

# Optical emission from Al target irradiated by FLASH

M Stránský and K Rohlena

Institute of Physics, Na Slovance 2, Prague 8-Libeň, 182 21 Czech Republic

E-mail: rohlana@fzu.cz

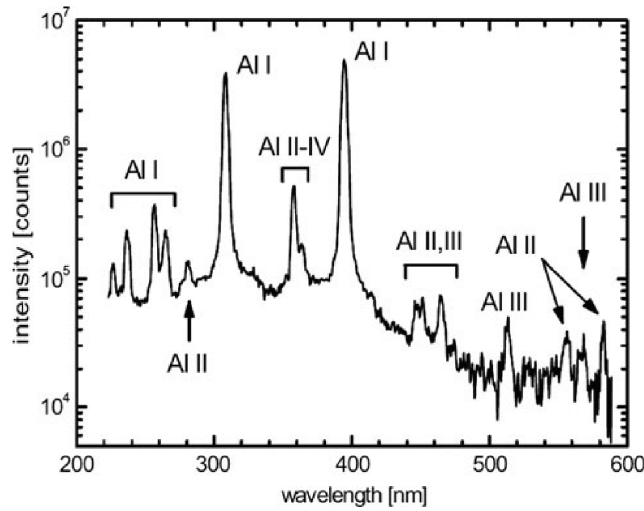
**Abstract.** The following text touches on some peculiarities in optical emission spectroscopy results from experiments on the free-electron laser FLASH [1, 2]. Aluminum targets were irradiated with 13.5 nm  $\sim$  25 fs pulses at intensities of  $10^{13}$  and  $10^{16}$  W/cm<sup>2</sup> (20 and 1  $\mu$ m foci). Surprisingly, only neutral atom lines for the case with wider focus and traces of ion lines in the tighter focus case were observed with the optical emission spectroscopy (200-600 nm range), [2]. The motivating idea behind this work is the suggestion in [1] by Zastrau that the optical spectrometer sees only emissions from a cold expanding lower-density ( $< 10^{22}$  cm<sup>-3</sup>) plasma plume. In this contribution the notion of UV range screening is analyzed in detail.

## 1. Introduction

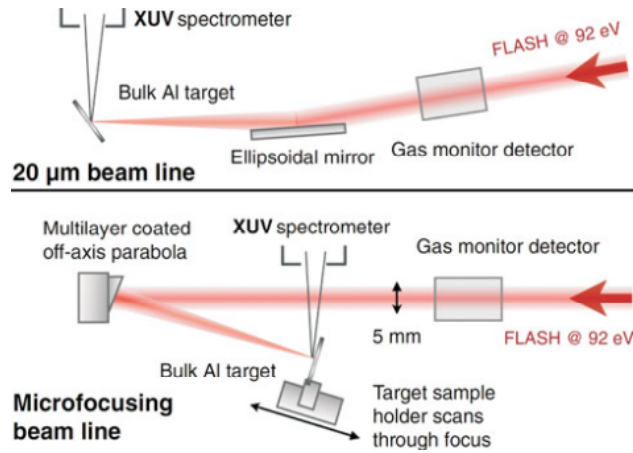
In the high energy density plasma experiment on the free-electron laser facility in Hamburg (FLASH), see [3], in which aluminum targets were irradiated with 13.5 nm  $\sim$  25 ns pulses at two different intensities  $10^{13}$  and  $10^{16}$  W/cm<sup>2</sup> (20 and 1  $\mu$ m foci), the FEL radiation is absorbed by a volumetric photo-ionization mechanism. During this absorption process one L-shell electron is knocked into the conduction band, leaving the ionized atom transparent to the incoming radiation, as the L-shell absorption edge is shifted to energy (93.6 eV) which is higher than that of the incoming photons (92 eV) – induced transparency phenomenon first described in [4]. The L-hole has a life time of about 40-60 fs before it is filled by an Auger decay process. The intermediate stage of energized crystalline lattice following the absorption process is often referred to as the warm dense matter (WDM, see [5] for a more accurate definition).

The non-thermal electrons in the conduction band then start to thermalize and their energy is redistributed over the lattice on the femto- to picosecond time scale. The lattice gradually disintegrates and finally, after a full thermalization, a non-ideal plasma is formed, which keeps expanding on a hydrodynamic pico- to nanosecond scale reducing further the density and temperature. However, at the very start of the expansion, as the density is reduced, and the band structure – the conduction band starts to disappear, and higher orbitals emerge. At the same time, the temperature also decreases, and some lower energy radiative transitions might occur between the newly appeared outer orbitals. For more details see Zastrau et al., [1], for the properties of the resulting non-ideal Al plasma governed by a complex equation of state, see [6]. In this experiment, the optical range (near UV and optical, 200-600 nm) was observed with a spectrometer. Cihelka et al. [2] note that the spectral lines referring to the transitions of ionized aluminum are either missing altogether or are weak (in the higher intensity case) while the neutral transitions dominate in this wave-length range. This intermediate time range during the expansion is studied in the following sections in order to explain the absence or weakness of the ionic lines in the optical wave-length range, see Fig. 1 for a typical spectrum as presented in





**Figure 1.** Time integrated optical spectrum of Al illuminated with the tighter ( $1 \mu\text{m}$ ) focus of the FEL beam. Some ion lines are visible, but the short wavelengths segment of the spectrum is almost void of the ionized Al. Taken from [2].



**Figure 2.** Experimental layout of optical spectra registration in the FEL vacuum chamber with the tighter ( $\sim 1 \mu\text{m}$ ) and the wider focusing ( $\sim 20 \mu\text{m}$ ), taken from [1]. The arrangement with the tighter focus had a slightly different geometry, see Fig. 3 and was installed in a separate chamber.

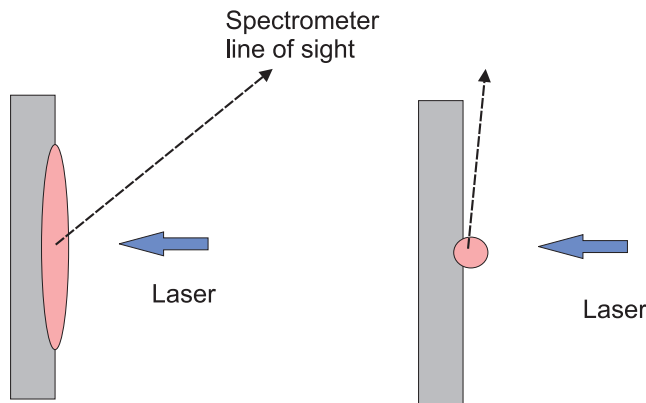
[2]. The experimental arrangement for measurement of the optical spectra emanating from the FLASH generated plasma on a solid Al target is described in [1], see Figs. 2 and 3.

## 2. Physical model

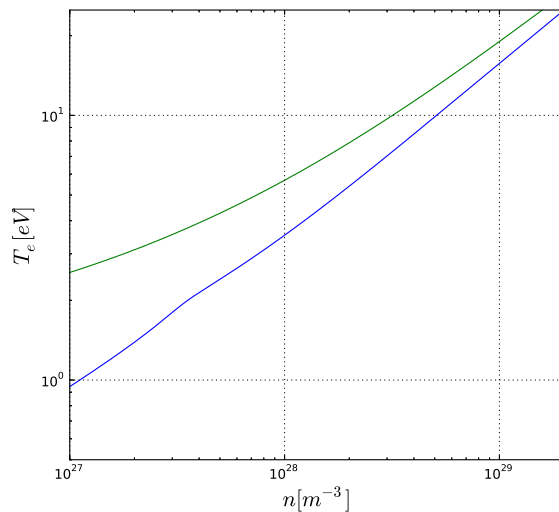
The plasma outflow was modelled using a 1D planar adiabatic expansion based on the self-similar model described in [7]. A slight complication is due to the presence of the recombination heat, which is released while the composition of the plasma follows the Saha equilibrium used to describe the ionization state during the adiabatic expansion. However, the additional heating can be incorporated in a modified adiabatic curve as it is expressed by the following energy balance

$$\frac{3}{2}N_T k_B dT = -\frac{N_T k_B T}{V} dV - \sum_{\alpha} \varepsilon_{i(\alpha)} \left( \frac{\partial N_{\alpha}}{\partial T} dT + \frac{\partial N_{\alpha}}{\partial V} dV \right) \quad (1)$$

where  $N_T$  is the total number of particles including electrons and all the ion species,  $\varepsilon_{i(\alpha)}$  is the sum of ionization energies to reach the ionization stage  $\alpha$  starting from the neutral atom, and the temperature  $T$  is assumed to be equal for all the particle species. The partial derivatives of  $N_{\alpha}$  are obtained from the Saha equation. Equation (1) was integrated, and the resulting dependence on both the electron and the overall heavy particle concentrations was plotted in Fig. 4. This modified adiabatic curve was then used in the adiabatic expansion model.



**Figure 3.** The measurement scheme showing the differences between the geometry of the wider and tighter focusing (out of scale).



**Figure 4.** The modified adiabatic curve for Al plasma including the recombination heating starting at the electron concentration  $1.5 \times 10^{23} \text{ cm}^{-3}$  and a temperature of 25 eV. The upper curve gives the temperature as a function of the electron concentration and the lower one as a function of the total heavy particle concentration with the electrons excluded. The slight kink visible on the lower curve marks the onset of the heating.

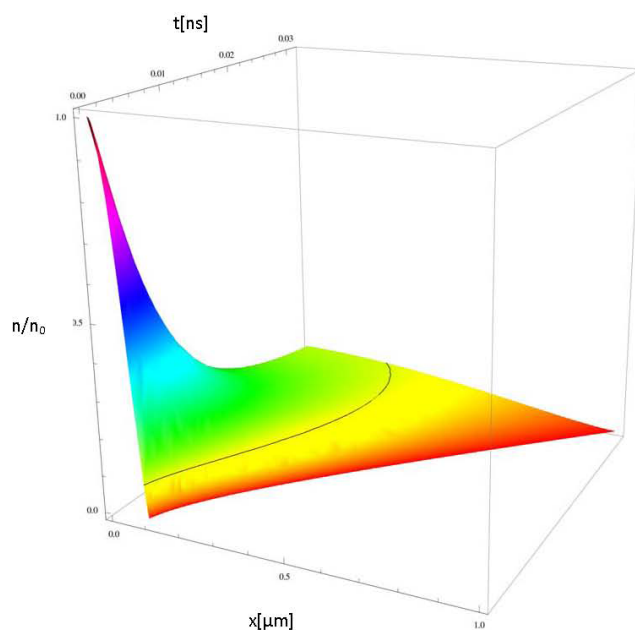
Of course, the Saha equilibrium as well as the adiabatic term in (1) are derived under the assumption of equation of state of an ideal gas. Neither other recently observed phenomenon occurring in a non-ideal plasma, see [8], namely the ionization potential lowering, has been included. This means that (1) is correct only after the expansion causes the diluted plasma to lose an essential part of its non-ideality. However, since the spectral measurement is integrated in time and the expansion time scale extends over a nanosecond scale, equation (1) is valid for most of the data collection interval.

### 3. Results

The expansion of the density profile as a function of time using the Schmalz [7] model is shown in Fig. 4. The ions have just a very restricted time window (few 10's of ps) to contribute to the emissions in a range of 200-600 nm. The ion line intensities at the critical density surface are less than 1/10 of the neutral lines for the wider focus case. Since the optical spectrometer was time-averaging the emissions over 2 ms interval, the neutral atoms have a much wider time window for the emissions, and therefore are the most prominent ones. In addition, an opacity calculation reveals that the expanding Al plasma is initially optically very dense (optical thickness  $>10000$  for the typical 280 nm Al II line - see the trajectory of the critical surface in Fig. 5), and only a very thin plasma cooled by the expansion would be sufficiently transparent for the ion lines to be visible for an outside observer. That is why the spectrometer records only neutral lines

corresponding to a temperature of 0.6-0.8 eV as it was indeed reported in [2].

In the case of the tighter focus ( $1\ \mu\text{m}$ ), in which traces of ion lines appear, Fig. 2, the expansion is governed by a different geometry, see Fig. 3. Whereas in the wide focus case the plasma expands in a 1D fashion forming a thin plasma layer before it cools down, the tighter focus case is more complex. The process is aided by the induced transparency mechanism (which happens at the WDM stage still before the plasma is formed, [4]), which might help to drill a slightly deeper heated hole into the target as against the linear absorption. The resulting hole is up to  $10\text{-}20\ \mu\text{m}$  deep, and it thus takes a longer time for the heated plasma to pour out. Assuming it would do so at the sound speed, the expansion would take long enough time ( $\sim 1\ \text{ns}$ ) to cause some of the ion (Al II) lines to be registered in the 2 ms averaged spectrum. A rough estimate renders an intensity ratio of  $1/170$  for the Al II lines over the neutral atom lines. The measured spectra gave an intensity ratio around  $1/100$ .



**Figure 5.** Density profile temporal evolution.  $n_0$  means the initial number density of heavy particles, the gray line marks the trajectory of the critical density surface belonging to  $\lambda = 280\ \text{nm}$  (one of the strongest Al II lines in the examined spectral range).

#### 4. Conclusions

Even though this topic concerns experiments with non-ideal plasmas, the peculiarity of the measured optical spectra can be attributed to the effects that are no longer non-ideal – an explanation involving the non-ideal plasma topics is not necessary in this case. The main reason for the absence of the ionic spectral lines in the wider focus case is a very narrow time window during which they can be recorded. In contrast, the time available for the collection of the part of the spectra belonging to the neutral lines is long enough to integrate a sufficient number of photons to render a clear signal, which is thus far outweighing the ionic lines. This is mainly due to the fact that the plasma is optically thick with respect to the ionic line wavelengths down to the very low temperatures at which only the atomic lines are emitted. In the higher intensity case of the tighter focus, when the screening of the hot outpouring plasma is less efficient and also the expansion of hotter plasma takes longer, the time window for the ionic lines is sufficiently long for the traces of the ionic lines to show up in the time-averaged spectrum.

#### Acknowledgments

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