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On The Dynamics of a Space-charge Structure in a Plasma Similar to an Ionosphere Plasma

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I) INTRODUCTION

Methods of study

- **I)**
  - **A) Ground-based instruments**
  - **B) Satellite-based instruments**
- **II)**
  - **A) Laboratory devices**
  - **B) Computer simulation**

Methods I.A-B provide much more realistic results and are expensive

Methods II.A-B are more versatile and much less expensive

The essential problem in the case II.A is the similarity between the two types of plasma:

-ionosphere plasma

- laboratory plasma

Similitude criteria methods:

I) Based on dimensional analysis:

- needs the system of equations

II) Based on scale transforms:

- identification of the dominant system parameters

II) IONOSPHERE CHARACTERISTICS

That part of the Earth's atmosphere which extends from about 50km to 1000 ….1500km. It is structured in three regions: F, E and D each of them having two layers.

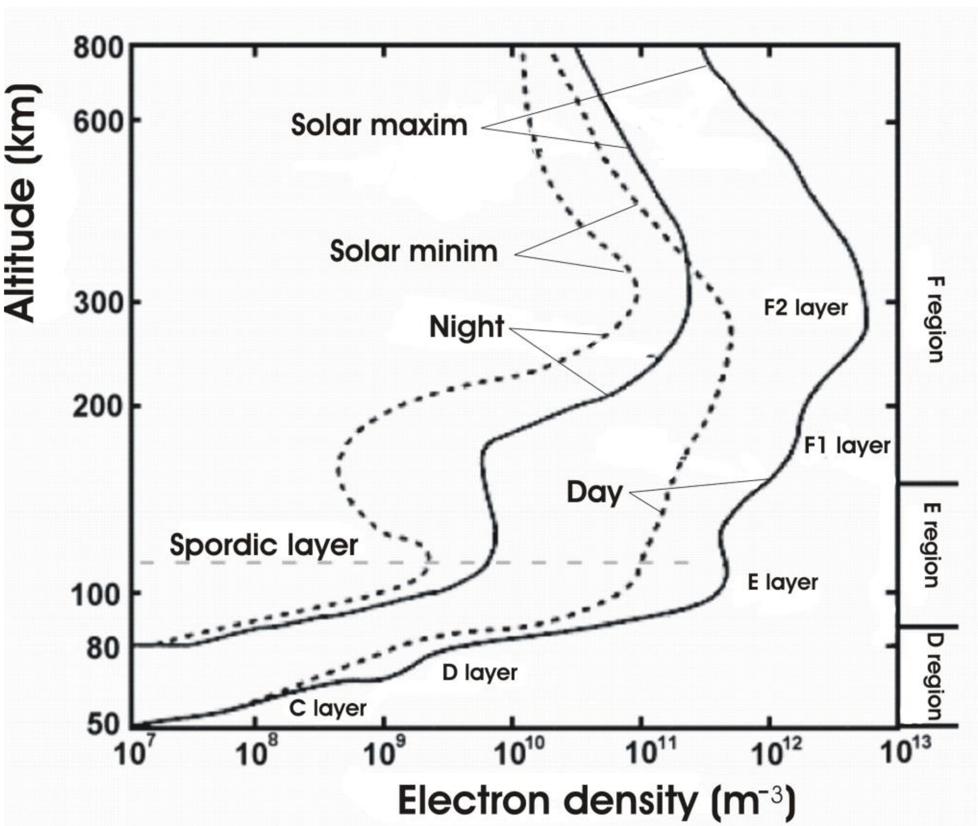


Fig. 1: ***The structure of ionosphere during day and night time, in the case of two extreme solar activities. The electron density vs. altitude in the three regions.***

Day						
z **(km)**	n_e **(cm^{-3})**	n_n **(cm^{-3})**	T_n **(K)**	T_e **(K)**	T_i **(K)**	***P*** **(mbar)**
60	80	7.0E+15	270	270	270	2.6E-01
70	2E+02	2.0E+15	200	200	200	5.5E-02
80	1E+03	2.9E+14	180	180	180	7.2E-03
90	8E+03	3.8E+13	190	200	190	1E-03
100	8E+04	9.6E+12	210	240	210	2.8E-04
110	1.2E+05	1.9E+12	270	320	270	7E-05
120	1.3E+05	7.8E+11	360	400	360	3.8E-05
130	1.5E+05	2.8E+11	460	500	460	1.8E-05
150	3E+05	6.9E+10	670	800	670	6.4E-06
200	5E+05	8.4E+09	1070	1300	1100	1.2E-06
250	1E+06	2.5E+09	1250	1700	1300	4.3E-07
300	1.6E+06	9.3E+08	1330	2000	1400	1.7E-07
400	1.5E+06	2.0E+08	1390	2400	1450	3.8E-08
500	9E+05	5.6E+07	1400	2600	1600	1E-08
600	4E+05	1.7E+07	1400	2700	2100	3.2E-09
700	2E+05	6.0E+06	1400	2800	2200	1.2E-09
800	1E+05	2.4E+06	1400	2870	2870	4.6E-10
900	7E+04	1.1E+06	1400	2940	2940	2.1E-10
1000	5E+04	6.0E+05	1400	3000	2500	1.2E-10

Night						
***z* (km)**	n_e **(cm^{-3})**	n_n **(cm^{-3})**	T_n **(K)**	T_e **(K)**	T_i **(K)**	***P* (mbar)**
60	0	7.0E+15	270	0	0	2.6E-01
70	0	2.0E+15	200	0	0	5.5E-02
80	10	2.9E+14	180	180	180	7.2E-03
90	60	3.9E+13	190	190	190	1E-03
100	1.2E+03	9.6E+12	210	210	210	2,8E-04
110	1.8E+03	1.9E+12	270	270	270	7E-05
120	2.1E+03	7.8E+11	360	360	360	3.8E-05
130	2.2E+03	2.7E+11	470	480	470	1.75E-05
150	2.4E+03	6.9E+10	650	670	650	6.2E-06
200	3E+03	8.4E+09	850	900	850	1E-06
250	1E+04	2.0E+09	910	1000	910	2.5E-07
300	1E+05	5.9E+08	930	1200	930	7.5E-08
400	3E+05	7.8E+07	940	1400	950	1E-08
500	2E+05	1.3E+07	950	1500	1000	1.7E-09
600	1.3E+05	3.2E+06	950	1600	1020	4.2E-10
700	8E+04	1.0E+06	950	1700	1100	1.3E-10
800	5E+04	4.8E+05	950	1800	1200	6.3E-11
900	3E+04	2.8E+05	980	1900	1300	3.8E-11
1000	2E+04	1.9E+05	980	2000	1400	2.5E-11

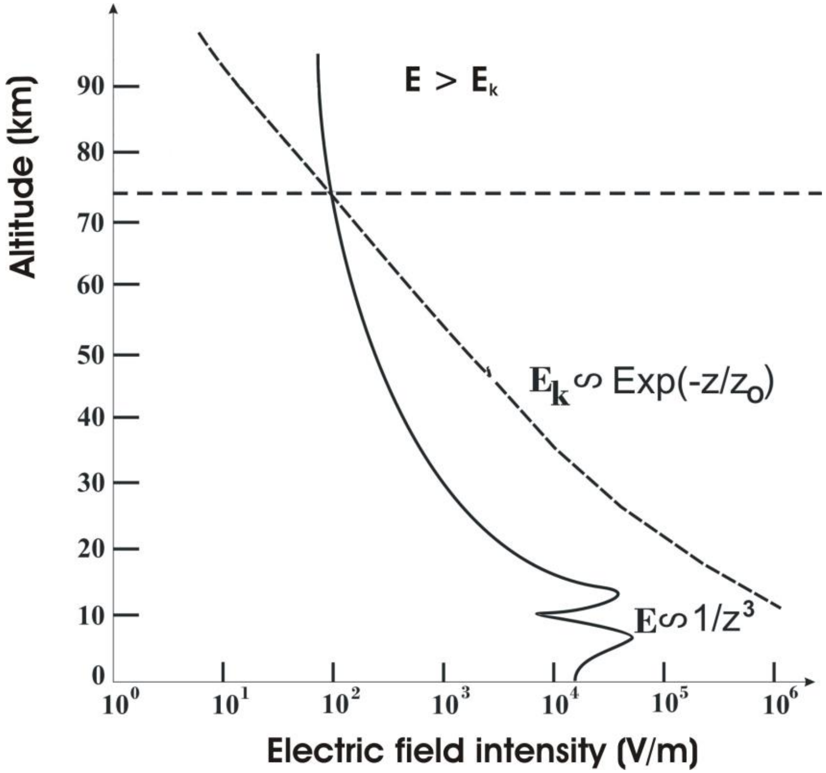


Fig. 2: *Electric field intensity versus altitude.*

E *= electric field due to charged clouds,*

$\boldsymbol{E_k}$ *= breakdown field due to charge separation.*

The E_k field corresponds to a maximum of the ionization rate (α_i) when a source of electrons exists in the ionosphere. This could be assured by the photo-ionization process in which case E_k is given by $E_k = B \cdot P_0 \exp(-z/z0)$, with $B = \sigma_i \cdot \varphi_i / KT$, where σ_i is the ionization cross-section, φ_i is the ionization potential [4] and P_0 is a reference pressure. For altitudes around 100km B = (275 – 300)V·m/N.

[4] Smirnov B.M. – *Physics of Weakly Ionized Gases*, MIR, Moscow, (1981)

III) THE EXPERIMENTAL DEVICE

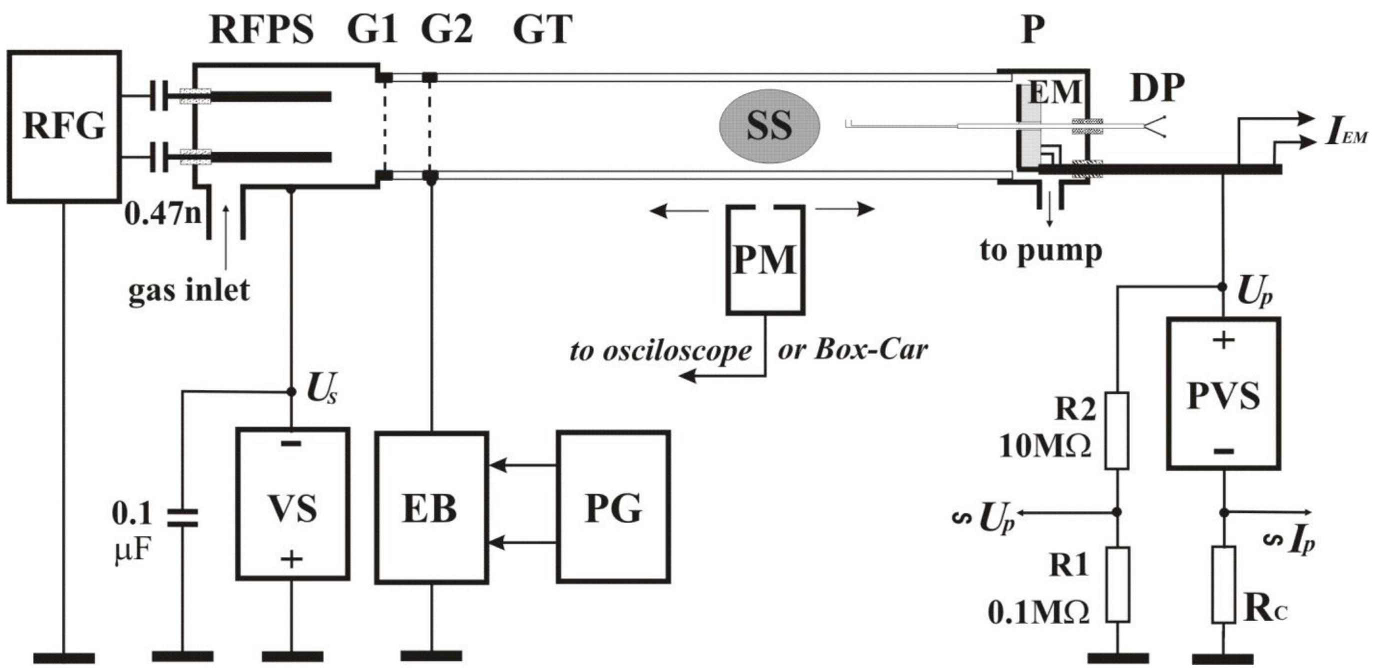


Fig. 3: *The experimental device.*

RFG = RF generator, RFPS = rf plasma source, G1, G2 = grids, GT = glass tube, DP = double probe, P = plane electrode, EM = electromagnet, VS = voltage supply, PVS = programmable voltage supply, PM = photomultiplier, EB = excitation block, PG = pulse generator, SS = self-organized structure.

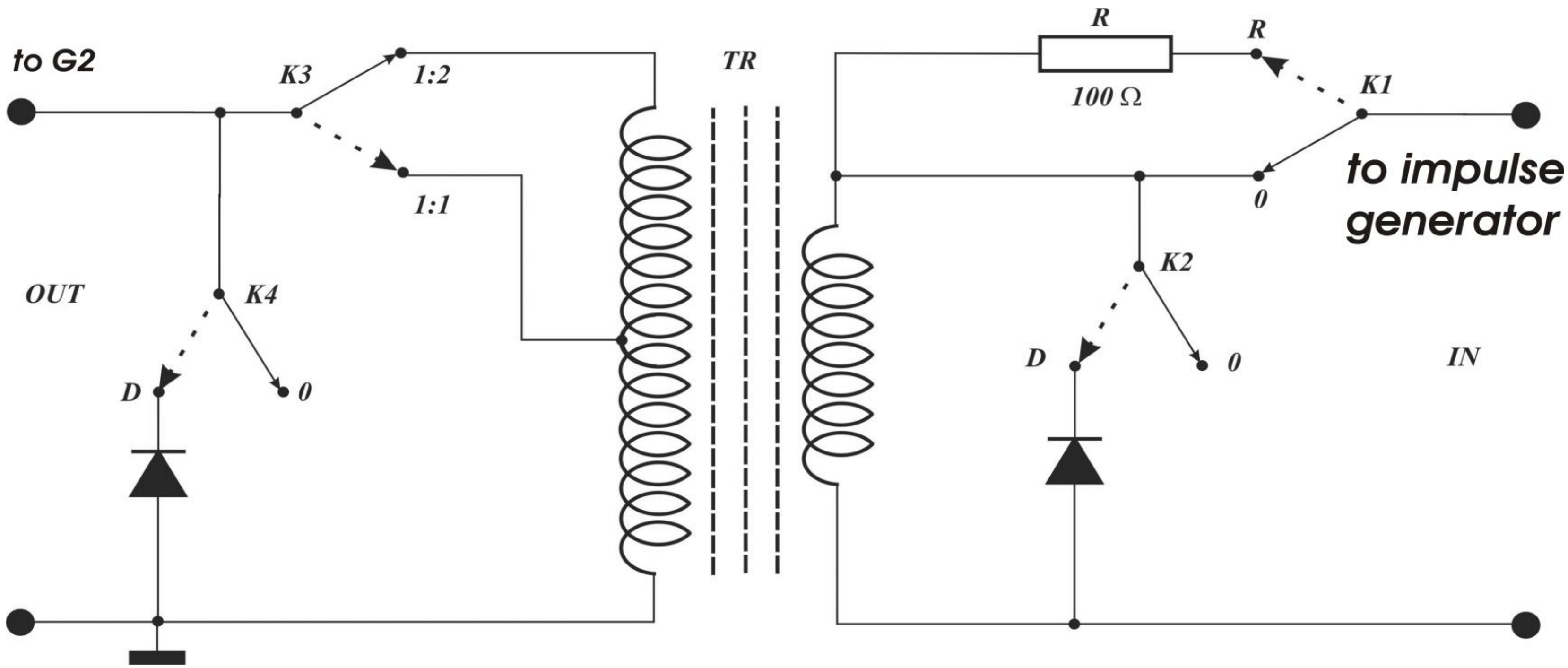


Fig. 4: *Electrical scheme of the excitation block EB.*

Different coupling ways are selectable with the switches K1 to K4. The impulse generator has adjustable frequency output.

The diffusion of the plasma from RFPS into the glass tube GT is controlled with both VS (U_s = 0 – 70V) and PG via EB. Here one obtains a relative homogeneous plasma column ($n_e = 10^{14}m^{-3}$, T_e = (0.3 – 1)eV) in which, depending on the voltages U_s, U_p and pressure, different space-charge structures (SS) could appear.

IV) SIMILITUDE CRITERIA

- The appearance of space-charge structures highly depends on the processes responsible for the production of charged particles in a certain region of the space. Therefore we have taken as dominant parameters the mean energy W_{en} gained by electrons along the mean free path due to acceleration in the electric field of the structure and the electron-neutral collision frequency v_{en}.
- The first similitude criterion will be formulated as the condition to have the same energy W_{en} both in the ionosphere plasma and in the one from the experimental device:

$$\left(\frac{E}{n_n}\right)_{Lab.} = \left(\frac{E}{n_n}\right)_{Ion.} = C_1$$

- The second similitude criterion will rely on the electron-neutral collision frequency and will take into account the scale factors (*k*) entering in the definition of this frequency:

$$\left(\frac{n_n \cdot T_e^{1/2}}{v_{en}}\right)_{Lab.} = \left(\frac{n_n \cdot T_e^{1/2}}{v_{en}}\right)_{Ion.} = C_1$$

- The collision frequency v_{en} is given by [5]: $v_{en} = 1.23^{-7} \cdot n_n \cdot T_e^{5/6}$

The C_1 criterion parameters for ionosphere plasma:

***z* (km)**	60	90	100	200	300	500
E_k **(V/m)**	300	30	8.4	$3.6\cdot10^{-2}$	$5.1\cdot10^{-3}$	$3\cdot10^{-4}$
n_n **(m^{-3})**	$7\cdot10^{21}$	$4\cdot10^{19}$	$9.6\cdot10^{18}$	$8.4\cdot10^{15}$	$9.3\cdot10^{14}$	$5.6\cdot10^{13}$
C_1	$4.2\cdot10^{-20}$	$7.5\cdot10^{-19}$	$8.7\cdot10^{-19}$	$4.3\cdot10^{-18}$	$5.5\cdot10^{-18}$	$5.4\cdot10^{-18}$

The C_1 criterion parameters for laboratory plasma:

***P* (N/m^2)**	$7.4\cdot10^{-1}$	$5.4\cdot10^{-1}$	$3.4\cdot10^{-1}$
***E* (V/m), var. 1**	$5\cdot10^{2}$	$5\cdot10^{2}$	$5\cdot10^{2}$
***E* (V/m), var. 2**	$2\cdot10^{2}$	$2\cdot10^{2}$	$2\cdot10^{2}$
n_n **(m^{-3})**	$1.3\cdot10^{20}$	$9.8\cdot10^{19}$	$6.2\cdot10^{19}$
C_1	$3.8\cdot10^{-18}$ $1.5\cdot10^{-18}$	$5.1\cdot10^{-18}$ $2\cdot10^{-18}$	$8\cdot10^{-18}$ $3.2\cdot10^{-18}$

From the above results one finds that C_1 criterion is accomplished with a maximum error of 50% and a minimum error of about 7.3% for an altitude range of (90 – 500)km.

The C_2 criterion parameters for ionosphere plasma:

***z* (km)**	60	90	100	200	300	500
n_n (m^{-3})	$7\cdot10^{21}$	$4\cdot10^{19}$	$9.6\cdot10^{18}$	$8.4\cdot10^{15}$	$9.3\cdot10^{14}$	$5.6\cdot10^{13}$
T_e (K)	270	200	240	1300	2000	2600
v_{en} (s^{-1})	$3.7\cdot10^{7}$	$1.6\cdot10^{5}$	$4.7\cdot10^{4}$	$1.7\cdot10^{2}$	26.5	2
C_2	$3.1\cdot10^{15}$	$3.5\cdot10^{15}$	$3.2\cdot10^{15}$	$1.8\cdot10^{15}$	$1.6\cdot10^{15}$	$1.4\cdot10^{15}$

The C_2 criterion parameters for laboratory plasma:

P (N/m^2)	$7.4\cdot10^{-1}$	$5.4\cdot10^{-1}$	$3.4\cdot10^{-1}$
n_n (m^{-3})	$1.3\cdot10^{20}$	$9.8\cdot10^{19}$	$6.2\cdot10^{19}$
T_e (K)	3480	3480	3480
v_{en} (s^{-1})	$5.8\cdot10^{6}$	$4.4\cdot10^{6}$	$2.8\cdot10^{6}$
C_2	$1.32\cdot10^{15}$	$1.31\cdot10^{15}$	$1.3\cdot10^{15}$

From the above results one finds that the second criterion is accomplished with a maximum error of 62% and a minimum error of 5.7% for an altitude range of (60 – 500)km.

V) EXPERIMENTAL RESULTS

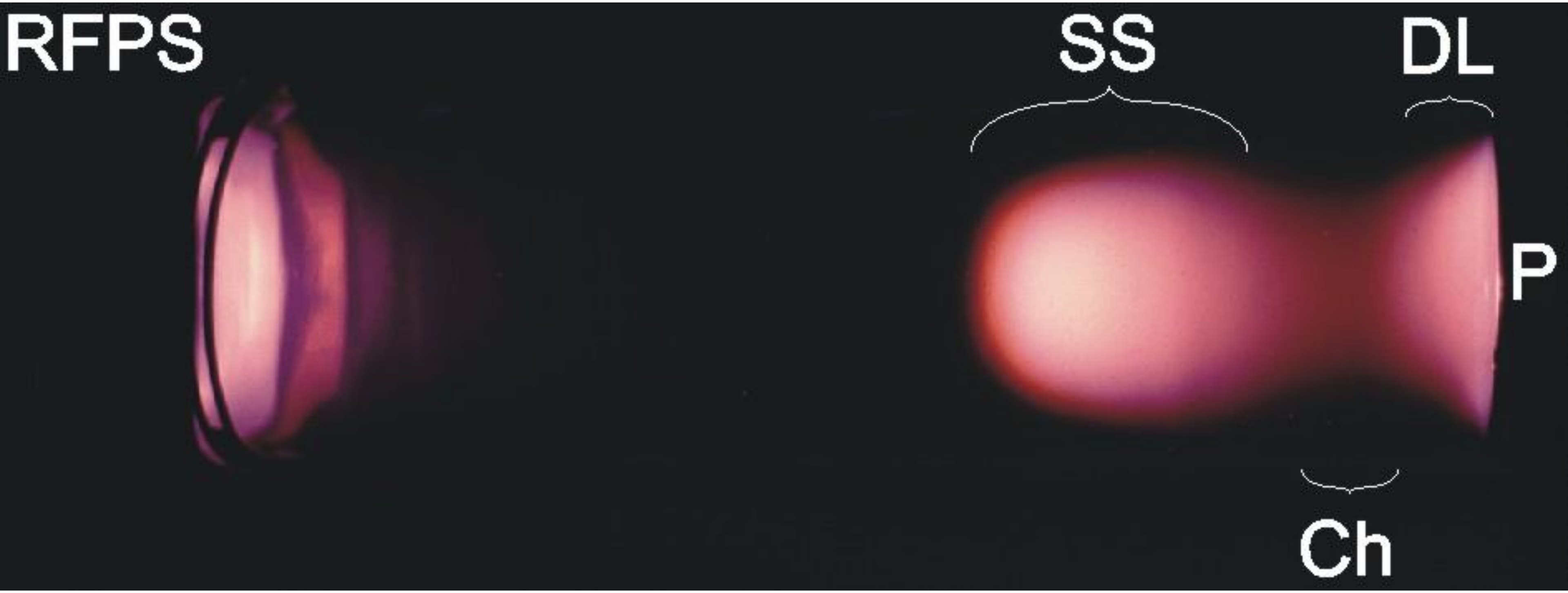


Fig. 5: *Example of a self-organized space-charge structure (SS) which is formed inside the plasma column between rf-plasma source (RFPS) and the plane electrode P. DL = plasma double-layer, Ch = connection channel between SS and DL.*

To see effectively how the structure is formed, one applies on the electrode P a rectangle-impulse voltage having the amplitude equals to the value *Up* at which the structure is formed and with a duty cycle sufficiently large for the structure to entirely forms and disappears. Registering the integral light emitted by the plasma column (by the help of PM) and the current flowing through it one obtains the result presented in Fig. 6.

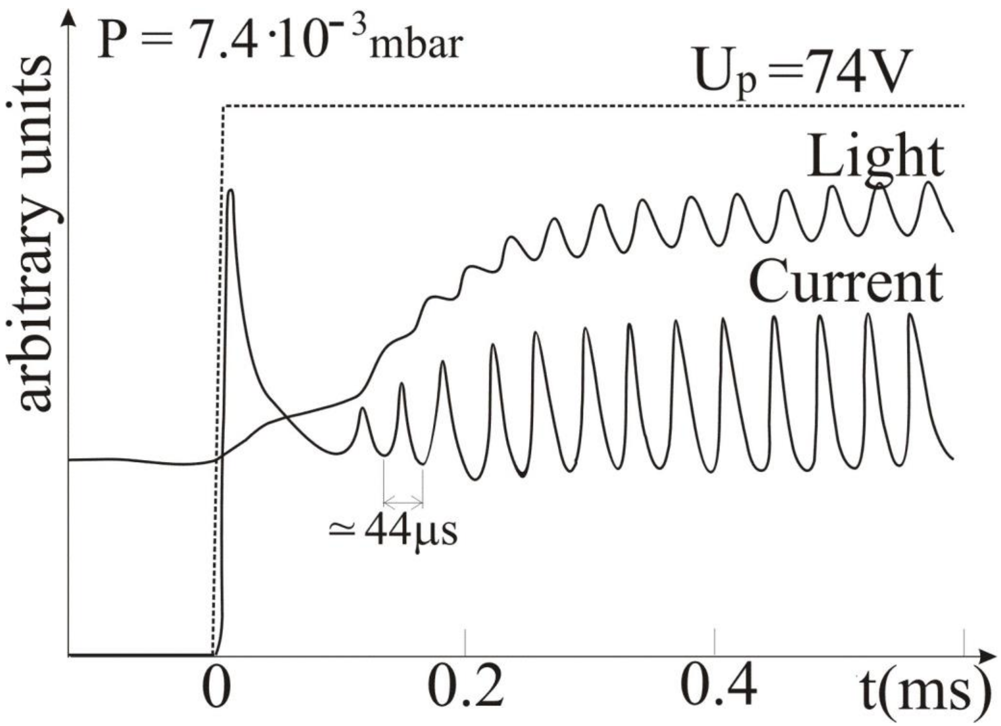


Fig. 6: *Instability development. When a rectangle-impulse voltage Up is applied to the electrode P the integral light picked-up by PM and the current through the plasma column show an instability which, beginning with a certain moment (about 0.4ms), saturates due to the dissipative processes.*

Using a box-car unit, to which the PM is connected, it is possible to construct the space-time distribution of the integral light emitted from the plasma column. The covered space interval is about 15cm in front of the electrode P.

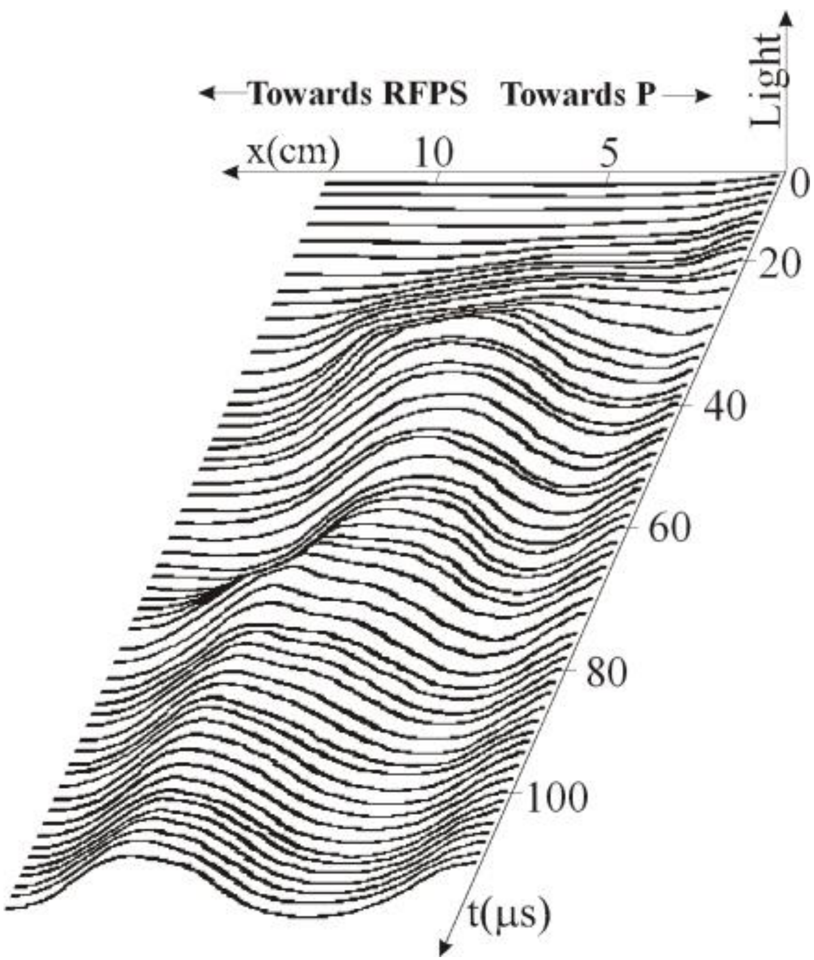
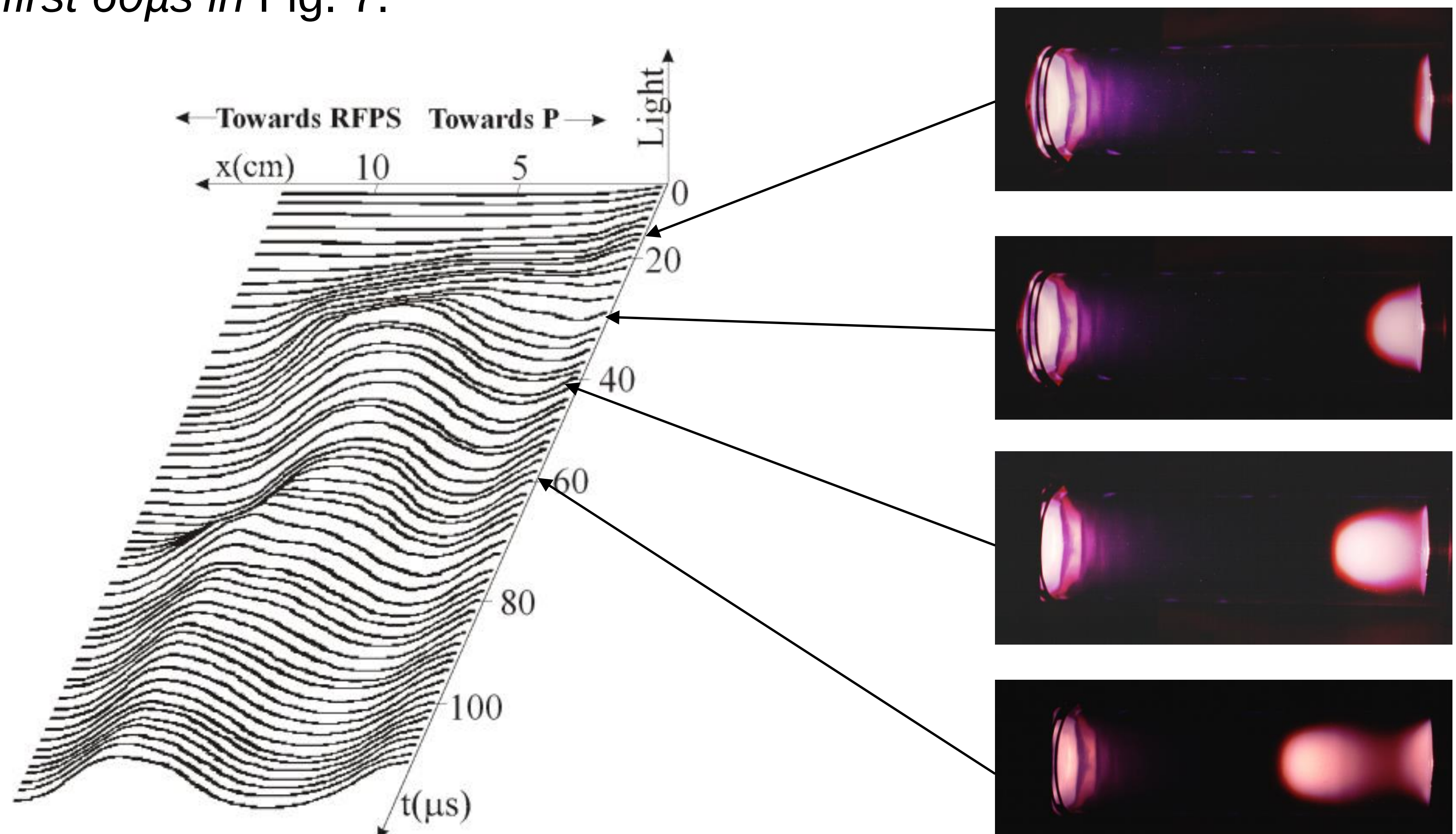


Fig. 7: *Space-time diagram of the integral light emitted from the plasma column during the formation and maintenance of the SS structure. The time interval between two adjacent curves is of 2µs.*

Different stages in the SS structure formation can be observed if one adjust the voltage U_P the electrode P. These stages are shown in the Fig. 8.

Fig. 8: *The stages presented corresponds to the first 60μs in* Fig. 7.



Investigating the phase-space portrait of the SS structure during its formation, as a result of the instability, one obtains the embedding dimension is 4 and the behavior is from chaos to limit cycle (Fig. 9).

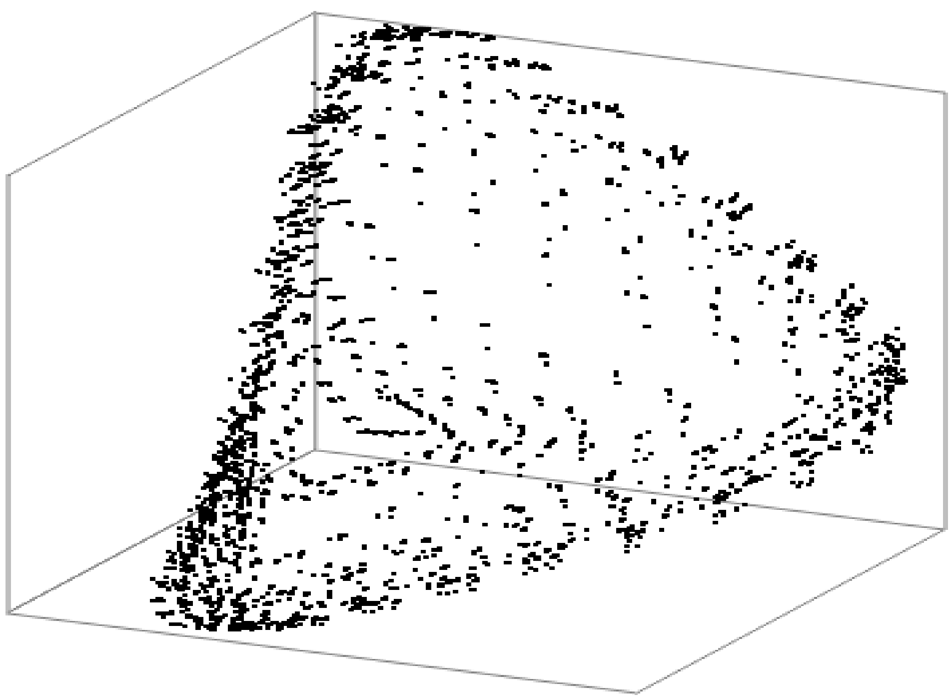
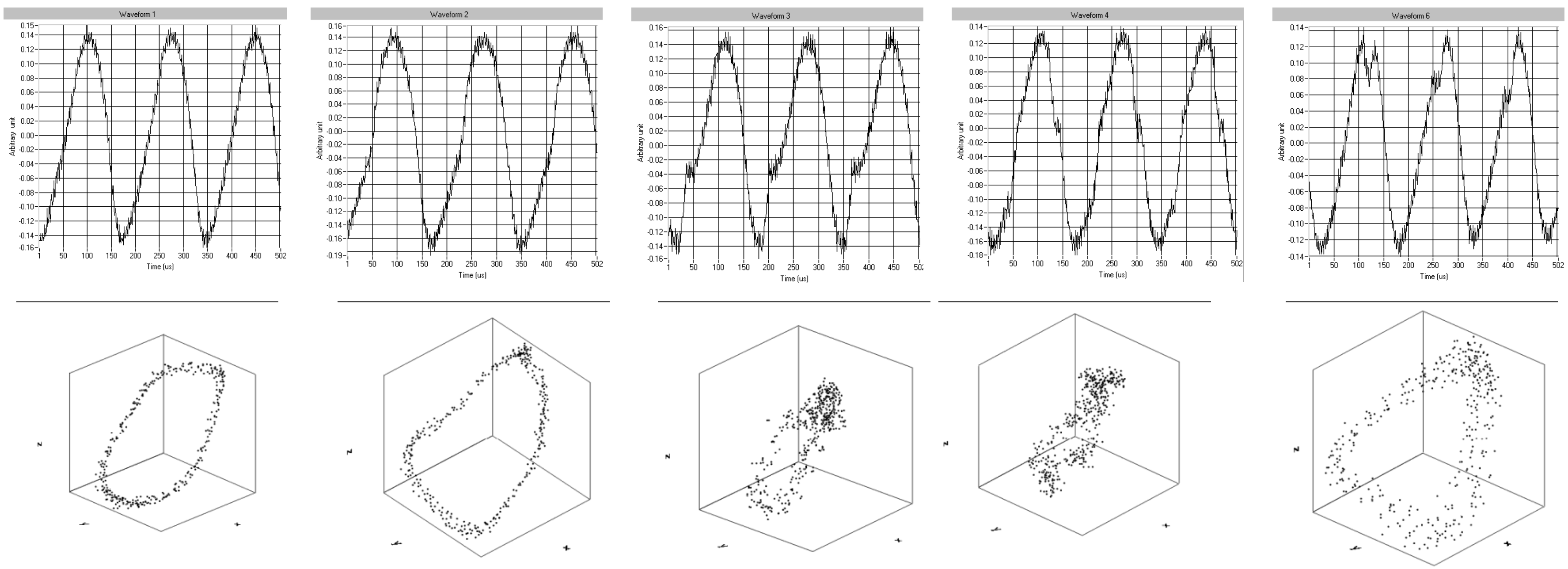


Fig. 9: *A 3D section of the attractor representing the phase-space portrait of the SS structure dynamics.*
This plot has been done using the nonlinear dynamics tools with the time series associated to the curves in Fig. 6.

A spectral investigation of the light emitted from the SS structure put in evidence the decisive role played by the excitation and de-excitation processes in the dynamics of this structure [14,15].

Because the dynamic equilibrium state of the SS structure is one of pulsation, we tried to perturb this by modulating the plasma diffusion from RFPS into GT. This was performed with a pulse generator connected to G2 through the excitation block EB. Adjusting the frequency of the generator one obtains changes of the SS size, current waveforms and amplitude. Also, a resonance phenomenon is observed at 35kHz.



f_{ex} = 0Hz f_{ex} = 27kHz f_{ex} = 30kHz f_{ex} = 60kHz f_{ex} = 35kHz

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THANK YOU

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