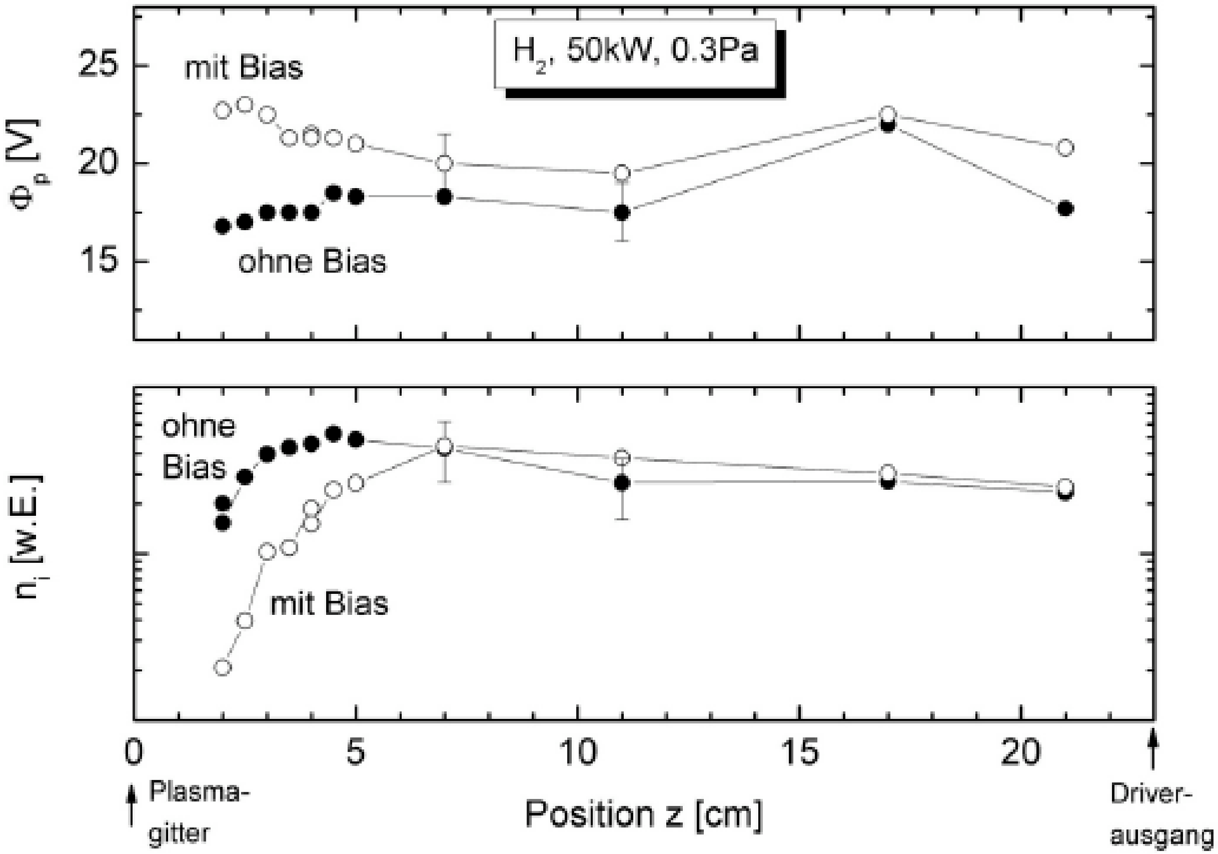
$10^{14} - 10^{15} m^{-3}$

RF Power: 100 kW

RF frequency : 1MHz

Experimental evidence

The experimental information about the profile of the plasma potential between the driver and the plasma grid is limited to an <u>off-axis variation</u> presented by Christ-Koch and Fantz (IPP Report 4/287 (2008)). In the central region the plasma potential should increase to 50 V beyond 21 cm.



Plasma parameters of the driver, from McNeely et al, PSST **18**, 014011(2009)

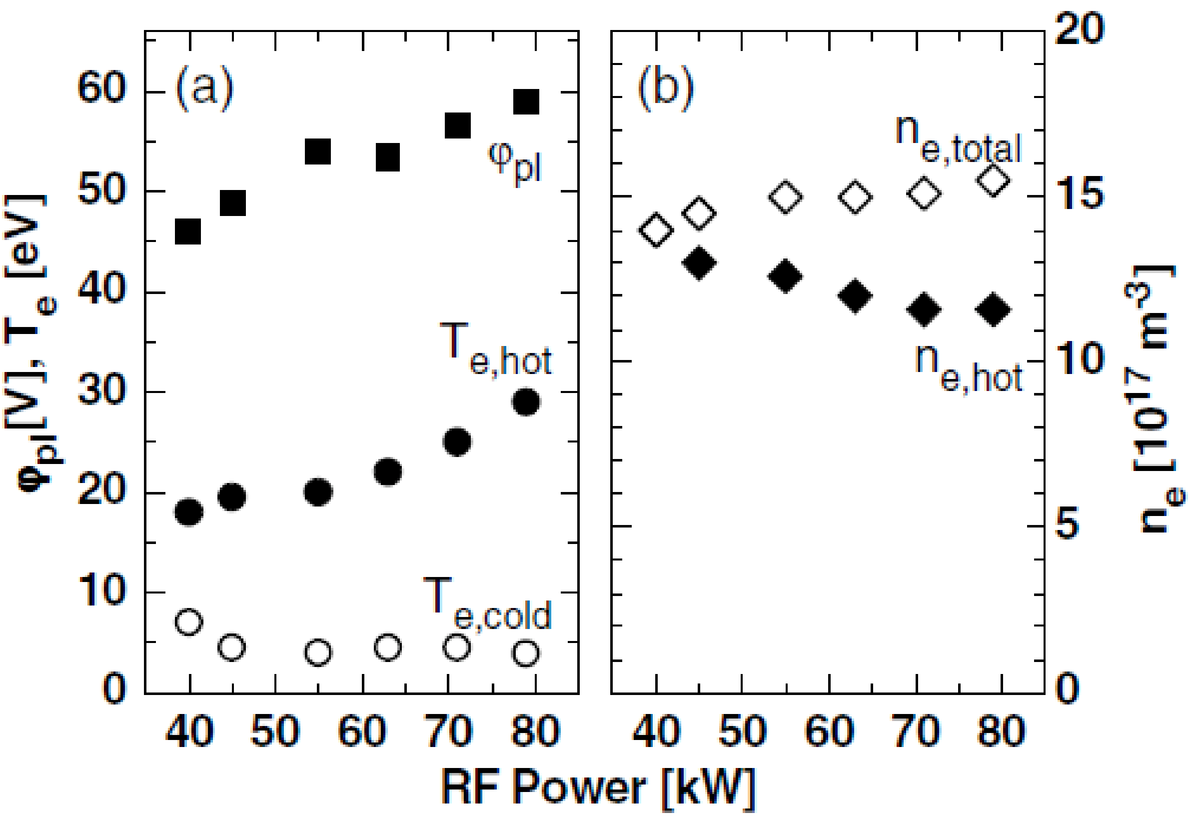


Figure 9. The dependence of plasma parameters on the RF power in the driver region for a hydrogen discharge at 0.3 Pa is shown. In (*a*) is shown the plasma potential and temperatures of the two components $T_{e,cold}$ and $T_{e,hot}$. In (*b*) is shown the electron density derived from integration of both the total EEPF and only part of the EEPF corresponding to $T_{e,hot}$.

Positive ion mean free path for ChX and elastic collisions

Elastic collisions $H^+ + H_2$

$$\lambda_{el} = (8.3 \text{ x } 10^{-21} \text{ x } 3.3 \text{ x } 10^{19})^{-1} = 3.65 \text{ m}$$

ChX collisions $H^+ + H$

$$\lambda_{ChX} = (3 \text{ x } 10^{-19} \text{ x } 3.3 \text{ x } 10^{18})^{-1} = 1 \text{ m}$$

The length of the expansion region is L = 0.244m

Obviously

$$\lambda_{ChX} > L \qquad \lambda_{el} >> L$$

Therefore the positive ions will have no elastic and ChX collisions in the expansion region and will not lose energy.

Neutral densities

In this work the neutral densities are taken from a recent work in which these densities are reported for the conditions of « neutral depletion » due to the presence of the plasma:

P. McNeely and D. Wünderlich
Plasma Sources Science&Technology, ***20****, 045005 (2011)*

Usually, only the « filling pressure » is reported and the neutral density is deduced from it.

The values used here are closer to the actual densities than in previous work. The different results obtained here compared to earlier work are in part due to this choice.

Positive ion current density extracted from the driver (I)

$$J_i = 0.4 e n_{e0} \sqrt{\frac{2kT_e}{M_i}} \qquad \text{(Eq. 1)}$$

Here T_e is the electron temperature in the driver,
n_{e0} is the electron density in the center of the driver.
All the positive ion species will be accelerated by the plasma potential difference between the driver (60 V) and the Plasma Grid (15 V) to an energy of 45 eV.

$$\Delta V_{DR-PG} = 60 - 15 = 45 \text{ V}$$

However the energy per nucleon will be different for the nucleons issued from different ion species: 45 V for H^+, 22.5 V for H_2^+ and 15 eV for those issued from H_3^+.

Species fractions, energy per nucleon

Species	**Species fraction**	**Energy / nucleon**
	%	*eV*
H^+	40	45
H_2^+	40	22.5
H_3^+	20	15

Positive ion current density extracted from the driver (II)

With the driver plasma parameters T_e= 29 eV and n_e=1.5x10^{18} m^{-3} we found from Eq. 1 the positive ion current density for each ion species (Column 4):

Species	**Species fraction**	**Energy / nucleon**	**Ji(H_n^+) from driver**
	%	*eV*	*A/m^2*
H^+	40	45	2863
H_2^+	40	22.5	2048
H_3^+	20	15	827

Positive ion and particle current incident on the plasma grid

We assume that the positive ion current density reaching the plasma grid is equal to that extracted from the driver (Column 5 in Table I) since the cross section of the driver (450 cm^2) is approximately equal to the cross section of the Plasma Grid (456 cm^2)

.

The number of nucleons contained in each ion species is taken into account in calculating the particle current density on the Plasma Grid (3 nucleons in H_3^+, 2 nucleons in H_2^+, 1 in H^+) - see Column 6.

Species	**Species fraction**	**Energy / nucleon**	**Ji(H_n^+) from driver**	**Ji(H_n^+) on Plasma Grid**	**Jp**
	%	*eV*	*A/m^2*	*A/m^2*	*equiv A/m^2*
H^+	40	45	2863	2863	2863
H_2^+	40	22.5	2048	2048	4096
H_3^+	20	15	827	827	2481

Negative ion formation by backscattering at the caesiated plasma grid

Seidl et al (J. Appl. Phys., **79**, 2896 (1996)) have measured the yields, Y (the fraction of the incident positive ions leaving the surface as negative ions), of H^- ions produced in backscattering of H^+ and H_2^+ from caesiated polycristalline Au, W and Mo surfaces in the energy range 2 - 30 eV.

They found that the yield per nucleus is the same for both H^+ and H_2^+. These authors concluded that the molecular ions are dissociated before colliding with the surface.

Based on these results we considered that all the molecular ions of the incident positive ion beam are dissociated when approaching the low work function plasma grid surface and all the particles are active in backscattering.

Experiments of Seidl et al (JAP, 1996)

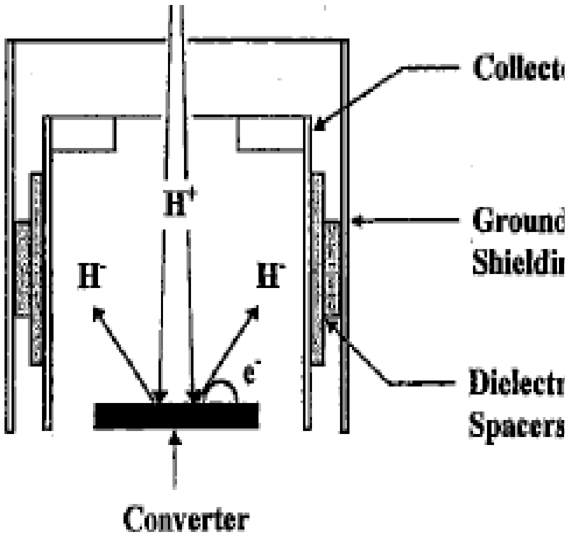


FIG. 1. Schematic of ion backscattering expe...

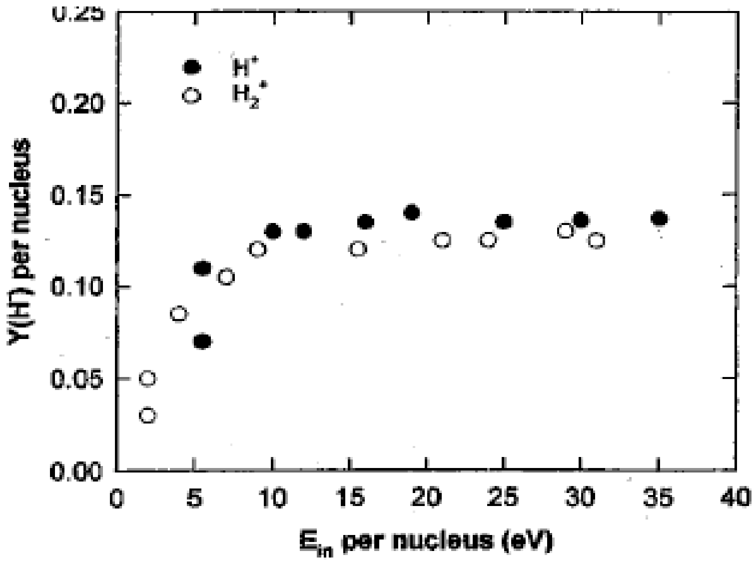


FIG. 4. H^- yield per nucleus as a function of incident energy per nucleus. Precesiated Au converter with work function of 1.5 eV. Filled circles: H^+ ions; open circles: H_2^+ ions.

Dependence of H^- yield on particle energy

Seidl's results are summarized by the equation

$$Y = R_N \eta_0 \left(1 - \frac{E_{thr}}{E_{in} R_E} \right) \quad \text{for} \quad E_{in} \geq \frac{E_{thr}}{R_E}, \quad E_{thr} = \phi - A$$

For a dynamically caesiated Molybdeum surface the following coefficients are recommended per nucleus:

$$R_N \eta_0 = 0.30 \qquad E_{thr} / R_E = 2.0$$

The values of the yield Y are shown in Column 7

The negative ion current density J(H-) is shown in Column 8.

Yield Y and Negative ion current density $J^-(H^-)$

Species	Species fraction	Energy / nucleon	$Ji(H_n^+)$ from driver	$Ji(H_n^+)$ on Plasma Grid	Jp	Y	$J(H^-)$
	%	*eV*	*A/m^2*	*A/m^2*	*equiv A/m^2*		*A/m^2*
H^+	40	45	2863	2863	2863	0.29	830
H_2^+	40	22.5	2048	2048	4096	0.27	1105
H_3^+	20	15	827	827	2481	0.26	645

The negative ion current density emitted from the plasma grid.

The negative ion current density $J(H^-)$ is shown in Column 8. It is the product of the yield Y (from Column 7) with the particle current density (from Column 6).

The total negative ion current density produced by fast ions is 2580 A/m^2.

If we would consider only one particle resulting from each molecular ion we would find the total negative ion current density 1600 A/m^2.

The actual extracted negative ion current contains also a fraction produced by backscattering of thermal atoms, which will be evaluated next.

Negative ion current due to thermal atoms

Seidl has reported the negative ion yield <Y> for different atomic temperatures

$$< Y > = R_N \eta_0 \exp\left(- \frac{E_{thr} / R_E}{kT} \right)$$

For the same dynamically caesiated Molybdenum surface the following coefficients are recommended:

$$R_N \eta_0 = 0.42 \qquad E_{th} / R_E = 1.05$$

For kT = 0.8 eV, <Y> = 0.113

With an atomic density 3.3x10^{18} m^{-3} we find

$$J^{-}\left(H_{thermal}\right) = 209 \ A / m^2$$

The ratio between the H^{-} produced by fast ions and thermal atoms is 2580 / 209 = 12

Extracted H^- current density - comparison with measured value

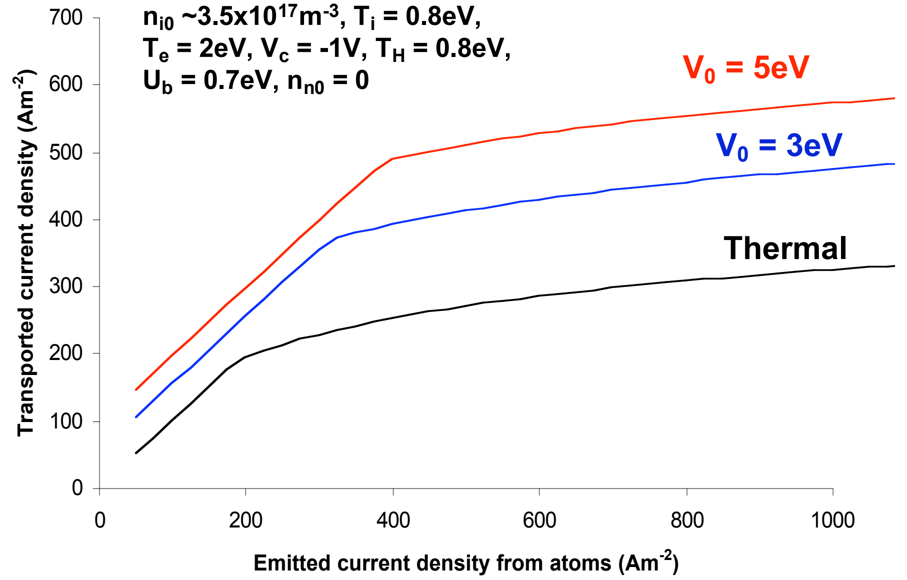
The produced H- current contains the part due to fast ions (2580A/m^2) and the part due to thermal atoms (209 A/m^2). Those produced by fast ions have probably a higher starting energy than those produced by thermal atoms.

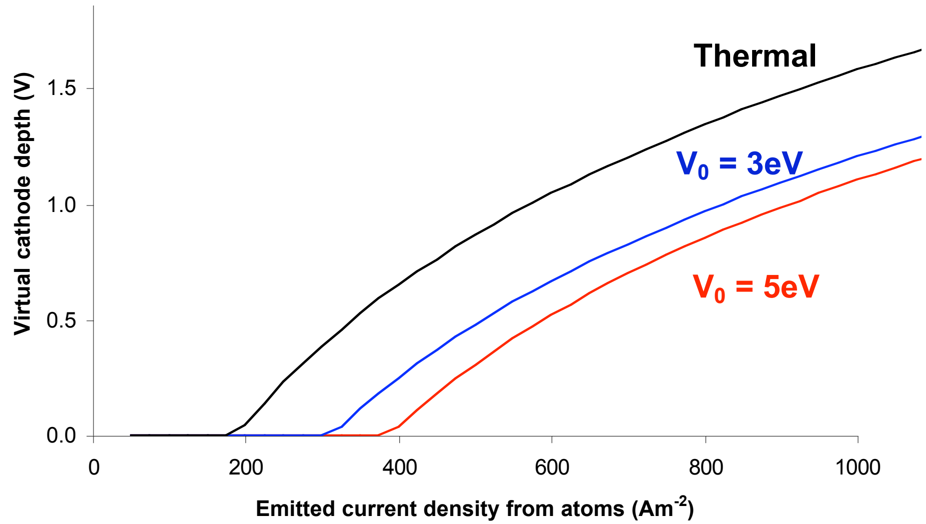
According to Gutser et al (PPCF, **52**, 045017 (2010) 23% of the negative ions are extracted, when their starting energy is 1 eV (with a magnetic filter field is 7mT), but only 15% when the starting energy is 5 eV. We applied these different extraction factors to the two groups of negative ions and found that 435 A/m^2 are extracted.

This compares favorably with the measured extracted current, 330A/m^2.

Effect of fast positive ions

- Even low energy positive ions have a significant effect on negative ion production and transport across the sheath
  - virtual cathode formed at higher emitted current densities
  - transported current density is increased
- Requirement (again) for high positive ion densities and energies in the plasma





CONCLUSION

- **The fraction of H^- ions produced by thermal ions is 12 times lower than that produced by fast ions. This is opposite to the conclusion of Wünderlich *et al* and Taccogna *et al*.**

- **This reduces the probability of formation and the depth of a potential well in front of the plasma grid.**

- **The calculated extracted current containing the sum of the fractions of H- ions due to fast positive ions and thermal atoms is 435A/m^2 which is close to the measured value, 330 A/m^2**

Further work should check the assumptions made here:

*positive ion species fractions

*positive ion current density on the plasma grid

*evaluate the effect of the work function of the ion source plasma grid being higher than the assumed value of 1.4 eV, which corresponds to the experimental conditions in the work of Seidl et al.