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Non-uniform structure of a large-scale low-pressure radio-frequency inductive discharge in magnetic field

© I.Yu. Zudin, S.V. Korobkov, A.V. Strikovskiy, A.A. Istomin, V.V. Kochedykov,
A.N. Katkov, D.S. Pleshkov, I.A. Petrova, K.N. Loskutov, M.E. Gushchin

Federal Research Center A.V. Gaponov-Grekhov Institute of Applied Physics of the Russian Academy of Sciences,
Nizhny Novgorod, Russia
E-mail: zudiniy@ipfran.ru

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It has been found out that a pulsed low-pressure radio-frequency (RF) inductive discharge in a large volume in external magnetic field has a non-uniform (filamentary) structure. At magnetic fields of several hundred gauss, the developing discharge irregularities whose transverse scale is about 10 cm are not smoothed out by diffusion and persist at the stage of plasma decay. Such instability should be considered when designing large-scale various-application pulsed devices employing RF discharges.

Keywords: magnetoactive plasma, RF discharge, instability.

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Large-scale setups with pulsed radio-frequency inductive (RFI) low-pressure discharges allow obtaining with moderate energy consumption a dense (up to $10^{12}-10^{13}\,\text{cm}^{-3}$), quiscent, quasi-uniform, low-temperature plasma in magnetic field in a volume of up to several cubic meters. This provides them with a number of advantages over other systems for creating large magnetized-plasma columns, which use wide-aperture filament cathodes [1] or theta-pinch [2]. Setups based on RFI discharge in magnetic field are used for basic research, for instance, for modeling phenomena in space plasmas (see, e.g. [3]). In different years, several pulsed systems with RFI discharges were created at IAP RAS; the largest of them is facility „Krot" [7].

Solving such problems as, e.g. modeling active radio-frequency experiments in the ionosphere [8] or generating transverse collisionless shock waves [9] requires a large laboratory plasma length across the external magnetic field in combination with high uniformity. If to conduct the experiment it is necessary to meet the requirements for strong magnetization of ions (i.e. the ion cyclotron frequency is to exceed the frequency of ion collisions with neutral particles) or ion gyroradius smallness with respect to the plasma transverse dimensions, then in practice it is necessary to look for ways to create plasma in magnetic fields with induction higher than 100 G having a smooth transverse profile on the scales of about a meter.

As the largest setup in its class, facility „Krot" allows for studying the effect of magnetic field induction on the uniformity of the RFI discharge plasma and reproducibility of its parameters from one facility operating cycle („shot") to another. Working section of the facility's vacuum chamber is 10 m in length and 3 m in diameter. The chamber accommodates a solenoid 3.5 m long and 1.5 m dia that creates magnetic field of up to 1000 G directed parallel to the chamber axis. Inside the solenoid, antenna inductors for igniting the RFI discharge are placed: the solenoid's overall dimensions determine the size of the magnetized plasma column. The plasma generation system consists of four two-phase vacuum-tube self-oscillators generators up to 1 MW in power each; they are adjusted to operating frequency of 5 MHz and loaded on inductors. The inductors are designed as circular coils of polyethylene-insulated cable RK50-11-13 cleared from sheath and copper braided screen. To ensure quasi-uniform filling of the solenoid internal space with plasma, eight inductors of different diameters (0.5 to 1 m) are used; they are placed in different solenoid sections. Two inductors are connected in parallel to each oscillator.

Under the conditions of the experiment described, the discharge was pulsed once every 30 s in the argon atmosphere at the pressure of $p = 10^{-3}$ Torr. Duration of the plasma-producing pulse was 1 ms. Power input into the plasma was calculated from the waveforms of RF currents in inductors and from applied RF voltages; it was approximately 450 kW. The plasma density was measured using a microwave-resonator probe on a quarter-wave section of the double line [10]; the probe moved in the radial direction. Electron temperature was measured by a single Langmuir probe. The plasma transverse structure in its dynamics at the breakdown and decay stages was examined by using a nanosecond electron-optical converter (EOC) SPU-1 produced by NPP NANOSCAN LLC (Moscow). Optical recording of the plasma glow was performed along the external magnetic field.

Fig. 1 presents the transverse profiles of electron density N_e obtained after the completion of RF generators operation at the stage of the plasma diffusion decay in moderate magnetic field ($B_0 = 90\,\text{G}$). Maximum plasma density $N_e \sim 3 \cdot 10^{12}\,\text{cm}^{-3}$ achievable when all the four

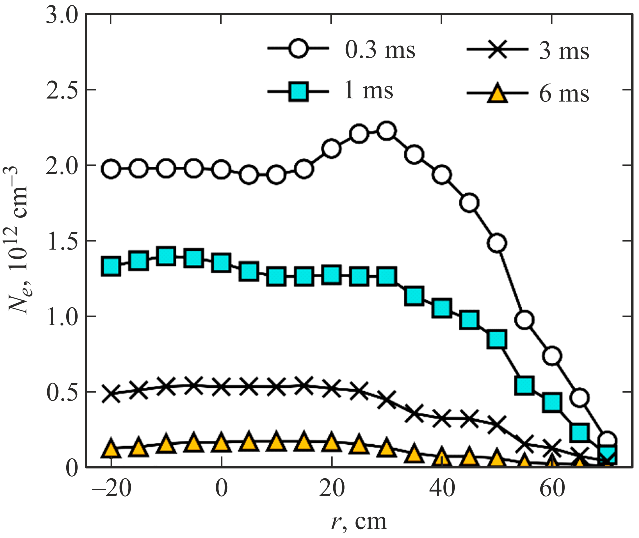

Figure 1. Transverse density profiles of the quasi-uniform decaying plasma in magnetic field $B_0 = 90$ G depending on the time after the end of the RF pulse.

generators operate by the end of the RF pulse corresponds, at the selected pressure, to approximately complete argon ionization near the inductors, provided a decrease in the neutral gas atomic concentration due to its heating is taken into account. By the end of the RF pulse, electron temperature is $T_e \sim 3$ eV, while at the decay stage $T_e \sim T_i \sim 0.3$ eV (T_i is the ion temperature). As shown in Fig. 1, by the end of the RF pulse it is possible to create plasma with a „flat“ density distribution whose diameter at the level of 0.5 from the maximum N_e is about 1 m. Such quasi-uniform quiet cold plasma is well-suited for modeling active experiments in the ionosphere, including generation of artificial ionospheric turbulence [11] and injection of barium clouds [12].

Fig. 2 presents the results of optical recording of plasma glow in dynamics for two magnetic fields (90 and 450 G). The difference in the discharge glow brightness at different stages reaches four orders of magnitude; therefore, optical recording at different time moments was performed with the exposure time varying from 10 ns (during breakdown) to $\sim 10\,\mu$s at the late decay stage. Evidently, the plasma is highly non-uniform, especially during the RFI discharge evolution. $100\,\mu$s after the RF pulse start, a ring-like glow concentrated near the minimum-diameter (0.5 m) inductors is observed at all the B_0 values: it is these inductors whose inductive electric field has the maximum strength. Almost immediately (within the time interval of 100 to $200\,\mu$s), instability begins developing: the discharge transforms into bright filaments (apparently, stretched along the magnetic field) distributed over the magnetic surface passing through small-diameter inductors. The higher field strength B_0, the smaller the filaments' scale in azimuth. The azimuthal size of irregularities is 10 to 15 cm for the fields of about 90 G and does not exceed 5 cm for the field of 450 G. The

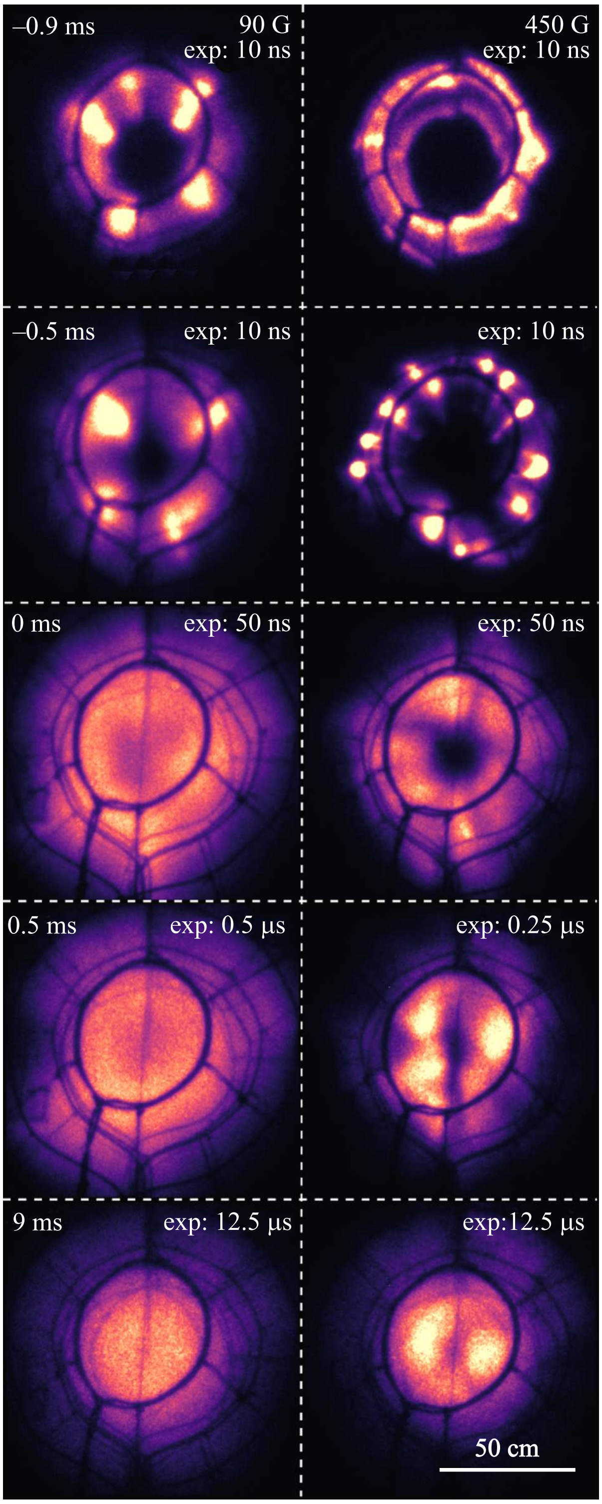

Figure 2. Plasma glow images obtained using EOC SPU-1 at different stages of the discharge development and plasma decay for different external magnetic field inductions (presented in pseudo-color on an adaptive color scale). The shooting direction was along the external magnetic field. A distance scale mark is given for the plane of the inductor closest to EOC. The images indicate the delay from the end of the plasma-producing pulse, external magnetic field strength, and exposure time.

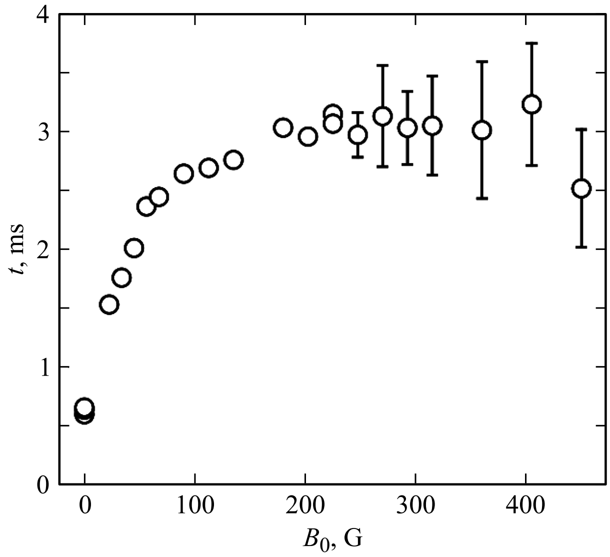

Figure 3. Plasma half-life versus the external magnetic field strength.

filaments get formed at the same places in each „shot“ probably, the places depend on the geometry and design details of inductors immersed in plasma. Further, as density N_e increases, the glow becomes brighter and wider, while irregularities merge together thus becoming larger. By the end of the RF pulse, plasma fills the entire solenoid volume, but the greatest glow brightness is fixed on the magnetic lines passing through inductors 0.5 m in diameter; this is consistent with measurements of the transverse density profile (Fig. 1).

In view of the purpose of such facilities as „Krot“, of the greatest interest is the stage of plasma decay at which most measurements are carried out. At low magnetic fields, irregularities that remain by the RF pulse end quickly disappear due to diffusion. For magnetic field $B_0 = 90\,\mathrm{G}$, the profile of glow (and density) has a smooth bell-shaped form already 0.5 ms after the decay onset. This profile which approximately matches the main diffusion mode [13] remains essentially unchanged onwards. The same dynamics is characteristic also of higher induction values (up to about 200 G). Although by the end of the RF pulse the plasma glow profile is non-uniform in radius and azimuth, the plasma distribution becomes quasi-uniform in 0.5−0.7 ms and remains so during the further decay.

When magnetic field is about 250 G and higher, the situation is different: diffusion does not smooth out the irregularities. Plasma filaments stretched along the magnetic field, which got formed by the end of the RF pulse, do not dissolve at the stage of decay. The decaying plasma consists of several filaments whose transverse dimensions are about 10−20 cm. The non-uniform plasma profile with a density dip near the chamber axis persists 10−15 ms after the end of the RF pulse (Fig. 2) and even later, i. e., over a long time period during which density n_e decreases by three orders of magnitude (from 10^{12} to $10^9\,\mathrm{cm}^{-3}$).

Analysis of the results of optical recording shows that, unlike the small-scale structures developing at the beginning of the RFI discharge, density profile of the decaying plasma does not get reproduced from one facility „shot“ to another. Transition to the unstable mode of plasma decay in strong magnetic fields is clearly visible in the half-life dependence on B_0 constructed based on large statistics of measurements with a microwave-resonator probe (Fig. 3). When $B_0 < 200\,\mathrm{G}$, plasma parameters on the chamber axis differ from „shot“ to „shot“ by about 1 % [14]. Starting from magnetic fields of about $B_0 \sim 250\,\mathrm{G}$, the plasma decay proceeds differently in each operating cycle of the facility; the plasma lifetime varies within ±20 %.

Presumably, the filament sizes and experimentally determined critical value of the magnetic field strength are dictated by the background gas type and pressure, as well as by temperatures to which particles of different types get heated during the discharge. When developing the model of instability, it seems important that magnetic field strength $B_0 \sim 200\,\mathrm{G}$, at which the decaying plasma column loses its uniform structure, meets with high accuracy condition $\omega_{ci} \approx \nu_{in} \approx 6 \cdot 10^4\,\mathrm{s}^{-1}$ (where ω_{ci} is the ion gyrofrequency, ν_{in} is the frequency of collisions between ions and neutral atoms) corresponding to the transition to the mode with magnetized ions. At the fields of about 450 G, when the decaying plasma filamentation is clearly observed, the ion magnetization parameter is $\omega_{ci}/\nu_{in} \sim 2$, while ion gyroradius $\rho_{ci} \sim 1\,\mathrm{cm}$ is at least an order of magnitude shorter than transverse scales of the observed non-uniform structures ($D > 10\,\mathrm{cm}$).

Note in conclusion that the transverse scale of the decaying plasma irregularities studied in experiments on the „Krot“ facility is comparable to the diameter of the entire plasma column in a number of the world's largest facilities at close B_0 values (e. g. facility LAPD [1]). We assume that, when the plasma parameters (N_e, T_e, T_i) and B_0 values are quite typical of laboratory setups, instability described in this paper manifests itself only in the case of large scales of the region of ionization across the magnetic field: in our case, it is possible to observe instability solely due to the record (about 1 m) transverse size of RFI discharge in the „Krot“ facility chamber. At the same time, solving a number of problems of experimentally modeling space phenomena needs creation of laboratory sources of plasma in large volumes (see, e. g. [15]), including those with maximum possible plasma dimensions across the external magnetic field. The RFI discharge is a promising tool for creating dense low-temperature plasma; therefore, instability described in this paper should be taken into account as a possible undesirable factor when designing new large-scale facilities, including setups for modeling space phenomena, plasma-chemical reactors, etc.

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Conflict of interests

The authors declare that they have no conflict of interests.

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