This set of slides consists of a collection of short presentations on different topics, all related to plasma diagnostics. During my presentation I will use the first ‘introductory’ presentation as a guideline. I will discuss some diagnostics in more detail, and make a selection of the applications of diagnostics, depending on the audience.
“your working gas mixture ≠ input gas mixture”
(at high dissociation degree)

quote from Prof. J. Winter during his lecture during the 2005 Summer School on Low Temperature Plasma Physics: Basics and Applications
Molecule Formation in Plasma

Introduction

O₂ plasma impinging on a substrate

taken from: A. Lebéhot et al. in ‘Atomic and Molecular Beams’, ed. R. Campargue
Molecule Formation in Plasma

$O(^3P)_{\text{atm}} + NO_{\text{ads}} \rightarrow NO_2\{^2B_1\} \rightarrow NO_2\{^2A_1\} + h\nu$

$N_2$ plasma with $O_2$ injected in the background
Molecule Formation in Plasma

Vibrational Excitation of Hydrogen via Recombinative Desorption of Atomic Hydrogen Gas on a Metal Surface

Groupe de Spectroscopie par Impact Electronique et Ionique, Université Pierre et Marie Curie, 75252 Paris Cedex 05, France
(Received 20 July 1987)

Recombinative desorption of atomic hydrogen on the walls of a gas cell has been observed to populate vibrational levels up to $v=9$. The vibrational populations follow a Boltzmann distribution near 3000 K up to $v=3$ and for higher levels the populations are well in excess of this temperature. These observations bring light to a new mechanism for vibrational excitation of $\text{H}_2$ in volume $\text{H}^-$-ion sources.

PACS numbers: 79.20.Nc, 34.80.Gs, 52.40.Hf

$\text{H}_2^{r,\nu}$ detection via QMS detection of $\text{H}^-$
$\text{H}_2 + e \rightarrow \text{H}^- + \text{H}$
Molecule Formation in Plasma

Dark (dense) clouds
- 10-30 K / 10^4-10^8 part./cm^3
- Universal molecule factory

Diffuse (translucent) clouds
- 40-100 K / 100 part./cm^3
- Unknown absorption features

(from: H. Linnartz, CRD meeting (2004))
Questions when studying molecule formation in plasma?
(when in contact with a surface)

- What particles are arriving at the surface?
- In which state are the particles arriving?
- New molecules are generated:
  - electronically and/or ro-vibrationally excited?
  - substrate material and temperature dependence?
- Is there flux dependence on the generation process?
Questions when studying molecule formation in plasma? (when in contact with a surface)

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What is needed to answer these questions?
Gas-phase optical diagnostics for the detection of stable molecules and atomic/molecular radicals

- (VUV) Laser Induced Fluorescence
  - relative densities, + spatial resolution

- Fourier Transform IR/UV absorption
  - line of sight, + absolute densities, + large wavelength-range (overview spectrum)

- (Cavity Ring Down) absorption
  - line of sight, + (very) high sensitivity

- (spontaneous) Raman spectroscopy
  - ‘low’ sensitivity, + every molecule Raman active, + spatial resolution
### Plasma Diagnostics (optical)

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<th>Optical diagnostic</th>
<th>Parameters</th>
<th>Examples</th>
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<td>Doppler LIF</td>
<td>$w, T, n$</td>
<td>Ar-metastable</td>
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<td>Two-photon LIF</td>
<td>$w, T, n$</td>
<td>H atom</td>
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<td>VUV LIF</td>
<td>$n(v,J), T$</td>
<td>$\text{H}_2^{r,v}$</td>
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<tr>
<td>IR absorption</td>
<td>$n(v,J), T$</td>
<td>NO, N$_2$O, NO$_2$</td>
</tr>
<tr>
<td>Cavity Ring Down absorption</td>
<td>$n(v,J), T$</td>
<td>NH, NH$_2$, NH$_3$</td>
</tr>
</tbody>
</table>
All diagnostics are complimentary
On diagnostics (general):


Laser Induced Fluorescence spectroscopy
Laser Induced Fluorescence (LIF)

- Number of laser photons $n_a$ absorbed in unit volume and time:
  $$n_a = \sigma_{li} I_L n_l$$

- Number of fluorescence photons $N_f(\lambda_{ik})$ originating from $V$:
  $$N_f = n_a V q_f = \sigma_{li} I_L n_l V \cdot \frac{A_{ik}}{A_i + R}$$

- Signal $S_f$:
  $$S_f = \frac{N_f \cdot \Omega}{4\pi} \cdot T \cdot q_{ph}(\lambda) \cdot G_{ph}$$
  $$S_f \propto n_l$$
Laser Induced Fluorescence (LIF)

Advantages
- sensitive
- extra info from time behaviour
- experimentally straightforward
- possibility of 2D-imaging

Disadvantages
- not quantitative
- depending on gas composition (quenching)

How to detect the hydrogen atom in the ground state with LIF?
Advantages

- no demanding VUV-generation
- non-resonant fluorescence detection possible
- self-absorption can be avoided

Disadvantages

- low 2-photon cross sections require high laser intensities
- 2-photon cross sections often not known

2 photon LIF

H excitation schemes

Advantages

- no demanding VUV-generation
- non-resonant fluorescence detection possible
- self-absorption can be avoided

Disadvantages

- low 2-photon cross sections require high laser intensities
- 2-photon cross sections often not known
Quantities deduced from LIF

- Integrated intensity: $n$
- Doppler width: $T$
- Doppler shift $\nu - \nu_0$: $\nu$

\[
\Delta \nu_D = \frac{1}{c} \sqrt{\frac{8 \ln 2 \cdot kT}{M}}
\]
Applications:  
- fast deposition of a-Si:H  
- H-source  
- surface passivation

Applications:  
- deposition of a-C:N  
- plasma etching (photo-resist)
(VUV) LIF on $H_2$ molecules

Excitation from $H_2(X, v=0)$ to $H_2(B)$

Photons with energy $\approx 11$ eV
($\lambda \approx 110$ nm, Vacuum UV)

Fluorescence of $H_2$ in B-state

$\lambda$ in the Vacuum UV
Absorption spectroscopy
Absorption spectroscopy

Lambert-Beer: \( I(\nu) = I_0(\nu) \exp[-\kappa_\nu l] \)

Absorption: \( \kappa_\nu = n(\nu, J) \sigma_\nu \)

If \( \kappa_\nu l \) is small: \( \frac{\Delta I}{I_0} = \kappa_\nu l \)
IR laser absorption spectroscopy
IR laser absorption spectroscopy

Trace gas detection

Transmission

Energy

Wavenumber [cm$^{-1}$]
Fourier Transform absorption spectroscopy

interferogram
**O₂ FTIR measurement in a vessel**

![Diagram of FTIR setup](attachment:diagram.png)

FTIR absorption

Graph 3: FTIR absorption of O₂ in a vessel

- **Intensity (a.u.)** vs. **Frequency (cm⁻¹)**
- **Background** (black line)
- **Sample** (red line)

**Graph 13120 13125 13130 13135 13140 13145 13150 13155 13160 13165 13170**

**Background**

**Sample**
O₂ FTIR measurement in a vessel
### IR Laser Absorption

- Very high wavelength resolution
- High sensitivity

### FT IR Absorption

- Multiplex advantage
- Very large wavelength range

### Comparison

<table>
<thead>
<tr>
<th>Feature</th>
<th>IR Laser Absorption</th>
<th>FT IR Absorption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multiplex advantage</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Very large wavelength</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>range</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Very high wavelength</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>resolution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High sensitivity</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>Low wavelength resolution</td>
<td></td>
<td></td>
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<tr>
<td>Sensitivity</td>
<td></td>
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</tbody>
</table>

**Note:**

Homo-nuclear diatomic species **not** detectable in IR.
Sensitivity

\[
\frac{\Delta I}{I_0} \geq 10^{-3} \quad \text{(pulsed lasers)}
\]

\[
\kappa \nu l \geq 10^{-3}
\]

Example: \( l = 0.1 \text{ m} \)
\[
\sigma = 10^{-18} \text{ m}^2
\]

\[
\Rightarrow n(\nu, J) \geq 10^{16} \text{ m}^{-3}
\]

Alternative schemes:
- Fourier Transform spectroscopy (multiplex, but low sensitivity)
- Cavity Ring Down spectroscopy (high sensitivity)
Sensitive direct absorption technique


- absorption per unit of pathlength (cavity loss):
  \[ \frac{1}{\tau} = \left( 1 - R + n\sigma L \right) / d \]

- non-intrusive and remote
- high sensitivity due to effective multipassing
- direct absorption -> line of sight measurement
Basic scheme of the pulsed CRD spectrometer

Ring-down time

$$\tau = \frac{d}{c(1-R+n\sigma L)}$$

Cavity loss

$$\frac{1}{c\tau} = \frac{1-R}{d} + \frac{n\sigma L}{d}$$
Performing a pulsed CRD experiment

Ring-down transient

CRD spectrum
Performing a pulsed CRD experiment

If cavity length is 45 cm, determine R.

1. R = 99%
2. R = 99.9%
3. R = 99.99%
4. Not enough information

\[
\frac{1}{c\tau} = \frac{1-R}{d} + \frac{n\sigma L}{d}
\]
optical technique
+ independent of intensity
+ direct absorption measurement:
  -- but: line-of-sight
+ high sensitivity due to effective multipassing
+ pulsed light sources: spectral range into the UV
+ experimentally straightforward (tunable laser, highly reflecting mirrors, PMT, ‘fast’ and ‘deep’ digitizer)

high potential for diagnostics in plasmas
ETP setup

Plasma created at high pressure (~400 mbar) in cascaded arc plasma source

Expansion into low-pressure chamber (0.2 mbar) + injection of e.g. SiH$_4$

Plasma in interaction with surface, leading to e.g. deposition or etching
CRD for the detection of SiH during a:Si-H deposition

CRD absorption during deposition
CRD spectrum of SiH measured during a:Si-H deposition

CRD absorption during deposition
CRD spectrum of SiH measured during a:Si-H deposition

CRD absorption during deposition
SiH detection: \( A^2 \Delta \rightarrow X^2 \Pi \), 405 – 430 nm

Experimental

Simulated (LIFBase)

\[ Q_1(11.5) \]

\[ Q_1(14.5) \]

\[ R_2(14.5) \]

\[ \text{Absorption (x10}^{-6} \text{)} \]

\[ \text{Wavelength (nm)} \]

\[ T_{\text{vibr}} = 3000K \]

\[ T_{\text{rot(v=0)}} = 1800K \]

CRD absorption on SiH
TALIF spectroscopy
on
H atoms
Ar/H₂ plasma expansion

stationary shock wave

subsonic flow
M < 1

supersonic flow
M > 1

Mach disk
M = 1

Plasma expansion

cascaded arc

cathodes (3)
anode (nozzle)

gas inlet
Rayleigh scattering on $\text{H}/\text{H}_2$ plasma expansion

$H_2$ density (m$^{-3}$)

$1/z^2$

100 Pa

20 Pa

axial position (mm)
TALIF detection of H atoms

- produce 205 nm via THG of a Nd:YAG pumped dye laser
- from spectral scans data on: n, T, v, f(v)

Ionization energy (eV):
- Lyman α: 121.56 nm
- Hα: 656.5 nm
- 205.14 nm

Schematic diagram:
- Cascaded arc: 3.5 slm H₂, I=40A, V=150V
- 205 nm slitmask filter gates PMT
H atom density along the jet axis
(TALIF)

Density (m$^{-3}$)

z (mm)

100 Pa
20 Pa
Effect of nozzle-length on H density

![Graph showing the effect of nozzle-length on H density.](image)

- H density (m$^{-3}$) vs. axial position (mm)
- Nozzle length: 6 mm (blue dots) and 14 mm (red dots)
Effect of nozzle-length on H flux

- short nozzle
- long nozzle (x5)

H flux density ($10^{25} \text{ m}^{-2} \text{s}^{-1}$)

radial position (mm)
Effect of nozzle-width on H flux
Conclusions

1. Large influence of nozzle geometry on H flux
2. Loss of H atoms due to surface association (volume association far too slow)

\[ \text{loss of } H \text{ atoms} = \text{production of } H_2^{rv} \text{ at the surface} \]

H flux: \( \Phi_H > 10^{21} \text{ s}^{-1} \)
Dissociation degree = 0.4

S. Mazouffre et al., Phys Rev. E 64 (2001) 066405
Doppler-LIF spectroscopy on Ar atoms
Expanding Thermal Plasma (ETP)

- Plasma creation
- Plasma chemistry
- Material processing

SiH$_3$ reflection ~85%

SiH$_3$ reaction ~15%:
- 5-fold bonded Si
- SiH$_3$ surface diffusion:
- Strong bond formation with dangling bond
- Dangling bond creation by Eley-Rideal H-abstraction
- Dangling bond creation by ion
Ar plasma expansion
Ar density as function of distance from the exit of the source

Axial position (mm)

Ar density (m$^{-3}$)

- 42 Pa
- 100 Pa

Rayleigh scattering
Typical result of a Doppler LIF measurement

- Argon lamp
- Fabry Perot
- LIF signal

piezo voltage (a.u.)

intensity (a.u.)
Ar velocity distribution functions

Doppler LIF

velocity (km/s)

intensity (a.u.)

z=59 mm

z=100 mm

z=174 mm
Ar atom velocity

Ar atom temperature

Doppler LIF

calculated with: \( \gamma = 1.4 \)  
\( z_{\text{ref}} = 0.0025 \text{ m} \) 
\( T_0 = 6000 \text{ K} \)
IR absorption spectroscopy on $\text{N}_2/\text{O}_2$ plasma
N$_2$/O$_2$ plasma setup
(IR diode laser absorption spectroscopy)

I = 55 A
p = 20 Pa

Ar, N$_2$, H$_2$, O$_2$
Molecule Formation in Plasma

\[ O^{(3P)}_{\text{atm}} + \text{NO}_{\text{ads}} \rightarrow \text{NO}_2^{2B_1} \rightarrow \text{NO}_2^{2A_1} + h\nu \]

N\(_2\) plasma with O\(_2\) injected in the background
NO formation in an Ar-N₂-O₂ plasma

\[ \text{N + NO} \rightarrow \text{N}_2 + \text{O} \]

\[ \text{N + NO}_{\text{ads}} \rightarrow \text{N}_2\text{O} \]
N$_2$O formation in an Ar-N$_2$-O$_2$ plasma

N$_2$O only formed at low O$_2$ flow.
Time behavior of NO formation in Ar-N$_2$-O$_2$ plasma

$\tau_{\text{res}} \approx 1$ s

- No O$_2$ flow $\Rightarrow$ no NO formation
- No N$_2$ flow $\Rightarrow$ NO formation $>> \tau_{\text{res}}$

N on/in the surface (no O storage)
Time behavior of N$_2$O formation in an N$_2$-O$_2$ plasma

$\tau_{\text{res}} \approx 1 \text{s}$

- $O_2$ off after 1 min
- $O_2$ off after 5 min

**no O$_2$ flow**

$\downarrow$

N$_2$O formation $>\tau_{\text{res}}$

**NO on/in the surface**

(depends upon O$_2$ conditioning)
Conclusions

1. Input gas mixture, N\textsubscript{2} and O\textsubscript{2}, changes into a mixture of N\textsubscript{2}, O\textsubscript{2} and NO, N\textsubscript{2}O and NO\textsubscript{2}.

2. Time-resolved measurements show that surfaces become saturated with N atoms and NO radicals.

3. In Ar-NO plasmas, up to 90\% conversion of NO into N\textsubscript{2} and O\textsubscript{2}
VUV-LIF spectroscopy on $H_2^{r,v}$ molecules in plasma
Why study hydrogen plasma expansions? (produced from a cascaded arc)

1. **Use of H\textsubscript{2} gas in processing plasma application**  
   - etching and cleaning  
   - passivation during deposition

2. **Astrophysical interest**  
   - ‘hot’ H\textsubscript{2}, formed at grains through surface association, and acts as precursor in astro-chemistry

3. **Fundamental study of H\textsubscript{2}/HD/D\textsubscript{2} Lyman transitions**  
   - extension of database

4. **The cascaded arc might be used as H\textsuperscript{-} ion source, because of high fluxes of H\textsubscript{2}r,v at low T\textsubscript{e} (around 1 eV)**
Plasma source and expansion

$I = 40 – 60$ A
$P = 5 – 10$ kW
$\Phi_{arc} = 3$ slm
$P_{arc} = 0.2 \times 10^5$ Pa
$P_{bg} = 100$ Pa
Plasma expansion

- $T = 2000 \text{ K}$
- $T = 1000 \text{ K}$
- $T = 6000 \text{ K}$
- $T = 400 \text{ K}$

Diagram:
- Cathode (3x)
- Cascade plates
- Anode plate
- $4 \text{ mm}$ H$_2$ inlet
- 3000 sccm 9000 Pa
- $40 \text{ mm}$
- $10 - 100 \text{ Pa}$
- Supersonic expansion
- Zone of silence: $M > 1$
- Shock front: $M > 1$
- Subsonic expansion: $M < 1$
- Mach disk: $M = 1$
PLEXIS setup
PLEXIS setup

Laser table
Nd:YAG
   (450 mJ/shot @ 355 nm)
dye laser
   (50 mJ/shot @ 460 nm)
   (8 mJ/shot @ 230 nm)

Vacuum chamber
cylindrical (2m x 0.3m)
9 Pa / 3000 sccm H₂

- Movable plasma source and substrate
- Axial magnetic field
  \( B_{\text{max}} = 0.2 \, \text{T} \)
Ar/H\textsubscript{2} plasma expansion
Two photon Absorption LIF (TALIF) on atomic hydrogen

- Produce 205 nm via THG of a Nd:YAG pumped dye laser
- From spectral scans data on: n, T, v, f(v)

- 205 nm via THG of a Nd:YAG pumped dye laser
- From spectral scans data on: n, T, v, f(v)
H atom density in H$_2$ plasma expansion (TALIF)

Mazouffre et al. Phys. Rev. E 64, 016411 (2001)
VUV-LIF detection of $H_2^{r,v}$

**$H_2$ energy scheme**

- Lyman series absorption and emission
- $X^1\Sigma_g^+$ to $B^1\Sigma_u^+$ transition in $H_2$ ($\sim 11$ eV)

**Excitation and detection**

- $X \rightarrow B$ transition in $H_2$ ($\sim 11$ eV)
- Detection of fluorescence in the VUV range
- Excitation with 120 – 165 nm photons, produced via SARS

![Graph showing energy levels and transitions](image)
VUV-LIF detection of $\text{H}_2^{r,v}$

**H$_2$ energy scheme**

- **X** → **B** transition in $\text{H}_2$ (~11 eV)
- Detection of fluorescence in the VUV range
- Excitation with 120 – 165 nm photons, produced via SARS
VUV-LIF detection of $H_2^{r,v}$

H$_2$ energy scheme

VUV-LIF detection scheme
VUV-LIF setup

Nd:YAG THG

Dye (C440)

NO cell

PMT

220 nm

440 nm

BBO

H2

LN2

Plasma

to pump

WSM

M

M

M

M

WSM

M

M

VUV mono

to pump
VUV-LIF setup
Measured $\text{H}_2$ Lyman spectrum

Fluorescence (a.u.) vs. SH frequency (cm$^{-1}$)

- AS8 frequency (cm$^{-1}$): 76890
- AS9 frequency (cm$^{-1}$): 81045

- 77140
- 81295
VUV-LIF setup

Nd:YAG THG

Dye (C440)

BBO

220 nm

440 nm

NO cell

220 nm to pump

440 nm to pump

PMT

PMT

PMT

VUV mono

LN₂

H₂

L

M

W

S

M
VUV-LIF setup

Fluorescence (a.u.)

TALIF spectrum of NO
P = 2 mbar

Fluorescence (a.u.)

Wavenumber (cm$^{-1}$)

440 nm

220 nm

NO cell

BBO

M

L

PMT

H$_2$

W

M

to pump

VUV mono

PMT

S

PMT

to pump
VUV-LIF spectroscopy

- NO via TALIF
- \( H_2(v=4,J=7) \) via VUV-LIF

TALIF spectrum of NO
\( P = 2 \text{ mbar} \)

Fluorescence (a.u.)

AS7 frequency (cm\(^{-1}\))

VUV-LIF spectroscopy
Measured H$_2$ Lyman spectrum

- state-selective
- spatially resolved
- non-intrusive

**dynamic range** $> 4$ orders

**detection limit** $\sim 10^{13}$ m$^{-3}$

Measured \( \text{H}_2 \) Lyman spectrum

Advantages multiplexing:
- spectrum more dense
- efficient measurement

H\( _2 \)\( ^{(v,J)=(3,7)} \)

Fluorescence (a.u.)

SH frequency (cm\(^{-1}\))
Measured H₂/HD/D₂ Lyman spectra

Measured and calculated $\text{H}_2/\text{HD}/\text{D}_2$ Lyman spectrum

Spectroscopic data for $\text{H}_2$

*All $\text{H}_2$ Lyman transitions*

Spectroscopic data for HD

*HD Lyman transitions $J < 11$*

Spectroscopic data for $\text{D}_2$

*D$_2$ Lyman transitions $J < 12$*
New calculated Lyman transitions including higher rotational states ($J > 10$), in collaboration with Abgrall and Roueff

O. Gabriel et al. J. Mol. Spectrosc 253 (2009) 64
Non-Boltzmann distribution for H$_2$

- 700 K for low J
- 3800 K for high J

"Hockey stick"
Non-Boltzmann distributions in $\text{H}_2/\text{D}_2$ jet

Low J: $T = 300$ K  
High J: $T = 3000$ K

Low J: $T = 500$ K  
High J: $T = 3400$ K

Results on $\text{H}^-$ production through DA process

Production rate of $\text{H}^-$ ions by dissociative attachment

$T_e = 5000 \text{ K}$

$\text{H}_2(0,0)$

$n_e = 10^{17} \text{ m}^{-3}$

CRD spectroscopy on \( \text{N}_2/\text{H}_2 \) plasma
NH₃ production in N₂/H₂ plasma

- SiH₃ reflection
- ~85% SiH₃ reaction
- ~15%: 5-fold bonded Si
- SiH₃ surface diffusion: strong bond formation with dangling bond
- dangling bond creation by Eley-Rideal H-abstraction
- dangling bond creation by ion
- dangling bond surface diffusion
- NH₃ production in N₂/H₂ plasma
NH\textsubscript{3} production in N\textsubscript{2}/H\textsubscript{2} plasma

N\textsubscript{2}/H\textsubscript{2} plasma creation

Plasma chemistry leading to e.g. NH\textsubscript{x}

NH\textsubscript{3} formation?
absorption per unit of pathlength (cavity loss):

\[
1 / c \tau = \frac{(1 - R + n\sigma L)}{d}
\]

- non-intrusive
- high sensitivity due to effective multipassing
- direct absorption \(\rightarrow\) line of sight measurement
Cavity Enhanced Absorption detection scheme

NH$_3$ production in N$_2$/H$_2$ plasma

CEA measurement recorded in a vessel in which N$_2$/H$_2$-plasma expands

Scanning frequency: 30 Hz
Frequency range: 15 GHz
Averages: 1000
Measurement time: 30 s

The absorption coefficient $\kappa(\nu)$ from intensity by:

$$\kappa(\nu) = \left( \frac{S_0(\nu)}{S(\nu)} - 1 \right) \times \left( \frac{1-R}{d} \right)$$
NH₃ production in N₂/H₂ plasma

Part of the absorption spectrum of NH₃ as measured in an expanding N₂/H₂ plasma

\[ \sigma \approx 10^{-22} \text{ m}^2 \]
\[ N \approx 10^{19} \text{ m}^{-3} \]

Line width
\[ T_{\text{tr}} = 600 \text{ K} \]
Saturation behavior explained by rate determining steps:

\[ \text{N}^+ + \text{H}_2 \rightarrow \text{NH}^+ + \text{H} \]

\[ \text{NH}^+ + \text{e} \rightarrow \text{N} + \text{H} \]

Total \( \text{N}^+ \) flow is consumed

**NH\textsubscript{3} production in N\textsubscript{2}/H\textsubscript{2} plasma**

Ammonia density produced in expanding N\textsubscript{2} plasma in which H\textsubscript{2} is injected in the background

\[ P_{bg} = 100 \text{ Pa} \]
NH₃ production in N₂/H₂ plasma

Ammonia density as function of background pressure at constant gas flow (N₂-arc/H₂-background)

- Linear with pressure (dNH₃/dt constant)
- 3 particle reaction
- Stable intermediate
- Wall production (?)

Graph: NH₃ density (10¹⁹ m⁻³) vs Pressure (Pa)
NH₃ production in N₂/H₂ plasma

NH₃ production in two different vessels

- Total gas flow of 2 slm through cascaded arc
- At maximum 12% of the background gas is NH₃

larger surface-to-volume ratio

Conclusions

Input gas mixture, N₂/H₂, changes into N₂/H₂/NH₃ mixture (12 % of the background gas is NH₃).

NH₃ is formed at surfaces.