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# Aluminium Lyman-beta satellite emission in non-Maxwellian dense laser produced plasmas

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High-energy decay channels of the Al Lyman-β satellite have been observed in X-ray emission from highly ionized plasma jets created by intense laser irradiation of aluminium foil targets. Atomic structure calculations show that the Lyman β satellite emission consists from six emission groups close to the He-like Al $1s^2$-1s4p ($He_\gamma$) and $1s^2$-1s5p ($He_\delta$) resonance lines. This provides new possibilities for space resolved analysis of high density plasmas. Non-Maxwellian simulations of the plasma emission carried out with the MARIA code demonstrate that the intensity ratios of the Lyman-β satellites and the $He_\gamma$ and $He_\delta$ resonance lines are very sensitive to the bulk electron temperature. In contrast to standard diagnostic methods, parameter studies show that this bulk electron diagnostics is practically unaffected by suprathermal electrons having less than 10% of the bulk electron density.



## 1. Introduction

The determination of the electron temperature and the fraction of suprathermal electrons are key parameters to understand the interaction of high-energy lasers with plasmas. Their importance, e.g., to basic research of kinetic instabilities [1] and inertial fusion applications [2] has created broad interest in independently measuring, i.e., diagnosis free from simulations, temperature and suprathermal electron fraction in hot dense plasmas. High-resolution spectroscopy of dielectronic satellites observed in X-ray plasma emission has turned out to be a key science in this activity. [3]

Gabriel [4] demonstrated that the line ratios of resonance lines and their accompanying dielectronic satellites provide a possibility to measure the electron temperature. The satellite method has also been proposed to diagnose the suprathermal electron fraction from qualitative changes to the charge state distribution (CSD) [5]. An overview of the potential of dielectronic satellite X-ray transitions to investigate non-equilibrium plasmas has been given in Ref. [3]. In the present work, we explore the dielectronic satellite emission of the Lyman-β resonance line ($Ly_\beta = 3l \rightarrow 1s$) of H-like aluminium ions. We demonstrate that these satellite transitions have the potential to characterise non-Maxwellian plasmas.

The autoionizing configurations 2l3l′ give rise to two different decay channels:

a) Low energy decay channel: 2l3l′ → 1s3l′, which lead to satellites to $Ly_\alpha$,
b) High-energy decay channel: 2l3l′ → 1s2l, which lead to satellites to $Ly_\beta$.

In Section 2 we describe the experimental setup, in Section 3 we present the experimentally observed spatially resolved X-ray spectra. Then in Section 4 non-Maxwellian non-LTE spectral

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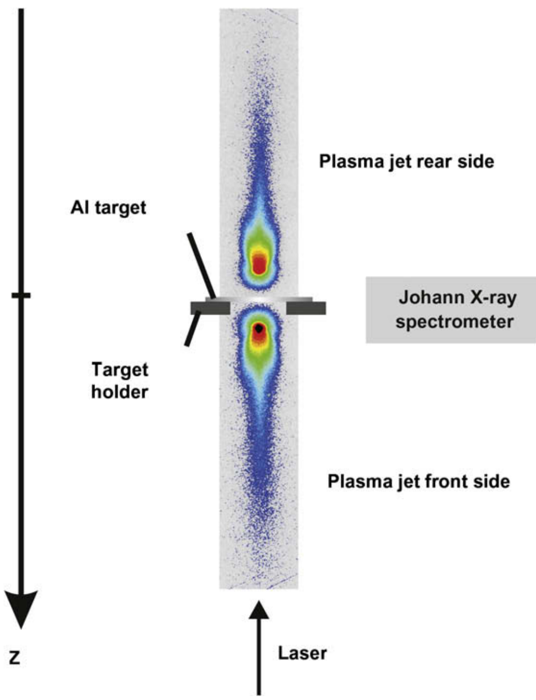


**Fig. 1.** Experimental setup.

simulations are performed and the structure of the Lyman β satellite emission is discussed with respect to the determination of the bulk electron temperature.

## 2. Experimental setup

The experiment was carried out at the PALS kilojoule laser facility [6]. The schematic experimental setup is depicted in Fig. 1, where a 0.8 μm thick foil of aluminium has been irradiated at normal incidence with the iodine PALS laser at 3ω (λ = 438 nm) at laser intensities $3.7 \times 10^{15}$ W/cm$^2$. The focal spot diameter was about 80 μm and the energy on target was 47 J. The laser pulse length was 0.25–0.3 ns. The pressure in the interaction chamber was maintained at 0.7 mbar.

The laser produced plasma emission was dispersed through a high resolution (λ/Δλ = 4000) spectrograph. A PET crystal, curved to a radius of 200 mm was used in Johann geometry [7]. The spectral window included aluminium hydrogen- and helium-like lines from 6.0 to 6.7 Å, which corresponds to $Ly_\beta$ and the He-like series up to $He_\beta$. A 10 μm thick beryllium window protected the Kodak CX film from the visible light.

As the aluminium plasma was 4 mm from the 10 μm wide spectrometer slit, the transverse magnification was 50. Spatial resolution was provided in a direction perpendicular to the target surface, the *Z*-direction in Figs. 1 and 2, which was centered at $Z = 0$ to provide simultaneous X-ray imaging from the front and rear non-irradiated side of the target, see Fig. 2. Spectra which were recorded on X-ray film were processed with a scanner at resolution of 1200 × 1200 pixel per inch, providing a spatial resolution of 0.4–0.5 μm of plasma per scanned pixel.

## 3. Space resolved Lyman-β emission

Fig. 2 shows the spectrally resolved X-ray image. The dominant spectral features are the He-like resonance line series ($He_\beta = 1s3p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$, $He_\gamma = 1s4p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$, $He_\delta = 1s5p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$, $He_\epsilon = 1s6p\ ^1P_1 \rightarrow 1s^2\ ^1S_0$) as well as the H-like $Ly_\beta$ resonance lines $3p\ ^2P_{1/2,3/2} \rightarrow 1s\ ^2S_{1/2}$. Also clearly visible are numerous transitions near $He_\delta$, which do not exist in the far target emission. These transitions have been identified as the high-energy decay channel of the Lyman β satellite transitions. Fig. 3 shows the spectral distribution at 3 different spatial positions: rear target side (a), the target surface (b), and front side (c). These spatial positions are also indicated in Fig. 2.

Based on spectral simulations carried out with the non-LTE, non-Maxwellian code MARIA [5,8,9], six emission groups designated as $\beta_1$–$\beta_6$ have been identified in Fig. 4. Additional transitions are visible between $He_\gamma$ and $He_\beta$ (Fig. 3c) which do not correspond

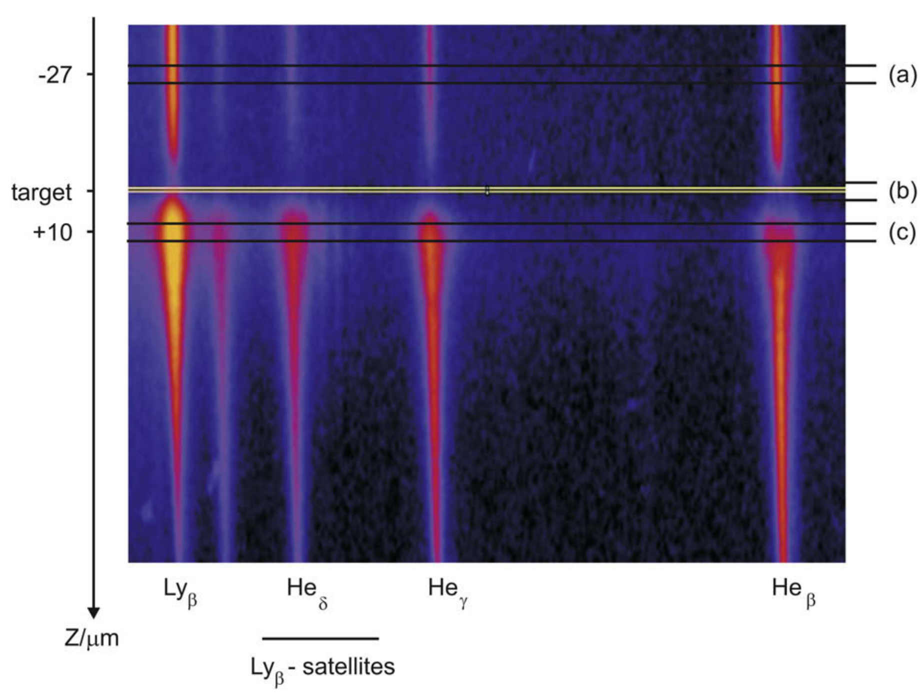


**Fig. 2.** Space resolved X-ray image of aluminium in the spectral interval from $Ly_\beta$ until $He_\beta$.