MICROWAVE DISCHARGE ON DIELECTRIC SURFACE IN VACUUM

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Abstract

The paper presents results of the experimental investigation on plasma created under interaction of strong microwave short pulse radiation (with power GW level of magnitude) with dielectrics in vacuum. Due to extremely high microwave power such kind of plasma has very unusual parameters that can be useful for number of applications.

The experiments were performed using a focused microwave beam generated by relativistic carcinotron (wavelength 3 cm, pulse duration ≈ 50 ns, power P ≈ 1 GW) at the microwave power density ≈ 25 MW cm^{-2}. Gas pressure in a chamber was 10^{-5} Torr.

Microwave discharge on pure dielectrics has a threshold nature (f.e. threshold on Teflon was ≈20 MW cm^{-2}). Evidently the plasma formation was a result of evolution of the first stage of discharge - a secondary emission discharge [1, 2]. Second stage - breakdown stage accompanied with significant microwave absorption and intensive evaporation of target material. Average quantity of evaporated atoms was 10^{18} per pulse. Breakdown of this vapour determined plasma dynamics.

Estimation showed that density of the vapour in the flow from the target reached 10^{19} cm^{-3}. Ionisation process in the ultra high intensity of microwave field leaded to fast creation of plasma with ionisation rate close to 1 in narrow region of vapour near the target.

The discharge showed up as a set of filaments stretched along the microwave electric field. Velocity of a discharge propagation along the dielectric at inhomogeneous microwave beam field achieved ~ 10^8 cm s^{-1}.

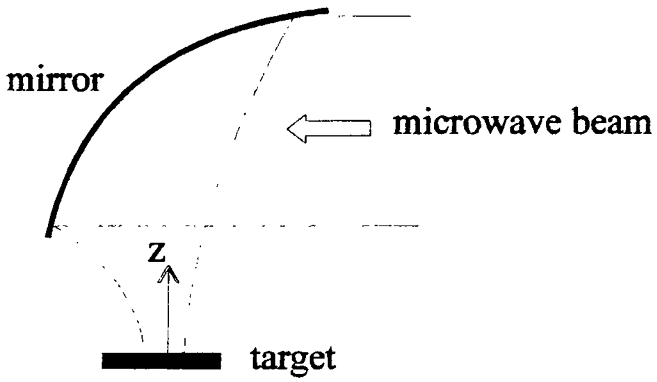
X-ray emission was observed. Multiply charged ions studied by 2 step ion analyser were validly generated (f.e. C^{+++}) in a dense plasma.

Plasma expansion after the microwave pulse was accompanied with formation of several plasma clusters moving with various constant velocities.

1. G.M. Batanov, V.A. Ivanov, I.A. Kossyi, K.F. Sergeichev in Russian Journal of Plasma Physics. **12**, p. 552, 1986.
2. G.M. Batanov, I.A. Ivanov, M.E. Konyshev in Russian Journal of Experimental and Theoretical Physics. **59**, n. 10, p. 655, 1994.

Experimental Set-up

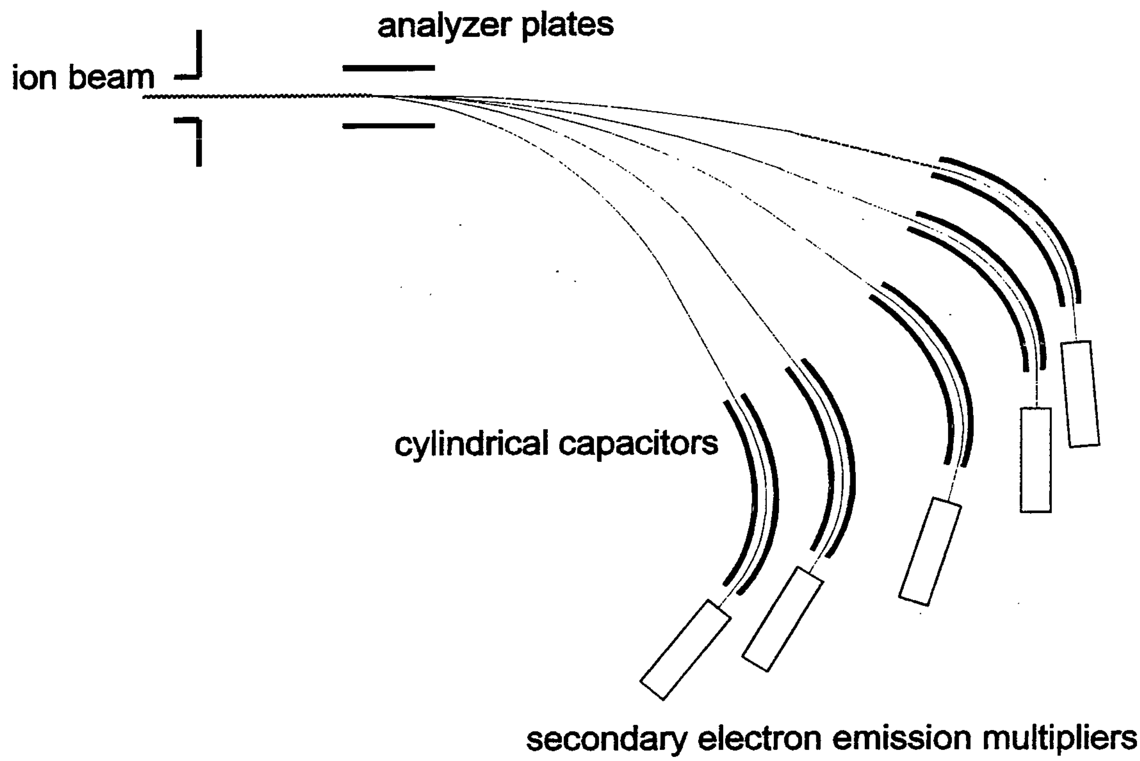
Microwave generators: relativistic carcinotron with parameters:
$f = 10\ GHz$,
$W_{max} \approx 100\ MW$,
$T = 10 - 40\ ns$,
$S \approx$ up to $25\ MW\ cm^{-2}$,
$E_{eff} \sim 100\ kV\ cm^{-1}$,
electron oscillation energy: $1\ keV$



Microwave beam cross section $s \approx 4\ cm^2$

Diagnostics:

- Photo,
- Streak camera,
- Microwave diagnostics,
- X-ray p-i-n diodes,
- Ion analyser,
- Electron energy analyser,
- Langmuir probes,
- Gas diagnostics.



5 channel mass analyzer

Discharge Evolution

Microwave breakdown on pure dielectrics was studied by

1. G.M. Batanov, I.A. Ivanov, M.E. Konyshev. Russian Journal of Experimental and Theoretical Physics. 1994, **59**, n. 10, p. 655.
2. L.V. Grishin, A.A. Dorofeuk, I.A. Kossyi, G.S. Luk'janchikov, M.M. Savchenko in Reports of Lebedev Physical Institute. 1977, **92**, p. 82.
3. G.M. Batanov, I.A. Ivanov, M.E. Konyshev, A.A. Rovaev, V.D. Seleznev, A.I. Khomenko. Proseeding of the Internatioanal workshop on Strong Microwaves in Plasmas, September 1990, Nizhny Novgorod. 1991. p. 553.

Two stages of the discharge were displayed:

secondary emission discharge

↓

gas evaporation

↓

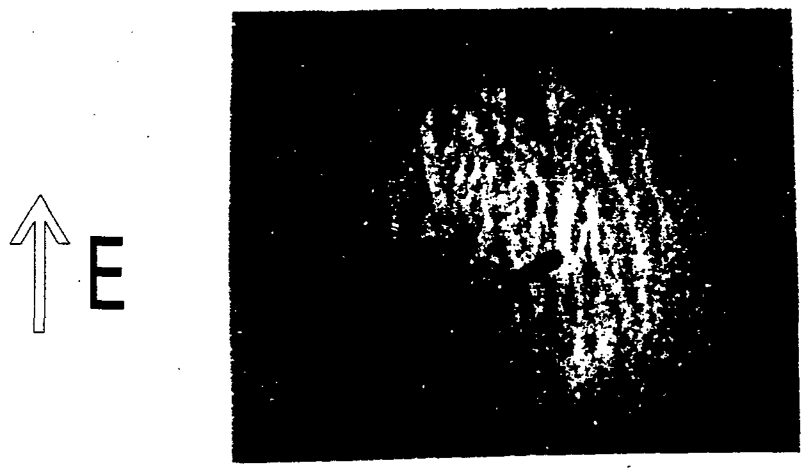
evaporated gas breakdown

A threshold value of microwave power
for discharge on pure dielectrics depended on material:

for Teflon	$W_T \approx 20$ MW cm^{-2}
for glass	$W_T \approx 8$ MW cm^{-2}
for Plexiglas	$W_T \approx 2$ MW cm^{-2}

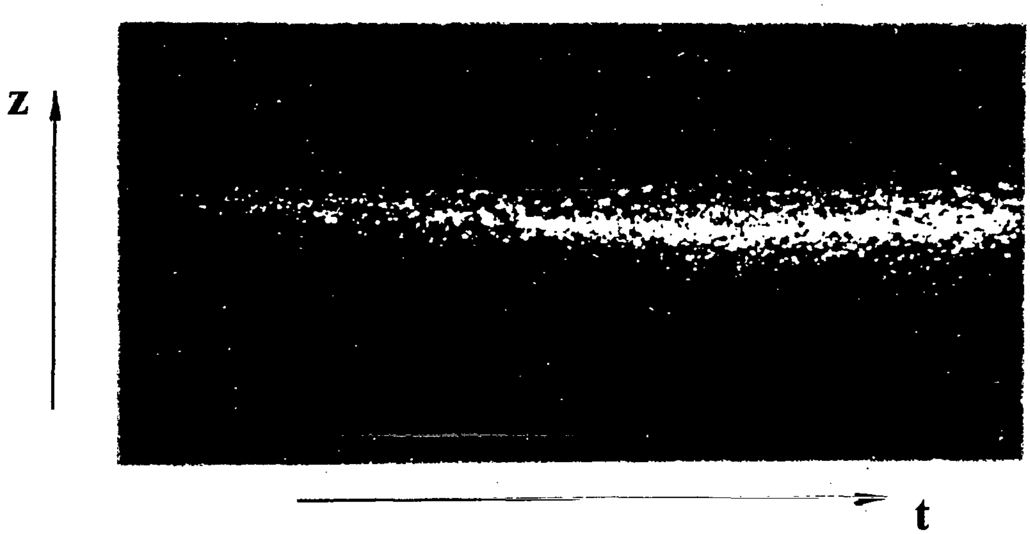
Photos

The discharge showed up as a set of filaments stretched along the microwave electric field. Diameter of filaments was *0,1 - 0,2 cm*, average distance between the filaments d ~ *0,3 -0,4 cm.* Plasma dimension along *Z* axis was $Z_0 \approx 0{,}5$ *cm.*



Integral glow emission of breakdown zone

Velocity of filaments propagation studied by the streak camera:
-velocity of a discharge propagation along the dielectric achieved $\sim 10^8\ cm\ s^{-1}$.
-velocity perpendicular the dielectric (along *Z* axis) $V_Z \sim 3\ 10^7\ cm\ s^{-1}$.



Chronogram of discharge formation perpendicularly the target surface

Gas Evaporation

One dimension estimations:

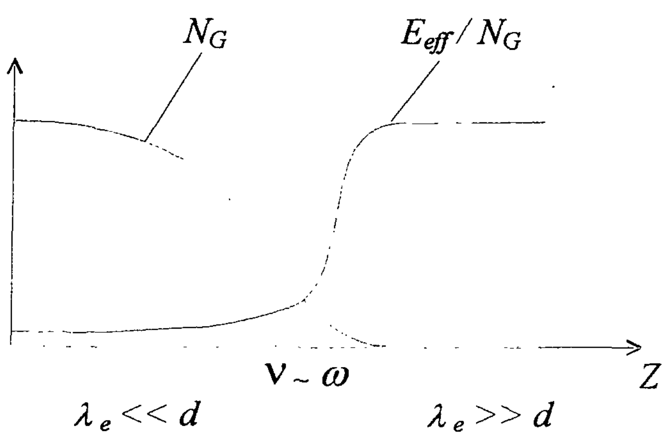
Quantity of evaporated gas: 10^{18} particles per pulse

Gas flow: $F_G > N / T \cdot s \sim 10^{18} / 4\ 10^{-8} \cdot 4 \approx 6 \cdot 10^{24}\ cm^{-2}\ s^{-1}$;

Gas density: $N_G \sim F_G / V_G \sim 6 \cdot 10^{24} / 10^{5} = 6\ 10^{19}\ cm^{-3}$;

Thickness of the gas layer: $d < V_G \cdot T \sim 10^{5} \cdot 4\ 10^{-8} = 4\ 10^{-3}\ cm < 0{,}1\ mm$;

Thickness of the plasma layer: $d_P < V_S \cdot T \sim 3\ 10^{7} \cdot 4\ 10^{-8} = 1{,}2\ cm$;



Breakdown of the gas layer under the condition $\lambda_e << d$:

$E_{eff} \sim 100\ kV/cm$; $N_G \sim 6\ 10^{19}\ cm^{-3}$

$k_i \sim 5\ 10^{-10}\ s^{-1} cm^{-3}$;

Ionisation frequency: $\nu_i = k_i \cdot N_G \sim 5\ 10^{-10} \cdot 5\ 10^{19} = 2{,}5\ 10^{10}\ s^{-1}$;

Limitation of the electron avalanche:

— microwave reflection

— dissociative recombination

Plasma density:

$N_e \sim \nu_i / \alpha$; if $\alpha \sim 10^{-8}\ cm^{-3} s^{-1}$,

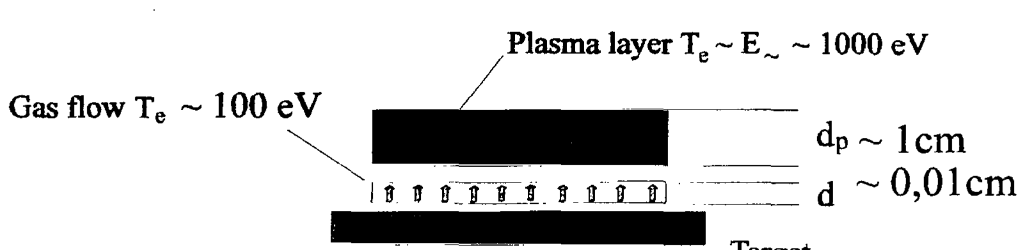
$N_e \sim 2{,}5\ 10^{18} cm^{-3}$

$\tau \sim \nu_i^{-1} \ln(N_e^f / N_e^i) \sim 10^{-9} s$

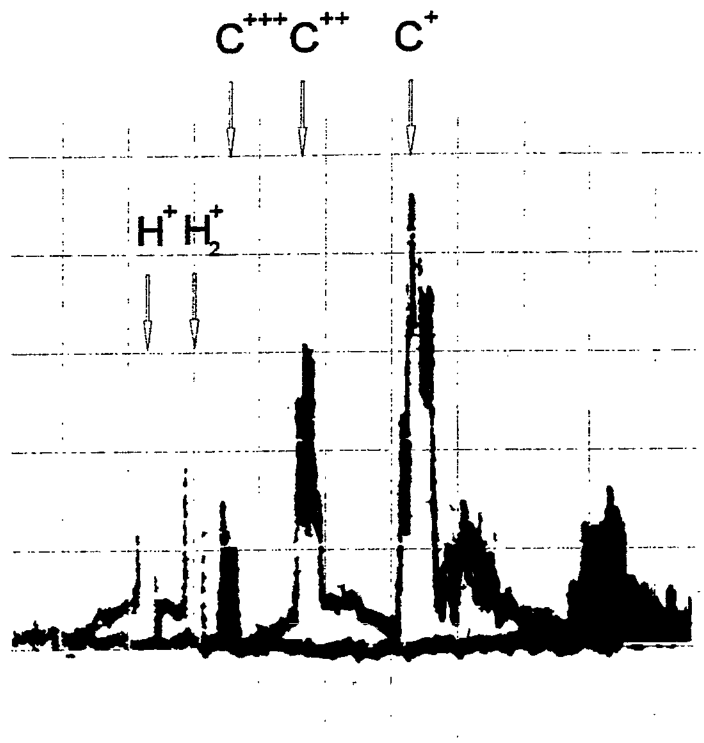
Even in the region when $\lambda_e << d$, the rate of ionisation is very high.

Region of $\lambda_e << d$ is

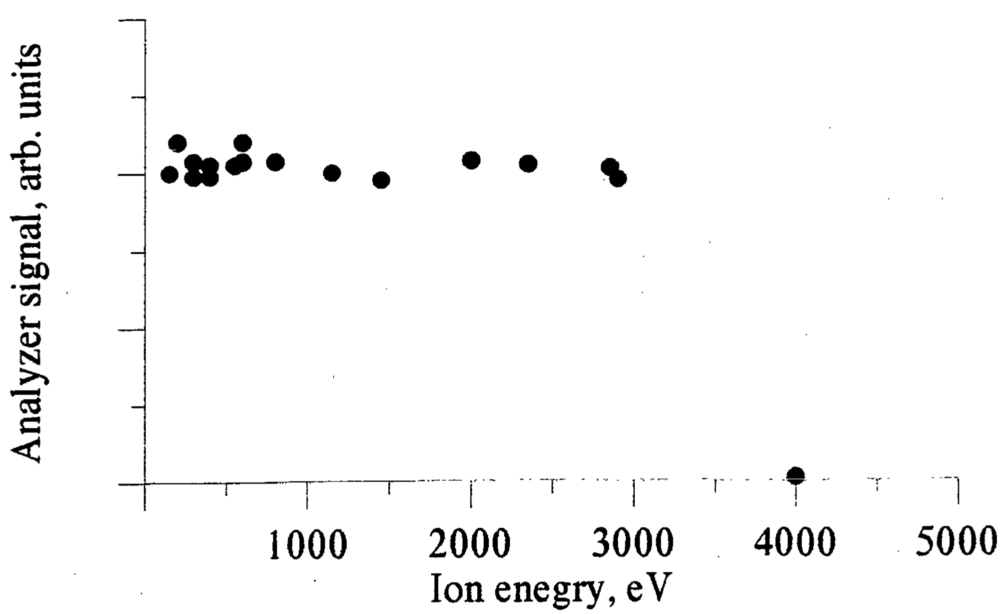
the region without fast expansion of the plasma ($V_{ex} \sim V_G$)



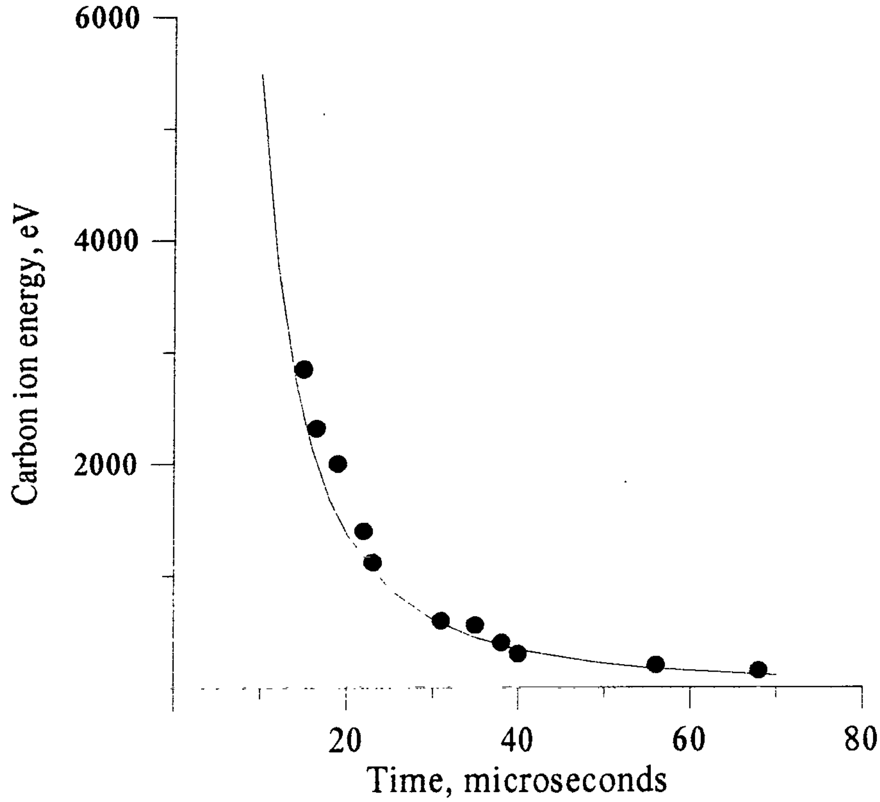
Plasma Expansion



Oscillogramm of analyser, 10 μ s per division.



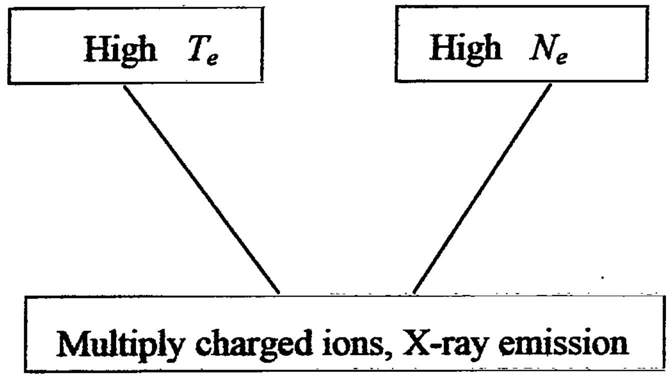
Plasma Expansion: Experiment and Theory



Blue points are time delays of carbon ions with different energy approaching mass analiser.

The red line is a result of analytic self-similar solution of the plasma expansion problem with arbitrary electron velocity distribution function at adiabatic collisionless electron cooling.

Multiply charged ions, X-ray emission



Experimental supervision of multiply charged ions generation (C^{+++}) by mass analyser.

Conditions necessary for the multiply charged ions creation in plasma:
$T_e \sim 1\ keV,\ N_e\,\tau \sim 10^8\ cm^{-3}s.$

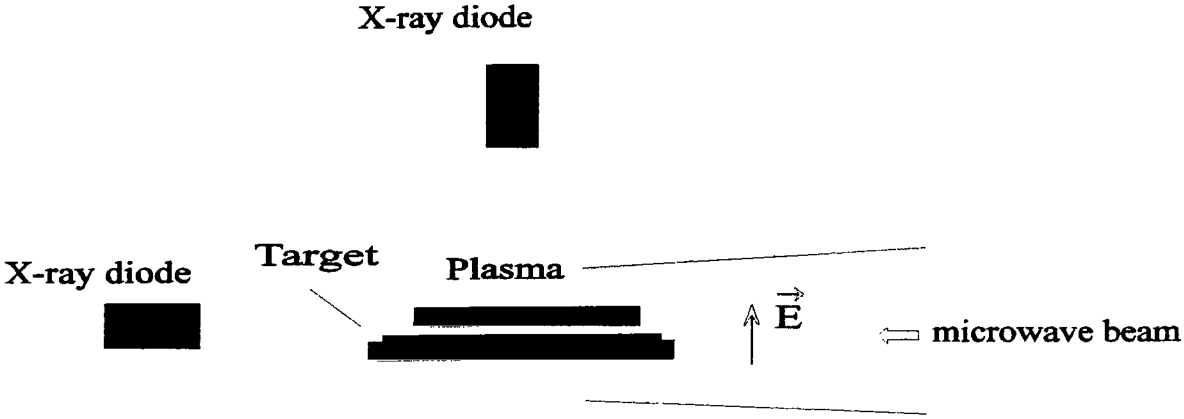
Estimation for $N_e\,\tau$:
$\tau \sim L/V_i \sim 1\ /\ 3\ 10^7 \approx 3\ 10^{-8}\ s^{-1}$.

Can be $N_e\,\tau \sim 10^8\ cm^{-3}s^{-1}$?
Yes, if $N_e \sim 3\ 10^{15}\ cm^{-3}$

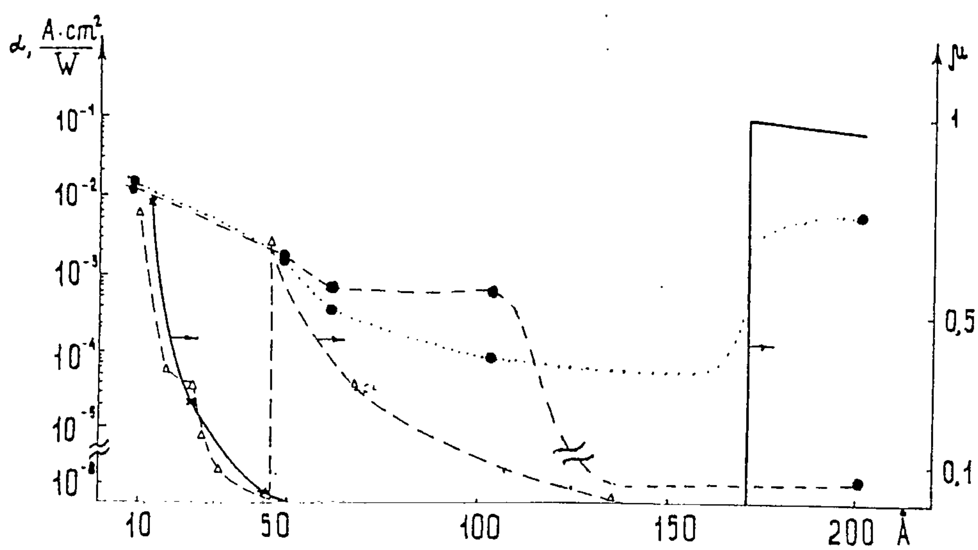
X-ray generation nature: — line emission of multiply charged ions;
— recombination emission

Absolutely calibrated X-ray p-i-n diodes allowed to measure X-ray power density. P-i-n diode spectral sensitivities and transmission factors of the filters are used in the experiments.

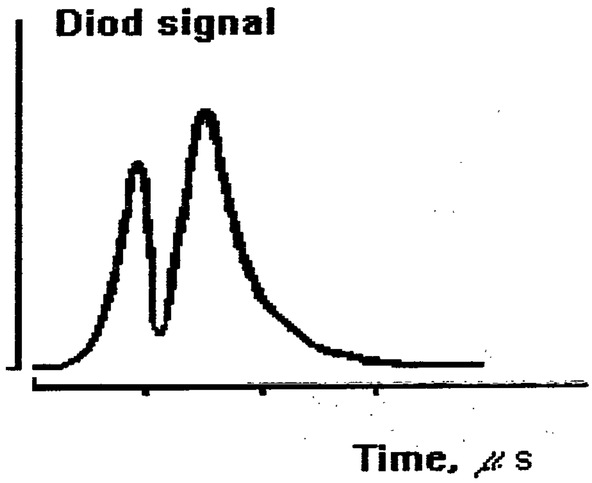
X-ray Experiment



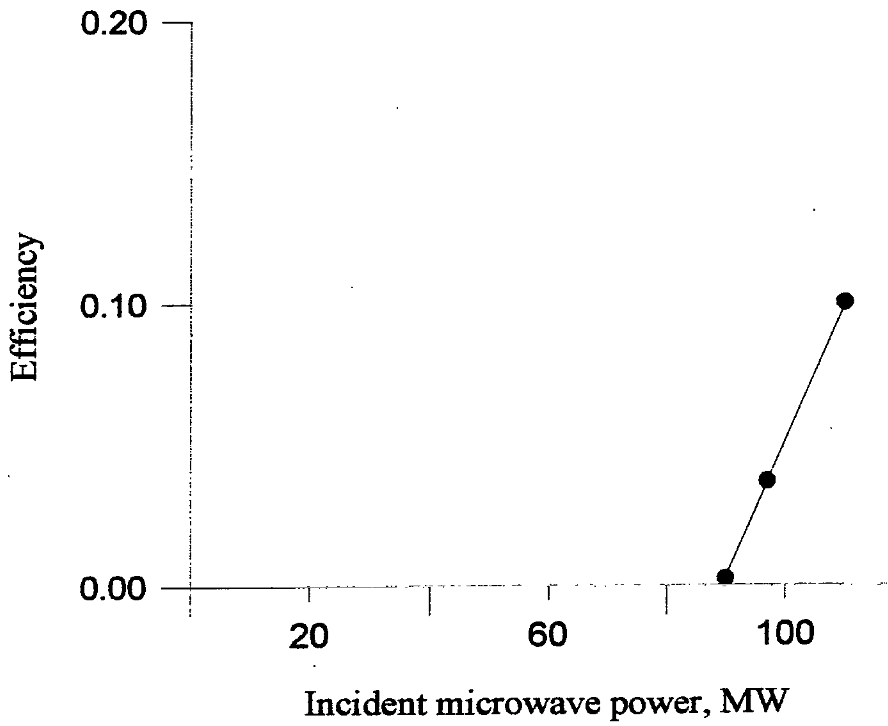
Diode sensitivities



Typical oscillogram of the X-ray diode signal:



- The signal duration >> the microwave pulse duration
- Two maximums



Conversion efficiency increased fast with increase of microwave power, and achieved *10%* at the power level *W =110 MW.*

Spectrum of X-rays

Signals of the diodes:

- was reduced by 10-15 times when Mylar filter was placed before the diodes;
- the aluminum filter reduced the signals to zero.

Ag-diode signal < Al-diode signal, the difference is 15 - 20 times.

Conclusions:

1) The signal reduction with using the aluminum and Mylar filters gives evidence that X-ray emission belongs to wavelength regions:
either 40 - 50 A
or 120 - 200 A,
where the transmission factors are close to the zero.

2)The sensitivity of Ag-diode is less than Al-diode one in the region $\lambda > 120$ A. The difference of sensitivities in the region $\lambda > 130$ A is too much.

So:

The spectrum of X-ray emission belongs to region 120A - 130 A.