Laboratory investigations of Terrella

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Terrella

The expression Terrella comes from Latin and means "little Earth". Probably the first one, who used this term was William Gilbert for a spherical magnet in his experiments (1600) [2]. Another scientist who worked with Terrella was the Norwegian physicist Kristian Birkeland. He, based on his experiments (20th century), explained the formation of auroras on the Earth, and in his honor, currents in the Earth's atmosphere were named after him [1].

In our case, Terrella is a small spherical neodymium magnet used as a model for magnetospheres of astronomical objects (e. g. neutron stars, white dwarfs, etc...). It has a diameter of 19 mm and a maximal residual surface magnetic induction of 1.315 T. It is located in a vacuum chamber, where we set pressure between 2 Pa and 200 Pa in an argon atmosphere, and it is conductively connected to an electrical circuit, in which we can supply voltage in the order of hundreds of volts ($\approx$ 400 V). In these conditions a discharge appeares.

Depending on the polarity of the applied voltage, the discharge occurs in a given area: with a positive voltage, the discharge appears in the polar regions of the magnetic field – **positive mode**; with negative voltage, the discharge appears in the equatorial plane of the magnetic field – **negative mode**. Our measurements were focused on the negative mode, where the discharge's disk profile was studied.

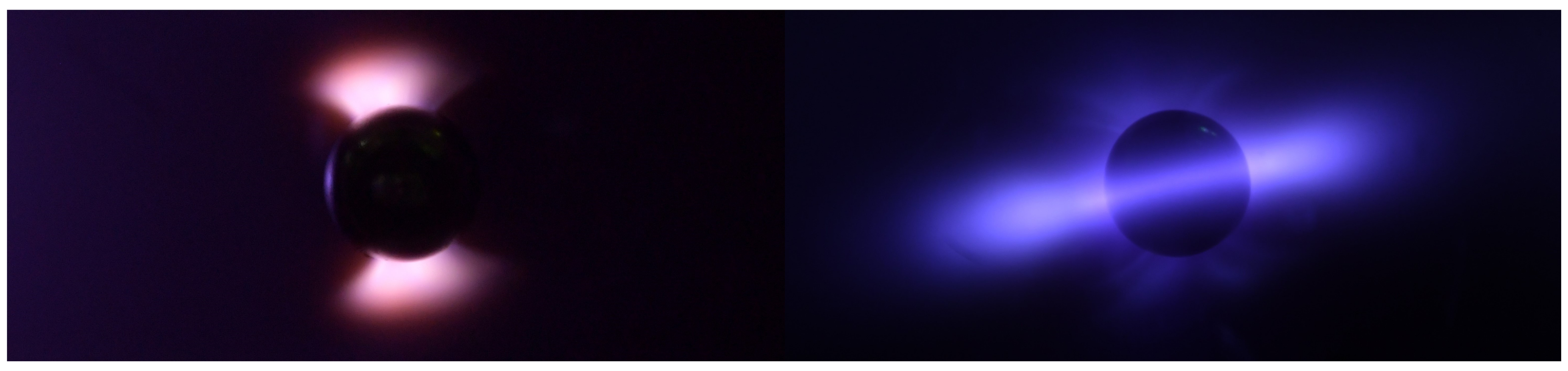

Figure 1. Left: side view in DC positive mode – the axis of the magnetic field passes through these polar regions – ISO: 1000, Exposure time: 5.0 s. Right: AC mode from the side, the axis of the magnetic field is perpendicular to the visible disc – ISO: 320, Exposure time: 5.0 s.

Optical emission spectroscopy measuring

Profile of the discharge in argon atmosphere was studied in optical emission spectroscopy (OES) with a spectrograph Andor-SR 750-B2-R. The pressure was set to 9 Pa and the exposure time to 60 s.

In Fig. 2, the argon spectral overview is shown (focused on strong Ar lines). Spectral lines were scanned in dependence on the distance from the center of the magnet (red circles in Fig. 3, left). For spectral lines in green was the radial dependence determined (see Fig. 3, right) and line ratios between them were established. Measurement has also shown that each argon line's intensity depends on time (linearly).

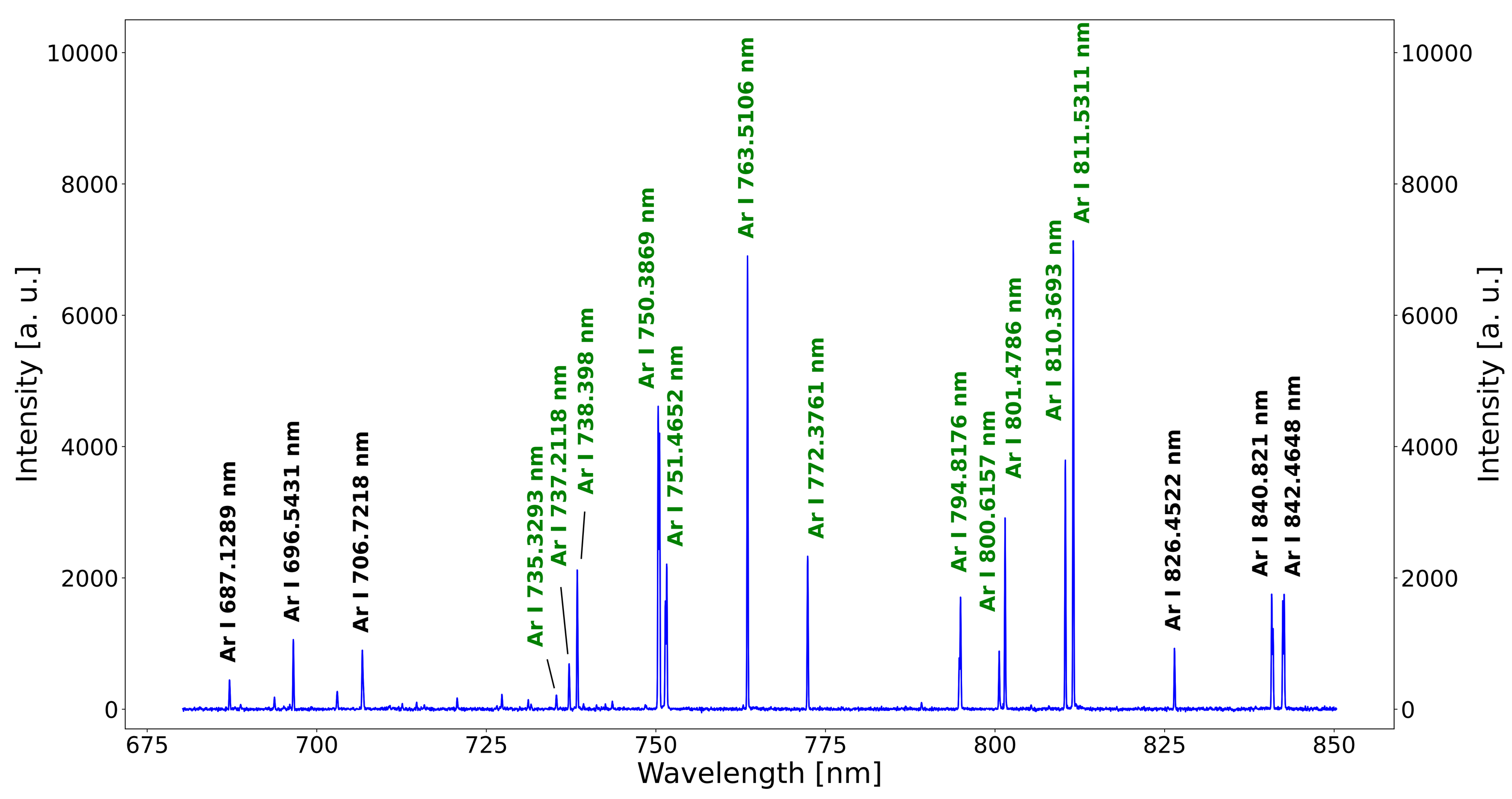

Figure 2. Argon spectral overview in the negative mode.

ICCD imaging

The disk was also examined with ICCD (Intensified Charged Coupled Device) camera PIMAX 3 (Princeton Intruments). With this camera were taken 3 frames of Terrella from the top at different pressures (2.1–200 Pa), and after removing the dark signal and averaging frames the average intensity in the area was calculated between angles $-10\,^{\circ}$ and $10\,^{\circ}$ with a step of Δr = 10 px.

This average intensity was plotted in dependence on the distance, where **15 px** corresponded to **1 mm** (size of each image was 1024 $\times$ 1024 px). The resulting graph is shown in Fig. 4, left.

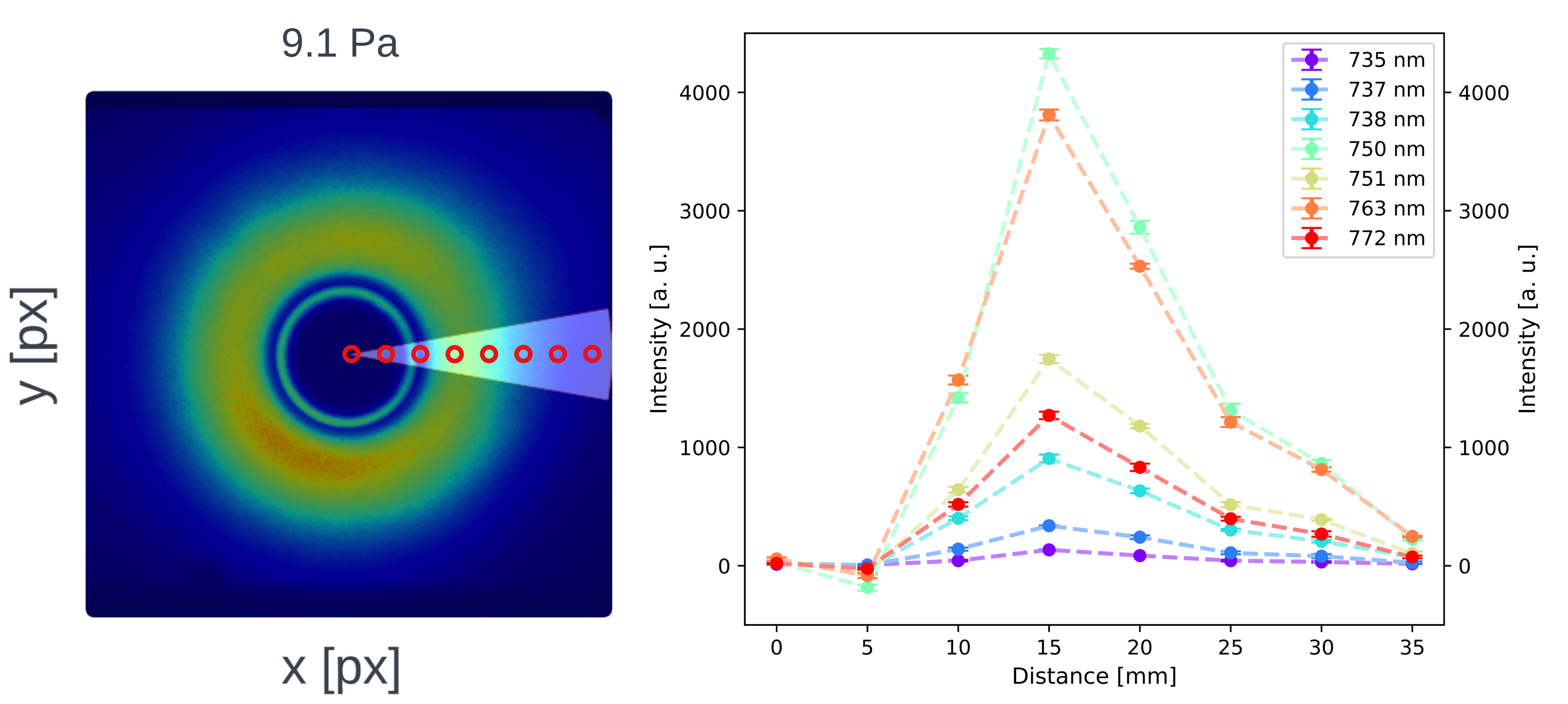

Figure 3. Left: Frame of Terrella in negative mode from the top under 9.1 Pa. Right: Radial dependence of intensities of selected argon spectral lines.

In Fig. 3, left, can be seen an example of one frame taken with ICCD in 9.1 Pa, where the brighter area was scanned. The red circles are points, where the intensity was measured with a spectrograph.

A common function that fits astrophysical disc profiles is the power-law function. Thus, the dependence of average intensity (surface brightness) measured with ICCD was also fitted to a distance of $1.1\ r_{\mathrm{Terr.}} - 2.44\ r_{\mathrm{Terr.}}$ from the Terrella's edge to obtain the power-law exponential coefficient of the dependence.

The general power-law function looks like this:

$$I(r) = k \cdot r^{-p}, \tag{1}$$

where, in our case, the p was determined. Results can be seen in Fig. 4, right and Tab. 1.

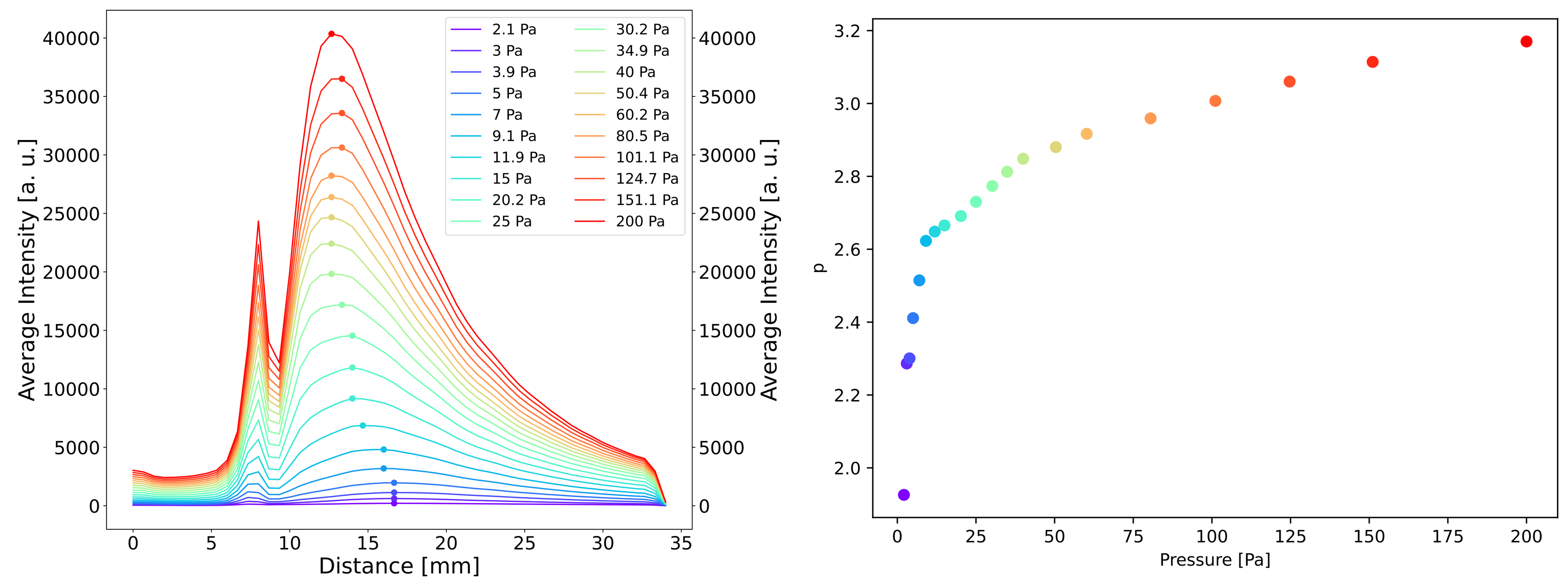

Figure 4. Left: Average intensity in dependence on the distance from the Terrella's center for each pressure, dots indicate the highest values. Right:The power-law coefficient determined in dependence on the pressure.

Pressure [Pa]	p	Pressure [Pa]	p	Pressure [Pa]	p	Pressure [Pa]	p
2.1	1.93	9.1	2.62	30.2	2.77	80.5	2.96
3.0	2.29	11.9	2.65	34.9	2.81	101.1	3.01
3.9	2.30	15.0	2.67	40.0	2.85	124.7	3.06
5.0	2.41	20.2	2.69	50.4	2.88	151.1	3.11
7.0	2.51	25.0	2.73	60.2	2.92	200.0	3.17

Table 1. Power-law fit coefficients.

The results show that in our laboratory model, the profile of the disk has a power-law index approximately between 2 and 3 (depending on the pressure).

We can now assess that our laboratory model has a similar dependence of surface brightness on the distance as it is in a broad-band spectral model AGNSLIM for a super-Eddington black hole accretion disc spectra [3]. Here, the emissivity changes from $L(r) \propto r^{-3}$ to r^{-2} when the local disc flux exceeds the Eddington limit.

Line ratios between spectral lines from OES and ICCD

To compare the radial profile of intensities from spectrograph and ICCD was the instrumental function of the entire optical system (including the optical fiber) established – see Fig. 5, left. The resulting function was used as a convolution kernel (mask) in the radial profile from the ICCD image (Fig. 3, left). This made it possible to determine the ratios of the line intensities from the spectrograph and ICCD.

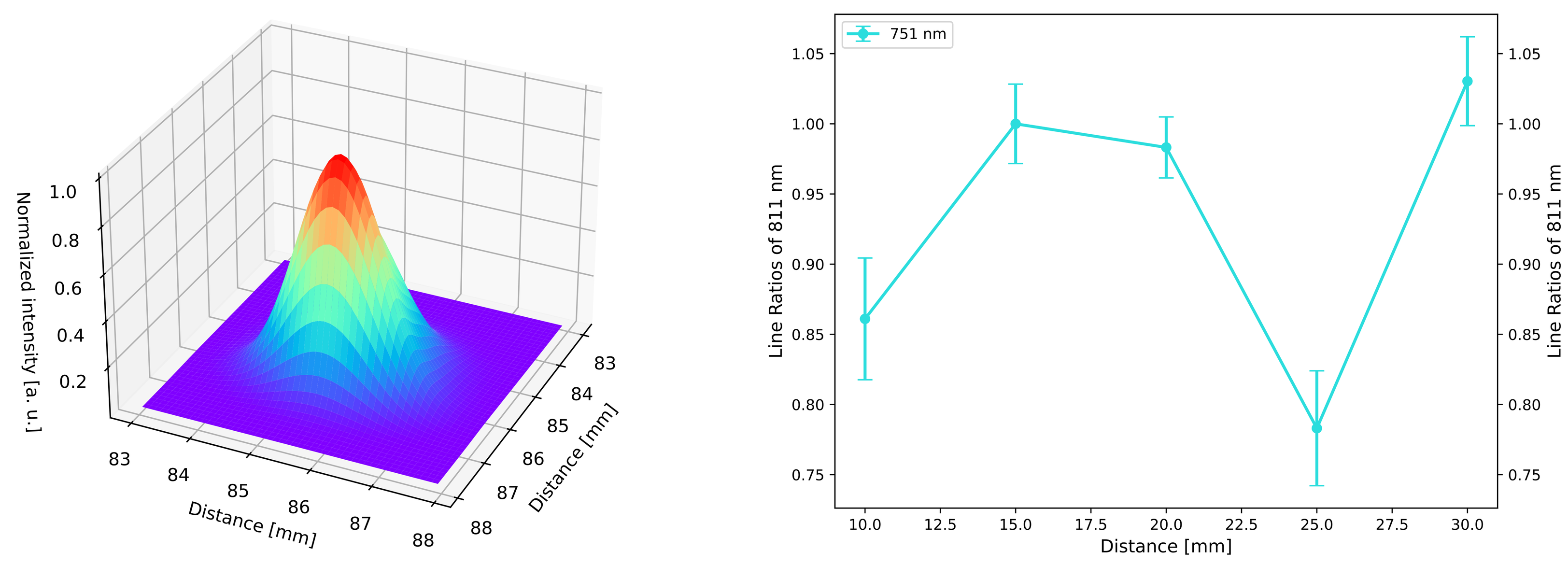

Figure 5. Left: Measured instrumental function. Right: Line ratio between intensity from 751 nm and intensity from ICCD in dependence on the distance.

Comparison of the line ratios calculated between intensities from ICCD and intensities from OES showed that there is an anomaly in the area of 25 mm from the Terrella's center (ICCD camera detects wavelengths in a continuous region). This could mean that the discharge characteristics change in some way with distance (there may be some emitted radiation that we did not detect with the spectrograph).

The discharge characteristics in the negative mode were also examined in time, results can be seen below:

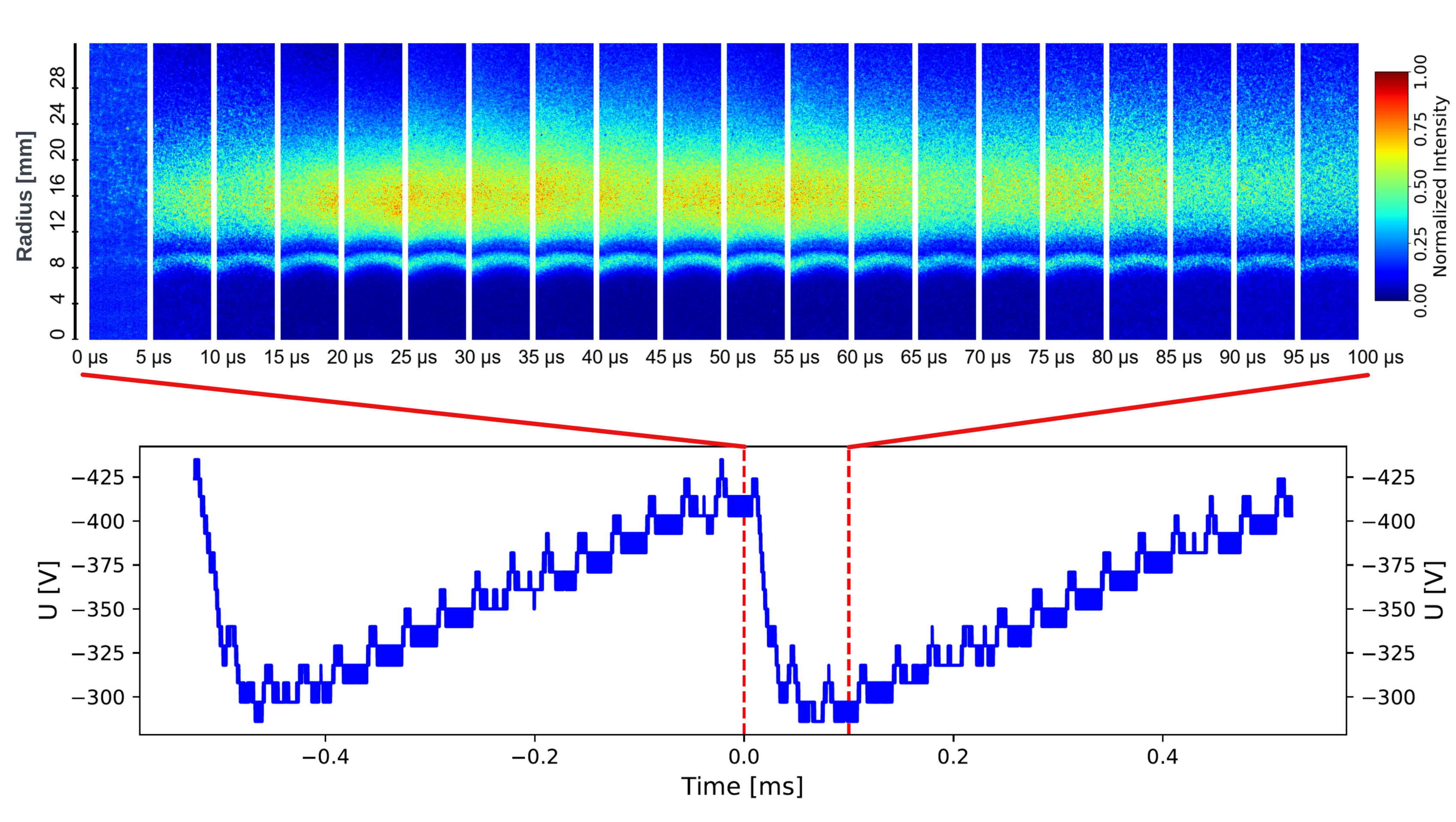

Figure 6. Upper image: Time synchronized ICCD imaging. Lower image: Evolution of the discharge voltage in time.

References

This research has been supported by Project LM2023039 funded by the Ministry of Education, Youth and Sports of the Czech Republic.

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