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

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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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF frequency</td>
<td>2 MHz, up to 100 kW</td>
</tr>
<tr>
<td>Duration of plasma pulse</td>
<td>500 µs</td>
</tr>
<tr>
<td>$H^-$ current</td>
<td>45 (80) mA</td>
</tr>
<tr>
<td>Beam energy</td>
<td>45 keV</td>
</tr>
<tr>
<td>Duration of beam extraction</td>
<td>400 µs</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>2 Hz</td>
</tr>
<tr>
<td>Nominal Emittance</td>
<td>0.25 π mm mrad</td>
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</tbody>
</table>

- Production of negative hydrogen ions...
  - ...in the plasma volume $H_2(v) + e_{\text{slow}} \rightarrow H^- + H$
  - ...at a caesiumated surface $H + e_{\text{surface}} \rightarrow H^-$
    - $H^+ (\text{or } H_2^+, H_3^+) + 2 e_{\text{surface}} \rightarrow H^- (\text{or } H^- + H, H_2)$
Setup of the Ion Source

- **Pulsed gas vale**
- **Cusp magnets** (octupole configuration)
- **RF solenoid** (surrounded by ferrites)
- **Caesium oven**
- **Extraction aperture** Ø 6.5 mm
- **Filter field magnets**

**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

  Emissivity of whole Fulcher transition

  CR models Yacora H₂ and Yacora H

  \( n_e, T_e, n(H), n(H_2), n(H^+), n(H_2^+), n(H_3^+), n(H^-) \)
Spectroscopic Setup

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

- Evaluation of H₂ 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

Droplines show positions of the Q lines for $v' = 0$, $v' = 1$, $v' = 2$ & $v' = 3$
Results – Rotational population & $T_{\text{gas}}$

- Hockey-stick population
  \[ n(N) = \tilde{n}(N, T_{\text{rot}, 1}) + \gamma n'(N, T_{\text{rot}, 2}) \]
  \[ \uparrow \quad \text{heavy particles} \]
  \[ \uparrow \quad \text{most likely electrons} \]

- $\tilde{n}(N, T_{\text{rot}, 1})$ not obvious
  \[ \rightarrow \text{Only the first two levels follow the cold population} \]

- Projecting $T_{\text{rot}, 1}$ to the $X \, ^1\Sigma^+_g$ state yields $T_{\text{gas}} = 304\, \text{K}$
  \[ \rightarrow T_{\text{gas}} \text{ virtually equivalent to ambient temperature} \]

- Hydrogen, 40 kW
  $d \, ^3\Pi_{u}, \nu' = 0$

- $N = 12$
- Overlapped lines

$T_{\text{rot}, 1} = 152\, \text{K}$
$T_{\text{rot}, 2} = 4360\, \text{K}$
$\gamma = 5.79$

\[ VANKAN \, \text{ET AL.}, \, \text{CHEM. PHYS. LETT.} \, 400 \ (2004) \, 196–200 \]
- Exceptional operation in D₂
- \( \bar{n}(N, T_{\text{rot}, 1}) \) much more distinct
  \( \Rightarrow \Delta E \) of rotational states smaller
  \( \Rightarrow \) More levels follow cold population

\[ T_{\text{gas}} = 310 \text{ K} \]

- Gas is supplied to the source at ambient temperature
  \( \Rightarrow \) Short plasma pulse (500 µs) prevents heavy particles from heating up

Independent of cusp field or RF power:  \( T_{\text{gas}} \approx 300 \text{ K} \)
Results – Emissivity over $P_{RF}$ without cusp

- Emissivity increases with RF power for Balmer lines
- Molecular Fulcher-$\alpha$ emission shows different behavior
Diagnostics – Yacora H

- Collisional radiative model for the hydrogen atom: Yacora H
  

Balances all relevant population and depopulation processes like

- **Electron impact excitation**
  \[
  H(k) + e^- \rightarrow H(i > k) + e^- 
  \]

- **Dissociative excitation**
  \[
  H_2 + e^- \rightarrow H(i) + H(1) + e^- \\
  H_2^+ + e^- \rightarrow H(i) + H^+ + e^- \\
  H_3^+ + e^- \rightarrow H(2) + H_2
  \]

- **Dissociative recombination**
  \[
  H^+ + 2e^- \rightarrow H(i) + e^- \\
  H^+ + e^- \rightarrow H(i) + h\nu
  \]

- **Recombination**

- **Mutual neutralization**
  \[
  H^- + H^+ \rightarrow H(i) + H(1) \\
  H^- + H_2^+ \rightarrow H(i) + H_2 
  \]

- 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
  $H_2(v) + e_{\text{slow}} \rightarrow H^- + H$
  balanced by
  $H^- + e_{\text{fast}} \rightarrow H + 2 \, e$

- Influence of $n_e$ cancels

- Low $T_e$ results in higher $H^-$ yield

- Highest vibrational population at 20 kW
  $\rightarrow$ 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

Best performance (highest $H^-$ current)

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(H₂) and T_gas ≈ 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