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Diagnostic Capabilities provided by an Ultra-Fast Multi-Wavelength Pyrometer

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Multi-wavelength pyrometry is the only experimental diagnostic able to measure high temperatures in Warm Dense Matter experiments on a nanoseconds timescale. An ultra-fast 5-channel pyrometer was built and tested on a set of metals in ion heating experiments at GSI. In addition to temperature measurements the set-up allows a further characterization of the shape and duration of the beam pulse.

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1. Introduction

Matter at extreme conditions of temperature and pressure occurs widely in the universe, making up such astrophysical objects as stars and planetary interiors. For understanding the essential properties of warm dense matter (WDM) and, for example, to address questions of planetary formation and evolution, a challenging procedure of high temperature measurement is required within an ultra-fast time scale.

Ultra-fast multi-wavelength pyrometry allows measuring the temperature of metals heated by an intense ion beam up to their melting with a nanosecond time resolution and a spatial resolution of 200 μm. We were able to measure the temperature of the tungsten, tantalum, iron, and copper foils, heated by the ion beam up to 1-4 kK in a set of experiments.

2. Experimental technique of multi-wavelength pyrometry

The main principles of multi-wavelength pyrometry consist of the pyrometrical determination of surface temperature by an analysis of thermally emitted light. It is practically the only method for temperature measurements in the WDM regime. The pyrometrical technique is based on measurements of wavelength-dependent thermal radiation or spectral radiance, and its comparison to that of blackbody (Planck) radiation or its Wien's approximation.

A pyrometer measures the temperature of the optically thick radiation layer via its emitted thermal radiation, while no disturbance of the existing temperature field occurs. The brightness temperatures are obtained from an analysis of the Planck radiation at a few wavelengths with the possibility for the application of various models of spectral emissivity that in some cases can lead to more precise temperature measurements [1]. Another type of optical radiation that can be registered by such a pyrometer is the luminescence of the metal during the beam bypass and gas fluorescence when the gas target is used.

The penetration of an ionizing projectile through a gas target will lead to the emission of light due to the collisional excitation of gas atoms. The concept for using this light emission to measure beam profiles is based on the observation of the glowing region with one or more cameras and using these images to reconstruct the beam profile via Abel inversion for a circular beam or by tomographic techniques in the general case [2].

3. Temporal diagnostic possibilities of the technique

It is important to know the duration of the light emission process, because when the light emitting particles move away from the place where they interacted with the beam during the light emission, that disturbs the measurement of the particle beam size. One of the techniques allowing to measure the beam temporal parameters can be ultra-fast pyrometry.

3.1 Optical transition radiation

The nature of OTR (Optical transition radiation) is based on light emission due to the processes of the interaction of the beam particles with the solid target material [3]. Transition radiation is emitted when a charged particle crosses the boundary between two media with different optical properties. This phenomenon has been used for beam diagnostics in high-energy accelerators for a long time [4]. The duration of such radiation is practically limited to the duration of the interaction itself, and the shape of the radiation intensity signal almost repeats the shape of the ion beam.

In our experiments, thin aluminum foil with a pinhole was placed in the intense lead ion beam (E_i = 450 AMeV, $N \approx 4 \cdot 10^9$ ions/pulse) focused to an approximately millimeter spot. The pinhole was used to roughly control the position of the beam at the target by the camera. The foil was oriented circa 45 degrees to the beam and practically along the direction of view of the pyrometer. Due to the shape of the pinhole, there are some parts of the foil surface with different orientations. The optical signal was clearly distinguishable allowing one to estimate the beam duration because most of the light was emitted while the beam traversed the sample.

3.2 Non-thermal luminescence of argon during heavy-ion irradiation

The mechanism of the light emission of gas fluorescence is described in [2] and is due to collisional excitation of energetically high levels in the target species, ionization and ionization plus excitation of the target species, where the ionization can lead to singly but also multiply ionized species. Secondary electrons formed in the ionization processes also cause excitations.

4. Experimental results

An example of the experimental signals for the argon fluorescence at 300 mbar in comparison with aluminum luminescence is depicted in Figure 1.

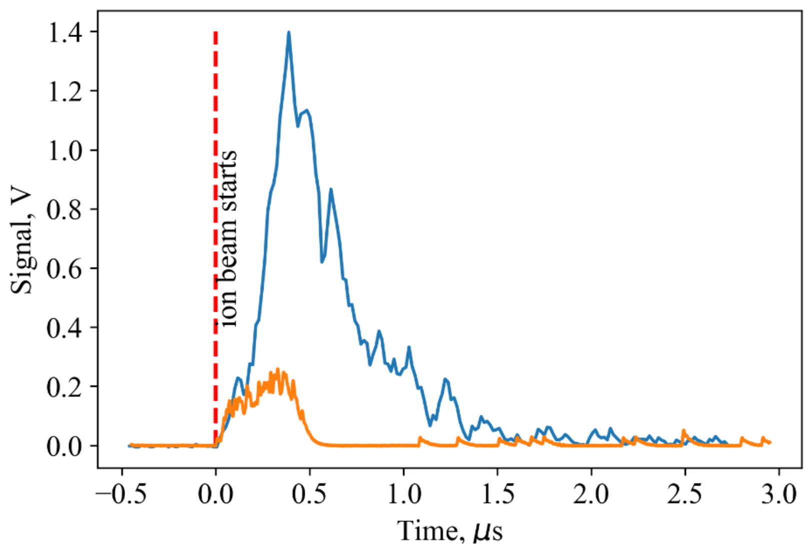

Fig. 1. Experimental signals for the argon (blue) and aluminum (orange) luminescence.

During the experiments, the chamber was vacuumed and then filled with argon with a purity of 99.998%. Different pressures from 50 to 600 mbar were used. The signal value increased with increasing the gas pressure but the typical shape of the signal stayed the same.

Pyrometrical signals for wavelengths 600, 700, 800, 850, 900 nm with filter widths 40, 40, 10, 10, 40 nm respectively were recorded. One should note that the sensitivity of the pyrometer is very high, there are single photon peaks visible for the aluminum luminescence signal after the main pulse.

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5. Data analysis

In Figure 1 one can see, that for argon fluorescence the duration of radiation is much longer, than for aluminum luminescence. The luminescence of the aluminum practically coincides with the duration of the ion beam, which is approximately 500 ns. The intensity of the metal luminescence is however low and only the detectors with high sensitivity can measure it, for example, Multi Pixel Photon Counters (MPPC) model C11209-110 by Hamamatsu.

On the other hand, the intensity of the argon fluorescence is much higher, making it suitable for beam diagnostic even for the low intensities of the beam. Nevertheless, one should keep in mind that the temporal shape of the signal of argon luminescence is much longer than a beam temporal shape.

6. Conclusion

A fast multi-channel pyrometer for temperature measurements of Warm Dense Matter has been successfully tested for temperature measurements in the temperature range 1000–4000 K during the experiments with heavy-ions heating at HHT experimental area of GSI.

This pyrometer can use simultaneously 5 wavelengths from 600 to 1550 nm and different types of detectors, such as photodiodes and two different types of MPPC. This allows one to measure the temperature in a broad temperature range up to a few thousand Kelvins with high temporal resolution up to nanoseconds.

It is shown, that this device can also be used for beam diagnostic, specifically the temporal shape of the beam. The pyrometer can detect non-thermal radiation from argon, which helps one to control the geometrical shape of the beam during its alignment. Precise control of the beam temporal shape can also be done by measuring the time dependences of non-thermal radiation appearing from the surface of the metal simultaneously with the beam. Both ingoing and outgoing beams can be used.

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