Negative hydrogen ion production in fusion dedicated ion sources

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OUTLINE

• Physics basis of volume and surface production
• Implications of positive ion acceleration between the driver and the extraction region
• Comparison of caesium ion formation by electron collision and ChX
• H- ion formation by double electron capture in proton collisions with caesium atoms
• Conclusion
Production of negative ions ($H^-$)

Volume production

- Dissociative attachment (DA)

$$H_2( X^1\Sigma_g^+, v''') + e(\text{slow}) \rightarrow H^- + H$$

Dissociative attachment cross sections for various rotationless vibrational states of $D_2$ from J. N. Bardsley and J. M. Wadehra.
Production of vibrationally excited molecules

Vibrationally excited molecules are strongly related to H⁻ ion production. They are produced by

- **e-V**
  \[ \text{H}_2 + \text{e} \text{ (slow)} \rightarrow \text{H}_2(\text{X} \, ^1\Sigma_g^+, \nu'') + \text{e} \]

- **E-V**
  \[ \text{H}_2 + \text{e} \text{ (fast)} \rightarrow \text{H}_2(\text{B} \, ^1\Sigma_u^+, \text{C} \, ^1\Pi_u) \rightarrow \text{H}_2(\text{X} \, ^1\Sigma_g^+, \nu'') + \text{hv} \]

Recombinative desorption (RD)
\[ \text{H} + \text{H} + \text{wall} \rightarrow \text{H}_2(\text{X} \, ^1\Sigma_g^+, \nu'') \]
The mean free path of vibrationally excited molecules for dissociative attachment

The mean free path of a vibrationally excited molecule for dissociative attachment is defined by the following equation:

$$\lambda \left[ H_2(v^n) \right]_{DA} = \frac{v_m}{N_e <\sigma v>_{DA}}$$

Here $v_m$ is the velocity of the molecule, $N_e$ is the electron density, $<\sigma v>_{DA}$ is the dissociative attachment rate coefficient, which can be found in the article of J.M. Wadehra, Phys. Rev. A. 29, 106 (1984).

Using $<\sigma v>_{DA} = 10^{-8} \text{ cm}^3/\text{s}$, i.e. the value for the highest vibrationally excited levels, $N_e = 10^{12} \text{ cm}^{-3}$, and a gas temperature of 0.05 eV, the mean free path of the vibrationally excited molecule is 27 cm.
Main difficulties with volume sources:

- molecules are necessary for increasing H- density. Low pressure operation is required for ITER and is difficult to achieve.
- low energy electrons are also necessary. They generate co-extracted electron currents, which are a major problem.
- The solution found was caesium seeding the volume sources, leading to «surface production».
What is the ‘Surface Production’?

Surfaces exposed to hydrogen plasma are irradiated by hydrogen atoms and ions. Some of them are reflected as negative ions. *Surface production of H- ions is based on electron tunnelling from a solid surface to an H atom moving away from the surface.* The fraction of incident particles reflected as negative ions can be considered to be the product of 3 factors:

- the backscattered fraction of incident particles
- the probability of conversion of hydrogen atoms to negative ions during the collision
- the probability of a negative ion surviving as it moves away from the metal surface
Corelation between Plasma Grid work function and extracted H- ion current

Why is a low work function surface required?

- As the atom approaches the surface the affinity level moves to higher values and broadens.
- Close to the surface the affinity level overlaps with the metal electronic states. Electrons from the metal can tunnel into the affinity level to form negative ions.
- The lower the work function the greater the overlap of the atomic level with the metal states and the greater the probability of negative ion formation.
- The process has a threshold:
  \[ E_{\text{thr}} = W_F - E_A \]
  Backscattering of atoms at low energy
- The energy distribution of H- ions is maxwellian with a temperature equal to the atomic temperature.
Potential energy of the negative ion

- The potential energy (or the electron affinity level) is determined by the image charge:

\[ U(z) = -A - \frac{e^2}{4\pi\varepsilon_0} \times \frac{1}{4(z+b)} \]

- \( A \) is the isolated atom electron affinity level, 0.75 eV.
- There is a crossing distance \( Z_c \) where the potential energy is equal to the work function \( WF \).
- When the atom is inside \( Z_c \) the affinity level is below the Fermi level, allowing electron transfer from filled surface state to atom.
- When the atom is outside \( Z_c \) transfer takes place from the occupied affinity level to empty surface states.
H⁻ Production Probability

The probability of H⁻ production was calculated by Rasser et al., Surf. Sci. (1982), where v is the atom velocity:

\[ P = \frac{2}{\pi} \exp \left[ -\frac{\pi(\phi - E_A)}{2av} \right] \]

![Graph showing H⁻ production probability vs. energy (eV)]
Implications of positive ion acceleration between the driver and the extraction region.

Measurements by McNeely et al (PSST, 2009) show that the plasma potential of the driver is 45 to 60 V positive. The arrival of 50 eV protons in the extraction region can have several implications:

- *Contribute to negative ion formation in the plasma volume*
- *Contribute to caesium ionization*
- Enhance the negative ion yield of the caesiated surface
- Affect the virtual cathode, compared to the case of thermal positive ions
- Modify the mutual neutralization

We will discuss here the first two effects, only.
Comparison of Cs atom ionization in electron collisions and by ChX with protons
Caesium ionization by charge exchange with protons

In the RF source studied at IPP Garching the plasma potential in the driver is positive by 45 V to 60 V with respect to the source walls. Positive ions from the driver flowing towards the plasma grid are accelerated by this potential difference and can access to the extraction region with an energy of several tens of eV. The charge exchange reaction

\[ H^+ + Cs \rightarrow H + Cs^+ \]

will convert H\(^+\) into neutrals, and the caesium atoms into ions. The cross section for this reaction, denoted \( \sigma_{+0} \), was calculated by Olson et al, Phys. Rev. A 13 180 (1976) for the case when all the available hydrogen atom states are considered. For an energy of H\(^+\) of 50 eV this cross section is \(3.5 \times 10^{-15} \text{ cm}^2\). The production of Cs\(^+\) ions by this reaction is:

\[
\frac{dN(Cs^+)}{dt} = N(Cs)N(H^+)\sigma_{+0}v(H^+)
\]

With a density of energetic positive ions \(N(H^+)=1 \times 10^{17} \text{ m}^{-3}\) one finds

\[
\frac{dN(Cs^+)}{dt} = N(Cs) \times 3420 \text{ m}^3 / s.
\]
Caesium direct ionization cross section

The cross section for direct ionization, reported by Nygaard, J. Chem. Phys., 49, 1995 (1968) was used by Diomede and Longo (2010, Private communication), to calculate the reaction rate coefficient shown on the next figure. They are relevant when the electron temperature is comparable to the ionization potential.

Multistep ionization occurs in low temperature, high electron density plasmas. The existing data are not relevant to the ion source case.
Caesium ionization in electron collisions
Caesium direct ionization in electron collisions

We are interested in calculating the caesium direct ionization by electrons in the extraction region of the RF source studied at IPP Garching, where the electron temperature is 0.75 eV. The production of Cs\(^+\) ions is:

\[
\frac{dN(Cs^+)}{dt} = N(Cs)N_e <\sigma v_e>
\]

The rate coefficient for direct electron ionization is \(\sigma v_e = 5 \times 10^{-16} \text{ m}^3 \text{ s}^{-1}\) (Diomede and Longo).

With \(N_e = 1 \times 10^{17} \text{ m}^{-3}\) (as reported for the extraction region at 0.3 Pa by McNeely) one finds

\[
\frac{dN(Cs^+)}{dt} = N(Cs) \times 50 \text{ m}^3 \text{ s}^{-1}
\]

It was shown that the Cs ionization by ChX is seven times larger than this value.
$H^-$ formation by double electron capture in collision of $H^+$ with caesium atoms.

The protons in collision with caesium atoms can produce negative hydrogen ions by double electron capture:

$$H^+ + Cs \rightarrow H^- + Cs^{2+}$$

The cross section is increasing when the proton energy is reduced. The value measured by Cisneros et al, Phys. Rev. A (1976) at the lowest energy, 250 eV for $H^+$, is

$$\sigma_{+-} = 1 \times 10^{-16} \text{ cm}^2$$

Further work is necessary in order to evaluate how efficient double electron capture is at the lower proton energies.
Cross section for single and double electron capture in $\text{H}^+ + \text{Cs}$ collision (Cisneros et al 1976)
CONCLUSION

The implications of protons from the driver having a few tens of eV is discussed.

The comparison between caesium ionization by ChX with protons and by electrons showed that the ChX ionization dominates.

The H- ion production by double electron capture is discussed. Study of its cross section at lower proton energy is suggested.