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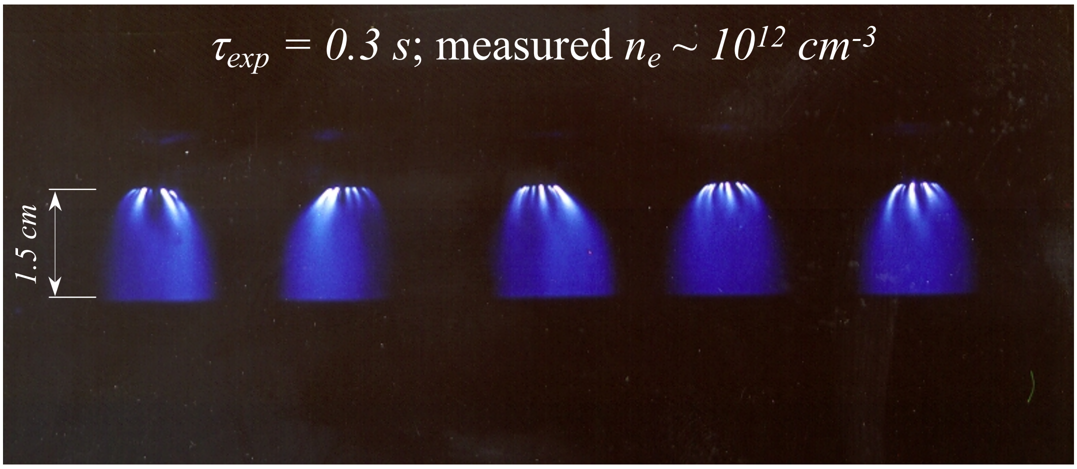

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SE-581 11 Linköping

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Author/s (editor/s) Y. Serdyuk [1] A. Bondeson [2] S. Gubanski [1] [1] CTH, Department of Electric Power Engineering [2] CTH, Department of Electromagnetics	**Project manager** Jonas Rahm	
	Approved by Svante Ödman	
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	Scientifically and technically responsible Jonas Rahm	

Report title

HIGH-PRESSURE PLASMAS FOR RADAR WAVE ABSORPTION

Abstract (not more than 200 words)

Possible ways of generating plasmas with sufficiently high electron density and gas pressure for efficient absorption of radar waves are studied by means of numerical solution of fluid equations and analytical estimates, using available coefficients on ionization and recombination. It is found that helium, or a helium-argon mixture are is the most suitable gas. The computational modeling in two dimensions indicates that stable discharges can be generated with dielectric-coated electrodes at driving frequencies in the range of 1 MHz. One-dimensional computations were undertaken and reached densities in the vicinity of the required values. One problem is the rather high power consumption that is expected for a sufficiently dense plasma. Both the numerical simulations and theoretical estimates indicate that the required power consumption is in the range of several tens of kW/m^2. In order to obtain more conclusive results, an experimental test would be necessary.

The study was carried out at the Department of Electrical Power Engineering and Department of Electromagnetics at Chalmers, from October 2001 until March 2002, and was supported by FMV and FOI.

Keywords

High-pressure plasma, radar wave absorption, radar cross section

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Y. Serdyuk [1]
A. Bondeson [2]
S. Gubanski [1]

[1] CTH, Institutionen för Elteknik
[2] CTH, Institutionen för Elektromagnetik

Projektledare
Jonas Rahm

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HÖGTRYCKSPLASMA FÖR ABSORPTION AV RADARVÅGOR

Sammanfattning (högst 200 ord)

Möjliga sätt att generera plasma med tillräckligt hög elektrontäthet och gastryck för effektiv absorption av radarvågor studeras med hjälp av numeriskt lösta flödesekvationer och analytiska estimat, baserade på tillgängliga jonisations- och rekombinationskoefficienter. Det visar sig att helium, eller en blandning av helium och argon, är den mest lämpliga gasen. Den tvådimensionella datamodellen visar att stabila urladdningar kan genereras med dielektriskt belagda elektroder vid drivfrekvenser i 1 MHz-området. Utförda endimensionella beräkningar gav tätheter i närheten av behövliga värden. Ett problem är att det krävs hög effekt för att generera ett tillräckligt tätt plasma. Såväl de numeriska simuleringarna som de teoretiska estimaten indikerar att erforderlig effektförbrukning är i storleksordningen flera tiotals kW/m^2. För att kunna erhålla ett mer slutgiltigt resultat krävs experimentella försök.

Denna studie har utförts vid Institutionen för Elteknik och Institutionen för Elektromagnetik vid Chalmers tekniska högskola, från Oktober 2001 till Mars 2002, och har finansierats av FMV och FOI.

Nyckelord
Högtrycksplasma, absorption av radarvågor, radarmålarea

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CONTENTS

1. General Information

The aim of the project was to study a possibility of generating a homogeneous layer of plasma with high electron density in a gas, which could be used as an absorber of electromagnetic radiation. The theoretical background and analysis of the absorbing properties of plasma has been developed in [1]. As an example, significant RCS reduction can be obtained with a plasma of electron density at least 5 x 10^{12} cm^{-3} in helium with a background pressure at least 50 Torr. To study such a possibility by means of electrical discharges in gas, in particular inert gases with small recombination losses, a mathematical model of high frequency electrical discharges has been developed and implemented in FORTRAN computer codes. Numerical simulations and parametric study of the behaviour of gas discharge plasma under different conditions have been performed. It was found that parameters of the plasma (densities of charged particles, stability, energy dissipation, etc.) could be controlled by combining the parameters of the system (arrangement of electrodes, gas composition and pressure, shape and frequency of the applied voltage, level of pre-ionisation of the gas, etc.). The results obtained from the numerical simulations are presented in Secs. 2-5.

2. Basic Processes in Gas Discharges

A gas under normal conditions is a perfect insulator. If a low voltage $U \sim 10^2\ V$ is applied between parallel plate electrodes placed in the gas and separated on a distance S, a current $I \sim 10^{-13}\ A$ can be registered. This current is observed as a consequence of a background ionisation due to cosmic rays, radiation of Earth, etc. But if the external field becomes high enough to accelerate charged particles, in particular electrons, at certain field they start to produce non-elastic collisions with neutral molecules (atoms). If the electron energy becomes higher than the ionisation potential of the gas, they create new electrons and positive ions according to the scheme

$$e + A \overset{k_i}{\rightarrow} A^{+} + e + e \qquad (1)$$

Here e, A and A^+ stand for the electron, atom and positive ion, respectively; k_i is the rate constant of the process, cm^3/s. The rate of the ionisation can be expressed as $dn_e/dt = k_i n_e N_a$, where n_e and N_a are the densities of electrons and atoms, cm^{-3}, and t is the time, s . Thus, the product $\nu_i = k_i N_a$ gives the ionisation frequency, i.e the number of ionising collisions per second. The number of ionisation acts per $1\ cm$ of length, which an electron passes in the field is the ionisation coefficient $\alpha = \nu_i / w_e = \nu_i / \mu_e E$ ($w_e = \mu_e E$ is the drift velocity of electrons, cm/s; μ_e is the mobility, $cm^2/(V\,s)$; and E is the electric field strength, V/cm). It is well known that the ionisation coefficient strongly (usually exponentially) depends on the electric field $\alpha / p = f(E/p)$ (p is the gas pressure). The actual dependence is unique for each gas or gas mixture. If the ionisation rate is higher than the rate of losses of electrons, an electron avalanche forms. On the way to the anode the electrons are concentrated in the avalanche head. The tail of the avalanche is formed by the produced positive ions, which are much slower and move in the opposite direction - to the cathode. The number of electrons in the avalanche can be found as $n_e = n_{e0} \exp(\nu_i t) = n_{e0} \exp(\alpha x)$, where n_{e0} is the density of initial electrons, and x is the length of the avalanche. The metallic anode absorbs the electronic cloud reaching its surface, while secondary electrons are emitted by the positive ions from the cathode surface. Under certain conditions this process becomes self-sustained and leads to the phenomenon called Townsend's (or silent) discharge. It should be noted that an electron avalanche could be considered as an initial stage of any kind of electrical discharges in gases.

Recombination of electrons and ions is one of the most important processes, which controls losses of electrons in gas discharge plasma. In particular, this is only one mechanism of losses in inert gases if losses on the surfaces of electrodes or on the walls of a discharge chamber are excluded, and this can be arranged if the plasma is completely surrounded by a dielectric.
Inert gases are of particular interest, because the recombination rates are much lower than in ordinary diatomic gases. The recombination involving monatomic ions is negligible. Nevertheless, there are several kinds of electron – ion recombination in inert gases, and the most effective are:

(i) dissociative recombination, which happens in two steps – first, atomic ions convert to molecular ions (reactions of conversion) $A^+ + A + A \to A_2^+ + A$, and then the dissociation of the molecular ions takes place $A_2^+ + e \to A^* + A$ (A^* stands for an exited atom);
(ii) recombination in three-body collisions $A^+ + e + e \to A^* + e$.

These processes have different rate constants (i.e. recombination frequencies) and each of them can dominate under certain conditions. It should be noted that at the rather high densities required for radar absorption, the ions in inert gases are predominantly molecular ones, because the process $A^+ + A + A \to A_2^+ + A$ is fast. The rate of single-electron-ion recombination is $dn_e/dt = -\beta n_e n_p$ (here β is the recombination coefficient, cm^3/s; n_p is the positive ion density, cm^{-3}). The recombination coefficient can be expressed as $\beta = k_r^{dis}$ and $\beta = k_r^{tr} n_e$ for processes (i) and (ii), respectively, with the corresponding rate constants k_r^{dis}, cm^3/s and k_r^{tr}, cm^6/s.

3. Mathematical Description of the Discharge Plasma

If variations of the electric field between electrodes are slow in comparison with the time scale of the motion of electrons, they are able to reach equilibrium with the field at each time moment. The time of electronic relaxation in plasma usually is $\sim 10^{-13} - 10^{-12}$ s, that corresponds to the frequency range $f > 10^{12}$ Hz. Up to this limit, plasma can be considered as a continuous matter and it can be treated as a composite liquid consisting of electronic and ionic components. In this case, the development of a gas discharge can be modelled using equations of hydrodynamics, namely the continuity equations for densities of charged particles, which express the charge conservation law

$$\frac{\partial \rho}{\partial t} + div\,\vec{j} = 0 \tag{2}$$

Here ρ is the charge density, and $\vec{j}$ is the vector of current density.

Equation (2) is the consequence of the system of equations of mass balance for charged particles. In the case of inert gases the system of equations consists of continuity equations for the densities of electrons and positive ions:

$$\begin{cases} \dfrac{\partial n_e}{\partial t} + \nabla \cdot \left(n_e \cdot \vec{w}_e + D_e \nabla n_e \right) = \alpha\, n_e |\vec{w}_e| - \beta n_e n_p \\ \dfrac{\partial n_p}{\partial t} + \nabla \cdot \left(n_p \cdot \vec{w}_p + D_p \nabla n_p \right) = \alpha\, n_e |\vec{w}_e| - \beta n_e n_p \end{cases} \tag{3}$$

Here D_e, D_p are the diffusion coefficients for electrons and positive ions, respectively.

The terms $\vec{\Gamma}_{e,p} = n_{e,p} \cdot \vec{w}_{e,p} + D_{e,p} \nabla n_{e,p}$ are the fluxes of charged particles consisting of the convective part (the first component) and the diffusive flux. The right-hand sides of the equations represent the sources of production (ionisation) and losses (recombination) of particles. All coefficients in equation (3) are dependent on electric field strength and the system of continuity equations should be coupled with Poisson's equation for the distribution of the electric potential ϕ:

$$\nabla(\varepsilon_0 \varepsilon \nabla \phi) = -\rho = -e(n_p - n_e - n_n); \quad E(x, y, z) = -\nabla \phi \tag{4}$$

Here *E(x, y, z)* is the distribution of electric field strength; *e* is the elementary charge; ε is the relative permittivity of the media, and $\varepsilon_0 = 8.854 \, 10^{-14}$ *F/cm* is the dielectric constant.

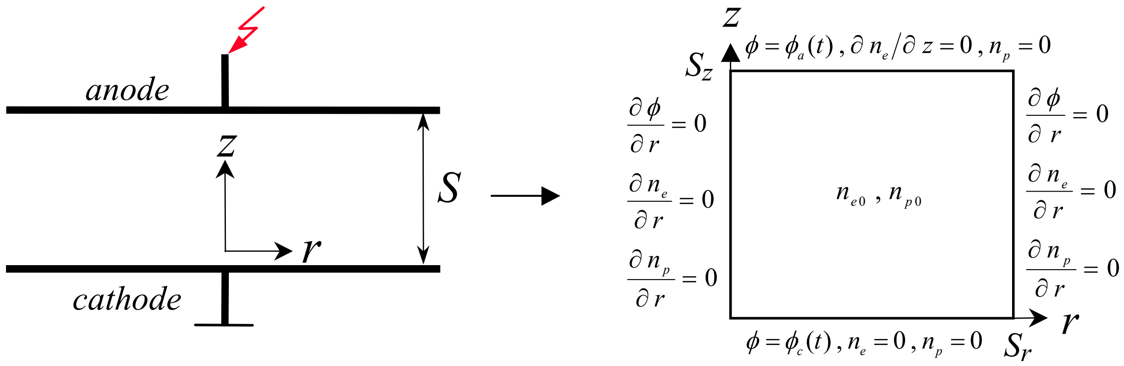
A set of boundary conditions for the equations above should be provided. The particular choice of boundary conditions depends on the problem and geometrical parameters of the domain. In the simplest case of two circular parallel plate electrodes a cylindrical symmetry can be used. This allows reducing the dimensionality of the problem to 2D (Figure 1) and the following boundary conditions can be used:

for particle densities anode: $n_e(t, S_z, r) = 0$ (absorbing boundary)
$n_p(t, S_z, r) = 0$ (reflecting boundary)
cathode: $n_e(t, 0, r) = \gamma \, n_p(t, 0, r) \, w_p(t,0,r)/w_e(t,0,r)$

(γ is the coefficient of secondary emission from the cathode due to positive ions impacts)

for potential anode: $\varphi(t, S_z, r) = \varphi_a(t)$; (Dirichlet b.c.)
cathode: $\varphi(t, 0, r) = \varphi_c(t)$; (Dirichlet b.c.)
symmetry axis: $\partial\varphi/\partial r = 0$; (Neumann b.c.)
outer boundary: $\partial\varphi/\partial r = 0$. (Neumann b.c.)

The electrodes forming a discharge gap can be covered with solid dielectric layers in order to avoid losses of charges. Thus, the set of boundary conditions should be changed. This case is also considered below.



(a) (b)

***Fig. 1**. The physical (a) and the computational (b) domain.*
The boundary conditions are shown on the right.

A solution of equations (3) and (4) is time dependent distributions of the densities of the particles and the electric field. Knowing these parameters several integral plasma properties could be obtained. The most important are:

- electric current $I = \frac{2\pi e}{\phi_a - \phi_c} \cdot \int_0^{S_r}\int_0^{S_z} \left(\vec{\Gamma}_p - \vec{\Gamma}_e\right) \cdot \vec{E}_L \, dz\, dr + \varepsilon_0 \cdot \int_0^{S_r}\int_0^{S_z} \varepsilon \frac{\partial \vec{E}}{\partial t} dz\, dr$, *A* (here the fist term is the conductive current and the second one is the displacement current; E_L denotes the distribution of the Laplacian field);
- electrostatic energy $P = \varepsilon_0 \varepsilon \left|\vec{E}\right|^2$, *J/cm*^{3};
- Joule dissipation $Q = \vec{j} \cdot \vec{E}$, *W/cm*^{3} (here $\vec{j}$ is the current density, *A/cm*^{2});
- conductivity of plasma $\sigma = j / E$, *S/cm*.

The coupled equations (3) and (4) with appropriate boundary conditions allow simulations of development of discharge plasma in different gases. This requires using kinetic coefficients and coefficients in source terms in equations (3) corresponding to a particular gas. In the project a He-plasma was considered, mainly because of low rate of electronic losses, and the following kinetic coefficients were used [2]:

- Ionisation coefficient $\alpha = p \cdot A \exp(-B / \sqrt{E/p})$, *cm*$^{-1}$.
  The constants: A = 8 and B = 16 were used for pure helium , and A = 4.4, B = 12.5 for the mixture He + Ar (5%). The dependencies $\alpha/p = f(E/p)$ are shown in Figure 2.
- Recombination coefficient $\beta = 10^{-7}; 10^{-9}\ cm^3 / s$.
- Drift velocities of electrons was calculated as $w_e = -8.6 \cdot 10^5 \cdot E / p, cm/s$, and for positive ions $w_e = 3.55 \cdot 10^3 \cdot E / p, cm/s$.
- Diffusion coefficients: $D_e = 2 \cdot 10^5 / p$, $D_p = 1.01 \cdot 10^2 / p$, cm^2 / s

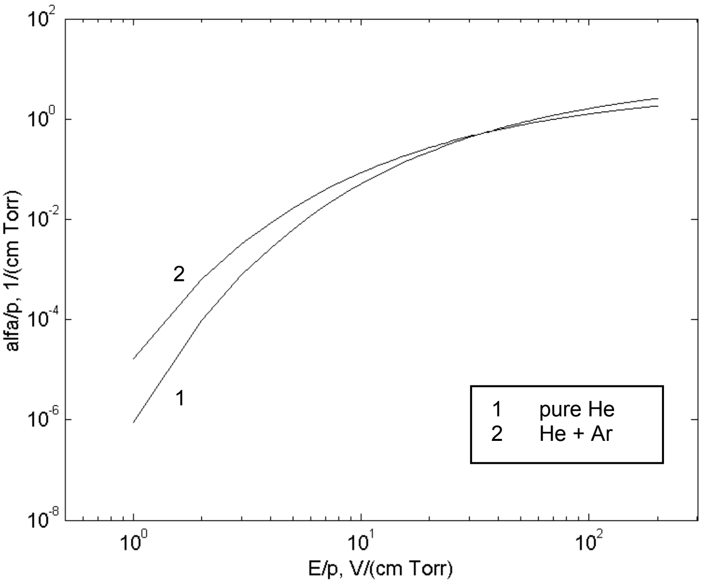


Fig. 2*. Ionisation coefficients for pure He and He + Ar (5%) mixture (upper curve).*

The multiparametric nature of the problem gives a great possibility of controlling internal plasma properties by means of changing external conditions. In general case the following parameters can be varied:

- Inter-electrode distance S_z.
- Configuration of electrodes.
- Gas pressure p.
- Gas composition (affects mainly ionisation coefficient α).
- Boundary conditions (solid dielectric covers, secondary emission, losses of particles through the boundaries, etc.).
- Applied voltage $U = \phi_a - \phi_c$ (amplitude; frequency; potentials of different shapes, for example, sinusoidal (on the anode) + impulse (on the cathode), etc.).
- Initial conditions (initial density of charges, a shape of the initial plasma spot)
- Characteristics of the external circuit (resistance, capacitance, and inductance).

The influence of several of them on discharge development was studied.

4. Numerical techniques

Solving a gas discharge problem is a challenging task. The system of continuity equations (3) is a stiff system (in the sense that different processes have significantly different time scales) and the equations become strongly non-linear when electric fields are high enough for ionisation. Another problem is short time steps and fine spatial grids needed for resolving steep gradients of densities of particles at the boundaries of moving plasma. This makes the problem to be very time consuming for computing and special algorithms are required.

Currently, the flux-corrected transport algorithm [3] was used for solving the system of equations (3). When densities of particles were obtained for a current time step, the electric field distribution should be calculated from the Poisson's equation (4). The equation (4) was represented in a discrete form using a finite-volume method and the resulting matrix problem was solved by an iterative method, in particular, the symmetric successive overrelaxation method [4] was employed for the present simulations. The new field distribution was used to compute new kinetic coefficients needed to perform the next time step in equations (3), and so on. The algorithm used for solving the problem is shown in Figure 3.

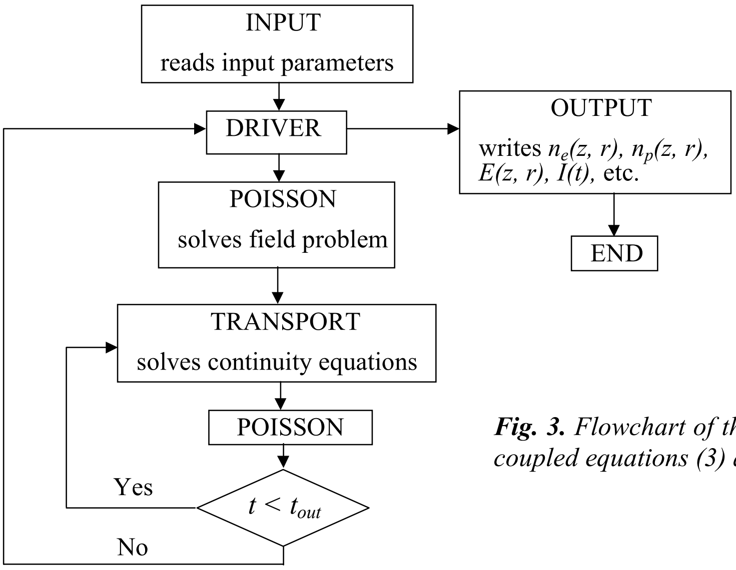


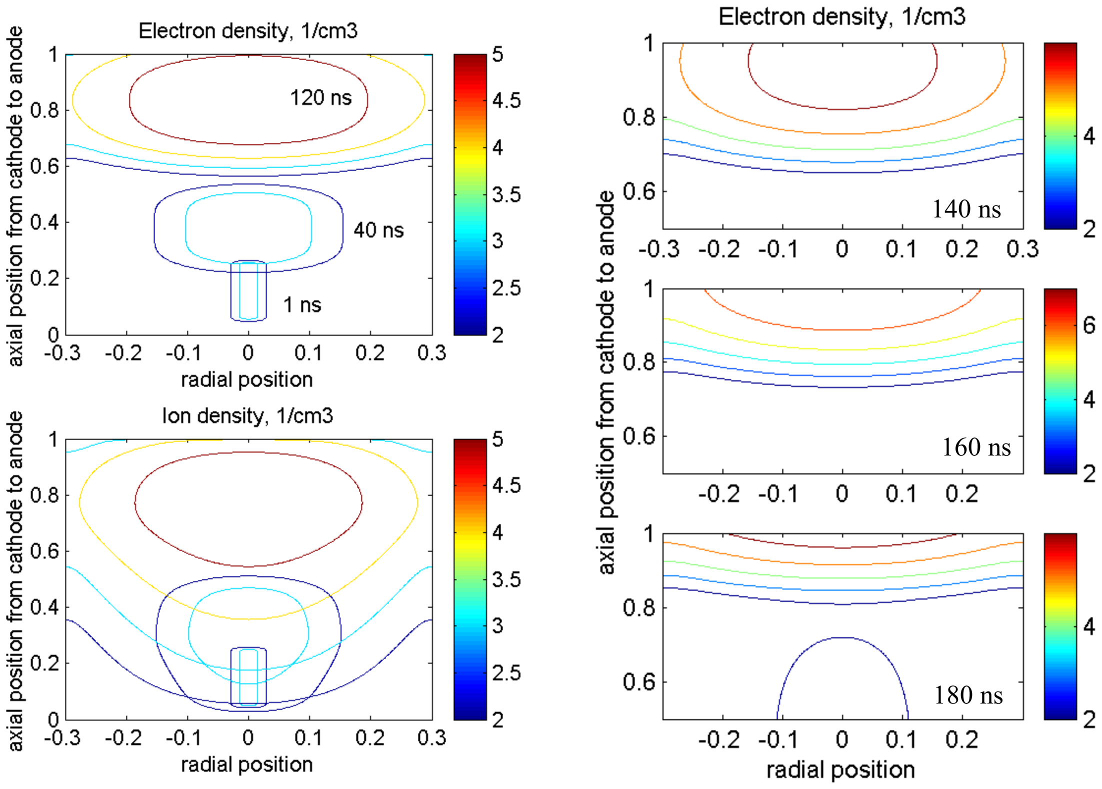
Fig. 3. *Flowchart of the algorithm of solving the coupled equations (3) and (4).*

5. The Results of the Plasma Modelling.

On the first stage of the project, the discharge development in pure helium in a gap of *1 cm* length with metallic electrodes was simulated. The voltage was a step function with the magnitude of *5 kV* and it was applied at *t = 0*. The discharge was initiated by an initial plasma spot with the densities of the particles of $n_{e0} = n_{p0} = 2\cdot 10^3\, cm^{-3}$ placed in the vicinity of the cathode. It was assumed that the discharge started from one single electron-ion pair, thus the volume of the spot was chosen equal to $5\cdot 10^3\, cm^3$.

Contour plots of electronic and ionic densities obtained for the avalanche phase of the discharge development are presented in Figures 4. The radial position *r = 0* corresponds to the symmetry axis. The indexes on the colour bars are the values of $\log_{10}(n_{e,p})$.

As it can be seen from Fig. 4a, the avalanche head approaches the anode surface at *~120 ns* after voltage application and the densities of the electrons and ions reach $\sim 10^5\ cm^{-3}$. At the same time, a radial expansion of the electronic cloud due to diffusion is observed. During the interaction with the anode surface (Fig. 4b), the electrons penetrate into the metal and they are lost for the discharge. The next generation of electrons emitted from the cathode due to secondary emission can be seen at *t = 180 ns*.



(a) (b)

Fig. 4. *Electron avalanche development (a) and its interaction with the anode surface (b). The cathode is located at z = 0 (lower boundary).*

The losses of electrons on metallic surfaces can be avoided by introducing dielectric barriers covering the electrodes. This leads to the opposite effect, namely to accumulation of particles on interfaces gas-dielectric and to formation of surface charges. A sketch of the system with dielectric covered electrodes is shown in Figure 5. Applying a voltage of high frequency, one can produce an electrical discharge in the system. Such a discharge is called a “discharge controlled by dielectric barriers”.

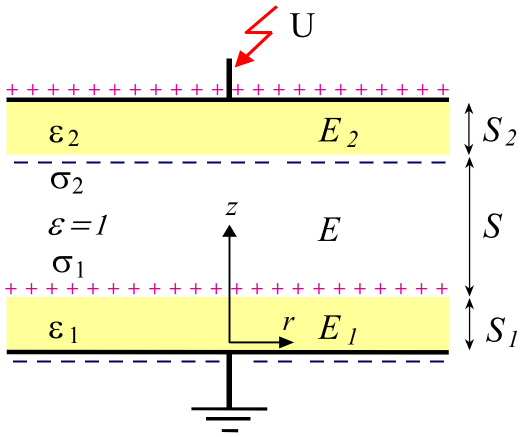


Fig. 5. *Electrodes with dielectric barriers . $S_{1,2}$ and $\varepsilon_{1,2}$ are the thicknesses and the dielectric permittivities of the materials of the barriers, respectively.*

The surface charge densities $\sigma_{1,2}$, C/cm^2 in the system can be calculated as

$$\sigma_1 = e\int_0^t \left(\Gamma_p(S_1,r,t') - \Gamma_e(S_1,r,t')\right)dt',\ \sigma_1 = e\int_0^t \left(\Gamma_p(S_1+S,r,t') - \Gamma_e(S_1+S,r,t')\right)dt'.$$

The influence of the barriers on discharge development is shown in Fig. 6. The simulations were done for pure helium with the parameters: $S = 1\ cm$, $S_1 = S_2 = 0.2\ cm$, $p = 750\ Torr$, $\varepsilon_1 = \varepsilon_2 = 5$, $U = 4.6\ kV$, $f = 1\ MHz$. Other conditions were the same as for the case with metallic electrodes. Time moments are indicated on the graphs (time of one period is 1 mcs).

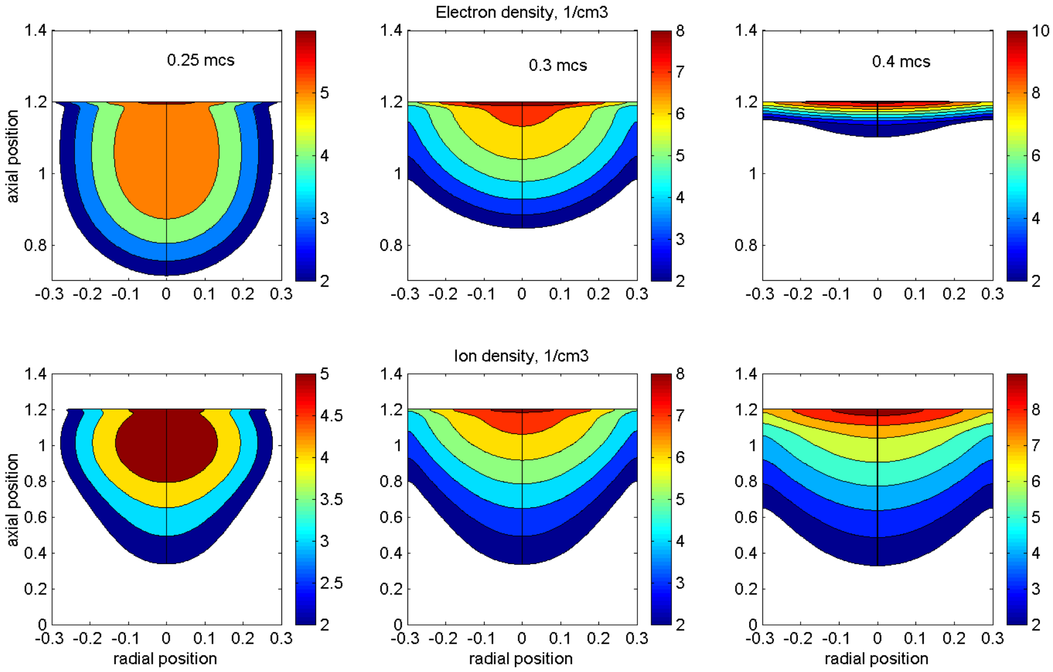


Fig. 6. *The densities of electrons and ions in the system with solid dielectric barriers.*

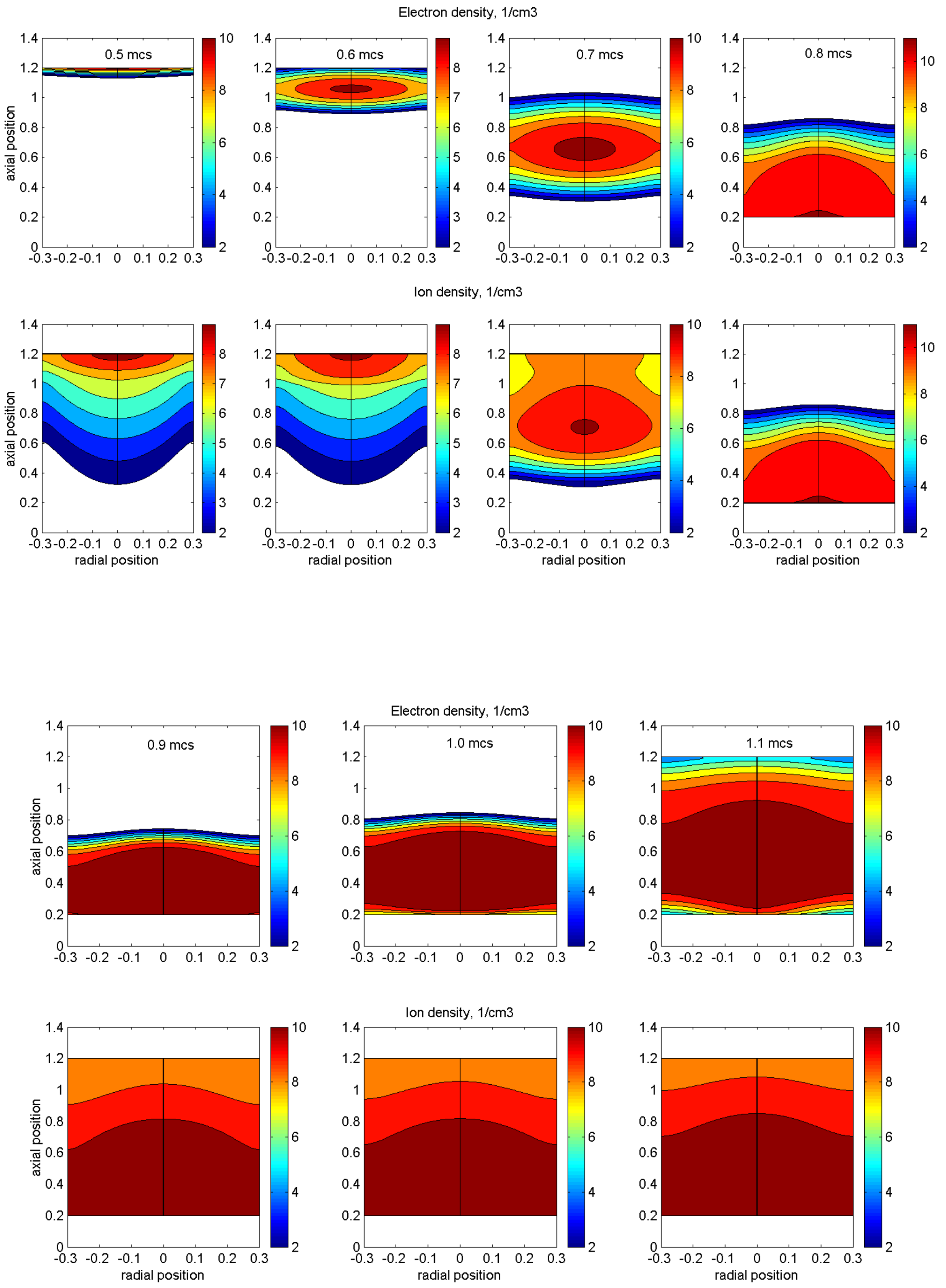


***Fig. 6**. (continued)*

The plots above show the evolution of the electron density and corresponding distributions of the ion density (lower row) during the positive half cycle of the applied voltage (the metallic anode is located at *z = 1.4 cm*). It is seen that when the avalanche approaches the surface of the positively charged dielectric barrier, a thin layer of the electrons is formed due to the radial expansion of charges and the density of electrons increases significantly. The ionic cloud is much broader due to low mobility of ions but radial diffusion is also observed. The layer of electrons becomes even thicker when polarity of the voltage is changing (graph for *t = 0.5 mcs*). During the negative half-cycle the electrons accumulated on the surface of the dielectric initiate a new avalanche propagating to the new anode (graphs for *t = 0.6, 0.7, 0.8 mcs*). At the end of the cycle a surface charge is formed on another barrier, but now its thickness is much larger and it is more homogeneous in radial direction (*t = 0.9, 1.0 mcs*) because of the higher total number of electrons taking place in ionisation. During the following cycles the process repeats itself and the densities of electrons and ions grow, and are distributed more and more uniform.

The observed homogenisation of the plasma allowed us to reduce the dimensionality of the problem and required computational time. The parameters of the discharge calculated using a 1D model for 50 cycles of the applied voltage in pure helium at *p = 450 Torr* and *U = 1.82 kV* are presented in Fig. 7. As can be seen, the amplitude of charge transported by the avalanche (graph (a)) remains practically constant in time. Accumulation of particles on the dielectric barriers produces increasing densities of surface charges (graph (b)), which distort the electric field and leads to its enhancement with time (graph (c)). Electrons generate more charges in a stronger field, which affect field intensity and so on. In practice, the possible consequence of this coupling is plasma instability known as a contraction [2], i.e. the discharge is observed in a filamentary form with high current density and high power losses. An increase of the power density is also obtained in the present calculations (graph (d)).

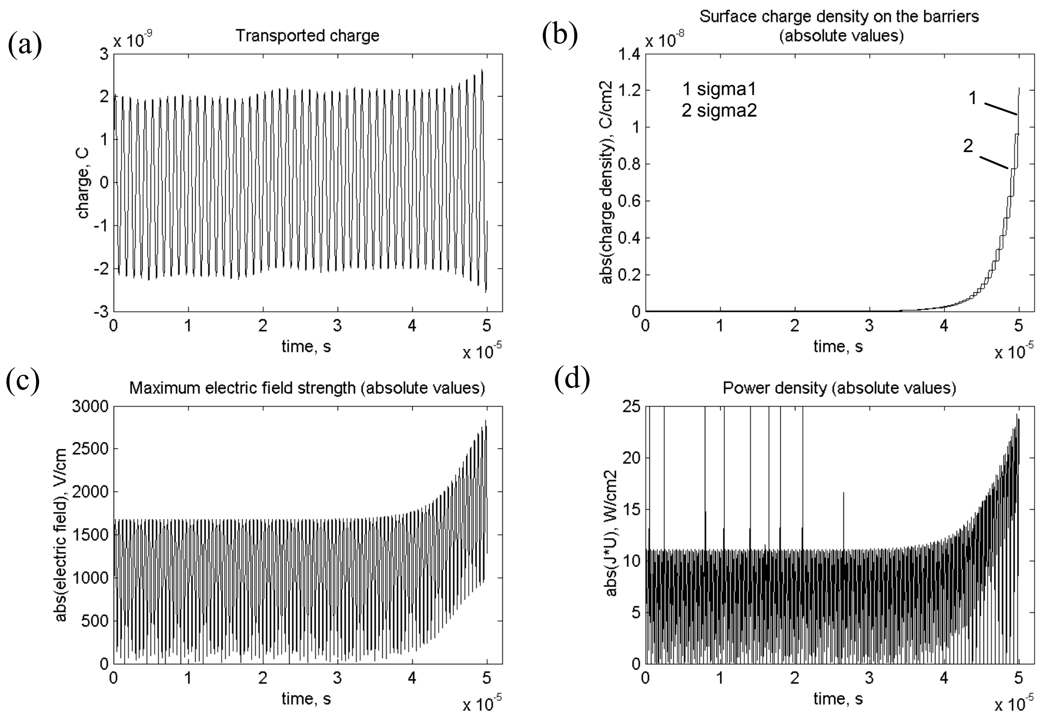


***Fig.** 7. Discharge parameters for 50 cycles of the applied voltage (f = 1 MHz)*

The main reason for the discharge instability is the unbalanced rates of production and losses of charged particles. The ionisation rate in **pure helium** plasma is much higher than the recombination rate $\alpha n_e \mu_e E >> \beta n_e n_p$. The estimated time for recombination is $\tau_{rec} = 1/\beta n_e \sim 1/10^{-7} \cdot 10^{10} = 10^{-3}\, s$ and the influence of losses of charges due to recombination is negligible in the considered time window. The unbalanced rate of production and losses of charges lead to increase of the plasma density. It is, however, difficult to compute accurately what the equilibrium density is, because the density loss and production rates are slow compared to the much faster time-scale for the electric discharge.

There are different ways to establish a balance of charged particles in plasma. One of them is to introduce limited losses on the surfaces of the barriers (or on one barrier). In practice, this could be done by using materials with relatively high conductivity. In the simulations, we changed the boundary condition for electron density on the surface of one of the barriers and introduced an absorption coefficient, which was in the rage *0.2 – 0.3*. At the same time, the discharge parameters were calculated for the mixture *He + Ar (~5%)* instead of pure helium. The dependence of the ionisation coefficient on electric field strength, shown in Fig. 2 (upper curve) was used. It is known that the so-called Penning ionisation takes place in the mixtures of *He* with other gases, in particular with *Ar*. This phenomenon occurs due to the differences in ionisation and excitation potentials of atoms of different gases. For example, the metastable atom He^* (2^3S_1) has excitation energy *19.82 eV* which is higher then the ionisation potential $\varphi_i = 15.8\, eV$ of argon atoms. If such two particles collide, ionisation of the argon atom occurs even in a low field. Thus, the effective ionisation coefficient is higher for the mixture, than for the pure helium that is observed in Fig. 2. The discharge parameters obtained for the mixture at *p = 450 Torr, U = 2.06 kV, f = 1 MHz*, are shown in Figure 8.

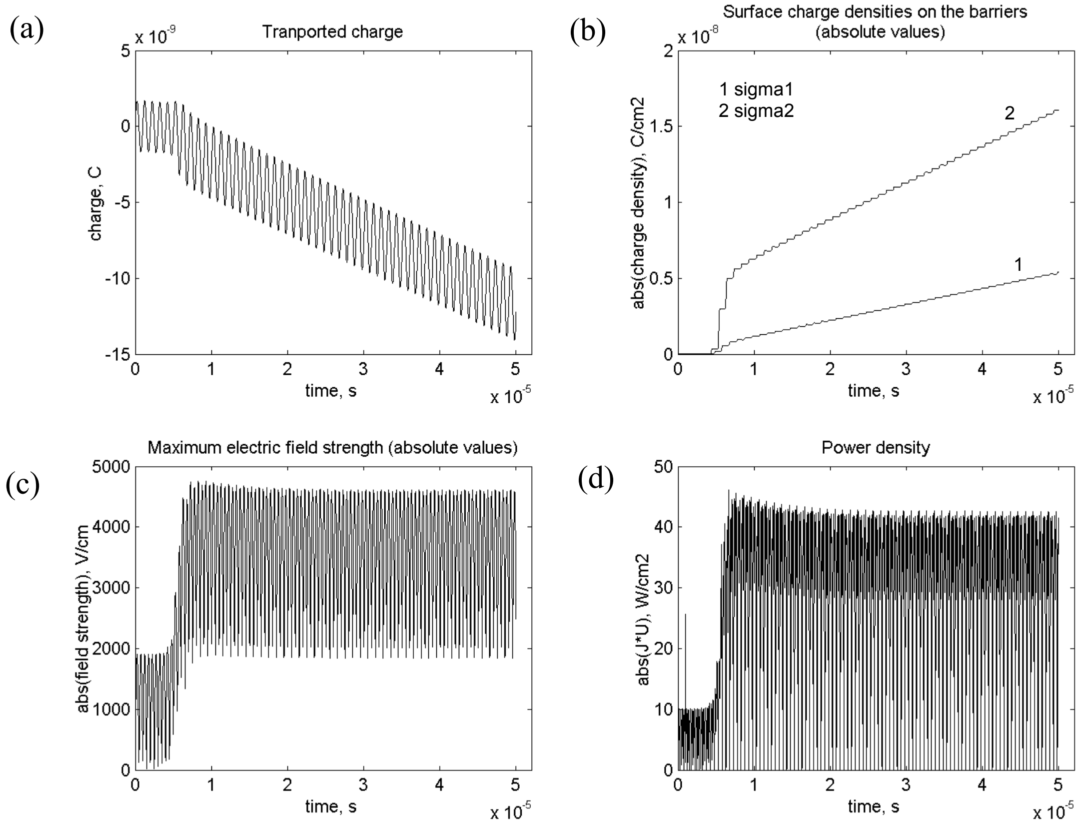


***Fig. 8**. Discharge parameters for He + Ar mixture with limited losses of electrons on the surface of one of the dielectric barriers*

The discharge plasma stabilises after *~10* cycles of the applied voltage. The magnitude of transported charge (graph (a)) grows in time in order to compensate losses of electrons on the "partially transparent" barrier. The surface charge densities reach equilibrium and increase slowly with time (graph (b)). The maximum electric field strength, as well as the power density dissipated in the plasma (graphs (c) and (d)), become practically constant at *t > 10 mcs*. This behaviour corresponds to the steady oscillating discharge current shown in Figure 9. The transients at *t < 10 mcs* are also clearly seen.

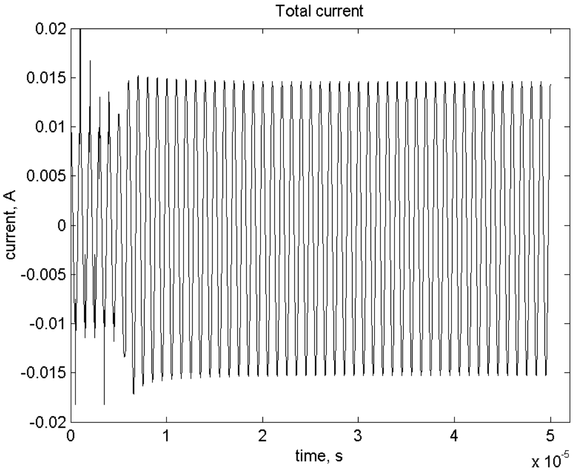


***Fig. 9**. Evolution of the discharge current with time.*

The computed distributions of densities of electrons and ions corresponding to the end of several cycles of the applied voltage (when the voltage is equal to zero), are presented in Figure 10. The densities of charges also reach steady state after approximately 10 cycles of the voltage. It is seen that the layer of electrons is formed (curves 1, 2 and 3), and since it was created, the thickness and the density of electrons within this layer does not change much (curves 4 and 5).

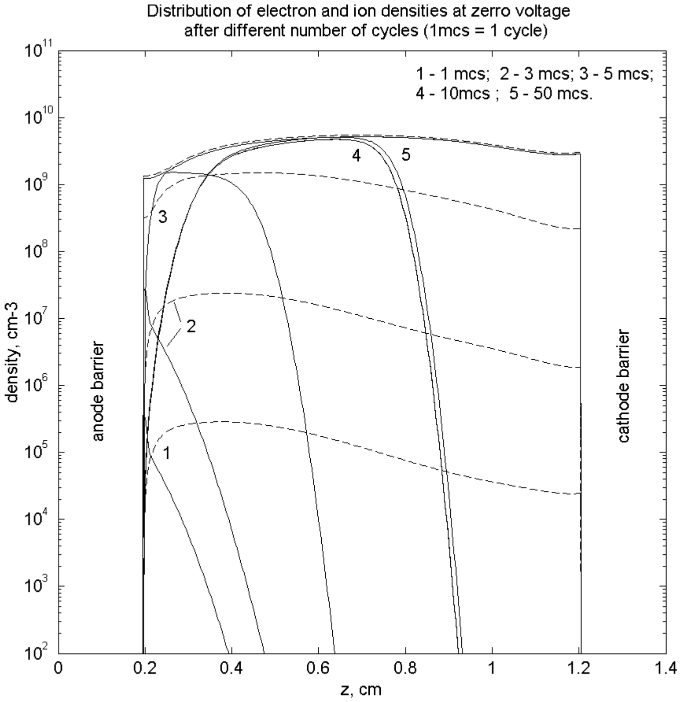


***Fig. 10**. Profiles of electron (solid lines) and ion (dashed lines) densities.*

Simple animations showing evolution of the electron density, the ion density and the electric field strength can be seen by running the avi-files attached to the report (**important** – movies could be seen with Windows Media Player or similar software).

Another way of obtaining stable discharge plasma is to use modulated voltages. For example, a combination of impulses and sinusoidal potentials applied to different electrodes can give promising results. In the simulations, the parameters were similar to the previous case, only the voltage was different. The impulse potential had the amplitude of *2.9 kV* and the decay time *~3 mcs*, and the sinusoidal (*f = 1 MHz*) potential had the amplitude of *1.6 kV*. The resulting voltage shape is shown in Figure 11a. The idea here was to generate the discharge by the impulse of the high amplitude and then to keep it stable using comparatively low voltage needed just to compensate losses of particles and power losses. The resulting discharge current (graph (b)) shows some transients at the beginning of the process and it reaches steady state afterwards. The transported charge and surface charge densities (graphs (c) and (d)) have similar behaviour as in the previous case (compare with Fig. 8a and 8b) excluding the initial stage of plasma formation. The maximum electric field strength (Fig. 11e) and the power density (Fig. 11f) reach steady state after 15-20 cycles and their magnitudes at *t > 20 mcs* are more than two times less in comparison with the case, when only the sinusoidal voltage was applied (Fig. 8c and 8d).

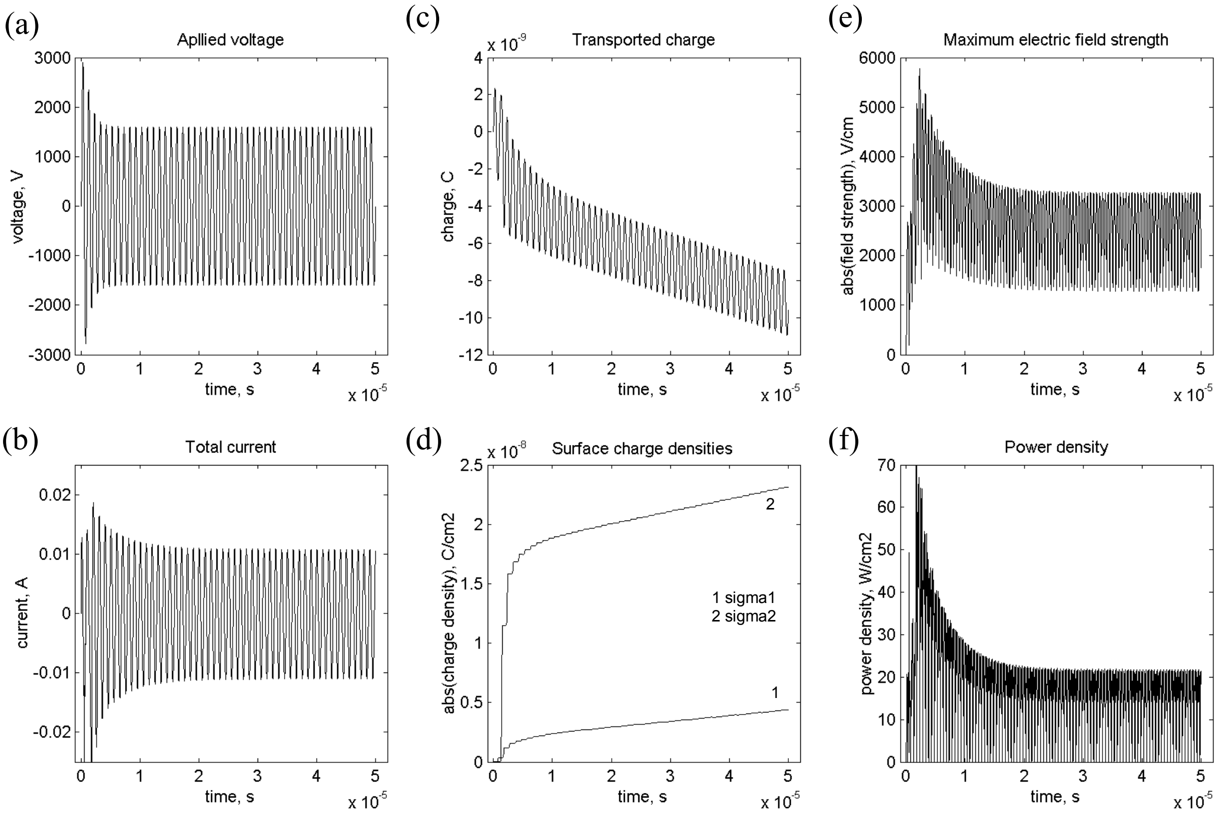


Fig. 11. Computed parameters of the discharge when combined voltage was applied to the gas gap.

6. Summary of numerical simulations

Efficient 1D and 2D computer codes for gas discharge plasma simulations have been developed. The parameters of the discharge plasma obtained from the simulations are not very far from the required parameters, although the densities are somewhat lower than required. Because of the low recombination rates in helium plasmas, it is not easy to obtain very accurate values of the steady-state density. This uncertainty is aggravated by the not-so-well-known values of recombination coefficients and the possible losses of electrons on dielectric surfaces, which can be strongly influenced by the choice of materials. The analysis of the processes taking place in the plasma has shown that there are several ways, which can be used to control discharge properties.

7. Theoretical estimates

Because of the rather slow time-scale for recombination in inert gases, it was difficult to establish the equilibrium between ionisation and recombination accurately in the full time-simulations. Certain conclusions can, however, be drawn with simpler models. For instance, one can easily find the electric field strength at which recombination and ionisation balance. This is obtained by ignoring the left-hand sides in Eq. (3), i.e.,

$$\alpha \cdot n_e \cdot |\vec{w}_e| = \beta \cdot n_e \cdot n_p$$

Using the approximation $\alpha = 4.4 p \exp(-12.5/\sqrt{E/p})$, cm^{-1}, $\beta = 1.3 \times 10^{-9}$ cm^3/s and $w_e = 8.6 \times 10^5 E/p$, then the electric field is determined by the transcendental equation $E \exp(-12.5/\sqrt{E/p}) = 3.4 \times 10^{-16} n_e$. Figure 12 shows the power consumption per square meter from a 1 cm thick layer of plasma generated under such DC conditions, as a function of plasma density for different gas pressures. Given that efficient radar absorption would require a plasma density of at least 5 x 10^{11} cm^{-3} and 50 Torr gas pressure, the power requirement is quite high. This is of course only an estimate, and it may be possible to generate the plasma more efficiently in an AC discharge where the ionisation is made predominantly in short pulses of rather high electric field, which makes the ionisation process

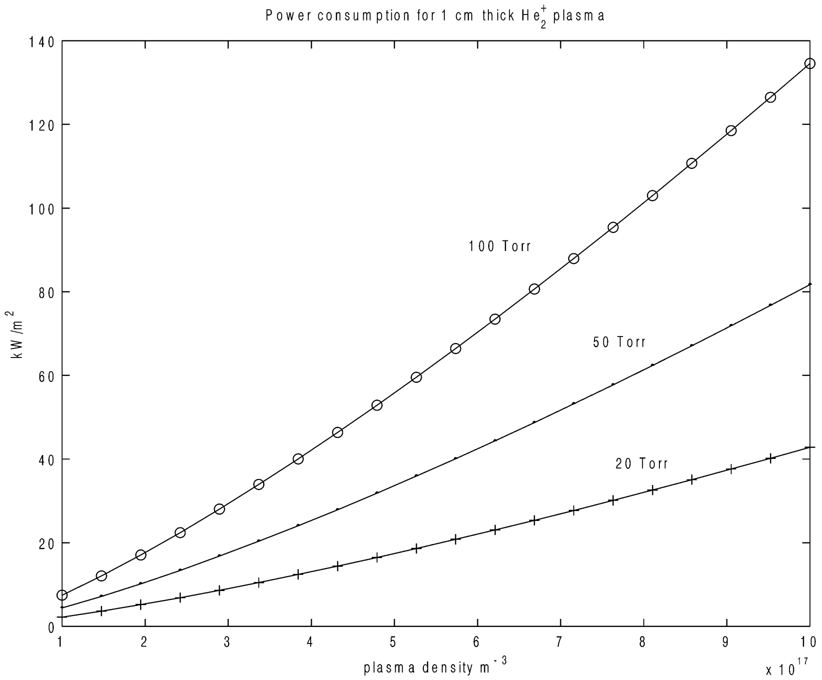


Fig. 12. Estimations of power consumption.

more efficient. Nevertheless, it gives a clear indication that plasmas of the desired type require rather high power for generation, several tens of kW/m^2 for a 1 cm plasma layer. We would also point to reference [5], where plasmas of high density $n_e = 10^{12}$ cm^{-3} were generated in so-called capillary discharges at power densities of *1.5 MW/m*^{3}, or *15 kW/m* for a *1 cm* plasma layer.

It is also possible to give an absolute lower bound for the power consumption by considering that the generation of a single electron costs a minimum energy about 80 eV. If we use a low estimate of the recombination rate $\beta = 1.3 \times 10^{-9}$ cm^3/s and a density of 10^{12} cm^{-3} of molecular helium ions, the minimum power consumption is 15 kW/m^3 or 150 W/m^2 for a 1 cm plasma layer. This suggests that if the discharge can be optimised so that the ionisation is made during short pulses of rather strong electric field the power consumption can be reduced. However, according to [2] the recombination rate is not very well determined and can be as much as 20 times higher.

8. Conclusions

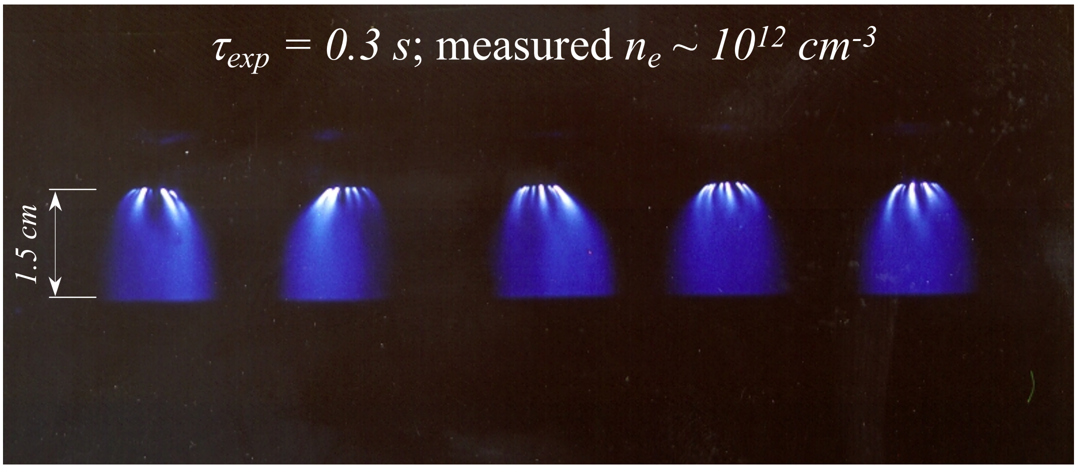
As established in [1] a plasma layer of at least 1 cm thickness and electron density 10^{12} cm^{-3} with background helium pressure of at least 50 Torr would give significant reduction of the radar cross section. Here we have explored the possibilities of generating such plasmas by numerical simulations and obtained estimates for the power consumption. The numerical simulations strongly suggest that it should be possible to generate the desired type of plasmas. Also published articles, such as [5], give such indications. However, one problem is the rather high power consumption that is expected for a sufficiently dense plasma. Because of poorly known recombination coefficients, and difficulties of accurately computing the slow process of recombination in the presence of faster effects, it has not been possible to give a very accurate number for the power consumption. However, estimates point to a few tens of kW/m^2 for a 1 cm thick layer, which is also consistent with the results of [5]. In order to obtain more conclusive results, an experimental test would be necessary.

9. References

1. Anders Bondeson , *Plasma som radarabsorbent*, Technical report, Center of computational electromagnetics, Chalmers University of technology, 2000.
2. Yu. P. Raizer, *Gas Discharge Physics*, Springer Verlag, 1997, ISBN 3-540-19462-2.
3. E. S. Oran, J. P. Boris, *Numerical Simulation of Reactive Flow*, New York: Elsevier, 1987, ISBN 0-444-01251-6.
4. J. W. Demmel, *Applied Numerical Linear Algebra*, Philadelphia: SIAM, 1997, ISBN 0-89871-389-7.
5. E. E. Kunhardt, IEEE Trans. Plasma Sci. vol. 28, 189 (2000).

Appendix

Experimentally obtained discharge plasma



Discharge parameters and conditions:
air at $p = 750\ Torr$; $U = 15\ kV$, positive DC; discharge current is $I = 10^{-3}\ A$; gas velocity $w = 10\ cm/s$; sectionalised electrodes were used, i.e. the number of electrodes can vary as well as the distance between them.
Photo courtesy of Dr. I. Bozhko, Institute of Electrodynamics, Kiev, Ukraine