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A collisional radiative model for low-pressure hydrogen–caesium plasmas and its application to an RF source for negative hydrogen ions

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ABSTRACT

A collisional radiative (CR) model for caesium in low-temperature, low-pressure hydrogen–caesium plasmas is introduced. This model includes the caesium ground state, 14 excited states, the singly charged caesium ion and the negative hydrogen ion. The reaction probabilities needed as an input are based on literature data, using some scaling and extrapolations. Additionally, new cross sections for electron collision ionization and three-body recombination have been calculated.

The relevance of mutual neutralization of positive caesium ions and negative hydrogen ions is highlighted: depending on the densities of the involved particle species, this excitation channel can have a significant influence on the population densities of excited states in the caesium atom. This strong influence is successfully verified by optical emission spectroscopy measurements performed at the IPP prototype source for negative hydrogen ions.

As a consequence, population models for caesium in electronegative low-temperature, low-pressure hydrogen–caesium plasmas need to take into account the mutual neutralization process. The present CR model is an example for such models and represents an important prerequisite for deducing the total caesium density in such plasmas.

1. Introduction

Caesium is the most electropositive non-radioactive alkali metal. Its work function is low (2.14 eV for bulk polycrystalline caesium [1]) and thus it is a very effective electron donor. This property is widely used for a variety of applications: pure caesium or caesium compounds like caesium iodide or caesium oxide are used in photoelectric devices like photomultipliers or photodiodes in order to increase the quantum efficiency and thus the sensitivity of the detector [2,3].

Another field of application is the generation of negative ions by charge exchange of positive ions or atoms with caesium. Such charge exchange processes can happen either in a caesium gas target [4] or on a converter surface covered by a caesium layer [5]. The latter reaction – surface production of negative ions – is applied in particle sources for accelerators [6,7] and in sources for negative hydrogen or deuterium ions used for the neutral beam injection (NBI) system in fusion experiments as LHD [8], JT60-U [9] or the future fusion device ITER [10–12]. In such surface production based sources for negative hydrogen ions the caesiated converter surface is in contact with a

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low-temperature, low-pressure hydrogen–caesium plasma: typically the electron temperature is below a few eV and the gas pressure is well below 1 Pa. Caesium is a minority species in the hydrogen background and thus the partial pressure of caesium is significantly smaller.

The efficiency for the surface production process depends inversely exponential on the surface work function [13]. Thus, desirable for obtaining a high negative ion yield is a work function as low as possible at the convertor surface. The work function of caesiated surfaces depends on the substrate material, the thickness of the caesium layer and the amount of impurities (from the plasma or the background gas) embedded into the layer. For pure caesium layers on metal surfaces a minimum work function is obtained for a layer thickness of well below one monolayer (ML) [14]. For example, 0.6 ML of caesium on a W(100) surface (bulk work function of tungsten: 4.52 eV [14]) result in a work function of 1.6 eV – which is significantly lower than the work function for bulk caesium. For thick pure caesium layers (above one ML) the work function approaches the work function of bulk caesium. Embedded impurities can result either in a decreased or increased work function compared to clean layers: while the work function for $Cs_{11}O_3$ is 1.35 eV [15], a work function of 2.2 eV, i.e. a value slightly above the one for bulk caesium, was observed [16] in a plasma environment similar to the one in negative hydrogen ion sources for NBI.

The caesium needed for obtaining the low work function is introduced to the ion sources by a caesium injection system containing a liquid [17] or solid [18] caesium reservoir. It is deposited at the inner surfaces of the source from which it is redistributed mainly by the influence of the plasma [19]. This redistribution process is strongly affected by the wall surface temperatures and the caesium chemistry, i.e. the formation of caesium compounds and the inclusion of impurities into the caesium layers at the surfaces [20].

Achieving and sustaining a low work function of the caesium-covered converter surface is one key issue in operating negative ion sources for fusion experiments. Thus, highly desirable is a diagnostic technique for determining in situ the work function of the converter. Although several techniques exist [21] for measuring the work function of a surface, these cannot be applied in a plasma environment due to interference of the plasma with the diagnostic or vice versa [16]. Due to different reasons (e.g. interference of the measurement device with the particle fluxes responsible for the caesium redistribution) pulsed operation of plasma and work function diagnostics – as described in [16] for a small laboratory experiment – has up to now never been applied in negative ion sources for fusion.

One important factor for reducing the work function (and maintaining this reduced work function) is a sufficient influx of fresh caesium onto the converter [16]. This caesium flux is correlated to the caesium density in the plasma volume. Thus, monitoring the caesium density in the plasma close to the converter surface is a promising technique for indirectly characterizing the converter work function. A diagnostic technique for the caesium density in a plasma is optical emission spectroscopy (OES) [22]. Depending on the intensity of the emitted light and the sensitivity of the detector, the population densities of some of the electronically excited states in the atom and the singly charged ion are accessible.

In order to deduce the total density of caesium (including the excited states and the ions), a population model has to be applied. The most simple kind of population models are corona models – balancing electron collision excitation from the ground state with spontaneous emission. More sophisticated are collisional radiative (CR) models where all exciting and de-exciting processes relevant (i.e. with a non-negligible reaction rate) in the plasma under investigation are balanced.

Some CR models for caesium have been described in the literature [23–25]. These models are based on reaction cross sections calculated using rather simplistic techniques, implying a large error bar of the cross sections itself (mainly close to the threshold energy) and consequently also of the CR model results. Additionally, the processes implemented in these models are appropriate only for describing pure caesium plasmas and processes relevant for hydrogen–caesium plasmas are not taken into account. One important example is mutual neutralization of positive caesium ions with negative hydrogen ions [26] – ending up in an excited caesium atom and a hydrogen atom in the ground state.

This paper describes a caesium CR model based on the flexible solver `Yacora` [27] and a new and comprehensive set of input data. This model predicts a high relevance of mutual neutralization for the population densities of excited states of caesium in the low-temperature, low-pressure hydrogen–caesium plasmas of negative hydrogen ion sources. In a second step, this predicted high relevance of mutual neutralization is experimentally demonstrated by applying the CR model to results of OES measurements at the IPP negative ion source prototype [12,28] for ITER NBI.

2. The CR model for caesium

2.1. Physics of the CR model for caesium

CR models describe how the population densities of excited states in atoms or molecules depend on plasma parameters like the electron temperature T_e, the electron density n_e, the ground state density and the densities of all other particles involved in populating and depopulating the excited states [29–31]. One important area of application for CR models is the interpretation of diagnostic results: by comparing measured population densities (determined e.g. by OES) with model results the plasma parameters can be deduced [22,27].

In general, CR models include a system of coupled ordinary differential equations describing the temporal evolution of the population densities of all excited states included to the model. These so-called rate equations balance the reaction rates of processes responsible for exciting and de-exciting excited states in the atom or molecule. Included to the model should be all excited states for that the population densities are to be calculated,