Wave Breaking in Inhomogeneous Plasma.

1. Electron Acceleration.

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OUTLINE

- **From parametric decay to wave breaking in one device.**

  Experimental scheme.

  Wave propagation scheme.

  Observation of nonlinear phenomena at small pump power.

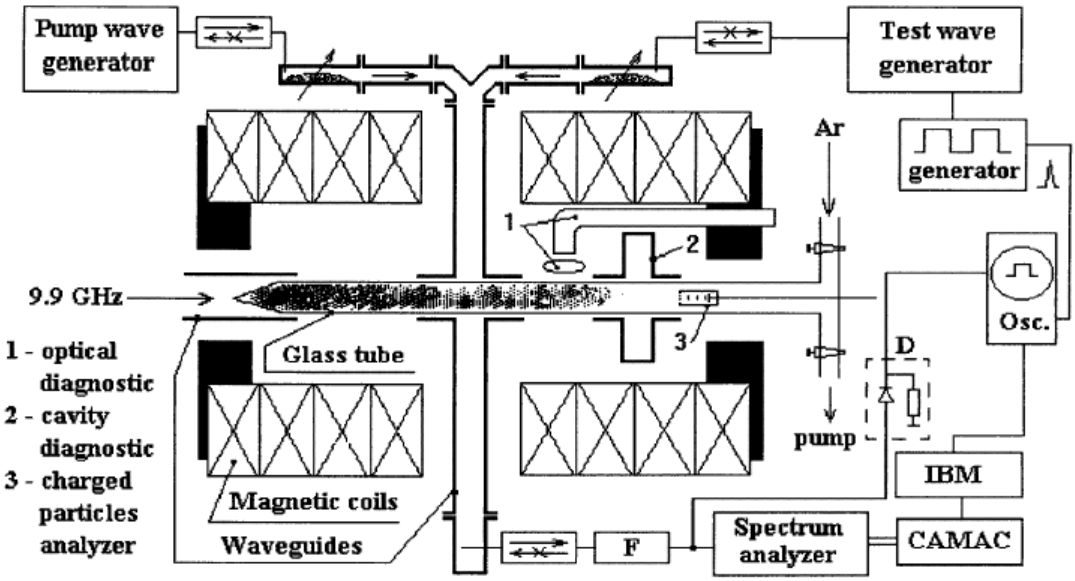
- **Electron acceleration accompanying wave breaking.**

  Theoretical estimations.

  Modification of electron distribution function with growing pump power.
  Measurements of fast electron current and estimation of their density.

- **Summary**

Experimental scheme.



Discharge parameters.

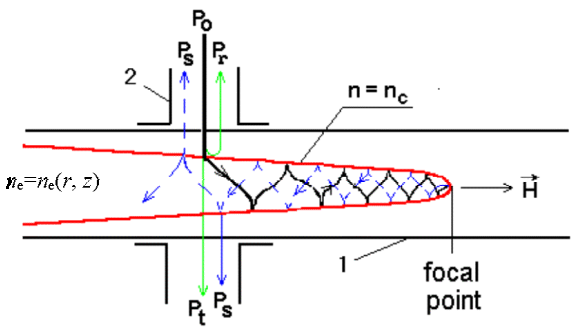
Electron cyclotron discharge at power 200W and frequency 9.9 GHz in a tube 2cm in diameter and 100cm long. Magnetic field $H = 3.5kG$, the argon gas pressure is 10^{-2} Torr, the plasma inhomogeneity scale along magnetic field and across it are L=5cm and r_0=0.8cm accordingly, the maximal electron density is $n_e = 10^{12} cm^{-3}$, electron temperature is $T_e = 2eV$. The density distribution:

$$n_e(r,z) = n_c \exp\left(-\frac{z}{l}\right)\left(1-\frac{r^2}{r_0^2}\right)^{\beta}$$

The pump wave propagation scheme.

Electron plasma wave dispersion:

$$k_{\perp}^{2} = \left[\frac{\omega_{pe}^{2}}{\omega^{2}} - 1 \right] k_{\parallel}^{2}$$



The pump frequency $F_0 = 2.84$ GHz

The pump power $10\text{mW} < P_0 < 10\text{kW}$

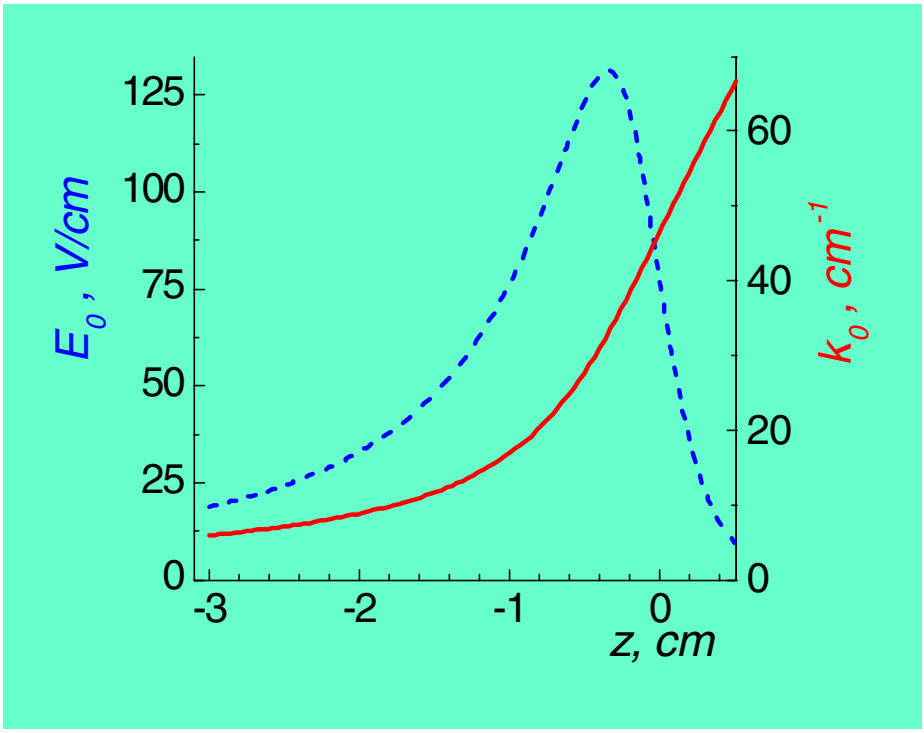
The pump electric field distribution:

$$E_o = \left(\frac{2P_0'}{\omega_o}\right)^{1/2} \frac{k_o^{3/2}}{\left(3r_d^2 b k_o^3 + 1\right)^{1/2}} \exp\left[i\int_{-\infty}^{z}\left(k_0 + ik_0''\right) - \frac{k_o}{2b}r^2 - i\omega_o t\right] + \kappa.c.$$

The pump axial wave number:

$$3r_d^2\left(k_0 + ik_0''\right)^2 - \frac{z}{a} - \frac{2}{\left(k_0 + ik_0''\right)b} + i\eta'' = 0,$$

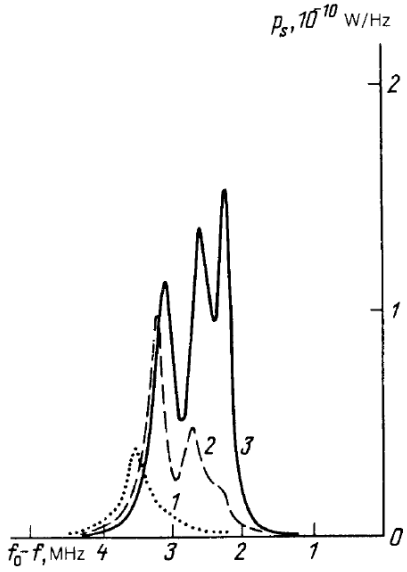
$a \approx 5cm$ $b \approx 0.4cm$

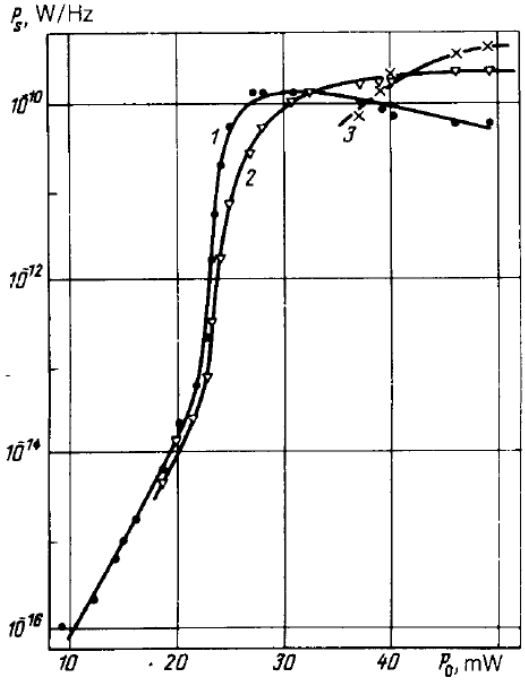


Backscattering decay instability

$$l_0 \rightarrow l_0' + s$$

and anomalous reflection





Control of the decay instability threshold by the pump frequency modulation.

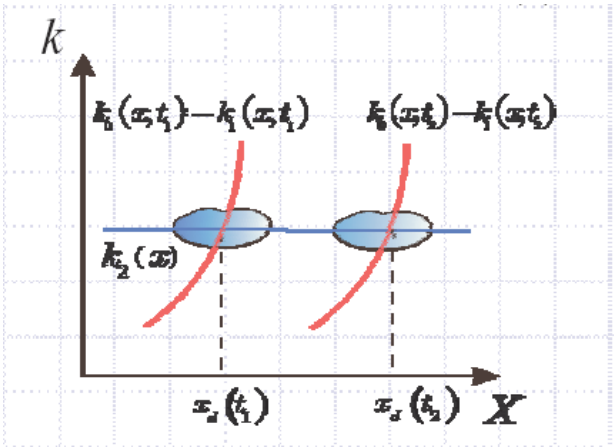
Decay wave amplification in inhomogeneous plasmas:

$$k_0(x,\omega_0) = k_1(x,\omega_1) + k_2(x,\omega_2)$$

$$S_{PR} = \exp\left\{\frac{\pi\gamma_0^2\ell^2}{|v_1||v_2|}\right\}$$

The decay point drift due to the pump frequency modulation:

$$\omega_0(t) = \omega_1(t) + \omega_2$$

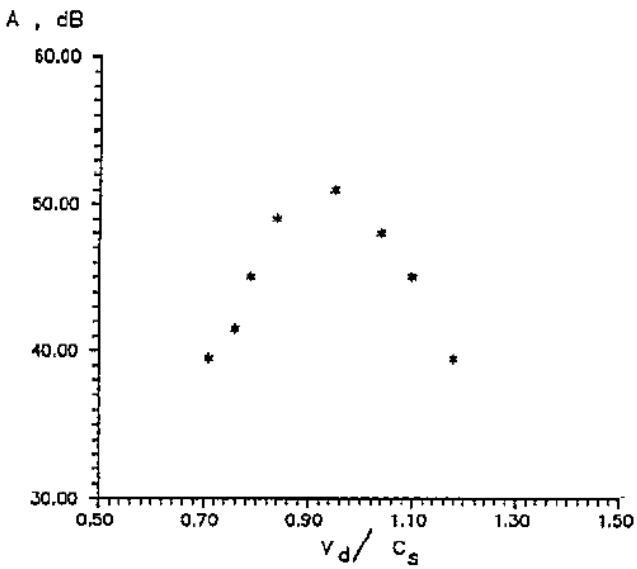


$$V_d = \frac{dx_d}{dt} = \frac{\partial x_d}{\partial \omega}\frac{\partial \omega}{\partial t}$$

Suppression of convective losses at

$$v_d = v_{1,2}$$

$$S = \exp\left\{\frac{\pi\gamma_0^2\ell^2}{\left|v_1 - v_d\right|\left|v_2 - v_d\right|}\right\}$$



One-dimensional model of the EPW breaking

Wave breaking condition

$$v_b \equiv \sqrt{\frac{2eE}{m_e k}} = \frac{\omega}{k}$$

The threshold power P_0=1-2 W

Scaling of the phase velocity at breaking

$$\frac{\omega}{k_{wb}} = \left(\frac{e}{m_e}\right)^{2/5} \left(8\kappa P_0\right)^{1/5}$$

Electron energy at breaking

$$W_{wb} \approx 2m\left(\frac{\omega}{k_{wb}}\right)^2 = 4\left(2e^4 m_e \kappa^2 P_0^2\right)^{1/5}$$

Density of accelerated electrons

$$\frac{n_h}{n_c} \approx \left(\frac{e}{m_e}\right)^{2/5} \frac{(8\kappa P_0)^{1/5}}{\omega b}$$

Current of accelerated electrons

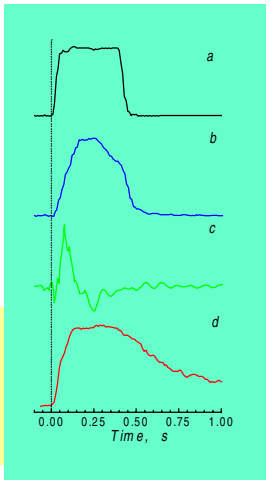
$$I \approx e n_h \frac{2\omega}{k_{wb}} \frac{\pi b}{k_{wb}} = 2\left(\frac{e}{2m_e}\right)^{1/5} (\kappa P_0)^{3/5}$$

Potential excited in plasma due to ponderomotive force

$$\varphi \approx \frac{W_{wb}}{8e}$$

Initial experimental results

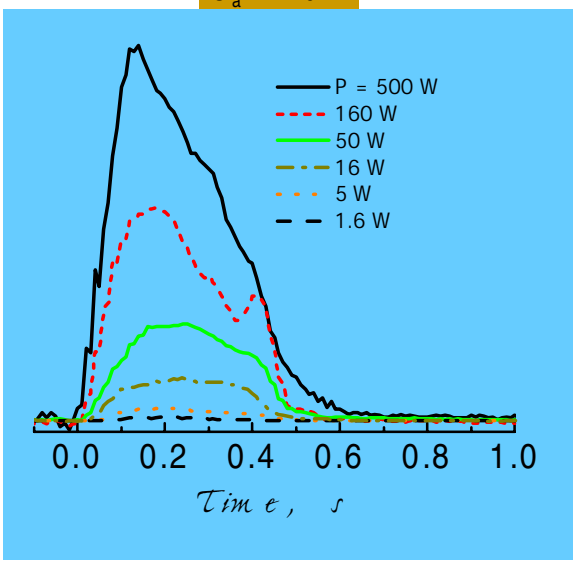
frequency $f_0 = \ /(2\ ) =$ **2.84 GHz**
microwave power $P \sim$ **0.5 – 5000 W**
pulse duration up to **0.5 s**
pulse rise time $t_f \sim$ **40 ns**
repetition frequency **300 Hz**.



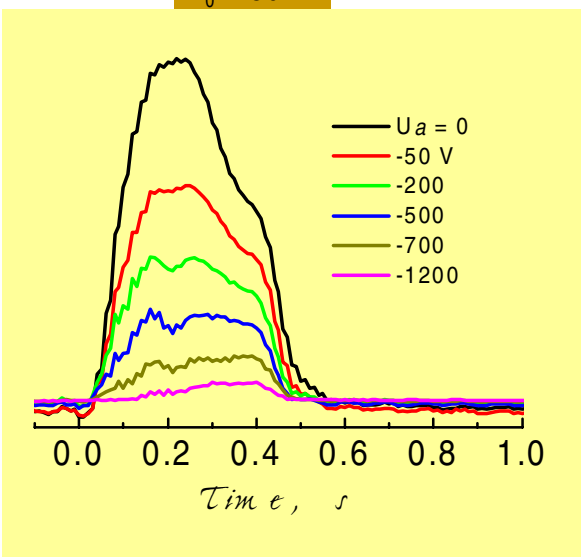
Oscillograms:
a – incident microwave pulse
b – analyzer current
c – Rogovskii coil signal
d – integral light from a focal region

Oscillograms of a multi-grid analyzer current

U_a = -10 V

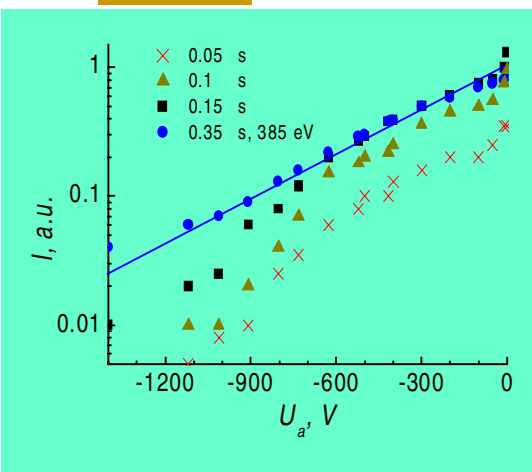


P_0 = 50 W

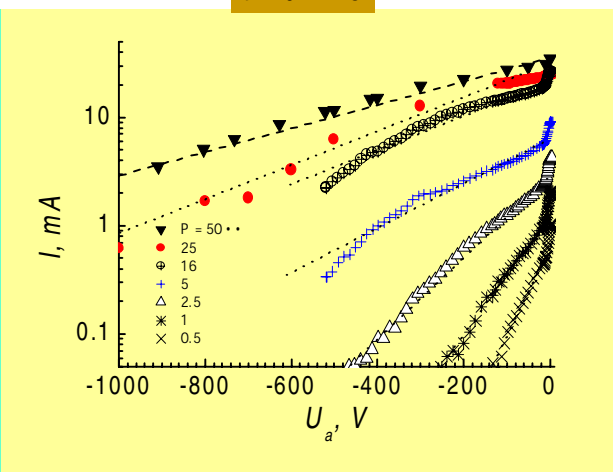


Distribution of accelerated electrons

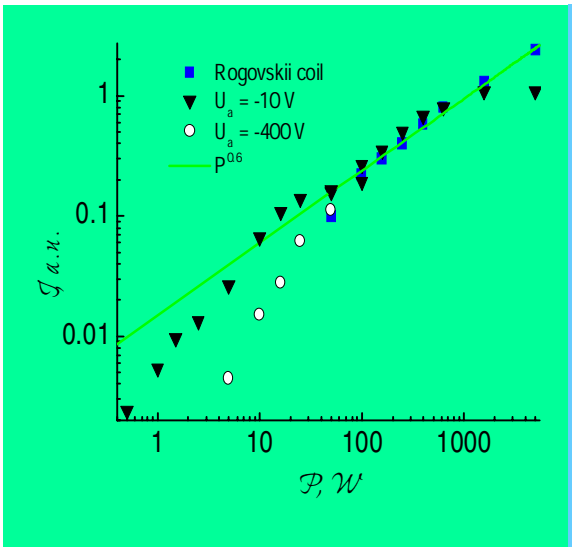
P_0 = 50 W

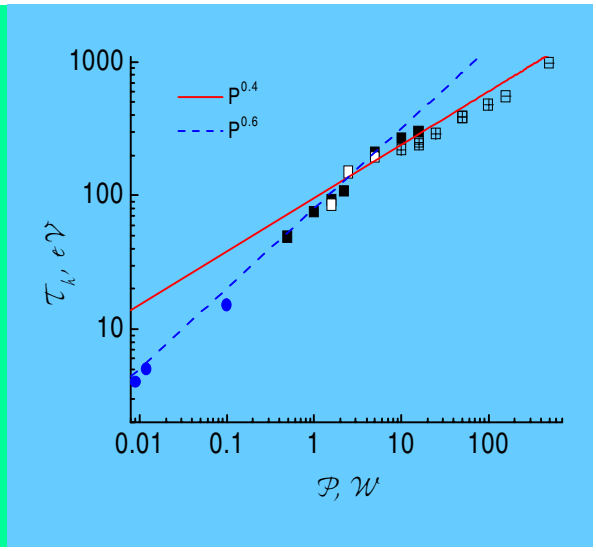


t = 0.2 s

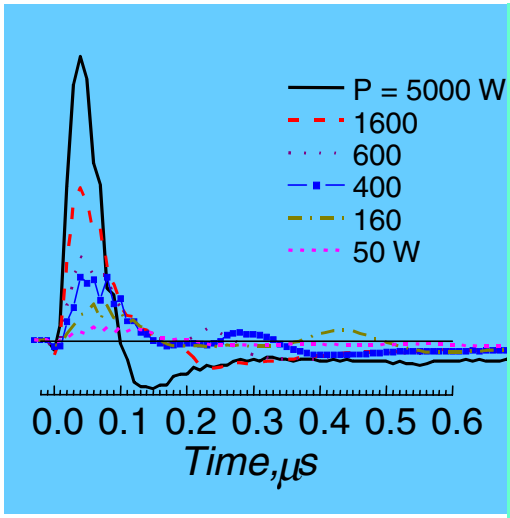


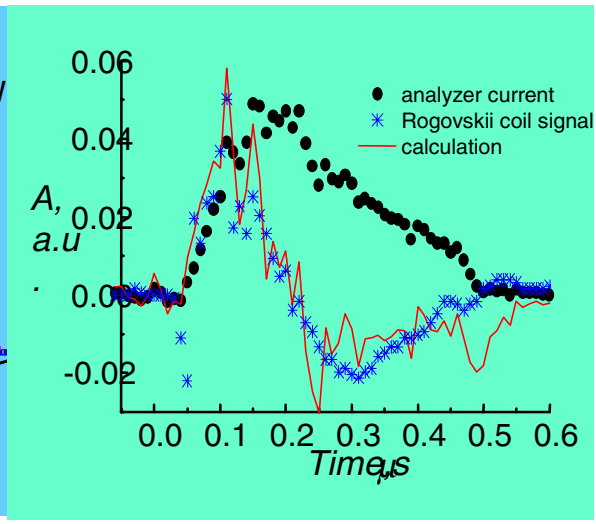
Current and effective temperature of accelerated electrons against a pulse power





Rogovskiicoil signal





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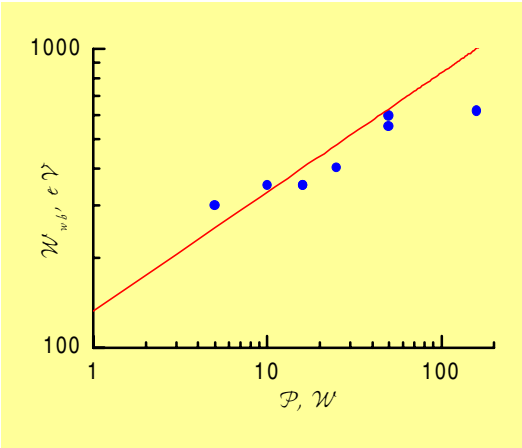
W_{wb} – maximal electron energy at the EPW breaking



The density of accelerated electrons

$$\frac{n_h}{n_c} \quad \frac{I_h}{e n_c \langle v_h \rangle S}$$

S 0.02 cm2 - electron flux cross-section

v_h $\sqrt{2T_h / m_e}$ - average electron velocity corresponding to temperature Th

For the maximal available power P_0 ~ 5 •• •
n_h/n_c ~ 0.5

SUMMARY

The electron plasma wave damping due to Landau mechanism and associated electron acceleration in the vicinity of plasma resonance is investigated for the power ranging from 10 mW up top 5 kW. The transition to the damping nonlinear regime is followed in experiment. It is shown that substantial fraction of electrons in the resonant point are accelerated in the wave breaking.

The obtained agreement of the experimental data to the predictions of a simple one-dimensional model points out to a possibility of significant ion acceleration in potential of about a few thousand Volts, which should be created due to the charge separation as result of the ponderomotive force action and wave breaking.

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