Modelling of laser triggered hollow electrode capillary discharge as a coherent EUV source at 13.38 nm wavelength

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Abstract

The soft X-ray laser may be considered as an alternative EUV actinic metrology source with much lower emission power than a conventional incoherent source due to much higher spectral contrast. One of appropriate medium for such lasing is a capillary discharge-produced plasma of nitrogen with collisional recombination pumped 3p-2s, 3s-2p, 3d-2p transitions in H-like ions, emitting at 13.38nm wavelength.

We have chosen the modelling configuration corresponding to an experimental setup with nitrogen filled alumina capillary of 100mm long with pulsed power supply providing the electric current of 60kA amplitude with 30ns rise time. The electrodes made of CuW composite have technological holes along the axis. These holes are required for radiation passage and diagnostics as well as for discharge triggering using hollow cathode effect. To make a discharge channel and pinching more compact (to reduce a contact of hot plasma with capillary wall and its ablation) and more straight (for lasing guiding expected) a picosecond 6mJ Nd:YAG laser beam may be applied along the axis at discharge triggering.

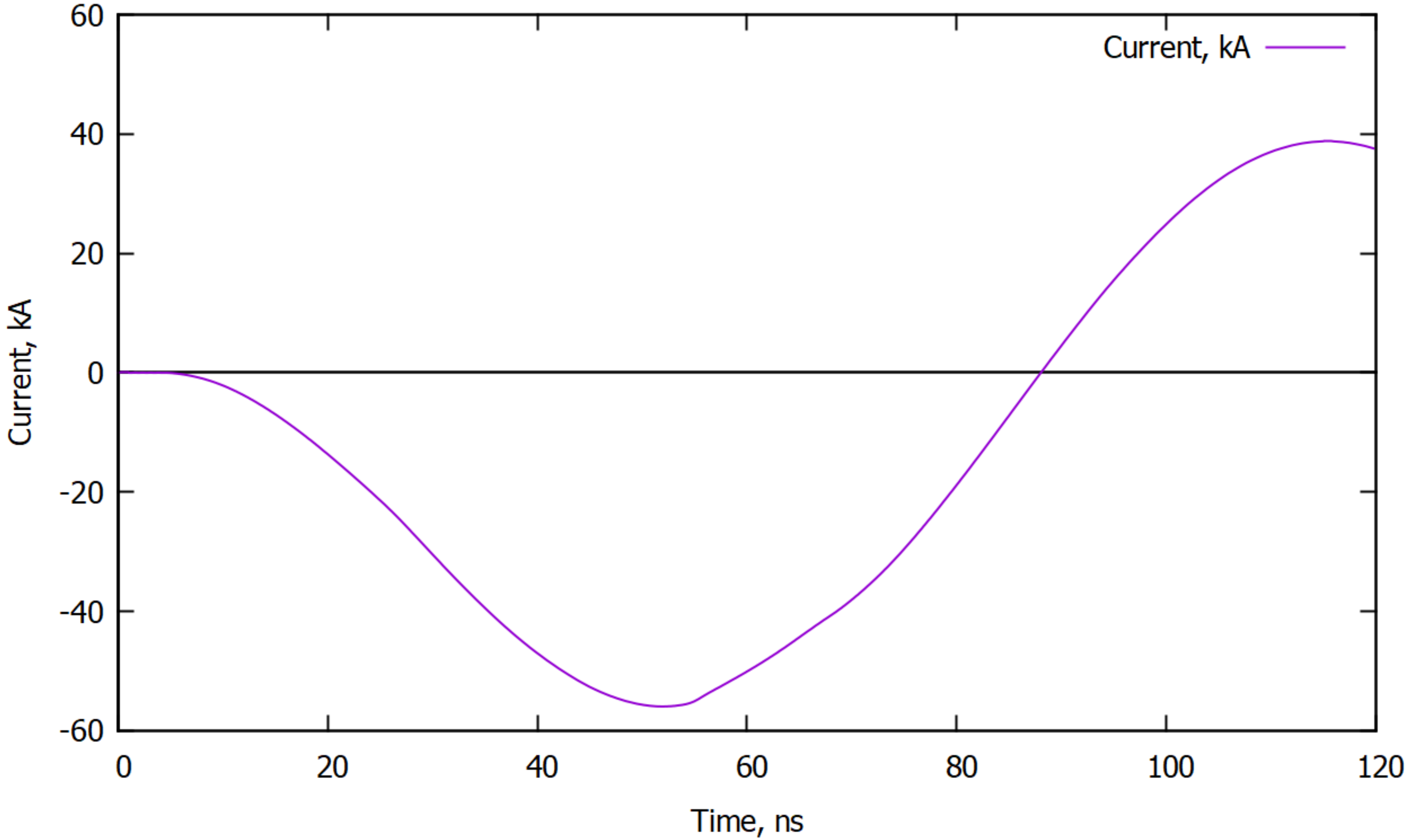
To explore the physical effects, discharge dynamics and to obtain plasma parameters as well as to optimize the experimental setup, the radiation-magneto hydrodynamic code Z* is used. The estimation of possible inversion in nitrogen ion level population in non-equilibrium transient discharge plasma is post processed by means of the atomic code Fly/Flychk.

When pulsed power circuit is switched-on and pulse voltage is applied to electrodes with nitrogen filled capillary between them, the discharge is triggered due to hollow cathode effect as a spark along the axis of the capillary, a tight ionized channel forms. If the laser triggering was applied to preheat the gas, the channel is tighter and its ionization degree is higher.

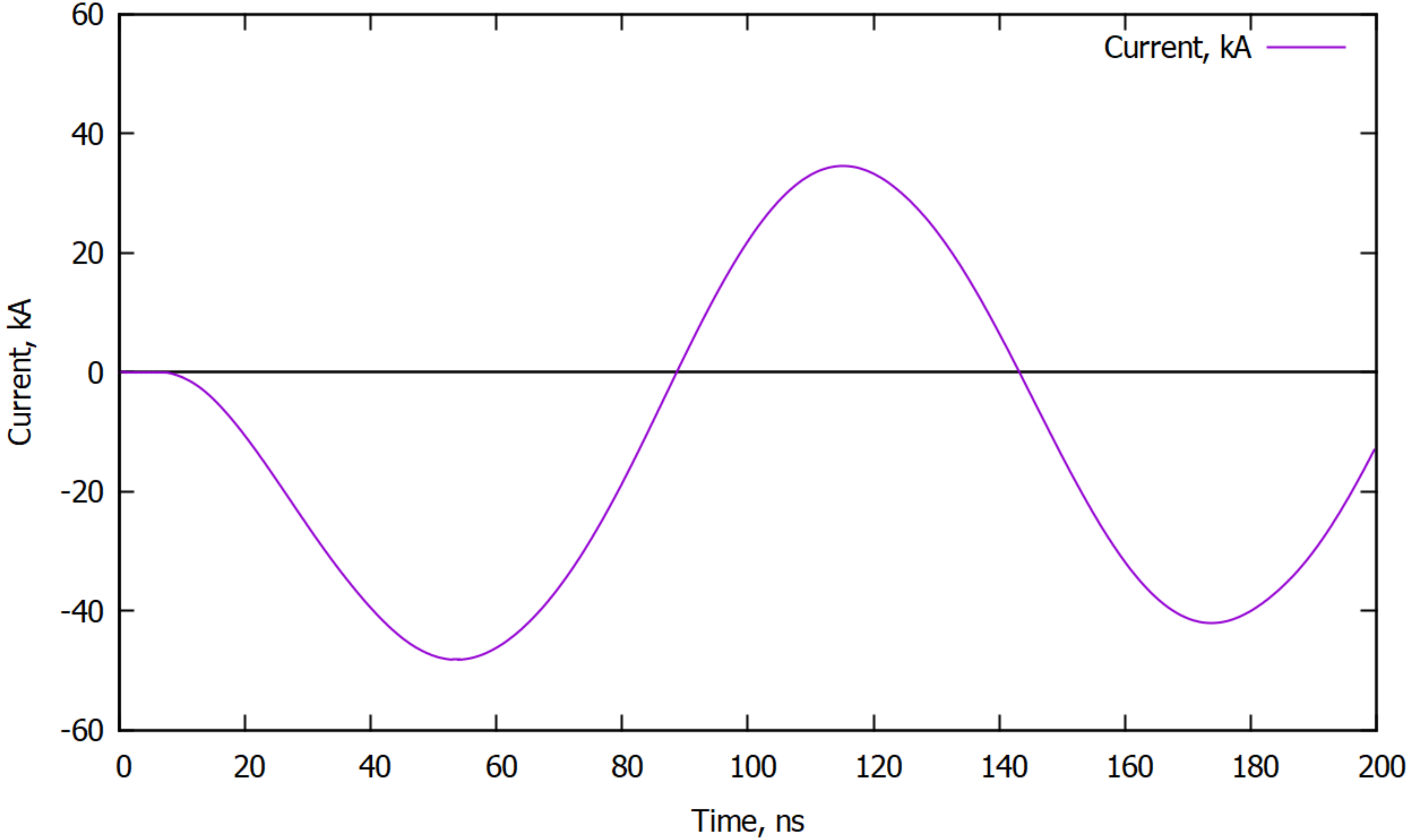
With discharge current rise, the plasma in the channel is heated up through joule dissipation, its pressure increase and the plasma expends. When plasma is heated up over tens electron-volts of temperature, it radiates intensely and ionizes the rest gas in the capillary. The rising current is intercepted by this surrounding plasma and mainly by the plasma near the inner capillary wall.

The plasma continues to be heated up through joule dissipation in whole volume. If the initial gas density is low enough the Ampere's force $j \times B$ overcomes the thermal pressure and pinching starts volumetrically. At some time-moment, around the current maximum (depending on initial gas pressure) the first pinching forms. During pinching, due to plasma compression by magnetic and inertial forces mainly the plasma electron temperature reaches a sharp maximum of 140-150eV (depending on initial gas pressure) near the capillary axis. If the laser triggering was applied the maximum electron temperature is higher by ~20eV. In the pinch, the nitrogen is ionized until NVI-NVIII. The plasma in the pinch is slightly inhomogeneous along the axis (z-direction). That pinching configuration exist during ~7ns, then plasma expands and is cooling down till ~70eV of temperature during 17-21ns. The plasma recombines, during this recombination the inversion between energy levels n=3 and n=2 of H-like nitrogen may appear. The recombining plasma radiates through photorecombination, in lines and through bremsstrahlung, it loses of 4-5J, significant part of its energy. Current decreases, but the Ampere's force overcomes the thermal pressure again, and in ~27ns after the first pinching the second pinch appears with lower temperature of 90-100eV. The decay of the second pinch to ~50eV of temperature takes place during ~17-23ns. The transient plasma recombines during all this time between pinches and after them, and under certain conditions the inversion between energy levels n=3 and n=2 of H-like nitrogen may be obtained.

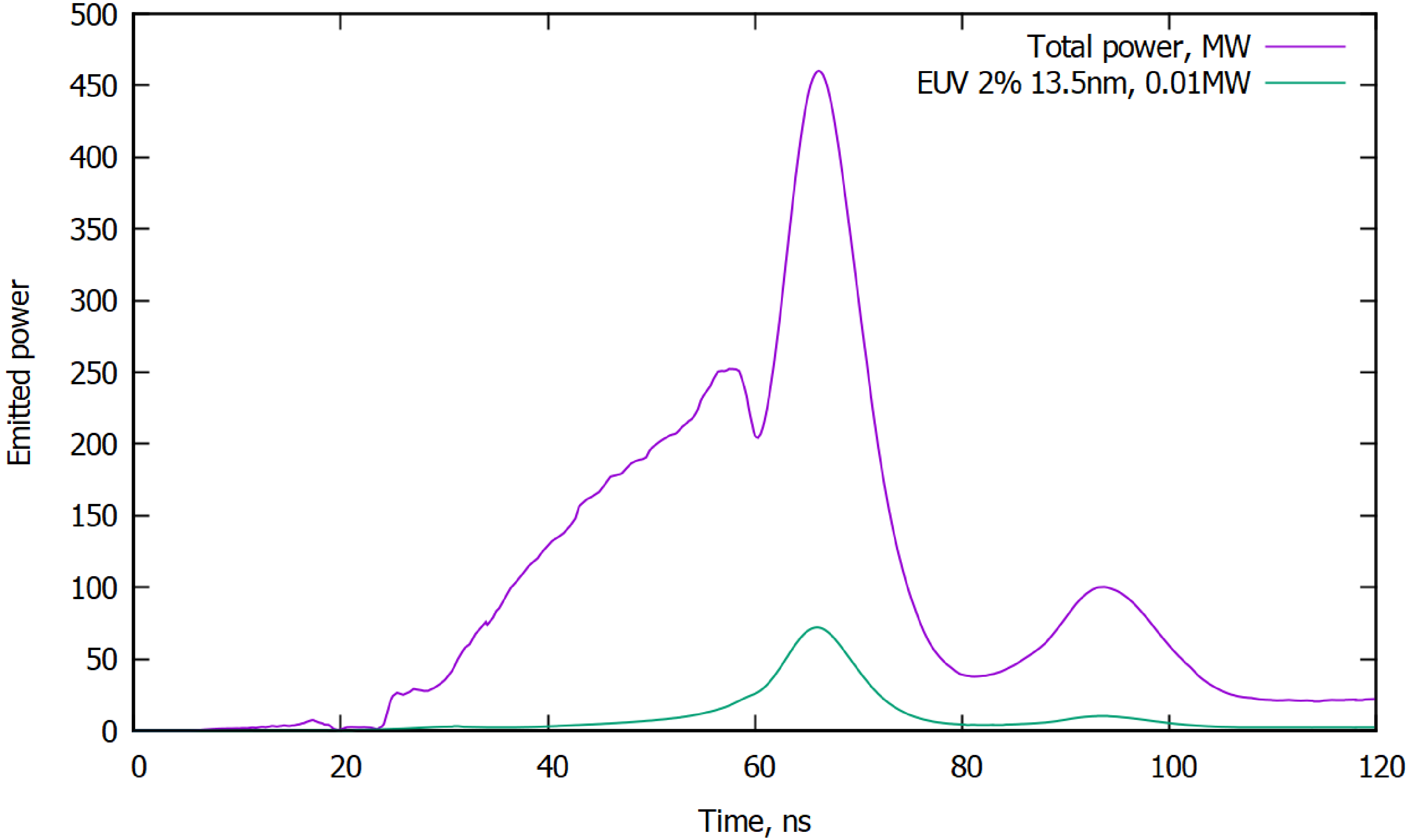
Capillary ∅ 3.2mm with N2 initial pressure of 5mbar discharge current



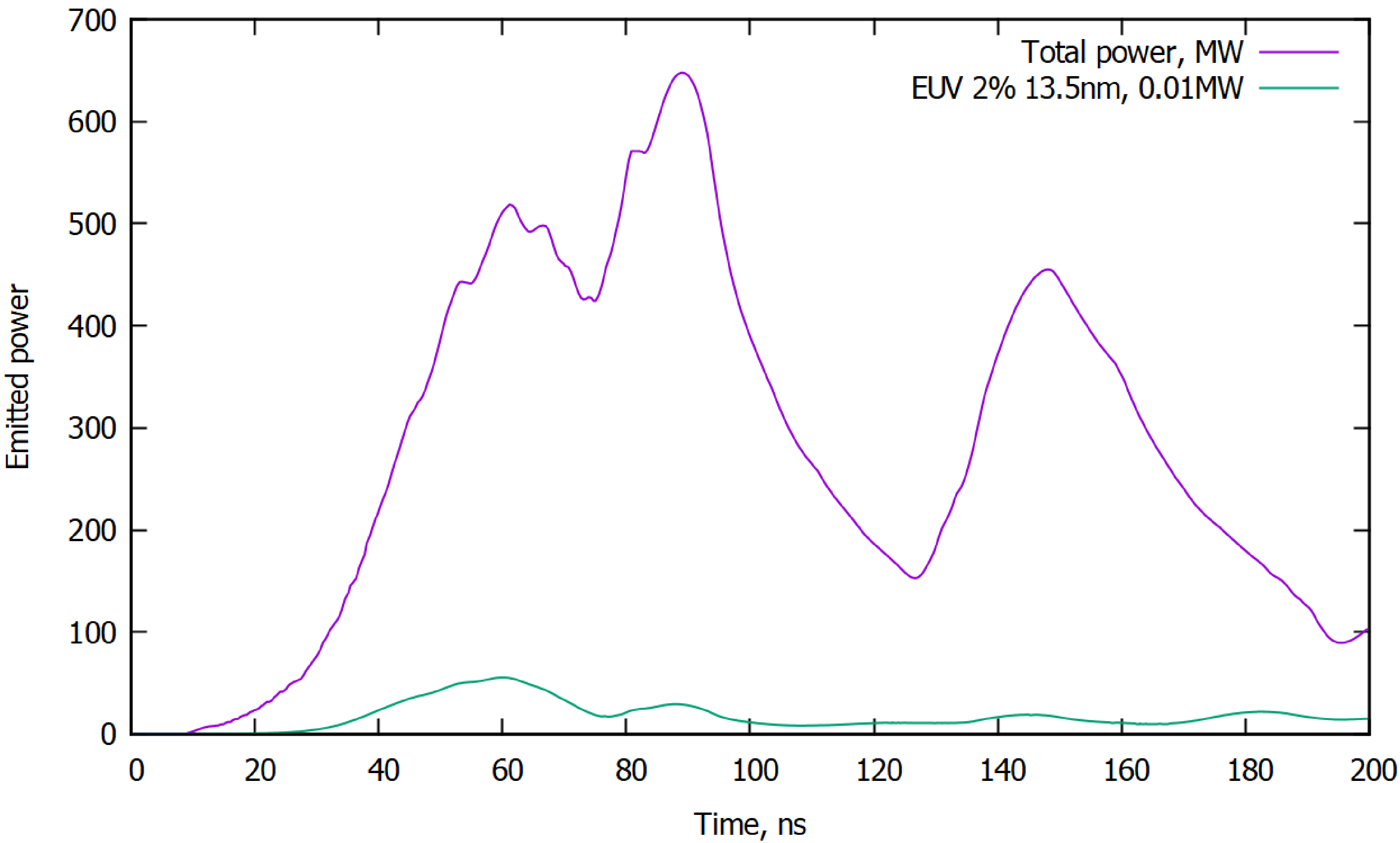
Capillary ∅ 2mm (r=1mm) with N2 initial pressure of 20 mbar discharge current



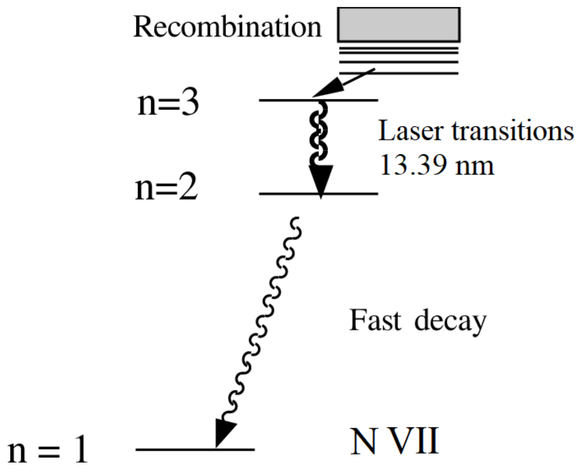
Capillary ∅ 3.2mm with N2 initial pressure of 5mbar emission from the discharge in full spectrum and in band



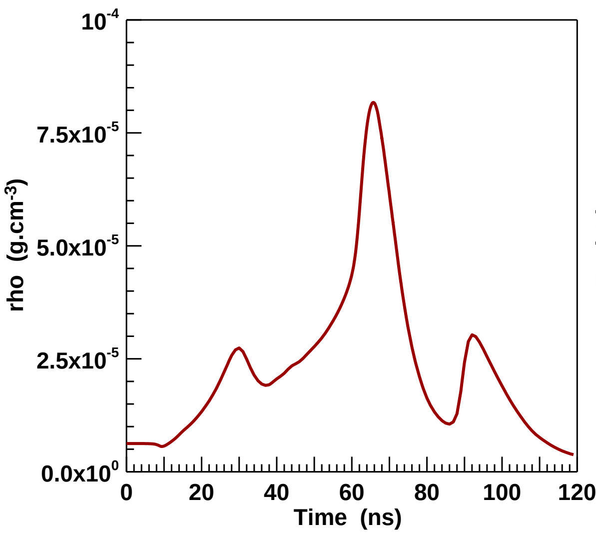
Capillary ∅ 2mm (r=1mm) with N2 initial pressure of 20 mbar emission from the discharge in full spectrum and in band

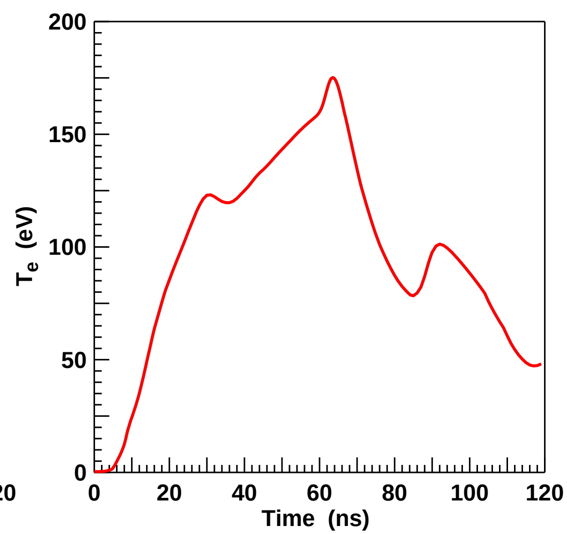


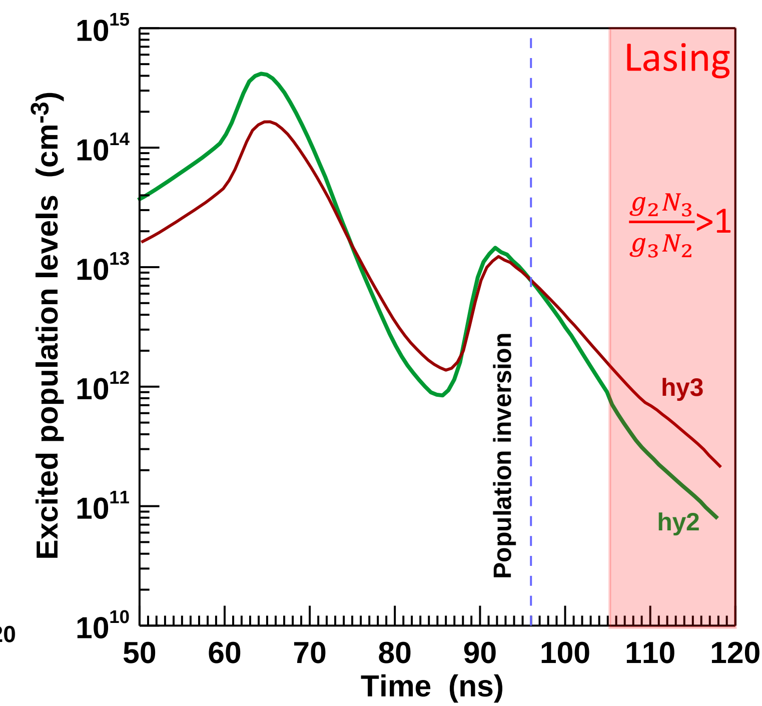
Capillary ∅ 3.2mm with N2 initial pressure of 5mbar lasing conditions (at central point of the discharge plasma)



$$G = c^{-1} N_2 B_{23} \left(\frac{g_2 N_3}{g_3 N_2} - 1\right)$$

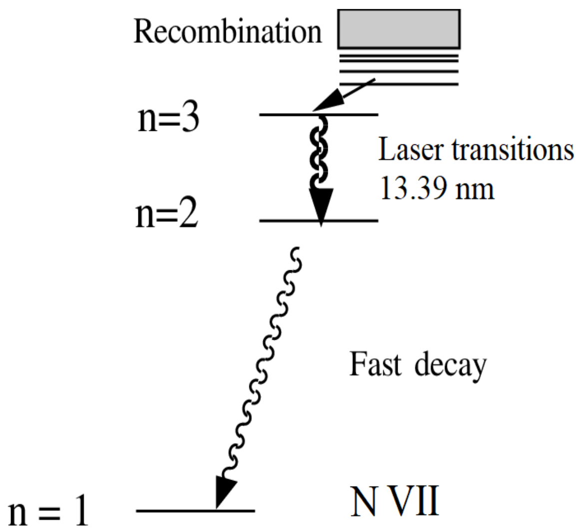


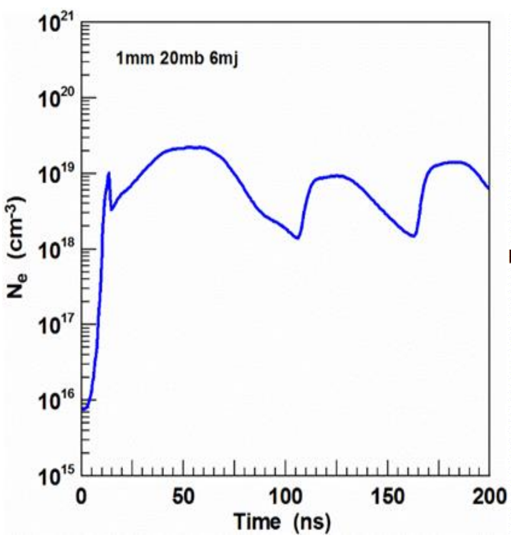


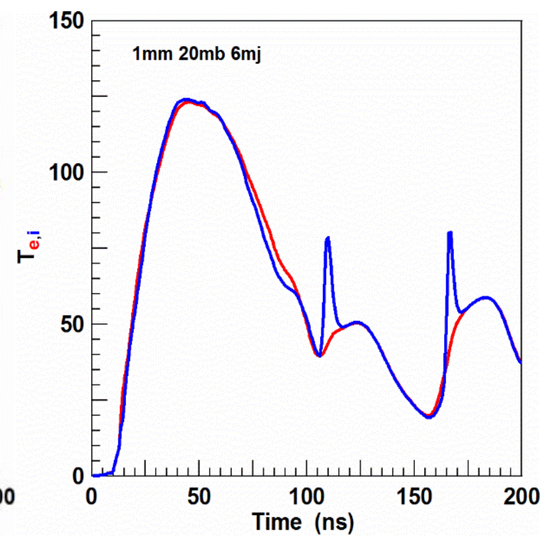


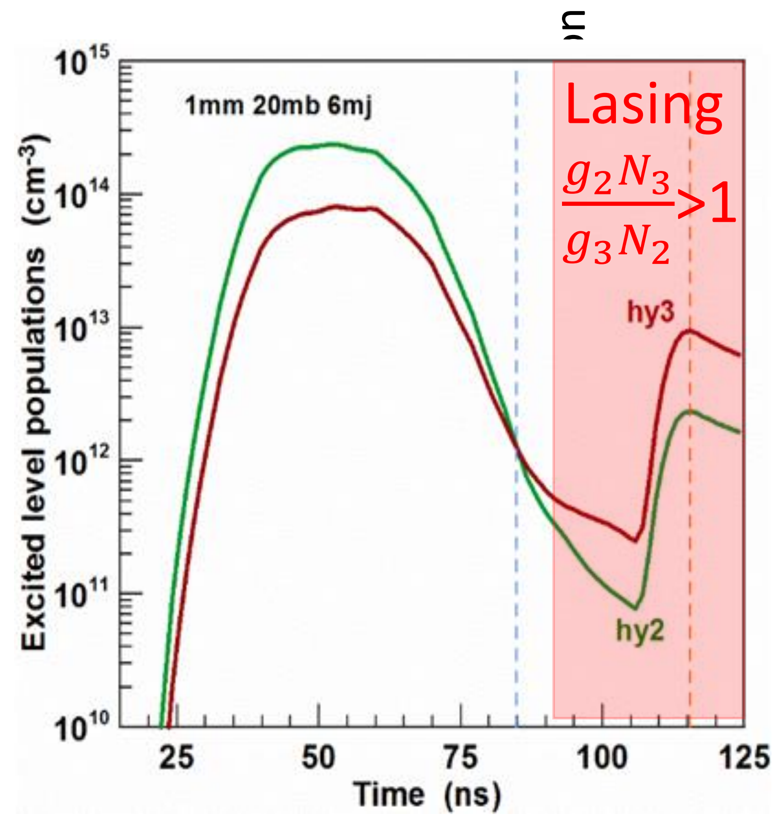
Capillary ∅ 2mm (r=1mm) with N2 initial pressure of 20 mbar lasing conditions (at central point of the discharge plasma)

$$G = c^{-1} N_2 B_{23} \left(\frac{g_2 N_3}{g_3 N_2} - 1\right)$$

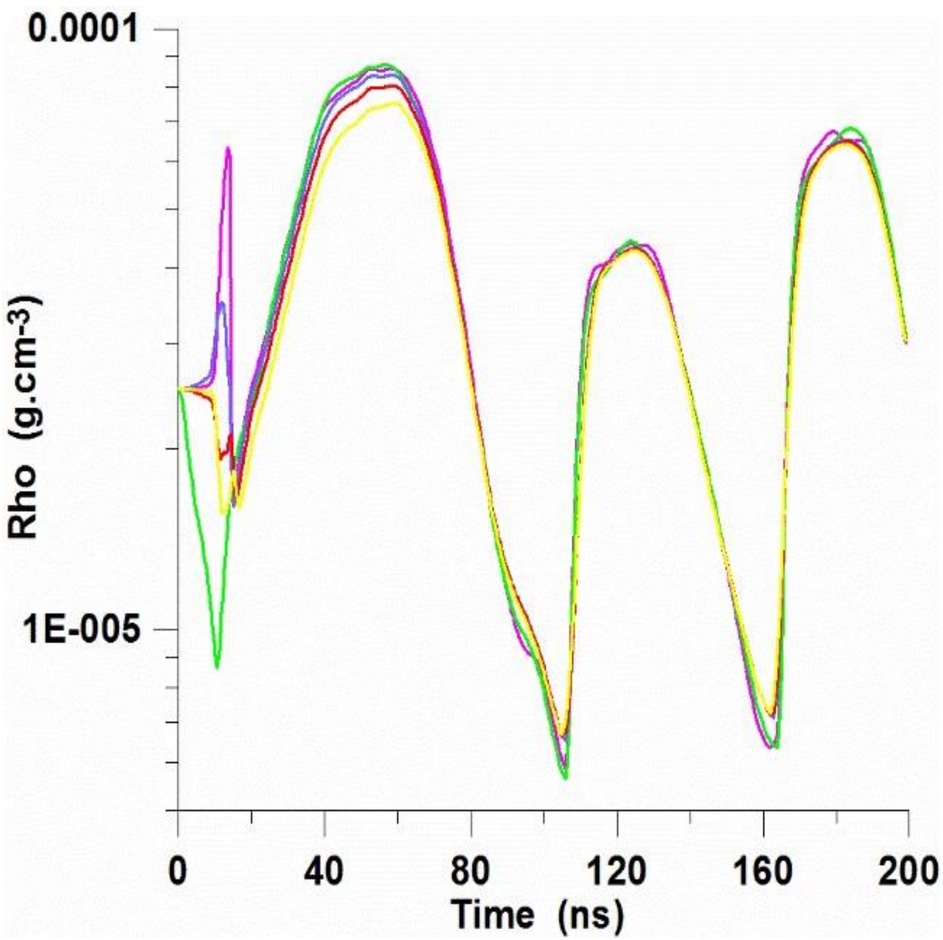


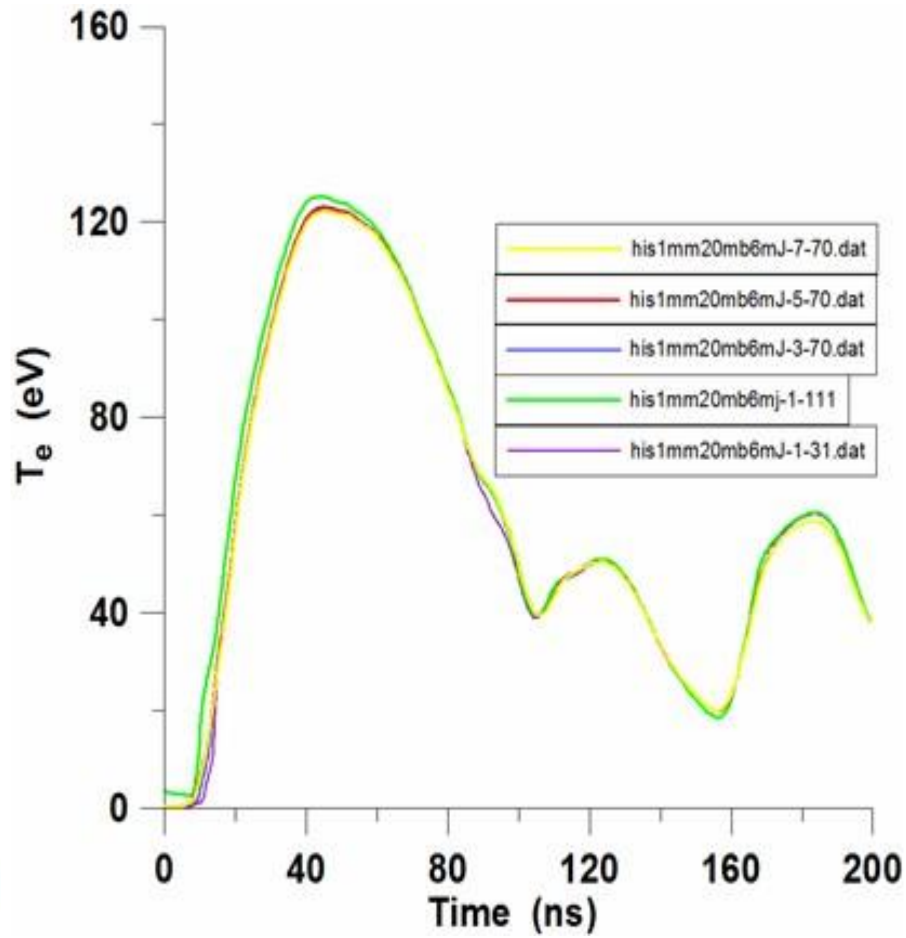






Capillary ∅ 2mm (r=1mm) with N2 initial pressure of 20 mbar data at the other points of the discharge plasma manifested the homogeneity required for lasing





Conclusion

For the given pulsed power generator parameters, various coupling of capillary with forming line and capillary dimensions with corresponding initial gas pressures (to obtain an effective electric energy transfer to the discharge) were examined. In capillary of 5mm diameter and 0.5-1mb gas pressure, the inversion between energy levels n=3 and n=2 was not obtained. In capillary of 3.2mm diameter and 4-5mb gas pressure, the inversion was obtained, but the lasing gain was not high enough to be observed. In capillary of 2mm diameter and 20-30mb gas pressure, the second pinching is relatively week, nevertheless the inversion of energy levels n=3-2 and H-like ions fraction estimated are high enough to probably obtain a bright laser burst at 13.38nm wavelength from plasma column of 100mm long.

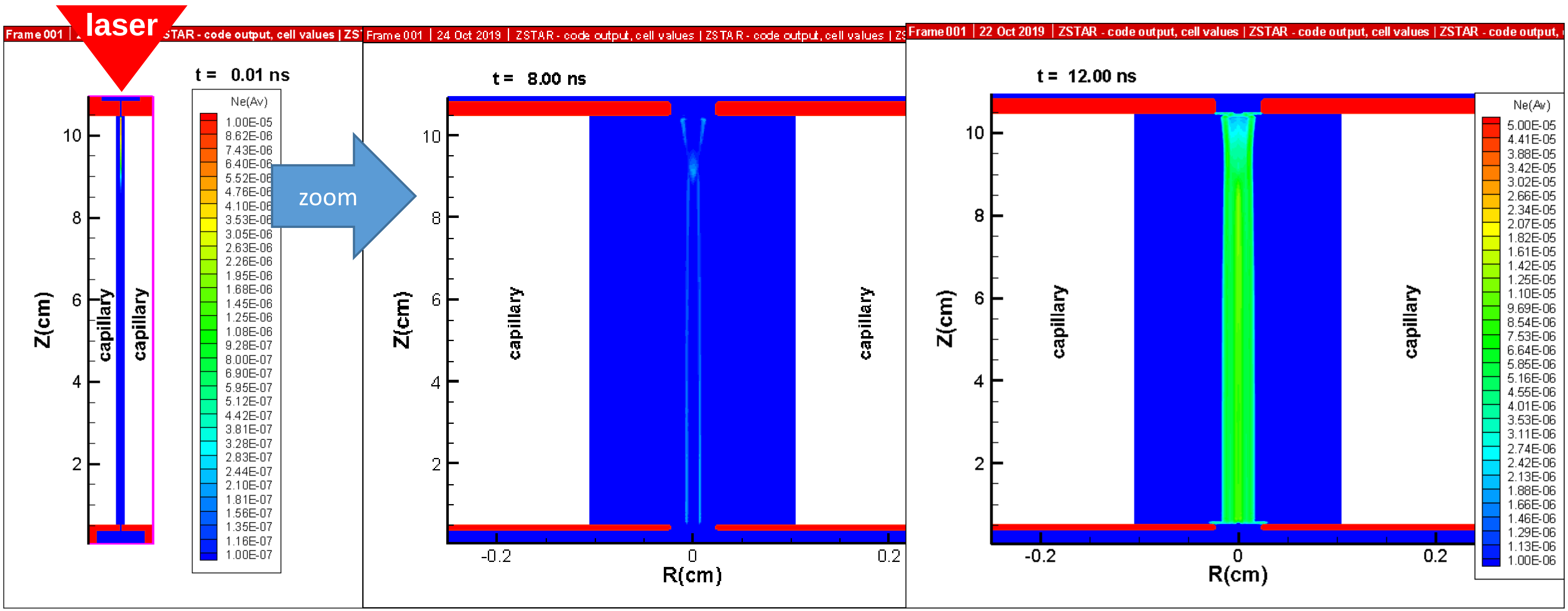
Acknowledgement

This work was supported by the grants of Ministry of Education Youth and Sports of Czech Republic (MEYS CR) in the frame of the program *INTER Excellence* on the Project No. *LTT17015,* on the Project CTU Mobility No. CZ.02.2.69/0.0/0.0/16_027/0008465 and Centre of Advanced Applied Sciences, CAAS No. CZ.02.1.01/0.0/0.0/16_019/0000778 from the ERDF.

Reference

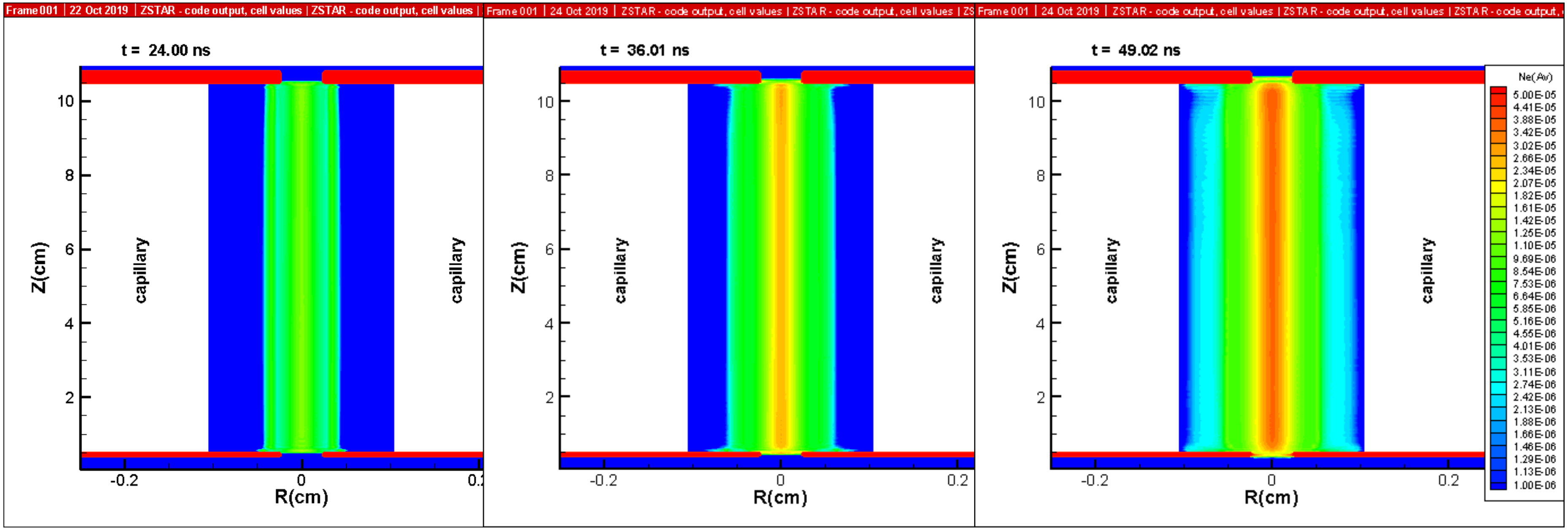
[1] Nevrkla M. et al.: Time-resolved EUV spectra from nitrogen Z-pinching capillary discharge, Proceedings of SPIE, Vol. 9510 (2015) 951013

Capillary ∅ 2mm with N2 initial pressure of 20mbar electron density dynamics at phase of triggering and plasma channel formation



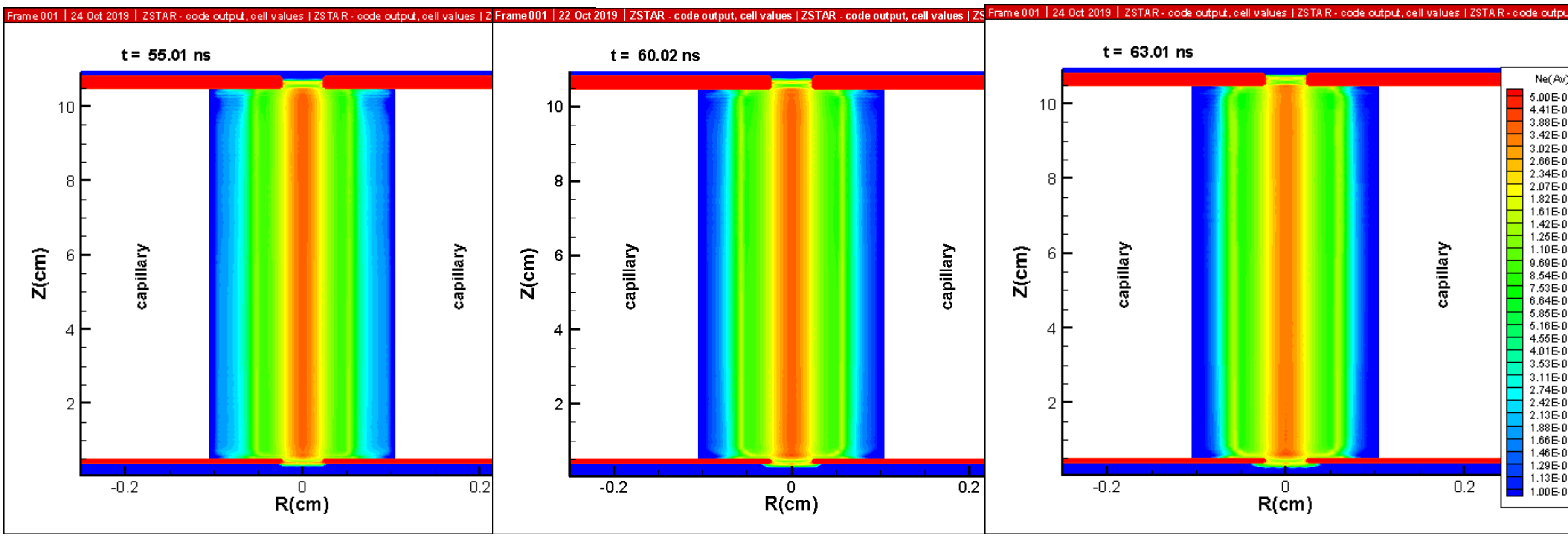
Due to hollow electrodes the electric field is concentrated around the axis. The plasma initiated by laser beam produces an ionization wave along the electric field and triggers the discharge forming a plasma channel around the axis.

Capillary ∅ 2mm with N2 initial pressure of 20mbar electron density dynamics at phase of dissipative heating of the channel and irradiation the surrounding gas



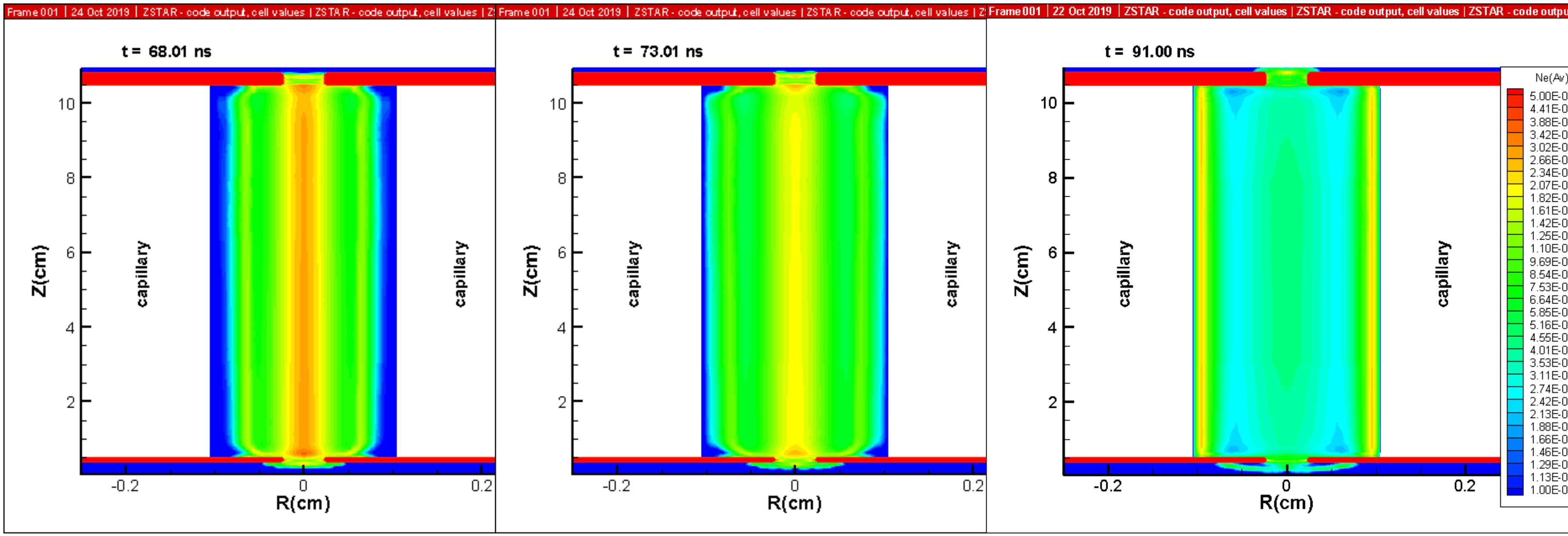
The plasma in the channel is heated up by joule dissipation of the discharge current, expands and emits in VUV range. The radiation is absorbed by sur-rounding neutral gas and ionizes it. The rising discharge current is intercepted and redistributed by the whole volume of the gas. The plasma continues to be heated.

Capillary ∅ 2mm with N2 initial pressure of 20mbar electron density dynamics at first pinching phase



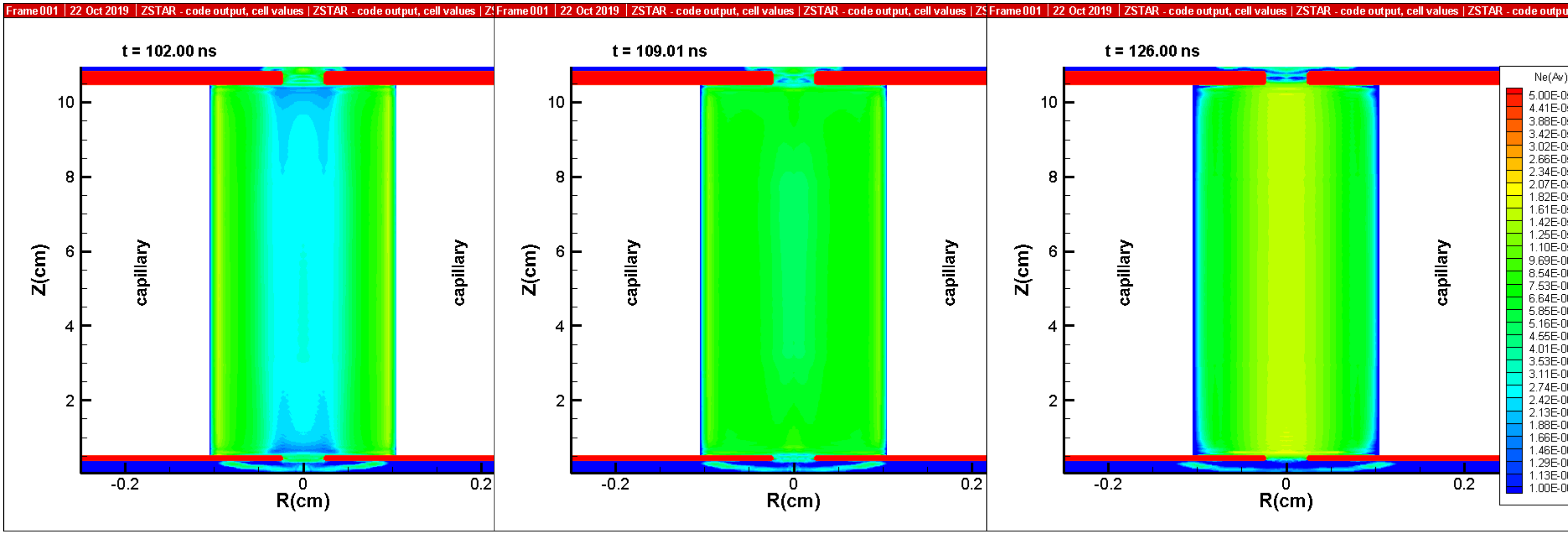
Because of redistribution and diffusion of the magnetic field the plasma is compressed by Ampere's force volumetrically (shockless). The hot plasma in the pinch radiates intensely.

Capillary ∅ 2mm with N2 initial pressure of 20mbar electron density dynamics at relief phase and plasma expansion after pinching



After pinching, the magnetic field decreases, the discharge plasma expands up to strike the capillary wall. The plasma cools down due to expansion and emission, and recombines.

Capillary ∅ 2mm with N2 initial pressure of 20mbar electron density dynamics at 2nd pinching phase



Capillary ∅ 2mm with N2 initial pressure of 20mbar electron density dynamics at 3rd pinching phase