

***In situ* density measurement for a thermal lithium beam employing diode lasers**

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We introduce a method for a spatially and temporally resolved density measurement of atomic beams. A semiconductor diode laser was employed for measuring both the absorption and the laser induced fluorescence emerging from the beam. Absorption measurements give an absolute value for the line integrated density, whereas laser induced fluorescence yields the relative density distribution. Thus, we were able to determine nondestructively absolute density distributions of thermal particle beams. © 1998 American Institute of Physics. [S0034-6748(98)03401-7]

Beam emission spectroscopy is widely used for spatially resolved measurement of plasma parameters in magnetically confined high-temperature plasmas, e.g., electron density and temperature, ion density, and temperature measurements.¹ The penetration depth of atom beams in plasmas is determined by the energy of the injected atoms. The probe beam must be neutral in order to prevent any deflection in the magnetic field of a fusion device. In the scrape-off layer of a tokamak, profiles of electron density up to $n_e \leq 5 \times 10^{12} \text{ cm}^{-3}$ are easily measured with thermal lithium beams ($E \approx 0.1 \text{ eV}$).² Higher electron densities are accessible using high energetic lithium beams ($E \approx 30 \text{ keV}$) that can be produced by electrostatic acceleration and subsequent neutralization of lithium ions. Neutralization may take place in a gaseous target and it is known, e.g., for fast helium beams,³ that the neutralized beam may contain a large fraction of excited atoms depending on the properties of the neutralization target. The evaluation of the plasma parameters requires a detailed knowledge of both the spatial and state distribution of the beam penetrating the plasma.⁴ Experiments suggest that predominantly ground state atoms are formed if a lithium beam is neutralized in Li or Na, but there are large uncertainties in the determination of the total flux of the neutralized lithium beam.⁵ Usually fluxes are measured by calorimetric methods or by quartz balances, which of course interrupt the beam. These methods are unsuitable for on-line flux monitoring of the particle beams.

In this note, we present a method that overcomes this limitation by employing a semiconductor diode laser and combining two diagnostics: laser induced fluorescence and atomic absorption spectroscopy, which allows the determination of the absolute density of the lithium atoms in the beam.

The thermal lithium beam was produced by an oven

filled with an alloy consisting of Al and Li. The temperature was measured by a thermocouple and the flux of lithium atoms was monitored by a quartz balance. The laser light passed the lithium beam perpendicularly.

Laser radiation was produced by a free-running semiconductor diode laser (Hitachi HL6714 with driving unit Profile TED420-3A, $\lambda = 671 \text{ nm}$, $\Delta\nu \approx 30 \text{ MHz}$).⁶ Tuning of the laser wavelength was achieved by varying the diode temperature and the diode current; the latter was used for a fine tuning. The absorption was detected by a photodiode. In order to cover all components of the transition the wavelength was scanned by a sawtooth modulation ($f_1 = 0.1 \text{ Hz}$) of the laser diode current. The signal-to-noise ratio was increased by applying a second high-frequency modulation ($f_2 = 50 \text{ kHz}$). The frequency f_2 was taken as reference frequency for a lock-in amplifier. Additionally, laser induced fluorescence was observed perpendicular to both the laser and the particle beam with a 128-element linear diode array that was aligned along the incident laser beam. The experimental arrangement was kept very simple because no wavelength selecting element for both the absorption and the fluorescence measurement was required.

For our measurements the Li I $2^2S_{1/2} \rightarrow 2^2P_{3/2}$ transition at $\lambda = 670.8 \text{ nm}$ (oscillator strength $f = 0.502$)⁷ was chosen. Due to the resonant de-excitation this excitation scheme did not affect the state distribution of the initial beam. The short lifetime of the excited atoms guaranteed that the excited particles returned to the initial state within a small distance and the beam injected into the plasma was not affected by the measurement. In this sense this method is nondestructive.

The technique of absorption spectroscopy is widely described in the literature (see e.g., Ref. 8). As the particle density n is related to the absorption α integrated over the line profile, absorption measurements yield the line integrated density. With Beer's law ($I_T = I_0 \exp[-\int_L \alpha(\nu, x) dx]$), L

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indicates integration along the incident laser beam) we arrive for the line integrated particle density at:

$$\int_L n(x) dx = \frac{4\pi\epsilon_0 m_e c}{f \pi e^2} \int_{line} \ln\left(\frac{I_0^\nu}{I_T^\nu}\right) d\nu. \quad (1)$$

I_T^ν and I_0^ν represent the frequency dependent transmitted intensities with (index T) and without (index 0) sample (beam), respectively. Thus, measuring the frequency dependence of the intensities, I_0^ν and I_T^ν , and subsequent integration with respect to the frequency ν yield the particle integrated along the line of propagation $\int_L n(x) dx$.

If the excitation is the same for all particles the fluorescence yield is proportional to the density.⁹ In our case the laser induced fluorescence intensities I_{fluor} give the relative distribution of the particles $n(x)$ along the line of excitation. Absolute density profiles are given by a comparison of the line-integrated fluorescence signal with the absorption [Eq. (1)]:

$$\int_L I_{fluor}(x) dx = \kappa \int_L n(x) dx. \quad (2)$$

The left hand side of Eq. (2) is given by the spatial distribution of the fluorescence light. κ represents a calibration factor. Since the fluorescence signals are calibrated by the absorption measurements the results obtained are absolute in density.

As an example of our results Fig. 1(a) displays an absolute density profile evaluated from the fluorescence measurements and subsequent calibration with absorption measurements. Figure 1(b) shows the temperature dependence of the density in the center of the lithium oven employed.

In order to calculate the detection limits of the method presented here, we determined the minimum absorption

$$A = 1 - \exp\left(-\int_L \alpha dx\right) \quad (3)$$

giving a value of $A_{min} > 2 \times 10^{-5}$ if a lock-in amplifier was applied.¹⁰

It should be noted that not only spatial but also temporal dependencies can be monitored. Time resolution depends on the time constants of the lock-in amplifier and is better than the higher detected densities are. This is essential not only

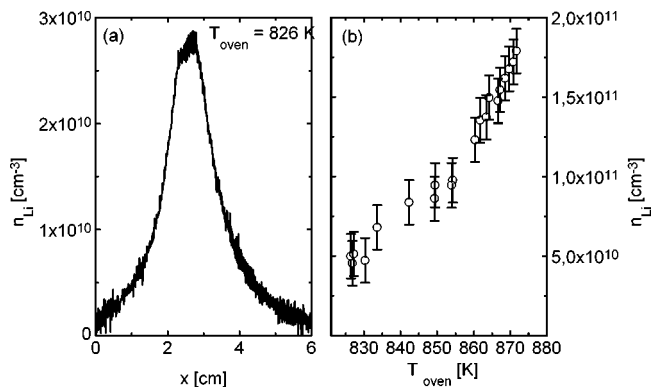


FIG. 1. (a) Radial density profile of a thermal lithium beam. (b) Displays the temperature dependence of the center density of the lithium beam.

for long term operation of the beam source but also for transient observation of the densities in the beam. Furthermore the method presented here should be applicable to density measurements of the lithium component in process plasmas.

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