GARPUN-MTW Ti: Sapphire / KrF laser capabilities for UV laser-matter interaction

V.D. Zvorykin (*zvorykin@sci.lebedev.ru*)

P.N.Lebedev Physical
Institute of the Russian
Academy of Science

P.N. Lebedev Physical Institute of
Russian Academy of Sciences

National Nuclear University MEPhI

34th European Conference on Laser Interaction with Matter ,
Moscow, Russia, September 18–23, 2016

Participants

LPI

Prof. Andrei Ionin
Dr. Igor’ Smetanin
Dr. Alexei Levchenko
Dr. Leonid Seleznev
Dr. Nikolai Ustinovskii
PhD St. Alexei Shutov
PhD St. Elena Sunchugasheva
PhD St. Daria Mokrousova

NRNU MePhI

St. Semen Goncharov
St. Sergei Ryabchuk

Outline

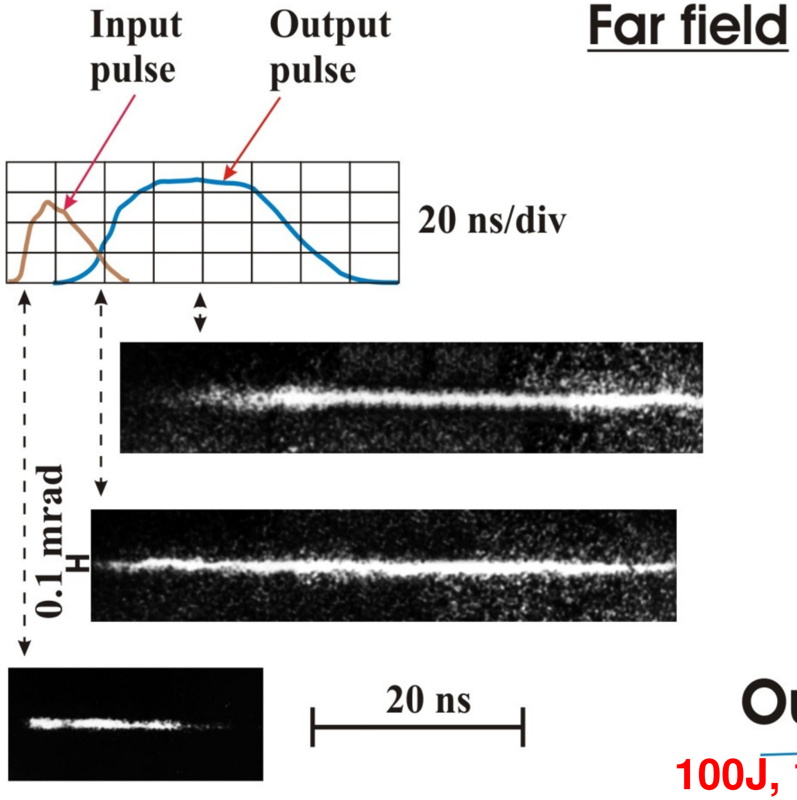
- 25 years of GARPUN KrF laser operation at LPI:
  - ➢ injection-controlled mode
  - ➢ amplification of 20-ns pulses
  - ➢ amplification of sub-ps pulses
  - ➢ simultaneous amplification of short & long pulses
- Initial target irradiation experiments with sub-ps pulses
- Filamentation of supercritical UV laser beam
- Suppression of filamentation and impact on the beam focusing
- Conclusions

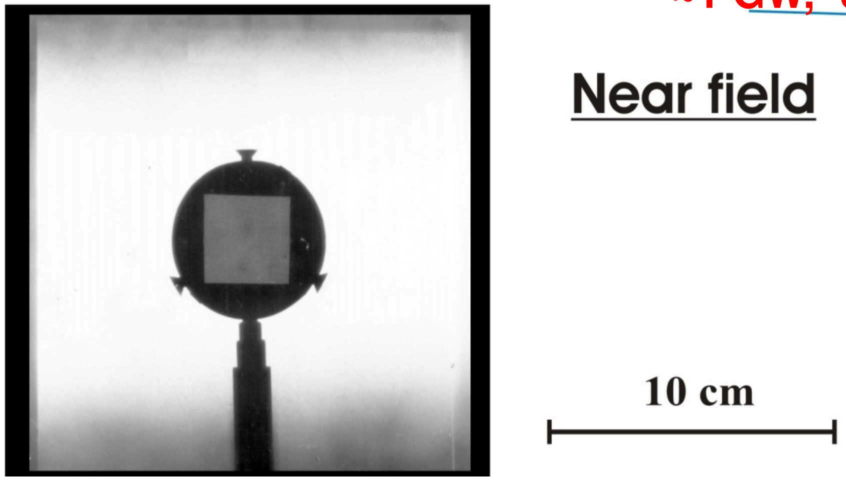
GARPUN: Multistage KrF Laser System (main steps for 25 years' operation)

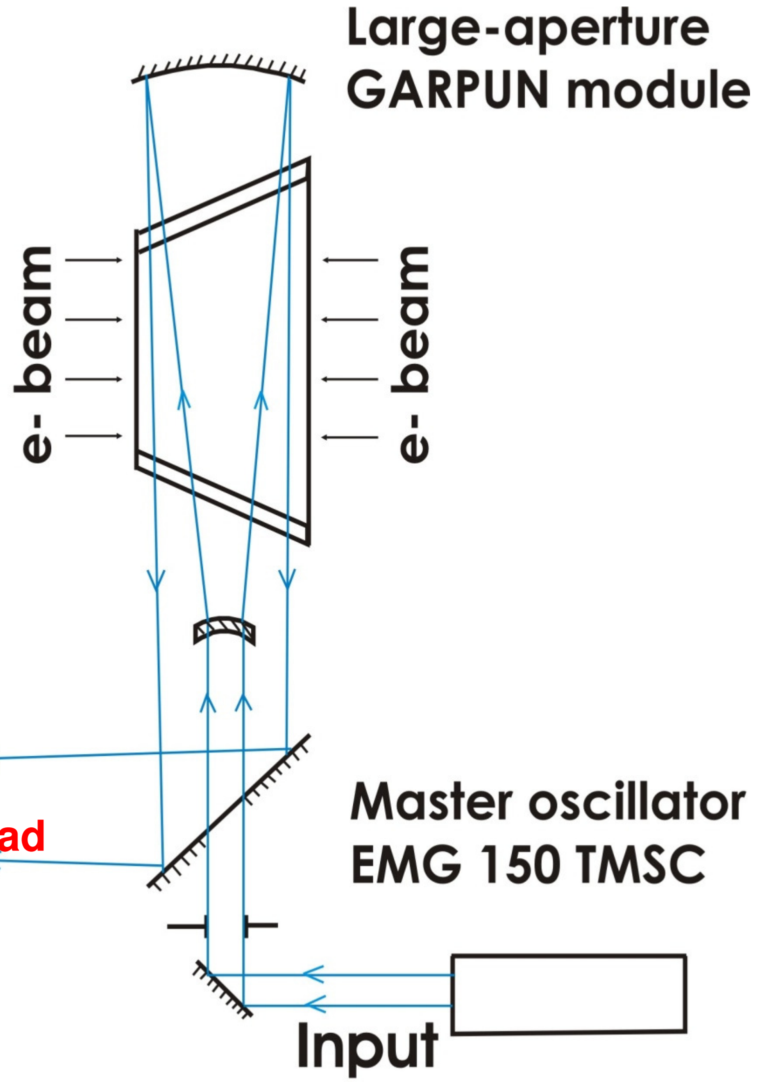
- 1991 – GARPUN KrF laser in injection-controlled (narrow-band) mode: 100 J, 100 ns, ~1 GW, 50 (0.2) cm^{-1}
- 1996 –amplification of ns (narrow-band) pulses: 30 J, 30 ns, ~1 GW
- 2006 – GARPUN-MTW hybrid laser with Ti: Sapphire front-end: amplification of sub-ps USP: ≤ 1 J, ≤ 1 ps, ~1 TW
- 2012 – amplification of USP train: ≤ 2 J, ~1 TW (each)
- 2012 – simultaneous amplification of the USP train & long pulse: 30 J, 100 ns

General view of GARPUN laser

Injection-controlled operation of GARPUN KrF laser





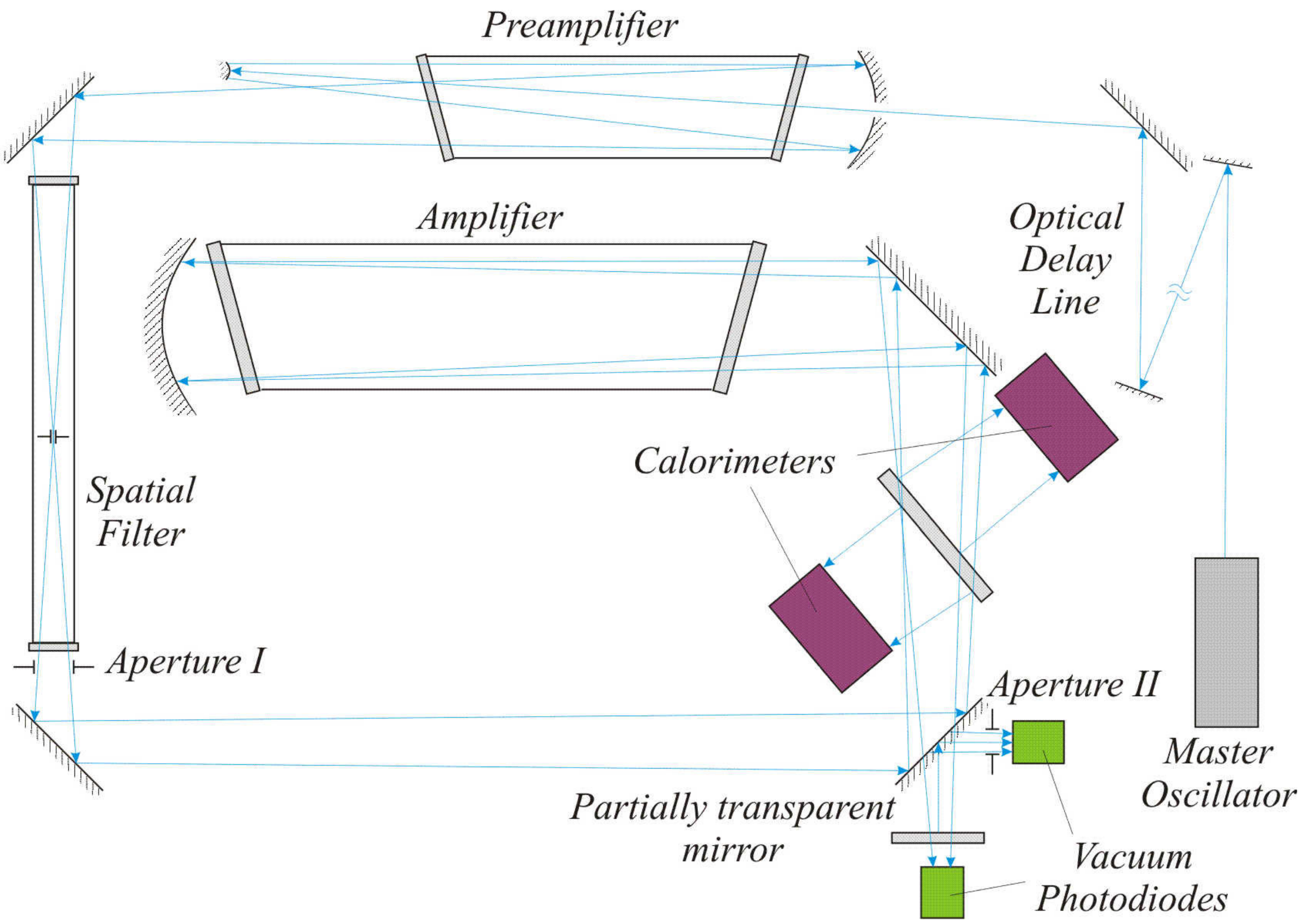


Output

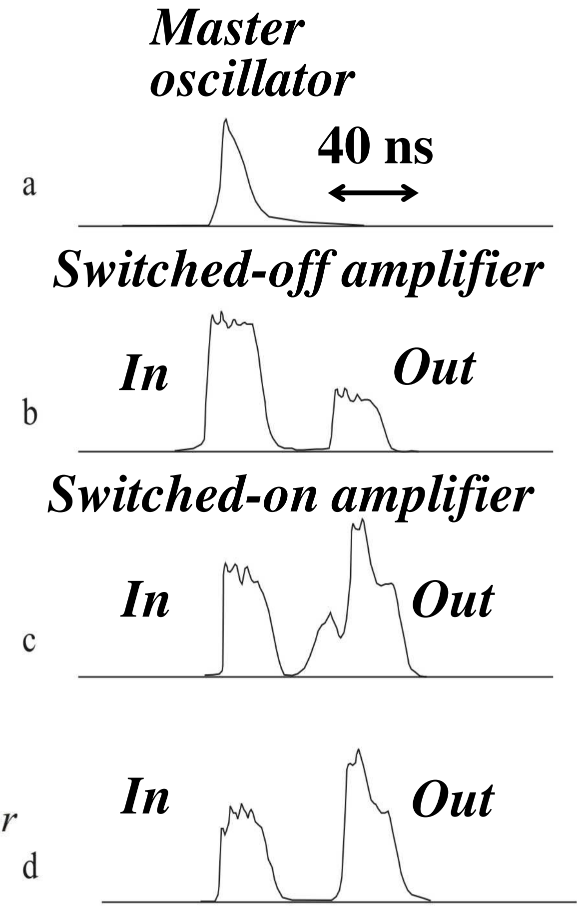
100J, 100 ns,
~1 GW, 0.1 mrad

0.01J, 20 ns

Amplification of ns pulses at GARPUN KrF laser



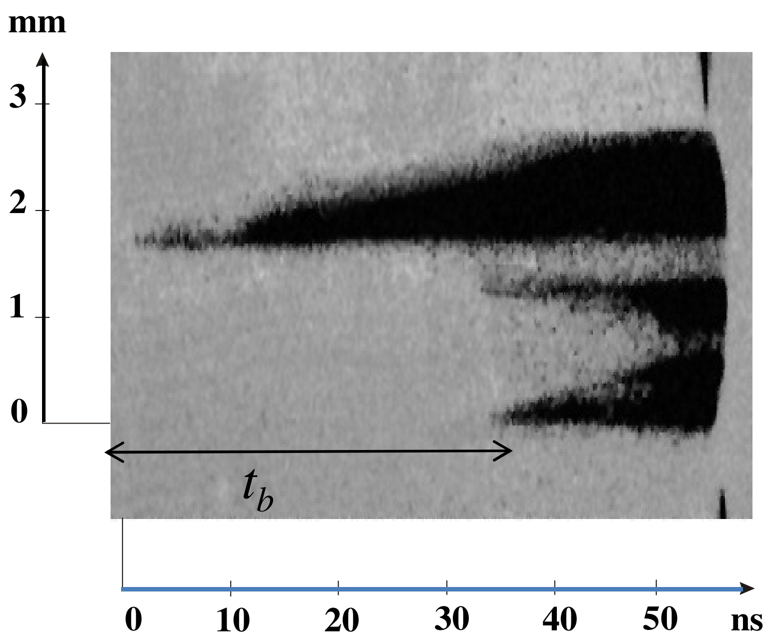
Layout of double-pass amplification experiments

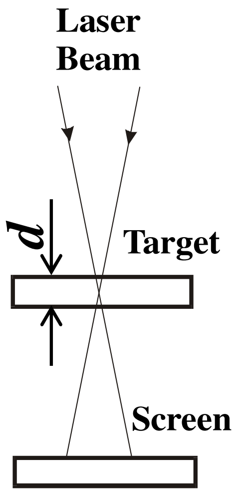


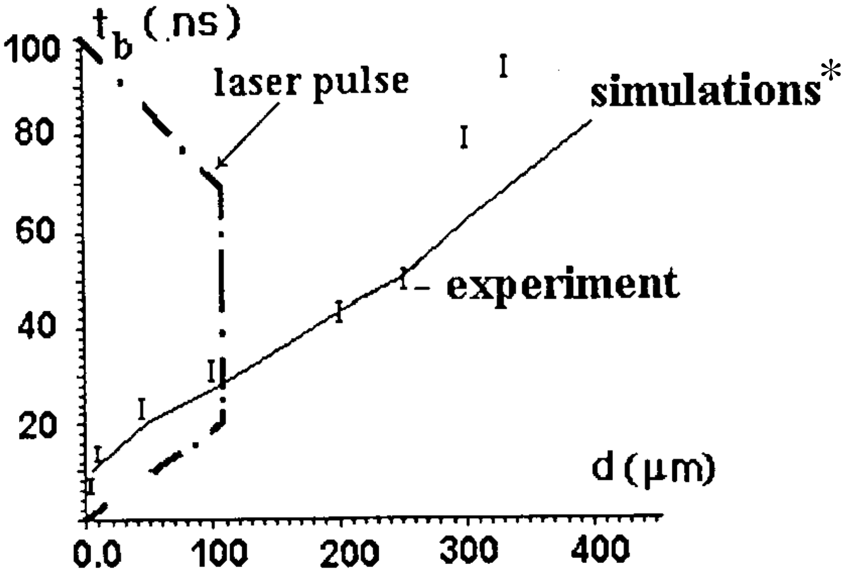
Laser pulse forms

$E = 30$ J, $\tau_p = 30$ ns, $P \sim 1$ GW, $\theta \sim 0.1$ mrad

Anomalously high penetration of 100-ns laser pulses was observed in burn-through experiments with foil targets





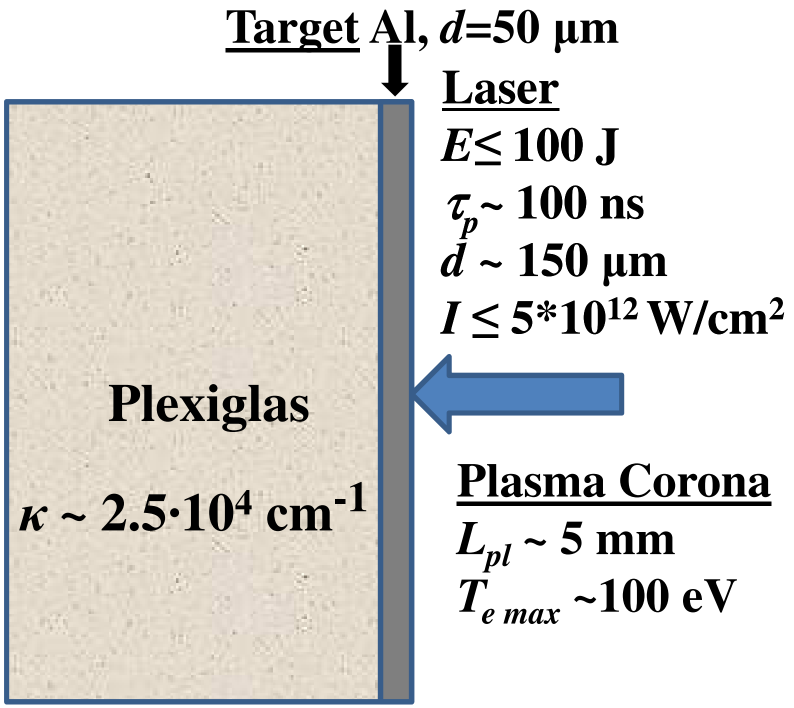


*2D simulations were done by I. Lebo

Ablation front velocity $V_{ab}=d/t_b$ in Al and graphite targets for 100-ns pulses reached 8 km/s, which is an order of magnitude higher than for ns pulses. This effect was caused by a radial squeezing out the matter.

Zvorykin & Lebo, *Laser and Particle Beams*, 1999, 17, 69

2D hydrodynamic structure and collimated e-beam formation



Target Al, d=50 μm

Laser

$E \leq 100$ J

$\tau_p \sim 100$ ns

$d \sim 150$ μm

$I \leq 5{*}10^{12}$ W/cm^2

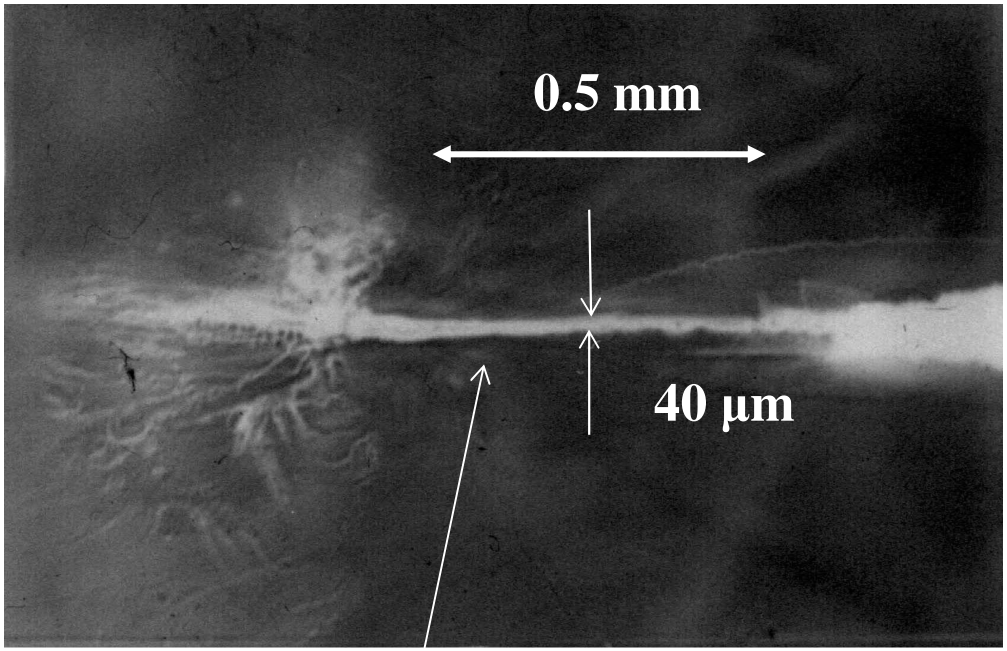
Plexiglas

$\kappa \sim 2.5{\cdot}10^4$ cm^{-1}

Plasma Corona

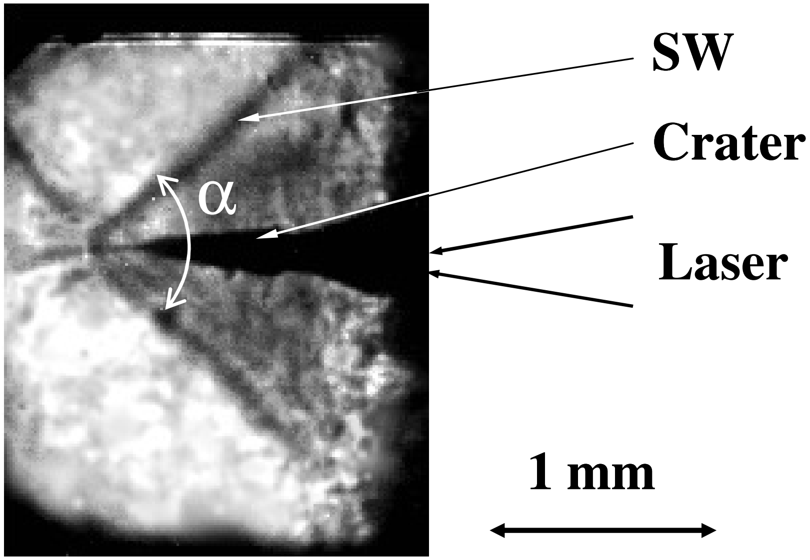
$L_{pl} \sim 5$ mm

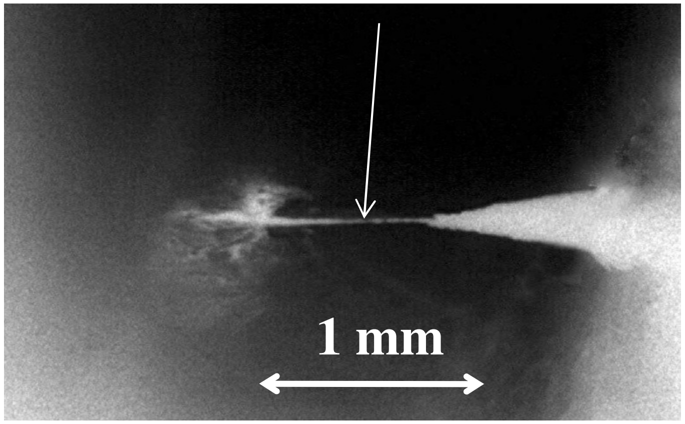
$T_{e\,max} \sim 100$ eV



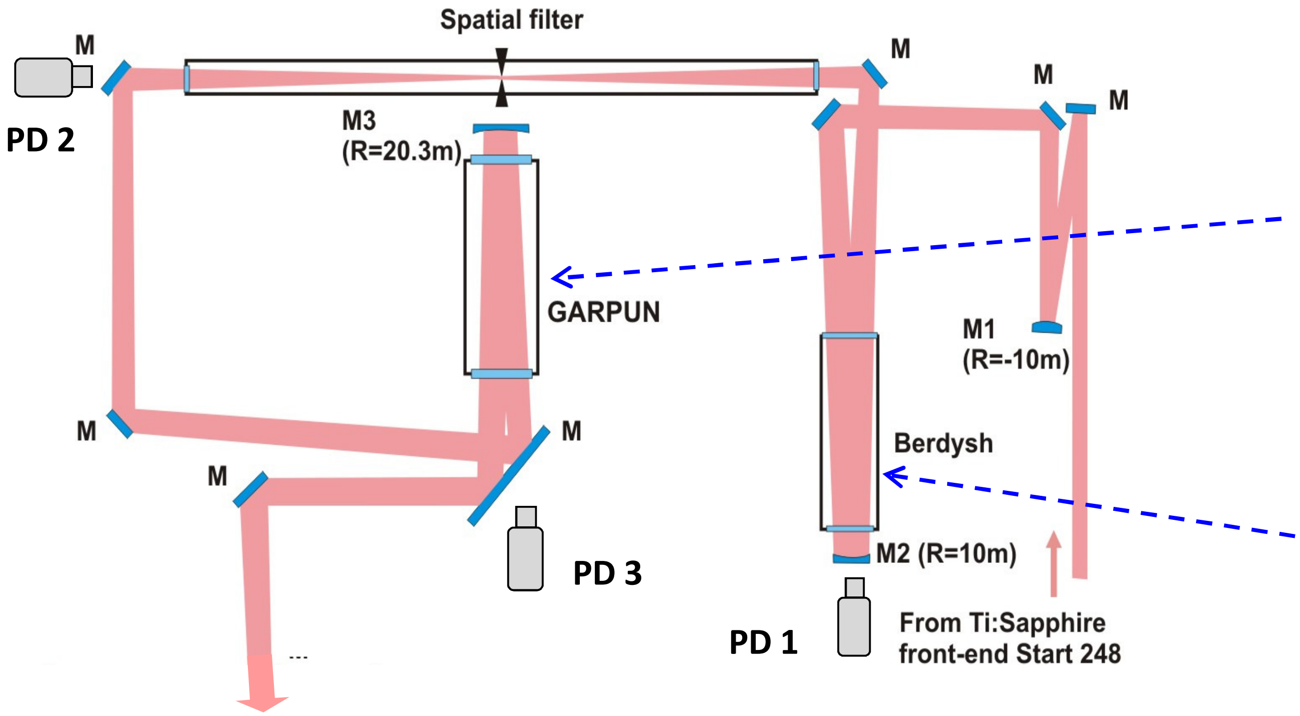
Collimated e-beam of ~ 0.4 MeV energy

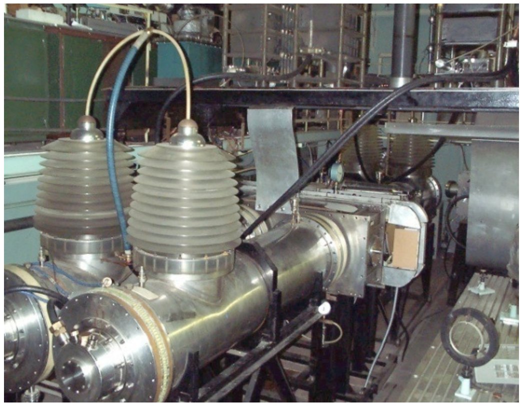
$$\sin(\alpha/2) = c/V_{ab} \longrightarrow V_{ab} \sim 5 \text{ km/s}$$

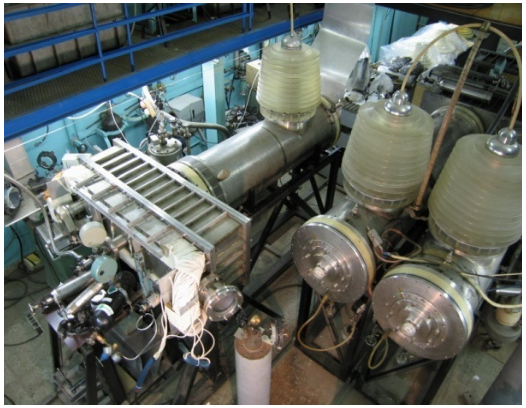


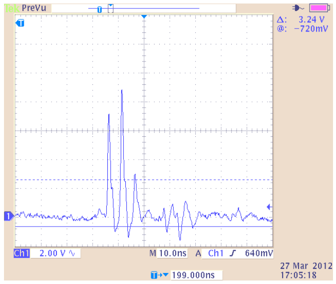


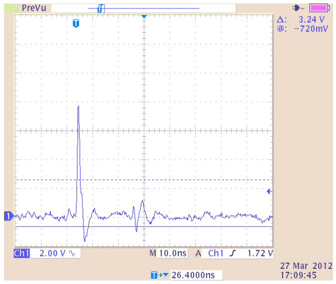
Amplification of sub-ps pulses at Ti:Sapphire/KrF laser system

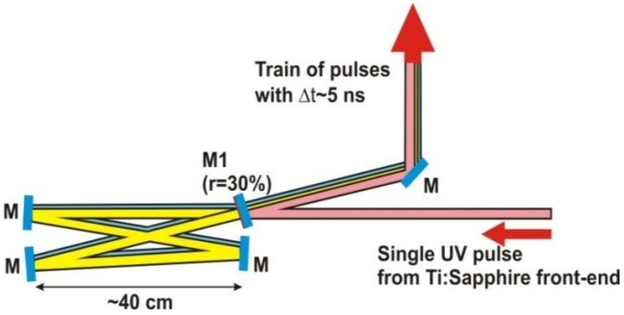












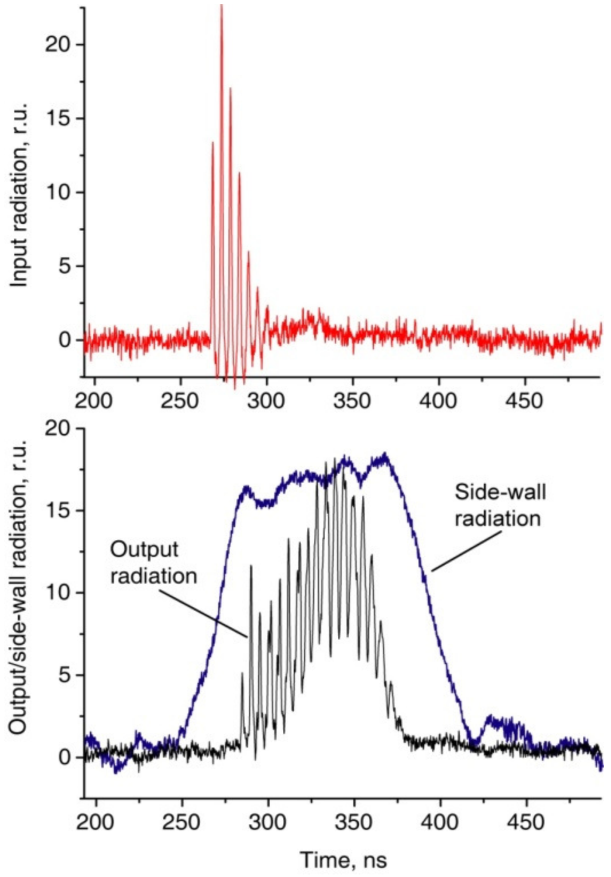
Single USP: $E_1 \leq 1$ J; $\tau_p < 1$ ps; $P_1 \sim 1$ TW

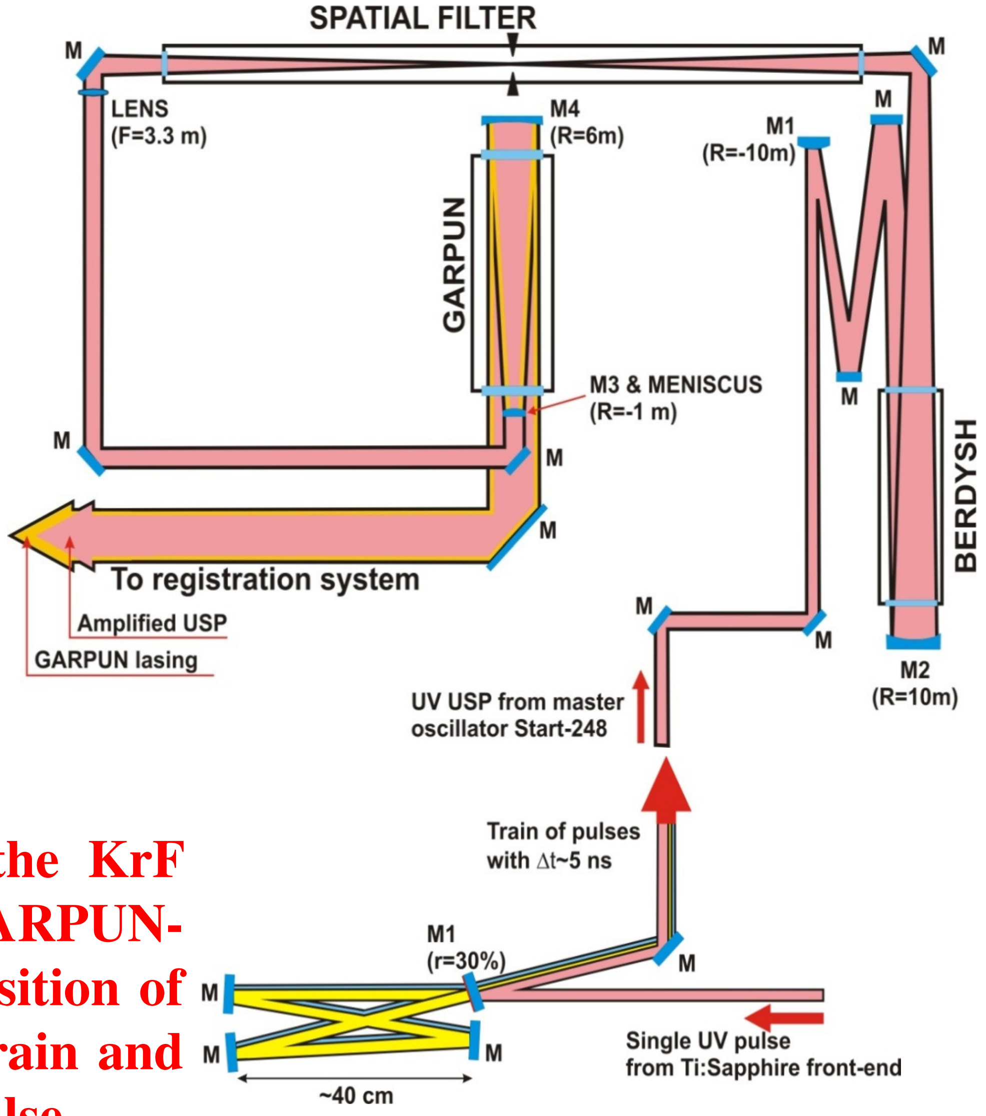
Train of the USP: $E_1 \leq 2$ J; P_1:P_2:P_3…=3:5:1.5:0.5…, $\Delta t = 3 \div 5$ ns

Contrast ratio $CR_\varepsilon \sim 10^6$ for energy and $CR_I \sim 10^{11}$ for intensity

Zvorykin et al, *Quantum electron.* 2014, <u>44</u>, 431

Simultaneous amplification of short & long pulses



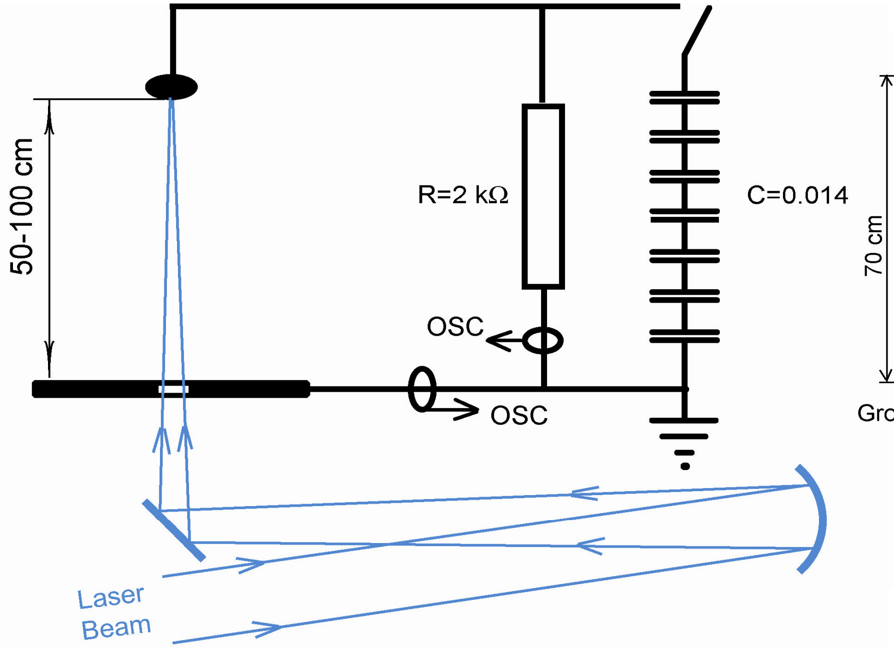


A short gain recovery time of the KrF laser medium ≤2.0 ns enables GARPUN-MTW laser to amplify a superposition of sub-ps, 0.2–0.3 TW short-pulse train and 30 J, 100 ns quasi-steady lasing pulse

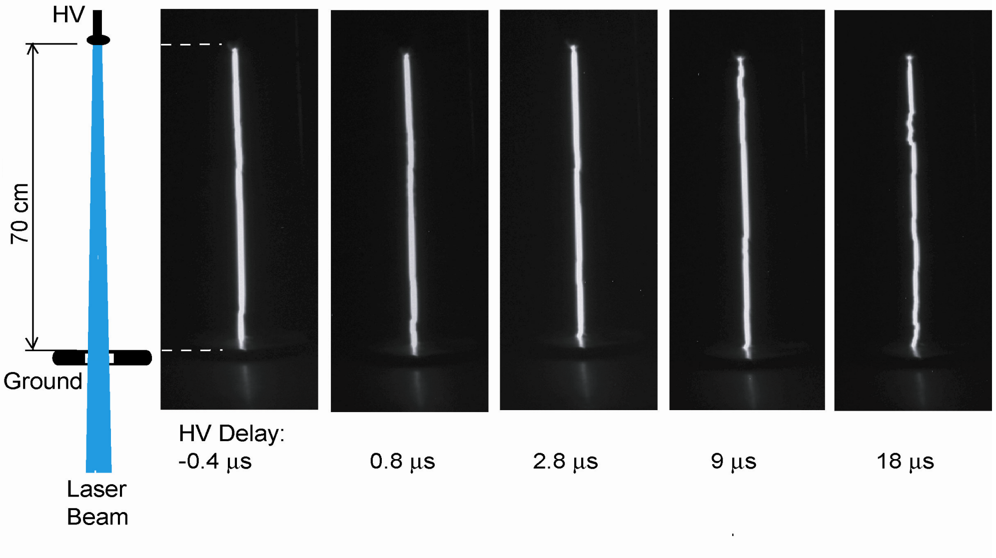
Zvorykin et al., *Quantum Electron*., 2013, 43, 332

Guiding of HV discharge by combined UV radiation

Layout of experiments



Images of discharges initiated by combined laser pulse (E_L= 6.3 J) for different delays of applied voltage (U= 420 kV).



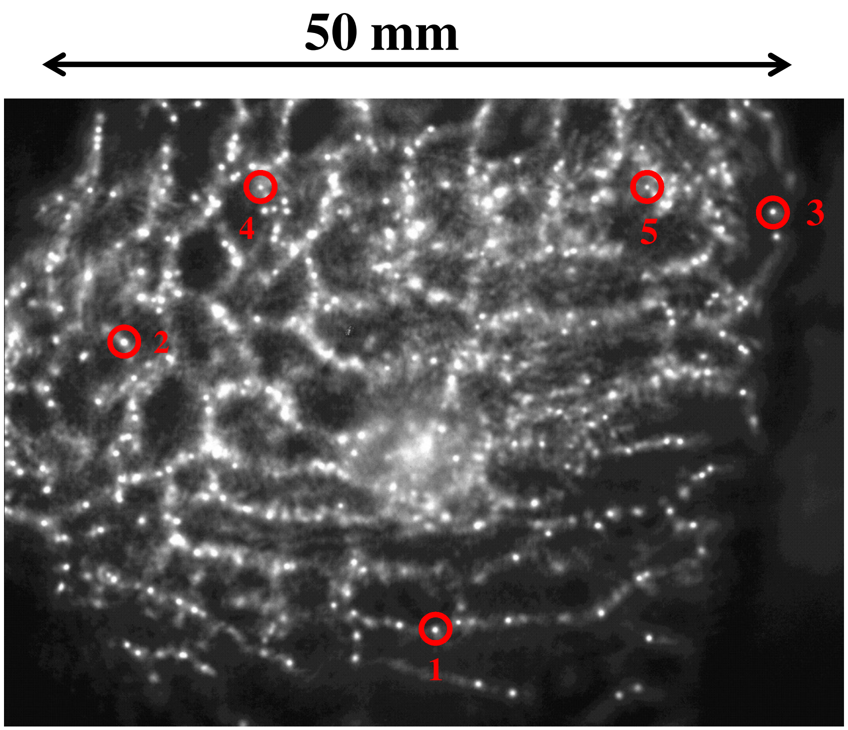
A combined (short-pulse train & 100 ns pulse) laser radiation effectively produces a long ionization trace in air, which initiates HV discharge and guides it along 70-cm gap. Short UV pulses ionize air via REMPI mechanism, while a long pulse suppresses electrons attachment to O_2 molecules.

Zvorykin et al, *Quantum electron.* 2013, 43, 239.

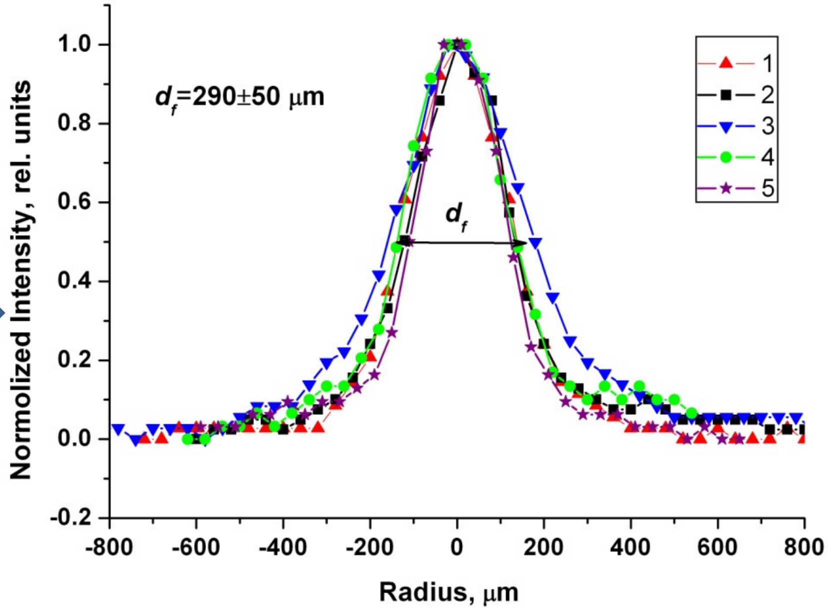
UV USP for particles acceleration

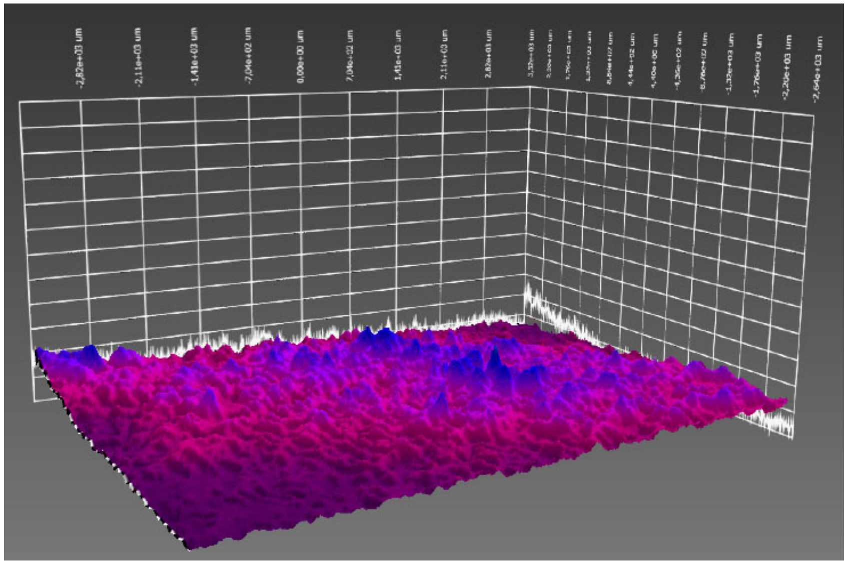
- **Multi-terawatt fs IR USP of Ti:Sapphire lasers (λ~800 nm) is commonly used for electrons and ions acceleration managed by a parameter $I \cdot \lambda^2$**
- **Deep penetration and efficient absorption of UV light in under-dense plasma ($n_{ecr} \sim \lambda^{-2}$) and potentially smaller focal spot ($S \sim \lambda^2$) are attractive for particles acceleration by UV USP in interaction with low-density nano-structured targets (Bychenkov et al, Phys. Usp. 2015, 58, 71)**
- **UV laser-plasma interaction is significantly less known than in the IR spectral domain**
- **TW-power GARPUN-MTW hybrid Ti:Sapphire/KrF laser facility was characterized for solid and low-density targets irradiation**

Kerr self-focusing produces filamentation of the USP beam



$E_1 = 0.23$ J; $P_1 \approx 2000 \times P_{cr}$



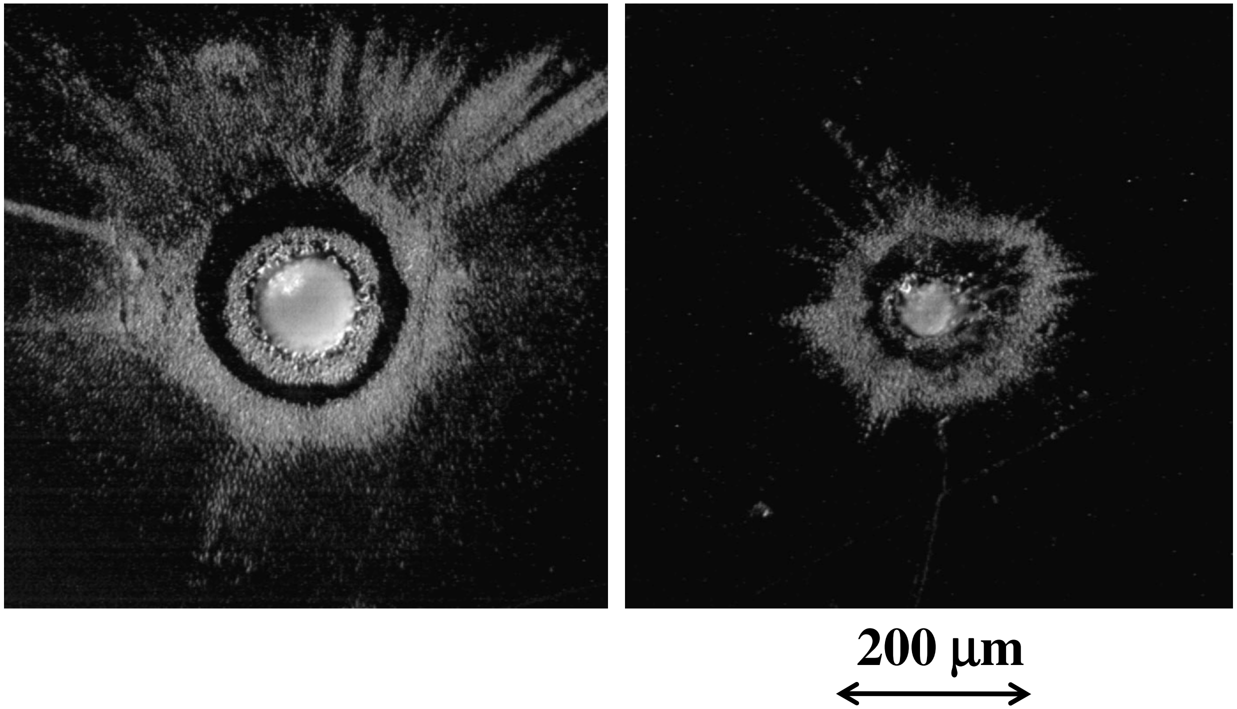


300 filaments of 240–340 µm diameter are formed in the supercritical ($P_{cr} \approx 100$ MW) beam containing 30% of the total USP energy. Peak intensity in filaments $I_f \sim 2 \cdot 10^{11}$ W/cm^2 and energy fluence $\varepsilon_f \sim 0.2$ J/cm^2 are 200-fold higher than the average ones. They are absorbed in KrF gain medium and laser windows, as well as make worse beam focusing. Suppression of the filamentation is required.

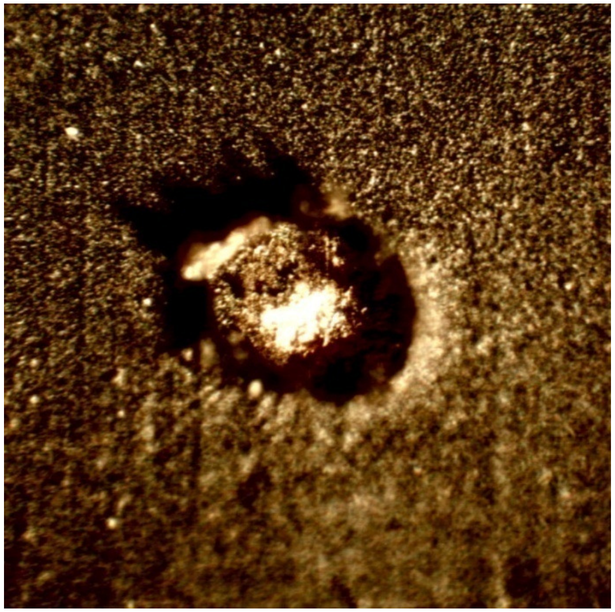
V.D.Zvorykin et al., *Appl. Optics*, 2014, 53, I31

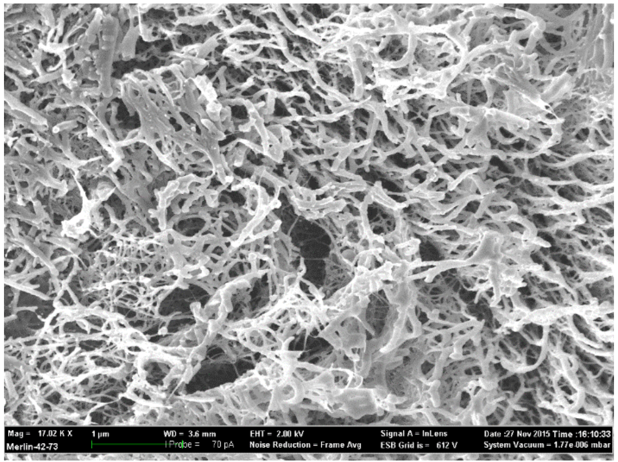
Craters in irradiated targets at different energies

Plexiglas



Low-density carbon*





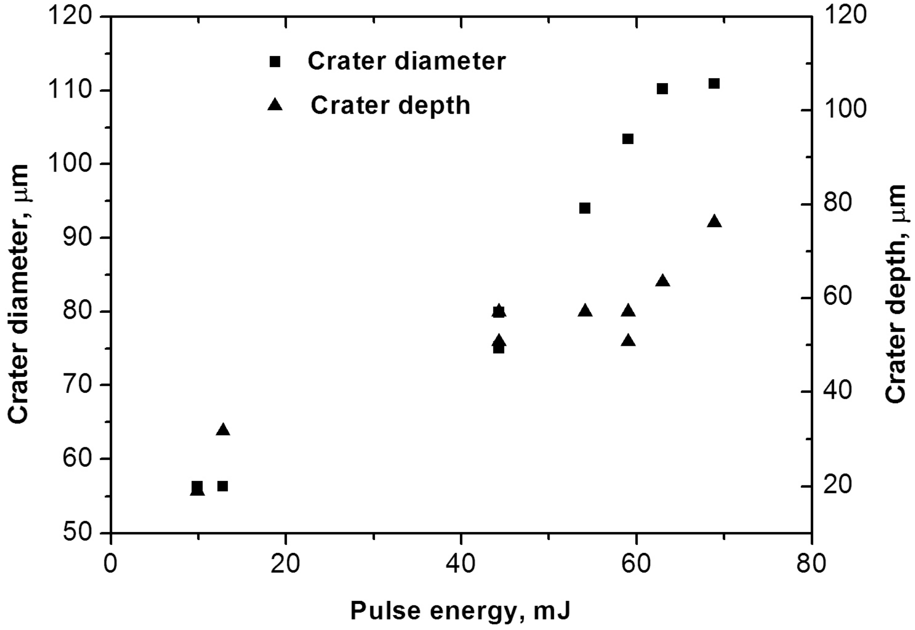
2 μm

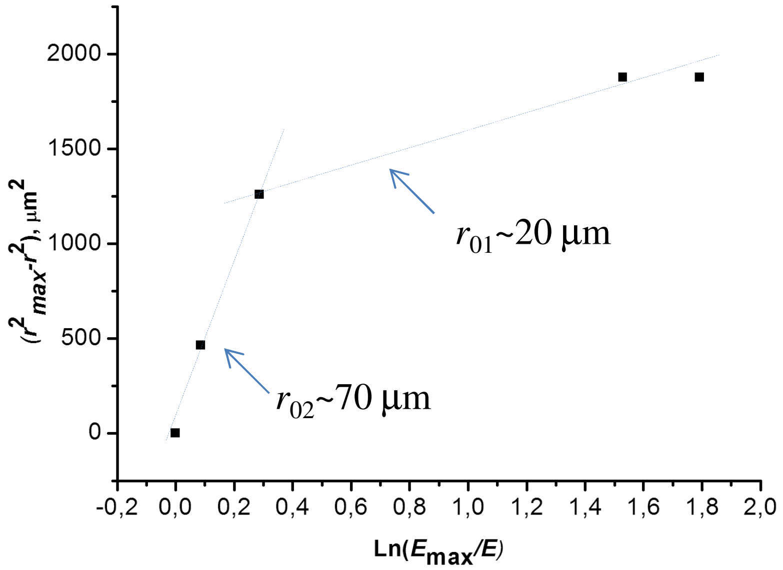
USPs are focused on targets by a spherical mirror with $F = 400$ mm. The spot diameter is determined by:

- spherical aberrations ≥ 100 μm;
- overall beam divergence ~ 40 μm;
- multiple filaments – weather they are in phase or not.

* ***Provided by E. Obraztsova (GPI)***

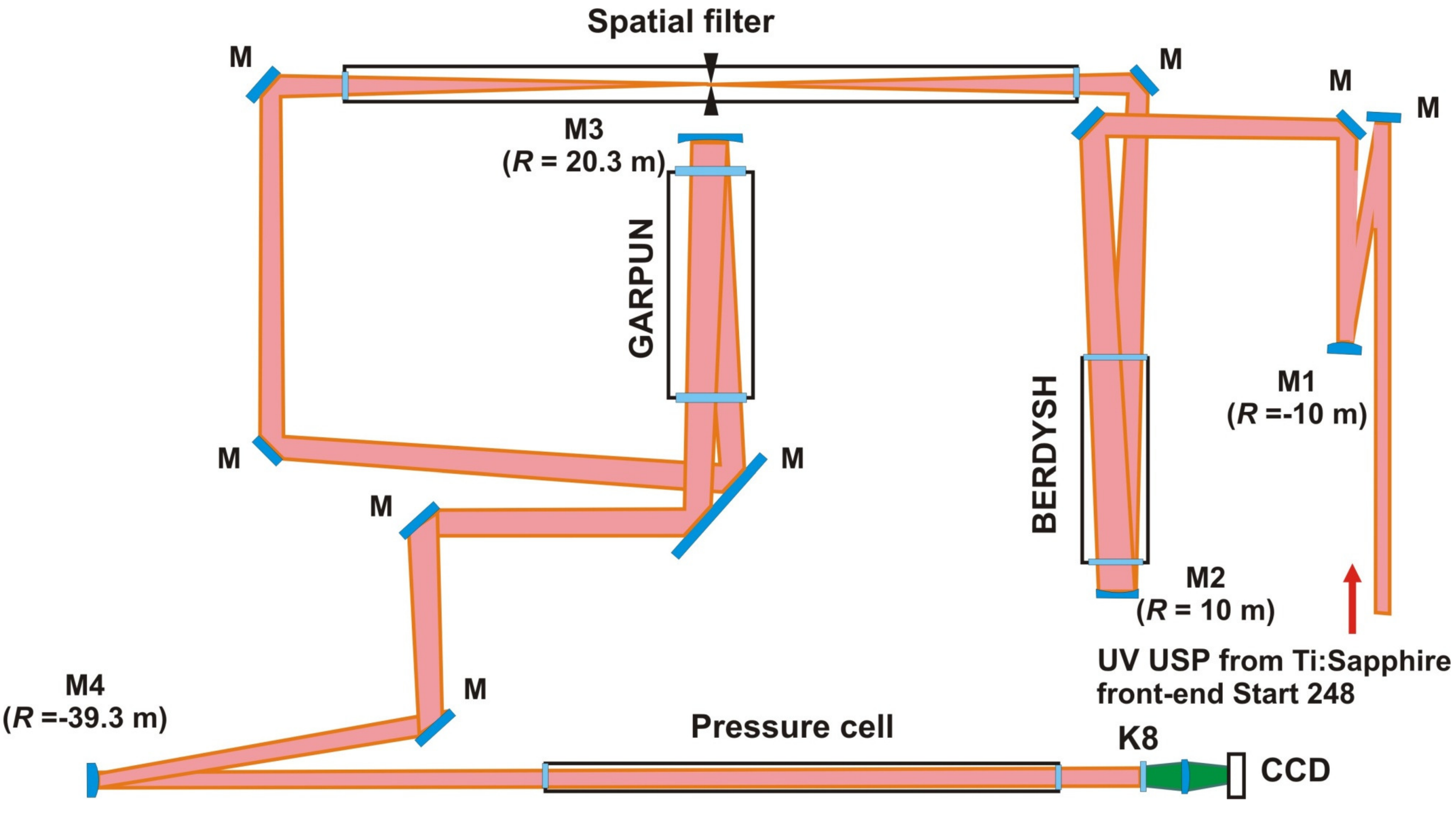
Energy distribution in the focal spot





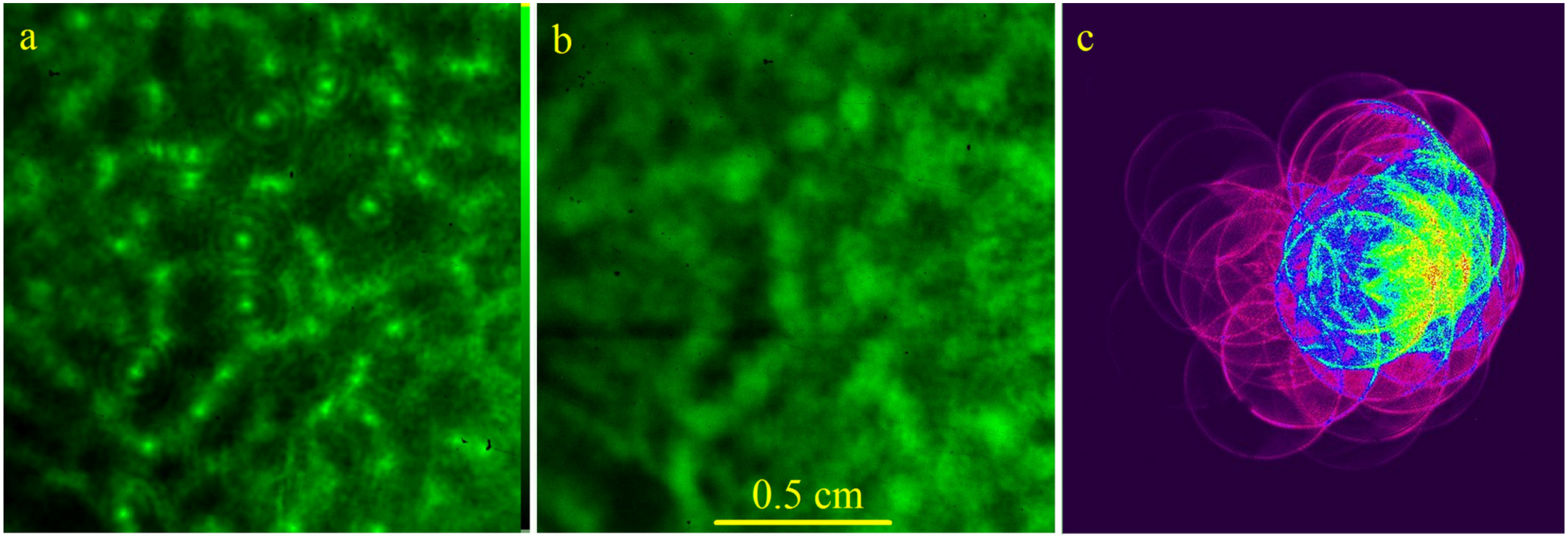
Central region with Gaussian radius of 20 μm contains 65% of total energy, the rest energy is in the wings with 70 μm radius. For the USP of ~ 1 ps duration and 0.5 J energy maximal peak intensity in the focal spot ~2·10^{16} W/cm^2.

Registration of the USP beam filamentation



- **Pressure cell was pumped out or filled with atmosphere air and Xe at ≤ 1 atm.**
- **Xe has a large negative nonlinear refractive index due to a 2-photon resonance of KrF laser radiation with 6*p* $[1/2]_0$ state**

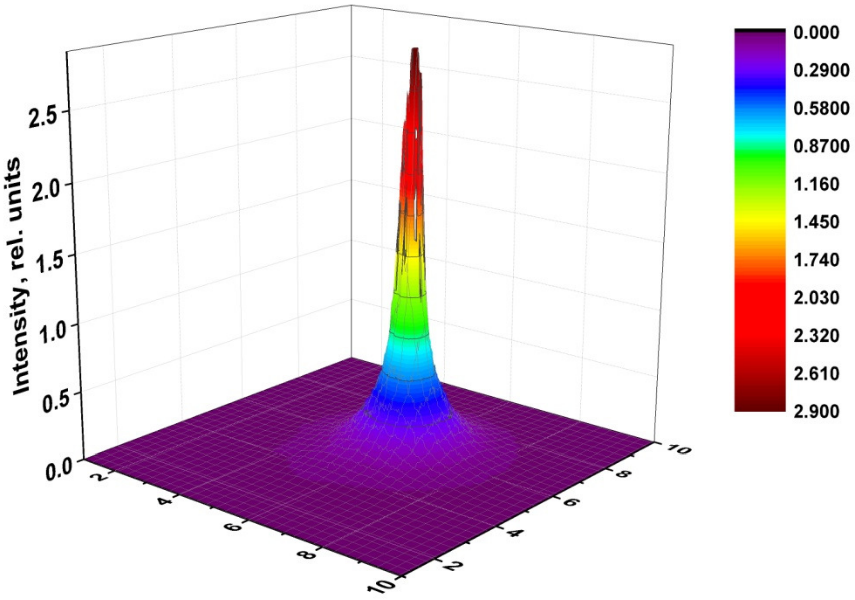
Suppression of filamentation in Xe



- **Self-defocusing of multiple filaments in Xe (a, b) which has a large 2-photon resonantly-enhanced *negative* nonlinear refraction index (Lehmberg et al, Opt. Commun, 1995, 121, 78).**
- **Coherent thin-wall cone emission at 828-nm wavelength (c) due to stimulated hyper-Raman scattering and ASE at 6*p*→*6s* transition in Xe (Tunnermann et al, Phys. Rev. A, 1992, 46, 2707).**
- **Multiple filaments are in the phase!**

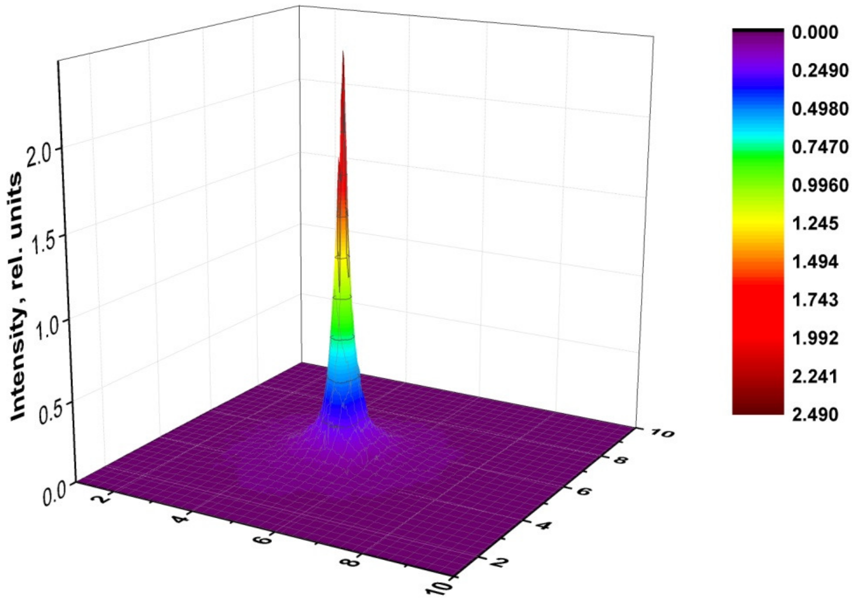
Focusing of filamented and compensated beams (*F*=2.5 m)

Multiple filamentation



$\theta_{0.1}$=2.4·10^{-4} rad

Suppressed filamentation



$\theta_{0.1}$=1.2·10^{-4} rad

Laser beam with suppressed filamentation has twice less divergence

CONCLUSIONS

- **Various operation regimes of a multistage KrF laser facility GARPUN were realized during the last decades providing a big deal of capabilities in UV light interaction with condensed, low-density structured and gaseous matter.**
- **In the present hybrid Ti:Sapphire/KrF version the laser generates single or a train of sub-ps UV pulses with TW-level peak power, which can be combined with 100-ns, 30 J pulse.**
- **Multiple filamentation of a supercritical (P/P_{cr} >1000) UV USP strongly saturates output USP energy. Suppression of filamentation along the amplification tract would increase energy in several times.**
- **Peak intensity $2 \cdot 10^{16}$ W/cm^2 was attained in initial target irradiation experiments being limited by aberrations of the focusing optics and beam filamentation.**
- **Kerr self-defocusing of multiple filaments was demonstrated with Xe cell.**
- **Better beam focusing was achieved for the USP beam with a suppressed filamentation.**
- **Peak intensity is expected to be up to 10^{18} W/cm^2 with a suppressed beam filamentation and proper focusing by parabolic mirror.**

Acknowledgments

The research was supported by Russian Science Foundation Project No. 14-12-00194 and by Russian Foundation for Basic Research Projects Nos. 15-02-09410 and 14-22-02021.