Long-Distance Transfer of Microwaves in Sliding-Mode Virtual Plasma Waveguides

Presented by V.D. Zvorykin

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Outline

- Initial considerations
- Experiments on MWs guiding at KrF GARPUN laser
- Theory of sliding modes propagation
- Further investigations
- Conclusions

Channeling of microwaves

- In a free space MWs have a large divergence $\beta \approx \lambda/D$: to obtain

$\beta \sim 10^{-3}$ rad for $\lambda \sim 1$ cm, the antenna size of $D \sim 10$ m is required.

- Metal waveguides with a transverse size $D \sim \lambda$ and high wall conductivity provide excellent MW transfer to long distances.
- Similar plasma waveguides with $D \sim \lambda$ were proposed on a base of filamentation effect of ultra-high intensity fs laser pulses in air (Dormidonov *et al.*, "Laser filament induced microwave waveguide in air", *Proc. SPIE*, 6733, 67332S (2007); Musin *et al.*, "Guiding radar signals by arrays of laser-induced filaments: finite-difference analysis", *Appl. Opt.*, 46, 5593 (2007)) . Electron density in filaments $n_e = 10^{16}$-10^{17} cm^{-3}.

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Realization of metal-like plasma waveguide

Chateauneut *et al*,. "Microwaves guiding in air by a cylindrical filament waveguide", *Appl. Phys. Letts*, 92, 091104 (2008)

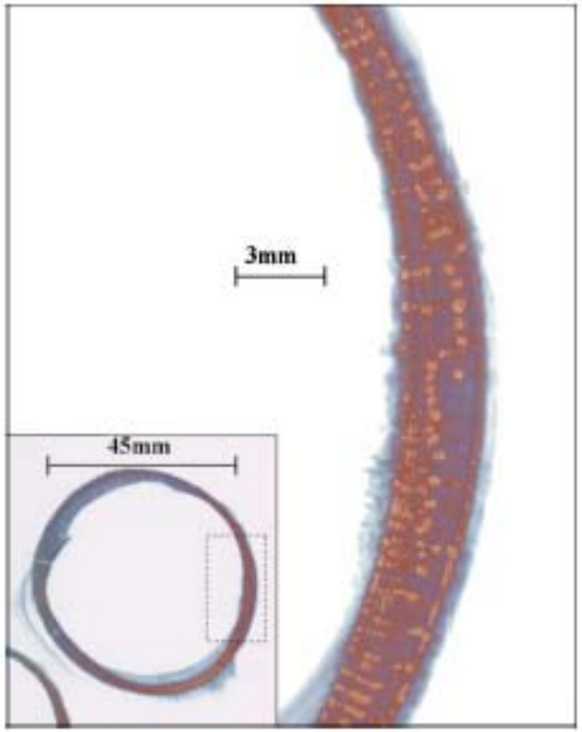


FIG. 1. (Color online) Beam pattern and filament distribution 30 cm after the geometrical focal plane of the DM. About 1030 filaments are distinguishable.

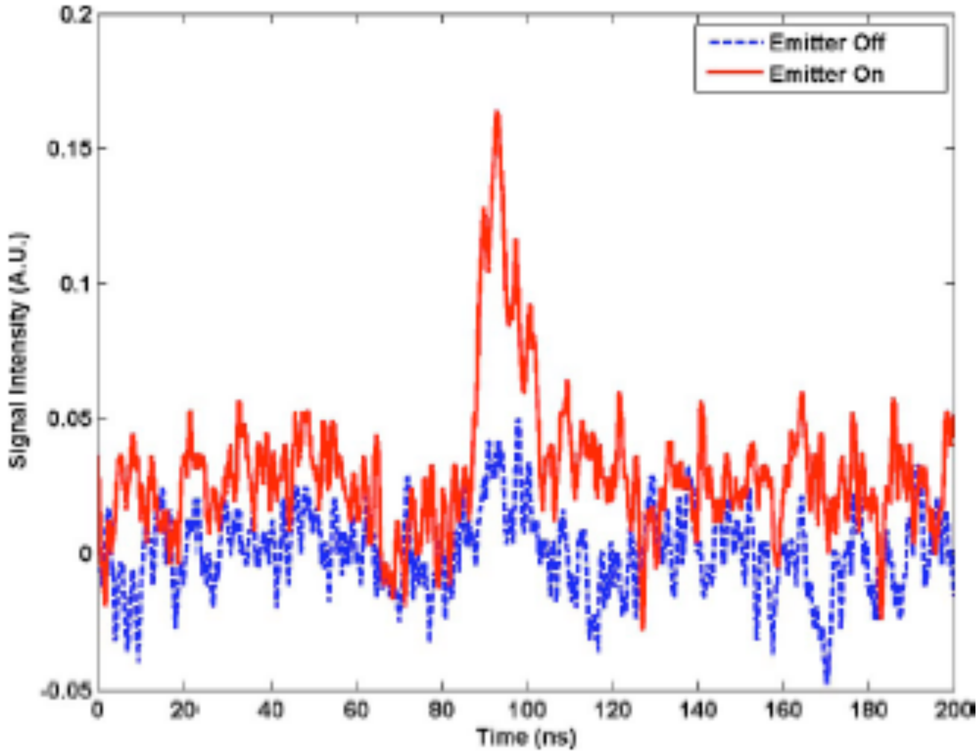


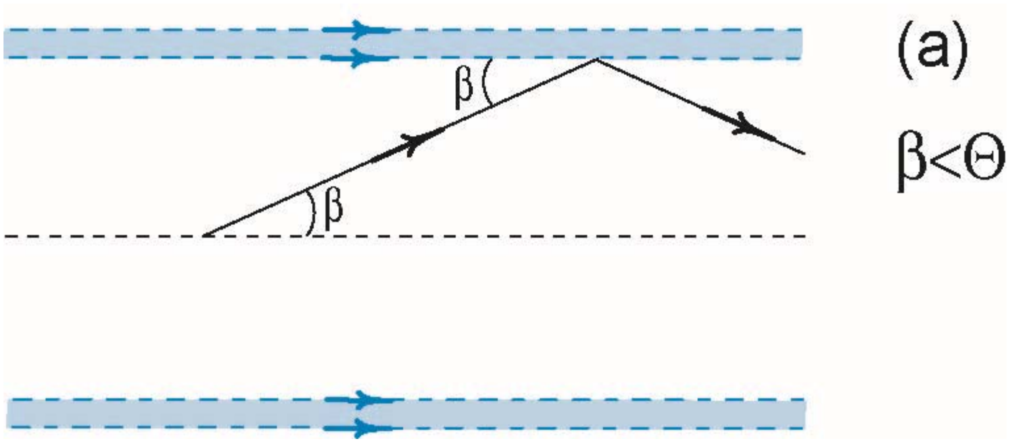
FIG. 2. (Color online) Microwave detected signal 16 cm from the emitter. The V-Wave was formed at t=85 ns.

Small propagation distance ~ 16 cm and short maintenance time ~10 ns were restricted by low electron conductivity and lifetime.

Sliding-mode MW propagation

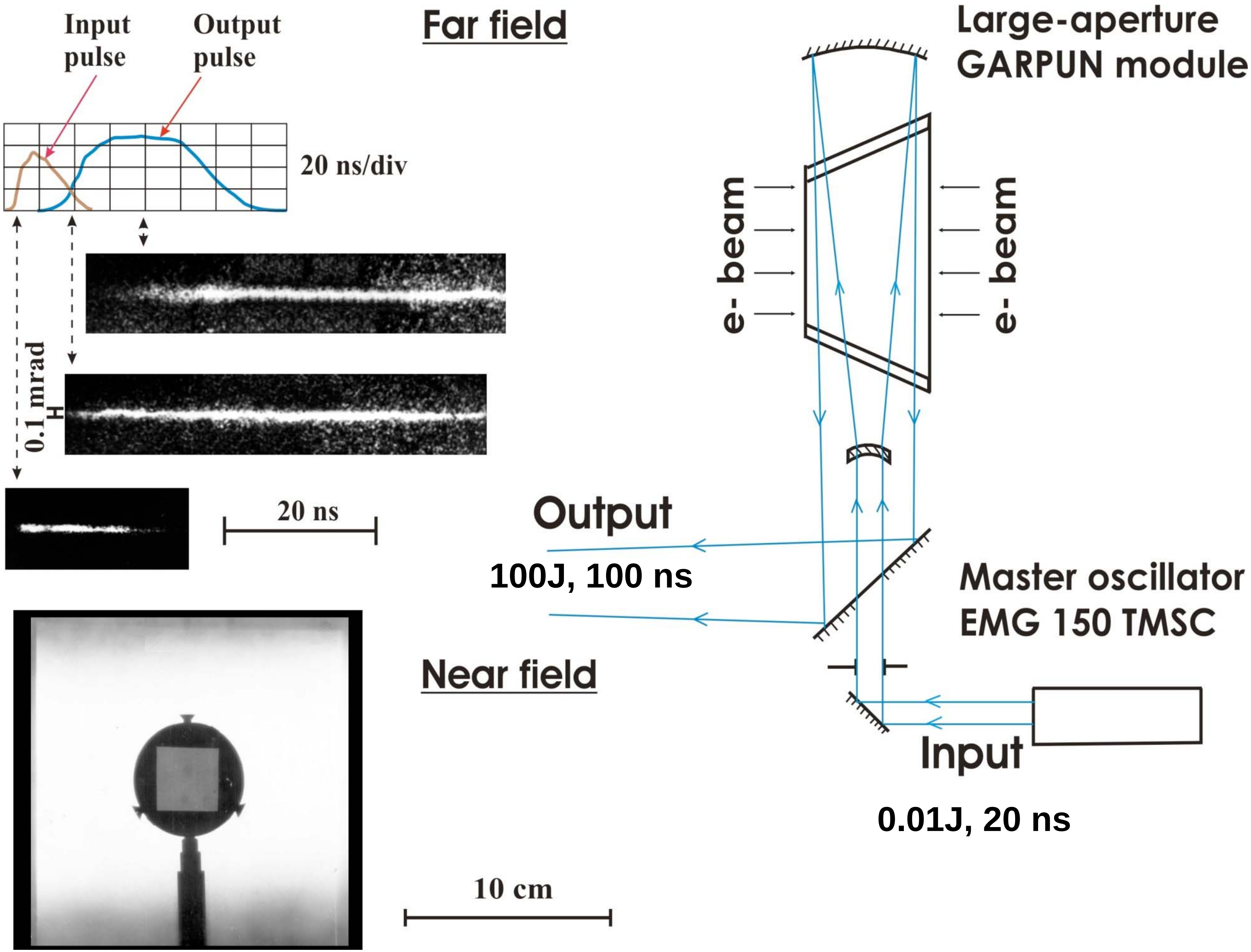
Askar'yan's suggestion (*JETP*, 28, 732, 1969): In a plasma waveguide diffraction angle of MWs should be less then the total reflection angle at the plasma-air boundary $\beta \le \Theta \approx \Omega_p / \left(\omega^2 + \nu_T^2\right)^{1/2}$ **;**

$\Omega_p = \sqrt{4\pi n_e e^2 / m_e}$ **is plasma frequency,** ν_T **- transport frequency.**

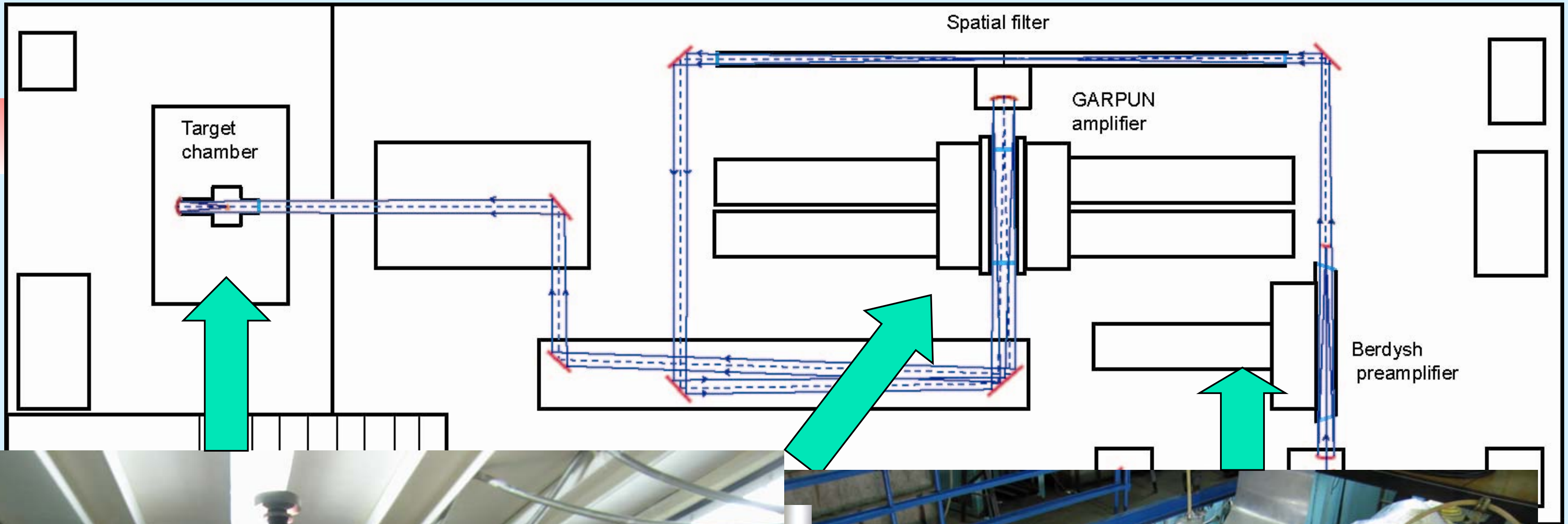


Such sliding mode regime can be realized for $D >> \lambda$ **and at moderate plasma density** 10^{11}**-**10^{14} **cm**$^{-3}$**.**

Layout of GARPUN KrF laser



Hybrid Ti:Sa/KrF laser facility GARPUN-MTW for amplification of short & long pulses



Target chamber

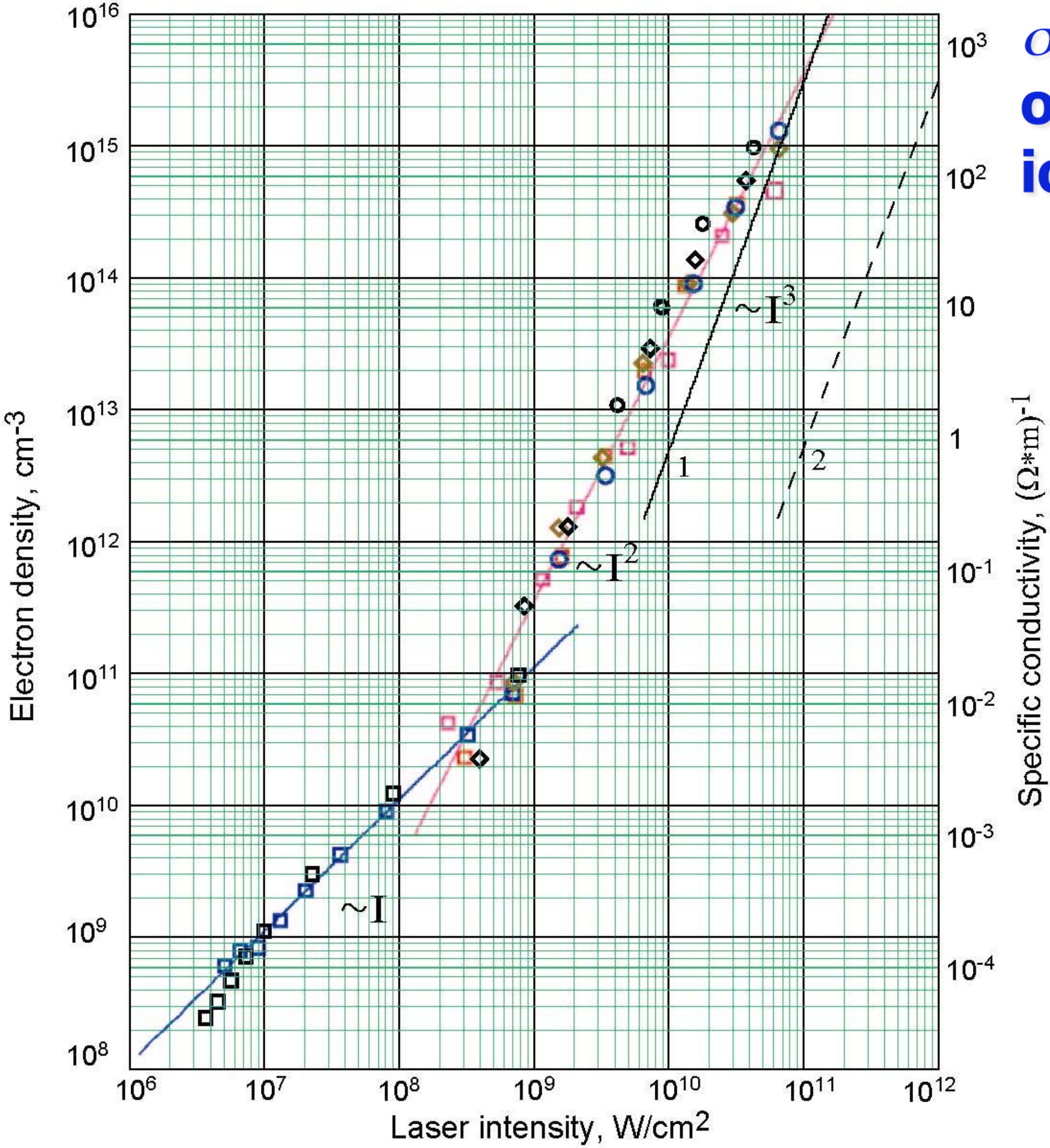
t 248M”: 10 Hz; 60 fs;
8 mJ (λ=744 nm) or 0.5 mJ (λ= 248 nm)

Obtained:

- **Single UV pulses at 248-nm wavelength of 0.6-J energy, 0.33-1.0 ps duration, peak power 1-2 TW, 20-μrad divergence.**

Expected:

- **Peak power up to 15-20 TW in single 100-fs pulses with improved beam quality to reach target intensity ~10^{19} W/cm^2.**
- **Combined 1.5-J short (from 100 fs to few ps) and 100-J long (from few ns to 100 ns) pulses to create long-distance ionized channels in air.**



σ and n_e dependences on laser intensity and ionization processes:

$I > 10^{11}$ W/cm² – air breakdown;

$I = 5 \cdot 10^8 \div 10^{11}$ W/cm² : $N_e \sim I^2$ – two-step resonance ionization ($2h\nu + h\nu$);

$I = 5 \cdot 10^6 \div 5 \cdot 10^8$ W/cm²: $N_e \sim I$ – photoionization or photoemission of impurities.

Addition of volatile hydrocarbons increases n_e in 10^3 times!

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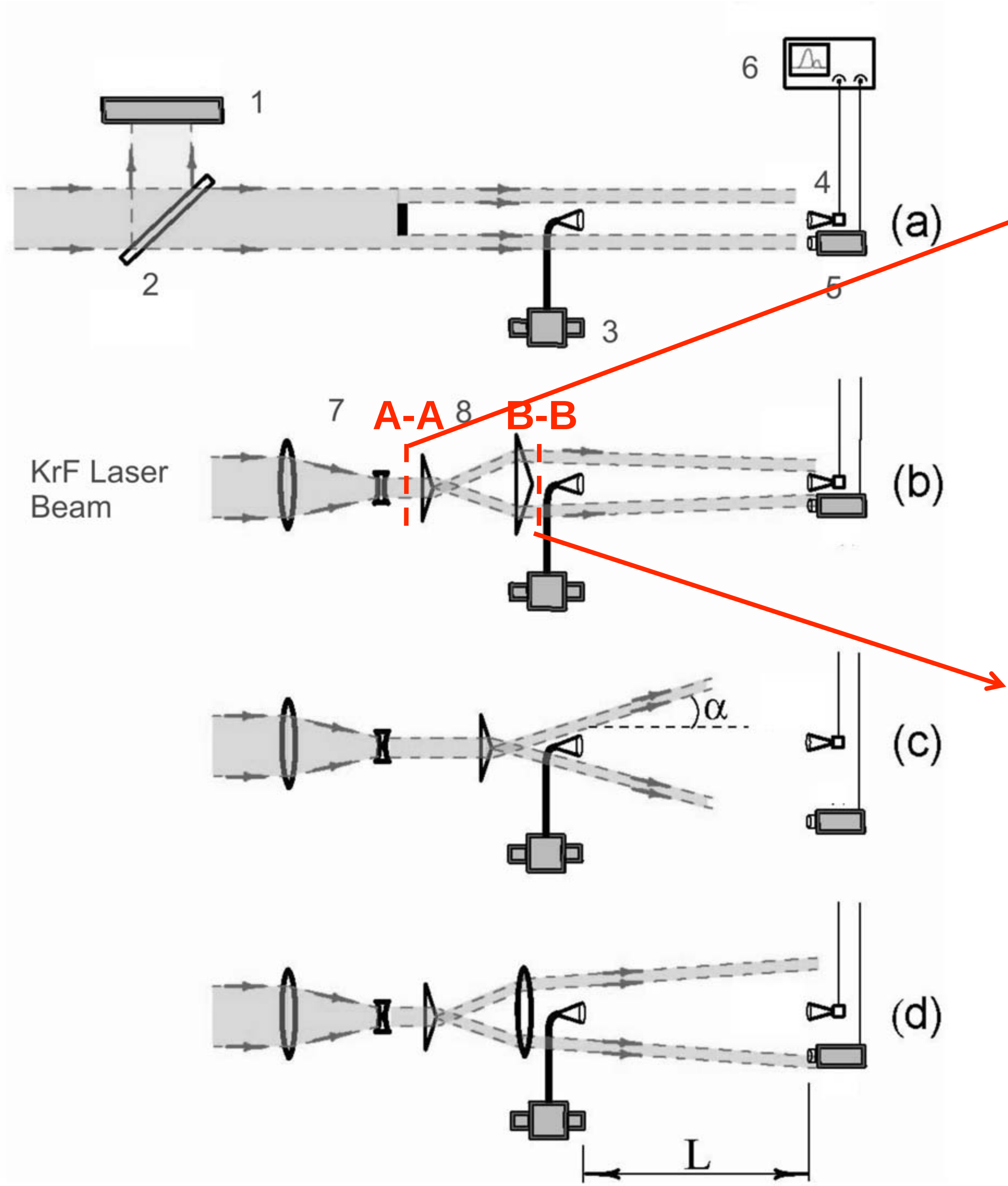
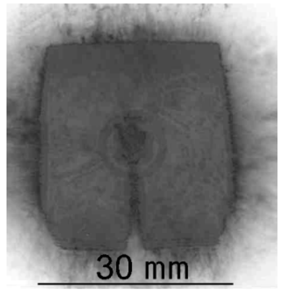
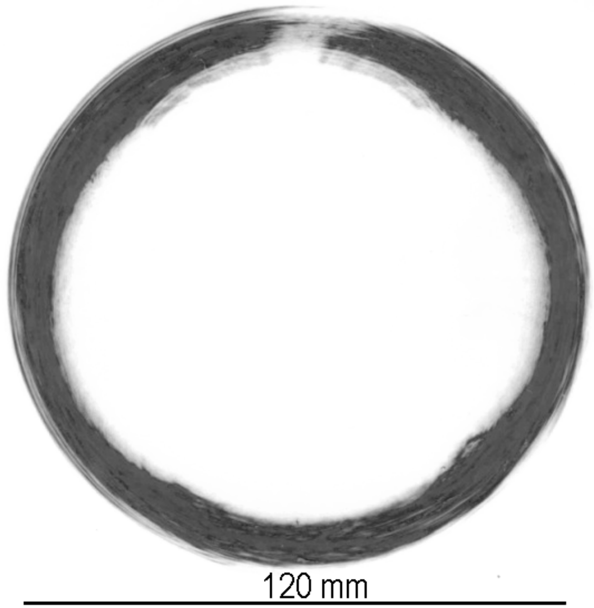
/ Guiding Experiments



A-A



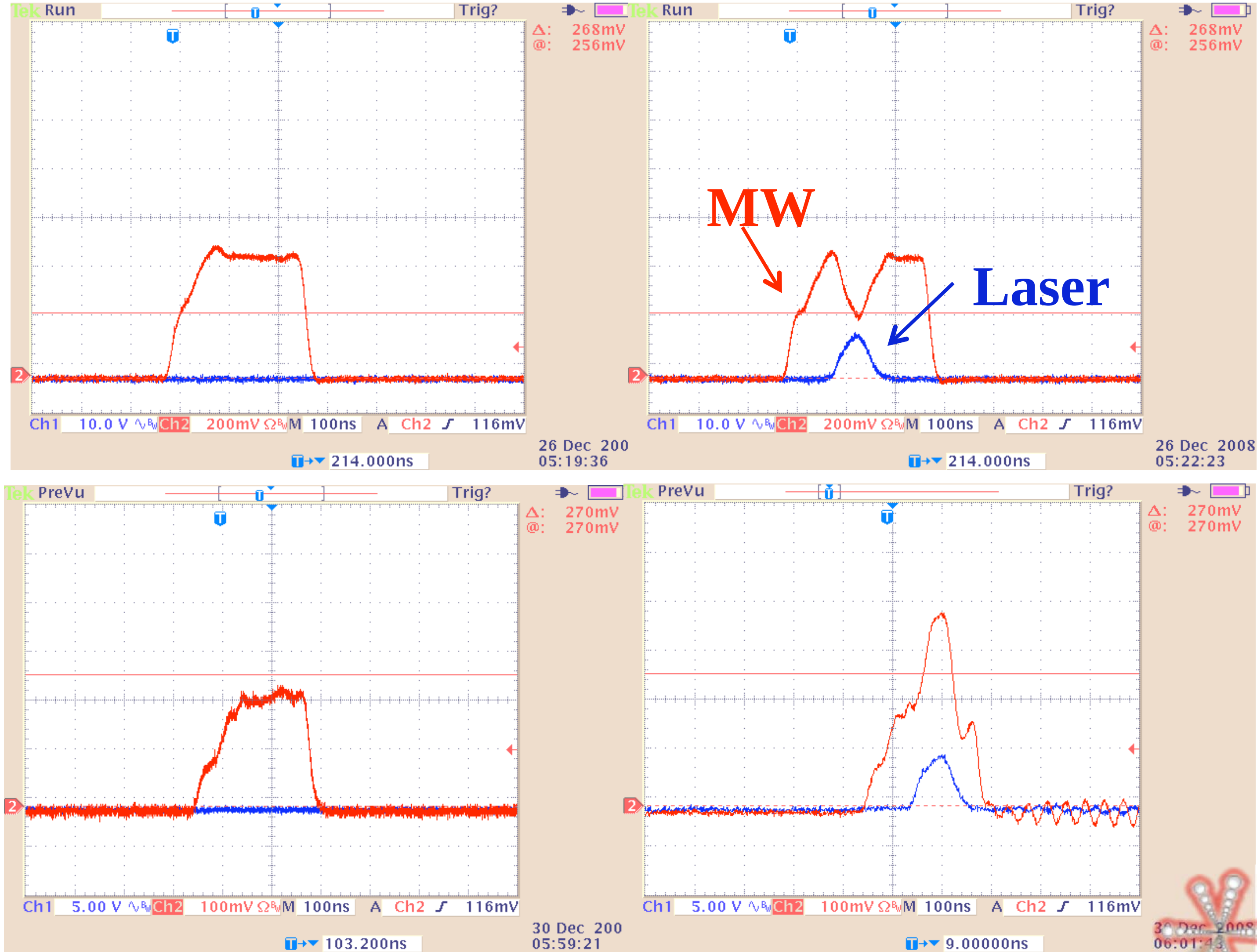
B-B



$_W$ =35.3 GHz (λ=8mm);

$'_p$ =20 kW; *L*=12÷60 m

MW signal increased in 6 times when propagated along 60-m distance in a tubular plasma waveguide with n_e~10^{12} см$^{-3}$



I=2*10^6 Вт/см^2

n_e~10^{11} см$^{-3}$

I=10^7 Вт/см^2

n_e~10^{12} см$^{-3}$

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Dielectric properties of air plasma

Permittivity $\varepsilon_p = 1 - \dfrac{\Omega_p^2}{\omega(\omega + i\nu_T)}, \quad \Omega_p = 5.65 \cdot 10^4 \cdot n_e^{1/2}[cm^{-3}]\sec^{-1}$

Electron transport collisions with neutrals $\nu_T \sim 10^{12} s^{-1}$

Coulomb $\nu_{ei} = \dfrac{3.7 n_e}{\sqrt{2} T^{3/2}(K)} \ln\Lambda\,[s^{-1}], \ \ln\Lambda = 7{,}47 + \dfrac{3}{2}\lg T(K) - \dfrac{1}{2}\lg n_e$

Coulomb collisions dominate at $n_e \geq 5 \times 10^{15} - 10^{16}\,cm^{-3}$

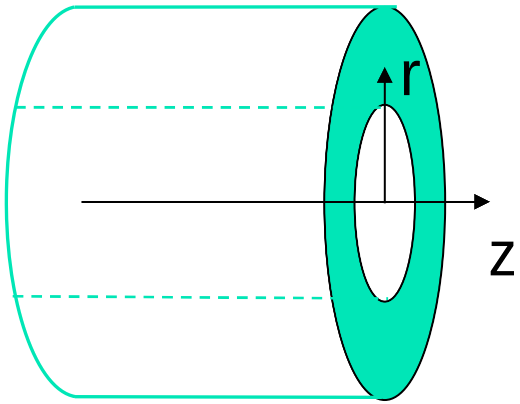
Small parameters $\xi = \dfrac{\Omega_p^2}{\nu_T^2} \approx 3.19 \times 10^{-3} \left[\dfrac{n_e}{10^{12}\,cm^{-3}}\right]$

For MWs with λ = 1 mm – 1 cm : $\omega / \nu_T << 1$

and $\mathrm{Re}(1 - \varepsilon_p) = \dfrac{\xi}{1 + \omega^2/\nu_T^2} << \mathrm{Im}(1 - \varepsilon_p) = \dfrac{\xi}{1 + \omega^2/\nu_T^2}\dfrac{\nu_T}{\omega}$

Axially-symmetric sliding modes in plasma waveguide

Minimum angle of incidence → Lowest axially-symmetric modes



***E_{01}* mode**

$$\frac{1}{\kappa_1}\frac{J_1(\kappa_1 R)}{J_0(\kappa_1 R)} = \frac{\varepsilon_p}{\kappa_2}\frac{H_1^{(1)}(\kappa_2 R)}{H_0^{(1)}(\kappa_2 R)}$$

***H_{01}* mode**

$$\frac{1}{\kappa_1}\frac{J_1(\kappa_1 R)}{J_0(\kappa_1 R)} = \frac{1}{\kappa_2}\frac{H_1^{(1)}(\kappa_2 R)}{H_0^{(1)}(\kappa_2 R)},$$

$$\kappa_1^2 = k_0^2 - h^2,\ \kappa_2^2 = \varepsilon_p k_0^2 - h^2,\ k_0 = \omega / c$$

Dimensionless parameters

$$\mu^2 = \frac{(\Omega_p / \nu_T)^2}{1 + (\omega / \nu_T)^2}(k_0 R)^2$$

$$\kappa_1 R = x\mu,\ \kappa_2 R = y\mu,\ x^2 - y^2 = 1 - i\nu_T / \omega$$

Sliding modes exist for $\mu \geq \mu_{th} \approx 1$

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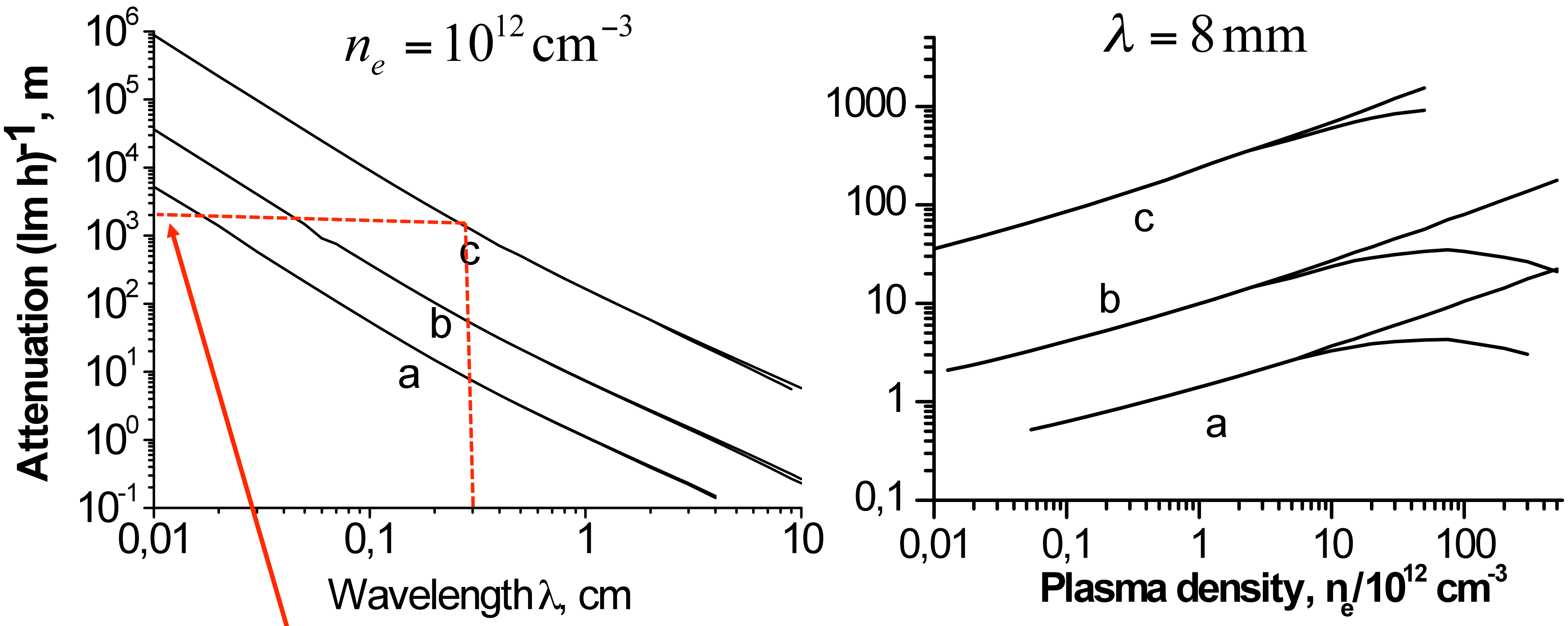
Attenuation lengths of the E_{01} and H_{01} modes



E_{01} (lower) and H_{01} modes (upper) in waveguides of radius R=5 cm (a), 10 cm (b), and 30 cm (c).

Attenuation length $(\mathrm{Im}\,h)^{-1} \propto R^3 \omega^{3/2} n_e^{1/2}$

MWs with λ~3 mm propagates in plasma waveguide (n_e=10^{12} cm^{-3}, R=30 cm) up to 2 km!

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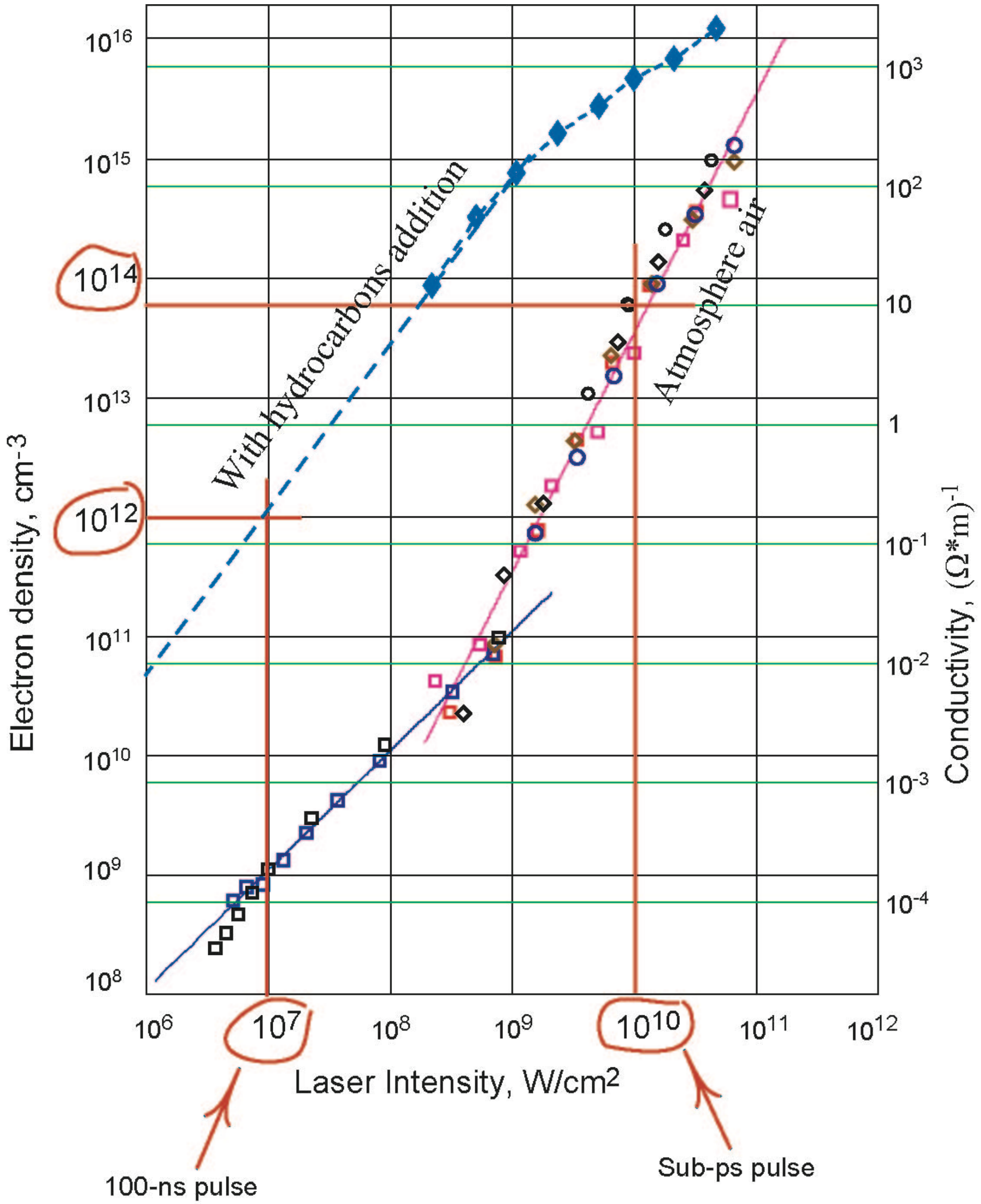
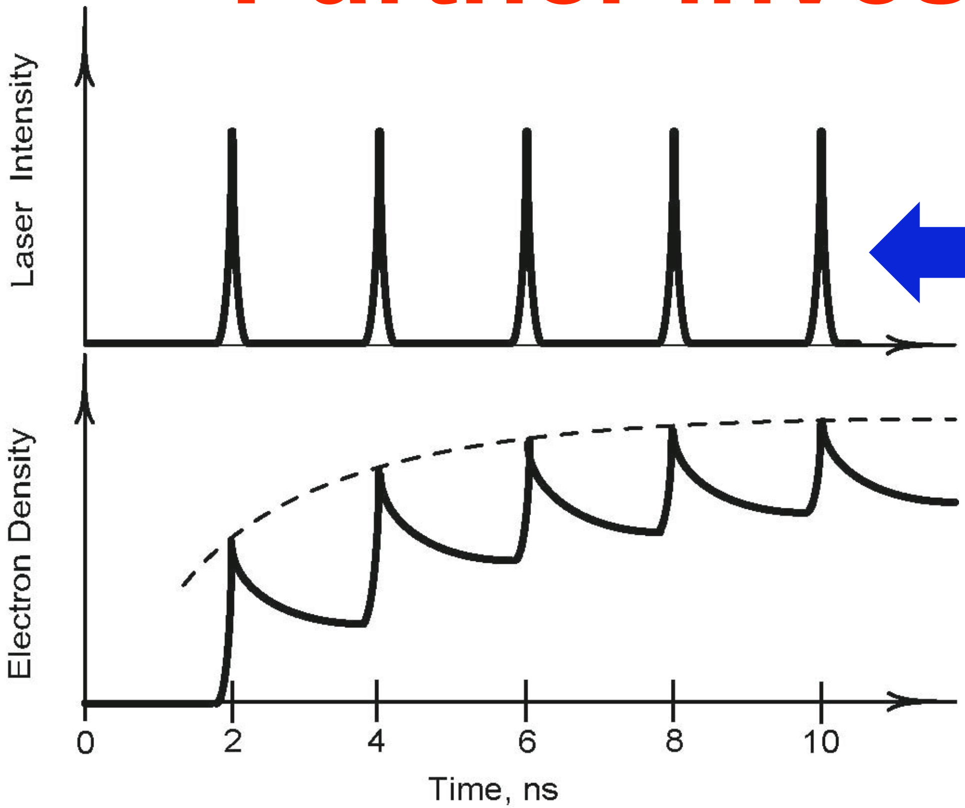
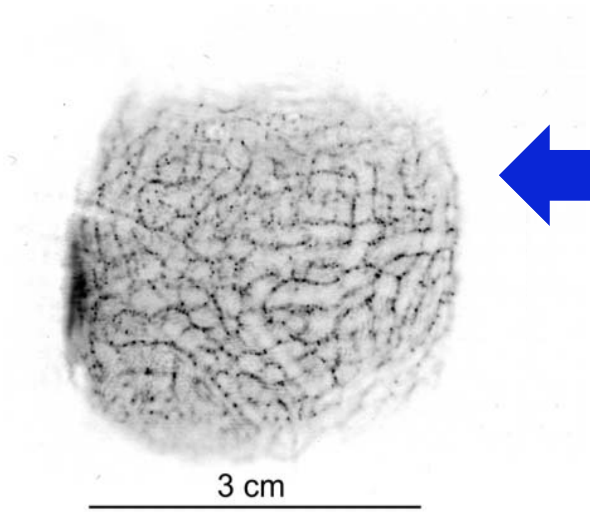
Further investigations



- **Sub-ps UV laser pulses are more efficient for air ionization through multiphoton processes as their probability increases with laser intensity ~I^k (k=2, 3).**
- **Multiterawatt peak intensities are already available at GARPUN-MTW hybryd Ti:Sa/KrF laser facility.**

Further investigations





- Multiple sub-ps pulses or their combination with 100-ns pulse are expected to increase the electron density in plasma waveguides and maintain it for longer time.
- Filamentation of the laser beam would be also favorable for plasma waveguides.

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CONCLUSIONS

- UV radiation of KrF laser (λ_L =248 nm, τ =20-100 ns) with intensities I= $3*10^6 \div 10^{11}$ W/cm^2 produces in air long ionized channels with electron densities n_e =$3*10^8 \div 10^{15}$ cm^{-3}.
- Transfer of a microwave signal with λ =1 cm along 60-m distance in the air with additives of hydrocarbons was demonstrated experimentally.
- Sliding –mode regime of microwaves propagation in hollow plasma waveguides was analyzed theoretically, being in a agreement with the experiment.
- Further investigations are going on including generation of trains of sub-ps UV laser pulses and combination of short & long laser pulses, as well as ionization processes in the atmospheric air.
- Propagation distance of microwaves as high as ~1 km is expected for higher electron density in the plasma wall and shorter wavelengths.