Determination of discharge parameters via OES at the Linac4 H^- ion source[a)]

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Optical emission spectroscopy (OES) measurements of the atomic Balmer series and the molecular Fulcher transition have been carried out at the Linac4 ion source in order to determine plasma parameters. As the spectroscopic system was only relatively calibrated, the data evaluation only yielded rough estimates of the plasma parameters ($T_e \approx 1.2\ eV$, $n_e \approx 1 \times 10^{19}$ m^{-3} and $n_{\mathrm{H}}/n_{\mathrm{H}_2} \approx 0.5$ at standard operational parameters). The analysis of the Fulcher transition revealed a non-thermal "hockey-stick" rotational population of the hydrogen molecules. At varying RF power, the measurements at the on-axis line of sight (LOS) showed a peak in the rotational temperatures between 25 and 40 kW of RF power whereas a steady decrease with power was observed at a tilted LOS, indicating the presence of strong plasma parameter gradients.

I. INTRODUCTION

In order to improve the beam brightness and the luminosity, an upgrade of the Large Hadron Collider (LHC) injector chain is currently realized at CERN. One part is the replacement of the Linac2 injector which accelerates protons to 50 MeV by Linac4 which will accelerate negative hydrogen ions to 160 MeV[1]. The H^- ions will be injected into the Proton Synchrotron Booster via charge-exchange injection. The Linac4 ion source must deliver a current of 45 mA (for some special cases also up to 80 mA) in pulses of 500 μs at a repetition rate of 2 Hz.

In general, the production of H^- ions can rely on the formation in the plasma volume from vibrationally excited H_2 or on the formation from hydrogen atoms or ions on a surface with low work function[2]. In the latter case, caesium is evaporated into the ion source for establishing a low work function surface. As the production rate of H^- (and also the destruction rate, e.g. by electron stripping) is strongly dependent on the plasma parameters, their knowledge is mandatory for a dedicated optimization of the ion current delivered by the source.

Due to the compact design of the ion source, the accessibility for diagnostic methods is very limited. Hence, the main access to plasma parameters was provided by simulations of the RF coupling up to now[3–5]. For the measurements presented in this paper, optical emission spectroscopy (OES) has been applied at the Linac4 ion source test bed. The obtained results were analysed by collisional radiative models for the hydrogen molecule and atom. During this campaign, the ion source was operated in volume mode, i.e. without adding caesium.

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II. ION SOURCE SETUP & DIAGNOSTIC METHODS

The plasma inside the cylindrical discharge vessel of the Linac4 ion source is generated via inductive RF coupling at a frequency of 2 MHz. RF power is available up to 100 kW but typically only 40 kW are used (RF pulse length 500 μs, repetition rate 2 Hz). In order to reduce the loss of charged particles to the ceramic plasma chamber wall, a Halbach-offset octupole cusp field is created by permanent magnets. Hydrogen gas is supplied to the ion source with a fast valve which opens for a short time prior to the RF pulse. For the typical pulse settings, the gas pressure is around 1 Pa in the discharge chamber during the RF pulse. A detailed description of the ion source can be found elsewhere[6].

For performing OES, the ion source is equipped with three lens heads which collect the light emitted by the discharge and focus it into optical fibres leading to a spectrometer. The lens heads are mounted in a way that they observe three different lines of sight (LOS): on-axis, 19° and 26° tilted with respect to the cylindrical axis of the discharge chamber (see figure 1). The high-resolution spectrometer (1 m focal length, grating 2400 grooves / mm) is equipped with an ICCD camera (FWHM of the Lorentzian apparatus profile is 8 pm). For acquiring data, only the last 400 μs of the plasma pulse are con-

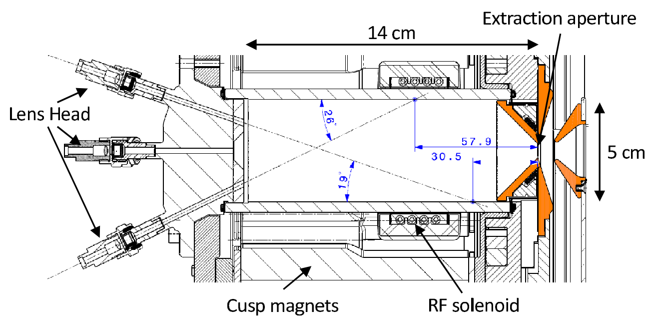

FIG. 1. Sketch of the plasma chamber of the Linac4 ion source.

sidered to avoid recording the ignition phase. An absolute radiation standard was not available for calibrating the spectroscopic system for the campaign, therefore only the relative wavelength-dependent sensitivity was determined via a tungsten reference lamp.

For evaluating plasma parameters from OES measurements the Balmer series of atomic hydrogen and the Fulcher transitions of molecular hydrogen ($d\ ^3\Pi_u \rightarrow a\ ^3\Sigma_g^+$, located between 590 and 650 nm) were recorded. For analysing the results, the collisional radiative models Yacora H for atomic[7] and Yacora H_2 for molecular hydrogen[8,9] are applied. Typically, the input parameters of the models are varied in order to match both the absolute emissivity and the intensity ratios of the measurements. However, as absolute intensities could not be determined, only the intensity ratios can be evaluated. In doing so, rough estimations of the electron temperature T_e, density n_e and of the ratio of atomic to molecular hydrogen $n_{\mathrm{H}}/n_{\mathrm{H}_2}$ can still be obtained. It should be kept in mind that the intensities measured by OES represent line-of-sight averaged values, which means that also the determined plasma parameters have to be treated as line-of-sight averaged. An absolute calibration of the spectroscopic system is going to be carried out to allow for the full evaluation of the measured data.

The rotational and vibrational population of the hydrogen molecule as well as the gas temperature of the discharge can be determined from the molecular Fulcher transition. Typically, the first five emission lines (rotational quantum number $J = 1, \dots 5$) of the Q branch ($\Delta J = J' - J''$) arising from the first four diagonal vibrational transitions (vibrational quantum number $v = 0, \dots 3$, $v' = v''$) are recorded. On the other side, the relative population in the ro-vibrational states of the $d\ ^3\Pi_u$ state is also simulated. In the simulation, the vibrational population in the electronic ground state (calculated assuming a Boltzmann distribution with the vibrational temperature T_{vib}) is projected into the $d\ ^3\Pi_u$ state after the Franck-Condon principle. In the next step, the rotational population (also calculated assuming a Boltzmann distribution with the rotational temperature T_{rot}) is derived for each vibrational state. $T_{vib}(X\ ^1\Sigma_g^+)$ and $T_{rot}(d\ ^3\Pi_u)$ are now obtained via adjusting the simulated relative population density to the measurements for the vibrational states $v' = 0, \dots 3$. Previous investigations showed, that the projection of $T_{rot}(d\ ^3\Pi_u, v' = 2)$ to the electronic ground state according to the rotational constants agrees well with the gas temperature T_{gas} of the discharge. A more detailed description of the Fulcher evaluation can be found elsewhere[10,11].

Due to the Lorentzian apparatus profile of the spectroscopic system, strong overlap of the particular emission lines occurs. Therefore the determination of the emissivity of the particular emission lines is sometimes difficult or even impossible. As those lines have to be excluded from the evaluation, the Fulcher analysis has been extended to consider the first twelve emission lines of the Q branch.

III. RESULTS

OES measurements have been performed for the typical operational parameters of the ion source (RF power 40 kW, 1 Pa pressure) with and without cusp field magnets and for varying RF power at constant pressure (1 Pa, without cusp field magnets). The evaluation of the collisional radiative models yields an electron temperature of 1.2 eV, an electron density of 1×10^{19} m^{-3} and a density ratio of atomic to molecular hydrogen of 0.5 for the typical operational parameters with cusp field magnets (measured at the on-axis LOS). However, as this evaluation only gives rough estimates of the plasma parameters (see previous section), no clear trends are obtained for the parameter variations. Therefore, only the results of the Fulcher evaluation are presented in the following.

All investigated parameter settings have in common that a highly non-thermal rotational population is present. The lower rotational levels (up to $J' \approx 4$) follow a population after a temperature in the range of the gas temperature whereas the higher levels are populated according to a much higher temperature very similar to the vibrational temperature. Such a non-thermal "hockey-stick" population, is often observed in hydrogen plasmas and arises most likely from the contribution of surface recombination of H atoms to H_2 to the rotational population[12]. In order to consider such a distribution, the simulation has been modified. In the improved version, the population of a rotational state $n(J')$ in the upper electronic state of the Fulcher transition is calculated according to

$$n(J') = \tilde{n}(J', T_{rot,\,1}) + \gamma\, \bar{n}(J', T_{rot,\,2}), \qquad (1)$$

where $\tilde{n}(J', T_{rot,\,1})$ denotes a Boltzmann distribution according to the "cold" temperature $T_{rot,\,1}$ and $\bar{n}(J', T_{rot,\,2})$ the population according to the "hot" temperature $T_{rot,\,2} \approx T_{vib}$. γ is a weighting factor that determines the relative amount of the hot population. As value for $T_{rot,\,2} \approx T_{vib}$ the vibrational temperature determined from the Fulcher evaluation has been taken.

A. Influence of the Cusp Field

Table I shows the results from the Fulcher evaluation obtained at the typical operational parameters of the ion source with cusp magnets and without cusp magnets. It can be seen that the cusp field has no influence on the determined temperatures within the error bars. For both cases, the rotational temperature decreases with increasing vibrational quantum number from 1800 ± 200 K for $v' = 0$ to 500 ± 100 K (600 ± 100 K without cusp) for $v' = 3$, a trend typical for the Fulcher system. The gas temperature is 2000 ± 200 K (1800 ± 200 K without cusp) and the vibrational temperature is 6000 ± 500 K (5500 ± 500 K without cusp). It should be noted that T_{vib} is only determined from the first four vibrational states which means a change of the population in higher vibrational states cannot be assessed. A distinct difference can be observed for the weighting factor of the hot rotational population γ which is higher in the case without cusp magnets up to a factor of 2 for $v' = 1, 2$. This means that the rotational population from surface recombination of H atoms to H_2 is higher without cusp field indicating that also the value of n_H/n_{H_2} is higher.

TABLE I. Plasma parameters obtained from the analysis of the Fulcher OES measurements (on-axis LOS).

Parameter	With Cusp	Without Cusp
$T_{rot,\,1}(d\,^3\Pi_u, v' = 0)$	1800 ± 200 K	1800 ± 200 K
$\gamma(v' = 0)$	0.6 ± 0.09	1.1 ± 0.16
$T_{rot,\,1}(d\,^3\Pi_u, v' = 1)$	1200 ± 200 K	1200 ± 200 K
$\gamma(v' = 1)$	0.6 ± 0.09	1.1 ± 0.16
$T_{rot,\,1}(d\,^3\Pi_u, v' = 2)$	900 ± 100 K	800 ± 100 K
$\gamma(v' = 2)$	0.4 ± 0.06	0.5 ± 0.07
$T_{rot,\,1}(d\,^3\Pi_u, v' = 3)$	500 ± 100 K	600 ± 100 K
$\gamma(v' = 3)$	0.3 ± 0.05	0.5 ± 0.07
$T_{vib}(X\,^1\Sigma_g^+) = T_{rot,\,2}(d\,^3\Pi_u, v' = 0, \ldots 3)$	6000 ± 500 K	5500 ± 500 K
T_{gas}	2000 ± 200 K	1800 ± 200 K

B. Variation of RF power

Figure 2 shows $T_{rot,\,1}$ and T_{gas} obtained for varying RF power at fixed gas pressure at the on-axis line of sight and at the 26° tilted LOS (only $T_{rot,\,1} v' = 0$ is shown for clarity as the temperatures have the same trends for $v' = 1, 2$ and 3). It can be seen that the on-axis measurements yield a peak of $T_{rot,\,1}$ and T_{gas} between 25 and 40 W whereas for the off-axis measurements a steady decrease with power is obtained. This reveals that power-dependent gas temperature gradients are present in the discharge. For the vibrational temperature, no variation with RF power could be observed, the value stays constant at 5500 ± 500 K for both lines of sight.

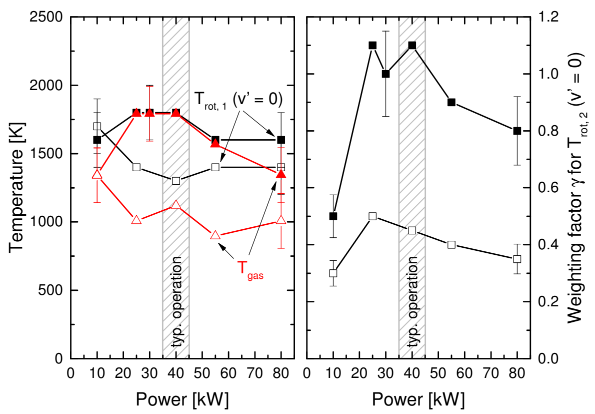

FIG. 2. $T_{rot,\,1}(v' = 0)$ and $\gamma(v' = 0)$ of the upper electronic state of the Fulcher transition together with T_{gas} for a variation of the RF power at a pressure of 1 Pa (filled symbols: on-axis LOS; open symbols: 26° tilted LOS).

Concerning the weighting factor γ which is shown in the right part of figure 2, a peak around 25 to 40 kW is observed for both lines of sight indicating a high density ratio of atomic to molecular hydrogen in this RF power range. It should furthermore be noted that the absolute value of γ is around a factor of two higher for the on-axis LOS. This would mean that the importance of rotational population by recombination of hydrogen atoms at the plasma chamber wall is higher on-axis but it is also possible that other effects contribute significantly to the hot rotational population[12]. OES measurements with an absolute calibration yielding a more precise determination of n_H/n_{H_2} can clarify this issue.

IV. SUMMARY

For the first time, optical emission spectroscopy measurements were carried out at the Linac4 ion source. As only a relative calibration of the spectroscopic system could be carried out, the electron density, temperature and the density ratio of atomic to molecular hydrogen could only be estimated roughly. The investigation of the molecular Fulcher spectrum revealed a non-thermal population of the rotational levels. The detailed analysis of the rotational population indicates, that n_H/n_{H_2} is higher without cusp field and that RF-power dependent gas temperature gradients are present in the ion source plasma. In the near future an absolute calibration is going to be carried out in order to allow for a precise determination of the discharge parameters.

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