Influence of the cusp field on the plasma parameters of the Linac4 H^- ion source

S. Briefi[1], S. Mattei[2], J. Lettry[2] and U. Fantz[1,3]

[1] AG Experimentelle Plasmaphysik, Universität Augsburg, 86135 Augsburg

[2] Linac4 ion source team, CERN-ABP, 1211 Geneva 23

[3] Max-Planck-Institut für Plasmaphysik, Boltzmannstr. 2, 85748 Garching

The authors would like to thank the Deutsche Forschungsgemeinschaft (DFG) for their support within the project BR 4904/1-1.

Introduction

- Upgrade in the first part of the injector chain of the LHC at CERN

  → Linac4 H^-, acceleration to 160 MeV, charge-exchange injection at PSB

  → Aim Doubling the beam intensity, improving the injection efficiency

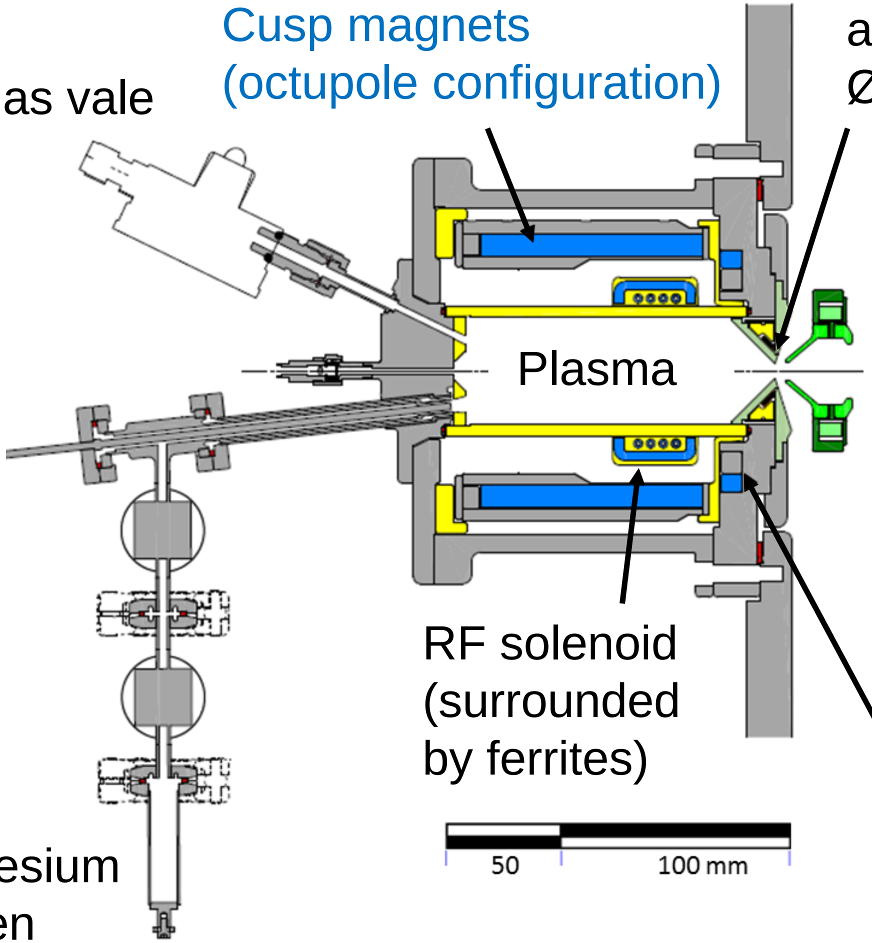
- H^- ion source based on DESY/SNS concept with adapted parameters

RF frequency	2 MHz, up to 100 kW
Duration of plasma pulse	500 µs
H^- current	45 (80) mA
Beam energy	45 keV
Duration of beam extraction	400 µs
Repetition rate	2 Hz
Nominal Emittance	0.25 π mm mrad

- Production of negative hydrogen ions…
  - …in the plasma volume $H_2(v) + e_{slow} \rightarrow H^- + H$
  - …at a caesiated surface $H + e_{surface} \rightarrow H^-$

    H^+ (or H_2^+, H_3^+) $+ 2\ e_{surface} \rightarrow H^-$ (or $H^- + H$, H_2)

Setup of the Ion Source



Pulsed gas vale

Cusp magnets (octupole configuration)

Extraction aperture
Ø 6.5 mm

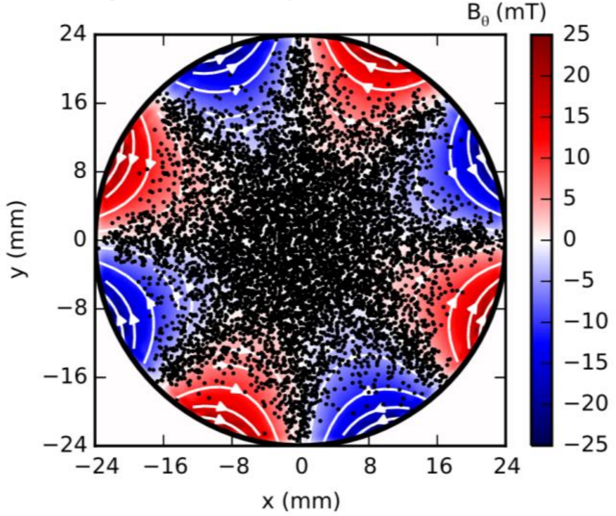
Plasma

RF solenoid (surrounded by ferrites)

Filter field magnets

Caesium oven

Cusp field layout



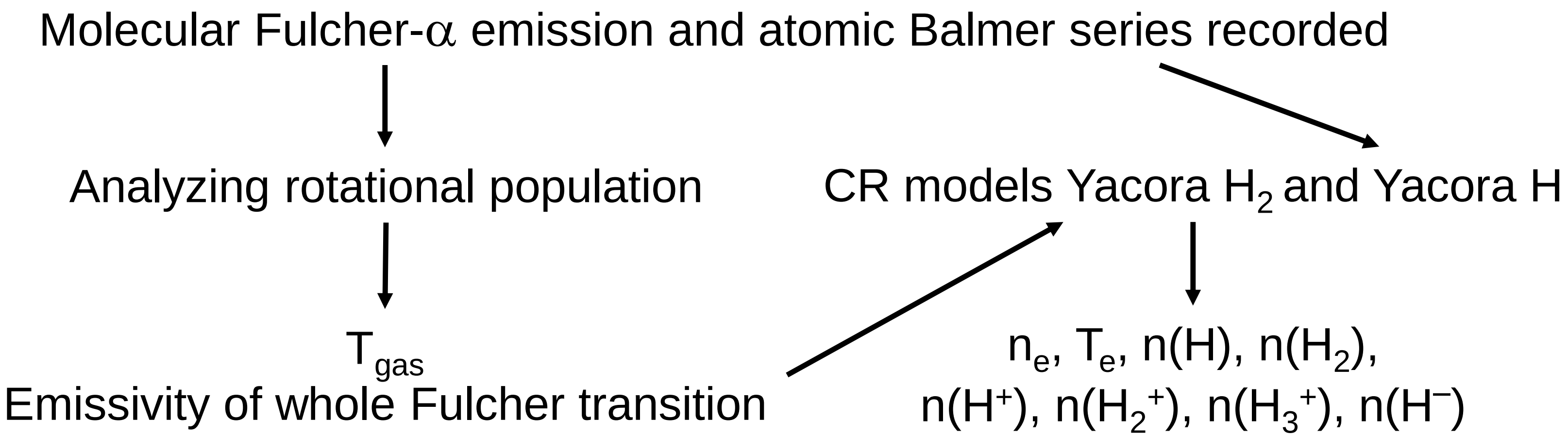
S Mattei et al., accepted for publication in PSST

Motivation

- In volume operation (i.e. without Cs) an H^- current of typically
  - 25 – 30 mA is reached with cusp magnets at an RF power of 40 kW
  - 15 – 20 mA is reached without cusp magnets at an RF power of 20 kW

Determine influence of cusp field on plasma parameters

- Optical emission spectroscopy measurements carried out with varying RF power with and without cusp magnets



Molecular Fulcher-α emission and atomic Balmer series recorded

Analyzing rotational population

CR models Yacora H_2 and Yacora H

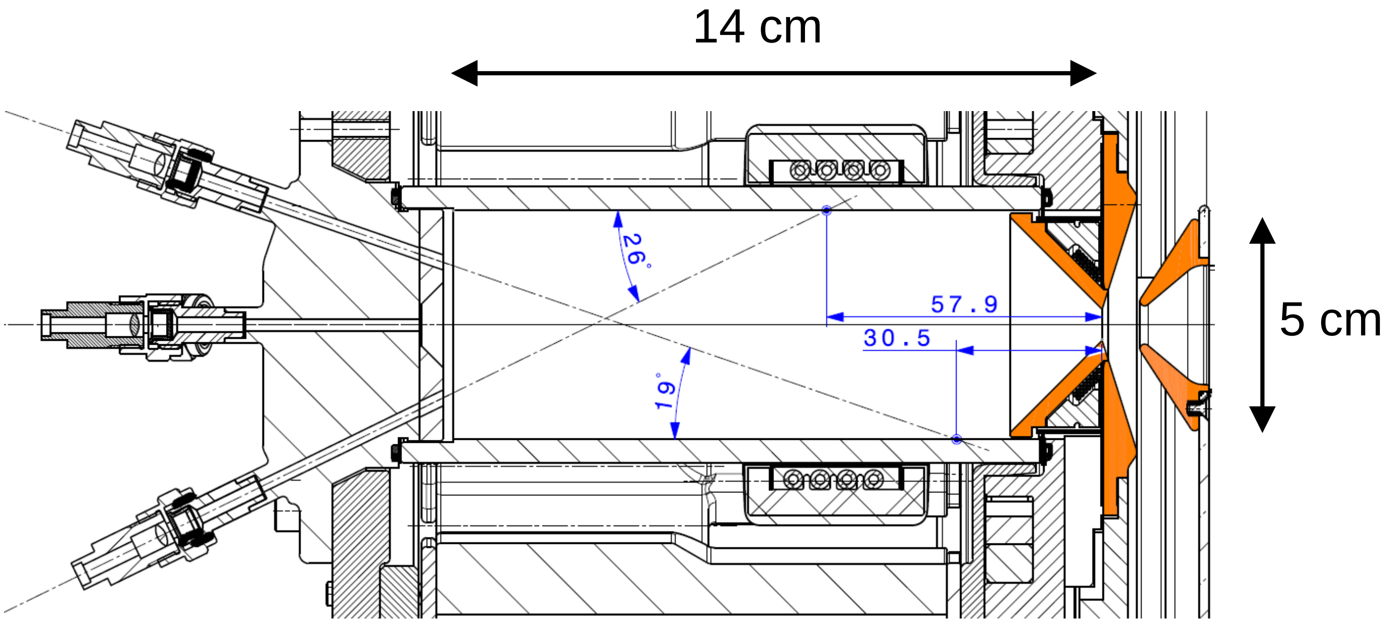
T_{gas}

Emissivity of whole Fulcher transition

n_e, T_e, $n(H)$, $n(H_2)$,

$n(H^+)$, $n(H_2^+)$, $n(H_3^+)$, $n(H^-)$

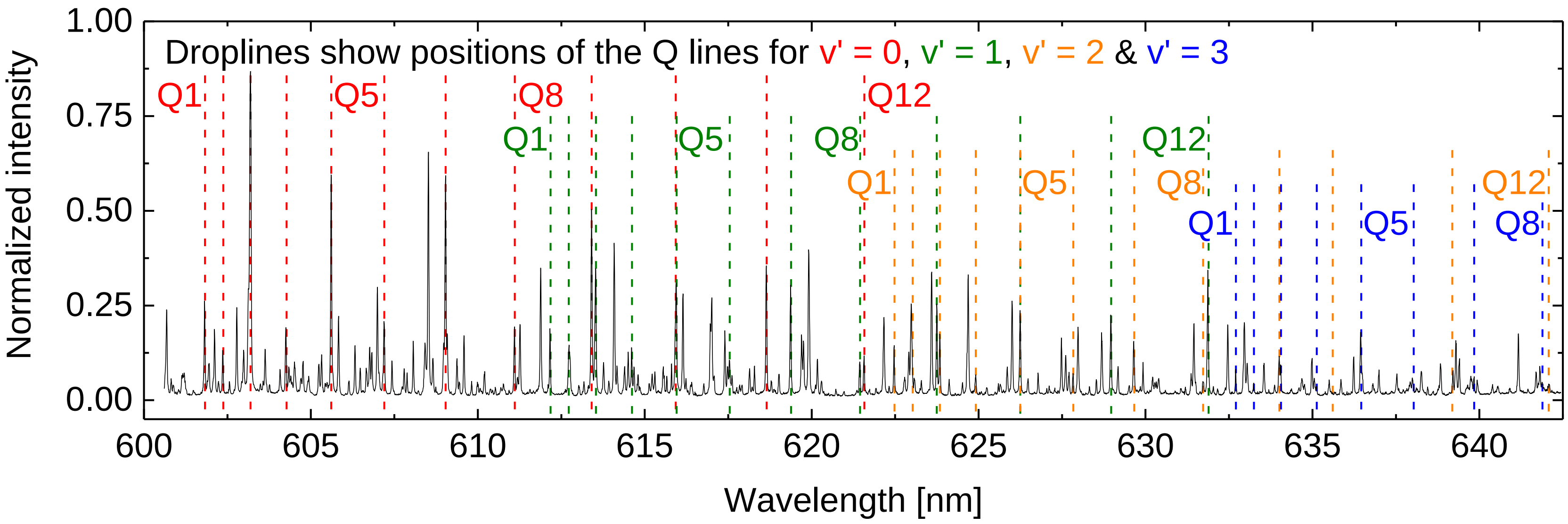
Spectroscopic Setup



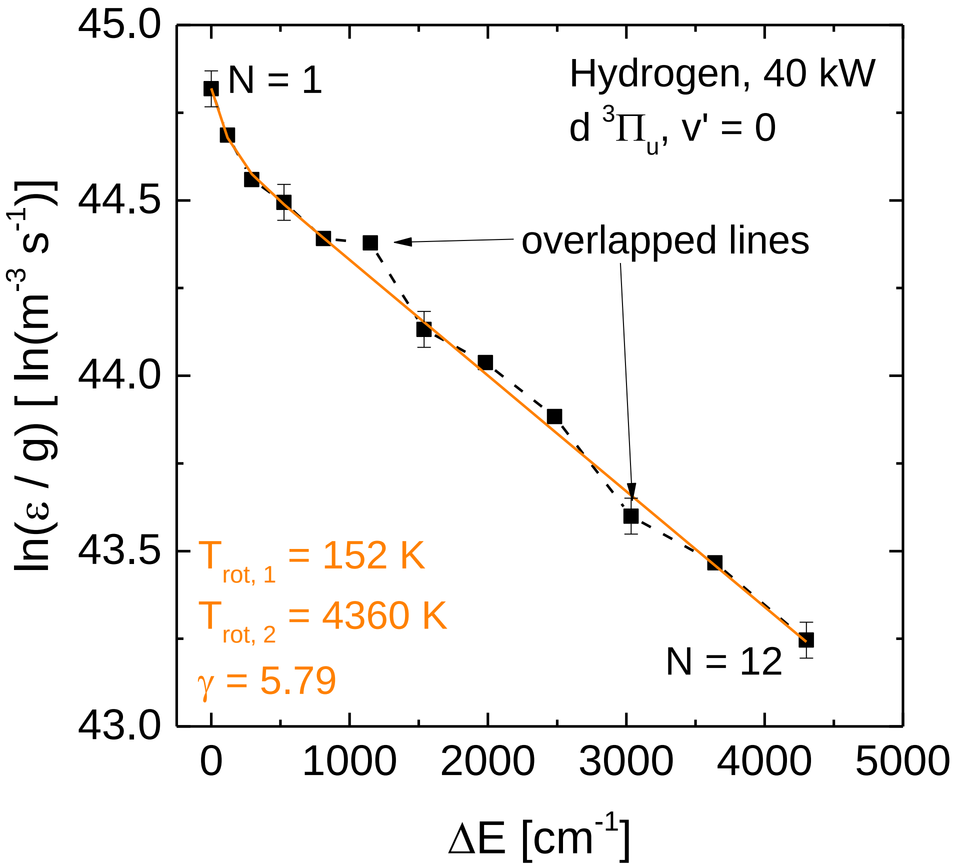
- Three windows available: on-axis, 19° or 26° tilted
- High resolution spectrometer with ICCD camera
  - $\Delta\lambda_{FWHM} \approx$ 8 pm, Lorentzian apparatus profile
  - Measurement duration: last 400 µs of the plasma pulse length of 500 µs

Diagnostics – Fulcher-α Transition

- Evaluation of H_2 Fulcher-α transition (d $^3\Pi_u \rightarrow$ a $^3\Sigma_g^+$, 590 – 650 nm)
  - Measurement: first 12 emission lines of Q branch (N' = N'') for v' = v'' = 0, 1, 2, 3
  - Adjusting a calculated rotational population yields T_{rot}, T_{vib} & T_{gas}
  - Scaling from measured ro-vibrational levels to full system yields emissivity of the whole Fulcher transition



Results – Rotational population & T_{gas}



- Hockey-stick population

$$n(N) = \underbrace{\tilde{n}(N, T_{rot,1})}_{\text{heavy particles}} + \gamma\, \underbrace{n'(N, T_{rot,2})}_{\text{most likely electrons}}$$

VANKAN ET AL., CHEM. PHYS. LETT. 400 (2004) 196–200

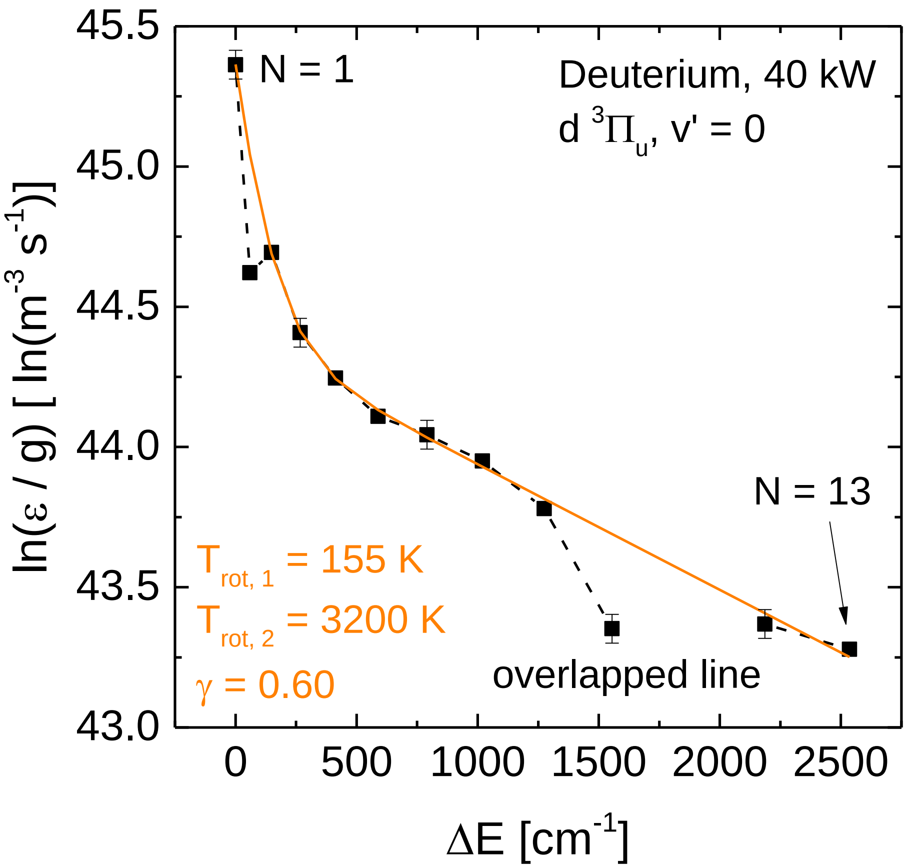
- $\tilde{n}(N, T_{rot,1})$ not obvious

  → Only the first two levels follow the cold population

- Projecting $T_{rot,1}$ to the X $^1\Sigma_g^+$ state yields T_{gas} = 304 K

  → T_{gas} virtually equivalent to ambient temperature

Results – Rotational population & T_{gas}



- Exceptional operation in D_2
- ñ(N, $T_{rot,\ 1}$) much more distinct

  → ΔE of rotational states smaller

  → More levels follow cold population

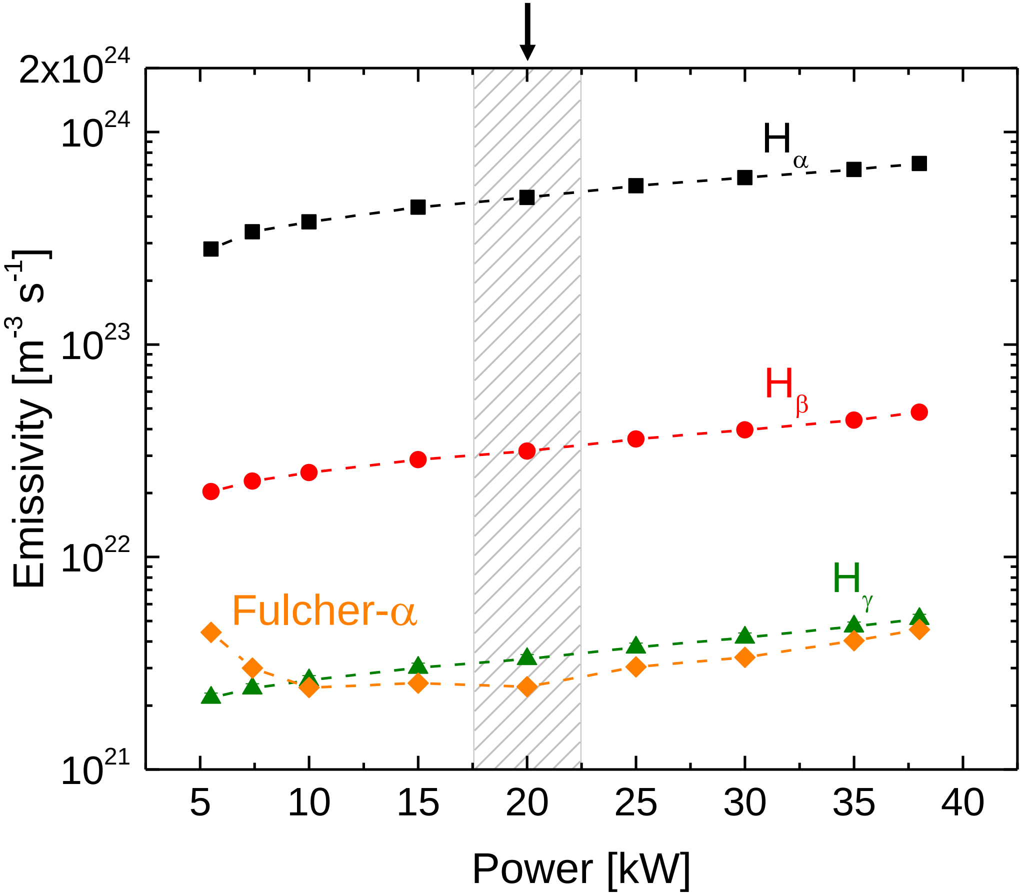
  T_{gas} = 310 K
- Gas is supplied to the source at ambient temperature

  → Short plasma pulse (500 µs) prevents heavy particles from heating up

Independent of cusp field or RF power: T_{gas} ≈ 300 K

Results – Emissivity over P_{RF} without cusp

Best performance (highest H^- current)



- Emissivity increases with RF power for Balmer lines
- Molecular Fulcher-α emission shows different behavior

Diagnostics – Yacora H

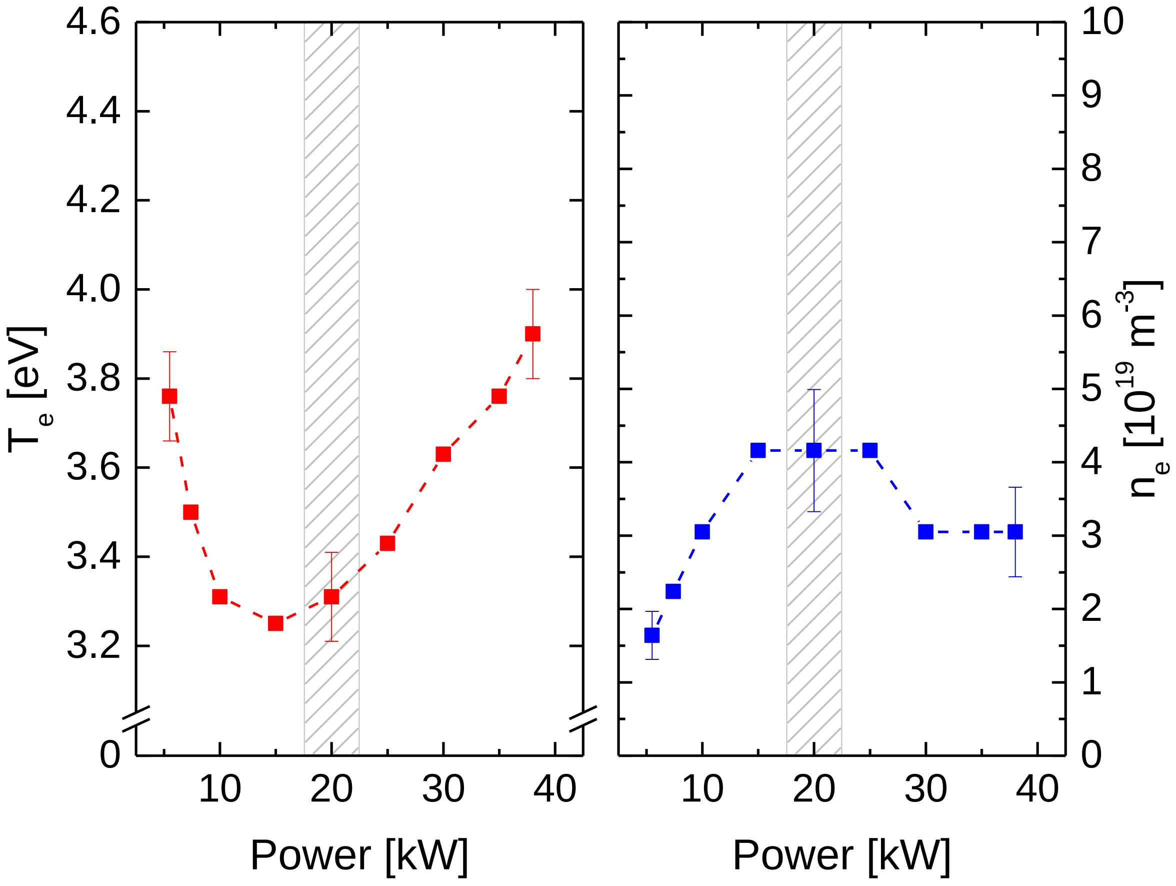
- Collisional radiative model for the hydrogen atom: Yacora H
  D. WÜNDERLICH ET AL., J. QUANT. SPECTROSC. RADIAT. TRANSFER 110, 62 – 71 (2009)

  Balances all relevant population and depopulation processes like

→ Electron impact excitation	$\mathrm{H}(k) + \mathrm{e}^- \longrightarrow \mathrm{H}(i>k) + \mathrm{e}^-$
→ Dissociative excitation	$\mathrm{H}_2 + \mathrm{e}^- \longrightarrow \mathrm{H}(i) + \mathrm{H}(1) + \mathrm{e}^-$
	$\mathrm{H}_2^+ + \mathrm{e}^- \longrightarrow \mathrm{H}(i) + \mathrm{H}^+ + \mathrm{e}^-$
→ Dissociative recombination	$\mathrm{H}_2^+ + \mathrm{e}^- \longrightarrow \mathrm{H}(i) + \mathrm{H}(1)$
	$\mathrm{H}_3^+ + \mathrm{e}^- \longrightarrow \mathrm{H}(2) + \mathrm{H}_2$
→ Recombination	$\mathrm{H}^+ + 2\mathrm{e}^- \longrightarrow \mathrm{H}(i) + \mathrm{e}^-$
	$\mathrm{H}^+ + \mathrm{e}^- \longrightarrow \mathrm{H}(i) + \mathrm{h}\nu$
→ Mutual neutralization	$\mathrm{H}^- + \mathrm{H}^+ \longrightarrow \mathrm{H}(i) + \mathrm{H}(1)$
	$\mathrm{H}^- + \mathrm{H}_2^+ \longrightarrow \mathrm{H}(i) + \mathrm{H}_2$

- First two processes dominate excitation within H
  - Evaluation not sensitive on n(H^+), n(H_2^+), n(H_3^+), n(H^-)
  - Only n_e, T_e, n(H), n(H_2) can be determined

Results – Plasma parameters without cusp



- For such high n_e values

  $H_2(v) + e_{slow}$ → $H^- + H$

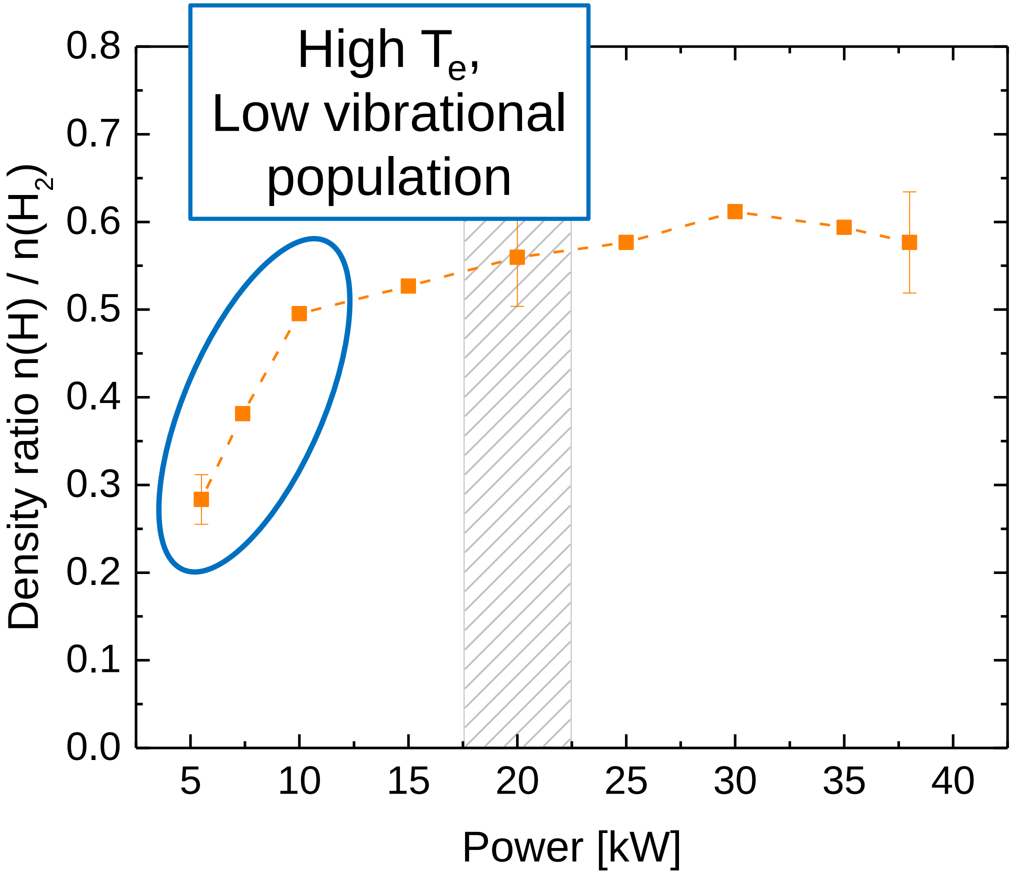
  balanced by

  $H^- + e_{fast}$ → $H + 2\,e$
- Influence of n_e cancels
- Low T_e results in higher H^- yield
- Highest vibrational population at 20 kW

  → Not in equilibrium

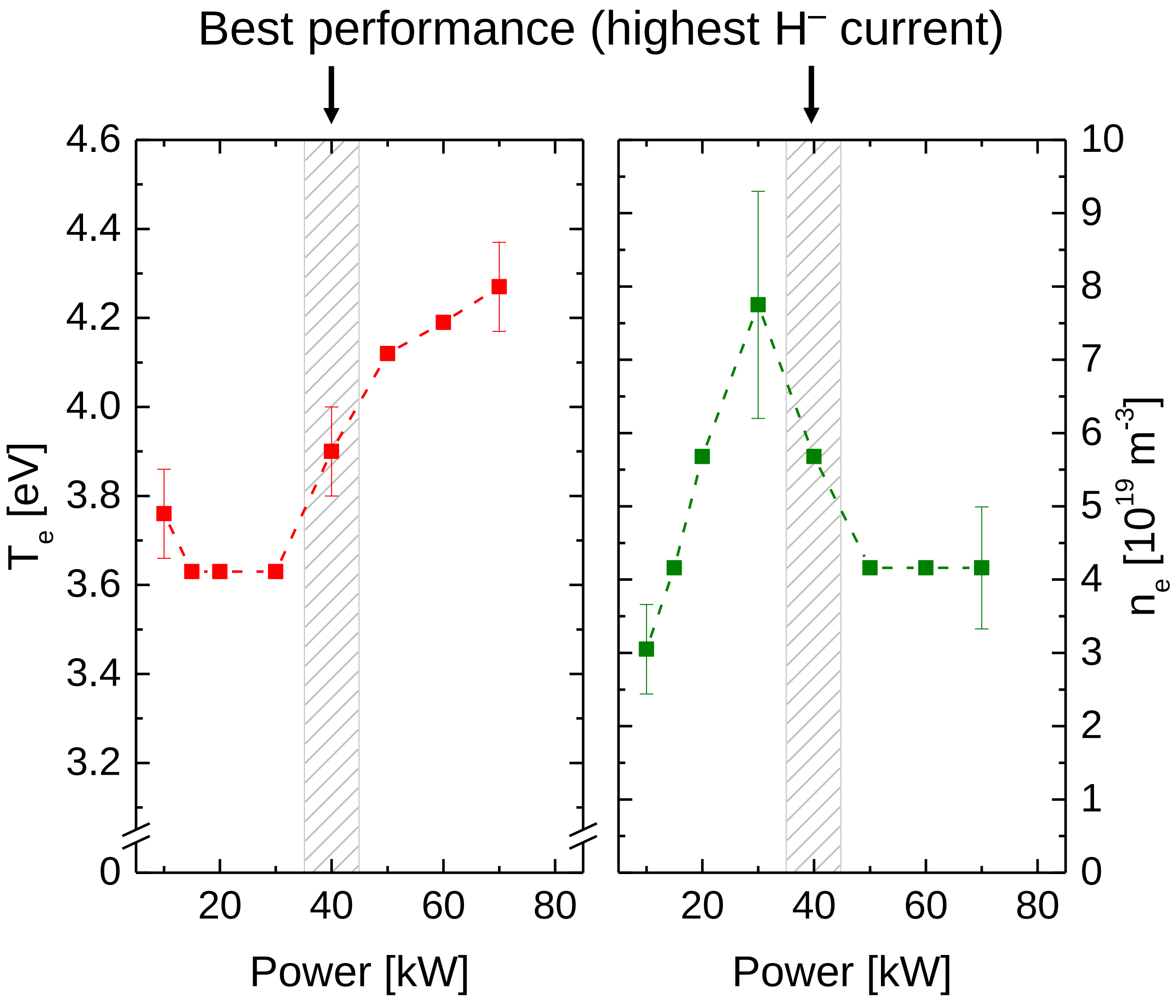
Best performance at 20 kW explained by highest H^- yield

Results – Plasma parameters without cusp



- High density ratios adhere to high H^- production → less molecules
- Influence of T_e and vibrational population dominate H^- yield

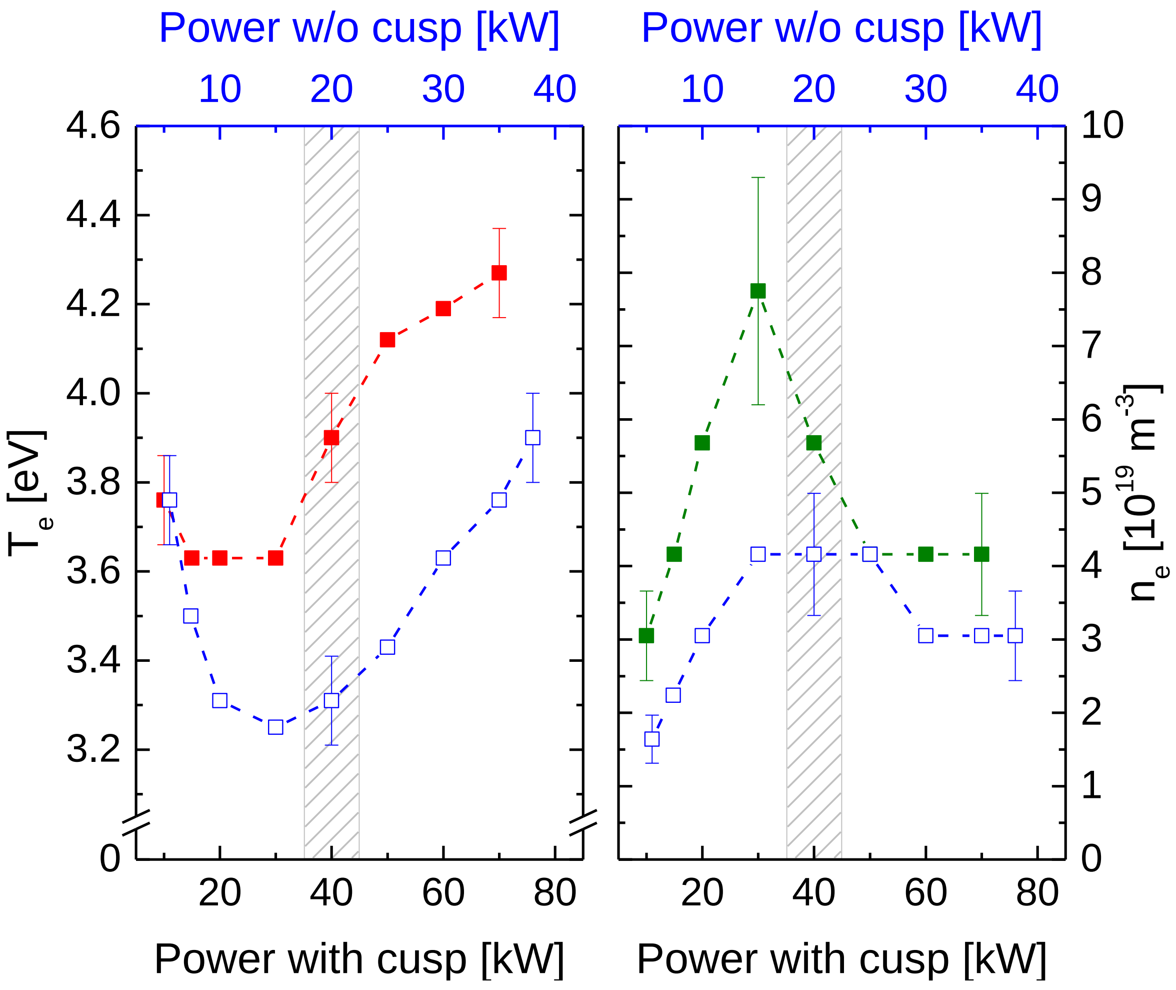
Results – Plasma parameters with cusp



- Same trends observed as without cusp field
  - Minimum in T_e
  - Maximum in n_e
  - Increase of $n(H)/n(H_2)$
- Required RF power a factor of 2 higher
  - Cusp field keeps electrons from wall
  - Higher RF fields for similar parameters

For comparing the two cases power scaling by a factor 2 is required

Results – T_e and n_e with & w/o cusp



- Best performance expected at 30 kW
  - Minimum in T_e
  - Maximum in vibrational population
- T_e shifted to higher values with cusp
- Best performance with cusp at 40 kW observed

→ Strong influence of cusp field on profiles

→ Spatially resolved modeling required

Summary

- Investigation of Linac4 H^- ion source in volume operation via OES for determining influence of cusp field on plasma parameters
  - With cusp: 25 – 30 mA at 40 kW, without them 15 – 20 mA at 20 kW
- Evaluation of molecular Fulcher-α emission & atomic Balmer series
  - No distinct influence of cusp on n(H) / n(H_2) and $T_{gas} \approx 300$ K
  - At varying RF power
    - → Minimum T_e & maximum vibrational population at 20 kW: high H^- yield
    - → Directly correlated with maximum in extracted H^- current without cusp
  - Application of cusp magnets increases required RF power by a factor of 2
  - Better performance with cusp despite higher T_e: Plasma profiles
- Proved that OES yields valuable results for explaining observed trends
  - Determined plasma parameters serve as input & benchmark for models