不安定共振器型マイクロチップレーザー

High brightness microchip laser with unstable cavity

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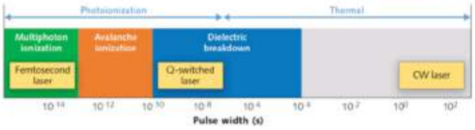
Outline

1. **Introduction**
   - Microchip lasers (MCL) and brightness for laser induced breakdown (LIB)
2. **Applications using MCL**
   - Laser ignition (LI)
     - Mechanism of pulse width scaling law of breakdown threshold in gas
   - Remote control laser induced breakdown spectroscopy (RC-LIBS)
     - MCL operation and SHG under high dose-rate irradiation
3. **Issue: brightness scaling-up of MCL**
   - MCL with unstable cavity
4. **Summary**

Laser induced breakdown (damage)

Laser
(τ, ω)



Matter

ΔT

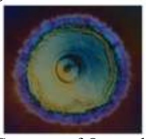
Plasma

Phase transition / breakdown (damage)

- Thermal explosion model
- Thermal lensing
- …

- Impact cascade (avalanche) ionization
- Photon ionization
- Kerr lensing for filamentation
- …

Damage on a dielectric coating



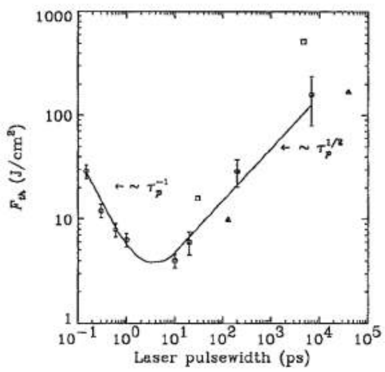
Courtesy of Quantel

Drilling in steel foils

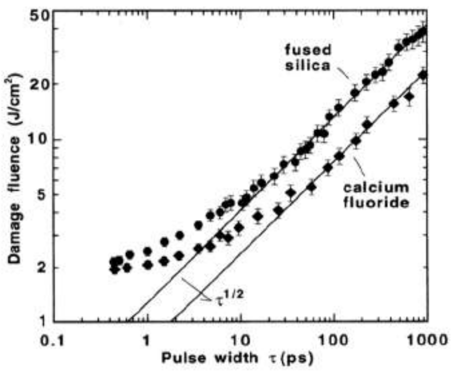
B. N. Chichkov, et. al. Appl. Phys. A **63**, 109 (1996).

Gas-lighter ignition using laser induced air-breakdown spark

LIB (damage) threshold vs. pulse width τ in fused silica

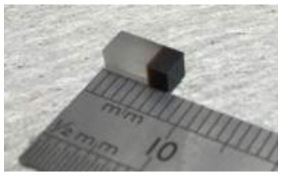


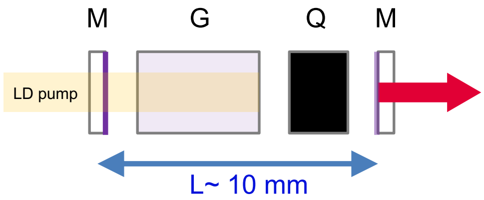
D. Du, et al., Appl. Phys. Lett. **64**, 3071 (1994).



B. C. Stuart, et al., Phys. Rev. Lett. **74**, 2248 (1995).

Microchip laser (MCL)



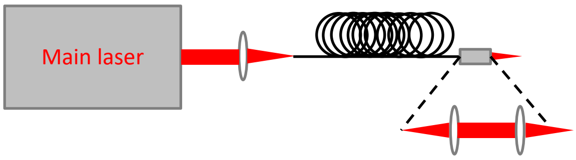


- Compactness
- Sub-ns giant pulse
- > MW peak power
- Single axial mode

Monolithic and coated
Ceramic material

- Simplicity
- Stability
- Low-cost

Fiber delivered laser vs. MCL



- Laser manufacturing
- Laser surgery
- Laser peening
- Remote laser induced breakdown spectroscopy (LIBS)

⋮

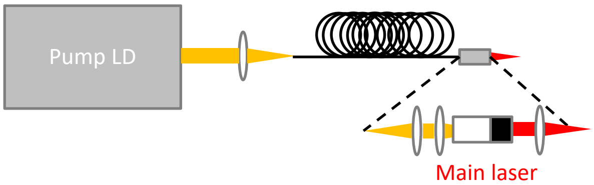
However,…trade-off between

	Peak power P_0 &	Beam quality M^2
Single mode fiber	☹	☺
Multi-mode fiber	☺	☹

→ Poor brightness $B \propto \frac{P_0}{(M^2)^2}$

→ Issue and challenge of developing high peak power resistant optical fibers such as hollow core and photonic crystal fibers

Fiber delivered laser vs. MCL

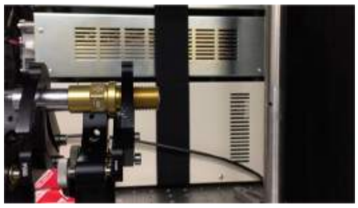


- Intense laser manufacturing
- Intense laser surgery
- Intense laser peening
- Laser ignition (I_b~TW/cm^2)
- Long-range remote LIBS

✓ Compactness

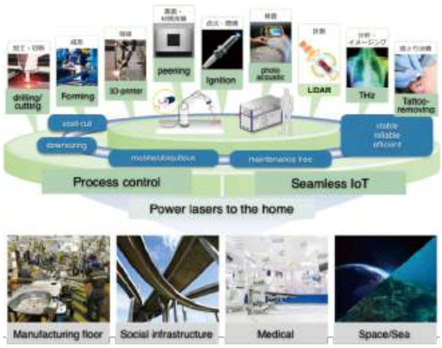
✓ High brightness

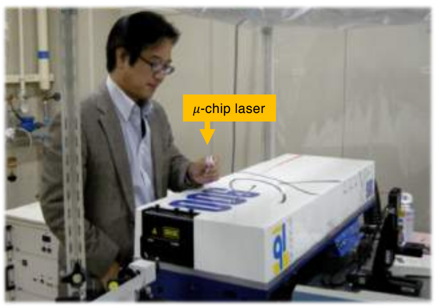
$$B \propto \frac{P_0}{(M^2)^2}$$



→ Issue and challenge of brightness scaling-up

Various applications using high brightness MCLs





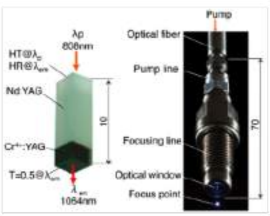
Application I: laser ignition

Advantages of laser ignition

- High degree of freedom of ignition point
- High-pressure and lean burn
- Multipoint ignition
- Fast flame propagation
- Less NOx emission

High thermal efficiency & less pollution

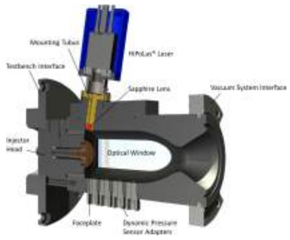
World's first laser ignited gasoline engine vehicle [1]



Monolithic Nd:YAG/Cr:YAG ceramic

Laser spark plug

Laser ignition for rocket engine [2]



Monolithic ceramic MCL can boost laser ignition field because of its high brightness, compactness, low cost, and stability!

[1] T. Taira, et. al., "World First Laser Ignited Gasoline Engine Vehicle," LIC'13, Yokohama, Japan, April 23-25, LIC3-1 (2013).

[2] C. Manfletti and G. Kroupa, "Laser ignition of a cryogenic thruster using a miniaturized Nd:YAG laser," Opt. Express 21, A1126 (2013).

Motivation

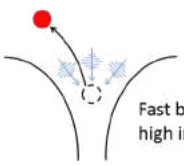
Laser ignition process

Ionization → **Plasma** → **Breakdown** → **Ignition**

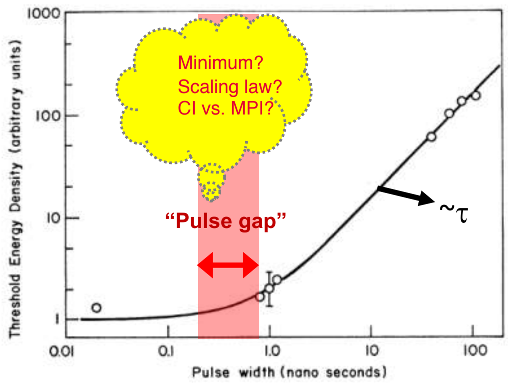
Cascade ionization (CI)

Slow due to collisional time!

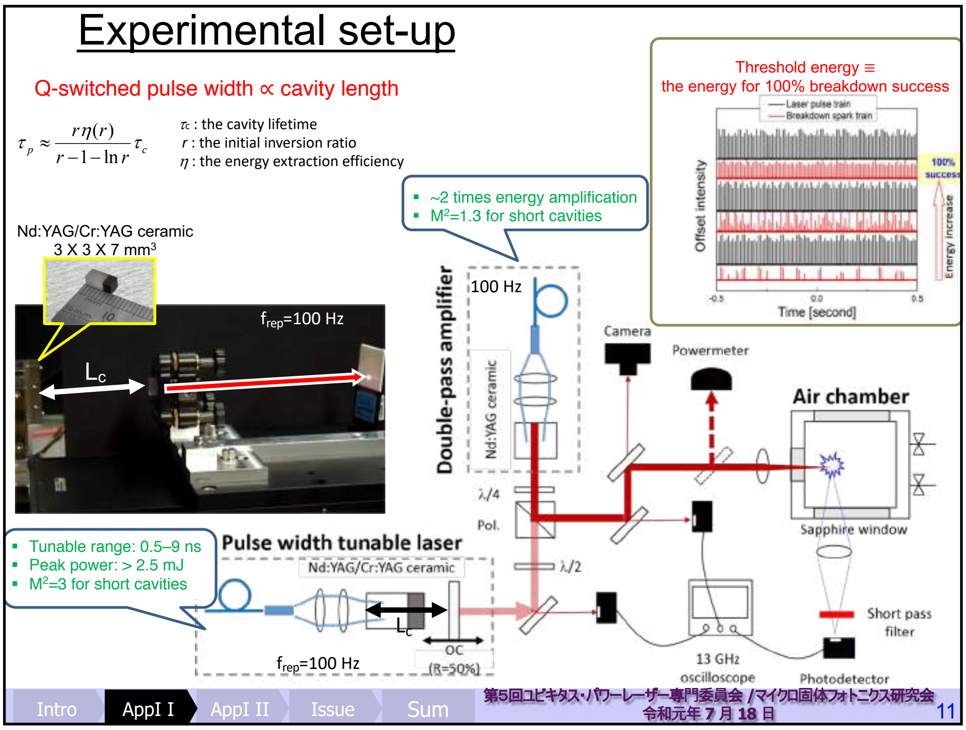
Multi-photon ionization (MPI)



Fast but high intensity!



C. C. Wang et al., Phys. Rev. Lett. **26**, 822, (1971).


Experimental set-up
Q-switched pulse width ∝ cavity length
$\tau_p \approx \frac{r\eta(r)}{r-1-\ln r}\tau_c$
τ_c : the cavity lifetime
r : the initial inversion ratio
η : the energy extraction efficiency
Threshold energy ≡
the energy for 100% breakdown success
Laser pulse train
Breakdown spark train
Offset intensity
Time [second]
100% success
Energy increase
~2 times energy amplification
M2=1.3 for short cavities
Nd:YAG/Cr:YAG ceramic
3 X 3 X 7 mm3
frep=100 Hz
Lc
Double-pass amplifier
100 Hz
Nd:YAG ceramic
Camera
Powermeter
Air chamber
λ/4
Pol.
Sapphire window
Tunable range: 0.5–9 ns
Peak power: > 2.5 mJ
M2=3 for short cavities
Pulse width tunable laser
Nd:YAG/Cr:YAG ceramic
λ/2
Lc
OC
(R=50%)
frep=100 Hz
13 GHz
oscilloscope
Short pass
filter
Photodetector
Intro
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Issue
Sum
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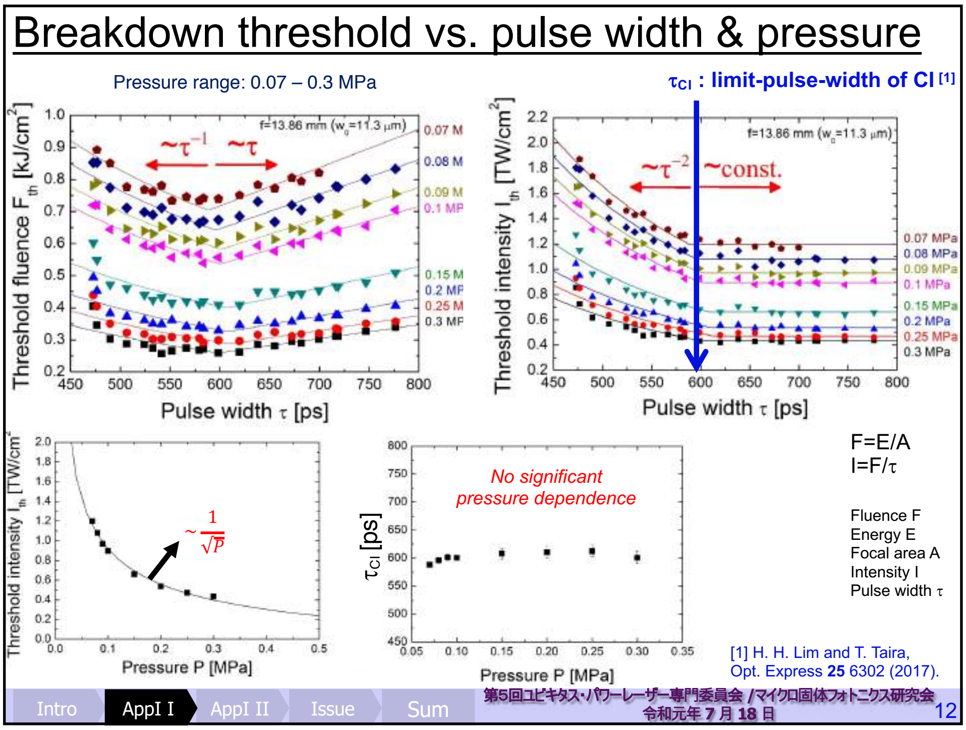
令和元年 7 月 18 日
11


Breakdown threshold vs. pulse width & pressure
Pressure range: 0.07 – 0.3 MPa
τCI : limit-pulse-width of CI [1]
Threshold fluence Fth [kJ/cm2]
f=13.86 mm (w0=11.3 μm)
~τ-1
~τ
0.07 M
0.08 M
0.09 M
0.1 MP
0.15 M
0.2 MP
0.25 M
0.3 MP
Pulse width τ [ps]
Threshold intensity Ith [TW/cm2]
~τ-2
~const.
0.07 MPa
0.08 MPa
0.09 MPa
0.1 MPa
0.15 MPa
0.2 MPa
0.25 MPa
0.3 MPa
Pulse width τ [ps]
Threshold intensity Ith [TW/cm2]
$\sim \frac{1}{\sqrt{P}}$
Pressure P [MPa]
τCI [ps]
No significant
pressure dependence
Pressure P [MPa]
F=E/A
I=F/τ
Fluence F
Energy E
Focal area A
Intensity I
Pulse width τ
[1] H. H. Lim and T. Taira,
Opt. Express 25 6302 (2017).
Intro
Appl I
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令和元年 7 月 18 日
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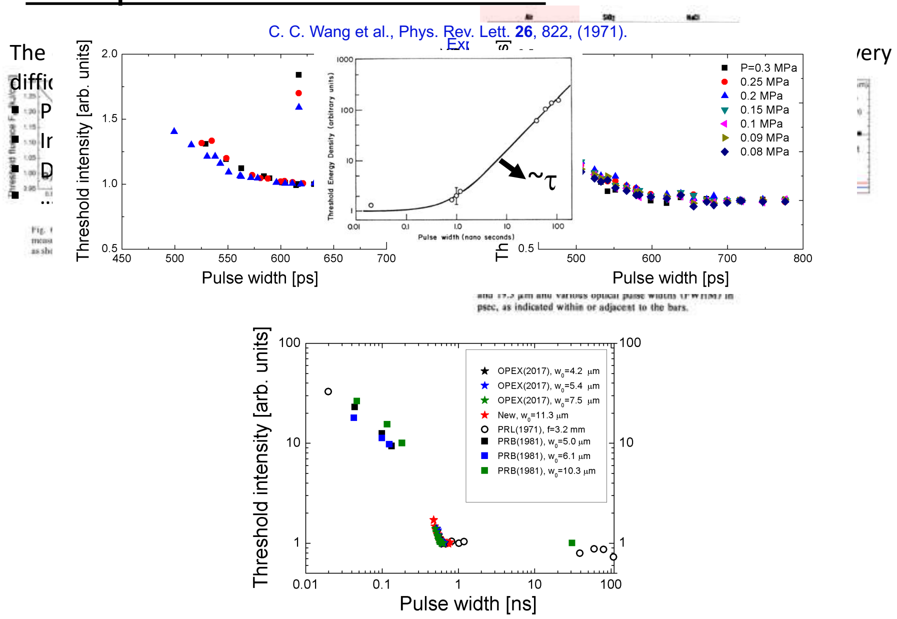
Comparison with other data



Theoretical model

- General rate equation of ionization process

$$\frac{dn_e(t)}{dt} = \eta_{CI} n_e(t) + \left[\frac{dn_e(t)}{dt}\right]_{PI} - \left[\frac{dn_e(t)}{dt}\right]_{loss}$$

- Proposed rate equation of ionization process

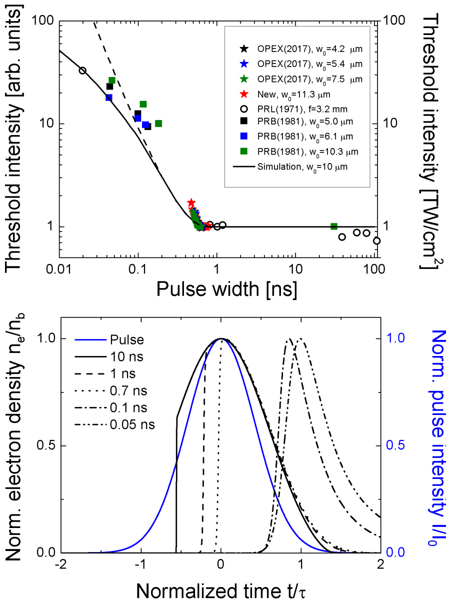
$$\frac{dn_e}{dt} = \eta_{CI} n_e + \left[\frac{dn_e}{dt}\right]_{MPI} - D\nabla^2 n_e - \alpha_r n_e^2 - \beta_r n_2^3$$

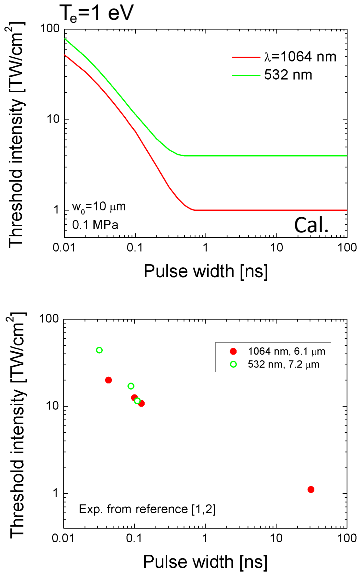
- $D\nabla^2 n_e$: Electron diffusion loss out of focal volume
- $\alpha_r n_e^2$: Two-body recombination loss
- $\beta_r n_2^3$: Three-body recombination loss

Simulation: I_{th} vs. τ

The electron density for breakdown
$n_{br}=2.8\times10^{18}$ cm^{-3}

$v_s=0.5\times10^{8}$ cm/s
$T_e=1$ eV

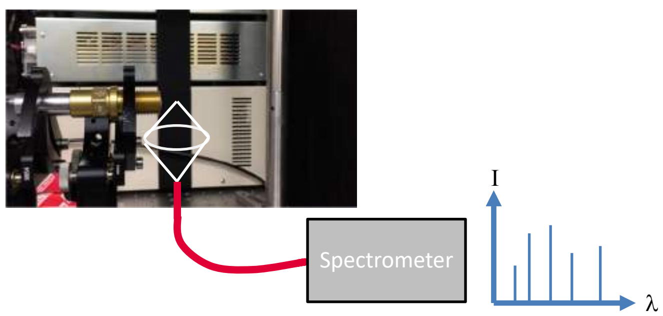




[1] For 1064 nm, E. V. Stryland et. al., Phys. Rev. B 23, 2144 (1981).
[2] For 532 nm, W. E. Williams et. al., Appl. Phys. Lett. 43, 352 (1983).

Application II: Long range remote control LIBS

Laser induced breakdown spectroscopy (LIBS)



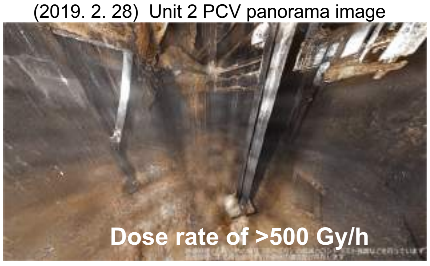
Advantages

- Versatile sampling of solids, gases or liquids.
- Little or no sample preparation is necessary.
- Almost non-destructive.
- Permits analysis of extremely hard materials that are difficult to digest or dissolve.
- Local analysis in microregions offers a spatial resolving power of ~1-100μm.
- Possibility of simultaneous multi-elemental analysis.
- Simple and rapid analysis (ablation and excitation processes are carried out in a single step)…

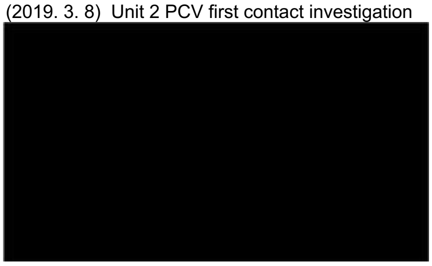
Long range remote control LIBS for harsh environments such as the meltdown inside Fukushima reactor

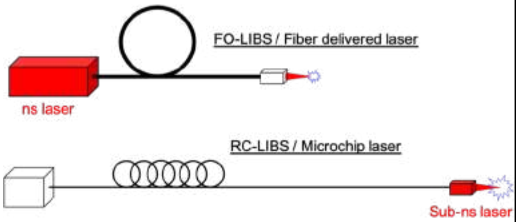
(2018. 1. 22) Unit 2 PCV internal investigation

(2019. 2. 28) Unit 2 PCV panorama image

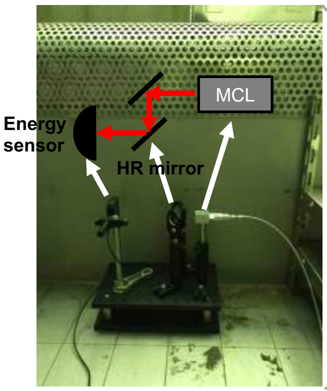


(2019. 3. 8) Unit 2 PCV first contact investigation



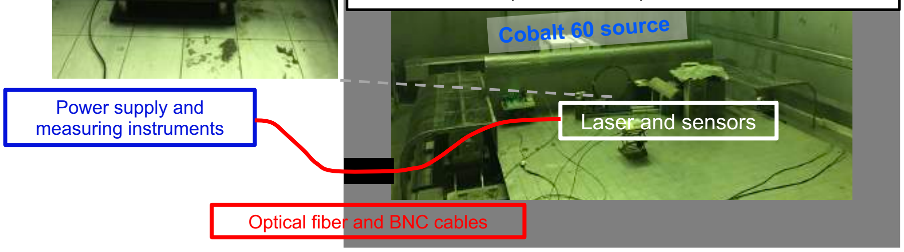


Experimental set-up

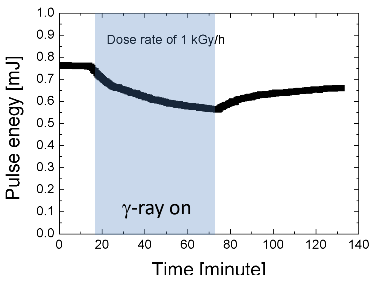


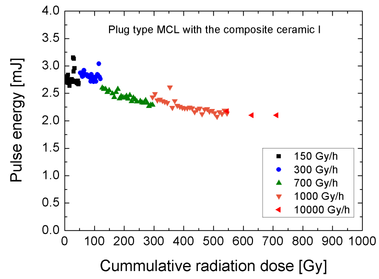
γ-ray effect to set-up

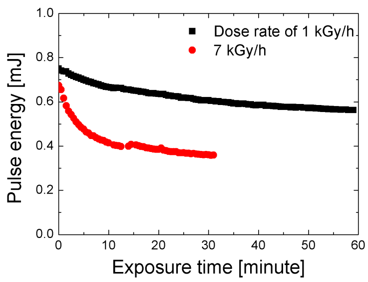
- ✓ Reflectance of HR mirrors
  → no effect
- ✓ Pyroelectric energy sensor and BNC cables
  → no effect
- ✓ Pump power through optical fiber and lenses
  → no effect
- ✓ Temperature of ceramics
  → no effect
- ✓ Transmittance of Cr:YAG at 1064 nm
  → no effect
- ✓ Transmittance of Nd:YAG at 808 (pump) and 1064 nm (laser)
  → reduction (808 > 1064 nm)



MCL performance under γ ray

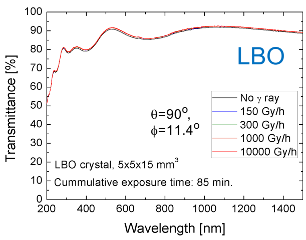


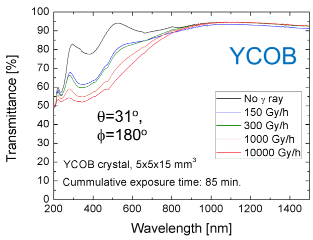


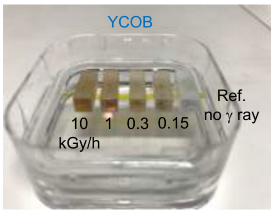


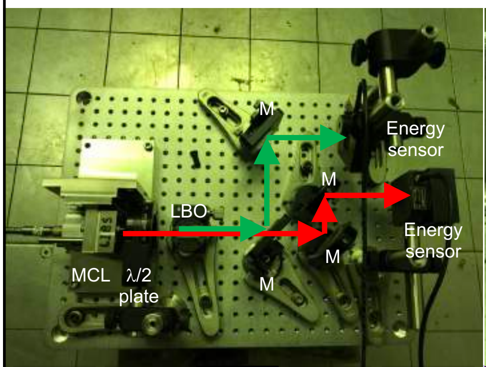
- Pulse energy and conversion efficiency decrease as cumulative radiation dose is increased.
- Operation was limited by the available pump energy.
- The degraded pulse energy is still enough for LIBS at >10 kGy/h.

SHG of MCL under γ ray

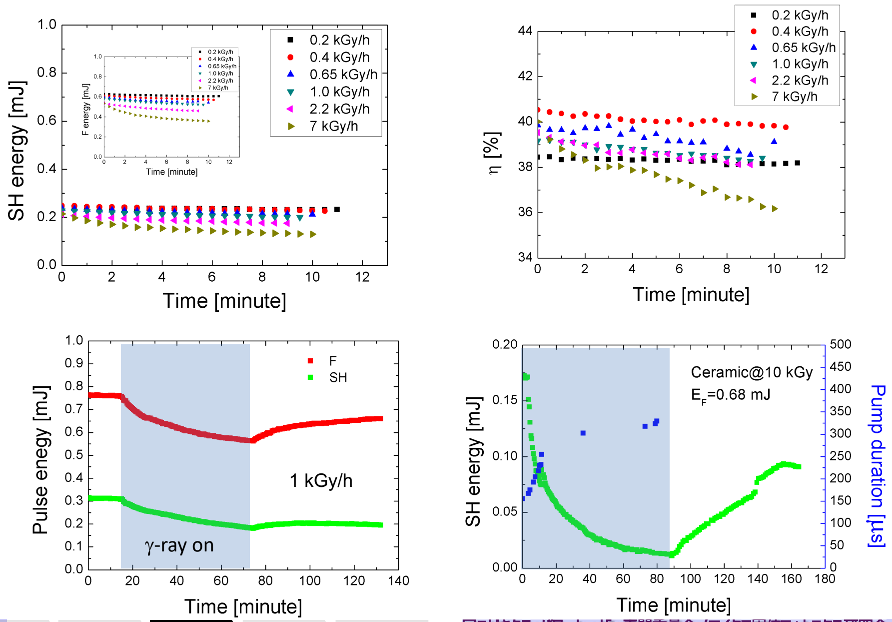








SHG of MCL under γ ray

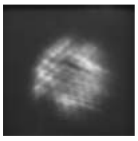


Issue: Brightness scaling-up of MCL

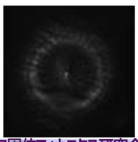
Goal: the higher brightness microchip laser

$$B \propto \frac{P_0}{(M^2)^2} = \frac{E}{\tau (M^2)^2}$$

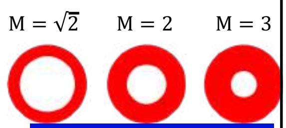
Current limit: beam quality degradation of larger laser modes having the higher energy because of poor beam pattern due to higher modes

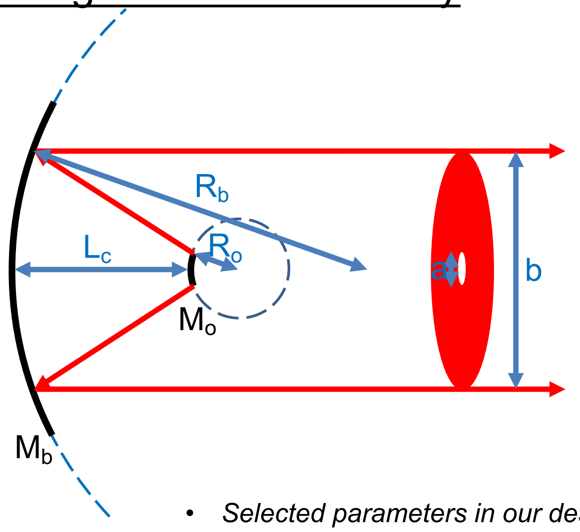


Solution: combination of microchip laser and unstable cavity having uniform beam pattern



Design of unstable cavity





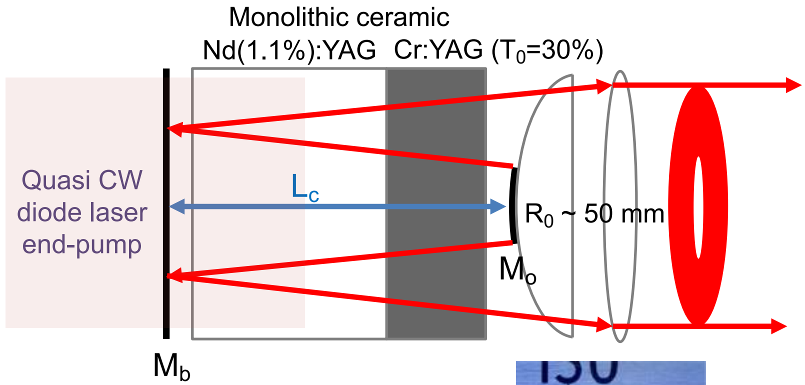
$$M = \frac{b}{a} = -\frac{R_b}{R_o}$$

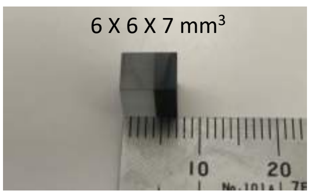
$$R_b = \frac{2\,M L_c}{M-1}$$

$$R_o = -\frac{2\,L_c}{M-1}$$

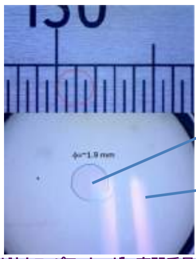
- *Selected parameters in our design*
  - *1)* $l_c = 10\,mm$ *for a sub-ns pulse width*
  - *2)* $M = \sqrt{2}$ *for a proper roundtrip loss of 50%*

Experiment 1 : MCL with unstable cavity





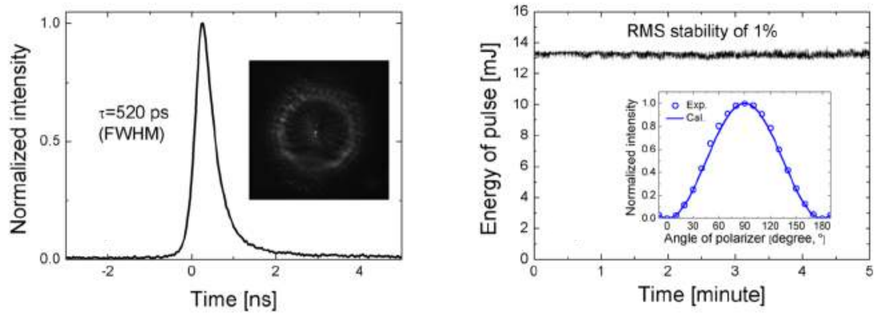
Konoshima Chemical Co., Ltd.



HR coating@1064nm
ϕ=~2 mm
AR coating@1064nm

Optoquest Co., Ltd.

Result 1: pulse and beam shape, pulse energy stability and polarization

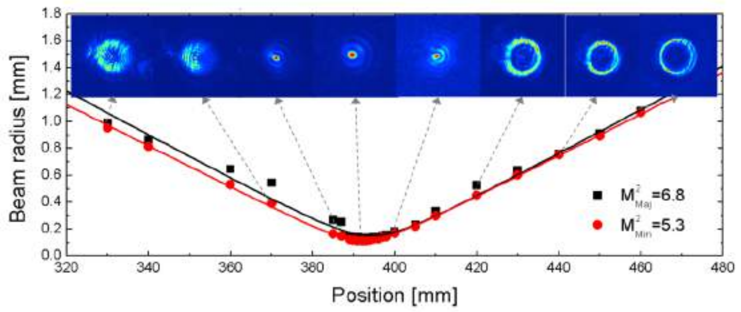


- Sub-ns pulse width of 520 ps
- Doughnut beam with Poisson spot

- 13.2 mJ with RMS stability of 1% at 10 Hz
- 25 MW peak power
- Linear polarization @ 10 Hz

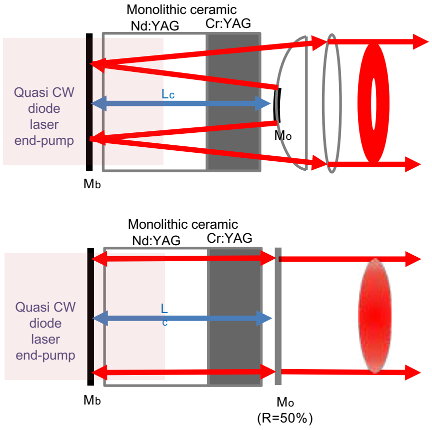
Result 1: beam quality M^2

Because the second moment-based beam width defines the M^2 factor mathematically, one can compare the M^2 values between different laser beams.
However, because the second moment-based beam width does not provide a constant value for the encircled power between different beam patterns such as Gaussian and flat top beam, and so on, the International Organization for Standardization allows for an alternative based on 86.5% power content beam width for practical usefulness. Therefore, we also estimated 86.5% power content based M^2 values M^2_{pc} for reference.



$$M^2\ (M^2_{pc}) \equiv \sqrt{M^2_{Maj} \times M^2_{Min}} = 6\ (5.8)$$

Experiment 2: unstable vs. stable cavity



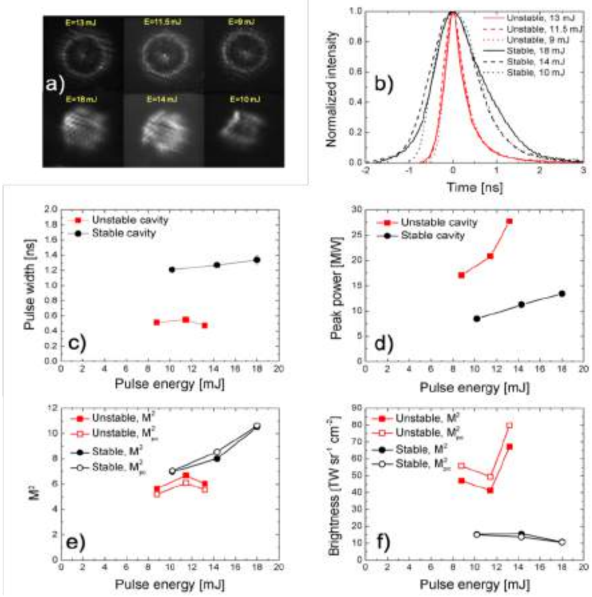
Compared characteristics for three different pump size:

- Pulse energy E
- Pulse width τ
- M^2

$$B \propto \frac{P_0}{(M^2)^2} = \frac{E}{\tau (M^2)^2}$$

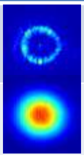
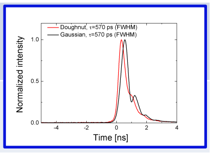
Only output cavity mirror was exchanged as keeping other conditions!

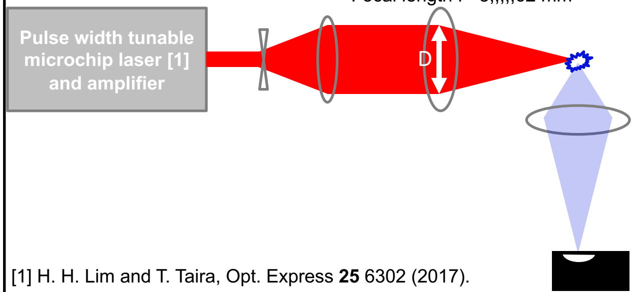
Result 2: unstable vs. stable cavity



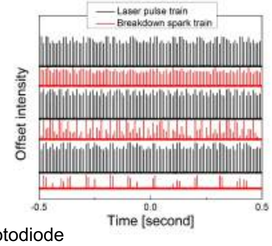
$$B = P_0/(\lambda M^2)^2$$

Experiment 3: doughnut vs. Gaussian for air breakdown capability

Mode	M^2	D (86.5%)		τ (FWHM)		λ
Doughnut	**6**	7.5 mm		570 ps		1064 nm
Gaussian [1]	**1.3**	7.5 mm		570 ps		1064 nm

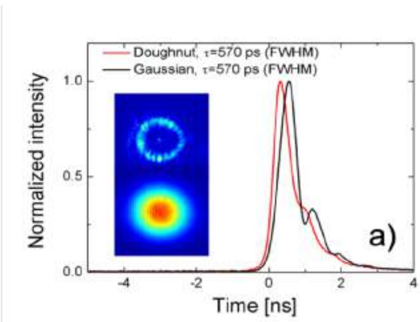


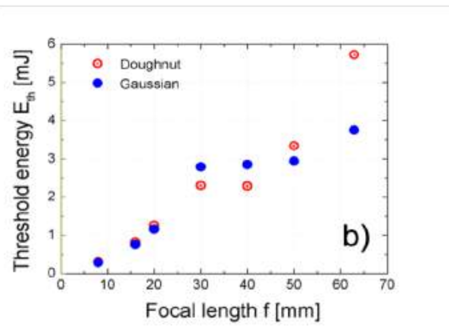
Threshold energy [1]: the minimum energy for 100% breakdown success



[1] H. H. Lim and T. Taira, Opt. Express **25** 6302 (2017).

Result 3: doughnut vs. Gaussian for air-breakdown capability





$$Doughnut(M^2 = 6) \approx Gaussian\ (M^2 = 1.3)$$

The ratio between focal beam waist of doughnut (w_d) and Gaussian (w_G) beam

$$\frac{w_G}{w_d} = \frac{M_G^2}{M_d^2} = \frac{1.3}{6} \approx 0.2$$

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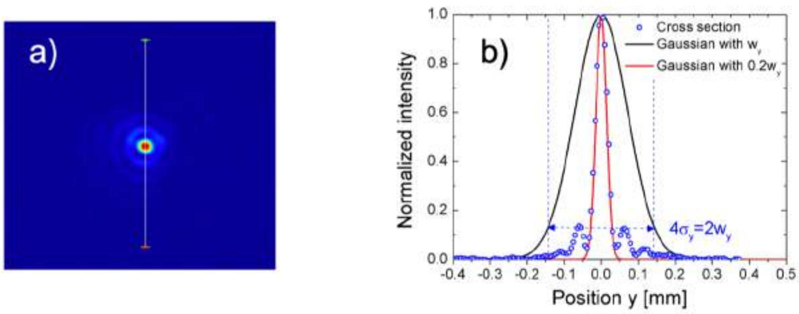

The effective 0.2 times smaller beam size makes the doughnut beam (M^2=6) to be comparable to the Gaussian beam (M^2=1.3) for air-breakdown

Summary

I. Confirmation of τ-scaling law of laser-induced plasma breakdown threshold in air for the first time.

II. Confirmation of SHG under a high dose-rate irradiation (~10 kGy/h) for the first time.

III. Demonstration of a high brightness (the highest peak power and a moderate M^2) MCL with unstable cavity.