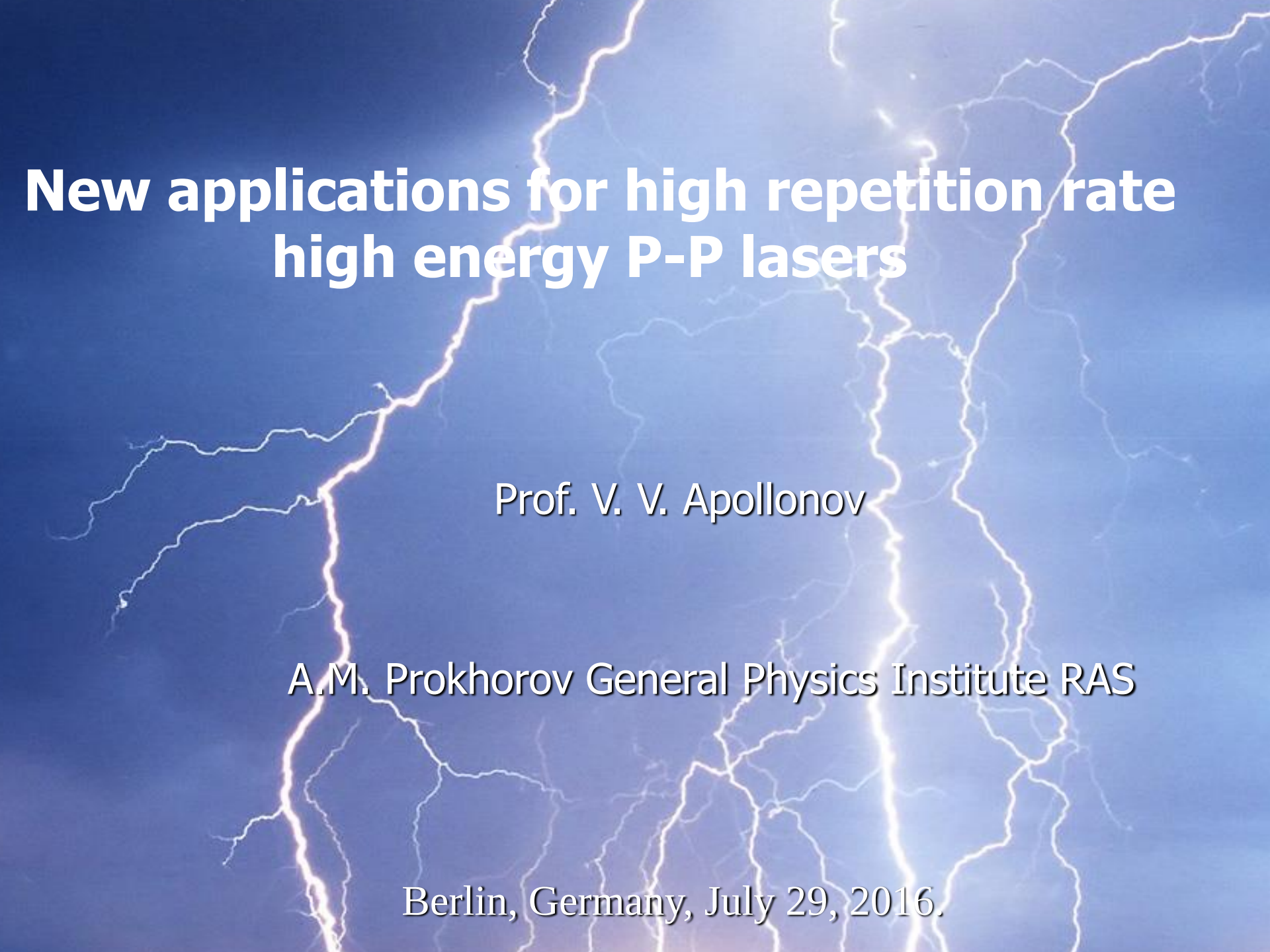


New applications for high repetition rate high energy P-P lasers

Prof. V. V. Apollonov

A.M. Prokhorov General Physics Institute RAS

Berlin, Germany, July 29, 2016.

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   a. Variable temporal structure of laser radiation – base of successful high-tech. applications.
   b. Mono-module disk laser with high rep. rate P-P mode of operation;

2. Regenerative regime of operation for high power P-P laser systems;

3. Experimental P-P laser systems : GDL, HF/DF, SSL (rod, slab, disk)

4. New applications:
   - cutting of super hard and fragile materials;
   - water and solid surface processing;
   - propulsion by laser;
   - conductive channel;
   - high efficiency interaction;
   - space cleaning;
   - ice breaking;

Main advantages of high rep. rate P-P mode of operation

(Had been investigated and demonstrated for CO2 , HF/DF and Nd YAG lasers)

1 Much higher efficiency of energy extraction from media and conversion into laser light, which is important for wide aperture lasers (gain x distance);

2. Plasma screening effect decreasing due to the decreasing of laser pulses duration and increasing of number of pulses up to a few hundreds of kHz;

3. Decreasing of laser beam thermal defocusing due to the optimal temporal structure of laser radiation;

4. Localization of energy deposition in space and time and elimination of stressed state of solids under laser action due to fast ablation process;

5. Possibility of unrolled 3d geometry of breakdowns in space due to a very high repetition rate of laser pulses generation, creation of optical, acoustical and electromagnetic fields far away of laser source

6. Much longer distances of optical breakdown conditions in air for the same optical systems (intensity is much higher) ;

The levels of output power for the best high rep. rate P-P lasers in our days

domain	technology	pulse duration	Repetition rate	energy/power	M^2
cw	single-oscillator			230 W	< 1.1
				98 W	
ns	q-switch	100..900 ns	up to 15 kHz	16 mJ @ 4 kHz	< 2
				6.3 mJ @ 10 kHz	
	regenerative amplifier	8 ns	up to 10 kHz	38 mJ @1 kHz	< 1.3
ps	regenerative amplifier	5 ps	up to 20 kHz	5 mJ @ 1 kHz	< 1.3
		1,5 ps		1.3 mJ @ 20 kHz	
fs	regenerative amplifier	700..900 fs	up to 45 kHz	100 μJ @ 45 kHz	< 1.3
		280 fs	up to 200 kHz	15 μJ @ 200 kHz	

High rep. rate P-P lasers with high average power will dominate in the nearest future for industrial applications (Slide from presentation at GCL/HPL -2010)

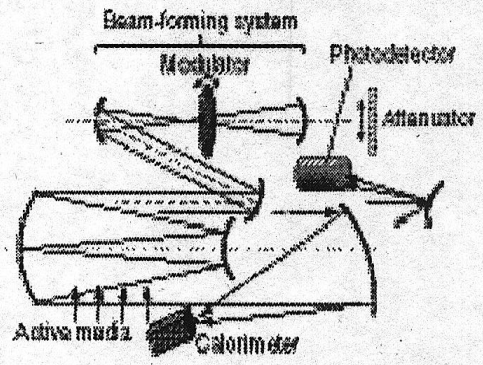
“Laser Focus World” August 2004,p.17.

Paper had been prepared and published by editor - John Walace)

Gas-dynamic laser enters pulse-periodic mode

A group of laser researchers led by Victor Apollonov at the Russian Academy of Sciences (RAS; Moscow) has developed a modification to high-power wide-aperture gas lasers that allows emission in a high-frequency pulse-periodic mode in which very short pulses are produced at a high rate without a sacrifice in average power.[1] The improvement can be made to gas-dynamic lasers, hydrogen fluoride/deuterium fluoride chemical lasers, and chemical oxygen-iodine lasers. Potential uses include launching and propelling spacecraft with ground-based lasers.

At output powers exceeding several kilowatts, producing short pulses based on high-frequency resonator modulation runs into several problems, caused by the wide apertures of the resonator elements. Existing schemes for beam modulation, which include magnetic modulation of gain and physical chopping of the beam, all have problems that greatly reduce average power when compared with continuous-wave (CW) operation.



In the scheme developed by the RAS researchers, a portion of the laser's output is extracted from the resonator, modified spatially and temporally, and then returned to the resonator (see figure). Injecting return light into the paraxial region of the resonator would require that the power of the injected beam be

Repetition rate – 30kHz.
Average power – 100kW.
Pulse duration- 100нс.
(Very much optimal for high power applications)

Regenertive P-P mode of operation had been developed by GPI RAS and published in QE (2001).

P-P modes of regenerative amplification for high power lasers

They are dependable on parameters of media, way of pumping and resonator geometry

COIL P-P mode starts at frequencies > 20 kHz.
Depth of modulation -100% at frequencies > 100 kHz.
Pulse duration < 250 ns. Ratio P peak. / Paver. = 100 -1000.

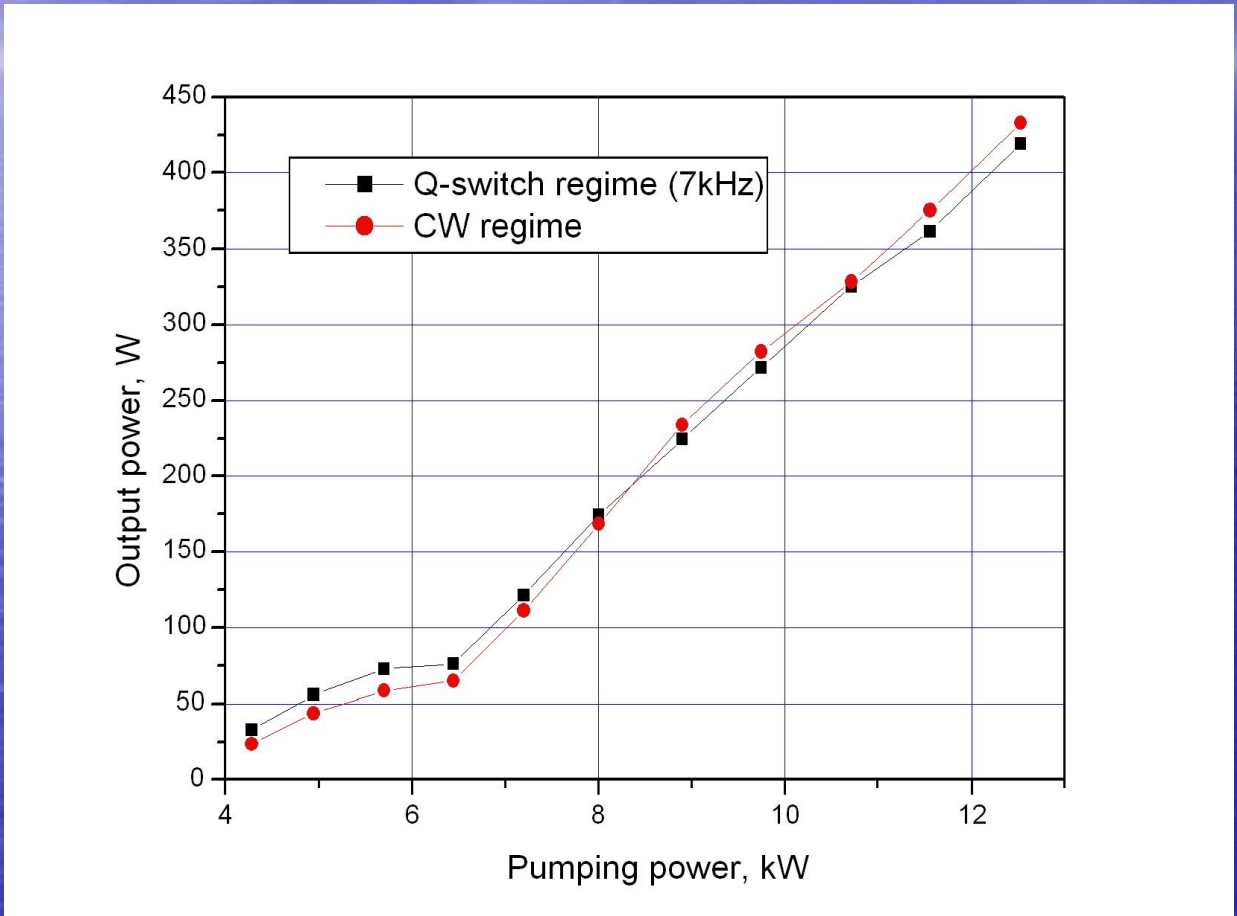
HF/DF P-P mode starts at frequencies > 100 kHz.
Depth of modulation -100% at frequencies > 150 kHz.
Pulse duration < 100 ns. Ratio P peak. / Paver. = 1000 -10000.

Yb YAG P-P mode of operation had been demonstrated at frequencies 5-100 kHz.

Disk for P=1000 W.
Scaling problems: >>100 kW is needed

V. V. Apollonov et al , *Quantum Electron.*, 33, 753 (2003). For CO2 and Nd YAG lasers

Output power of P-P и CW modes of generation for Nd YAG laser



Threshold of regenerative amplification for P-P mode start in case of CW laser has increased more than 8 orders of magnitude in comparison with gain switch mode for single pulse

Nd YAG pumped by lamps P=1000 W (CW/P-P)

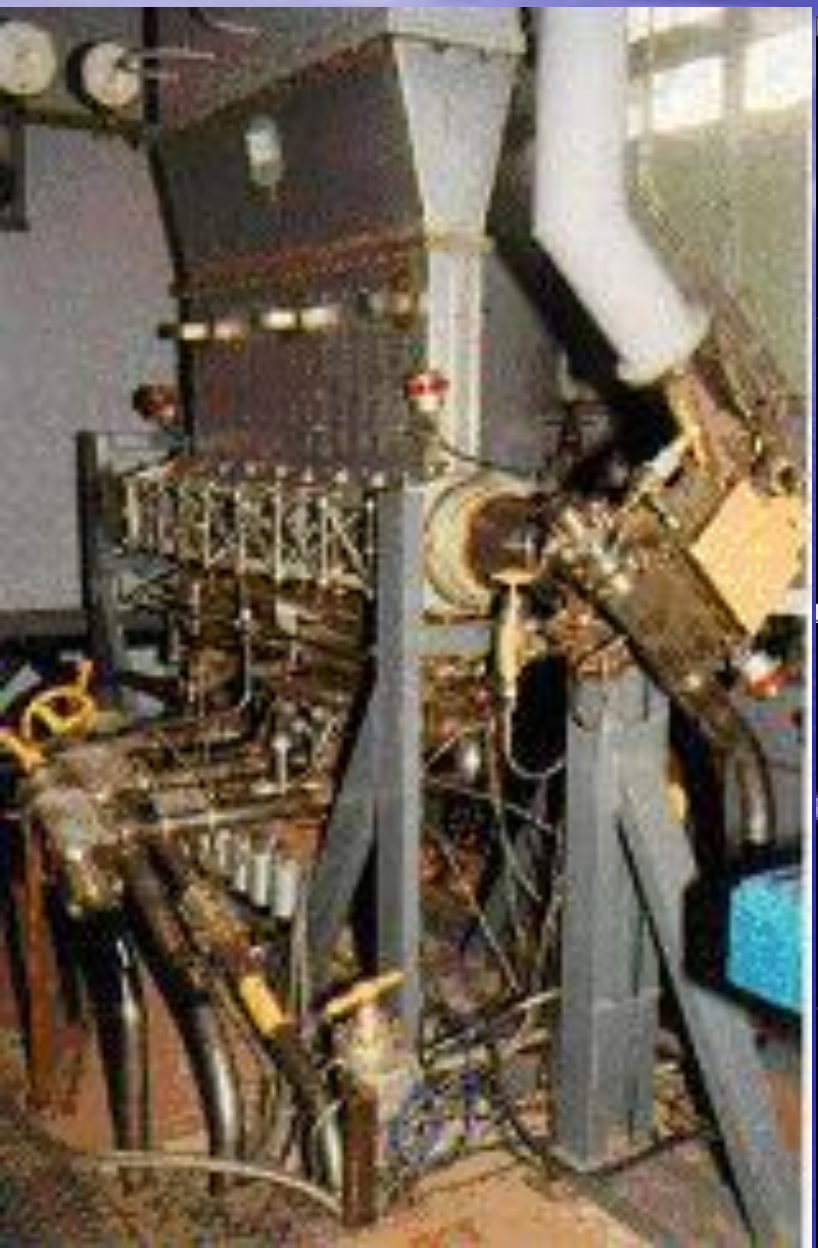


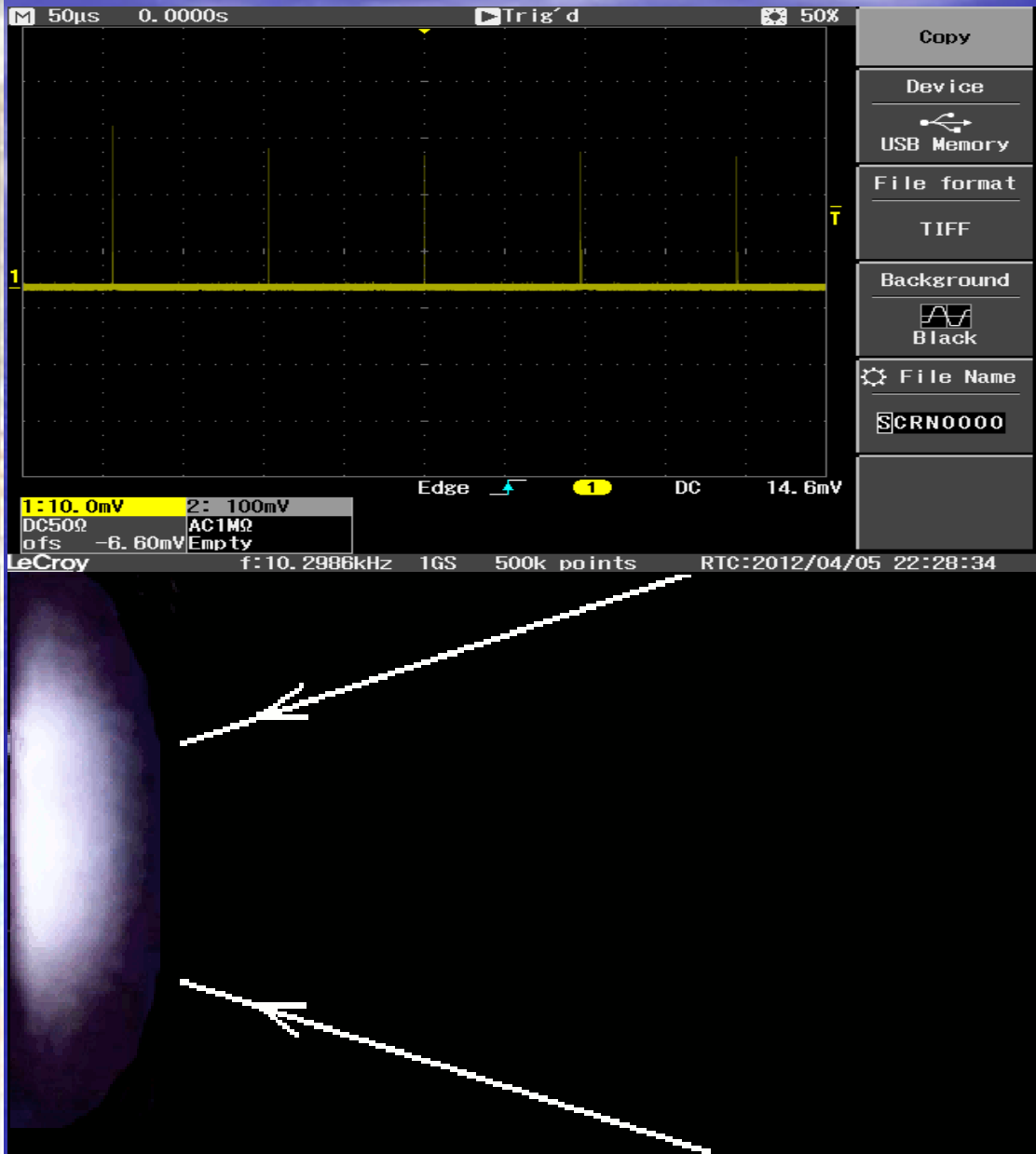


1kW　LD pumped SSL



P-P/CW GDL system-100kW

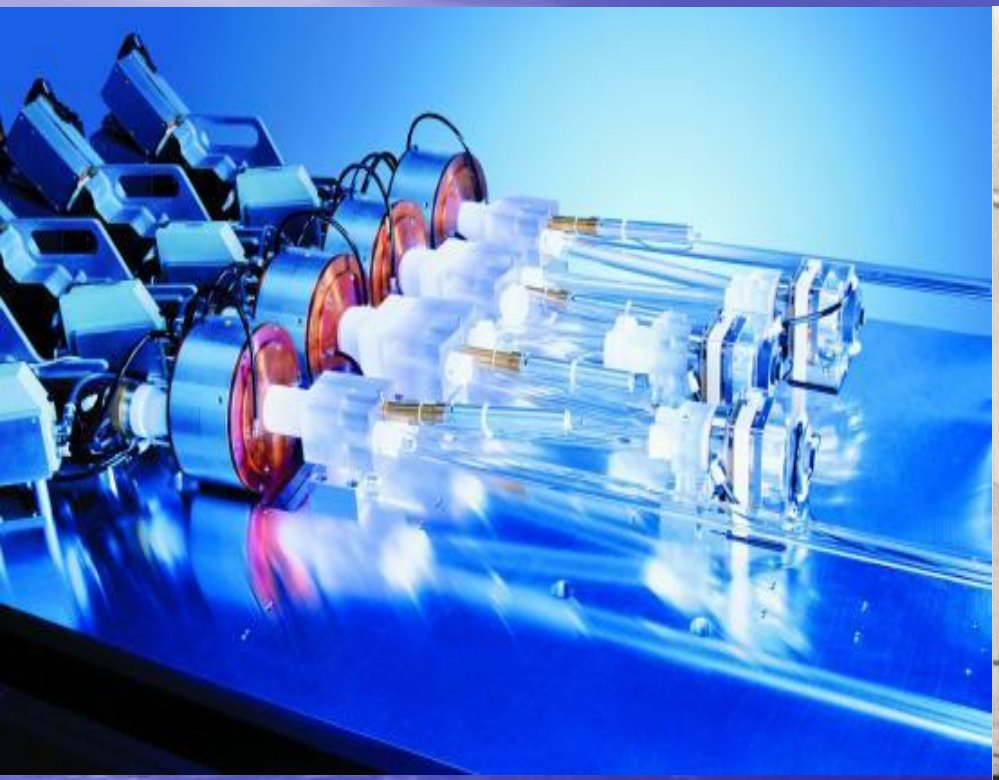


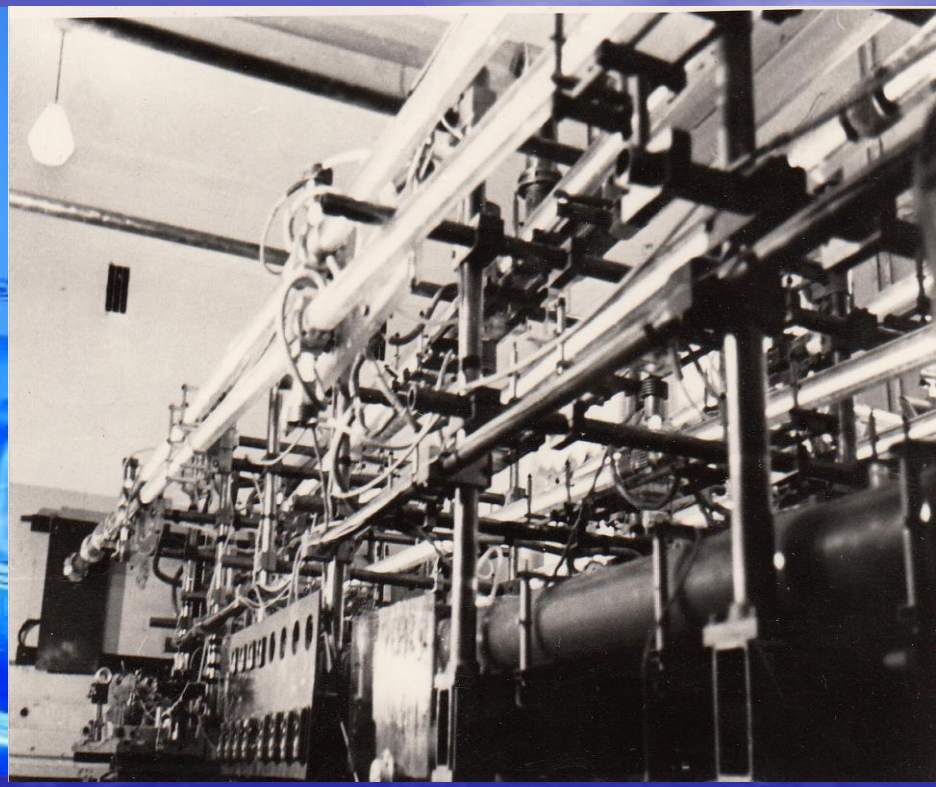


Disk laser- first Russian publications

- **1. N.G. Basov, O.V. Bogdankevich, A.Z. Grasiuk JEEE of QE-2(9), 1966.**
- **2. "Diode Pumped Solid State Laser with Adaptive Hybrid Resonator and Disk Active Element"**
- V. V. Apollonov, S.A. Chetkin, acad. A. M. Prokhorov
- General Physics Institute, Moscow, Russia
- The design of compact solid state laser system with adaptive hybrid resonator and disk active element pumped by laser diodes has been proposed. Sufficient improvement of laser radiation spatial characteristics and energy extraction efficiency from the active element will be demonstrated and discussed in details. The results of computer modeling of sophisticated structure will be compared with data of experimental investigations, based on disk active element pumped by Ti-sapphire laser. The applicability of proposed design for extremely efficient high power wide aperture scalable technological laser manufacturing with minimal weight and size is concluded.
- "Scientific –technical conference USSR", 25-27 September 1986.
- <5kg/kW this is the goal !

Disk laser evolution



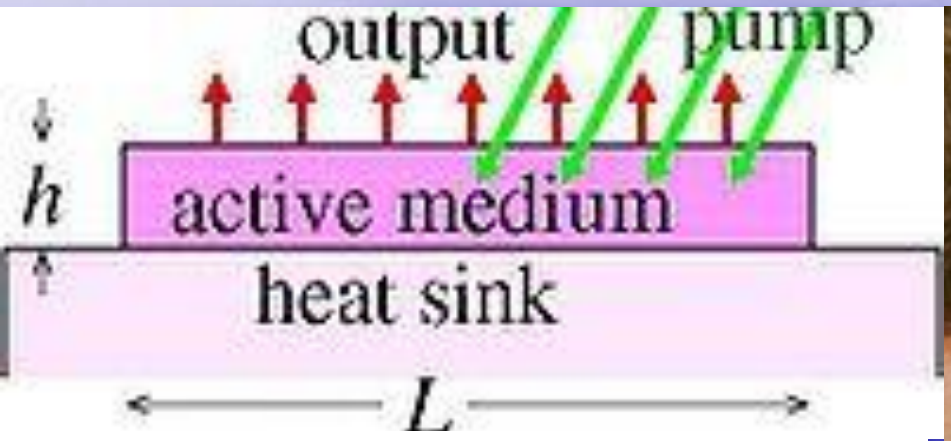


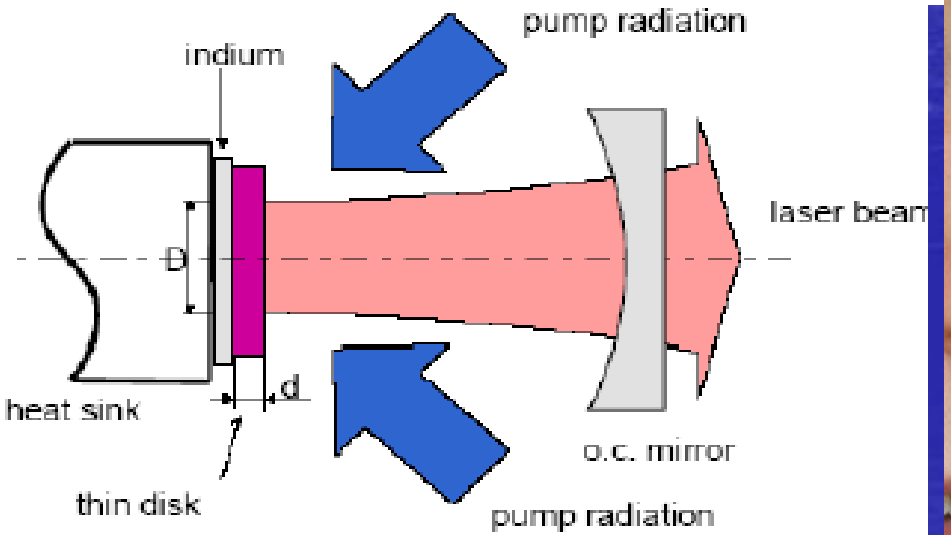
.”Zig-Zag” disk laser consisting of a series of disk modules in a single cavity (TRUMPF, Lockhid-Martin, Boeing, Hamamatsu).

“Zig-Zag”- CO2-laser consisting of series of tubes in a single cavity **(FIAN 1970)**

Well known that the disk geometry of a laser was proposed 52 years ago by N.G. Basov. Now the solution to the problem of the ASE suppression with great transverse dimensions of an active medium (the case of big diameter mono-module disk) is found!

Ceramics Yb:CaF2 - very effective laser material







Applications

- All of them are based on a high enough energy (average power):
- 1 J X 100 kHz = 100 kW
- (just for beginning! 150kW is better)
- For orbital scale distances
- the goal is >1MW.

History, estimations and perspectives

1.Idea of beamed propulsion technology has been suggested by A Kantrowitz and Demonstrated by A.N. Pirri I=250-300 N/MW.(1972)

2.By high repetition rate operated Laser by V. Apollonov (GPI RAS) and colleagues specific thrust of "Impulsar" has been increased up to I=1200-3500 N/MW.(2004)

Spacecraft "Soyuz" :
1.Mgr.=313,5 t;

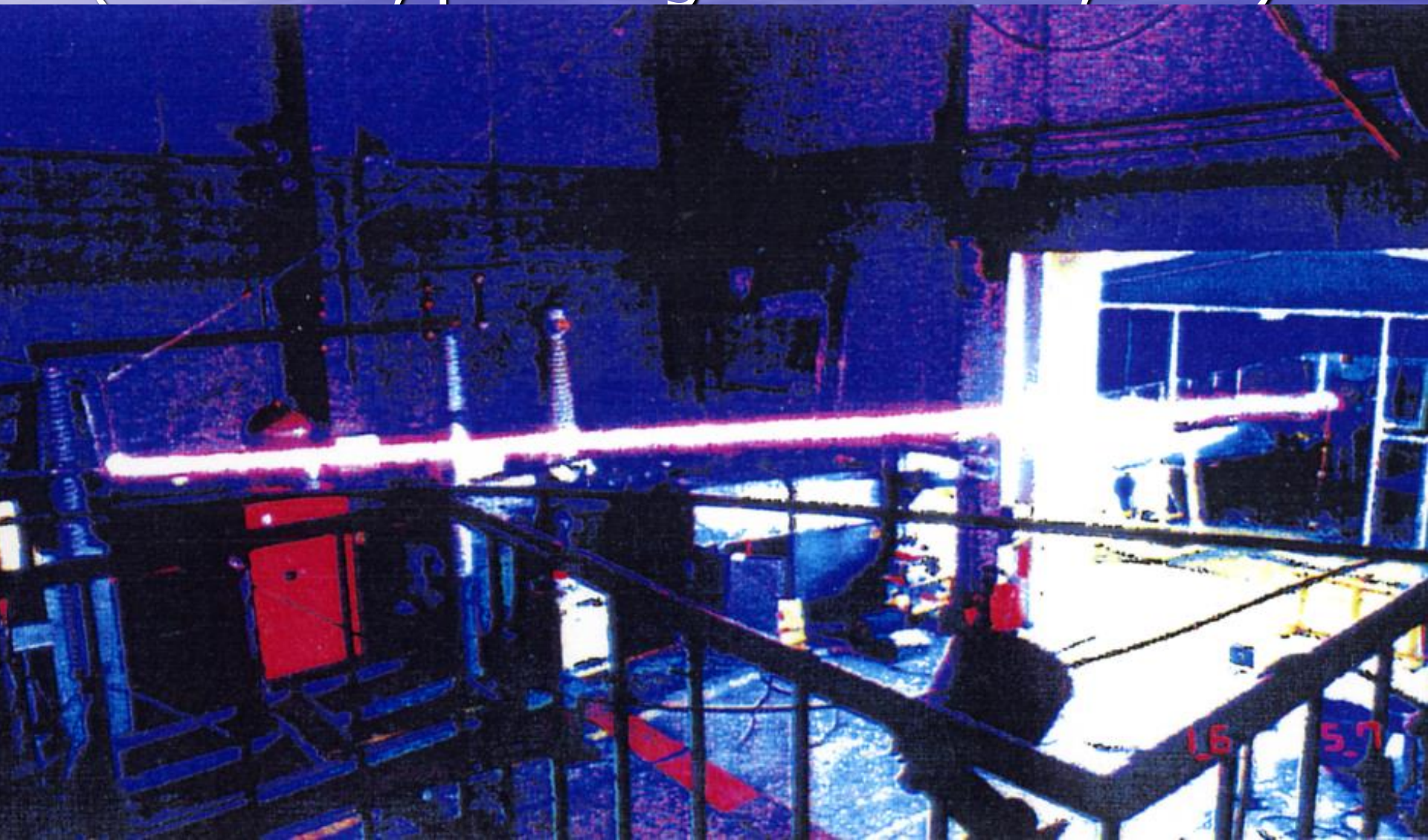
2.M fuel=44,5 t (1^{st} stage)+95,3 t (2^{nd} stage) +22,7t(3d stage)+440-892 kg(ship) =163,6t;

3.Action time:
410,8 t (504) for Mgr.=313,5 t during t = 140 s;
76 t (96) for M 2^{nd}. st. =99,9 t during t = 180 s;
Total action time – 529 sec.
4.Energy storaged on the board "Soyuz":
30kw/kg x 163,6 t =5 GJ;
Energy for launching: 10 MW x 50 sec =0,5 GJ;
Conclusion: 10 launches of M=2,5 т. may be done by energy storaged on the board of "Soyuz".

Advantages of high rep. rate operation had been demonstrated by GDL и Nd YAG (CW/P-P):

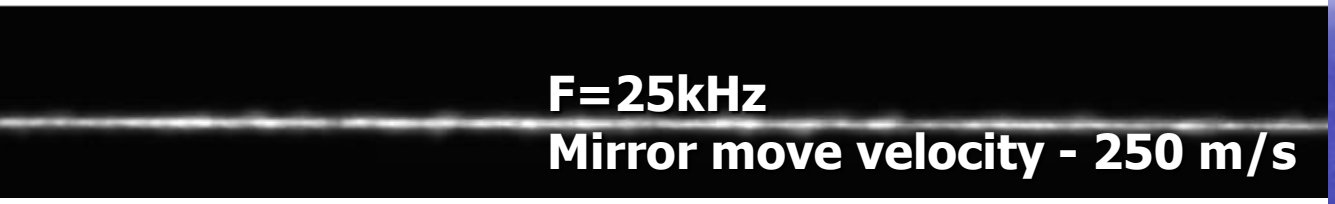
1.high efficiency of energy extraction for big volume of active media;
2.absence of plasma screening effect;
3.decreasing of laser beam blooming.
4. localization of energy deposition in time and space.

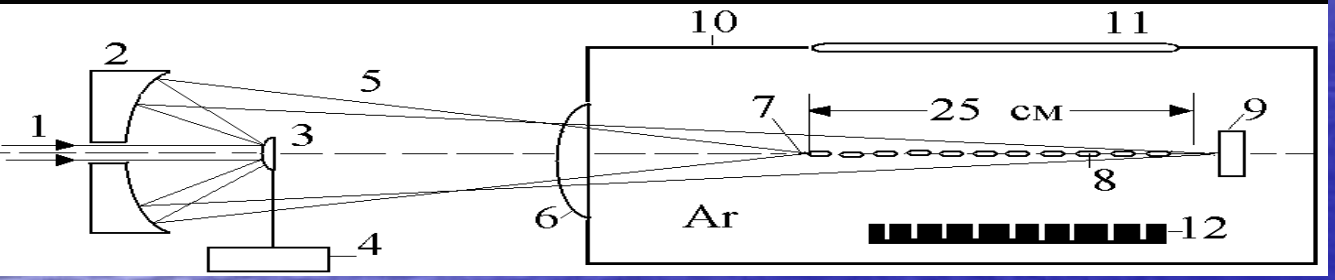
Electrical discharge along laser spark (L = 24 м, pulsed generator - 4,5 Mv)



OPD in gas as a tool for conductive channel creation







For the frequency of pulses-100kHz and average size of plasma ball -1cm the length of conductive channel about 1 km can be realized.

1m long conductive channel had been demonstrated by 500 W, 25 kHz, CO_2 - laser.

1. **The mirror of large diameter is immobile, while the small mirror can move according to a certain law. When moving the mirror, the common real focus of the system changes its position in time from infinity to some min. value, which is determined by the optical scheme of the telescope. Calculations show that for certain repetition rate of laser pulses and for certain motion law of the moving mirror continuous extended plasma channel can be formed.**
2. **The volume within which energy is concentrated is proportional to the focal length in the fourth power. To form a homogeneous plasma channel of several kilometres long, one must use a P-P laser with a shaped pulse energy and moving small telescope mirror.**

Conductive canal in space based on “Impulsar” and high voltage high rep. rate generator technologies

Thrust is materialized under powerful P-P laser radiation. Active impulse appears due to air breakdown (<30 km.) or due to breakdown in evaporated special polymer material with metal nano - particles (>30km.), close to the surface of focusing mirror - receiver of the air - blast. Main advantage of new approach is in fact that the source of motional energy and means of output are loosen in the space that leads to increasing of a part of payload in start weight of the apparatus. K. Tciolkovskiy proclaimed that the launches of missiles in the future will be carried out with the help of electromagnetic waves, directed from outside source of energy. With each impulse of powerful laser "Impulsar" goes up, leaving after itself very dense trace of products with high concentration of conductive nano - particles and plasma. High frequency transformer provides an additional heating of canal and maintains it`s stability during "Impulsar" climbing up.

Experimental test results

1. P-P CO2 –laser with train of pulses and total energy-20J;
Dust particles (a=50-250 nm, N=10 to 10-12 power)
Dust plasma modeling:
- **For laser ablation dust plasma(** paraffin wax + graphite or permalloy powder) **-300v/cm,**
- **Nano-particles of Al, Fe, segnetoelectrics -350v/cm.**

2. Another approaches:
- 100 ohm/m for canal by conical optics breakdown (100V/cm);
- 0,1 mohm/m for long canal by filaments (7,5kV/cm);
- 10 ohm/m for canal by wire explosion (60V/cm);
- 97V/cm-124V/cm-166V/cm corresponding to delays:10mks -50mks -75mks;

3.Min. resistance measurements for L=1,5 m ,Capacitor with U=7.5kv and E=100J,1kW CO2 laser with RR=30kHz; 10 ohm/m,(50 V/cm)
Which means -**5 MV is enough for channel with length about 1 km**.

4. Min. resistance value is very much dependable on cross-section of dust particles sheaf, concentration and size of particles, repetition rate of laser pulses, average power of laser, humidity and many other parameters are involved.

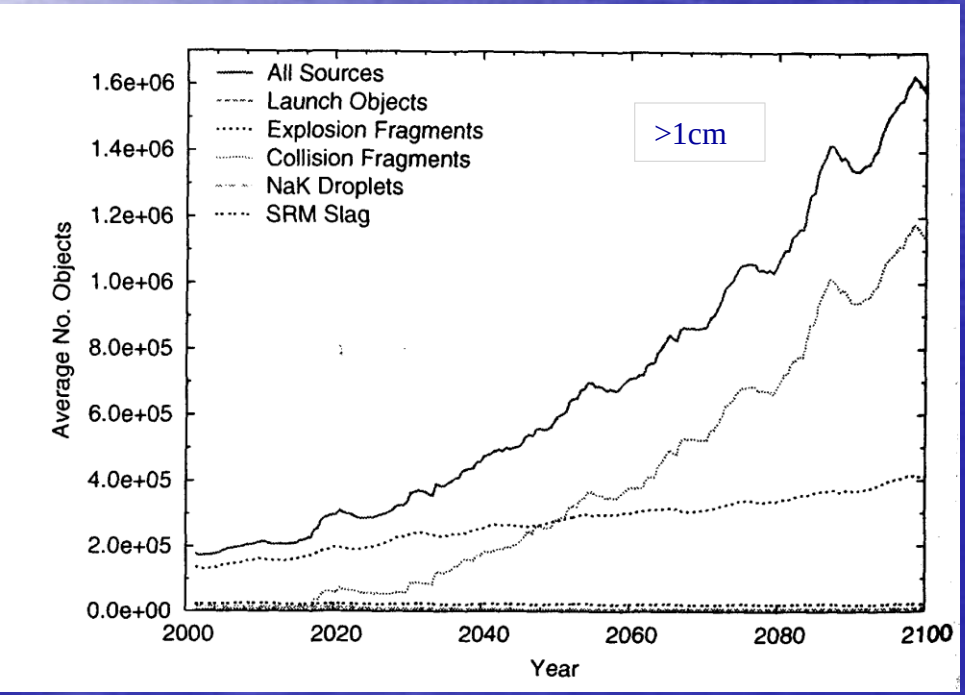
Nice approach for hot and cold dust plasma investigations!

Why Space Debris are a Problem

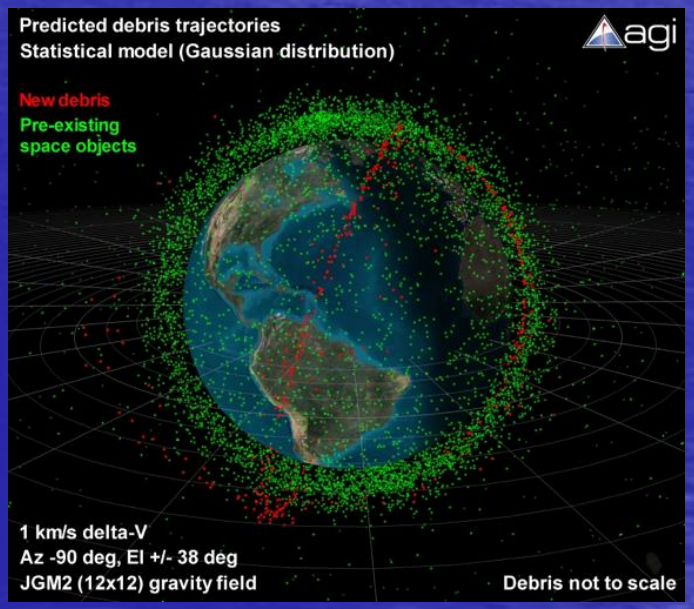
- Cause: 50 years of poor housekeeping in space
  - Derelict stages, deliberate detonation, NaK marbles, "Westford Needles"
- Kessler Syndrome: Collisions create more debris, which create more debris above a certain density where new debris creation overbalances natural attrition
- Collisions forced astronauts to evacuate Station few years ago;
- "Iridum" collision (2/10/09) got everyone's attention
- 20 orbit changes last year;
- New surprises are coming.

What's New since 1957?

- "Kessler Syndrome" critical density has been reached
  - No longer a theoretical event
  - Collisions are overpowering natural attrition
  - Collisional cascade will eventually deny us the use of LEO-MEO space



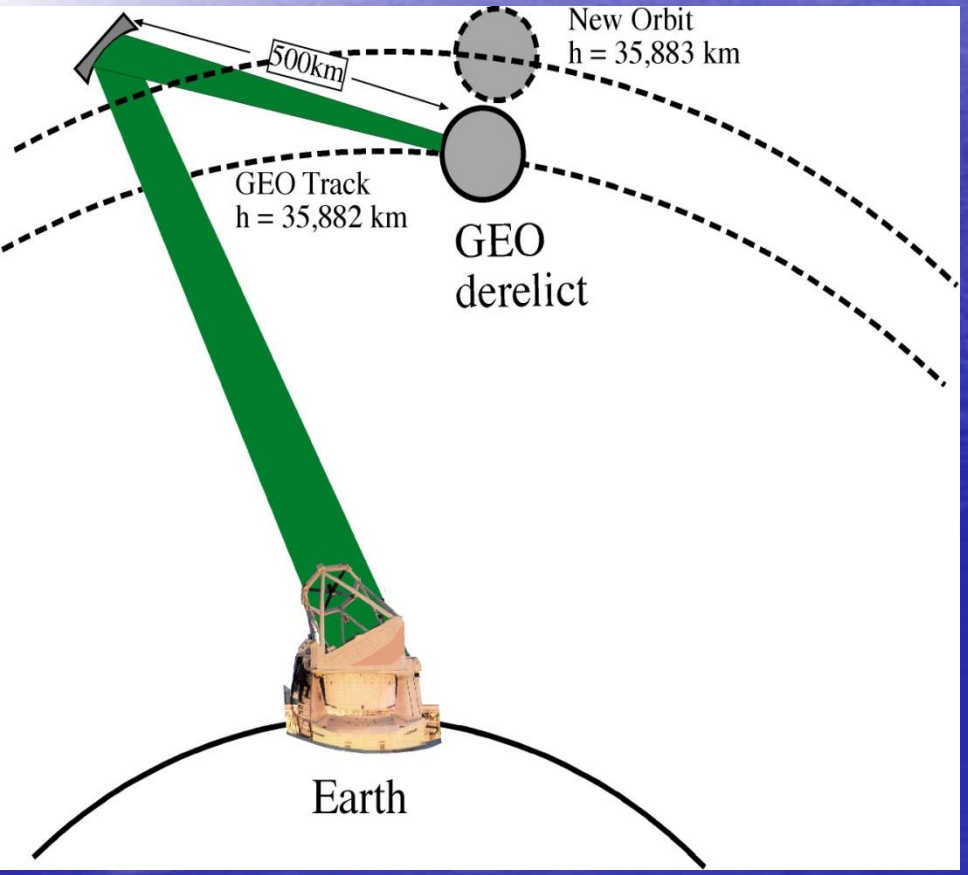
Source: H. Klinkrad, *Space Debris, Models and Risk Analysis*, Springer 2006 p. 158



The Iridium/Cosmos Collision

Credits: AGI

Dual Use: GEO Object Removal



- 8 m relay mirror redirects beam from Earth to derelict

GEO object raised few km

- Required Δv is only 5-10 cm/s
- Mission is accomplished in few sec. with just 500 kW average beam power
  - 100 ns, 3J/pulse, 150kHz
  - Operating fast, we can avoid colliding with another satellite
- Targets are easy to find!
- Dual use for LEO small object ODR system

Elimination of space debris and objects of natural origin by laser radiation

- 1. Repetitively pulsed laser systems with a high repetition rate are an important tool in solving the problem of efficient elimination of space debris and objects of natural origin or their removal to a safer orbit.
- 2. The problem of advance protection from space debris can be solved with the help of ground-based high-frequency repetitively pulsed DF lasers directly irradiating the debris , when the size of the telescope mirror is 30 m. At $t \sim 10$ ns and $f = 10$ kHz the laser system should generate an output no less than ~1.0 MW.
- 3. The problem of protecting the spacecraft from space debris or meteor particles can be most effectively solved with the help of a standalone space-based high-frequency repetitively pulsed solid-state laser system mounted on a spacecraft or near it. When the size of the telescope mirror is about 3 m the average output power of a Nd : YAG laser system lies in the range 100 – 500 kW, depending on the pulse repetition rate and duration.

Useful data for the Earth

1. There are 280 lightning discharges per year in average take place for one km.2 of Earth surface;

2. There are 10 to the 10th . power of thunderbolts per year ,1000 thunderbolts per second take place at the Earth;

3. Power density of solar energy on the orbit of Earth -1.366kW./m2;

4. Total power coming to the atmosphere of the Earth-274 PW;

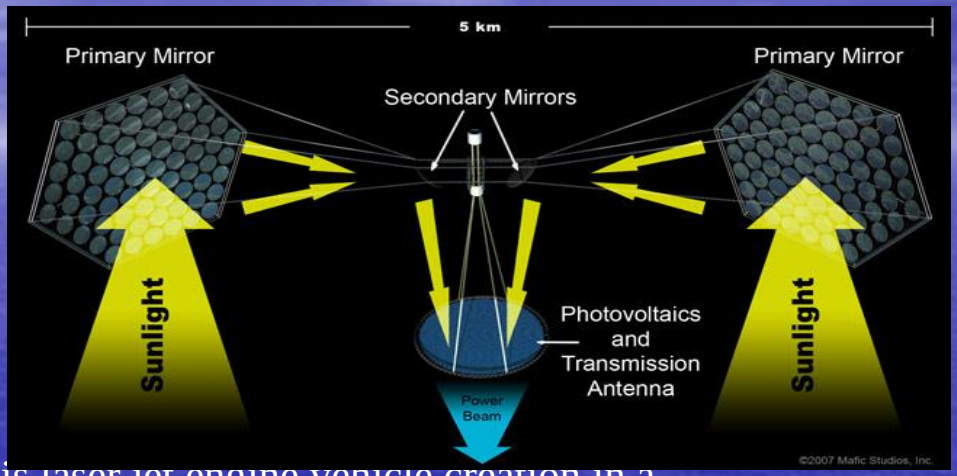
5. Total power in average used by mankind in 2004 -15 TW.
and plan for 2020 - 20TW, which means 4 orders of magnitude less;

6. Sunlight bathes us in far more energy than we could ever need -if we could just catch enough.

No forms of energy is more abundant than the Sun!

"Renaissance of N. Tesla ideas" for the days of high power lasers.

The attempts to create a conductive channels were taken in order to study the upper atmosphere and to settle special tasks, related to the energy transmission. Solar energy delivery to the ground

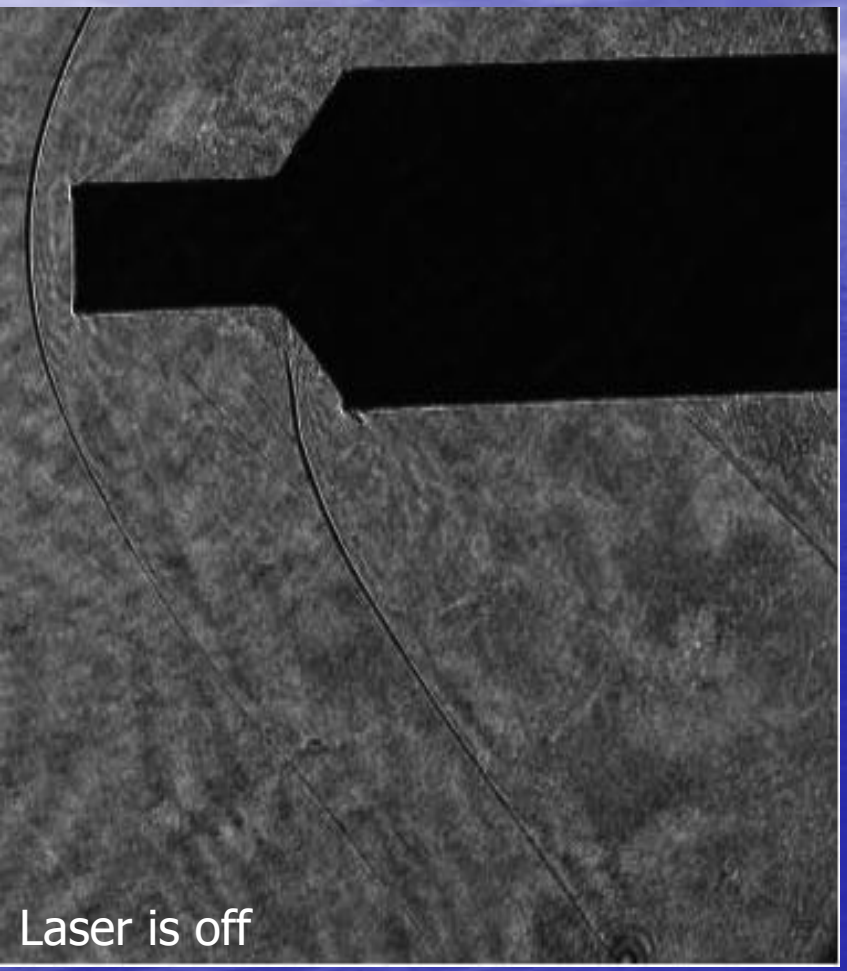


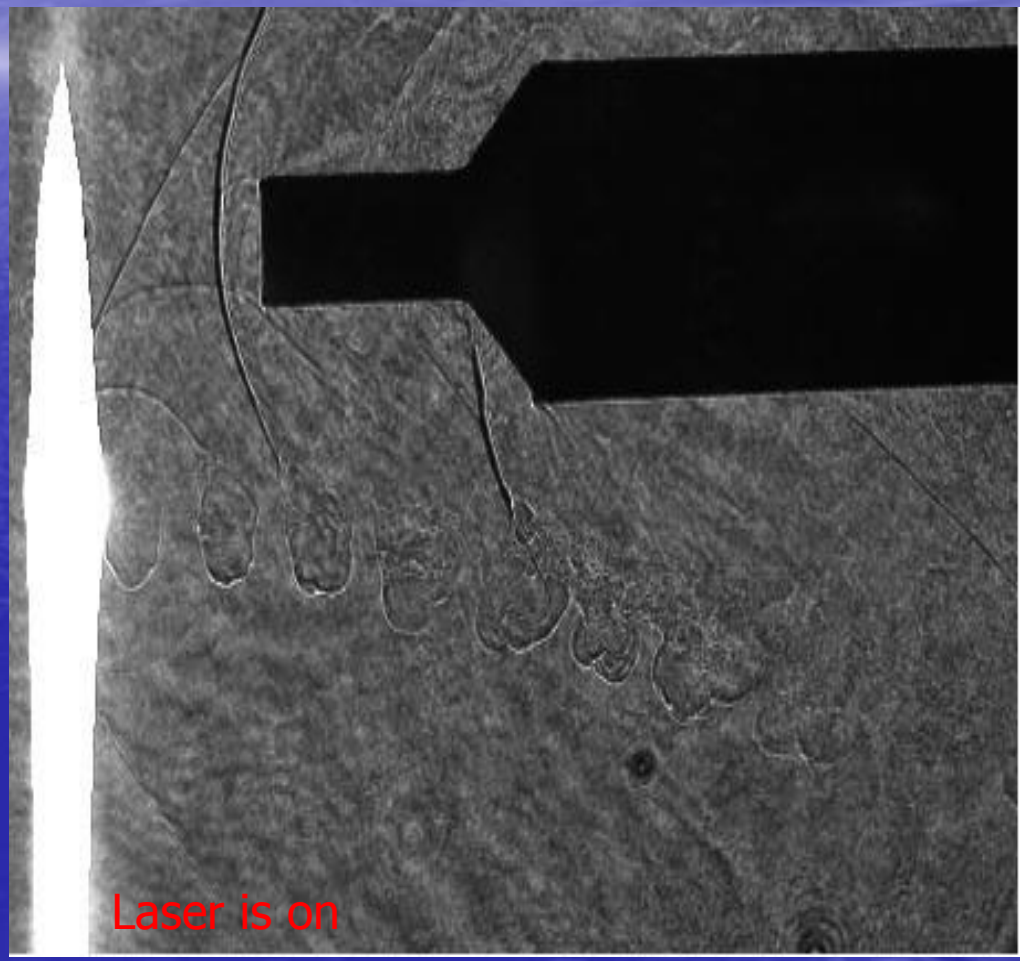
The "Impulsar" program represents an interest, as this laser jet engine vehicle creation in a combination with high-voltage high repetition rate electric source can solve the above mentioned problems.

Vehicle propulsion take place under the influence of powerful high repetition rate pulse-periodic laser radiation. Active impulse appears due to the breakdown of ablated material on the board, placed in the vicinity of the focusing mirror-acceptor of the breakdown waves. With each pulse of powerful laser the vehicle rises up, leaving a dense trace of products with high degree of ionization and metallization by conductive nanoparticles due to the ablation process.

Conductive dust plasma properties investigation in our experiments can be produced on the basis of two approaches: high power laser controlled ablation of materials and by electric explosion of wire.

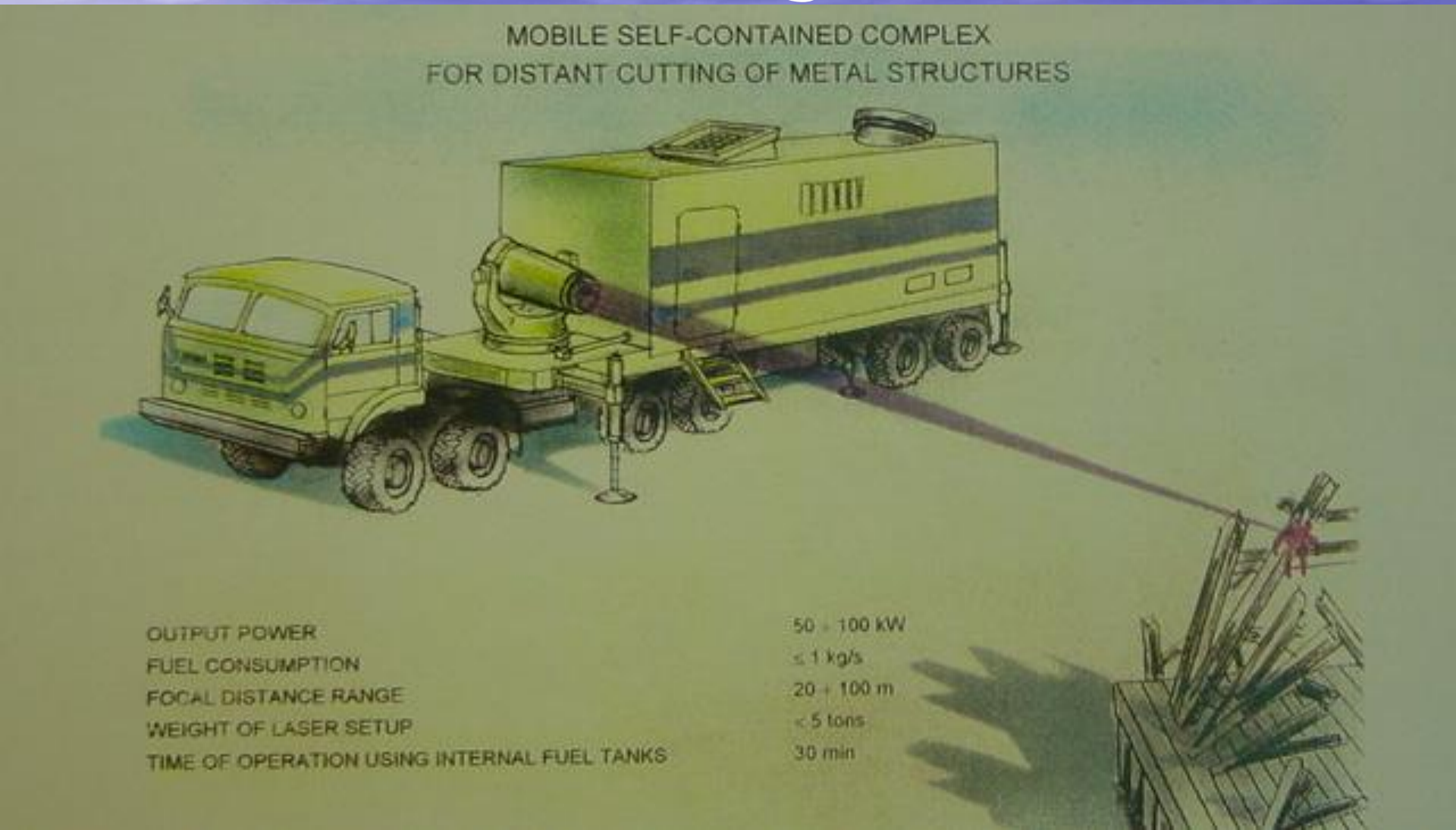
Shock waves suppression





Shock waves are gone due to the plasma balls appearance with rep. rate about 150 kHz, V=1,5M

Distant Cutting of Oil / Gas Wells after Conflagrations

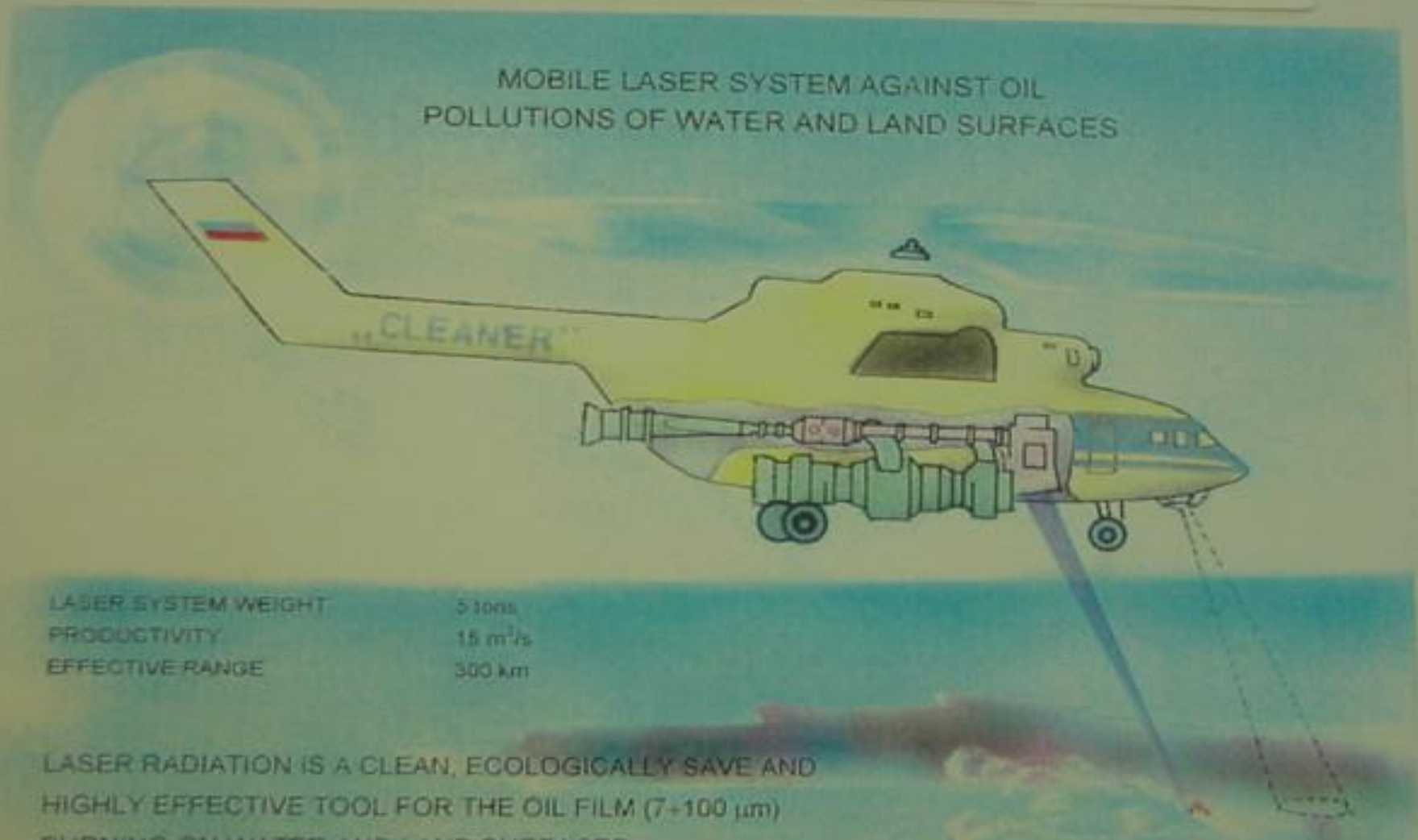


New applications of high power lasers in the Arctic

- In the case of a high-repetition-rate, P-P CO2 laser with an average power of 100 kW, we obtain the following estimates for 10-cm deep cut in ice: the estimate is 30 m/s



Mobile Laser System for Water Surface Cleaning



Experimental oil films elimination by P-P mode of laser operation



Conclusions

1. **Successful development of high rep. rate P-P laser system technology allows to create a super long conductive channels for a long range energy transmission;**

2. **Wide spectrum of high power high rep. rate P-P lasers development and production for scientific and technological purposes is the agenda of our days.**

3. **New innovative applications of high power high rep. rate P-P lasers: cutting of super hard and fragile materials, water and solid surface processing, propulsion by laser, conductive channel, high efficiency interaction, space cleaning, ice breaking, are the agenda of our days.**

4. **The future of high power laser applications with variable temporal structure of radiation is very bright !**