WAVE BREAKING IN INHOMOGENEOUS PLASMA.
2. PLASMA CHANNEL FORMATION.

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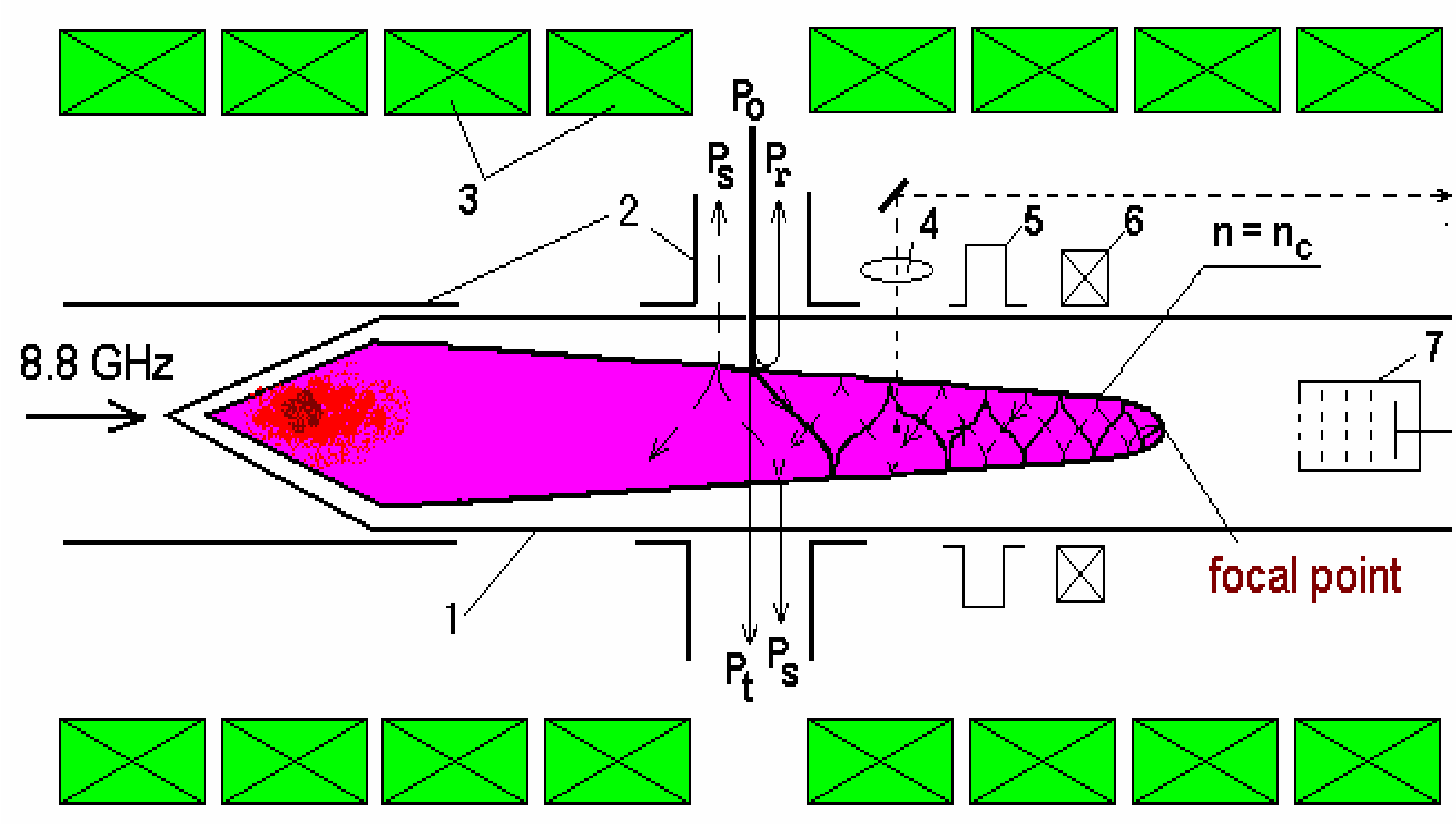
Outline

1. Introduction
2. Experimental situation
3. Plasma channel formation
4. Frequency up-shift
5. Conclusion

Scheme of excitation and propagation of the EPW



1 – glass tube
2 – waveguides
3 – magnet coils
4 – optical system
5 – resonator
6 – Rogowskii coil
7 – charge particle analyzer

P_0, P_t, P_s, P_r are incident, transient, scattered and reflected power correspondingly

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

Argon, p ~ 1 – 2 Pa, H ~ 3.5 kG

***l* = 5 cm, β = 4 – 5**

$N_e \sim 10^{12}$ cm^{-3}, $T_e \sim 1 – 2$ eV

EPW – fundamental Trivelpiece-Gould mode

$$k_{\perp}^{2}=\left(\frac{\omega_{pe}^{2}(r,z)}{\omega_{o}^{2}}-1\right)\cdot k_{\parallel}^{2},$$

$k_{\perp}$ and $k_{\parallel}$ - perpendicular and parallel wave vector components

$$E_{o}=\left(\frac{2P_{0}'}{\omega_{o}}\right)^{1/2}\frac{k_{o}^{3/2}}{\left(3r_{d}^{2}bk_{o}^{3}+1\right)^{1/2}}\exp\left[i\int_{-\infty}^{z}\left(k_{0}+ik_{0}''\right)-\frac{k_{o}}{2b}r^{2}-i\omega_{o}t\right]+c.c.$$

$$3r_{d}^{2}\left(k_{0}+ik_{0}''\right)^{2}-\frac{z}{a}-\frac{2}{\left(k_{0}+ik_{0}''\right)b}+i\eta''=0,$$

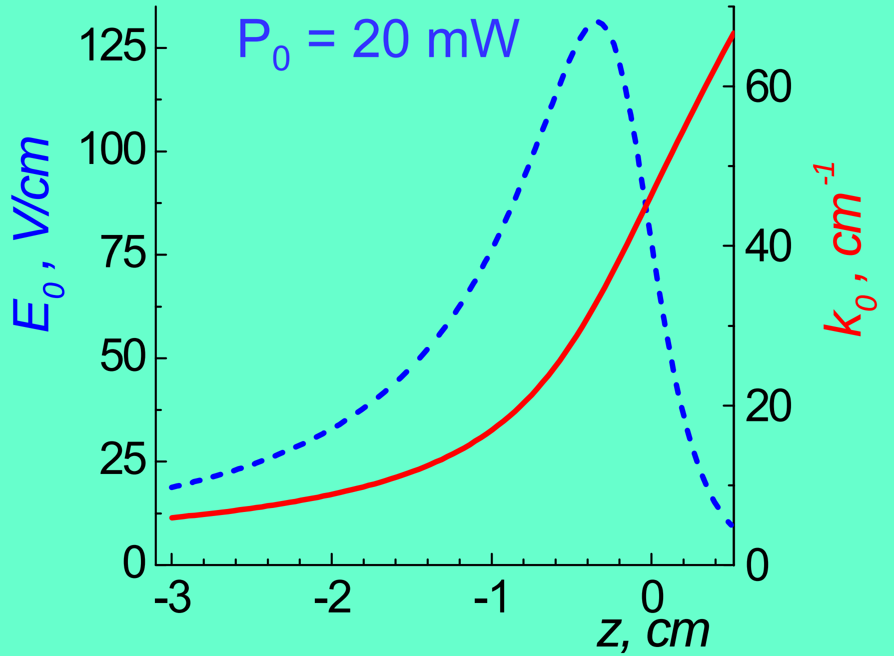
$$\eta=1-\frac{\omega_{pe}^{2}(r,z)}{\omega_{0}^{2}}\left(1+3r_{d}^{2}k^{2}\right)+i\eta'',$$

$$\eta''=\frac{\nu_{ea}}{\omega_{0}}-\pi\frac{\omega_{pe}^{2}}{k_{0}^{2}}\frac{\partial f_{e}}{\partial w}\pi\frac{\omega_{pe}^{2}}{k_{o}^{2}}\frac{\partial f_{e}}{\partial w}\bigg|_{w=\frac{\omega_{0}}{k_{0}}},$$

$$\ln b_{\ell}=-\int_{-\infty}^{z}k''dz'=-\frac{\nu_{ea}}{\omega_{o}}k_{o}a-\pi a\omega_{o}f_{e}(\omega_{o}/k_{o}).$$

$a\approx l$ **= 5 cm,** $b=\frac{r_{0}}{\sqrt{\beta}}$ **~ 0.4 cm**

Nonlinear phenomena



Landau damping

$$n(w)=n_c\left[\left(\frac{m_e}{2\pi T_e}\right)^{1/2}\exp\left(-\frac{m_e w^2}{2T_e}\right)+\delta\left(\frac{m_e}{2\pi T_h}\right)^{1/2}\exp\left(-\frac{m_e w^2}{2T_h}\right)\right],$$

Resonance nonlinearity

$P_0 \geq 10$ mW

$l \rightarrow l' + s$ parametric instability of stimulated backscattering

Nonresonance nonlinearity

$P_0 \geq 1$ W

- ***charge separation under the influence of ponderomotive force***
- ***wavebreaking***

Ionization nonlinearity

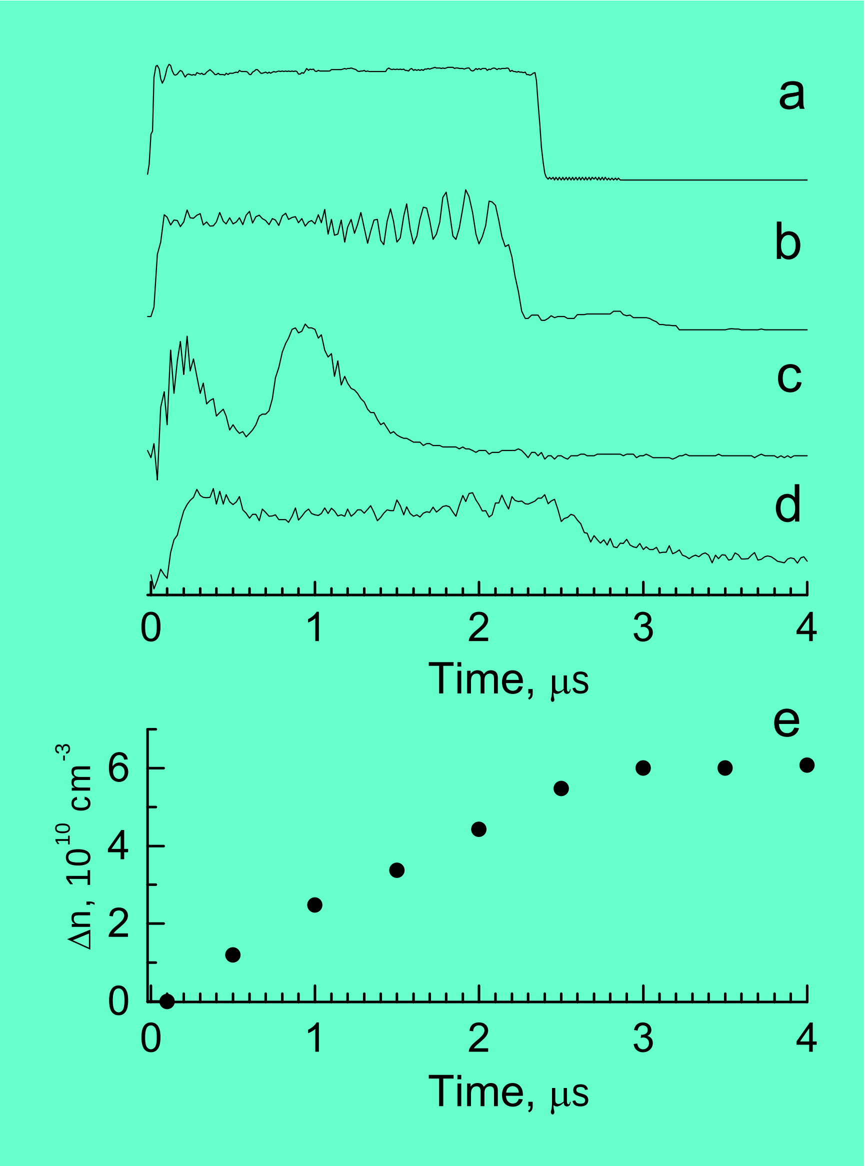
$W_\sim$(eV) ≈ 3.2P_0(W) – ***oscillating energy of electrons***

P_o = 5 W → $W_\sim$ ≈ 16 eV ≥ E_i = 15.76 eV.

Initial experimental results

$f_0 = \omega/(2\pi)$ = **2.84 GHz**
incident pulse power is P ~ **50 – 200 W**
pulse duration is up to **2.5 μs**
pulse rise time is t_f ~ **40 ns**
repetition frequency is **300 Hz**.

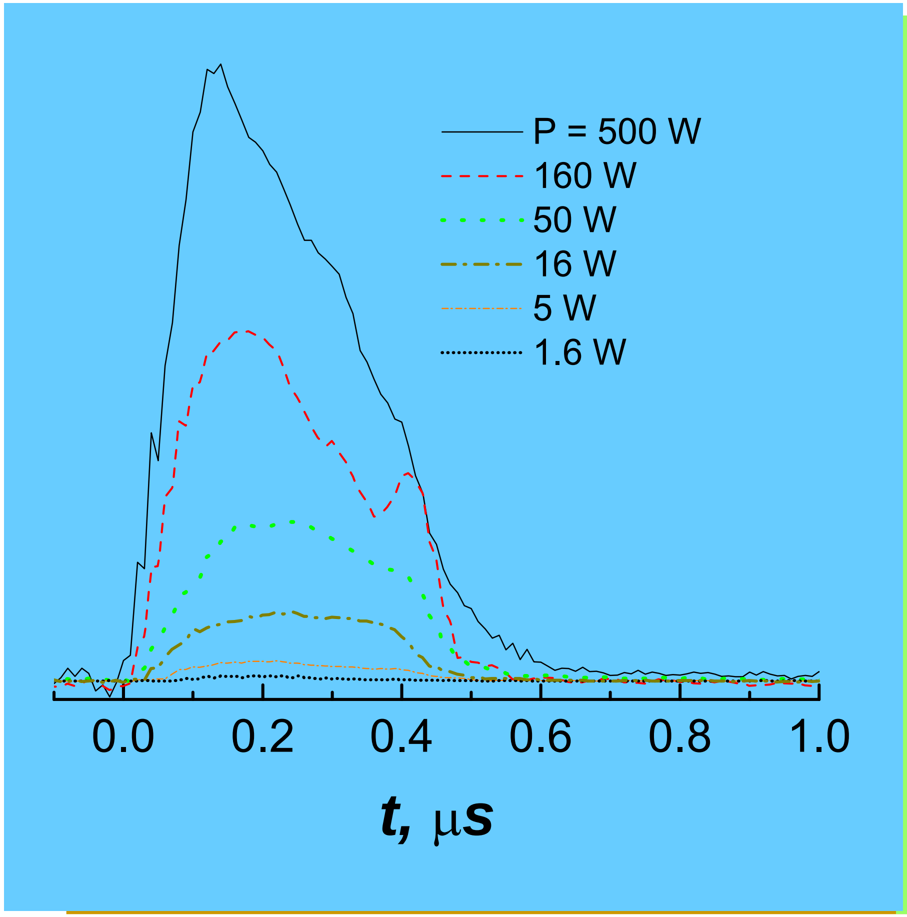
Oscillograms:
a – incident microwave pulse
b – pulse after an interaction with plasma
c – analyzer current
d – integral light from a focal region



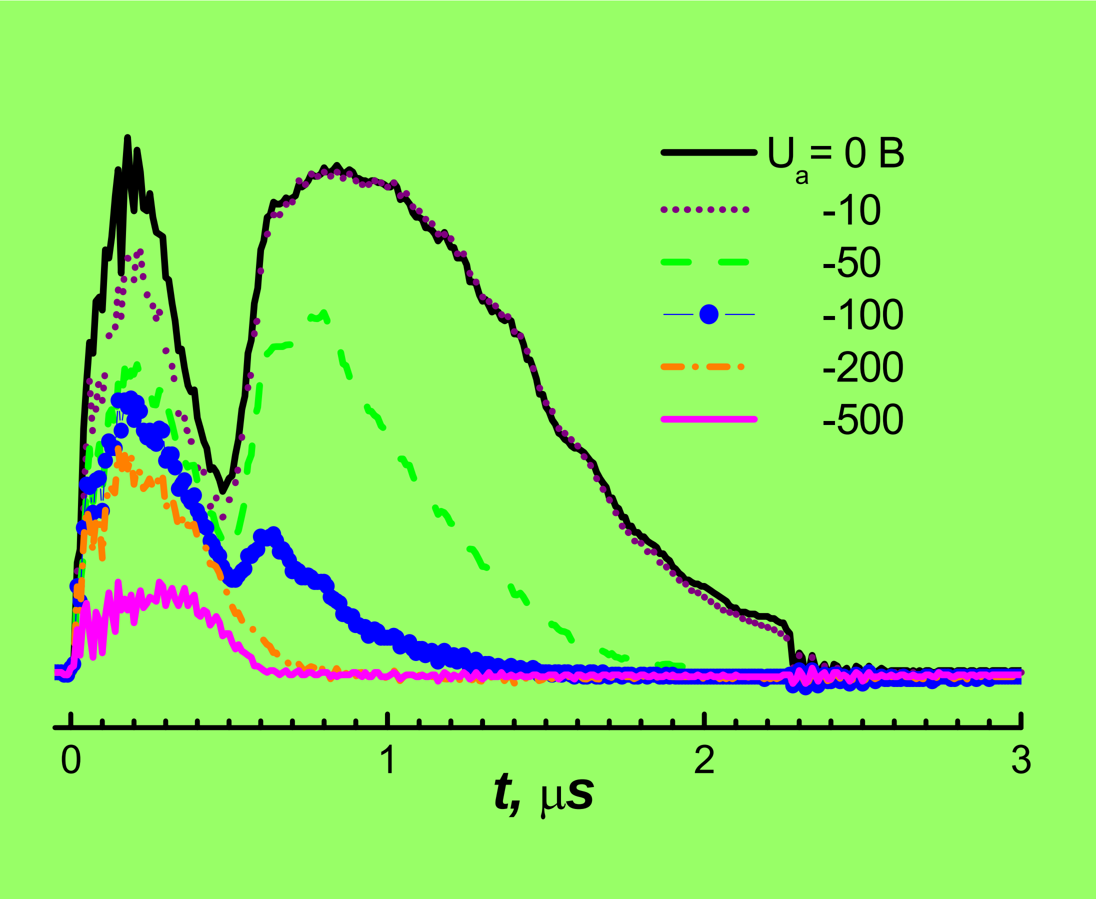
e – electron density increase in focal region

Oscillograms of a multi-grid analyzer current

U_a = -10 V

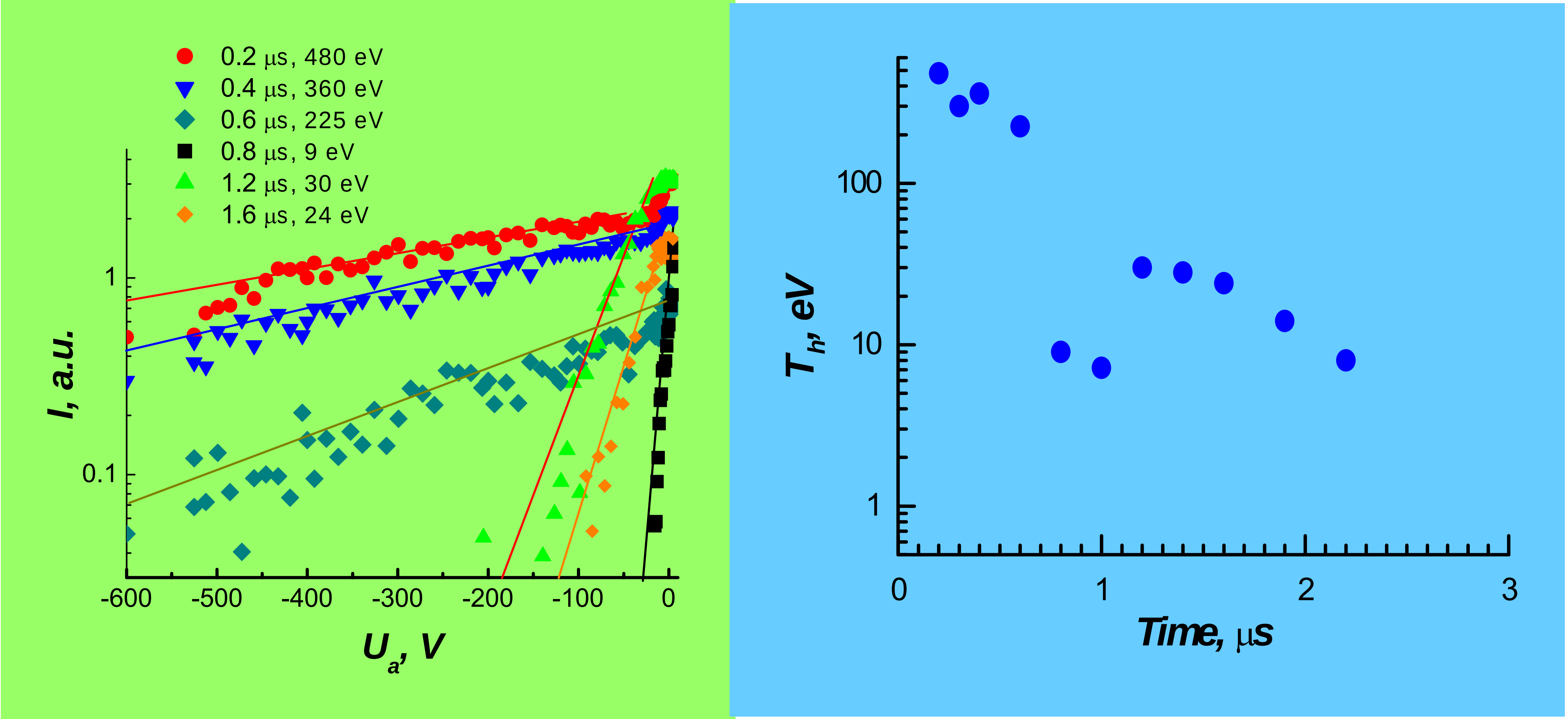


P_0 = 50 W

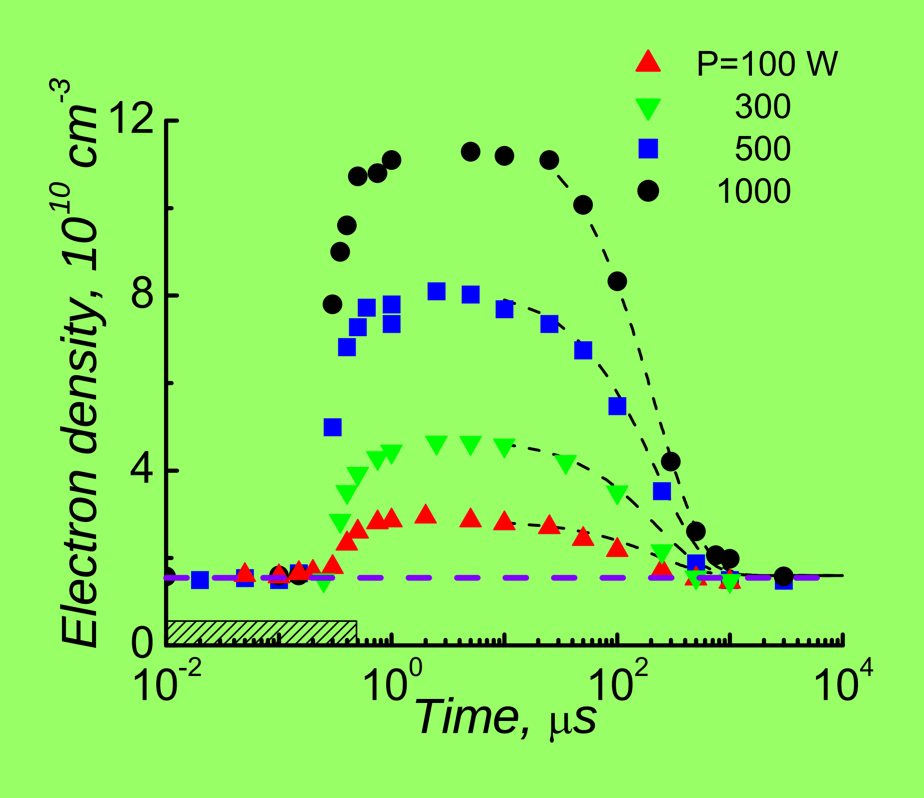


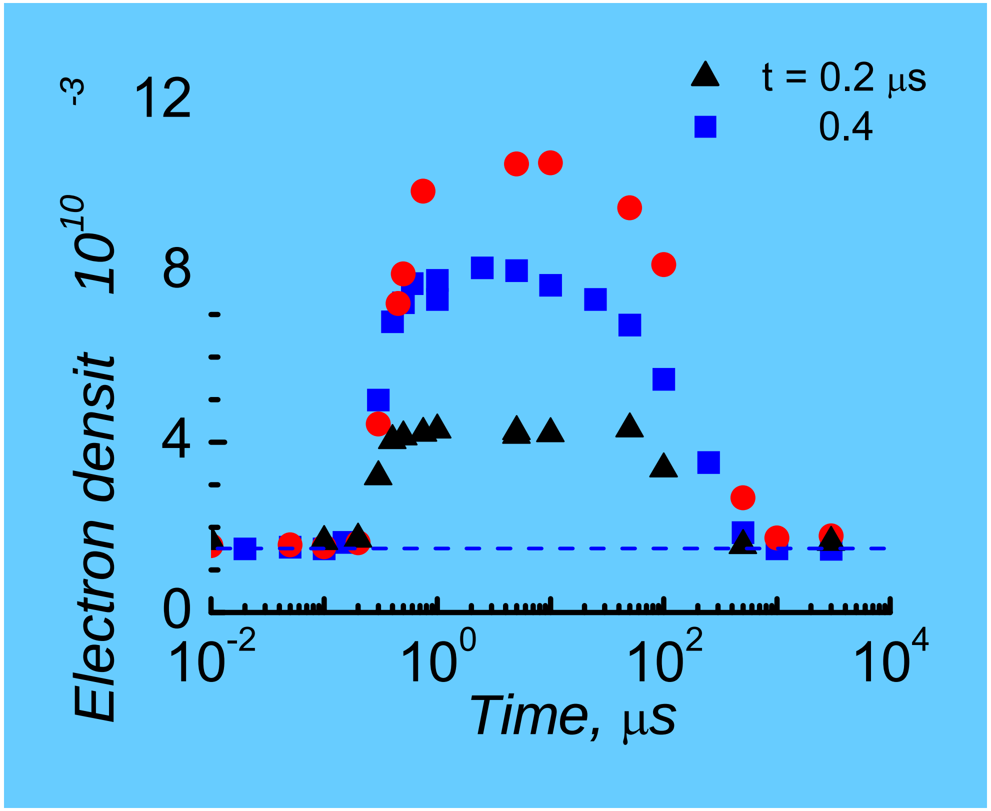
Effective temperature of accelerated electrons

P_0 = 50 W



Electron density dynamics

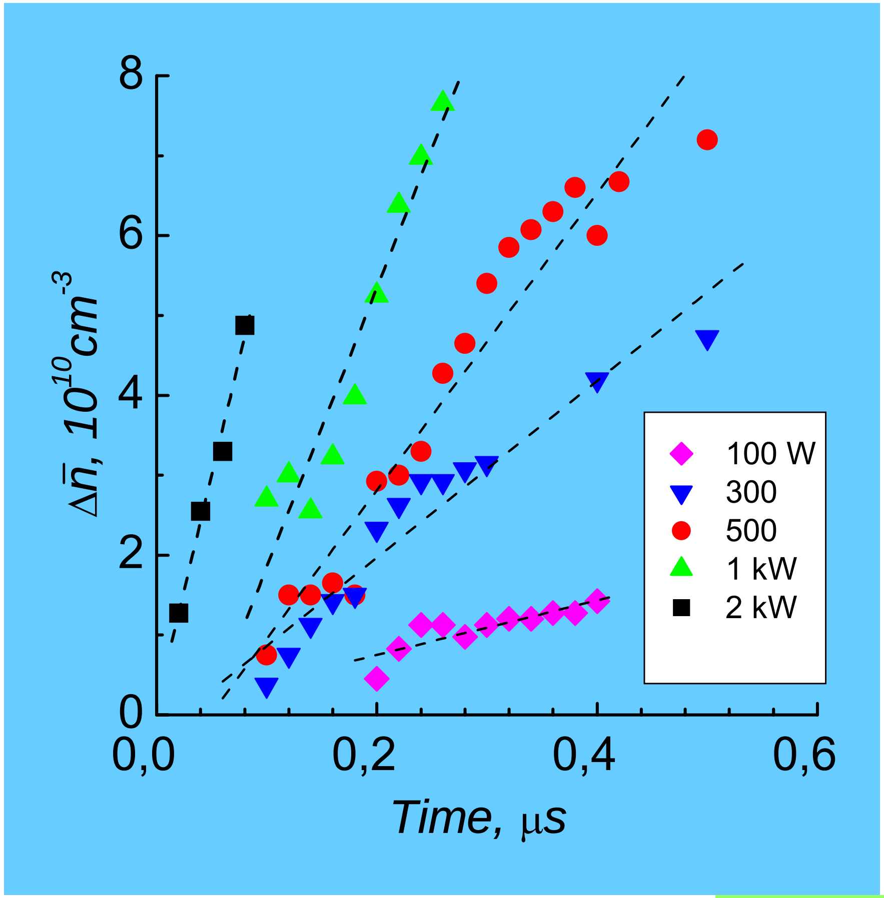


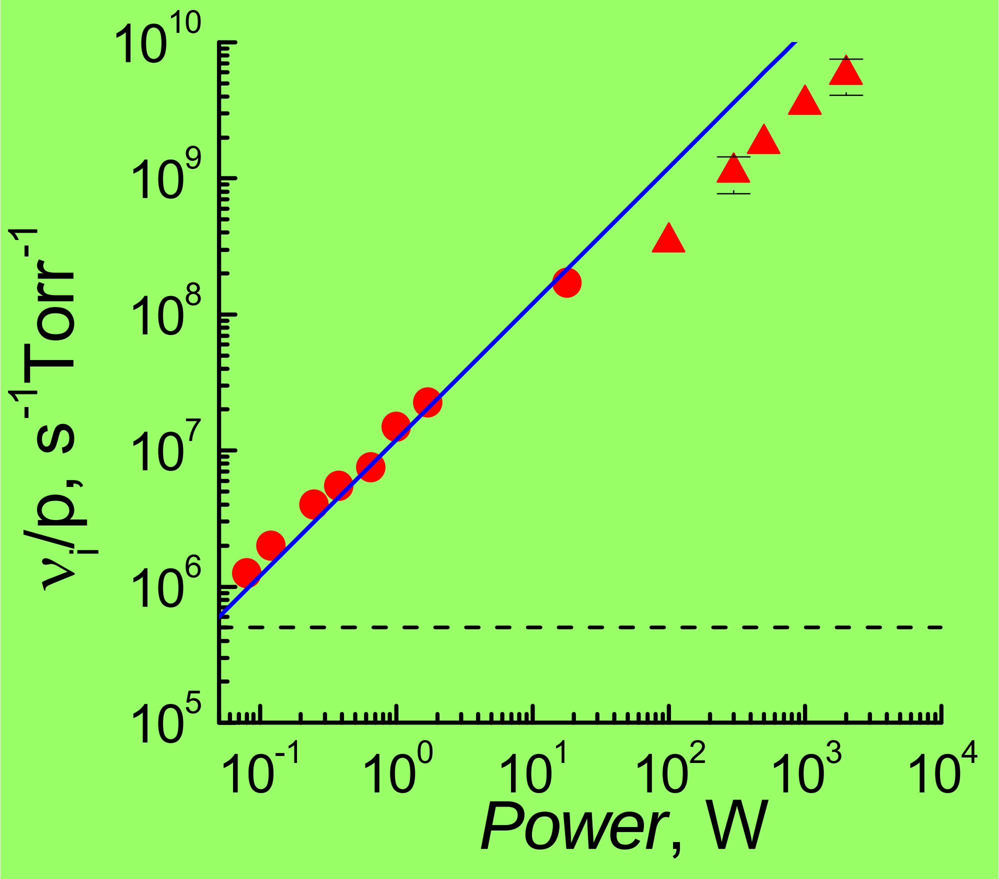


$$n = n_m \exp(-(t-t')/\tau_d)$$

$\tau_d = 200\ \mu s$

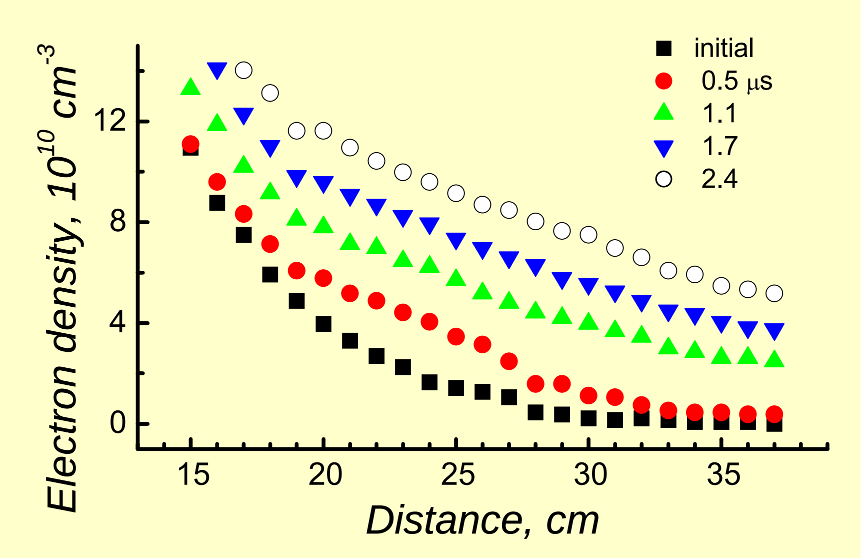
Ionization rate

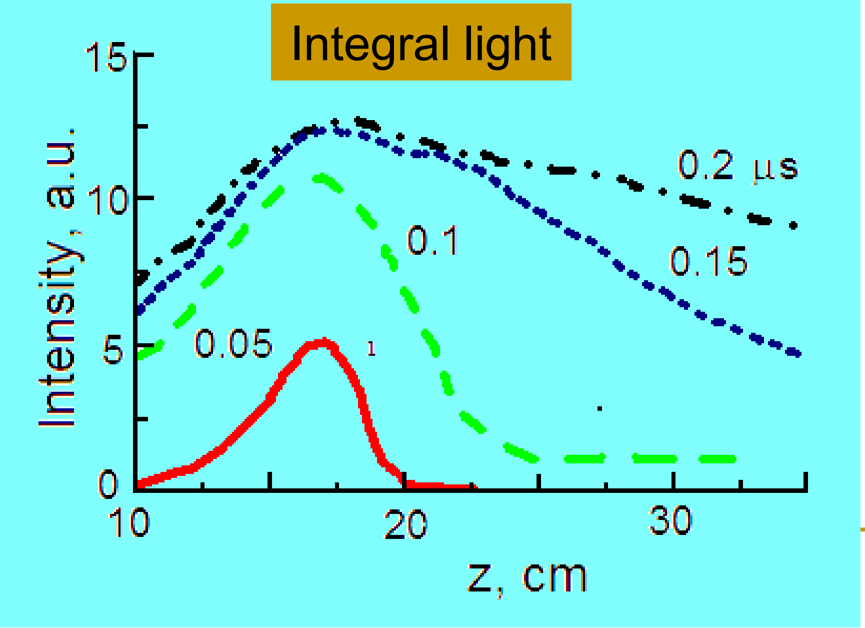




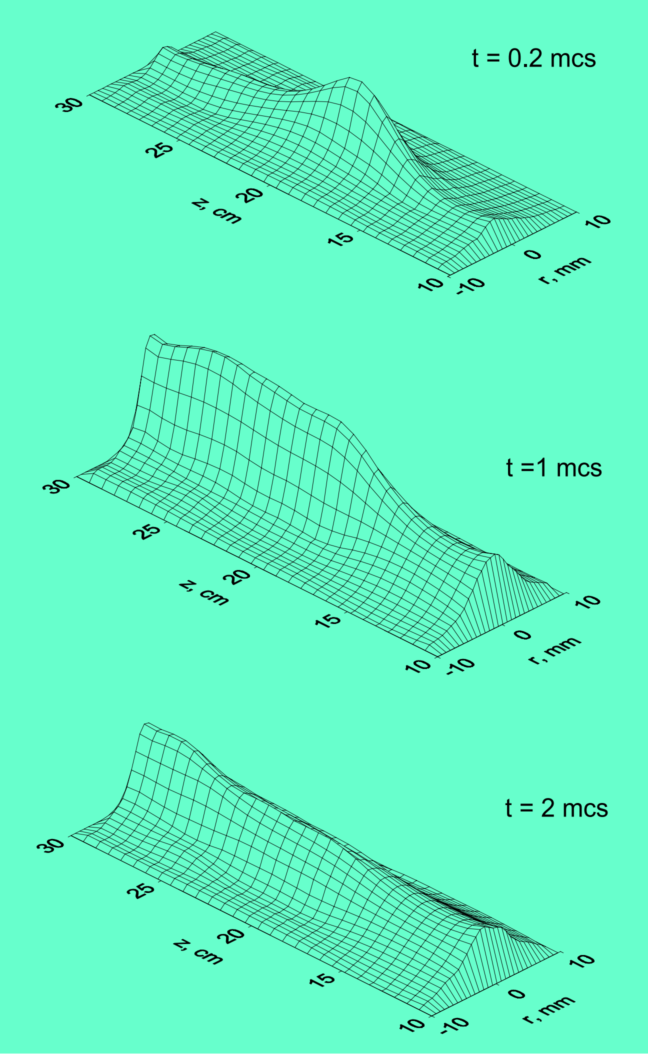
$$\frac{\nu_i}{p} \approx \frac{1}{p n_c} \frac{\partial n}{\partial t}$$

Electron density and light distributions

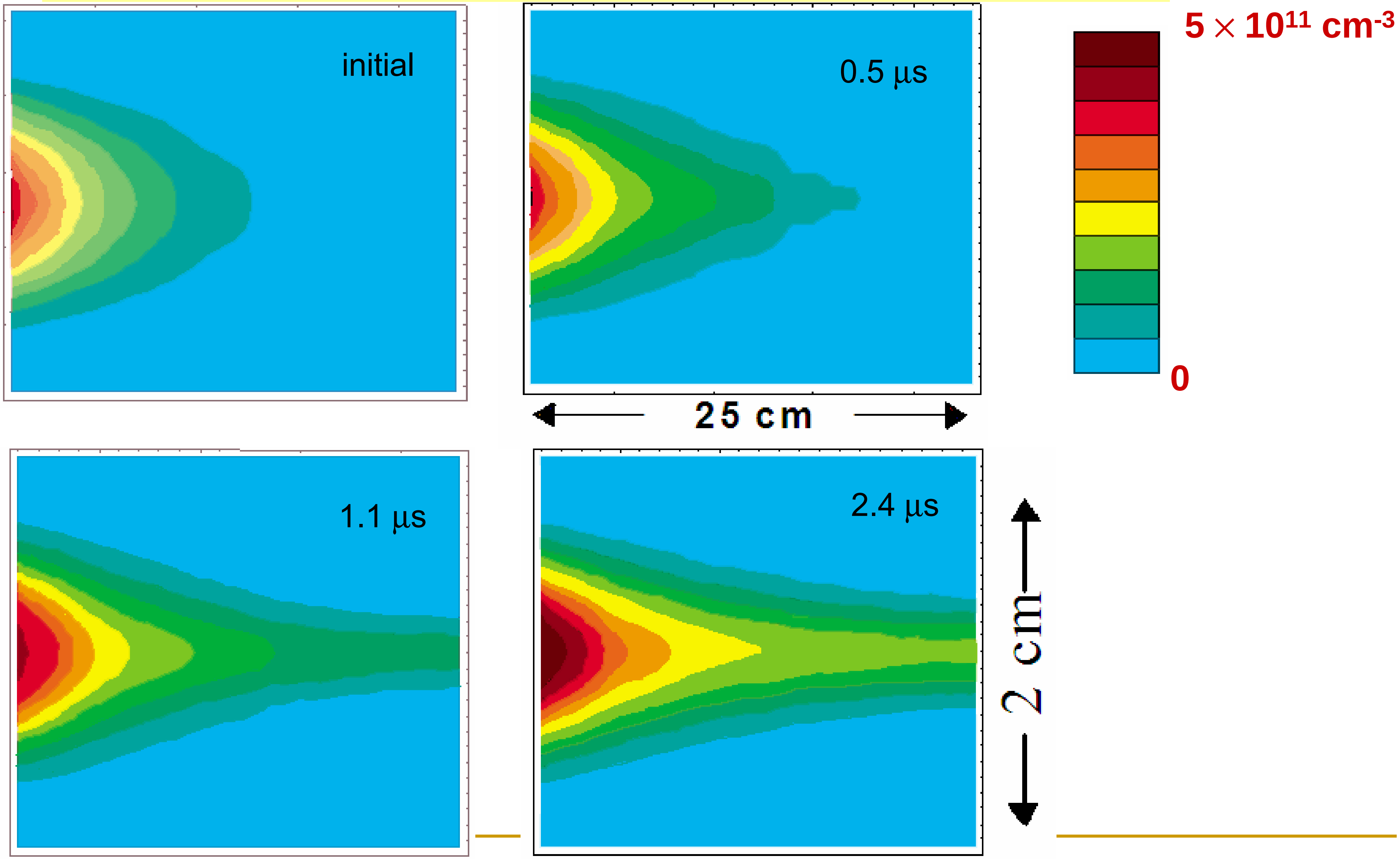



Integral light

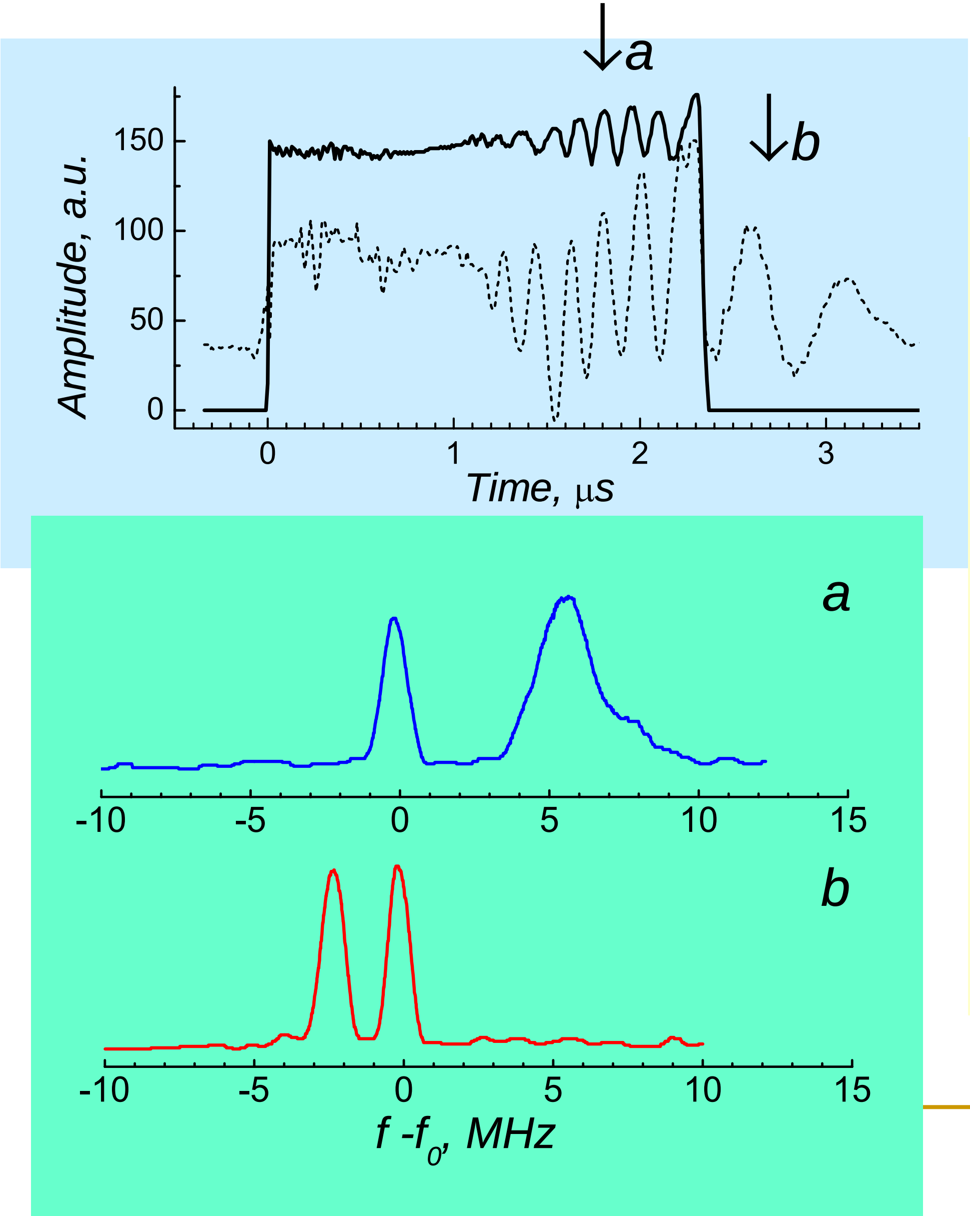
Ar II 454.5 nm

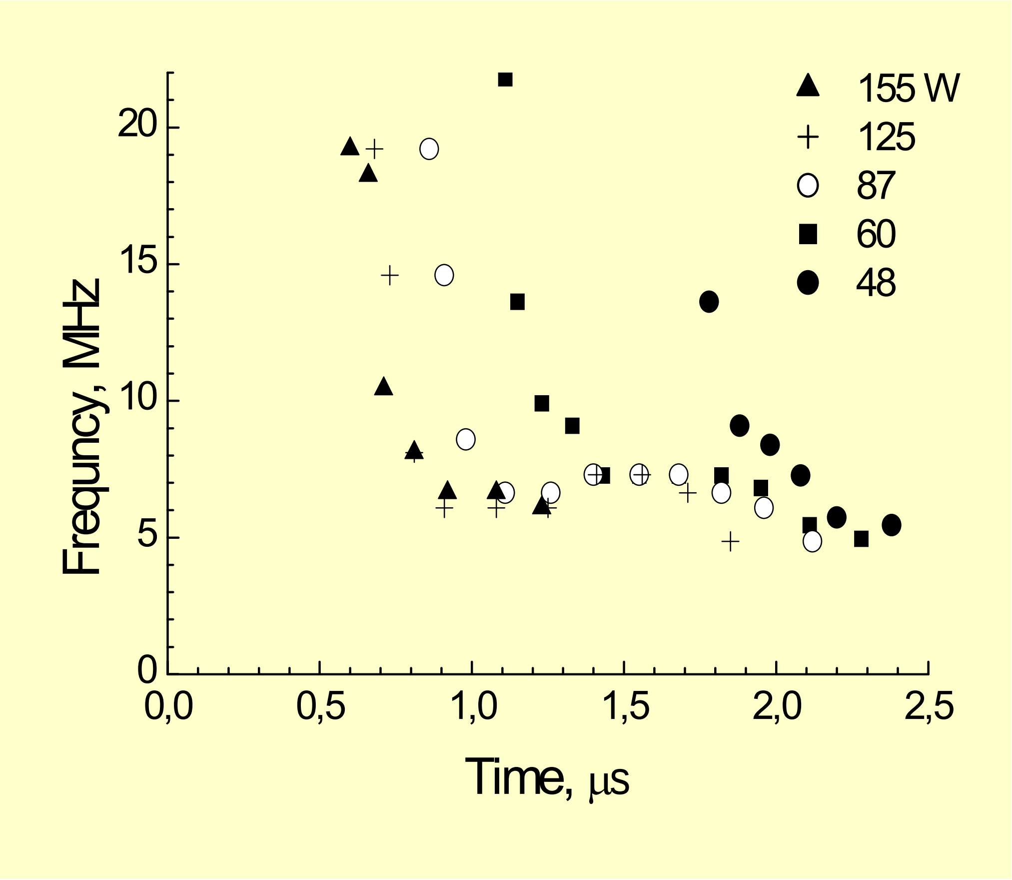


Dynamics of a plasma waveguide channel



Low frequency oscillations





Theoretical model

$$\delta\Phi = -2k_0L$$

$$\delta\Phi = -2\frac{L}{b}\frac{n_c}{n_e(z,t)-n_c}$$

$$\Phi = \omega_0 t - 2\oint k_0\,dz \qquad \omega = \frac{d\Phi}{dt} = \omega_0 + \frac{d\delta\Phi}{dt}$$

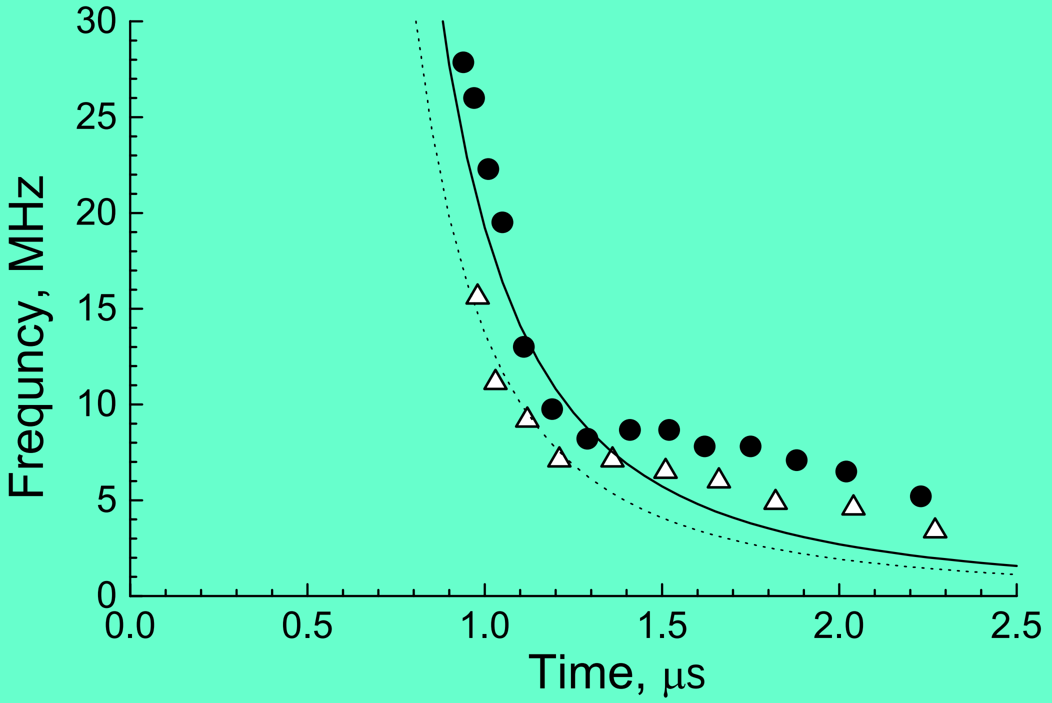
$$n_e = \left[1+\alpha(t)\right]n_c$$

$$\delta f = \frac{\delta\omega}{2\pi} = \frac{1}{\pi}\frac{L}{b}\frac{n_c}{(n_e(z,t)-n_c)^2}\frac{dn_e}{dt}$$

$$\delta f = \frac{L}{\pi b}\frac{dn_e/dt}{\alpha^2 n_c}$$

$$\frac{dn_e}{dt} = \frac{d\alpha}{dt}n_c = const \qquad \alpha \cong \frac{dn_e}{dt}\frac{t-t_*}{n_c}$$

$$\boxed{\delta f = \frac{1}{\pi}\frac{L}{b}\frac{n_c}{dn_e/dt\,(t-t_*)^2}}$$



Conclusion

The interaction of an electromagnetic pulse with inhomogeneous magnetized plasma results in acceleration of electrons due to the wave breaking in vicinity of a resonant point (focus). The acceleration period is less than 0.5 μs at power about 50 W. At large times (t > 0.5 μs) a narrow homogeneous plasma channel is created due the fast ionization caused by oscillations of electrons in a wave field. It results in both the increase of collision absorption of the EPW and suppression of electron acceleration effect.

The reflection of the EPW at the edge of the plasma waveguide takes place later ($t > 1$ μs). The propagation of a reflected wave in the plasma waveguide with a increasing electron density results in a phase taper variation and frequency up-shift of the reflected wave.

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