Physical basis and topical applications of a new type gas discharge excited by powerful pulse microwave beams in the high-pressure gases

G.M.Batanov, N.K.Berezhetskaya, A.M.Davydov, I.A.Kossyi, K.A.Sarksyan, N.K.Kharchev.
Prokhorov General Physics Institute of RAS, Moscow, Russia

Results of fundamental problems of microwave gas discharge physics investigations performed in General Physics Institute of RAS (GPI) have been used as the basis for creation of original plasma sources meant for application in the physical laboratories as well as for modern techniques needs reduction. Among the most promise and needed are plasma sources ("plasmatrons") based on the discovered and being studied in the GPI strongly subthreshold selfsustained discharges excited by microwave beam in the high-pressure gases [1,2].

New type of microwave discharge consists in the extraordinary combination of sequence self-sustained and non-self-sustained gas discharges (SNS-discharge) excited by pulse microwave beams. This discharge appears under the certain circumstances:

a) Microwave beam propagates through the gas medium with such a high pressure that relation: $\nu_{eff} >> \omega$ is satisfied (ν_{eff} is effective electron-neutrals collisions frequency, ω is cyclic frequency of microwave radiation);

b) Value of a reduced microwave electric field is such a small that in the all microwave beam bulk strongly subthreshold conditions in relation to the self-sustained discharge development are satisfied: $\gamma \equiv E_0/n_m < [E_0/n_m]_{thr}$ (E_0 is amplitude of microwave electric field, n_m is concentration of neutral particles, $[E_0/n_m]_{thr}$ is threshold reduced electric field);

c) Presence of a local initiator of SNS-discharge in the volume V_d much smaller then volume occupied by microwave beam V_{MW} : $V_d << V_{MW}$. Time of this initiator operation τ_i is much smaller than the duration of microwave pulse: $\tau_i << \tau_{MW}$

Almost all presented in literature experimental researches of SNS-discharge have been performed under the gas pressures lower then atmospheric one (p   200 Torr), at a centimeter wavelengths ($\lambda \approx 2 - 5$ cm) and under microwave beam power lower than 100 kW.

This work objective is broadening of fundamental research area with shifting of gas pressures in direction to the close (or higher) than atmospheric one, microwave beam power in direction such a high values as $P \leq 1$ MW and going from cm sizes of microwaves to the mm ones ($\lambda \approx 2 - 8$ mm). Interest in realization of above mentioned area of gas medium and microwave radiation parameters is explained by desire for advance in problem of an adequate model of observed gas discharge phenomenon development as well as in plasmachemical applications of SNS-discharges.

The search of a possibility to realize a microwave generation of a plasma, which is unusual in its physical properties and, at the same time, holds promise for a number of technological applications, such as a strongly subthreshold SNS-discharge in large gas volumes at pressures that are more, or are of the order of the atmospheric one, led us to the creation of the installation TORCH, which is assembled at the GPI and is shown schematically in Fig. 1.

This installation is assembled around the MIG-3 gyrotron complex ((1) in the figure).which generates a microwave beam with the following parameters: peak shot microwave pulse power $P_i \leq 600$kW, pulse duration $\tau_i \leq 20$ ms, wavelength $\lambda \approx 0.4$ cm. The complex is destined for operation in a closed (toroidal) magnetic confinement system (L-2M Stellarator) and is so designed as to create and confine a high-temperature plasma. The complex is provided with a quasi-optical system designed and manufactured at the GPI. The quasi-optical system forms a microwave beam propagating from the exit window of the gyrotron toward the entry window of the discharge chamber (2). The electric field distribution in the cross-section of the microwave beam is close to Gaussian.

The mirror system allows us to choose any prescribed direction and to input the beam into the region destined for excitation of the SNS-discharge. Even at maximum powers in the microwave pulse, the values of the reduced electric field in the bream do not exceed $\gamma \leq 10^{-16}$ V cm^2, which value is more than one order lower than the threshold for generation of a self-sustained discharge in free space, namely $\gamma_{thr} \approx 10^{-15}$ V cm^2.

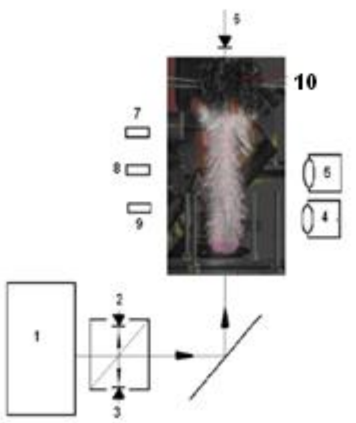


Fig.1. Scheme of experiment. 1-Gyrotron; 2,3-detectors of incident and reflected microwave; 4-FER; 5-photographic camera; 6-microwave Detector; 7,9-photomultipliers FEU 106; 8-optical spectrometer; 10-discharge initiator

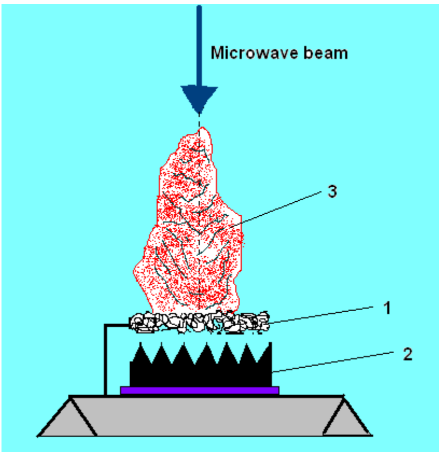


Fig.2. Scheme of experiment on freely localized in air SNS-discharge. 1-initiator; 2-microwave absorber; 3-SNS-discharge

In the TORCH installation, we have studied the possibility of exciting the SNS-discharge in free space in atmospheric air as well as in the closed chamber filled with various gases or gas mixtures at pressures also close to the atmospheric one. The experiments with microwave subthreshold discharge in the air atmosphere and in the closed chamber ate shown schematically in Figs. 2, 3, respectively. And, there is absorbent load (2) behind the initiator (1).

The experiments conducted on the TORCH have been demonstrated the possibility of exciting the SNS-discharge (in both free space and a closed chamber) at atmospheric pressure in individual shot microwave pulses (at a wavelength of 0.4 cm) beginning with a peak power on order of $P_i \approx 200$ kW and up (to 600 kW) and a shot microwave pulse duration of $\tau_j \approx 200\mu s$ and up (to 20 ms). The discharge, which was excited in a narrow layer situated in a certain cross-section with the help of a special-purpose initiator, occupies the volume that is the greater, the larger is the power level and shot microwave pulse duration, We have taken some photographs of the discharge excited following the scheme in Fig. 3 with two microwave powers (200 and 400 kW) and at different pulse durations. A typical photograph of the discharge is presented in Fig. 4.

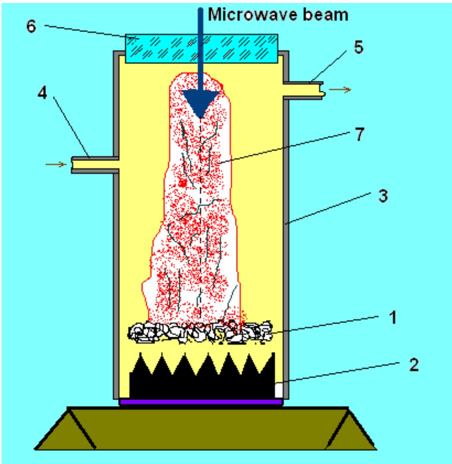


Fig.3.Scheme of experiment on SNS-discharge excited in reactor chamber. 1-initiator; 2-microwave absorber; 3-reactor chamber; 4-gas intake fitting; 5-treating gas exit fitting; 6-window for microwave input; 7-SNS-discharge

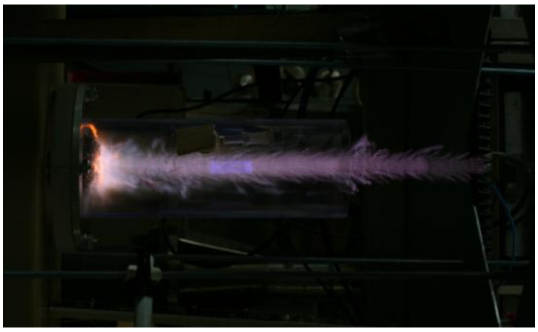


Fig. 4. Photograph of SNS-discharge in reactor chamber.

A few methods were used to determine the velocity of axial advance of the SNS-discharge. The velocity of axial development of the SNS-discharge that is freely localized in the air atmosphere is found to be $\sim 10^4$ sm/s.

The gas temperature in the region emitting optical radiation, according to the treatment of optical spectra is found to be ~ 4000 - 4500 K.

In operating with methane-hydrogen and methane-water mixtures, the H_α. line clearly showed in the emission spectra and was used to determine the electron density; assuming a

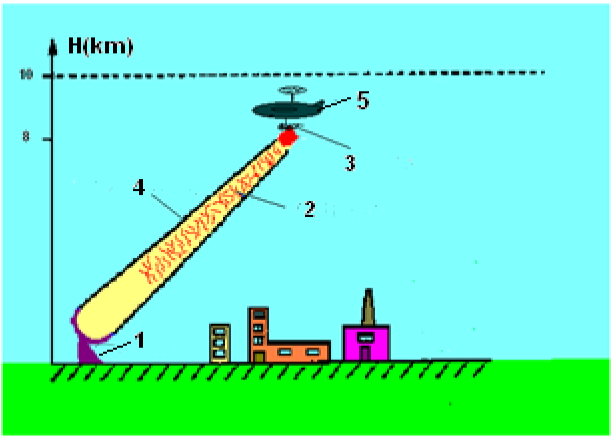
Stark mechanism of broadening of this line, the electron density in the discharge exceeds 10^{16} $см^{-3}$.

The results obtained in the foregoing experiments allow us to begin the development of a laboratory plasmochiemical reactor based on a powerful beam of millimeter wavelength radiation. The main studies in the area of plasmochemistry are promising for current technology, and in particular, for solving the problems of methane conversion into synthesis gas, water-vapor conversion of methane into synthesis gas, and utilization of carbon dioxide.

The results obtained are of interest in the application of microwave beams for cleaning atmosphere by exciting the SNS-discharge in air as in the scheme of Fig. 5 for cleaning atmosphere of fluorinechlorinecarbons, for which physical aspects were developed in a circle of works presented by the GPI and IAP RAS [3].

The achievement of meter axial lengths of the SNS-discharges in shot microwave beams may be used also for creating an electric-discharge system capable of cleaning fluxes of industrial gas ejections (see Fig. 6).

This work has been partly supported by Program of Fundamental Research (FNI) 2014-2016, 01200953487



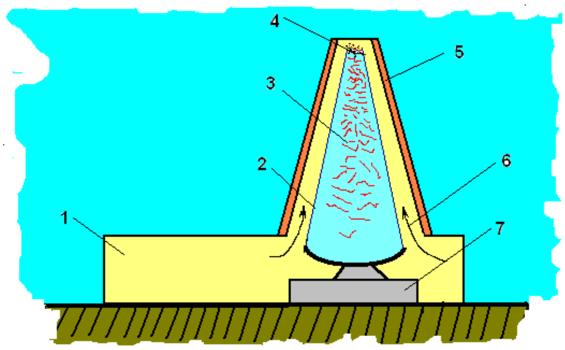


Fig. 5. Scheme of atmosphere cleaning with SNS-disxcharge. 1-antenna; 1-SNS-discharge; 3-initiator; 4-microwave beam; 5- pilotless vehicle.

Fig. 6. Scheme of industrial gas ejections cleaning. 1-plant building; 2-microwave beam;3-SNS-discharge; 4-initiator; 5-plant chimney; 7-Girotron

References

[1] G.V.Batanov, S.I. Gritsynin, I.A. Kossyi, A.N. Magunov, V.P. Silakov, N.M. Tarasova. High-Pressure Microwave Discharge // Transact. FIAN, 1985, T. 160, pp. 174-202.

[2] I.A.Kossyi. Self-/Non-Self sustained Microwave Discharge as a New Type of Large-Size Plasma Source // 44th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, 2006, Report AIAA-2006-1457

[3] G.V. Batanov, I.A. Kossyi, V.P. Silakov. Gas Discharrge in atmosphere as a means for ameliorating its environmental characteristics. Review, In remembrance of G.A. Askaryan // Plasma Physics Reports, T. 28, No 3, 2002, pp. 229-257.