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THE PINCH EFFECT IN MICROWAVE RESONANT STREAMER DISCHARGE

Igor I. Esakov, Lev P. Grachev and Kirill V. Khodataev
Moscow Radiotechnical Institute RAS, Russia
khodata@online.ru Fax: (095) 314-1053

The work is devoted to experimental and theoretic study of a streamer discharge in the focus of microwave radiation in the open resonator. The observations show that if a gas pressure more than 0.1 atmosphere the single streamer discharge appears in the focus. When the resonant length of the streamer is achieved, the all energy storage of resonator is adsorbed by the streamer with very high efficiency. The simulations show that if gas pressure is quite enough the pinch force of the current inducted in the resonant streamer compresses the discharge plasma. One can hop that the forecasted high plasma parameters can be achieved and be applied not only for design of a gamma or neutron sources but for creation of a fusion reactor

Introduction

The electrodeless microwave discharges in a gas of high pressure demand appropriately high level of the electromagnetic field. For example the normal pressure air breakdown needs the microwave radiation specific energy flow 1 MW/cm^2.The high amplitude microwave field can be achieved in a focus of a radiation beam. Even in the case when the focusing system has a short focus so that the area of the focus cross section equals approximately wave length squared the needed generator power for 10 cm wave length is 100 MW with pulse duration more than few microseconds. It is difficult to provide so high power during some microsecond in a laboratory. But the field level needed for breakdown of a gas with high pressure (more than some atmosphere) can be achieved in a resonator because the resonator quality can be very high.

The open resonator created by two spherical copper mirrors was used in our experiments [1]. The resonator allows us to create a discharge in air and other gases with pressure which does exceed one atmosphere. A high-pressure discharge in the focused traveling-wave radiation beam represents a net of the thin hot strings (connected among themselves), consistently appeared one from another (of course if the radiation intensity in the focus and pulse duration are enough). But the discharge in the resonator represents the single hot string. The string is a single because the stored energy in resonator is finite. Usually the all stored energy is adsorbed by one resonant streamer. The length of developed streamer is close to half of wave length. It is electrodynamic resonance. Appropriately the high current is inducted in the streamer. The inducted current heats the streamer plasma up to high temperature because the streamer diameter is very small. The heating up specific power related to the gas density is proportional to gas pressure because the breakdown electric field (and inducted current) is proportional to one. If the gas density is quite enough the magnetic pressure force of inducted current is able to compress the plasma in streamer. The pinch instability in central part of the resonant streamer can cause strong local dissipation of energy in the pinch region. The attributes of this phenomena are observed in our experiments as a bright core. The courageous estimations clearly show that very high temperature (up to thermonuclear temperature) can be achieved in the resonant streamer if the gas pressure is more than some decades of atmosphere [2]. We will show the key experimental and simulation results and discuss extrapolating estimations based on simplified theory of a resonant streamer discharge.

Experimental data

The scheme of experimental installation is shown on Fig.1.

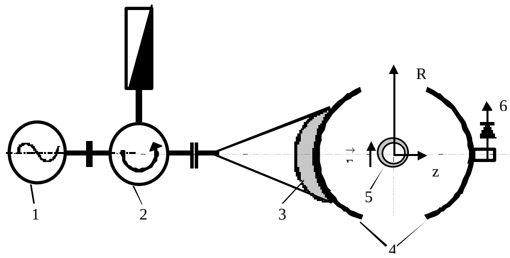

Fig.1 The scheme of the experimental installation. 1 – magnetron generator, 2 – circulator, 3 – lens, 4 – spherical mirrors of the open resonator, 5 -quarts retort, 6 – field prob.

The open resonator 4 consists from two spherical copper mirrors displaced along common axis z. The curve radius a_s, diameter $2a_m$ and distance between them L equal 35 cm, 55 cm and 51.7 cm correspondingly. The quarts retort 5 fulfilled by a gas is displaced in the center of resonator. The retort represents the quarts long tube with the inner diameter equaled to 8 cm and has the optical windows on the ends. The gas pressure in the retort can be varied from small value up to several atmosphere. The magnetron generator feed the resonator through wave guide with circulator 2 and reactive attenuator 3 with the feeding coefficient ~10^{-3}. The output power of generator is 10 MW with pulse duration 40 μs. Wave length of radiation λ is 8.9 cm. The repetition frequency is less than 1 Hz. The amplitude envelop of field in resonator is monitored by the probe 6.

The application of the resonator allows to increase the field in the focus in η times $\eta = \sqrt{\frac{c \cdot \tau}{L}}$, (c- light velocity). The measurements show that the used resonator has τ = 5 μs. It means that in our case η=52. The most part of experiments was performed in air and hydrogen.

The main results of experimental study of microwave discharge in a gas of high pressure (p>0.2 atm) in the open resonator can be formulated by following [3,4,5]. The electron avalanche starts from one electron and represents the expanding the immovable in average spherical electron cloud with increasing electron number and radius. The streamer evolution is shown by Fig, 2.

(a) (b) (c)

Fig.2 The streamer development.
(a) – the photo of the streamer by the exposed lens, (b) – the scanned image of the streamer (the total time durance is 70 ns), (c) – the shadow of the shock wave, generated by the exploded streamer. The vertical size of the plot is 5 cm

When the electron number in avalanche is quite enough the electron cloud starts to transform to a string which is oriented along vector of electric field. It is streamer (Fig.2a and Fig.2b). The speed of the streamer arising can exceed 10^8 cm/s if the pressure is quit enough [6].

When the streamer length achieve the resonant value (near half wave length) the field in resonator breaks down and farther exists on a small level. The streamer development is stopped.

After breakdown the shock wave runs out from the streamer (see Fig.2c) [7]. The measured shock wave parameters show that the streamer adsorbs almost all energy stored by resonator and explodes.

If gas pressure equals or more than 0.5 atm the bright core is observed in central part of the resonant streamer (see Fig2a and Fig.3). In hydrogen some times two bright cores can arise near center of the streamer. One can suppose that the most part of stored energy is adsorbed in the core. It is important to note that the hard boundary on gas pressure exists between state with the core and without one.

The theoretical model of the discharge

The streamer development is the very complicated nonlinear process. The simulation model must to describe many complicated factors of the real process: the electrodynamic interaction the system generator-resonator-discharge with the developing streamer taking into account the main physical-chemical processes in the streamer. The MW generator provides the energy to the resonator but refraction and heat losses caused by the streamer decrease the stored energy. Both factors is took into account in differential equation for electric field at the resonator focus. It is supposed that resonator is tuned in resonance with generator frequency. The evolution of the streamer is defined by the ionization front velocity [8], that defined by the local values of electric field on the ends of the streamer and unperturbed gas density and temperature.

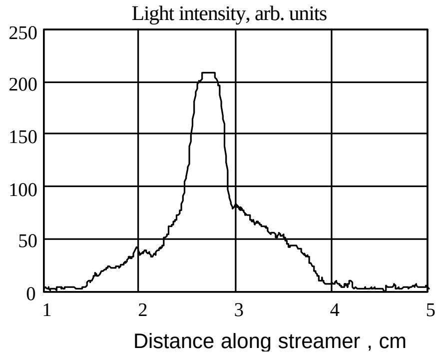

Fig.3 The measured light intensity distribution along the streamer axis

The estimations show that at high unperturbed gas pressure the pinch force of the inducted current can be more than the discharge plasma pressure gradient thus the pinch force is included in the movement equation

The calculated state equation, thermal capacity in and electric conductivity for diatomic molecular gas for wide diapason of a temperature and the electron continuity equation for the not equilibrium ionization pretend to be near to realty:

The task parameters are the microwave length, power of generator, the resonator parameters, the gas pressure and the moment of appearance of initial free electron.

The simulation results and its comparison with experimental data

The task parameters was the same that in the experiment: maximum field in resonator in stationary regime E_m = 35 kV/cm, time constant of resonator τ = 5μs, the initial free electron appears in the focus of resonator when electric field in the focus achieves the critical value depending on gas pressure. The gas pressure was varied from 50 Torr up to 760 Torr.

The simulation shows that independently on the gas pressure if electric field exceeds the critical value the electron avalanche starts to develop and transforms into the streamer. The streamer length, electric conductivity and inducted current rise up to maximum value limited by finite energy stored by resonator. Electric field in the resonator decreased quickly, it is breakdown. The streamer radius rises initially up to value limited by ambipolar process and after heating rises quickly because of the explosion. The electron temperature T_e and gas temperature T is the same and achieve the value 30,000 K at the gas pressure 760 Torr.

The maximum inducted current and maximum velocity of streamer ends are near the theoretic limit if the pressure is quit high. The current is limited by the radiation resistance of an ideal resonant vibrator in the critical external field E_{cr}. The ends velocity is limited by the product of the free electron diffusion and maximum ionization frequency. The product almost do not depends on the gas pressure.

The streamer has the maximum temperature at the its middle only. It means that the light intensity of the middle of the streamer must be strongly higher than one of the streamer branches. The observing bright corn at the middle of the streamer can be explained by the high gas temperature at the middle. It is clear why the corn arises if the pressure is more than 500 Torr.

The calculated and measured values of the streamer radius are in a quite good agreement. It gives us some assurance that designed model has relation to the realty. This assurance gives us a good possibility to forecast the discharge parameters by means of designed model if the pressure is much more 1 atm.

If the gas pressure is more than 10 atm, the magnetic pressure is able to exceed the plasma pressure so the pinch effect can be observed [9]. The simulation at gas pressure 10 atm confirms this conclusion. The Fig.4 demonstrates the simulation result. One can see the pinch effect.

Possible applications

The experimental results simulation and theory data specify the possible ways of the MW discharge streamer discharge in an opened resonator. This type of discharge has the important peculiarities.

At the moment of resonance the plasma density is rising instead of usual decreasing at lower gas pressure. It is consequence of the pinch effect. Also one can see that at resonance the ion temperature is near to the electron one. Estimations show that the temperature increases proportionally to gas pressure. If the gas pressure will be increased up to some tens of atmosphere the temperature some keV can be achieved. The pinch influence is important both for density increasing and for ion heating. If plasma temperature is high the electron-ion relaxation time is comparable with time of the process so as electrons do not able to heat ions through Coulomb collisions. But MW pinch effect generates the strong shock wave every half period of MW oscillations. The shock waves are dissipated by ion component and ions are being heated directly during the pinch time. Of course the discharge at the pressure about several atm needs the significantly deeper experimental and theoretic study than it is performed here.

The simulations show that if gas pressure is quite enough the average pinch force of the current inducted in the resonant streamer strongly compress the discharge plasma. The dense very hot plasma can be created for a short time about several nanoseconds. The pinched plasma can have the parameters up to needed for fusion in DT mix if the mix pressure is more than 40 atmosphere. At the compress stage the gas dynamic time of plasma is compared with period of microwave field. In this condition the pinching force generates the periodical shock waves which are cumulated at the axis of the filament. Thus the work of the pinch force is transformed into ions temperature directly. This discharge need not electrodes and arises far from the walls of device chamber. It means that only work gas takes part in the process without any impurities.

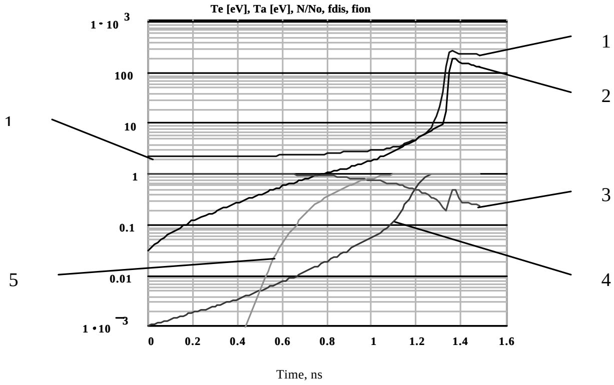

Fig.4. The simulation result achieved by means of complete model for discharge at 10 atm. 1 – electron temperature T_e, 2 – gas temperature T, 3 – plasma density r/r_0, 4 – dissociation coefficient, 5 – ionization coefficient

The small scale of phenomena and the device size, very high efficiency of the energy utilization, absence of electrodes and surfaces contacting with the hot plasma, direct pumping of energy to the ion heating allows us to hop that forecasted high plasma parameters really can be achieved and applied not only for design of a gamma or neutron sources but for creation of a fusion reactor. It is the nearest possibilities. We also dream that the Lowson criteria will exceeded at a high pressure of DT mix and may be the resonant streamer discharge is one from possible realistic ways to create the nuclear fusion reactor.

References

1. L.P.Grachev, I.I.Esakov, G.I.Mishin, K.V.Khodataev. Tech. Phys. 39(2), February 1994, pp.130-136.
2. L.P.Grachev, I.I.Esakov, G.I.Mishin, K.V.Khodataev. Preprint of LFTI im. A.F.Joffe, 1992, ¹ 1577
3. L.P.Grachev, I.I.Esakov, G.I.Mishin, K.V.Khodataev, V.V.Tsyplenkov. Pis'ma v JTF, 26 November 1992, v.18, No. 22, pp. 34-38.
4. L.P.Grachev, I.I.Esakov, K.V.Khodataev. JTF, 1998, ò.68, No4, pp. 33-36.
5. L.P.Grachev, I.I.Esakov, G.I.Mishin, K.V.Khodataev. JTF, 1996, v.66, No. 7, pp. 32-45.
6. K.V.Khodataev. Proc. XXIII ICPIG, Contributed papers, IV-24.
7. K.V.Khodataev. Proc. of the ICPIG-XX (Piza, 1991), Invited papers 1991, pp. 207-217.
8. A.L.Vikharev, V.B.Gildenburg, A.V.Kim, A.G.Litvak, V.E.Semionov. Proc. Of scientific works «High frequency discharge in the wave fields», Gor'kiy, 1988, pp. 41-135.
9. K.V.Khodataev. Abstracts of the XXVI Zvenigorod conference on plasma physics and control thermonuclear fusion (5-9 April 1999, Zvenigorod), Ï - Ñ2-26.