High-temperature quasi-stationary terahertz optical discharge on NovoFEL

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Outline

- Introduction. Shot history of THz optical discharge at NovoFEL

- Motivation:
  – Fundamental gas discharge physics
  – Applications of THz Optical Discharge (TOD)

- Experiments:
  – Breakdown of Terahertz Optical Discharge. Thresholds of TOD.
  – Plasma regime of TOD. Plasma parameters.
  – Auto-oscillations in TOD. Suppression of the auto-oscillations.

Motivations. Applications of the THz Optical Discharge (TOD)

- Fundamental gas discharge physics: TOD as a form of gas discharge:
  – Threshold of laser beam intensity for production of TOD
  – Kinetics processes in TOD plasma

- Gas dynamics applications of TOD (pulsating discharge, shock waves, ionization waves etc.)

- Nonlinear phenomena in TOD:
  – Second harmonics generation by TOD oscillations at double plasma frequency
  – Nonlinear MHz gas dynamics oscillations in intensive TOD

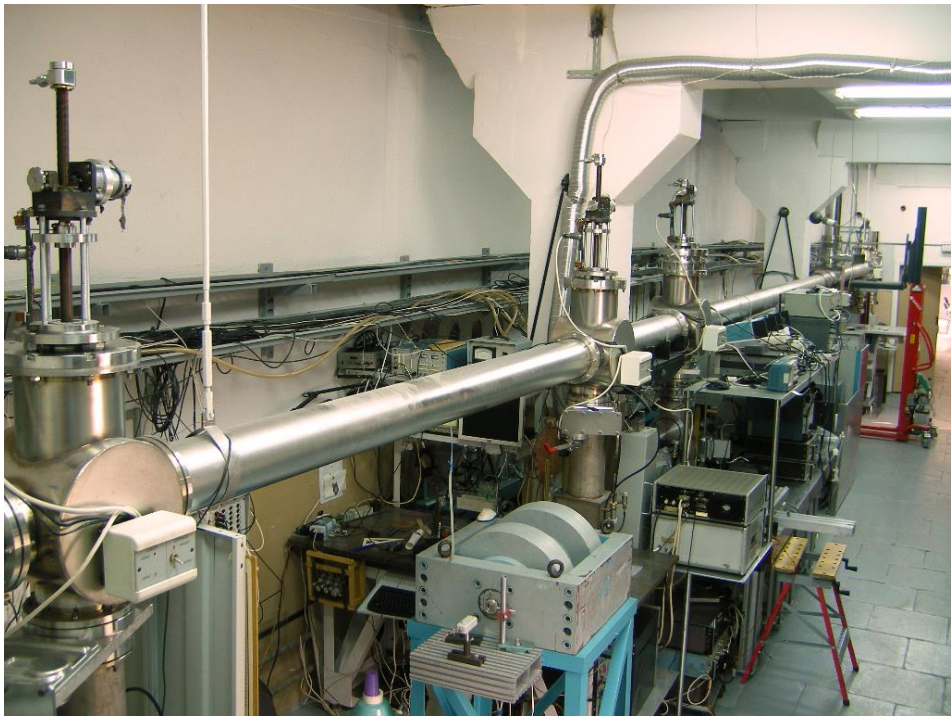
- Joint using of TOD and ablation for nanomaterial production (carbon nanotubes, fullerenes, nanopowders etc.)

- TOD as source EUV radiation for photolithography

Novosibirsk terahertz free electron laser (THz NovoFEL)

Accelerator hall

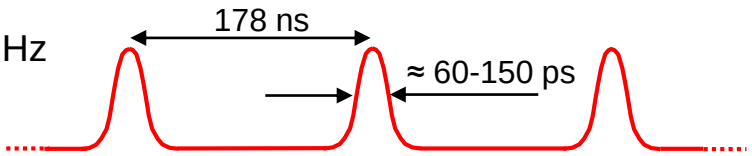
User's hall



Radiation parameters of THz NovoFEL:

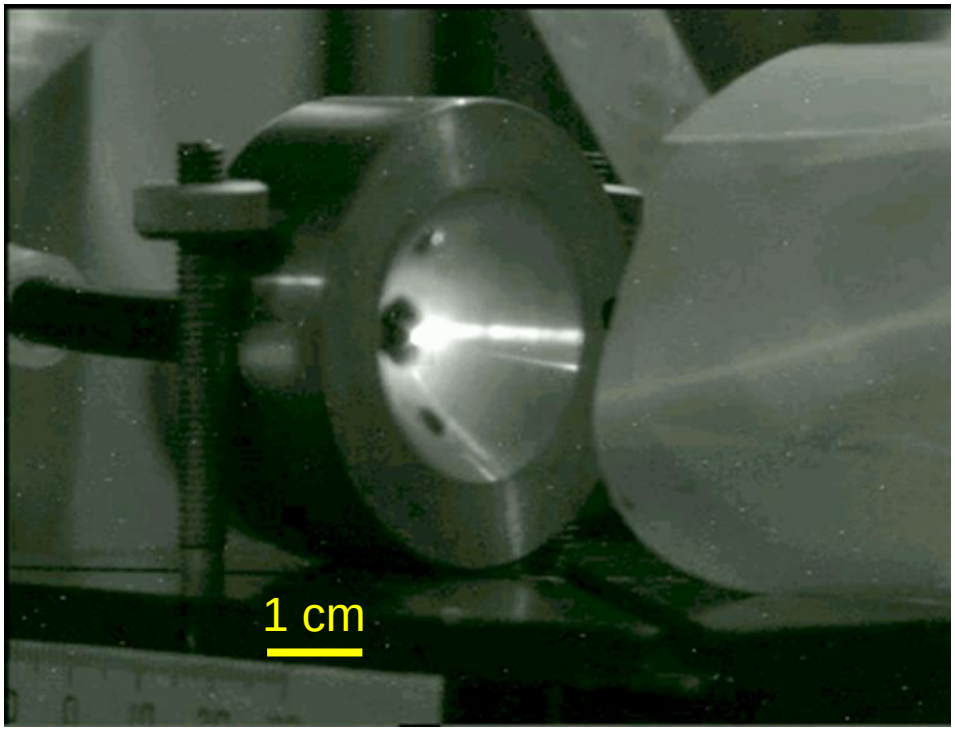
λ = 90 – 240 μm, $P_{average} \leq$ 500 W, $P_{pulse} \leq$ 0.9 MW, $(\Delta\lambda/\lambda)_{min} = 2 \cdot 10^{-3}$, f ≤ 22.4 MHz

Routine regime of THz NovoFEL: f = 5.6 MHz



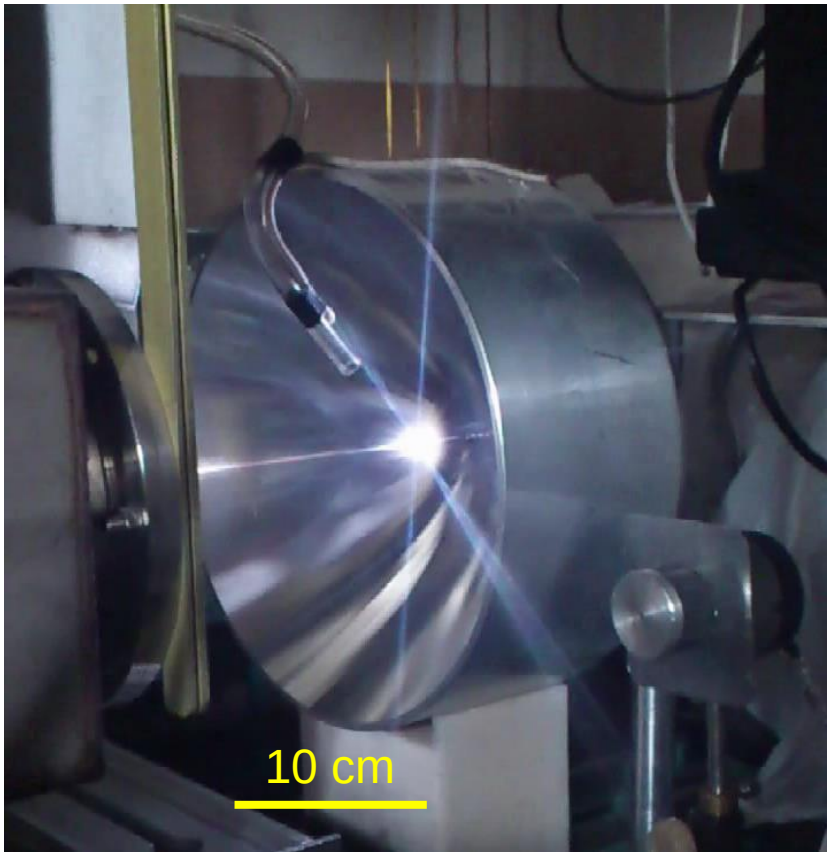
Terahertz optical discharge at NovoFEL

2004:



Publicity and estimations

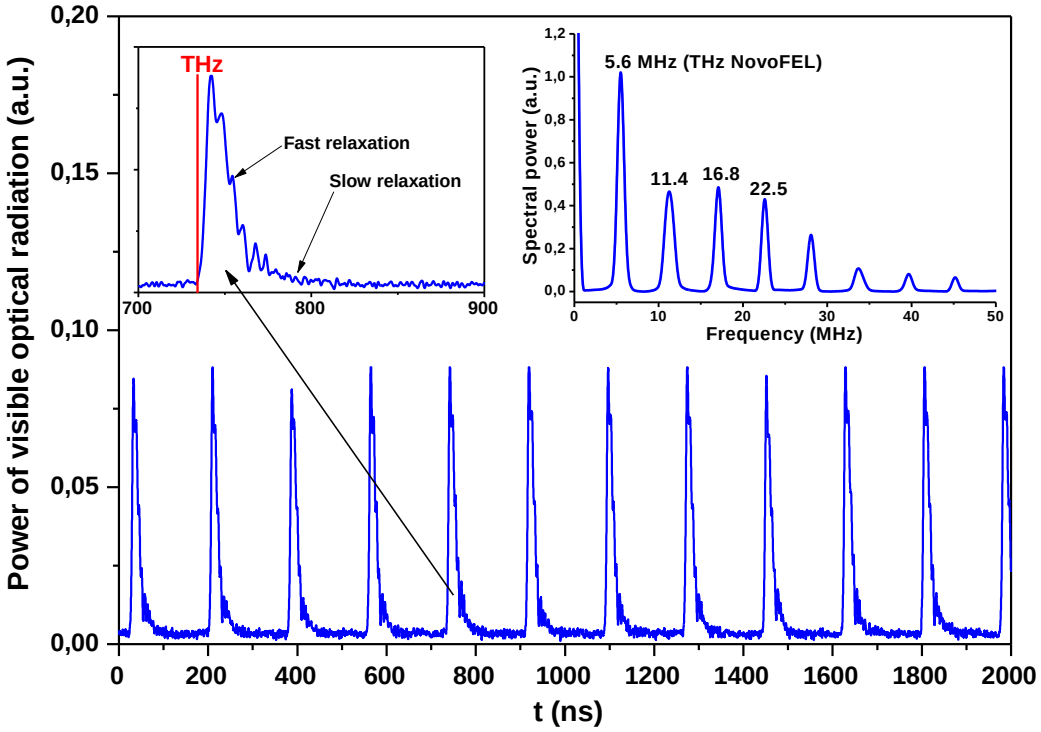
2013:



Publicity, measurements and science applications

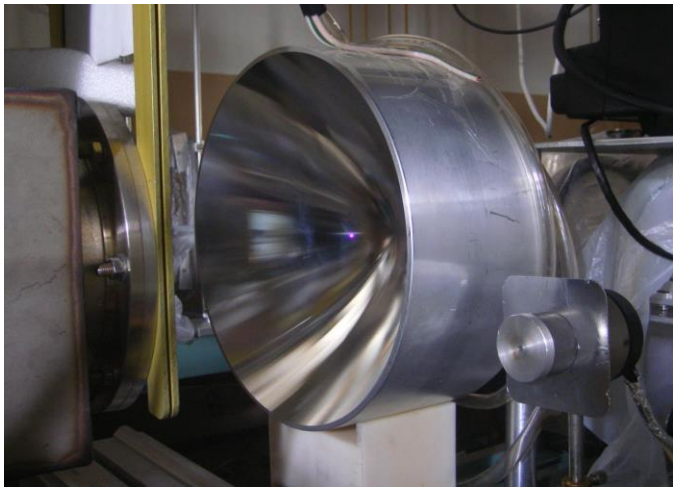
Threshold THz laser pulse intensity ~ 1 GW/cm^2

Fundamental gas discharge physics. TOD near threshold



Breakdown intensity:

$$I = \frac{cm_e}{4\pi e^2}\frac{\mathrm{E}_e(\omega^2 + \nu_{em}^2)}{\nu_{em}\Delta t_h}$$



Theory of TOD as microwave breakdown in gases

Many experiments (Yu.P. Raizer, 1991):

Optical discharge in gas ≡ appearing of ~10^{13} free electrons in discharge volume

$$(\nu_i - \nu_D)\Delta t \approx \nu_i \Delta t = \ln(10^{13}) = 30 \quad (1)$$

$$\nu_i = n_0 \langle \sigma_{ie} V_e \rangle_e \quad (2)$$

$$P_e = \frac{d\mathsf{E}_e}{dt} = \frac{e^2 E_0^2 \nu_0}{2m_e(\omega^2 + \nu_0^2)} \quad (3)$$

(1), (2), (3) → Breakdown parameter ~ $I \cdot \Delta t \cdot \lambda^2$

(3) Stochastic electron heating in gas by microwave (A.D. McDonald, 1966)

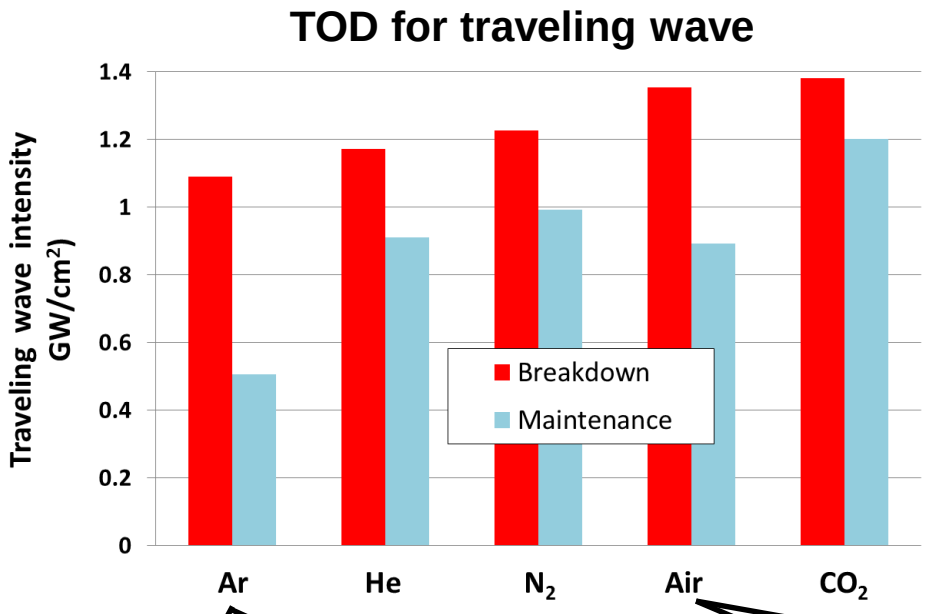
For Ar gas and 66 ps NovoFEL pulses:

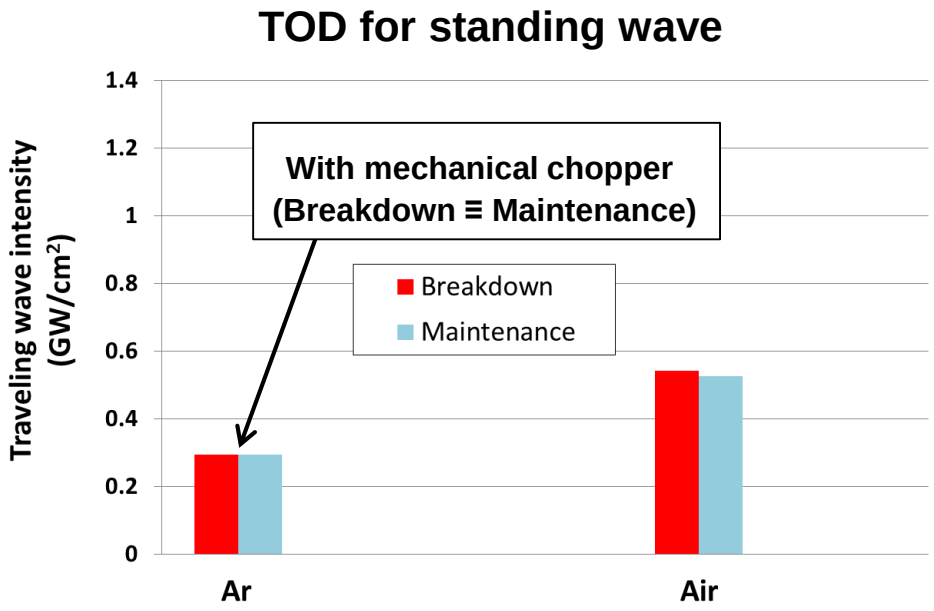
(1)-(2): $$P_e^{3/2} \cdot \int_{16/P_e}^{2.2} \left(t - \frac{16}{P_e} \right) \cdot t^{1/2} dt = 25.3, \qquad P_e = 12.5\ eV/ps$$

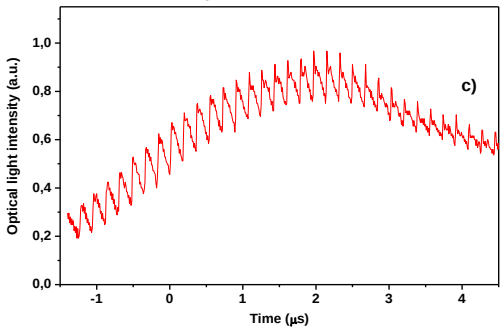
(3): $$\langle I_{breakdown} \rangle = \frac{cE_0^2}{8\pi} = 0.54 \frac{GW}{cm^2}$$

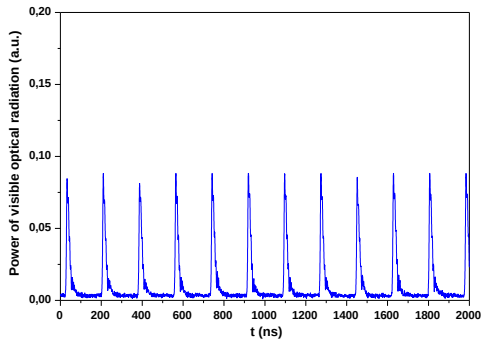
$$I_{breakdown}^{Max} = 2\frac{cE_0^2}{8\pi} = 1.08 \frac{GW}{cm^2}. \quad \longleftrightarrow \text{OK} \longleftrightarrow \quad I_{\exp}^{Max} = 1.1 \frac{GW}{cm^2}$$

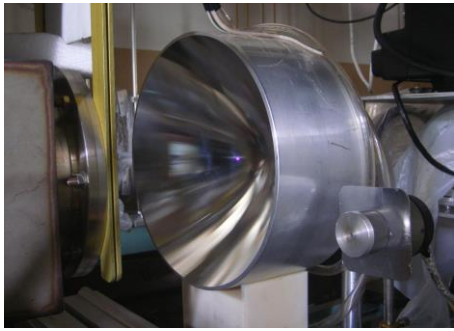
Thresholds of breakdown and maintenance of TOD



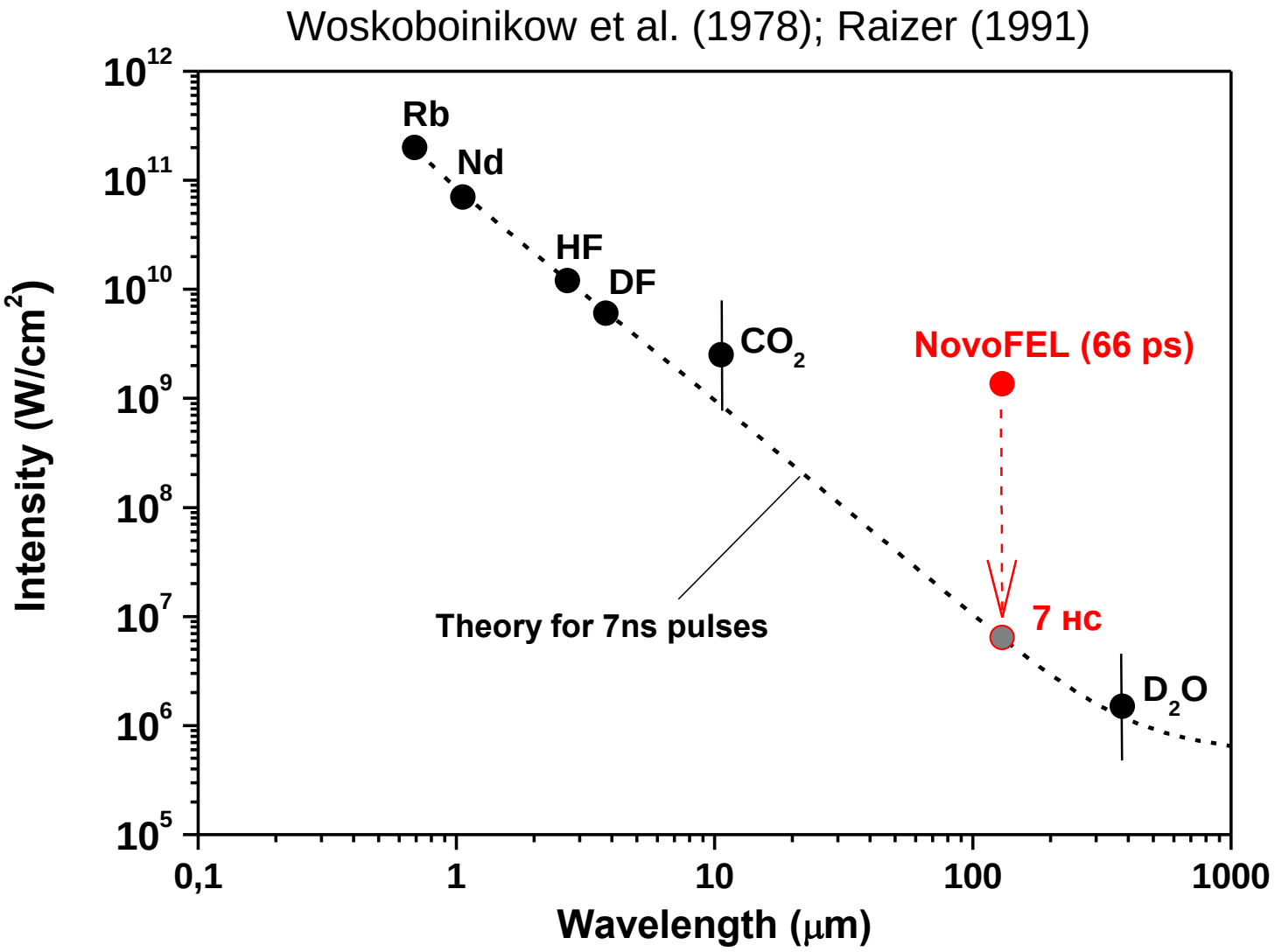




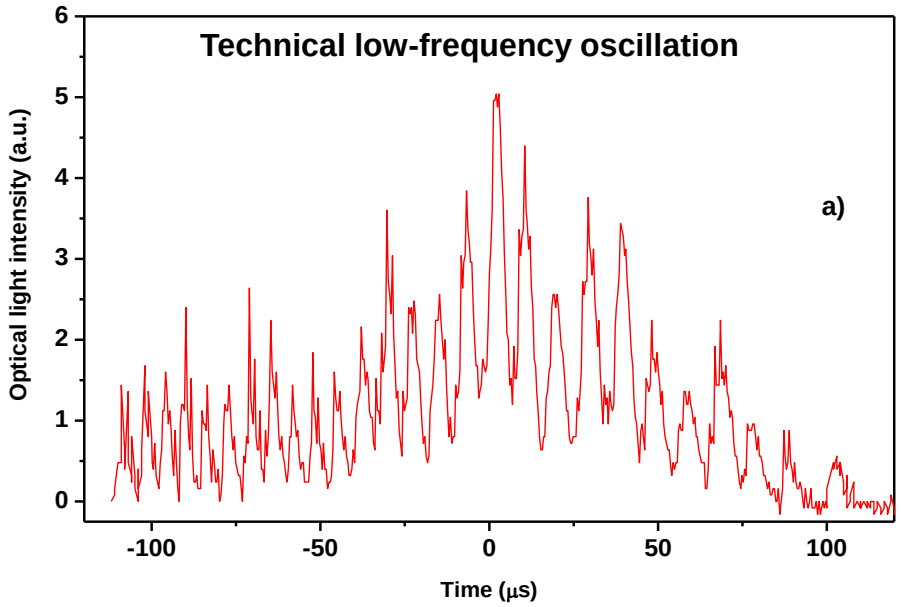


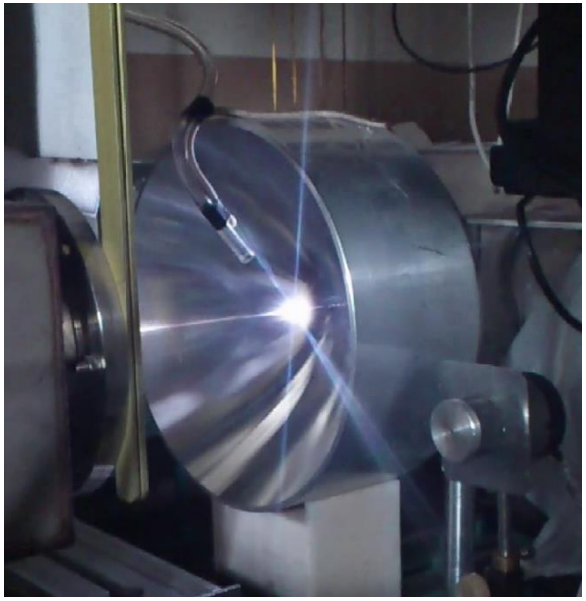


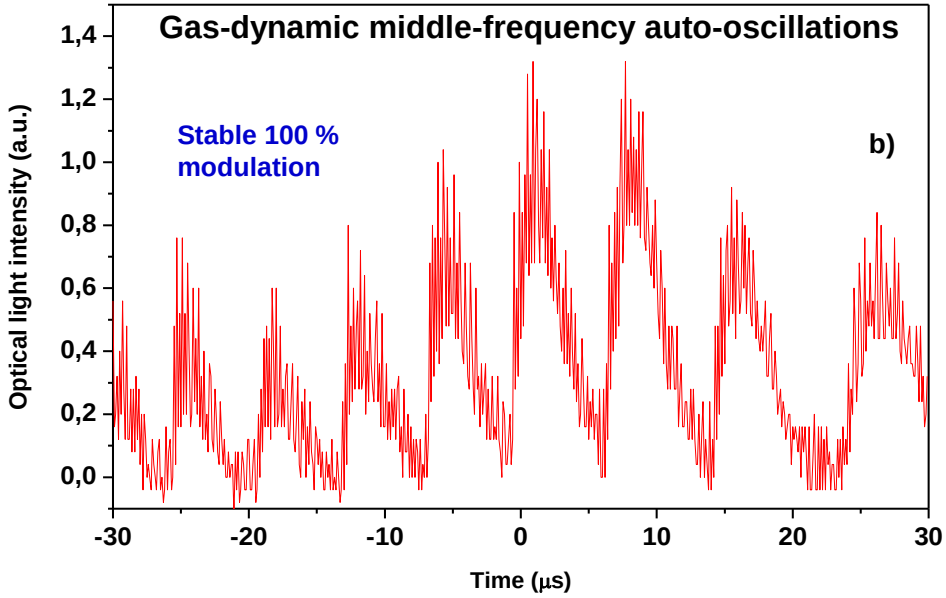
Optical Breakdown of Air

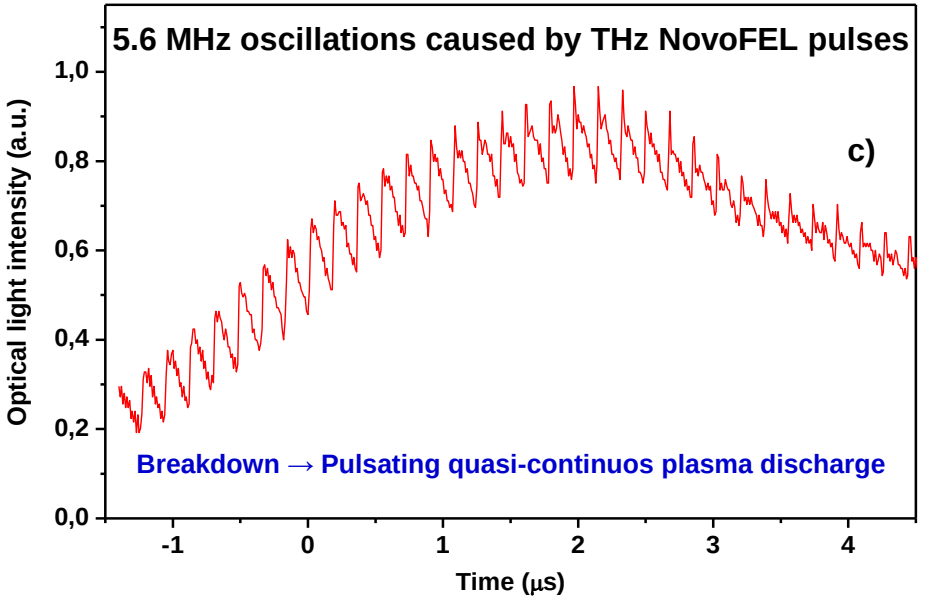


Three modulation frequency ranges in intensive TOD

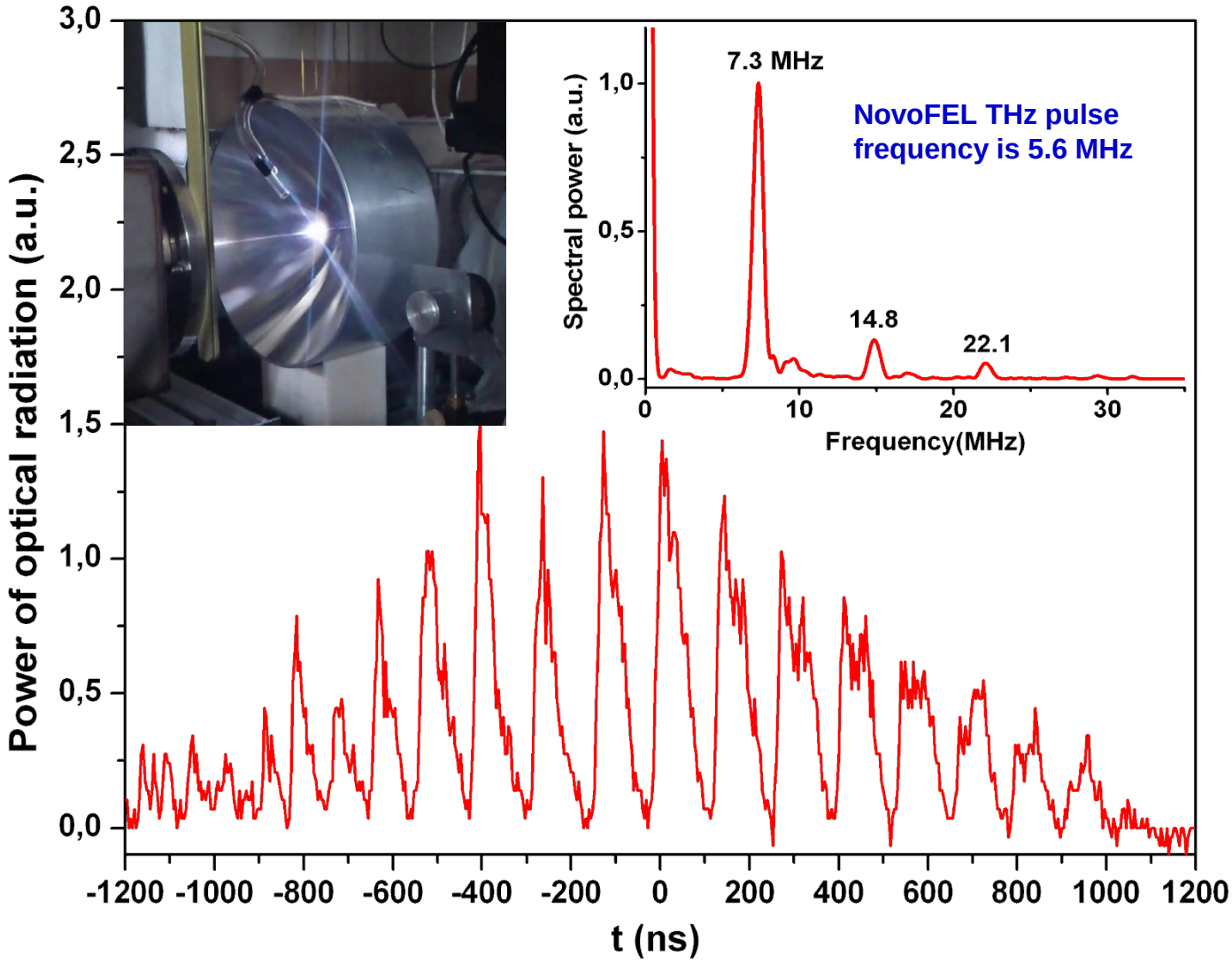




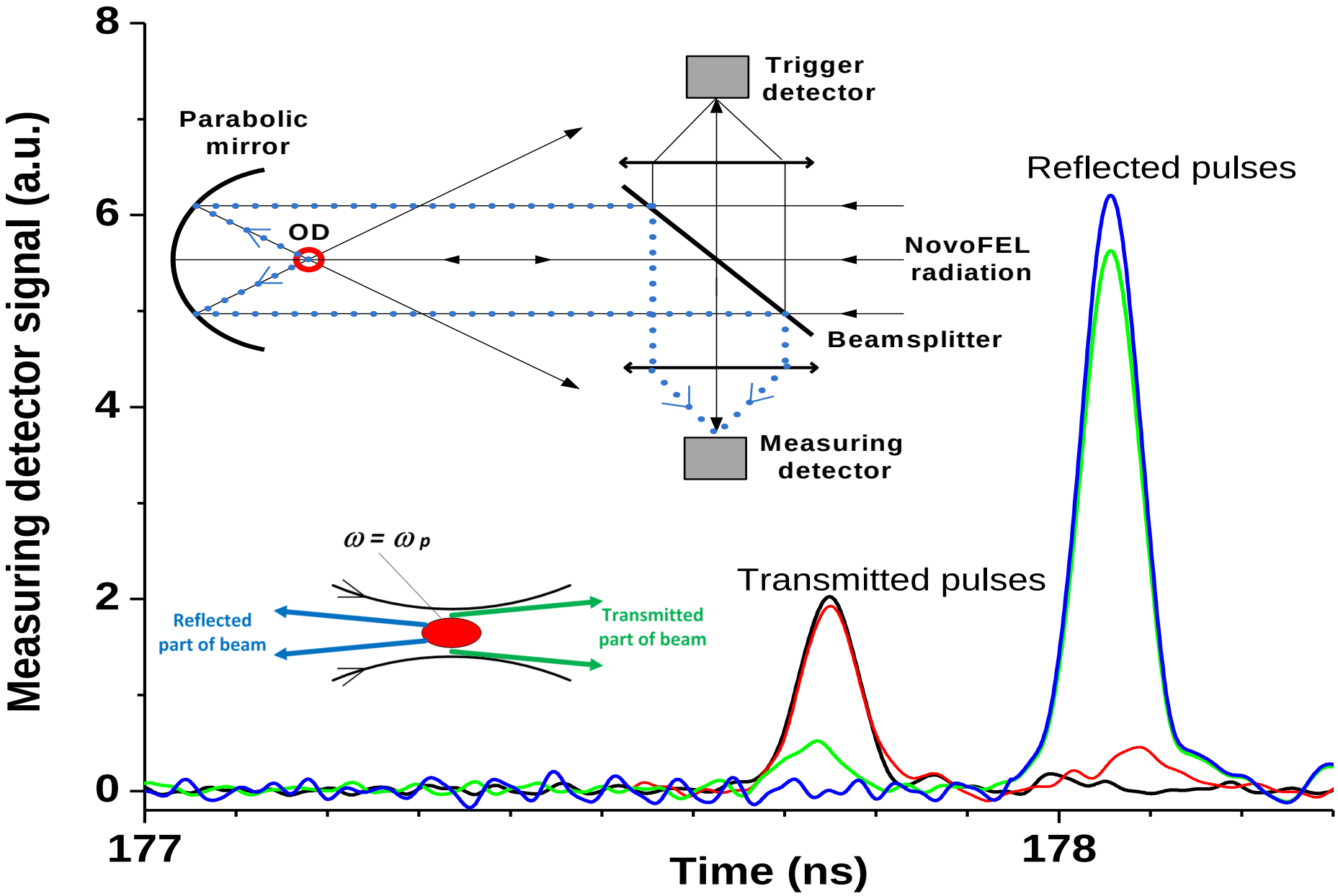




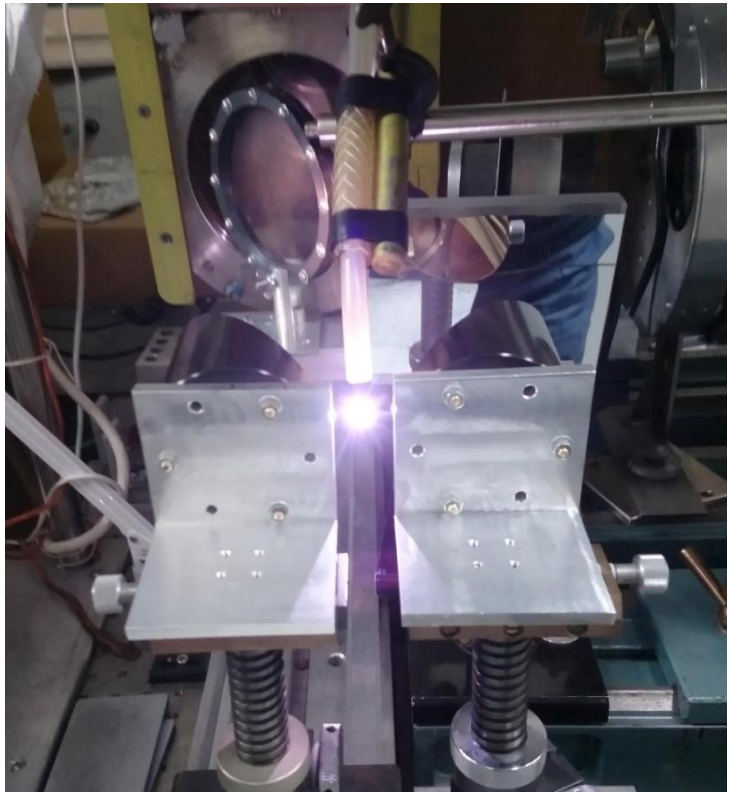
Very strong TOD. Nonlinear gas-dynamic oscillation

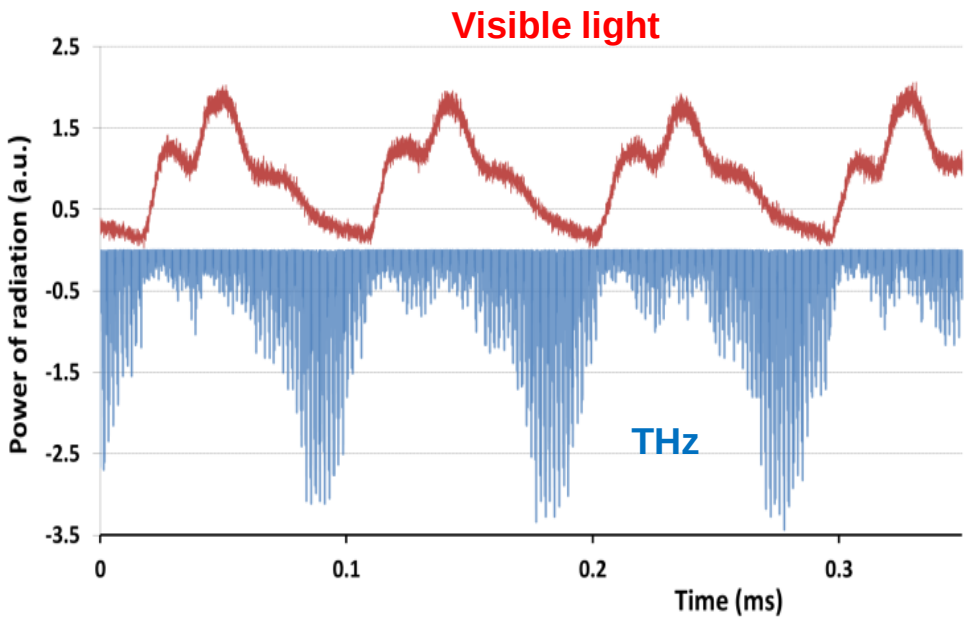


Ultrafast pump-probe experiment

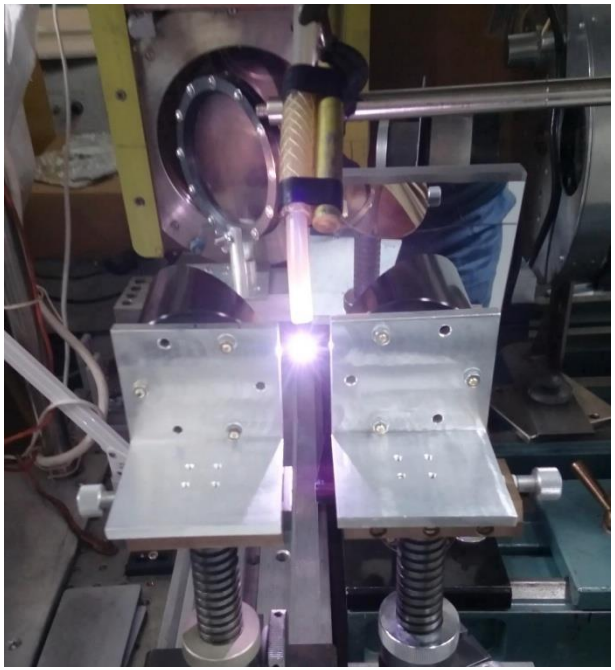


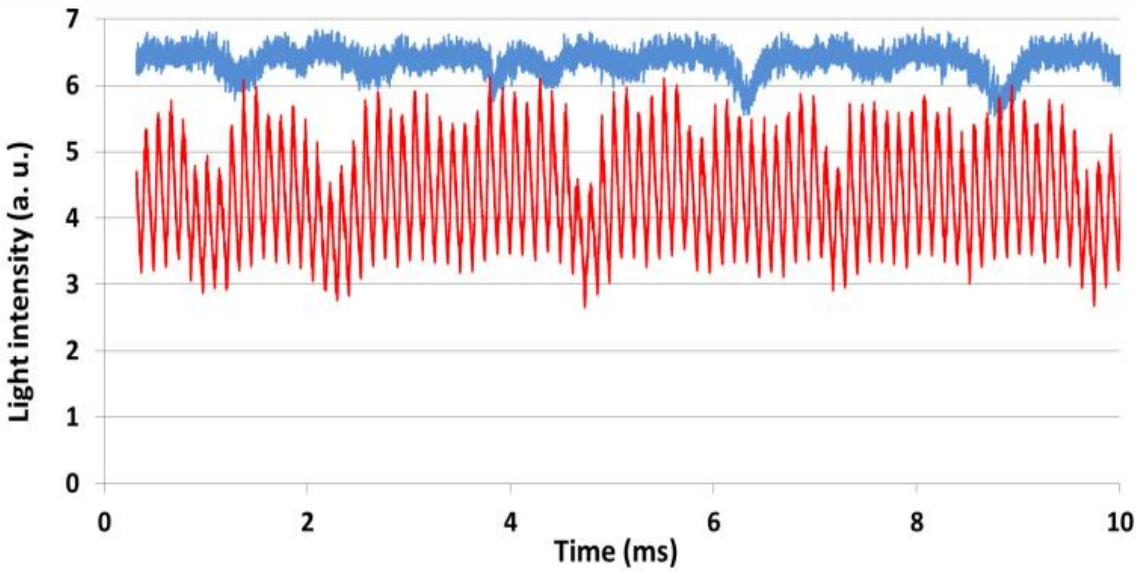
Low-frequency auto-oscillation in TOD

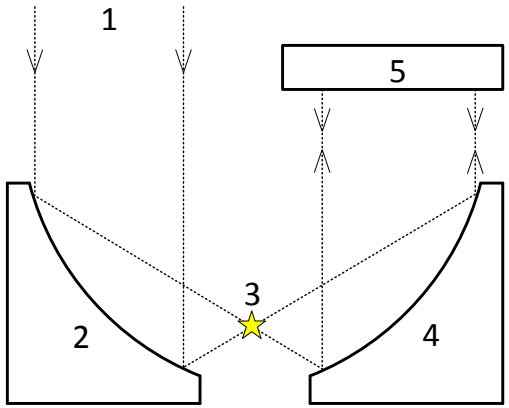




Dumping auto-oscillations in TOD by negative optical feed-back



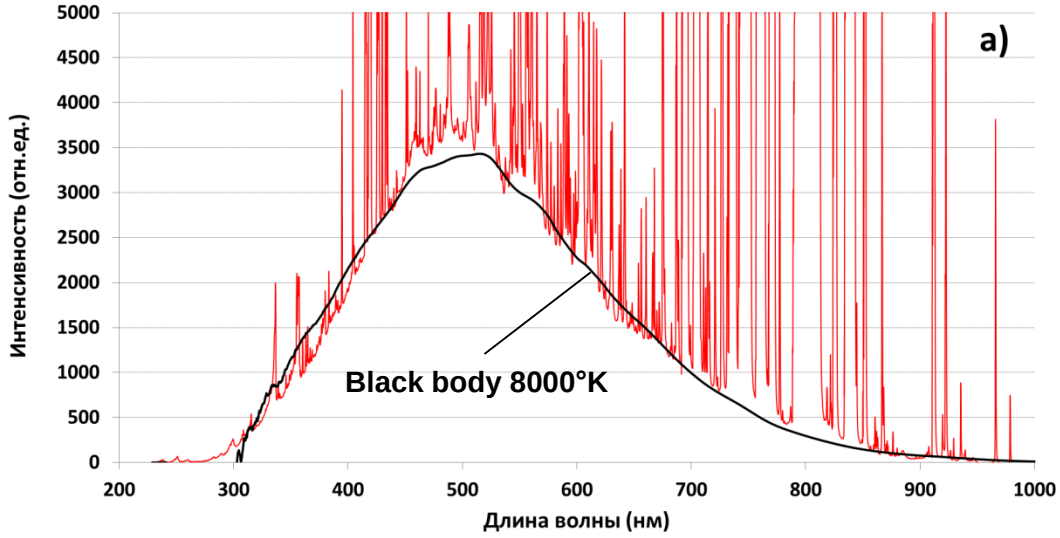


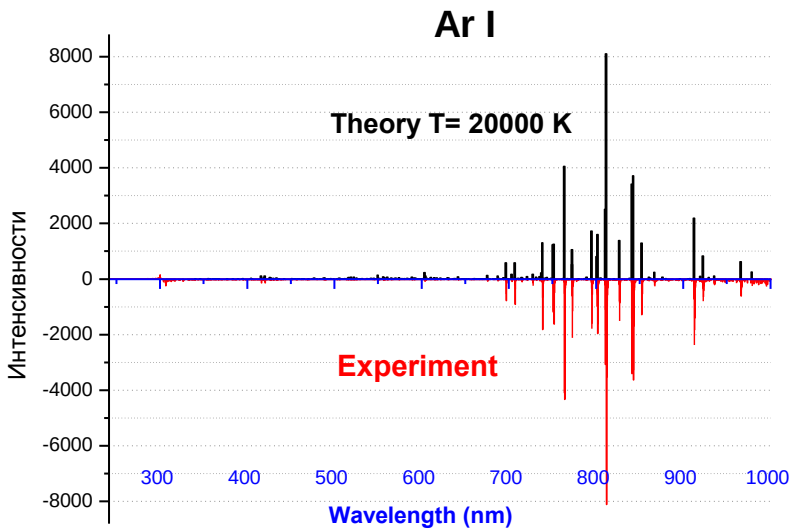


Quasi-continuous terahertz laser discharge and optical scheme of negative optical feedback for its stabilization:

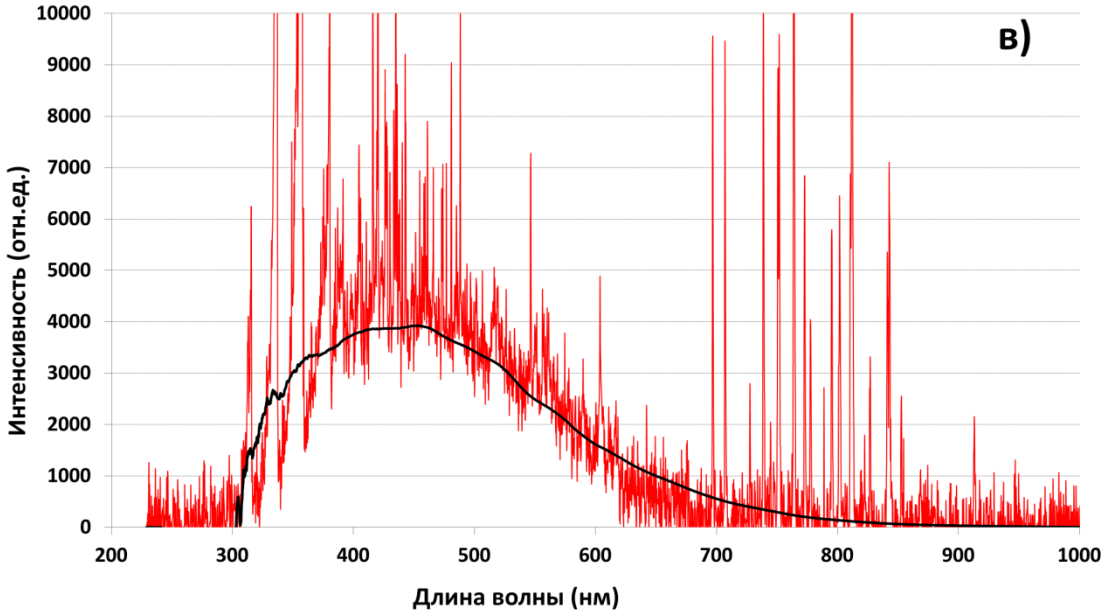
1 – radiation of terahertz NovoFEL,
2 – main focusing parabolic mirror,
3 – optical discharge,
4 – stabilizing parabolic mirror,
5 – stabilizing plane mirror.

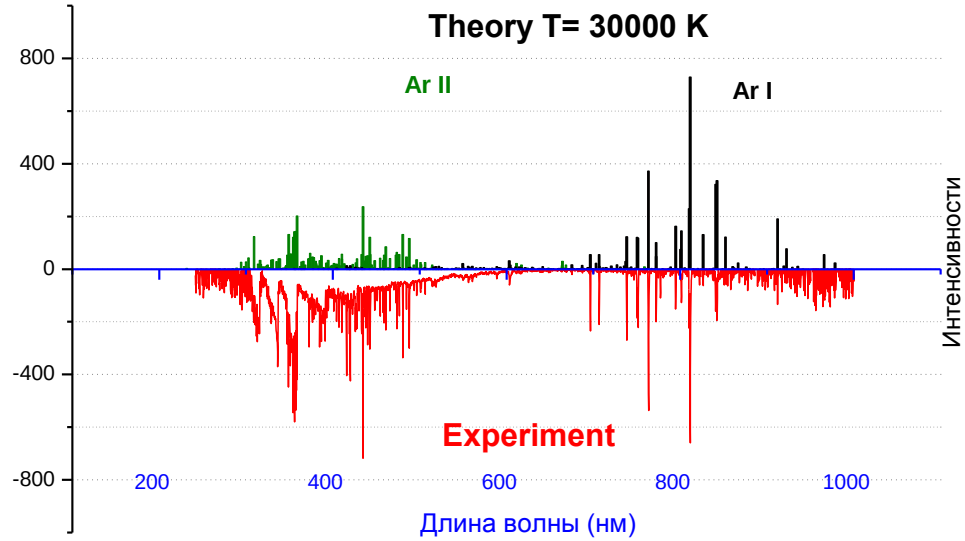
Temperature in typical plasma TOD

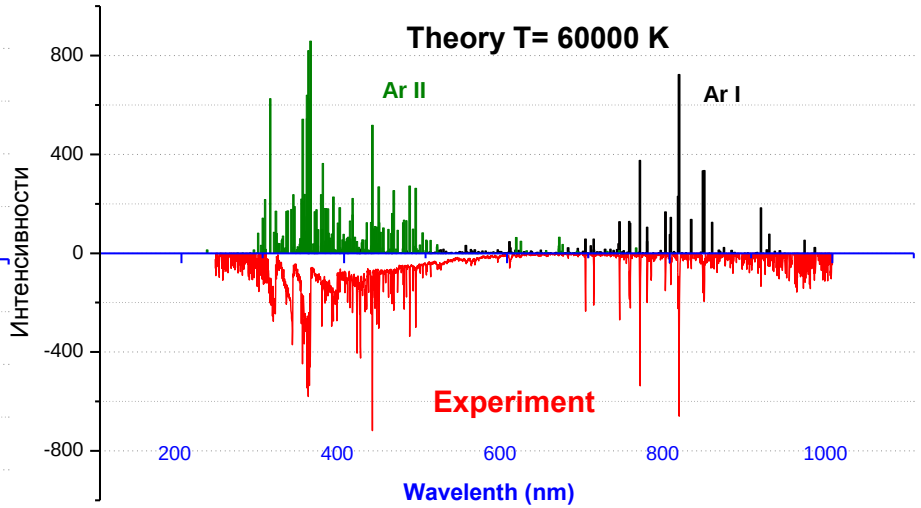




Temperature in high-temperature plasma TOD







Thank you for attention !