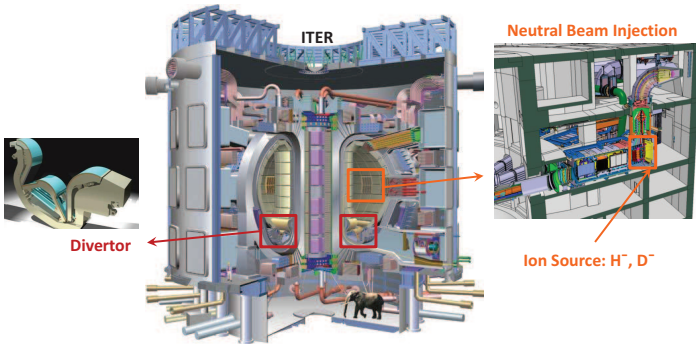
Relevance of Molecules in Ionizing and Recombining Plasmas in the Divertor and in Negative Ion Sources for Fusion

Ursel Fantz and Dirk Wünderlich



Molecules in fusion plasmas

Cold plasma edge:
SOL and divertor region

Wide parameter range

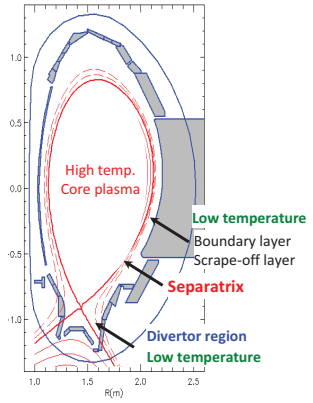
$T_e \approx 50$ eV ⟶ few eV ⟶ below 1 eV

$n_e \approx 10^{18} - 10^{21}$ m^{-3}

Ionising plasma ⟶ Recombining plasma

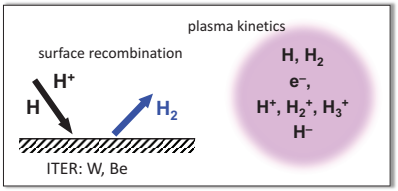
- Different recycling regimes
- Similar to laboratory plasmas
  low temperature, low pressure plasmas
- Relevance of diagnostics and modelling

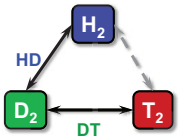
Atomic & molecular data



Molecules in fusion plasmas

Hydrogen molecules and molecular ions (H_2^+, H_3^+)





Recombination coefficient ⟶ f(material, T, $H_{adsorption}$ ...)

Vibrationally excited molecules $H_2(v) + H^+ \rightarrow H_2^+(v) + H$

Dissociative recombination $H_2^+(v) + e \rightarrow H + H(n)$

Molecular Assisted Recombination

Balmer line emission
Collisional Radiative model

Relevance of molecules in the transition regime towards detachment

Achievement of the recombining regime by atoms and / or molecules?

Electron Ion Recombination EIR

$H^+ + e + e \rightarrow H + e$ 3-body rec. and/or

$H^+ + e \rightarrow H + h\nu$ radiative recombination

$n_e \approx 10^{20}$ - 10^{21} m^{-3}, $T_e < 1.5$ eV

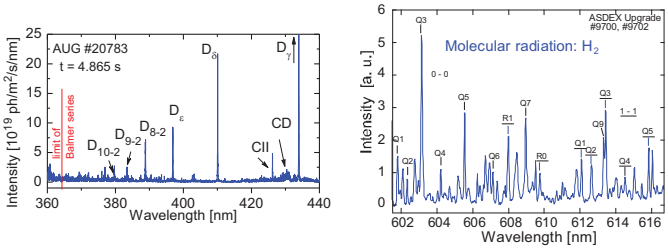
Molecular Assisted Recombination MAR

$H_2(v) + H^+ \rightarrow H_2^+(v) + H$ charge exchange with

$H_2^+(v) + e \rightarrow H + H^*$ dissociative recombination

$n_e \approx 10^{19}$ - 10^{21} m^{-3}, $T_e \approx 2$ - 10 eV

Divertor of ASDEX Upgrade (carbon machine): modelling & diagnostics



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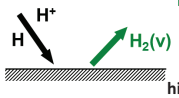
Divertor of ASDEX Upgrade (carbon machine): modelling & diagnostics

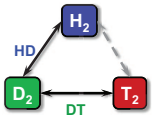
MAR: overall effect of some percent

Key role of vibrational population $H_2(v)$



Transferability to ITER ?

W divertor higher temperature — **isotope dependence**

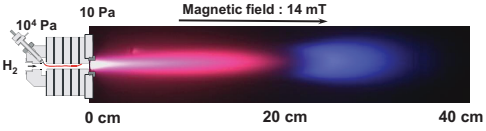


Further investigations with W wall and N_2 seeding needed !

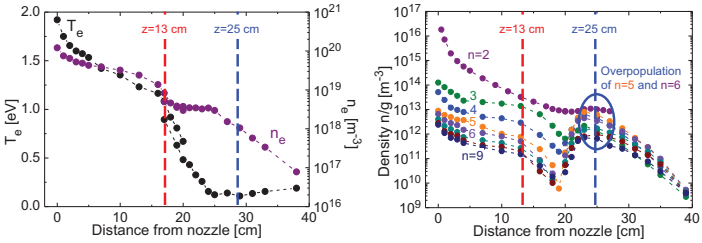
$N_2 \leftrightarrow H_2$

Relevance of molecules in the transition regime towards detachment

Linear plasma device: cascaded arc at TU/e Eindhoven

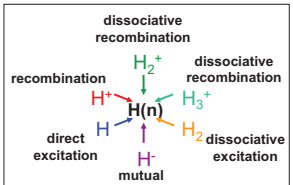


Plasma parameters from Thomson scattering, probes, OES, ...

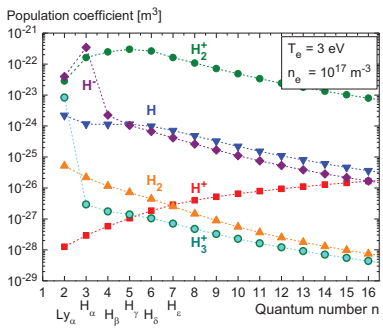


Role of molecules in the Balmer line analysis

Collisional radiative model for H with coupling to different particle species: Yacora



$$n(p) = R_H(p)\, n_H\, n_e + R_{H^+}(p)\, n_{H^+}\, n_e + R_{H_2}(p)\, n_{H_2}\, n_e + R_{H_2}(p)\, n_{H_2}\, n_e + R_{H_3^+}(p)\, n_{H_3^+}\, n_e + R_{H^-}(p)\, n_{H^-}\, n_e$$

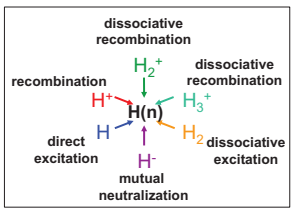


Many free parameters !

Role of molecules in the Balmer line analysis

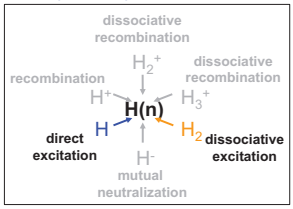
Collisional radiative model for H with coupling to different particle species: Yacora

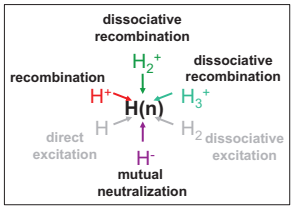
Yacora: full model



Ionizing plasma

Recombining plasma

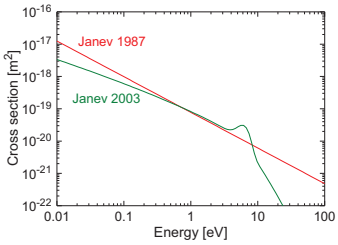




Role of molecules in the Balmer line analysis

Collisional radiative model for H with coupling to different particle species: Yacora

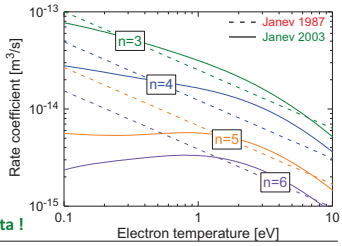
Data sets for dissociative recombination $H_2^+ + e \rightarrow H(n) + H$



R.K. Janev, W.D. Langer, J.K. Evans
D.E. Post *Elementary Processes in Hydrogen/Helium Plasmas*
Springer, Berlin (1987)

Fixed branching ratio

n=2: 0.1	n=5: 0.12
n=3: 0.45	n=6: 0.69
n=4: 0.22	n>6: 10/n³



Data set changed

R. Janev, D. Reiter, U. Samm, Juel-Report 4105 (2003)

Branching ratio vibrationally resolved and energy dependent

Much better agreement with experimental data !

Role of molecules in the Balmer line analysis

Collisional radiative model for H with coupling to different particle species: Yacora

Data for dissociative recombination of H_3^+

$H_3^+ + e \rightarrow H + H + H$ ①

$\rightarrow H_2 + H(n)$ ②

R. Janev, D. Reiter, U. Samm:
Juel-Report 4105 (2003)

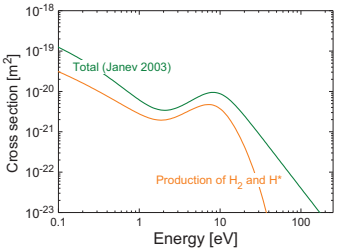
Branching ratio ① well known

S. Datz et al., Phys. Rev. Lett. **74**(1995) 896

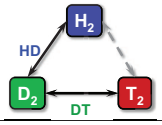
Branching ratio ② uncertain

② all in n=1 or n=2 for low E_e

F.C: Kulander et al., J. Phys. B **12** (1979) L501

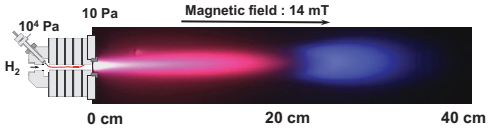


Open Issue: data for deuterium D_2^+, D_3^+

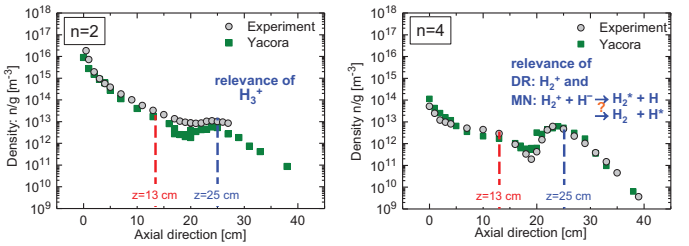


Relevance of molecules in the transition regime towards detachment

Linear plasma device: cascaded arc at TU/e Eindhoven



Balmer line analysis: measurement and CR modelling results (Yacora)



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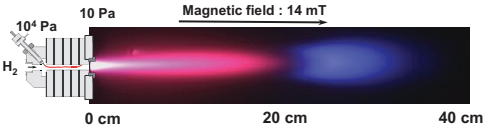

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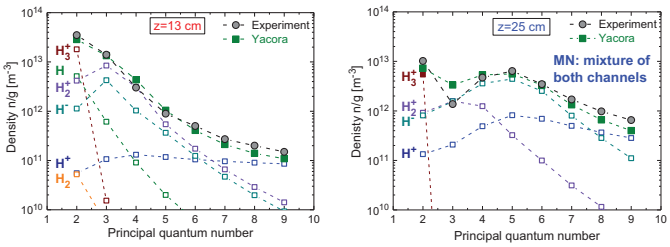
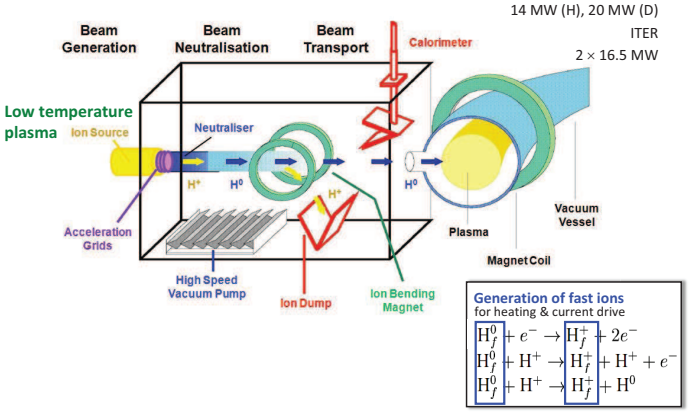


Molecules in negative hydrogen ion sources

Ion sources for neutral beam injection in fusion experiments

ASDEX Upgrade
14 MW (H), 20 MW (D)
ITER
2 × 16.5 MW



Generation of fast ions
for heating & current drive

$H_f^0 + e^- \rightarrow H_f^+ + 2e^-$

$H_f^0 + H^+ \rightarrow H_f^+ + H^+ + e^-$

$H_f^0 + H^+ \rightarrow H_f^+ + H^0$

Molecules in negative hydrogen ion sources

Ion sources for negative hydrogen ions: volume production

$e^- + H_2 \rightarrow H_2(B,C) + e^- \rightarrow H_2(v) + e^- + h\nu$

hot electrons

Vibrational excitation

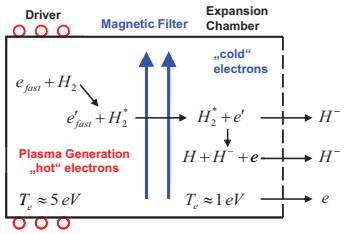
cold electrons

$e^- + H_2(v) \rightarrow H^- + H$

Dissociative attachment

high electron density and high pressure

Concept of a tandem source



Problems:

- high co-extracted electron current
- pressure and thus stripping losses in accelerator
  $H^- + H_2 \rightarrow H + H_2 + e$
  p ≈ 0.3 Pa: 30% losses
- low ion current for low pressure

Molecules in negative hydrogen ion sources

Ion sources for negative hydrogen ions: surface process via volume process

Volume production dissociative attachment

$H_2(v) + e^- \rightarrow H^- + H$ $\quad j_{H^-} \approx 4$ mA/cm², $j_e/j_{H^-} > 30$

Surface production

H, H_x^+ + surface $e^- \rightarrow H^-$ Cs evaporation

Cs layer

low work function

much higher j_{H^-}

much lower j_e/j_{H^-}

Destruction: volume processes

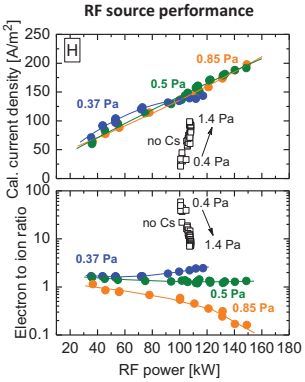
$H^- + e^- \rightarrow H + 2e^-$ electron stripping

$H^- + H_x^+ \rightarrow H + H$ mutual neutralisation

$H^- + H \rightarrow H_2 + e^-$ or $H + H + e^-$ associative detachment (non-associative)

Survival length of H^- ≈ few cm

RF source performance

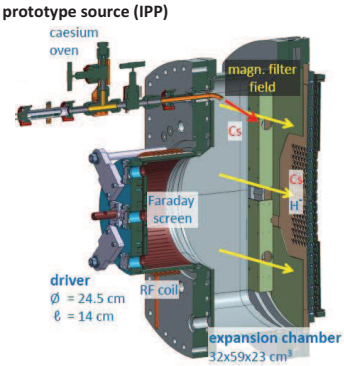


Molecules in negative hydrogen ion sources

Ion sources for negative hydrogen ions: ionising – recombining plasma

H, H_x^+ + surface $e^- \rightarrow H^-$ Cs evaporation → low work function

ITER prototype source (IPP)



Plasma generation ionising plasma

- ionisation: α ≈ 0.1
- dissociation: δ ≈ 0.3
- $T_e \approx 10$ eV
- $n_e \approx 5\times10^{18}$ m⁻³

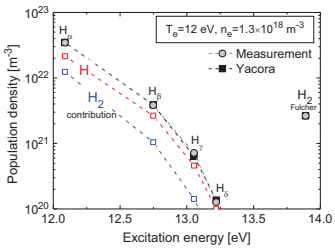
H^- generation recombining plasma

- $T_e \approx 1$ eV
- $n_e \approx 5\times10^{17}$ m⁻³
- $H^-/n_e \approx 0.1 - 5$
- $Cs^+/n_e \approx 0.01 - 0.1$

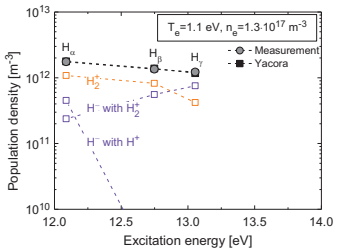
Balmer line analysis in negative hydrogen ion sources for fusion

Collisional radiative model for H with coupling to different particle species: Yacora

Ionising plasma



Recombining plasma



Relevance of H and H_2

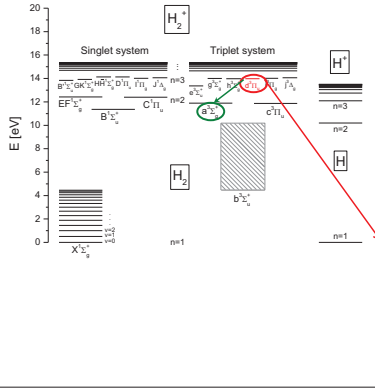
Relevance of H_2^+ and H^-

→ additional parameter: density of H_2^+ and H^-

Molecular emission in negative hydrogen ion sources for fusion

Collisional radiative model for H and for H_2: Yacora

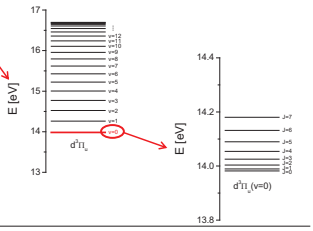
Important parameter: density ratio H/H_2 obtained from the intensity ratio H_γ / Fulcher band



Large number of excited states

- Electronic excitation
- Vibrational excitation
- Rotational excitation

Requires a comprehensive data set !

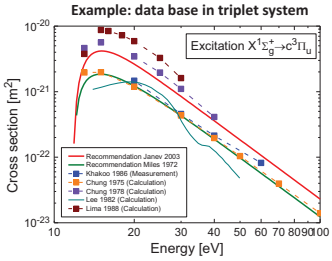


Molecular emission in negative hydrogen ion sources for fusion

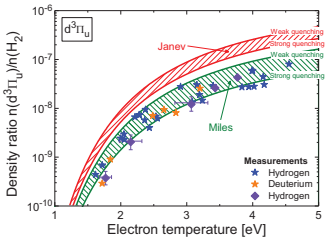
Collisional radiative model for H and for H_2: Yacora

Important parameter: density ratio H/H_2 obtained from the intensity ratio H_γ / Fulcher band

Example: data base in triplet system



Benchmark with experiments:
better agreement for
the semi-empiric Miles data
but
uncertainty of a factor of 3 remains

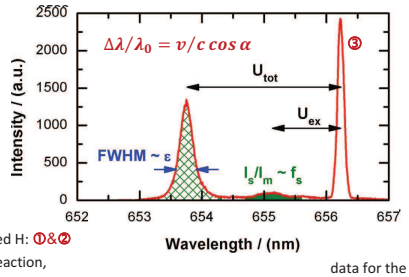


Beam Emission Spectroscopy (BES): analysis of Doppler-shifted H_α line

Determination of beam parameter

- Divergence
- Homogeneity
- Intensity
- Stripping losses in accelerator

$H^- + H_2 \rightarrow H + H_2 + e^-$



Three peaks

- Fully shifted peak from fully accelerated H: ①&②
- Medium shifted peak from stripping reaction, i.e. not being fully accelerated: ①&②
- Non-shifted peak at λ_0 from slow H: ③

Simple system, no calibration necessary

- divergence ε from FWHM of main shifted peak
- amount of stripped atoms f_s from ratio of stripping peak (I_s) to main peak (I_m)

Excitation reactions: ✓ data for the high energy range

① $H_f^- + H_2 \rightarrow H_f(n=3) + H_2 + e$

② $H_f + H_2 \rightarrow H_f(n=3) + H_2$

③ $H_f + H_2 \rightarrow H_f + H + H_s(n=3)$

D^-, D, D_2 ✘

Beam Emission Spectroscopy (BES): analysis of Doppler-shifted H_α line

Determination of beam parameter

- Divergence
- Homogeneity
- Intensity
- Stripping losses in accelerator

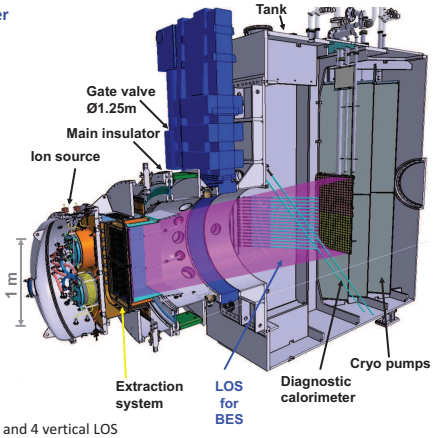
$H^- + H_2 \rightarrow H + H_2 + e^-$

½ size ITER source:

ELISE test facility (IPP)

Beam size: 1 × 1 m^2

640 apertures, 8 beamlet groups



BES in 2 m distance with 16 horizontal and 4 vertical LOS

Relevance of molecules in ionizing and recombining plasmas

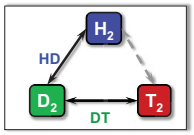
Hydrogen plasmas in fusion with molecules (H_2, H_2^+, H_3^+)

$H_2(v) + H^+ \rightarrow H_2^+(v) + H$

$H_2^+(v) + e \rightarrow H + H(n)$

$H_3^+ + e \rightarrow H + H + H$

$\rightarrow H_2 + H(n)$

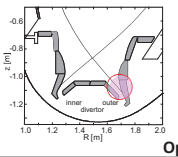


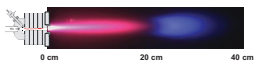
Molecular Assisted Recombination — ①

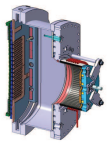
Balmer line emission Collisional Radiative model — ②

③

Divertor plasmas – **Linear plasma devices** – **Ion sources and beams (H^-, D^-)**







Open issue: W surface, N_2 seeding