

Spaced resolved analysis of suprathermal electrons in dense plasma

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Abstract. The investigation of the hot electron fraction is a crucial topic for high energy density laser driven plasmas: first, energy losses and radiative properties depend strongly on the hot electron fraction and, second, in ICF hohlraums suprathermal electrons preheat the D-T-capsule and seriously reduce the fusion performance. In the present work we present our first experimental and theoretical studies to analyze single shot space resolved hot electron fractions inside dense plasmas via optically thin X-ray line transitions from autoionizing states. The benchmark experiment has been carried out at an X-pinch in order to create a dense, localized plasma with a well defined symmetry axis of hot electron propagation. Simultaneous high spatial and spectral resolution in the X-ray spectral range has been obtained with a spherically bent quartz Bragg crystal. The high performance of the X-ray diagnostics allowed to identify space resolved hot electron fractions via the X-ray spectral distribution of multiple excited states.

1. INTRODUCTION

Non-equilibrium electron statistics (or non-Maxwellian energy distribution functions) are at the center of worldwide research because they play an exceptional role for fusion research [1–5]: a) in the indirect drive scheme (hohlraum) of inertial fusion, hot electron production may lead to a preheat of the DT capsule and hinder subsequent compression above solid density to obtain ignition, b) in the direct drive scheme (fast ignition), hot electrons are created purposely by a PetaWatt laser via “hole boring” to initiate burn in the DT capsule, c) in atomic physics, suprathermal electrons lead to strong changes of almost all radiative properties like, e.g., ion charge state distributions, radiative losses, line intensities and line ratios. As plasma simulations of hot electrons are exceedingly difficult (and under continuous discussion) it is important to provide independent (from plasma simulations) data about suprathermal electrons. As high-resolution X-ray spectroscopy can provide a unique characterization of hot electrons [5], benchmark experiments are requested to validate non-Maxwellian atomic physics codes. An essential point of well characterized experiments is to have a well defined symmetry axis of hot electron propagation in dense plasmas. This is difficult to achieve in laser produced plasmas but can be quite well realized in X-pinch experiments.

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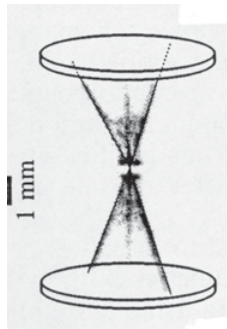


Figure 1. A schematic view of the X-Pinch.

2. THE EXPERIMENTAL SETUP: X-PINCH

An X-pinch principle is similar to those of the well known Z-pinch where plasma pressure is balanced by magnetic field pressure that is driven by a high current [6–9]. The X-pinch geometry is realized by crossing 2 or more wires – Fig. 1. At the crossing point, the magnetic pressure is highest and a hot dense plasma spot is formed.

The device used for the present experiments is a pulsed power generator developed for radiography needs [10, 11]. The capacitors can deliver 850 J energy when charged with 40 kV. A peak current of 290 kA can be obtained with a rise time of about 200 ns. High purity (99.99%) aluminum wires with 25 μm diameter have been chosen.

In order to obtain space resolved information about the hot electron induced X-ray emission we implemented a spherically bend quartz crystal ($2d = 8.52$ Angstrom) in the so called FSSR-2D scheme [12, 13]. The distance between the source and the crystal was 40 cm which impose for the detector with the geometry to be at 117.7 mm from the crystal. As detector we used X-ray film: Kodak INDUSTREX 8800, with a grain size of 4 μm . In order to have only the X-ray on the film, we add a filter made of 1 μm of polpropylen covered by 100 angström of aluminum. This spectrometer setup allowed to record single shot high-resolution ($\frac{\lambda}{\Delta\lambda} = 5000$, $\Delta z = 40 \mu\text{m}$) X-ray images of the dense plasma emission.

3. EFFECT OF HOT ELECTRONS ON LEVEL EXCITATION IN PLASMA

Only well selected line emission is suitable for the analysis of hot electrons. In dense hot non-homogenous plasmas X-ray emission of dielectronic satellites permits a unique characterization [5]. Of particular importance is that dielectronic satellite emission is not sensitive to radiative recombination (in contrast to resonance lines) confining their emission “naturally” to the dense hot plasma volume. In the present work we analyze the optically thin He β satellite emission ($1s2l3l' - 1s^22l$) with respect to its hot electron sensitivity. The principle idea is to separate in the highly resolved spectral distribution satellite transitions (about 60 E1-transitions originating from the 66 LSJ-split autoionizing levels $1s2l3l'$) that are sensitive to different excitation channels:

a) Inner-shell excitation proceeds from the Li-like ions



b) dielectronic capture proceeding from the He-like ions.

The radiative transitions, the so-called dielectronic satellites (near He β), are given by



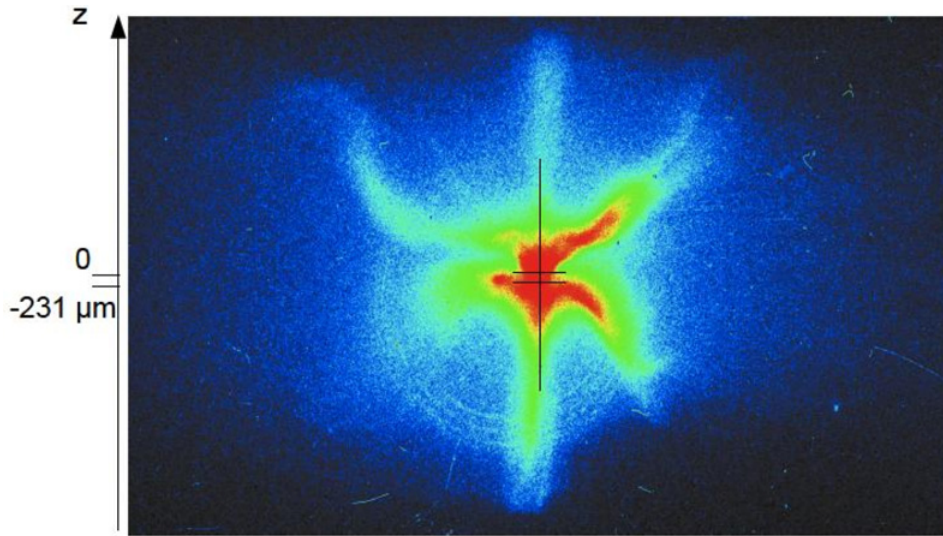


Figure 2. Pinhole image of the plasma, without any filter.

The inner-shell excitation channel is strongly enhanced by hot electrons whereas the dielectronic capture channel is only weakly perturbed. Hot electrons can therefore be characterized comparing the spectral distribution of both channels.

In dense plasmas, population can also be redistributed via electron collisions among different autoionizing states thereby allowing to detect density effects on the spectral distribution [14, 15].

4. RESULTS

Figure 2 shows the time integrated pinhole image: hot spot emission at the crossing point, emission from the heated wires and an emission along the z-direction. The z-direction corresponds to the propagation direction of the hot electrons that provoke emission when colliding with atoms and ions.

The Fig. 3 shows the x-ray image of the spherical quartz spectrometer. Aluminum He γ , He β and Ly α show faint emission in positive z-direction but very strong emission in negative z-direction, satellite emission, however, extends almost exclusively in the negative z-direction. Comparing Fig. 2 with Fig. 3 we suspect that hot electrons propagating in negative z-direction are responsible for the observed emission. Emission along the wavelengths axis (horizontal base line) with narrow spatial extension corresponds to the bremsstrahlung emitted from the hot spot (highest intensity).

The space resolved satellite emission shows important characteristic changes along the z-axis, Fig. 4. Near the hot spot region (Fig. 4a) the $\beta 4$ transition is the most intense whereas far from the spot (Fig. 4b) $\beta 3$ is the most intense. The simulations show [14, 15] that the spectral distribution of Fig. 4a is almost close to the Boltzmann limit whereas a spectral distribution like in Fig. 4b can neither be obtained for any realistic temperature and density changes.

5. SIMULATIONS

In order to study the spectral emission of dense plasmas containing hot electrons, we approximate the electron distribution function $F(E)$ by [2]

$$F(E) = (1 - f_{\text{hot}}) \times F_M(E, T_{\text{bulk}}) + f_{\text{hot}} \times F_M(E, T_{\text{hot}}) \quad (3)$$

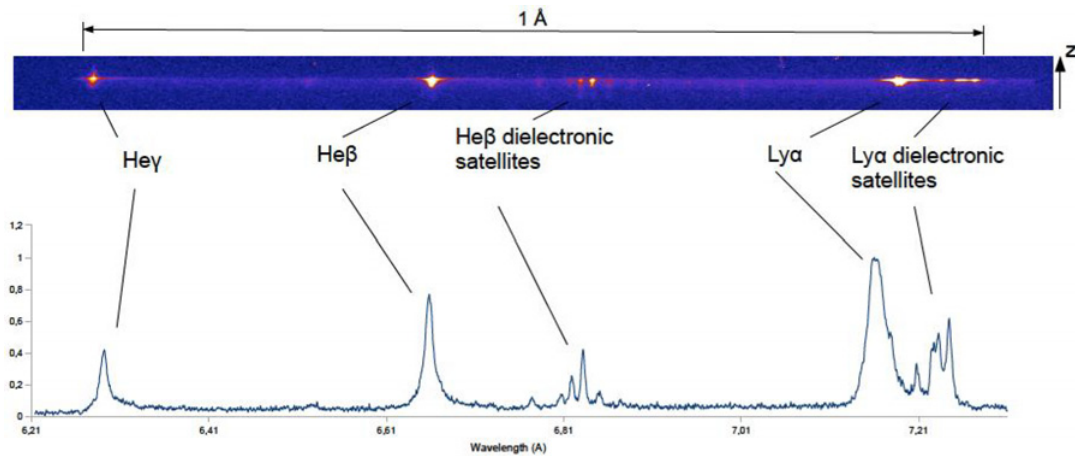


Figure 3. Image of the film, z corresponds to the spatial resolution and λ to the spectral resolution.

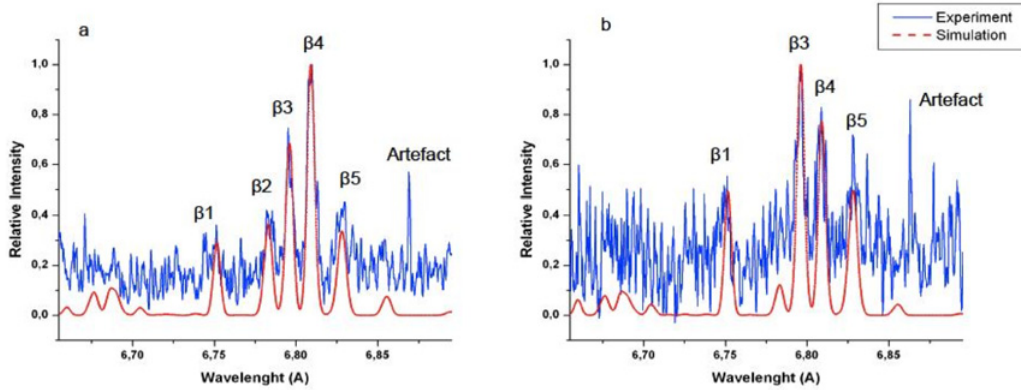


Figure 4. Space resolved spectral distribution of the He β satellite lines, a) $z = 0 \mu\text{m}$, b) $z = -231 \mu\text{m}$.

where $F_M(E, T)$ is a Maxwellian distribution function, f_{hot} is the fraction of hot electrons characterized by a temperature T_{hot} . The generalized population matrix W_{ij}

$$W_{ij} = A_{ij} + n_e \times C_{ij} + \Gamma_{ij} + n_e \times DC_{ij} + n_e \times I_{ij} + n_e^2 \times T_{ij} + \dots \quad (4)$$

contains then the rate coefficients that are integrated over the distribution function given in eq. 3. The atomic populations (ground states, single excited states as well as multiple excited autoionizing states) are given by a system of differential equations:

$$\frac{dn_i}{dt} = -n_i \times \sum_j W_{ij} + \sum_k n_k \times W_{ki}. \quad (5)$$

In order to compare the simulations directly with the observation, we calculate the spectral distribution according

$$I = \sum_i \sum_{j>i} \frac{1}{4\pi} \hbar \times \omega_{ji} \times n_j \times A_{ji} \times \phi_{ij} \quad (6)$$

where i, j are the atomic levels, n_j is the population of level j , $\hbar \times \omega_{ij}$ is the transition energy (transition from j to i), A_{ji} is the Einstein's coefficient of spontaneous emission and φ is the line profile. Among other levels included in the simulation, we include exactly all LSJ-split $1s2l3l'$ -levels. Atomic data, cross sections and rate coefficients have been calculated with the FAC-code [16]. More details are described elsewhere [14].

As mentioned above, the simulations show that the spectral distribution (in particular the high emission of the $\beta 3$ satellite group) can only be reasonably described invoking hot electrons with a fraction of some percent: $f_{hot} = 3\%$. For the temperature T_{hot} , we have assumed 10 keV. Other parameters used in the simulation are: $T_{bulk} = 100$ eV, an electronic density $n_e = 10^{20}$ cm $^{-3}$. The simulations of Fig. 4a indicate that the electronic density is about $n_e = 10^{22}$ cm $^{-3}$ indicating a spectral distribution close to a Boltzmann one, $T_{bulk} = 100$ eV and $f_{hot} = 0$ was used in the simulation.

6. CONCLUSION

We have proposed the He β satellite emission as a sensitive diagnostic to the hot electron fraction. The method was successfully validated at an X-pinch facility with high-resolution X-ray spectroscopy. Hot electron fractions of some percent have been identified from the space resolved satellite spectral distribution far away from the central hot spot.

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