Distributed ferromagnetic enhanced inductively coupled plasma for large-scale plasma processing

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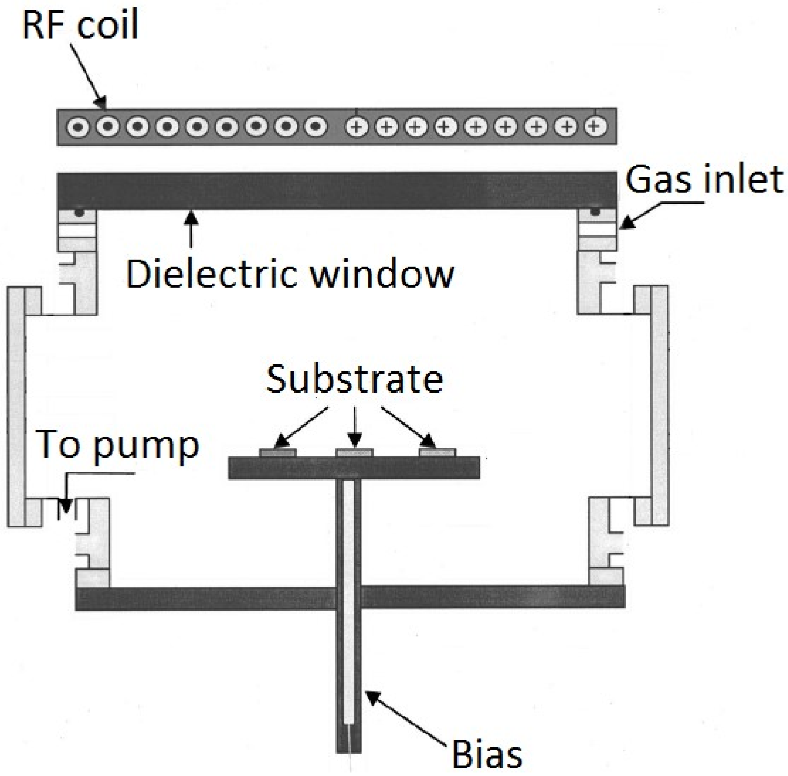

Fig. 1. Radio-frequency (~10 MHz) inductively coupled plasma (RF ICP) source for plasma processing.

Limitations of the RF ICP sources:

- Weak magnetic coupling between the ICP coil and plasma, high leakage inductance of the ICP coil L_s

- High coil reactance $\omega L_s >> R$, low power factor of the ICP coil $\cos \varphi < 1$

- A resonant-matching network is required to compensate the coil reactance and improve the power transfer efficiency, leading to high current and high voltage in the coil

- At high driving frequencies (~10 MHz) a capacitive coupling exists between the ICP coil and plasma. The high coil voltage affects plasma through the capacitive coupling. As the coil voltage is increasing with the coil size, this undesirable effect becomes a growing problem for large-scale plasma systems.

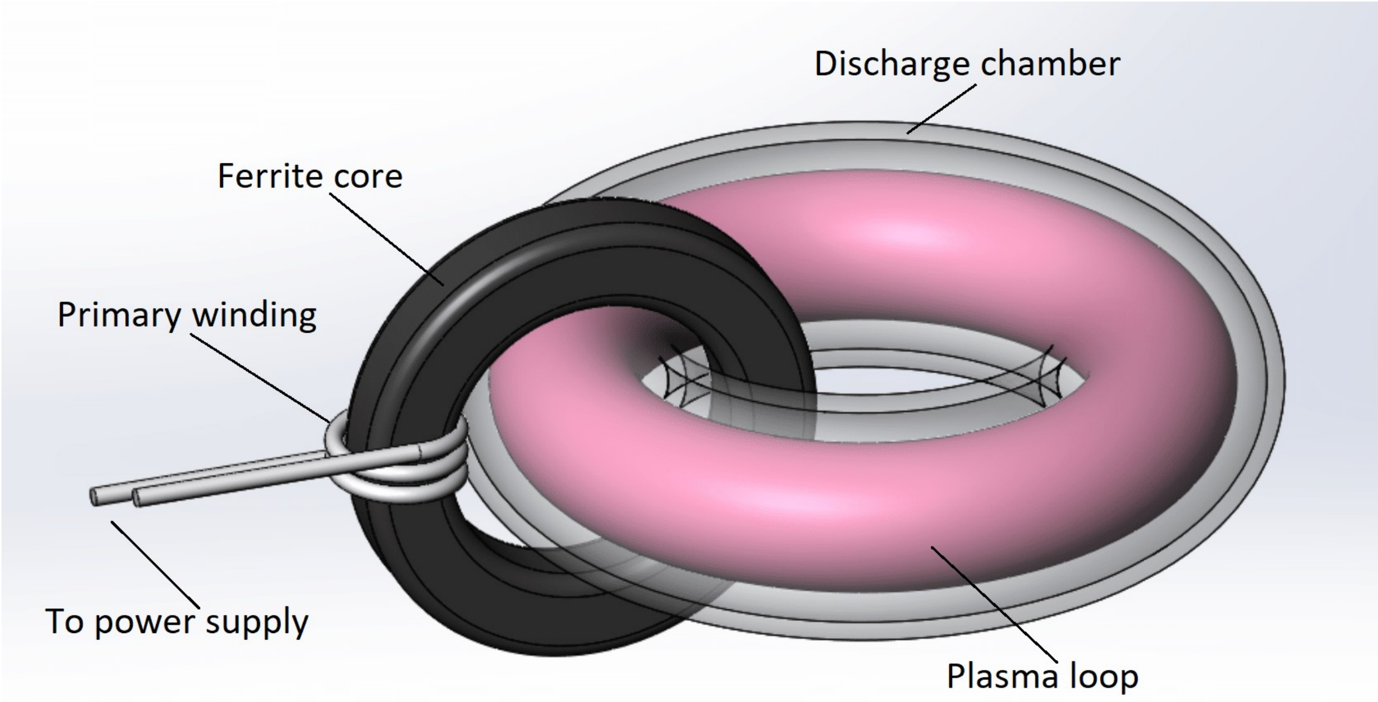

Fig.2. Ferromagnetic enhanced inductive discharge.

Advantages of the ferromagnetic enhanced ICP sources:

- High magnetic coupling between the ICP coil and plasma, low leakage inductance of the ICP coil L_s and coil reactance $\omega L_s << R$, high power factor of the ICP coil cos $\varphi \approx 1$

- High magnetic flux density in the core ~0.1 T, low driving frequency ~100 kHz

- Due to a low frequency, the capacitive coupling between the coil and plasma is eliminated

- New devices for large-scale plasma processing can be developed on the basis of the low-frequency ferromagnetic enhanced ICP sources*.

* V. Godyak, “Ferromagnetic enhanced inductive plasma sources,” J. Phys. D: Appl. Phys., vol. 46, pp. 283001 (1-23), June 2013.

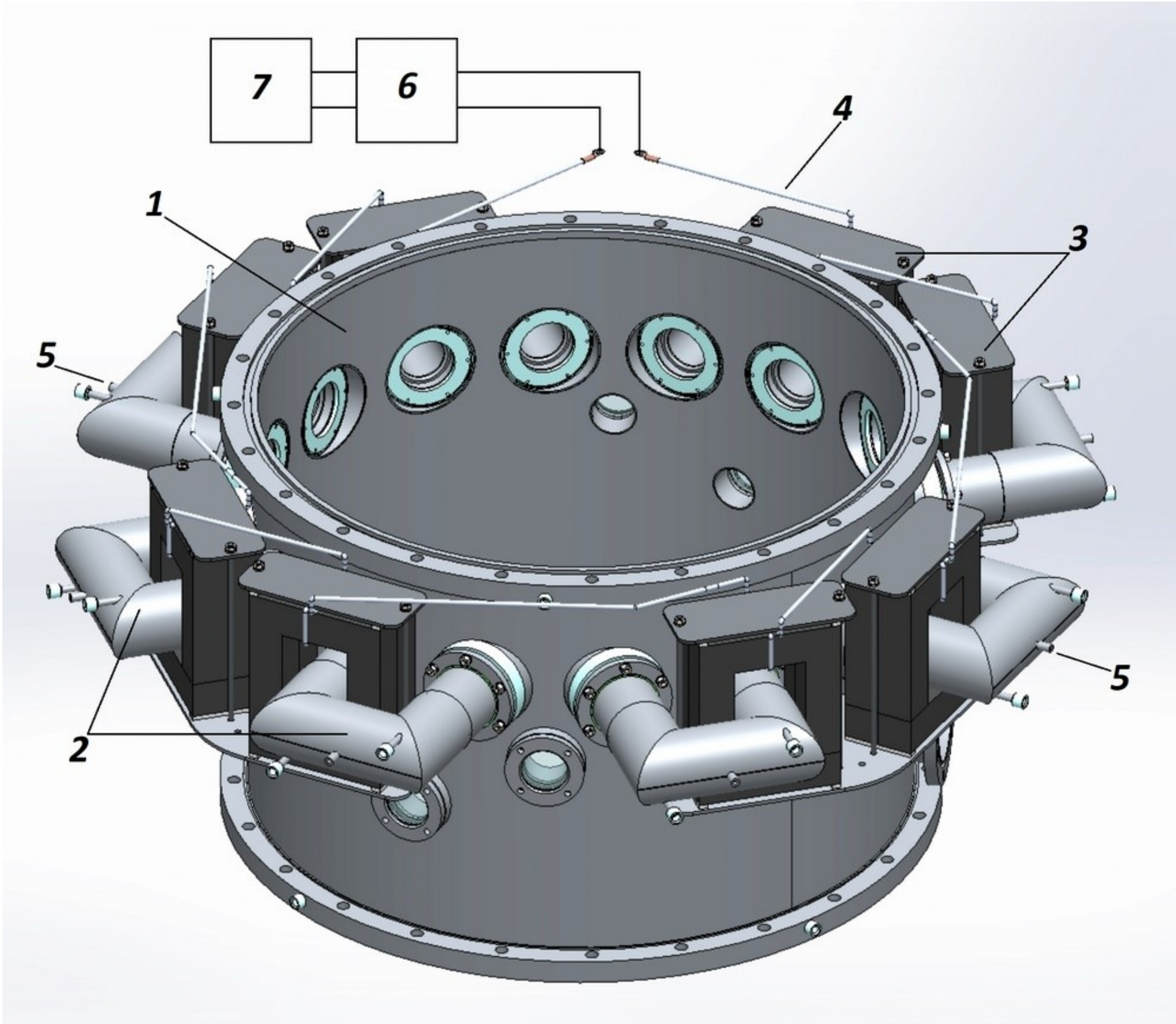

Fig. 3. Distributed ferromagnetic enhanced ICP (without the top flange).

1 – Vacuum chamber (*D*=700 mm, *H*=500 mm), 2 – U-shaped discharge tubes (*D*=50 mm), 3 – ferrite cores, 4 – primary winding, 5 – gas inlets, 6 – matching network, 7 – 100 kHz, 500 V, 40 kVA power supply.

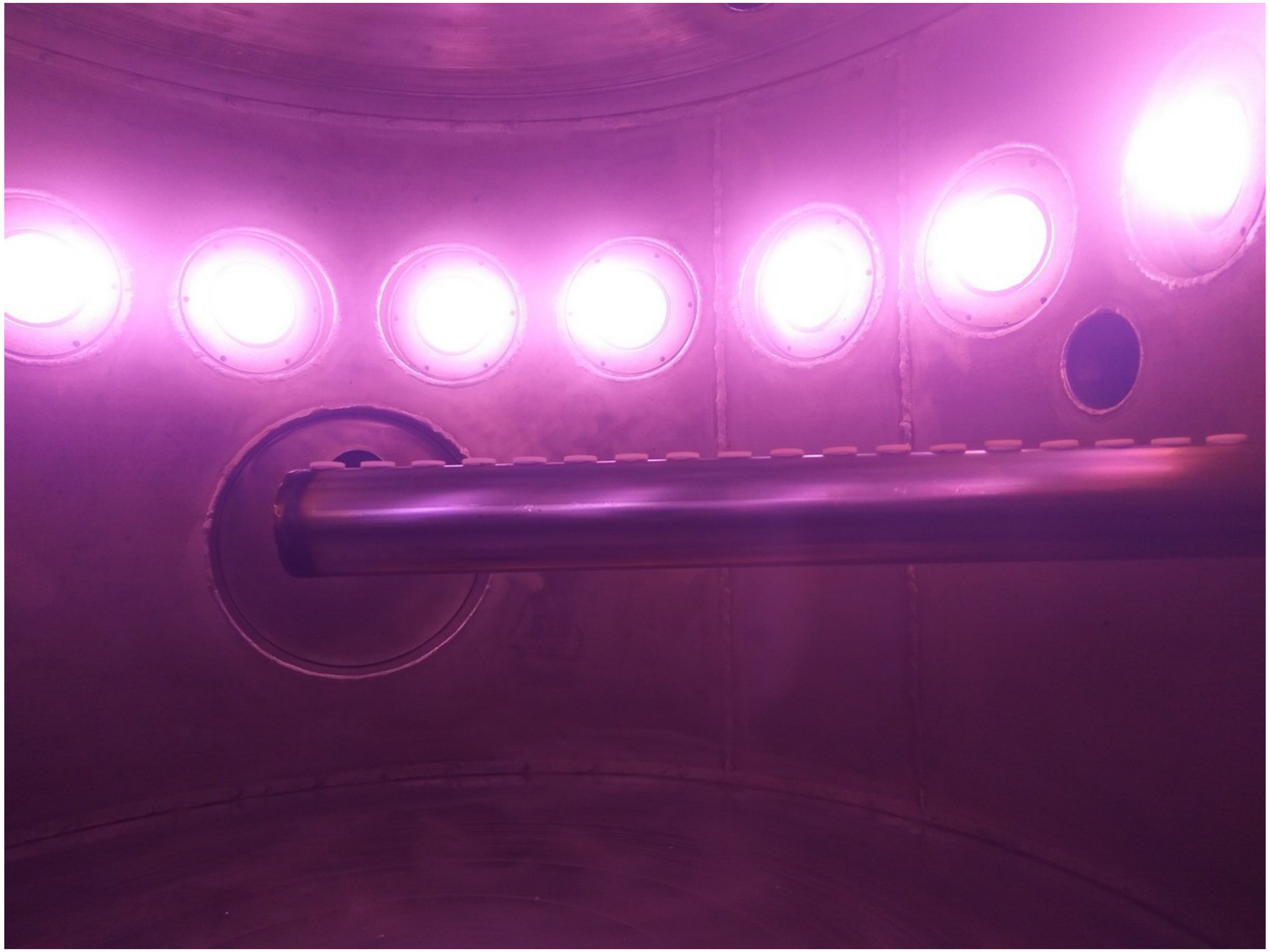

Fig. 4. Vacuum chamber with simultaneously operated ferromagnetic enhanced inductive discharges (driving frequency 100 kHz, gas pressure 10 Pa, discharge current 10 A).

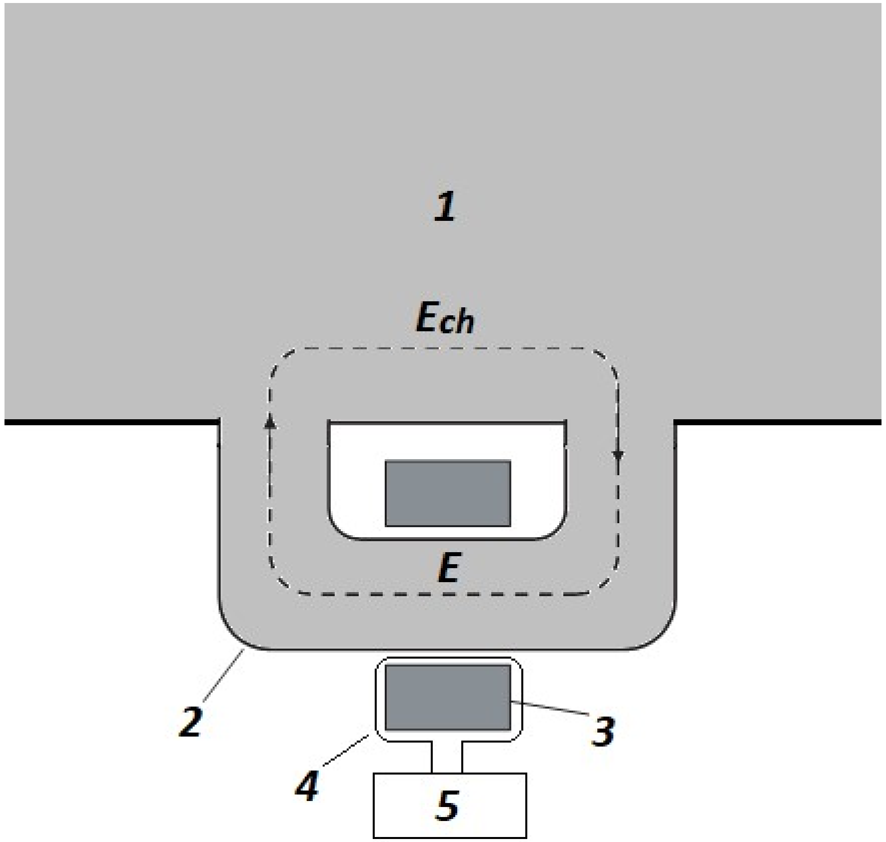

Fig. 5. A model representation of a single U-shaped tube.

1 – Vacuum chamber, 2 – U-shaped discharge tube, 3 – ferrite core; 4 – primary winding, 5 – power supply with matching unit.

E – discharge electric field strength inside the U-shaped tube

E_{ch} – discharge electric field strength inside the vacuum chamber.

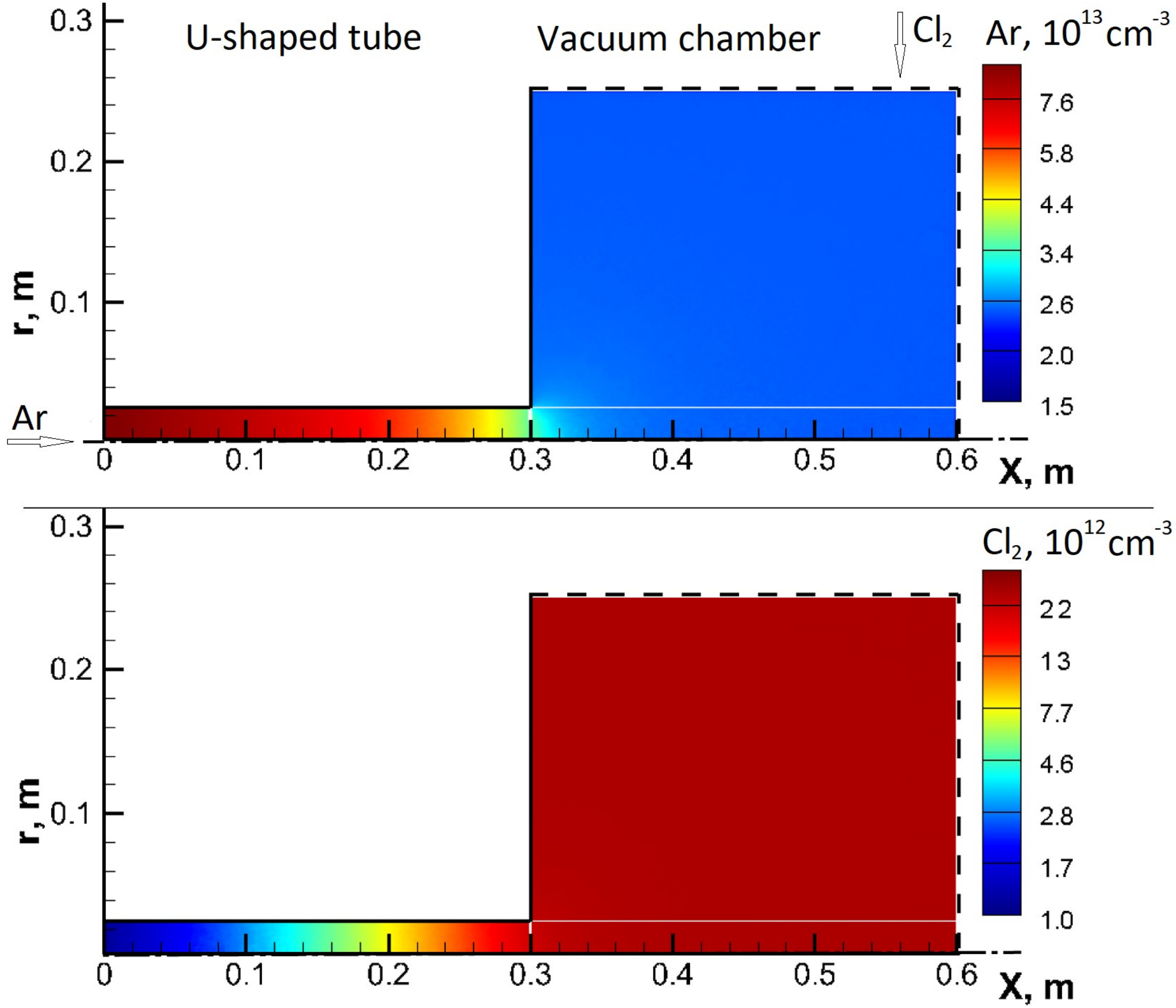

Fig. 6. Spatial distribution of the Ar (above) and Cl_2 (below) densities in the U-shaped tube and vacuum chamber. Gas pressure 0.1 Pa, argon flow rate 10 sccm, Direct Simulation Monte Carlo method. Gas discharge is turned off.

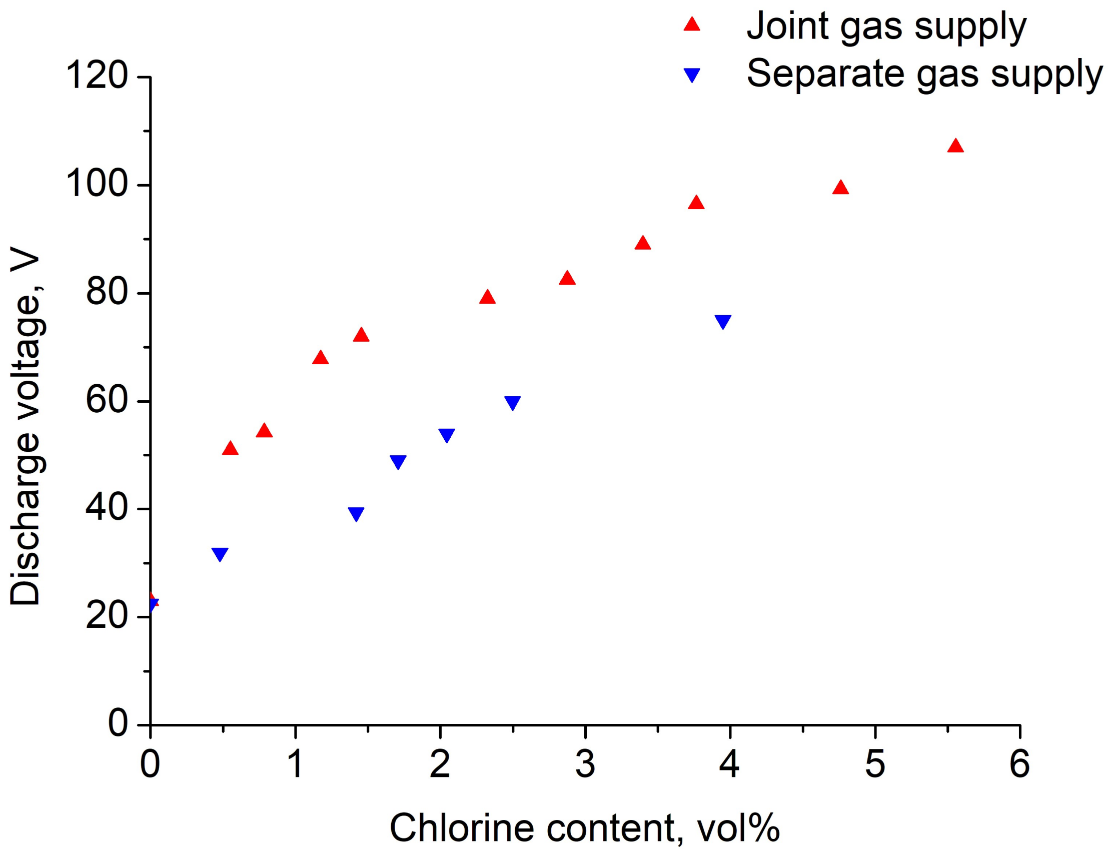

Fig. 7. Ferromagnetic enhanced inductive discharge voltage (single discharge) vs. chlorine content $Q_{Cl2}/(Q_{Ar}+Q_{Cl2})$, for the discharge current of 10 A and gas pressure of 10 Pa. Total argon flow rate Q_{Ar} = 25 sccm.

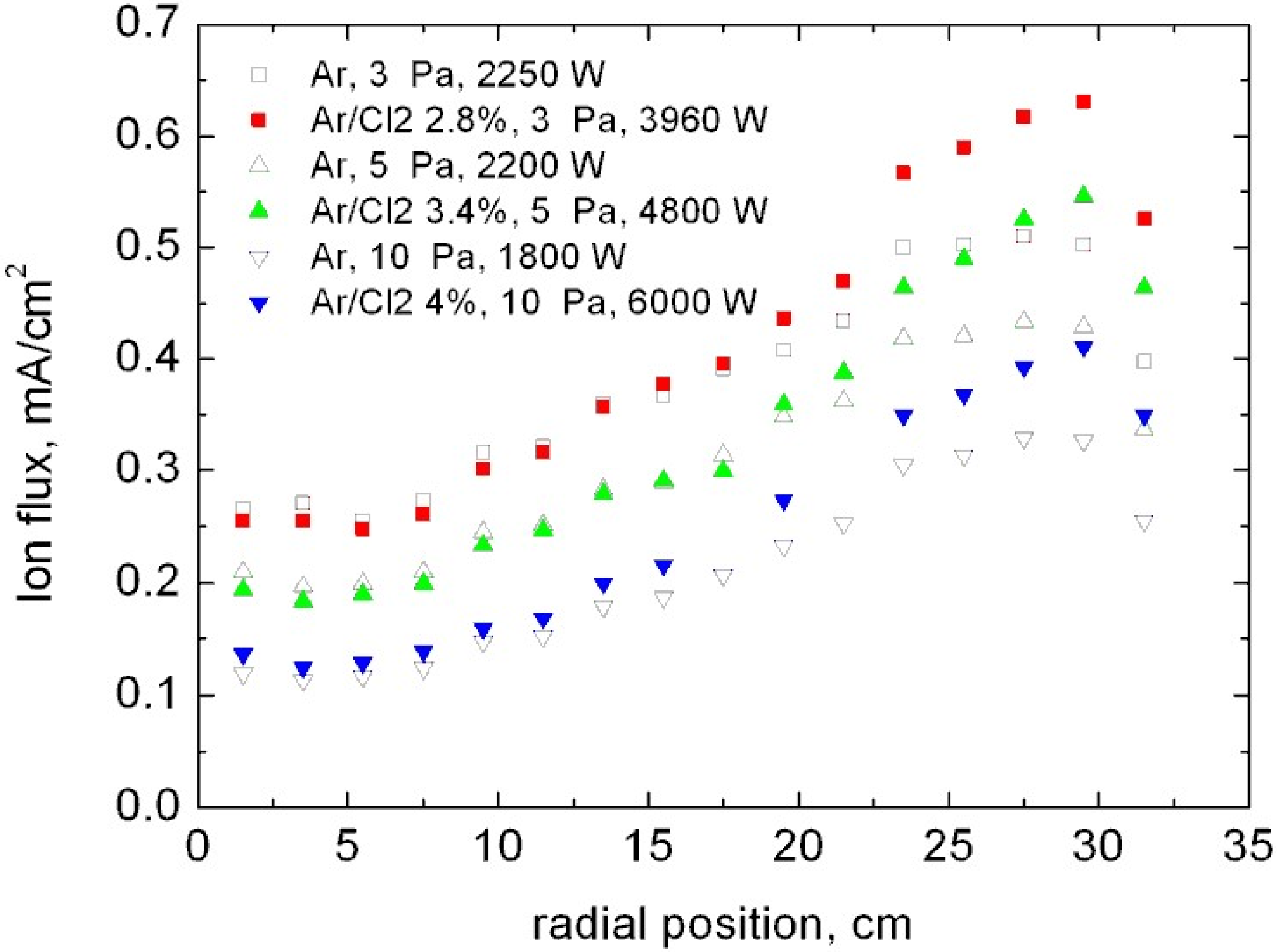

Fig. 8. Ion flux density radial profiles for various gas pressures and chlorine content. Discharge current 10 A, probe bias -50 V.

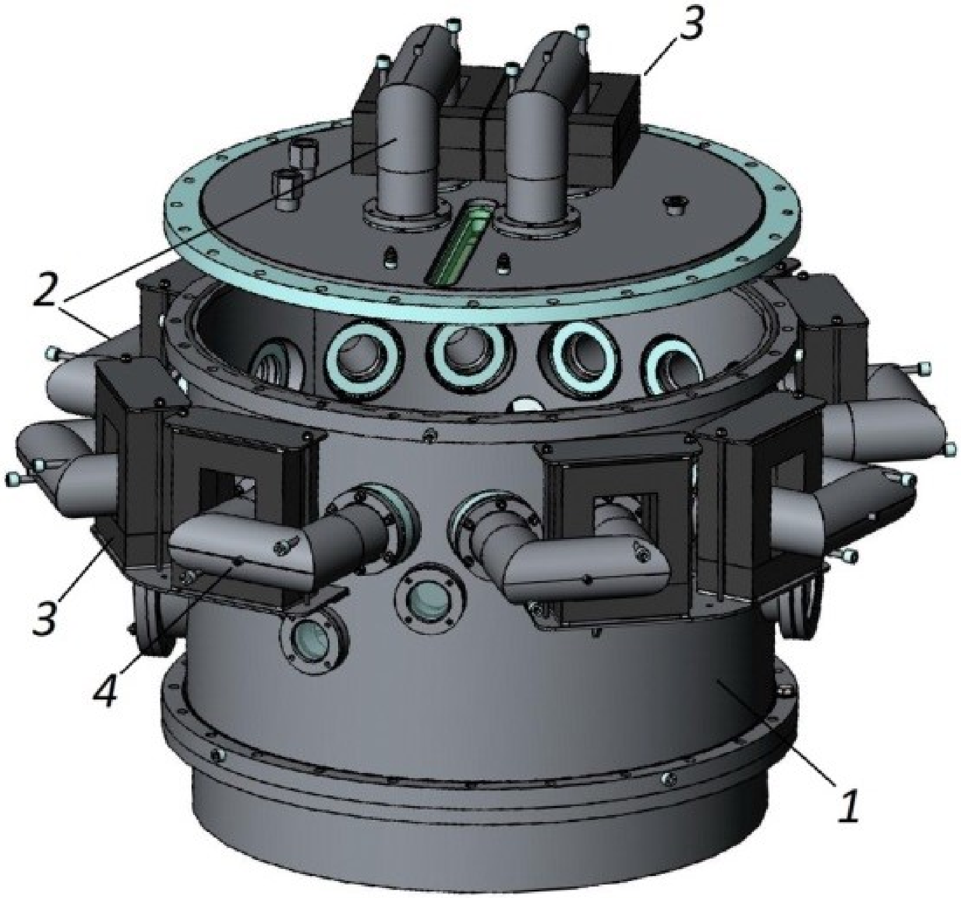

Fig. 9. Distributed ferromagnetic enhanced ICP with additional plasma sources to control the spatial distribution of plasma density.
1 – Vacuum chamber, 2 – U-shaped discharge tubes, 3 – ferrite cores, 4 – gas inlets.

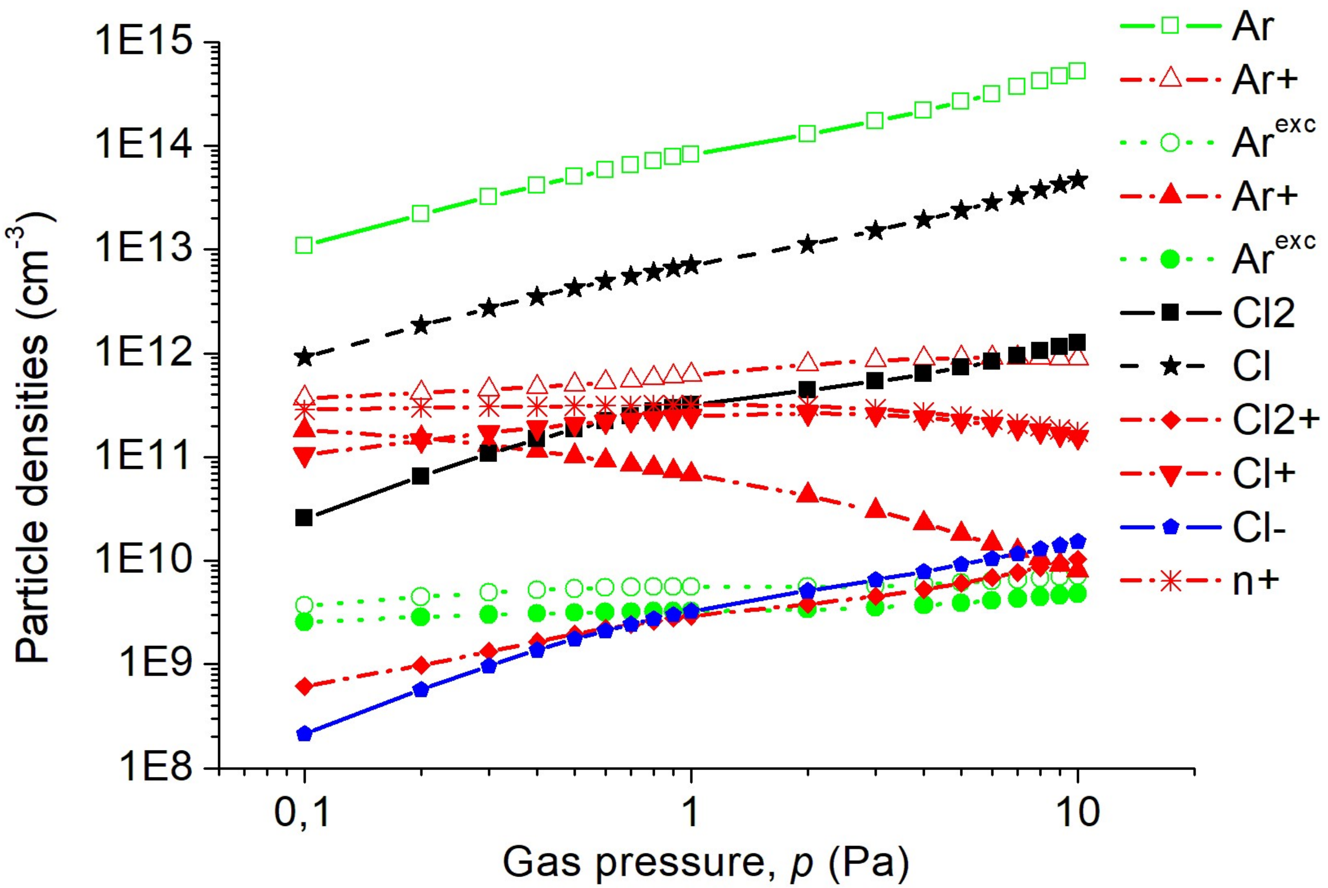

Fig. 10. Plasma particle densities in the main discharge chamber vs. total gas pressure, for the absorbed power of 1000 W (5 mW/cm^3), calculated with the global model of Ar/Cl_2 discharge*. Empty symbols represent the case of argon as plasma forming gas, solid symbols are for the mixture of 95 vol% Ar and 5 vol% Cl_2. Ar^{exc} represents the sum of all excited argon atom states, n+ represents the sum of positive ions Cl^+, Ar^+ and Cl_2^+.

* E.G. Thorsteinsson, and J.T. Gudmundsson, “A global (volume averaged) model of a Cl2/Ar discharge: I. Continuous power,” J. Phys. D: Appl. Phys., vol. 43, pp. 115201 (1-12), March 2010.

CONCLUSIONS

- The features of the large-scale distributed ferromagnetic enhanced ICP source have been investigated for the case of a strong electronegative gas (chlorine) addition into plasma.

- An effect of the U-shaped tube electric field strength decrease was demonstrated for the separate gas supply (argon into the U-shaped tubes, Cl_2 into the main chamber), which allows to improve the efficiency of the setup.

- Effects of chlorine addition on the plasma parameters of the large processing chamber with a volume of about 200 l were analyzed for a pressure range of 0.1−10 Pa using the global (volume averaged) model. A high positive ions density of order of 10^{11} cm^{-3} with a high (up to 90%) fraction of chlorine ions Cl^+ was demonstrated at relatively low specific discharge power of about 5 mW/cm^3 and chlorine content of 5 vol%.

ACKNOWLEDGEMENTS

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