Field Emission Electric Thruster Optical Diagnostics Based on an Indium Collisional-Radiative Model

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Abstract: A Collisional-Radiative (C-R) model incorporating the first two spectra of the In homo-nuclear sequence (In I and II) is being developed to help the study of field emission electric thrusters functioning with molten In. The present model provides an explanation of their shape. It is also meant to further study their functioning and to contribute to their optimization.

Nomenclature

$A_{i,j}$	=	transition probability, level j to i
ACE	=	atomic collisions with electrons code
CATS	=	Cowan atomic structure code
CbA	=	Coulomb approximation code
C-R	=	collisional – radiative model
CTMC	=	classical-trajectory Monte-Carlo method
FAC	=	flexible atomic code
FEEP	=	field emission electric propulsion
In I, II,..	=	successive spectra of the indium homo-nuclear sequence
l	=	orbital quantum number, $s = 0$, $p = 1$, $d = 2$, $f = 3$, …
LTE	=	local thermodynamic equilibrium
n	=	principal quantum number, here $n = 5, 6, 7$, …
n_e	=	electronic density
T_e	=	electronic temperature

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Xe I, II,..	=	successive spectra of the xenon homo-nuclear sequence
λ	=	wavelength
σ_e	=	electron collision excitation cross section

I. Introduction

PLASMA thrusters are taking more and more importance in space propulsion, as they are efficient and allow for using a reduced mass in a given mission, due to the high velocity of the expelled ions. We are interested here in **F**ield **E**mission **E**lectric **P**ropulsion (FEEP), by studying a thruster in which liquid metal at the tip of a needle is ionized and accelerated to high velocity (100 km/s) in the very high electric field formed in a small gap, about 1 mm, between the needle polarized at about 8 kV and a surrounding cathode. Molten Indium or Cesium can be used for this type of thrusters due to their low melting temperature and high atomic mass, but we are interested here specifically in an Indium fed device. The thrust is controlled by the ion current, between 1 and 200 µA for a thrust in the 0,1 – 10 µN range. In this context, a detailed analysis of the plasma parameters near the tip, where it is not possible to introduce a probe, is of paramount importance. As the density in the region of interest is low and the number of collisions severely reduced, development of an adequate model was proven necessary to interpret the obtained spectra. The basis of the modeling task consist of a **C**ollisional – **R**adiative (C-R) model, which alone is sufficient for local optical diagnostics. It also constitutes an indispensable tool for the numerical description of the properties and status of all the atomic species encountered in the plasma.

II. General Features of the In I and In II Spectra

Indium has some interesting atomic properties: high atomic weight and a low ionization potential which is due to the two *s* and one *p* electron of the external part of its outer $n = 5$ shell. These are easily ionized because of the presence of ten $4d^{10}$ electrons just lower. Moreover, the numerical part of the present study devoted to the calculation of the missing atomic data, takes advantage of the fact that Xe VI belongs to the In I iso-electronic series (subsequently, In II is iso-electronic to Xe VII etc). Xe being currently used as propellant in plasma thrusters[1], the atomic properties of its ions have been the subject of extensive investigations[2] and the obtained data[3] for its ions can give a glimpse of those belonging to In ones. The necessary methods for In I and In II data calculation, summarily listed in the next paragraph, are those which have been proved effective in the case of the Xe homo-nuclear sequence. The C-R model developed here uses a technique totally similar with the one used in the case of Xe. The C-R model of the Xe homo-nuclear series is described in another separate paper[4] of this Conference, also referred as Paper I.

For the moment we are interested solely in the study of the In I and In II spectra, which are entering in our In C-R model in its present form. These spectra are in fact quite different: The characteristics of the In I spectrum come mainly from the excited states of the sole outer p electron left from the six $5p^6$ electron layer encountered in

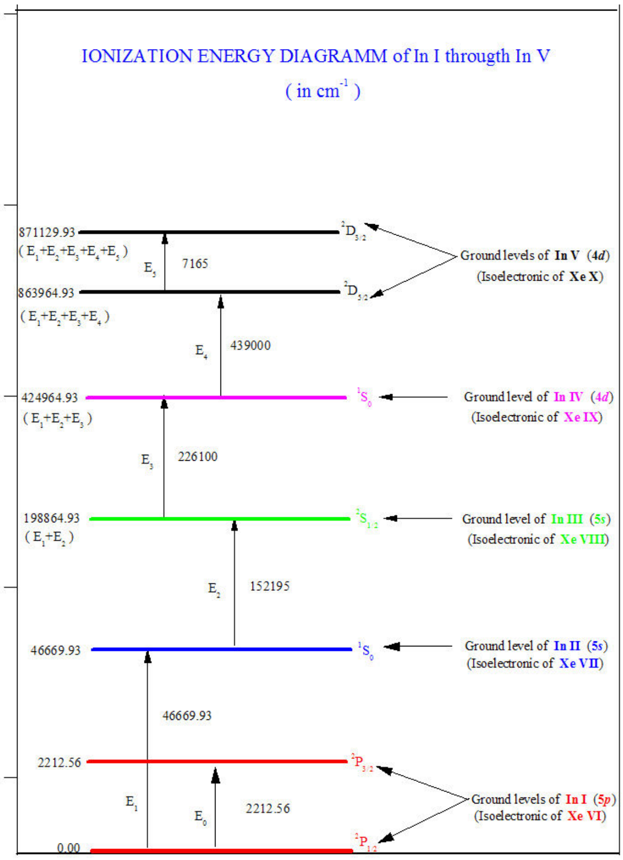

Figure 1. Ground levels of In I to V.

the Xe^0 while the In II and In III spectra, reflecting the properties of the two $5s^2$ electrons left, remind the He I and II ones. An important difference from the He spectra is due to the presence here of ten $4d^{10}$ electrons which can be easily excited, generating numerous inner shell excitation spectral lines. Depending on the ionization stage, the ground levels of the first few terms of the In homo-nuclear sequence consist of one (In II, III, IV), or of a compound of two (In I, In V) levels. In the Fig. 1 are shown the successive ground levels compound for the neutral In and its first four ionization stages. The corresponding ionization energies in cm^{-1} are also included. Useful information concerning the first five terms of the In homo-nuclear sequence (ground level description and terms, total number of levels) is contained in Fig. 2

Indium Spectra

Indium / Z=49 (neutre)					
Order of spectrum	**I**	**II**	**III**	**IV**	**V**
Ionization state	**0**	**+1**	**+2**	**+3**	**+4**
Ground level description	$5s^2\mathbf{5p}$	$4d^{10}\mathbf{5s^2}$	$4d^{10}\mathbf{5s}$	$4p^6\mathbf{4d^{10}}$	$4p^6\mathbf{4d^9}$
Isoelectronic Xe species	**Xe VI**	**Xe VII**	**Xe VIII**	**Xe IX**	**Xe X**
Ground level terms	$^2P_{1/2}$ $^2P_{1/2}$	$^1S_0$	$^2S_{1/2}$	$^1S_0$	$^2D_{3/2}$ $^2D_{5/2}$
Total level number used $n = 6$, $\ell = 0$ (s) à $\ell = 3$ (*f*)	$s = 1$ $p = 2$ $d = 2$ $f = 2$	$s = 2$ $p = 4$ $d = 4$ $f = 4$	$s = 1$ $p = 2$ $d = 2$ $f = 2$	$s = 4$ $p = 12$ $d =$ $f =$	

Figure 2. General characteristics of In I to V spectra.

The neutral In atom spectrum presents a number of metastable levels, either belonging to the *s* and *d* configurations when some of the *p - s*, *p - d* transitions, notably those concerning the 5*p* ground level compound, are forbidden, or because the entire *np* configurations cannot directly decay to the ground level configuration ($\Delta l = 0$). Besides, a number of transitions leading to $\Delta l > 1$ variations and transitions involving inner shell or doubly excited levels are present in the spectrum of In I. Still, the existence of only two ground levels ($^2P_{1/2}$, $^2P_{3/2}$) and of one sole continuum ($^1S_0$) simplifies somehow the spectrum. On can get an idea of the In I excited levels structure from inspection of the simplified In I Grotrian diagram shown in the Fig. 3. Also, in Fig. 4 is given the simplified In II Grotrian diagram, where both the ground level ($^1S_0$) and the continuum ($^1S_{1/2}$) are unique. The metastable levels of this spectrum are in this case similar to those of He I.

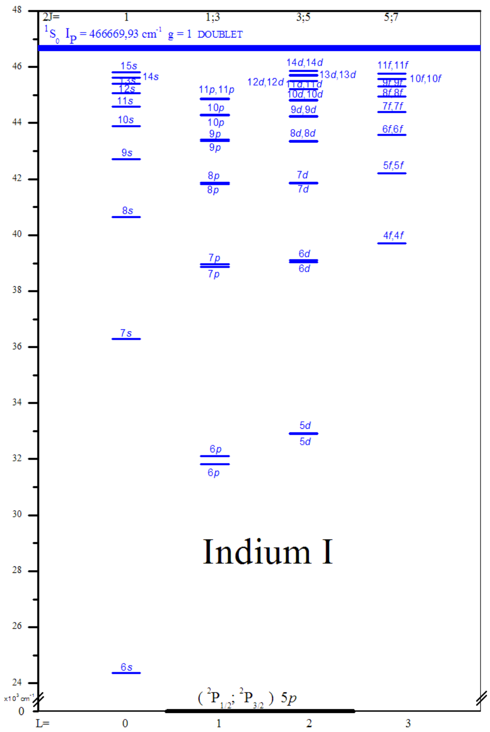

Figure 3. Grotrian Diagram of In I.

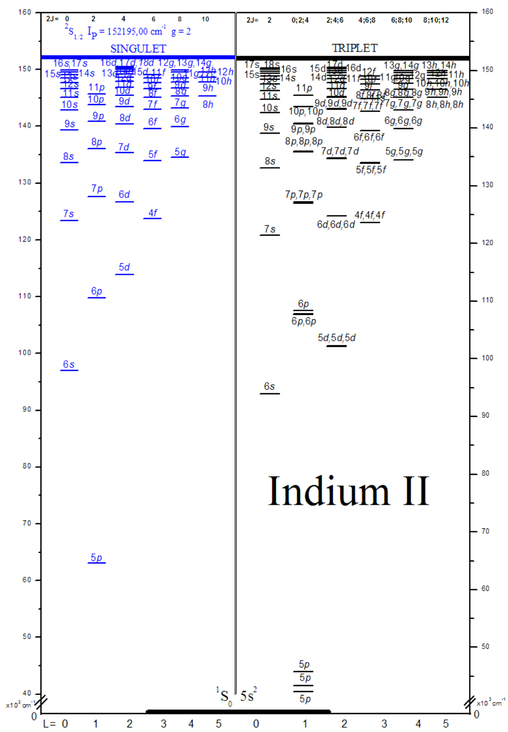

Figure 4. Grotrian Diagram of In II.

III. Evaluation of the In I and In II Atomic Data

Besides providing information on the constituents and on the ionization stage of the plasma and, moreover, on the most important processes encountered during the thruster functioning, non-intrusive emission spectroscopy plasma diagnostics allows primarily for the evaluation of the local electronic density n_e and electronic temperature T_e which are needed for the study and the optimization of the FEEP. Typically, for optical emission diagnostics the intensities of neutral and ionized In I and In II lines, are calculated and compared with the experimental relative intensities to get the electronic density and temperature of the examined plasma in the region where the spectrum was registered. In the case of FEEP the plasma is far from being in **L**ocal **T**hermodynamic **E**quilibrium (LTE) and as in this case the line intensities cannot be calculated by the equilibrium lows (Saha, Boltzmann), a C-R model must be used. Therefore, a satisfactory application of this powerful diagnostic tool lies on the constitution of a full C-R model which is necessary[5] in order to take into account all of the species present, both neutral and ionized, together with their excited state level structure and transition probabilities between the levels. In such a model, all contributing processes are taken into account through their respective reaction rates. For the moment being, calculation in the present C-R model of the reaction rates influencing the functioning of the FEEP thruster, has been made on the basis of a sole Maxwellian distribution for each species. This constitutes a first approach of the modeling development. We are looking forward to introduce a second distribution for the electrons, meant to take account of the presence of a distinct family of fast electrons.

A. Evaluation of Structure, Transition Probabilities and Electronic Excitation Data.

Structure data are essential for the constitution of a C-R model, as they give the position and characteristics of the energy levels and hence the expected spectral line wavelengths. Furthermore, transition probabilities $A_{i,j}$ and electron collision excitation cross section σ_e are mainly determining the relative intensities of the spectral lines for each ionization stage. A considerable amount of structure and of transition probability data for the In atom and the In^+ ion, both experimental and theoretical, is available in the literature. In view of the plasma modeling and of the optical diagnostics of FEEP, we have evaluated in addition a large amount of atomic data, which we have subsequently used in building the C-R model. For the needs of the present evaluation, well known theoretical methods and codes developed and successfully applied previously (see Paper I) in atomic data evaluation, have been extensively used. Specifically, the structure, transition probabilities and excitation cross sections of the In atom and of the In^+ ion used here come from:

1) The set of codes[6] developed at Los Alamos National Laboratory (LANL), CATS for the structure and the transition probabilities[7] and ACE for the electron collision excitation[8] calculation.

2) The SUPERSTRUCTURE code as developped by Eissner and his collaborators[9], currently used in Meudon Observatory for the transition probability calculation.

3) The FAC code, by Gu[10], a version of which was recently installed at Meudon Observatory. This code calculates transition probabilities and excitation cross sections meant to be subsequently used in the constitution of C-R models.

4) A code[11] based in the Coulomb Approximation (CbA), developed by K. Katsonis.

The $A_{i,j}$ and σ_e atomic data which we have used in our model for the In plasmas constitute a database which will be available in due time from the GAPHYOR Atomic Data Center[12].

B. Other Atomic Data Used in the Model.

Among the various types of theoretical atomic data used in the present model, we mention here:

1) The electronic ionization data. These have been mostly calculated by two quasi-classical codes, 3CTMC and 4CTMC, which are based on the **C**lassical **T**rajectory **M**onte **C**arlo (CTMC) method with a three- and four-body Hamiltonian correspondingly. Cross sections of photo-ionization have also been evaluated, although in our case the photon intensity is estimated as being to low to result to considerable cross sections, because of their utility to calculate the corresponding electronic recombination from the detailed balance principle.

2) The recombination data, mostly consisting in electronic recombination (see 1)) and dielectronic recombination. The three body recombination is not expected to be significant here, because of the relatively low n_e .

IV. Spectra of the Field Emission Type In Thruster

We report here on the characteristics of a C-R model taking into account only neutral and once ionized In and on its application on the diagnosis of the relatively low temperature In plasmas present in the FEEP.

Extended comparisons of the theoretical spectra generated from our model with those obtained experimentally for the In plasma at ONERA/DMPH, Palaiseau campus, are underway[13]. They will be used both for optical diagnostics and modeling of the In FEEP and for validation of the atomic data and of the theoretical approaches used throughout.

Typical results of the obtained experimental spectra are given in the Figs. 5 to 8. They concern the optical spectrum in the wavelength λ region from 240.0 nm to 397.0 nm as measured at ONERA/DMPH. In order to obtain the signatures of the important resonant lines of the ultraviolet region, the spectral measurements have to be extended to shorter wavelengths.

Presently, we have introduced in our model 60 excited levels of In I and 61 of In II, including the ground levels shown in the Fig. 1. For In I they belong to the configurations with

n = 5 to 14, excluding configurations with *l* other than *s, p, d, f*

and for In II they belong to the configurations with

n = 5 to 9, excluding configurations with *l* other than *s, p, d, f , g*

Configurations of highly excited levels could easily be added to the model, if this could be proved to be necessary. This extension depends on the calculated absolute line intensities belonging to middle *n* and *l* configurations.

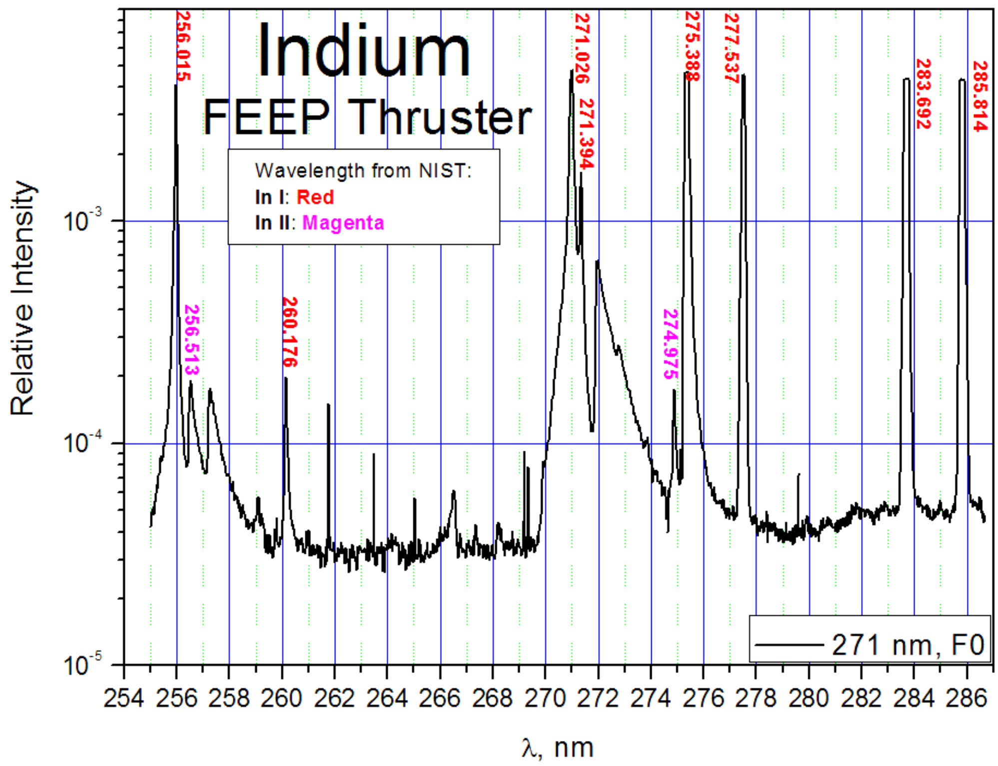

Figure 5. **Partial Indium spectrum of the FEEP Thruster.**

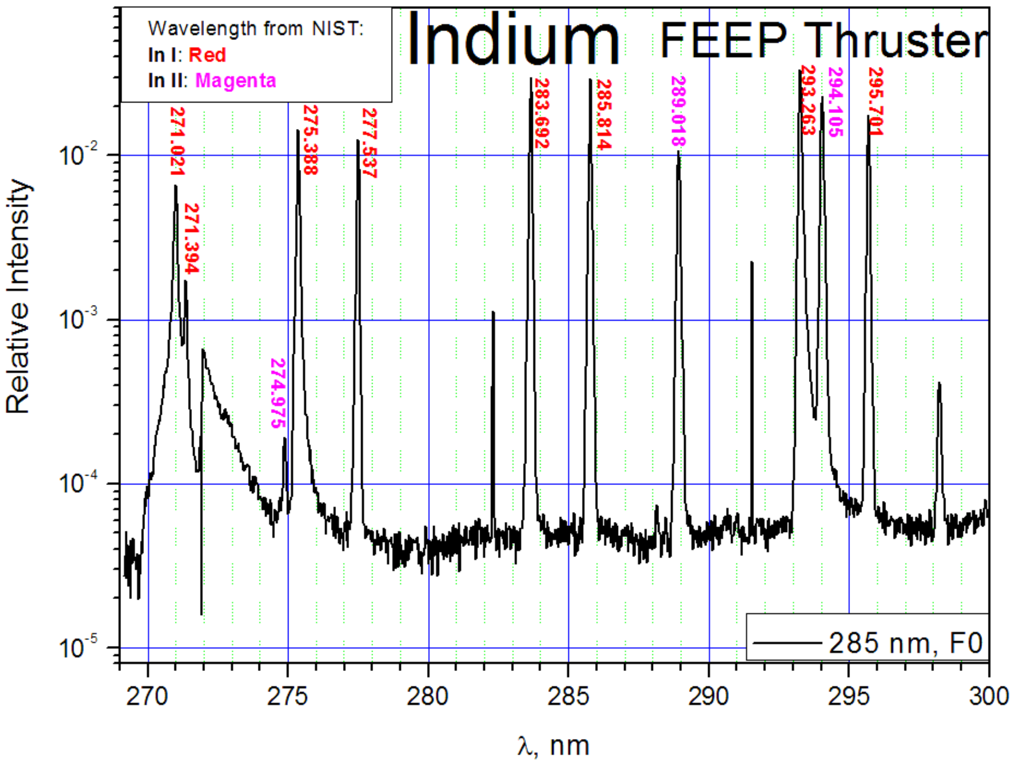

Figure 6. **Partial Indium spectrum of the FEEP Thruster.**

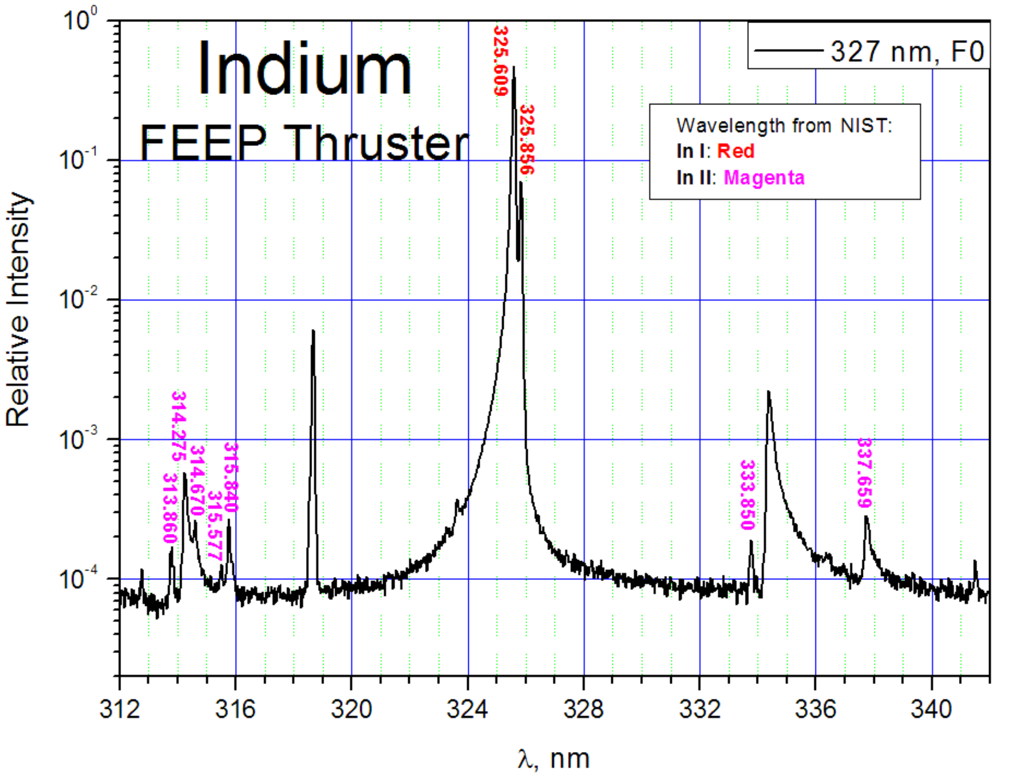

Figure 7. **Partial Indium spectrum of the FEEP Thruster.**

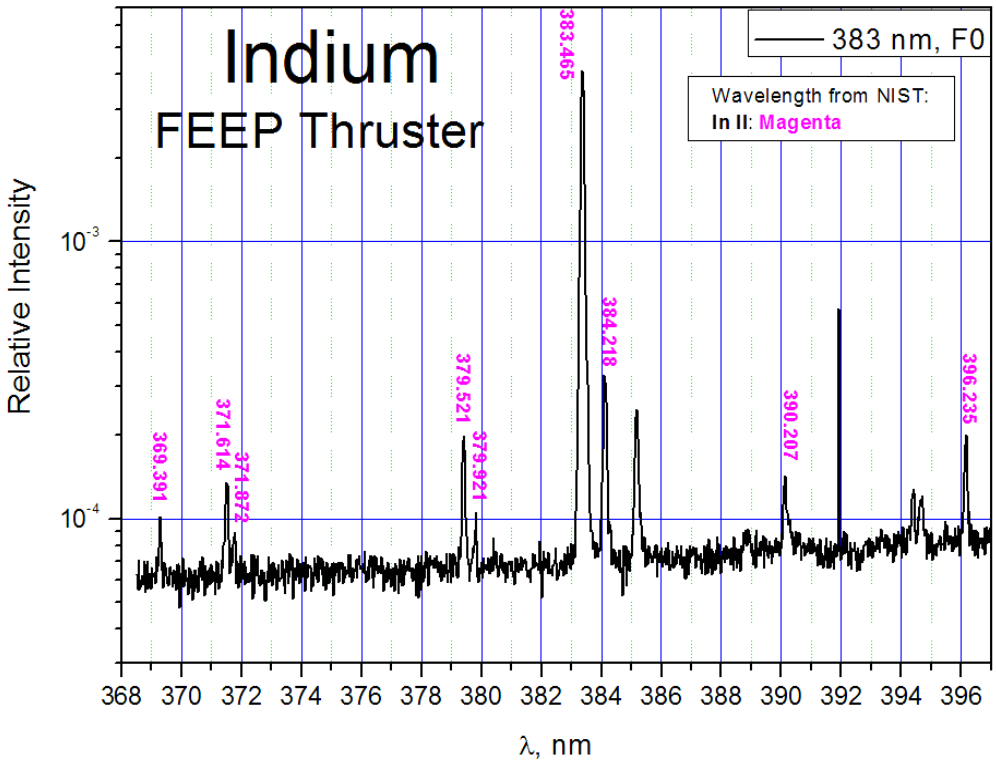

Figure 8. Partial Indium spectrum of the FEEP Thruster.

The main In I and In II lines have been identified in Figs. 5 to 8, following our C-R model. The corresponding wavelengths are noted in the figures with a dedicated color for each species (red for In I and magenta for In II). The exact λ values noted are coming from the NIST[14] site; these values were obtained through evaluation of experiments which are fully referenced in this site. We are giving in Tables 1 and 2 a partial list of the lines which have been identified for the moment in the thruster spectra shown in Figs. 5 to 8 by using our model, together with identification data according to the NIST tables. Other data, including transition probabilities and statistical weights appear occasionally in these tables.

We have identified a considerable number of In I and In II transitions appearing in spectra covering higher λ regions up to around 900 nm.

Table 1. Identified Indium I experimental lines (see text).

Observed Wavelength Air (nm)	Rel. Int.	A_{ki} (s^{-1})	J_i	J_k	g_i	g_k	Observed Wavelength Air (nm)	Rel. Int.	A_{ki} (s^{-1})	J_i	J_k	g_i	g_k
256.015	1100	4.0e+07	$^1/_2$	$^3/_2$	2	4	283.692	180c					
260.176	200						285.814	30c					
271.026	1600	4.0e+07	$^3/_2$	$^5/_2$	4	6	293.263	1100					
271.394	300						295.701	20c					
275.388	700						325.609	13000	1.3e+08	$^3/_2$	$^5/_2$	4	6
277.537	40						325.856	3000					

Table 2. Identified Indium II experimental lines (see text).

Observed Wavelength Air (nm)	Rel. Int.	A_{ki} (s^{-1})	J_i	J_k	g_i	g_k	Observed Wavelength Air (nm)	Rel. Int.	A_{ki} (s^{-1})	J_i	J_k	g_i	g_k
256.513	70						337.659	75c					
274.975	130bl						369.391	180c					
289.018	120bl						371.614	380w					
294.105	100	1.4e+08	1	0	3	1	371.872	160c	1.4e+08	1	0	3	1
313.860	130c						379.521	170w					
314.275	80c						379.921	230c					
314.670	130bl						383.465	250c					
315.577	150						384.218	200c					
315.840	100c						390.207	100c					
333.850	90c						396.235	250w					

It is to be noted that the relative intensity of the lines given in the Tables 1. and 2. are not those of our experiment (which can be seen in the figures), but those proposed in the NIST site[14] . The latter provide a general qualitative description of the In I and In II spectra in low density plasmas, and therefore are different from those we have registered for the In FEEP thruster and presented in Figs. 5 to 8. Also, complex and wide lines are marked by c and w. bl stands for blended lines, in which both wavelength and intensity may be affected in the experiment.

V. Conclusion

Indium emission spectra of an In FEEP thruster have been registered and used in conjunction with a C-R model aiming the diagnosis of the n_e and T_e in various device places. The evaluated atomic data are sufficient for the constitution of a quite detailed model, which in the present status has demonstrated the applicability of this diagnostic method in the FEEP.

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