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Spectroscopic determination of plasma parameters in front of heat shield materials for reusable spacecrafts under re-entry conditions

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Introduction

One of the unsolved problems in re-entry technology as well as in fusion research is the question of material choice. Therefore, it is necessary to develop diagnostic methods for the investigation and understanding of the processes dominating the interaction of these materials with the plasma under these extreme environments.

Future spacecraft systems ought to be reusable for many flights without a high expenditure of cost and maintenance. One of the most important problems to be solved is the high erosion of the heat shield material at components with high thermal loads. For a spacecraft these high thermal loads occur during the re-entry process at an altitude of about 80 km.

One of the most promising materials is the fiber reinforced compound material C/C-SiC with a TiO_2 protection layer. For the basic understanding of the erosion processes it is necessary to know the plasma parameters in the interaction zone of the plasma with the material.

In this work the density of a component of the material and the density of a component of the protection layer in front of the surface are determined from their line intensity ratios. Presently the Si I multiplet at 251 nm and the Ti I multiplet at 365 nm are used for density determination of the respective species by the self absorption method. In this contribution the spectroscopic method will be explained by considering silicon as example, and first experimental results for titanium will be presented as well.

Experimental Setup

In Fig.1 the experimental setup, the plasma wind channel (PWK II), is shown together with the diagnostics relevant for this investigation. The thermal load occuring during a re-entry process is simulated in this device by an electrical discharge in a plasma generator RD5 [Auw1995]. The surface temperature of the material samples is measured by a pyrometer through a window in the cover of the plasma wind channel. The spectra are measured by a 0.75 m spectrometer in connection with an ICCD-camera.

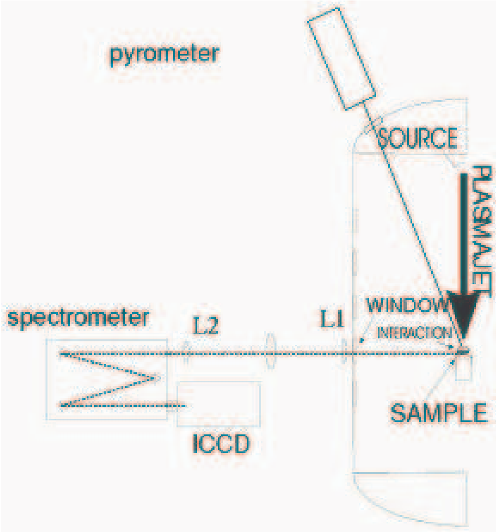

Figure.1: Experimental setup of the PWK with the diagnostics for surface temperature and particle densities.

Particle Density Determination by the Self Absorption Method

In Fig. 2 one can see an example of a measured intensity distribution. On the left hand side a picture taken with the ICCD camera displaying the spatial distribution of the six lines of the silicon triplet at 251 nm ($1s^2 2s^2 2p^6 3s^2 3p4s \rightarrow 1s^2 2s^2 2p^6 3s^2 3p^2$) is shown. On the right hand side you can see the intensities of the triplet at the central position.

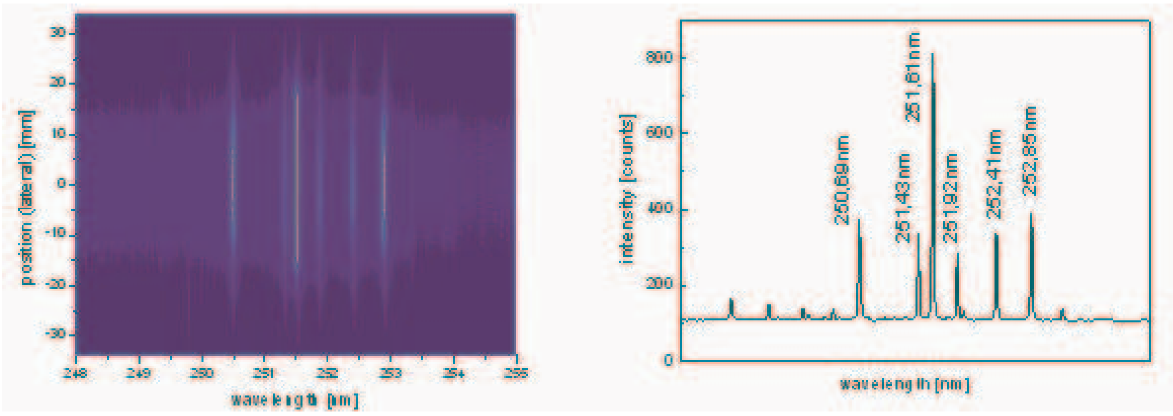

Figure.2: Example for a measured silicon spectrum

Primarily, the intensities of the lines depend on the emission coefficient, but in a certain density range they also strongly depend on the absorption coefficient and therefore on the optical depth of the line. Self absorption occurs [Loc1968, Uns1955, Jen1998, Kle1998]. Making the simple presumption of a constant density profile one can calculate the ground state density of the triplet with the following simple equation:

$$n_{Si} = \tau_0 \frac{8 \pi^{3/2} c \, g_k}{2 \sqrt{\ln 2} \, d \, \lambda_0^4 \, g_i \, A_{ik}} \delta$$

were τ_0 is the optical depth derived from the relative intensity ratios of the spectral lines [Jen1998, Kle1998], c is the speed of light, g_i and g_k are the statistical weights, A_{ik} the Einstein coefficient, λ_0 the central wavelength, δ the Full Width Half Maximum (FWHM) and d the optical pathlength. In Fig.3 the resulting density distribution is shown.

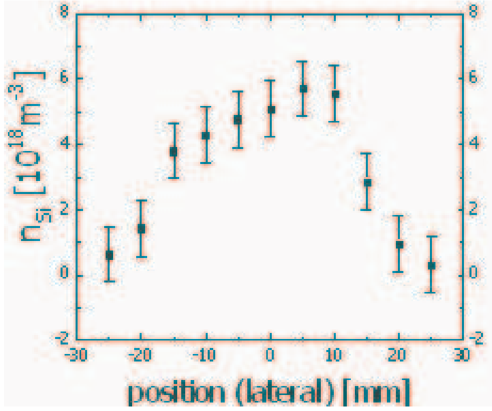

Figure.3: Resulting distribution of the silicon ground state density

For non-constant density profiles it is necessary to calculate the solution of the equation of radiative transfer [Loc1968] numerically. This has been done for the silicon triplet at 251 nm, the simulated spectra reproduce the measured one very good, for the optically thin case as well as for the optically thick one.

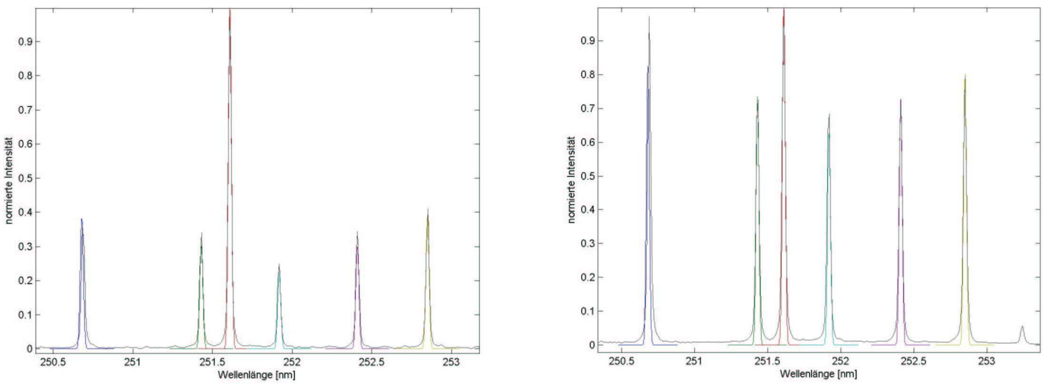

Figure.4: Measured and simulated spectra for the optically thin (left) and optically thick (right) case.

First results for titanium

The other element we are able to detect is titanium which is part of the protection layer applied on the surface of the C/C-SiC samples. It is a ground state transition in the wavelength range from 363 nm to 368 nm ($1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 \rightarrow 1s^2 2s^2 2p^6 3s^2 3p^6 4s4p$). As you can see in Fig. 4 the three most intensive lines clearly show self absorption. The stars in the graph represent the intensities of the lines in the optically thin case normalised to the first line, the straight line shows the measured spectrum. In the second graph of Fig.5 the normalised intensity ratios are presented as a function of the lateral position.

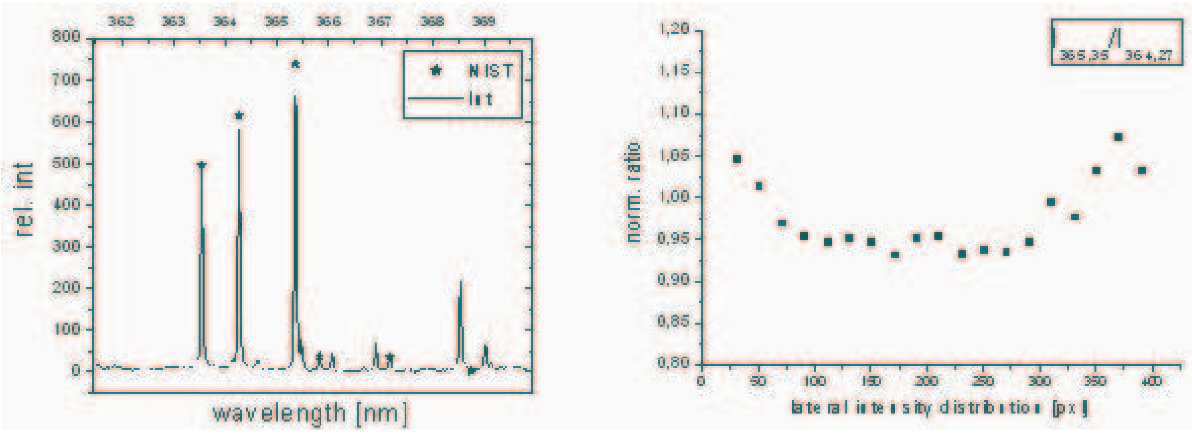

Figure.5: Titanium spectrum (left) and lateral distribution of the normalized intensity ratios.

Summary

This diagnostic allows the insitu time correlated determination of ground state densities in a re-entry plasma at a temperature of about 2000 K for silicon and titanium. The densities are determined as a function of space, time and surface temperature. The surface temperature correlation additionally allows a determination of surface binding energies of silicon in the C/C-SiC material. The simulations are in very good agreement with the experimental results and allow the presupposition of various density profiles.

References

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