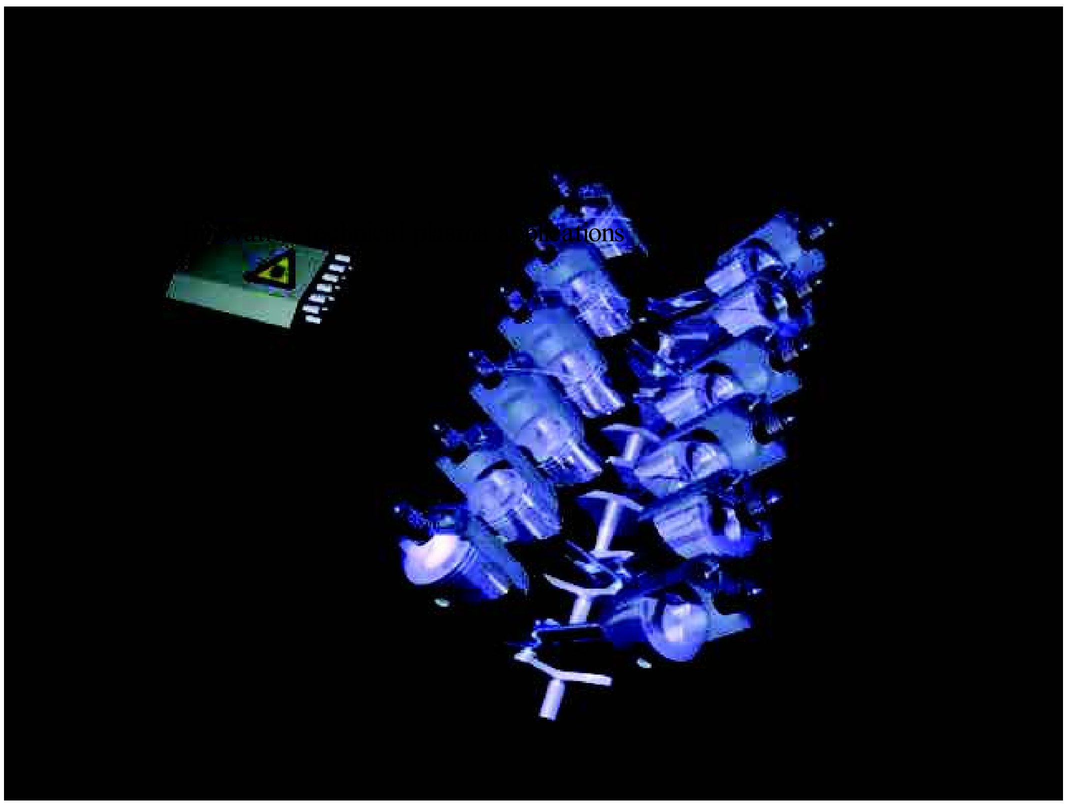
Innovative Technical Plasma Applications:

Laser Ignition of Engines



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Plenary paper
5th Int. Conf. on the Frontiers of Plasma Physics and Technology
Singapore, April 18, 2011

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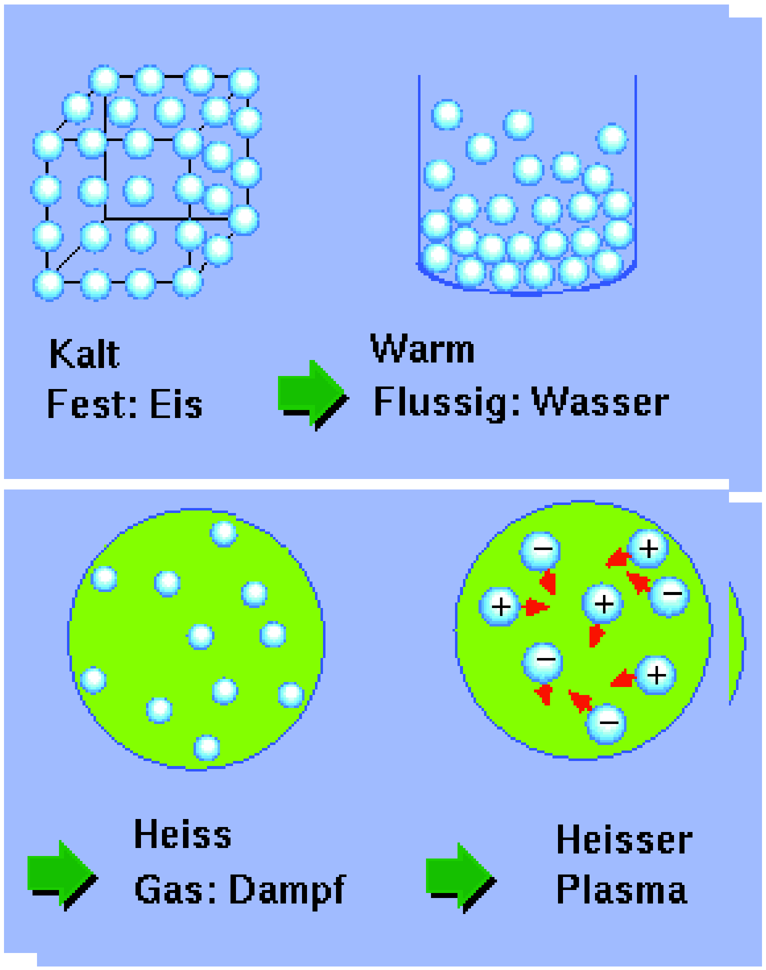
Plasma, the 4th State of Aggregate

Plasma: Greek: the “formed“ stuff



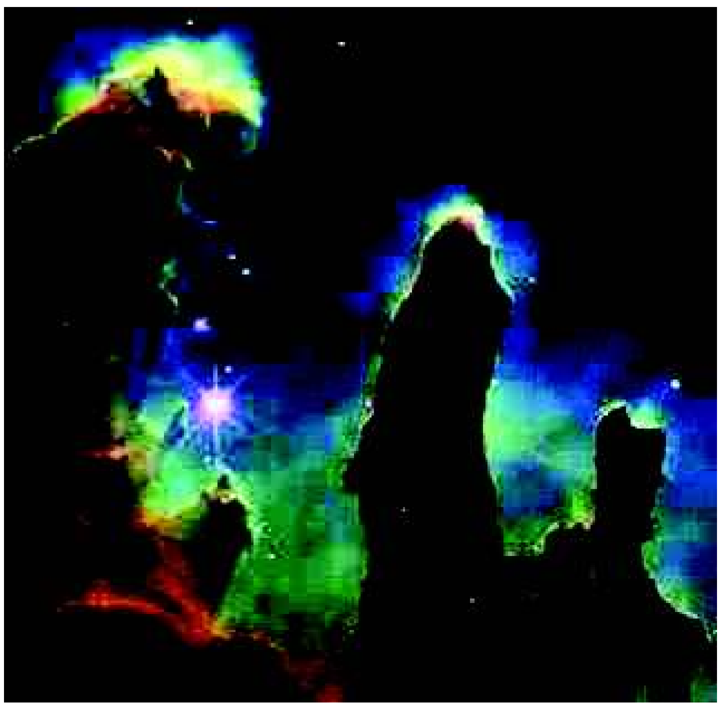
Sir William Crookes described it in 1879 as “radiant matter”, Irving **Langmuir created the name “plasma” in 1928** in some association with blood plasma

- Free electrons and ions
- good electrical conduction
- far reaching interaction
- sometimes high thermal conductivity
- influenced by magnetic fields

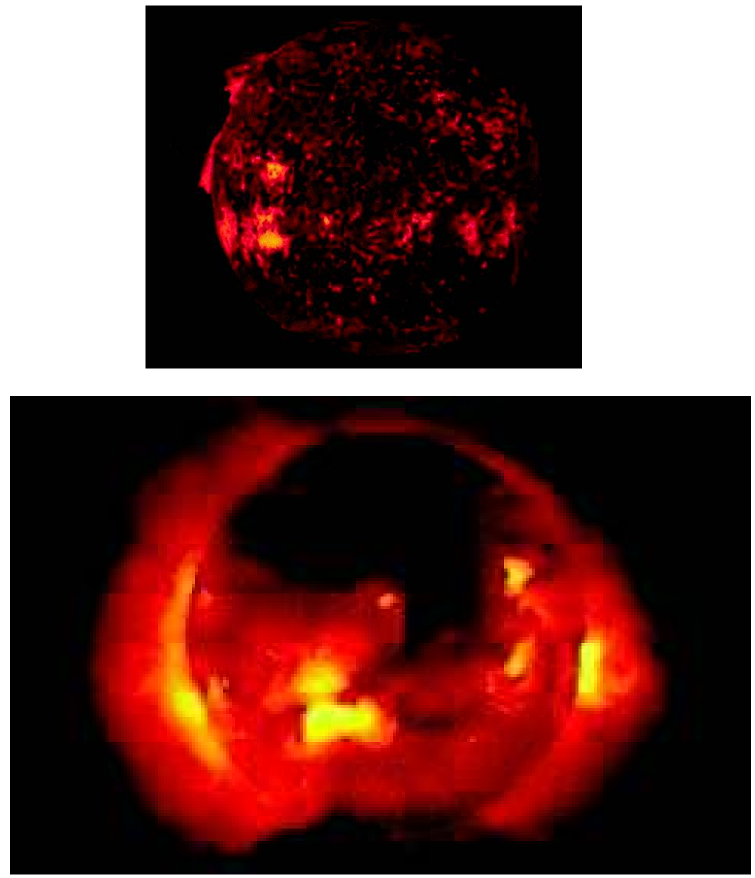
Plasmas in Astrophysics, i.e. the Universe

Ca. 99% of visible matter, i.e. the "normal" state of aggregate

Interior of stars, stellar atmosphere, interstellar plasma

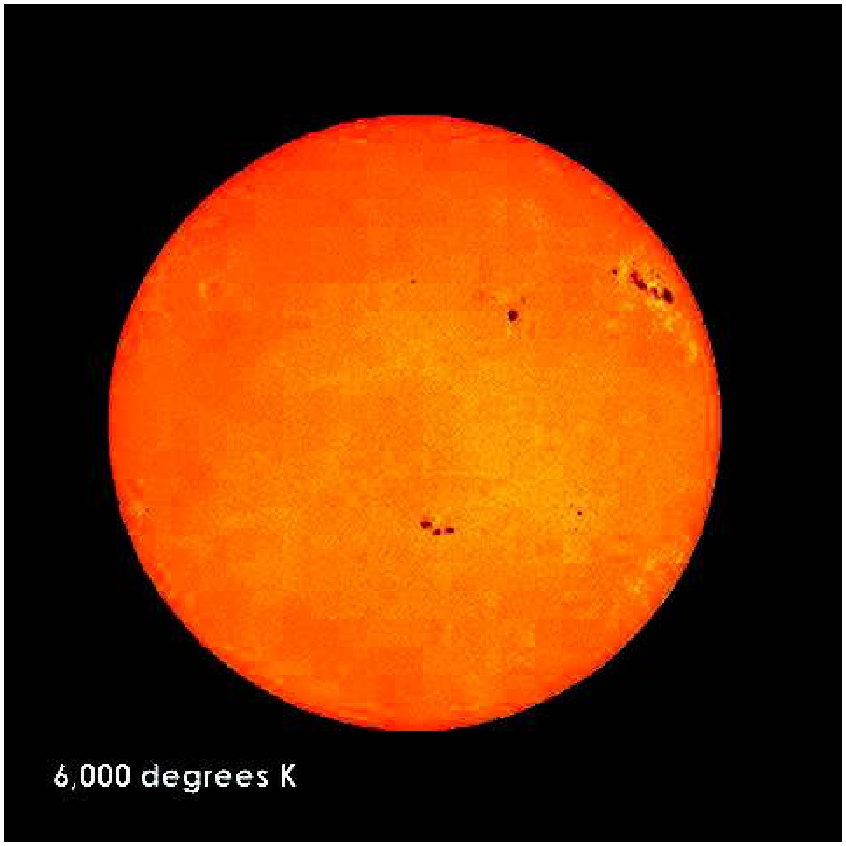


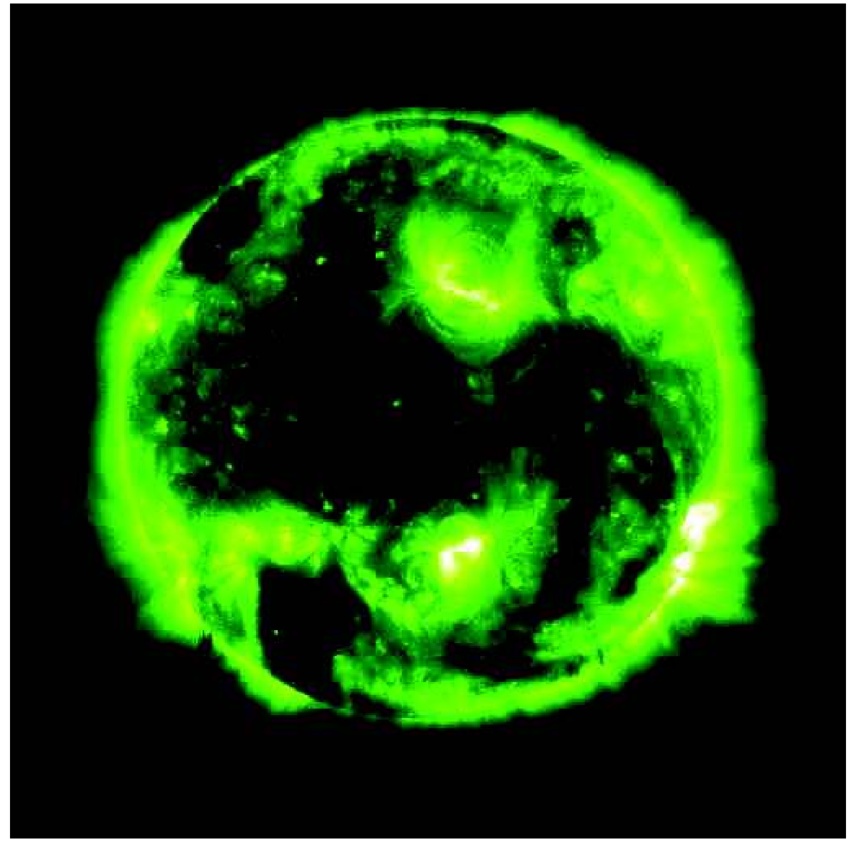
Star formation in the Eagle Nebula



X-ray view of the sun, Yohkoh

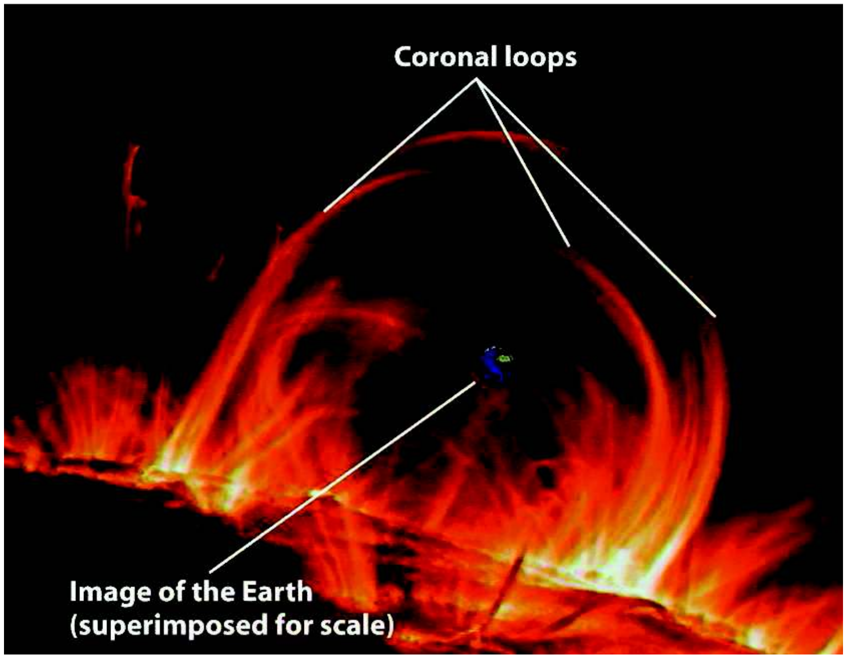
Different Solar Plasmas





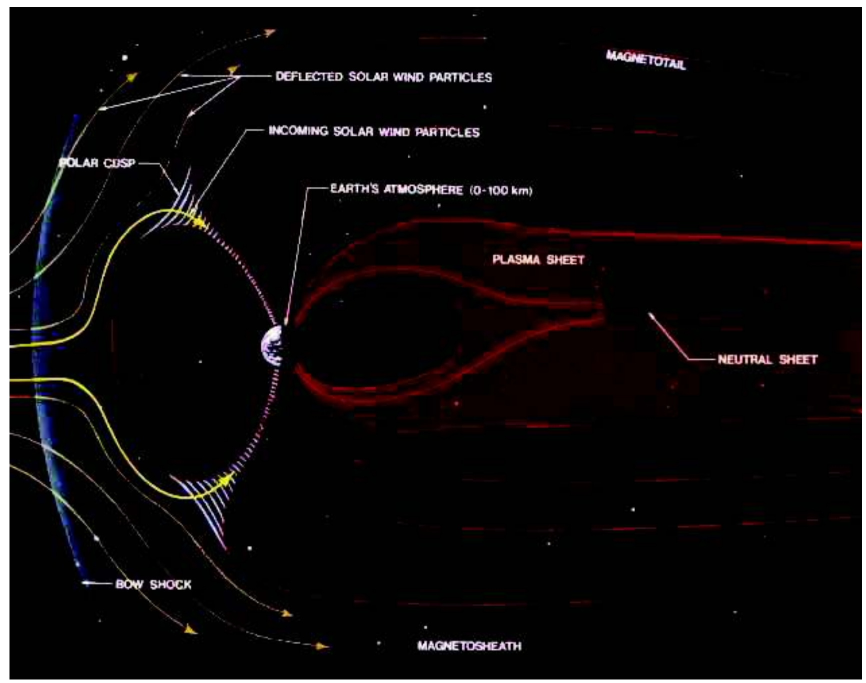
Photosphere: 5 800 K
(300 -400 km thick)

Chromosphere: 10 000 K;
Fraunhofer lines via little
absorption



Plasma in the Vicinity of the Sun

Corona



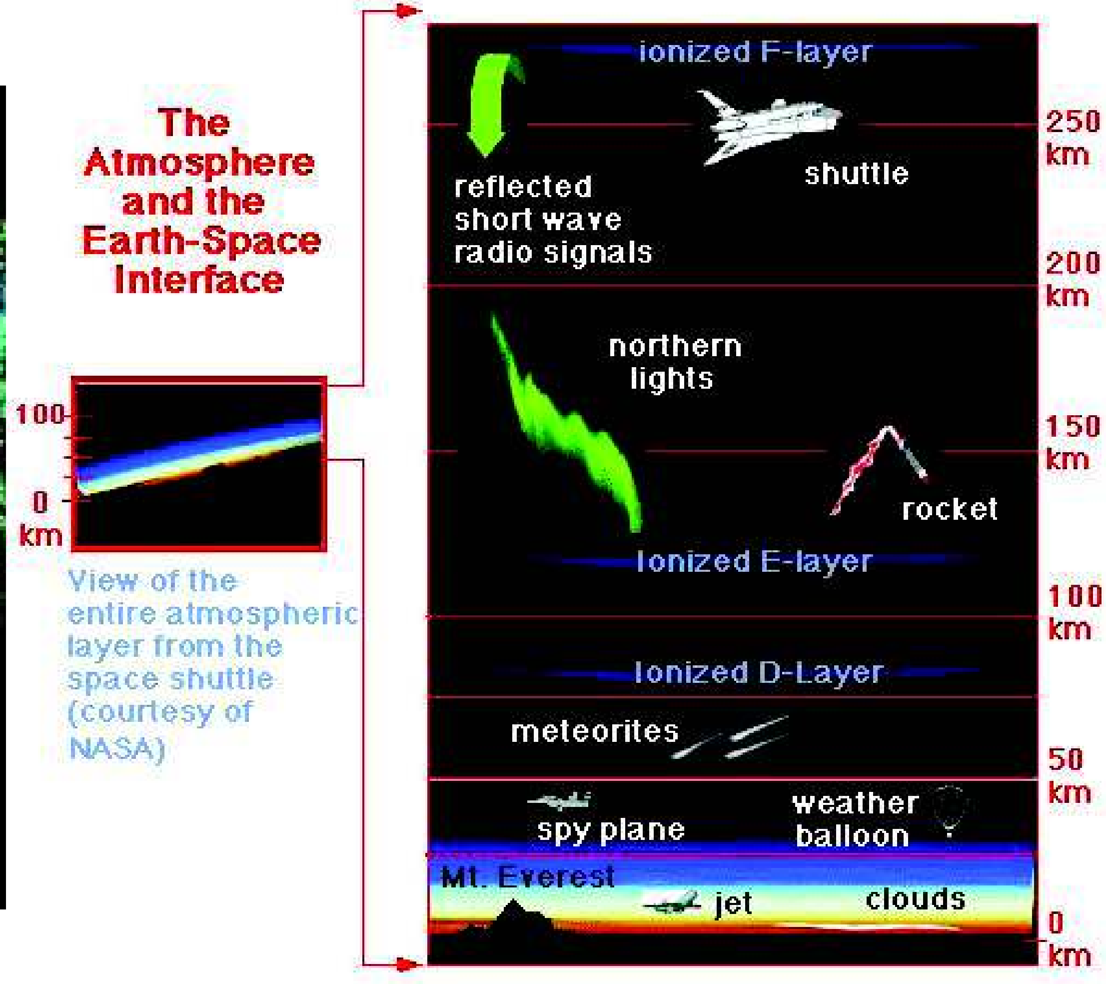
and the Earth

Magnetosphere

Plasmas in Geophysics

Ionosphere, polar light, flashes

Aurora



Plasma Technology

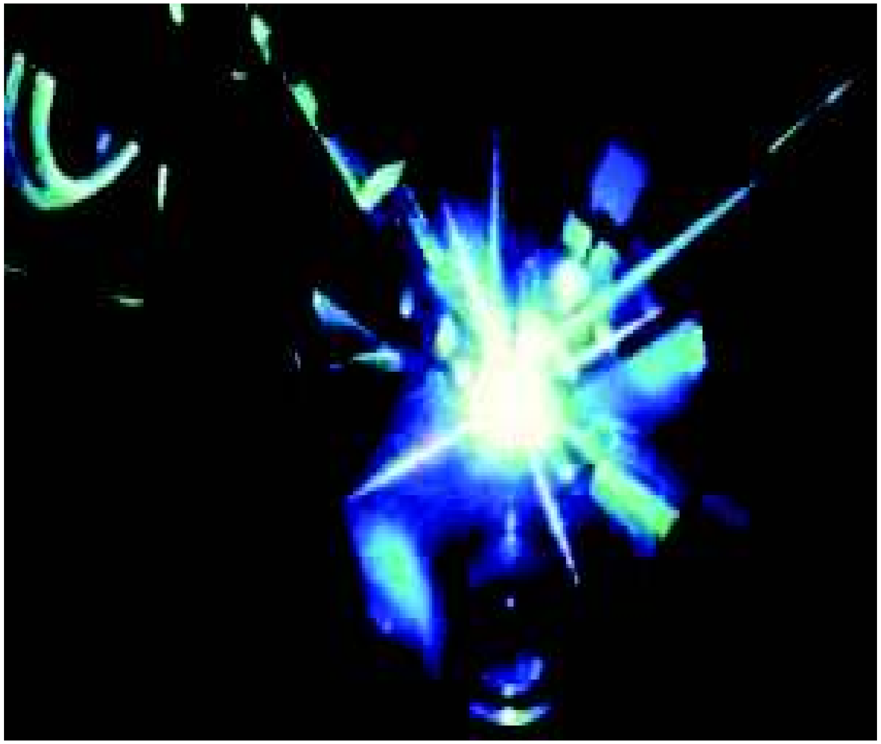
Switching technology, light generation technology (90% of all artificial light), melting furnaces, surface technology, plasma propulsion, future energy generation

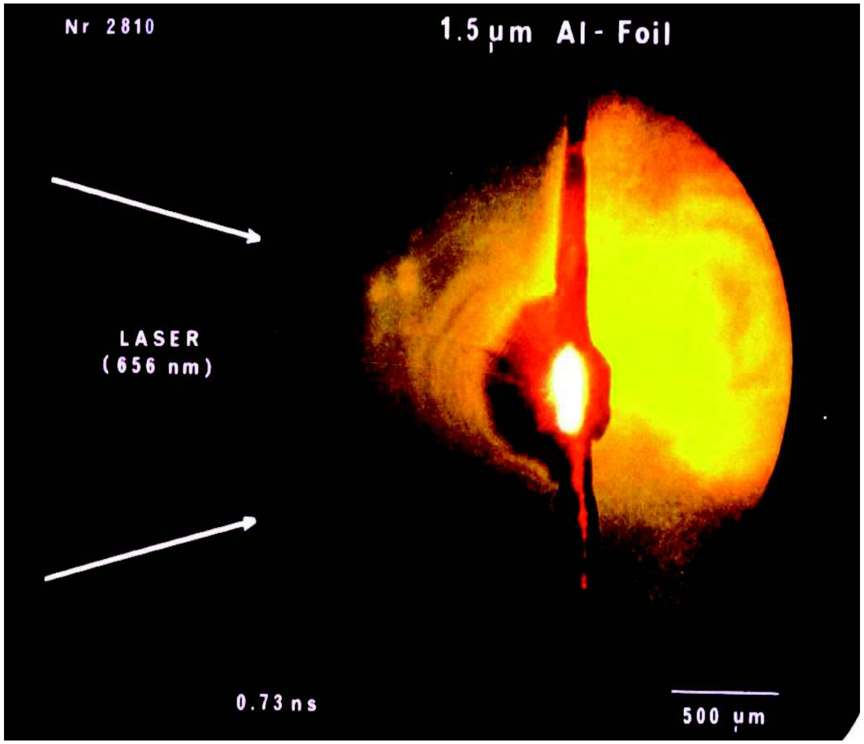
Plasma arc lamp

Plasma spraying

Laser-Generated Plasmas for Materials Processing

Involves short (ns) and ultra-short laser pulses





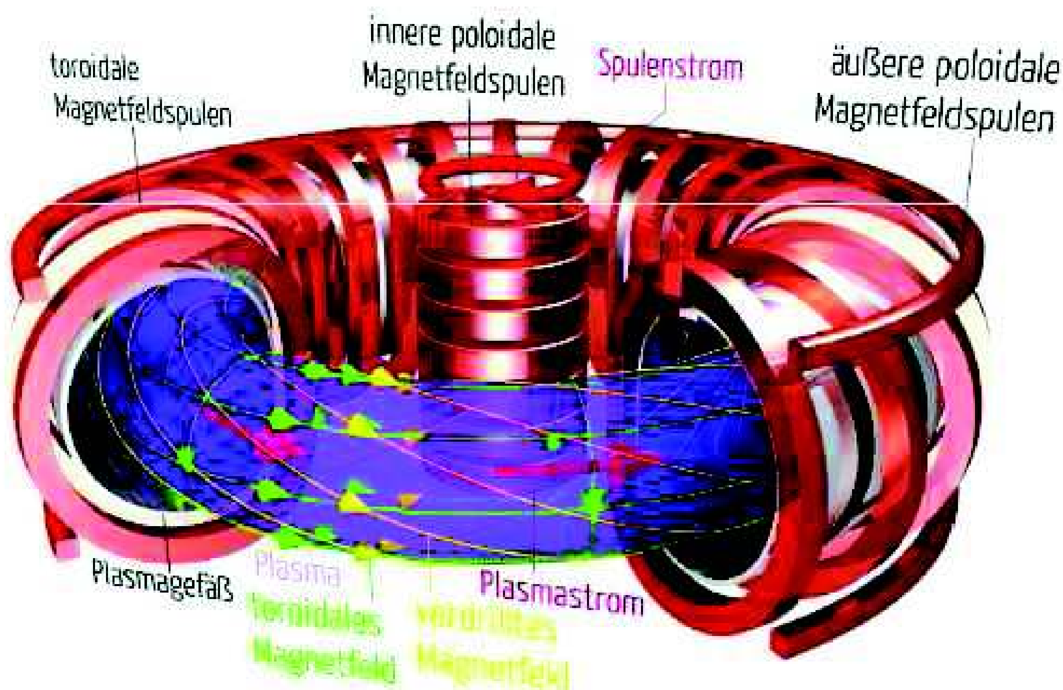
Plasma for Energy Production:
Magnetically Enclosed Plasmas I

Tokamak (1951 Sacharov und Tamm)

тороидальная **ка**мера в **ма**гнитных **к**атушках

(toroidalnaya kamera magnitnaya katishka)

„toroidale Kammer in Magnetspulen“



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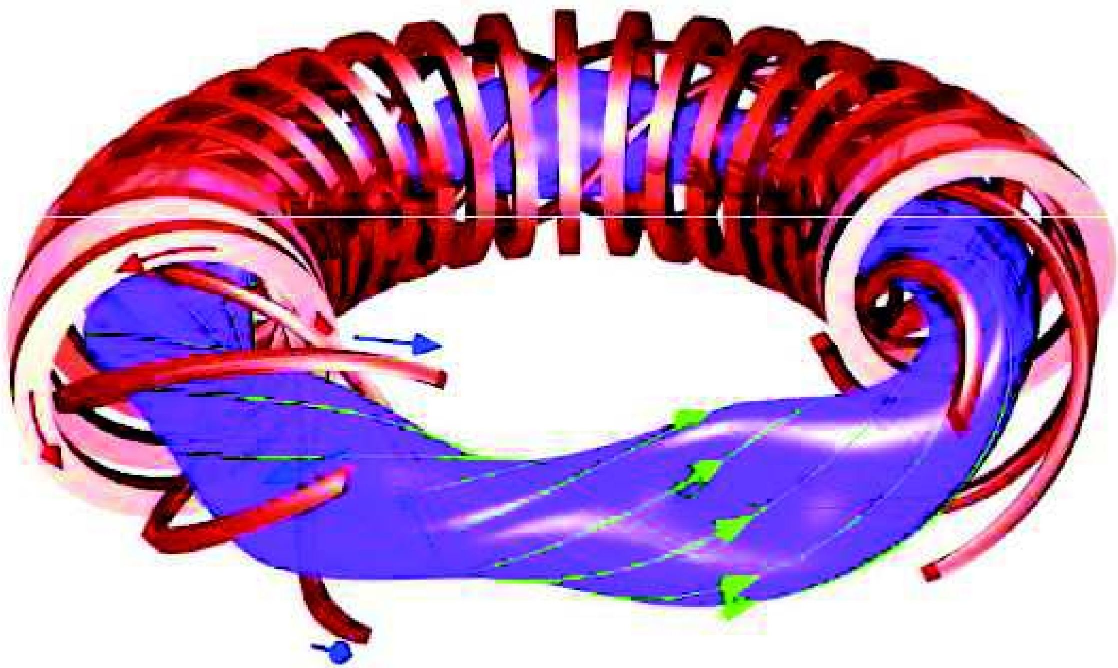
Plasma for Energy Production:
Magnetically Enclosed Plasmas II

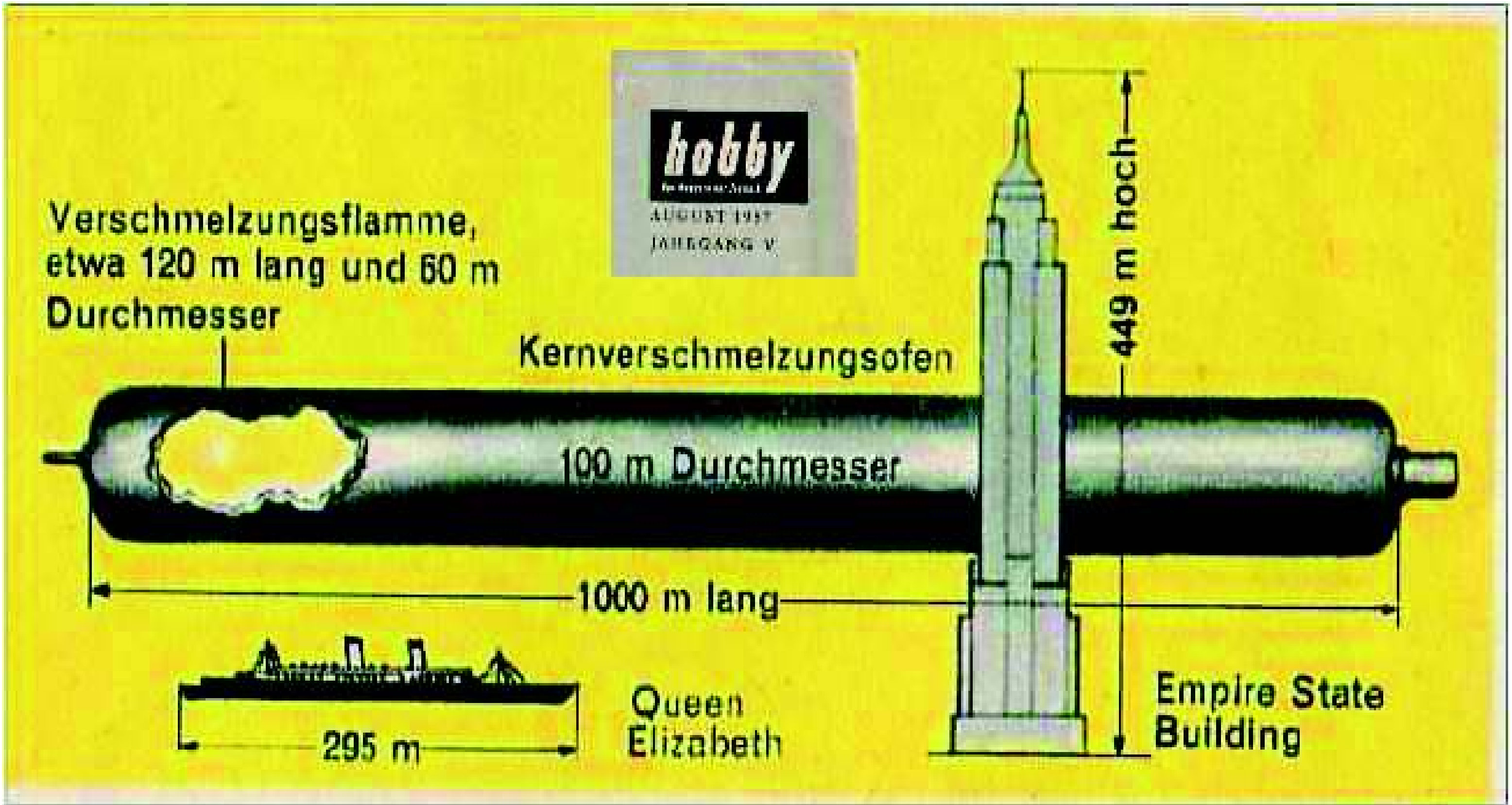
Stellarator (1951 Spitzer)

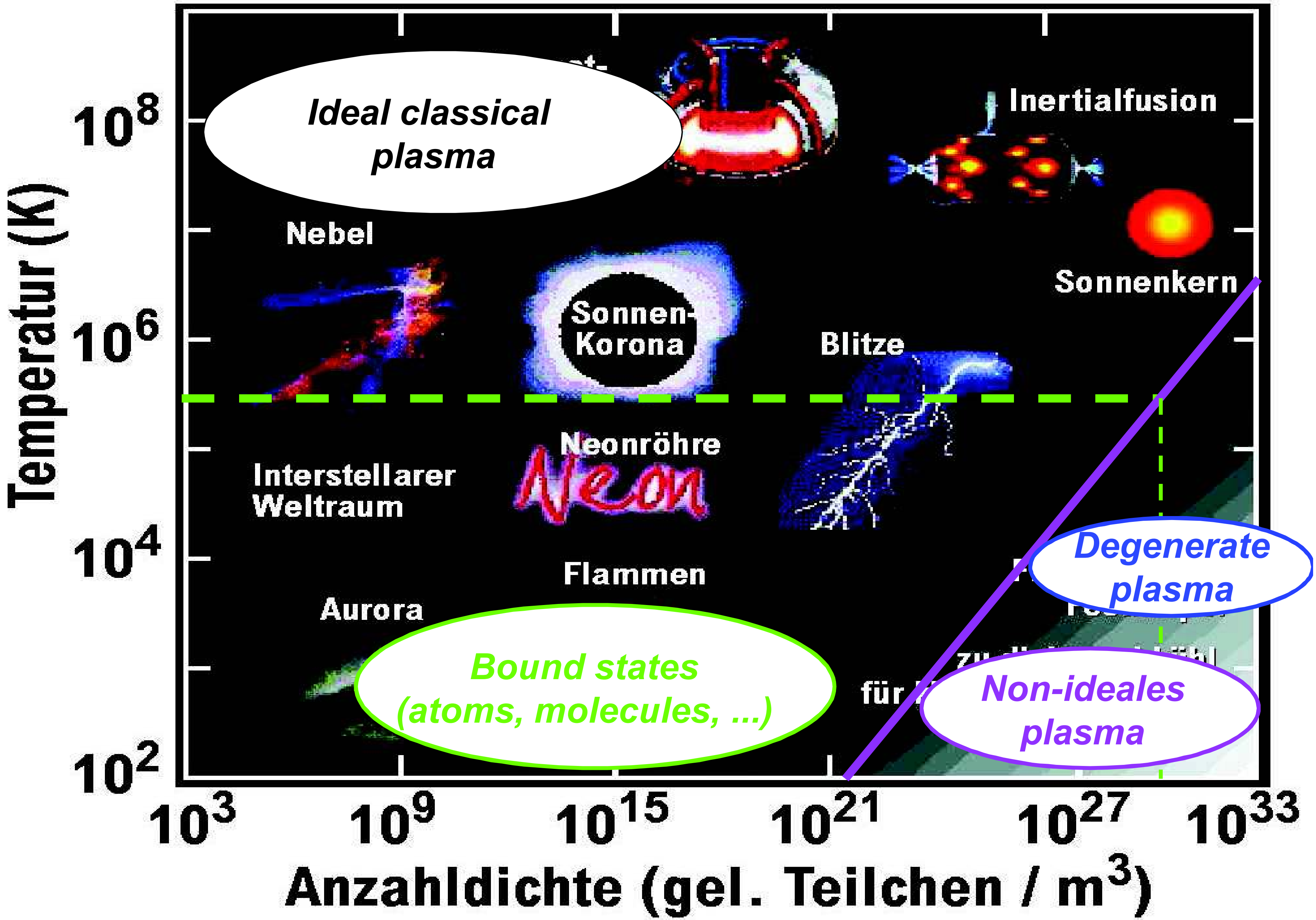
Stella = Der Stern

„der Sternenbringer“



First „Prohibitive" Estimations 1957





Ideal classical plasma
Inertialfusion
Nebel
Sonnenkern
Sonnen-Korona
Blitze
Neonröhre
Neon
Interstellarer Weltraum
Flammen
Aurora
Degenerate plasma
Bound states (atoms, molecules, ...)
Non-ideales plasma
für
Temperatur (K)
10^2
10^4
10^6
10^8
10^3
10^9
10^{15}
10^{21}
10^{27}
10^{33}
Anzahldichte (gel. Teilchen / m^3)

Differentiation of Plasmas

Relativistic Plasma*:*

Very hot electrons $\langle E_e \rangle \gg m_e c^2$ (511 keV)

Thermal Plasma:

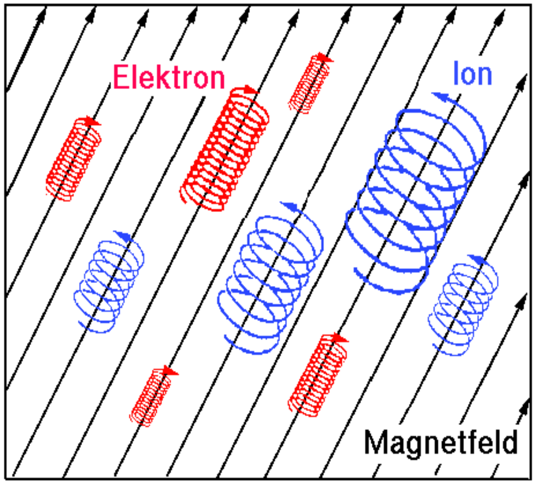
$T_e = T_i$, many collisions

(gen. high density, low temperature)

Magnetized Plasma:

$\omega_c / \nu_{coll} \gg 1$

many gyrations before collision



Characteristic Plasma Parameters

	λ_D	N_D
Fusion plasma (10 keV, $10^{20}m^{-3}$)	75 m	$2{\cdot}10^8$
Technical Micro-plasma (5 eV, $10^{17}m^{-3}$)	50 m	$6{\cdot}10^4$
Astrophysical plasma (1 eV, 10 m^{-3})	75 km	$5{\cdot}10^{11}$
Dense arc plasma (1.5 eV,$10^{24}m^{-3}$)	0.01 m	3 = limit towards non-ideal plasma

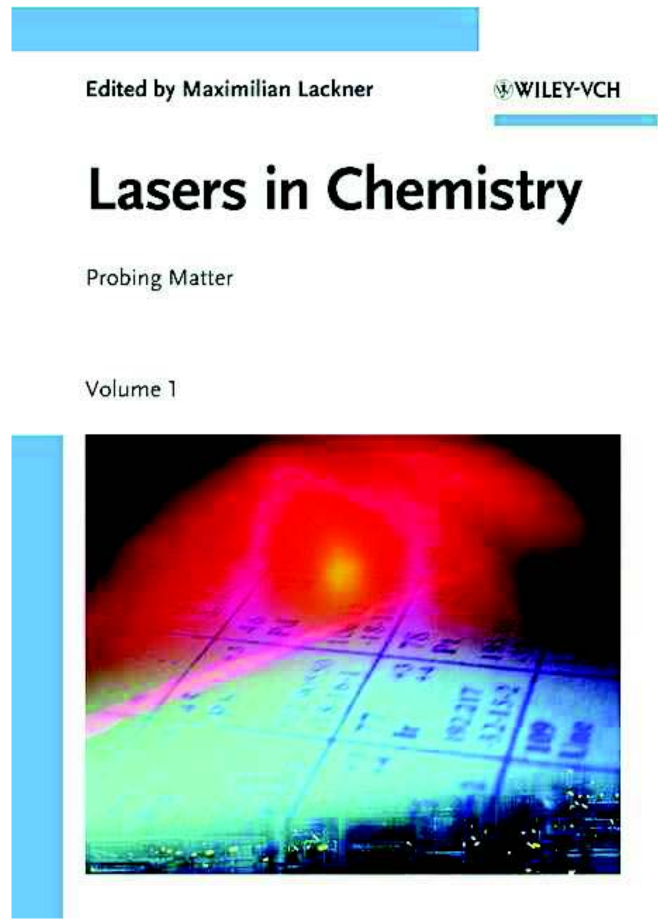
1 eV = 11 600 K bzw. 10 keV ~ 100 Mio^0

Broad Range of Applications of Laser Plasma Initiation of Chemical Processes

Laser-initiated chemical processes

New book:

Lackner, M. (ed.): Lasers in Chemistry. Probing and Influencing Matter (978-3-527-31997-8), 2 volumes



Overview

- Introduction and fields of application
- Fundamentals and principle of laser ignition
- Diagnostics and simulation
- Experiments and realized advantages
- Ignition systems and problems
- Laser sparkplug development
- Engine tests
- Conclusions

Introduction to Laser Ignition

- **Historical**

J.D. Dale, P.R. Smy, R.M. Clements: *Laser ignited internal combustion engine – an experimental study*; SAE Congress, paper 780329, Detroit (1978) by CO_2 laser!

- **Our objectives until 2010**

Reliable and efficient ignition with clean exhaust of

gas engines

(lean burn internal combustion engines)

automotive engines

(in direct gasoline injection mode or HCCI mode - homogeneous charge compression ignition)

Other Developers in the World

ARGONNE NATIONAL LABORATORY

Southwest Research Institute

NETL — THE ONLY U.S. NATIONAL LABORATORY DEVOTED TO FOSSIL ENERGY TECHNOLOGY

Colorado State University

DENSO

BOSCH

Ford

BMW

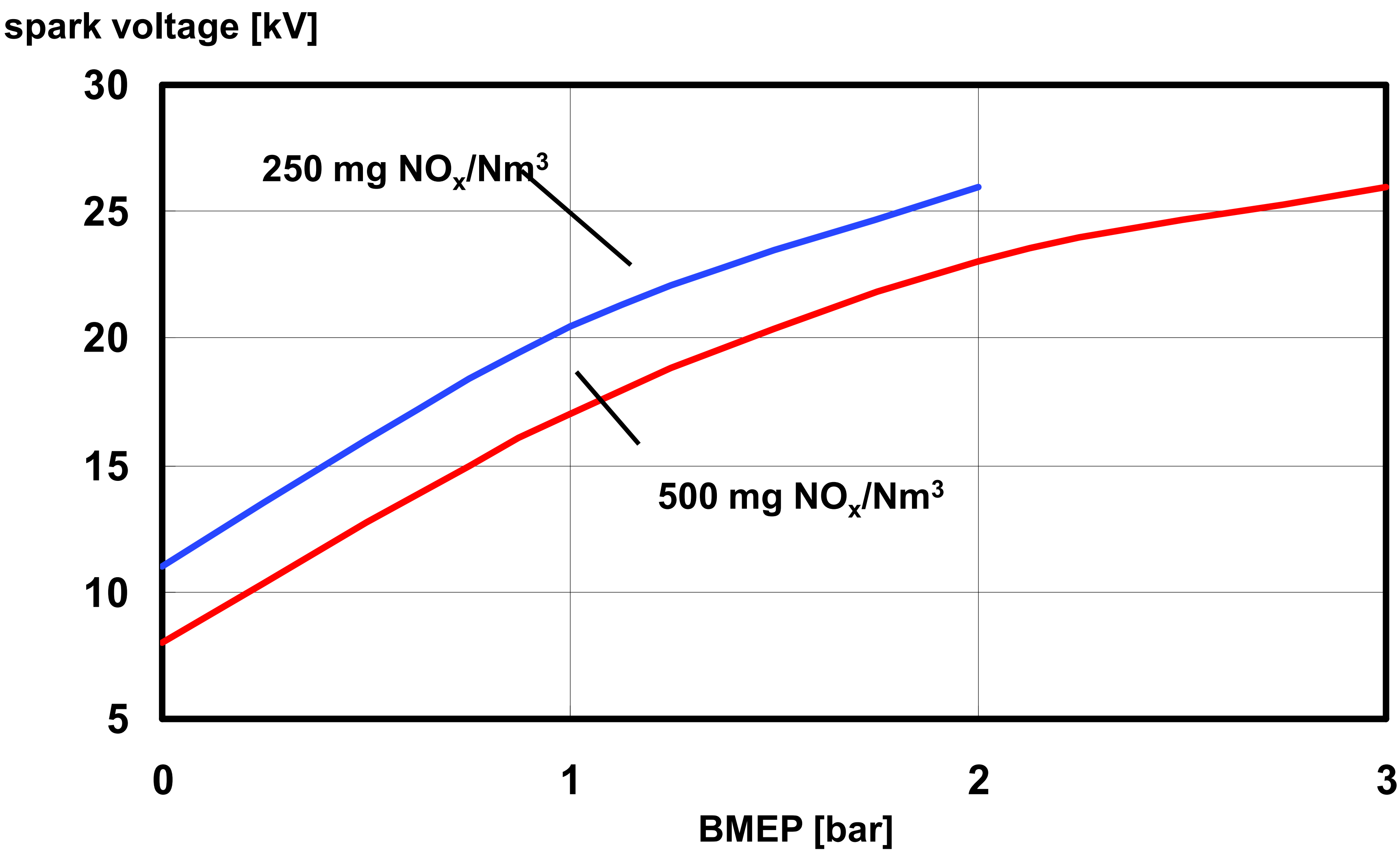
Daimler

Toyota

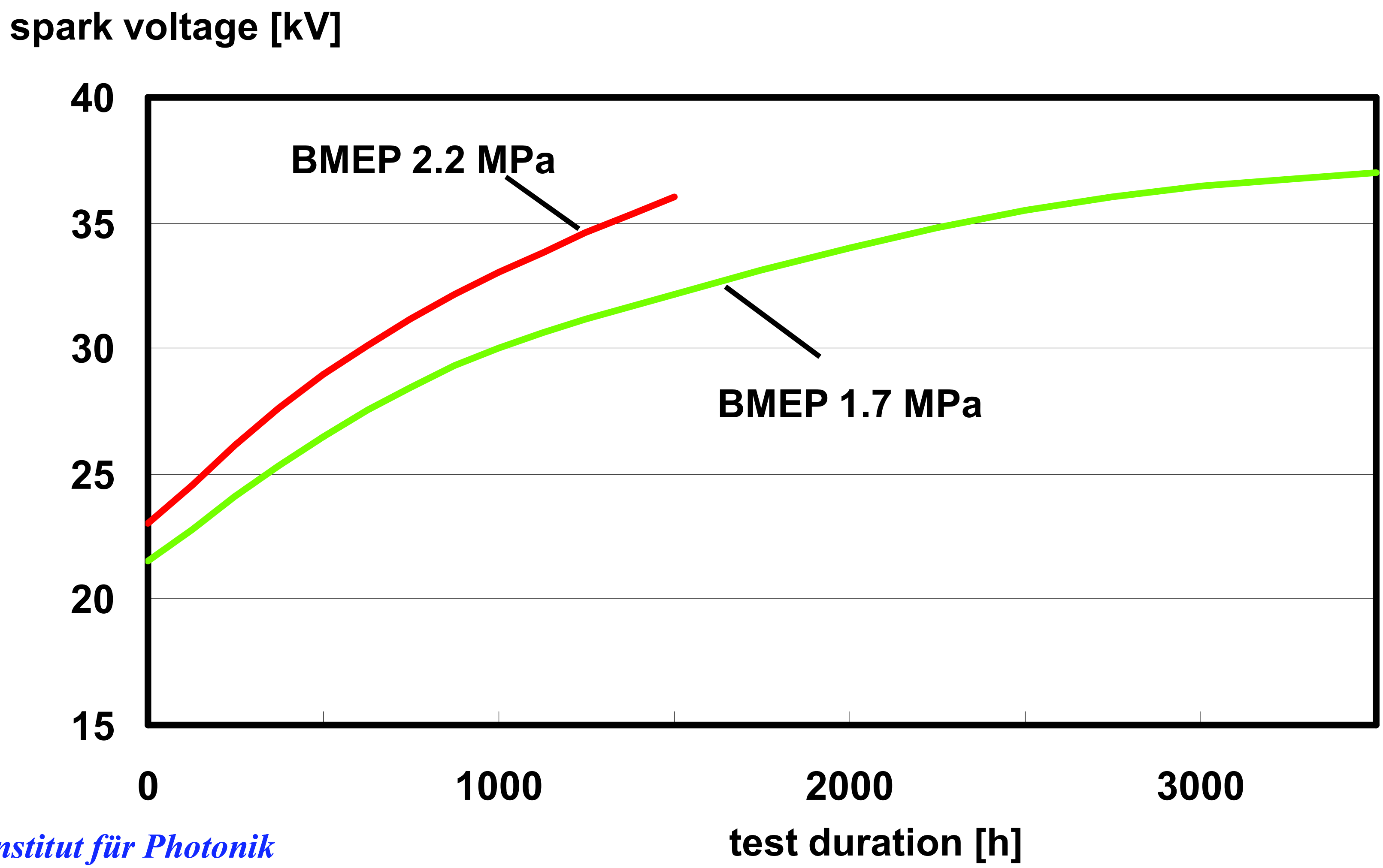
AVL

Megawatt Gas Engine

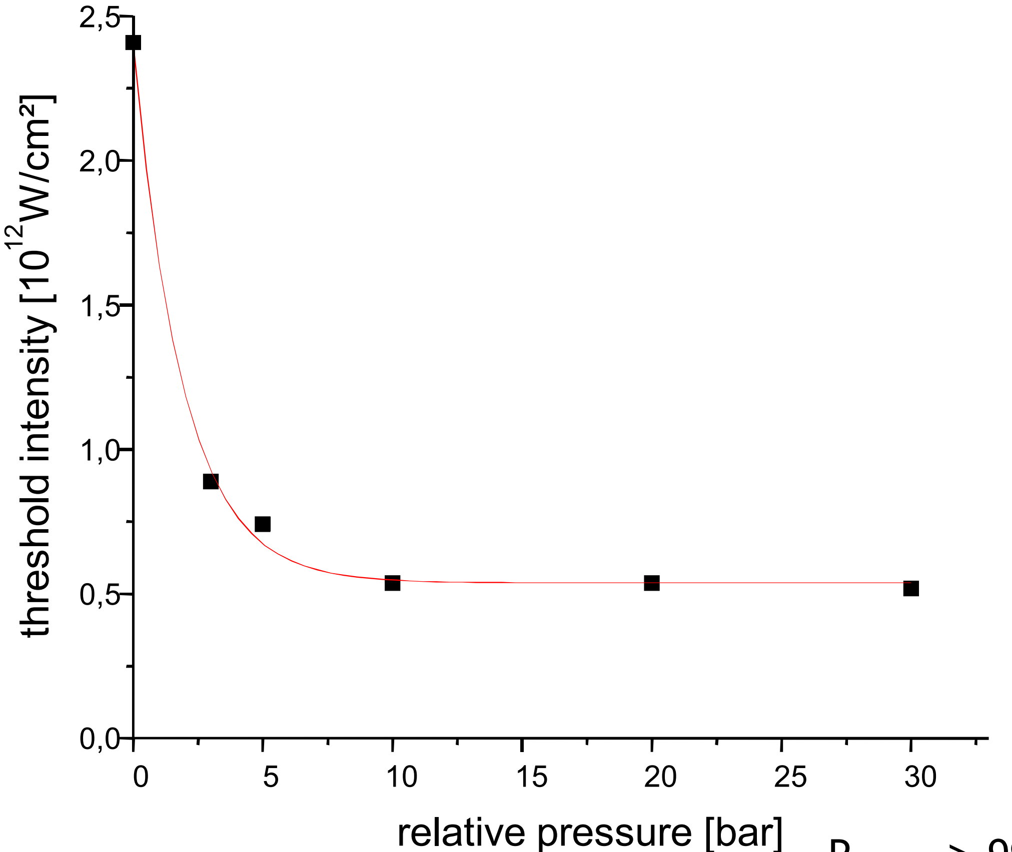
Spark Voltage vs BMEP



Increase of Spark Voltage
Comparison BMEP 2.2 / 1.7 MPa



Focus Intensity for Plasma Formation vs. Pressure



P_{plasma} > 99%, T = 293 K, air

Potential Future Engine Ignition Systems

- Plasma Ignition
- High Frequency Ignition
- Auto Ignition
- Laser Ignition
- Pressure Wave Ignition
- Diesel Pilot Ignition
- ... Corona Ignition

1^{st} Application: Gas Engine

Production of electricity and heat

→ overall efficiency up to 90 %

- High ignition pressures

→ limited lifetime of the spark plug through electrode erosion

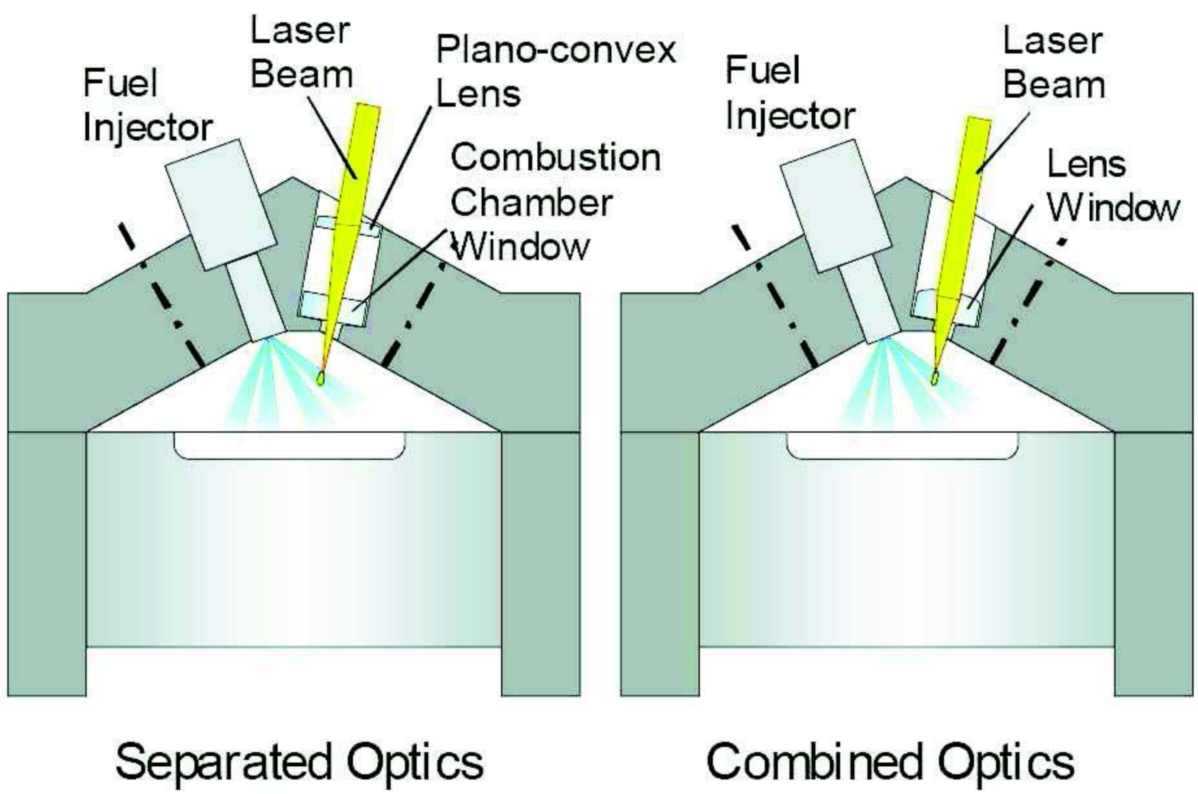
- Lean mixtures
- High costs of the ignition system

GE Jenbacher

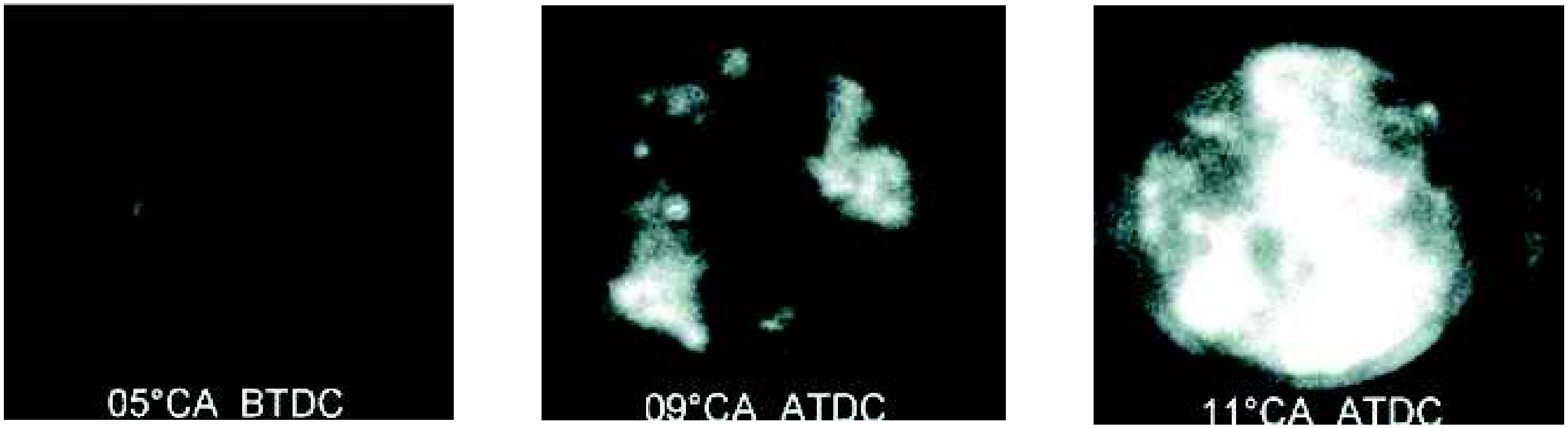
2nd Application: Spray-guided Combustion

Direct injection auto-motive engines:

reliable ignition at all load conditions



3^{rd} Application: Laser-initiated HCCI



Chemiluminescence pictures @ λ_{em} = 308 nm
80 % isooctane and 20 % n-heptane, λ = 2.8
image size: 14 x 14 cm; λ = 2.8
ignition time: -25° CA BTDC

To be realized by laser plasma ignition or resonant laser ignition
In Germany: Dies-Otto Engine

4th Application: Laser Ignition of Rocket Engines

Especially for **positioning** of space crafts

Advantages: avoiding of poisonous self-igniting fuels;

Light weight also in case of redundant installation; long lifetime, multiplexing option

To be realized by plasma or resonant ignition

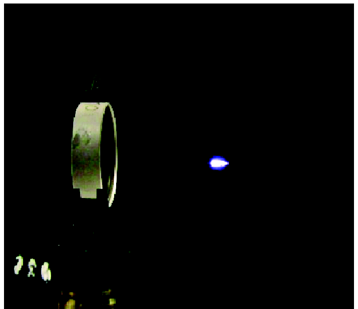
Foto: Falcon I von SpaceX

5^{th} Application: Laser ignition of turbines in jet airplanes

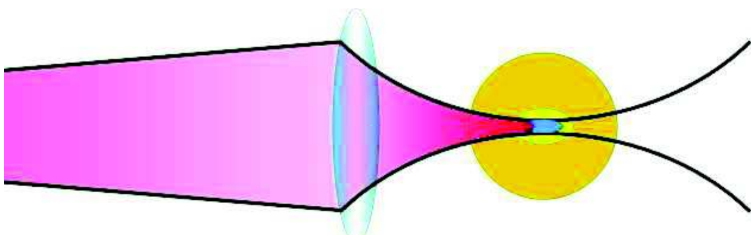
The turbines can be re-ignited repetitively after extinguishing;
potential advantage: free positioning of the spark, no quenching of the ignition

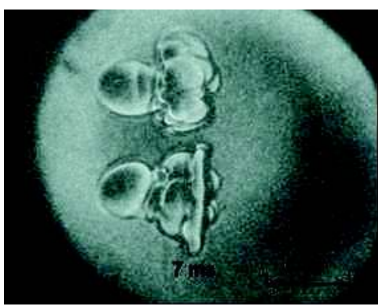
To be realized by laser plasma or resonant ignition

Principle of Laser Plasma Ignition



Lens





focused laser beam

↓

plasma
$I > I_{thr}$

↓

flame kernel
$MPE > E_{thr}$

↓

start of combustion

Plasma threshold mainly determined by pressure (~100 GW/cm^2)

Pressure, temperature, mixing ratio and turbulence determine the minimum required laser pulse energy

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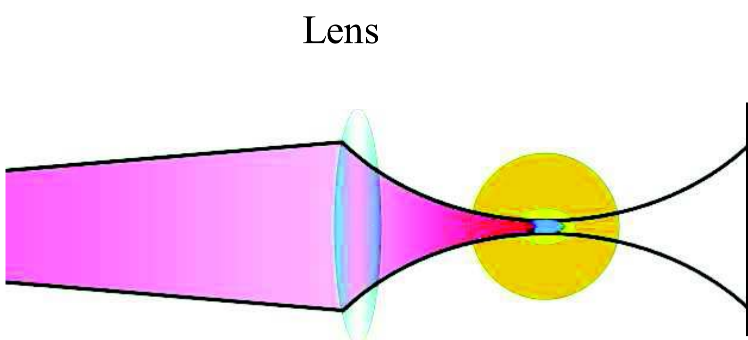
Principle of Resonant Laser Ignition

focussed laser beam

↓



flame kernel
MPE > E_{thr}

↓

start of combustion

Focal geometry, absorption, pressure, temperature, mixing ratio and turbulence determine the minimum required laser pulse energy

No ns pulses required!

Basic Research Involved (I)

Laser development

- *"Experimental Development of a Monolithic Passively Q-Switched Diode-pumped Nd:YAG Laser,* H. Kofler, E. Schwarz and E. Wintner, Eur. Phys. J. D **58**, 209-218 (2010).

Fiber optics

- *"Transportation of Megawatt Millijoule Laser Pulses via Optical Fiber?",* J. Tauer, H. Kofler, E. Schwarz, and E. Wintner, Centr. Eur. J. Phys. **8**(2), 242-248 (2010).

Applied plasma physics

- *"Laser-Induced Optical Breakdown Applied for Laser Spark Ignition",* E. Schwarz, S. Gross, B. Fischer, I. Muri, J. Tauer, H. Kofler, and E. Wintner, Laser & Particle Beams **28**, 109-119 (2010).

Plasma threshold simulation (wavelength dependance)

"Simulation of optical breakdown in gaseous N_2", G. Tartar , H. Ranner , F. Winter , and E. Wintner, Laser & Particle Beams **26**, 567-573 (2008).

Basic Research Involved (II)

- **Diagnostics**

  "Investigation of the Early Stages in Laser-induced Ignition by Schlieren Photography and Laser-induced Fluorescence Spectroscopy", M. Lackner, S. Charareh, F. Winter, K. F. Iskra, D. Rüdisser, T. Neger, H. Kopecek, E. Wintner; Optics Express, **12**, 4546-4557 (2004).
- "*Optical Diagnostics of Laser-induced and Spark Plug-assisted HCCI Combustion*"; M. Weinrotter, E. Wintner, K. Iskra, T. Neger, J. Olofsson, H. Seyfried, M. Lackner, F. Winter, A. Vressner, A. Hultqvist ;
  SAE Technical Paper Series, **1963**,129-140 (2005).

Effects Leading to Non-resonant Breakdown

- Electron cascade growth

↓

needs initial electrons

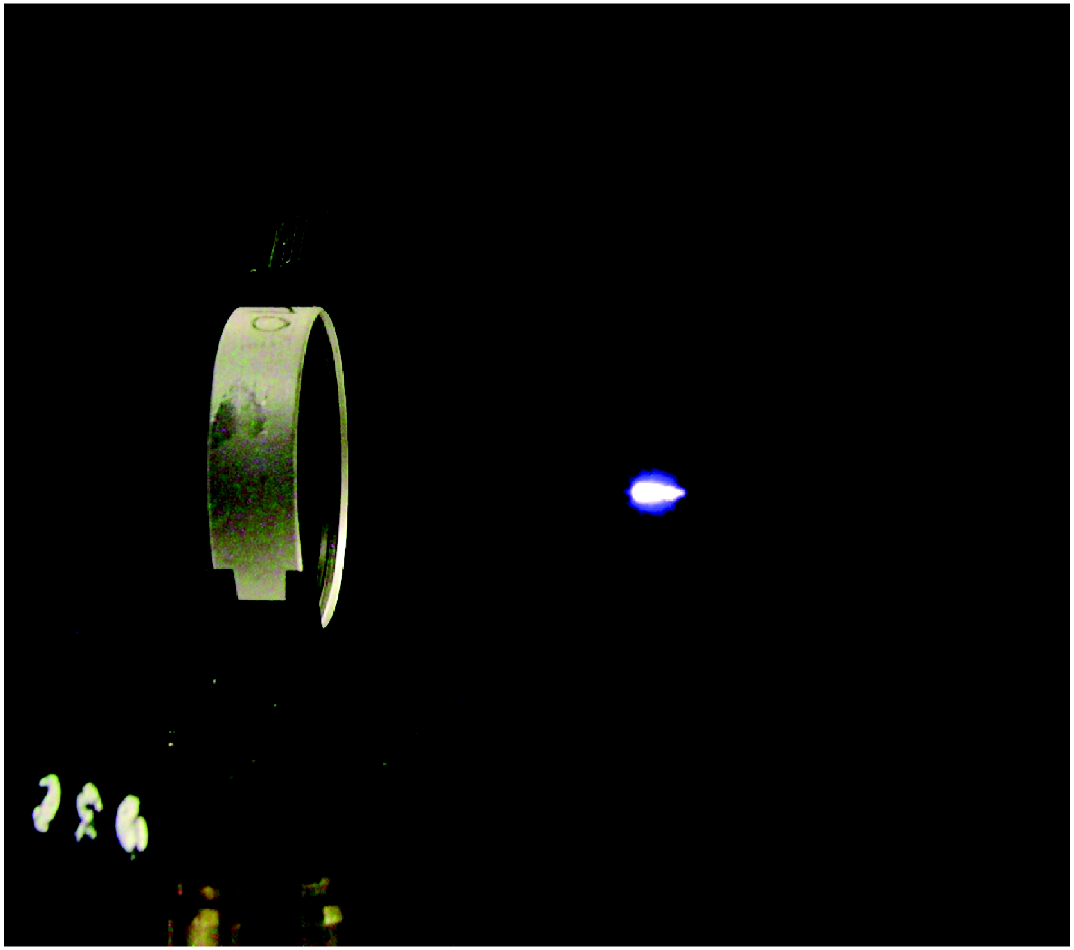
↓ ↓

- multiphoton ionization
- electron tunnelling

(relevant only at intensities higher than 10^{14} W/cm^2)

laser energy absorption by impurities in the gas

Plasma Spark in Air



Simulation of Plasma Breakthrough

Spatial and Temporal Development of Laser-induced Plasma

Comparing UV emission at 2 pulse energies:
left at plasma threshold and
right far above

K. Iskra et al.

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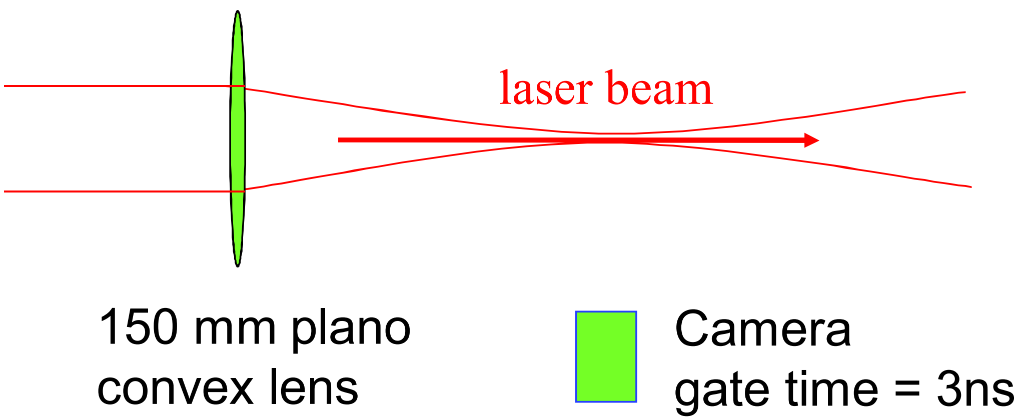
Experimental Setup

Measurement of plasma light emission at 310 nm

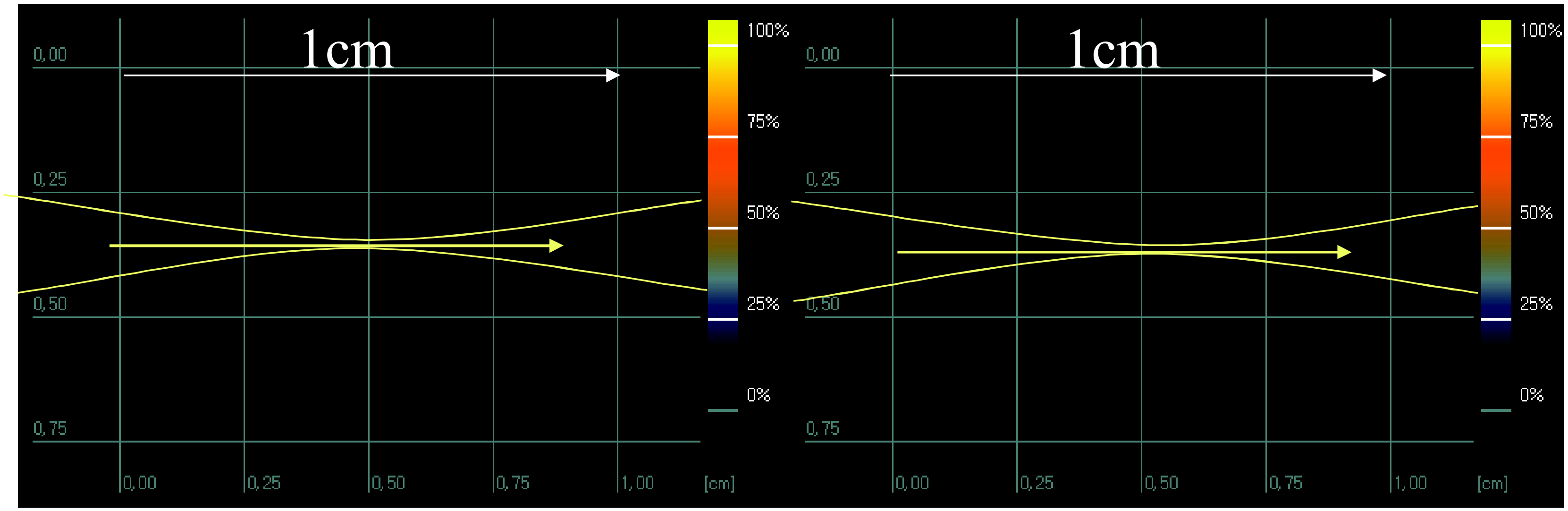


Unseeded Nd:YAG-Laser: 1064 nm, 12 ns, flat top spatial profile

air, atmospheric pressure

0 ns after rising edge of laser pulse

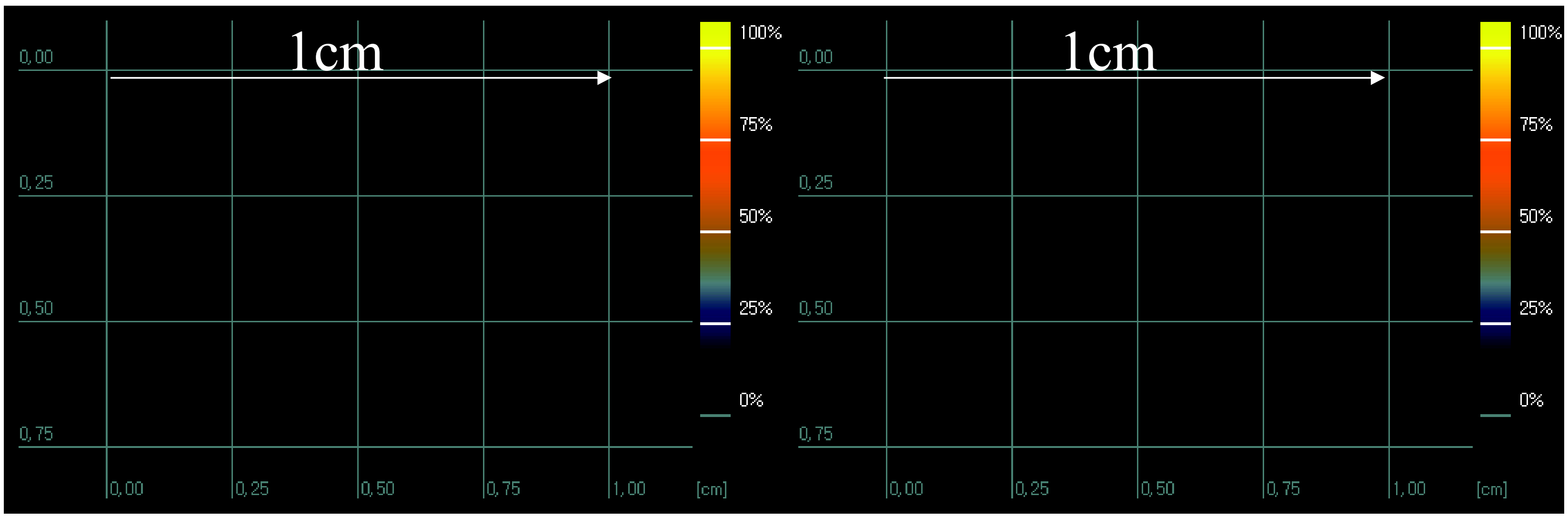
pulse energy = 47 mJ | pulse energy = 235 mJ



20 ns after rising edge of laser pulse

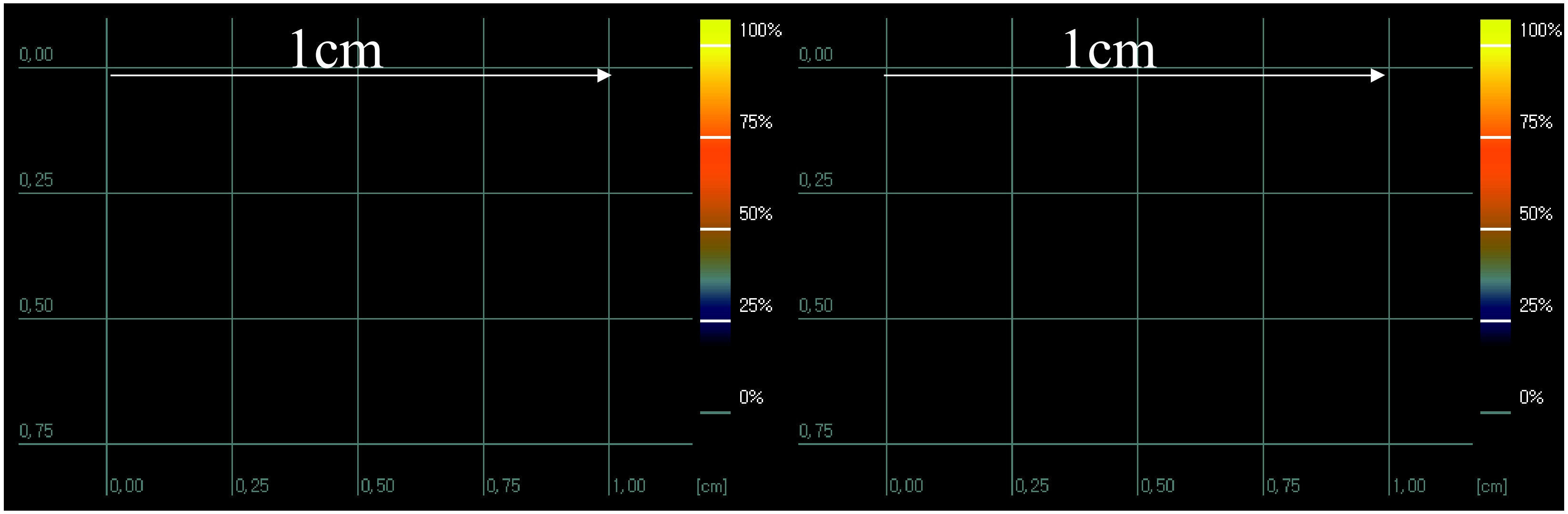
pulse energy = 47 mJ

pulse energy = 235 mJ



40 ns after rising edge of laser pulse

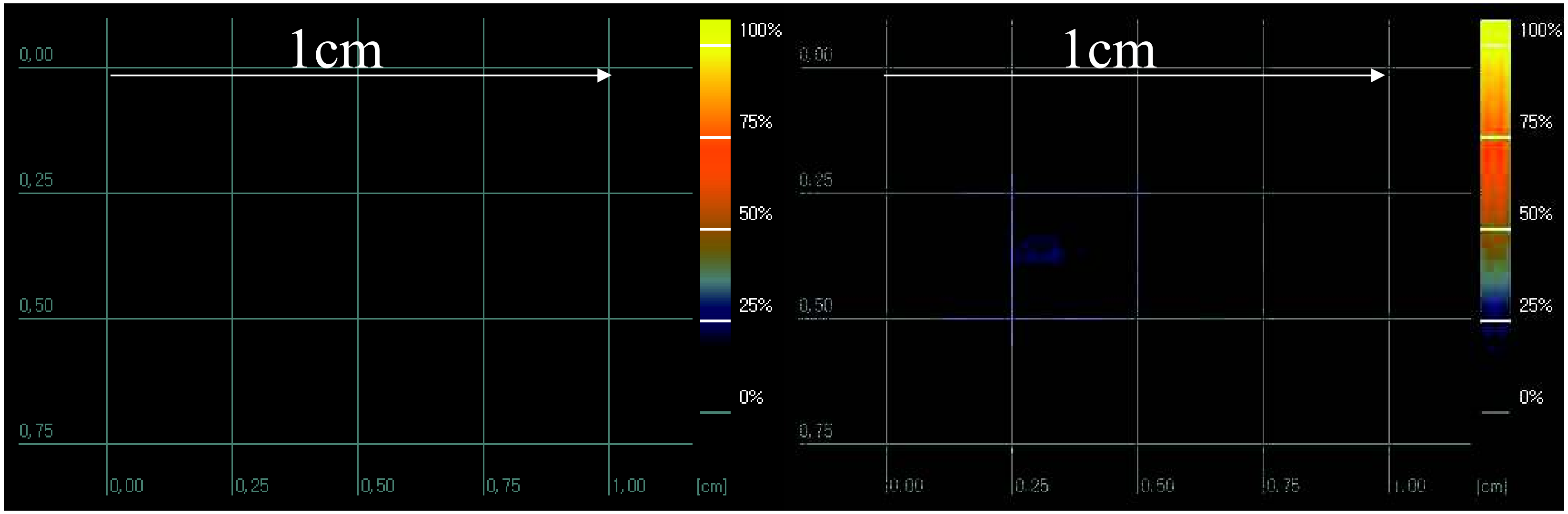
pulse energy = 47 mJ   pulse energy = 235 mJ



60 ns after rising edge of laser pulse

pulse energy = 47 mJ

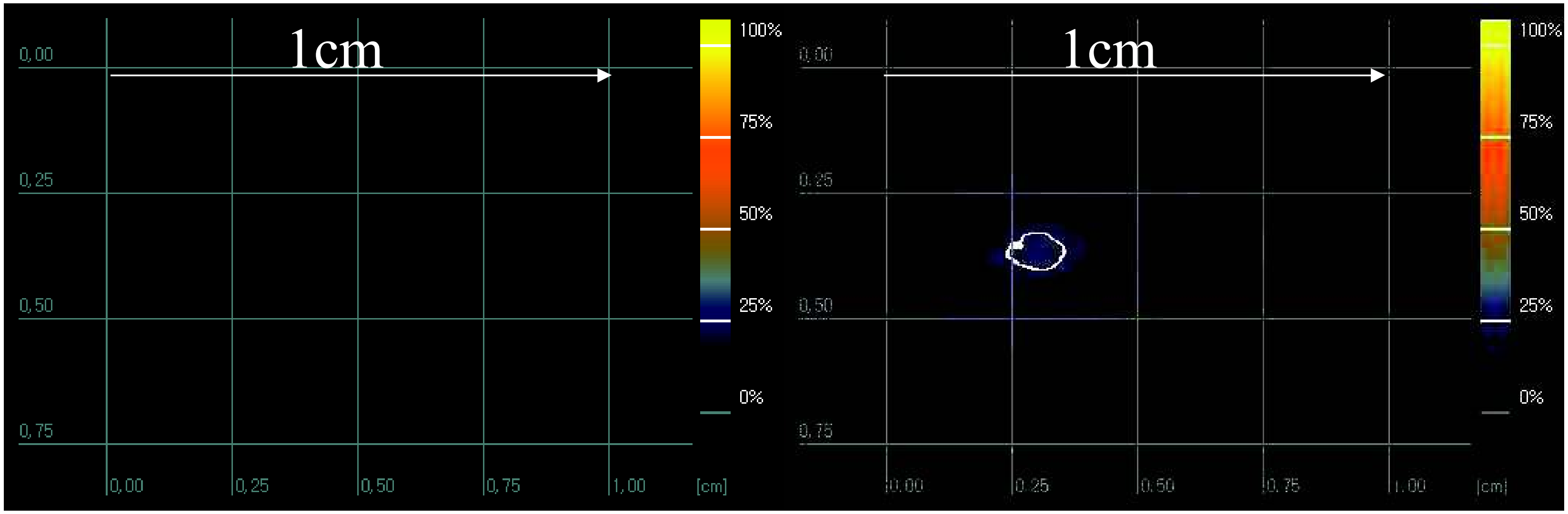
pulse energy = 235 mJ



80 ns after rising edge of laser pulse

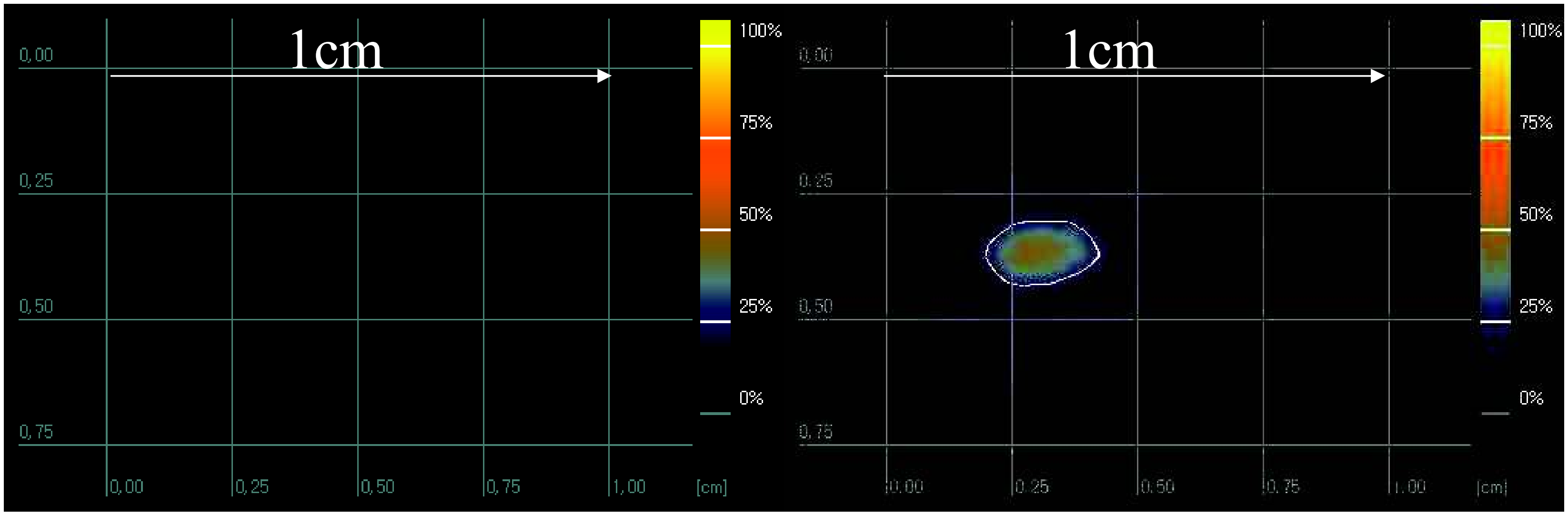
pulse energy = 47 mJ

pulse energy = 235 mJ



100 ns after rising edge of laser pulse

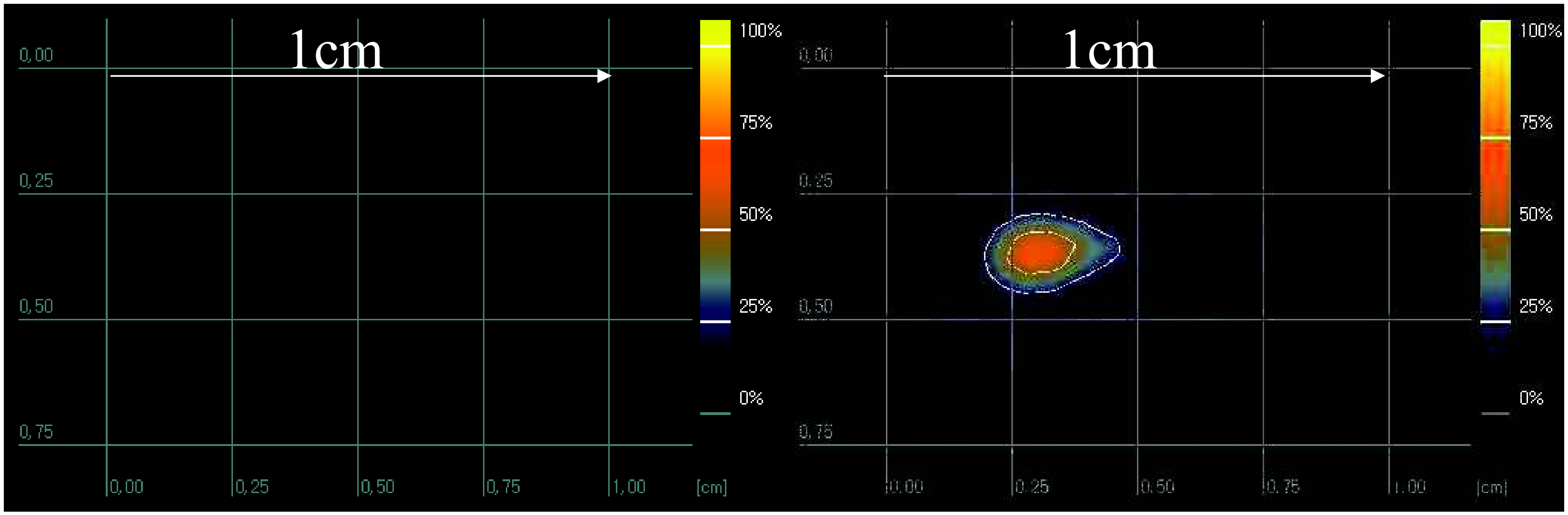
pulse energy = 47 mJ   pulse energy = 235 mJ



120 ns after rising edge of laser pulse

pulse energy = 47 mJ

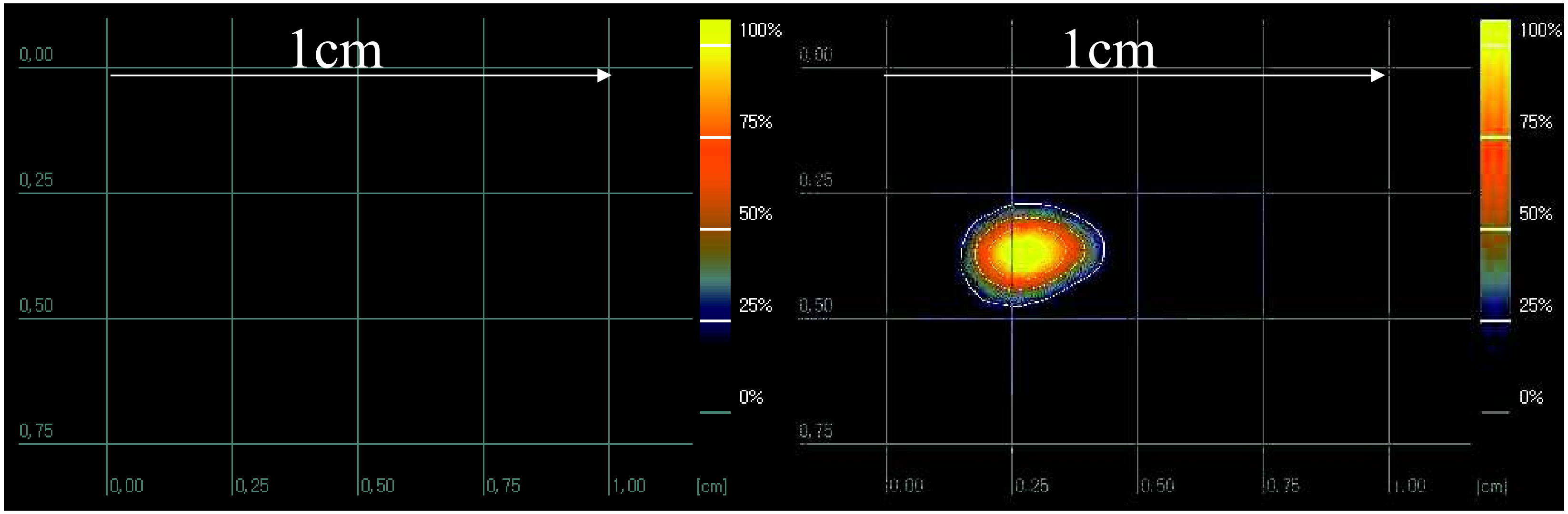
pulse energy = 235 mJ



140 ns after rising edge of laser pulse

pulse energy = 47 mJ

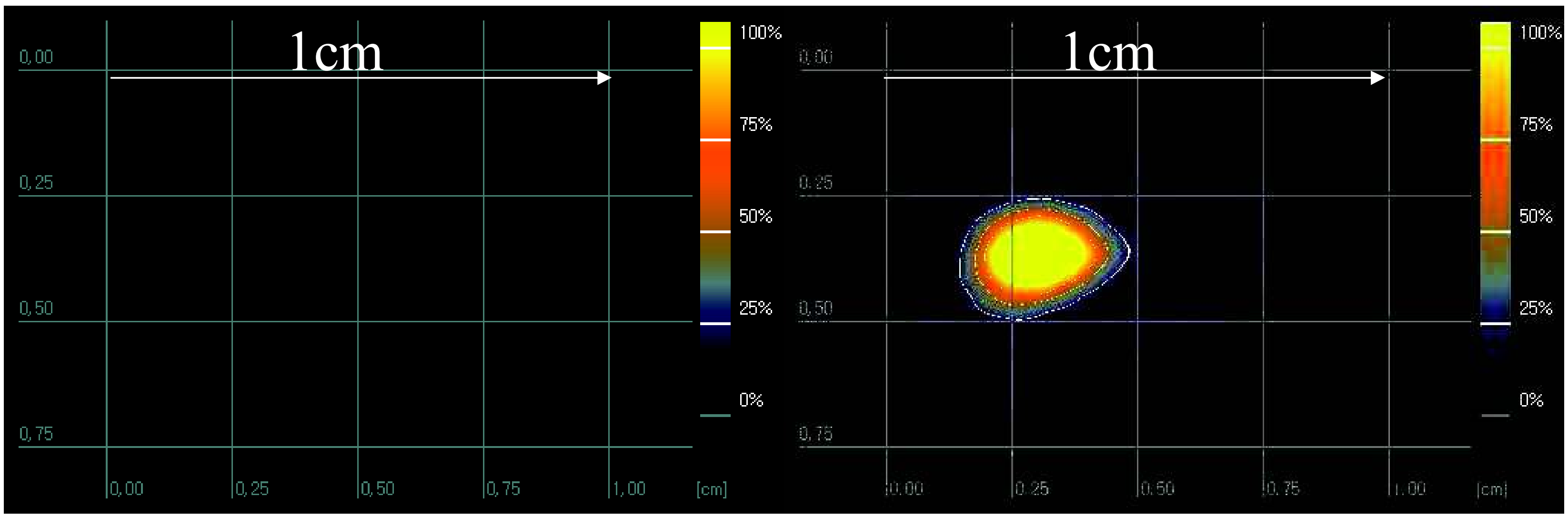
pulse energy = 235 mJ



160 ns after rising edge of laser pulse

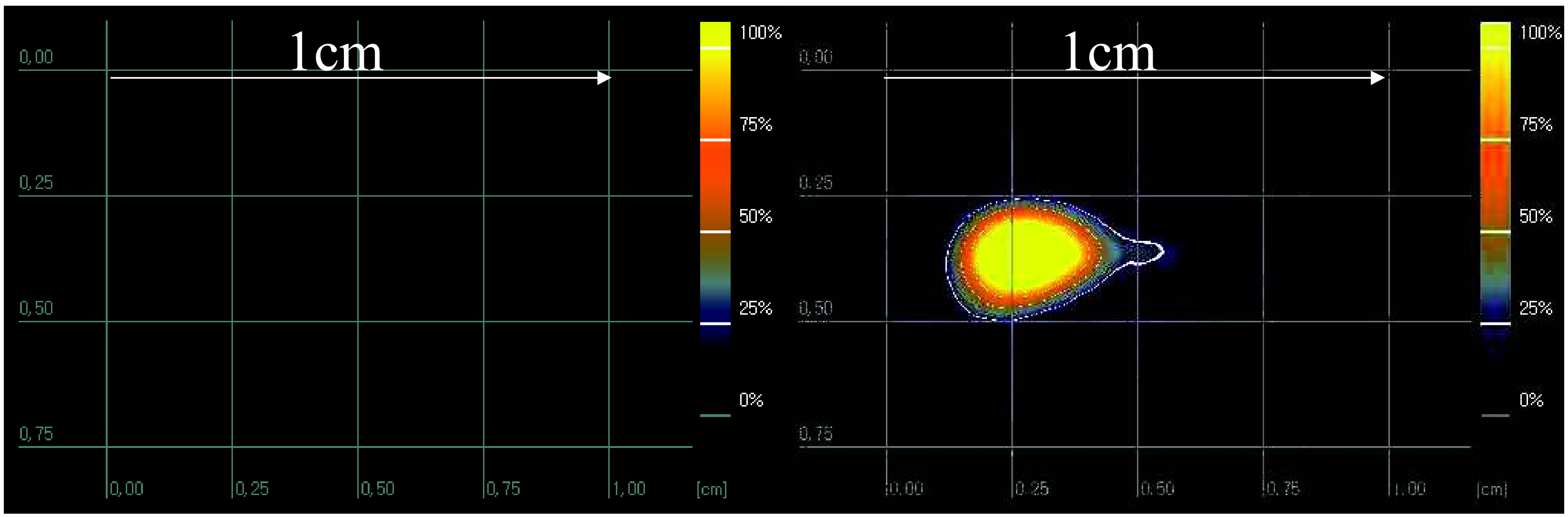
pulse energy = 47 mJ

pulse energy = 235 mJ



165 ns after rising edge of laser pulse

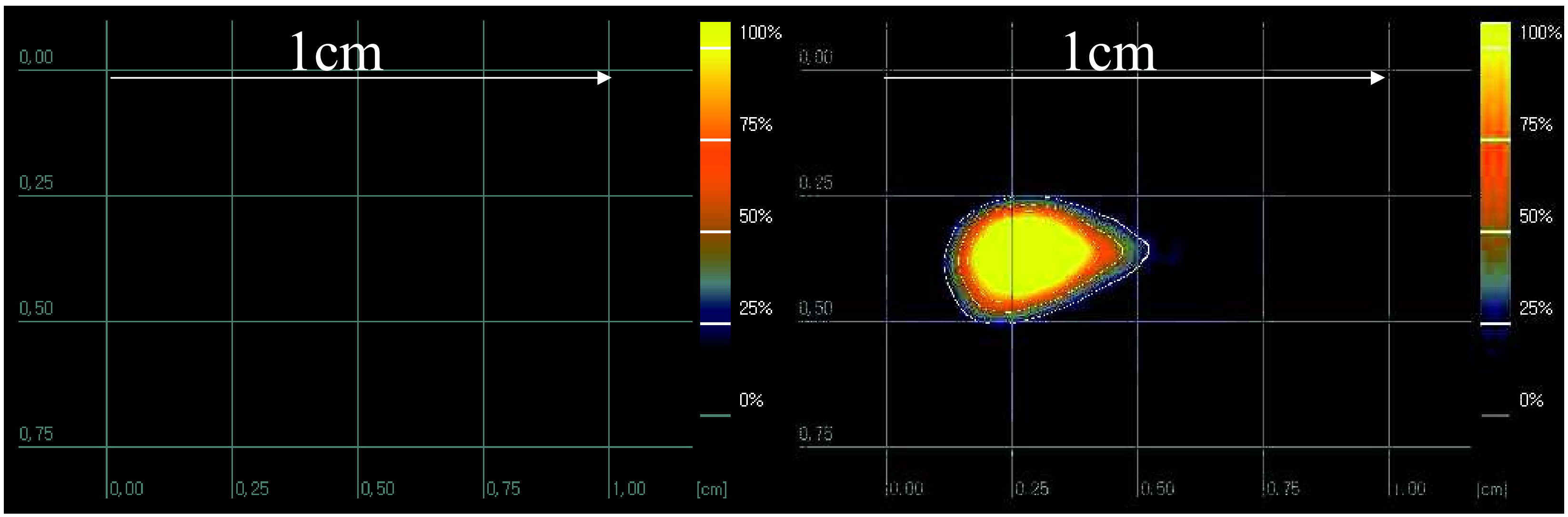
pulse energy = 47 mJ　　　　pulse energy = 235 mJ



170 ns after rising edge of laser pulse

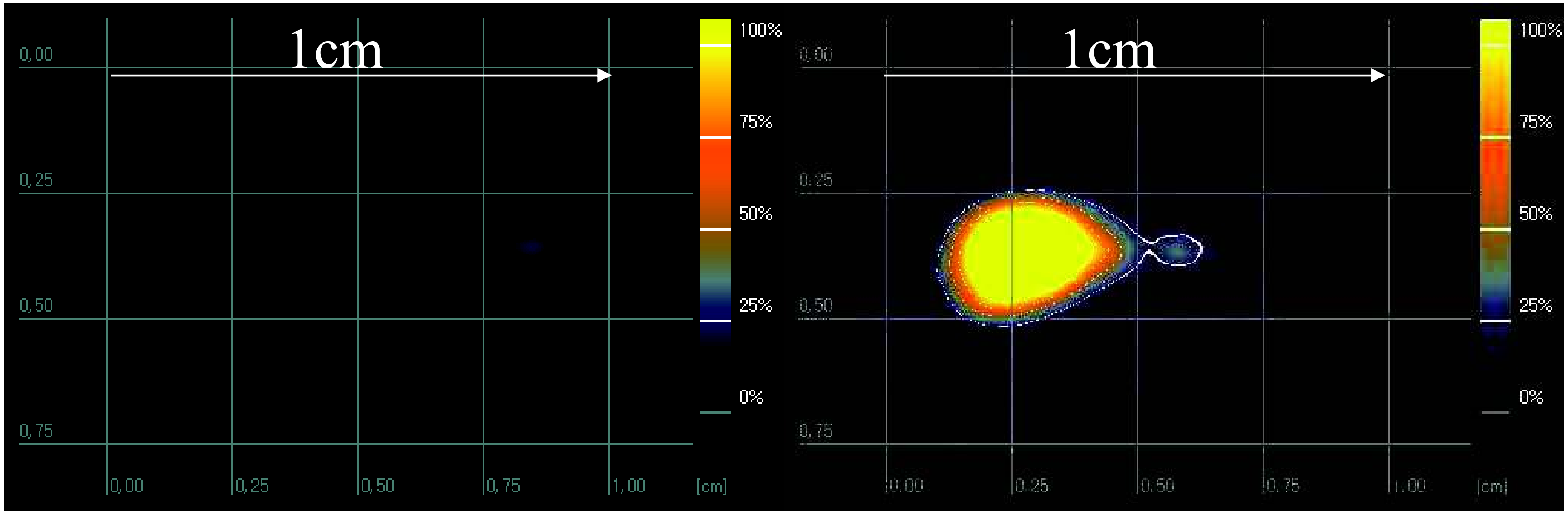
pulse energy = 47 mJ

pulse energy = 235 mJ



175 ns after rising edge of laser pulse

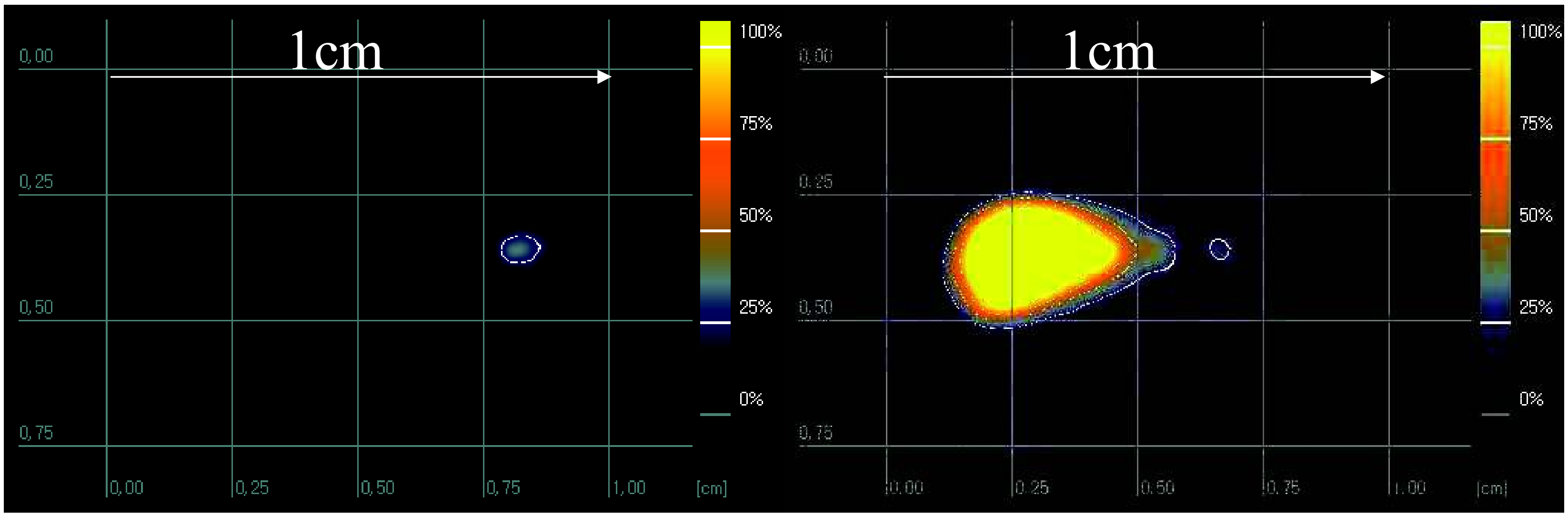
pulse energy = 47 mJ　　pulse energy = 235 mJ



180 ns after rising edge of laser pulse

pulse energy = 47 mJ

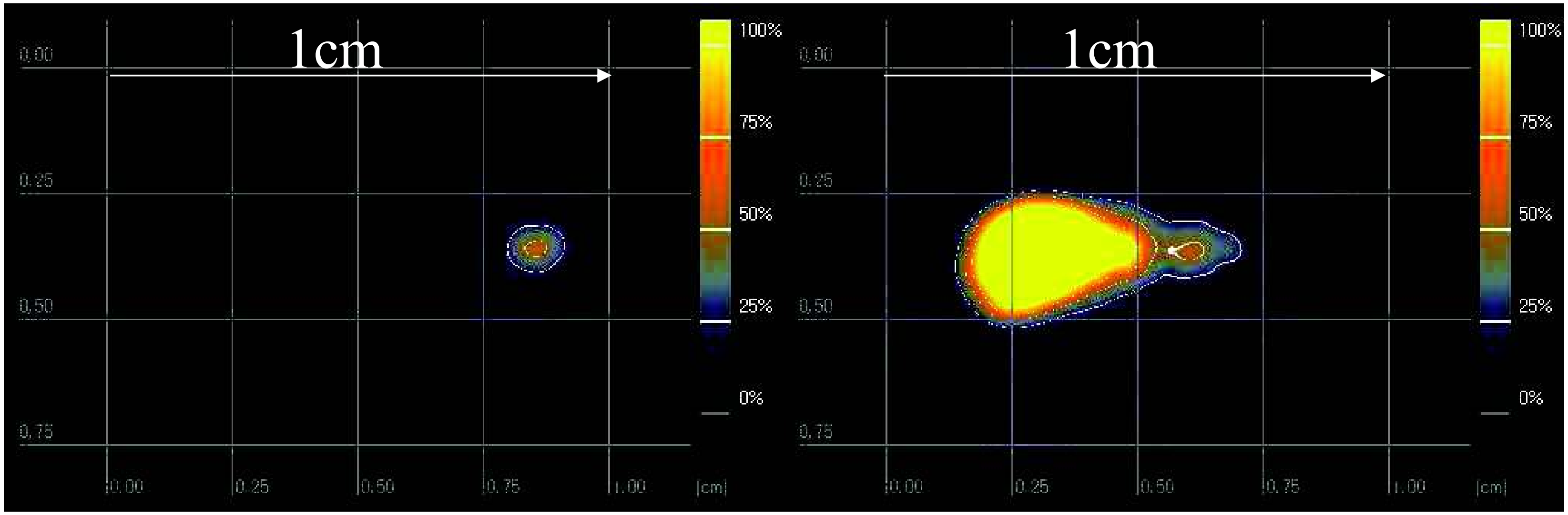
pulse energy = 235 mJ



185 ns after rising edge of laser pulse

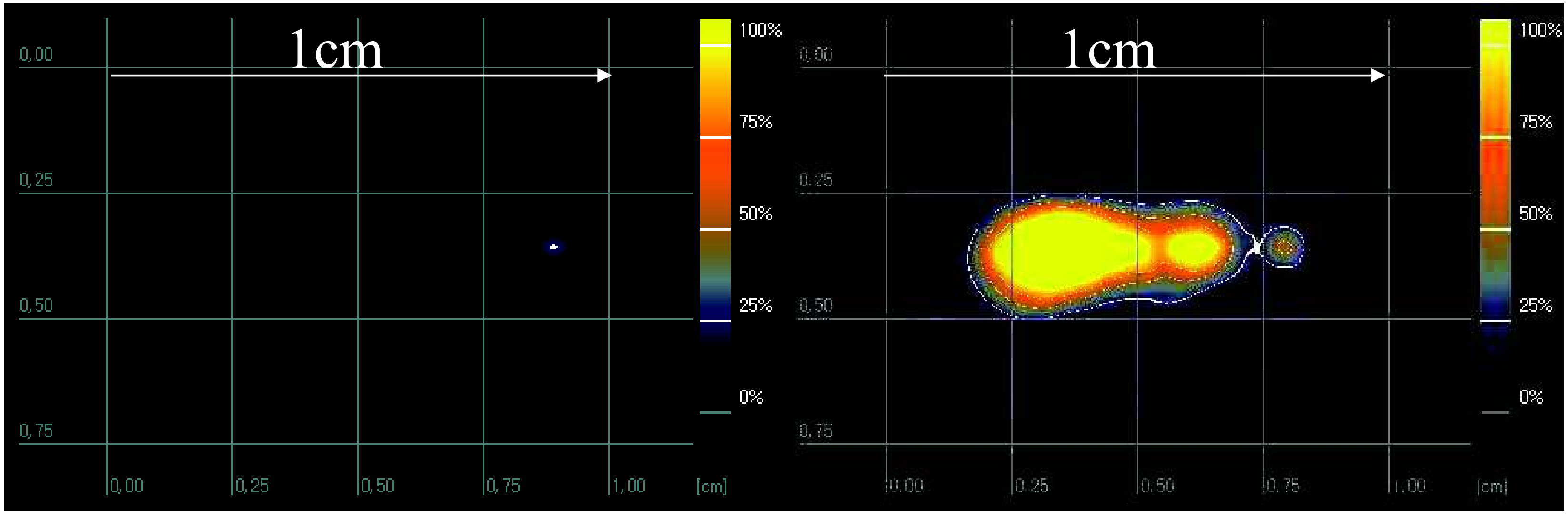
pulse energy = 47 mJ

pulse energy = 235 mJ



190 ns after rising edge of laser pulse

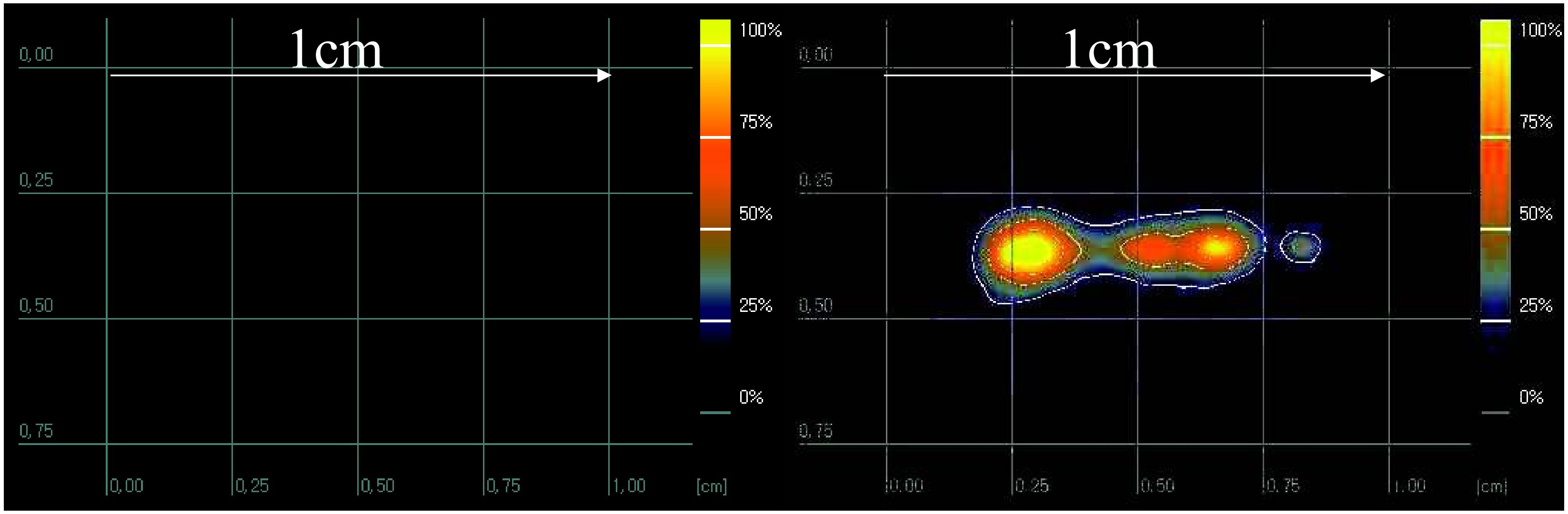
pulse energy = 47 mJ　　　　pulse energy = 235 mJ



195 ns after rising edge of laser pulse

pulse energy = 47 mJ

pulse energy = 235 mJ



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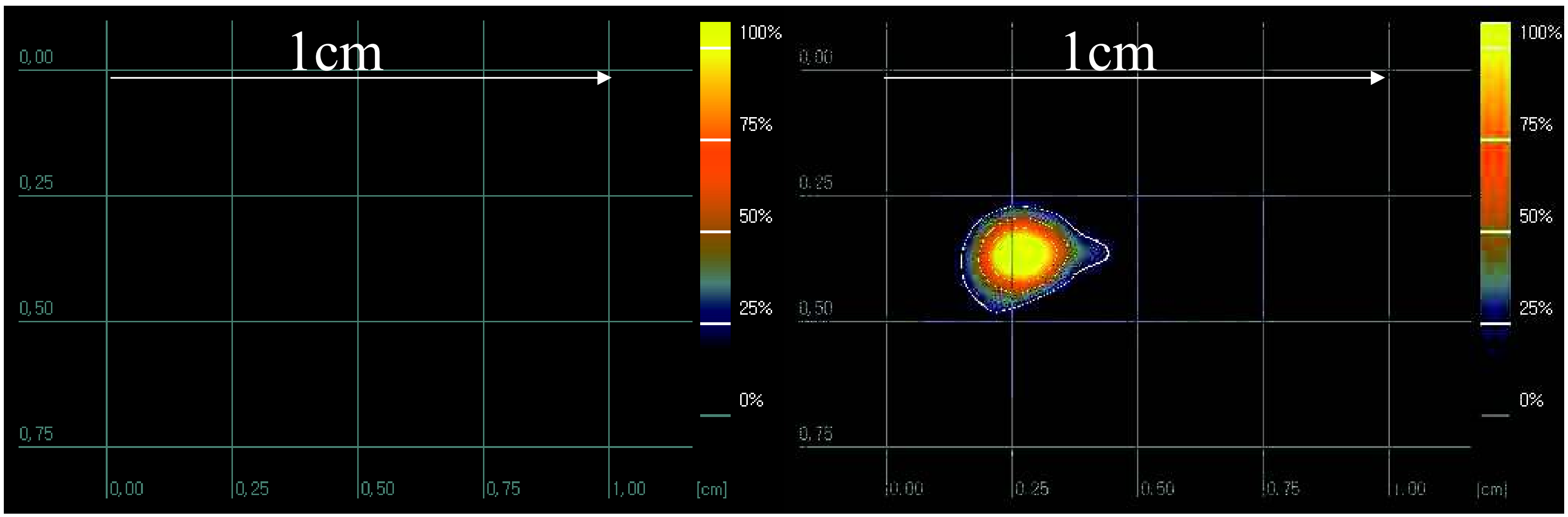
200 ns after rising edge of laser pulse

pulse energy = 47 mJ

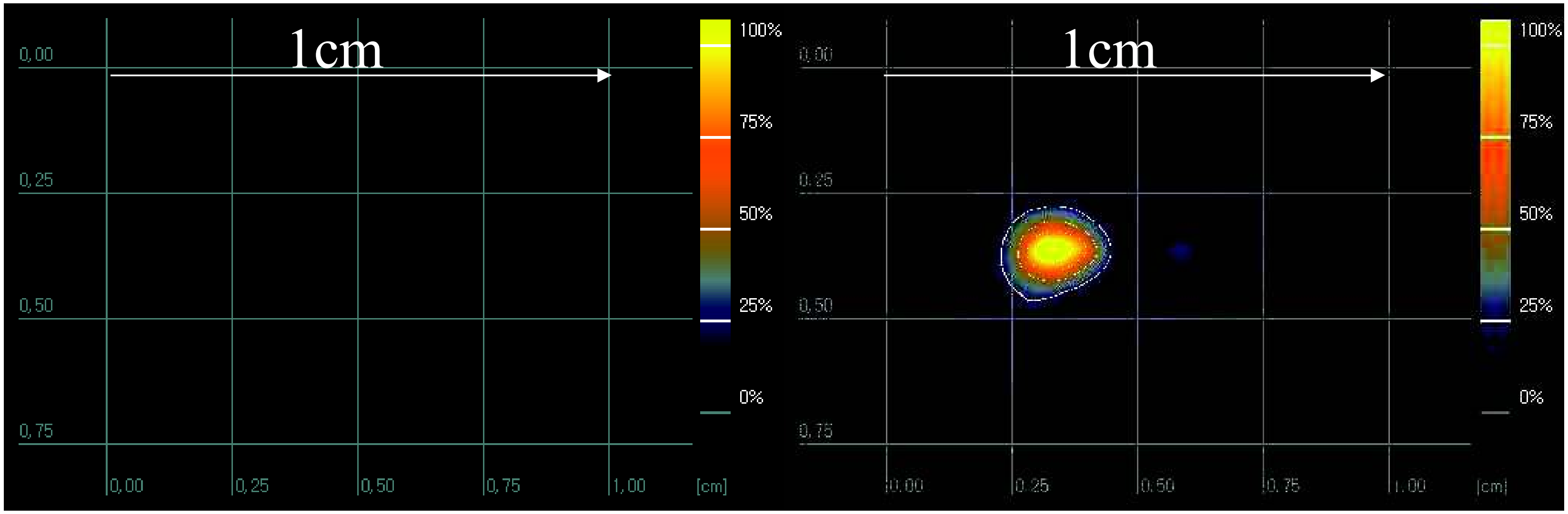
pulse energy = 235 mJ



205 ns after rising edge of laser pulse

pulse energy = 47 mJ

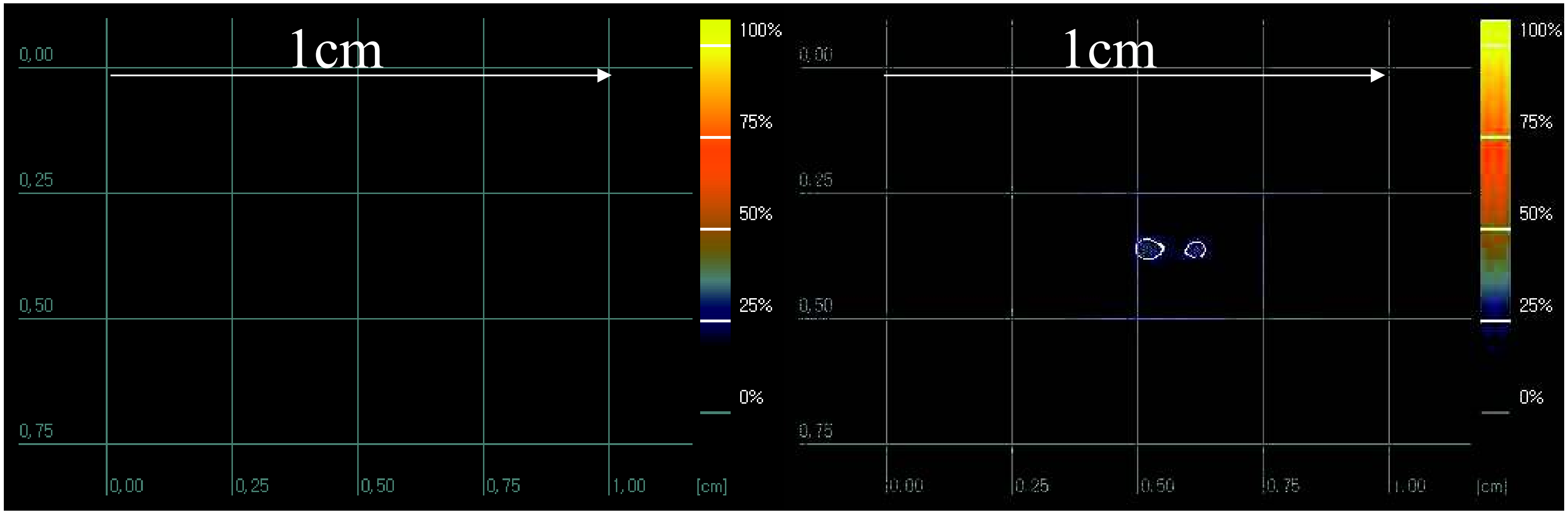
pulse energy = 235 mJ



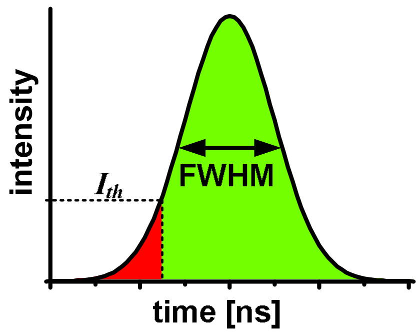
210 ns after rising edge of laser pulse

pulse energy = 47 mJ

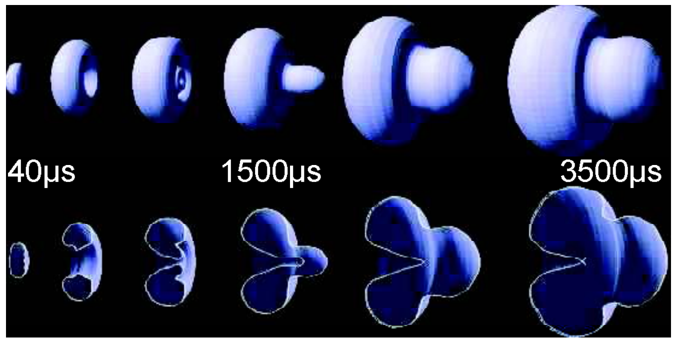
pulse energy = 235 mJ



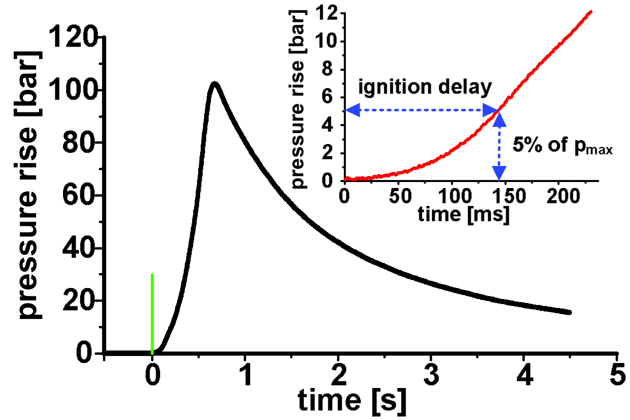
Temporal Evolution of Ignition



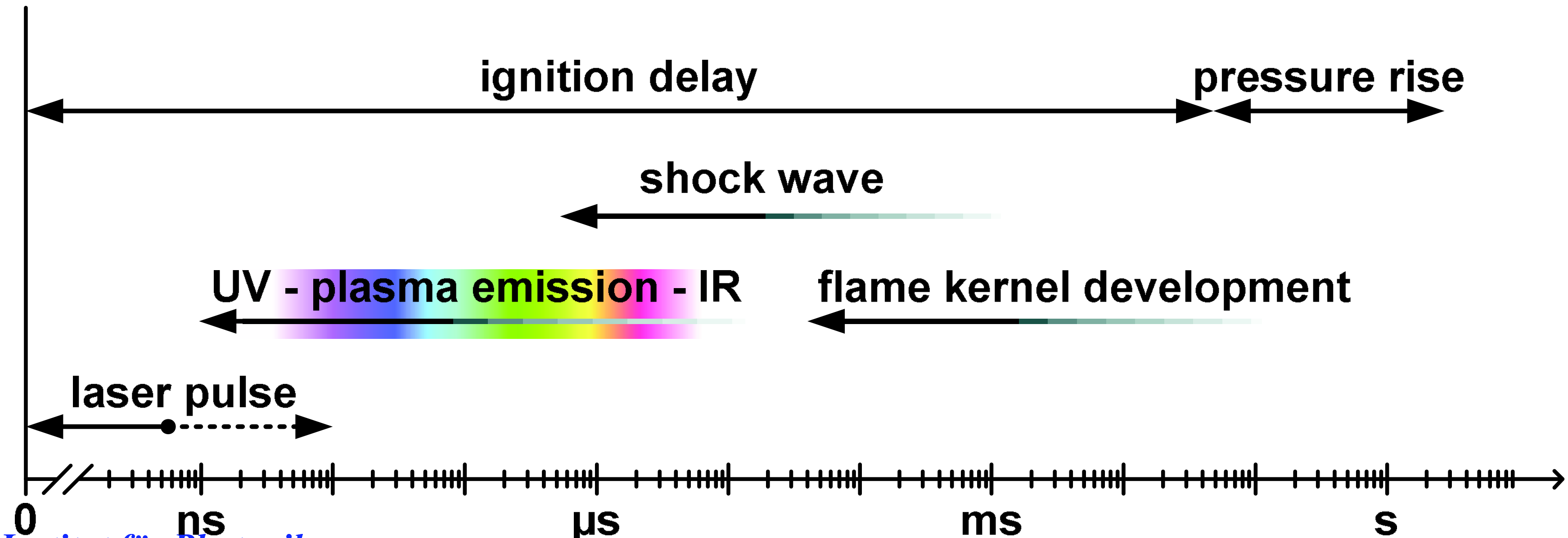
laser pulse



developing flame kernel



pressure pattern



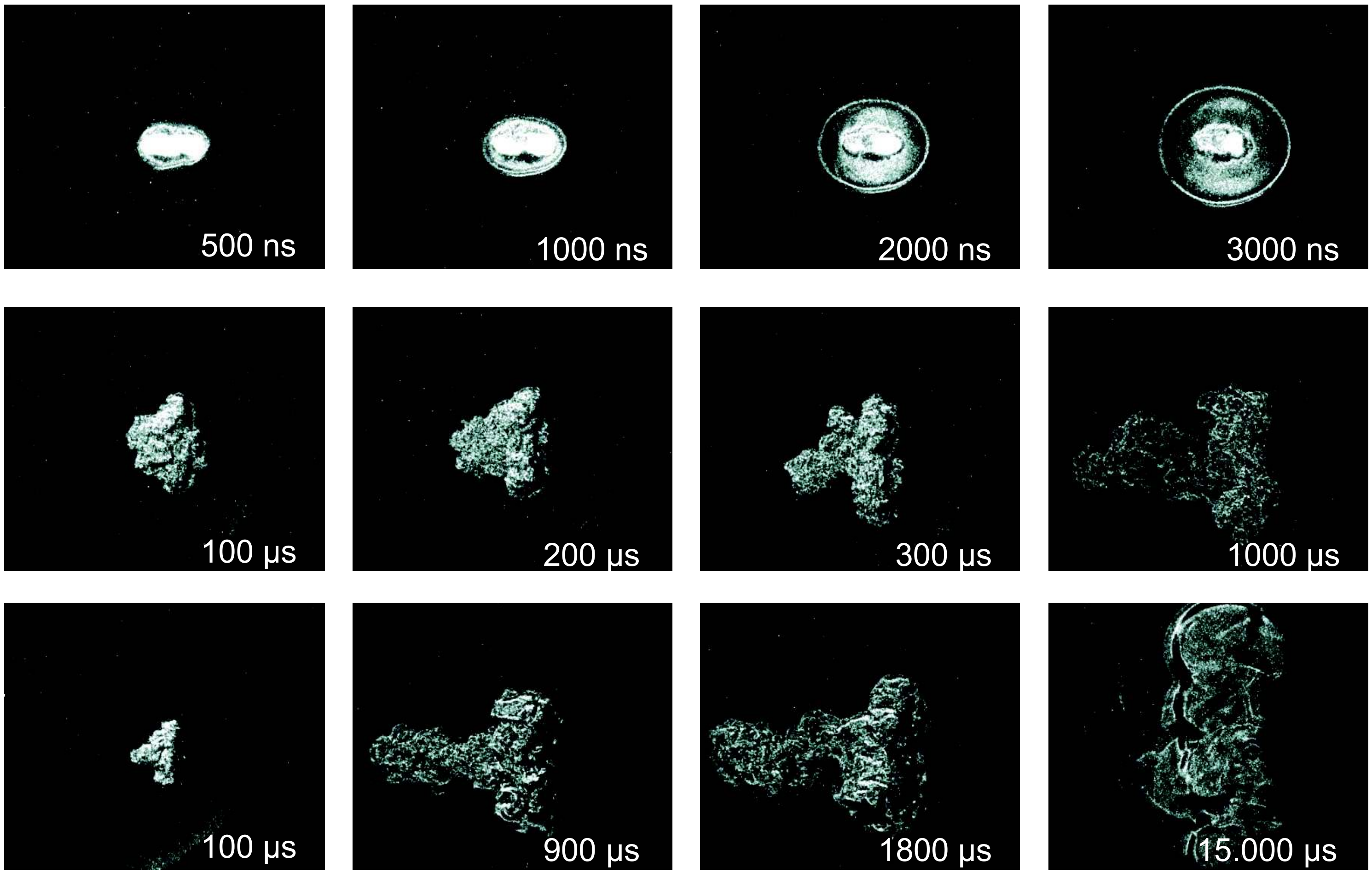
Diagnostics I: Schlieren photography

11.6 mm x 9.15 mm

air
25 bar

H_2/air
25 bar
λ = 6.0

biogas/air
25 bar
λ = 1.8



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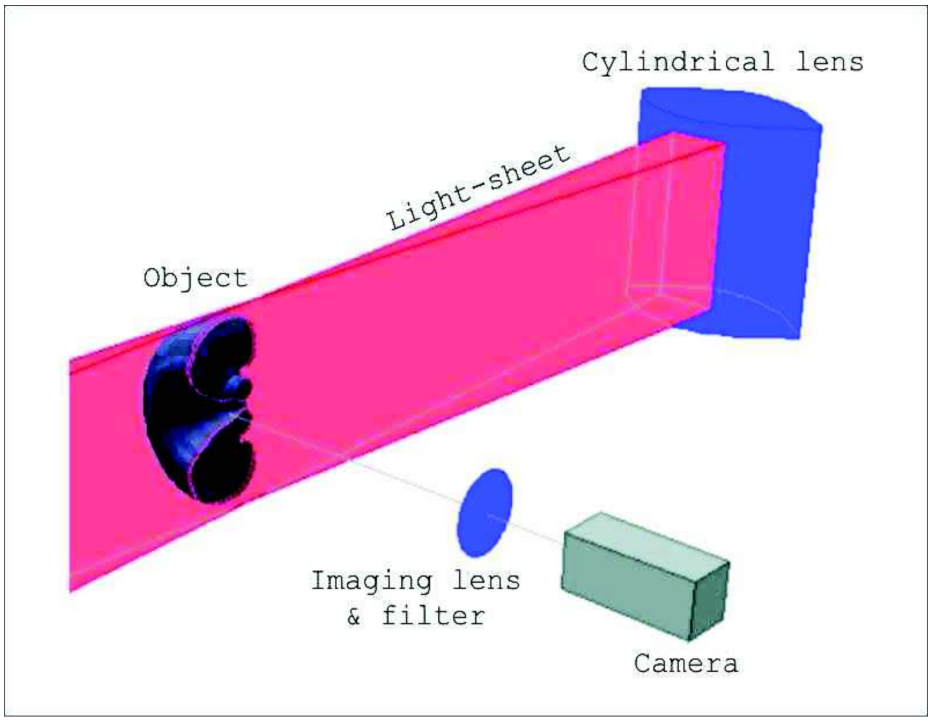
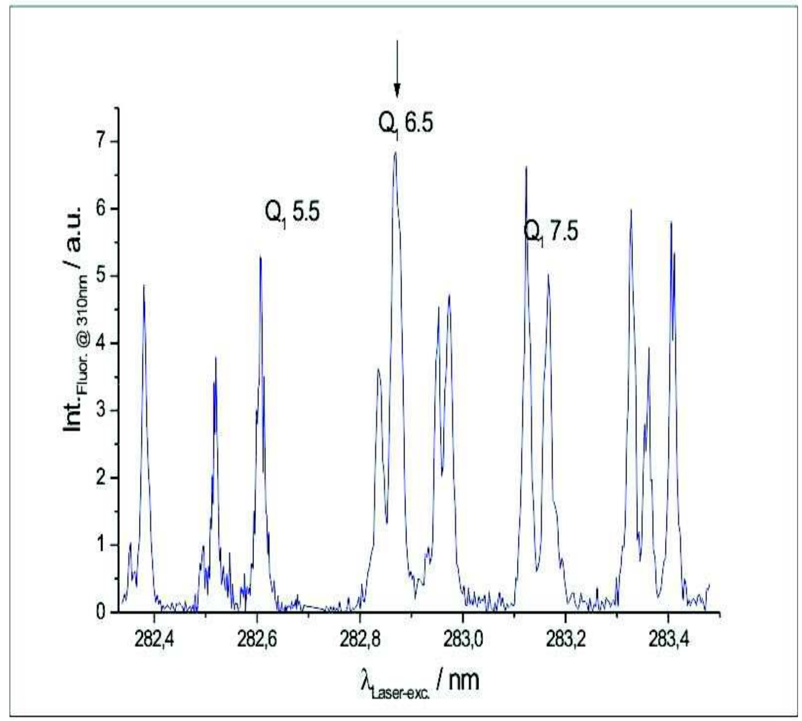
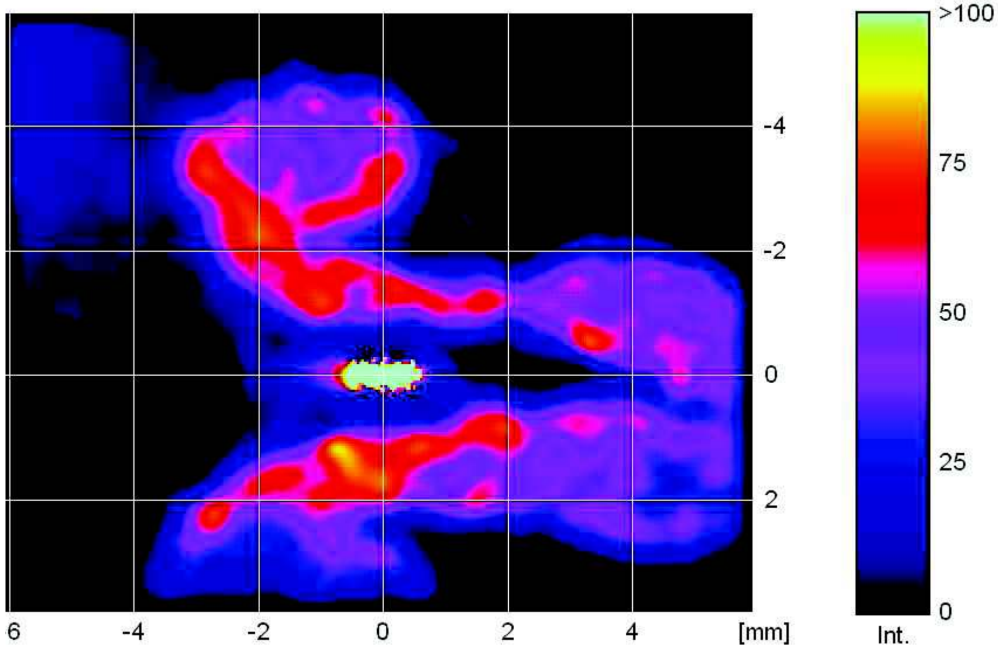
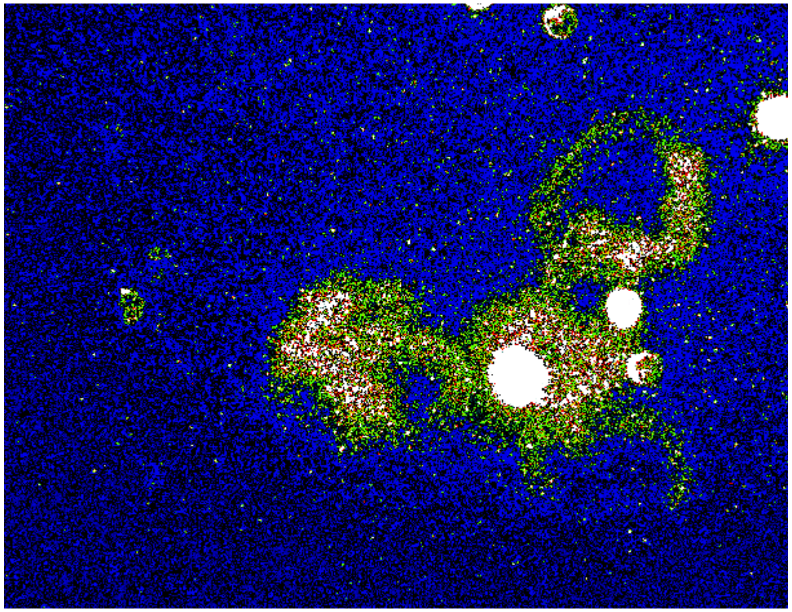
Diagnostics II: Planar Laser-induced Fluorescence PLIF



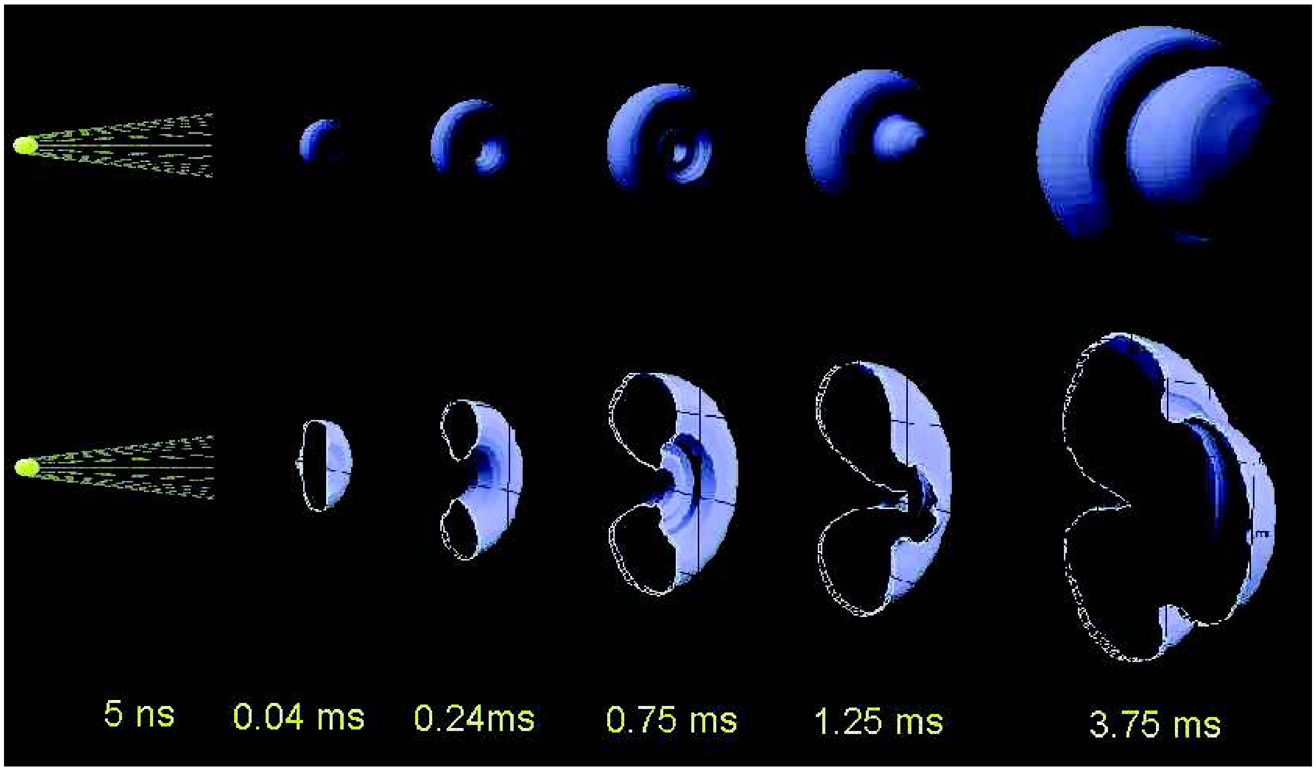


Comparison OH- vs. Formaldehyde-PLIF





Laser-induced Fluorescence: 3D Calculated

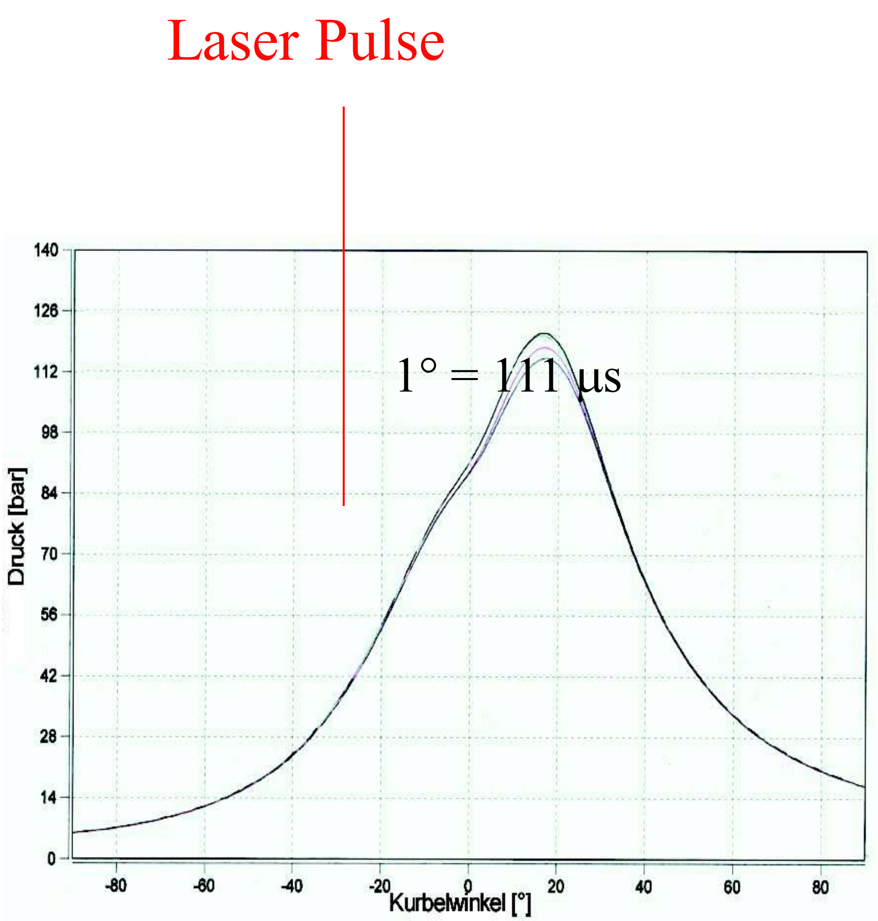


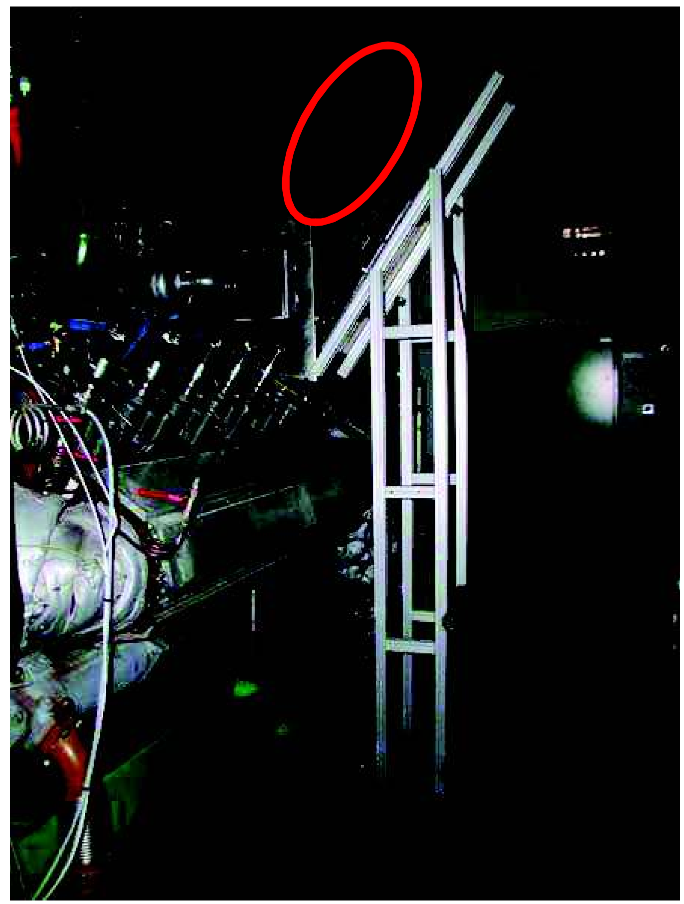
Advantages of Laser Ignition

- Higher ignition pressures possible → increase in efficiency
- Ignition of lean mixtures → lower flame temperatures → reduction of thermal NO_x formation
- Location of ignition to be nearly arbitrarely chosen
- Less wear due to absence of electrodes → reduced maintenance
- More effective energy transfer from plasma to fuel-air mixture (no quenching effects)

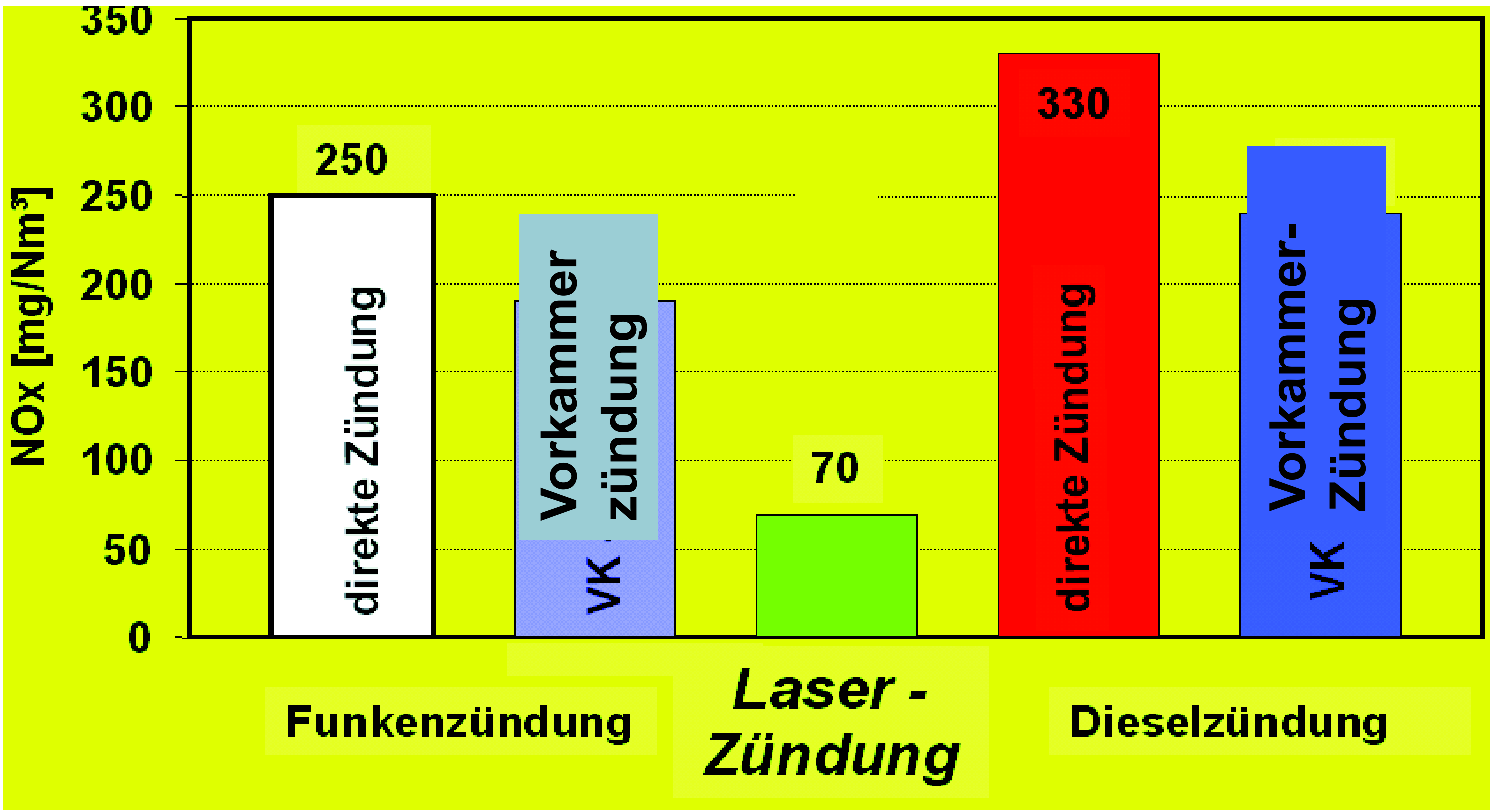
substantial reduction of NO_x and increase in efficiency!

First Experiments on 1MW Engine in 2000



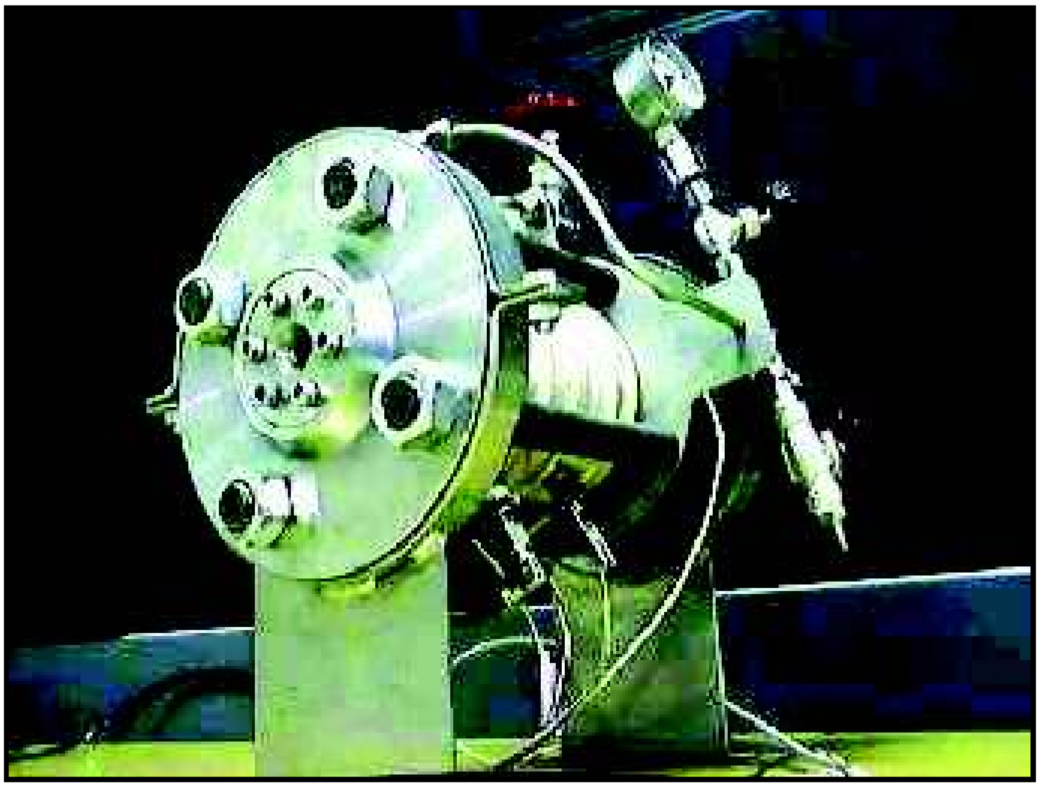


NO_x Emission Potentials



Source: GE Jenbacher GmbH & Co OHG

Combustion Chamber



Diploma thesis M. Tesch

net volume = 1.2 dm^3

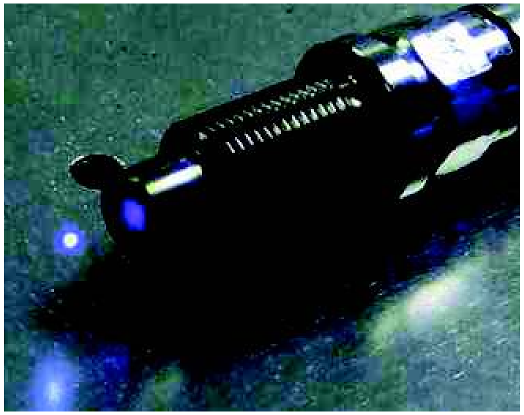
maximum permissible pressure = 300 bar

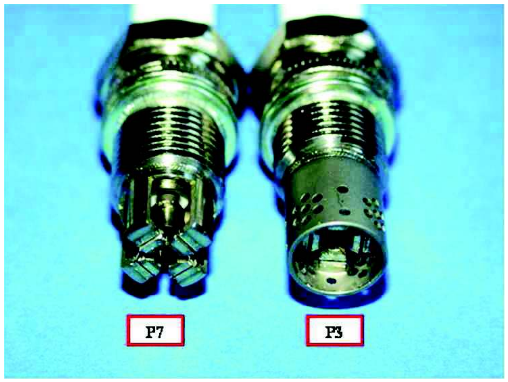
stabilized at
70 °C, 200 °C and
400 °C

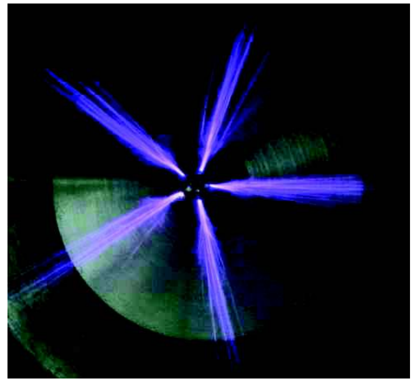
sapphire (lens) windows of 13 mm clear aperture for longitudinal and transversal transmission

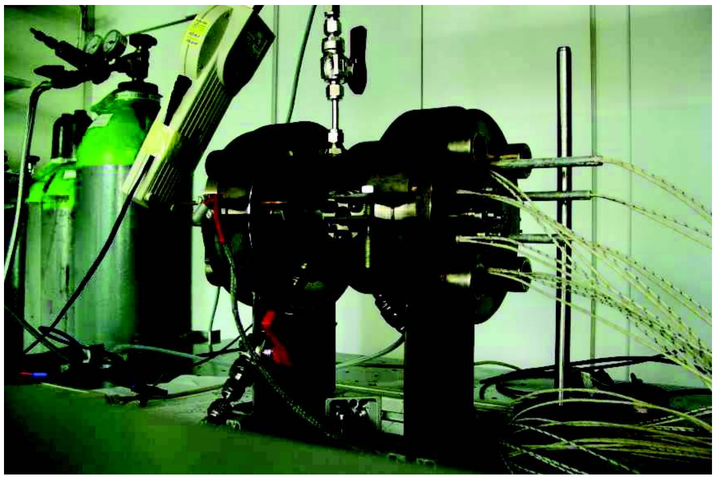
Comparison of Ignition Capability

Laser ignition – electric spark ignition – Corona ignition



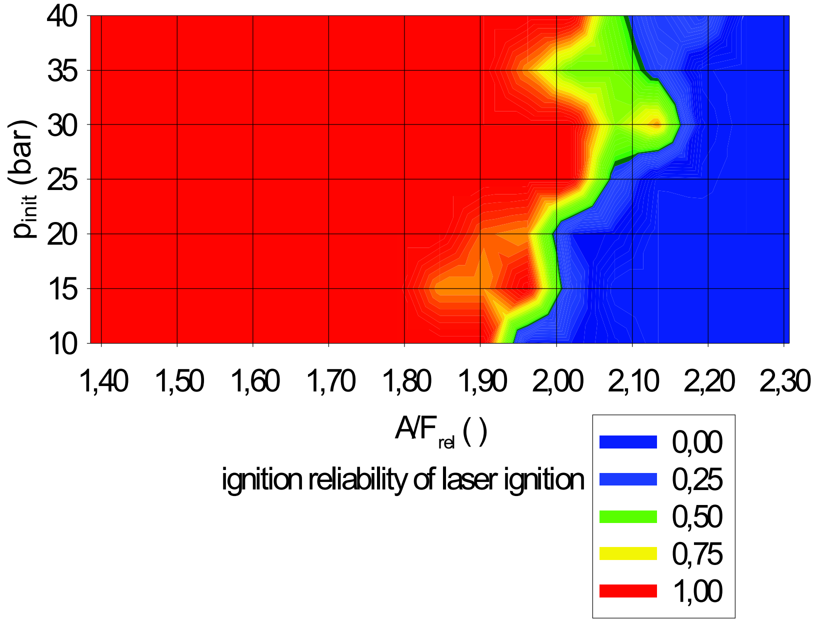


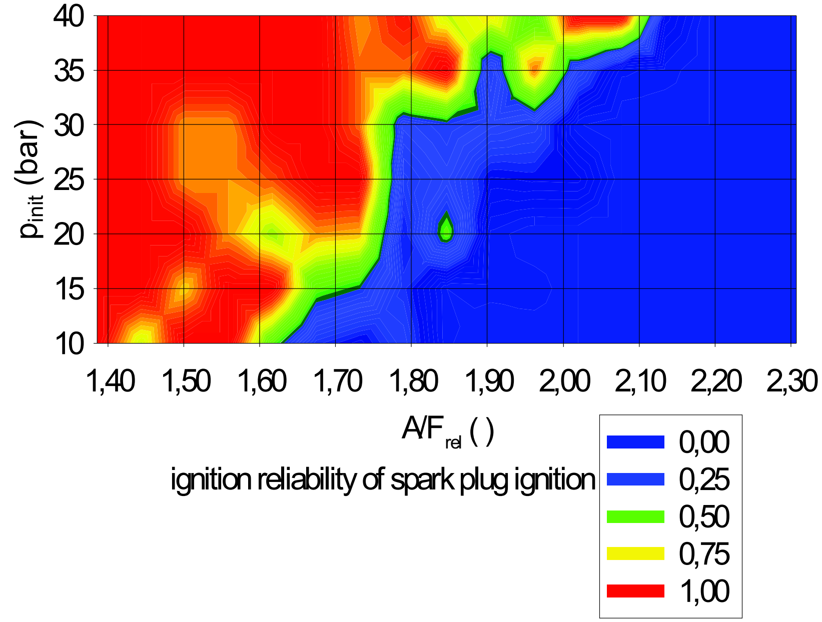




Ignition of methane–air mixtures @ different λ

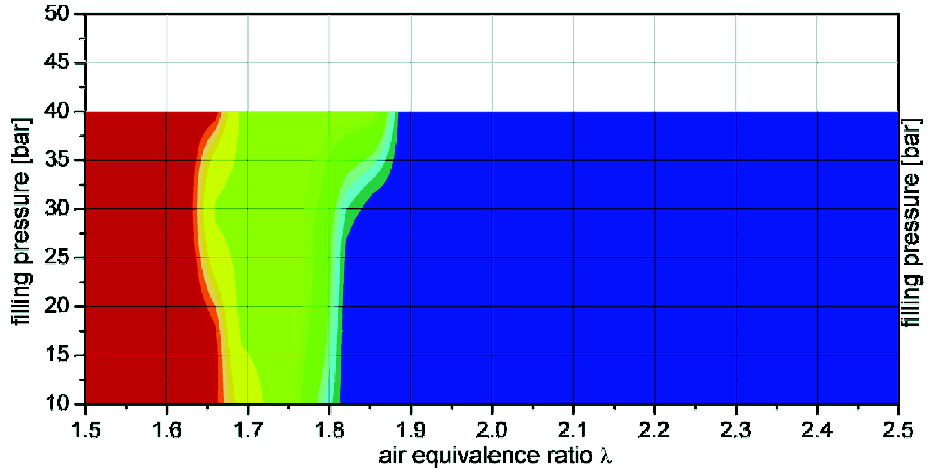
Direct Comparison
Laser Ignition – Spark Plug Ignition



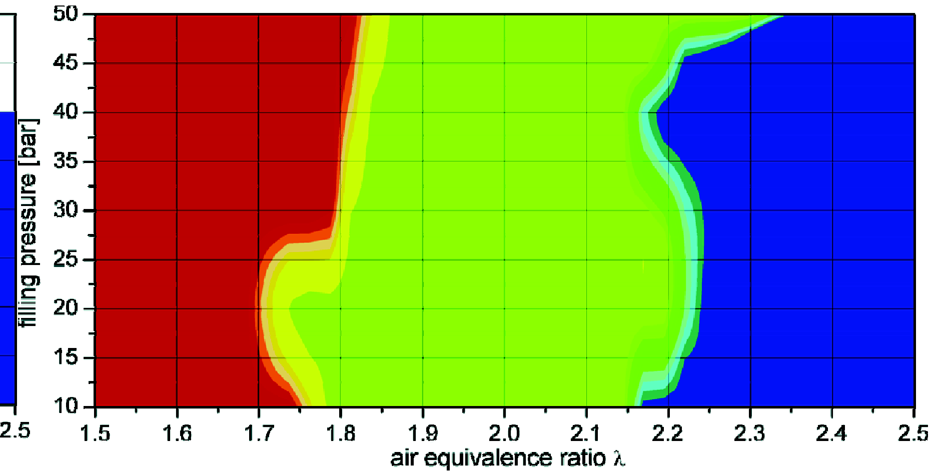


Combustion chamber of constant volume; methane-air, Tgas = 200°C; A/F_{rel} =1.77 on the engine for reliable run, maximum BMEP = 19 bar, typical spark duration = 400 – 500 µs; laser $M^2 < 1.2$; laser pulse energy constant 25 mJ well above the plasma breakdown threshold for all conditions, overall ignition attempts: 1201 for spark plug, 642 for laser; **Diploma thesis G. Ast**

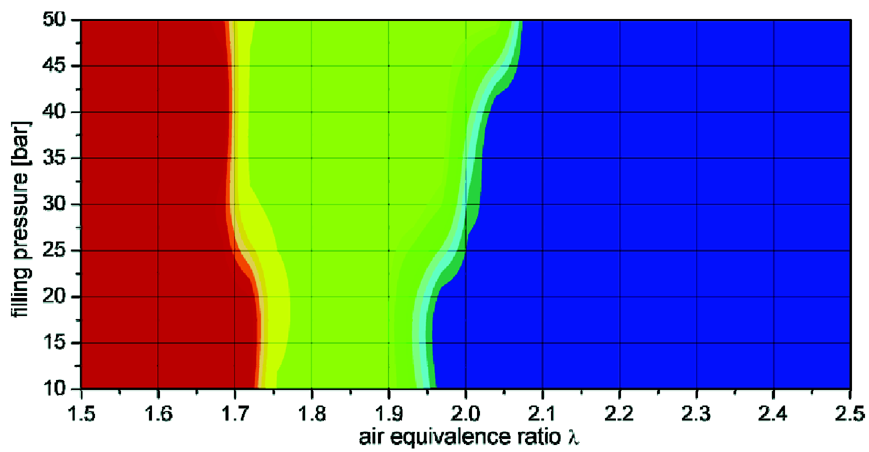
Comparison of Ignition Capability



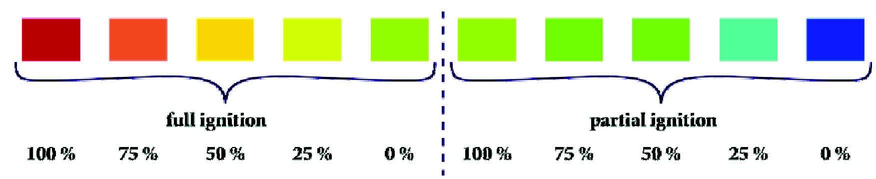
Electric spark ignition



Corona ignition



Laser ignition



Corona ignition so far not applicable, as regulation under engine-like conditions extremely difficult to realize (no Corona or spark only) Diploma thesis M. Puhl: ***(http://www.amazon.de/Prognostizierbarkeit-Finanzzeitreihen-Stochastische-Marktanomalien-Hedgefondsstrategie/dp/3836480727/ref=sr_1_1?ie=UTF8&s=books&qid=1290528335&sr=8-1)***

Realized Goals by Combustion Chamber Experiments

Determination of plasma threshold intensity and minimum laser pulse energy for ignition (MPE) of several fuel gas –air mixtures and mixtures depending on

- methane-air
- hydrogen-air
- hydrogen-methane-air
- biogas
- isooctane

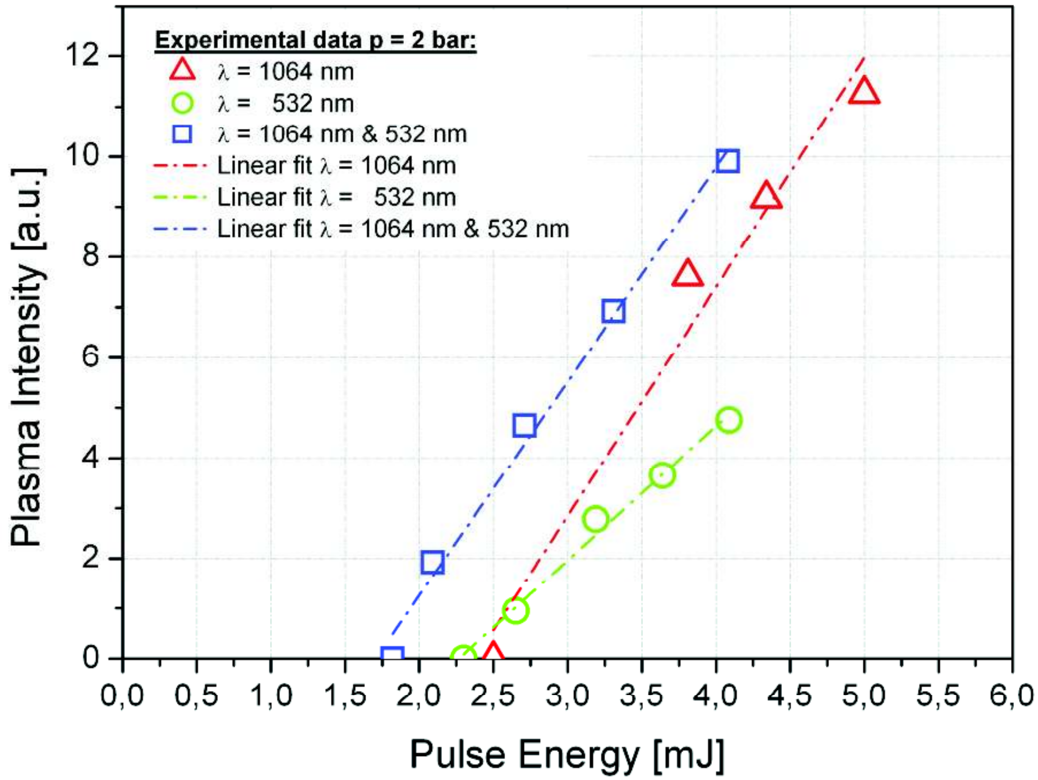
Minimum ignition energy (MIE) not important for practical considerations, however for comparison with theory

Realized Goals by Combustion Chamber Experiments

Determination and optimization of

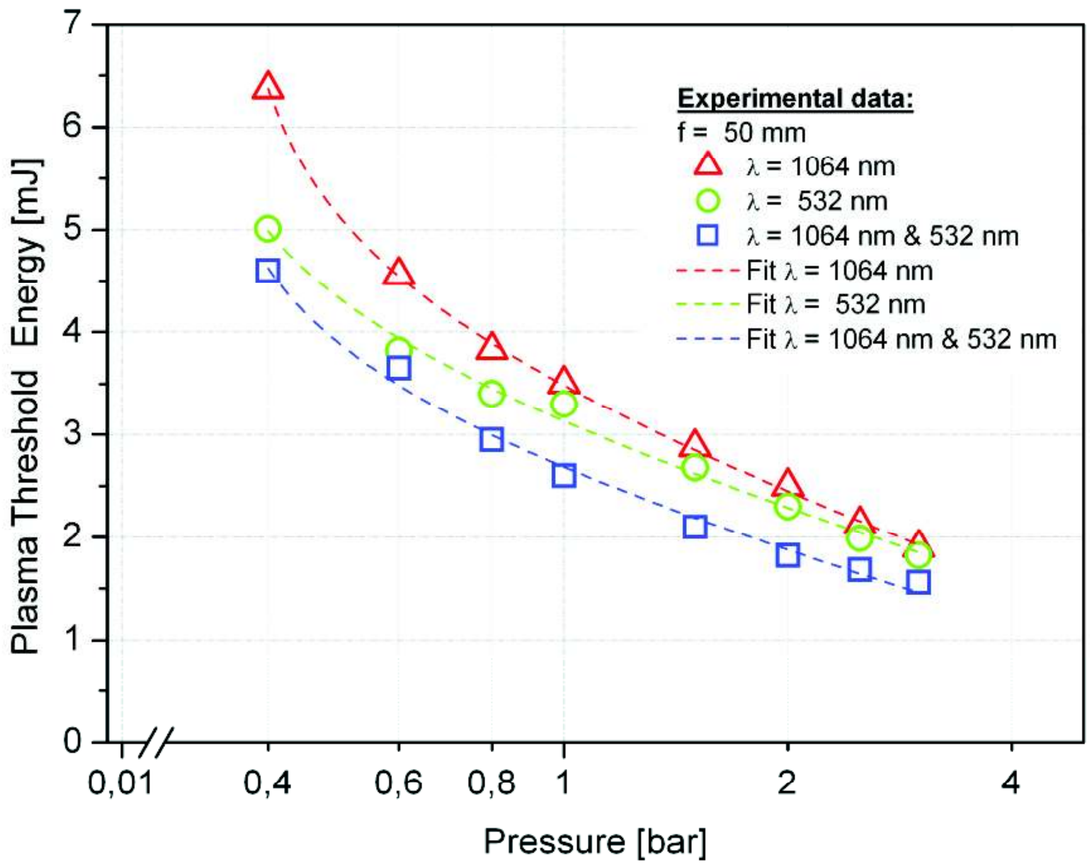
- laser wavelength (1064 nm, 532 nm, 355 nm)
- focusing optics
- MPE dependance on fill pressure ($\leq$40 bar)
- MPE dependance on gas-air equivalence ratio Λ (especially lean side limit)
- MPE dependance on temperature

Plasma Formation by two Wavelengths



Plasma brightness vs. pulse energy of IR, SH, and 2-color excitation: pulse energy for which about 50% of the pulses yielded a visible spark. The SH (λ = 532 nm)-threshold energy is about 63% of the IR (λ = 1064 nm) value. For all measured SH/ IR ratios, the threshold for a SH-IR superposition is lower than the IR threshold, and for SH/IR ratios around 0.3 it is actually lower than the pure SH threshold.

Plasma Formation by two Wavelengths



Plasma threshold energy vs. air pressure: measured for λ = 1064 nm, 532 nm, and a mix-ture (35% 532 nm and 75% 1064 nm) in air @ p = 0.4-3 bar. For lower pressures p, MPE of green and the mixture converge. At higher p, MPE of green and IR are approximately the same. A clear advantage of the mixture exists at a p-range from 0.4-2.5 bar.

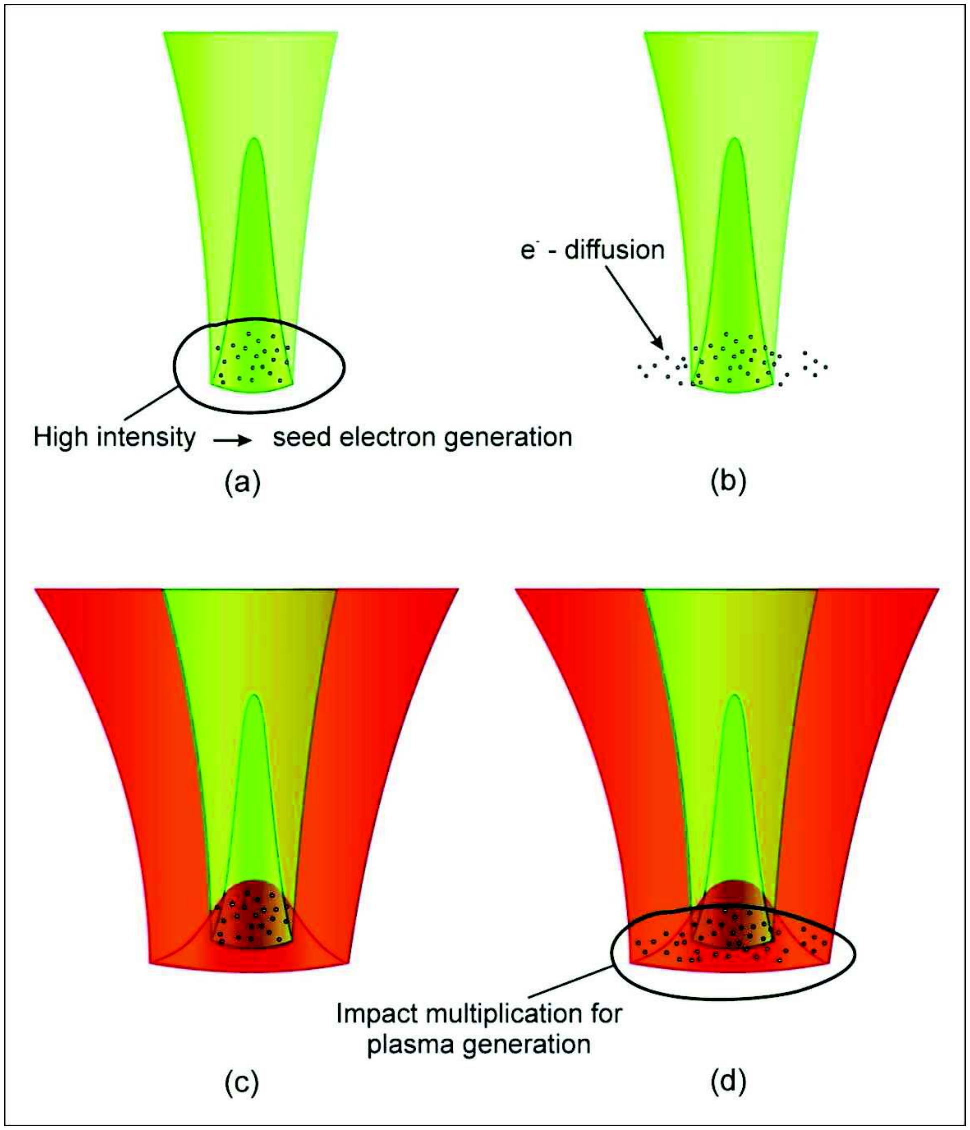


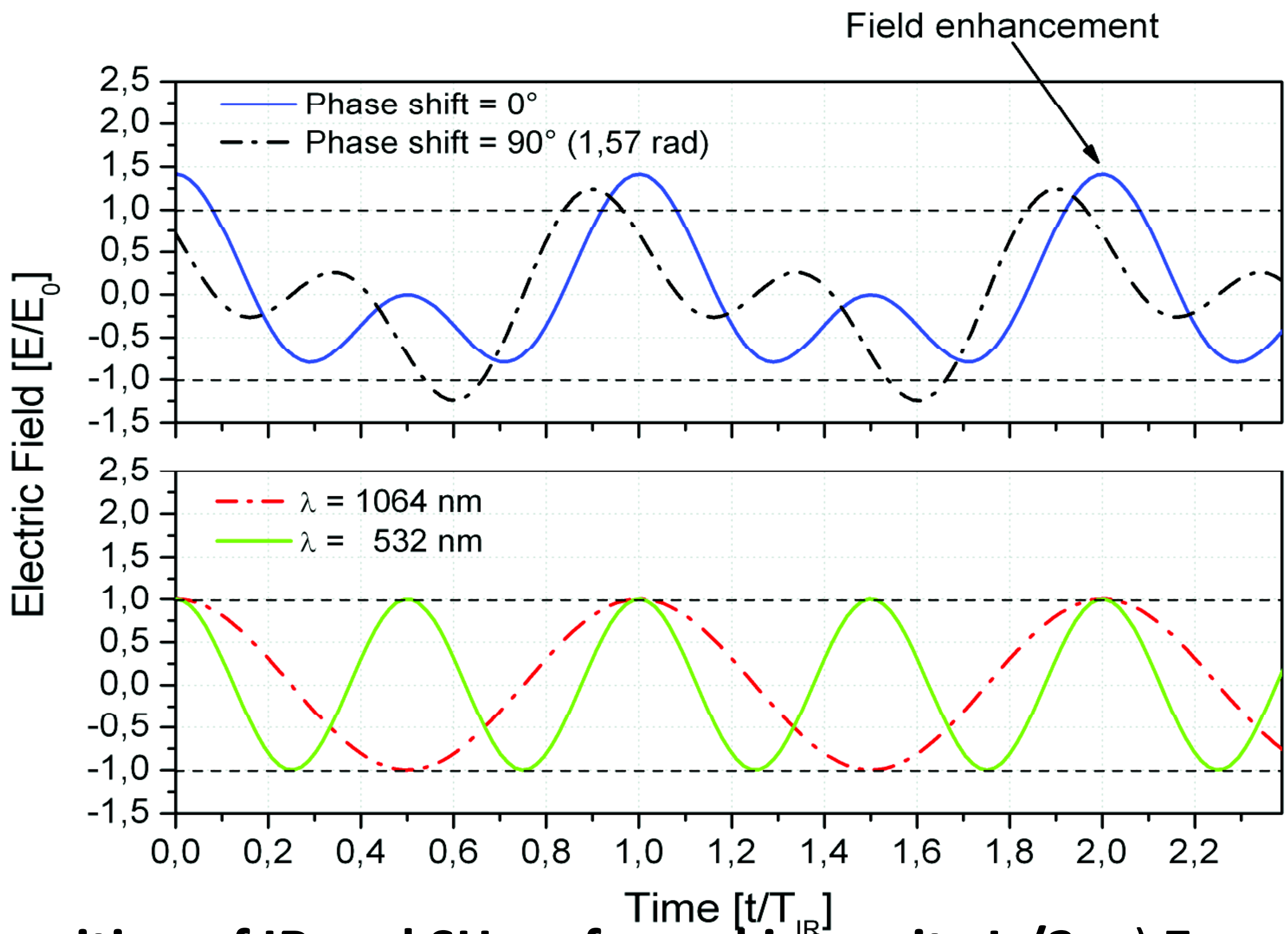
Illustration of the intensity inside the focal region:

(a) Seed electrons are generated in the focal region of the SH beam.

(b) Electron diffusion out of the green focus (e^- loss).

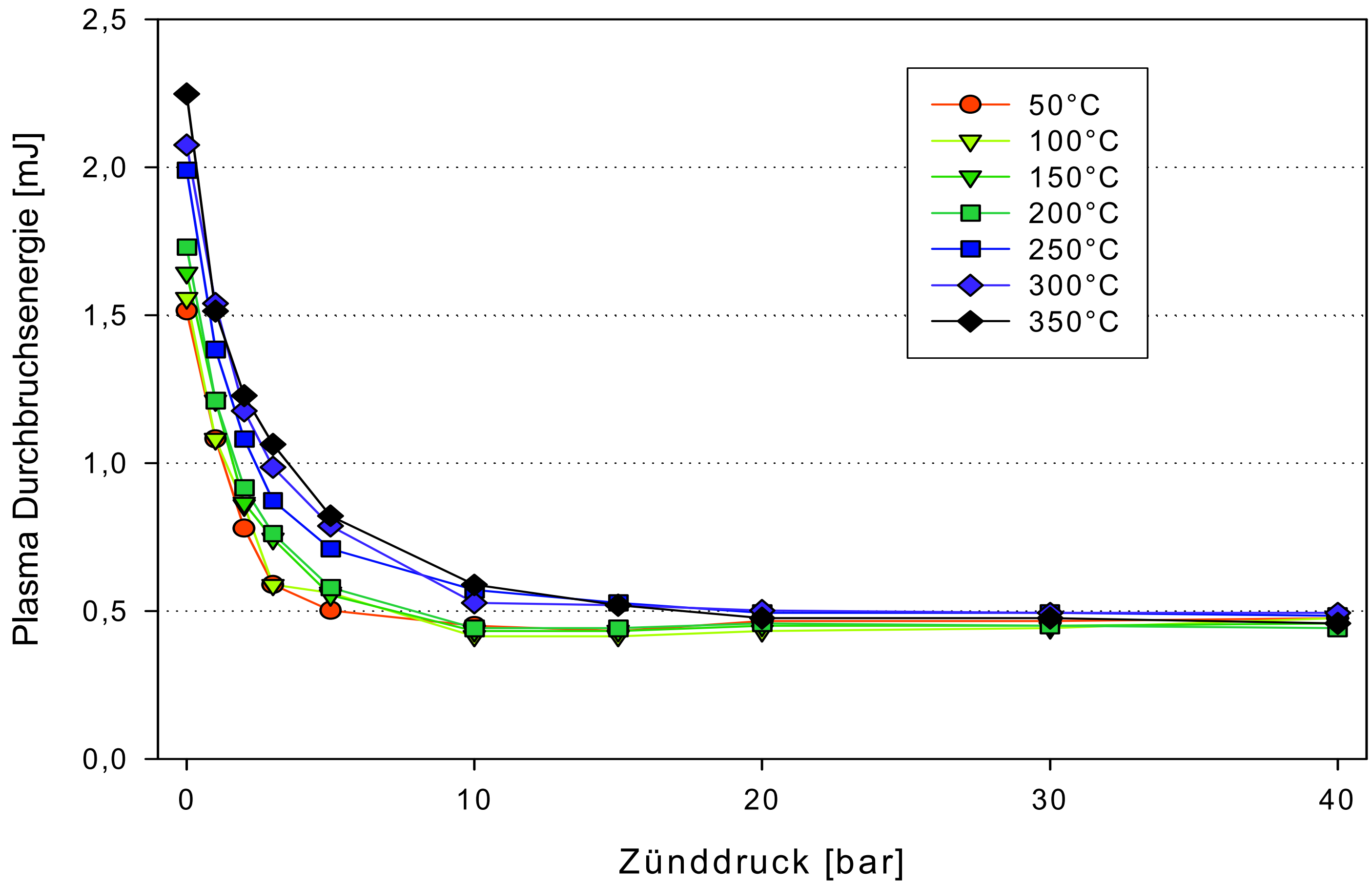
(c) Combination of IR and SH radiation.

(d) The electrons out of the green focus absorb the IR radiation.



Superposition of IR and SH n of equal intensity $I_0/2$: a) Zero and π/2 phase shift between the fields are shown. b) For non-monochromatic field superposition, the field amplitude can be much higher than for monochromatic field. For intensities > 10^{11} W/cm² the ionization cross section is increased [5].

Influence of temperature on plasma formation



Ignition pressure

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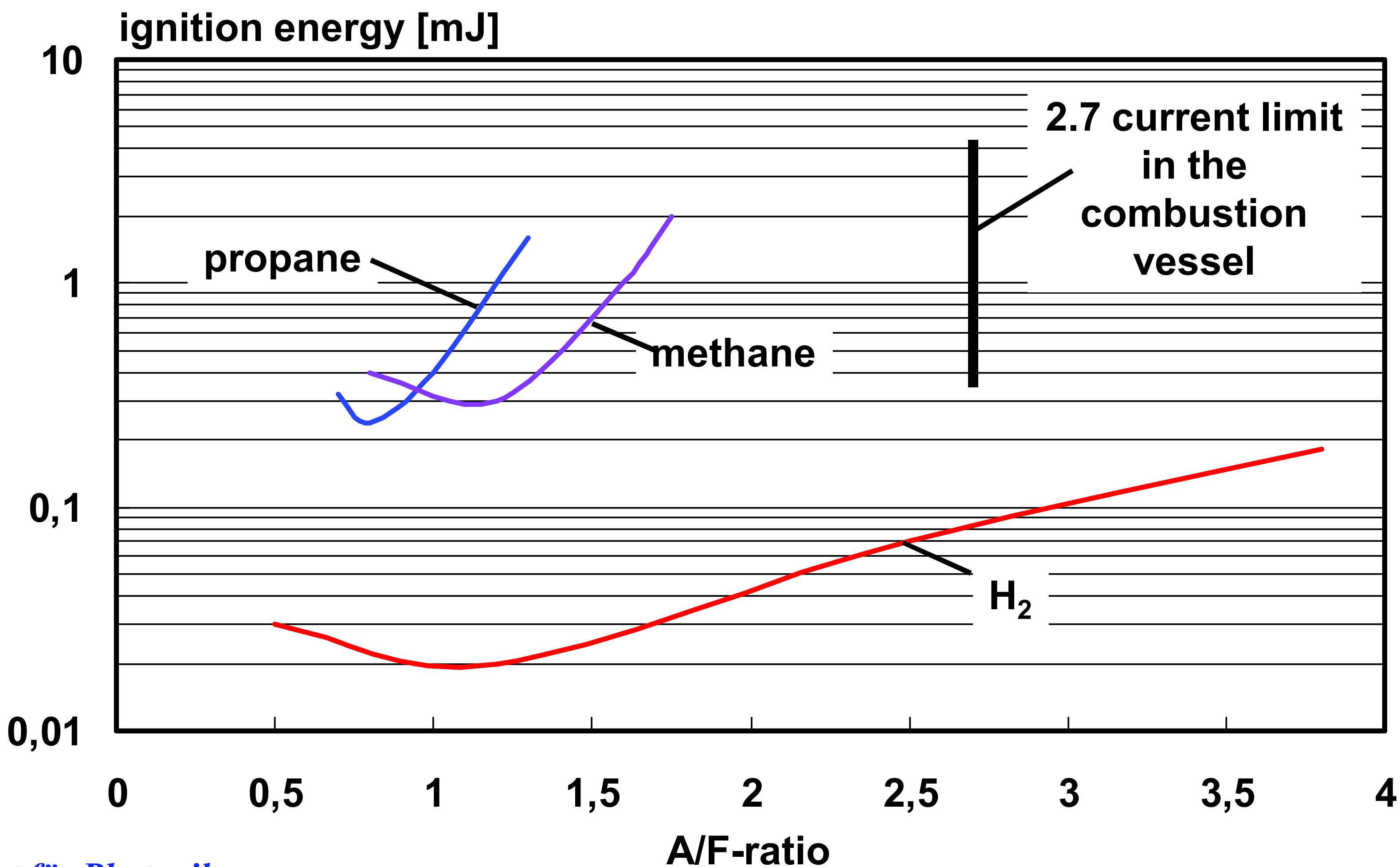
Minimum Ignition Energy
U. Maas/B. Lewis

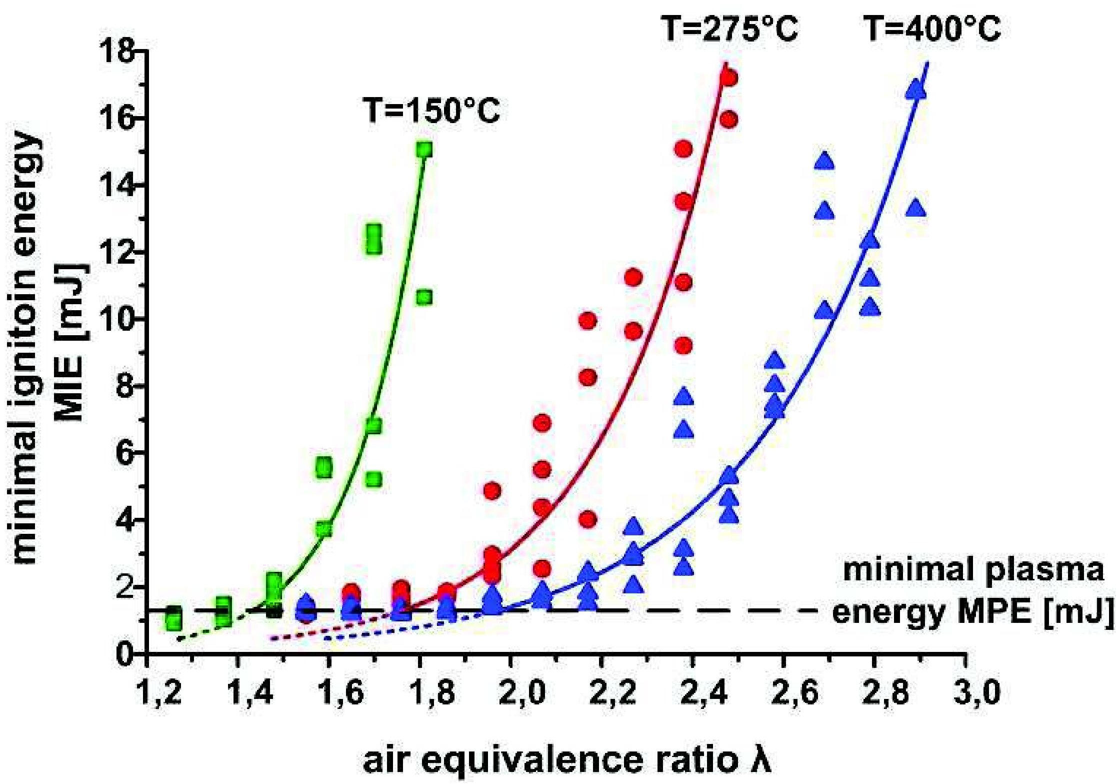


Minimum Ignition Energy vs. Excess Air Ratio λ for 3 Temperatures

Allows to define the requirements for the ignition laser

- < 5 ns pulse duration
- > 10 mJ pulse energy
- stable against mechanical & thermal stress

Methane-air mixture

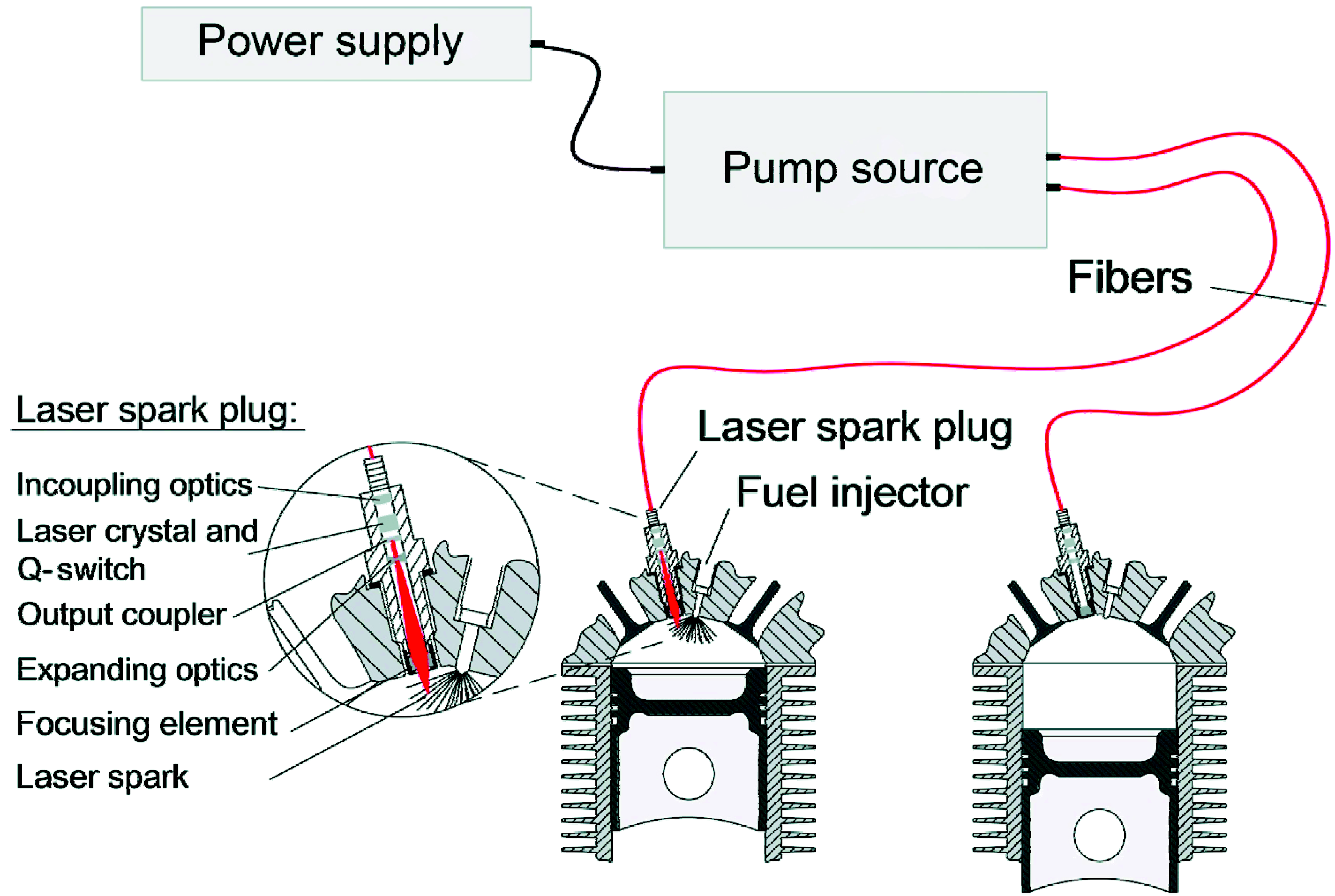


Selected Commercial Laser Systems

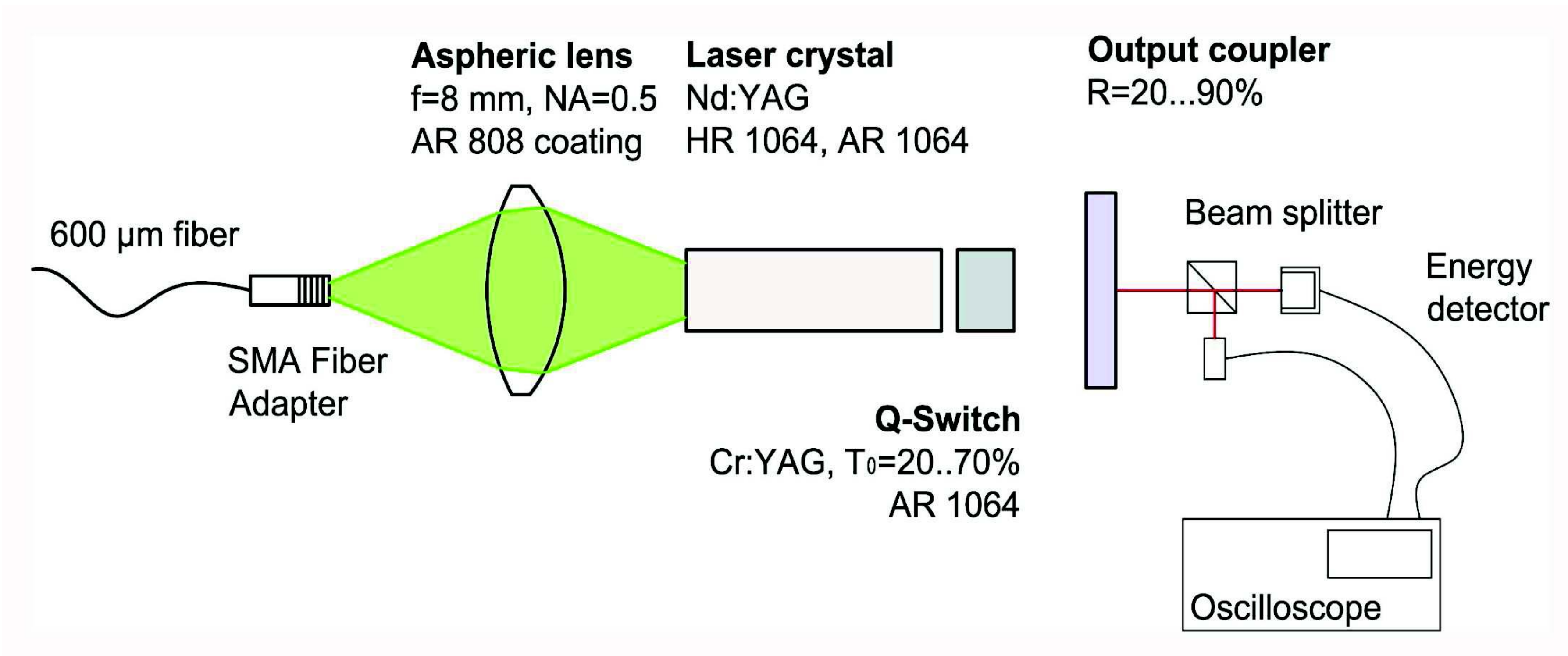
Q-switched
Nd:YAG Laser
pulse duration = 6 ns
wavelengths:
1064 nm, 532 nm, 355 nm
beam quality parameter M^2=1.8
and later M^2=1.1

Generally unsatisfactory!

Basic Setup of an "Ideal" Laser Ignition System



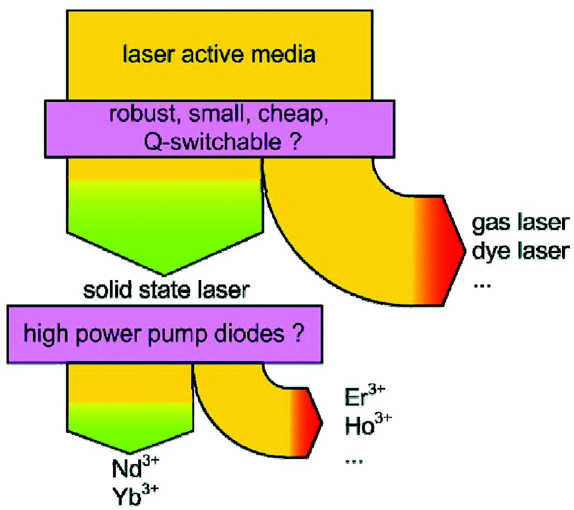
Setup of Developed Laser

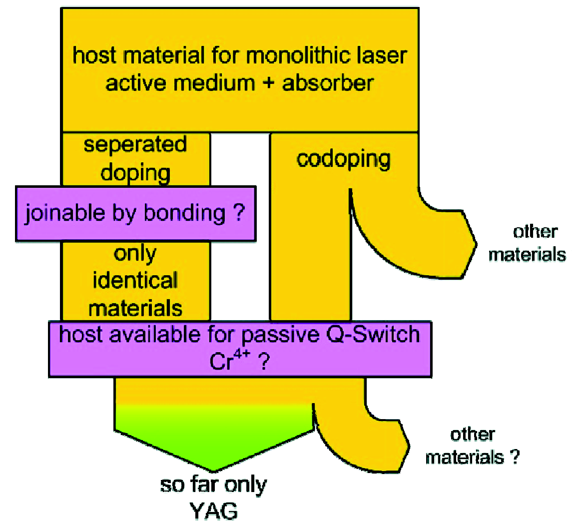


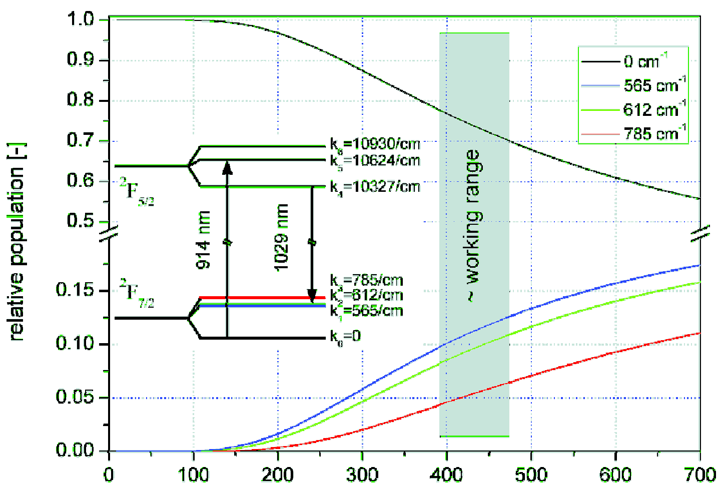
PhD thesis H. Kofler

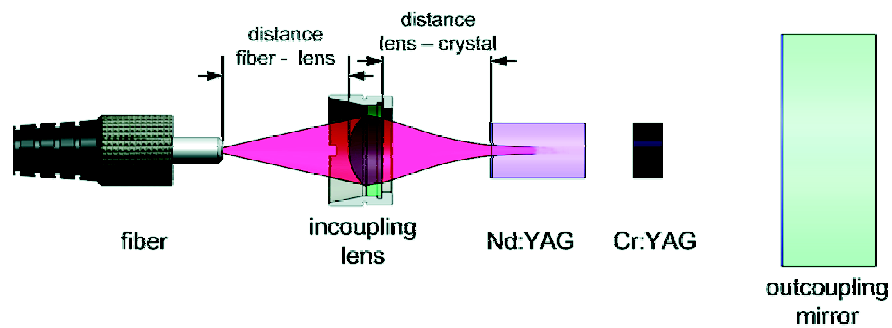
Laser Sparkplug Development

Selection of suitable laser materials and laser setup









Solid-state laser – longitudinally diode-pumped fiber-coupled – monolithic

Simulation

Rate equations

$$\frac{d\phi}{dt}=\left[\sigma N_i-\sigma_{13}N_g-\sigma_{24}\left(N_{g0}-N_g\right)-\frac{1}{2L_c}\left(\ln\frac{1}{R}+l_{rt}\right)\right]\phi c+\frac{N_i}{\tau}$$

$$\frac{dN_e}{dt}=\sigma_{13}N_g\phi c-\frac{N_e}{\tau_e}=-\frac{dN_g}{dt}\qquad\frac{dN_g}{dt}=-\sigma_{13}N_g\phi c+\frac{N_e}{\tau_e}$$

$$\frac{dN_i}{dt}=-\sigma N_i\phi c+W_p-\frac{N_i}{\tau}$$

Modell adapted
- for pulsed laser systems
- variable pump volume to achieve laser pulse formation at the end of pump pulse

ϕ	intracavity photon density	R	reflectivity of the output mirror
σ	stimulated emission cross-section	l_{rt}	round trip losses
N_i	instantaneous population inversion density	W_p	volumetric pump rate density
N_g	SA ground population density	L_c	cavity length
N_{g0}	SA total population density	c	speed of light
σ_{13}	SA absorption cross-section ground state	τ	lifetime upper laser level
σ_{24}	SA absorption cross-section excited state	τ_e	SA lifetime excited state
SA	saturable absorber		

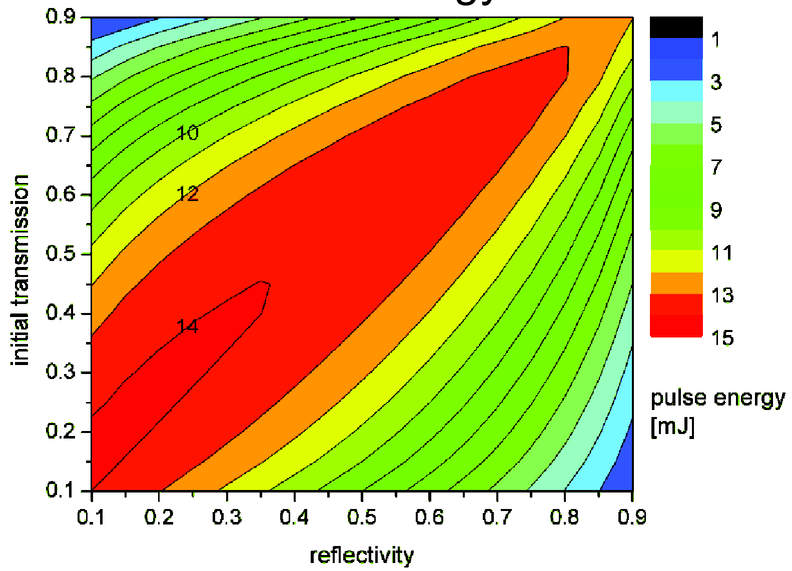
Simulation

Results

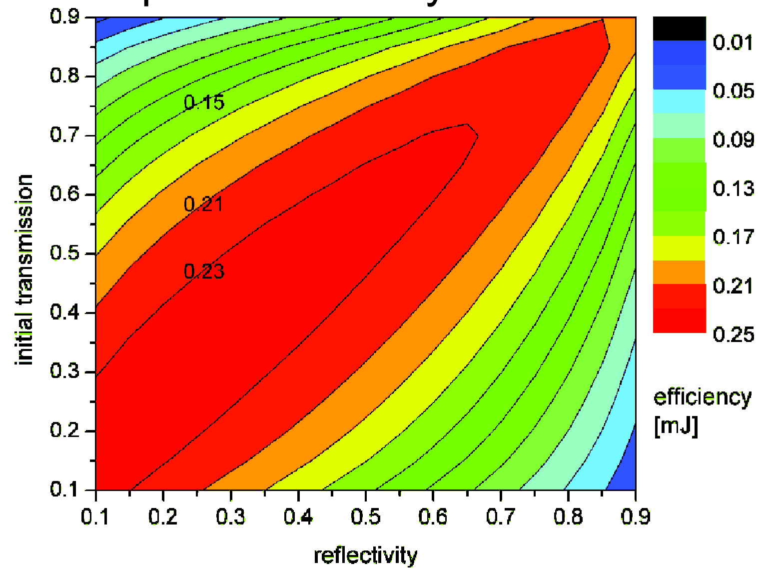
Assumptions:

- Pump duration: 200 µs
- Inversion lifetime: 240 µs
- Pump power: 300 W
- Length of cavity: 10 mm
- Reflectivity: 0.1-0.9 %
- Initial transmission: 0.1-0.9 %

Pulse energy



optical efficiency



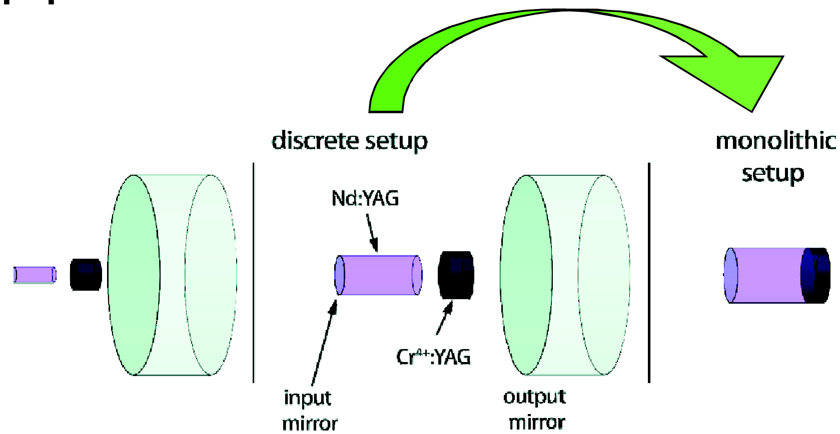
Simplified result → $R \approx T_0$

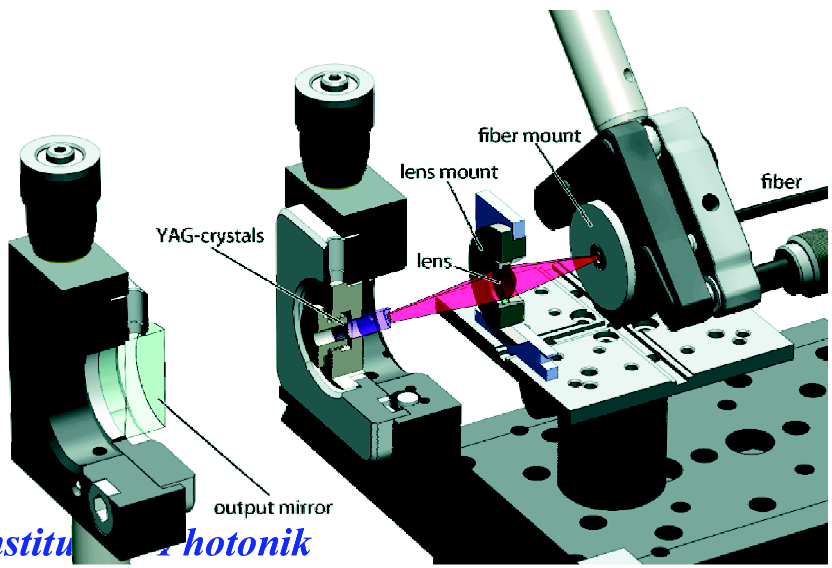
Adjustable Parameters

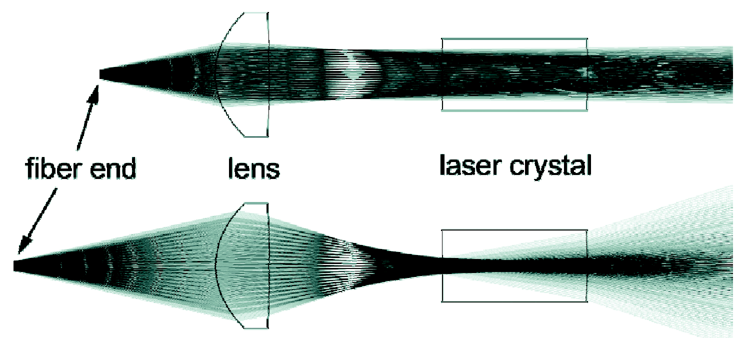
- **Laser crystal: Nd:YAG**
  - Doping: 0.8 – 1.4 %
  - Dimensions: Ø = 2-5 mm, l = 5-15 mm
- **Resonator length:**
  - 1 - 10 cm
- **Q–switch: Cr^{4+}:YAG:**
  - Initial transmission I_0: 10 – 80 %
- **Outcoupling mirror:**
  - Reflectivity R: 20 – 90 %
  - Curvature: no, konvex, konkave
- **Incoupling optics:**
  - Pump geometry
  - 1 or 2-lens system
- **Pump power:**
  - up to 600 W
- **Light waveguide:**
  - Ø 300 – 1000 µm
- **Repetition frequency:**
  - 20 Hz
- **Pump duration:**
  - up to 500 µs

Experimental Setup

Pump power: 70 W → 300 W → 600 W





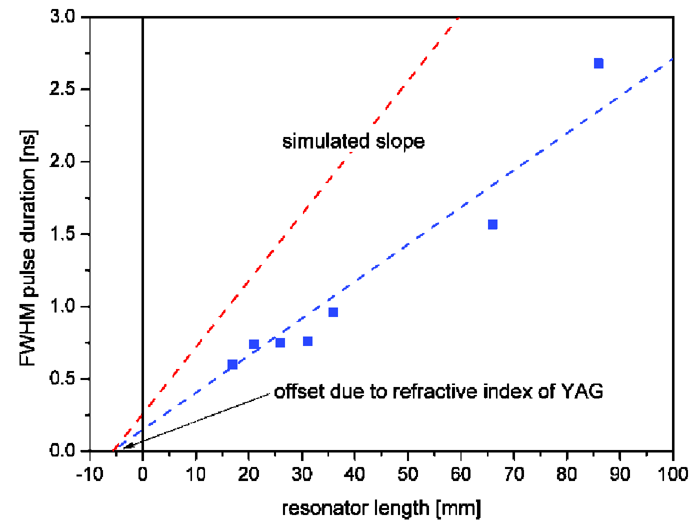


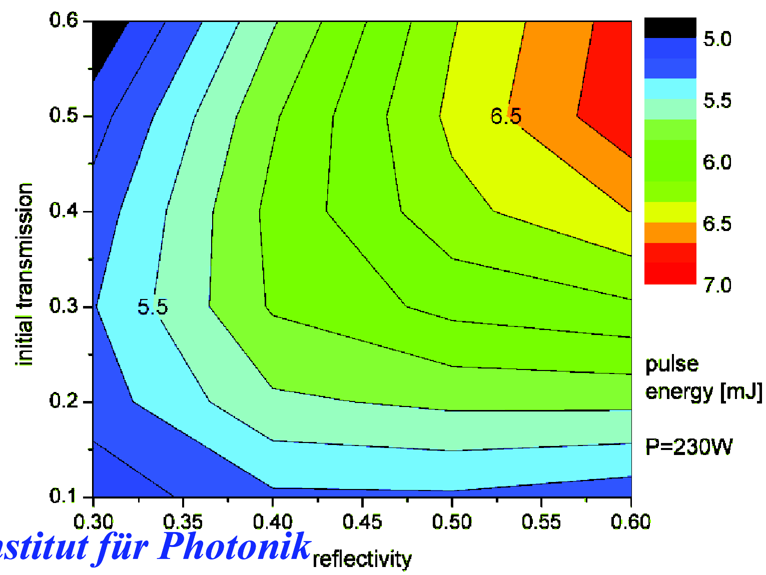
Experimental Results

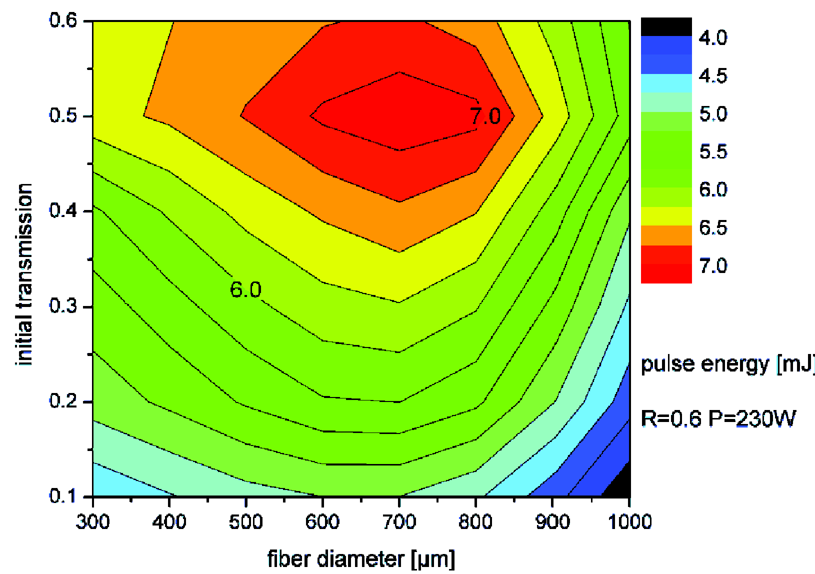
Pulse duration vs. resonator length

R: T_0 – Pulse energy

Fiber ∅:T_0 – Pulse energy

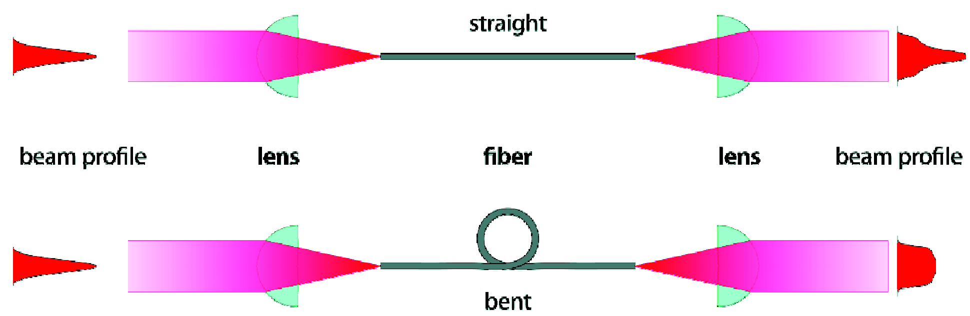


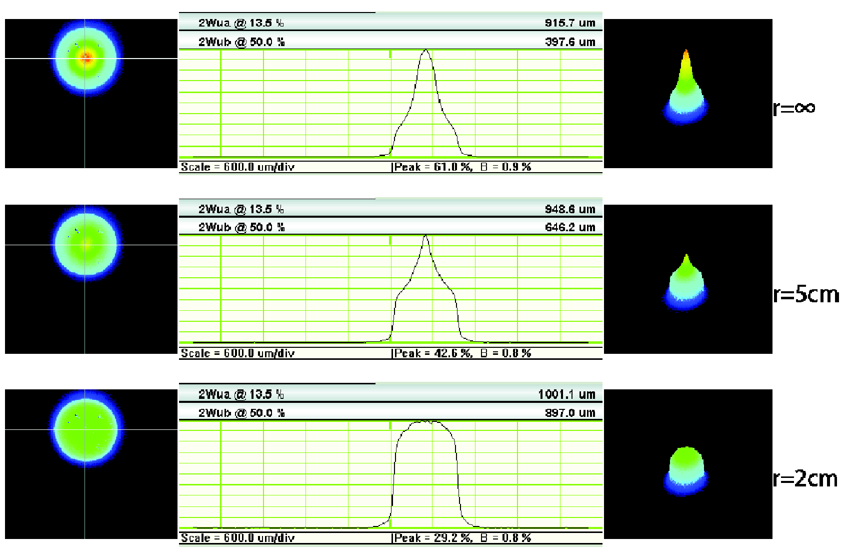


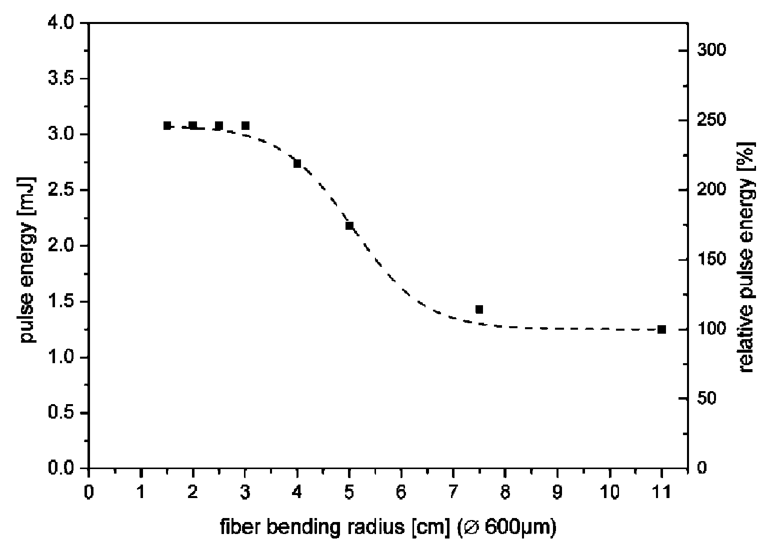


Experimental Results

Influence of pump light distribution







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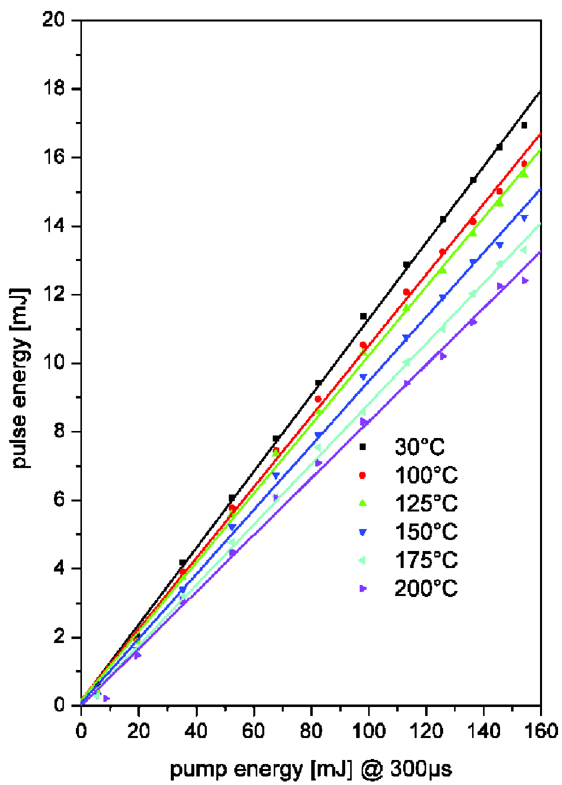
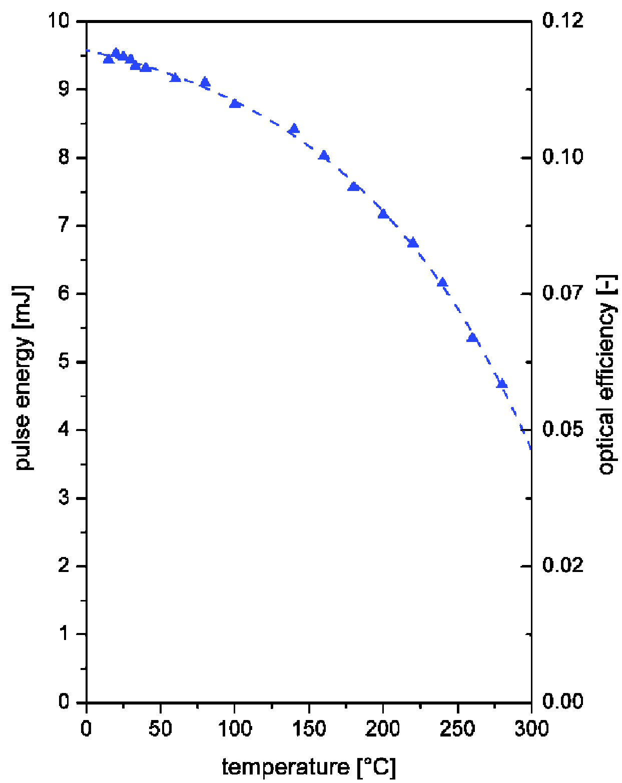
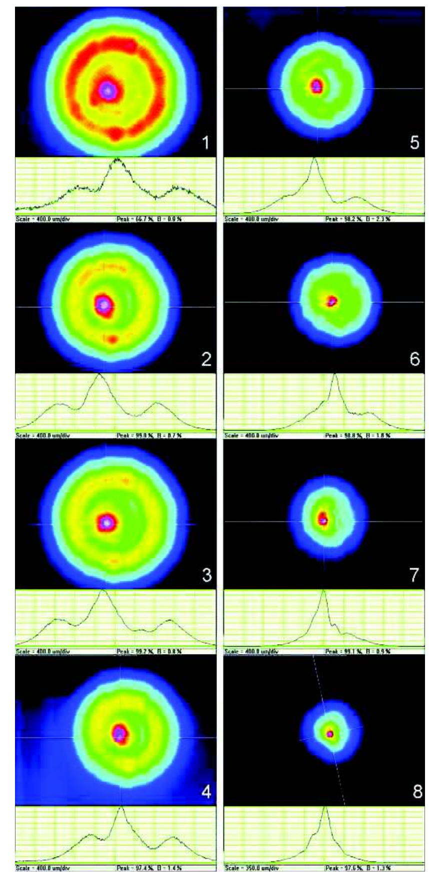
Experimental Results

Influence of temperature

- tested up to 275°C
- distruction limit of dielectric layers reduced
- operation at 150°C with no problems





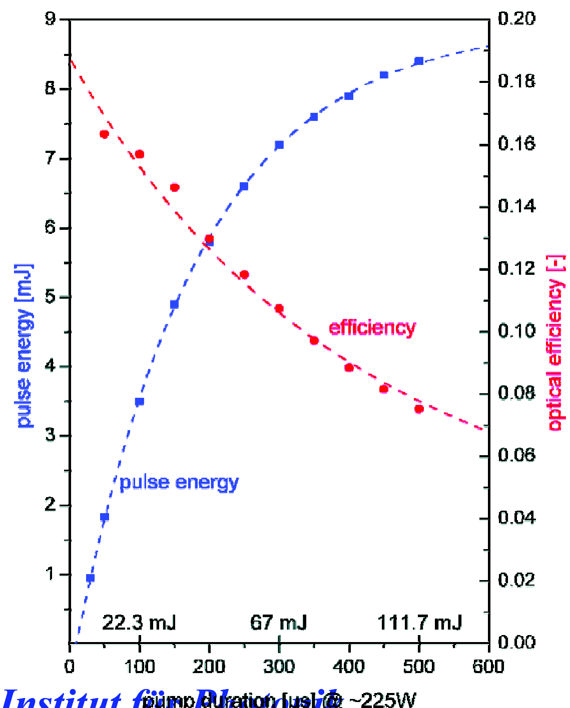


Experimental Results

Pump duration determines optical efficiency decisively

$$\eta_p = \frac{\tau}{t}\left[1-\exp\left(\frac{t}{\tau}\right)\right]$$

$$\tau \approx 235\ \mu s$$

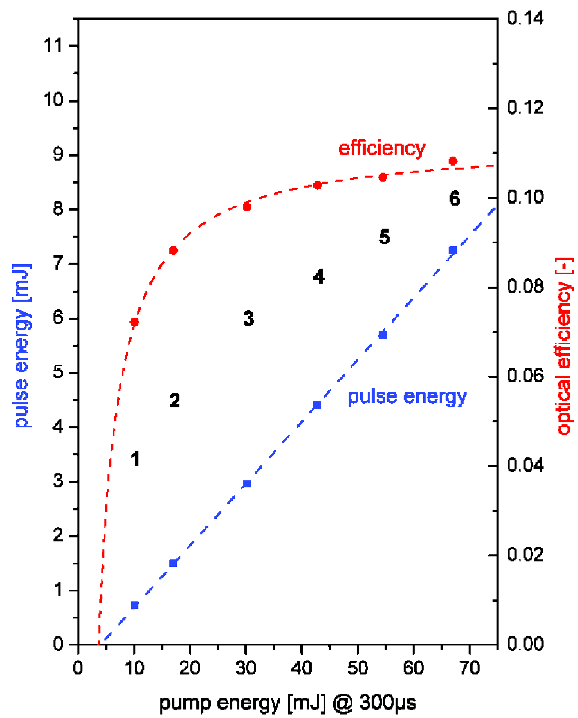


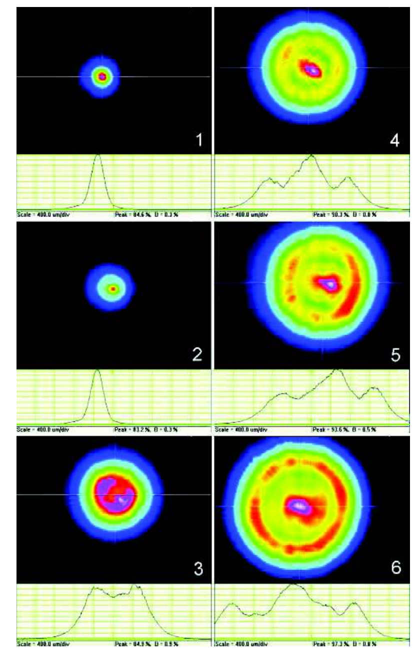
Beam quality of laser

- temperature dependant
- depending on pump energy (power)

$TEM_{00} \rightarrow TEM_{10}$ / TEM_{01*}

up till 17 mJ stable @ $M^2 \approx 2.8$



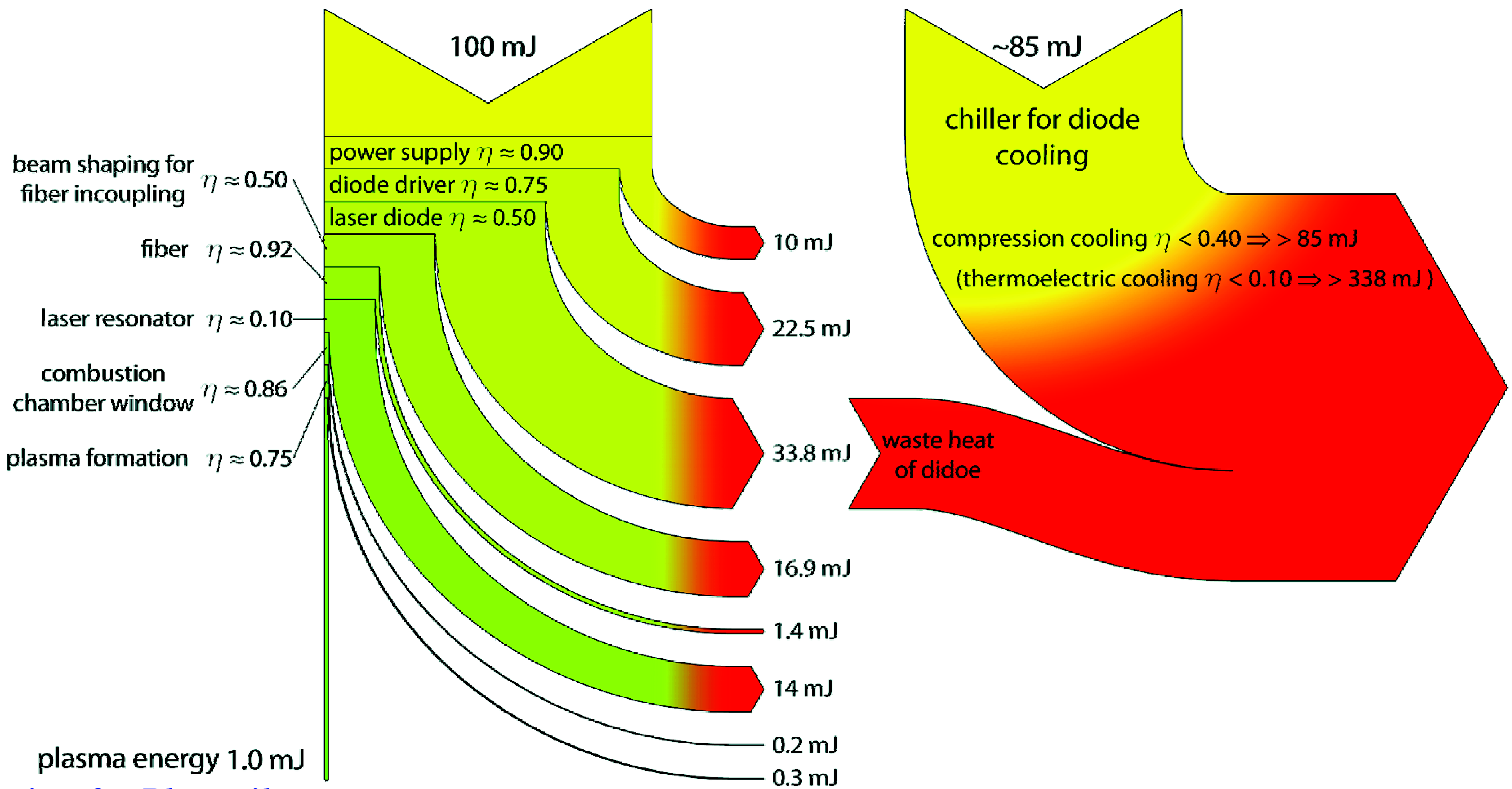


Experimental Results

Total efficiency

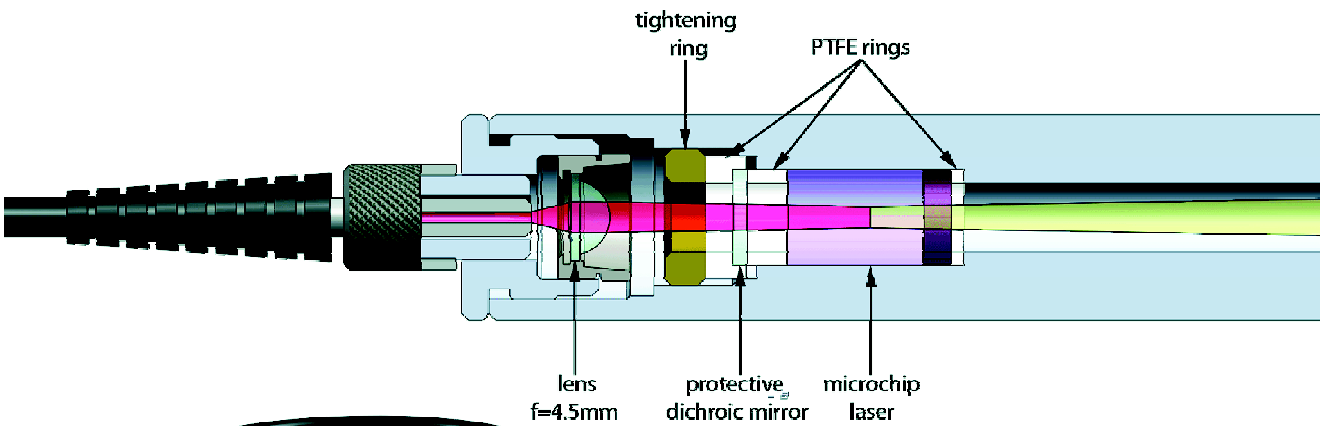
Laser only:
electrical energy → plasma energy
$\eta \approx 1\%$

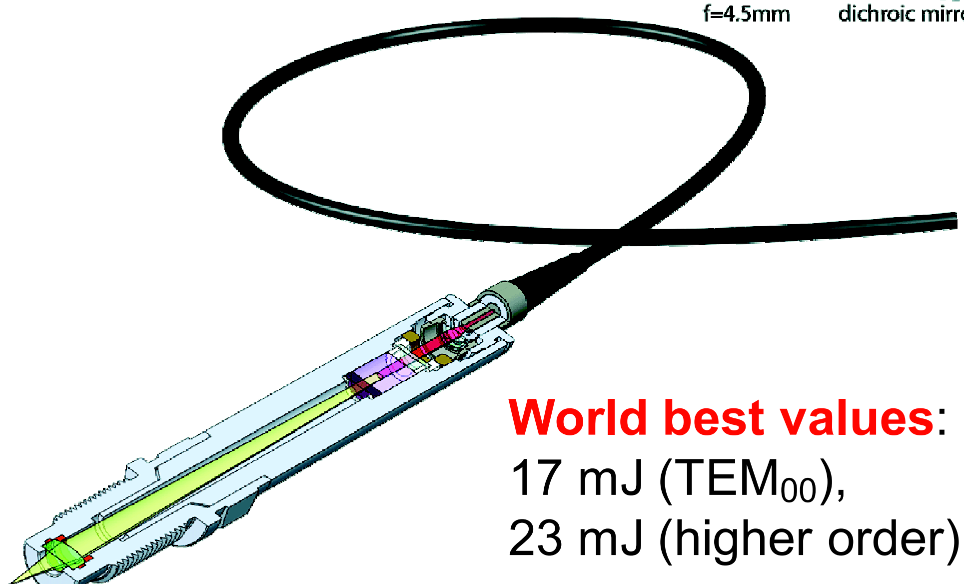
Laser + cooling:
electrical energy → plasma energy
$\eta \approx 0.5\%$ resp. $\eta \approx 0.2\%$

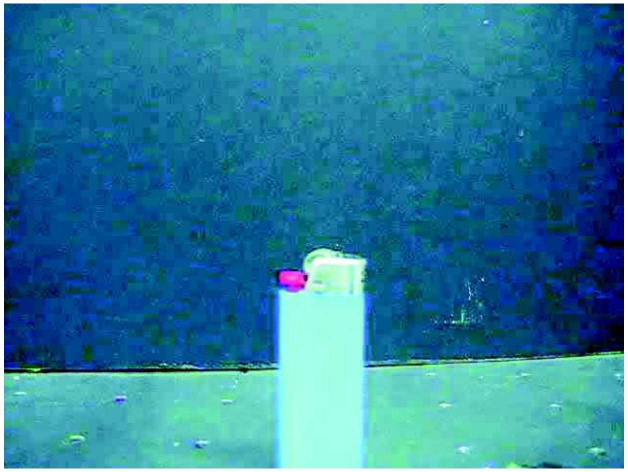


Experimental Results

Setup of laser sparkplug







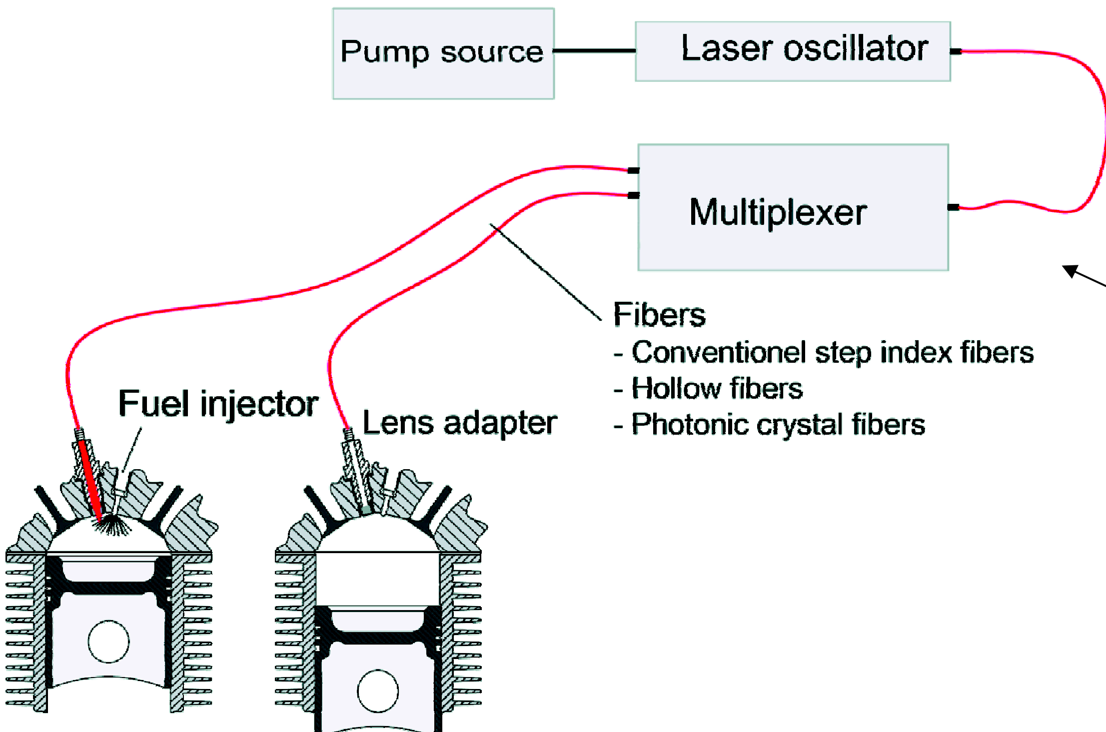
World best values:
17 mJ (TEM_{00}),
23 mJ (higher order)
1 – 1,5 ns duration

Institut für Photonik
Technische Universität Wien

Propagation of Ignition Pulses in Optical Fibers

(hollow coated capillaries or hollow core photonic crystal fibers)

Idea: Laser radiation produced off engine – no disturbing influences (e.g. ~160°C at GEJenbacher Gas Engine) or vibrations



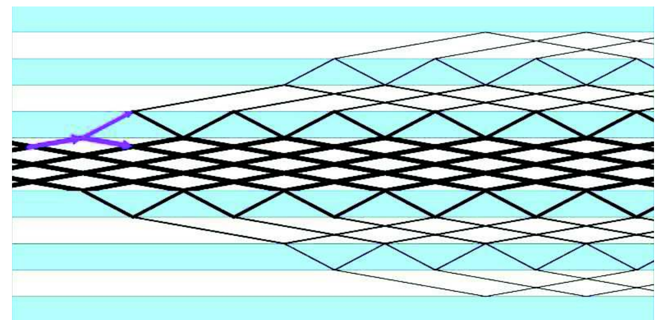
Optional: Multiplexer – distributes ignition pulses to several cylindes

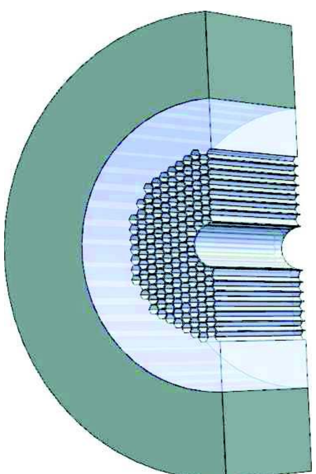
PhD thesis H. Tauer

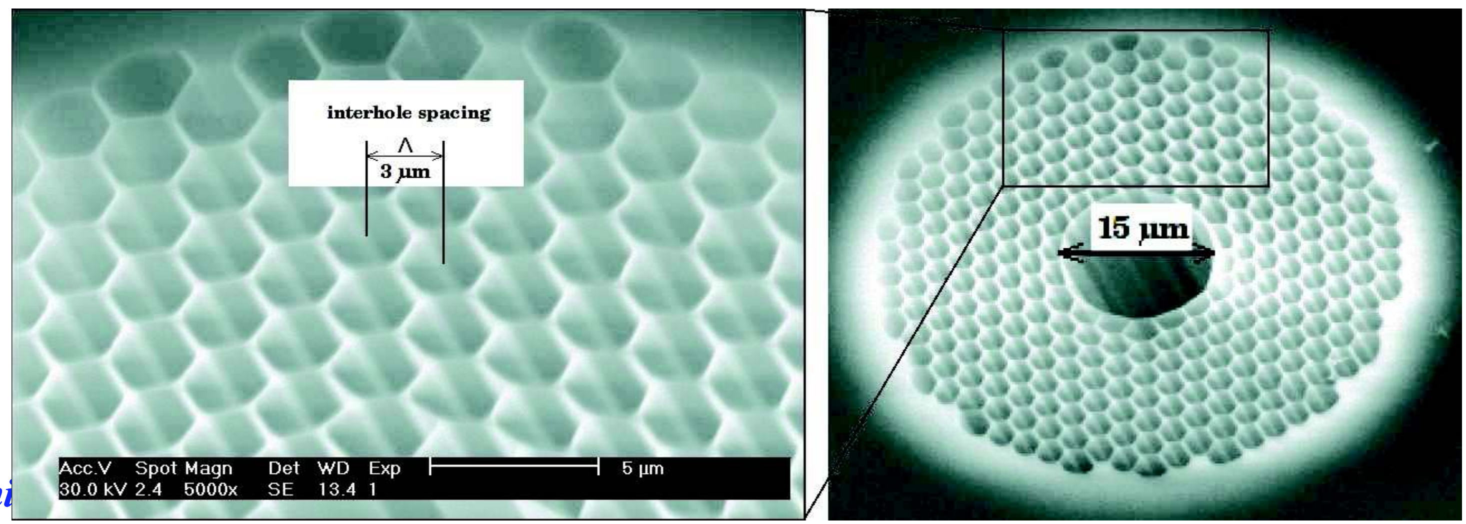
Propagation of Ignition Pulses in Photonic Fibers

Photonic Fibers: Light confinement via cellular structure

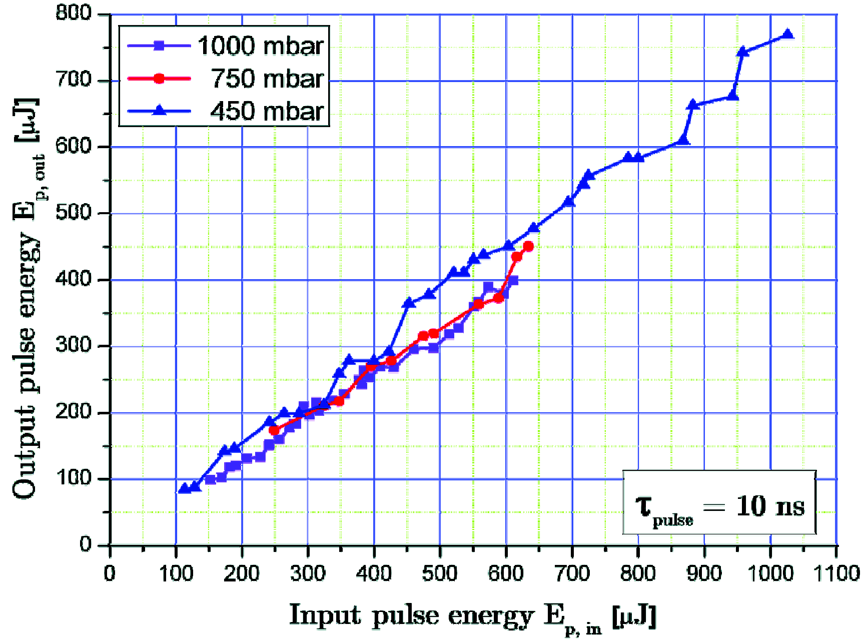
\+ excellent beam quality at exit,
hence good focusability!
\- available core diameters too small →
prone to damage of the cellular structure
\- bending?
\- very expensive (100-500 x more than SIF)







Propagation of Ignition Pulses in Photonic Fibers

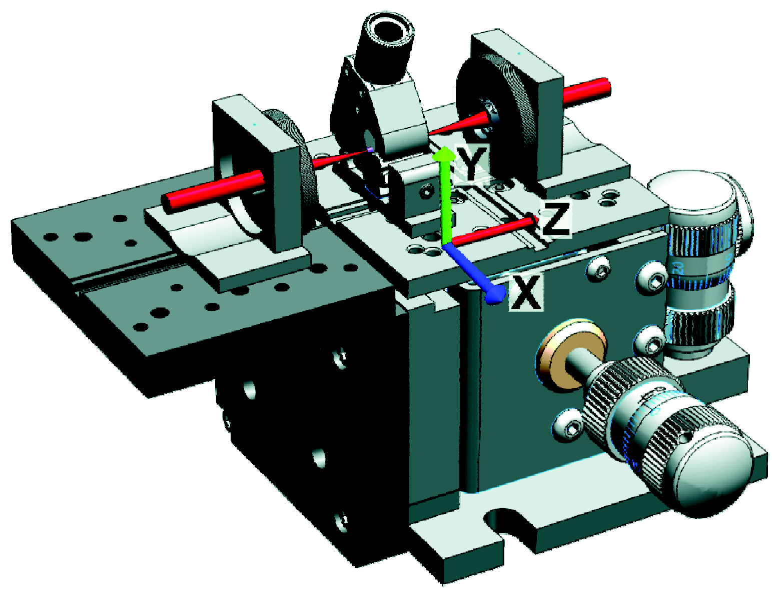


Best values of fiber coupling

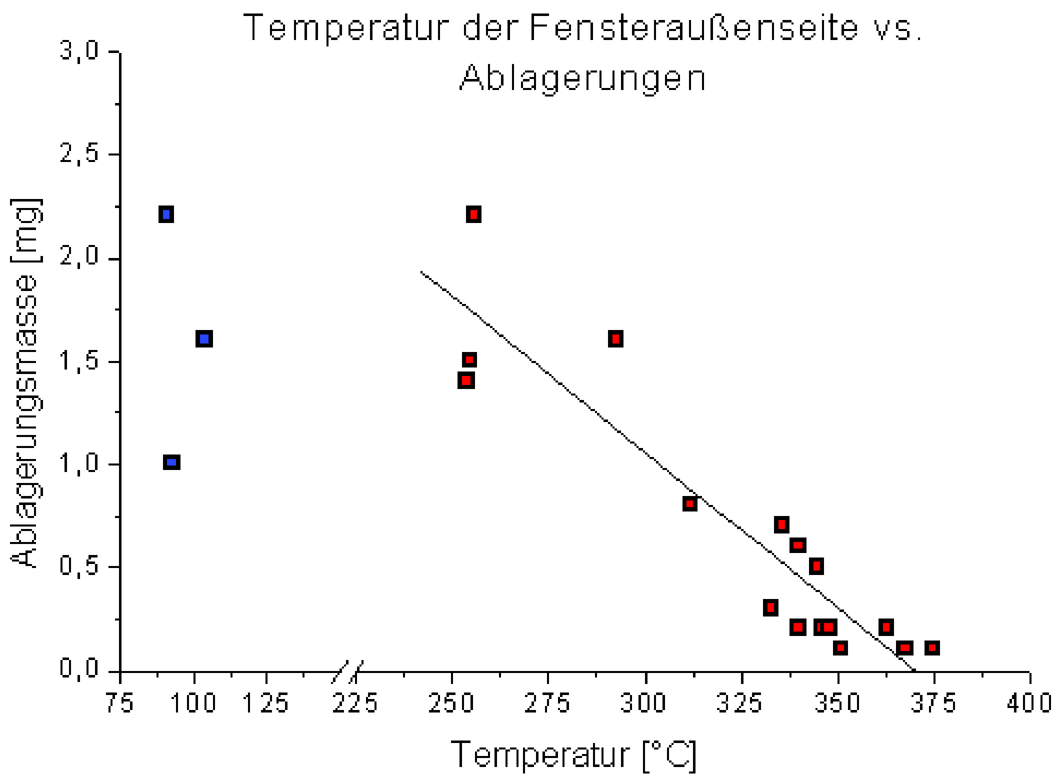
Summary:

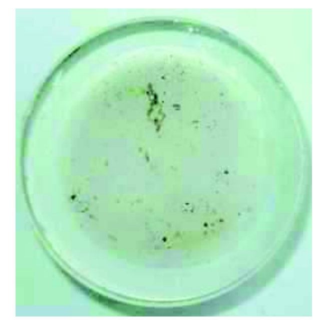
Fiber not suited for laser ignition as only ca. 1 mJ can be coupled in without fiber damage.

Higher energies potentially possible @ larger core diameters.

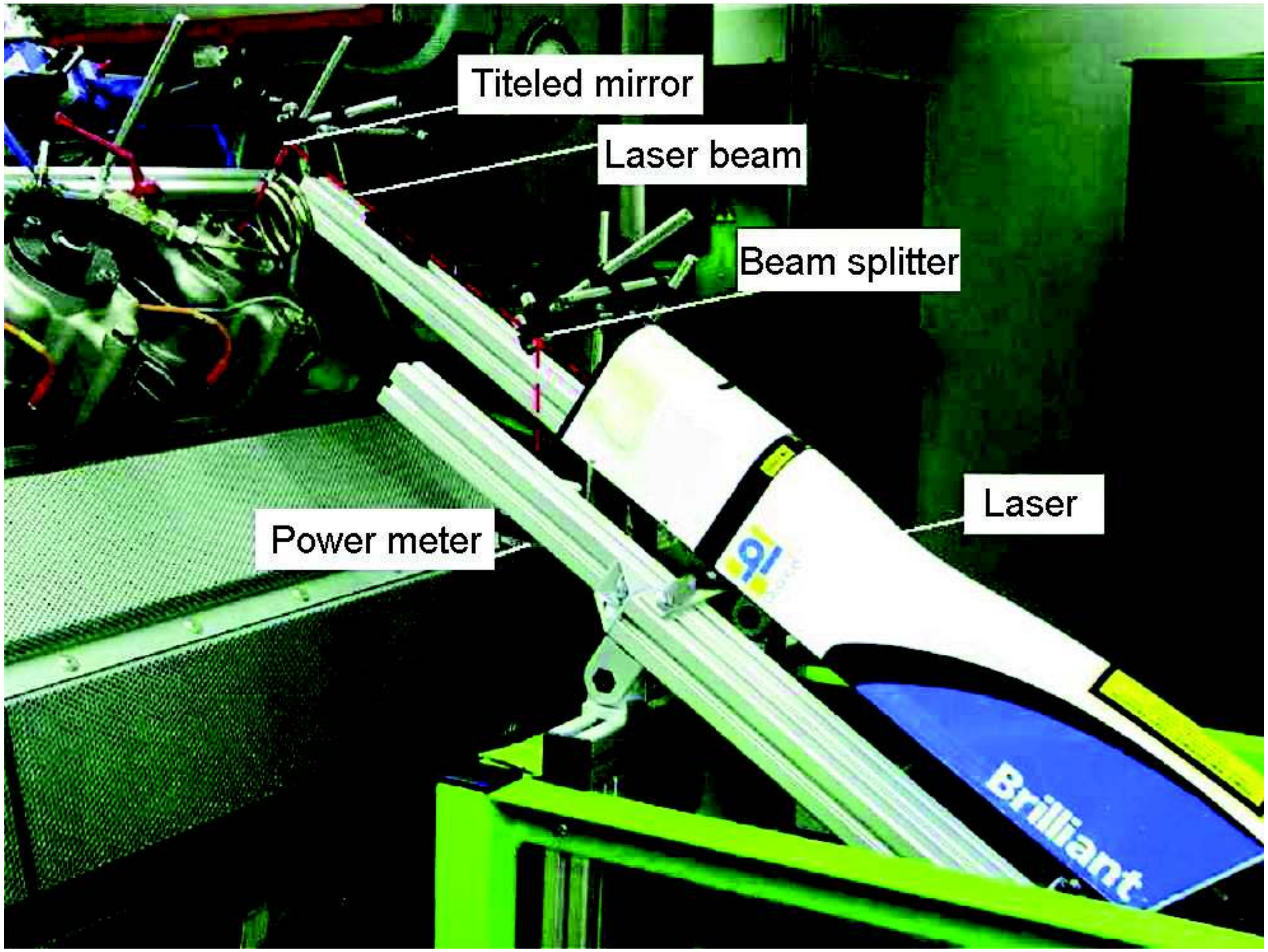


Depositions – Window Temperature



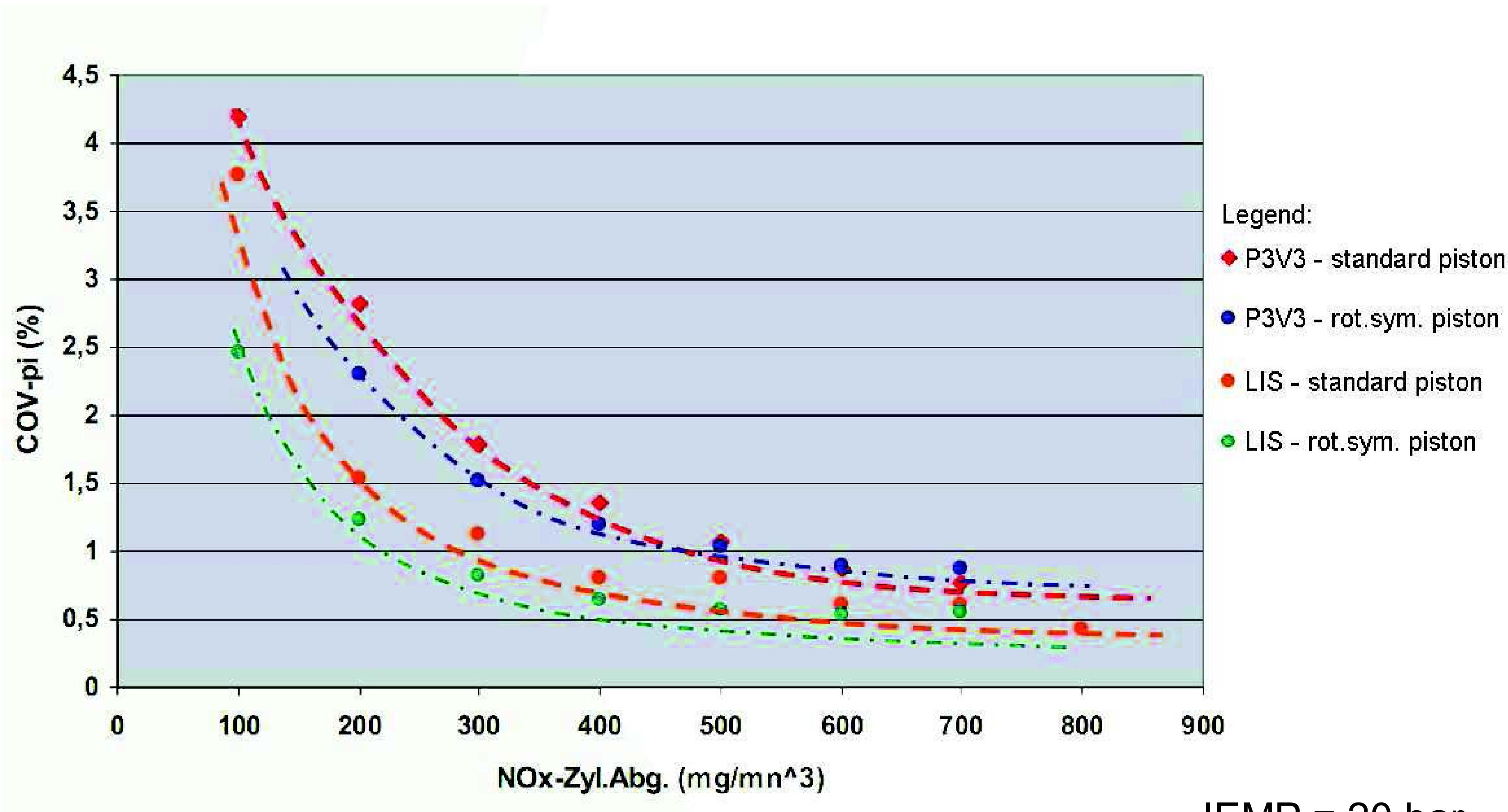


Engine Tests on J412 GEJenbacher Engine



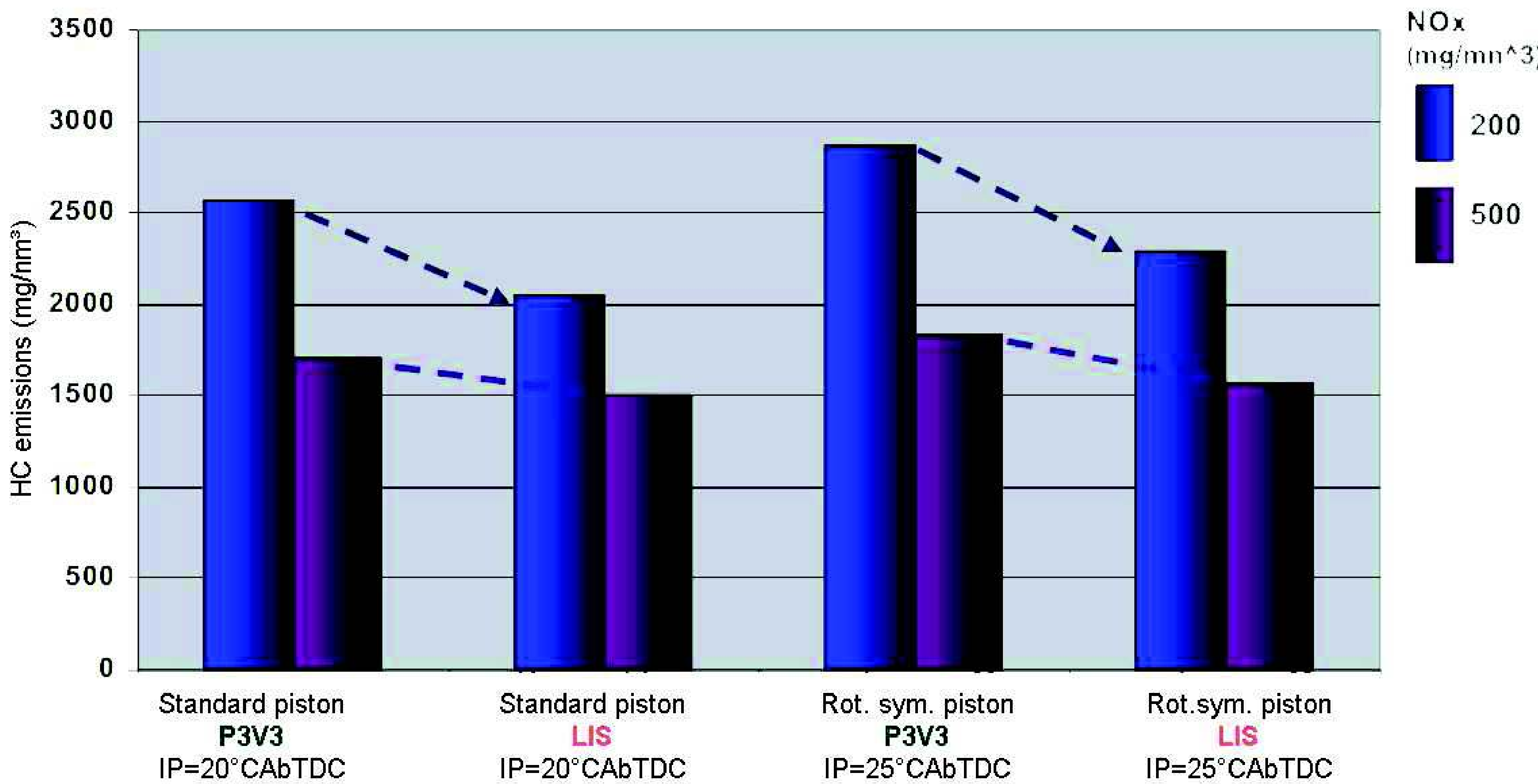
COV-pi vs. NOx Emissions

for LIS and standard ignition system (P3V3) for standard (heart-formed) piston bowl and rotation-symmetric piston bowl



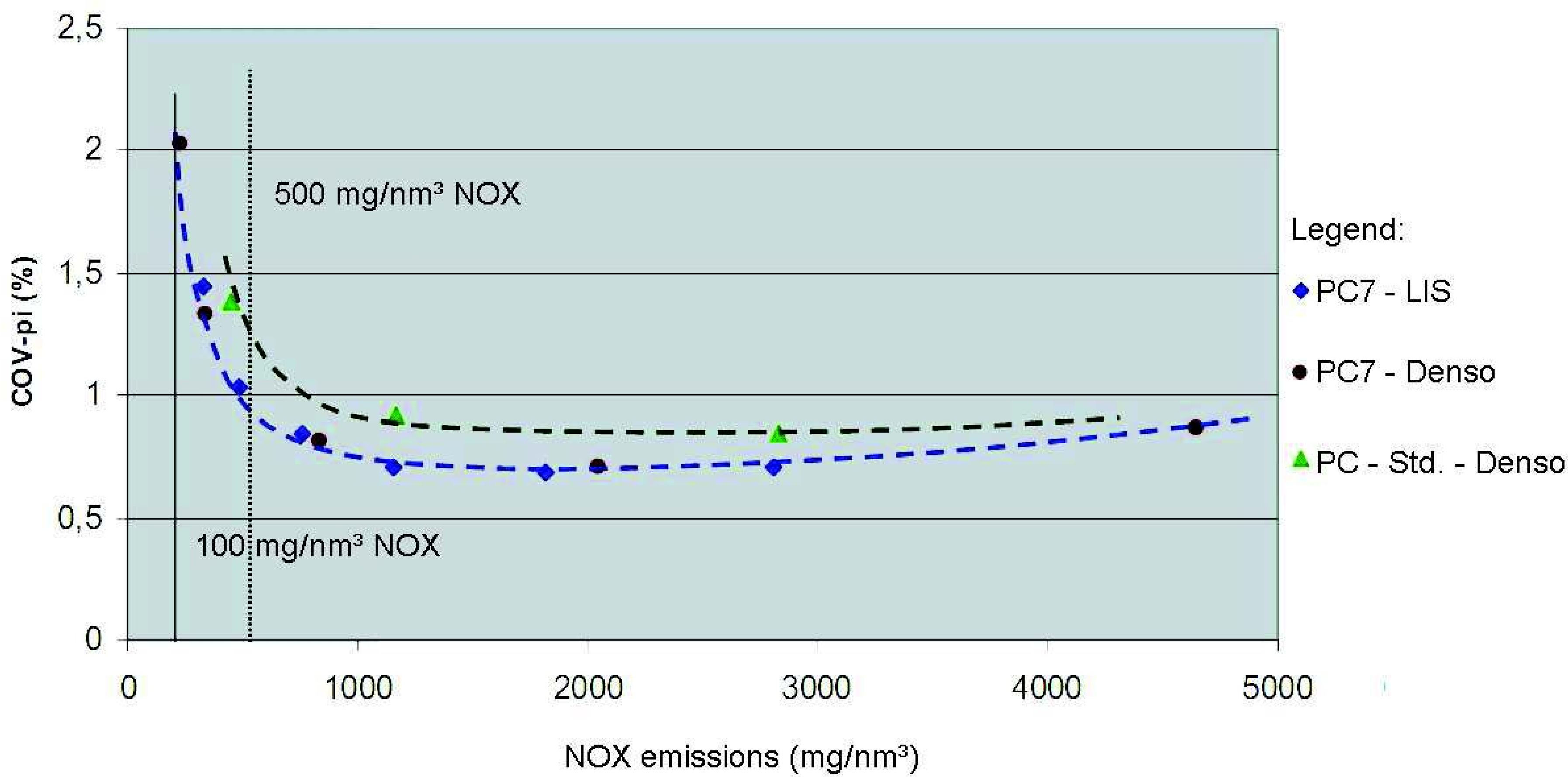
IEMP = 20 bar

HC Emissions for LIS and Standard Ignition System



IEMP = 20 bar, IP = ignition point

COV-pi versus NOx Emissions for Different Pre-chambers



IEMP = 22 bar; Ignition point = 22° CA b. TDC

Conclusions

→ Laser ignition affects advantageously the ignition of very lean mixtures – the COV-pi value for NO_x emission level < 200 mg/nm³ is definitely below the curve for a corresponding electrical ignition system

→ Generally, laser ignition tends to yield better smooth-ness of engine operation, but therefore also other parameters like pre-chamber design have to be taken into account

→ Shorter ignition delays leading to shorter burning times reducing losses are a potential benefit of laser ignition. Burning time: compromise between degree of turbulence and allowable flow velocity must be found

Conclusions

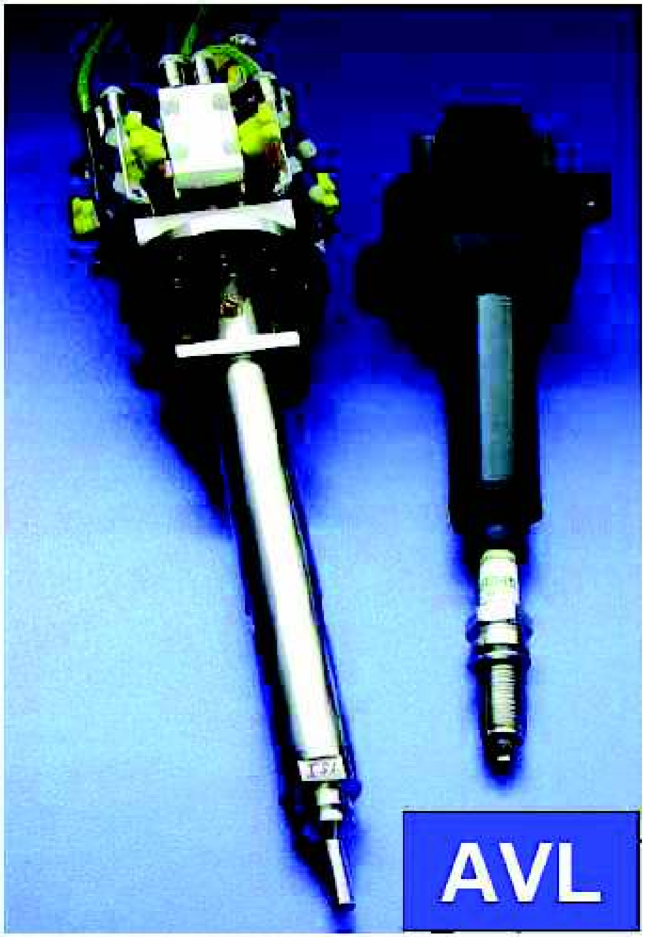
→ A high degree of turbulence influences a laser-induced spark not as much as it does on conventional electrically generated sparks to be attributed to the different lifetimes.

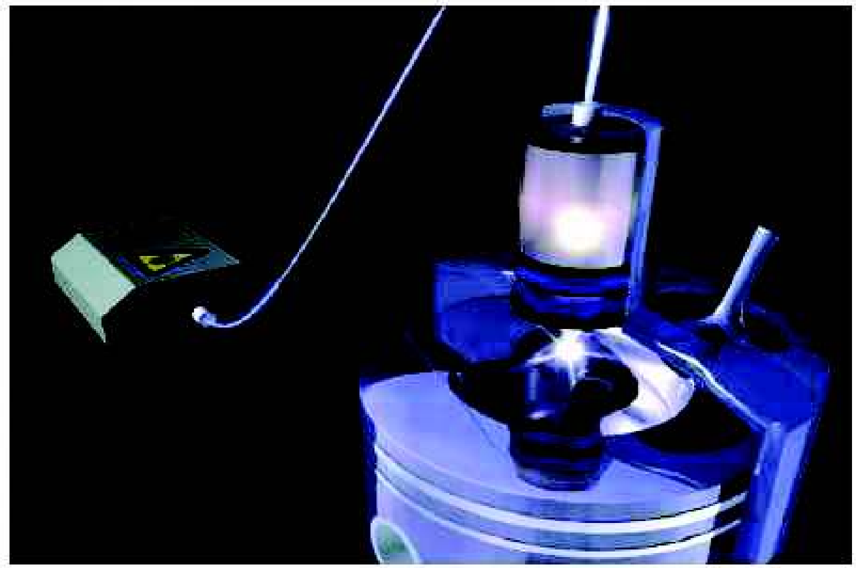
→ An increase in effective mean pressure of the engine prefers laser ignition, while conventional spark plugs suffer from increasing pressure in the chamber.

→ Focusing element: almost no differences observable between spherical or aspherical lenses. Even the focal position only slightly influences the combustion behavior.

→ Another potential benefit of laser ignition could be the longer maintenance intervals since laser ignition systems are unaffected by electrode erosion.

Alternative System: CTR - AVL





GE-Jenbacher

CTR - AVL
TU Vienna - GE Jenbacher

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