Determination of plasma parameters via optical emission spectroscopy at CERN's Linac4 H^- ion source

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Introduction

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

  Ion source → Linac2 (50 MeV) → PSB, PS, SPS (450 GeV) → LHC (7 TeV)

  – Up to now: H^+, acceleration to 50 MeV
  – Linac4: H^-, acceleration to 160 MeV, charge-exchange injection at PSB

- **AIM** → Doubling of the beam intensity inside PSB
  → Improvement of 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	0.5 ms
H^- current	45 (80) mA
Beam energy	45 keV
Duration of beam extraction	0.4 ms
Repetition rate	2 Hz
Nominal Emittance	0.25 π mm mrad

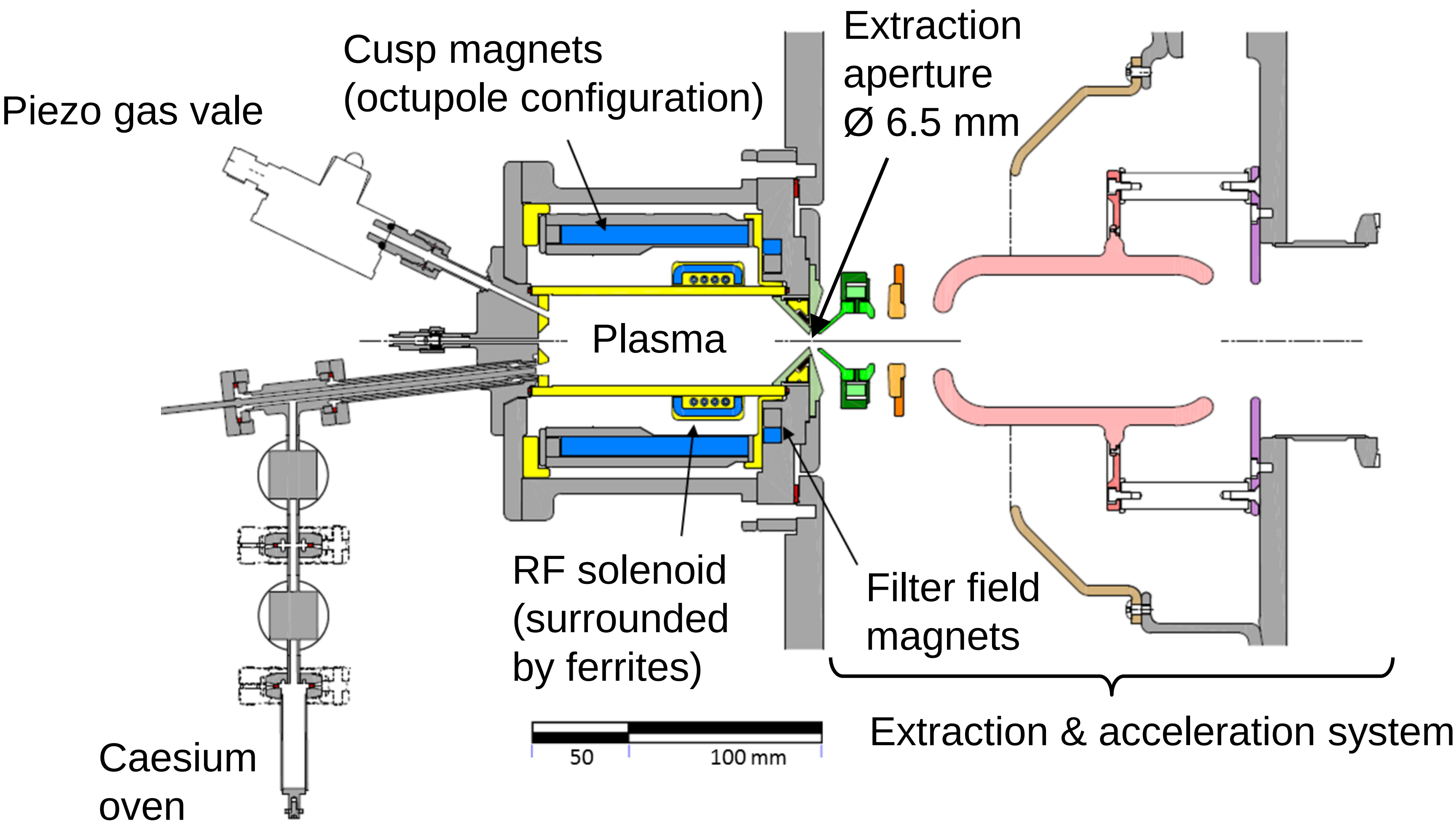
Motivation

- Production of negative hydrogen ions…
  - …in the plasma volume $H_2(v) + e^- \rightarrow H^- + H$
  - …at a ceasiated surface $H + e^-_{surface} \rightarrow H^-$
    H^+ (or H_2^+, H_3^+) $+ 2\ e^-_{surface} \rightarrow H^-$ (or $H^- + H$, H_2)

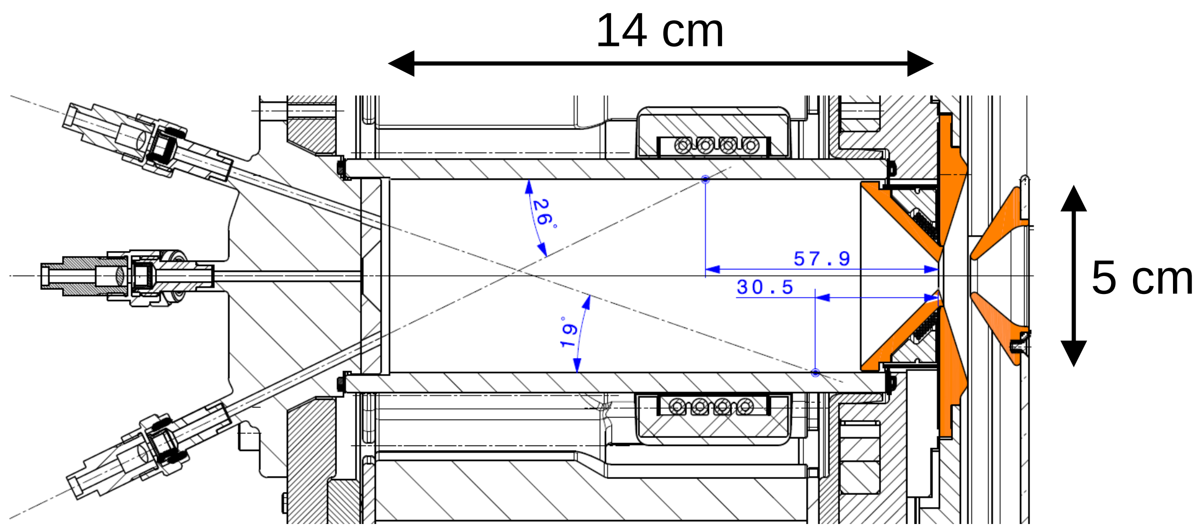
Knowledge of plasma parameters (esp. n_e, T_e, T_{vib}, n(H)) mandatory for dedicated optimization of H^- production

- Ion source design very compact → bad accessibility for diagnostics
  - Optimization of performance mainly based on varying external parameters
  - Discharge parameters determined by simulating RF coupling
- Determination of plasma parameters via optical emission spectroscopy
  - Dedicated evaluation of relevant process via collisional radiative models
  - Establish the link between external, plasma parameters & performance

Setup of the Ion Source



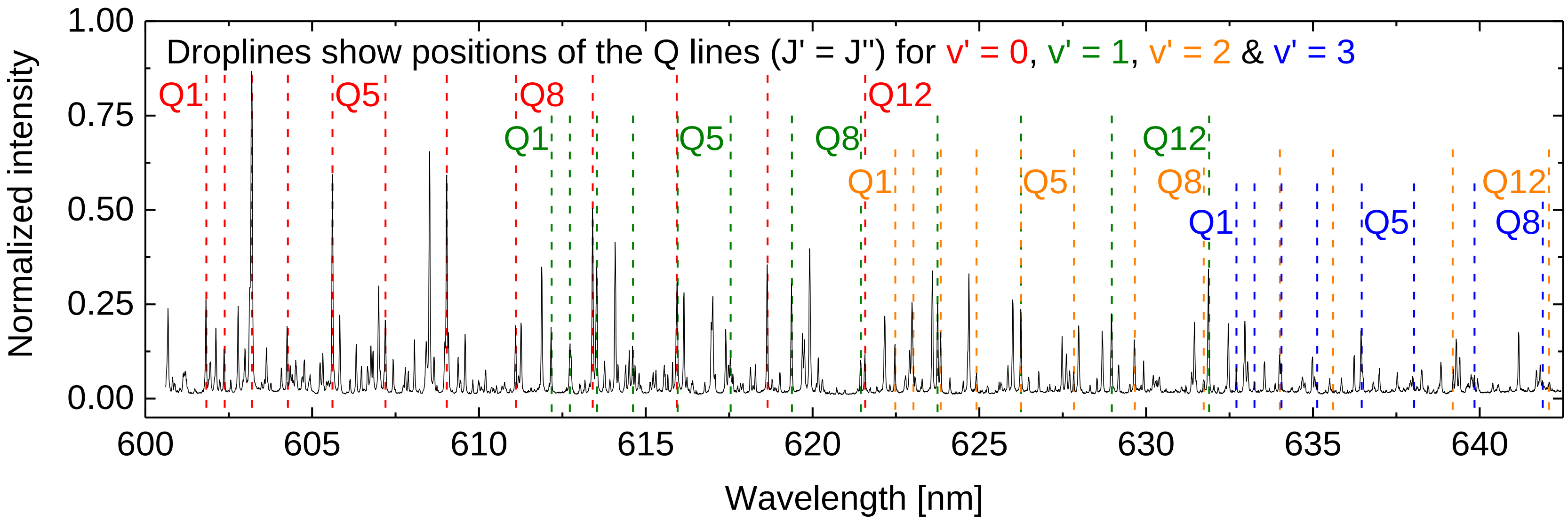
Setup of the Ion Source



- 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
- Results in this talk: on-axis LOS, without cusp & without caesium

Diagnostics – Fulcher Transition

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



Diagnostics – Yacora H

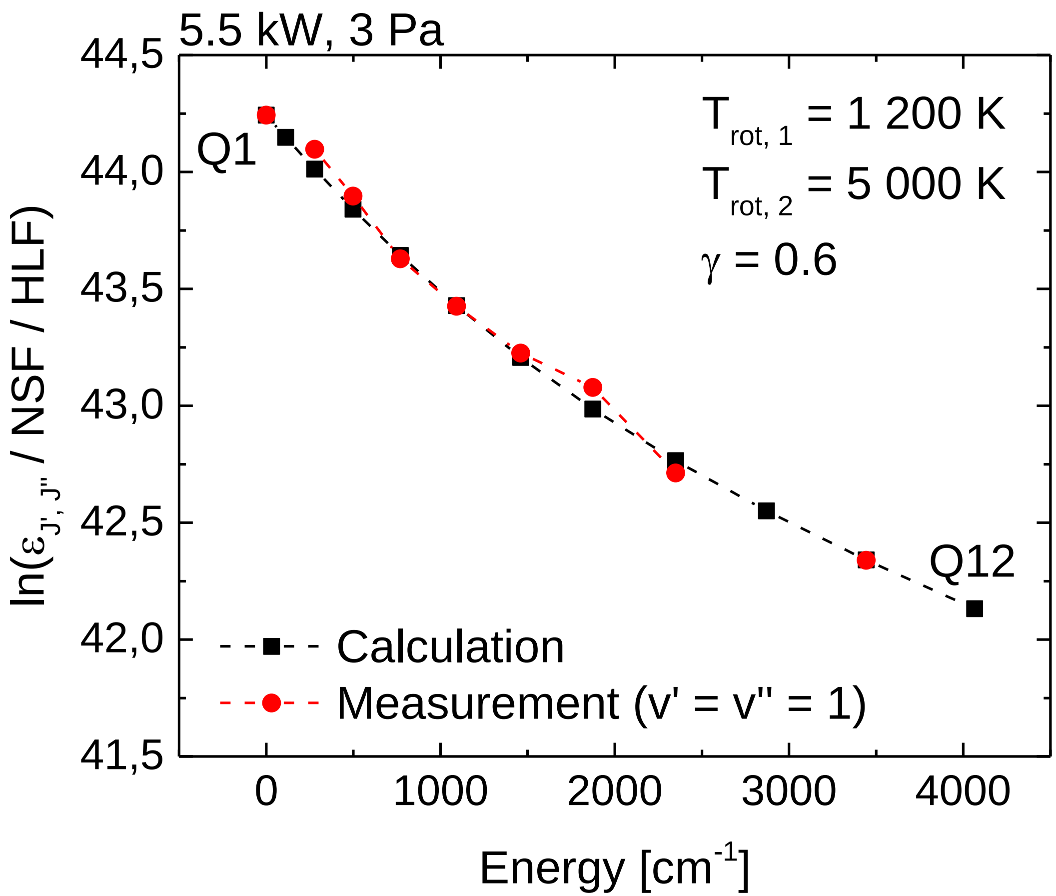
- Collisional radiative model for the hydrogen atom: Yacora H
  D. WÜNDERLICH ET AL., J. QUANT. SPECTROSC. RADIAT. TRANSFER 110, 62 – 71 (2009)

  Balances all relevant population and depopulation processes like

→ Electron impact excitation	$H(k) + e^- \longrightarrow H(i > k) + e^-$
→ Dissociative excitation	$H_2 + e^- \longrightarrow H(i) + H(1) + e^-$
	$H_2^+ + e^- \longrightarrow H(i) + H^+ + e^-$
→ Dissociative recombination	$H_2^+ + e^- \longrightarrow H(i) + H(1)$
	$H_3^+ + e^- \longrightarrow H(2) + H_2$
→ Recombination	$H^+ + 2e^- \longrightarrow H(i) + e^-$
	$H^+ + e^- \longrightarrow H(i) + h\nu$
→ Mutual neutralization	$H^- + H^+ \longrightarrow H(i) + H(1)$
	$H^- + H_2^+ \longrightarrow H(i) + H_2$

- Adjustment of measured emissivities H_α H_β, H_γ, H_δ, H_2(Fulcher) yields
  n_e, T_e, n(H), n(H_2), n(H^+), n(H_2^+), n(H_3^+), n(H^-)

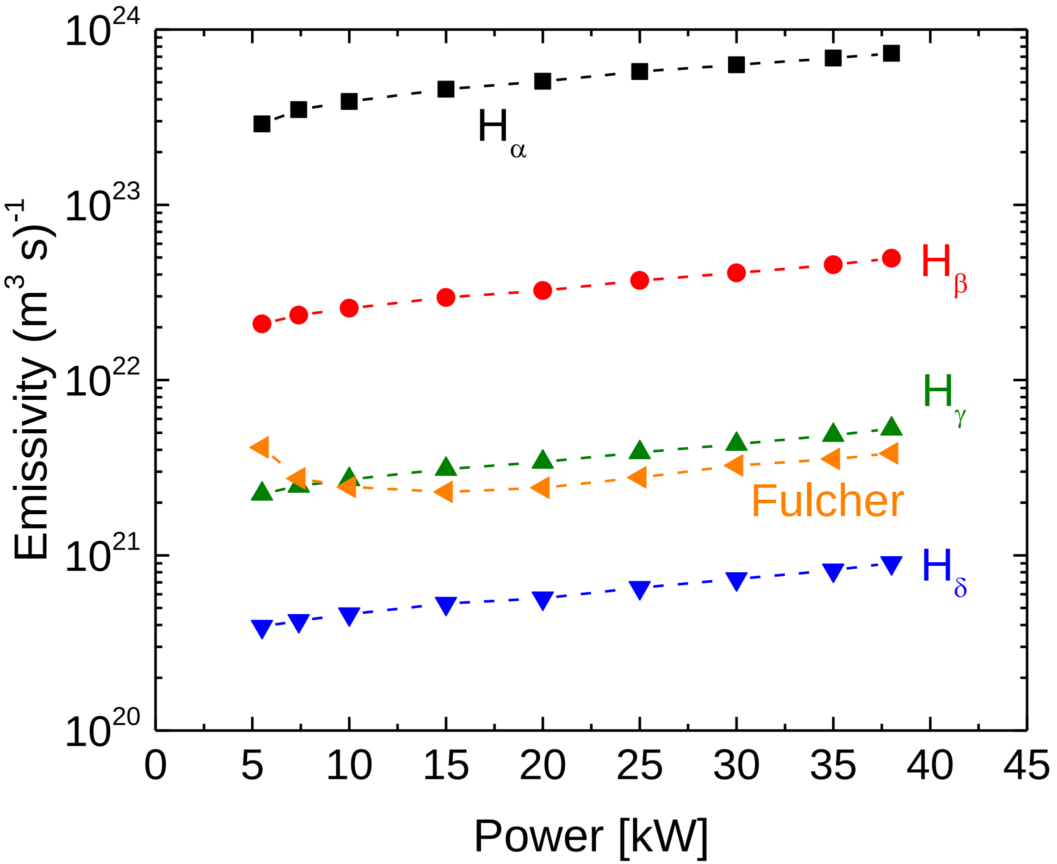
Results – Rotational population of H_2



- $T_{rot, 1}$ reflects population via heavy particles
  → T_{gas} = 2 500 K
- $n(J', T_{rot, 2})$ caused by recombination of H atoms to H_2 on surface VANKAN ET AL., CHEM. PHYS. LETT. 400 (2004) 196–200

- Two-temperature ("hockey-stick") rotational population observed:
  $n(J') = \tilde{n}(J', T_{rot, 1}) + \gamma\, n(J', T_{rot, 2})$ with $(T_{rot, 1} < T_{rot, 2} \approx T_{vib})$

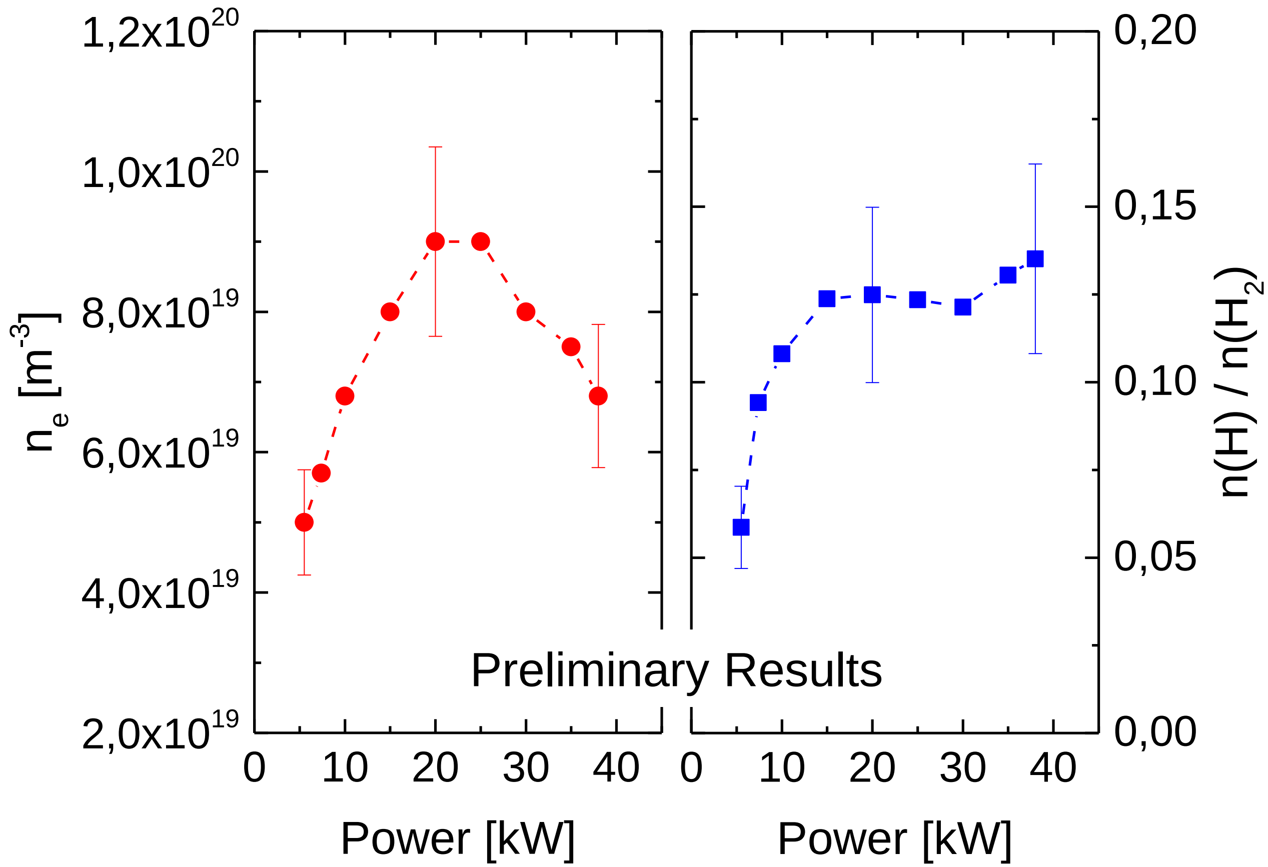
Results – Emissivity over P_{RF}



Without cusp and without caesium best performance achieved at 20 kW

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

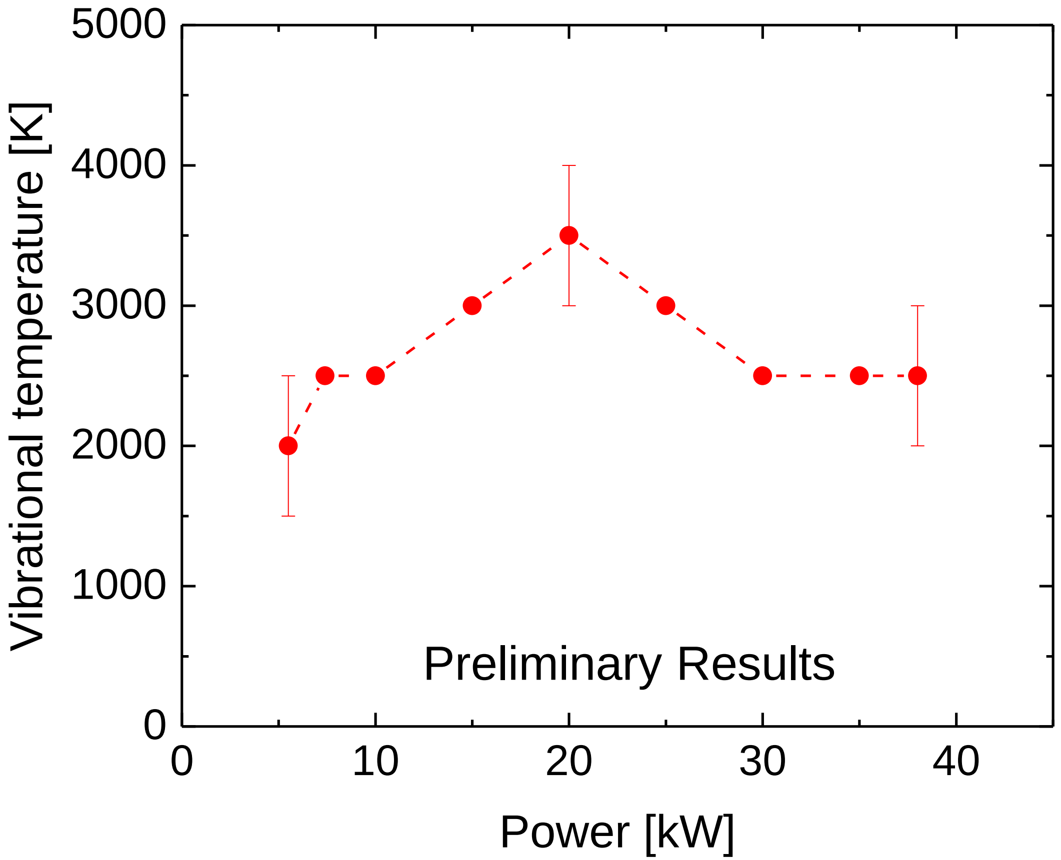
Results – Plasma parameters over P_{RF}



- Electron density shows maximum at 20 - 25 kW (T_e always ~1 eV)

  → Degree of ionization reaches 13%

Results – Plasma parameters over P_{RF}



- Without adding caesium to plasma: $H_2(v) + e^- \rightarrow H^- + H$
- Best ion source performance at 20 kW $\rightarrow$ Maximum in T_{vib}

Summary

- Investigation of Linac4 H^- ion source via optical emission spectroscopy for establishing link between external parameters & performance

- Project aim
  - Determination of influence of external parameters (p & P_{RF}) and ion source design aspects (cusp field,…) on plasma parameters
  - Assessment of relevant process via collisional radiative models
  - Link the changing plasma parameters to ion source performance

- Evaluation of plasma parameters via OES, first results:
  - Two-temperature ("hockey-stick") rotational population for H_2
  - High degree of ionization (up to 13%)
  - Best ion source performance without caesium where T_{vib} is maximal