Subthreshold self-sustained discharge initiated by a microwave beam in a large volume of high-pressure gas

K V Artem’ev, G M Batanov, N K Berezhetskaya, A M Davydov, I A Kossyi, V I Nefedov, K A Sarksyan and N K Kharchev

1 Prokhorov General Physics Institute, Russian Academy of Sciences, Moscow, 119991 Russian Federation
2 Moscow State University of Information Technologies, Radio Engineering, and Electronics, Moscow, 119454 Russian Federation
3 E-mail: kossyi@fpl.gpi.ru

Abstract. The presented results are based on the experimental studies of generating a long plasma column in gas (or gas mixtures) at atmospheric pressure both in free space and in a closed chamber. The microwave generator GYROTRON was used as an energy source. Its parameters were as follows: the microwave pulse power was in the range of 200 ≤ P ≤ 600 kW, the wavelength was λ ≈ 0.4 cm, and the pulse duration was in the range of 0.5 ≤ τi ≤ 20 ms. Under strong subthreshold conditions, a plasma column with a length of up to L ≤ 50 cm was created using a microwave beam that was formed using a quasi-optical mirror system. The discharge initiation system had an original design. Based on the discharge structure, expansion dynamics and typical discharge plasma parameters, this discharge can be attributed to the type of microwave discharges that are known as self/non-self-sustained discharges. The discharge properties and advantages of using this discharge as a basis of a plasma-chemical reactor are discussed.

1. Introduction

Studies of the fundamental physical problems of microwave-driven discharges in gases, which are carried out at the Prokhorov General Physics Institute, have provided the basis for the development of a series of original plasma sources that are intended for the use both in laboratory experiments and for solving modern technological problems. The most promising plasma source from the technological point of view is the plasmatron, which is based on the subthreshold discharge that is initiated by a pulsed microwave beam [1, 2]. This new type of microwave discharge, which was named as a self/non-self-sustained (SNSS) discharge [3–6], occurs when the following initial conditions are fulfilled:

(i) Pressure of the gas in which the microwave beam propagates should be high so that the strong inequality is true:

\[ \nu_{\text{eff}} >> \omega \]  

(here, \( \nu_{\text{eff}} \) is the effective frequency of electron-neutral collisions, and \( \omega \) is the microwave frequency);

(ii) Initially, the reduced microwave electric field should be low so that a self-sustained discharge could not be excited anywhere over the beam volume:
\[ \gamma \equiv \frac{E_0}{n_m} \ll \left[ \frac{E_0}{n_m} \right]_{\text{thr}} \]  

(here, \( E_0 \) is the amplitude of the microwave electric field, \( n_m \) is the density of neutrals, and \( \left[ \frac{E_0}{n_m} \right]_{\text{thr}} \) is the threshold reduced electric field that is needed for the initiation of a self-sustained discharge);

(iii) There should be a discharge initiator installed in a volume \( V_d \), which is much smaller than the microwave beam volume \( V_{\text{MW}} \), so that

\[ V_d \ll V_{\text{MW}}, \]

and the initiation time \( \tau_i \) should be shorter (or much shorter) than the duration of the microwave pulse \( \tau_{\text{MW}} \):

\[ \tau_i \ll \tau_{\text{MW}} \]

Under the conditions when the microwave electric field is smaller (or much smaller) than the breakdown field, the discharge may be excited locally inside the region occupied by the microwave beam where either the electric field of the electromagnetic wave increases locally or the density \( n_m \) decreases so that relation (2) becomes reversed. The schematic sketch for the three versions of initiation of an SNSS-discharge, which is used at the (GPI General Physics Institute), is presented in Figure 1.

**Figure 1.** Schemes of the SNSS-discharge initiation. a) Metal-dielectric target; b) Ring-shaped source of UV-radiation; c) CO\(_2\) laser spark. 1-microwave beam; 2-SNSS-discharge; 3-metal-dielectric initiator; 4-annular multispark initiator; 5-non-self-sustained discharge that initiates the SNSS-discharge; 6-first local microplasma formation; 7-CO\(_2\) laser spark; 8-CO\(_2\) laser; 9-lense; 10-CO\(_2\) laser beam.

Thus, metal-dielectric targets were installed at some cross section for the initiation of an extremely “subthreshold” self-sustained discharge in [6] (scheme figure 1a). In [7], to initiate the excitation of a localized discharge in the microwave beam, we used a CO\(_2\) laser spark (scheme in figure 1b). Figure 1c shows a schematic of the experiment, in which the SNSS-discharge was initiated using a ring multispark source of UV radiation, which produces photo-ionization plasma, namely the non-self-sustained microwave discharge. Eventually, its instability may result in the self-sustained plasma stage near the axis because bright filaments appear along the microwave beam electric field [8, 9].

All of the initiation methods in our experiments, which were conducted at the GPI, demonstrated that the local excitation of a self-sustained discharge in a volume that is much smaller than the volume occupied by the microwave beam is accompanied by an ionization wave. This wave propagates toward the microwave generator and builds an axial plasma column. Therefore, when the beam pulse duration is larger, the plasma column length is larger. Thus, we unexpectedly observed a new phenomenon, namely, the formation of an extended gas-discharge plasma column in microwave fields that are smaller (and even substantially smaller) than the threshold fields for exciting a self-sustained discharge in gas in free space. The characteristic photographs of SNSS-discharges, which are initiated using metal-dielectric targets and a CO\(_2\) laser spark, are presented in figures 2a and 2b.
Figure 2. a) Photograph of the SNSS-discharge excited in air using a subthreshold microwave beam via the metal-dielectric target (p = 200 Torr; λ = 2.5 cm); b) Photograph of the SNSS-discharge excited in air using a subthreshold microwave beam through the initiation via the CO₂ laser spark (p = 200 Torr; λ = 2.5 cm).

Note that all known experimental data on SNSS-discharges were obtained under the following conditions:
- Gas pressure below the atmospheric pressure (p ≤ 200 Torr);
- Centimeter wavelengths of microwave radiation (λ ≈ 2–5 cm);
- Moderate microwave pulse power (P ≤ 100 kW).

The purpose of the present work was to extend the area of fundamental studies of the discharge: to shift the pressure range toward values that are close to (and even somewhat larger than) the atmospheric pressure, to extend the range of pulsed microwave beam powers up to P ≈ 1 MW, and to switch to the millimeter range of the microwaves (λ ≈ 0.2–0.8 cm). The recent interest in the realization of these ranges of parameters – gas and microwave beam – is motivated by our firm intention to advance toward the construction of an adequate physical model of the gas-discharge phenomenon, as well as, by our interest in promising plasmachemical applications.

The present paper is devoted to a brief analysis of the physical processes underlying this unusual microwave gas-discharge formation. The pioneering experiments and research on SNSS-discharges in gases at atmospheric pressure, which have been conducted at the GPI using a high-power pulsed microwave beam in the millimeter wavelength range, are described below. The properties and advantages of the SNSS-discharge as the bases for the plasmachemical reactor are formulated.

2. Physical processes underlying the SNSS microwave discharge

It is generally accepted that all known and described in literature gas discharges belong to one of the two categories: self-sustained and non-self-sustained discharges [10]. However, the research, which was carried out at the GPI [1–6], permits us to amend this supposedly unbreakable partition by introducing a third form of discharge. Namely, the SNSS-discharge, which represents unusual transition sequences from the self-sustained to non-self-sustained stage via the strong nonlinear phase of ionization-overheating instability.

The physical analysis, which was carried out in [3, 11, 12], explains the mechanisms of formation of an ionization wave in an initially extremely subthreshold microwave beam in high-pressure gases. The model, which is presented in [3, 11], is based on the assumption about a decisive role of ultraviolet radiation that arises in both the initiation stage and later stages, specifically, in its front. The model is illustrated in figure 3, which shows schematic boundaries of the microwave beam and ionization wave at some time. In addition, discharge channels (filaments) are shown, which arise near the initiator as well as in the formed propagating axial ionization wave, specifically in its front, as a result of the transformation of the non-self-sustained discharge into the self-sustained discharge via the
strongly nonlinear stage of ionization-overheating instability. Discharge channels in the front of the ionization wave play a part of a UV radiation source ahead of the ionization wave front at a distance of \( l \leq l_f \) (\( l_f \) is the average free path of the ionization radiation). The microwave beam interacts with this plasma, becomes partially absorbed, and heats the gaseous medium via the electron component.

**Figure 3.** Scheme of the SNSS-discharge formation. 1-microwave beam; 2-metal-dielectric initiator of local discharge; 3-self-sustained-discharge; 4-non-self-sustained-discharge.

As it has been revealed in [3], the velocity of SNSS-discharge propagation toward the microwave beam in the air medium at a high pressure (\( \nu_{\text{eff}} \gg \omega, \nu_{\text{eff}}^* \)) can be estimated using the following relation:

\[
\nu_{Zi} \approx 10 n_e E_0^2/p_0^4 \approx 6.8 \times 10^{-5} n_e I_f^{3/2}/p_0^4
\]

Here, \( \nu_{\text{eff}}^* \) is the electron-neutral collision rate, which corresponds to the gas molecular density \( n_m^* \) such that \( \gamma = \gamma_{\text{thr}} \), \( n_e \) is the electron density of photoionized plasma ahead of the SNSS-discharge front, \( p_0 \) is the initial pressure of gas in Torr, \( E_0 \) is expressed in kV/cm, and \( I_f \) is the microwave intensity in W/cm^2.

The nonlinear stage of the ionization-overheating instability growing in the non-self-sustained microwave discharge has been studied theoretically in [13]. In this paper, the plasma parameters of the created filaments have been estimated. The final electron temperature in the filaments is calculated using the formula

\[
T_e \approx (\nu_{\text{eff}}^0/\omega)^2 T_{e0}
\]

and the electron density has the form of

\[
n_e \approx (\nu_{\text{eff}}^0/\omega)^{\beta+1} \nu_T/n_{e0}
\]

Here, \( \beta \approx 5-6; \nu_{\text{eff}}^0 \) is the electron-neutral effective elastic collision rate; \( n_{e0}, T_{e0} \) are the initial density and temperature of electrons in the uniform plasma of a non-self-sustained discharge, respectively. \( \nu_T = 1/\tau_T \), where \( \tau_T \) is the characteristic of electron loss time (due to attachment, recombination or diffusion).

\[

\nu_T \approx 10^{-9} \sigma_0 E_0^2/p_0
\]

Here, \( \sigma_0 \) is the initial plasma conductivity in electrostatic units, and \( E_0 \) is in units of V/cm.

After substituting the values of \( \nu_{\text{eff}}^0, T_{e0}, \sigma_0 \) and \( \nu_T \), which are characteristic of the experiments described in [3, 11, 14], we find that the final plasma state in the channels corresponds to an almost total ionization at the electron temperature of several hundreds of electron volts. However, the real values of the electron density and temperature can be limited by the number of unaccounted processes in [13], in particular, the reflection of microwaves from the filaments, etc. Nevertheless, the estimation results show that the discharge filaments are indeed the regions of dense and high-temperature plasma, which fit the measurements conducted in [14] that gave values of \( n_e \approx 10^{16}-10^{17} \) cm\(^{-3}\) and revealed the presence of a photoionized plasma 'aureole' around the discharge channels. The gas temperature in the
filaments was measured in a number of works [11] and found to be approximately $T_g^* \approx 5000 – 7000$ K.

There is reason to believe that the SNSS-type discharges, which possess regions of fast and high heating of gas with a subsequent fast cooling of gas, may be a very efficient means for processing gaseous media.

3. Subthreshold self-sustained discharge (SNSS) in a microwave beam of millimeter waves in atmospheric pressure gases

3.1. Scheme of the experiment
The search for a possibility to realize microwave generation of plasma, which looks unusual in its physical properties and, at the same time, is promising for some technological applications, namely the SNSS-discharge in large gas volumes at pressures above or on the order of the atmospheric pressure, led us to the construction of the TORCH installation at the GPI. This installation is assembled around the MIG-3 GYROTRON complex that generates a microwave beam with the following parameters: microwave pulse power of $P_m \leq 600$ kW, pulse duration of $\tau_{MW} \leq 20$ ms, wavelength of $\lambda \approx 0.4$ cm. The complex is designed to create and confine a high-temperature plasma in an L-2M stellarator [15] (see the scheme in figure 4). The installation is provided with a quasi-optical system, which is designed and manufactured at the GPI [16]. A quasi-optical system forms a microwave beam that propagates from the outlet window of the gyrotron toward the input window of the stellarator chamber. The electric field distribution in the cross section of the microwave beam is approximately Gaussian.

![Figure 4. Scheme of the experimental setup designed for the creation and confinement of a high-temperature plasma in an L-2M stellarator. 1-MIG-3 Gyrotron complex; 2-microwave beam; 3-microwave reflecting mirrors; 4-input window of the stellarator.](image)

In the experiments carried out in the TORCH installation, SNSS-discharges were excited in divers cross sections of microwave beam, which was generated via the MIG-3 GYROTRON complex using special elaborate initiators (see figures 5 and 6). Many experiments were performed with initiators being placed into the beam cross sections at distances of 650 mm and 440 mm from the outer window of the GYROTRON.

The minimum beam cross section at a distance of 650 mm is elliptical with semi-axes of $a = 3$ cm and $b = 1$ cm. The cross sectional area is $S = \pi ab = 9.5$ cm$^2$. At a distance of 440 mm, the beam cross section is circular with a radius of $3$ cm: $S = \pi r^2 = 28$ cm$^2$. The electric field in the beam may be calculated using the formula $E_{max} = 27.5 \left(\frac{P}{S}\right)^{0.5}$ V/cm, where $P$ is the microwave power expressed in watts, and the beam area $S$ is in cm$^2$. At the minimum beam cross section at the specified power of 200 kW, we have $E_{max} = 3990$ V/cm, whereas in the circular region, $E_{max} = 2300$ V/cm.
Even at the maximum powers of the microwave pulse, the values of reduced electric field in the beam do not exceed $\gamma \leq 10^{-16} \text{ V cm}^2$. Note that this value is more than one order lower than the threshold for generation of a self-sustained discharge in free space [10]: $\gamma_{\text{thr}} \approx 10^{-15} \text{ V cm}^2$.

Figure 5. Scheme of the experimental setup designed for the SNSS-discharge excitation using a subthreshold microwave beam in free space of atmospheric air. a) 1-MIG-3 Gyrotron complex; 2-microwave beam; 3-microwave reflecting mirrors; 4-SNSS-discharge; 5-initiator; 6-microwave absorber; 7-high-speed video camera; 8-streak camera FER-7; 9-optical spectrograph; 10-photomultiplier. b) 1-initiator; 2-microwave absorber; 3-SNSS-discharge.

Figure 6. Scheme of the experimental setup designed for the SNSS-discharge excitation in a closed cylindrical chamber using a subthreshold microwave beam. a) 1-MIG-3 Gyrotron complex; 2-microwave beam; 3-microwave reflecting mirrors; 4) microwave transparent window; 5) SNSS-discharge; 6-initiator; 7-high-speed video camera; 8-streak camera FER-7; 9-optical spectrograph; 10-photomultiplier; 11-microwave absorber; 12-cylindrical chamber. b) 1-initiator; 2-microwave absorber; 3-cylindrical chamber; 4-working gas intake fitting; 5-working gas withdrawal fitting; 6-microwave transparent window; 7-SNSS-discharge.
The construction and properties of the initiator, which is specially designed for our experiment, are such that it does not require any external energy source and does not reflect any substantial portion of the incident microwave radiation energy, which would otherwise entail disruption of microwave generation. The initiator is a tangle of chaotically arranged thin metal filaments with a diameter of ~0.5 mm. This construction (chaotically arranged metal wires) forms an arch system, which can be easily deformed to cover a substantial part of the microwave beam cross section. Testing of this construction in air at normal pressure (1 atm) demonstrated its efficiency for creating a thin layer of self-sustained discharge plasma adjacent to the initiator. The breakdown mechanism is rationalized as a result of formation of chaotically positioned half-wave cavities, in which the field increases up to breakdown values for atmospheric air. The Q-factor of such cavities for the field amplification must be as high as ~100.

In the TORCH installation, we studied the possibility of exciting an SNSS-discharge in free space in atmospheric air as well as in the closed chamber filled with various gases or gas mixtures at pressures close to the atmospheric pressure. The microwave subthreshold discharge experiments in atmospheric air and in a closed chamber are represented diagrammatically in figures 5 and 6, respectively. Here, behind the initiator, an absorbent load takes place. The two elements presented in figure 5b and figure 6b are indeed those parts, which ensure the SNSS-discharge generation.

The cylindrical chamber can be made of either dielectric or metal. Its diameter may not be less than the beam diameter. The end that faces microwave radiation is closed by a radio transparent window, which is meant for the microwave beam input. The initiator and the microwave absorber are placed near the opposite end of the cylinder.

We used the following diagnostic methods:
- Integral photography of the discharge during the time of the microwave pulse;
- Detection of the transmitted and reflected levels of microwave radiation;
- Recording of dynamics of axial propagation of the SNSS-discharge using a high-speed video camera;
- Streak camera registration of the SNSS-discharge axial propagation using FER-7 GPI operating in the continuous sweep mode;
- Recording of the optical spectrum of emission from the discharge using AVASPEC 2048, 3648 and HR2000 spectrographs;
- Recording of the temporal and spatial behavior of the optical radiation from the SNSS-discharge using FEU-106 photomultipliers.
- Recording of the SNSS-discharge UV-radiation (240 – 360 nm) using GUVA-S12SD UV-photodiodes.

3.2. Results of the experiment
The experiments, which were conducted using the TORCH bench and are illustrated in the schemes of figures 5 and 6, demonstrated the possibility of exciting an SNSS-discharge (in free space and in a closed chamber) at atmospheric pressure in single microwave pulses beginning with a peak power on the order of $P_i \approx 200$ kW and up to 600 kW and pulse duration of $\tau_{MW} \approx 200 \mu$s and up to 20 ms. The discharge excited using a special-purpose initiator occupies an extended volume. When the power is large or when the microwave pulse is long, the discharge axial length is large.

We captured photographs of the discharge, which was excited following the scheme in figure 5, using microwave beams with powers of 200 and 400 kW at different microwave pulse duration. The photographs of the discharge are presented in figures 7 and 8.

From the photographs, we determined the axial advance velocity of the SNSS-discharge that is freely localized in the atmospheric air. The measurement data are summarized in figure 9. The axial size of discharge achieved the value as high as $L \approx 50$ cm.

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Figure 7. Photographs of SNSS-discharges in a free space of atmospheric air under different durations of microwave pulses. $P_i = 200$ kW.

Figure 8. Photographs of SNSS-discharges in a free space of atmospheric air under different durations of microwave pulses. $P_i = 400$ kW.

Figure 9. Time dependence of the SNSS-discharge excited in the atmospheric pressure air. The axial velocity is determined from the photographs (curves 1 and 2) and from the UV-photodiode signals (curve 3). $P_i = 400$ kW (curve 1) and 200 kW (curves 2 and 3, respectively). $\tau_{MW} = 6$ ms.
UV radiation of the SNSS-discharge excited in the atmospheric pressure air was registered during one microwave pulse with a help of five GUVA-S12SD UV-photodiodes that were placed 5 cm apart on a slat. The spatial resolution of radiation on the beam axis is \(\Delta L \approx 2\) cm. Time dependence of the SNSS-discharge axial velocity is shown in figure 9 (curve 3).

To determine the axial advance velocity of the SNSS-discharge during one microwave pulse, we treated the streak camera images of the SNSS-discharge obtained using FER-7 operating in a continuous sweep mode. This photograph is presented in figure 10. The slit of the camera was oriented along the discharge axis (which is vertical in the figure), where the horizontal coordinate is the time. Typical temporal and spatial scales are indicated in the figure. As evident from figure 10, the discharge moves toward the microwave radiation with a velocity of \(\sim 10^4\) cm/s. This result agrees well with the results obtained from the photos and UV-photodiode measurements.

![Figure 10. Streak camera image of the SNSS-discharge in the atmospheric pressure air obtained using FER-7 operating in a continuous sweep mode. Free space conditions. \(P_i = 200\) kW.](image)

Note that the maximum brightness is observed at the background of the discharge front, whereas the brightness weakens behind the front.

We captured photographs in air using a high-speed video camera in the frame mode. The characteristic photographs are presented in figure 11. The time between frames is 4 ms; the exposure time is \(2/5000\) s = 200 \(\mu\)s. The microwave power is 200–300 kW, and the duration is 6 ms.

![Figure 11. High-speed photography of the SNSS-discharge (air, free space conditions). \(\tau_{MW} = 6\) ms; \(P_i = 200\) kW. a) Starting stage of the discharge; b) a 4-ms delay after the first frame; c) post-discharge stage.](image)
One can see from the photographs and UV-photodiode oscillograms that the intensity is maximal at the front. However, it weakens behind the front, which may be explained by the reduction in microwaves. A similar picture is observed in oscillograms, which were recorded using a photomultiplier. The discharge emission dynamics, which were recorded using FEU-106 positioned at a distance of 8 cm from the initiator, are presented in figure 12. Collimation ensures that the spatial resolution is approximately 2.5–3.0 cm. The microwave power is 200 kW, the duration is 4 or 6 ms. One can see how the intensity initially rapidly increases and then decreases behind the discharge front.

![Figure 12. Photomultiplier signal oscillogram. SNSS-discharge in air (free space conditions). L = 8 cm; P_{i} = 200 kW; t_{MW}=4 ms.](image)

The optical emission spectrum of the discharge in air was studied using AVASPEC 2048, 3648 and HR2000 spectrographs. The most representative spectrum was obtained using an HR2000 spectrometer in the range of 300–400 nm. The second positive system of nitrogen falls precisely in this range. Figure 13 shows the spectrum of microwave discharge in air with identification of bands of the second positive system of nitrogen. The treatment of spectra similar to those presented in figure 13 confirms that the gas temperature in the observed region is ~4000–4800 K.

![Figure 13. Optical spectrum of the SNSS-discharge in air (free space conditions). P_{i} = 200 kW; t_{MW} = 6 ms.](image)

Figure 14 presents a photograph of the SNSS-discharge, which is excited according to the experimental scheme in figure 6, in the CH_{4}:CO_{2} mixture filling a closed chamber at atmospheric pressure. When we used methane-hydrogen and methane-water mixtures, the Hα line was present in the emission spectra (see figure 15). Based on the assumption that the Stark mechanism is responsible for the broadening of this line, we conclude that the electron density in the discharge exceeds $10^{16}$ cm$^{-3}$. 

![Figure 14. A photograph of the SNSS-discharge.](image)
3.3. Discussion of the experimental results

The structure of the discharge, which is excited according to the schemes in figures 5 and 6, as well as the dynamics of its propagation in the microwave beam correspond to the characteristics of SNSS-discharges described in [3, 5, 14]. The fact that the axial velocities observed in the present work fall outside the previous values (e.g., in [3]) may be primarily due to the experimental conditions. When using MIG-3, we managed, for the first, time to increase the level of the working gas pressure to atmospheric. Taking into account the strong dependence of velocity, $V_{Zi}$, on pressure ($\sim 1/p_0^4$), as predicted by expression (5), the reduction in axial velocity in the described experiments is well substantiated. The relatively large values of $\nu_{\text{eff}}/\omega$, exceeding 10, are in line with (7) and explain the high electron density of $n_e \approx 10^{16}$ cm$^{-3}$, which was obtained from the Stark broadening of the H$\alpha$ line. The gas temperature in the discharge region, which was determined in our experiment, was found to be 4 000–4 800 K. These values are lower than the values of 5000–7000 K, which were found in the early experiments [3, 5, 14] in the centimeter wavelength range at gas pressures substantially below the atmospheric pressure.

Using the physical model of the SNSS-discharge, which was developed in [3, 13], estimations of the specific energy input, $\epsilon$, in the elementary discharge “thread” can be made:

$$\epsilon \approx \sigma E_0^2 \tau_i$$

(9)
where, $\sigma$ is the conductivity of the structural “thread”, and $\tau_i$ is the time of the “thread” interaction with microwave radiation during the ionization wave propagation.

Proceeding from the position that [10]:

$$\sigma \approx n_e e^2 \nu_{eff}/m(\omega^2 + v_{eff}^2)$$

(10)

with the assumption that $\nu_{eff} >> \omega$, we obtain:

$$\sigma \approx 2.82 \times 10^{-4} n_i/\nu_{eff} \quad \Omega^{-1} \text{ cm}^{-1}$$

(11)

Here, $n_i$ is in $(\text{cm}^{-3})$, and $\nu_{eff}$ is in $(\text{s}^{-1})$.

Thus, the estimation formula for the specific energy input takes the form of:

$$\varepsilon \approx 2.82 \times 10^{-4} n_i/\nu_{eff} E_0^2 \tau_i$$

(12)

where, $E_0$ is in $(\text{V/cm})$, and $\tau_i$ is in $(\text{s})$.

If we insert in (12) the characteristics of our experiment data ($n_i \approx 10^{16} \text{ cm}^{-3}$, $\nu_{eff} \approx 2 \times 10^{11} \text{ s}^{-1}$, $\tau_i \approx 5 \mu\text{s}$ and $E_0 \approx 2 \times 10^3 \text{ V/cm}$), the specific energy input in the “thread” will be as high as

$$\varepsilon \approx 0.4 \text{ kJ/cm}^3$$

Hence, the discharge observed in our experiment can be classified as an SNSS-discharge for the following reasons:

- The discharge is excited under conditions that the reduced electric field in the gas volume occupied by the beam is substantially below the threshold for the excitation and maintenance of the self-sustained discharge;
- Structurally, the discharge forms from thin separated channels (filaments) that are stretched along the microwave electric field;
- The axial propagation velocity of the plasma in each channel, and both gas and gas-discharge plasma parameters agree with the SNSS-discharge physical model.
- As it has been predicted by the physical model [3, 5], the discharge excited in this experiment is the source of intense UV-radiation.

The results obtained in the described experiments allow us to begin the development of a laboratory plasmachemical reactor, which is based on a high-power beam of millimeter-wavelength radiation, by following the scheme depicted in figure 6 based on the MIG-3 GYROTRON complex.

The main studies in the area of plasmachemistry that are promising for the current technology would be pertinent to the following problems:

- carbon dioxide conversion of methane into synthesis gas;
- water vapor conversion of methane into synthesis gas;
- utilization of carbon dioxide.

A series of foregoing experiments and theoretical (calculation) work (see [17–20]) have shown that the peculiarity of this type of discharges is the “filament” plasma structure, which is characterized by a high electron density, both high electron and gas temperature, and by record-breaking high specific energy deposition. It is very attractive for solving some plasmachemical problems, including the abovementioned problems. This phenomenon is explained by the fact that the extremely high gas temperatures attainable in filaments at the nonlinear stage of the ionization-overheating instability lead to the almost total decomposition of the working gas molecules into radicals and atoms. The fast cooling of the “thread” structures is accompanied by quenching the gas volume processed with the discharge composition. In the framework of the “Chemical Bench” program [21], calculations were performed, in which a filament was modeled sequentially using two reactors at thermal equilibrium. In one of the reactors, the gas was heated up to the temperatures corresponding to those attained within our experimental times and measured in our experiment. For the other reactor, the process of cooling was reproduced according to the dynamics observed in our experiment. The design-theoretical efficiency of plasmachemical processes was close to the experimentally measured value.

The approximate expression for the axial dimension $L_a$ of the SNSS, in accordance with (5), may be represented in the form:
Based on relation (13) and taking it into account in our experiments in air for $\tau_{MW} = 2$ ms and $P_i = 200$ kW, the length of $L_b \approx 15$ cm was observed. We considered the possibility of the formation (in both free space and cylindrical chambers) of extended SNSS-discharges. We assumed the parameters of a single pulse: $\tau_{MW} = 20$ ms and $P_i = 600$ kW, which is maximal during the operation using the MIG-3 GYROTRON complex. In addition, we investigated a possibility of extending the discharge length up to 10–15 m, which is required for the practical implementation of the method.

The possibility of exciting long SNSS-discharges in atmospheric pressure gases can significantly expand their application area by including the problems of global gas-discharge cleaning of atmosphere from ozone-destructing impurities as well as industrial waste gas cleaning from ecologically harmful contaminations.

The physical aspects of the specific problems of cleaning atmosphere from chlorofluorocarbons (Freon) have been discussed in a series of works at the General Physics Institute and Institute of Applied Physics [17, 22–24]. As an approach for destroying chlorofluorocarbons, subthreshold microwave beams, which are generated by an earth-based station and focused at the chosen altitudes, have been considered. Realization of these objectives for the SNSS-discharges, which are excited using the presented scheme in figure 16, can be performed due to the characteristics that are typical for this discharge form. Among them, the most critical are the following:

- Use of a relatively low microwave power value (lower than the threshold value), which leads to the cheapening of the cleaning technology;
- Higher specific energy input in a gas medium than in the threshold beams due to the low (subsonic) velocity of SNSS ionization wave extension;
- Simplicity of SNSS-discharge initiation and its size control;
- Possibility within the limits of modern microwave technique to excite a plasma column as long as 20–30 m.

The achievement of meter axial lengths of SNSS-discharges in microwave beams may be also used to design an electric discharge system for cleaning industrial gas ejections (a schematic version is depicted in figure 17).

![Figure 16](image)

**Figure 16.** Schematic representation of the atmosphere cleaning system, which is based on the SNSS-discharge. 1-GIROTRON and microwave antenna; 2-SNSS-discharge; 3-initiator; 4-microwave beam; 5-pilotless vehicle.
4. Conclusions
Due to the performed at the GPI experiments, the area of realization of a new form of the deeply subthreshold self/non-self-sustained (SNSS) discharge has been considerably expanded. For the first time, the excitation of this discharge at gas pressure of the order of (and higher) than atmospheric pressure was demonstrated in free space of atmospheric air as well as in a closed cylindrical chamber filled with different gases.

For the first time, the SNSS-discharge was created using millimeter wavelength microwave beams at a high pulse power of ≈600 kW. For the first time, the discharge was initiated in any beam cross section using a specially made construction, which is composed of metallic thin threads. In this case, discharge initiation as well as its maintenance in the form of axially propagating ionization wave was carried out using only one microwave energy.

Discharge parameters are compatible with those predicted by the physical model, which considered the SNSS-discharge as a progression of sequential transitions of non-self-sustained and self-sustained discharges through the excitation and development of ionization-overheating instability.

GYROTRON was applied, which is capable of generating in a pulse-periodical regime a microwave radiation with an average power of several hundred kW (at the peak pulse power of ≈600 kW). Due to its relative simplicity, this microwave radiation, interfaced with a cylindrical reactor chamber as well as high efficiency value of microwave energy contribution to the deeply subthreshold discharge and through it in a gas medium, allows to draw conclusions about the feasibility of plasmachemical reactor creation based on the GYROTRON and SNSS-discharge, which can satisfy modern industrial requirements of various chemical technologies such as methane conversion in syngas, CO$_2$ utilization, industrial gaseous waste cleaning, etc.

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